
From: Frank Sciortino <frankscio@yahoo.com>
Sent: Tuesday, October 10, 2023 1:20:56 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Statement for Public Scoping Meeting on 10/11/2023

I wish to submit the attached written comments regarding what my wife and I would like to see addressed in the DEIS for the Micron project and I would also like to pre-register to make a public statement at the Public Scoping Meeting to be held at10/11/2023 at 6:30 pm at the North Syracuse Jr. High.

Thank you,

Frank and Elaine Sciortino
8853 Van Hoesen Road
Clay, NY 13041
(315) 447-8095
frankscio@yahoo.com

October 10, 2023

Statement For Public Scoping Meeting

My name is Frank Sciortino, and I live at 8853 Van Hoesen Road in the Town of Clay with my wife Elaine. Elaine and I are not opposed to the project; however, we do face the potential for significant impact to the character of our neighborhood and the value of our property if the Micron project is approved. We live on the corner of Verplank Road and Van Hoesen Road and the potential impacts we face are "traffic" related and directly associated with the plans for improvements to local roads; namely, Caughdenoy Road, Mudmill Road, Verplank Road and Van Hoesen Road. The "Impact on Traffic" paragraph in the Notice of Intent to Prepare a DEIS" dated September 14, 2023 identifies several areas of concern:

- Construction and operation of the proposed Micron Project is expected to generate a substantial number of new vehicular trips on the local and regional highway network including local roads, I81 and NYS Route 481,
- Approximately 12,000 parking spaces are proposed,
- There are approximately 10-30 commercial trucks/peak hour anticipated during operation of the proposed facility,
- Additional vehicles are anticipated for construction over the approximately 20 year buildout, and
- Modification of existing roads is anticipated.

We request that the EIS address and provide specific details for the proposed improvements to the local roads named above. Details regarding the size (number of lanes), speed limits, expected volume of traffic and expected changes to the surrounding neighborhoods along with a specific timetable for the proposed improvements must be provided in order to honestly assess the potential impacts and give the surrounding residents adequate notice of the changes they face. Anything less will be deemed unacceptable and a failure to address one of the most significant impacts associated with the project.

A second topic that my wife and I would like to see addressed is the proposed project's impact on property taxes in the Town of Clay. I understand that determining the precise impact at this stage of the project would be difficult; however, for future accountability, we would like to see a discussion of the anticipated impacts on property taxes with a general conclusion that states the proposed project is likely to 1) cause an increase in property taxes 2) cause a decrease in property taxes, or 3) have no impact on property taxes.

Thank you for the opportunity to have input in the preparation of the DEIS for the Micron project.

Frank and Elaine Sciortino
8853 Van Hoesen Road
Clay, NY 13041

From: Debra DeSocio <debradesocio@gmail.com>
Sent: Thursday, October 12, 2023 1:43:38 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Written statement

To: OCIDA I am providing my written statement for my oral statement provided on 10/11/23.
Onondaga County Industrial Development Agency
ATTN: Micron Project
335 Montgomery Street, 2nd floor
Syracuse NY 13202
email: micron@ongov.net

Semiconductors have a carbon problem. The public should be informed about the plan to prevent fluorocarbons from being introduced to our local air. Harvard University research states the semiconductors industry contributes to 31% of greenhouse gases.
It is imperative to reduce emissions through clean energy usage initiatives and energy conservation projects. The benefits will make the semiconductor industry more sustainable. This must take place and the public should be informed.

Debra A. DeSocio
Fayetteville NY
debradesocio@gmail.com

Central and Northern NY Sierra Club
member of conservation committee

From: Steve Erwin <serwin@clintonsditch.com>
Sent: Thursday, October 19, 2023 6:23:45 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Micron Environmental Impact Statement

Thank you for taking the time to review my comments and information.

Stephen Erwin

Central Region Vice-Chairman

Trucking Association of New York

Transportation Manager

Clinton's Ditch Coop Co Inc.

8478 Pardee Rd.

Cicero, NY 13039

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315-699-8603

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NEW YORK STATE PEPSI COLA BOTTLER

CLINTON'S DITCH
COOPERATIVE COMPANY, INC.

Transportation Department
8478 Pardee Road, Cicero, New York 13039
Phone 315-699-8603 Fax 315-698-2334

October 19, 2023

Onondaga County Industrial Development Agency
Attn: Micron Project
335 Montgomery Street, 2nd floor.
Syracuse, New York 13202

I am writing in response to your request for comments for your Draft Scoping Document in preparation for the EIS for the proposed Micron project. I realize that more than likely, you will rely heavily on the DOT for information for this document. While the Micron project itself may not have a negative impact on our industry, the additional vehicle traffic will. Put that increased vehicular traffic on a poorly designed interstate, and the results will be disastrous for our industry. Please do not interpret this letter as a negative on Micron. Nothing could be farther from the truth. I am submitting this because the DOT did not consider the impact of Micron in their DEIS. In fact, the DOT did not consider our industry and the impact the grid will have on it in their decision-making process. It is imperative that Micron be considered in the EIS for I-81. Once the viaduct comes down, there is no going back, so it must be done right the first time. Therefore, it is imperative you look at the errors and omissions by the DOT in their DEIS and take those into consideration when considering the EIS for Micron. If I-81 is done right, Micron will have negligible effect. However, if done wrong, it will have a major effect. I am hoping that you will take the time to look at the information I am providing, as well as the documents I have attached.

The DOT unfortunately completely ignored the trucking industry, mostly because it did not fit their narrative. There were, and still are, major flaws in their DEIS, which were brought out in a study conducted by an independent consulting & engineering firm from Minnesota, who was hired by the Trucking Association of New York (TANY). I have attached a copy of that study, which was provided to the DOT in 2021. TANY was especially disappointed in the fact that the DOT almost totally excluded commercial trucks and commerce in the study conducted for the DEIS. Since day one, the DOT has always talked about the impact on vehicles traveling north or south. They never talk about traffic going west from the south or the north. The fact is, there are over 25 major companies located west of I-81. While some of these are trucking companies, most are companies that rely on the trucking industry to conduct their business. These are major corporations employing hundreds of people. Likewise, the major fuel supply depot is located west of I-81 as well. This affects 3 major fuel haulers, as well as the end users. The DOT never speaks about any of these companies, as again, it does not fit their narrative.

The fact is, the Community Grid option has an extremely negative impact on not only the trucking industry, but Interstate Commerce as well. All of which has been ignored by the DOT to get to their pre-determined result. They never really cared what our industry had to say. My hope is that you will at least take the time to look at this information and attached reports to make an educated determination as to the extremely negative impact a Community Grid will have not only on our industry, but the Central NY economy as well.

The unfortunate truth is that the DOT has gotten numerous highway projects wrong repeatedly. Unfortunately, our industry lives with their mistakes every day. There are at least 6 major highway design deficiencies located right here in Central NY. So, forgive us if we do not take the DOT seriously when they say their engineers are experts. Their engineers are like everyone else, they have opinions. Unfortunately, opinion-based findings do not make for good solutions. They typically only lead to bigger problems than the ones trying to be solved.

I am listing some of the major flaws in the DOT DEIS. These are all **<u>facts</u>**, not opinions.

1) It will result in additional miles, emissions and other externalities associated with freight movement such as:
    1.76 million impacted truck trips.
    19.8 million additional truck miles traveled.
    3.04 million gallons of diesel fuel.
    Approximately $32 million in trucking costs.
    $500,000 in monetized emission externalities from 20.5 million additional tons of hydrocarbon, NOx, and fine particulate matter.

2) Their analysis completely ignores commercial vehicle traffic demands, including the Syracuse Metropolitan Planning Council's own freight profile.

3) Their analysis ignores the social, economic, and environmental impacts because their study was within 1-mile of the viaduct, thereby eliminating the effects on those areas located more than 1 mile from the viaduct. The American Transportation Research Institute (ATRI) GPS dataset in fact shows that less than 3%of trucks stop in this area. This grossly underestimates the effects of the grid on the trucking industry and in fact, will impose a significant impact on our industry. In fact, their analysis mostly excludes the interstate trucking industry sector. Freight and trucking industry reps were not consulted in this decision process.

4) FHWA, NYSDOT and SMTC ignored USDOT guidance on engaging the private sector in the planning process. Freight and freight movement is not specifically included in any of the I-81 DEIS project purpose.

5) The I-81 DEIS completely ignores safety issues like truck parking, which is currently one of the top 3 problems facing our industry today. It completely removes the only full-service truck stop with truck parking from I-81 by routing trucks around the city.

The DOT has and continues to push the narrative that the relocation of I-81 to I-481 will only have a minimal impact on the trucking industry because it is only a few miles more to go around and only takes an extra minute or two. While there may be a small amount of truth to that statement, it only applies to trucks going north and south, but still does not consider the impact of losing the only full-service truck stop. In fact, it was the DOT that closed the only rest area on the southbound side of I-81 (Central Square), between Watertown and Cortland. The reality is the trucking companies and businesses to the west are severely impacted by the grid, and nowhere does the DOT mention or even attempt to mention or address this issue.

At a time when there is a massive state, federal and social push for all of us to become environmentally greener, how in the world can anyone justify the additional miles, fuel and emissions that will be created by the grid? Something that is being totally ignored by the DOT. Trucking companies have worked long and hard to become more environmentally friendly, and it has come at a significant cost to our industry. The grid will only add to that cost, which unfortunately, is going to end up getting passed down to the consumer. Drivers' hours of service are another huge issue facing our industry. Our industry is already facing a massive shortage of drivers. Causing drivers to drive longer will hurt our operations even more. All these issues are not only going to affect our industry, but the consumer as well. The DOT completely ignored these impacts. Again, we can only assume because they would raise more questions about the validity of the grid.

CLINTON'S DITCH
COOPERATIVE COMPANY, INC.

Transportation Department
8478 Pardee Road, Cicero, New York 13039
Phone 315-699-8603   Fax 315-698-2334

Thank you for taking the time to review the materials I have presented and the information I have given. I have been in this industry for over 45 years and have seen a lot of changes. I can tell you this one will have an effect like we have never seen before. We just need to make sure we take an honest look at everything before we make this decision. The wrong decision will have major irreversible consequences for not only the trucking industry, but also our community and economy as well. Never has a decision like this had the potential to affect the number of people and businesses as this one does.

Sincerely,

Stephen D. Erwin

Stephen D. Erwin
Transportation Manager
Clinton's Ditch Cooperative Co Inc
Cicero, NY

Central Region Vice-Chairman
Trucking Association of New York

NEW YORK STATE PEPSI COLA BOTTLER

SmartWay
Transport Partner
Getting There With Cleaner Air

TANY TRUCKING ASSOCIATION OF NEW YORK

Kendra Hems
President

7 Corporate Drive
Clifton Park, NY 12065
P 518.458.9696
nytrucks.org

October 14, 2021

Mark Frechette, P.E.
Project Director
New York State Department of Transportation,
Region 3
333 East Washington Street
Syracuse, NY 13202

Rick Marquis
Division Administrator
Federal Highway Administration
Leo W. O'Brien Federal Building
11A Clinton Avenue, Suite 719
Albany, NY 12207

RE: I-81Viaduct Project - Draft Environmental Impact Statement and Draft Section 4(f) Evaluation

Gentlemen:

The Trucking Association of New York (TANY) respectfully submits the following comments, as prepared by Quetica Consulting in response to the Draft Environmental Impact Statement (DEIS) and Draft Section 4(f) Evaluation for the I-81 Viaduct Project.

TANY has significant concerns about the preferred alternative for replacing the I-81 Viaduct through downtown Syracuse. Federal Regulations Title 23, Chapter 1, Part 658.11 requires that any request for deletion of an interstate highway ***must analyze the impact on interstate commerce.*** Upon review of the DEIS it is clear that a complete analysis on the impacts of this project on freight activity has not been conducted. Moving forward with the preferred alternative absent the required analysis would be irresponsible and has significant economic, environmental and safety implications that have not been considered.

TANY appreciates the opportunity to comment on the DEIS. Before moving forward with the preferred alternative of the Community Grid, TANY requests that a comprehensive review of the movement, routing and cost of freight/interstate commerce be evaluated.

Sincerely,

Kendra Hems

Kendra L. Hems

Commerce and Commercial Vehicle Analysis of the I-81 Draft Environmental Impact Statement for the Trucking Association of New York

By Quetica, LLC

OCTOBER 2021

Point of Contact: Mark Berndt, Lead Consultant Quetica, LLC

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Executive Summary

The trucking industry is critical to the economic success of not only our nation and the State of New York but to the City of Syracuse and surrounding region as well. For that reason, the Trucking Association of New York (TANY) is deeply concerned about the preferred alternative for replacing the I-81 Viaduct through downtown Syracuse as presented in the ***Interstate 81 Viaduct Project – Draft Environmental Impact Statement (DEIS)***. On behalf of our 580 members, TANY is especially disappointed in the near total exclusion of commercial trucking interests and commerce in the analysis conducted for the DEIS. With the short timeline provided to respond to the nearly 3,000 page I-81 Viaduct DEIS that resulted in the recommendation for the Community Grid Alternative, TANY would like to go on record with the analysis presented in the attached report. TANY is also submitting the following comments related to our concerns about the entirety of the I-81 Viaduct study process and the DEIS Community Grid Alternative:

> **The Community Grid Alternative will negatively impact the competitiveness of the nation and the Syracuse Region:** Our impact analysis using the latest Freight Analysis Framework (FAF-5) data from U.S. Department of Transportation (USDOT), suggests that the majority (83 percent by volume) of the commerce on I-81 moving into, out of or through Syracuse supports domestic trade. In addition, 2.92 million tons of foreign trade valued at $8 billion moves across the Syracuse section of I-81 going to and from Canada.
>
> One of the primary motivations for creating the Interstate Highway System was to facilitate interstate commerce. Recently, in an interview with Bloomberg TV, USDOT Secretary Buttigieg reiterated the need to invest to be competitive:
>
> > *"People everywhere are very much mindful of how America has fallen behind and how America would be better off if we invested in our roads and bridges and our ports and airports… We're dealing with the consequences of about 40 years of disinvestment in the infrastructure that we count on to stay competitive."*
>
> The Syracuse Metropolitan Planning Council (SMTC) Freight Profile published in July 2017 notes: "*…the freight industry plays an integral role for our country and our region… Interstate 81 is the primary facility through this area with international connections with Canada to the north."* However, the I-81 DEIS fails to provide anything close to a thorough analysis of the impact on freight movements resulting from the Community Grid Alternative. In addition, the Community Grid Alternative proposes to delete the viaduct section of I-81 through Syracuse. Federal Regulations Title 23, Chapter 1, Part 658.11 states that any request for deletion must analyze the impact on interstate commerce.

The Community Grid Alternative will result in additional truck miles, more truck emissions and more negative externalities associated with freight movements on an annual basis, including:

- 1.76 million impacted truck trips
- 19.8 million additional truck miles traveled
- 3.04 million gallons of diesel fuel
- $32 million in trucking costs
- $500 thousand in monetized emission externalities from 20.5 million additional tons of hydrocarbons, NO_X and fine particulate matter

These numbers correspond to three separate trip types: (1) Those utilizing the I-81 Corridor to traverse through the Syracuse region from south to north or north to south; (2) those utilizing the corridor to traverse the Syracuse region from west to south or south to west; and (3) those originating or terminating to the north and west of the I-81/I-690 interchange and travel along I-81 to the south of Syracuse. Results are based on a 15-day sample of GPS data from the American Transportation Research Institute (ATRI), average annual daily truck traffic (AADTT) estimates from New York State Department of Transportation (NYSDOT) traffic count stations, stakeholder feedback as to rerouting impacts, ATRI's analysis of operational trucking costs, emission rates from the U.S. Environmental Protection Agency, and benefit-cost analysis guidance from the U.S. Department of Transportation. The trucking costs estimate underscores the impact as it does not include the New York State Highway Use Tax.

Underlying analysis tools completely ignore commercial vehicle traffic demands: The I-81 Challenge Website also provides numerous background reports including the travel demand model developed for SMTC. Our review of the SMTC Travel Demand Model documentation found **no mention of trucks or commercial vehicles**! While the model discusses non-motorized trips extensively, the model appears to completely ignore trips by large trucks. This same blind eye towards commercial interests is carried over to the DEIS.

Chapter 6 of the DEIS: *Social, Economic and Environmental Considerations* narrowly defines impacts on the regional economy to the retail sector.

- The Local and Regional Economies Analysis focused on (1) locations within the region where shippers and carriers would be marginally impacted or not impacted by the Viaduct Project and (2) locations which are adjacent to or in close proximity to the Viaduct Project Priority Area as outlined in the NYSDOT Scoping Report. In fact, less than 3 percent of the stops in the ATRI GPS dataset were located within a 1-mile buffer of the Viaduct Project Priority Area. Furthermore, the analysis ignored the impacts to the shippers and carriers located to the west of I-81 and north of I-690 which account for half of the stops in the ATRI GPS dataset.

- Tools and methods employed to assess the impacts and traffic operations did not consider the impacts on trucking companies or trucking dependent industries in the Syracuse area. Based on our data analysis and interviews with trucking firms operating in the Syracuse region, there are 17 trucking companies located west of the I-81/I-481 interchange that operate approximately 400 trucks on a daily basis in and through Syracuse. Also, half of the stops in the ATRI GPS dataset were located in these areas (see **Exhibit 8**). It is estimated that for trucks having to reroute via I-481 and/or I-690 to get to I-81, the additional mileage added to a one-way trip is approximately 14-18 miles longer than the current route (up to 36 miles round trip). In 2019, results from an annual industry survey by ATRI found that the average cost per mile of operating a truck in the Northeast Region of the U.S. was $1.844. Resulting in added costs of approximately $66.38 for each round trip per truck. **As a result, the Community Grid Alternative will impose a significant tax on the trucking industry.**
- The data source used for the Local and Regional Economies Analysis relied on StreetLight GPS data. All GPS data products are samples of the total vehicle/trip population. StreetLight's GPS truck trip data comes from location-based services (LBS) found on cell phone apps. The Federal Motor Carrier Safety Administration (FMCSA) restricts the use of all hand-held mobile devices by commercial motor vehicle drivers:[1]
    - *Using a hand-held mobile phone while driving a CMV can result in driver disqualification. Penalties can be up to $2,750 for drivers and up to $11,000 for employers who allow or require drivers to use a hand-held communications device while driving.*
    - Disqualification - Multiple violations of the prohibition of using a hand-held mobile phone while driving a CMV can result in a driver disqualification by FMCSA. Multiple violations of State laws prohibiting use of a mobile phone while driving a CMV is a serious traffic violation that could result in a disqualification by a State of drivers required to have a Commercial Driver's License.
- Short-haul delivery drivers and package or parcel delivery services in or near major metropolitan areas are more likely to use cell phones due to the stop and start nature of their trip legs. Most long-haul carriers employ satellite communication devices in the cab of the truck, with many banning the use of cell phones while drivers are on the road. The analysis conducted by TANY uses GPS data sourced by ATRI. The ATRI truck GPS data sample comes from carriers who employ satellite tracking devices on their power units, which is an industry standard for most large interstate carriers. **As a result, the Local and Regional Economies analysis conducted for the I-81 DEIS Community Grid Alternative**

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[1] https://www.fmcsa.dot.gov/driver-safety/distracted-driving/mobile-phone-restrictions-fact-sheet

suffers from an inherent data bias that mostly excludes the interstate trucking sector.

The Federal Highway Administration (FHWA), NYSDOT and SMTC ignored USDOT guidance on engaging the private sector in the planning process: The NYSDOT I-81 Viaduct Project Website discusses the Corridor Study Report and refers readers to the I-81 Challenge website. That website discusses a public involvement process designed to be as "inclusive as possible" yet commercial interests, especially the trucking industry appear to have largely been ignored and overlooked in the final evaluation process. For example, early in the study process focus groups were used to identify key study activities and metrics going forward, when asked:

- *What other community stakeholders should be engaged in the I-81 study process?* **Trucking companies** is prominently listed, however there is no indication that the study made any effort to explicitly include the trucking companies in its follow-up engagement efforts.
- *What impacts should be evaluated*? **Freight Businesses** (e.g., mileage and travel time) is listed third, however the final DEIS does not adequately assess the overarching impacts to the freight industry, including trucking costs associated with additional travel times, truck parking and services such as the impacts to the Pilot Travel Center.

Furthermore, detailed discussions with freight industry reps, who could enlighten the evaluation team as to the direct and indirect impacts to the industry were inadequate in that a clear understanding as to the fiscal and functional impacts to this mobile industry **WAS NOT** evaluated. The following excerpts are from the ***July 2021 EXECUTIVE SUMMARY*** *(*PIN 3501.60 S-1) ***S.2 PROJECT PURPOSE, NEEDS, GOALS, AND OBJECTIVES***. Review of these key framework components of the study reveal little consideration for freight related impacts and affects:

- *The need to improve traffic flow and safety*
- *The need to address aging infrastructure*
- *The need for transportation infrastructure to support long-range planning efforts*
- *The need to improve pedestrian and bicycle infrastructure*
- *The need for improved transit amenities*
- *Improve safety and create an efficient regional and local transportation system within and through greater Syracuse*
- *Provide transportation solutions that enhance the livability, visual quality, sustainability, and economic vitality of greater Syracuse*

While the aforementioned purpose, needs, goals and objectives are consistent with sound project evaluation, it is important to note that **FREIGHT is not specifically included** in any of the I-81 DEIS project purpose, needs, goals or objectives. Given the level of freight volumes and the importance of both regional and long-distance freight activity, including international trade, addressing freight impacts specifically is an **oversight and shortcoming** of the DEIS.

The I-81 DEIS Completely ignores safety issues like truck parking: Jason Rivenburg lived in Fultonham NY, about two hours east of Syracuse. Jason was killed in 2009, while sleeping in the cab of his truck at an abandoned gas station in South Carolina. Jason was early for a scheduled delivery to a facility that did not allow loads on-site more than an hour ahead of a scheduled drop time and had nowhere else to park. Following Jason's death, his widow, Hope Rivenburg worked to pass Jason's Law establishing truck parking safety and security as a national priority. Jason's Law was introduced in the U.S. House of Representatives by Congressman Paul Tonko, and in the Senate by Senators Charles Schumer and Kirsten Gillibrand. The law requires the USDOT and states to regularly evaluate the provision of safe truck parking.

Jason's death and tireless efforts of his widow Hope sparked a national response. TANY finds it unconscionable that despite years of study by SMTC and NYSDOT into the impacts of removing a segment of the Interstate Highway System in a metropolitan area, that no effort has been made to examine the issue of truck parking in the Syracuse Area. Currently, the only commercial truck stop in the area is the Pilot Travel Center located in Liverpool, north of downtown Syracuse just off the I-81 on Seventh Street North. It is anticipated and shown through our analysis that the Community Grid Alternative will add drive time for truck drivers making pick-ups or deliveries to the Syracuse downtown areas or area west of downtown. Interstate truck drivers are regulated by federal hours of service limits. The additional time required for making deliveries, staging for delivery windows in a less reliable drive time environment will increase the demand for truck parking in Syracuse under the Community Grid Alternative.

Project Overview

If you bought it, a truck brought it is more than just a catchy phrase: The U.S. economy runs on trucks; the trucking industry moves over 80 percent of the nation's goods by value, over 72 percent by weight. [2] In the State of New York, the trucking industry employs nearly 300,000 people – one in every 28 jobs in the state. There are 46,000 trucking companies in New York, mostly small locally owned businesses. In 2019, the New York trucking industry paid over $16.7 billion in wages, and approximately $1.3 billion in state and federal roadway taxes.[3]

The trucking industry is critical to the economic success of not only our nation and the State of New York but to the City of Syracuse as well. For that reason, TANY is deeply concerned about the preferred alternative for replacing the I-81 Viaduct through downtown Syracuse as presented in the I-81 Draft Environmental Impact Assessment (DEIS).

The purpose of this evaluation is to present a detailed review of the truck- based freight related activity levels and goods movement information as to origins, destinations, freight types and travel characteristics in the Syracuse Region. Specifically, this evaluation represents an official review and comment on the ***Interstate 81 Viaduct Project – Draft Environmental Impact Statement (DEIS)*** report prepared by the New York State Department of Transportation (NYSDOT).

The Syracuse region is an important freight related area with regional, statewide, and international origins/destinations. The use of Interstate 81 (I-81) through the central business district by freight trucks, both long distance and regional deliveries is evident by the level of truck traffic levels. The I-81 corridor is a major north-south corridor carrying passengers and commerce between the US/Canadian border with Maritime Provinces down the east coast along the Appalachian Mountains to Dandridge Tennessee.

The purpose of this evaluation is to present specific freight related impacts related to the proposed I-81 viaduct decommissioning through Downtown Syracuse, as documented in the I-81 DEIS.

The evaluation sought to answer the following key evaluation questions:

1. ***What is the estimated share of truck trips using I-81 to access impacted businesses in the Syracuse region?*** The share of truck trips using I-81 to either originate a freight trip or arrive at a destination for deliveries is an important component of the overall freight truck levels. However, not all areas within the Syracuse region will be impacted equally by the I-81 Viaduct Project.
2. ***What percentage of truck trips utilizing the I-81 Corridor are the result of accessing parcels in close proximity to the I-81 Viaduct Project Priority Area?*** These local or

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[2] American Trucking Associations, online industry data: https://www.trucking.org/

[3] New York Trucking Fast Facts at: https://nytrucks.org/

downtown and central business district related origins/destinations using I-81 have been the focus of previous analysis. Downtown interchanges and alternate routes will be required for these businesses to service their clients.

3. ***What is the estimated impact to local businesses using the I-81 Corridor in terms of additional mileage and fuel consumption on an annual basis?*** Rerouting deliveries and freight movements for businesses in the region will increase their number of truck miles traveled and costs to do so. It will also increase their consumption of diesel fuel and associated emissions.
4. ***What is the estimated impact to through traffic using the I-81 Corridor in terms of additional mileage and fuel consumption on an annual basis?*** Just like the impacts on local businesses, what will be the monetary impact to freight moving through the region?

Commodity Profile of Syracuse and Onondaga County, New York

To better understand the flow of commerce through the I-81 corridor, the analysis begins with an examination of USDOT Freight Analysis Framework-5 (FAF-5) commodity flow data. FAF-5 is produced by the FHWA and is derived from the Commodity Flow Survey (CFS) conducted every five years by the Census Bureau and Bureau of Transportation Statistics. The 43 commodities represented in FAF are categorized using the Standard Classification of Transported Goods (SCTG) at the two-digit level.

A weakness of FAF data is its lack of geographic detail. To address this weakness a linear regression approach was used to assign 43 commodity groups to the county-level, and specifically examine the goods moving into, out of and within Onondaga County. The FAF disaggregation process uses employment with other public data exhibiting strong correlations to either production or attraction functions for specific commodity groups. A goal of this analysis is to understand the importance of the I-81 corridor in moving goods in and out of the Syracuse region, and what products are most important from a transportation standpoint to the region.

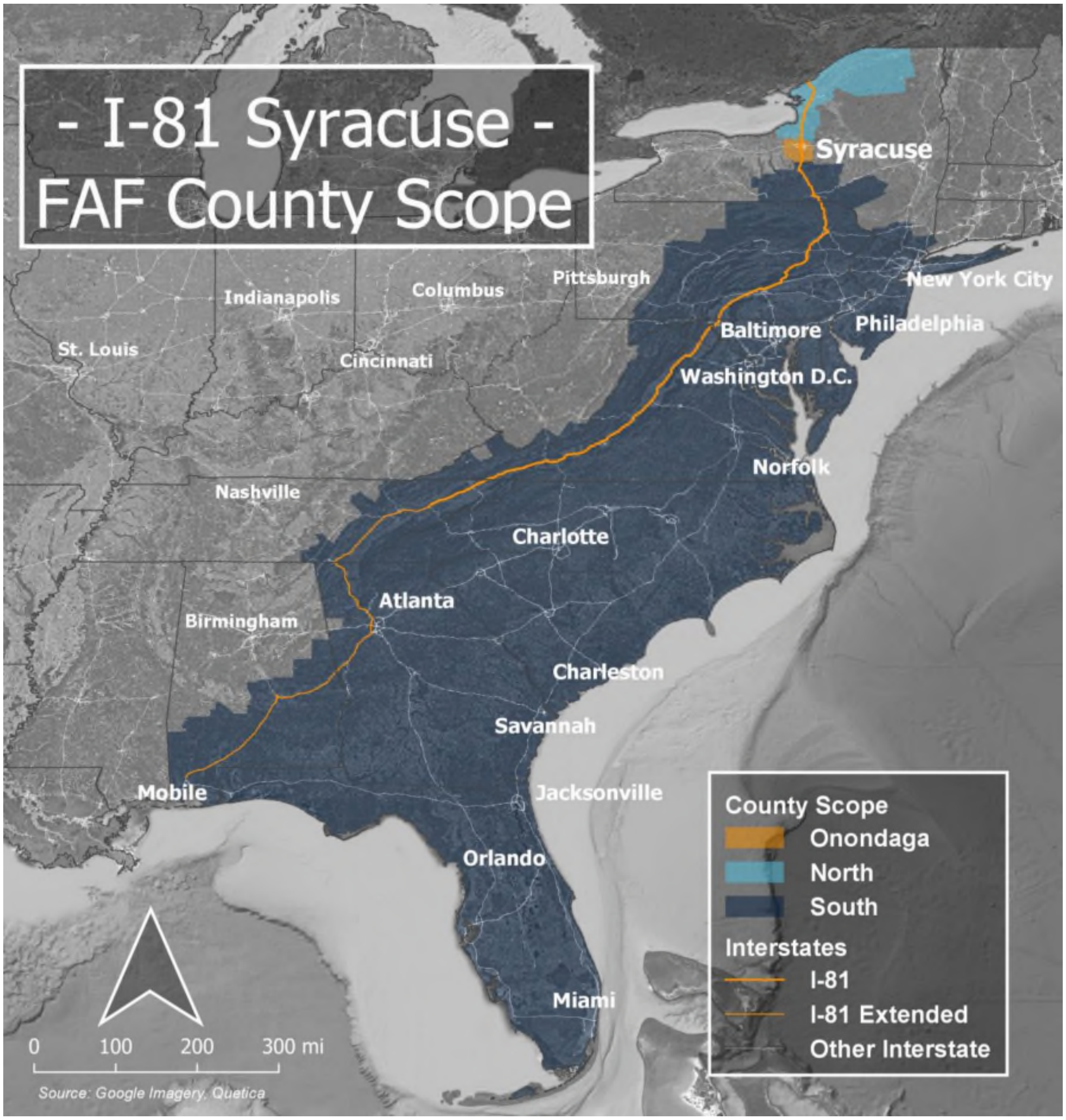
The scope of the freight flow analysis is depicted in **Exhibit 1**, and includes the following flow types:

1. Those originating and terminating in Onondaga County
2. Those originating in Onondaga County and terminating in a southern county
3. Those originating in Onondaga County and terminating in a northern county
4. Those originating in a southern county and terminating in a northern county
5. Those originating in a northern county and terminating in a southern county

The total estimated annual flow of freight utilizing the I-81 Corridor in and through Syracuse is 17.3 million tons of goods, with an estimated value exceeding $24.5 billion.

The majority (83 percent by volume) of the commerce on I-81 moving into, out of or through Syracuse supports domestic trade. Of the foreign trade using the I-81 corridor in Syracuse, imports (1.72 million tons) slightly outweigh exports to (1.2 million tons). Imports were valued at $4.2 billion and exports at $3.8 billion.

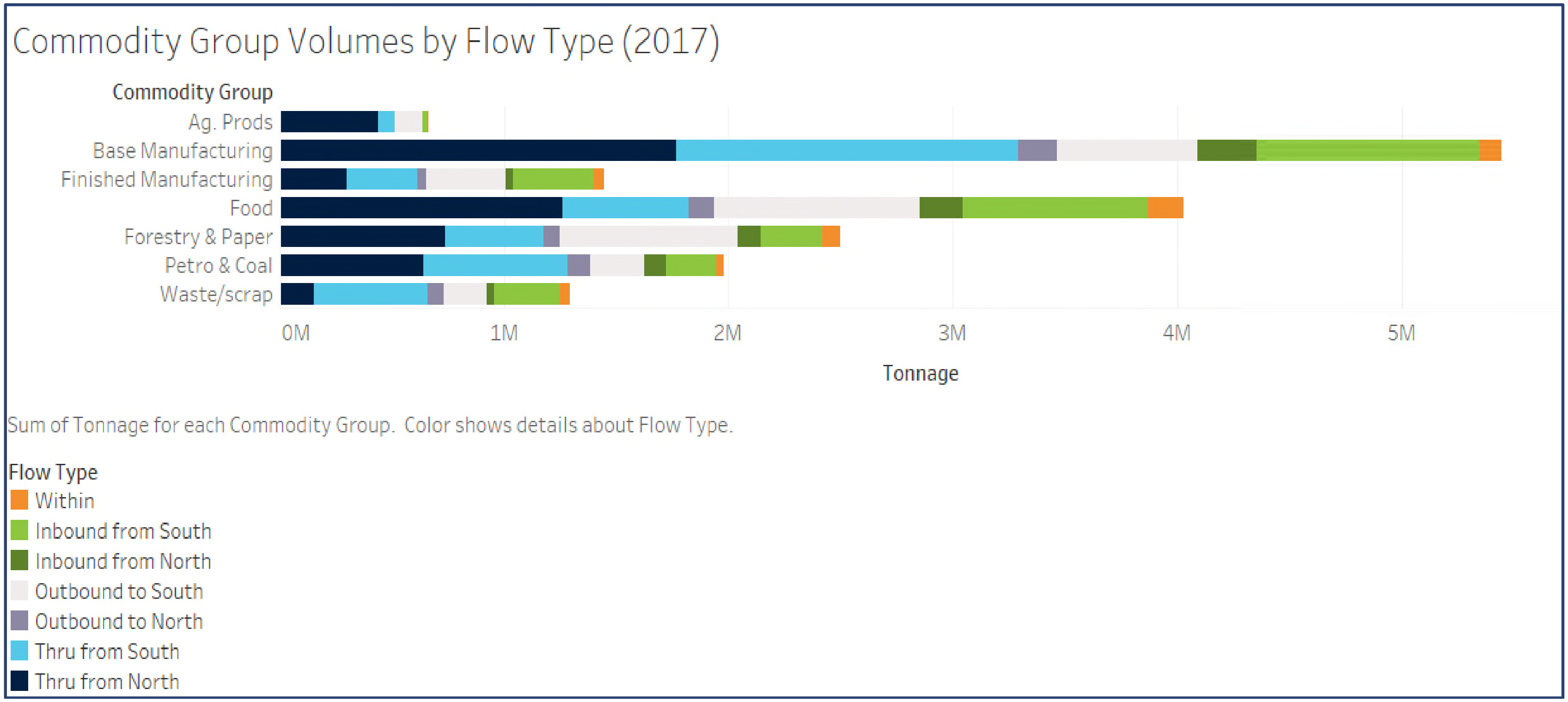
Exhibit 1 Freight Flow Scope



Source: Google Imagery, Quetica

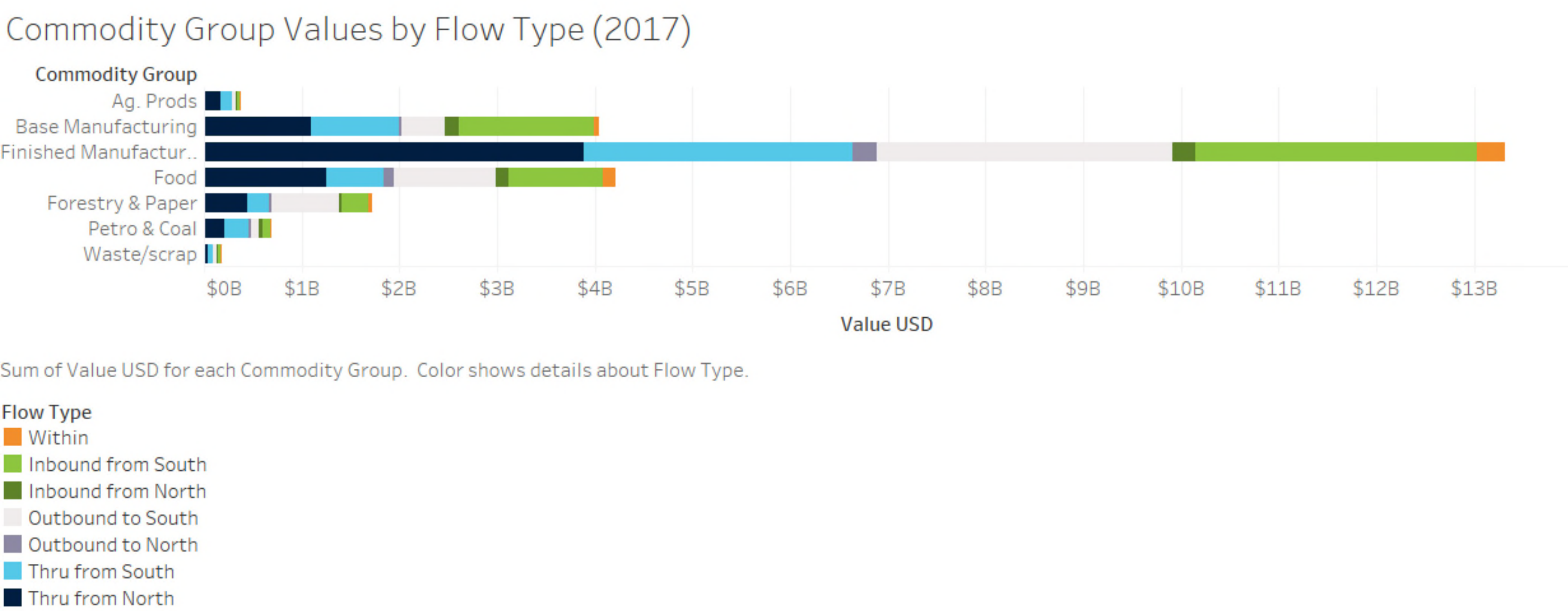
Commodities related to base manufacturing accounted for the largest share of corridor flows by volume with nearly 5.5 million tons (**Exhibit 2**). Just under 3.3 million tons was associated with through traffic. Food products totaled roughly 4 million tons. Forestry and paper products totaled almost 2.5 million tons while petroleum and coal products totaled nearly 1.98 million tons.

Exhibit 2 Corridor Flow Volumes by Commodity Group (2017)



In terms of commodity group flows by value, finished manufactured products account for roughly 54 percent of all corridor flow value worth $13.3 billion (**Exhibit 3**). Food products (17 percent) and base manufactured products (16 percent) represented the second and third most valued group of commodities.

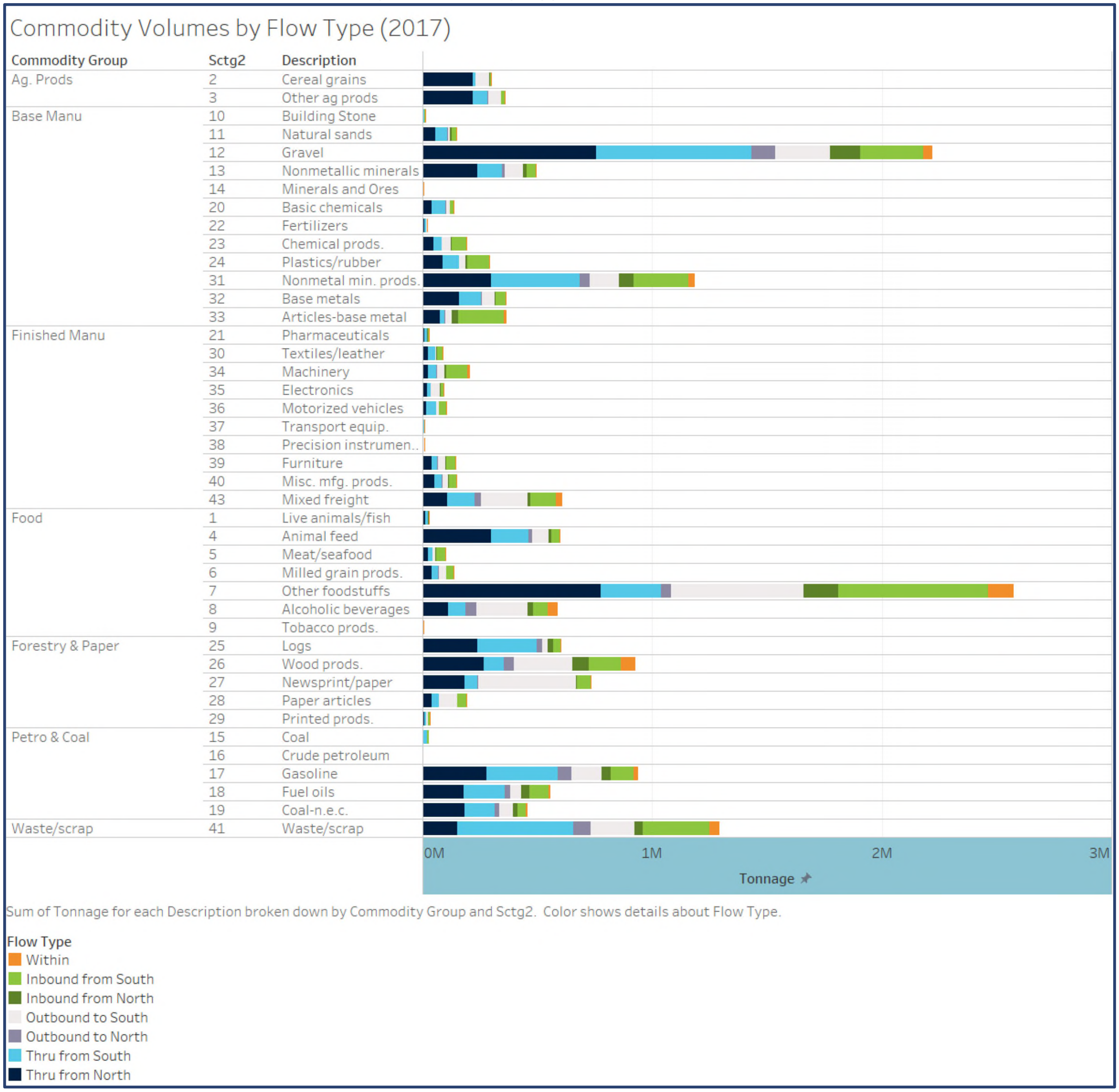
Exhibit 3 Corridor Flow Values by Commodity Type (2017)



Sum of Value USD for each Commodity Group. Color shows details about Flow Type.

Flows of both Other Foodstuffs and Gravel totaled more than 2 million tons with the former surpassing 2.5 million tons and the latter 2.2 million tons (**Exhibit 4**). Flows of Waste/Scrap totaled nearly 1.3 million tons while non-metallic mineral products exceeded 1.18 million tons.

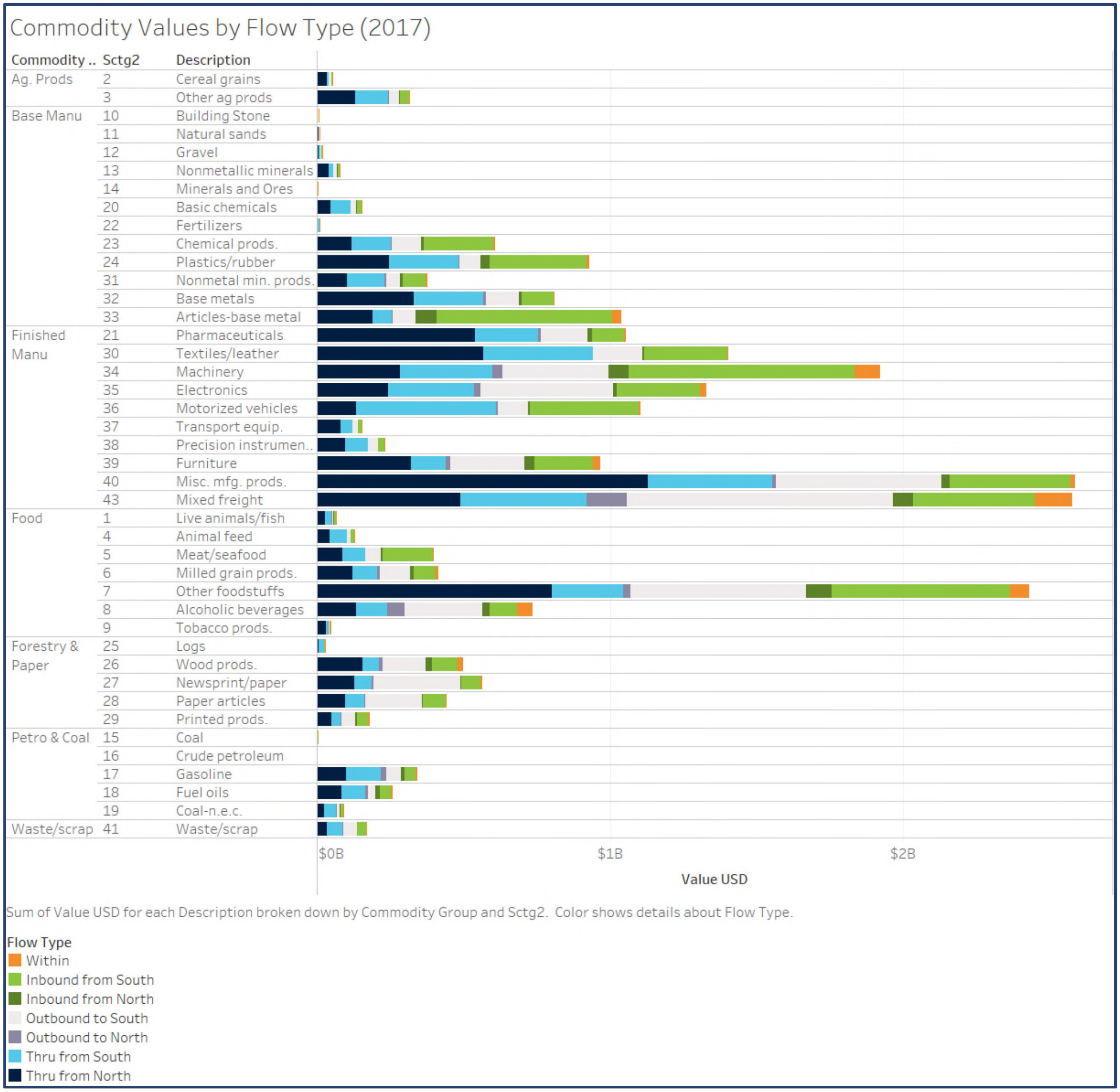
Exhibit 4 Corridor Flow Volumes by Commodity Type (2017)



In terms of value, both Miscellaneous Manufactured Products and Mixed Freight exceeded $2.5 billion while other foodstuffs totaled just under $2.5 billion (**Exhibit 5**). A number of commodity types exceeded $1 billion in value including Machinery ($1.9 billion), Textiles/Leather ($1.4

billion), Electronics ($1.3 billion), Motorized Vehicles ($1.1 billion), Pharmaceuticals ($1.05 billion), and Articles of Base Metal ($1.04 billion).

Exhibit 5 Corridor Flow Values by Commodity Type (2017)



Commodity Flow Conclusions

Commodity flow data is a commonly used data source by public planners for establishing baseline analyses about important commodity movements, total freight demands, modes used to move goods, and important trade markets to an urban area, region or state.

As was documented in the *Freight Transportation Profile* completed by SMTC in 2017:[4]

> *"Employment and the number of firms for the general freight dependent industries (i.e. construction, manufacturing, retail, transportation/warehousing, and wholesale) follow. The five industries account for 33% of all employees and the number of firms respectively, in Onondaga County,* ***which makes the freight sector an integral component of the economic condition of the SMTC planning area.*** (emphasis added).

Our updated analysis of freight movements in the Syracuse Region using the most current FAF-5 day continues to bear out the importance of freight and freight dependent industries, including transportation and warehousing to the regional economy. The total estimated annual flow of freight utilizing the I-81 Corridor in and through Syracuse is 17.3 million tons of goods, with an estimated value exceeding $24.5 billion.

The majority (83 percent by volume) of the commerce on I-81 moving into, out of or through Syracuse supports domestic trade. Of the foreign trade using the I-81 corridor in Syracuse imports (1.72 million tons) slightly outweigh exports to (1.2 million tons). Imports were valued at $4.2 billion and exports at $3.8 billion.

Inexplicably, the I-81 DEIS analysis chooses to ignore most of these important economic sectors and chooses to focus very narrowly on retail related activity.

Our review of the I-81 DEIS Section 6-3-2 found that the analysis seemingly avoids examining the impacts on the trucking industry and freight dependent industries such as manufacturing and construction:

> Page 6-142**: "***Indirect business displacement is the involuntary displacement of businesses that results from a change in economic conditions created by a project. Not all businesses are vulnerable to indirect displacement as a result of changes in traffic patterns; the potential effects on any individual business are dependent upon the specific characteristics of the business, as well as scale of change within a business' consumer trade area. Specific to the Community Grid Alternative, the types of business identified as warranting assessment are:*
>
> *Businesses dependent upon specific types and/or volumes of consumer traffic, such as those dependent upon pass-by traffic;*
>
> *Businesses sensitive to drive-time changes, changes in the volume of local consumer base within a business' trade areas; and*
>
> *Businesses that are particularly sensitive to changes in workforce availability or changes in supply chain dynamics.*

---

[4] Freight Transportation Profile, Syracuse Metropolitan Planning Area. Syracuse Metropolitan Transportation Council. 2017.

> *The indirect displacement of an individual business due to market change is an economic issue, not environmental, and is not, in itself, the subject of this DDR/DEIS. However, the DDR/DEIS does consider the potential effects of displacement at a neighborhood level, i.e., whether a project could lead to indirect displacement that in turn leads to disinvestment in a neighborhood, which is an environmental concern. For business displacement assessments within this context, "anchor" business uses are typically of greatest concern. Anchor uses are prominent, unique, or well-visited uses that draw consumers who also support other local businesses (e.g., smaller retailers, service businesses, and restaurants).*

Based on TANY's data analysis and interviews with trucking firms operating in the Syracuse Region, there are 17 trucking companies located west of the I-81/I-481 interchange that operate approximately 400 trucks on a daily basis. It is estimated that for these trucks to reroute going east via I-481 or I-690 to get to I-81 south, or the reverse, the additional mileage added to a one-way trip is between 14-18 miles longer than the current route (28-36 miles round trip). In 2019, results from an annual industry survey by ATRI found that the average cost per mile of operating a truck in the Northeast Region of the U.S. was $1.844. Resulting in added costs of approximately $51.63 to $66.38 for each round trip per truck. It is important to note this calculation does not include the NYS Highway Use Tax.

Truck Stop Analysis

ATRI truck GPS data was analyzed to identify trucks that utilized the I-81 corridor between May 1st and May 15th and made a stop within the Syracuse, NY region. Stop information includes a truck ID, the stop location in latitude and longitude, and the duration of the stop calculated from a start and end time. A stop includes instances where a truck was immobile for the entire duration, but it also includes instances where the starting location of a stop is less than 2,000 feet of its ending location. An example of this is when a truck is moving within a warehouse parking lot or has stopped to refuel and then park at a truck stop. After processing the ATRI data, a total number of 19,272 stops were identified for 3,541 trucks. 17,305 of these stops occurred within an Onondaga County parcel. The average stop duration was 5 hours.

An initial analysis shows that commercial parcels captured the largest number of stops with 9,680 while industrial parcels were second with 3,044 (**Exhibit 6**). Parcels coded as vacant captured 2,172 stops. To speed up processing at the parcel level, parcels coded in the 200 (Residential) and 900 (Wild, Forested, Conservation Lands, and Public Parks) ranges were removed from the dataset which is why those codes are not showing any stop counts.

Exhibit 6 Top Stop Locations, by Property Class

Code	Property Class Description	Count
100	Ag	9
200	Residential	-
300	Vacant	2,172
400	Commercial	9,680
500	Recreation and Entertainment	2
600	Community Services	944
700	Industrial	3,044
800	Public Services	529
900	Wild, Forested, Conservation lands, and Public Parks	-

The Onondaga County parcel dataset also contains information related to the associated land use. Parcels coded as distribution facilities accounted for the largest number of stops with 3,642, followed by Manufacturing with 2,927, and Trucking Terminal with 2,626 (**Exhibit 7**). Parcels classified as Vacant Industrial Land and Commercial Vacant with Minor Improvement captured nearly 1,900 stops combined. These include parcels that do not have buildings present and are adjacent to industrial parcels or commercial parcels such as the Pilot Travel Center located south of the I-81/I-90 interchange. As can be seen by the 942 stops for

Road/Street/Highway, some of these ROW facilities are captured within the parcel data, such as the State of New York Thruway Authority (also known as Interstate 90).

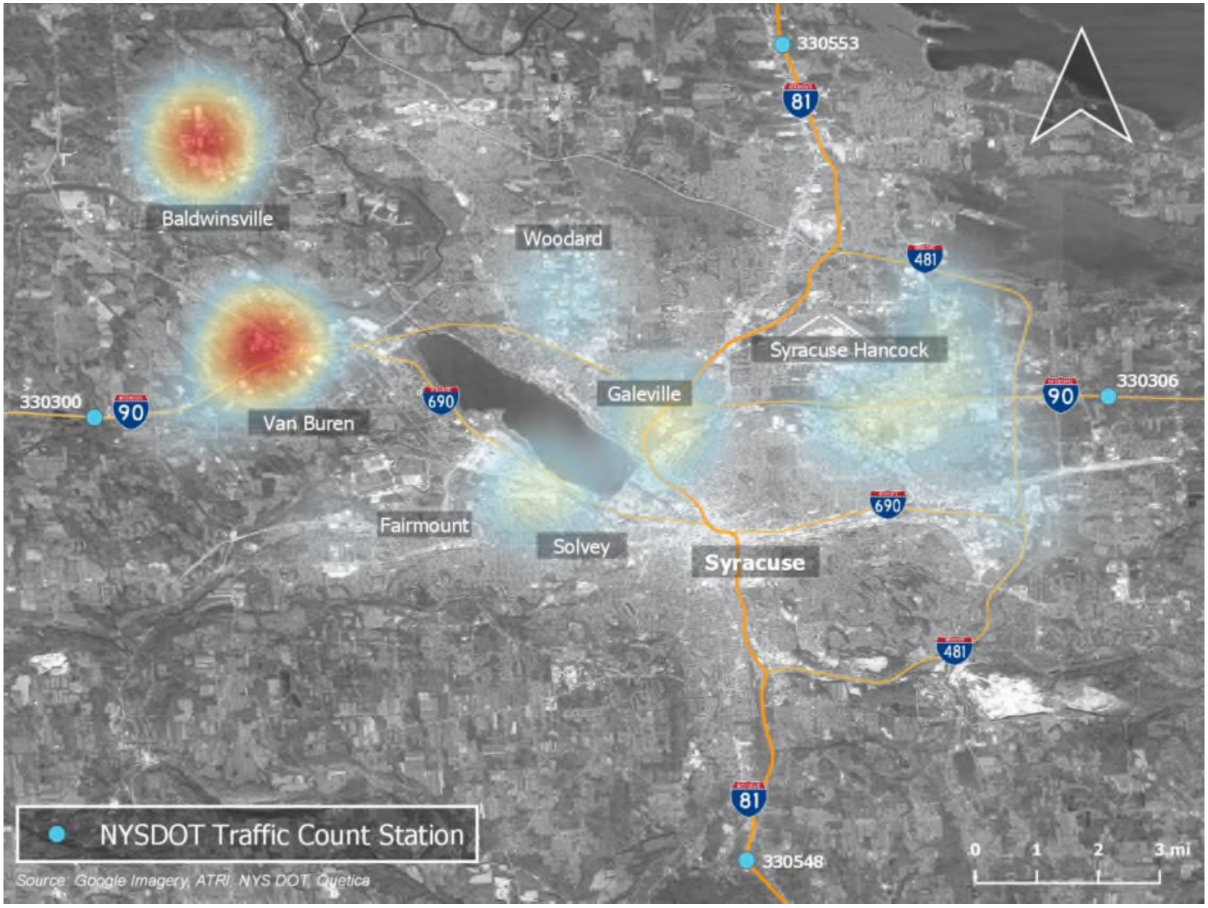
Exhibit 7 Top Stop Locations, by Land Use

Land Use Description	Count
Distribution Facility	3,642
Manufacturing	2,927
Trucking Terminal	2,626
Vacant Industrial Land	1,302
Road/Street/Highway	942
Service Or Gas Station	772
Commercial Vacant with Minor Improvement	589
Gas Storage/Distribution	428
Large Retail Store	384
Neighborhood Shopping Center	292

However, not all stops are impacted equally by the proposed I-81 Viaduct Project. For trucks which regularly utilize the I-81 Corridor to reach an origin or destination, stakeholder feedback has indicated the impact is an additional 14-18 miles of travel by traversing around downtown Syracuse via I-481 or I-690. Associated with those additional miles traveled are an additional 15-20 minutes of travel during free flow and potentially double that during AM and PM peak travel times. Thirty to forty minutes of extra travel will have a significant impact on truck drivers whose hours-of-service drive time is tracked to the minute through electronic logging devices, and the supply chains they support. The alternative to the rerouted trip around Syracuse would be a truck trip through the community grid including a traffic circle, nearly 20 traffic signals, and a series of turns to get back to I-81.

Shippers in the north and northwest portions of the Syracuse region, as well as trucks completing through trips to and from the west of Syracuse utilizing I-90, would be most impacted by the loss of the I-81 Corridor through Syracuse. **Exhibit 8** shows the locations of major freight generators within the Syracuse region along with concentrations of trucks making stops using the ATRI GPS data sample. As can be seen, major concentrations are located in Baldwinsville and Van Buren. Prominent shippers in the Baldwinsville area include McLane Distribution, Anheuser-Busch Budweiser, Gypsum Express, among others while major freight generators in the Van Buren area include FedEx Ground, Terpening Trucking Co., A. Duie Pyle Inc., Sysco, G&C Foods, Americold Logistics, and Old Dominion Freight Line. Lesser concentrations occur in Galeville and into the Lakefront area as well as Woodard where freight generators such as the Pilot Travel Center, Lockheed Martin, DOT Foods, the Regional Market, Packaging Corp of America, Victory Packaging, XPO Logistics, Raymour & Flanigan's distribution center, and a number of others are located.

Exhibit 8 Syracuse Region Truck Stop Hot Spots



Source: Google Imagery, ATRI, NYS DOT, Quetica

Utilizing the ATRI truck GPS sample data, freight generators in these four regions accounted for roughly 22 percent of the northbound trucks passing station 330548 and 20 percent of the southbound trucks. In addition, northbound trucks along I-81 which then pass through the region and station 330300 westbound along I-90 accounted for 35 percent of northbound trucks passing station 330548 while trucks passing through the region in the opposite direction accounted for more than 31 percent of the southbound trucks. Taken together, these trips represent roughly 40 percent of the northbound truck traffic passing station 330548 and 36 percent of the southbound trips (the percentages are not additive since some trucks made a stop and then traveled out of the region in the same day). On an annual basis, this equates to over 1.06 million impacted truck trips, an additional 17 million truck miles traveled in the Syracuse region, and more than 2.6 million more gallons of diesel fuel consumed. In terms of costs, companies will expend an additional $15.7 million in vehicle and $11.8 million in driver costs while the region will incur more than $431 thousand in monetized emissions from more than 17.6 tons of hydrocarbons, NO_X and fine particulate matter[5]. However, the vehicle costs do not include New York State's Highway Use Tax meaning they are conservative estimates.

The impact on freight generators in the Solvey and Fairmount areas such as the West Rock Paperboard Mill, Syracuse Fiber, and others will depend on the travel route: either along I-481 and I-690 or along state and local roads. Both will increase congestion on the new routes. While the I-481/I-690 route would slightly increase the mileage traveled and the state and local routes would slightly decrease the mileage traveled, both would increase the travel time for shippers and carriers. Based on the ATRI sample, shippers in these areas account for 5 percent of the northbound traffic and 4 percent of the southbound traffic at station 330548.

Truck trips that travel the length of the I-81 Corridor through downtown Syracuse, either south to north or north to south past stations 330548 and 330553, would only be slightly impacted by an additional 4-miles by having to travel I-481 around Syracuse. The ATRI data suggests approximately 23 percent of the northbound trucks traveling past station 330548 is through traffic while 26 percent of the southbound trucks represent through trips. Combined, these trips represent 692 thousand annual truck trips through the region and an additional 2.77 million miles of truck traffic and 426 thousand gallons of diesel fuel. In terms of costs, the additional travel would cost shippers and carriers \$2.56 million in commercial vehicle costs, \$1.9 million in driver costs, and \$70 thousand in monetized emissions along with the added congestion by rerouting the truck traffic from I-81 to I-481.

Truck trips that are originated or terminated within the Syracuse region east of the I-81 Corridor (those that utilize I-90, I-481, or I-690) along with those that travel into and out of the region past station 330306 via I-90 would not be impacted by the I-81 Viaduct Project other than from the additional congestion brought on by the rerouted truck traffic. Freight generators that fit this description and are located east of Syracuse Hancock International Airport include FedEx Freight, UPS, ABF Freight, Meadow Brook Dairy, Swift Transportation, and Estes Express Lines while FedEx Ground, Carrier Transicold, Byrne Dairy Dry Warehouse, and Cavalier Transport are located south of the airport with access via I-90. Also not impacted by the project, are the truck trips traveling past station 330548 on the way to pick-up or drop-off containers at CSX's intermodal terminal located south of the I-481 and I-90 interchange. The

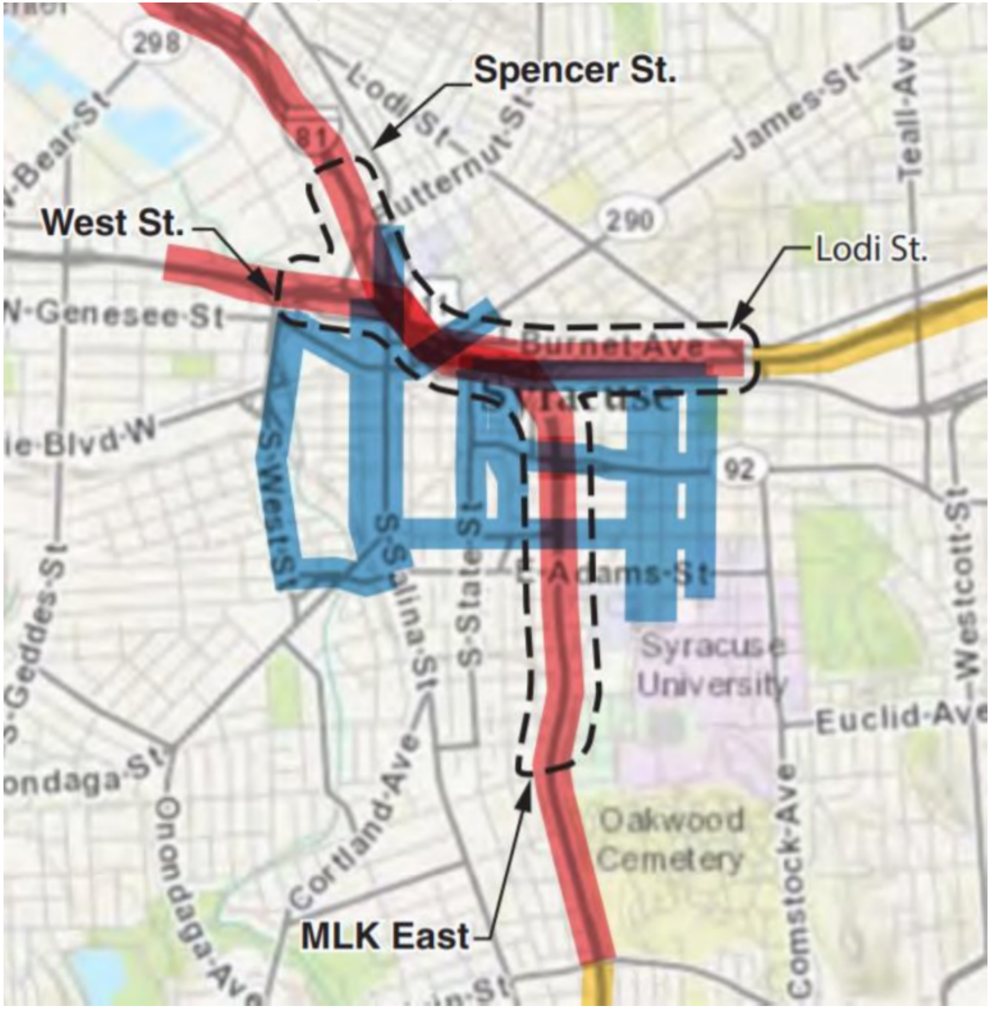
---

[5] Based on Quetica's analysis of ATRI's truck GPS sample, combined AADTT counts at NYSDOT's station 330548 (https://www.dot.ny.gov/tdv), per mile trucking costs and fuel consumption from the American Transportation Research Institute's *An Analysis of the Operational Costs of Trucking: 2020 Update* (https://truckingresearch.org/wp-content/uploads/2020/11/ATRI-Operational-Costs-of-Trucking-2020.pdf), heavy-duty vehicle emission rates from the U.S. Environmental Protection Agency (https://www.bts.gov/content/estimated-national-average-vehicle-emissions-rates-vehicle-vehicle-type-using-gasoline-and), and the U.S. Department of Transportation's *Benefit-Cost Analysis Guidance for Discretionary Grant Programs* (https://www.transportation.gov/sites/dot.gov/files/2021-02/Benefit%20Cost%20Analysis%20Guidance%202021.pdf).

ATRI data suggests just under a quarter of the truck trips carrying intermodal containers to and from the terminal pass the southern I-81 station.

Lastly, previous analysis of impacts to shippers and truck trips have focused on those businesses in the immediate vicinity of the Viaduct and most directly impacted by the I-81 Viaduct Project. **Exhibit 9** from the NYSDOT's I-81 Viaduct Project Scoping Report in 2015, shows the project's priority area in dashed lines beginning in its southernmost point at Martin Luther King East, Lodi Street to the east, West Street to the west, and Spencer Street to the northwest. While shippers located adjacent and in close proximity to the project will be most directly impacted by having to route through the local street grid to reach more distant interchanges, the number of these truck trips are minimal when compared to the region's total truck trips. Less than 3 percent of all of the truck stops made in the ATRI GPS data sample were made within a 1-mile buffer of the project's priority area. When expanded using the NYSDOT traffic count station data, the total daily truck trips to the buffered priority area totals roughly 100 stops.

Exhibit 9 I-81 Viaduct Project Priority Area



Draft Environmental Impact Statement Assessment & Evaluation of Freight

Based upon our review of ***Interstate 81 Viaduct Project – Draft Environmental Impact Statement (DEIS)*** report, it is our opinion that freight, logistics and related industries and businesses were not evaluated fully to objectively assess the potential impacts to businesses, increases in freight costs or potential negative industry impacts. While the recognition that other industries, neighborhoods, and other social and environmental justice are important aspects that should be considered, it appears the freight industry was NOT given equal footing in terms of fiscal and physical impacts of the I-81 decommissioning.

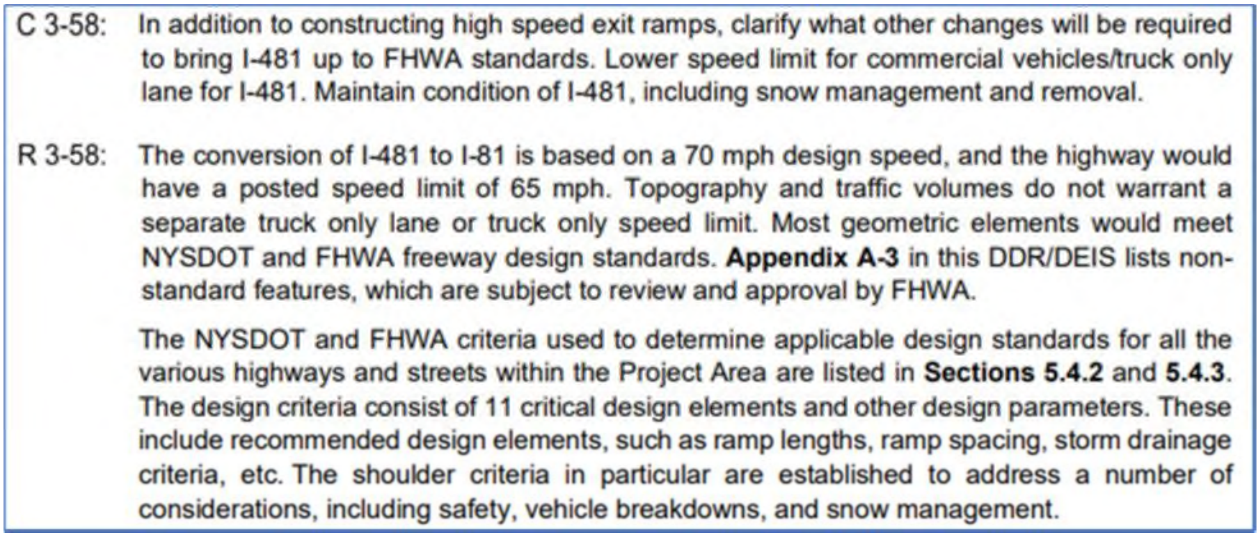
Below is an assessment of the baseline traffic related data, analyses, and findings as presented in the Appendices and chapters of the DEIS. For each of the report chapters and/or Appendices, a brief statement of findings is presented.

Appendix C-2 VISSIM Development and Calibration Report – while truck/trucks are mentioned six times in the Appendix, there are no specific evaluation numbers presented for existing or future conditions.

Appendix C-3 Traffic Volumes and Levels of Service (LOS) – neither trucks nor any vehicle classification is presented in this Appendix that allow differentiation of vehicle types for either existing or future conditions.

Appendix D-2 Economic Considerations – while truck(s/ing) is mentioned 35 times in this Appendix, the references are related to the Pilot Truck Stop or to truck related economic impacts being minimal such as, "Overall, the Community Grid Alternative would not impede freight movement in the study area." *H. SPECIFIC BUSINESS TYPES FREIGHT (TRUCKING) – page 30*

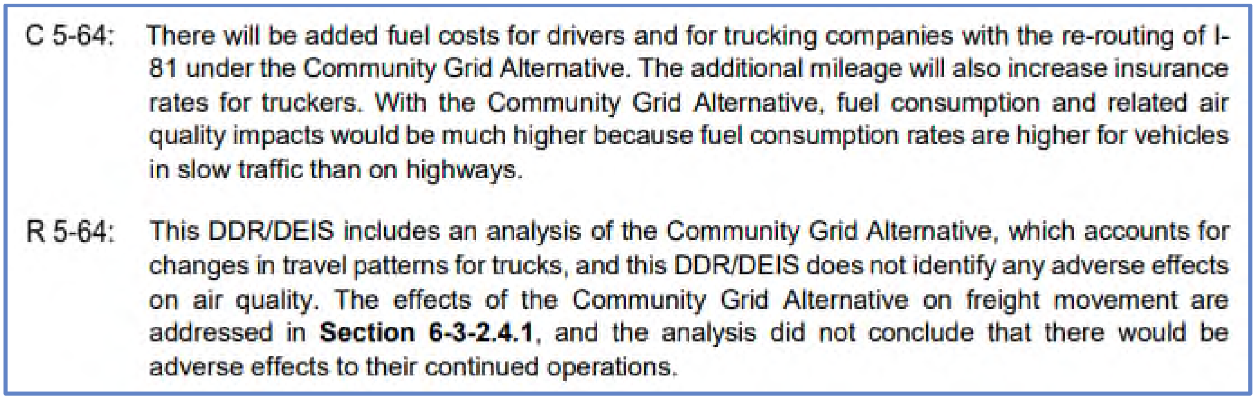
Appendix M-5 Responses to Comments Received – The following are truck related references contained in the responses to comments received at various forums, etc. While truck(s/ing) is referenced 54 times in the document, most are related to limiting trucks on local streets and mitigation for potential increases. However, below are several pertinent references to truck(s/ing) including comments (C) and official responses (R).



C 3-58: In addition to constructing high speed exit ramps, clarify what other changes will be required to bring I-481 up to FHWA standards. Lower speed limit for commercial vehicles/truck only lane for I-481. Maintain condition of I-481, including snow management and removal.

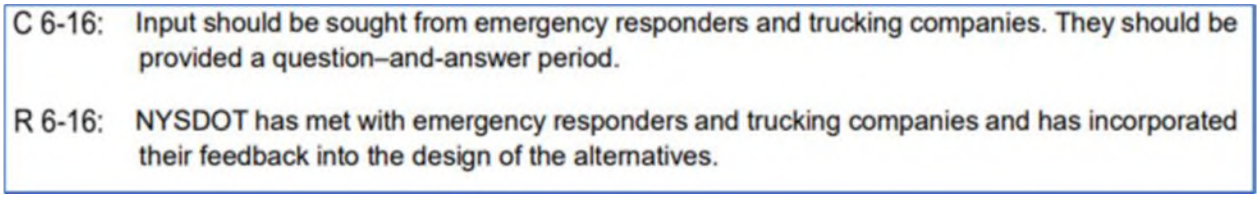
R 3-58: The conversion of I-481 to I-81 is based on a 70 mph design speed, and the highway would have a posted speed limit of 65 mph. Topography and traffic volumes do not warrant a separate truck only lane or truck only speed limit. Most geometric elements would meet NYSDOT and FHWA freeway design standards. **Appendix A-3** in this DDR/DEIS lists non-standard features, which are subject to review and approval by FHWA.

The NYSDOT and FHWA criteria used to determine applicable design standards for all the various highways and streets within the Project Area are listed in **Sections 5.4.2** and **5.4.3**. The design criteria consist of 11 critical design elements and other design parameters. These include recommended design elements, such as ramp lengths, ramp spacing, storm drainage criteria, etc. The shoulder criteria in particular are established to address a number of considerations, including safety, vehicle breakdowns, and snow management.



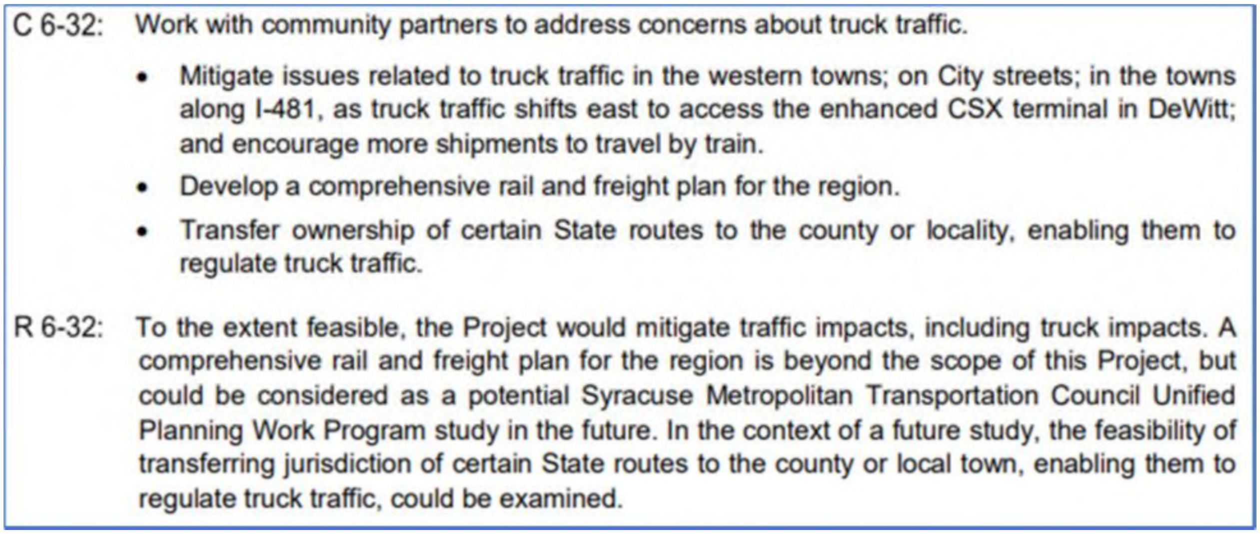
C 5-64: There will be added fuel costs for drivers and for trucking companies with the re-routing of I-81 under the Community Grid Alternative. The additional mileage will also increase insurance rates for truckers. With the Community Grid Alternative, fuel consumption and related air quality impacts would be much higher because fuel consumption rates are higher for vehicles in slow traffic than on highways.

R 5-64: This DDR/DEIS includes an analysis of the Community Grid Alternative, which accounts for changes in travel patterns for trucks, and this DDR/DEIS does not identify any adverse effects on air quality. The effects of the Community Grid Alternative on freight movement are addressed in **Section 6-3-2.4.1**, and the analysis did not conclude that there would be adverse effects to their continued operations.



C 6-16: Input should be sought from emergency responders and trucking companies. They should be provided a question–and-answer period.

R 6-16: NYSDOT has met with emergency responders and trucking companies and has incorporated their feedback into the design of the alternatives.



C 6-32: Work with community partners to address concerns about truck traffic.

- Mitigate issues related to truck traffic in the western towns; on City streets; in the towns along I-481, as truck traffic shifts east to access the enhanced CSX terminal in DeWitt; and encourage more shipments to travel by train.
- Develop a comprehensive rail and freight plan for the region.
- Transfer ownership of certain State routes to the county or locality, enabling them to regulate truck traffic.

R 6-32: To the extent feasible, the Project would mitigate traffic impacts, including truck impacts. A comprehensive rail and freight plan for the region is beyond the scope of this Project, but could be considered as a potential Syracuse Metropolitan Transportation Council Unified Planning Work Program study in the future. In the context of a future study, the feasibility of transferring jurisdiction of certain State routes to the county or local town, enabling them to regulate truck traffic, could be examined.

As demonstrated in the beforementioned referenced meeting comments and subsequent I-81 Viaduct Team responses, the lack of sound and comprehensive evaluation of the freight related impacts associated with the I-81 Viaduct project is evident. The industry, while supportive of improved and safe infrastructure, as it IS OUR WORKPLACE, feels additional freight related considerations need to be made to fully address future impacts to the industry and the local, regional, state and national economies as well, which depend on the freight industry.

Conclusion

Our review of the associated documents revealed that the ***Interstate 81 Viaduct Project – Draft Environmental Impact Statement (DEIS)*** was prepared with a significantly affected industry **NOT FULLY CONSIDERED**. In fact, this appears even more significant given that this project involved the removal of an existing section of Interstate 81. It is clear that according to federal statutes and guidance, listed below, the I-81 DEIS in fact, **DID NOT** fully consider the impacts of the freight industry and, more specifically, interstate commerce or commercial motor vehicles which is a critical component of interstates' role to facilitate interstate commerce.

> § 658.11 Additions, deletions, exceptions, and restrictions.
>
> > (d) Deletions and use restrictions - Federal-aid interstate.
> >
> > > **(1)** The deletion of, or imposition of use restrictions on, any specific segment of the Interstate Highway System on the National Network, except as otherwise provided in this part …
> > >
> > > **(2)** The justification accompanying a request shall be based on the following:
> > >
> > > > **(i)** Analysis of evidence of safety problems supporting the deletion or restriction as identified in § 658.11(c).
> > > >
> > > > **(ii)** Analysis of the impact on interstate commerce.
> > > >
> > > > (**iii**) Analysis and recommendation of any alternative routes that can safely accommodate commercial motor vehicles of the dimensions and configurations described in §§ 658.13 and 658.15 and serve the area in which such segment is located.
> > > >
> > > > **(iv)** Evidence of consultation with the local governments in which the segment is located as well as the Governor or the Governor's authorized representative of any adjacent State that might be directly affected by such a deletion or restriction.

To understand the impact to interstate commerce, a comprehensive understanding of the movement, routing and cost of freight/interstate commerce must be evaluated, and our review suggests this evaluation **DID NOT** occur. Additionally, we believe that the overarching environmental impacts to air quality from higher concentrations of motor vehicles, including trucks, to both the Downtown Syracuse as well as the new I-81 (former I-481) segments was not fully considered, especially given the recent changes in freight movement/delivery during the COVID-19 pandemic, which will likely continue in the future.

From: Charles Garland <garlandbros@outlook.com>
Sent: Friday, October 20, 2023 8:34:08 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <Micron@ongov.net>
Subject: Charles Garland - Micron EIS Concerns With Compressed Census Tract Maps

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From: Charles Garland
Sent: Friday, October 20, 2023 2:58 PM
To: 'Nancylowery@ongov.net' <Nancylowery@ongov.net>
Cc: CEG County Legislature <charlesgarland@ongov.net>
Subject: Charles Garland - Micron EIS Concerns With Compressed Census Tract Maps

Good afternoon,

Can you please share my attached letter and supplemental maps with the OCIDA Board Members and staff, regarding Micron, the EIS and community and regional environmental, social and economic concerns.

Please free to contact me for further discussion.

Charles E. Garland, Mgr.

Garland Bros. Funeral Home

Onondaga County 16th District Legislator

143 Martin Luther King West

Syracuse, NY 13205

Cell: 315-243-5941

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Anjela D. Garland, L.F.D.

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October 19, 2023

Onondaga County Industrial Development Agency
335 Montgomery Street -- 2nd floor
Syracuse, New York. 13202

attention: Micron Project

Dear OCIDA Staff and Board Members:

It is my understanding you will be preparing an Environmental Impact Statement for the forthcoming Micron project development and in preparation of that you have sought input from members of the public, specific to any potential significant adverse impacts that might occur.

I write to you now on behalf of myself and on behalf of the residents of Onondaga County 16th Legislative District whom I represent and who comprise most of the minority populations living south of downtown Syracuse, New York.

I have had an opportunity to review documents that were made available for public viewing, including an Environmental Assessment Form, a draft scoping document and a 'Positive Declaration'. Please accept from me the following important considerations – adverse impacts that would most likely occur unless planned for and appropriately mitigated.

I've noted from several of the maps attached to the Environmental Assessment Form that you have chosen to examine traffic considerations in the northern half of the County, but apparently none in the southern half of the County – an area which contains the majority of the University populations of the County as well as all of the principal higher education campuses – including the campus facilities of

LeMoyne College, Syracuse University and Onondaga Community College. LeMoyne College and Syracuse University are located near that edge, but Onondaga Community College is not, and in all cases, educational interaction and subsequent commute to resultant employment would certainly be made more difficult, more expensive and more environmentally impacted if these considerations were not properly understood, analyzed, and physically provided for. Environmental impacts of this degree must certainly be understood and accommodated.

And of equal importance to much of the population of that southern half of the County, the education and opportunity for employment and ability to easily and efficiently commute to employment is of similar importance to the minority populations of Central New York. Without a doubt, significant adverse environmental impacts would result if these populations and the present and future transportation character and air quality were not analyzed, and planned and provided for.

You may be aware that the New York State Department of Transportation had a plan to effectively cut off a similar area from all things to the north. Fortunately, a New York State Court action brought by local citizens and government bodies succeeded in cutting that plan off, sending the state back for actual environmental analysis, and in fact, inclusion of Micron impacts at the same time.

In any event, it surely would hurt potential employees and employers if full interaction of those parties were not thoughtfully and logically considered in any environmental analysis and consideration.

To further explain the minority population issue, I've attached census maps that identify, in each case, those census tracts where each minority population lives in the same or greater percentage as their overall share of the population of Syracuse based on the latest 2020 US Census. It becomes obvious by examining these maps that making access to employment in the north much more difficult for those in the south would harm the economics of the employment picture as well as all the environmental transportation issues – those of air quality, fuel consumption, global warming and important employment and economic considerations.

And one more consideration – even though it was the plan of the state of New York, and I sincerely doubt OCIDA or Micron would consider in their environmental review certain quirks that New York State had included in theirs, NYS had intended to further cut off the populations of the south side of Syracuse by terminating Dr Martin Luther King Street, the south side's principal access to the university hill enclave of medical and educational and emergency services. I'm certain that component would never show up in your analyses, but I mention it to you here just to make certain.

For clarity, I am fully supportive of the Micron project and greater economic prosperity for all local residents of Syracuse and Central New York. I want to be sure that our collective efforts ensure a pathway out of poverty for all of the residents I represent.

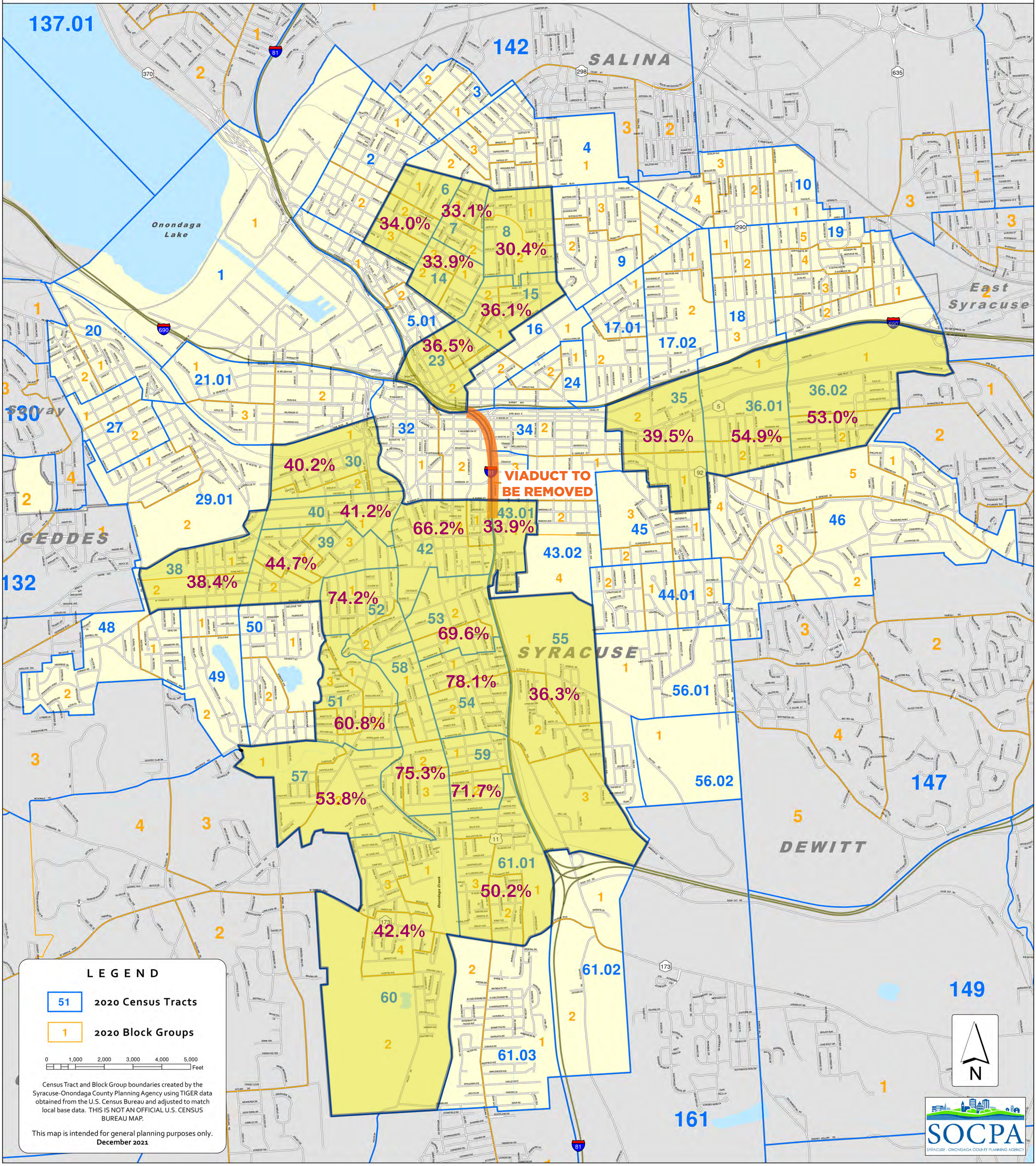
Very truly yours,

Charles E. Garland

Charles Garland, Mgr., Garland Bros. Funeral Home
Onondaga County 16th District Legislator

Attachments

2020 Census Tracts and Block Groups
City of Syracuse



LEGEND

51	2020 Census Tracts
1	2020 Block Groups

0 1,000 2,000 3,000 4,000 5,000 Feet

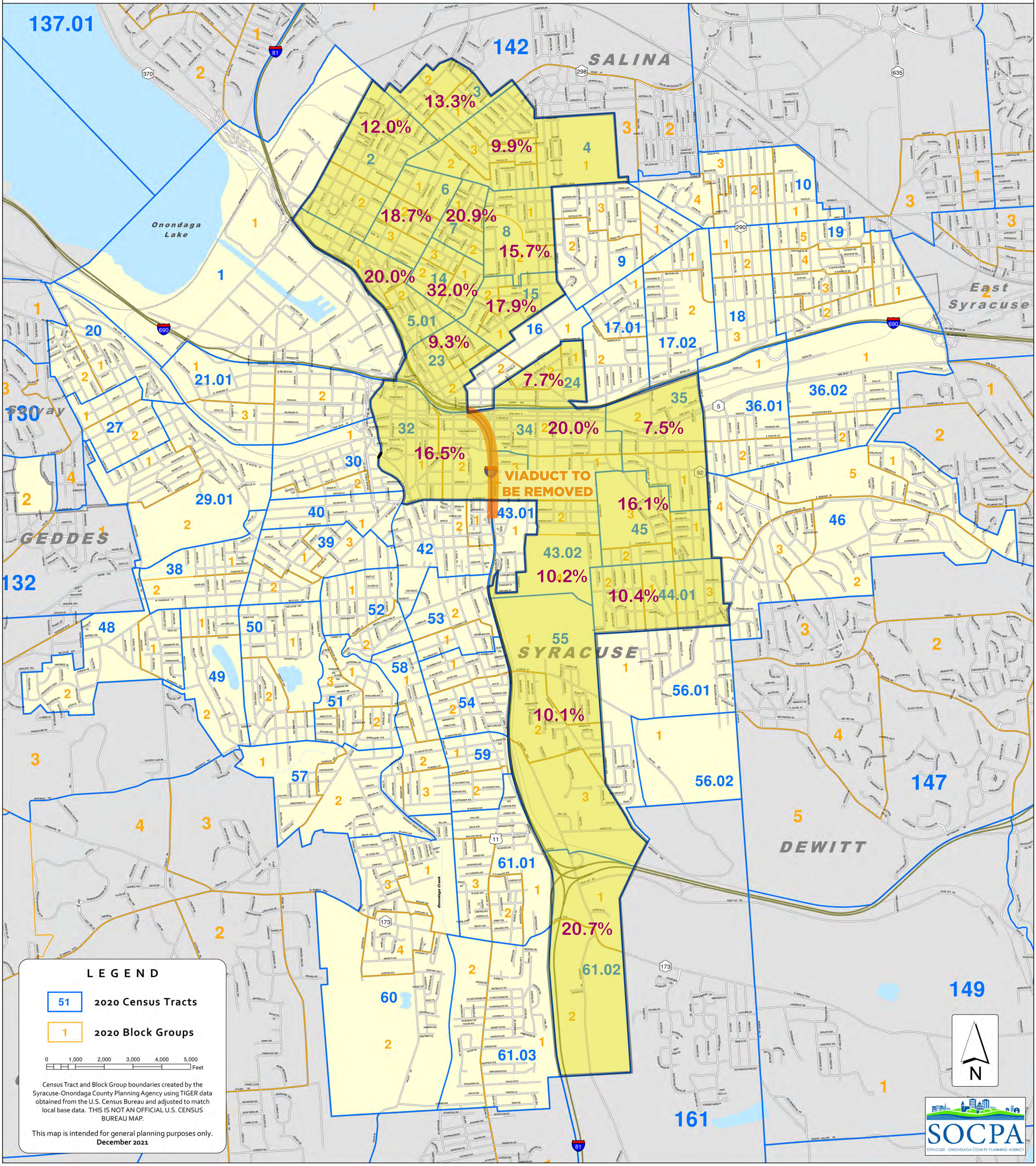
Census Tract and Block Group boundaries created by the Syracuse-Onondaga County Planning Agency using TIGER data obtained from the U.S. Census Bureau and adjusted to match local base data. THIS IS NOT AN OFFICIAL U.S. CENSUS BUREAU MAP.

This map is intended for general planning purposes only.
December 2021

Source: US Census Bureau: 2020 Census
Census Demographic Map Viewer
August/September 2022

Census Tracts Greater Than 30.7%
BLACK OR AFRICAN-AMERICAN

2020 Census Tracts and Block Groups
City of Syracuse



Census Tract and Block Group boundaries created by the Syracuse-Onondaga County Planning Agency using TIGER data obtained from the U.S. Census Bureau and adjusted to match local base data. THIS IS NOT AN OFFICIAL U.S. CENSUS BUREAU MAP.

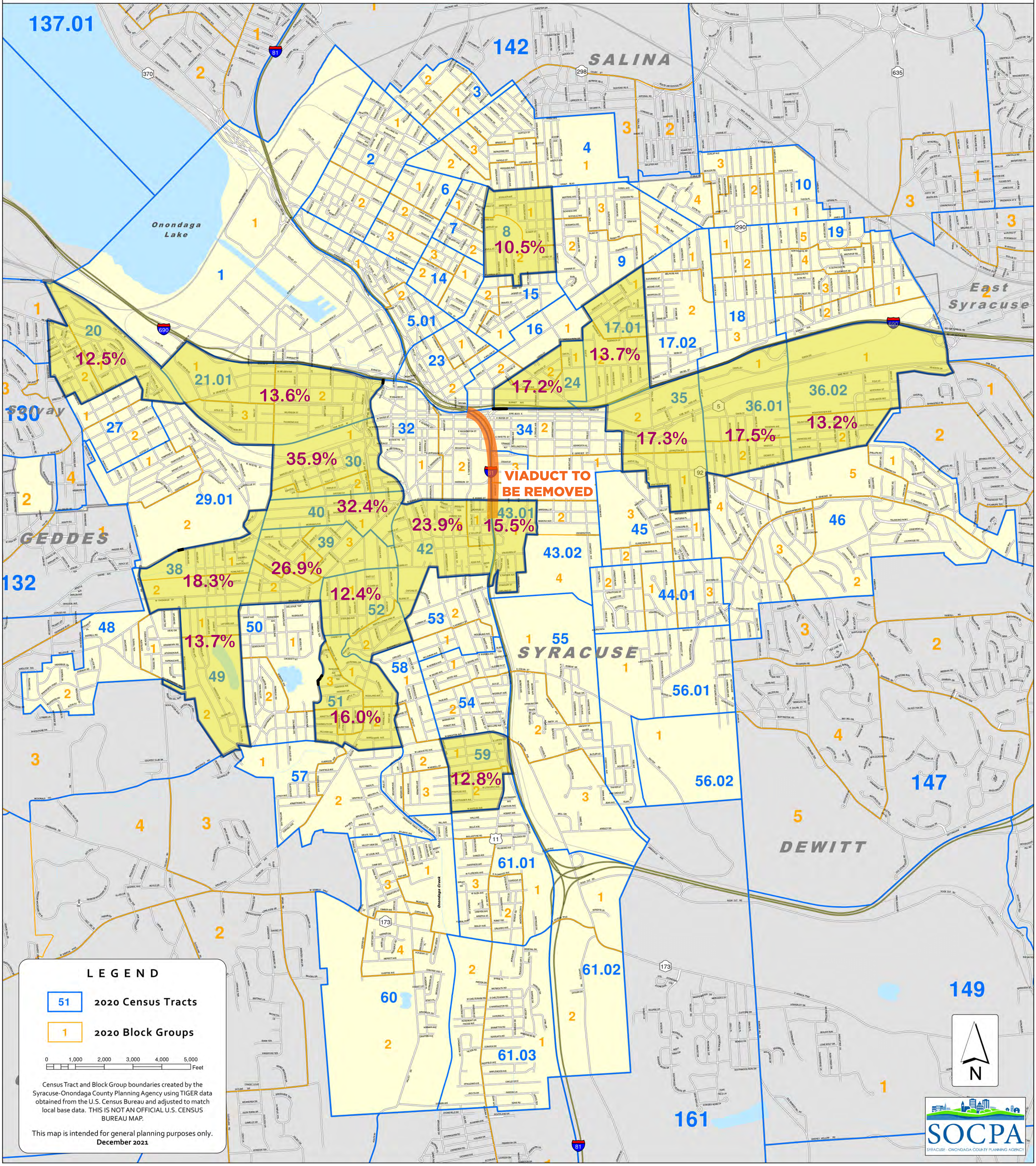
This map is intended for general planning purposes only.
December 2021

Source: US Census Bureau: 2020 Census
Census Demographic Map Viewer
August/September 2022

Census Tracts Greater Than 7%

ASIAN

2020 Census Tracts and Block Groups
City of Syracuse



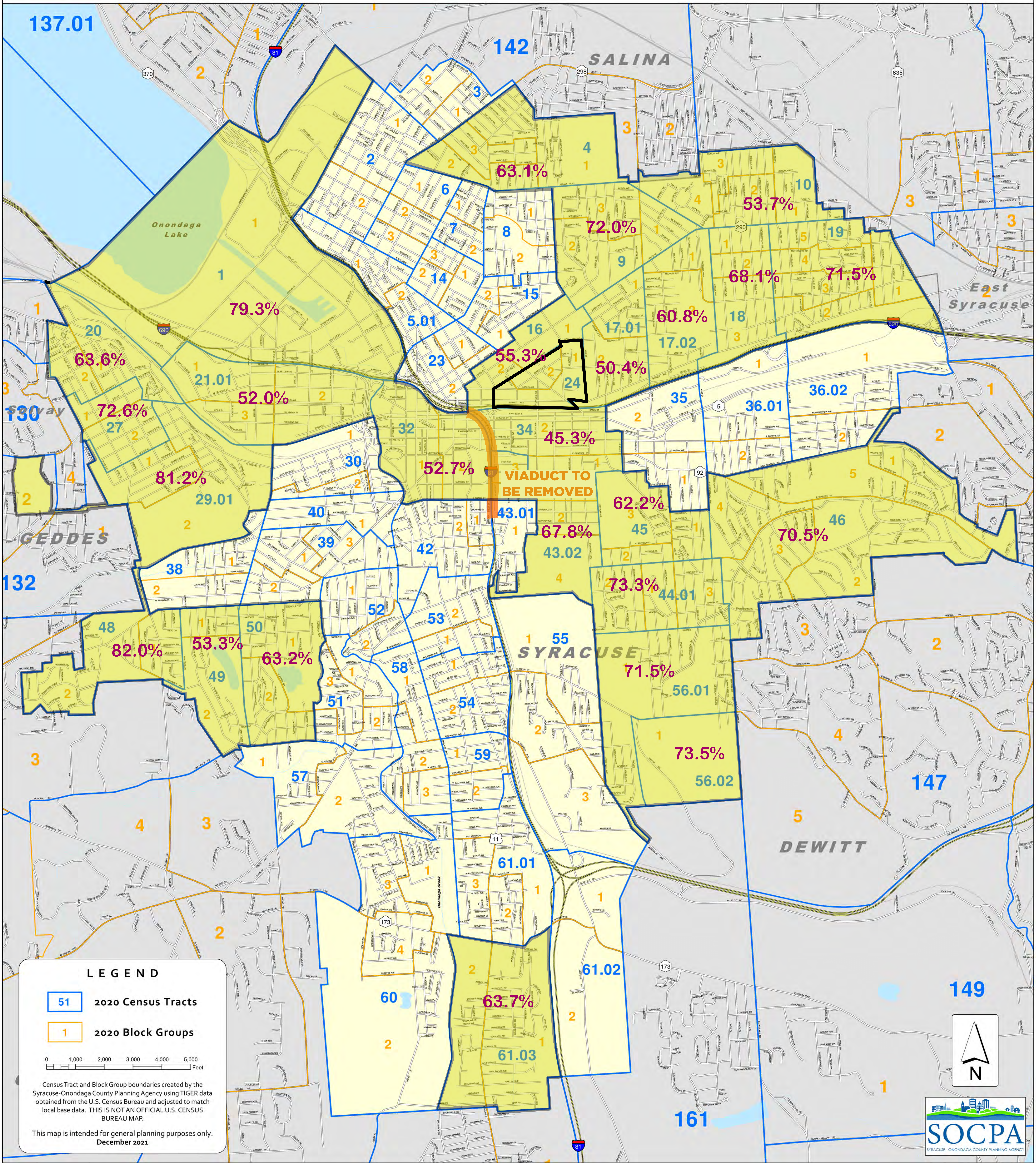
Census Tract and Block Group boundaries created by the Syracuse-Onondaga County Planning Agency using TIGER data obtained from the U.S. Census Bureau and adjusted to match local base data. THIS IS NOT AN OFFICIAL U.S. CENSUS BUREAU MAP.

This map is intended for general planning purposes only.
December 2021

Source: US Census Bureau: 2020 Census
Census Demographic Map Viewer
August/September 2022

Census Tracts Greater Than 10.4%
HISPANIC

2020 Census Tracts and Block Groups
City of Syracuse



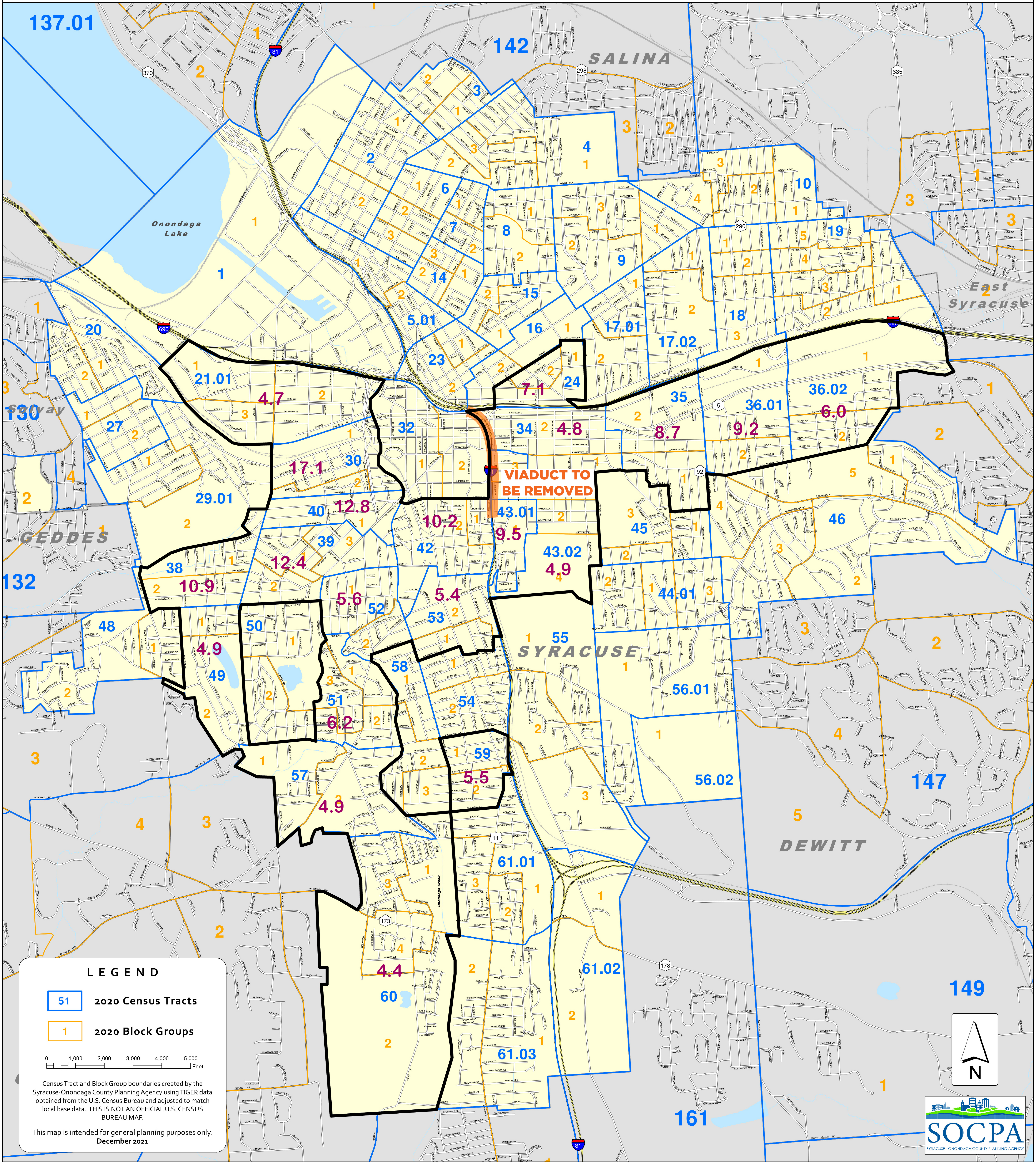
Census Tract and Block Group boundaries created by the Syracuse-Onondaga County Planning Agency using TIGER data obtained from the U.S. Census Bureau and adjusted to match local base data. THIS IS NOT AN OFFICIAL U.S. CENSUS BUREAU MAP.

This map is intended for general planning purposes only.
December 2021

Source: US Census Bureau: 2020 Census
Census Demographic Map Viewer
August/September 2022

Census Tracts Greater Than 47.9%
WHITE

2020 Census Tracts and Block Groups
City of Syracuse



LEGEND

51	2020 Census Tracts
1	2020 Block Groups

0 1,000 2,000 3,000 4,000 5,000 Feet

Census Tract and Block Group boundaries created by the Syracuse-Onondaga County Planning Agency using TIGER data obtained from the U.S. Census Bureau and adjusted to match local base data. THIS IS NOT AN OFFICIAL U.S. CENSUS BUREAU MAP.

This map is intended for general planning purposes only.
December 2021

Source: US Census Bureau: 2020 Census
Census Demographic Map Viewer
August/September 2022

Census Tracts Greater Than 4.4%
OTHER RACE

Nathan S Gunn
113 Ambergate Rd
DeWitt, NY 13214

October 19, 2023

To: Onondaga County Industrial Development Agency (OCIDA)

Re: Micron Project – request for written comments

The proposed Micron project and the investment in both public and private dollars into the regional economy of Central New York is most welcome! What an incredible opportunity to reset the future and the fortunes of our residents for generations to come. This project is also a rare "win-win" because it addresses a vital national security interest by returning chip manufacturing to our own shores in an era of apparent global divergence.

In response for the request of public comment regarding the proposed Micron Project and any potential adverse environmental impact, I submit the following:

- In his February 2023 ruling on the NYS DOT's compliance with State-mandated environmental statutes, Judge Neri gave the State a failing grade. Specifically, Judge Neri required the State to halt any tear-down of the I-81 corridor through the City of Syracuse until two required and reasonable actions were taken by the State:
    - Complete air testing related to increased traffic along the current I-481 corridor and
    - Revision of the plan and the environmental review including consideration for the proposed Micron project.
- Rather than comply with these very reasonable requirements, the State has ignored both the concerns of the residents of Onondaga County and the order of a State Supreme Court Judge and has chosen to appeal the decision.
- The very action of choosing to appeal rather than produce air quality samples and compliance with a regional traffic plan forces one to conclude that the State is already guilty of neglecting to follow its own environmental review statutes. I engaged this logic directly with Betsy Parmley at a recent open forum regarding the I-81 project and she showed complete contempt and disregard for the requirement of air sampling based on proposed increased traffic on the current I-481 corridor. Rather than make the air sampling public, the State has chosen to appeal. <u>This action is highly concerning</u>.
- My concern for the lack of consideration of future traffic on this corridor was heightened when I saw Appendix A (Automatic Traffic Counter Locations) for this project's environmental review. In what can only be considered a bizarre array of counter "drops", there were NO TRAFFIC COUNTERS UTILIZED ON I-481 AT THE RT92/5 EXCHANGE NOR IN THE CITY OF SYRACUSE. How is this omission possible? Why would the traffic be counted in Cato-Meridian and not Fayetteville or the Syracuse Southside? This omission causes another set of reasonable questions?
    - Will residents of the City of Syracuse <u>not</u> be involved in the future workforce at Micron? Is the County planning to omit the residents of the City in the plans for 1000s of construction and higher-paying jobs at the new facility? One begins to wonder how the future plans of the "community grid" will impact access from the City to the Micron plant, especially if the environmental review intentionally does not measure future traffic impact.

  - Will traffic on the newly constructed I-481 be unaffected by a project that claims to produce up the 40,000 new “regional” jobs?
  - Is there possible collusion between the NYS DOT and whomever determined these traffic counter locations to keep the public in the dark about current and potential increases in traffic given the status of the failed environmental review discovered by a NYS Supreme Court Judge?
  - How can any regional traffic environmental statement be considered serious if it does not include two of the most significant population centers in the region?

Finally – Judge Neri concluded correctly that the Micron project and its traffic impact must be considered in any redesign of I-81. While the environmental reviews of the two projects may be singular and separate, the impacts and the best solutions are necessarily linked. The reason for the statute is so that future generations can be considered when current leadership makes decisions for the community as a whole.

I strongly urge the Onondaga County leadership to recognize the opportunity to truly represent your citizens and demand the NYS DOT comply with the NYS Supreme Court and perform both a serious and thorough environmental review of the Micron project while simultaneously ensuring that the I-81 redesign best serves *every* member of our greater community.

Sincerely,

Nathan S. Gunn
DeWitt, NY

Frank L. Fowler
216 Long Meadow Drive
Syracuse, NY 13205

October 16, 2023

Onondaga County Industrial Development Agency
335 Montgomery Street, 2nd floor
Syracuse, New York. 13202

att: Micron Project

Dear OCIDA Staff and Board Members:

You have requested submittal of written comments regarding potential significant adverse impacts that should be addressed in the Draft Environmental Impact Statement which will be prepared for the proposed Micron New York Semiconductor Manufacturing Action that is being considered by the Agency.

I enthusiastically support this project as it has been described in the press and I have reviewed the Agency's draft scoping document and SEQRA Positive Declaration as well as the application materials and the Environmental Assessment Form that has been made available for public review. I feel it is important that the Agency specifically review and consider the following.

In OCIDA's SEQRA EAF Addendum, you indicate that Micron has initiated consultation with, among others, the New York State Department of Transportation (NYSDOT) to identify requirements for a comprehensive traffic impact study that will be included in the DEIS.

I strongly urge the Agency to avoid making the mistakes made by the NYSDOT in the preparation of their 2022 Interstate 81 Project Final Environmental Impact Statement (FEIS). The NYSDOT incorporated significant traffic projection errors in their effort to justify removal of Interstate 81 from Syracuse.

That FEIS was fortunately rejected by the Courts of New York State and the NYSDOT was sent back to create a fundamentally acceptable FEIS that would, among other requirements, include the needs and impacts of this Micron Project.

Specifically, allow me to identify several of the fundamental errors that render NYSDOT's conclusions invalid. We must not make similar errors here.

1. Study Area:

a. The Study Area chosen by the NYSDOT in that case was much too narrow for a project with the scale of impacts that would result from it – the "Study Area" identified in that case was approximately one quarter mile each side of the viaduct which they chose to remove. In this case, that of the Micron Project, a much broader study area has been indicated, for instance, in figures A-1 through A-3 of *Appendix A.*

However, oddly enough, virtually no traffic count locations are identified in *Appendix A* in any of Onondaga County south of Interstate 690, eliminating most of the city of Syracuse and all the communities south of there from consideration in the traffic and related impacts of this project. Clearly, that geographic area and everything south of it is today full of potential employees and potential material suppliers and product customers. While the NYSDOT chose to examine their project in that manner for reasons of their own, OCIDA certainly should not choose to do the same.

2. Traffic Growth Projections:
    a. The daily traffic volumes accumulated and publicly published by the NYSDOT during the 19-year period prior to preparation of the analyses they relied on and incorporated in their FEIS grew annually at a rate of 2.7% per year, yet for reasons of their own, NYSDOT chose to project traffic volume growth from that point on at an essentially non-existent growth rate of 0.2% per year. Such distortion of data is not good engineering practice and cannot be justified in analyzing the environmental impacts of vehicular movements.

    b. Similarly, in downtown Syracuse, the Interstate 81 viaduct that NYSDOT had hoped to remove today carries traffic directly aboive and at the same time as the traffic flow on Almond Street directly below it.

    In their 2022 FEIS, NYSDOT projected that in the Peak Hour each day (ie: the 'rush hour') their so-called 'no-build' plan of combined traffic volume on both levels would total 6,700 vehicles.

    Yet in their so-called 'community grid' plan, with the viaduct removed from above, NYSDOT projected only 1,700 vehicles making that same Peak Hour trip on Almond Street alone.

    NYSDOT's assumption was that, because they would not be providing comparable replacement capacity, in the daily Peak Hour 5,000 vehicles would divert to somewhere else or else become discouraged altogether from making the trip. Again, such distortion of data is not good engineering practice and cannot be justified in analyzing the environmental impacts of vehicular movements.

All of this is to identify the distortions made by the NYSDOT, whom OCIDA may be relying on for vehicular-related environmental considerations – employment, economic, air quality, energy consumption, global warming and all other environmental considerations. For the benefit of local residents it is critical that errors such as those identified above are not made.

I believe all of us in Central New York are fully behind this development and strongly urge that steps be taken to make sure we welcome the project population growth of more than 100,000 new residents.

While moving firmly in that direction, we cannot stumble along the same path that the NYSDOT took. Given the magnitude of the Micron project, it is timely that OCIDA and all government partners take a fresh look at reconnecting our communities and making sure residents on Syracuse's southside have access to those new jobs at Micron.

Sincerely,

Frank L. Fowler

From: Audrey Fletcher <afletcher@darcomfg.com>
Sent: Friday, October 20, 2023 8:36:29 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Micron Project: comments to Draft Scoping Document

To: Onondaga County Industrial Development Agency

As a long-time resident of Syracuse, I have a few comments regarding the project's EIS.

First, it is thrilling that Micron is coming here. What an incredible opportunity for the region. I believe that Syracuse has been on a positive trajectory in recent years and Micron will strengthen that trajectory.

But such an enormous project requires uncompromising commitment to monitor the impact it will have on the environment and on the community.

The operation will use enormous amounts of water. What will be the long-term effect of such water demands? Is there a chance it could compromise this critical natural resource? Who will be responsible for maintaining the infrastructure?

Once the megafab is operational, there will be a huge demand for new housing. Do we have the capacity to build that much new housing? It will certainly be at the expense of farmland and forests. Would that be detrimental?

With new jobs and housing comes increased traffic and therefore noise and air pollution. What impact will this have on residents’ health and how will it be mitigated?

Regarding traffic, I have real concern that eliminating I-81 through Syracuse would be a huge mistake. This route is heavily used now. Considering the potential for 9,000 new Micron jobs and 40,000 community jobs over 20 years, it makes no sense to eliminate a thru-route, especially one that connects to a potential source of workers. The viaduct should be rebuilt.

It is fair and reasonable that residents of the region expect valid answers to these questions.

Sincerely,

Audrey Fletcher

Audrey Fletcher

Project & Resource Manager

6756 Thompson Rd, Syracuse NY 13211

315-432-8905 p

DARCO Manufacturing Inc.

Precision Machining for Industry

Office of Economic Development
333 West Washington Street
Suite 130
Syracuse, New York 13202

Re: Micron SEQRA

With a long-time family history (over 160 years) on Burnet Road, I would like to help promote the Micron Project. Yes, there is negative feelings that the Baker family was interrupted and now has moved on. Time has passed and the families have been relocated to other areas.

As an owner of a construction company JBS Dirt has worked on The Wolfspeed Project in Marcy, New York. The safety on site is of high standards. There are all kinds of safety plans and safety protocols in place to protect the environment and the workers. Not everyone will be happy with this kind of change in the community. Over all the economics of the region will be breath taking. There is so many things that need to happen in the infrastructure to make this all happen.

Traffic is a large problem now and will only get worse as time moves forward. There are a few options that I have attached. Exit off route 81 near the NYSPA tower crossing is in a great place. The area is on highland area and out of wetlands. Building a beltway around the Micron Project would limit the traffic congestion around the existing area. Adding a third lane on Route 31 for a turning lane is needed now before the extra Micron traffic starts. It will be hard to add access off and on ramps at Rt 481 due to the wetland in that area. Caughdenoy Road could be widen and straighten to come up to Rt 31. Caughdenoy Road north of Rt 31 should be widen to support extra traffic for construction and the ability to get to the Child Day Care Center.

The wetlands in the Burnet Road area are caused by the lack of funding to keep the Young Creek clear of debris. Back in the 50-60's most of the existing wetland was farmland. The property on the far North of the new OCIDA property once was a muck farm growing vegetables. Other area of newly form wetland grew crops of corn and hay and was harvested from this area to support the farming community. The local farmer and land owners asked for help to keep the channel of Young Creek open, but there was no funding to help. As the creek kept backing up soon the beavers started moving and backing up the water even more. Today the once good farmland is under water and classified as wetlands.

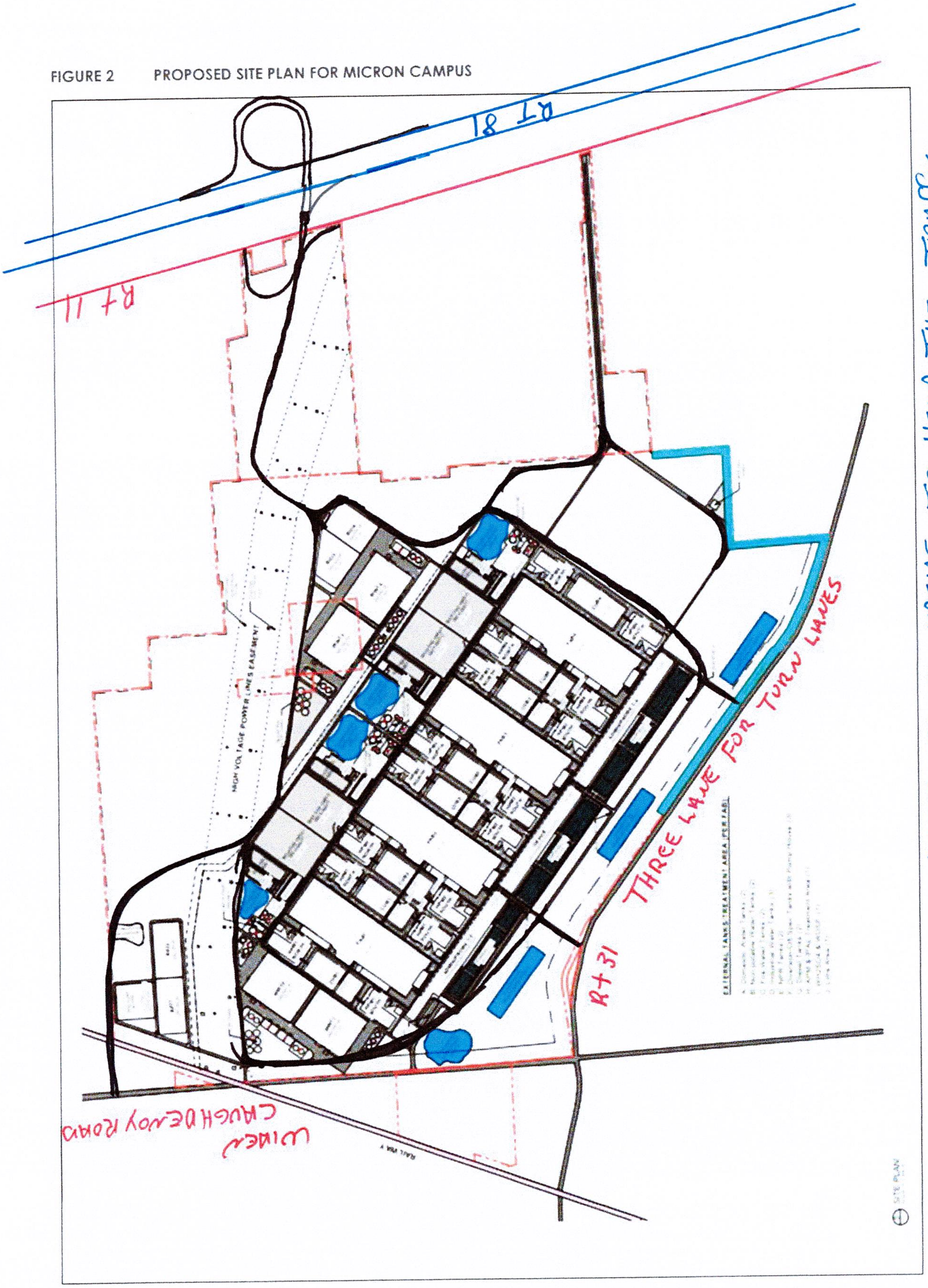
I would like to see the White house on the corner of Burnet Road saved and used in the future for something productive, as a land mark of the past history of the area. Other building that could be saved would be French's red barn on the South side of RT 31 to protect some of the past. Both areas seem to be out of the major build out of the Micron project.

As a long-time family member of Burnet Road, I will support the Micron Project. Change sometimes is hard to except but time moves forward.

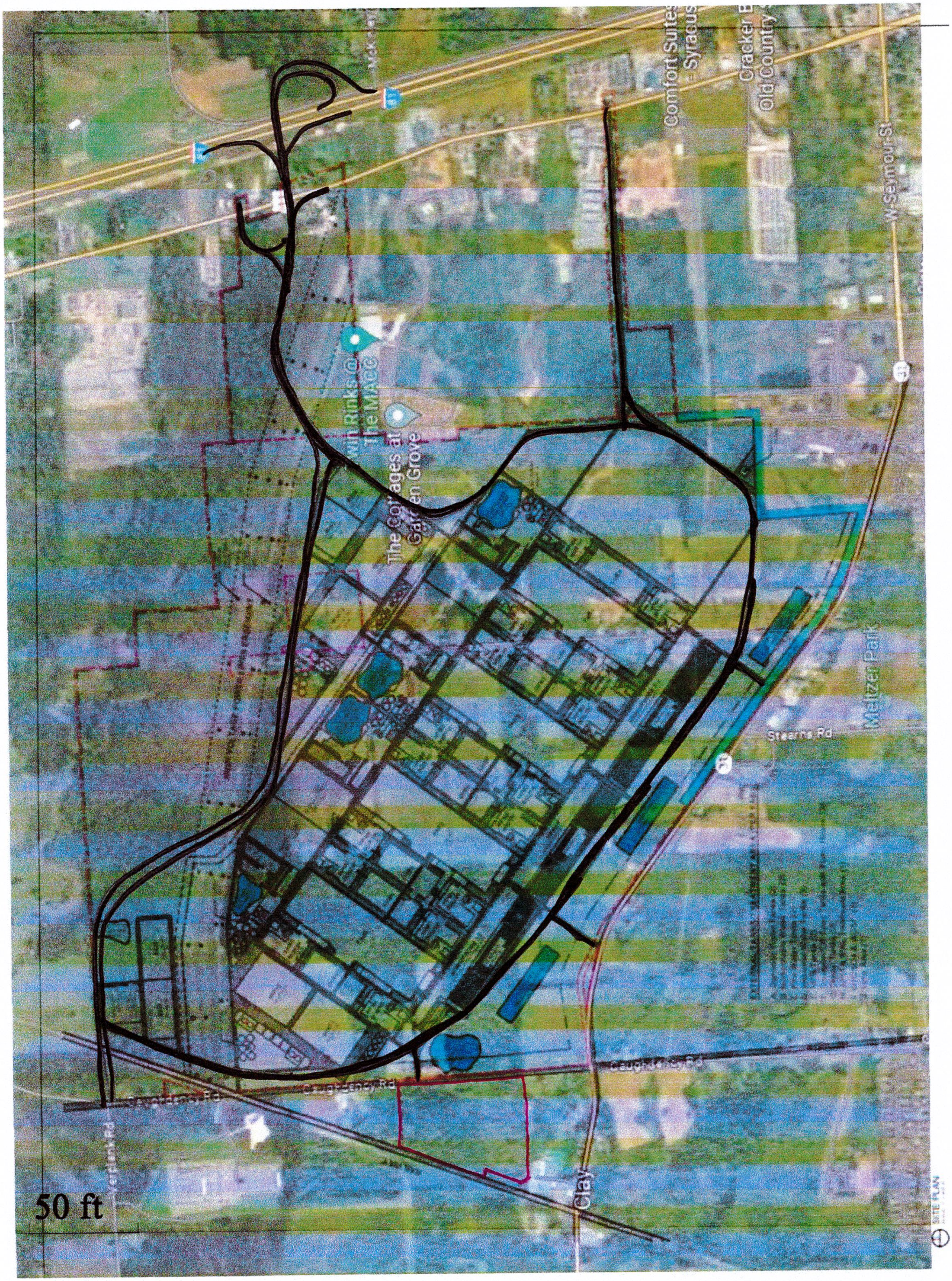
Thanks for your time and efforts,

Jim Baker Cell 315-427-3306
7901 Gee Road
Canastota, New York 13032

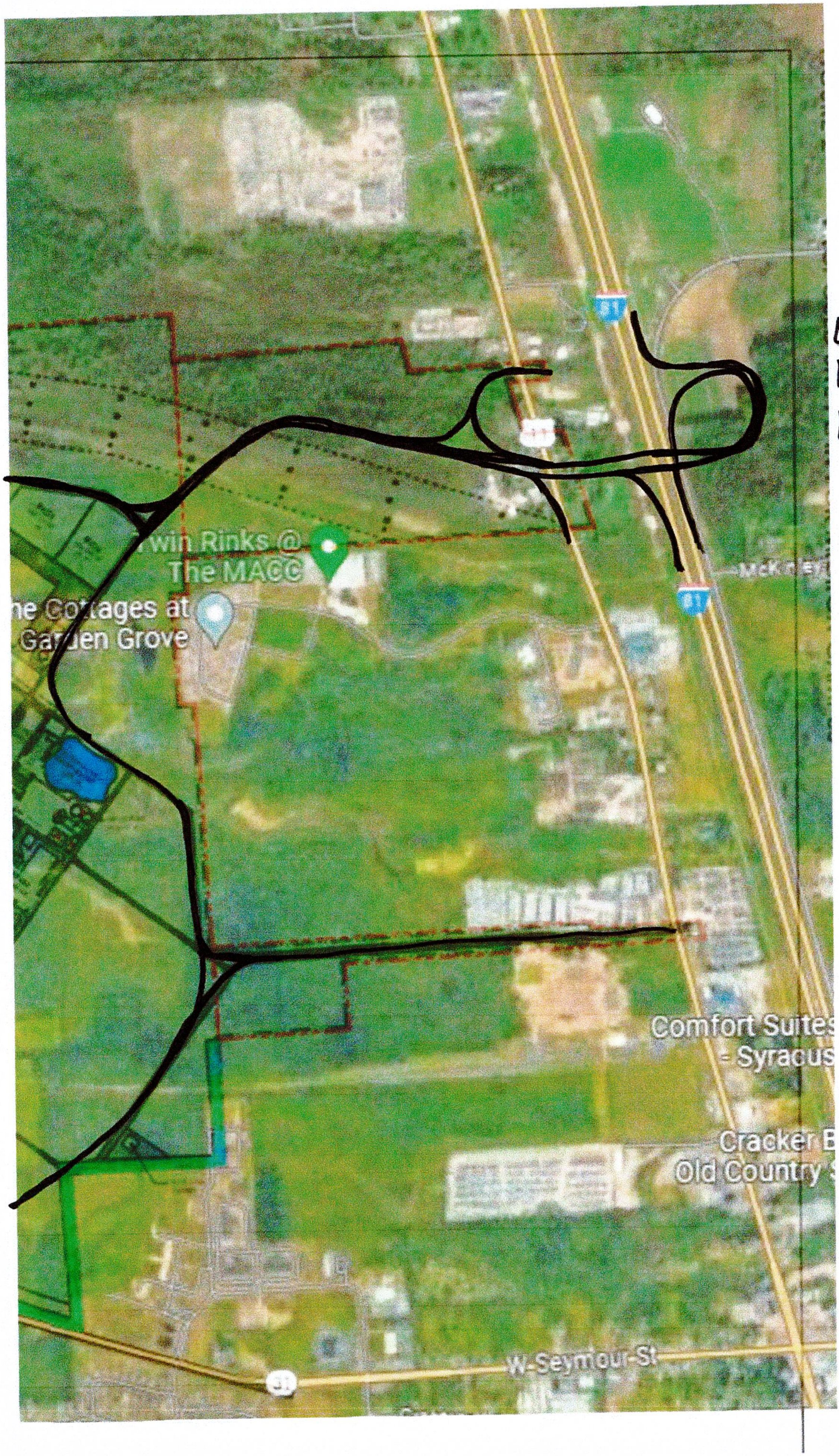
FIGURE 2 PROPOSED SITE PLAN FOR MICRON CAMPUS



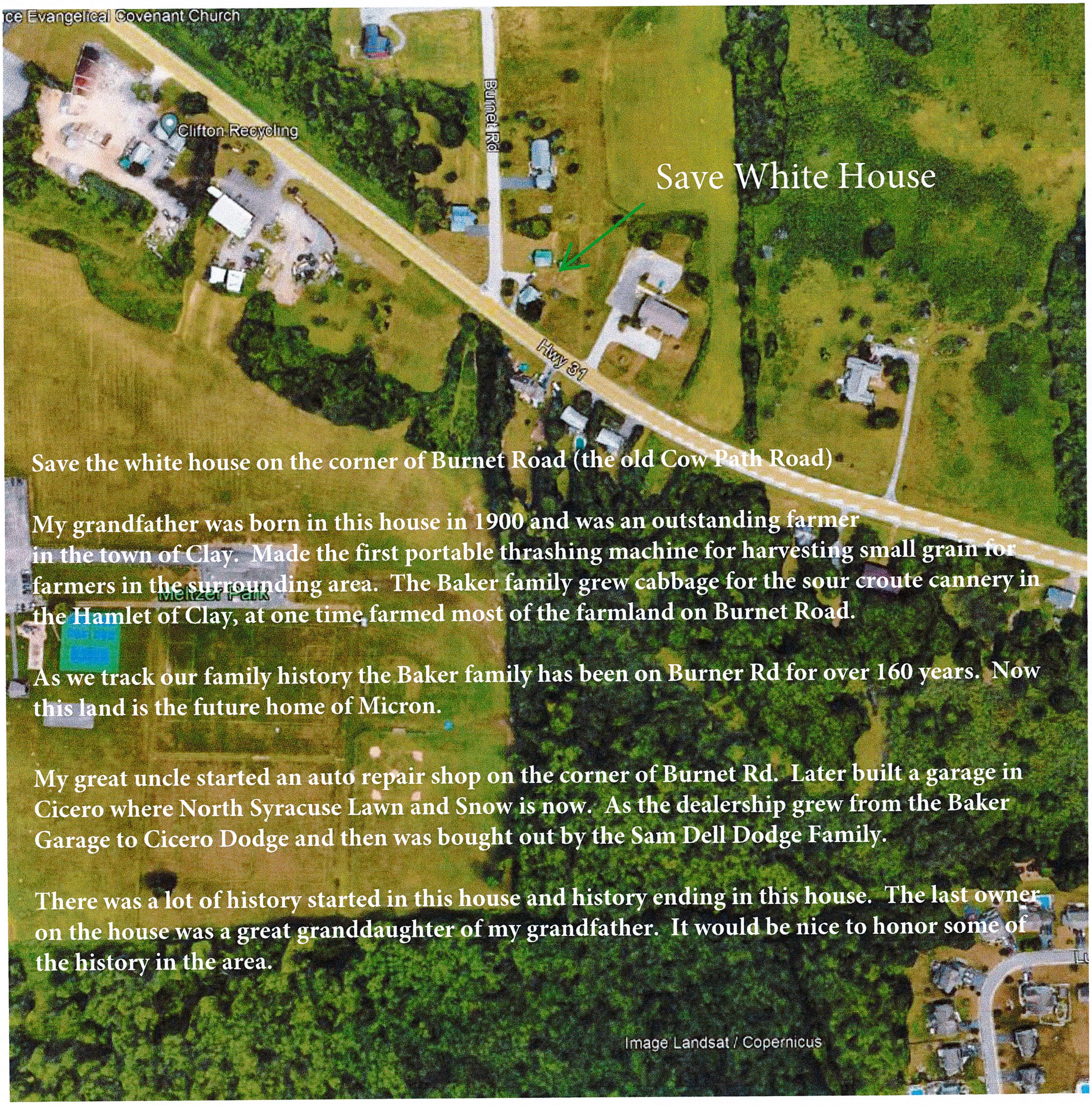
JUST SOME IDEAS TO HELP THE TRAFFIC PROBLEM WITHE AREA. I THINK THIS LIMITS THE WETLAND AREAS.


Comfort Suites
- Syracus
Cracker B
Old Country
W Seymour St
Twin Rinks @ The MAGG
The Cottages at Garden Grove
Meltzer Park
Stearns Rd
Caughdenoy Rd
Caughdenoy Rd
Verplank Rd
Clay
SITE PLAN
50 ft

Rt 11 & Exit Rt 81 To Micron



Exit
Rt 81 &
Rt 11
to MICRON



Save White House

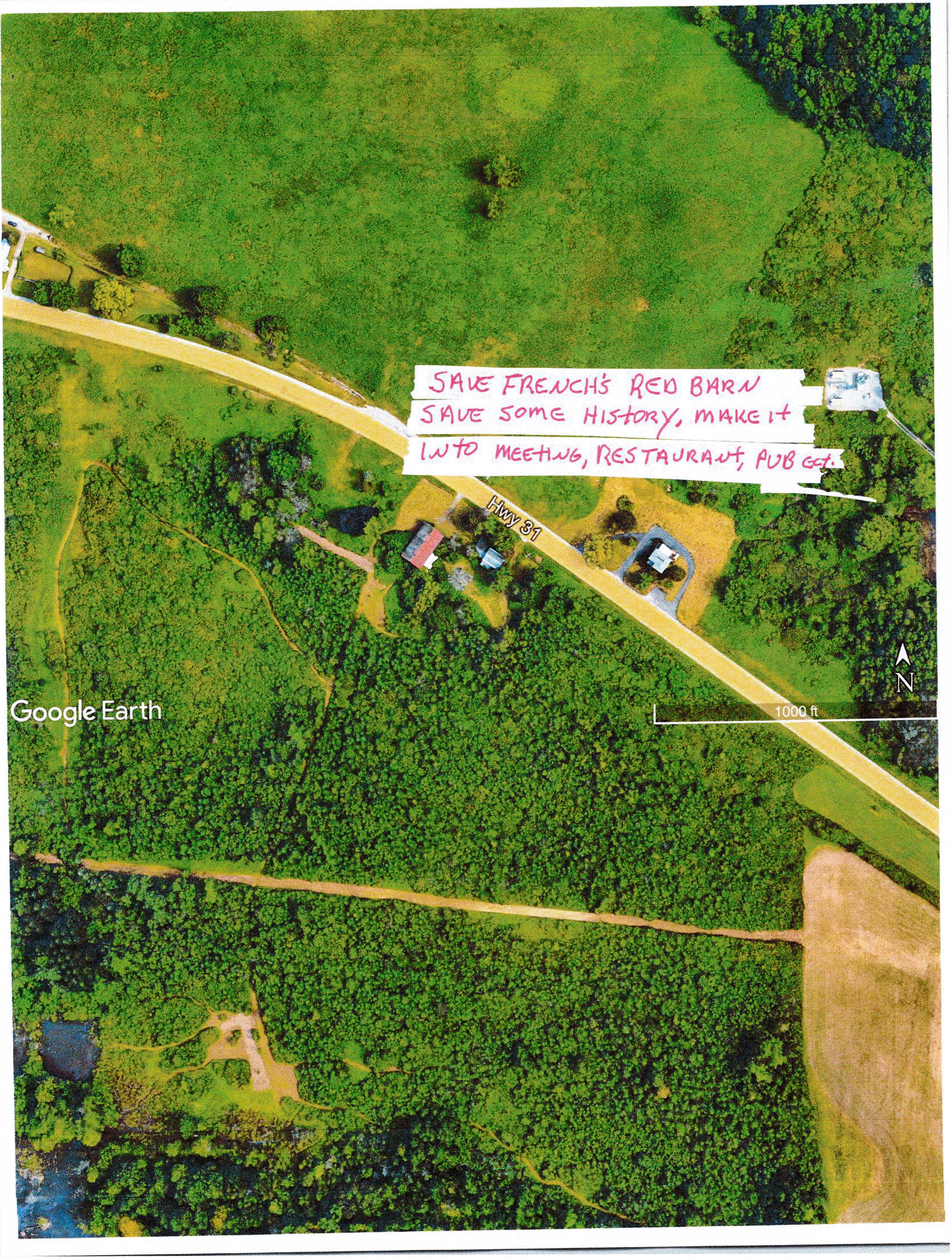
Save the white house on the corner of Burnet Road (the old Cow Path Road)

My grandfather was born in this house in 1900 and was an outstanding farmer in the town of Clay. Made the first portable thrashing machine for harvesting small grain for farmers in the surrounding area. The Baker family grew cabbage for the sour croute cannery in the Hamlet of Clay, at one time farmed most of the farmland on Burnet Road.

As we track our family history the Baker family has been on Burner Rd for over 160 years. Now this land is the future home of Micron.

My great uncle started an auto repair shop on the corner of Burnet Rd. Later built a garage in Cicero where North Syracuse Lawn and Snow is now. As the dealership grew from the Baker Garage to Cicero Dodge and then was bought out by the Sam Dell Dodge Family.

There was a lot of history started in this house and history ending in this house. The last owner on the house was a great granddaughter of my grandfather. It would be nice to honor some of the history in the area.



SAVE FRENCH'S RED BARN
SAVE SOME HISTORY, MAKE it
INTO MEETING, RESTAURANT, PUB ect.

From: Minchin G Lewis <mglewis@syr.edu>
Sent: Friday, October 20, 2023 7:57:56 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Cc: Minchin G Lewis <mglewis@syr.edu>
Subject: Comments on the Draft Scoping Document for the Micron development

To: Onondaga County Industrial Development Agency

ATTN: Micron Project

I have attached a document with my comments regarding the draft scoping document for the Micron development. I hope they are helpful for this transformational project.

Please let me know if there are questions or if any additional information is needed.

Respectfully submitted,

Minchin G Lewis, MPA, CGFM
Adjunct Professor

Maxwell School, Syracuse University

Department of Public Administration and International Affairs

315 Maxwell Hall

Syracuse New York 13244-1020

(315) 443-4000 FAX: (315) 443-9721

Cell: (315) 243-2530

To: **Onondaga County Industrial Development Agency (OCIDA)**
From: **Minchin G. Lewis**
Re: **Comments on the Micron Draft Scoping Document**
Date: **October 20, 2023**

Introduction:

The Micron proposal has created more potential for the Central New York Community than we have seen in the past 50 years. These comments are designed to enhance the substantial contribution that Micron is making to this community and to both ensure that environmental impacts are mitigated and that the intended outcomes are maximized. Please note that I support the planned Micron development.

These comments are being submitted to be considered in the preparation of the final scope of the EIS and may inform the related technical analyses and environmental resources to be evaluated. They are limited in content to comments on the potential significant adverse impacts that should be addressed in the preparation of the EIS.

Context:

The Micron development is taking place at a time when a plan proposed by the New York State Transportation Department would change the traffic patterns for over 100,000 daily travelers. NYS DOT's I-81 Viaduct Project plan proposes to remove the portion of I-81 through the city and replace it with a "Community Grid." According to DOT's plan, 60,000 vehicles would be diverted to what is now I-481. The remaining 40,000 vehicles would be diverted to city streets.

The traffic, air quality, and social impacts for Micron must be evaluated in the context of the existing and proposed infrastructure. It should be noted that the Community Grid Plan is subject to a court order requiring the need for additional diligence related to the Micron development[1] among other factors.

Comment 1: ***Significant adverse impacts could result in the assessment of environmental impacts from traffic if Automatic Traffic Recorder (ATR) counts and Vehicle Classification Counts (VCC) data sites are not added to collect data from sites in the City of Syracuse.***

Basis:

1. **The NYS I-81 Viaduct Project would eliminate a portion of I-81.** If allowed to commence, the interstate roadway through the city would be replaced with a boulevard and series of city streets (the Community Grid). The elevated section of the roadway would be removed. This interstate highway currently is the direct link for traffic northbound on I-81 from areas south of

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[1] News summary of the court decision: "A judge on Tuesday (2/14/2023) ruled that the process of the Interstate 81 project in Syracuse can continue but no demolition can take place until further environmental impact studies are conducted to address some deficiencies outlined in a lawsuit filed last fall by the group Renew 81 For All. State Supreme Court Justice Gerard Neri ruled the state Department of Transportation must now account for potential regional traffic and population changes that the $100 billion Micron project will make in the coming years." Accessed at https://spectrumlocalnews.com/nys/central-ny/traffic/2023/02/14/judge--further-environmental-impact-studies-must-be-done-on-i-81-project on 10/20/2023

the I-81/I-481 northern interchange (Interchange 29). Some of the traffic bound for Micron would be adversely affected by the changes proposed in the I-81 Viaduct Project. (See Footnote 1 below).

2. **The importance of I-81 is recognized for its impact in the draft scoping document.** The majority of the Micron Campus is contained within the Town of Clay, Onondaga County, New York and is accessible from I-81 from an interchange with NYS Route 31 (see Figure 1) OCIDA deemed the Radisson Corporate Park as an unviable choice because it lacked . . . specific advantages such as the proximity to Interstates 81 and 481. The draft scoping document notes that the lack of "access to multi-modal transportation" is often a point of failure for most other sites. Changes to I-81 should be evaluated for potential adverse impacts on the Micron development.

3. **Traffic issues potentially affect environmental justice.** Micron will operate three (3) shifts over a 24-hour day. Day and night shifts will be utilized to sustain 24-hour manufacturing activities as well as a maintenance shift. (1.1.2) Current projections for additional housing to accommodate the economic growth related to Micron call for 2,000 to 2,500 residential living units per year for the next two decades. Onondaga County's plan[2] suggests that much of that growth will take place in Syracuse, a "Strong Center" and the only "City Center" in the region. It is likely that many of Micron's employees will reside in the city. Those living south of I-690 would potentially be negatively affected by NYS DOT's proposed Community Grid Plan. Traffic data should be collected from that geographic area to be used in projections, especially since the southwest side of the city has been a concentration of historically disadvantaged populations. With well over 100,000 new residents projected, it is critical that the infrastructure is designed to support the planned growth.

4. **Consideration has been given to many other strategic locations**. The attached Appendix A maps show a selection of locations for data collection. Data sites are in diverse communities such as Fulton. Central Square, and the northside of Syracuse. Comparable data sites should be located in the City of Syracuse.

5. **The scoping document shows concern for local roadways**. A rail spur will be developed to supply construction materials and avoid impact on local roadways. (1.1.2). Many local roadways in the City of Syracuse will be affected by on-going Micron traffic.

Conclusion: Based on the above factors, significant adverse impacts could result if the Draft EIS does not analyze data from impacted locations. Specifically, ATR and VCC data collection should also take place at strategic locations in the City of Syracuse south of the I-690 corridor.

1. Access to the Micron facility may come from those locations.
2. Those locations could have an impact on environmental justice by reducing convenient access to Southwest side of the city.
3. The Community Grid, if implemented to remove the I-81 Viaduct, will increase the negative impacts for employees and suppliers accessing Micron from I-81 south of I-81/481 Interchange 29.
4. Air quality should be monitored at all the traffic locations.

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[2] See "Plan Onondaga," the County's Comprehensive Plan, accessed at plan.ongov.net/the-plan/ on 10/19/2023.

5. The additional sites would provide data to establish a baseline for future planning.

Comment 2: Significant adverse impacts could result from relying on prior studies.

1. The draft scoping document suggests that "to the extent applicable, prior studies completed by OCIDA as part of its generic environmental impact statements will be referenced in the site-specific assessments completed as part of the current environmental impact statement."

2. Many studies were conducted as part of the I-81 Viaduct project. A court found that those studies did not adequately address the environmental impacts of the proposed alternative being evaluated by NYS DOT. (See Footnote 2)

3. To mitigate the possibility that adverse impacts could result from relying on prior studies, the Draft EIS should call for new traffic studies to be conducted by independent professional traffic engineering firms. The firms should have a national reputation for independence. They should be charged with collecting totally new data to replace most of the data cited in the I-81 Viaduct Project, data was collected prior to 2013.

4. To ensure that the Micron project achieves the desired outcomes for all local residents, it is essential that OCIDA not rely on NYS DOT for matters related to I-81, and conduct its own due diligence related to traffic.

Submitted by:

Minchin G. Lewis
205 Rigi Avenue
Syracuse, NY 13206
Cell: 315-243-2530
Email: Mglewis@syr.edu

APPENDIX A:

Automatic Traffic Recorder (ATR) Counts: ATR volume data summaries will be summarized in 15- minute intervals by location.

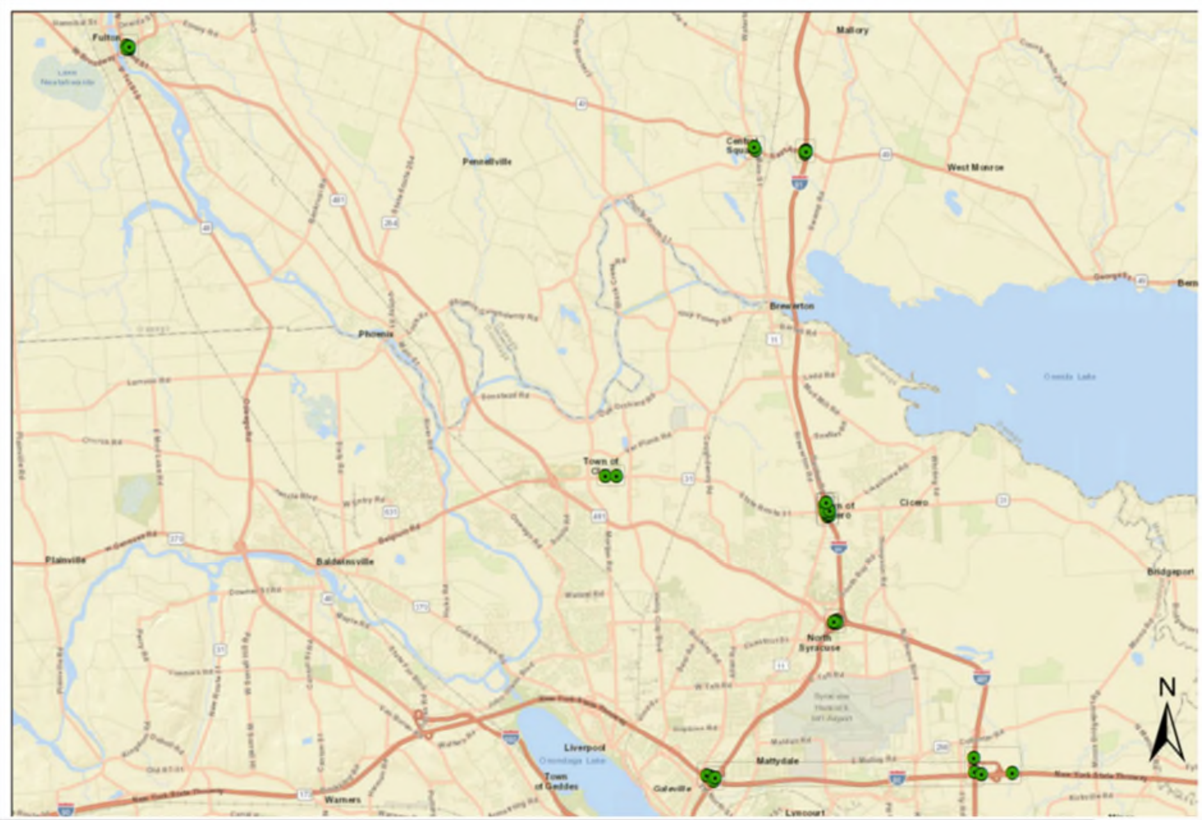

FIGURE A-3 VEHICLE CLASSIFICATION COUNT LOCATIONS

Vehicle Classification Counts: The VCC volume data summary will be summarized by location in 15-minute intervals. Traffic recorded for the VCCs will be sorted into four vehicle classifications: Autos, Buses (which would include non-articulated buses, articulated buses, and jitneys), Medium Trucks, and Heavy Trucks.

From: go <goldtailedhermit@aol.com>
Sent: Saturday, October 21, 2023 3:57:56 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: ATTN: Micron Project

October 20, 2023

Onondaga County Industrial Development Agency
335 Montgomery St
Syracuse, N.Y. 13202

To Whom it May Concern:

As Conservation Chair of Onondaga Audubon, I feel that I should send a comment regarding the Micron megafab site coming to Clay, New York. The consideration of the changes that this development brings with it is quite overwhelming and I am not sure if it is possible to mitigate for them.

Open space is something that residents of upstate New York have taken for granted for many years. We enjoy it and the members of Onondaga Audubon enjoy outdoor activities, especially birding. It is obvious that the land use impacts of the Micron project will be significant. Within the 1400- acre project area, there will be a loss of 315 acres of forest, 430 acres of meadows/grasslands/brushlands, and 131 acres of wetland. Roads, buildings, and impervious surfaces will grow from 5 acres to 514. In addition to these changes, the region outside of the project's direct footprint will be modified in order to support influx of as many as 100,000 new residents. Zoning maps have already been changed to increase the amount of land available to be developed for housing.

All of these things will diminish the amount of "wild" or unused land in our locale. Space like this is valuable to many people because it supports birds, wildlife and biodiversity. This is a huge loss to many. Does the economic gain that Micron will bring to Onondaga County cancel this loss?

As a leader in technology, I would hope that the lighting used on the Micron campus will be aimed downward so as not to brighten the night sky. I would also hope that there will be some sort of mitigation for the loss of forest, meadow, and wetland that is simply unavoidable as the Micron site is developed. I have also learned about the plans for several housing developments along the Route 31 corridor with dining, shopping, and entertainment opportunities to be included. Along with this sort of mindful development, the landscaping needs to be done mindfully as well. The use of native plants and trees would help mitigate the loss of the many acres of native vegetation that had been present on the development site.

Thank you for reading this.

Sincerely,
Maryanne Adams
Conservation Chair
Onondaga Audubon
P.O. Box 620
Syracuse, NY 13202

From: Paul Goldsman <pgoldsman@gmail.com>
Sent: Saturday, October 21, 2023 1:04:11 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Comments on the Draft Scoping Document for Micron project

Both the original generic SEQRA and the revised SEQRA documents note a number of historic properties located on Burnet Road and other parts of the White Pine site, some of which are eligible or potentially eligible for listing on the NY State Register of Historic Places. These properties were supposed to be surveyed/assessed in conjunction with the NY State Historic Preservation Office (SHPO, and possibly other state authorities). For example, in the "Full Environmental Assessment Form, Part 1 - Project and Setting," on p13, section E3e, it states: "Updated consultation with NYS SHPO will be conducted," and "Coordination with NYS SHPO will be conducted." (https://www.ongoved.com/assets/Uploads/files/projectfiles/Revised-SEQRA-EAF-Part-I.pdf)

Nearly all of the properties owned by OCIDA along Burnet Road, and others elsewhere on the site are currently in various phases of demolition by OCIDA. I spoke with a representative from Micron at their public meeting on August 1. She said that the survey/study was due to be performed in the Fall. She was surprised to learn that demolitions were already in progress. Has the proposed survey/coordination with SHPO been completed? Was it completed before the demolitions began? Is the report available to the public?

P Goldsman, Liverpool, NY

From: Jill Shultz <jills@stny.rr.com>
Sent: Wednesday, October 25, 2023 1:34:47 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron
Subject: Micron Project

Micron's huge campus will gobble up a lot of land, causing a range of environmental problems. I'd like to see them prevent as many of them as possible.

One often overlooked mitigation is the use of native plants in landscaping instead of the typical ornamentals, which are usually nonnative and contribute almost nothing to our pollinators and wildlife.
Ask for 80% native plants, especially in the shrub and tree layer -- ideally provided by our local native plant nurseries. Native plants are beautiful and once established, far hardier than their foreign counterparts, as well as easier to maintain, requiring less water, fertilizer, and mulch. And they'll attract birds and butterflies.

Cities around the world are updating their building codes to require the installation of native plant landscaping to offset the environmental costs of buildings and hardscapes. This also makes the community so much more beautiful and inviting, a better place to live and work.

I'd also like to see requirements for the installation of renewable energy projects.

Our natural heritage belongs to all of us, not just corporations that want to consume it for their profits, and protecting it is vital to survival.

Sincerely,

Jill Shultz

From: Peter Wirth <pwirth2@verizon.net>
Sent: Wednesday, October 25, 2023 3:26:52 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron
Subject: ATTN: Micron Project. -you can send written comments to OCIDA at

NOTICE: This email originated from outside of Onondaga County's email system. Use caution with links and attachments.

Questions for OCIDA regarding Micron Project

Statements by our County Exec. and Micron officials the Micron project in Clay NY will use 100% renewable energy. I have the following questions.

1. My understanding is the fab plants and all buildings on what is referred to as the campus will be heated & cooled by nonfossil fuel technologies ie. electric They will be heat pumps or a similar technology for heating. For cooling they will also use electric based appliances such as electric chillers. Is that correct? If not what sources of energy will be used for heating and cooling?

2. My understanding is that cooking facilities (cafeteria, kitchen for day care center etc.) in all the buildings will be electric and will not be gas based. Is that correct? Why would greenhouse gas based appliances be considered since the commitment is to 100% renewable energy ie. nonfossil fuel.

3. If hydrogen is used as an energy source will it be green hydrogen?

4. Re. solar will there be roof top solar installed and any additional solar farms on adjoining property?

5. If rooftop solar will be installed when will the new architectural drawings be finished as current drawings in the Syracuse Post Standard do not show rooftop solar.

6. Re. the breakout for the electrical usage will there be a breakout showing what percentage is coming from wind, solar etc. How will we know the electricity is sourced from renewable sources?

7. According to Micron documents National Grid is constructing a 16 inch high pressure gas line to the plant. What is the capacity of that gas-line?

8. Why are Micron officials using terminology "100% renewable energy" when referring to the plant when massive amounts of methane will be used at the plant? Methane is a much more potent greenhouse gas than CO2

Thank you for considering these questions.

Looking forward to your reply

Peter Wirth

Vice President

Climate Change Awareness and Action

A local, CNY organization with 1,600 members

From: Mary Lou Bender <bendermarylou8@gmail.com>
Sent: Thursday, October 26, 2023 2:12:02 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Micron Project

TO OCIDA & MICRON:

I reside in an apartment complex called Tocco Villaggio located on Legionnaire Dr. which is approximately 1/2 mile away from Burnet Rd. There is a tree line to the north of Micron's site which esthetically enhances our view, and acts as a sound and visual buffer. At Tocco Villaggio, we are set back from Rt. 31 and enjoy the quiet quality of life. There is a pond on the property where geese & herons are protected and the soothing sounds of crickets or other creatures that inhabit the pond enhance our quiet and nature driven quality of life.

We are very concerned that all the construction and Micron related heavy duty equipment & traffic will have a negative impact on the quality of our life. Also, we implore the tree line not be torn down, and in fact, several hundred more trees should be planted in the Micron complex. We are basically a rural community, and want to preserve our quality of life. My questions are what is OCIDA/Micron planning to do to preserve the trees and other environmental aspects and quality of life issues that greatly impact our rural community?

Thank you for your consideration and the courtesy of a reply.

Mary Lou Bender
5501 Legionnaire Dr.
Apt. 311
Cicero, NY 13039

From: Craig Polhamus <craig@zausmerfrisch.com>
Sent: Thursday, October 26, 2023 11:18:03 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: ATTN: Micron Project

Dear Members of the Environmental Review Committee,

As a licensed architect and a concerned citizen, I am writing to express my deep concerns about the proposed $100 billion expansion of Micron in Central New York. This expansion represents a significant step forward in our technological capabilities and economic growth. However, it also presents potential risks that must be thoroughly evaluated and mitigated to ensure the safety and well-being of our community and environment.

History is replete with examples of disasters that have resulted from overlooked or underestimated risks. The sinking of the Titanic and the Hindenburg disaster serve as stark reminders of the devastating consequences that can occur when potential risks are not fully considered and addressed. These incidents were not inevitable accidents, but rather the result of a failure to adequately assess and mitigate known risks.

Closer to home, we have seen the devastating impacts of industrial and environmental disasters. The pollution of Onondaga Lake by Allied Chemical, the Love Canal disaster, and the Split Rock explosion have all had profound impacts on our community and environment. These incidents have caused immeasurable harm to human health and the environment, and their effects are still being felt today.

The semiconductor industry is not immune to these risks. The production process is complex and global in nature, subject to numerous risks including geopolitical tensions, earthquakes, extreme weather events, and supply chain disruptions. Moreover, the manufacturing process involves the use of hazardous materials that can pose significant risks to human health and the environment if not properly managed.

As we consider Micron’s proposed expansion, it is crucial that we fully understand these risks and take all necessary steps to mitigate them. This includes conducting a comprehensive review of the facility’s architecture for best practices in containment, safety, and resiliency. We must ensure that all potential environmental impacts are thoroughly assessed and adequately addressed before proceeding.

I urge you to consider these cautionary tales from history as well as more from this list of industrial disasters as examples to keep in mind as we evaluate Micron's proposed expansion. It is our responsibility to learn from these past mistakes and ensure that they are not repeated.

We have an opportunity here to demonstrate that economic growth and environmental responsibility can coexist. By taking a proactive approach to risk management, we can ensure that this expansion proceeds in a manner that is safe, sustainable, and beneficial for all.

Thank you for your attention to this matter. I trust that you will give these concerns the serious consideration they deserve.

Sincerely,

Craig Polhamus, AIA

Registered Architect

ZAUSMER·FRISCH
SCRUTON & AGGARWAL
DESIGNERS / BUILDERS

219 Burnet Ave., Syracuse, NY 13203

Tel: (315) 475-8404

Email: craig@zausmerfrisch.com

From: Richard Ellenbogen <richard@alliedconverters.com>
Sent: Friday, October 27, 2023 2:28:42 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron
Cc: Richard Ellenbogen
Subject: Ellenbogen Comments on the Micron Technologies Draft Scoping Plan 10-27-2023.pdf

Onondaga County Industrial Development Agency
ATTN: Micron Project
335 Montgomery Street, 2nd Floor
Syracuse, New York 13202

Please see the attached comments regarding the Draft Scoping Plan for Micron Technologies.

Thank you.

Richard Ellenbogen

President
Allied Converters, Inc.

Ellenbogen Comments on the Micron Technologies Draft Scoping Plan

I have some comments on potential significant adverse impacts that should be addressed on the Draft Scoping Document. I am a former Bell Labs Engineer that worked in their Power Systems Laboratory. My research has been used by the NY State Public Service Commission as the basis of a utility conference to address transmission line loss that resulted in significant energy savings in NY State. I was also the Keynote Speaker at the 2023 Business Council of NY State Renewable Energy Conference.

Issues

The current plans for powering the Micron facility in Clay, NY, while looking good on paper, will in fact increase emissions on energy used to supply the Micron facility, raise Micron's costs above what they could be, and are not achievable in any realistic time frame using renewable energy. Forcing Micron to purchase Renewable offsets may look good on paper but will do nothing for the environment. The reality is that NY State is going to have major difficulties just providing renewable energy for its existing electric load, let alone the predicted additional 16 Terawatt hours (TWh) of the Micron facility. To put that amount of energy in perspective, it is nearly as much as was produced by the 2 Gigawatt Indian Point Nuclear Plant in its last full year of operation.

The New York Power Authority has said that it will provide 140 Megawatts of Hydroelectric Power to Micron, however that Hydropower does not exist, even at night. Any hydropower provided to Micron will force whoever is using it presently to switch to fossil fuel generation. It is an energy "shell game".

The reality is that Micron is going to be powered by Fossil Fuel Generation that is transmitted over long distances, very likely from out of state in Pennsylvania or Ohio that have generation carbon footprints far higher than those in NY State. As GHG emissions are not cognizant of political boundaries on a map, those emissions will end up affecting NY State residents. Additionally, transmitting that much power over those long distances is going to greatly increase line losses. It will also increase the strain on the transmission system in Western and Central NY State, raising costs for that as well. Just a 3% line loss on that amount of energy will result in losses totaling close to 500 Gigawatt hours (GWh) annually. To put that in perspective, Cornell University uses 200 GWh annually to operate the entire University, so just the energy loss getting the power to Micron could operate Cornell for 2-1/2 years. Importing electric power to the Micron facility from off- site is a foolish concept and there are far better solutions. Instead of making Micron look "Green" on paper to satisfy some prescribed number in a document, Micron could be "Green" in reality with far lower holistic emissions and lower operating costs simultaneously. It would be better for the environment, better for the bottom line of Micron Technologies, and better for the economy of Central New York.

Solutions

To address these issues and the associated potential significant adverse impacts, the Draft Environmental Impact Statement should include an alternative to add a Combined Cycle generating plant on the Micron Property. By adding a 2 GW combined cycle plant on the Micron Property, it would save the 500 GWh of line loss annually. That is the annual output of a 500 Megawatt solar array that would cover approximately 1500 acres (2.35 square miles). As energy is fungible, eliminating those losses would make that wasted renewable energy available to help green the rest of the state. Further, by siting the Generating Center on the Micron site, the waste heat resulting from the generating process would be made available to Micron. As they have an enormous thermal load, they could make use of nearly the entire energy content of the combusted gas used to generate electricity. That sized facility is roughly twice the size of the recently built Crickett Valley Energy Center. In 2018, the cost of that facility was approximately $1.5 Billion. Adjusted for the recent bout of inflation, that could be $2 Billion today, making the total cost of a combined cycle facility for Micron approximately $4 Billion. However, Micron will recoup that money in energy savings and reduced costs, making the site even more attractive for development. As Micron will be expanding over time, the generating center would not need to be built at its full capacity initially. It could be expanded over time and if newer, more efficient technologies were developed, those could be incorporated as part of the later expansion of the energy center..

There are also possibilities for using the CO2 emissions of the generating facility for agricultural purposes, further reducing the carbon footprint of the plant.

Common sense solutions to energy issues have to be adopted if NY State is going to reduce its Carbon Footprint and remain a cost competitive state in which to do business. Blindly following an ideology that contradicts math and physics is not an intelligent way to create a sound environment for either business or the health of NY State residents.

Richard Ellenbogen

President
Allied Converters, Inc
New Rochelle, NY

richard@alliedconverters.com

From: roger.caiazza@gmail.com <roger.caiazza@gmail.com>On Behalf OfRoger Caiazza <nypragmaticenvironmentalist@gmail.com>
Sent: Sunday, October 29, 2023 7:51:03 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Comment on the Draft Scoping Document and Proposed Content of the Draft EIS.

My comments on the draft scoping document and proposed content of the Draft EIS.for the Micron New York Semiconductor Manufacturing Action are attached.

--
Roger Caiazza
7679 Bay Cir
Liverpool, NY 13090
Pragmatic Environmentalist of New York
NYpragmaticenvironmentalist@gmail.com
315.529.6711

Caiazza Comments on the Micron Technologies Draft Scoping Document

I have some comments on potential significant adverse impacts that should be addressed in the Draft Scoping Document. I am a retired air quality meteorologist and live less than seven miles from the White Pine Commerce Park. I recognize the tremendous opportunity that this project affords this area and provide these comments in that context. I recommend that Section 5.3 – Methodologies for Technical Analyses include recent permitting requirements related to proposed disadvantaged community guidance. I suggest two co-generation alternatives be analyzed in the Draft Environmental Impact Study (DEIS). The associated benefits and adverse impacts of co-generation relative to the benefits and adverse impacts using electricity from the grid and natural gas only for thermal load requirements on-site should be considered in the environmental analyses. In the short-term because natural gas apparently is going to be used for process applications and heat, I believe a natural gas fired combined cycle combustion turbine(CCGT) should be included to support process applications and heat as well as provide electricity for the facility. In the long-term I believe that the facility should be designed so that a small modular nuclear reactor could be built to replace the CCGT when the technology is proven and available.

Disadvantaged Community Requirements

There is a draft permitting requirement that should be considered in the Technical Studies section of the DEIS. The New York State Department of Environmental Conservation (DEC) recently proposed a new policy that will require an analysis of impacts on disadvantaged communities (DACs) as part of most environmental permitting actions. The draft policy, DEP-23-1: *Permitting and Disadvantaged Communities*, was proposed by the Division of Environmental Permits on September 27, 2023. While this is a draft policy it will be in place by the time the DEIS is complete. My initial reading of this policy suggests that it is so comprehensive that it would not surprise me that, even though the facility is not in or adjacent to a disadvantaged community, that it still could be a consideration.

Co-Generation Alternatives

Section 4.3 Alternatives to be Analyzed in the DEIS should include options for co-generation. In brief, I believe there is a compelling argument that the proposed facility is so large that its energy use has ramifications not only to the facility but also New York State policy.

On Page 18 in the discussion of project locations the rationale for this location was described:

> While all four New York State sites were among the most expensive in terms of construction costs, personnel, water and wastewater, and real estate and personal income taxes, the New York State sites had a competitive advantage on electricity and natural gas costs. On balance, the study concluded that New York State led all competitors in terms of the capacity, capability, and probability of delivering a meaningful incentives package.

There may be a competitive advantage today for electricity and natural gas costs today but when the electric grid is transitioned to “zero-emissions” in the future electricity costs will increase dramatically. The likelihood of the complete buildout improves if energy costs are kept low and that would be best accomplished if Micron contains costs by on-site generation. Furthermore, I suspect, but do not know, that natural gas will have to be used anyway for system processes and heating. If that is the case then this option is a pragmatic energy-efficient solution.

According to the information provided so far, the amount of electric power required by Micron if everything is built will be equivalent to the electric power used by Vermont and New Hampshire. An article by James Hanley at the Empire Center that describes potential ramifications:

> Computer chip manufacturer Micron has revealed that by the 2040s its Onondaga County factories are going to be sucking up enough electricity to power New Hampshire and Vermont combined. Put another way, in a single year Micron will use enough energy to power the city of Buffalo for more than six years.
>
> All of it is supposed to come from renewable energy—but to date, despite offering Micron $6.3 billion in taxpayers' money to move to New York, the state has no plan for providing that much renewable power.
>
> Micron predicts it will use over 16,000 gigawatt-hours of electricity annually. To get a sense of how much that is, a gigawatt-hour is roughly the amount of energy produced by a single large nuclear reactor in one hour. Micron's expected demand is almost exactly what the two reactors at the Nine Mile Point nuclear plant produce each year.
>
> But since their factories will allegedly use 100 percent renewable energy, the big question is where it will come from.
>
> Micron will need to draw 1.85 gigawatts of power from the grid continually, 24 hours a day, to power its operations. The New York Power Authority has offered Micron 140 megawatts (0.14 gigawatts) of hydropower. It may not have that much to spare, except at night when statewide electricity demand drops. But even if it can steadily provide Micron that much power, that's just over 7 percent of the company's needs.
>
> Micron has also signed a 178-megawatt (0.178 gigawatt) onshore wind power agreement. That will produce less than 467 gigawatt-hours annually, a mere three percent of Micron's needs. Add those together, and 90 percent of Micron's power demand remains to be determined. Even before Governor Hochul bribed Micron to come to New York, the state faced a 10 percent deficit in its energy supply by 2040, creating a risky future of probable blackouts due to insufficient power production.
>
> The danger is caused by the state's climate policies. As consumers are mandated to buy electric cars, and households are forced to switch from natural gas to electric heat, electricity demand is expected to as much as double by midcentury. And 70 percent of that future electricity demand must be supplied by renewable energy.
>
> Because hydropower output will not increase significantly, solar and wind power must increase from their current output of approximately 7,600 gigawatt-hours to as much as 185,000

> gigawatt-hours by 2050. When Micron is added to the mix, the need will rise to almost 200,000 gigawatt-hours of wind and solar, a 2,600 percent increase from today.
>
> That's a challenge New York simply has no real plan for achieving, because the state's renewable and clean energy goals are based more on wishful thinking than hard-headed analysis about the technical challenges of radically restructuring the state's power system.

Richard Ellenbogen submitted relevant comments to the New York State Public Service Commission (PSC) "Order initiating a process regarding the zero-emissions target. Ellenbogen argued that natural gas-fired combined cycle power plants are a viable alternative during the transition. He makes a persuasive case that the huge electricity load of the proposed Micron chip fabrication plant should include a combined cycle co-generation plant that would provide both electricity and heat for the facility.

He explains:

> With regard to Micron Technologies, one could be built on-site that would eliminate 500 GWh of line loss while also providing Micron easy access to high temperature thermal energy. The Energy on Demand aspect of the generating plants also eliminates the need for trillions of dollars of battery storage. It is not a perfect solution, but it is a far better solution than "ideal" solutions that can't be executed because of the previously documented issues.

I recommend that the DEIS include the option for a co-generation facility. If small modular nuclear reactors were a proven technology, then using that approach would provide long-term zero-emissions consistent with the Climate Leadership and Community Protection Act. Unfortunately, reality is that this technology is not available but neither is all the technology necessary for an electrical grid dependent upon wind, solar, energy storage, and a dispatchable emissions-free resource that the New York Independent System Operator, the Climate Act Integration Analysis, and the aforementioned PSC order all agree is necessary. Therefore, to ensure that this vitally important project has the affordable power it needs to come to fruition, natural gas co-generation is a logical option that should be included. The DEIS should consider phasing in sufficient co-generation to provide the on-site electricity and thermal load requirements as the facility expands. The DEIS should also assess an alternative with a project layout that could eventually enable deployment of a nuclear option.

Personal Background

I have extensive experience with air pollution permitting and regulatory analysis with over 40 years' experience in the sector. The opinions expressed in these comments do not reflect the position of any of my previous employers or any other company I have been associated with, these comments are mine alone.

Roger Caiazza
Pragmatic Environmentalist of New York Blog
NYpragmaticenvironmentalist@gmail.com
Liverpool, NY

From: Michelle Fanelli <fanellirm@icloud.com>
Sent: Sunday, October 29, 2023 10:04:43 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: ATTN: Micron Project

How will Micron drawing up to 48 million gallons of water daily, affect dairy farms? Other agriculture? How will the water use affect people in the region? How much water will be wasted during the manufacturing process? Is it possible to treat and reuse the treated water? What is the water used for?
How will the daily use over time impact the water level of Lake Ontario? Will the cleaned waste water be returned to the lake? How will the local water levels be impacted by the water use? Are they gonna keep their promises on cleaning the water before letting it hit the environment? What if somewhere down the line this causes a shortage of water?
Will there be air pollution that will impact the people? What will be done about gas wastes that could affect surrounding communities? How will green energy be used? How badly will the energy bills rise? Can solar panels be used? Or hydro electricity? What type of emissions would it emit? If there are emissions, will special carbon/particulate scrubbers be used? How will the process of creating the factory impact the air? Will the gas coming from this company be contained or just go out into the environment?
How is this huge building going to affect the air and the environment around it? Why was the location near a marsh selected? What is the plan to limit the impact on the organisms near and in the marsh?
Will the water use impact the drinking water? Is there a set list of contaminants that will be shared with the local community? Is Micron aware of the history of Onondaga lake as a Superfund site? How will Micron handle the disposal of toxic chemicals and waste?
How will the waste water be treated? Can the process be described for the community? Will the local pipes be fixed/changed in order to support the projected changes to the water use? How do we know the returning wastewater has been thoroughly cleaned? How will the amount of water Micron uses affect the amount of water available to me and my family?
Will Onondaga county be playing a role in water purification from the site? How is OCWA planning on handling the increase in water production? How will the increase in this infrastructure expansion be covered financially?
How does the county/NYS plan on regulating the manufacturing site? How will the county ensure that the environmental use will be regulated in order to keep it from becoming a Superfund site (ex. Onondaga lake history)
How long will the environmental impact be felt after the production site is up and running? Will local water sources be tested regularly to prevent water contamination? Where will the solid wastes go after they have been used/after the water

has been cleaned? How will this effect wild life around and in the area, by ripping down the woods, grass land, and houses?
Are they gonna be working through the Clay water purification center or making their own on-site? Or both?
Why does Micron need to be built in Clay of all places? Will the local community be impacted financially due to the building of the pipeline to carry the water? How is the expense being covered? Why should the public have to pay for water bill if they already pay enough? Will there be a clean up plan if the site does become contaminated? Where would local members go while the site is cleaned?
What species will be affected by this and will populations be monitored? What will be done for organisms living in this area (animals, humans, etc.)? Will water testing records be widely available to the public? Will this have a major impact on our wildlife? How will the endangered species be affected?
Can windows have cling-ons or dots on them so birds can see them?Can lights be shut off at night because of the bird migration session? We have endangered bird species that come here for the winter season who are Snow Owls.
Can native plants be used in landscaping and could they be a green roof? Can part of the swamp be perserved? If not can artificial marsh buoys be made and native plants used for landscaping?
Will the community life around the project be affected?
How many local jobs are projected? (to off set the environmental impact) What are the projected benefits for the local community? What does Micron have to offer the local community as they plan their environmental impact? This is going to affect the housing market, are there any plans in order to ease this transition or combat this? Will this massive strain on the electricity affect my electricity (more blackouts)? Will first responders need specialized training in order to handle any environmental toxic concerns? How will carbon emission levels be kept low? Will taxes be raised to pay for water? Will this extra use of water make water prices go up? How will the negative effects of this infrastructure affect me economically in the beginning and through to the future? Will internships be offered for local school students? If flooding would happen and major damage be done to the plant, how will this effect taxpayers? How will this effect the Traffic? What if this affects the flow of traffic so they have to take more land to make more roads? It's already getting bad because of this project and other companies. What will salary look like for the workers? How will the whole micron building effect homeowners around the site? How much money will it take to pay for the whole building? This is also gonna cause many economic concerns what are we going to do about that? Why should we have to be worried about paying more money for utilities, for the success and operation of a company? Will this have a major impact on out energy?
Thank you for your time and consideration,
Michelle Fanelli

From: Brian Cocca <briancocca@gmail.com>
Sent: Monday, October 30, 2023 4:10:04 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Environmental concerns

Hello, I'd like the following to be on the record as areas of concerns for the EIS, as well as general input for Micron on how they can help support the community. Thank you.

We have heard a lot of the expected benefits of the proposed Micron chip plant; $100 billion invested in the community over 20 years- that's on average $5 billion a year. To add some perspective to that number, that's over 3 times the entire budget of the county this year ($1.5 billion) and more than 5 times the total budget of the City of Syracuse ($869 million). This is a very significant investment.

Primarily the benefits of these investments will manifest as new jobs and educational avenues to qualify for those jobs. Micron has been working strategically to ally itself with the organizations and communities that have traditionally been critical of such large industrial developments, by reaching out and giving opportunities (and promotional items) to many groups that are historically disenfranchised and often negatively impacted by these types of projects.   This is good, even if it's simply a stipulation of their federal subsidy. We hope those communities make some strong and wise demands.

One group that seems to be left out of the strategic partnership conversation is the natural environment. We do not hear about a single environmental benefit, only impacts.

When Micron asked the community how to invest $500 million toward community projects, their focus was squarely on housing units, education, and programs for their workers and nothing about making the community a healthier, more enjoyable place to be outside of the school-to-work-to-house triangle. The community investment can be summed up as "how do we create good workers and where can we put them?".

So far what we can expect from an environmental aspect is that they will simply comply with whatever regulators force them to do. Literally, the bare minimum.

This is a big, sprawling project that will have lots of direct and indirect impacts. Impacts that we can anticipate as well unforeseeable impacts; here are some of my concerns:

-**The 48 million gallons of water per day they intend to use** and then, presumably, pump back into the wild in a form that's not clean enough for them, yet (we hope) not so contaminated that it's dangerous to nature…or at least clean enough that it is not illegal.

- The clearing and development of thousands of acres of greenfield sites. The 1,200+ acres of what is billed as the White Pine Commerce Park (currently just wooded and agricultural land) for the main project, plus 5 times as many supply chain businesses (6,000 acres? that's not clear), and the many various other greenfield sites in the county which will be cleared to add 12,000+ new housing units that are starting to spring up in advance of the facility.

-Fewer places for humans to enjoy peace and quiet in the natural world. People who grew up in the area 40 years ago or more will likely remember having woods nearby where they would play. Those wild, open spaces have been steadily vanishing to make room for housing developments and commercial enterprises. We will never have those wild spaces back in our lifetime. Numerous studies have demonstrated the benefit to humans of having green spaces nearby, and the size and quality of those spaces matters too. Children are especially being deprived of quality outdoor spaces and it's manifesting itself in many negative ways.

-The further fragmentation and destruction of habitat for hundreds of species of plants and animals. As humans we tend not to think about green space as anyone's home, however whenever we bulldoze, pave and build on an area we kill/evict all the plants and creatures that lived there and justify it by doing an Environmental Impact Study that tells us it's an acceptable sacrifice.

-Increased noise, light, air, and water pollution. We already live in a community where the drone of traffic can be heard from almost everywhere. We live in a place where seeing the stars at night is becoming harder and harder. And the air and water quality of our area are some of our greatest features- let's not ruin these natural treasures any further in the name of earning dollars.

-**Increased traffic and the dangers associated with increased traffic.** With more traffic will inevitably come more accidents, injuries and death, not to mention the more mundane daily headache of more vehicles on the roads, more road construction and more delays and more noise.

I challenge Micron and the people of Central New York to demand that Micron's environmental impact not just be seen as an inevitable cost in the name of economic progress, and instead be seen as an opportunity to create a world-class model of how industry can not only lift people up economically, but also provide real improvement to the natural world we all depend on.

Here are a few ideas;

Donating enough money to the CNY Land Trust to create public green spaces that exceeds the footprint of their facilities and the support infrastructure. I would like to see 6,000+ acres preserved.

Donate enough money to the Onondaga Earth Corps to exceed their annual funding needs. This organization helps teach young people about ecology and fits in with Micron's STEM education mission goal.

Demand that new housing have walkable community parks that exceed the WHO recommendation of green space per person, and demand current brownfield sites be the priority sites of new development.

Completely utilize their rooftop space and parking areas for solar PV generation.

Demand outdoor lighting be minimal and not face upward or outward if possible.

Create a transportation plan that prioritizes walkability, bicycling and mass transit over automobiles

From: Lenny Siegel <LSiegel@cpeo.org>
Sent: Monday, October 30, 2023 9:46:17 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: CPEO Comments on the SEQRA Scope of Work for Micron Semiconductor Fabrication

Please find attached our comments on the SEQRA Scope of Work for Micron Semiconductor Fabrication, as well as two reference documents.

Lenny Siegel

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TO: Micron Project, Office of Economic Development, Onondaga County
FROM: Lenny Siegel, Center for Public Environmental Oversight
DATE: October 30, 2023
SUBJECT: SEQRA Scope of Work for Micron Semiconductor Fabrication

Thank you for the opportunity to comment on the September 12, 2023 Draft SEQRA Scope of Work for Micron Semiconductor Fabrication. I have been asked by residents of Onondoga County to offer my comments.

I have nearly five decades of experience monitoring and influencing the worker health and environmental impacts of the semiconductor industry, through the Pacific Studies Center, the Project on Health and Safety in Electronics, the Silicon Valley Toxics Coalition, and the Center for Public Environmental Oversight, as well as my service as Council Member and Mayor of Mountain View, the birthplace of the commercial semiconductor industry.

The semiconductor industry produces remarkable products that we all use. Unfortunately, its environmental and workplace health record is less than remarkable. The MEW Superfund Area here in Mountain View was the home of some of the earliest successful integrated circuit manufacturers. The wafer fabs are gone, but despite the scores (hundreds?) of millions of dollars spent thus far on subsurface remediation, the contamination—including the risk of public exposure—will remain for decades more, if not longer. The same is true at other Silicon Valley sites.

The SEQRA process provides an opportunity to identify and minimize, in advance, the environmental hazards of semiconductor production. By doing so, it can lead to appropriate regulation, research on waste management and pollution prevention, and investments in safer facilities.

Semiconductor production is essentially a series of chemical processes that use a wide variety of hazardous substances. The industry explains, "While in the 1980s semiconductor fabs used

fewer than 20 elements, today they are using over 50% of the nonradioactive elements in the periodic table."[1] Those include toxic heavy metals. The industry is a major user of Per- and Polyfluorinated Substances (PFAS), also known as "Forever Chemicals" because they persist and bioaccumulate in the environment and even human bloodstreams. As New York state agencies are well aware, these compounds are toxic, even at extremely low exposure concentrations, through multiple pathways. But industry has become reliant on PFAS without first examining the human and environmental risks. It explains, "Without PFAS, the ability to produce semiconductors (and the facilities and equipment related to and supporting semiconductor manufacturing) would be put at risk."[2]

Use and release of the industry's hazardous building blocks are regulated by both state and federal statutes and regulations, but the public is generally unaware of the series of upcoming permit applications that Micron is expecting to make. The SEQRA review should list **all** anticipated permitting processes, with the anticipated schedule of public comment periods, and it should require public notification to interested parties of each permit application as it is submitted.

It should also identify hazardous substances, whether or not they currently have promulgated exposure standards. For example, the industry reports, "Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS."[3]

Furthermore, potential workplace exposures should not be ignored because exposures are below the Occupational Exposure Level (OEL) or even a fraction of the OEL, as industry suggests.[4] In most cases OELs, such as the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limits (PELs), are orders of magnitude above what the science—including U.S. EPA studies—dictates.

While the draft Scope of Work proposes many useful Technical Chapters, there is room for more specificity. I focus on the use and release of hazardous substances.

For **Solid Wastes and Hazardous Materials**, the Scope of Work states, "The chapter will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect

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[1] "Background on Semiconductor Manufacturing and PFAS," Semiconductor Association (SIA) PFAS Consortium, May 17, 2023, p. 54. The SIA PFAS Consortium is made up of chipmakers and their suppliers of equipment and materials. To sign up to receive their technical papers, go to https://www.semiconductors.org/pfas/ . I am attaching this document.

[2] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3. I am also attaching this document.

[3] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3

[4] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 25.

against releases to the environment. Any warranted remedial approaches for addressing identified or potential contaminated materials would be described." I suggest that the Review describe any permitting required for the Treatment, Storage, and Disposal of hazardous materials and solid wastes, and that it list the storage requirements, such as double-walled tanks and piping, necessary to prevent environmental releases. Furthermore, how will employees be educated about the risk from leaks and spills, as well as what to do when they occur?

To what degree will disposal—including landfilling and incineration—create off-site hazards? Industry reports, "Organic waste, including organic liquids containing PFAS, is typically segregated, collected, and containerized to be treated at an offsite licensed treatment and disposal facility, as a blended fuel by high temperature incineration or reprocessing."[5] Perfluorinated compounds are particularly difficult to destroy using incineration. Furthermore, even when permitted by regulatory agencies, incineration may release products of incomplete combustion into the atmosphere.

For **Air Quality**, the Scope of Work barely mentions the potential emissions of highly toxic air contaminants. Historically the industry has used lethal gases such as arsine and phosphine, as well as toxic gases such as hydrogen chloride (the gaseous form of hydrochloric acid). Micron should identify plans to notify first responders and public of any toxic air releases, and first responders should be provided in advance with training and equipment to respond safely to such releases. Employees should be warned about the toxicity of gases used by the industry and trained to protect themselves from potential releases, both at low levels associated with chronic toxicity as well as higher levels with acute toxicity.

I am surprised and disappointed that no chapter is listed for **Wastewater and Stormwater**. The release of toxic contaminants through water pathways is one of the most serious threats of semiconductor productions. Releases of certain contaminants in wastewater could compromise the operations of the Oak Orchard Wastewater Treatment Plant, even undermining compliance with its discharge permit. The draft Scope of Work mentions industrial pre-treatment. Not only should that be described in an environmental review chapter, but the review should identify ways to pre-treat hazardous chemicals, perhaps even reusing some, before comingling with other wastes. This is particularly important for PFAS, because in the future more PFAS compounds are likely to be subjected to enforceable environmental standards, many at very low concentrations.

In fact, given the vast number of PFAS used by the semiconductor industry, the Review should identify methods for sampling total organic fluorine, not just targeted compounds. "At present, only a small percentage of PFAS compounds within typical semiconductor wastewater are detectable and quantifiable using conventional U.S. EPA analytical methods for PFAS-containing

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[5] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 30.

materials."[6] However, U.S. EPA has a draft method (1621) for measuring total organic fluorine.[7] Furthermore, academic researchers are finding that failure to measure total fluorine misses discharges of significant quantities of PFAS pollutants. "[B]ecause many studies of total organic fluorine have shown that total PFAS concentrations are at least 10 times higher than the sum of target PFASs. However, this does reinforce the idea that PFAS monitoring should incorporate complementary target and nontarget analyses or otherwise include measures of total organic fluorine to accurately assess PFAS abundance and potential environmental impacts."[8]

Furthermore, there should be a chapter on **Life-Cycle Environmental Impacts.** What hazardous substances remain in the finished semiconductor products, including packaging. At the end-of-life, are there mechanisms for preventing the environmental release of semiconductor hazardous substances? Industry's PFAS Consortium reports, "At the end-of-life of the product containing the semiconductor, or any parts replaced during the manufacture of semiconductors, would enter waste disposal streams where any PFAS contained therein could enter the environment."[9] Are manufacturers responsible for end-of-life pollution?

Finally, there are those who argue that a thorough environmental review, as I have suggested, would unnecessarily delay the operation of new, advanced wafer fabrication plants. I find it hard to believe that documenting potential hazardous substance and waste impacts in advance would hamper the construction of a factory that is not expected to begin production until 2032. Micron—indeed, all semiconductor manufacturers—**should** already know what hazardous substances it uses and releases. Shouldn't the public also know? The semiconductor and computer manufacturing industry, such as IBM's complex in Endicott, New York, has a long history of causing pollution that threatens public health and the environment. An industry that claims that PFAS—chemicals that are persistent, bioaccumulative, and extremely toxic in low concentrations—are essential to its operations should be required to **come clean** about its environmental and public health hazards.

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[6] "PFOS and PFOA Conversion to Short-Chain PFAS-Containing Materials Used in Semiconductor Manufacturing," SIA PFAS Consortium, June 5, 2023, p. 11.

[7] Draft Method 1621: Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (CIC), U.S. EPA, April 2022, https://www.epa.gov/system/files/documents/2022-04/draft-method-1621-for-screening-aof-in-aqueous-matrices-by-cic_0.pdf

[8] Paige Jacob, Kristas Barzen-Hanson, and Damian Helbling, "Target and Nontarget Analysis of Per- and Polyfluoralkyl Substances in Wastewater from Electronics Fabrication Facilities," *Environmental Science & Technology,* February 16, 2021, p. 2353. https://pubs.acs.org/doi/10.1021/acs.est.0c06690

[9] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 90,

Background on Semiconductor Manufacturing and PFAS

Semiconductor PFAS Consortium

May 17, 2023

Acknowledgments: The consortium would like to acknowledge the contributions of the Semiconductor PFAS Consortium for their efforts to compile this information. The consortium would also like to acknowledge the assistance provided by David Medeiros of Entegris, Edward Watkins and Thomas Dory of Fujifilm Electronic Materials, Brooke Tvermoes of IBM, Dawn Graunke and Patrick Gottsacker of Intel, David Speed of Global Foundries, Jim Snow of SCREEN Semiconductor Solutions, Sarah Wallace and Tim Yeakley of Texas Instruments Inc., Robert Hanley supporting TSMC, Laurie Beu of Laurie Beu Consulting, and Melissa Gresham of Melissa Gresham Consulting.

This publication was developed by the Semiconductor PFAS Consortium. The contents do not necessarily reflect the uses, views or stated policies of individual consortium members.

Also published in the Semiconductor PFAS Consortium white paper series:

Case Study	PFOS and PFOA Conversion to Short-Chain PFAS Used in Semiconductor Manufacturing
Case Study	PFAS-Containing Surfactants Used in Semiconductor Manufacturing
Case Study	PFAS-Containing Photo-Acid Generators Used in Semiconductor Manufacturing
White Paper	PFAS-Containing Fluorochemicals Used in Semiconductor Manufacturing Plasma-Enabled Etch and Deposition
White Paper	PFAS-Containing Heat Transfer Fluids Used in Semiconductor Manufacturing
White Paper	PFAS-Containing Materials Used in Semiconductor Assembly, Test and Substrate Processes
White Paper	PFAS-Containing Wet Chemistries Used in Semiconductor Manufacturing
White Paper	PFAS-Containing Lubricants Used in Semiconductor Manufacturing
White Paper	PFAS-Containing Articles Used in Semiconductor Manufacturing

About the Semiconductor PFAS Consortium

The Semiconductor PFAS Consortium is an international group of semiconductor industry stakeholders formed to collect the technical data needed to formulate an industry approach to perfluoroalkyl and polyfluoroalkyl substances (PFAS).

Consortium membership comprises semiconductor manufacturers and members of the supply chain including chemical, material and equipment suppliers. The consortium includes technical working groups, each focused on the:

Identification of PFAS uses, why they are used, and the viability of alternatives.
Application of the pollution prevention hierarchy to (where possible) reduce PFAS consumption or eliminate use, identify alternatives, and minimize and control emissions.
Development of socioeconomic impact analysis data.
Identification of research needs.

This data will better inform public policy and legislation regarding the semiconductor industry's use of PFAS and will focus R&D efforts. The Semiconductor PFAS Consortium is organized under the auspices of the Semiconductor Industry Association (SIA). For more information, see www.semiconductors.org.

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Executive Summary

Semiconductors are essential components of electronic devices and are integral to modern society. A number of semiconductor manufacturing processes and applications use PFAS chemicals, a group of chemicals that contain two or more fluorine atoms bonded to a carbon or hydrocarbon backbone.

The Semiconductor PFAS Consortium, which comprises semiconductor manufacturers and semiconductor equipment and chemical and material suppliers, has established seven working groups to:

Identify the principal applications of PFAS-containing materials in the industry.
Assess the application-specific performance requirements.
Determine the role of fluorocarbons in fulfilling performance requirements.

By collecting this information, the consortium has determined where PFAS-containing materials are essential and where they are not. Technical areas of focus for the working groups are photolithography, wet chemistry, heat transfer fluids (HTFs), fluorocarbon uses in plasma etch and deposition, chip packaging, lubricants, and manufacturing equipment and its associated infrastructure (also known as “articles”). The working groups have prepared white papers and case studies presenting their findings, which are based on semiconductor manufacturer and supplier survey responses, literature and patent reviews, and expert input.

The results of this work have shown that in a majority of cases, PFAS-containing materials provide properties integral to the semiconductor industry that are not found in known, non-PFAS alternatives. Eliminating PFAS-containing materials from this industry will require years of research and development (R&D) to identify, demonstrate, integrate and implement alternatives. Minimizing emissions may be a more feasible route for most applications.

This white paper contains information that supplements and supports each of the working group’s work products, including a discussion of:

- Different regulatory bodies’ PFAS definitions, including the consortium’s definition, which is any organic chemical with a perfluorinated methylene group (-CF_2-) and/or perfluorinated methyl group (-CF_3) moiety.
- Actions that the industry has taken to eliminate and replace long-chain PFAS-containing materials with more environmentally benign substitutes.
- The global supply chain associated with this industry, and the interconnected relationship between suppliers, manufacturers and end users.
- The organization of modern advanced semiconductor manufacturing facilities.
- A summary of fluorine and organofluorine properties that make them critical for some applications.
- Human health and environmental controls.
- The R&D necessary to find acceptable substitutes for PFAS-containing materials, and, where PFAS-containing materials are essential to this industry and substitutes are not possible, the development of environmental emissions-reduction technologies.

1.0 Overview of the Semiconductor Industry

Over the past three decades, the semiconductor industry has experienced rapid growth and delivered enormous global economic impact. Chip performance and cost improvements made possible the evolution from mainframes to PCs in the 1990s, the World Wide Web and online services in the 2000s, and the smartphone revolution in the 2010s.

These chip-enabled innovations created significant economic benefits. For example, from 1995 to 2015, an estimated $3 trillion in global gross domestic product (GDP) was directly attributable to semiconductor innovation, along with an additional $11 trillion in indirect impact (SIA 2022).

Semiconductors have become essential to our modern world, which is why long-term market demand remains strong. The impact of semiconductor availability to other industries was brought to the fore during the first two years of the COVID-19 pandemic, when COVID-19-induced reductions in chip manufacturing created bottlenecks in downstream manufacturing. Figure 1 shows global semiconductor sales growth from 2001 through 2021. Global semiconductor industry sales totaled $573.5 billion in 2022 (SIA 2022), the highest-ever annual total and an increase of 3.2% compared to the 2021 total of $555.9 billion.

Figure 1: 20 years of global semiconductor sales growth (2001-2021).

2.0 Introduction

The semiconductor industry uses PFAS-containing materials in numerous critical applications. Because of human health and environmental factors associated with the persistence, bioaccumulation and toxicity of some fluorinated organic chemicals, legislative and regulatory efforts worldwide are seeking to categorize a majority of fluorinated organic chemicals under a single class termed PFAS, and initiate restrictions that could limit the use of PFAS-containing materials to only those considered essential to the function of society.

Given the criticality of fluorinated organic chemicals to semiconductor manufacturing, the Semiconductor PFAS Consortium has developed six white papers that identify PFAS uses in semiconductor manufacturing and assess where use meets the definition of “essential” (Cousins, et al. 2019). To the extent that PFAS-containing formulations are essential to manufacturing semiconductors, the papers present the socioeconomic factors and data that support continued use, under exemptions with near-zero release. To the extent that nonfluorinated alternatives may be available that can satisfy application-specific performance requirements, the papers will identify the key steps necessary to develop, qualify and implement new materials into high-volume semiconductor manufacturing. They also outline potential avenues of R&D for new materials.

Six white papers and three case studies prepared by the consortium collectively address the principal areas where semiconductor manufacturing uses fluorinated organic chemicals. The seven areas covered in these white papers and case studies are:

> **Photolithography.** Photolithography is a patterning process that defines where to add or remove materials in each step of the fabrication of integrated circuits. Specialized fluorinated organic chemicals serve several important roles in performing photolithographic patterning processes (Ober, Kafer and Deng 2022). There are three supporting case studies on photoacid generators (PAGs), surfactants, and the history of perfluorooctyl sulfonate (PFOS) and perfluorooctyl acetate (PFOA) phaseouts.
>
> **Wet chemical processing.** A number of different semiconductor manufacturing operations, including cleaning, etching, plating and planarization, employ aqueous- or solvent-based formulations. Some of these applications use fluorinated organic chemicals.

Fluorocarbon uses in plasma etch and deposition. Perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) are essential gases for directional etching and cleaning of silicon compounds**.** Silicon and silicon compounds are the fundamental semiconductor components; they provide the conductive properties of metal as well as operating as an insulator. Additionally, fluorinated organometallic compounds are essential for the deposition of metal-containing films.

HTFs. Many semiconductor manufacturing processes entail physical and chemical processes that require precisely controlled temperatures, and thus are highly reliant on HTFs. In both cooling and heating applications, fluorinated HTFs (F-HTFs) help ensure the ability to provide the precise temperature control required in specific manufacturing operations within the semiconductor fabrication process, and enable the testing of products to ensure the appropriate performance of semiconductor chips within finished electronic products.

Assembly, test and packaging materials. A semiconductor package encloses one or more semiconductor devices or integrated circuits, protecting the device from the environment. The package connects the semiconductor to the printed circuit board (PCB); dissipates heat; and provides protection from the surrounding environment, particularly from moisture, shock/vibration, dust, etc.

Semiconductor manufacturing and related equipment (SMRE) and infrastructure articles. Semiconductor manufacturing facilities and the manufacturing equipment and infrastructure within them contain a multitude of articles. An article is any object made from one or more substances and mixtures which during production is given a special shape, surface or design that determines its function to a greater degree than its chemical composition, whether on its own or in an assembly with other articles, substances and mixtures. PFAS-containing articles include those made of a fluoropolymer, articles coated or painted with a fluoropolymer, or other PFAS-containing materials (such as oligomers) and those made of non-PFAS polymers containing PFAS processing/machining aids or additives. Many semiconductor manufacturing applications require the use of PFAS-containing articles for safety, contamination control, resilience and other factors.

Pump fluids and lubricants. Semiconductor manufacturing relies on the extensive use of robotics, automation and vacuum systems to achieve nanometer-scale precision. The use of lubricants, many of which need to be fluorinated, is essential to the precision and reliability of these systems.

Figure 2 is a broad overview of the scope of the Semiconductor PFAS Consortium’s analysis, showing both front- and back-end semiconductor processing, as well as facility support functions and device assembly, test and packaging operations. The scope of the operations considered by the Semiconductor PFAS Consortium starts with a bare silicon wafer entering a manufacturing facility and ends at the packaging of semiconductor devices.

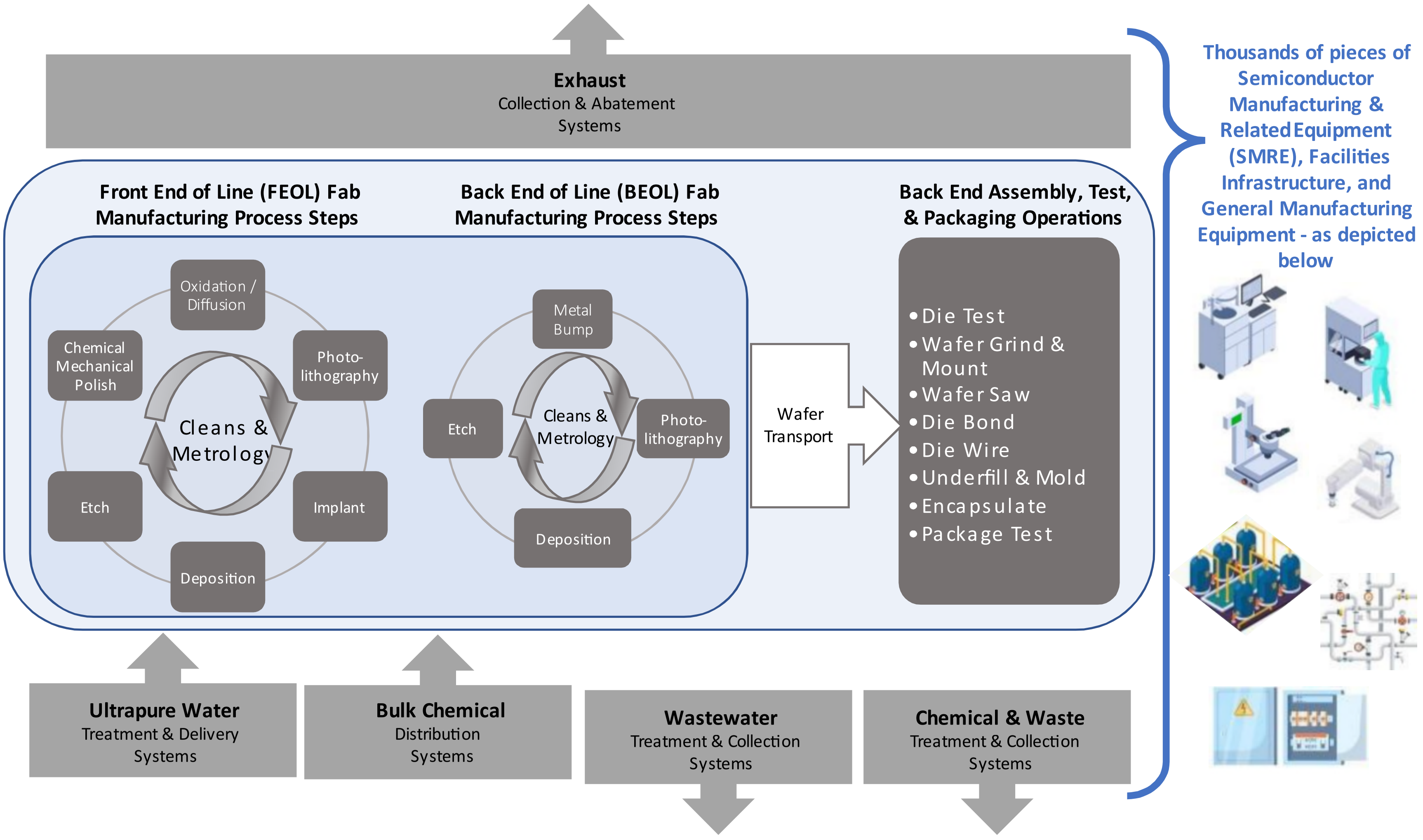


Figure 2: General overview of semiconductor manufacturing process steps, operations and systems evaluated by Semiconductor PFAS Consortium working groups.

3.0 PFAS Definition

The term PFAS gained use with a publication by Buck et al. (Buck, Franklin, et al. 2011) that presents a rational chemical nomenclature for describing fluorinated organic chemicals. Since then, many organizations have adopted the term PFAS, each applying somewhat different criteria to the definition, and affecting the span of compounds covered (OECD 2018); (OECD 2021); (US EPA 2021). Under the current Organization for Economic Co-Operation and Development (OECD) definition, the term PFAS includes virtually every compound that contains a $-CF_2-$ or $-CF_3$ group (OECD 2021).

The purpose of the white papers is to identify the use of all materials that could potentially meet a regulatory definition of PFAS; therefore, the consortium has defined the scope of materials to include all chemistries and materials that contain molecules with $-CF_2-$ and/or $-CF_3$. As such, this definition closely aligns with the OECD definition.

However, as noted by the OECD, the term PFAS is a broad, general, nonspecific term that does not indicate whether a compound is harmful or not, but communicates only that the compounds under this term share the same trait for having a fully fluorinated methyl or methylene carbon moiety (OECD 2021). In fact, the application of this definition lumps together gases, liquids and solids with vastly different properties, and that range in size from difluoromethane (CF_2H_2) to large, highly complex organic polymers and surfactants.

4.0 History of Semiconductor Industry Voluntary Actions on PFAS

The semiconductor industry has been attuned to environmental concerns about the substances it uses, and quick to act proactively with voluntary elimination and reductions. For instance, when evidence of the persistence, bioaccumulation and toxicity of PFOS surfaced in the early 2000s, the World Semiconductor Council (WSC) initiated an international voluntary commitment in 2006 to phase out PFOS use worldwide, a goal that it achieved in 2011 (Council 2011). The WSC also committed to voluntarily phase out the use of PFOA by 2025. Companies began this phaseout in 2010 and, today, the majority of companies have eliminated PFOA.

Similarly, in the face of global warming concerns, the U.S. Environmental Protection Agency (EPA) and Semiconductor Industry Association initiated a voluntary Perfluorocarbon Reduction Climate Partnership in 1996, which expanded into voluntary worldwide commitments that resulted in nearly a 50% reduction in the emissions of PFC gases between 1995 and 2010 (WSC 1999-2014), and which continues today.

Our experience with these initiatives has taught consortium members valuable lessons regarding the resource, effort and timeline required to introduce alternative chemicals into some of the world’s most complex technologies.

The manufacture of semiconductor devices requires the use of manufacturing tools and processes that are highly integrated, with hundreds to thousands of interdependent steps that must be conducted at nanometer scale using materials that have complex relationships. Once a material has been engrained into a semiconductor manufacturing process, it can be excruciatingly difficult to find a viable alternative, prove that the alternative can be substituted without disrupting interdependencies, and then integrate the alternative into a high-volume manufacturing (HVM) process. This challenge makes it important to conduct collaborative R&D at the pre-competitive level, ideally with pooled resources like the Semiconductor Research Corp. (SRC), Interuniversity Microelectronics Center (IMEC), Industrial Technology Research Institute, the Semiconductor PFAS Consortium, and now-inactive SEMATECH. Industry-funded collaborative efforts have resulted in the publication of many dozens of PFAS-related research papers in peer-reviewed literature.

No known alternatives exist for many of the industry's uses of fluorocarbons. Given its carbon-fluorine chemistry, PFAS-containing materials offer a unique set of surface tension, stability and chemical compatibility that many semiconductor applications require. For example, despite years of extensive research, there have been no viable PFAS-free alternatives identified for the fluorocarbon gases used in plasma etch processes, fluorinated chemicals used in photolithography, or fluorinated chemicals used as refrigerants and HTFs.

If an alternative is found, the process of qualifying and replacing critical materials in the semiconductor industry is a highly complex, multistep, multiyear, supply-chain stakeholder technical challenge.

The possibility of regrettable substitution, in which a well-intentioned alternative is instituted and then later found to have undesirable characteristics, is an ever-present concern. The four perfluorocarbon sulfonic acids in wide use today – such as the acid anion in PAGs, for instance – were a widely endorsed solution to PFOS PAGs that were replaced just over 10 years ago, and yet now are the target of U.S. EPA and European Union (EU) regulatory actions. Similarly, some of the fluorinated refrigerants and HTFs in use today represent a fourth generation of replacements, where the intention of each generation has been to remedy the environmental, health and safety concerns of the previous generation. From this, it has become obvious that the selection of alternatives must be well-informed.

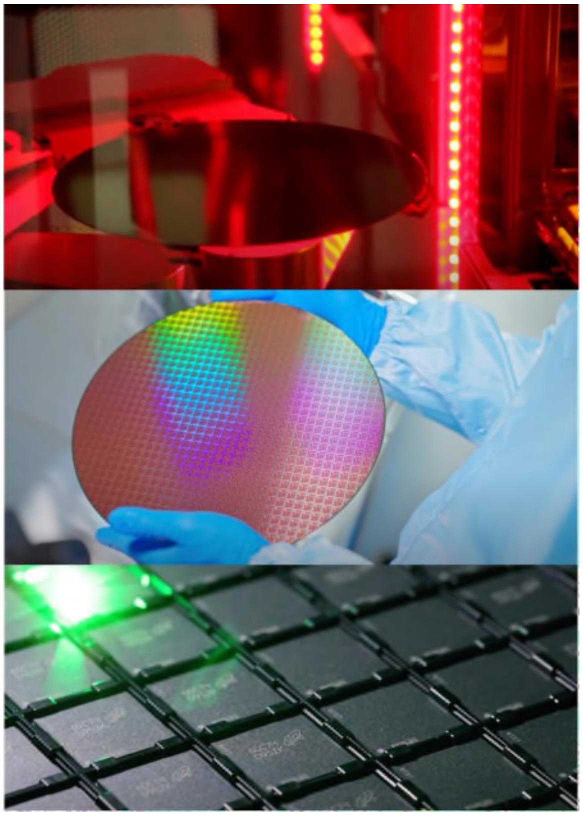
The semiconductor industry will continue to focus on using PFAS chemistries safely and responsibly until it can find viable and proven alternatives.

5.0 Semiconductor Overview

Semiconductors power our world. In health care, they make robotic surgery, advanced imaging, pacemakers, continuous glucose monitoring and insulin pumps possible. Semiconductors enable safety systems in automobiles such as blind-spot detection, backup cameras, emergency braking systems, lane-change assistance and adaptive cruise control. Semiconductors are the brains and memory in computers, mobile phones and smartwatches.

The first computer based on silicon-integrated circuits was the Apollo guidance computer that took humans to the moon. Those computers could perform 85,000 operations per second (Fishman 2019). In 1965, Gordon Moore postulated that the number of components on an integrated circuit would double every two years (Moore 1965); mobile phones in 2023 can perform 17 trillion operations per second (Wiggers 2022). In a span of 60 years, semiconductors have seen a 200 million times increase in computing power.

Semiconductor chips are the most complicated mass-produced devices that humans have ever made, and the processes used to manufacture them are among the most complex and expensive in modern manufacturing. Chips are made on a silicon wafer, as shown in Figure 3, using complex photolithographic, deposition, plasma etching, cleaning and planarization processes. There are hundreds of required chemical formulations. For information on the increasing complexity of semiconductor devices, technology changes driving increased chemical usage and an overview of the manufacturing process, see Appendix B.



Individual devices (die) are built on pure silicon wafers in the fabrication facility (fab).

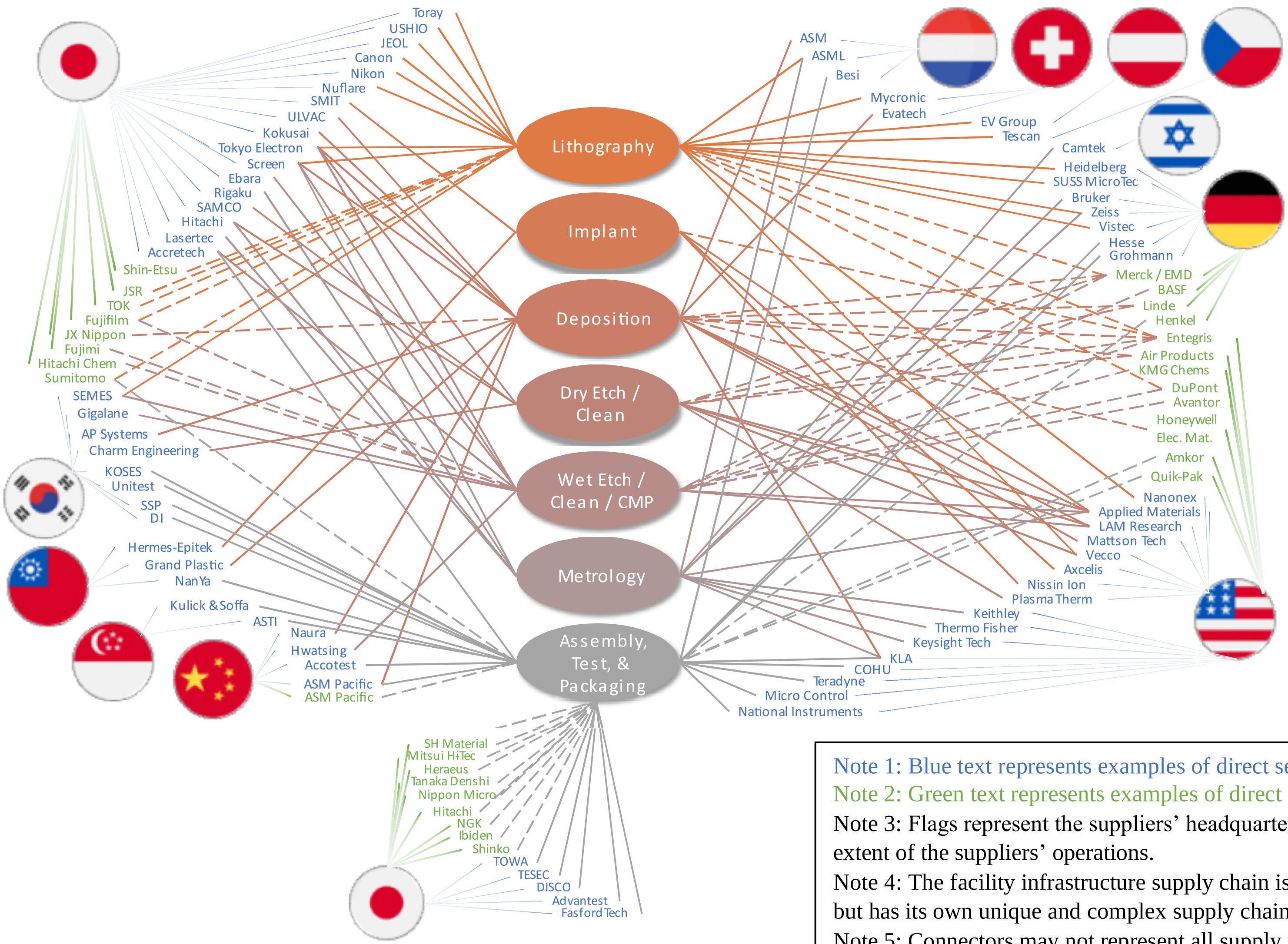
Finished wafer.

Packaged devices are marked with identifying information using a laser marking system.

Figure 3: The manufacturing process from wafer fab through packaged device (Source: Micron Technology Inc.).

6.0 Supply-Chain Complexity

Advances in the efficient and controlled use of materials are critical to improving semiconductor device performance. The manufacturing supply chain, a subset of the industry ecosystem, is global and highly integrated. It depends on a range of articles provided by specialized and supporting equipment suppliers as well as the specialty chemical suppliers shown in Figure 4. The SMRE used for semiconductor manufacturing is enormously complex, comprising thousands of components and subcomponents coming from many different supply-chain tiers, and equally many suppliers from start to finish.



Note 1: Blue text represents examples of direct semiconductor equipment suppliers.
Note 2: Green text represents examples of direct semiconductor material suppliers.
Note 3: Flags represent the suppliers' headquarters and do not represent the global extent of the suppliers' operations.
Note 4: The facility infrastructure supply chain is not represented in the figure above but has its own unique and complex supply chain.
Note 5: Connectors may not represent all supply pathways but rather are representative.

Figure 4: The semiconductor global supply chain in 2019: example tier-1 SMRE and material suppliers *(The Center for Security and Emerging Technology 2019)*.

SMRE itself is enormously complex, with a large, international supply chain. In a New York Times article, Dario Gil, a senior vice president at IBM, described the current leading-edge photolithography exposure tool, which uses extreme ultraviolet (EUV) light, as “ ... definitely the most complicated machine humans have built” (Clark 2021). Figure 5 shows an EUV tool, manufactured by Dutch firm ASML, containing 100,000 parts and 2 km of cabling (Levi 2021). If any part is faulty, the machine will fail to produce chips that can be sold for commercial use. Specialized components of the machine are made in facilities in Germany, the U.S., the U.K. and Japan; it would not have been possible to build the tool were it not for international, cross-industry and supply-chain collaboration.

SMRE such as the EUV tool incorporates many articles made from (or that contain) PFAS-containing materials because PFAS articles possess a unique set of characteristics required for certain semiconductor manufacturing processes, including inertness, purity, chemical and permeation resistance, a wide range of temperature stability, a low coefficient of friction, electrical properties, bacterial growth resistance, nonflammability, and a long service life (>25 years).

Figure 5: ASML’s latest EUV lithography patterning machine (Source: ASML).

Tier-1 (or direct) suppliers, in turn, have a supply chain of their own (tier-2 and tier-3 suppliers), with dependencies, for example, on components such as valves, tubing and machined parts for SMRE manufacturers or raw materials for chemical suppliers. Additionally, these subsuppliers have suppliers as well, leading to a supply chain much more complicated than depicted in Figure 4.

The depth and complexity of the SMRE supply chain makes tracing the presence of PFAS-containing materials in individual components quite difficult. For more information on supply-chain complexity, see the Semiconductor PFAS Consortium white paper, “PFAS-Containing Articles Used in Semiconductor Manufacturing.”

The supply chain for semiconductor chemicals is also international; Figure 4 shows example tier-1 material suppliers in green text. Every gas or liquid that touches the wafer must have its impurities (substances that could negatively impact yield) controlled to levels less than a few parts per billion (ppb) and even to less than a few parts per trillion (ppt). One part per trillion is equivalent to 1 second in 32,000 years. The current technology node of 5 nm (an expression of the size of features fabricated into semiconductor devices) is tremendously difficult to make. Any impurity present, even if nanoscale in size, can result in malfunctioning devices.

For additional information on supply-chain complexity, see Appendix B.

7.0 Clean-Room Design

The fabrication of semiconductors is conducted in specialized buildings known as “fabs” that use clean rooms, and a hierarchy of design features that isolate workers and wafers from chemicals. Fabs comprise clean-room spaces that house manufacturing tools, and support spaces that house the many electrical, mechanical and chemical systems that contain manufacturing tools. The building can be divided between clean-room and support space in a number of alternative ways, such as “bay and chase” designs where the support space surrounds the clean-room space horizontally. However, most modern fabs employ a ballroom-type design where the clean-room space consists of one or more very large rooms that house hundreds of individual manufacturing tools, with the ancillary support systems provided from below (subfab) and above.

A fab’s clean-room design approach protects manufacturing personnel and is also critical to semiconductor wafer product quality. Figure 6 illustrates a typical 300-mm ballroom fab consisting of an interstitial and fan deck; a clean room, where manufacturing operations are conducted; the subfab, which contains pumps and other ancillary equipment to support process tools; and the utility level, which contains chemical- and air-handling equipment, emission controls, and other infrastructures.

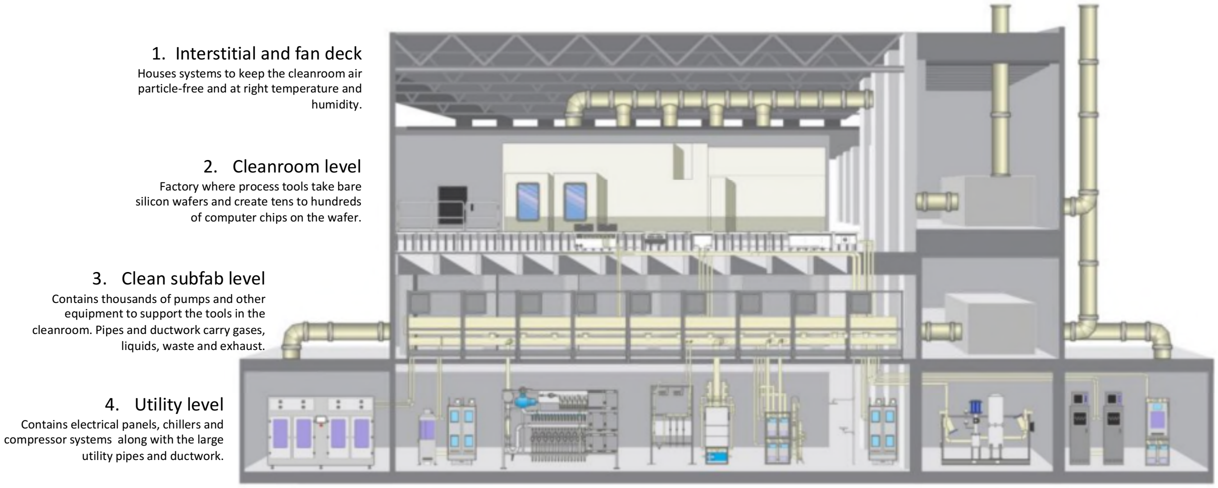


Figure 6: Example semiconductor manufacturing facility layout (CPS an Exyte Group Company 2019)**.**

On the interstitial and fan deck level, clean-room airflow recirculates vertically downward through filters mounted in the clean-room ceiling to the clean-room floor, where the air exits and returns through a plenum system, where it mixes with conditioned fresh air from outside the building before being recirculated back through the clean room. Fabs typically employ high-efficiency particulate air (HEPA)- or ultra-low particulate air (ULPA)-rated filters. ULPA filters are rated to remove 99.999% of particles larger than 120 nm (0.12 μm) and provide an exceptional level of particle removal. Vertically downward laminar airflow carries the freshest air past the typical personal breathing zone (PBZ) of fab workers, past the manufacturing tools, and then down and out through the return plenums located in or at the floor level.

In a typical 300-mm wafer manufacturing fab, the entire volume of air in the clean room is replaced every four to seven minutes, and the entire volume of air in the clean room is recirculated through ULPA filters at a rate of once every 30 seconds to one minute. This extensive level of air circulation and replacement provides an exceptional level of cleanliness.

The fabrication of an integrated circuit on a silicon wafer occurs in the clean room and involves a sequence of hundreds of additive, subtractive, photolithographic and cleaning steps that entail shuttling wafers between specialized manufacturing tools. Boxes of wafers or front-opening unified pods (FOUPs) transport wafers through an automated material handling system (AMHS) (see Figure 7), which uses thousands of autonomous vehicles to carry FOUPs containing as many as 25 wafers to the required process step (Intel 2020). Manufacturing tools, engineers and operators are located in the clean room. Virtually every tool has its own exhaust system, which maintains the tool enclosure under negative pressure relative to the clean room, thus preventing worker exposure to chemicals. Great care is taken to avoid any contact of wafers with workers, in order to prevent contamination.

The subfab contains thousands of pumps and other equipment to support tools, as well as laterals to convey gases, liquids, waste and exhaust to and from production tools.

The utility level, typically housed on the bottom level (but also in separate rooms on the side of the building or in separate structures) provides services that include ultra-pure water (UPW), bulk high-purity gases such as nitrogen and argon, exhaust gas handling and disposal ducts, electrical panels, chillers, and compressor systems. There are compressed gas cabinets and bulk chemical distribution systems located in separate rooms segregated by hazard class. Much of the supporting infrastructure is made up of fluoropolymers and other PFAS-containing articles used for their functional characteristics.

Fabs are capital-intensive facilities, costing billions of dollars to construct. A state-of-the-art fab of standard capacity requires roughly between $5 billion (for an advanced analog fab) and $20 billion (for advanced logic and memory fabs) of capital expenditure (including land, buildings and equipment). The primary threats to safe and continuous fab operations include fires/explosions, fluid leakage and critical service interruptions (FM Global 2019). Many semiconductor manufacturers limit the amount of combustible material that can be present in a tool to 1 pound per square foot of tool to reduce flammable loading; so does Factory Mutual (FM), a major insurer of the industry (FM Global 2019). Fluoropolymers exhibit a high resistance to combustion (FM 4910 compliance; American Society of Testing and Materials [ASTM] E84 25/50 rating), a property that is critical to minimize factory damage from smoke and other risks, and to meet combustible material limits.

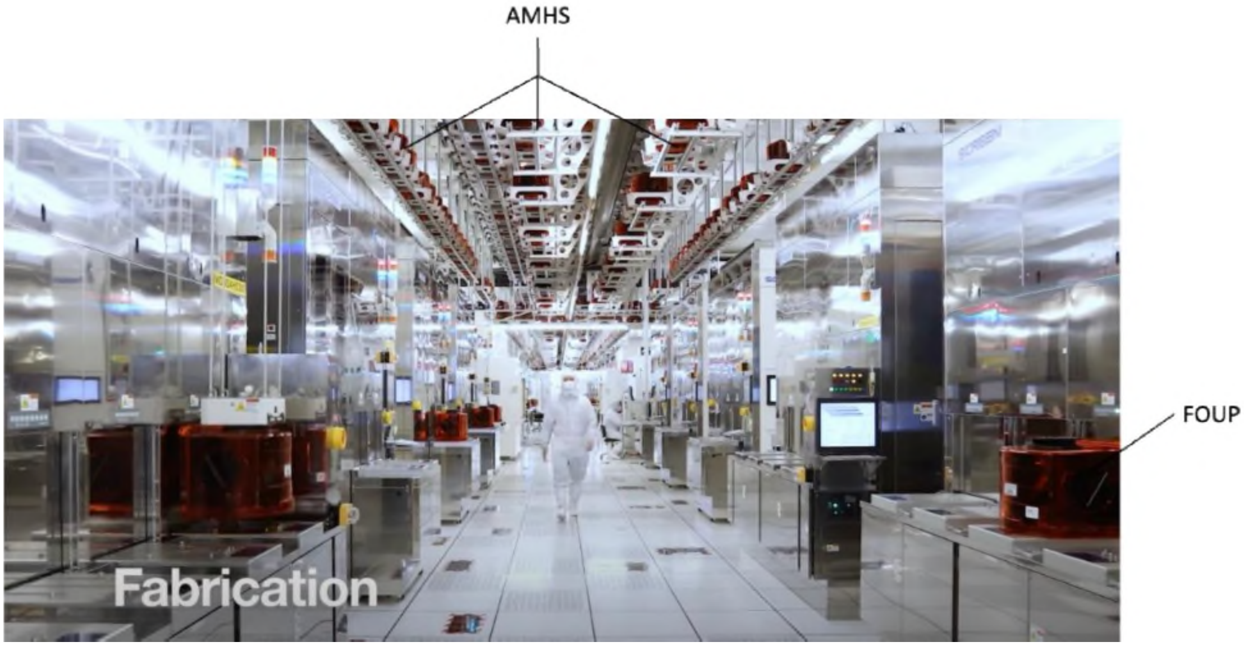


Figure 7: Inside a wafer fab, a worker walks down a row lined with process tools. Wafers are loaded into each tool via FOUPs. An AMHS carries FOUPs throughout the fab to the appropriate tool for processing.

8.0 Tool Exhaust

Chemical processes are designed to isolate chemicals from workers. These processes are conducted in tools equipped with process exhaust that route to either an abatement system or to general exhaust, as appropriate to the nature and quantity of the chemicals used within the tool's processing chambers.

Tool exhaust systems are typically balanced to maintain processing chambers at a negative pressure relative to the rest of the tool, with the tool itself typically maintained at negative pressure relative to the clean room. Collectively, these measures assure the capture of chemicals used in tool-specific process chambers directly at their source so that they do not migrate elsewhere within the tool or clean room. For additional information about fabrication and assembly, test and packaging facility exhausts and abatement, see the Environmental Controls section.

9.0 The Importance of Contamination Control

Smaller device features and increasingly more complex 3D structures require strict contamination controls to achieve acceptable wafer production yields. Contamination control is an essential aspect of semiconductor manufacturing. Trace amounts of contamination in the form of particles, impurities or other unwanted materials can lead to yield or reliability issues in semiconductor devices. Sources of contamination may be the fab manufacturing environment or workers; process chemicals and gases; the UPW used to rinse wafers; or the packaging and delivery of chemicals, gases and UPW.

Manufacturers implement stringent protocols to mitigate sources of potential defectivity. At the highest level, such protocols include precise control over the quantity of airborne particles in the clean room through careful control of the airflow, proper filtration of the ambient air, and the appropriate isolation of fab workers through proper gowning and hygiene procedures.

Wafers used in manufacturing are enclosed in highly engineered containers as they are processed in fabs. Carefully maintaining tooling prevents the introduction of particles. It is important to hold materials such as specialty gases, wet chemistries, solid precursors, solid metal targets and UPW to exacting specifications of purity and deliver them to process equipment in a pristine manner.

PFAS-containing materials, in particular fluoropolymers, play a critical role in affording the level of cleanliness required for high-yielding, high-reliability semiconductor devices, as they are often the only materials that possess the unique combination of chemical inertness, heat resistance, lack of particle shedding or metal leaching, processability, and other attributes required to meet rigorous requirements.

Today's most advanced technologies are made with EUV lithography, capable of feature sizes in the single nanometer scale and gate lengths of ~10 nm or less. Thus, defectivity in the tens- to single-nanometer domain can be detrimental to device yields, performance and reliability. In order to enable manufacturing at these dimensions, cleanliness afforded by fluoropolymer plastics and other PFAS-containing articles used for piping, tanks, seals and coated valves is often essential.

10.0 Properties of Fluorine and Organofluorine Compounds

Fluorine is the most electronegative element in the periodic table, with a dense, closely held electron cloud (Lemal 2004). When bonded with carbon, fluorine's high electronegativity (3.98 vs. 2.55), relatively small size and three lone sp^3 nonbonding electron pairs result in the carbon-fluorine bond having the highest bond strength known to organic chemistry (O'Hagan 2008). The high electronegativity differential polarizes the C-F bond and creates a Coulombic attraction between carbon and fluorine that contributes to the bond strength of the covalent C-F bond (Liang, Neumann and Ritter 2013). The dense electron cloud around the F also helps shield and strengthen the skeletal C-C bonds in fluorocarbon chains (Lemal 2004).

Compared to the C-H bond, the C-F bond is stronger (13 kcal/mole higher) and longer (1.35 Å vs. 1.09 Å), with a larger dipole moment (1.85 D vs. 0.3 D) that is opposite in direction to that of the C-H group (Biswas and Singh 2020). The combination of high C-F bond strength and shielded C-C bonds make fluorocarbons much less flammable relative to hydrocarbons, while also resistant to degradation by oxidants, reductants, acids and bases, photolysis, and microbial and multicellular metabolic processes (Kovalchuk, et al. 2014); (Krafft and Riess 2015).

Because of the strength of the C-F bond and the small size of F, it is possible to substitute fluorine for hydrogen in virtually any kind of organic molecule (Lemal 2004). Consequently, most fluorinated commercial organic chemicals are created by replacing one or more of the hydrogens in a hydrocarbon molecule with fluorine atoms. For instance, when fully fluorinated, methane (CH_4) becomes carbon tetrafluoride (CF_4); methane sulfonic acid (CH_3SO_3H) becomes triflic acid (CF_3SO_3H); and octanoic acid ($CH_3(CH_2)_6COOH$) becomes perfluorooctanoic acid ($CF_3(CF_2)_6COOH$), also known as PFOA. Much of what we understand about fluorocarbons comes from comparisons to the corresponding hydrocarbon analog.

Individual C-F bonds are highly polar, yet perfluorocarbon molecules have low polarizability and are among the most nonpolar solvents known (Kirsch 2013). The seeming contradiction between the high polarity of individual C-F bonds and the low polarity of overall perfluorocarbon molecules is a consequence of the individual local dipole moments canceling one another, which renders a perfluorocarbon molecule nonpolar overall (Kirsch 2013). As a result of the low molecular polarizability, the van der Waals-type intermolecular attractions between perfluorocarbons and between perfluorocarbons and other organic molecules are weak (Kirsch 2013). Weak attraction between perfluorocarbons of the same type makes them volatile (Krafft and Riess 2015). Perfluorocarbons tend to be lipophobic, and because C-F bonds are also poor hydrogen bond acceptors, perfluorocarbons also tend to be hydrophobic (Han, et al. 2021); (Krafft and Riess 2009).

The strength of the intermolecular forces between two molecules of the same type governs physical properties such as melting and boiling points, vapor pressure, enthalpy of vaporization, and viscosity (Krafft and Riess 2015). Because of the weak intermolecular attraction between perfluorinated molecules, neutral perfluorocarbons have low melting and boiling points, high vapor pressures, low enthalpies of vaporization, and relatively low viscosities (Krafft and Riess 2009). Carbon tetrafluoride (CF_4, molecular weight [MW] 88) has a much lower boiling point (–128°C) than n-hexane (MW 86, boiling point [BP] = 69°C), with both compounds having nearly the same molecular mass (Kirsch 2013). On the other hand, ionic perfluorocarbons such as perfluoroalkyl carboxylates and perfluoroalkyl sulfonates are well-solvated in water, and have low volatility.

The larger size of fluorine compared to hydrogen (with a 23% larger van der Waals radius) make perfluorocarbons bulkier and impose steric requirements that make fluorocarbon chains more rigid than hydrocarbon chains (Krafft and Riess 2015). Given their bulkiness and repulsive fluorine-fluorine interaction, longer fluorocarbon chains tend to adopt a helical geometry, which differs from the planar structure and behavior of the corresponding hydrocarbons (Krafft and Riess 2009). More specifically, the helical geometry is caused by the interaction of the back lobe of an sp^3 C-F bond orbital with the front lobe of a C-F orbital on a neighboring carbon.

Consequently, the anti-dihedral angle of F-C-C-F is a local maximum with global minima approximately ±5 degrees from the anti-conformation (Watkins and Jorgenson 2001). The larger effective surface area of fluorocarbon chains contributes to the hydrophobicity of perfluorocarbon relative to hydrocarbon chains (Krafft and Riess 2015). For instance, the free energy change associated with the transfer of a $-CF_2-$ group from bulk water to the air-water interface is about twice that of a CH_2 group (Krafft and Riess 2009). This strongly promotes the partitioning of a fluorocarbon to an air-water interface.

In partially fluorinated compounds where a combination of C-F and C-H bonds occur within the same molecule, the local dipole moments may not cancel, with the result that these molecules may have an appreciable overall dipole moment (Kirsch 2013). Partially fluorinated organics often have much higher heat of vaporization and much higher dielectric constants than perfluorocarbons (Kirsch 2013).

10.1 Perfluoroalkyl Acids

Two of the most commercially important types of fluorinated organic molecules are the homologous series of perfluoroalkyl carboxylic acids (PFCAs, $CF_3(CF_2)_nCOOH$) and the homologous series of perfluoroalkyl sulfonic acids (PFSAs, $CF_3(CF_2)_nSO_3H$). Collectively, they are known as perfluoroalkyl acids. The electron-withdrawing characteristics of perfluoroalkyl tails stabilize the anion of the acid head group, rendering PFSAs and PFCAs as strong acids with a very low acid dissociation constant (pK_a). Perfluoroalkyl acids are much stronger than their corresponding hydrocarbon analogs and are sometimes referred to as “super acids.” There is relatively little increase in acidity with an increase in perfluoroalkyl chain length. For example, the first $-CF_2-$ group adjacent to the sulfonic acid moiety is responsible for most of the acid strength (Olah, et al. 2009). The smallest perfluorosulfonic acid, CF_3SO_3H, is one of the strongest known monoprotic organic acids and has extreme thermal stability, with resistance to both oxidative and reductive cleavage (Howells and McCown 1977).

10.2 Surfactants

Fluorocarbon surfactants reduce the surface tension of water to much lower values (~15 to 20 dyne/cm) than hydrocarbon surfactants (~30 dyne/cm) because the fluorocarbon groups are bulkier, with a higher molecular surface area, and have stronger hydrophobicity (Krafft and Riess 2015). The cross-sectional area of a fluorocarbon (27 Å^2 to 32 Å^2) is much larger than the corresponding hydrocarbon (18 Å^2 to 21 Å^2), and a significant contributor to its high surface activity (Kovalchuk, et al. 2014). Since the fluorocarbon tail is both oleophobic and hydrophobic, it is surface-active in hydrocarbons as well as water. Surfactant head groups include those that are anionic (sulfonates and carboxylates, phosphates), cationic (quaternary ammonium), nonionic (polyethylene glycols, acrylamide oligomers) and amphoteric (betaines) (Buck, Murphy and Pabon 2012).

Given the electron-withdrawing characteristics of the fluorocarbon tail, perfluoroalkyl acids have low pK_a, and thus are fully ionized even under very acidic conditions. This can be especially important in wet etch and clean formulations that need to preserve the polar head group, even in the presence of strong mineral acids like hydrofluoric acid (HF).

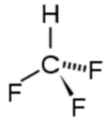
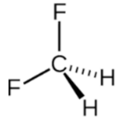
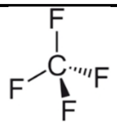
The critical micellar concentration (CMC) of a surfactant in water is the concentration at which it aggregates into micellar structures that have a hydrophobic interior and a hydrophilic exterior, and above which no further decrease in surface tension occurs. The CMC of fluorocarbon surfactants are typically equivalent to those of hydrocarbon surfactants, with 50% longer chains (Mukerjee 1994).

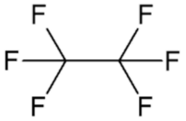
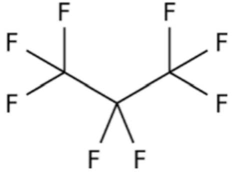
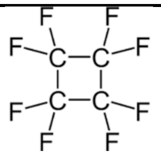
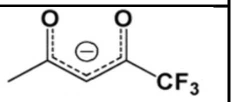
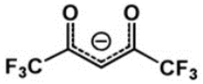
In water, high hydrophobicity causes fluorinated surfactants to partition to interfaces where they can lower air-liquid, water-oil and air-solid interfacial tensions. The free energy of adsorption for the transfer of each CF_2 group from bulk water to the air-water interface is roughly twice as large as for a CH_2 group (–5.1 kJ/mole vs. –2.6 kJ/mole) (Krafft and Riess 2015).

10.3 Fluorochemicals in Semiconductor Plasma-Enabled Etch and Deposition Processes

Fluorinated chemistries used in semiconductor plasma (dry) etch and chamber cleaning include HFCs/PFCs, nitrogen trifluoride (NF_3) and sulfur hexafluoride (SF_6). Thin-film deposition and plasma chamber cleaning can be gases (predominantly), liquid or solid (organometallic precursors). Table 1 lists some examples of substances used in these semiconductor manufacturing processes.

Table 1: Example PFC, HFC and organometallic precursors used in plasma-enabled etch, clean and deposition processes.

Classification	**Name**	**Chemical Structure**
HFC gas	Trifluoromethane (CHF_3)/ HFC-23	
HFC gas	Difluoromethane (CH_2F_2)/ HFC-32	
PFC gas	Tetrafluoromethane (CF_4)/ PFC-14	

PFC gas	Hexafluoroethane (C_2F_6)/ PFC-116	
PFC gas	Octafluoropropane (C_3F_8)/ PFC-218	
PFC gas	Octafluorocyclobutane (C_4F_8)/freon-C-318	
Organometallic precursor ligands	tfac (1,1,1-trifluoro-2,4-pentane-dionate)	
Organometallic precursor ligands	hfac (1,1,1,5,5,5-hexafluoro-2,4-pentane-dionate)	

HFC and PFC gases are used in plasma etch tools as a safe source of fluorine, carbon and hydrogen for the precise and selective etching of silicon and other materials to form the often-geometrically complex features of a semiconductor device. Another process using HFC and PFC gases and a plasma source – commonly known as a “chamber clean” – involves the controlled removal of residual films from the interior of chemical vapor deposition (CVD) tools, while minimizing damage to the process chamber.

Since the 1980s, semiconductor manufacturers have used PFC gases such as C_2F_6 and CF_4 as fluorine generation sources for CVD chamber cleans because they are nonflammable, less corrosive and less toxic than many other options. Concerns arose, however, about the high global warming potential (GWP) and long atmospheric lifetimes of fluorinated greenhouse gases (GHGs) (for example, C_2F_6 has a GWP100 of 12,400 and an atmospheric lifetime of 10,000 years; the GWP100 of CF_4 is 7,380, with an atmospheric lifetime of 50,000 years).

In response to the GWP of PFC emissions, the industry undertook extensive voluntary actions to eliminate the use of PFCs where possible and to reduce emissions. NF_3 remote plasma clean (RPS) has replaced fluorocarbon chamber clean processes in 300-mm tools; however, the increased use of NF_3 has resulted in the generation of large quantities of HF and F_2, which require the installation of additional air abatements and wastewater treatments to prevent their release to the environment.

When disassociated in a plasma, CF_4 produces CF_3 radical, electron and fluorine atoms, as indicated by Equation 1. The fluorine reacts with solid silicon, as indicated in Equation 2, to produce the volatile tetrafluorosilicon species, which is evacuated from the plasma etch chamber.

$$CF_4 + e^- \Rightarrow CF_3^* + F^* + e^- \qquad (1)$$

$$4F^* + Si(s) \Rightarrow SiF_4(g) \qquad (2)$$

The use of plasma etch in the semiconductor industry enables the directional (anisotropic) etching of materials, and therefore overcomes the "isotropic" nature of the etching in a conventional aqueous etching solution like hydrofluoric acid. An aqueous etchant removes material (etches) at a uniform rate in all directions (isotropic), resulting in an undercut of the film that requires etching. In contrast, the plasma etch process operates vertically downward (anisotropically), without undercutting the film that requires etching (see Figure 8).

It's common to need specific mixtures of PFC and/or HFC gases in order to selectively etch one material, and/or to form a protective polymer coating on the sidewall of the feature being etched that helps maintain the precise, uniform geometries of etched features. In this manner, the equilibrium between etching and deposition reactions provides a way to modulate the etching action.

For instance, the addition of H, $C_xF_yH_z$, serves to control silicon dioxide (SiO_2) and silicon nitride (SiN) uniformity and SiO_2/SiN selectivity. Similarly, the use of CHF_3 helps prevent the lateral etching of aluminum sidewalls. Employing different PFC gases and/or a combination of gases makes highly precise and selective etching at the nanometer scale possible.

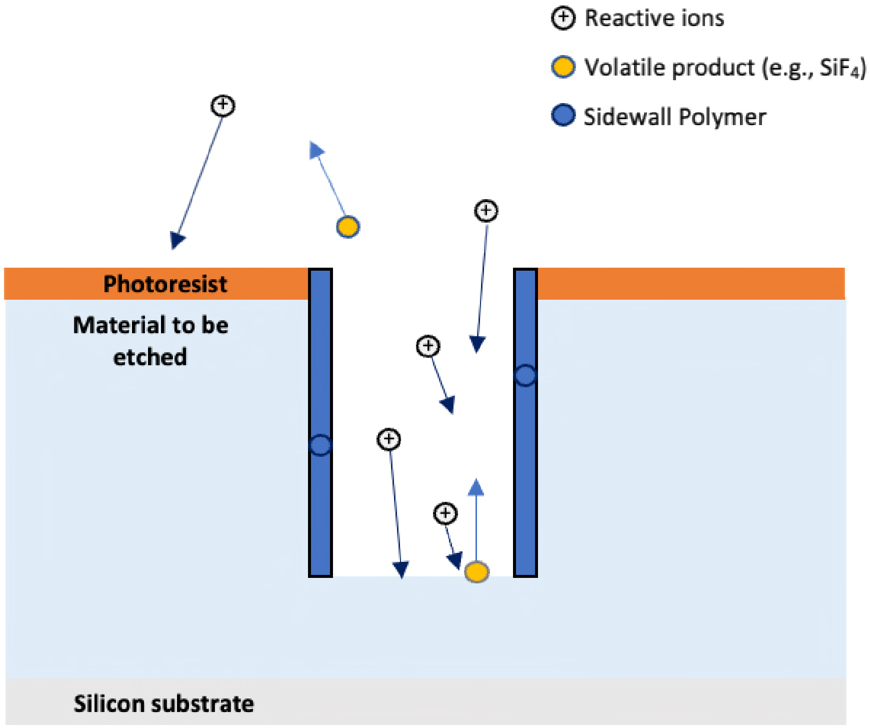


Figure 8: An anisotropic etch.

In certain limited situations, it is possible to use fluorine gas (F_2) with additive gases as the gas phase reactant for plasma etching; however, this involves replacing a nontoxic PFC gas with highly hazardous F_2. The use of F_2 requires significant human health and safety controls. F_2 has limited applications in plasma etching because it represents an acute life/safety trade-off relative to currently used PFC and HFC gases. Exhaust abatement technologies effectively destroy residual PFC and HFC gases from plasma etch and chamber clean processes.

11.0 Sustainability and the Semiconductor Technology Timeline

As the complexity of semiconductor technology increased, the semiconductor industry realized the need for cooperation and pre-competitive R&D. Device makers, SMRE and material suppliers, academia, consortia and national labs came together to develop the first National Technology Roadmap for Semiconductors (NTRS) in 1992, an effort that continued with the International Technology Roadmap for Semiconductors (ITRS); the International Roadmap for Devices and Systems (IRDS) in 2017 and 2023, respectively; and the 2023 SRC Microelectronic and Advanced Packaging Technologies Roadmap. The SRC roadmap defines a 15-year timeline of technology requirements to continue on the path of Moore's law, as well as highlighting priority environmental, health and safety (EHS) research needs. In 1994, the NTRS stated, "The roadmap is analogous to paved roads of proven technology, unimproved roads of alternative technologies, footpaths toward new technologies, and innovative trails yet to be blazed."

The semiconductor technology timeline consists of four distinct phases:

> Research. Fundamental research at universities and government labs occurs as much as 15 years before manufacturing ramp. Research addresses fundamental barriers to the extension of existing technologies, following multiple paths. Much research never makes it to subsequent phases.
>
> Development. Development entails the evaluation of a pared-down number of alternative technologies, with a focus on proof of concept. Device makers, tool suppliers, chemical suppliers and consortia conduct research and develop prototype materials, processes and equipment, with an understanding of the application requirements.
>
> Integration. Semiconductor manufacturers focus on the integration and qualification of fab processes, chemicals, tools, test protocols, and the verification of the physical and electrical design of new products, with a focus on developing functional, reliable and high-yielding products.
>
> Ramp to HVM. This phase is the implementation of next-generation tools, chemicals and processes throughout a fab.

EHS is an essential element of the technology roadmap (see Figure 9), addressed through various means at each phase of the timeline.

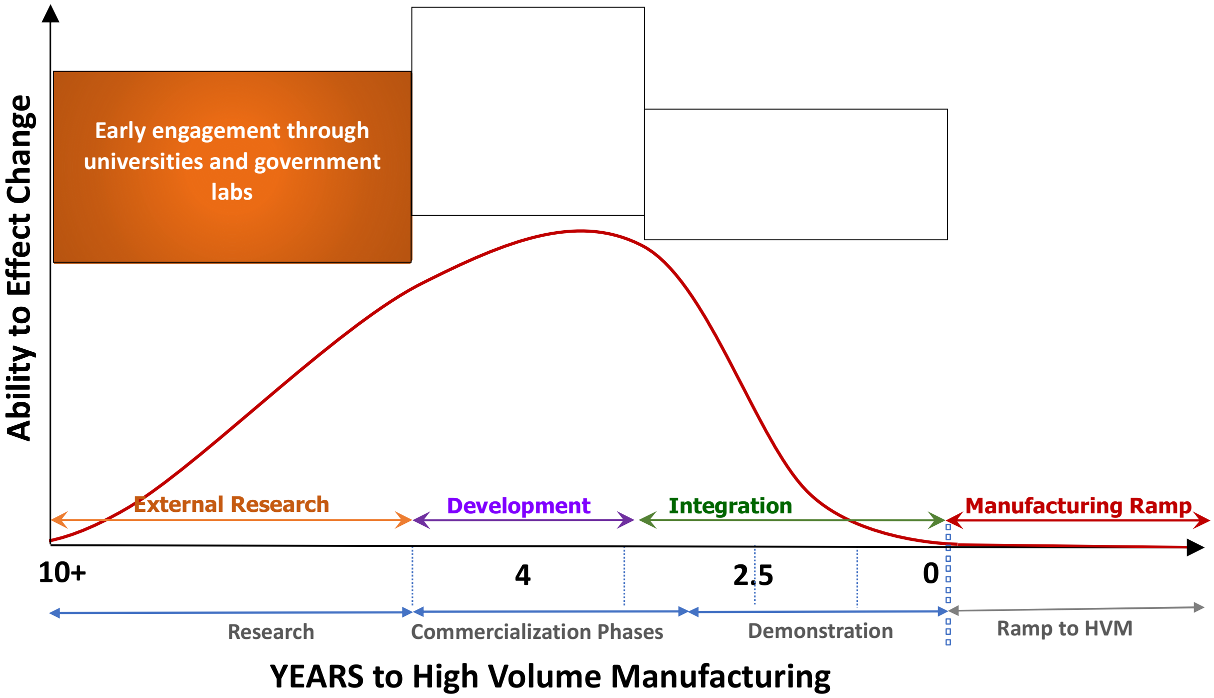


Figure 9: EHS engagement model.

The industry's ability to apply a pollution prevention hierarchy both quickly and cost-effectively (Figure 10) tracks with the technology timeline. It is easiest to address sustainability issues during the R&D phases, when an EHS assessment enables the identification of issues early enough to be resolved before transfer to HVM. It is possible to avoid materials of concern or to replace them with less hazardous substances at the research stage, although the majority of new materials evaluated in research do not progress to development because they do not meet the performance requirements.

It is important to evaluate basic physical-chemical properties and some aspects of environmental fate during research. But it is rare to pursue extensive EHS studies until materials are demonstrated because such studies take years to complete, and the material may never be commercialized. The impetus to address sustainability is most effective if driven from the funding side of the R&D equation.

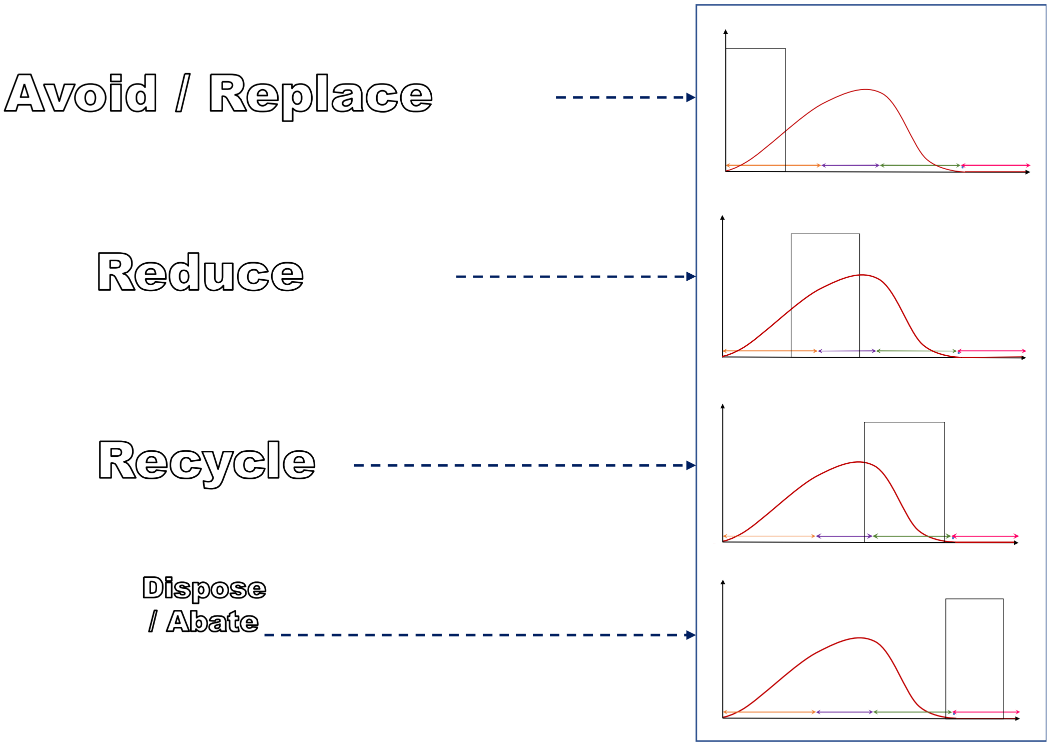


Figure 10: Implementation of a pollution prevention hierarchy.

The development and integration phases entail efforts to optimize processes and reduce chemical and resource consumption. Many semiconductor processes are transformative; for example, in plasma-enhanced CVD, a plasma reaction deposits input gas as solid thin films (see Figure 11); other processes use thermal energy to generate reaction products.

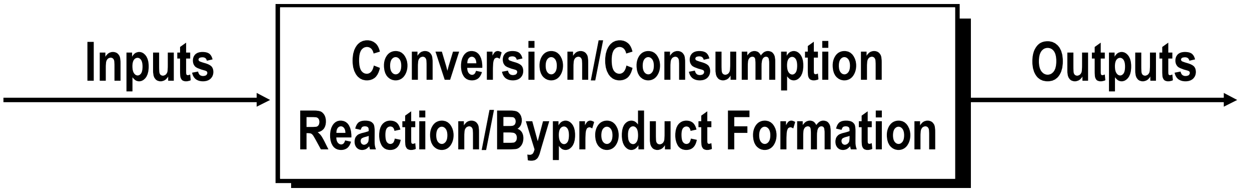


Figure 11: The emissions characterization process involves the evaluation of inputs, outputs, and conversion or reaction byproducts.

Emissions characterization and mass-balance models provide an understanding of process efficiency and enable process optimization to minimize chemical consumption and increase utilization efficiency; moreover, you can identify process byproducts and assess and address EHS risks. Assessing emissions to determine whether they can be recycled or reclaimed often occurs at the integration stage.

The progression of new technologies in the development cycle reduces the options for addressing EHS issues because SMRE, chemicals, processes and controls are set at HVM ramp. Changes at HVM are time-consuming and costly; thus, disposal and abatement are the primary solutions available once a technology has reached HVM.

Major barriers exist to implementing alternatives after HVM ramp. It is important to evaluate and demonstrate that any alternative has equivalent process performance, requiring research and invention that may not be successful. To prevent regrettable substitutions, any evaluation of alternatives includes emissions and byproducts characterization to understand what is potentially emitted, and in what concentrations; it is also imperative to consider the EHS characteristics of alternatives and reaction byproducts. After selecting an alternative, environmental fate and toxicity data is often not available and testing may take several years. If an alternative provides equivalent process performance but is more hazardous to workers, risk assessments will identify the controls necessary to protect workers. Alternative materials must also be evaluated from an environmental perspective.

A proven alternative requires the requalification of processes, an effort that can take six months to several years; moreover, customers of semiconductor products used in applications that require extended lifetimes and reliability (such as automotive and defense) are reluctant to allow process changes and, if a process change is allowed, require product requalifications that can take an additional five to eight years (PFAS Consortium 2023).

In summary, the timeline to identify and implement PFAS alternatives is:

- **Three to four years.** If an existing non-PFAS alternative is available, does not require infrastructure alterations, and demonstrates adequate performance for a specific application, then it typically takes three to four years to conduct the trial testing and implement the alternative into HVM.
- **Three to 10-plus years.** In some applications, an existing non-PFAS alternative may be viable, but requires tooling and/or process changes before its successful introduction into HVM. In these cases, it may take between three and 10-plus years to introduce changes to the SMRE and/or processes, perform qualification testing, and implement the non-PFAS alternative into HVM.
- **Five to 25-plus years – successful invention required.** For some applications, it may not be possible to demonstrate that an available non-PFAS alternative can fulfill the application-specific performance requirements. In those cases, it may be necessary to invent and synthesize new chemicals, and/or develop alternative approaches to fabricating a device structure that provides the necessary electrical and computational performance. Invention is an open-ended endeavor, with no guarantee of success.
- **No alternative achievable.** In some cases, a non-PFAS alternative may not be capable of providing the required chemical function.

12.0 EHS Controls

12.1 Occupational Exposure Control Strategy

The design and operation of fabs to stringent building codes and EHS clean-room standards, in combination with strict EHS controls managed by on-site industrial hygienists and engineers, greatly minimizes the opportunity for workers to be exposed to chemicals, including PFAS-containing materials.

There are several fundamental features of a semiconductor clean room and fab environment that protect employees:

- The isolation of chemicals from the manufacturing floor space by locating chemical supply, air-handling and other ancillary systems outside of manufacturing areas, either by using support spaces located below the clean room (subfab and utility levels), outside the clean-room space (bay and chase-type design), or in specifically designed bulk chemical storage and dispensing areas.
- The provision of 10-plus air changes per hour (1 cfm/ft^2 of outside air to the space, with a typical minimum of total recirculated air of 20 cfm/ft^2), whereby fab air recirculates through high-efficiency filters with a time constant on the order of seconds, replaced entirely with fresh outdoor air in a time constant on the order of minutes.

Robotic process automation provides a high level of automation, including enclosed process tools and robotics, that inherently isolates workers from chemicals. Throughout the manufacturing process, manufacturing tools shuttle wafers in enclosed FOUPs. Robots typically transfer wafers from the FOUP into the interior of a tool, where they are processed and further handled robotically.

The use of manufacturing tools built to Semiconductor Equipment and Materials Institute (SEMI) safety guidelines and certified to maintain chemical concentrations below defined occupational exposure threshold levels during normal operation and maintenance procedures and in the event of a tool failure.

Where there is a potential risk of exposure to chemicals, qualified EHS staff design any manual work tasks to minimize contact with chemicals and select personal protective equipment (PPE) for workers that are suitable for the task. Employees who work with chemicals will have extensive chemical safety training, with annual refreshers.

12.2 SEMI Safety Guidelines for Tool Design

Most semiconductor manufacturers have a company requirement to purchase semiconductor manufacturing tools designed and certified to comply with SEMI safety guidelines; for a complete list of these safety guidelines, see Appendix C. SEMI safety guidelines cover many aspects of manufacturing tool standardization and design conventions that have an enabled a fungible supply of immensely complex and specialized manufacturing tools for installation in fabs across the world.

In particular, the SEMI S2 safety guideline addresses design and performance standards for assuring the isolation or protection of clean-room workers from the chemicals used in semiconductor manufacturing tools. The SEMI S2 safety guideline distinguishes between the concentration of a chemical in the general ambient air surrounding a semiconductor manufacturing tool and the concentration within a “worst-case” PBZ. The SEMI S2 safety guideline also differentiates between three states of tool operation:

SEMI S2, 23.5.1 states that there should be no chemical emissions to the workplace environment during normal equipment operation. Measurements that show the air concentration to be less than 1% of the occupational exposure limit (OEL) in the worst-case PBZ demonstrate conformance to this requirement.

SEMI S2, 23.5.2 states that chemical emissions during maintenance activities should be minimized. Measurements that show a concentration in the anticipated worst-case PBZ during maintenance activities as less than 25% of the OEL demonstrate conformance to this requirement.

SEMI S2, 25.5.3 states that chemical emissions during equipment failure should be minimized. Measurements that show a concentration in the anticipated worst-case PBZ during a realistic worst-case system failure as less than 25% of the OEL demonstrate conformance to this requirement.

A third-party engineering company typically demonstrates conformance with SEMI safety guidelines on new models of manufacturing tools. Performance testing of chemical isolation relative to OEL entails the direct measurement of a chemical of concern under operating conditions, or by using a tracer test with a benign tracer gas. At present, there are no U.S. Occupational Safety and Health Administration, U.S. EPA or other published regulatory standards that address vapor-phase PFAS-containing materials.

The third-party engineering company documents their evaluations (which typically also include process hazard evaluations) in a comprehensive, several-hundred-page report. Since these reports contain extensive detail on the design and operating characteristics of highly proprietary manufacturing tools, the test reports are usually classified as confidential business information (CBI). The tool supplier only shares the test reports with direct customers under the protection of nondisclosure agreements.

12.3 Safety Procedures and On-Site Industrial Hygiene Staff

Semiconductor fabs have on-site industrial hygienists, safety specialists and environmental engineers who review and approve chemicals before their purchase and ensure the existence of process-specific safety procedures. In addition, EHS professionals develop and provide chemical and safety training, and review and approve all new tool and chemical infrastructure installations before startup.

When a manual task includes a potential risk of exposure to chemicals, EHS staff reviews those work tasks and designs work procedures to minimize contact with chemicals. Where appropriate, employees wear PPE selected for the task by qualified EHS staff. Employees who work with chemicals will have extensive chemical safety and PPE training, with annual refreshers. The availability of on-site EHS staff gives workers an ongoing opportunity for consultation with qualified experts.

12.4 Qualitative and Quantitative Chemical Risk Assessments

During a typical chemical review process, industrial hygienists perform qualitative and quantitative risk assessments. A qualitative hazard identification or risk assessment can help risk managers set priorities and make policy decisions to allocate resources to sampling. Many factors influence the decision to conduct a qualitative versus a quantitative risk assessment. In the case of PFAS use in the semiconductor industry, the very small quantities within chemical mixtures located in highly controlled equipment with locally exhausted ventilation essentially make exposure to PFAS by inhalation virtually nonexistent.

12.4.1 SEMATECH PFOS Industrial Hygiene Monitoring in and Around Track Tools

The results of PFOS measurements conducted during industrial hygiene sampling in a semiconductor fab by SEMATECH in 2005 provide the best-known available validation of the high level of protection against PFAS exposure provided by fab manufacturing tool design and operation.

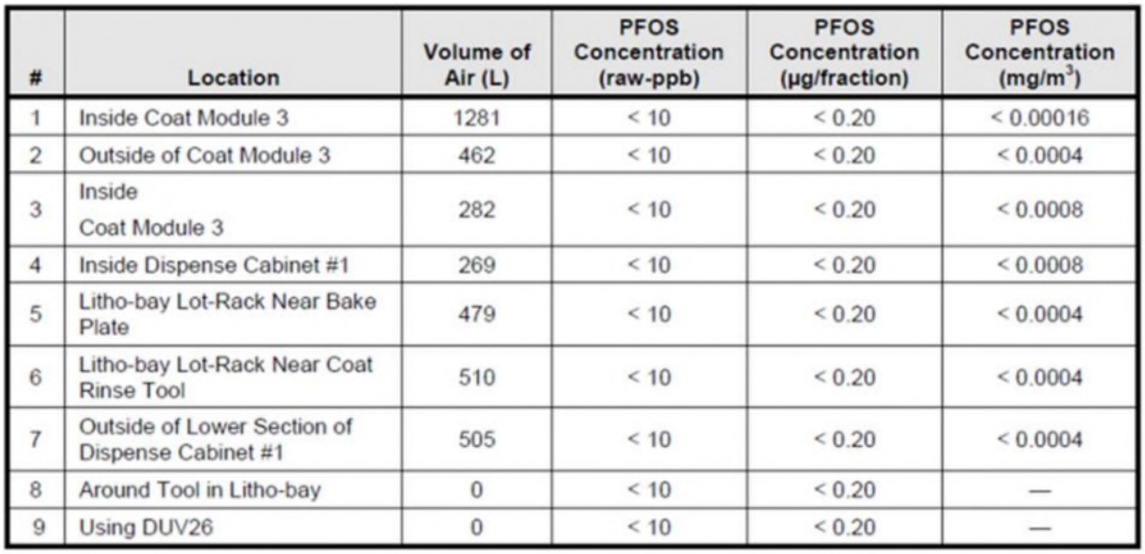
The use of PFOS has long since been eliminated from semiconductor fabs. But in 2005, SEMATECH’s study assured that there were appropriately protective designs and procedures in place to protect workers from exposure during the evaluation and implementation period of PFOS alternatives.

The SEMATECH study involved the collection of a total of nine air samples from within and around photolithography track tools that were known to be using PFOS-containing photoresists at the time of collection. Industrial hygienists collected the samples over a five-day period between May 21 and May 25, 2005, using established industrial hygiene sampling protocols and available analytical methods (Kaiser, et al. 2005); (Reagen, et al. 2004).

The results of all samples were less than the method detection limits, which ranged from <160 ng/m^3 to <800 ng/m^3 in air, as listed in Table 2. The range in detection limits is attributable to the location-specific sample volumes, which varied with the duration of the sample collection (Reagen, et al. 2004). At the time, the OEL recommended by a PFOS formulator was 100,000 ng/m^3.

The SEMATECH report also summarized the results of industrial hygiene samples collected from at least nine fabs across four semiconductor manufacturing companies. PFOS measurements were all below the method detection limits and were therefore two to three orders of magnitude (100 to 1,000 times) below the OEL of 100,000 ng/m^3 recommended by the PFOS supplier at the time.

Table 2: PFOS concentrations measured in air by SEMATECH in 2005.



#	Location	Volume of Air (L)	PFOS Concentration (raw-ppb)	PFOS Concentration (µg/fraction)	PFOS Concentration (mg/m^3)
1	Inside Coat Module 3	1281	< 10	< 0.20	< 0.00016
2	Outside of Coat Module 3	462	< 10	< 0.20	< 0.0004
3	Inside Coat Module 3	282	< 10	< 0.20	< 0.0008
4	Inside Dispense Cabinet #1	269	< 10	< 0.20	< 0.0008
5	Litho-bay Lot-Rack Near Bake Plate	479	< 10	< 0.20	< 0.0004
6	Litho-bay Lot-Rack Near Coat Rinse Tool	510	< 10	< 0.20	< 0.0004
7	Outside of Lower Section of Dispense Cabinet #1	505	< 10	< 0.20	< 0.0004
8	Around Tool in Litho-bay	0	< 10	< 0.20	—
9	Using DUV26	0	< 10	< 0.20	—

The American Conference for Governmental Industrial Hygienists (ACGIH) has established threshold limit values (TLVs) for three PFAS chemicals in air: perfluoroisobutylene (a short-term exposure limit of 0.01 ppm), perfluorobutyl ethylene (a 100-ppm time-weighted average) and ammonium perfluorooctanoate – a salt of PFOA (a 0.01-mg/m^3 time-weighted average).

12.4.2 NIOSH Research on PFAS

The industry is monitoring the development of scientific and regulatory information on the potential occupational toxicity of fluorinated organic compounds. The National Institute for Occupational Safety and Health (NIOSH) reports that their future research will continue building industry knowledge about potential exposure routes and advance practices to reduce the prevalence of PFAS exposure. The industry welcomes these developments.

12.4.3 Environmental Controls

The industry has an extensive track record on implementing strict controls on environmental releases including wastewater treatment, air emissions abatement technologies and waste management. The semiconductor industry is actively working to assess, test and implement process controls where they may be needed to reduce PFAS releases to the extent that they may occur. The industry is also sponsoring an extensive amount of university research on PFAS alternatives, emissions abatement, wastewater treatment and waste destruction, as summarized in the following sections.

12.4.4 Wastewater Discharges and Treatment

Semiconductor fabs typically have complex wastewater drain systems that carry process-specific wastewater through pre-treatment, equalization and neutralization steps before merging into a combined facility effluent. Segregated wastewater drain and treatment systems include those for certain metals, fluoride, certain acids and chemical-mechanical planarization (CMP) processes, but vary according to the fab design and applicability of local and federal pre-treatment requirements.

Typical pre-treatment requirements for the semiconductor industry include the removal of fluoride, ammonia, copper and other plating metals; solids and dissolved solids removal; and pH adjustments. To the extent that PFAS-containing materials are present in fab wastewater systems, the fate of PFAS-containing materials depends on their particular type, and the type of treatment processes used on PFAS-containing wastewater. PFAS-containing materials have been detected in the wastewater of typical fabs (Jacob, Barzen-Hanson and Helbling 2021).

If it is necessary to remove PFAS-containing materials from a fab's wastewater, they should ideally be intercepted and/or treated close to their source, where flows are typically lower and concentrations higher. Typical fab effluents can be on the order of 12,000 m^3/day to 23,000 m^3/day, and removing low concentrations of PFAS-containing materials from a final effluent discharge point that operates at a high flow will be very expensive and, in some cases, infeasible.

It is not likely that the conventional precipitation-coagulation-clarification treatment processes typically used to remove dissolved metals and fluoride from on-site fab wastewater systems would exert a high removal efficiency for soluble PFAS-containing materials. The partitioning of some PFAS-containing materials to waste solids may be possible and could represent a relevant vector for PFAS migration in treatment processes.

Similarly, it is unlikely that microfiltration processes can remove significant amounts of soluble PFAS-containing materials. Nanofiltration (NF) and reverse osmosis (RO) membranes could potentially remove a significant fraction of long-chain PFAS and lesser amounts of short-chain PFAS into membrane concentrate streams (Boo, et al. 2018); (Jin, Peydayesh and Mezzenga 2021); (Tow, et al. 2021).

There are two types of treatment process technologies for removing PFAS-containing materials: technologies that remove or separate PFAS constituents from wastewater, and technologies that destroy the PFAS-containing material. A treatment process such as granular activated carbon (GAC), for instance, can remove PFAS-containing materials from wastewater, but following the completion of the sorption cycle, the used GAC itself becomes waste.

Table 3 summarizes the principal separation and destruction technologies currently in use or under development for treating PFAS-containing wastewater. The principal, commercially available technologies applicable to the removal of PFAS-containing materials from wastewater are adsorption onto GAC, anion exchange (AIX) and membrane filtration (Crone, et al. 2019). The capacity of GAC to remove a given PFAS-containing material is typically expressed in terms of the milligrams of PFAS per kilogram of GAC and varies considerably depending on the particular type of PFAS-containing material. AIX can be an effective way to remove anionic PFAS-containing materials from water. AIX typically has a higher sorption capacity than GAC, and some similar (but not quite as strong) constraints regarding a preference for longer- over shorter-chain PFAS-containing materials, as well as a preference for sulfonic acid vs. carboxylate groups (Franke, et al. 2021). High-pressure membrane techniques like RO and NF (as illustrated in Figure 12) can be an effective way to separate PFAS-containing materials from an aqueous waste stream and concentrate it for further treatment (Lee, Speth and Nadagouda 2022); (Liu and Strathmann 2021); (Liu, et al. 2022). RO, in particular, can serve as a near-absolute barrier to most typical PFAS-containing materials.

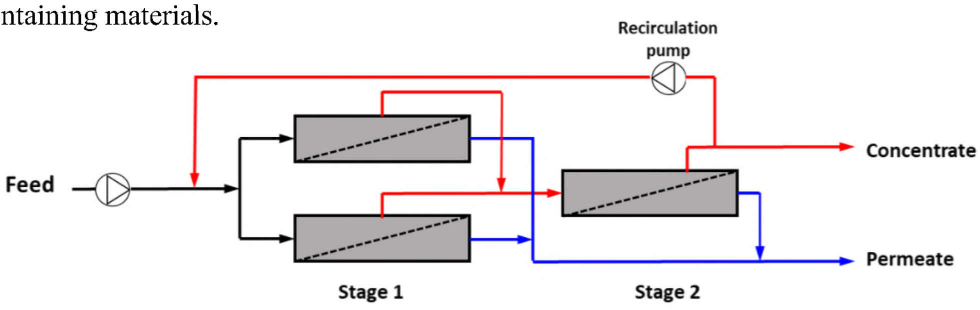
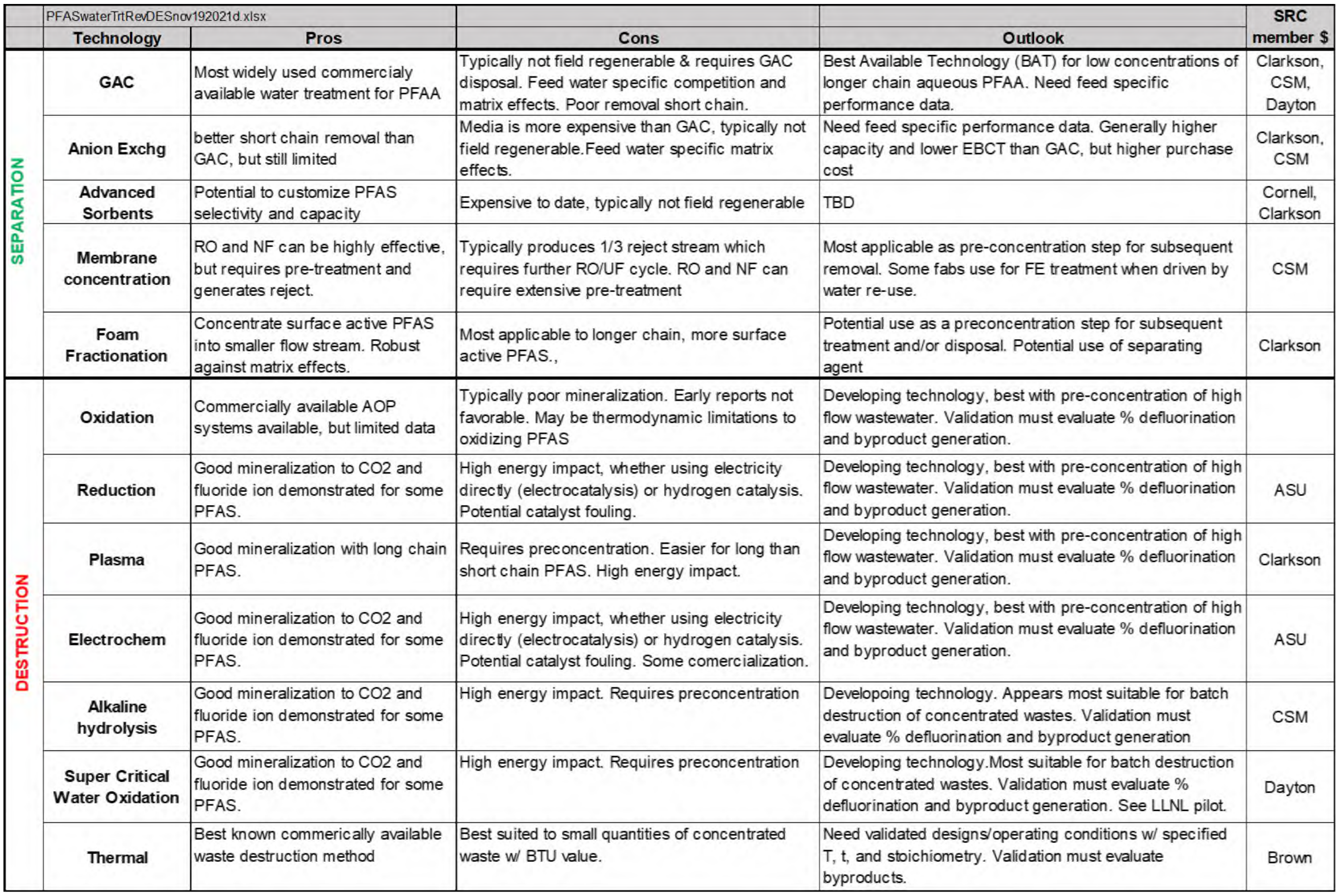


Figure 12: A two-stage nanofiltration system (Franke, et al. 2021)**.**

The semiconductor industry is funding university research to study a number of different types of PFAS treatment technologies. The right-hand column in Table 3 lists universities that are either receiving funding from the SRC or companies that are SRC members. In general, the state of technology for PFAS wastewater treatment is immature, with significant improvements needed to increase the number and types of PFAS-containing materials that can be removed cost-effectively from wastewater. Existing separation and destruction methods are generally best suited to the removal of longer-chain perfluoroalkyl acids, with more difficulty removing shorter-chain and/or neutral PFAS-containing materials (Murray, et al. 2021); (Liu and Strathmann 2021); (Liu, et al. 2022).

There are numerous methods to destroy PFAS-containing materials under evaluation, with new technologies and refinements of existing technologies reported in literature virtually every day. The bottom half of Table 3 lists several of the most promising PFAS destruction technologies under development. Generally, reduction, plasma and electrochemical methods appear to be more effective than oxidation methods, which face thermodynamic barriers (Vecitis, et al. 2008); (Bentel, et al. 2020). Alkaline hydrolysis and supercritical water oxidation (SCWO) are high-temperature, high-pressure processes that aim to mineralize PFAS-containing materials and show promising results.

Table 3: Summary of PFAS wastewater treatment methods.



	PFASwaterTrtRevDESnov192021d.xlsx				SRC
	Technology	**Pros**	**Cons**	**Outlook**	**member $**
SEPARATION	**GAC**	Most widely used commercialy available water treatment for PFAA	Typically not field regenerable & requires GAC disposal. Feed water specific competition and matrix effects. Poor removal short chain.	Best Available Technology (BAT) for low concentrations of longer chain aqueous PFAA. Need feed specific performance data.	Clarkson, CSM, Dayton
	Anion Exchg	better short chain removal than GAC, but still limited	Media is more expensive than GAC, typically not field regenerable.Feed water specific matrix effects.	Need feed specific performance data. Generally higher capacity and lower EBCT than GAC, but higher purchase cost	Clarkson, CSM
	Advanced Sorbents	Potential to customize PFAS selectivity and capacity	Expensive to date, typically not field regenerable	TBD	Cornell, Clarkson
	Membrane concentration	RO and NF can be highly effective, but requires pre-treatment and generates reject.	Typically produces 1/3 reject stream which requires further RO/UF cycle. RO and NF can require extensive pre-treatment	Most applicable as pre-concentration step for subsequent removal. Some fabs use for FE treatment when driven by water re-use.	CSM
	Foam Fractionation	Concentrate surface active PFAS into smaller flow stream. Robust against matrix effects.	Most applicable to longer chain, more surface active PFAS.,	Potential use as a preconcentration step for subsequent treatment and/or disposal. Potential use of separating agent	Clarkson
DESTRUCTION	**Oxidation**	Commercially available AOP systems available, but limited data	Typically poor mineralization. Early reports not favorable. May be thermodynamic limitations to oxidizing PFAS	Developing technology, best with pre-concentration of high flow wastewater. Validation must evaluate % defluorination and byproduct generation.	
	Reduction	Good mineralization to CO2 and fluoride ion demonstrated for some PFAS.	High energy impact, whether using electricity directly (electrocatalysis) or hydrogen catalysis. Potential catalyst fouling.	Developing technology, best with pre-concentration of high flow wastewater. Validation must evaluate % defluorination and byproduct generation.	ASU
	Plasma	Good mineralization with long chain PFAS.	Requires preconcentration. Easier for long than short chain PFAS. High energy impact.	Developing technology, best with pre-concentration of high flow wastewater. Validation must evaluate % defluorination and byproduct generation.	Clarkson
	Electrochem	Good mineralization to CO2 and fluoride ion demonstrated for some PFAS.	High energy impact, whether using electricity directly (electrocatalysis) or hydrogen catalysis. Potential catalyst fouling. Some comercialization.	Developing technology, best with pre-concentration of high flow wastewater. Validation must evaluate % defluorination and byproduct generation.	ASU
	Alkaline hydrolysis	Good mineralization to CO2 and fluoride ion demonstrated for some PFAS.	High energy impact. Requires preconcentration	Developoing technology. Appears most suitable for batch destruction of concentrated wastes. Validation must evaluate % defluorination and byproduct generation	CSM
	Super Critical Water Oxidation	Good mineralization to CO2 and fluoride ion demonstrated for some PFAS.	High energy impact. Requires preconcentration	Developing technology.Most suitable for batch destruction of concentrated wastes. Validation must evaluate % defluorination and byproduct generation. See LLNL pilot.	Dayton
	Thermal	Best known commerically available waste destruction method	Best suited to small quantities of concentrated waste w/ BTU value.	Need validated designs/operating conditions w/ specified T, t, and stoichiometry. Validation must evaluate byproducts.	Brown

When evaluating PFAS destruction technologies, it is important to measure the extent of mineralization (conversion to carbon dioxide plus fluoride ion or hydrogen fluoride gas) and the extent to which potentially harmful byproducts are generated. Often, the removal efficiencies reported for targeted parent compounds are much higher than the overall defluorination (Wang, et al. 2022).

12.4.5 PFAS Waste Disposal and Destruction by Incineration

PFAS-containing materials are present in some semiconductor manufacturing solvent wastes. Residual photoresists and anti-reflective coatings, for instance, are largely captured directly at the photolithography tool dispensing step and shipped for off-site disposal.

Organic waste (including PFAS organic liquids) is typically segregated, collected, and containerized for off-site treatment, and disposed of as a blended fuel through high-temperature incineration or reprocessing. Often regulated because of its flammability (rather than the presence of PFAS-containing materials), liquid organic waste that cannot be treated on-site is collected and shipped off-site to a licensed treatment and disposal facility. These facilities will either reclaim solvent constituents, manage the solvent for energy recovery as fuel for cement kilns, or incinerate the hazardous waste.

There are currently no published PFAS-specific regulations or regulatory guidance governing the design, operation or monitoring of commercial waste incinerators used to destroy PFAS waste. The U.S. EPA has indicated that it is working to establish such guidance in late 2023. A number of technical papers describe laboratory or simulation studies that address the temperature at which certain PFAS-containing materials decompose, and some of the fluorinated decomposition products that form, but these papers generally lack specific information regarding the temperature, residence time, and other process and design variables directly applicable to commercial incineration (Wang, et al. 2022); (U.S. EPA 2020). Based on calculated bond energies, for instance, the most difficult fluorinated organic compound to decompose is CF_4, which requires temperatures over 1,400°C for effective destruction (Tsang, Burgess Jr. and Babushok 1998).

A typical commercial hazardous waste incinerator in the U.S. is a rotary kiln with a primary combustion chamber that has solid retention times of 0.5 to 1.5 hours and gas residence times around 2 seconds, with kiln flame temperatures from 650°C to 1,650°C (U.S. EPA 2020). The rotary kiln is typically followed by an afterburner that operates at a temperature between 1,100°C and 1,370°C, with a gas phase residence time of 1 to 3 seconds (U.S. EPA 2020).

In some cases, hazardous waste is burned in cement kilns, where temperatures may rise above 1,650°C with gas phase residence times on the order of 4 to 16 seconds, depending on the design (U.S. EPA 2020). In addition to operating at high temperatures and having long gas phase residence times, cement kilns have the additional advantage of providing a caustic environment for halogen reaction and acid neutralization (U.S. EPA 2020).

Based on the high temperatures and long gas phase residence times reported for the kiln-type incinerators commonly used to destroy hazardous waste, PFAS destruction or removal efficiency (DRE) should be very good.

12.4.6 Air Emissions Control and Abatement

Fab exhaust systems are designed to remove chemical vapors or gases and heat from manufacturing tool exhausts. PFCs and HFCs are essential for plasma etching, plasma cleaning and other low-volume applications, as their uses balance the process requirement for high chemical and ion reactivity with the need for safe and effective manufacturing.

The chemistries used in photolithography have a relatively low vapor pressure, and the industry does not anticipate emissions from photolithography. The industry’s commitment to reduce GHGs has successfully reduced PFC and HFC emissions through a combination of process optimization, substitution and abatement. Point-of-use (POU) technologies on many tools using PFCs and HFCs have reduced the potential exposure risk to employees, as well as reducing GHG emissions.

The F-HTFs used in chillers and test equipment are contained with intent to minimize release during use. Before any maintenance activities, qualified workers drain F-HTFs contained in equipment into collection containers that are managed for direct use or reclamation at the F-HTF supplier. If any of the F-HTF fluid requires management as waste, certified waste management facilities destroy the fluid by incineration.

There are four general categories of exhaust systems (Li, et al. 2021); (Sherer 2018):

- General exhaust is a centralized exhaust system consisting of air from exhausted enclosures, typically uncontaminated with hazardous or toxic chemicals and heat exhaust. General exhaust does not require abatement.
- Acid and alkali (corrosive) exhaust, the highest-volume exhaust stream, is primarily generated from the use or generation of acid or alkali gases within etch, deposition and cleaning processes. Chlorine, fluorine, fluorinated GHG and hydrides are components of acid exhaust. Alkali exhaust is usually segregated from acid exhaust in order to prevent the clogging and formation of submicron particles, and to treat the exhaust more effectively. Acid and alkali exhaust treatments often occur in centralized pH-controlled packed-bed wet scrubbers.
- Organic exhaust is primarily generated from the use or generation of volatile organic compounds (VOCs) within photolithography and organic cleaning processes.
- Organic solvent exhaust typically has a high volume and a low concentration, which often leads to a concentrated exhaust stream before treatment with centralized thermal, catalytic or plasma oxidizers.

Certain SMRE requires the installation of POU abatement devices to remove contaminants before their discharge to centralized exhaust systems. POU abatement devices prevent the clogging of exhaust lines and thus increase process uptimes; they also prevent fires, explosions and corrosion, and protect workers and the environment.

The main components of any exhaust collection and distribution system consist of ductwork, fans, pumps and possibly treatment technologies. The materials used to construct exhaust systems in fab and assembly test manufacturing facilities must be chemically resistant, in order to prevent corrosion and release of the exhaust. Ethylene chlorotrifluoroethylene (ECTFE)- or polytetrafluoroethylene (PTFE)-lined stainless-steel ductwork helps ensure safe conditions within fab and assembly, test and packaging operations, especially in high-heat, chemically corrosive or chemically unstable environments.

POU abatement systems have evolved over time to meet safety, environmental and risk-reduction targets. They facilitate effective and safe treatment for pyrophoric, toxic, flammable and corrosive gases. Researchers, suppliers and semiconductor manufacturers have undertaken extensive efforts to develop and improve fluorinated GHG abatement technologies over the last 30 years (see Figure 13). Abatement technologies including combustion with a wet scrubber, electrical heating with a wet scrubber, chemisorption/adsorber and plasma have been shown to remove PFCs and other fluorinated GHGs from process exhaust (Beu 2019).

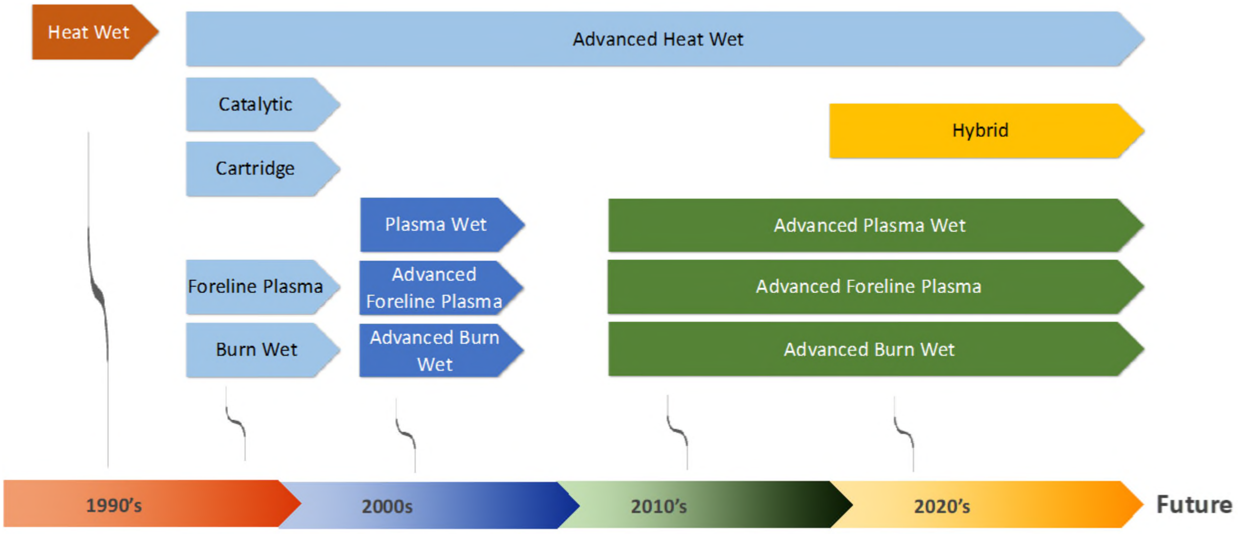


Figure 13: Semiconductor industry fluorinated GHG abatement development timeline.

For additional information about fluorinated GHG abatement, see the Semiconductor PFAS Consortium white paper, "PFAS-Containing Fluorochemicals Used in Semiconductor Manufacturing Plasma-Enabled Etch and Deposition."

13.0 R&D Needs

The fluorinated organic molecule possesses numerous attributes that provide unique functionality across a wide spectrum of applications. In many situations, it is not just one particular attribute (like low surface tension) that makes a fluorinated organic chemical effective for an application, but the combination of several attributes that enable fluorinated organics to satisfy multiple, overlapping performance requirements.

For many PFAS-containing materials, there is an absence of basic validated physicochemical data, which makes it virtually impossible to determine their toxicity and environmental fate and transport. Given their potential persistence, bioaccumulation and toxicity, regulators and policymakers both in the U.S. and globally are taking actions to mitigate the potential impacts of these chemicals.

A growing number of jurisdictions are addressing or proposing the categorization of PFAS as an entire class. To maintain industry growth and avoid regrettable substitutions, it is imperative to:

> Fund and conduct research to understand basic physicochemical data to better model the potential environmental and human health risks associated with these chemistries, and to identify alternative chemistries where possible that are more environmentally preferable.
>
> Develop recycling, treatment and abatement technologies to prevent environmental releases for uses with no known alternatives at this time.

Further, given the multiple properties that PFAS-containing materials instill, it is more likely that there will be a combination of application-specific solutions rather than a universal replacement.

It is recommended that the semiconductor industry, academicians, national labs and suppliers collaborate on semiconductor PFAS-focused R&D efforts to:

> Advance the development of analytical methods to measure and control PFAS-containing materials in the work environment, wastewater and air emissions streams.

- Develop a higher level of knowledge regarding the environmental behavior and toxicity of PFAS-containing materials, their potential degradation products, and potential alternatives, using the data to:
  - Develop and validate predictive toxicology, environmental fate and behavior tools for PFAS-containing materials and potential PFAS alternatives for use in semiconductor manufacturing.
  - Improve knowledge of the factors that cause PFAS-containing materials to be toxic, which will aid the development and identification of potentially more benign substitutes.
- Quantify and improve technology that minimizes potential environmental releases.
- Quantify and validate the efficacy of workplace exposure controls.
- Optimize processes to reduce or reuse materials where possible in support of a circular economy.
- Develop, design, test and validate PFAS destruction technologies.
- Identify opportunities for process enhancements that reduce the total use of fluorinated gases.
- Develop HFC and PFC abatement options for POU or house (end-of-pipe) abatement of exhaust emissions that can achieve higher DREs while minimizing the generation of other regulated emissions.
- Promote development of additional reuse and recycling options for PFAS-containing liquid waste streams.
- Evaluate options to facilitate the recovery and reuse of articles containing PFAS.
- Evaluate alternative plasma etch/wafer clean gases and processes that are effective, safe and have a lower GWP than fluorinated gases.
- Develop low-temperature, high-efficiency processes and look for materials that can work at lower temperatures (bottom-up processes such as directed self-assembly) to help facilitate the transition away from F-HTFs.
- Identify and characterize process performance and EHS characteristics of more benign nonfluorinated alternatives such as:
  - PFAS-free anions in PAGs capable of making strong acids.
  - PFAS-free anti-reflective coatings.
  - PFAS-free immersion barriers.
  - PFAS-free surfactants.
  - PFAS-free lubricants.
  - PFAS-free HTFs with a lower GWP used in chillers to control wafer temperatures during manufacturing processes or device testing.
  - PFAS-free ligands for metal-organic CVD precursors.
- Identify and evaluate:
  - Fluoropolymer alternatives for use in SMRE and facilities infrastructures.
  - The potential of additive processing techniques.
  - Non-PFAS semiconductor assembly, test and packaging materials that can perform at sustained high temperatures, low temperatures, wide thermal excursions and under large thermomechanical loads.

13.0 Conclusions

PFAS chemicals contain two or more fluorine atoms bonded to a carbon or hydrocarbon backbone. Their carbon-fluorine bonds and structure give them unique physical and chemical properties, such as repelling both water and oils, remaining stable over a wide temperature range, and having low coefficients of friction, making them useful in many industrial and consumer applications, including semiconductor manufacturing. However, many of these same properties make PFAS-containing materials resistant to decomposition when released to the environment, which has led them to be called “forever chemicals.”

Semiconductors are essential components of electronic devices and are integral to modern society. According to the World Economic Forum, semiconductor-enabled technologies such as digital technologies can reduce GHG emissions by 15% – almost one-third of the 50% reduction required by 2039 (World Economic Forum 2019).

Manufacturers and suppliers have identified seven areas where PFAS chemistry supports advanced semiconductor manufacturing: photolithography, wet chemistry, HFC and PFC gases, HTFs, chip packaging, fabrication tools and associated fixtures, and lubricants.

Modern semiconductor manufacturing fabs consist of thousands of tools, and each of these perform a specific process operation to construct and assemble a chip wafer. Fabs have strict requirements to maintain clean-room environments to capture and remove contaminants such as dust, and to control humidity and chemistry. In many applications, PFAS-containing materials are the only chemicals known to provide the required physical and chemical properties for advanced semiconductor manufacturing.

The industry has strict controls to minimize working exposure to chemicals, including PFAS-containing materials used in the chip manufacturing process. Some materials are sent off-site for treatment, such as incineration, or disposed of in regulated solid waste disposal facilities. Fabs also have wastewater pre-treatment or treatment systems before discharge.

The semiconductor industry continues actively identifying, testing and implementing improved process controls that minimize releases to the environment, including PFAS-containing materials. The industry is also researching prospective PFAS substitutes, which is expensive and time-consuming. The identification and validation of alternatives is a lengthy process that entails identifying potential substitutes, evaluating their potential human and environmental risks, conducting laboratory and pilot tests, designing and retooling equipment, conducting verification tests, and finally implementing a substitution.

The semiconductor industry recognizes the need for and is undertaking additional R&D to:

Characterize the human health and environmental risks associated with PFAS-containing materials used in the industry.
Develop analytical methods to characterize PFAS-containing materials.
Evaluate PFAS releases to air and/or water.
Identify, test and implement substitutes to either eliminate PFAS-containing materials, or substitute PFAS-containing materials with those having lower human health or environmental risks.
Evaluate and test abatement technologies to capture or destroy PFAS-containing materials before their release to the environment.

Based on the consortium’s findings and as documented in each of the accompanying white papers, until the industry can identify, test and qualify suitable substitutes, PFAS-containing materials are essential to semiconductor manufacturing operations and equipment.

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Appendix A: Glossary of Acronyms and Terms

Terms	Definition
3D	three dimensional
5G/6G	Fifth- and sixth-generation cellular technology for wireless internet connections and communications.
ABT	manufacturing equipment abatement
ACGIH	American Conference of Governmental Industrial Hygienists
AI	artificial intelligence
AIX	anion exchange
ALD	atomic layer deposition
Aluminum etch	An aqueous mixture that includes phosphoric acid, nitric acid and acetic acid.
AMHS	automated material handling system
ANSI	American National Standards Institute
Anti-EBO	anti-epoxy bleedout
Antireflective coatings	Top- or bottom-surface coatings used to reduce light reflection at surface interfaces to better control line width in photolithography.
APM	A mixture of ammonium hydroxide (28 wt %), hydrogen peroxide (30 wt %) and water, also known as SC1.
Aqueous-based	A mixture in which water is the solvent.
ARC	anti-reflective coating
ArF	argon fluoride
Article(s)	An object or objects made from one or more substances and mixtures given a special shape, surface or design during production that determines its function to a greater degree than its chemical composition, whether on its own or in an assembly with other articles, substances and mixtures. Also, materials used in the construction of semiconductor processing equipment, support equipment, facilities equipment, and other purchased or produced items containing PFAS.
Assembly, test and packaging	The processing steps necessary to test and attach individual semiconductor devices into chip packages that can then be used in electronic devices.
ASTM	American Society for Testing and Materials
ATP	assembly, test and packaging
ATPS	assembly, test, packaging and substrate
AWN	acid waste neutralization
Back end of line	Processing to create the interconnect wiring for a device.
BARC	bottom anti-reflective coating
Barrier layers	Film between the silicide and metallization layers in an interconnect.
BCD	bulk chemical delivery
BEOL	back end of line
Bespoke parts	Parts or articles that are made to order or custom fabricated.
BGA	ball grid array

Terms	Definition
BHF	buffered hydrofluoric acid etch
Bioaccumulation	A gradual accumulation of substances or chemicals in an organism.
BMS/QA	business management system/quality assurance
BOE	buffered oxide etch
BOM	bill of materials
BP	boiling point
Buffered oxide etch	An aqueous mixture of hydrofluoric acid and ammonium fluoride.
C4	Perfluorinated and polyfluorinated alkyl substances with a chain length of four carbons. C4 can sometimes refer to controlled collapse chip connect, the steps in semiconductor manufacturing between front-end fab manufacturing and assembly test and packaging steps.
CAGR	compound annual growth rate
CARs	chemically amplified resists
CBI	confidential business information
C-C backbone	All organic compounds are made up of carbon-carbon bonds, creating a carbon skeleton or backbone in the compounds.
CD-SEM	critical dimension-scanning electron microscope
C-F bond	carbon-fluorine bond
CFCs	chlorofluorocarbons
Chalcogen	Any element in group 16 of the periodic table such as oxygen, polonium, sulfur, selenium or tellurium; the latter three are typical chalcogens in a dichalcogenide.
Chamber clean	A process in chemical vapor deposition that removes deposition residues from chamber walls and other interior surfaces.
Chemical mechanical planarization slurries	Abrasive and corrosive chemical slurry (commonly a colloid) used to remove material and even out irregular topography, making the wafer flat or planar.
Chemical mechanical polishing	A process that smooths and polishes the surface of a wafer to extreme levels of precision, used during multiple steps of wafer manufacturing.
Chemical vapor deposition	Microfabrication processes used to deposit thin films of materials in various forms, including monocrystalline, polycrystalline, amorphous and epitaxial.
Chip	The common name for an integrated circuit.
Clean room	An engineered space that maintains a very low concentration of airborne particulates.
CMC	critical micellar concentration
CMP	chemical-mechanical planarization
CMR	carcinogenic, mutagenic and toxic for reproduction substances
CNT	carbon nanotube
C-O Bond	carbon-oxygen bond
Coax	The abbreviated term for a coaxial cable.
Component	An identifiable part that a manufacturer of SMRE or facilities equipment has purchased to produce a more complex assembly.
CTE	coefficient of thermal expansion

Terms	Definition
CVD	chemical vapor deposition
CZ	The Czochralski crystal growth process (for making silicon ingot that silicon wafers are then cut from).
D4, D5, D6 ring	Cyclosiloxanes containing four, five and six silicon atoms in the ring, respectively.
Deep ultraviolet	The wavelength of light (249 nm and 193 nm) used to produce fine features on semiconductor devices.
Dense feature bias	A critical dimension swing resulting from a shifted resist depth of focus caused by a change in thickness of a lithography film stack as it coats over various pitches, critical dimensions and aspect ratios of substrate topography.
DEP	deposition equipment
Deposition	A semiconductor manufacturing step where thin films of materials are added in various forms to the surface of a wafer.
DETCH	dry etch equipment
Device	An electronic component that relies on the electronic properties of a semiconductor material (primarily silicon, germanium and gallium arsenide, as well as organic semiconductors) for its function.
Dichalcogenides	Any chalcogenide (a compound that contains a chalcogen and a more electropositive element) that contains two chalcogen atoms per molecule.
Die	A single instance of a particular end device produced simultaneously on a wafer; a wafer comprises hundreds of die, and a single die may contain millions of integrated circuits.
Die-attach adhesives	Adhesive used to mount or bond die to a support structure using an epoxy-based adhesive.
Die overcoat	Protective polymer coating applied to a bare die surface for small form packages.
Die passivation	The application of a PFAS anti-stiction material as a microcoating of micro-electromechanical system structures so that they become passive (less readily affected by the environment, while also reducing the surface work of adhesion to improve the surface energy properties necessary for actuation).
Dilute HF(DHF)	An aqueous mixture containing 0.1% to 0.5% hydrofluoric acid in water.
Drop-in replacement	An alternative substance that that performs in a functionally equivalent way and does not require the modification of existing manufacturing equipment.
Dry etch	The removal of a masked pattern of semiconductor material by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons or oxygen).
Dry vacuum pump system	A vacuum pump system that does not use a liquid sealing system, and is oil- and water-free.
DSC	die-side components
DUV	deep ultraviolet
E-beam	Electron-beam processing, also called electron irradiation.
EBI	electron irradiation
EC	European Commission
ECD	electrochemical deposition
ECHA	European Chemicals Agency

Terms	Definition
ECTFE	ethylene chlorotrifluoroethylene
EEA	European Economic Area
EEE	electrical and electronic equipment
EFEM	equipment front-end modules
EHS	environmental, health and safety
Electronegativity	The tendency of an atom such as fluorine to attract electrons in a molecule.
Electronic mold compounds	Cured resin used to protect semiconductor components from moisture and mechanical damage, and to serve as a mechanical structure.
Embedded barrier layers (photolithography)	A component of top-coat-free photoresists used for immersion lithography that contains an oligomeric or low-molecular-weight PFAS.
Encapsulant	A processing step in which a semiconductor chip is encased with a certain material to protect it from the external environment.
Environmental fate and transport	How chemicals released to the environment move in response to wind, rain and human activities.
EoL	end of life
EPDM	ethylene propylene diene monomer
Equipment	See SMRE.
ESIA	European Semiconductor Industry Association
Etching	The removal of unnecessary materials from a wafer’s surface during the photolithography process so that only the design pattern remains.
ETFE	ethylene tetrafluoroethylene
EU	European Union
EUV	extreme ultraviolet
Extreme ultraviolet	The wavelength of light (13.5 nm) used to pattern the finest features required on foundation layers of advanced semiconductor devices.
Exposure latitude	The extent to which a light-sensitive material can be under- or overexposed and still achieve an acceptable result.
Fab	The abbreviated term for fabrication plant or fabricator, where semiconductors are manufactured on wafers (typically silicon wafers).
Facilities infrastructure	Systems within a factory that support manufacturing operations; for example, the storage, supply and disposal of gaseous and liquid chemicals, ultrapure water production, and exhaust abatement.
Far back end of the line	Processing that occurs after the fabrication of a semiconductor device in preparation for subsequent packaging.
FBEOL	far back end of the line
FC	flip chip
FCBGA	flip-chip ball grid array
FCCSP	flip-chip chip-scale package
FCLGA	flip-chip land grid array
FEOL	front end of line
FEP	fluorinated ethylene propylene
FFU HEPA	fan filter unit high-efficiency particulate air

Terms	Definition
F-gas	Fluorinated gases, particularly those that are perfluorocarbons and hydrofluorocarbons and may be considered PFAS-containing materials.
F-HTF	fluorinated heat transfer fluid
Final resolution	The smallest mask feature size that a photoresist can pattern.
FinFET	A multigate metal-oxide semiconductor field-effect transistor.
FKM	The American Society of Testing and Materials' name for fluoroelastomers or fluoro rubber material.
Fluorine	A chemical element with the chemical symbol F and atomic number 9.
Fluorine gas/F_2	A diatomic gas consisting of two fluorine atoms covalently bonded.
FFKM	The American Society of Testing and Materials' name for perfluoro elastomers or perfluoro rubber material, which typically contains higher levels of fluorinated materials compared to FKM.
Fluoroelastomer	Fluorocarbon-based synthetic rubbers; part of the fluoropolymers family.
Fluoropolymer	A distinct subset of fluorinated high-molecular weight polymers with fluorine atoms directly attached to their carbon-only backbone.
FM	Factory Mutual
Focus window	A range of focus values for which a photoresist simultaneously meets linewidth, wall angle, absence of residues and top retention criteria.
FOSB	front opening shipping box
FPD	flat panel display
Front end of line	The steps of semiconductor fabrication, from a blank wafer to a completed wafer that has not yet been separated into individual chips.
FOUP	front opening unified pods
f-TTF	fluorinated-tetrathiafulvalene
GAC	granular activated carbon
GaN	gallium nitride
Gas cluster ion beam	A technology for nano-scale modification of surfaces. The process can smooth a wide variety of surface material types to within an angstrom of roughness without subsurface damage, and is also used to chemically alter surfaces through infusion or deposition.
Gasket	Flat, circular seals (often manufactured with flexible materials, but sometimes designed with harder materials) that sit between two flat surfaces designed to prevent leakage.
GDP	gross domestic product
GHG	greenhouse gas
GHS	globally harmonized system
GWP	global warming potential
H_2O	water
H_2O_2	hydrogen peroxide
H_2SO_4	sulfuric acid
H_3PO_4	phosphoric acid
HAR	high aspect ratio

Terms	Definition
HCl	hydrochloric acid
HDI	high-density interconnect
HDPE	high-density polyethylene
HEPA	high-efficiency particulate air
HF	hydrofluoric acid or hydrogen fluoride gas
HFC	hydrofluorocarbon
HFFR	halogen-free flame retardants
HFPO-DA	hexafluoropropylene oxide-dimer acid
High aspect ratio	Very tall and narrow device features such as dynamic random access memory capacitor cells; the higher the aspect ratio of a feature, the more challenging it is to create.
HNBR	hydrogenated nitrile butadiene rubber
HNO_3	nitric acid
HPDE	high-density polyethylene
HPM	A mixture of hydrochloric acid and hydrogen peroxide, also known as SC2.
HTF	heat transfer fluid
HUPW	high ultra-pure water
HV	high voltage
HVM	high-volume manufacturing
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IH	industrial hygiene
IHS	integrated heat spreader
IMEC	Interuniversity Microelectronics Centre
Immersion topcoat	A thin film, containing PFAS, applied over the photoresist to prevent the leaching of resist components into the water of the immersion tool, and likewise, to prevent water from permeating into the resist.
IMP	implant equipment
Implantation	A low-temperature process by which the ions of one element are accelerated into a solid target, thereby changing the physical, chemical or electrical properties of the target.
Integrated circuit	Also known as a chip, microchip or semiconductor device; a set of electronic circuits on one small flat piece of semiconductor material, usually silicon, with large numbers of integrated, miniaturized transistors and other electronic components.
Ion implantation	A low-temperature process in which a beam of ions is created from a source material and implanted (or injected) into the surface of a patterned wafer substrate.
IP	intellectual property
IPA	isopropyl alcohol
IRDS	International Roadmap for Devices and Systems

Terms	**Definition**
ISO	International Organization for Standardization
ITRI	Industrial Technology Research Institute
ITRS	International Technology Roadmap for Semiconductors
KOH	potassium hydroxide
KrF	krypton fluoride
LAN	local area network
Land-side components	The bottom side of a controlled collapse chip connection (C4) package, on which the package is mounted to a printed circuit board.
Laser release layers	A thermoset polymer-based layer that enables the stress-free debonding of glass-carrier wafers using ultraviolet laser irradiation.
LGA	land-grid array
LITH	lithography equipment
Lithography/litho	Abbreviated terms for photolithography.
L-PFC	liquid perfluorocarbon
LSC	land-side components
MAC	multiple-alkylated cyclopentane
Mask/mask set	See photomask.
MEMS	micro-electromechanical systems
MET	metrology equipment
Metrology	Measuring the various dimensions or physical or chemical characteristics of a semiconductor integrated circuit on a wafer.
Micro-electromechanical system devices	The technology of microscopic devices incorporating both electronic and moving parts.
Micron	A unit of length equal to one-millionth of a meter.
Mold releases	Materials applied to molds (for example, of plastic parts) to create a nonstick barrier.
Mold release sprays	An aerosol that forms a layer or barrier between the mold and casting agent that facilitates demolding.
Moore’s law	Gordon Moore’s principle that the number of transistors incorporated in a chip will approximately double every 24 months.
MTBC	mean time between cleans
MW	molecular weight
NAND	A type of flash memory that is nonvolatile, and does not require any power to keep data in it.
Nanometer	A unit of length equal to one-billionth (short scale) of a meter.
NaOH	sodium hydroxide
NBR	nitrile butadiene rubber
NEC	National Electrical Code
NF	nanofiltration
NH_4OH	ammonium hydroxide
NIOSH	National Institute for Occupational Safety and Health

Terms	Definition
nm	nanometer
Node	Each new generation process designated by its minimum feature size in nanometers or its transistor gate length.
NTRS	National Technology Roadmap for Semiconductors
O_2	oxygen
O_3	ozone
OECD	Organization for Economic Co-Operation and Development
OEM	original equipment manufacturer
OEL	occupational exposure limit
Oleophobic	A substance that repels oil or organics.
Optical proximity correction	A photolithography enhancement technique used to compensate for image distortion caused by light diffraction or process effects.
Organic-based	Chemicals or formulations where the principle constituents are carbon-containing molecules.
O-ring	A donut-shaped gasket that helps seal joins between separate parts and prevents the leakage of fluids and gases.
Outgassing	The release of a gas that was dissolved, trapped, frozen or absorbed in a material.
Package	Metal, plastic, glass or ceramic casing containing one or more discrete semiconductor devices or integrated circuits.
PAGs	photoacid generators
PAO	polyalphaolfins
PAS	polyalkyl substances
PBGA	plastic ball grid array
PBT	persistent bioaccumulative toxins
PBZ	personal breathing zone
PC	personal computer
PCB	printed circuit board
PCD	planar chemical delivery
PCTFE	polychlorotrifluoroethylene
PDMS	polydimethylsiloxane fluids
PE	polyethylene
PECVD	plasma-enhanced chemical vapor deposition
PEEK	polyether ether ketone
Pellicle	A thin, transparent membrane used to prevent the deposition of unwanted particles on a photomask.
Perfluorocarbon gases	Gases used in plasma etching, gas deposition and chamber cleaning.
PERR	post-etch residue remover
PFA	perfluoroalkoxy copolymer
PFA-CF	perfluoroalkoxy-carbon fiber-reinforced composite
PFAS	perfluoroalkyl and polyfluoroalkyl substances

Terms	Definition
PFC	perfluorocarbons
PFEPE	polyfluoroethyl propyl ether
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFPE	perfluoropolyether
PFSA	perfluorosulfonic acid
PGA	pin grid array
Photoacid generator	Molecules that generate a strong acid upon the absorption of light used in chemically amplified resists.
Photolithography	Techniques that use light to produce minutely patterned thin films of suitable materials over a substrate, such as a silicon wafer, to protect selected areas of it during subsequent etching, deposition or implantation operations. Typically, ultraviolet light is used to transfer a geometric design from an optical mask to a light-sensitive chemical (a photoresist) coated on the substrate. The photoresist either breaks down or hardens where it is exposed to light. Removing the softer parts of the coating with appropriate solvents then creates the patterned film.
Photomask	A glass substrate with a pattern of transparent and opaque regions used to selectively expose the photoresist used in the photolithography process.
Photoresists	A light-sensitive material used in photolithography to form a patterned coating on a surface.
Pin grid array	A means of connecting a semiconductor package to a circuit board using metal pins.
Piranha etch	A mixture of sulfuric acid and hydrogen peroxide used to clean organic residues off of substrates.
Plasma cleaning	The use of a plasma gas to remove particles, residues and films from a wafer surface before or after adjacent processes.
Plasma dry etch	The removal of a masked pattern of semiconductor material by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons or oxygen).
Polymer	A substance or material consisting of very large molecules called macromolecules, composed of many repeating subunits.
POU	point-of-use abatement
PP	polypropylene
ppb	parts per billion
PPE	personal protective equipment
ppm	parts per million
ppt	parts per trillion
Pre-clean	See season.
PTFE	polytetrafluoroethylene
Pulse dampeners	A device in a pumping system that reduces pulsation during a pump cycle.
Pump fluids and lubricants	Chemicals that prevent the generation of particles and offgassing (in a vacuum), while ensuring the smooth and precise functionality of fabrication and processing equipment.

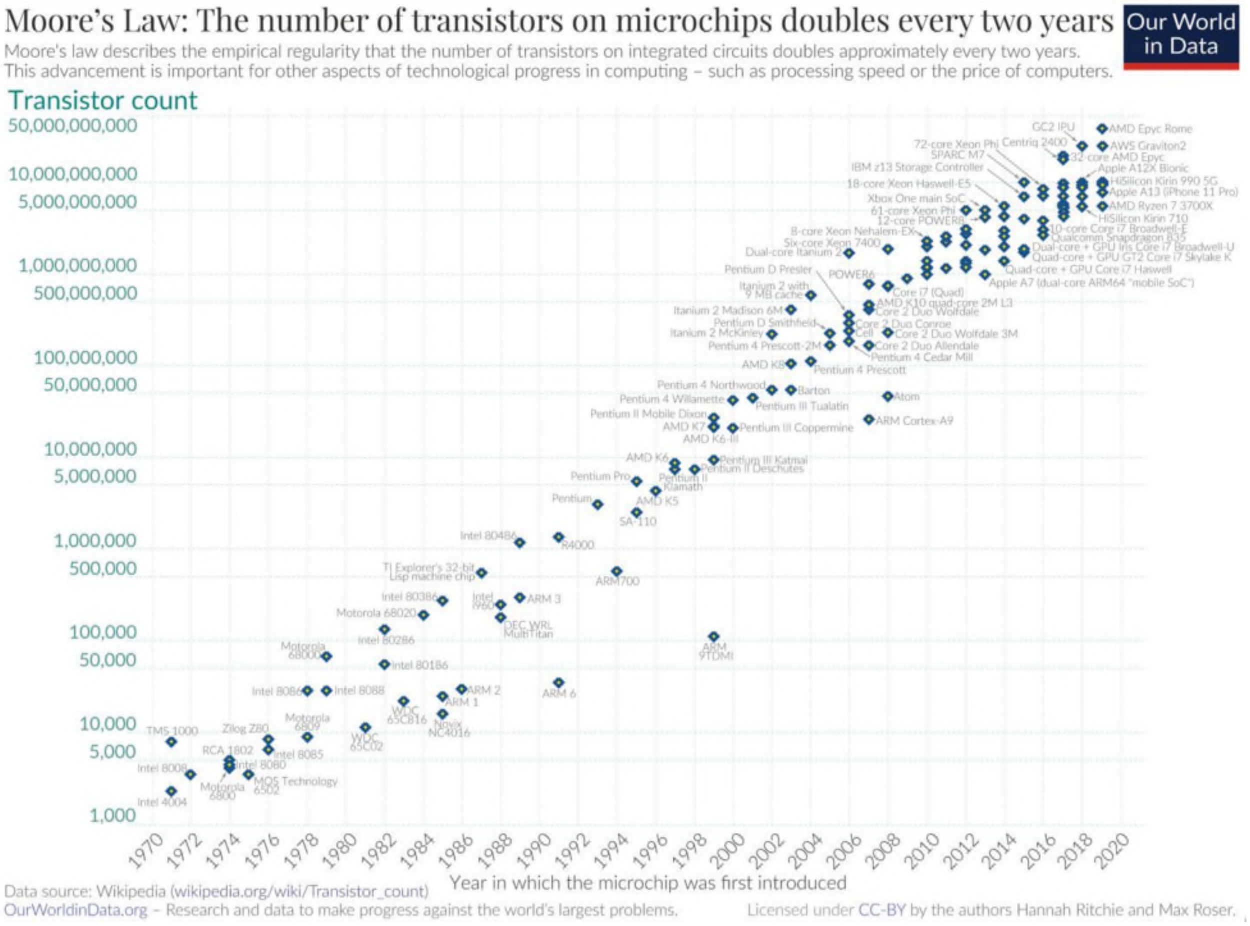
Terms	Definition
PVC	polyvinylchloride
PVD	physical vapor deposition
PVDF	polyvinylidene fluoride
QFN	quad-flat no-lead package
QFP	quad-flat pack
R&D	research and development
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
Registration, Evaluation, Authorization and Restriction of Chemicals	European Union Regulation 1907/2006.
RF	radio frequency
RFO	restrictive flow orifice
RO	reverse osmosis
Standard Clean 1/SC1	A mixture of ammonium hydroxide (28 wt %), hydrogen peroxide (30 wt %) and water, also known as APM.
Standard Clean 2/SC2	A mixture of hydrochloric acid and hydrogen peroxide, also known as HPM.
SDS	safety data sheet
Season	A step in dry-etch processing that conditions the tool chamber with plasma gases to reduce chamber wall contamination or defects to production wafers.
SEM	scanning electron microscope
SEMI	Semiconductor Equipment and Materials International
Semiconductor Equipment and Materials International	A global industry trade association for the semiconductor and electronics supply chain.
SFE	semiconductor facility equipment
Si_3N_4	silicon nitride
SIA	Semiconductor Industry Association
SiARC	silicon anti-reflective coating
SiC	silicon carbide
Siloxanes	A functional group in organosilicon chemistry with the Si-O-Si linkage.
SiO_2	silicon oxide
SMD	surface-mount device
SMIF	standard mechanical interface
SMRE	semiconductor manufacturing and related equipment
SMT	surface modification treatment
SOIC	small-outline integrated circuit
SOP	small-outline package
Spin-on barriers	Layers applied by spin casting that separate lithographic elements from each other; for example, spin-on topcoats in immersion lithography that separate photoresists and the immersion liquid.

Terms	Definition
Spin-on low-K dielectrics	A material with a small relative dielectric constant (κ, kappa) relative to silicon dioxide that is deposited on the surface of a wafer spinning on a rotating vacuum chuck.
Sputtering	Microscopic particles of a solid material ejected from its surface after the material is itself bombarded by energetic particles of a plasma or gas.
SRC	Semiconductor Research Corp.
SS	stainless steel
Substrate (packaging)	Supporting material upon which or within which the elements of a semiconductor device are fabricated or attached.
Surfactants	Chemical compounds that decrease the surface tension or interfacial tension between two liquids, a liquid and a gas, or a liquid and a solid.
SUS	steel uses stainless
SVHC	substance of very high concern
TAG	thermal acid generator
TARC	top anti-reflective coating
TCU	temperature control unit/thermal control unit
Temporary bonding/debonding	A process to offer temporary mechanical support for thin or to-be-thinned wafers in the advanced packaging and heterogeneous assembly of semiconductors.
TFE	tetrafluoroethylene
Thermal test method	A variety of techniques in which a property of a sample is continuously measured as the sample is programmed through a pre-determined temperature profile.
Thickener	A formulation component that increases the viscosity of the formulation.
TIM	thermal interface materials
TLV	threshold limit values
TMAH	tetramethylammonium hydroxide
TOC	total organic carbon
Tool	Another term for SMRE, often used to describe semiconductor manufacturing and related equipment.
Top retention	A lack of film thickness from the photoresist top.
Transistor	A semiconductor device used to amplify or switch electrical signals and power.
TSV	through-silicon via
TTF	thermal test fluids
UHP	ultra-high purity
ULPA	ultra-low particulate air
Underfills	An electrically insulating adhesive used to provide a stronger mechanical connection, provide a heat bridge, or prevent solder joint stress caused by differential heating of the chip and the rest of the system.
UPW	ultra-pure water
USA	United States of America
U.S. EPA	United States Environmental Protection Agency

Terms	Definition
USD	United States dollar
UV	ultraviolet
VAC	vacuum equipment
Vacuum dry etching	The removal a masked pattern of semiconductor material by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons).
Vacuum pump system	A pump and its associated appurtenances, such as tubing, piping and seals used to draw a vacuum.
van der Waals radius	A measure of the size of an atom that is not chemically (ionically or covalently) bound.
VF_2	vinylidene fluoride
VMB	valve manifold box
VMQ	vinyl methyl silicone
VOC	volatile organic compound
vPvB	very persistent very bioaccumulative
VTM	vacuum transfer module
Wafer	A thin, round slice of a semiconductor (usually crystalline silicon) used for the fabrication of integrated circuits.
Wall angle	The angle formed by a photoresist sidewall and a substrate.
WCLN	wet cleaning
WEEE	waste electrical and electronic equipment
Wet chemistry	Liquid substances used in processes such as wet etching, cleaning, chemical-mechanical planarization, surface modification treatments and other liquid applications in chip manufacturing.
WETCH	wet etch equipment
WLP	wafer-level packaging
WSC	World Semiconductor Council
WSTS	World Semiconductor Trade Statistics
WTE	waste to energy

Appendix B: Semiconductor and Supply-Chain Complexity

Semiconductor devices, also known as chips, are the foundation of all modern electronics. In 1965, Gordon Moore hypothesized a doubling every two years of components on an integrated circuit (see Figure B-1). As the number of transistors on devices has increased, the capability that they deliver has likewise increased, and the cost per transistor has decreased. Semiconductors are faster, smaller, less expensive, more energy efficient and more important than ever.


Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.
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Figure B-1: Moore's law – a semi-log plot of transistor counts for microprocessors against dates of introduction, nearly doubling every two years (Roser and Ritchie 2020)**.**

In 1972, the Intel 4004 microprocessor contained 2,250 transistors and was manufactured using critical dimensions (transistor gate width) on the order of 10 µm (or 10,000 nm). Compare that to Apple's M2 Max processor, launched in January 2023, which contains 67 billion transistors manufactured using critical dimensions on the order of 5 nm (Shankland 2023). That corresponds to >29 million times more transistors per chip, built using critical dimensions that are >2,000 times smaller, and just a dozen water molecules wide. If you applied this same boost in performance to automobiles, a car that got 20 mpg in 1972 would be able to go to the moon 2,500 times on a single gallon of gas in 2023.

The efficient and controlled use of materials has been an important component in achieving these advances. Increased computing power attributed to improved semiconductors has enabled advances in communications (mobile phones and smartwatches), computing, medical devices and health care (portable ultrasounds, magnetic resonance imaging, robotic surgery and telemedicine), military systems, transportation (advanced driver assistance systems, electric vehicles), clean energy, enhanced and advanced safety applications (anti-lock and auto-braking technology), GPS, and many other applications that impact all facets of society. See Figure B-2. These advances would not have been possible without proportionally immense innovations in semiconductor manufacturing.

Successive device generations have required increasingly complex chip designs and a continuous downscaling in feature size. The number of processing steps used to manufacture each semiconductor device has also grown dramatically, necessitating increasingly high yields in each step (>99.999%) to achieve cost efficiency (De Backer, et al. 2018). Achieving features at nanoscale requires rigorous control and great precision in manufacturing; however, without a consistently reproducible means to achieve such high yields, semiconductor manufacturing would not be possible at the scale required for today's computerized world.

Figure B-2: Semiconductors enable technologies from aerospace and automotive to artificial intelligence, consumer products, medical, and robotics applications.

The supply chain required to support the semiconductor industry is dispersed and complex. In their 2021 report, the Center for Security and Emerging Technology (Alam, et al. 2020) stated that "The half-trillion-dollar semiconductor supply chain is one of the world's most complex. The production of a single computer chip often requires more than 1,000 steps passing through international borders 70 or more times before reaching an end customer."

The semiconductor industry ecosystem involves several different layers of companies, each serving distinct roles from enablement software and intellectual property (IP), to chip designers, to the raw materials, tooling and facilities infrastructure needed in manufacturing facilities, to manufacturers where chips are built, to packaging houses that test and package chips for use in a wide range of applications.

The Proprietary Nature of Semiconductor Chemicals

Suppliers invest considerable time, money and resources to develop proprietary chemicals that meet the exacting requirements to manufacture at nanometer dimensions. They need to protect their investment. Many semiconductor materials are complex chemical formulations. Given that a specific chemical identity is highly guarded IP, suppliers usually require a signed nondisclosure agreement before sharing this information with their customers (semiconductor device manufacturers).

Releasing information about proprietary chemicals to the public would give competitors an unfair advantage and could cause substantial harm to a company's competitive market position. In addition, when companies submit CBI to the U.S. EPA, they certify that they have gone through reasonable measures or internal controls to protect that information as confidential. If companies were to provide proprietary chemical information to the public, the claim of CBI with the U.S. EPA would also be at risk.

Device Technology Must Evolve to Meet the Demands of an Increasingly Complex World

The industry has maintained the Moore's law trajectory by continually shrinking minimum feature sizes; this has required continuous evolution in designs, chemicals and tools. Along the way, the complexity and number of materials used in chip manufacturing has grown tremendously.

While in the 1980s semiconductor fabs used fewer than 20 elements, today they are using over 50% of the nonradioactive elements in the periodic table (Figure B-3). As an example, to maintain sufficient conductivity of ever-finer metal structures, the metal used for highly conductive in-chip wiring has moved from aluminum and tungsten to copper, and is further migrating to cobalt (at present) and possibly ruthenium. These new metals not only require new precursors and processes but the development of new barrier layers and liners to help them maintain their integrity and prevent their migration to other parts of the chip structure.

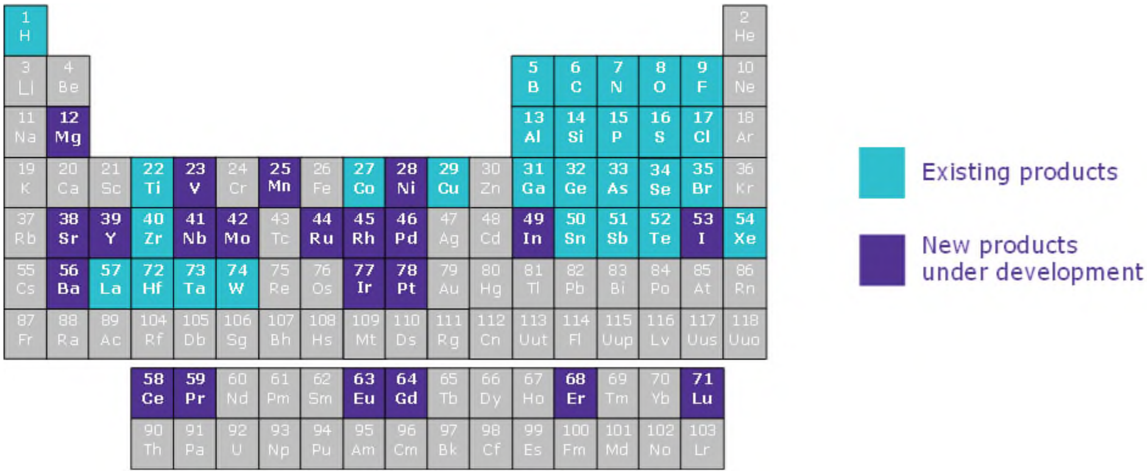


Figure B-3: Advanced semiconductor manufacturing now uses over 50% of the nonradioactive elements in the periodic table. The portfolio of a major materials vendor offers existing precursors containing 28 elements, with another 22 under development.

The Belgian research organization IMEC has predicted that the dimensional scaling underlying Moore's law will continue through 2036 for logic devices. See Figure B-4. Maintaining and improving the performance of photolithography processes is key to staying on this roadmap as critical feature sizes shrink down to 12 nm, or about 50 silicon atoms. At these ranges, the demands on photoresist and other imaging chemicals and processes become extreme, with the need to control line widths to a single monomer unit in a lithographic polymer.

Figure B-4: IMEC's vision of the future logic roadmap, with dimensional scaling predicted to continue through 2036 (IMEC 2023)**.**

Beginning with the A5 logic node, transistors will begin moving into the third dimension. This is the start of a development that will ultimately see the advent of 3D logic circuits. Logic chips will thus follow the trajectory already blazed by 3D not-and (NAND) nonvolatile memory chips, which have overcome the limitations of two-dimensional NAND designs by stacking hundreds of memory cells on top of each other.

The dynamic random access memory (DRAM) volatile memory chips that constitute a computer's working memory are on the verge of following this path, with all major memory makers working on 3D DRAM designs to replace the 2D versions, which are increasingly hard to make as feature sizes shrink. See Figure B-5.

Figure B-5: A 3D NAND complementary metal-oxide semiconductor under-array design with 232 memory cell layers in two stacks (Micron Technology Inc. 2022)**.**

Stacked 3D structures demand highly advanced dry-etch processes. While highly performing photolithography remains a key prerequisite, high-aspect-ratio etch steps are highly demanding: they have become some of the most critical processes and can only be carried out with advanced PFAS-type etch gases. All of these developments will rely on evolving existing materials and processes to a higher level of performance. At present, for the most advanced chips, the number of photolithography layers used to successively build circuits has exceeded 70 (see Figure B-6), many of which are highly interconnected: a seemingly small change in one layer can impact the yield of a process three or four steps further down. Integrating these successive patterning steps is highly complex. There is therefore little to no room for compromise in accepting substitutions of photolithography materials with even slightly inferior alternatives.

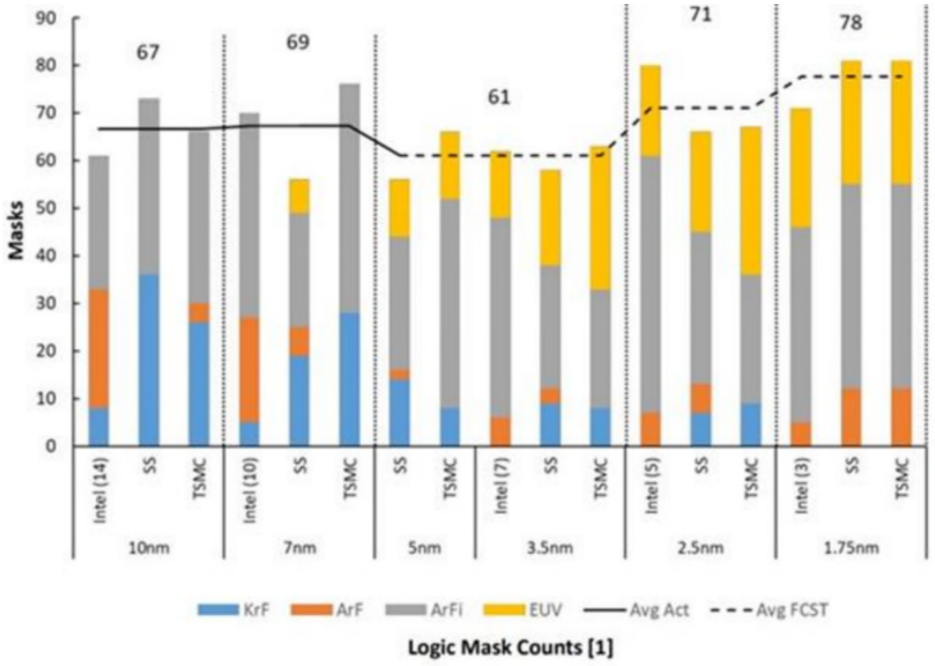
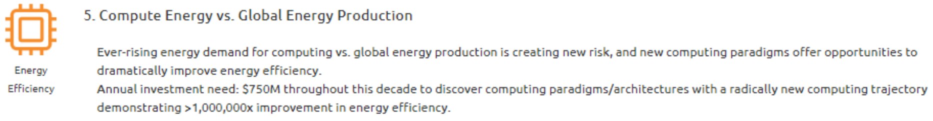


Figure B-6: Layer numbers for advanced logic device nodes by exposure technology.

A highly beneficial side effect of shrinking feature sizes is the higher energy efficiency of advanced node chips. This is visible to consumers through improved battery life of the latest-model smartphone, but it is also critical in terms of overall world energy use. We are on track to use about 25% of the world's electricity production for computing by 2025, with demand rising further thereafter – clearly an unsustainable development. There have been calls for computing efficiency improvements by 1,000 or even 1 million times (see Figure B-7).



Energy Efficiency

5. Compute Energy vs. Global Energy Production

Ever-rising energy demand for computing vs. global energy production is creating new risk, and new computing paradigms offer opportunities to dramatically improve energy efficiency.
Annual investment need: $750M throughout this decade to discover computing paradigms/architectures with a radically new computing trajectory demonstrating >1,000,000x improvement in energy efficiency.

Figure B-7: The SRC's Decadal Plan has identified five "seismic shifts" that will define the future of semiconductors and information/communications technology (SRC 2022). **No. 5 calls for a millionfold improvement in computing efficiency.**

As the world transitions to an information-based society, computational demands will skyrocket. Intel has estimated that the implementation of the metaverse vision will require a thousandfold increase in available computing power (Gartenberg 2021). The computing requirements of advanced artificial intelligence (AI) models will serve as another example. The rate of increase in computational demands for the training of advanced AI models such as Google's DeepFold AI or OpenAI's ChatGPT have exceeded the benefits provided by Moore's law by a factor of over 100 (Figure B-8). These high demands on computing power are already beginning to slow down the development of advanced AI.

The computing power and energy efficiency necessary to enable continued AI development will require new chip designs, most likely neuromorphic designs modeled after the human brain. While it is yet uncertain what these new chip designs will be and what new materials they will require, it is certain that their manufacturing processes will build as much as possible on existing photolithographic processes and materials.

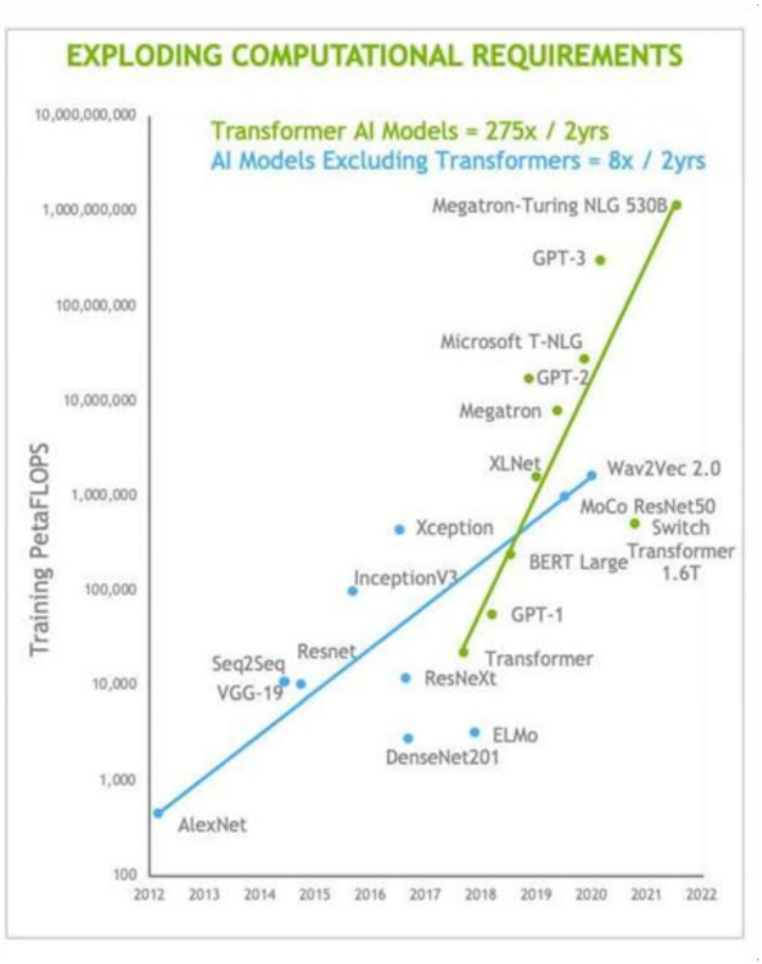


Figure B-8: Exploding computational requirements for the training of advanced AI models (Binus University Faculty of Engineering 2022)**.**

Overview of Semiconductor Manufacturing
Semiconductor device fabrication is the process used to create integrated circuits, which are an essential component of electronic devices. OECD emissions scenario documents provide an overview of the semiconductor manufacturing process (OECD 2015); (OECD 2004). The fabrication process (see Figure

B-9) begins with a wafer of semiconductor material (typically silicon) varying in size from 150 mm to 300 mm in diameter.

In the fab, a sequence of photographic and chemical processing steps gradually create electronic circuits on the wafer substrate. These electrical circuits are made one layer at a time through the combination of depositing a layer on the surface of the wafer and using a patterning process to then remove designated parts of the layer and leave behind a specific shape. For more information on the use of PFAS chemicals and articles in semiconductor manufacturing, see the Semiconductor PFAS Consortium white papers.

These are the basic steps that occur in a fab:

Oxidation, usually performed at 800°C to 1,200°C in a tube furnace, is a batch process that diffuses O_2 or water H_2O vapor into a silicon wafer to form an SiO_2 layer that protects the wafer surface during subsequent steps.

Photolithography, also known as lithography, is a process that transfers the specific device pattern onto the wafer. It can create extremely small patterns, down to a few tens of nanometers in size, with precise control of the shape, size and placement of the images it produces. These patterns are used to create the tens of billions of transistors and connecting wiring on a modern microprocessor.

- In a typical processing scheme, a photoresist polymer formulation is applied to a spinning wafer and then subjected to a pre-exposure bake to drive off the solvent, rendering a solid film. The coated wafer substrate is then exposed through a patterned photomask, with actinic radiation from a light source of specified wavelength. Reflectivity of a semiconductor material during light exposure can be problematic; a layer of anti-reflective coating helps absorb light and reduce reflections during exposure. An anti-reflective coating applied after the photoresist is known as a top anti-reflective coating (TARC) agent and an anti-reflective coating applied before the photoresist is known as a bottom anti-reflective coating (BARC) layer.

After exposure, the coated wafer substrate undergoes a development process in which the previously exposed regions are selectively dissolved and removed from the photoresist film. This leaves the wafer surface with a patterned coating of photoresist, where in selected regions the resist material is completely removed, and in the remaining areas the photoresist forms a protective coating. The open areas of the substrate may then undergo additive processes like physical vapor deposition, CVD, diffusion, ion implant or plating, or subtractive processes like a plasma etch. In doping/diffusion, atoms with one less electron than silicon (such as boron) or one more electron than silicon (such as phosphorus) are introduced into the area exposed by the etch process in order to alter the electrical character (conductivity) of the silicon. In thin-film deposition, a type of which is known as CVD (OECD 2015), adding thin layers or films to the wafer surface can change its electrical properties or serve as masks. Etching chemically removes specific areas of a deposited film in order to expose an underlying material or deposit another material. Etching may be performed in a wet process using solutions of acids, bases or oxidizers, or in a dry process using various gases in a plasma. After the etch or deposition process, the residual photoresist and anti-reflective coating are removed from the wafer surface. This final step, known as photoresist strip, occurs in a way that completely and uniformly removes the residual photoresist, without adversely impacting the surfaces of the materials comprising the underlying wafer substrate.

Semiconductor devices are highly susceptible to various kinds of contamination such as particles, metal ions, chemicals, bacteria and airborne molecular contaminants; thus, surface preparation in etching and cleaning tools is a necessary step at multiple points in the manufacturing flow to remove contaminants and ensure high yields. Following completion of the “front end,” the individual devices are interconnected using a series of alternating metal depositions and dielectric films, with their respective patterning.

CMP uses chemical and physical forces to remove excess material from the wafer’s surface, creating a perfectly flat surface for the next layer of circuit features.

After the last metal is patterned, the depositing of a final insulating layer known as passivation protects the circuit from damage and contamination. Etching openings in this film allow access to the top metal layer with electrical probes and subsequent wire bonds. Passivation may occur in the wafer fab or at an assembly and packaging facility.

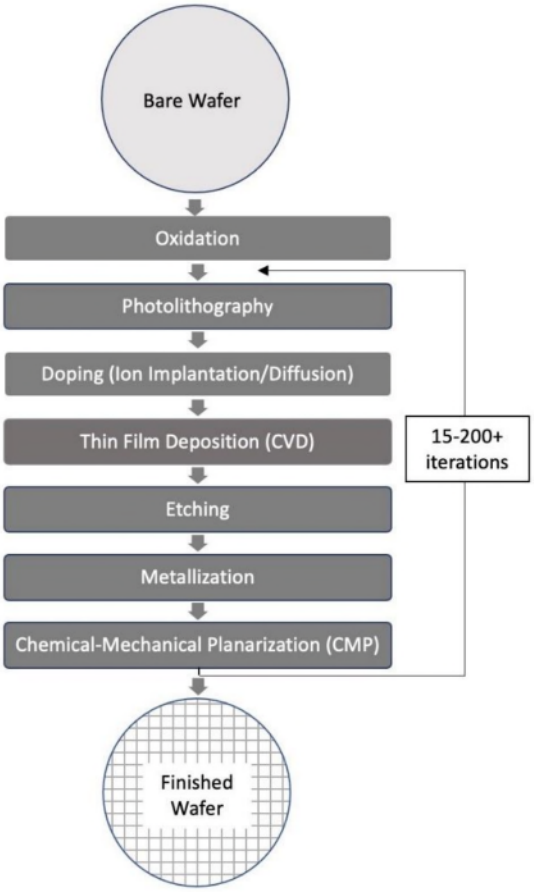


Figure B-9: Overall process flow diagram – semiconductor manufacturing (OECD 2010)**.**

After passivation, wafers are shipped to assembly, test and packaging facilities. At this stage, a probe of each chip on the wafer identifies defects, and then a diamond-embedded saw blade slices the wafer into individual die. Packaging functional die then facilitates electrical connections; dissipates heat; and protects the die from external factors such as humidity, chemicals, impact and vibration. The packaged integrated circuit is then shipped to customers for incorporation into their products.

PFAS-containing articles are found in many SMRE used to perform the processes described here and in the manufacturing facility infrastructure. For examples of PFAS-containing articles, see the Semiconductor PFAS Consortium white paper, "PFAS-Containing Articles Used in Semiconductor Manufacturing."

Appendix C: List of SEMI Safety Guidelines

SEMI AUX005 – Comparison Matrix Between SEMI S2-93A and S2-0200
SEMI S1 – Safety Guideline for Equipment Safety Labels
SEMI S2 – Environmental, Health and Safety Guideline for Semiconductor Manufacturing Equipment
SEMI S3 – Safety Guideline for Process Liquid Heating Systems
SEMI S4 – Safety Guideline for the Segregation/Separation of Gas Cylinders Contained in Cabinets
SEMI S5 – Safety Guideline for Sizing and Identifying Flow Limiting Devices for Gases
SEMI S6 – Environmental, Health and Safety Guideline for Exhaust Ventilation of Semiconductor Manufacturing Equipment
SEMI S7 – Safety Guideline for Evaluating Personnel and Evaluating Company Qualifications
SEMI S8 – Safety Guideline for Ergonomics Engineering of Semiconductor Manufacturing Equipment
SEMI S10 – Safety Guideline for Risk Assessment and Risk Evaluation Process
SEMI S12 – Environmental, Health and Safety Guideline for Manufacturing Equipment Decontamination
SEMI S13 – Environmental, Health and Safety Guideline for Documents Provided to the Equipment User for Use With Manufacturing Equipment
SEMI S14 – Safety Guideline for Fire Risk Assessment and Mitigation for Semiconductor Manufacturing Equipment
SEMI S16 – Guide for Semiconductor Manufacturing Equipment Design for Reduction of Environmental Impact at End of Life
SEMI S17 – Safety Guideline for Unmanned Transport Vehicle (UTV) Systems
SEMI S18 – Environmental, Health and Safety Guideline for Flammable Silicon Compounds
SEMI S19 – Safety Guideline for Training of Manufacturing Equipment Installation, Maintenance and Service Personnel
SEMI S21 – Safety Guideline for Worker Protection
SEMI S22 – Safety Guideline for the Electrical Design of Semiconductor Manufacturing Equipment
SEMI S23 – Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment
SEMI S24 – Safety Guideline for Multi-Employer Work Areas
SEMI S25 – Safety Guideline for Hydrogen Peroxide Storage and Handling Systems
SEMI S26 – Environmental, Health and Safety Guideline for FPD Manufacturing System
SEMI S27 – Safety Guideline for the Contents of Environmental, Safety and Health Evaluation Reports
SEMI S28 – Safety Guideline for Robots and Load Ports Intended for Use in Semiconductor Manufacturing Equipment
SEMI S29 – Guide for Fluorinated Greenhouse Gas (F-GHG) Emission Characterization and Reduction
SEMI S30 – Safety Guideline for Use of Energetic Materials in Semiconductor R&D and Manufacturing Processes

SIA PFAS Consortium

The Impact of a Potential PFAS Restriction on the Semiconductor Sector

Report No. 2022-0737 Rev. 0

Project No. REG4720-001

Rev.	0
Description	Final Report
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Approved by	Chris Robertson
Date	13th April 2023

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Note on report approval

The persons identified above have signed off each stage of this report in accordance with RINA’s Business management system and quality assurance procedure.

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Issue and Revision Record

Rev.	Description	Prepared by	Controlled by	Approved by	Date
0	Final report	Emily Tyrwhitt Jones	Maitheya Riva, Liz Kimber	Chris Robertson	13/04/2023

EXECUTIVE SUMMARY

RINA Tech UK Limited (RINA) were engaged by the Semiconductor per- and polyfluoroalkyl substances (PFAS) Consortium to gather information from members, to establish an evidence base, to inform the semiconductor sector in support of their respective information gathering activities, when considering the potential impact of PFAS restriction. This report comprises an assimilation of this evidence.

The Semiconductor PFAS Consortium represents 69% of worldwide semiconductor manufacturing capital expenditure as well as 70% of global sales of semiconductor equipment in 2021. Its members represented over $400 billion dollars in revenue and directly provide over 500,000 jobs worldwide. The Semiconductor PFAS Consortium is organized under the auspices of the Semiconductor Industry Association (SIA). For more information, see www.semiconductors.org.

Semiconductor devices (also known as “chips”, or “integrated circuits”) are essential components of electronic devices. Semiconductor devices are extremely complex to manufacture, with leading devices requiring more than 2,000 process steps, hundreds of production materials, and approximately 26 weeks to manufacture and test. This requires the utilisation of process chemicals, manufacturing equipment, and manufacturing facility infrastructure which may contain PFAS. PFAS provide specific and unique capabilities within semiconductor process chemistries, semiconductor manufacturing equipment and facilities, as well as the electronic products they drive. Without PFAS, the ability to produce semiconductors (and the facilities and equipment related to and supporting semiconductor manufacturing) would be put at risk. Considering that the semiconductor industry was estimated as having global sales of $574 billion USD in 2022, the withdrawal of PFAS will have severe economic impacts. These impacts are significantly larger, if the consequential effects of chip supply and the societal impact of loss of device functionality are also considered.

The semiconductor industry has a history of proactively adopting voluntary elimination and reduction strategies, as a result of new information on the environmental concerns of the substances it uses. An example of best industry practice is the substitution of perfluorooctanesulfonic acid (PFOS) in the early 2000's that was found to be persistent, bioaccumulative, and toxic. The World Semiconductor Council (WSC) initiated an international voluntary commitment to phase out PFOS uses worldwide and announced the elimination of PFOS in 2011.[1]

The following are the key challenges the Semiconductor PFAS Consortium members have highlighted, due to their deep understanding of the effort required in terms of resources, challenges, and timeline, are necessary to introduce alternative chemicals into some of the world's most complex technology:

- Semiconductor manufacturing is highly integrated, uses thousands of process steps, and occurs at the nanometre scale.
- Some materials are unique and have such specific technical requirements that it is extremely challenging to find a viable alternative. No known alternatives exist for many of the industry’s uses of fluorocarbon-containing materials and in many instances a successful invention of an alternative substance needs to occur before subsequent steps of qualification can be undertaken.
- The organisation of collaborative research and industry alignment is sometimes needed when making significant changes. For instance, the industry’s voluntary commitments to a PFOS phase-

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[1] WSC-May-06-Charter-Amendment-SIGNED.pdf (semiconductorcouncil.org)

out and perfluorocarbon (PFC) emission reduction were only effective due to the alignment and efforts of the industry as a whole.

- The timeline needed to develop, qualify, and implement alternatives falls into the following four broad categories:
  - **3 to 4 years**: If an existing non-PFAS alternative is available, does not require infrastructure alterations, and can be demonstrated to provide adequate performance for a specific application, then it typically takes 3 to 4 years to conduct the necessary manufacturing trials and implement the successful alternative into high volume manufacturing (HVM).
  - **From 3 to more than 10 years:** In some applications, an existing non-PFAS alternative may be viable but requires tooling and/or process or facility changes before it can be successfully introduced into high volume manufacturing. In these cases, it may take from 3 to more than 10 years to introduce changes to the semiconductor manufacturing and related equipment (SMRE) and/or processes, and then perform qualification testing, and implement the non-PFAS alternative into HVM.
  - **From 5 to more than 25 years and successful invention is required**: For some applications, it is not currently possible to demonstrate that a non-PFAS alternative can fulfil the application-specific performance requirements. In these cases, it may be necessary to invent and synthesise new chemicals, and/or develop alternative approaches to device fabrication that provides the necessary electrical and computational performance. Invention is an open-ended endeavour without a fixed timeline or guarantee of success.
  - **No alternative is achievable:** In some cases, it may ultimately be found that a non-PFAS alternative is not capable of providing the required chemical function. If a non-PFAS alternative chemical cannot be invented, then the integrated circuit device structure may need to be abandoned in favour of an alternative device structure that may or may not provide equivalent performance. In some cases, the fundamental laws of chemistry and physics prevent the use of PFAS-free alternatives.
- This is only an overview and potential alternatives must be evaluated on a case-by-case basis considering technical, regulatory, as well as economic aspects. By its nature, the invention of an alternative has no clearly defined timeline, and, for some applications, there may be no known alternative. **When the alternative is not viable, the process will loop back to invention, research and development steps to find a different chemistry or technology that does not have the same issues.**
- Stringent qualification also has to take place with semiconductor customers to ensure that the semiconductor product guarantees the same function as the semiconductor product did previously.
- Qualification and replacement of critical materials is a highly complex, multi-step, multi-year, challenge which impacts multiple parts of the semiconductor supply chain.
- The possibility of regrettable substitution is an ever-present concern. The selection of alternatives must be well informed and consider current and potential future concerns.
- If alternatives decrease production yield even by very small percentages, significant increases are required in semiconductor manufacturing facility size, resulting in correspondingly increased chemical, water, and energy consumption, as well as waste generation.
- A decrease in the performance of PFAS-free alternatives would increase the consumption of parts and waste generation for some uses.

Figure 0-1 provides a general overview of the semiconductor manufacturing process steps, operations, and systems evaluated by the Semiconductor PFAS Consortium and is based on the best and current knowledge of consortium members.

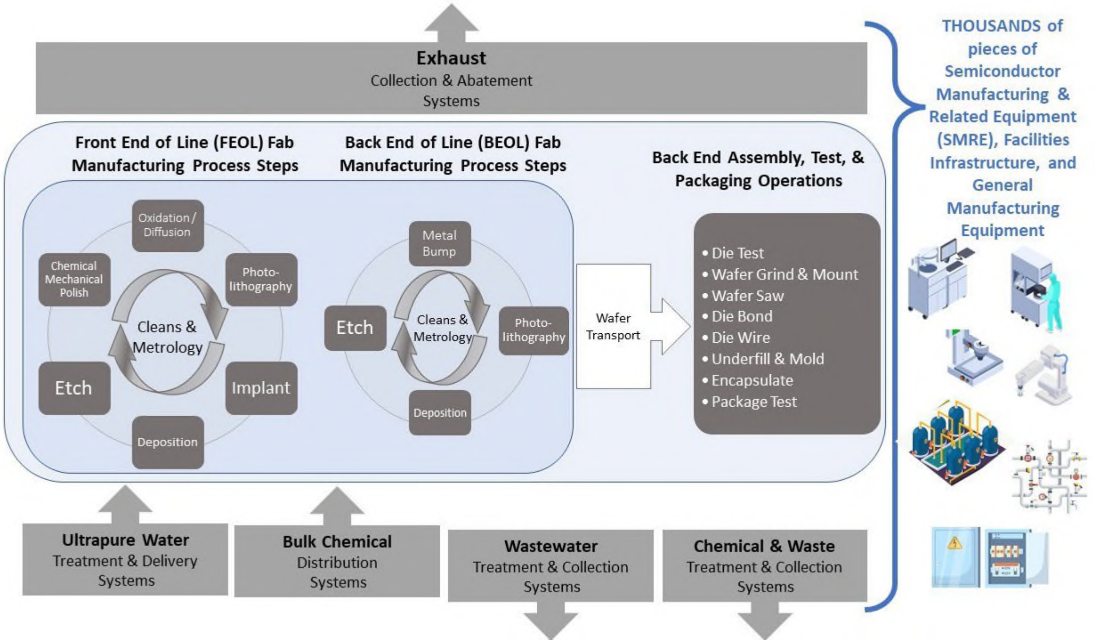

Figure 0-1 General overview of the semiconductor manufacturing process steps, operations, and systems evaluated by the Semiconductor PFAS Consortium.

The following highlights key uses and challenges in each of the application groupings which are critical to the semiconductor industry:

- **Photolithography** is a critical semiconductor manufacturing function, providing cutting-edge semiconductor transistor device dimensions from 2 to 180 nanometres in width with tolerances below these dimensions. For context the diameter of a human hair is about 100,000 nm. PFAS-containing materials within photolithography enable nanometre-scale semiconductor dimensions. Photolithography materials containing PFAS are a critical component used within photoacid generators in chemically amplified resists and bottom antireflective coatings, top antireflective coatings, surfactants, barrier layers, photo-imageable polybenzoxazoles and polyimides for dielectric and buffer coat applications, and photoresist applications.

  After more than 25 years of development, whilst some PFAS-free material substitutions may be possible, PFAS-free materials have not been shown to be successful or effective in the vast majority of photolithography applications. Possible PFAS-free alternatives would require total reinvention for many applications. The process of identifying and implementing alternatives involves academic research, material supplier research and development (validation) and scale-up, followed by device manufacturer efforts toward demonstration (verification), integration and implementation, and scale-up to HVM. Although each PFAS use has its own challenges and timelines for development, most lithography uses are expected to take from **15 to more than 20 years** to develop and qualify a PFAS-free alternative, with the exception of PAGs which are expected to take **more than 25 years**. A detailed explanation of photolithography applications and the use of PFAS materials is found in Section 4.

- **Wet chemistries** are applied within semiconductor manufacturing for cleaning, stripping, wet etching, chemical mechanical planarization, metal plating, and to facilitate other processes. The use of PFAS in some wet chemistries is necessary to achieve the nanometre-sized transistor dimensions. Most wet chemistry applications do not contain PFAS; however, there are some applications that rely on PFAS materials for specific performance requirements. Examples of these applications include but are not limited to; post-plasma photoresist strip, high aspect ratio collapse mitigation, selective film inhibition, wetting of low surface energy substrates, and specific parts cleaning.

  Wet chemistry alternatives are highly application specific and depend on the technology and application for which they are used. What may be a suitable alternative for one application, will not necessarily be a suitable alternative for another. The timeline for implementing alternatives is estimated from **3 to 15 or more years after an alternative is found to be suitable**. A detailed explanation of wet chemistry applications and the use of PFAS materials is found in Section 5.

- **Fluorocarbon uses in plasma (or "dry") etch / wafer clean, and deposition**. Silicon and its compounds are the fundamental components of silicon-based semiconductors; they provide the conductive properties of metal as well as being an insulator. Cutting edge semiconductor technology exists because of the unique properties of fluorocarbon gases which enable extremely high process yields at nanometre width scales. Perfluorocarbons and hydrofluorocarbons[2] are essential for directional etching and cleaning of silicon compounds**.**

  In the plasma etch/wafer clean application, there are no known viable substitutes for fluorocarbon chemistries due to the basic chemistry and physics of etching silicon and its compounds which are critical for forming semiconductor devices. While some non-PFAS alternatives have been identified for specific applications – for instance, the use of nitrogen trifluoride in chamber cleans – the alternatives may produce PFAS-containing emission by-products if carbon-containing films are present and may not be suitable for all applications. In some cases, alternatives, such as fluorine gas, may present additional worker and environmental safety concerns. The semiconductor industry has reduced the use of PFAS-containing chamber clean gases over a period of more than 30 years, due to concerns regarding greenhouse gases. While no fluorine-free alternatives have been identified that meet manufacturing needs, the air emissions of PFCs and HFCs have been significantly reduced through industry level best practice initiatives.

  Alternatives would **require a fundamental reinvention of semiconductor devices to replace silicon as well as the process of fabricating semiconductors**. A detailed explanation of fluorocarbon gas applications and the use of PFAS materials is found in Section 6.

- **Fluorinated heat transfer fluids** in use include refrigerants and liquid fluorinated heat transfer fluids (F-HTF) to meet operational temperature requirements in the manufacturing processes and device test applications. Semiconductor devices are tested under a range of conditions to ensure device integrity. Burn-in, thermal shock, and device reliability testing use F-HTFs to ensure that semiconductors can be used within the customers' requirements – including but not limited to aerospace and medical device requirements. F-HTFs provide the unique ability to be simultaneously: electrically non-conductive, compatible with all materials of construction including sensitive electrical components, within suitable toxicity and flammability limits, and resistant to catastrophic contamination.

  PFAS-free alternatives to F-HTF, such as glycol/water, require the complete re-design of SMRE in the limited number of applications where these can be used. For the remaining cases suitable

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[2] Such as octafluorocyclopentene, octafluoro-2-butene, hexafluoro-1,3-butadiene, octafluoropropane, hexafluoroethane and carbon tetrafluoride.

alternative materials have not been invented yet which offer the required technical performance. Key attributes include high boiling points, low pour points, low kinematic viscosity (fluidity) at working temperatures and lower operating temperatures, electrical non-conductivity, compatible with all materials of construction, suitable toxicity/flammability ratings and the prevention of contamination. This unique combination of properties is what enables every manufacturing step to be virtually perfect, with yields well above 99%, which is essential due to the thousands of process steps involved in semiconductor manufacturing.

In the limited number of instances where alternatives are available, from **8 to more than 14 years** is required to implement needed equipment redesign and infrastructure installation. A similar timeline is also required for the substitution of refrigerants within process equipment chillers. Where there are currently no alternatives, an alternative would need to be invented and then an **additional 5 to more than 15 years** would be required to implement (although this could be significantly longer depending on the number of affected cooling systems at a single manufacturing facility). For PFAS-free thermal test methods, **once an alternative has been invented from 8 to more than 14 years** would be required to implement (although this could be significantly longer if a new method is required). A detailed explanation of the uses of fluorinated heat transfer and thermal test fluids is found in Section 7.

- **Semiconductor assembly, test, and packaging** are processes that occur after the semiconductor devices are built on the silicon wafer. A semiconductor package encloses one or more semiconductor devices (also known as die or integrated circuits), protecting the device from the environment. Assembly, test, and packaging processes include the processes of die test, wafer grind, wafer mount, wafer saw, die bond, die wire, underfill, mold, encapsulate, and final semiconductor packaging and device test. Assembly, test, and packaging also has the key function of preparing the semiconductor package so that it can connect to customers' products.

  As packaging becomes more and more complex due to decreased semiconductor size, increased processing speed, and/or increased packaging complexity, the combination of properties necessary are frequently only found in the fluorinated hydrocarbon family. PFAS materials are used to ensure hermetic sealing against moisture, provide environmental and mechanical isolation and stability, to reduce stress on solder joints increasing device durability, and other product reliability purposes. PFAS are used in some packaging fluxes, surfactants, adhesives and encapsulants and as anti-stiction agents inside specialty microelectromechanical system (MEMS) packages. While more simple uses like packaging fluxes are expected to take more than 5 years to qualify an alternative, the vast majority of package related uses of adhesives have sought alternatives for 18 years without success and alternatives are expected to take **20 years or more** to identify and implement.

  Changes to assembly package materials due to their interactions with both the silicon die and the end customer product require additional customer product change notification, product requalification and approval, which require additional time to the timeframes listed above. Customer requalification activities are required to start at least **1-2 years prior to change**, with some applications requiring 6+ years. A detailed explanation of semiconductor assembly, test, and packaging applications and the use of PFAS materials is found in Section 8.

- **Pump Fluids & Lubricants** use PFAS such as polyfluorinated polyether oils (PFPE), or polytetrafluoroethylene (PTFE) micropowders which are critical for use in semiconductor manufacturing.

  Although non-PFAS lubricants such as silicone oil exist, they are unable to meet critical performance requirements such as inertness when used in harsh conditions, low off-gassing and particle generation which is important due to the cleanliness requirements during manufacturing. In addition to this they have a higher likelihood for increased failure rates and human health and safety impacts. As such it is expected that **more than 10 years** would be required to substitute PFAS lubricants in general applications and **more than 25 years** for lubricants used in photolithography due to the need for ultraviolet (UV) stability. A detailed explanation of semiconductor uses of PFAS-containing lubricants is found in Section 9.

- **Articles** PFAS-containing articles are critical to the manufacture of semiconductor devices. SMRE and facility support equipment use millions of articles to enable the technical requirements of clean, and safe manufacturing. Fluoropolymers are a subclass of PFAS that possess a unique set of characteristics that are required for many of the critical articles, including inertness, purity, low flammability, temperature stability, resistance to chemical permeation, low coefficient of friction, optical properties, mechanical properties, contamination control, electrical properties, processability, resistance to bacterial growth, and long service life (>25 years). SMRE and facility support equipment are exposed to environments that include corrosive, high temperature, flammable and toxic materials and therefore, the use of fluoropolymers is often required by safety and insurance guidelines. To maintain the cleanroom and assembly test purity requirements, fluoropolymers are also needed to prevent particle generation, which is detrimental to semiconductor production yield.

  Possible PFAS-free alternatives would require total reinvention for many applications. Depending on the material and its application, **more than 15 years** are needed to implement a suitable alternative**.** Additionally, the semiconductor industry's supply chain is both specific and complex as well as generic and multi-layered, depending on the article or equipment supplied. Substitutions require an industry effort to drive change throughout the supply chain. A detailed explanation of semiconductor PFAS-containing articles is found in Section 10.

More detailed technical information can be found in the respective white papers and case study reports written by the Semiconductor PFAS Consortium (listed in Table 1-2).

It is worthwhile noting that the timelines outlined above have a significant degree of uncertainty. For many of the substances there are no alternative theoretical material chemistries to use as a basis for invention and a whole new area of chemistry and/or technology will be required. There are also concerns that a change process as large as designing out all PFAS has never taken place and the timelines are based on the time to undertake a single change. As highlighted above, there may be interactions between multiple stages in processing which will need to be explored. There will also be limitations on how many suitably knowledgeable people are available given the magnitude and complexity of the task at hand. As such, the timelines could easily be much longer than those estimated.

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ABBREVIATIONS AND ACRONYMS

ARC	Antireflective coating	PCB	Printed circuit board
ATPS	Assembly, testing, and packaging	PCTFE	Polychlorotrifluoroethylene
BARC	Bottom Antireflective Coating		
BHF	Buffered hydrofluoric acid etch	PDMS	Polydimethylsiloxane fluids
BOE	Buffered oxide etch	PFA	Perfluoroalkoxy alkanes
C4	Per and polyfluorinated alkyl substances with a chain length of 4 carbons or less.	PFAS	Per- and polyfluoroalkyl compounds or substances
CARs	Chemically Amplified Resists	PFC	Perfluorocarbons
CFCs	Chlorofluorocarbons	PFEPE	Poly fluoro ethyl propyl ether grease
CMP	Chemical Mechanical Planarization	PFOA	Perfluorooctanoic acid and its salts (a chemical family of substances)
CN5	Pentacyanocyclopentadiene	PFOS	Perfluoro octane sulfonic acid and its salts (a chemical family of substances)
CTE	Coefficient of thermal expansion	PFPE	Polyfluorinated polyether oils
CZ	Czochralski crystal growth process (for making silicon ingot that silicon wafers are then cut from)	PI	Polyimides and their precursors
D4, D5, D6 - ring	cyclosiloxanes containing 4, 5 and 6 silicon atoms in the ring respectively.	POU	Point of use emission abatement system
E-beam	Electron-beam processing, also called electron irradiation	PTFE	Polytetrafluoroethylene
EG/DI	Ethylene glycol and deionised water	PVDF	Polyvinylidene fluoride
ETFE	Ethyl tetrafluoroethylene	R&D	Research and development
EU	European Union	RINA	RINA Tech UK Limited
EUV	Extreme Ultraviolet, a type of photoactivation for photoacid generators	SDS	Safety Data Sheet
Fab / Fabs	Fabrication (facility(ies))	SEMI	Global industry trade association for electronics manufacturing and design
FEP	Fluorinated ethylene propylene	SIA	Semiconductor Industry Association
FFKM	American standard (ASTM) short form name for perfluoro elastomers or perfluoro rubber material. Also called Kalrez™.	SiARC	Silicon anti-reflective coating
F-HTF	Liquid fluorinated heat transfer fluids	SiC	Silicon Carbide
FKM	American standard (ASTM) short form name for Fluoroelastomers or fluoro rubber material. Also called Viton™.	SMRE	Semiconductor manufacturing and related equipment
HDPE	High density polyethylene	SVHC	Substance of Very High Concern
HFC	Hydrofluorocarbon	TARC	Top Anti reflective coating
HFE	Hydrofluoroethers	TIM	Thermal interface materials
HFO	Hydrofluoroolefins	UPW	Ultra-pure water
HTF	Heat transfer fluid	US / USA	United States of America

HVM	High Volume Manufacturing	US EPA	United States Environmental Protection Agency
IPA	Isopropyl alcohol	USD	United States Dollar
MEMS	Microelectromechanical systems / micromachines	UV	Ultra-violet
PAG / PAGs	Photoacid generators	WSC	World Semiconductor Council
PBO	Polybenzoxazoles and their precursors	WSTS	World Semiconductor Trade Statistics

1 INTRODUCTION

RINA Tech UK Limited (RINA) was requested by the Semiconductor PFAS Consortium to gather information from members to provide evidence for the semiconductor sector to support information gathering considering the potentials impact of PFAS restriction.

The Semiconductor PFAS Consortium comprises thirty-nine Member Companies representing 69% of worldwide semiconductor manufacturing capital expenditures, as well as 70% of global sales of semiconductor equipment in 2021. Semiconductor device and equipment manufacturing operations performed by Semiconductor PFAS Consortium members represented over $400 billion dollars in revenue and directly provide over 500,000 jobs worldwide. The Semiconductor PFAS Consortium was formed to collect the technical data needed to better inform public policy and legislation, including the:

- Identification of critical uses of PFAS,
- Application of the pollution prevention hierarchy to, where possible: reduce PFAS consumption or eliminate use, identify alternatives, and minimise and control emissions,
- Identification of research needs, and
- Development of socioeconomic impact assessments.

Table 1-1 PFAS Semiconductor PFAS Consortium members business breakdown.

Type of Business	Description	Number of Member Companies	% of market represented in Semiconductor PFAS Consortium
Semiconductor Device Manufacturers	Semiconductor device design and manufacturing firms with operations in Europe, Asia, and North America. Companies include fab, assembly, test, and packaging operations for individual device manufacturers as well as foundries. Semiconductor devices include logic and memory chips, microelectromechanical (MEMs) and image sensor devices.	10	69% of worldwide capital expenditures in 2021
Semiconductor Manufacturing Equipment Suppliers	Specialised semiconductor manufacturing equipment manufacturers and suppliers with operations in Europe, Asia, and North America. Companies include manufacturing equipment for fab, assembly, and device packaging as well as facility support and emissions control equipment.	8	70% of global sales of semiconductor equipment in 2021
Chemical / Material Suppliers	Manufacturers and suppliers of specialised semiconductor process chemicals and formulations as well as semiconductor material suppliers. Chemical / Material suppliers provide: Raw materials, fab chemicals and formulations, device packaging materials, and facility materials.[3]	21	Varies

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[3] These materials include, but are not limited to photoresists, chemical mechanical planarization slurries, deposition and etching gases, wet clean formulations, chip package substrates, packaging encapsulant and die attach materials, as well as specialised materials for ultrapure water systems and emissions control and abatement.

1.1 Reporting Methodology

PFAS are used in chemical formulations, components of manufacturing process tools, facilities infrastructure and packaging used to make the semiconductor devices that are integral to our modern world. Given the widespread uses of PFAS in Semiconductor PFAS Consortium members applications, this report has grouped PFAS uses into similar groups to aid in the understanding of this complex picture. The following groupings of use have been used in this report:

- **Photolithography** - A crucial phase in the process of manufacturing semiconductors, of transferring a component or circuit pattern by applying a photoresist and exposure.
- **Wet Chemistry** - Liquid substances used in processes such as wet etching, cleaning, chemical mechanical planarization, surface modification treatment, and other liquid applications in chip manufacturing.
- **Fluorocarbon uses in plasma etch and deposition** - Gases used in plasma etching and chamber cleaning, and metalorganics used in deposition.
- **Heat Transfer Fluids** - Coolants used in the manufacture of semiconductors, during the testing of devices, and in equipment such as chillers.
- **Assembly, Test, Packaging, and substrate material uses** - Materials used to test and attach individual semiconductor devices into chip packages.
- **Pump Fluids & Lubricants** - To provide smooth and precise functionality of fabrication and processing equipment while preventing the generation of particles and outgassing (under vacuum).
- **Articles** - Physical materials used in the construction of semiconductor processing equipment, support equipment, facilities equipment, and infrastructure, and other purchased or produced items containing PFAS. Examples include components within a billion-dollar extreme ultra-violet (EUV) semiconductor lithography machine, plasma tool O-rings, ultra-pure water systems and piping, and environmental control systems such as lined ductwork and wet scrubbers. These PFAS articles are used during semiconductor manufacturing and also in forms which may be present in certain final products.

This report outlines key PFAS uses which are indicative of the technical challenges faced by each use. In addition to this report, the Semiconductor PFAS Consortium has written seven white papers (listed in Table 1-2) and three case study reports to collectively address the principal areas in which fluorinated organic chemicals are used in semiconductor manufacturing, which has been utilised in writing this report.

Table 1-2 Semiconductor PFAS Consortium papers.

Paper Type	Paper Title
Whitepaper	Background on Semiconductor Manufacturing and PFAS
Case Study	PFOS and PFOA conversion to short chain PFAS used in the Semiconductor Manufacturing
Case Study	PFAS-Containing Photo-Acid Generators used in Semiconductor Manufacturing
Case Study	PFAS-Containing Surfactants used in Semiconductor Manufacturing
Whitepaper	PFAS-Containing Wet Chemistries used in Semiconductor Manufacturing
Whitepaper	PFAS-containing Fluorochemicals used in Semiconductor Manufacturing Plasma-enabled Etch and Deposition

Paper Type	Paper Title
Whitepaper	PFAS-Containing Heat Transfer Fluids (HTF) PFAS-containing Heat Transfer Fluids used in Semiconductor Manufacturing
Whitepaper	PFAS-Containing Materials used in Semiconductor Manufacturing Assembly Test Packaging and Substrate processes
Whitepaper	PFAS-Containing Lubricants used in Semiconductor Manufacturing
Whitepaper	PFAS-Containing Articles used in Semiconductor Manufacturing

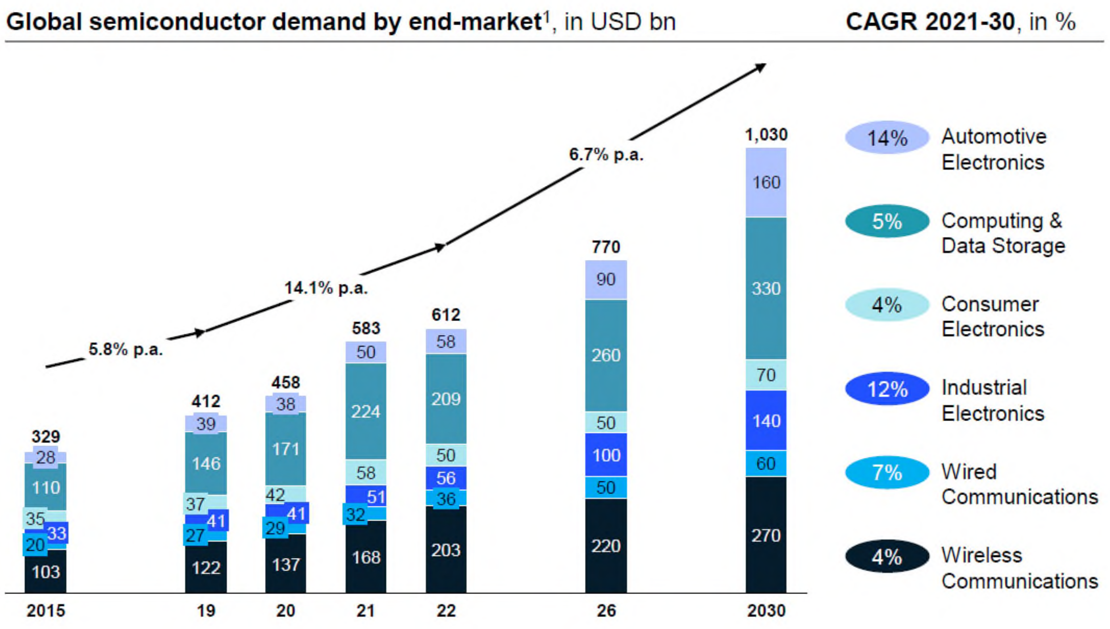
The information shared by the Semiconductor PFAS Consortium membership in this report provides a snapshot at the point of the information being gathered. RINA devised a questionnaire which was circulated by the Semiconductor PFAS Consortium to its members. The responses from the questionnaire were collated and analysed for common themes, to give a representation of the whole membership. It is understood that many Semiconductor PFAS Consortium members are still developing their strategies and responses to PFAS concerns, and as such have not been able to answer all of the questions asked at this time. It is to be expected, therefore, that views may change or develop with time as more work is done, evidence is discovered, and as requirements emerge.

1.1.1 Terminology used within the report

Where the term ‘No known alternative’ is used within this report it is meant that there is no known alternative chemistry or technology within the semiconductor industry and its supply chain that could be investigated as a replacement for this use at this time.

2 SEMICONDUCTOR TECHNOLOGY

The overall global semiconductor market was valued at $440 billion in 2020 and increased to $555.9 billion in 2021, an increase of over 26.2% according to data from the World Semiconductor Trade Statistics (WSTS) 2021. In February 2023, the Semiconductor Industry Association (SIA) reported global semiconductor industry sales totalled $574 billion in 2022, the highest-ever annual total and an increase of 3.32% compared to the 2021 total of $555.9 billion.



1. Includes ASP increase of 2.0% p.a. for 2022-30

Figure 2-1 Global semiconductor demand by end-market, in USD.[4]

Based on information from SIA[5] and shown in Figure 2-1, the semiconductor industry serves a number of end-use markets, and the information and communication technology sectors typically account for a majority of global sales at two-thirds. However, from 2021 to 2022, the automotive, industrial, and consumer electronics markets' share of sales revenue grew, indicative of demand trends demonstrated by end market growth projections.

The semiconductor value chain is highly complex, as indicated in Figure 2-2, requiring the co-operation of many different companies to support the end use equipment consumers are familiar with.

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[4] Omdia (Q3 2022) McKinsey

[5] *Semiconductor Supply Chain Deep Dive Assessment,* U.S. Department of Energy Response to Executive Order 14017, "America's Supply chains" February 24, 2022. https://www.energy.gov/sites/default/files/2022-02/Semiconductor%20Supply%20Chain%20Report%20-%20Final.pdf

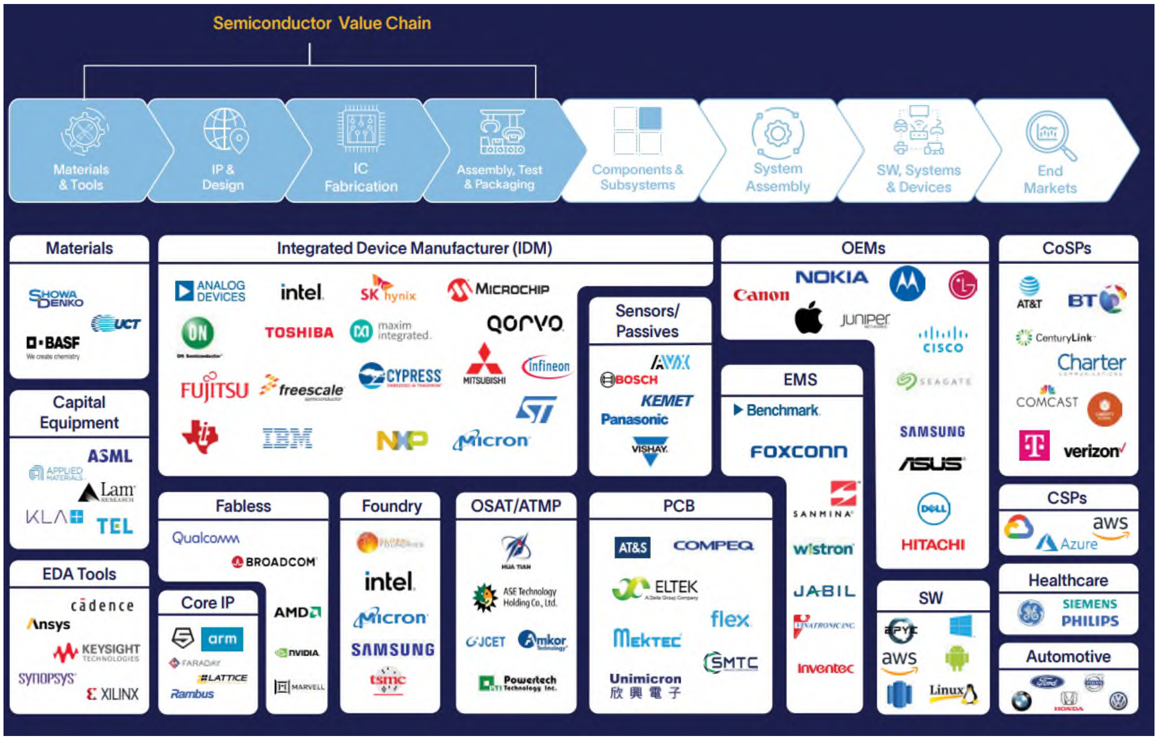

Figure 2-2 Illustrative (non-comprehensive) companies involved in different stages of the value chain.[6]

2.1 Importance of Semiconductors to Society

Semiconductor devices are central to the digital economy and an enabling technology for a number of key applications as shown in Figure 2-3.[7]

Semiconductors are at the centre of technological advancements that can make a significant contribution to society. Due to their complexity and key role in technological development, semiconductors have been defined as one of the most complex devices ever created by humans. For example, innovative uses of semiconductor technology have the potential to make significant contributions towards solutions to global climate change. According to the World Economic Forum, semiconductor-enabled technologies, such as digital technologies, can **reduce greenhouse gas emissions by 15%** - almost one-third of the 50% reduction required by 2030.[8]

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[6] Source: The Semiconductor Ecosystem: Complex, Global, and Specialized - Altman Solon, EDA - Electronic Design Automation, IP - Intellectual Property, OSAT - Outsourced Semiconductor Assembly & Test, ATMP - Assembly, Test, Markup & Packaging, EMS - Electronic Manufacturing Services, PCB - Printed Circuit Board, OEM - Original Equipment Manufacturer

[7] Sourced from Alex Capri, “Semiconductors at the Heart of the U.S.-China Tech War: How a New Era of Techno Nationalism is Shaking Up Semiconductor Value Chains,” Hinrich Foundation, January 2020, p. 13.

[8] https://www.weforum.org/agenda/2019/01/why-digitalization-is-the-key-to-exponential-climate-action/

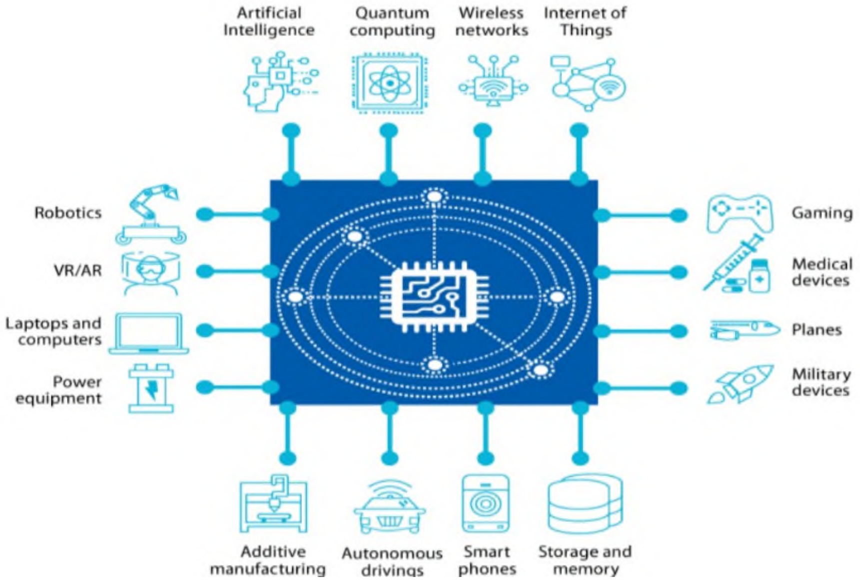

Figure 2-3 Technologies enabled by semiconductors.

Within the past several years, industry has witnessed disruptions in the supply of chips, causing shortages across multiple economic sectors and potentially serious societal consequences. Many sectors, including automotive, energy, communication, and health, as well as strategic sectors such as defence, security, and space are under threat by such supply disruptions. Any further disruptions due to PFAS restrictions will likely make the situation more severe.

The current supply chain disruptions have revealed structural vulnerabilities of the value chains. The global semiconductor shortage has exposed dependency on supply from a limited number of companies and geographies, and its vulnerability to third country export restrictions and other disruptions in the present geopolitical context. Building new facilities to manufacture the latest semiconductor devices technologies requires a considerable upfront investment of at least €15 billion and several years to achieve production-readiness with adequate yields. The expenditures to design such chips can range from €0.5 billion to well over €1.0 billion. Research and development (R&D) intensity in the sector is high with more than a 15% investment percentage with respect to sales.[9]

It is estimated that in 2021 the capital expenditure invested was close to $150 billion and was expected to rise to above $150 billion in 2022.[10] This trend will only continue as demand for electronics and connectivity grows. In the automotive space, new vehicles increasingly rely on semiconductor devices for fuel efficiency, safety, and other features. The expected growth in electric cars will only further this reliance. In the long term, as semiconductor devices play an even bigger role in an ever-expanding array of products, global demand for semiconductor devices will continue to rise.

In addition to this the semiconductor industry is growing substantially, with the following calculated by the World Semiconductor Trade Statistics (WSTS)[10]:

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[9] *A Chip Act for Europe*, "Brussels, 8.2.2022 COM(2022) 45 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0045

[10] WSTS Semiconductor Market Forecast Fall 2022

- Worldwide sales have a yearly growth of 12%.[11]
- The American market is supposed to grow 17.0%.
- The European market is supposed to grow 12.6%.
- The Japanese market is supposed to grow 10.0%.
- The Asia Pacific market is supposed to decline 2.0%.

2.2 Semiconductor Manufacture and Supply Chain

Semiconductor devices are extremely complex to manufacture, with leading devices requiring more than 2,000 process steps, hundreds of production materials, and approximately 26 weeks to manufacture and test.[12] A simplified diagram of the supply chain is outlined in Figure 2-4. The materials used for the manufacture of semiconductors have been specially formulated and engineered to meet the exacting standards of the industry which continue to be more and more demanding as the technology evolves. Each step in the process requires extremely high purity, exacting process control and high yields for the overall production to be viable.

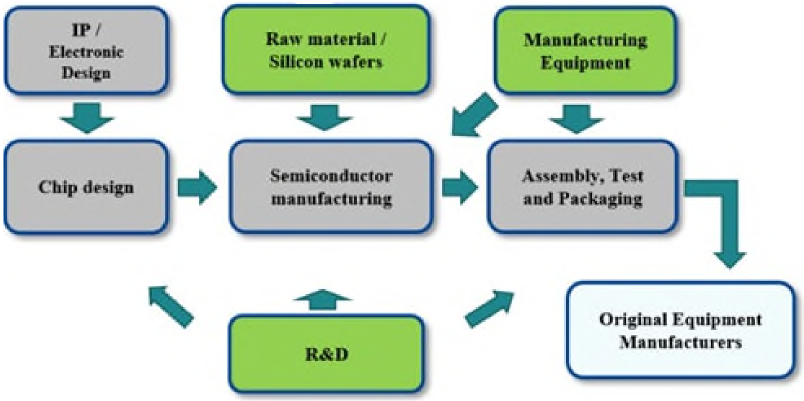

Figure 2-4 Schematic of semiconductor supply chain.[13]

The supply chain for semiconductors starts with a range of unique materials, chemicals and sophisticated equipment and services provided by special vendors to meet the unique needs of this sector. The semiconductor supply chain has a **global footprint and relies upon key technology holders across the globe**. The full supply chain uses components and materials supplied by many tiers of suppliers and sub-suppliers, and those components and materials will typically pass multiple borders before final distribution. If this complex supply chain is broken due to a restriction being placed on the use of PFAS, the effects will be felt globally.

The processes and equipment used are enormously complex. A simplified step by step workflow of the semiconductor manufacturing process indicating where PFAS are used is shown in Figure 0-1, which

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[11] Based on 2016-2021 global data.

[12] According to Consortium members.

[13] *A Chip Act for Europe*, "Brussels, 8.2.2022 COM(2022) 45 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0045

describes the use of PFAS in the semiconductor product manufacturing process and associated waste streams.

2.3 Importance of Innovation

In the past 50 years, semiconductor performance has increased from 10 thousand floating point operations per second, or FLOPs[14], to more than 400 quadrillion FLOPs for the fastest super computers.[15] The need for semiconductor enabled technology to be faster and more powerful comes from the developing and evolving need for digitisation. The demand for faster and more powerful devices is anticipated to continue, requiring the semiconductor industry to invest in next generation innovations.

Further miniaturisation continues, towards smaller node[16] dimensions in the mainstream process technologies along the lines of Moore's law[17], while more energy-efficient solutions are in high demand to ensure that the ever-growing processing footprint remains sustainable. According to the International Roadmap for devices and systems 2022 update[18], by 2037 a 0.5 nm equivalent node size on semiconductors will be necessary. Since the 1970's semiconductor speed and performance has grown exponentially due to these innovations, as outlined by Figure 2-5.

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[14] FLOP is a measure of computer performance representing the number of floating point operations performed by a computer in a second.

[15] TOP500 Supercomputer Database.

[16] Typically refers to the technology node, a term used to describe the size of the features in the finished product. Quoted in terms of nanometres (or larger for earlier nodes), the node name refers to half the distance between identical features.

[17] Moore's law is an observation based on historical trend in the semiconductors industry, which shows the density of transistors on an integrated circuit doubles approximately every two years.

[18] International Roadmap for Devices and Systems, 2022 Update, More Moore, IEEE, https://irds.ieee.org/editions/2022

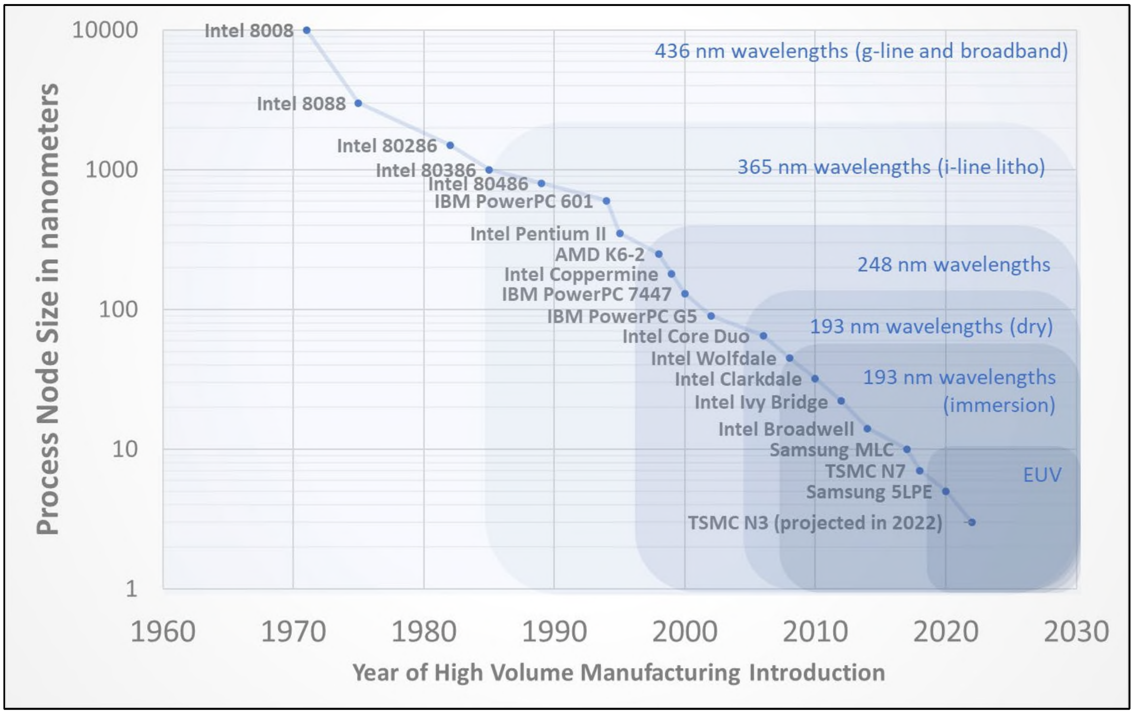

Figure 2-5 Sample of semiconductor products: exponential decrease in critical dimensions over time (and associated lithographic wavelengths).[19]

For context the diameter of a human hair is 100,000 nm with Figure 2-6 showing semiconductor node sizes compared to biological references, which explains why the extreme miniaturisation of semiconductors poses so many technical challenges. Many **PFAS are intrinsically linked into the technological advances which have allowed the current node sizes to be achieved**.

Node sizes, and the wavelengths used to create them, are not necessarily replaced by smaller nodes, rather devices can have multiple node sizes or rely on legacy node size technologies. As such, all of the above-mentioned wavelengths are still in use today with the most advanced (i.e., most capable, and most expensive) lithographic technology being used for the most critical layers, and older, less costly technologies for the less demanding ones. Any changes to each of these layers can influence the next, causing a reduction in yield or even catastrophic process failure.

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[19] File:Comparison semiconductor process nodes.svg - Wikimedia Commons

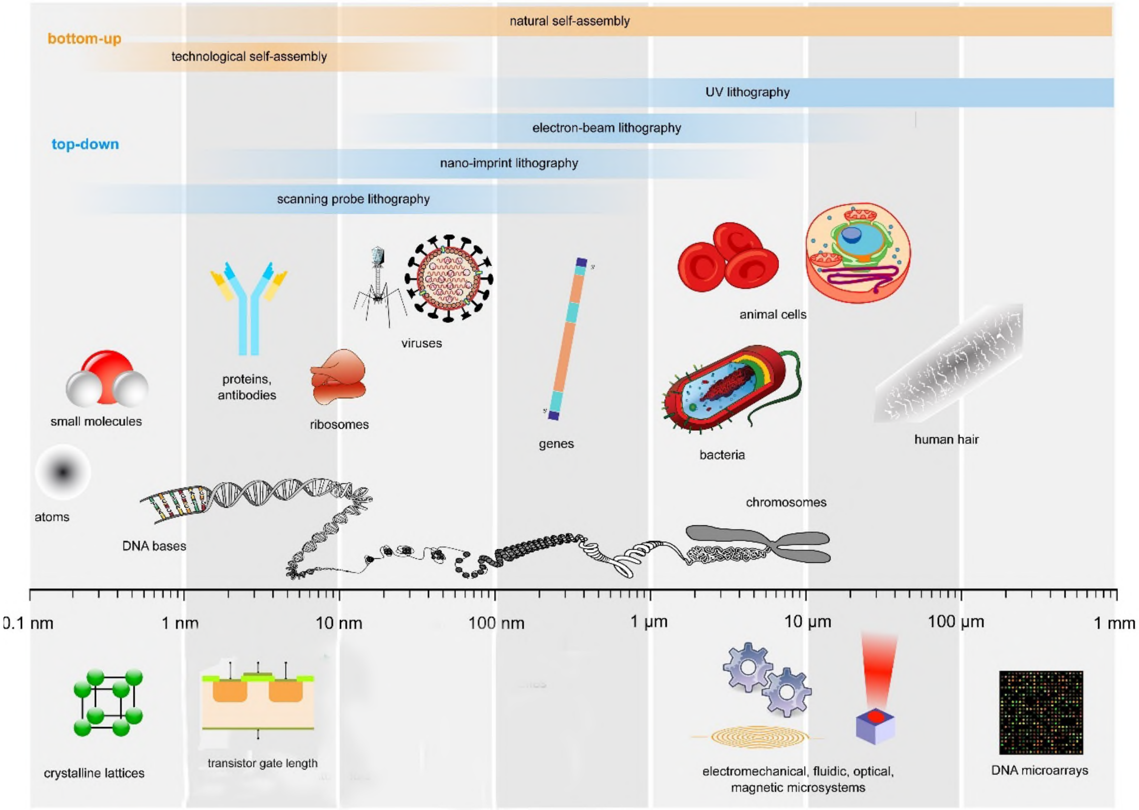

Figure 2-6 Comparison of various biological assemblies and technological device.[20]

Products containing semiconductors are essential technologies in everyday life and form the backbone of the technical strategic value chain with strategic objectives in multiple jurisdictions, including Europe via the European Green Deal and digital autonomy.[21] To renew its pledge to innovation, the European Union is committed to its strategic goal to reach at least 20% of world production in value of cutting-edge, innovative, and sustainable semiconductors by 2030, as set out in the Digital Decade Policy Programme.[22]

Innovation fuels continuous advances in microelectronics technologies, which is why semiconductor companies spend so much on research and development expenditure as outlined in Figure 2-7 and is necessary to make the advances in technology. It is only as a result of the high-level innovation that the objectives of the US CHIPs act[23] and the EU Digital Decade Policy are possible.

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[20] Modification of Guillaume Paumier, Philip Ronan, NIH, Artur Jan Fijałkowski, Jerome Walker, Michael David Jones, Tyler Heal, Mariana Ruiz, Science Primer (National Center for Biotechnology Information), Liquid_2003, Arne Nordmann & The Tango! Desktop Project, CC BY-SA 2.5 via Wikimedia Commons

[21] https://www.semi.org/en/blogs/semi-news/fluorinated-chemicals-are-essential-to-semiconductor-manufacturing-and-innovation

[22] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en

[23] *A Chip Act for Europe*, ”Brussels, 8.2.2022 COM(2022) 45 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0045

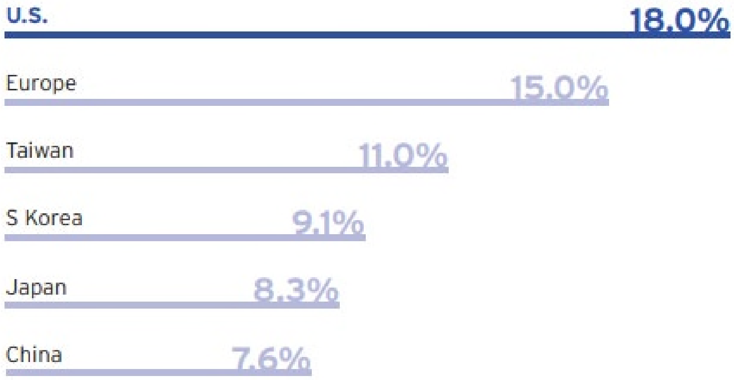

Figure 2-7 Semiconductor R&D expenditure as a percentage of sales.

Innovation fuels continuous advances in microelectronics technologies, which is necessary to make the advances in technology which are required to underpin the objectives of the US CHIPs act[24] and the EU Digital Decade Policy.[25]

Moore's law describes the trend whereby the number of transistors on a microchip doubles every two years shown in Figure 2-8. This advancement is important for other aspects of technological progress in computing such as processing speed or the cost of computing.

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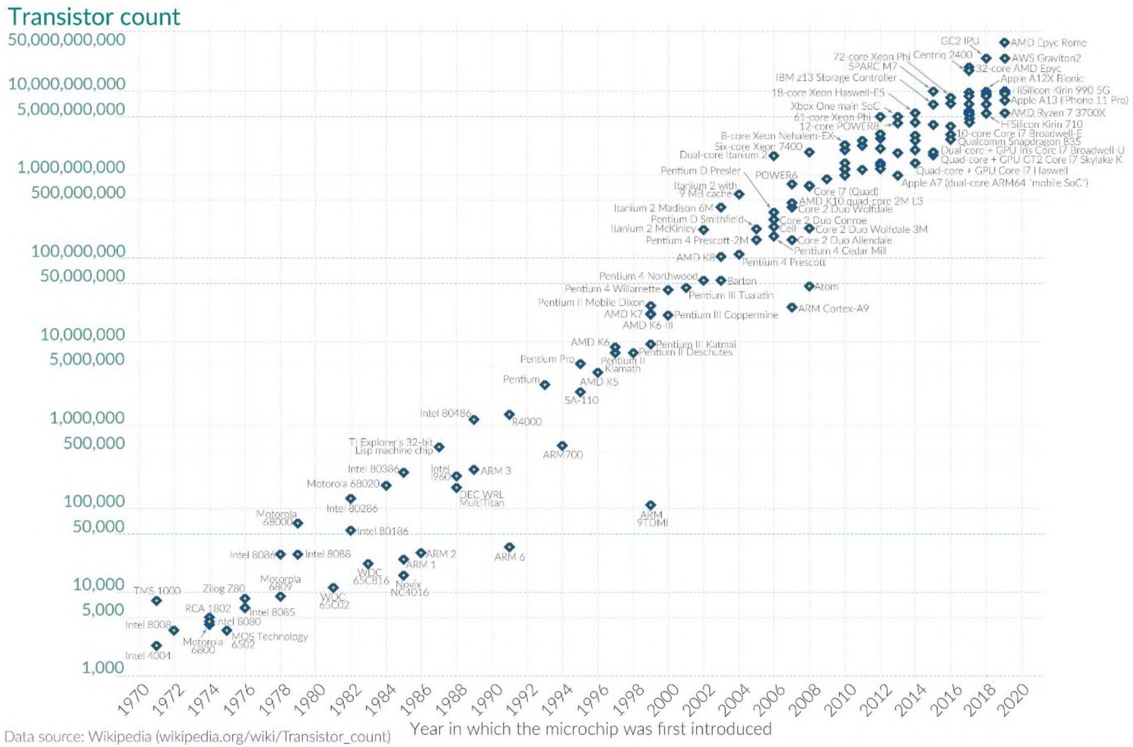
[24] *A Chip Act for Europe*, "Brussels, 8.2.2022 COM(2022) 45 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0045

[25] Europe's Digital Decade: digital targets for 2030 (europa.eu)



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

Figure 2-8 Moore's Law- exponential technological advancement through time.

The continuing validity of Moore's law for technology could be disrupted by the loss of PFAS which is a key enabling technology to make ever smaller transistors, through the ability to have extremely high purity, high quality, highly directed manufacturing. This is based on the PFAS applications explained in this report. **The impact on the global economy derived from denying access to state-of-the-art semiconductor technology would be significant, because PFAS provide multiple, critical functions which are crucial to production.**

In many instances, PFAS are the only substances known currently to offer the necessary technical performance in semiconductor production. If manufacturers are no longer able to invest in innovations relying on PFAS, a further consequential impact would be significant disruption to the technology roadmap[26] as manufacturers attempt to develop the next materials and equipment, which would be a lengthy and demanding process with no certainty of success. These impacts pose an enormous competitive disadvantage for semiconductor producers based in jurisdictions where there are PFAS restrictions compared to their non-affected competitors.

2.4 Importance of Yield

Production yield is the single most important factor for semiconductor manufacturing as not only does it influence the cost, but also the output per unit of input resources, waste generation, environmental and financial sustainability. During the manufacture of semiconductors yield loss is caused for example by defects, faults, process variations and contamination. Examples of contamination and mechanisms

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[26] The direction of research and timelines of semiconductor development in the future.

responsible for yield loss include airborne molecular contamination by the environment or by the tools, process-induced defects, process variations resulting in attributes such as different layer thickness, and many others.

The complexity and sensitivity of semiconductor manufacture and the occurrence of defects have a huge impact on the ability to produce designs, with each individual step needing to meet process control limits set in order to achieve wafer level yields **of greater than 90%**[27] and in lithography well above 99%.

Many PFAS are intrinsically linked to achieving the highly demanding yields, either by contributing to the cleanliness of the system or accuracy of the processing, and so they enable the manufacturing of current semiconductor devices. It is important to keep in mind that the factors which affect yield can rarely be attributed to a single process parameter, which is why multiple variables have to be considered concurrently, as outlined in multiple papers.[28, 29] Considering the widespread uses of PFAS, this too will pose a significant challenge due to the concurrent need to identify possible PFAS-free alternatives.

2.5 Essential Use

The Chemicals Strategy for Sustainability Towards a Toxic-Free Environment[30] proposes the development of a widespread essential use concept to apply across chemicals legislation.

The Chemicals Strategy[31] programme has not yet published its definition of ‘Essential Use’ but will develop criteria for essentiality. At this point it is known that the definition will be based on the criteria that there are no alternatives and that the use of the substance is necessary for health, safety or is critical for the functioning of society.

As is outlined in the respective sections of this report, PFAS substances in most applications do not have a known viable alternative and are key enablers of semiconductors. Semiconductors themselves are essential to the functioning of society and also essential for health as they are embedded in medical devices, power stations, satellite, and every home.

3 PFAS SUBSTITUTION OPPORTUNITIES AND CHALLENGES

3.1 PFAS substance identification

Many PFAS used in mixtures have not been classified as hazardous per the Globally Harmonised System for classification and labelling. In addition, they have not been listed as Substances of Very High Concern (SVHC) or included on the Candidate List of SVHC for Authorisation. Therefore, **many PFAS are not shown on safety data sheets even though the substance is present**.

In addition to this, chemical supplier companies invest significant time, money, and resources into developing proprietary chemicals to meet the exacting requirements to manufacture semiconductors at nanometre dimensions. In some instances, the use of PFAS is considered to be the intellectual property

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[27] Enhancing the Production Yield of Semiconductors | Infosys, 2022.

[28] Data Science in Semiconductor Process Yield | by Brian Mattis | Towards Data Science

[29] Taking the next leap forward in semiconductor yield improvement | McKinsey, April 2018.

[30] https://ec.europa.eu/environment/pdf/chemicals/2020/10/Strategy.pdf

[31] https://eur-lex.europa.eu/resource.html?uri=cellar:f815479a-0f01-11eb-bc0701aa75ed71a1.0003.02/DOC_1&format=PDF

of the chemical supplier, so the identification of the specific substance is not communicated to customers as companies need to ensure that their investment is protected. Releasing information about certain chemicals to the public would give competitors an unfair advantage and is likely to cause substantial harm to the company's competitive market position. Moreover, when PFAS are used as articles or articles in complex objects, the parts suppliers are currently under **no regulatory obligation to highlight the presence of PFAS**.

As a result of these various factors the discovery of PFAS uses in this sector is extremely challenging.

3.2 Timeframes for substitution

Due to the unique attributes of organofluorine chemistry, and the highly specialised function that PFAS provide in numerous semiconductor manufacturing applications, it is not known if PFAS-free alternatives will be viable for all applications. In any case, the timelines to qualify and implement alternatives are lengthy for the semiconductor industry as the following stages need to be undertaken:

1. The first stage in substitution is reviewing all potential alternatives currently marketed, to determine if they offer suitable performance. Sources can vary between commercial off the shelf products, and specialised alternatives developed specifically for the semiconductor sector, with the determining factor of whether they can be taken forward based on the technical needs of the application.

2. For many applications, investment in fundamental research and development is needed to identify a PFAS free alternative, as there is not one currently marketed which is suitable for the semiconductor's industry needs. This can start from fundamental external research undertaken by universities or research laboratories.

3. Once a possible alternative is identified this needs to be researched and developed by the material supply chain and then the semiconductor/semiconductor equipment manufacturer to assess the impact on the product, such that it offers the necessary technical performance through the following:
   a. Integration,
   b. Demonstration including re-qualification to standards or safety evaluations,
   c. Ramp to HVM,

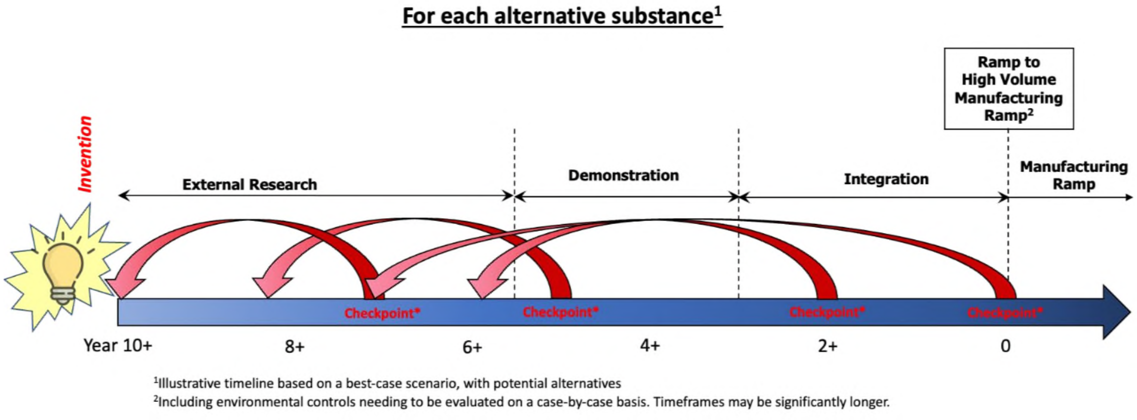
      This can involve significant timeframes as it potentially includes the development, installation, and integration of new equipment and/or new facility installations that manage environmental controls. Additionally, there are checkpoints along the development process to assess the viability of the alternative and the functionality of the material to manufacturing and product requirements.

   d. Impact on the market.

      The concurrent processes of semiconductor design and PFAS material alternative identification and qualification can cause additional delay in overall time to market as well as additional qualification resources to both semiconductor manufacturers and customers.

   Components and substances used in semiconductor equipment often require bespoke parts to be developed and qualified, with solutions potentially only being suitable alternatives for certain applications and therefore **not being a one-for-all replacement**. Therefore, the redesign and testing requirements for each use often is very significant and needs to be **undertaken by each company** due to differences in process. It is anticipated that significant innovation loops will take place between the semiconductor manufacturers and suppliers in feasibility testing of new innovations for PFAS replacement chemicals, to discover the appropriate technology platform for PFAS replacement for the numerous uses within the industry.

4. Suitable time to complete supplier change management, including changes to part numbers/drawings/technical and safety information, consumption of stock parts throughout multiple levels in the supply chain. The impact on production yield of a small change can be very significant, therefore the change control process within the semiconductor industry is strictly followed.
5. Assessment of unintended consequences, such as an alternative causing damage or an increase in defects present (Impact to production), which leads to increased safety risk (Impact to people). **When the alternative is not viable, the process has to loop back to earlier steps to find a different chemistry or technology that does not have the same issues.**
6. Additionally, stringent qualification also has to take place with semiconductor customers to ensure that the semiconductor product guarantees the same function as semiconductor product did previously.


For each alternative substance[1]

[1]Illustrative timeline based on a best-case scenario, with potential alternatives
[2]Including environmental controls needing to be evaluated on a case-by-case basis. Timeframes may be significantly longer.

Figure 3-1 Illustrative timeline for qualification of a single alternative.

Of course, this is only an overview and potential alternatives must be evaluated on a case-by-case basis, considering technical, regulatory as well as economic aspects. By its nature, the invention of an alternative has no estimated timeline as it can vary significantly, and for some applications there may be no known alternative.

Aspects such as the following further increase the uncertainty of the timelines:

Technical

- The alternative may not be a drop-in replacement and alternative design changes need to be made, solution may not be backward compatible to designs of equipment which are already in service.
- The technical requirements at each stage must be met, and may require multiple iterations of testing and development, as indicated by the red arrows in Figure 3-1.
- The solution may not address the long-term reliability of the alternative, which may only introduce additional design needs or technical limitations once the alternative has been used for a considerable length of time.

- The solution may need to be qualified by a certified body which can add additional time.

Supplier factors

- Difficulties in identifying a new supplier and their qualification can add considerable additional time to envisaged timeline in Figure 3-1.
- The alternative substance needs to be available in sufficient quantities to meet demand.

The supply chain for semiconductors can be narrow and varied, and highly, highly specialised. An impact to any one of these unique supply chain elements can have dramatic impacts to downstream customers. For instance, only a handful of chemical suppliers have the research and materials capability to support the critical lithographic materials needed for the entire semiconductor industry.

Delays in testing

- Unavailability of testing labs due to the expected increase in the demand for testing of other applications/alternatives, or delays in receiving test material from supplier or prototypes for testing.

Environmental

- PFAS articles are exposed to hazardous substances during use which might contaminate the proposed alternatives differently, and thus impact recyclability. Therefore, alternative waste manage streams would need to be identified. Additional information about the semiconductor industry's environmental impact, end of life and waste considerations can be found in Section 11 of this report.
- **Technical resources** Significant additional specialised highly educated technical resources will be required in the innovation and commercialisation of PFAS replacement materials. As such there may be additional time required to recruit and train additional people.

The timeframes for qualification of alternatives outlined in this report are wherever possible extrapolated from other qualifications, such as for PFOS and perfluorooctanoic acid (PFOA). Substitutions like these are only single changes and not a full re-engineering of the product, which is unprecedented, as discussed further in Section 3.4.1. Where previous substitutions are not applicable, timelines have been estimated on engineering judgement based on the information to the best of the Semiconductor PFAS Consortium's knowledge at the time of publication of this report. However, many of the timelines have a degree of uncertainty due to the number of steps still left to be undertaken and the possibility of unforeseen challenges yet to be identified.

In addition to these impacts, chemical, material and equipment suppliers would be significantly disrupted if PFAS were no longer able to be used because so many applications in semiconductor production are reliant on these substances. This would represent a critical and continual innovation challenge to industry.

3.3 Incentives for PFAS substitution

The semiconductor industry is a global leader in promoting environmental sustainability in the design, manufacture, and use of its products, as well as the health and safety of its operations and impacts on workers in semiconductor fabrication facilities (fabs).

Semiconductor industry companies recognise the importance of substituting PFAS where possible and where it does not create worker or community safety concerns. Despite this, there are still significant technical challenges to be overcome for a large number of PFAS uses in semiconductor applications due to the critical functionality they provide to the industry.

3.4 Challenges to substitution

Capabilities in the fluorochemical and semiconductor industries have evolved synergistically since 1971 with fluorocarbons being a key enabling technology to node size development in all aspects of semiconductor manufacturing. Finding another chemistry and technology which can match and exceed the PFAS application will require for many applications, investment in fundamental research and development to identify a PFAS free alternative.

In broad terms, PFAS offer a unique set of technical characteristics, which include exceptional heat and chemical resistance, high electrical insulation resistance, high purity, low-outgassing and low coefficient of friction. One of the characteristic features of the C─F bond is its strength compared with the C─C bond, due to the intrinsic electron-withdrawing power (electronegativity) of the fluorine atom. This intrinsic attribute is the basis of many of the technical benefits of fluorinated materials in semiconductor processing, but this also leads to its chemical stability and environmental persistence. Fluorination brings unique physiochemical properties and consequent qualitative improvements that are the enabler of semiconductor, performance and manufacture, advancements. These unique properties make substituting PFAS a challenge.

PFAS is used in gaseous, liquid, and solid forms, and is used in many different applications, which need to work together to form a coherent production process. Some of the uses, such as cleaning fluids and lubricants, have dependencies on one another, and finding alternatives for cleaning fluids can only be started once all PFAS containing lubricants are substituted. Removing PFAS from earlier process steps can result in deterioration of performance which makes the later steps in the process impossible due to excessive defect rates, such as moving to a silicone-based alternative resulting in excessive defects. This complexity and interdependency are discussed in Section 2.2.

Elimination or substitution of a whole class of chemicals, like PFAS, is unprecedented and will add a significant amount of time to identify and implement each alternative due to the following:

- Each alternative must first show suitable performance in its technical parameters or the combination of its technical parameters but will also need to be tested to ensure that there are no negative impacts to all other substitutions as well. Parameters such as yield, and production performance need to be maintained. This could require changes in the design of the devices, as well as changes in the manufacturing process to accommodate the properties of alternate materials – thus triggering the need for rigorous testing to ensure it does not have a detrimental impact on the function and performance of the device. Due to the number of changing parameters which need to be investigated this poses a significant challenge.
- Availability of skilled engineers and leadership within the market has already been highlighted as limited, moreover, owing to the complexity of the products this shortage has an even higher impact. This limits the ability of manufacturers to implement all of the solutions at any one time and would result in the decrease or halt of research and development activities (R&D). It is important to note that those engineers will be diverted from their normal function of R&D for new innovations and products, production optimisation, and quality improvement activities.

3.4.1 Regrettable Substitution

For a PFAS alternative to be successful, it must not only pass through all the qualification timeline stages successfully and provide effective performance for the application, but it must also be a sustainable alternative that can be used without impact to human health or the environment.

When deciding whether to restrict a substance it is always important to consider whether safer alternatives exist. Where alternatives are identified which are more harmful than, or no better than, the substances currently in use, these substances should not be considered as a potential alternative and should not be taken forward (e.g., for development) in the Semiconductor PFAS Consortium's opinion.

Potential alternatives can be relatively new substances and/or substances made in smaller quantities where much less research has been carried out regarding their health and environmental hazards, as compared to current substances in use that have been thoroughly studied. Alternatives and their hazards are not always known, and for many of these instances it is not unreasonable to assume that they are likely to present similar concerns to PFAS. This is based on the understanding that their desired characteristics and therefore environmental controls and concerns would be of similar nature to the ones implemented for the use of PFAS. **Informed substitution is therefore crucial.** If the replacement is not carefully considered for its own potentially deleterious effects, regrettable substitution can easily occur.

A sufficiently long transition time is crucial to ensure proper research into alternatives. Indications of these timeframes are given in each of the sections below which consider the various stages where PFAS are used.

4 PHOTOLITHOGRAPHY USES

Summary:

PFAS has been an enabling technology in the development of ever smaller and more advanced semiconductors over the last 30 years through cutting edge lithographic developments.

- **Photoacid generators** (PAGs) are key components of the Chemically Amplified Resists (CARs) that are used in advanced lithography. They generate strong acids on exposure to UV light, and the chemistry requires sulfonium and iodonium-acid salts with fluorinated anions. The strong electronegativity of the fluorine atom creates a super acids capable of causing the solubility change of the photoresist. All successfully demonstrated PAGs are fluorinated, some down to one CF_2 unit, and there are no universally applicable viable fluorine free alternatives for a vast array of lithographic materials. Current photoacid generators have been in development for 25 years, and alternatives are expected to take from **15 to more than 20 years** to reach production. For an alternative to be successful it would have to show acidity comparable to perfluoro sulfonic acids, show similar lack of side reactions, lack volatility, and show minimum diffusivity for high resolution patterns.
- **Top antireflective coatings (TARCs)** require a very low refractive index, low surface energy and excellent barrier properties, which are provided in fluorinated acrylate / methacrylate / styrene-based copolymers. The requirements differ between “193 nm” and “193 nm immersion” lithography, but **no currently, viable alternative materials exist for either application**. Fluorine free systems have resulted in patterning failure in immersion processes.
- **PFAS Surfactants** have unique properties, such as very low surface tension and a combination of hydrophobic and oleophobic behaviour, that have been utilised in various types of photolithographic materials. Applications include photoresists (248nm, 193nm, immersion, thick film, etc.), BARCs, TARCs, colour resists for image sensing, and rinse solutions. The surfactants are used to improve film quality, alter surface interaction, wetting characteristics, and component mixing, all of which helps to minimise various defectivities in the lithographic process and thus increase lithographic impacted yield. It may be possible to find non-PFAS alternatives for less advanced applications using current known potential alternatives, such as siloxane-based surfactants. However, for most advanced applications, siloxane (or other) alternatives cannot duplicate performance characteristics that PFAS surfactants offer and would lead to compromised performance.
- **Immersion top coatings** require very low surface energy (resulting in very high water contact angles), excellent barrier properties and a lack of intermixing with the photoresist, which are provided in fluorinated acrylate / methacrylate / styrene-based copolymers. The requirements differ between “193 nm” and “193 nm immersion” lithography, but currently, **no viable alternative materials exist for either application** and there are not even any concepts for PFAS replacement for this application. Fluorine free systems have resulted in patterning failure in immersion processes.
- Current PFAS materials were designed, developed, and optimised as dedicated substances to satisfy many functions and performance needs in lithographic imaging products. Thus, replacement with a new non-PFAS material will likely require **multiple solutions** depending on the application, which has a significant impact on the estimated timelines.
- The consumption of PFAS for photolithography is quite low with very small releases when compared to global releases.[32]

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[32] When compared to 470 Tons of PFAS surfactants in fire foams as described in the European Chemicals Agency reports.

Photolithography is a patterning process in which a photosensitive film, called a photoresist, is selectively exposed to light to provide a pattern to an underlying substrate, with the chemistry of photoresists and role of PFAS different for different wavelengths. Photolithography is a critical process step in the mass production of a semiconductor, with the most advanced devices requiring over 70 photolithographic steps in their production. On average a minimum of 10 years is required to take a new product to market, from concept through development and deployment. This is assuming alternatives are known and commercially available.

Although the total amount of PFAS used in photolithography is small when compared to global consumption and releases of PFAS[32], the addition of small quantities of fluorinated materials enables patterning capabilities that are otherwise not possible to achieve, this leads to superior device performance. In comparison to the 836,787 tonnes of 2020 EU PFAS brought new to market,[33] the semiconductor industry uses less than 2.3 tonnes per year of PFAS in photolithography in the European Economic Area.

The following uses of PFAS in photolithography have been listed, with a short description of their technical criteria:

1. Component of surfactants,
2. Component of photoacid generators (PAGs) in chemically amplified resists (CARs) and bottom anti-reflective coatings (BARCs),
3. As low refractive index materials in top antireflective coatings (TARCs), which are used to control thin film interference effects in photoresist layers as substrates are not perfectly flat and otherwise this will detrimentally affect the photoresist imaging fidelity,
4. As barrier layers in immersion lithography,
5. Photo-imageable polybenzoxazoles and polyimides for dielectric and buffer coat applications, and
6. Photoresist applications.

The various types of photolithographic materials and their applications have recently been reviewed in the 2022 Ober paper[34], with a key summary of PFAS uses outlined in Table 4-1.

Table 4-1 Key photolithography PFAS uses and technical criteria.

PFAS use area	Function	Types of compounds used	PFAS provide
Photoresists and BARCs – Surfactants	Improved coating uniformity. Post develop rinses: prevention of pattern collapse.	Longer chain PFAS (C6-C8) and telomer alcohols pending form polymer backbones. Now mostly replaced by C4 pendant chains. Rinses: C4 surfactants.	Low surface tension, control of contact angle.

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[33] ANNEX XV RESTRICTION REPORT, Proposal for a restriction, Per- and polyfluoroalkyl substances (PFAS) by European Chemicals Agency 2023, Annex XV reporting format 040615 (europa.eu)

[34] Christopher K. Ober, Florian Käfer, and Jingyuan Deng, "*Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing,*" Journal of Micro/Nanopatterning, Materials, and Metrology, Vol. 21, Issue 1, 010901 (March 2022). https://doi.org/10.1117/1.JMM.21.1.010901

PFAS use area	Function	Types of compounds used	PFAS provide
Photoresists and BARCs – PAGs	Precursor for the photoacid catalyst needed for CARs and BARCs.	Perfluoroalkylsulfonates C4 or lower and C4 or lower substituted superacid anions such as C1. For some advanced resists, these are bound to polymers.	PFAS component of PAGs generates strong acids that do not show side reactions that interfere with the chemical amplification process.
Photoresists – polymers	Control pattern profile in EUV.	C1 PFAS polymer.	Increases absorbance, improves the dissolution properties, increases resolution.
TARCs	Control of thin film interference effects in resists.	Fluorinated water and developer soluble polymers.	High fluorine content is needed to achieve the low refractive index needed to effectively suppress film interference effects.
Immersion barriers	Protection of the resist from immersion liquid and of the exposure tool from contamination. Prevent water film pulling and resist component leaching in immersion topcoats.	Spin-on barriers: Water insoluble and developer soluble polymers with fluorinated side chains. Embedded barriers: oligomeric or low molecular weight polymeric highly fluorinated compounds. Fluoroalcohol methacrylate polymers with high water contact angles (in the order of >90°).	Barriers that are soluble in casting solvents, insoluble in water but soluble in developer, and that show no intermixing with photoresists. Hydrophobicity and control of contact angle, inert under 193nm radiation, and transparency.
Dielectric Polymers (PBO/PI)	Provide electrical, thermal, and mechanical protection for the semiconductor device. Also protects the device components from the impact of moisture.	Water-insoluble C1 PFAS polymers.	C1 PFAS groups attached to the polymer backbone provide solubility in environmentally friendly casting solvents and enable aqueous development.

Owing to the changing technological challenges as the wavelength of exposure decreases, different PFAS uses are required depending on the technology used. Table 4-2 aims to outline this differing need at a high level.

Table 4-2 PFAS use in photolithography according to exposure technology.

Wavelength (nm)	PFAS use	Technical requirement
365 nm and larger	• Mostly surfactants • Some PAGs in niche photoresists • Photoimageable polybenzoxazoles • Polyimide	Surface levelling, resolution enhancement.
248 nm	• Surfactants • Photoimageable polybenzoxazoles and polyimide • PAG	365nm resists were insufficiently transparent so alternative CAR resists were developed requiring PAG.

Wavelength (nm)	PFAS use	Technical requirement
193 nm	- Surfactants - Photoimageable polybenzoxazoles and polyimide - A limited number of PAGs - Immersion barriers	248 nm resists were insufficiently transparent, requiring a new chemistry for 193 nm resists that only works with PAGs that make very strong acids.
13.5 nm (EUV resists)	- Surfactants - PAGs (frequently polymer bound)	Low acid diffusivity in photoresists and underlayers. Increases absorbance, improves the dissolution properties, increases resolution.

Material changes for lithographic materials are not easy nor quickly achieved, with PAGs in chemically amplified resists having been under development for at least 25 years. Current PFAS materials were designed, developed, and optimised as dedicated substances to satisfy many functions and performance needs in lithographic imaging products. Thus, replacement with a new non-PFAS material will likely require multiple solutions depending on the application.

Each new material must satisfy multiple performance characteristics that may be impacted by the change, as outlined in Table 4-3. As a result, each new non-PFAS replacement product containing the new non-PFAS material(s) must be optimised to satisfy multiple performance characteristics, while not detrimentally impacting others to fully meet all customer requirements.

Table 4-3 Photolithography potential PFAS replacement viability and timeline uses and technical criteria.

PFAS use area		Timeline to develop	Concern of alternative	Criticality for manufacture
Surfactants	CARs and BARCs: silicon-based surfactants developed for some applications; not suitable for all applications.	Commercial replacement materials exist. For applications that do not have existing commercial replacements, invention is required.	At high levels, silicon surfactants may cause etch defects.	Replacement maybe possible in many applications, but there will be exceptions due to replacement capability/functionality.
	Rinses: non-PFAS aqueous surfactants – active area of research.	Active area of research; time to prototype 1-2 years.	Still need to demonstrate equivalent performance.	Critical for advanced lithography.
		Total development time for surfactants up to 15 years after invention.		
PAGs in CARs and BARCs	PFAS free alternatives do not show suitable performance.	PFAS free PAG 5+ years of invention, estimated	A PFAS free PAG of equivalent performance has never been	Critical: currently most CARs for any node use PFAS. PAGS and all production of chips below

PFAS use area		Timeline to develop	Concern of alternative	Criticality for manufacture
		timeline to implement from **15 to more than 20 years after invention.**	developed so this may not be technically possible for all applications or wave-lengths. Any substitution will likely have to be limited to certain applications only.	40 nm node is impossible without PFAS CARs. See Table 4-4 for more information.
	Currently only possible to replace for 248nm resists or those exposed at larger wavelength.			
	Replacement with shorter chain, lower molecular weight PFAS fails due to volatility and diffusivity.	Substitution with lower chain PFAS: **10+ years** to re-qualify and assess impact on subsequent process steps.	Substitution with lower chain PFAS: requires significant work to be undertaken and resources would have to be diverted from developments in innovation.	
TARCs	Originally salts of PFOA or PFOS were used but replaced ~ 2004 with other PFAS that show lower bioavailability and bioaccumulation.	New research needed.	Refractive index of 1.3 -1.4 needed to be effective. For ease of use and defect control, it is advantageous to spin TARCs on using water as the solvent.	Current implant processes use TARC as an effective way of reflectivity and defectivity control. Alternatives are more complex and require additional processing.
	Concepts for replacements exist but are unproven and need to offer suitable performance in terms of thickness, uniformity, coat quality, surface energy, edge bead, roughness, gap-fill, and aging at various temperatures.	Timeline for invention 5+ years and development another 8+ years.	Some concepts for PFAS-Free TARCs unavoidably lead to significant loss of wafer throughput, e.g., dyed TARCs[35] have a 20-30% wafer throughput loss.	
	Silicon anti-reflective coating materials are under evaluation.	**Total development time from 11 to more than 13 years after**		

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[35] Ralph R. Dammel and Robert A. Norwood, “Light-absorbing antireflective coatings with improved performance due to refractive index optimization,” US patent 6,274,295 B1 (2001) and, Wu-Song Huang, William H. Heath, Ranee Kwong, Wenjie Li, Kaushal Patel, Pushkara Rao Varanasi, "New 193-nm top antireflective coatings for superior swing reduction," Proc. SPIE 6153, Advances in Resist Technology and Processing XXIII, 61530S (29 March 2006); doi: 10.1117/12.656641

PFAS use area		Timeline to develop	Concern of alternative	Criticality for manufacture
		invention for TARCs.		
Immersion barriers	There currently is no known concept for a non-PFAS material that can combine all the necessary properties. Properties include soluble in casting solvents and developer, but insoluble in water, no intermixing with photoresists, very high-water contact angles (>90°) to prevent watermark defects.	Current assessment is that replacement requires invention, but **no concept currently exists for replacement**.	Production of chips below the 40 nm node is not possible without immersion barriers.	Critical – no known alternatives to PFAS, no concepts for replacements.
Dielectric Polymers (PBO/PI)	PFAS free alternatives either don't show suitable performance or require the use of highly toxic casting solvents.	New research needed to develop soluble PFAS free polymers.	PFAS free alternatives currently require the use of highly toxic casting solvents.	Critical for advanced semiconductor packaging.
		Total development time of 15+ years after invention for PBO/PI.	Lack of PFAS in the backbone can result in resolution and aqueous development issues.	

4.1 Photoacid Generators (PAG)

Photoacid generators (PAG), are photoactivated acid compounds which, when irradiated with high energy light (deep ultraviolet or EUV), undergo photodissociation generating extremely strong, non-reactive and stable acids. Currently there are somewhere between 100 and 150 PAGs used in CARs worldwide. They are used in relatively small quantities overall.[36] The individual use of a PAG is dependent upon the overall parameters that must be met in the CAR – the chemical, physical and imaging/print quality characteristics. Because of this, there is no single PAG that is suitable for use in all CAR applications.

PAG precursors need to be sufficiently soluble in good casting solvents. The acids need to be sufficiently strong to cause the solubility change, non-absorbing at key wavelengths to avoid pattern disruption, have a low volatility to not evaporate from the resist films and not undergo side reactions which would destroy the acid catalyst.[37] In addition to this, with smaller node sizes the right amount of diffusivity is also required. However, when investigating alternatives, the following properties also need to be investigated; final resolution, exposure latitude, focus window, wall angle, top retention, or isolated to dense feature bias. These parameters result in different optical proximity correction requirements and

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[36] As outlined in Table 4-5 Organic Polymers of which PAGs are a portion thereof has a consumption figure of 9,276 kg/year globally for 2021.

[37] Something that standard strong acids such as hydrogen chloride or bromide would readily do.

hence in the need to procure a new mask set for the resist. Finally, the wafers patterned with new resist have to be tested for performance in subsequent process steps. This process is sufficiently demanding that most chip manufacturers have special integration teams assigned to it and this often takes 3 years or more.

Non-PFAS PAGs generally lack the acidity to perform in current platforms and this prevents the required reactions from progressing. Potential alternatives such as pentacyanocyclopentadiene (CN5) were investigated,[38] however, it was found to have strong absorption at 248nm preventing it being used at that wavelength. Its use in 193nm was found to have half of the processing speed of PFAS alternatives, and toxicological testing in rats found the presence of cyanide. Nitro-substituted thiophene was also investigated by the same team but also found to have an inferior standard of performance. There are initial indications that bis-sulfonyldiazomethanes might be suitable in 248nm but not at 193nm due to the weaker acids generated, however this needs to be fully investigated.

Amongst known substitutes, IBM have developed non-PFAS PAGs (CN5 and thiophene sulphonate), which has highlighted the difficulty of developing formulations that meet all performance criteria simultaneously, as shown in Table 4-4. As such, non-PFAS PAGs are for a narrow range of use applications only, as no known non-PFAS PAG/photoacid exhibits the same level of performance for all criteria. While a candidate chemistry might show good acid strength, it will have lower photospeed[39] because of lower acid diffusivity, and at the same time the acid anion might be transparent for a single wavelength only. PFAS PAGs, on the other hand, present simultaneously good to excellent performance for all listed performance criteria with the notable exception of environmental persistence.

Table 4-4 Comparison of the performance of PAGs versus alternatives.

Performance criterion	PFAS PAGs/photoacids	CN5 non-PFAS PAG/photoacid	Thiophene sulfonate PAG/photoacid
Photospeed[39]	Excellent	Poor	Good
Acid strength	Excellent	Excellent	Good
Diffusivity	Good to excellent[40]	Lower than PFAS acids	High to too High
Pattern quality/ Line width roughness	Good	Line width roughness higher than commercial resists	Line width roughness much higher than commercial resists
Transparency at all exposure wavelengths	Excellent	Not transparent at 248nm	Not transparent at 248nm
Solubility of PAGs in casting solvent	Good	Good	Poor to moderate
Lack of side reactions	Excellent	Excellent	Excellent
High process temperature requirement	None	Yes	None

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[38] Martin Glodde, Sen Liu, and Pushkara Rao Varanasi, "*Fluorine-free photoacid generators for 193 nm lithography based on non-sulfonate organic superacids*," J. Photopol. Sci. Technol. 23 (2), 173-184 (2010) and Sen Liu, Martin Glodde, and Pushkara Rao Varanasi, "*Design, Synthesis and Characterization of Fluorine-free PAGs for 193nm Lithography*," Advances in Resist Materials and Processing Technology XXVII, Proc. of SPIE Vol. 7639, 76390D (25 March 2010); doi: 10.1117/12.846600

[39] Photospeed is a composite of acid strength, acid diffusivity, and PAG quantum yield.

[40] Low diffusivity requires polymer-bound photoacids.

Performance criterion	PFAS PAGs/photoacids	CN5 non-PFAS PAG/photoacid	Thiophene sulfonate PAG/photoacid
Uniformity of PAG distribution	Good	Good	Good
Toxicity	Moderate to high	High[41]	Moderate
Environmental persistence	Highly persistent	Assumed to be biodegradable	Assumed to be biodegradable

So far, the only non-PFAS alternatives for 193 nm applications or lower are not technically viable due to their potential for a prohibitively high decrease in yield (estimated by a Semiconductor PFAS Consortium member to be 1-2%), and lower performance. If alternatives decrease yield even by very small percentages at a fab production site, this results in significant **increases in extremely high-cost waste generation**. The current feature sizes would not be able to be achieved as a significant invention still has to be undertaken, moreover it is not certain if suitable materials can be developed for all applications. As such all **manufacturing of these devices have to rely on PFAS** until wavelength-specific, alternative superacids have been developed. This significantly increases the amount of invention and development that needs to be done as all of the above-mentioned steps would need to be completed for each alternative analysed.

Additionally, even if performance criteria can be met, the replacement of PFAS PAGs by non-PFAS alternatives with fundamentally different acidity and diffusion profiles are likely to result in even larger differences in photoresist behaviour, which means that the above-mentioned task of resist re-qualification and integration is even more demanding. This would be in addition to the requirements for product development, customisation, product scale-up, commercialisation, customer product evaluation (with potential product optimisation/evaluation loops between suppliers and customers), and final qualification at the customer site.

4.2 Top antireflective coatings (TARCs)

Top antireflective coatings (TARCs) previously used PFOS and PFOA. Activities to replace these began in 2004 to use other fluorinated polymers that show lower bioavailability and bioaccumulation. This replacement has been completed and it is believed that no PFOA/PFAS-based TARCs are on the market. This substitution activity highlights challenges in identifying and qualifying alternatives as it took manufactures between 4-15 years depending on their use of PFOS and PFOA. As a result of this change, a number of unintended consequences also occurred; the developer use increased by 25%, the cycle time increased ~25% and in some cases of previous PFOS use the yield significantly dropped, all of which have **negative environmental and production cost impacts**.

4.3 Immersion Barriers

Immersion barriers include spin-on barriers and embedded barriers. Spin-on barriers are coated on the resist from an alcohol solvent, whereas embedded barriers as part of the photoresist solution are initially homogeneously distributed in the resist but migrate to the resist surface through phase separation. Both types are removed during the development step of production and are a key part of the immersion lithography process. Chip manufacture at and below the 40 nm node is not currently possible without them.

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[41] Cyanide ion is found in rat stomachs when fed CN5.

Although PFAS-free silicon-based barriers are available, they are not developer-soluble, are not stable under 193 nm exposure and could lead to SiO_2 deposits on the lens element. If deposits occur, the entire production tool would need to be shipped back to the manufacturer for repairs, causing it to be out of commission for 6 months or more. No other potential alternative has yet been identified offering suitable technical performance, as such the replacement of PFAS in immersion barriers is currently considered **technically not possible at this time**.

4.4 Surfactants

Another fundamental application of PFAS compounds in photolithography is the use of PFAS surfactants. Surfactants in general are “surface-active agents” that consist of a hydrophobic segment and a hydrophilic unit. Surfactants can be used in a variety of coating applications for improving film quality and component mixing, and changing surface interaction, and wetting characteristics. One specific performance advantage of fluorinated surfactants is that the surface activity is much higher than equivalent hydrocarbon or silicone surfactants as indicated by the requirement for less surfactant material in a formulation to achieve its critical micelle concentration. Fluorinated non-ionic surfactants have been used in a wide range of lithographic processes due to their very low surface energy, thermal- and mechanical stability, and low refractive index and they can be used to improve photoresist deposition and eliminate defects during photoresist coating.

The majority of non-PFAS alternatives contain silicon, which can lead to potential compatibility and defectivity issues as outlined in Section 4.3. Polyalkylene glycol based and alcohol ethoxylate based surfactants were also screened in bottom anti-reflective coatings but were not able to show suitable performance. Replacements are most likely to be **less problematic for older, less advanced technologies** (i.e., i-line photoresists[42]), but for **advanced lithographic photoresist technologies**, direct replacement of PFAS surfactant with non-PFAS options is more challenging and **requires invention**. There is the concern that PFAS-free surfactants will lead to shorter shelf-life stability due to the comparative strength of the carbon-fluorine bond not being able to be matched, which would impact the supply chain logistics 40otentiallly result in an increase in extremely high-cost wasted products.

4.5 Dielectric Polymers: polyimides (PI) and polybenzoxazoles (PBO)

The development of next-generation semiconductor products has become reliant upon advanced semiconductor packaging technologies. These advanced packaging technologies have enabled the modular integration of several small chiplets[43] designed to meet specific functions within a larger completed package, like on-chip memory, accelerators, controllers, and chip-to-chip interconnections. Advanced semiconductor manufacturing technologies have new performance requirements, such as the need to control heat generation within the new stacked configurations, as well as the need to maintain electric integrity through control of electrical leakage and mechanical integrity during thermal cycling in operation. These materials are non-fugitive and stay with the device for its service life. The cured material is insoluble in either aqueous or organic media and is sandwiched between inorganic layers. These materials must therefore have sufficient thermal, mechanical, and electrical properties to survive the harsh environments in which the devices made with them are used, as predicted by highly accelerated stress testing.

The new performance requirements of advanced semiconductor packages have been met through the development and implementation of novel photo-imageable dielectric materials. These dielectric

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[42] A general purpose, multi-wavelength resist designed to cover a wide range of film thicknesses, 1–10 µm, with a single coat process.

[43] Chiplets are small, modular chips which are part of a processing module that makes up a larger integrated circuit.

materials are virtually exclusively selected from two families of polymers: polyimides and polybenzoxazoles. These polymeric materials protect the semiconductor device by effectively preventing electrical leakage, thermal stress, and corrosion of the underlying semiconductor circuitry. The PI and PBO materials are required to be photo-imageable to meet the required high-resolution requirements for chiplet interconnects through the use of PFAS ingredients typically found in photolithographic chemistries such as surfactants, photoacid generators and polymers. PI and PBO materials used in advanced packaging applications typically employ C1 PFAS groups attached directly to the polymer backbone to impart solubility, transparency, and moisture resistance in the dielectric film as well as clean development of patterns in aqueous processing.

The essential properties enabled by the use of the C1 PFAS in the polymer are:

- Optical transparency
- Thermal stability
- Low moisture absorption
- Lower cure temperature
- Cleaner development
- Aqueous development of PBO materials
- Higher resolution of solvent developable polyimides
- Good mechanical properties (e.g., elongation at break)
- Improved electrical properties
- Solubility in environment, health & safety friendly solvents elimination the need for more toxic solvents

Currently no PFAS-free materials are known to be viable as photo-imageable dielectric materials for use in advanced semiconductor manufacturing processes.

Photo-imageable dielectric materials can be deposited through either a spin-on process, or as a dry film. Wastes generated from spin on application is similar to that from a photoresist, where waste photo-imageable dielectric chemistry and solvent based developer is collected within a bulk waste solvent collection system and managed as hazardous waste through thermal destruction at an incinerator or within a cement kiln. Aqueous based developer waste is collected in a separate, aqueous waste stream, neutralised, and filtered/separated prior to release to the aqueous waste stream.

With the demands of the industry for improvements in lithography and packaging, the replacement of C1 PFAS moieties on the polymer backbone with currently known alternatives would significantly compromise the performance required for these applications.

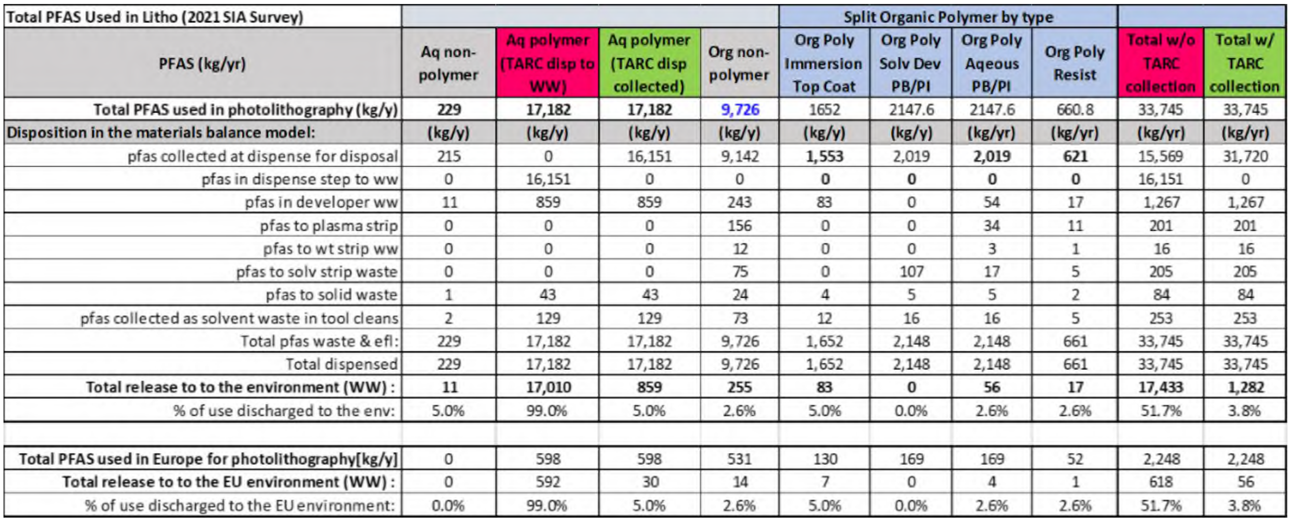
Moving away from PFAS in photoresist applications, is likely to require a **change in the entire photolithographic process**. Photoresists are not interchangeable; they are designed to work with a specific photolithography method and are needed for the life of that manufacturing facility which is dedicated to the particular device technology (generation) being manufactured. Qualifying an alternative as a drop-in photoresist replacement part way through the life of a facility would not be possible in many cases and would need assessing for each facility individually.

4.6 Environmental Considerations in Photolithography

Worldwide, a total of 33,745 kg of PFAS are used by semiconductor manufacturers in photolithography annually based on SIA's members survey of 2021 sales capturing well over 90% of the materials market, as shown in Table 4-5. TARCs are the largest single product type, accounting for over 50% of total PFAS use in photolithography. The total PFAS use for photolithography in Europe is estimated to be **2,248 kg** annually, or about 6.7% of the worldwide semiconductor use.

The total worldwide PFAS discharges from photolithography range between **1,282 to 17,433 kg/year** (of which the EU is estimated at 6.7%, or 86 to 1,168 kg/year), depending on the amount of spin bowl waste collection. SIA estimates from previous surveys that about 50-60% of TARC users collect and properly dispose of the waste so the emissions are expected to be on the lower end of this scale. With full TARC spin bowl waste collection, the **estimated amount discharged to wastewater in the European Union is 56 kg per year**.

Table 4-5 Results of SIA 2021 sales survey and an example release mass balance.[44]



Total PFAS Used in Litho (2021 SIA Survey)					Split Organic Polymer by type					
PFAS (kg/yr)	Aq non-polymer	Aq polymer (TARC disp to WW)	Aq polymer (TARC disp collected)	Org non-polymer	Org Poly Immersion Top Coat	Org Poly Solv Dev PB/PI	Org Poly Aqeous PB/PI	Org Poly Resist	Total w/o TARC collection	Total w/ TARC collection
Total PFAS used in photolithography (kg/y)	**229**	**17,182**	**17,182**	**9,726**	1652	2147.6	2147.6	660.8	33,745	33,745
Disposition in the materials balance model:	**(kg/y)**	**(kg/y)**	**(kg/y)**	**(kg/y)**	**(kg/y)**	**(kg/y)**	**(kg/yr)**	**(kg/yr)**	**(kg/yr)**	**(kg/yr)**
pfas collected at dispense for disposal	215	0	16,151	9,142	**1,553**	2,019	**2,019**	**621**	15,569	31,720
pfas in dispense step to ww	0	16,151	0	0	**0**	**0**	**0**	**0**	16,151	0
pfas in developer ww	11	859	859	243	83	0	54	17	1,267	1,267
pfas to plasma strip	0	0	0	156	0	0	34	11	201	201
pfas to wt strip ww	0	0	0	12	0	0	3	1	16	16
pfas to solv strip waste	0	0	0	75	0	107	17	5	205	205
pfas to solid waste	1	43	43	24	4	5	5	2	84	84
pfas collected as solvent waste in tool cleans	2	129	129	73	12	16	16	5	253	253
Total pfas waste & efl:	229	17,182	17,182	9,726	1,652	2,148	2,148	661	33,745	33,745
Total dispensed	229	17,182	17,182	9,726	1,652	2,148	2,148	661	33,745	33,745
Total release to to the environment (WW) :	**11**	**17,010**	**859**	**255**	**83**	**0**	**56**	**17**	**17,433**	**1,282**
% of use discharged to the env:	5.0%	99.0%	5.0%	2.6%	5.0%	0.0%	2.6%	2.6%	51.7%	3.8%
Total PFAS used in Europe for photolithography[kg/y]	0	598	598	531	130	169	169	52	2,248	2,248
Total release to to the EU environment (WW) :	0	592	30	14	7	0	4	1	618	56
% of use discharged to the EU environment:	0.0%	99.0%	5.0%	2.6%	5.0%	0.0%	2.6%	2.6%	51.7%	3.8%

The following assumptions were used in the calculation:

- During spin on processes, 95% of the dispensed material was left in the spin bowl as waste, whereas 5% remained as a coating on the wafer.
- For aqueous development, 100% of the TARC and immersion topcoat material was removed in development and discharged to wastewater.
- For photoresists, an average of 50% of the coating is dissolved in aqueous developers and discharged to wastewater, and the other 50% would remain on the wafer and be removed in subsequent strip operations.

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[44] For this table, the presented acronyms and their meaning are as follows: Litho (photolithography), Aq (aqueous), Org (organic), Poly (polymer), Solv (solvent), Dev (developer), PB/PI (polybenzoxazole / polyimide), wt (wet), efl (effluent), env (environment), WW (wastewater), w/o (without), and y or yr (year).

5 WET CHEMISTRY USES

Summary: Wet chemical processing is the terminology used to describe several different semiconductor fabrication processes that involve dispensing a liquid chemical mixture to clean, etch, dry, planarize, or electroplate. The composition of wet chemical process formulations varies greatly depending on the application-specific performance requirements. Different companies and even different fabs within the same company do not all manufacture the same products, and therefore there are important inter- and intra-company differences in the wet chemical processing formulations and technologies in which they are employed. It follows that the need for a PFAS component in a wet chemical formulation depends on the application-specific performance requirements that, in turn, depend on the specific wafer processing technology being manufactured.

The timeline needed to develop, qualify, and implement alternatives falls into the following four broad categories:

- **3 to 4 years**: If an existing non-PFAS alternative is available and can be demonstrated to provide adequate performance for a specific application.
- **3 to 15+ years**: In some applications where an existing non-PFAS alternative may be viable but requires tooling and/or process changes before it can be successfully introduced into high volume manufacturing (HVM).
- **Successful invention required (from 5 to more than 12 years):** For some applications it may not be possible to demonstrate that an available non-PFAS alternative can fulfil the application specific performance requirements. In these cases, it may be necessary to invent and synthesise new chemicals, and/or develop alternative approaches to fabricating a device structure that provides the necessary electrical and computational performance. Invention is an open-ended endeavour with no guarantee of success.
- **No alternative achievable**: In some cases, it may ultimately be found that a non-PFAS alternative is not capable of providing the required chemical function. If a non-PFAS alternative chemical cannot be invented, then the integrated circuit device structure may need to be abandoned in favour of an alternative device structure that may or may not provide equivalent performance.

Fluorinated organic chemicals have several unique physicochemical properties that, in some applications, are essential to the successful performance of the process. However, there is no general *a priori* means to determine whether a non-PFAS alternative will be capable of working for a particular application. Instead, the evaluation of potential alternatives must begin with experimental trials using available non-PFAS candidates as guided by chemical theory and experience. The timeline as outlined in the Executive Summary and Wet Chemicals uses Summary.

The majority of wet chemical formulations do not utilise a PFAS additive. Where PFAS are used in wet chemical processing they are typically shorter chain PFAS (4-perfluorocarbon or less). Many of the shorter chain PFAS have been implemented relatively recently as alternatives to the longer chain homologues like PFOS and PFOA that they replaced. For instance, one device maker spent 8 years replacing the PFOS (8-perfluorocarbons) in a buffered hydrofluoric acid (BHF) formulation with a 4-perfluorocarbon alternative by working with several chemical suppliers. In contrast to the technical challenge in substituting from a long chain to a shorter chain PFAS homologue, it can be anticipated that substitution from a short chain PFAS to an entirely PFAS-free alternative represents a significantly more difficult technical challenge.

The move to shorter chain PFAS, despite there being evidence that they have lower bioaccumulation factors[45], is now seen as a regrettable substitution and highlights the need for comprehensive cross discipline evaluations of the alternatives that are offered as replacements for currently used PFAS.

5.1 Wet Chemical Processing

Wet chemical processing encompasses several different semiconductor fabrication processes including wet chemical etching, planarization, electroplating, and also wafer cleaning, rinsing, and drying. Although these involve very different wafer processing operations, with different objectives, the common factor is that they involve contacting a wafer with a liquid chemical mixture.

Wet chemical etching and cleaning operations are typically conducted in specialised “wets” SMRE or tools that bring a liquid chemical mixture into contact with wafers either by dispensing it onto a spinning wafer or by immersing one or more wafers into a tank for “batch processing wets tools”.

In most wet etch, chemical mechanical planarization (CMP), electroplating operations, and in many wafer cleaning operations, the areas of the wafer that are operated on by a wet chemical processing step are isolated to very specific regions of the wafer defined by a photolithography “masking” operation. In assessing the complexity and challenge of conducting a wet chemical process, therefore, it is essential to consider the dimensions and geometric complexity of the integrated circuit features that are being fabricated. Although semiconductors are typically fabricated from crystalline silicon “wafers” that are generally either 200 mm or 300 mm in diameter, and in the order of 0.8 mm thick; the individual integrated circuit device structures often have critical dimensions that typically measure in nanometres and thus are often at the molecular scale. It is the dimensions and materials complexity of the device features, not the wafer as a whole, that presents the challenge in wet chemical processing.

Figure 5-1, for instance, illustrates schematically a typical wet chemical etching operation where a patterned photoresist is used to delineate the region of the wafer substrate that the etchant operates on. The etchant must transport into, react with, and transport reaction products out of the region that is masked by the photoresist layer, and must “stop” at, and not remove material from the underlying substrate. The difficulty of the wet etch application generally increases with the need to etch features that are very narrow and deep (high aspect ratio). The difficulty of an etch operation also depends on the number and type of materials that are exposed to the etchant, and the relative removal rate for each material.

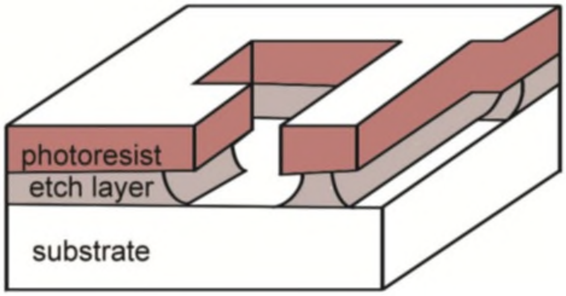

Figure 5-1 Conventional simple wet etch application.

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[45] Burkhard, L.P., 2021. Evaluation of published bioconcentration factor (BCF) and bioaccumulation factor (BAF) data for per- and polyfluoroalkyl substances across aquatic species. Environmental toxicology and chemistry, 40(6), pp.1530-1543.

Figure 5-2 illustrates the geometry of a current generation memory cell, where the etchant needs to penetrate between “nano sheets” that may be only tens of nanometres wide, and down into a channel that can be thousands of nanometres deep. The aspect ratio of the region into which etchant must transport, and etchant products must be removed, is more than 100 which introduces highly demanding technical requirements.

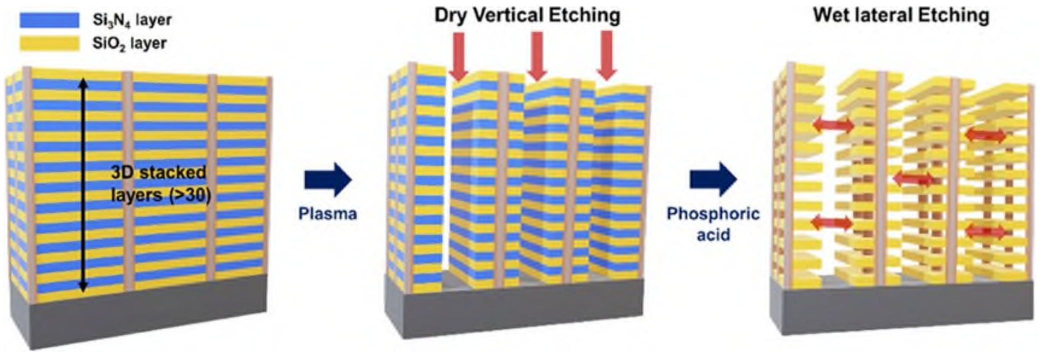

Figure 5-2 3D NAND flash memory manufacturing process and wet lateral etching. Each layer is on the order of 25-40 nm thick, and 4,000 nm deep.[46]

The rinsing and drying of a modern wafer is also challenging due to the narrow dimensions causing immense capillary forces to be generated by the liquid on the walls of the structure, as illustrated in Figure 5-3 and can result in “pattern collapse” as illustrated in Figure 5-4. The phenomenon of pattern collapse requires the use of specialty fluids, these are used to either reduce the surface tension of the fluid that enters a channel or change the surface properties of the channel walls. Fluorinated surfactants and fluorinated surface modification chemicals, which are capable of lower surface forces than other known materials are often required to solve pattern collapse issues. With the increasing geometric complexity and narrow dimensions associated with advance integrated circuit fabrication, there will be continuing, if not increasing need to employ specialty fluorinated liquids in these applications.

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[46] Lee, H.I., Kim, H.S., Tikue, E.T., Kang, S.K., Zhang, H., Park, J.W., Yang, S. and Lee, P.S., (2021). Green Manufacturing of Silyl-Phosphate for Use in 3D NAND Flash Memory Fabrication. ACS Sustainable Chemistry & Engineering, 9(14), pp.4948-4956.

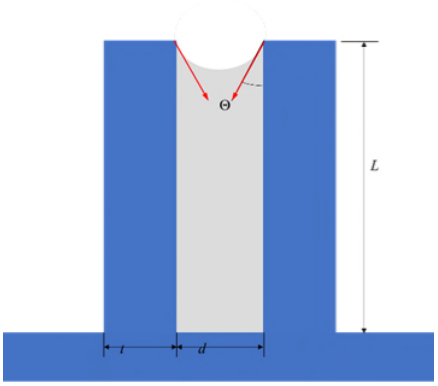

Figure 5-3 Diagram illustrating the capillary forces exerted by a wetting fluid on the walls of the material holding the fluid.[47]

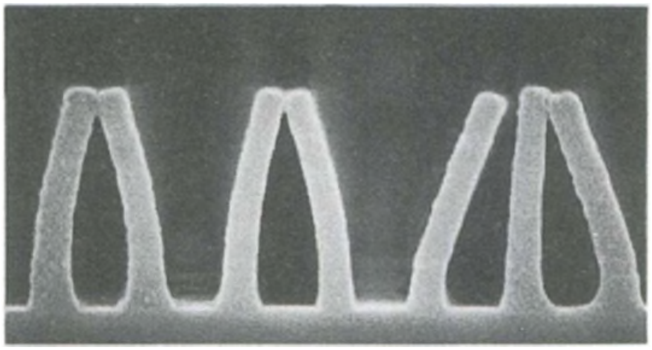

Figure 5-4 Image of line collapse that has been caused by capillary forces.[48]

5.2 Surfactants

Wet chemical formulations vary greatly depending on the particular application. Surfactants are commonly needed in wet chemical formulations, and in some applications, a fluorinated surfactant is used because of the superior performance they provide as described below. However, in addition to use as surfactants, other types of PFAS are also employed as surface modifying agents and solvents. Additional detail regarding these uses is provided in the Wet Chemical Processing White Paper, as outlined in Table 1-2.

In general, surfactants are often added to semiconductor chemical formulations to achieve the necessary process performance which include:

- The ability to reduce surface tension at low concentrations and to allow for the penetration of aqueous solutions into narrow, high aspect ratio features with hydrophobic sidewalls,

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[47] https://www.tel.com/product/cellesta.html

[48] Image provided by Bassett (2019) TEL.

- Stability in strong mineral acids and bases,
- Rapid adsorption at solid/liquid interface to provide improved wetting which improves etch rate uniformity of films,
- Adsorb to a surface to prevent the deposition of metals that are introduced into the solution during an etching process,
- Adsorb to a surface to suppress etching of one material while another material is preferentially removed. For instance, in the removal of SiO_2 from the surface of a Si substrate, a surfactant is employed to selectively adsorb to the Si surface and suppress its etching while the SiO_2 is removed,
- Ease of rinsability from surfaces, and
- Low foaming to mitigate the formation of air bubbles that can form and cause failure of the etching of contact holes.

The selection of a particular surfactant for one of these applications varies depending on the application specific requirements. Important factors that can drive a requirement for a fluorinated surfactant include the following:

- If the surfactant must resist decomposition under chemically reactive conditions, including acidic, basic, oxidising, or reducing conditions, then organofluorine (a PFAS substance) surfactants may be required. Fluorocarbons have the strongest bonds known in organic chemistry.
- If the mixture must achieve very low surface tensions or contact angle, then a fluorinated surfactant may be required. Fluorinated surfactants can achieve lower aqueous surface tensions (15 – 20 dyne/cm) than hydrocarbon (~ 30 dyne/cm) and other known materials including fluorosilicates. This is due to a combination of low polarizability, high molecular surface area, and conformation of the perfluorocarbon tail groups.
- If the surfactant must retain its surface activity at very low pH, then a fluorosurfactant may be required. Fluoroalkyl acid surfactants, for instance, typically have near zero pKa[49] values and therefore their headgroup remains ionized and hydrophilic even if the pH approaches zero.
- If the surfactant must be surface active in a non-aqueous media, then a fluorinated surfactant may be required. Surfactants with perfluorinated tail groups are oleophobic as well as hydrophobic.

In many applications, several if not all of these factors together are essential to the performance of a fluorosurfactant.

5.2.1 Wet Clean applications

Wet cleaning occurs after virtually every wafer processing step, to remove residue and restore the substrate surface to a pristine state before proceeding to the next wafer fabrication step. Aqueous clean processes such as those known as standard clean 1 (SC1 =H_2O_2 and NH_4OH) and standard clean 2 (HCl and H_2O_2) are typically simple inorganic formulations that generally do not contain surfactants or other additives.

Organic solvent etch and clean formulations are used in some applications due to their unique solvency properties, and/or surface activity. Among the physicochemical attributes that are important in certain

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[49] pKa, or acid dissociation constant, is a measure of the strength of an acid.

applications are specified melting and boiling points, viscosity, surface activity and polarizability, solvency, hydrophobicity, and dielectric properties.

Multiple stage wet cleans use both aqueous and organic based cleaners and may be critical to ensuring the nanometre level device critical features and high aspect ratios. Each cleaning regime is specific to the product being cleaned, technology, type of chip and its end function.

5.2.2 Wet Chemical Etching

Wet chemical etch processes are used to selectively remove one material in the presence of others, often in the presence of extreme geometric complexity. Each etching operation must be highly uniform across a wafer, from wafer to wafer, from run to run, and regardless of variations in feature sizes and pattern densities. A variety of different aqueous etchant formulations are used in wet chemical processing. Commonly used aqueous etchants include BHF, the generically named “metal etchant” that typically consists of a mixture of phosphoric and other acids and aqueous tetramethylammonium hydroxide.

BHF, for instance, is used to wet etch or clean a variety of different wafer substrate materials including silicon, polysilicon, silicon oxide, silicon nitride, aluminium, copper, and photoresists. The challenge in conducting these operations varies greatly depending on the juxtaposition of materials and the geometric complexity of the feature being etched. In one common application of BHF, silicon oxide is selectively removed from a silicon surface. Another common application involves the etching/cleaning of contact holes, which vary significantly in their critical dimension and aspect ratio depending on the particular application.

PFAS-free BHF formulations are known to work for some BHF applications, but not all as fluorinated surfactants are still required where the following requirements are needed: very low pKa as needed to maintain a charged headgroup for surfactant properties at a low pH, very low surface tensions, or resiliency in highly aggressive chemical solutions. As such, depending on the number of technical challenges yet to be overcome and the need for systems level qualifications, the exact timeframe for qualification is very uncertain.

5.2.3 Chemical mechanical planarization (CMP) and Post CMP Cleans

CMP utilises water-based slurries typically comprised of mixtures of abrasive particles with chemical components such as acids, bases, oxidisers, chelating agents, metal passivating agents, surfactants, and other selectivity control agents to remove a wide range of film types (SiO_2, SiN, W, Cu, etc.). Surfactants are routinely used in the formulation of CMP slurries and post-CMP cleaning solutions, and in some applications the surfactant may be a PFAS. Typically, the surfactants serve to disperse the particles, improve slurry stability, control the wettability of films and polishing pads, and reduce corrosion of some films. Although only used in very specialised instances, fluorosurfactants can be found in the formulation of certain types of CMP slurries for targeted performance improvements, including the enablement of selective film inhibition and the wetting of low surface energy substrates.

5.2.4 Metal Plating

A variety of electrolytic and electroless plating operations are used in semiconductor wafer manufacturing (fab) and post fab packaging operations. Plating solutions commonly contain surface-active components, that in some formulations may contain PFAS to:

- Lower surface tension to:

  - Improve wetting and access of the plating bath solution to geometric features with high aspect ratios,
  - Mitigate the inclusion of hydrogen gas that is generated at electrodes, into the metal deposit,
  - Reduce bubble size and mitigate acid mist formation.
- Provide a surface-active material as a co-reactant to form a deposition conjugate with the plating metal.

In addition to conventional plating operations, electroless plating of Cu is conducted in trench/via fill operations, and sometimes requires a surfactant to prevent interference from the hydrogen that is generated as a by-product. In these applications, a surfactant may need to be fluorinated in order to achieve the particular surface tension and wettability requirements, and/or for resiliency to the oxidation and reduction reactions.

Table 5-1 provides an overview of the PFAS uses in wet chem applications, all of which require from **3 to more than 15 years** to develop a PFAS-free alternative depending on whether qualification and implementation of existing alternatives, or invention of new materials and processes is required.

Historically, there were many more wet chemical uses of PFAS, but the majority of uses have already been substituted, in some cases to a shorter chain PFAS, with a limited number remaining. One such example, is the historical use of PFOS and PFOA as surfactants, which were substituted with shorter chain perfluoroalkyl sulfonic and/or perfluoroalkyl carboxylic acids. This change was the result of substantial effort over a period of up to 16 years for this application. Substitutions have impact across the supply chain. For example, one chemical manufacturer changed the design of over 20 products by incorporating alternatives. Those products were then, in turn, qualified and used by a hundred different customers. Some PFC gases are also used for cleaning, and these are discussed in Section 6.

The semiconductor industry expects PFAS-free alternatives to be much more difficult to find than the transition from PFOA or PFOS to shorter chain PFAS substances. This is because in many cases there are no known chemical alternatives that are capable of providing equivalent chemical functionality and performance to fluorinated organic chemicals. In some applications, a non-PFAS chemical may be viable, whereas in other applications currently known alternatives may not be able to provide the necessary performance requirements and therefore may be essential.

In some situations, it is likely that entirely new molecules may need to be synthesised and evaluated. To prevent regrettable substitution, the timeline must include evaluations of the chemical behaviour and toxicity of the proposed alternatives, including characterisation of the controls necessary to prevent impact to human health and the environment. Owing to these considerations, a specific timeline cannot be predicted. However, once the invention of a viable alternative has been accomplished, the demonstration, qualification, and transfer to HVM may take **more than 15 years**.

Table 5-1 Examples of etches and cleaning operations utilising PFAS.

PFAS use area	Role of PFAS additives	Concern of alternative	Criticality for semiconductor devices manufacture
Aqueous etch/clean formulations **Organic based etch formulations**	a) Facilitate entry of the wet etchant into, and reaction products out of, a capillary space by reducing the surface tension of the fluid and the contact angle with the solid. b) Adsorb to a surface to prevent the deposition of metals that are introduced into the solution during an etching process. c) Mitigate the formation of air bubbles. d) Adsorb to a surface to suppress etching of one material while another material is preferentially removed.	a) The surface-active agent must resist decomposition under chemically reactive conditions. b) Fluorinated surfactants can achieve lower aqueous surface tensions (15 – 20 mN/m) than hydrocarbons (~ 30 mN/m) and other known materials including fluorosilicates. c) Fluoroalkyl acid surfactants have uniquely low pKa values that enable them to remain ionized and hydrophilic even if the pH approaches zero. d) Surfactants with perfluorinated tail groups are oleophobic as well as hydrophobic, and therefore are surface active in organic solvents as well as aqueous etchants.	PFAS additives are **critical for some, but not all wet etch applications**. The requirement for a PFAS additive depends on the physical dimensions and aspect ratio of the device feature being etched, and the particular set of materials exposed to the etchant during etching.
Chemical Mechanical Planarization	Surfactants and surface-active materials are critical components of CMP slurries and post-CMP cleaning solutions. These components must: a) Disperse the particles. b) Provide slurry stability. c) Control the wettability of films and polishing pads; and d) Reduce corrosion of some films. Fluorosurfactants are critical to achieving CMP performance requirements in certain situations. In particular, they are used where necessary to enable selective film inhibition and the wetting of low surface energy substrates.	a) The surface-active agents must rapidly adsorb to the substrate during polishing and rapidly desorb with water rinse. b) they must be non-foaming to prevent foaming. c) In situations where a very low surface tension is required, only PFAS surfactants can lower surface tension of aqueous solutions to values below ~ 20 (mN/m) rapidly. d) In chemically aggressive CMP formulations a PFAS surface active agent may be necessary to prevent degradation by reactive oxygen species produced in oxidising systems.	PFAS additives are **critical for some, but not all CMP applications**. The requirement for a PFAS depends on the materials properties of the exposed surfaces that need protection, surface tension reduction requirements, and aggressiveness of the CMP formulation.

PFAS use area	Role of PFAS additives	Concern of alternative	Criticality for semiconductor devices manufacture
Organic solvent based clean formulations	Organic solvents are required for some wafer clean/strip formulations and also some cleaning operations that are conducted on parts outside of the fab cleanrooms. In some applications these mixtures are comprised of fluorinated organic solvents and/or fluorinated organic alternatives in order to provide the necessary solvency and fluid handling characteristics.	The ability of a solvent to dissolve and solubilise a material from the surface of a wafer or part depends on their respective chemical characteristics, as often represented by the Hansen Solubility parameters (dispersion, polar, and H-bonding intermolecular forces). In some cases, therefore, a fluorinated component is necessary to remove fluorinated materials from a surface.	PFAS containing solvent mixtures are **critical for some, but not all solvent clean applications**. The requirement for a PFAS depends on the materials properties of the substance that needs removal.
Pattern collapse mitigation	PFAS are used in a number of different formulations that are used to mitigate pattern collapse issues, including surfactants, surface modification treatment materials, displacement fluids, and organic solvents. Historically associated with photoresist, pattern collapse is now a critical and evolving challenge in the etching and drying of narrow dimensioned, high aspect ratio device features like nanosheets and 3DNAND structures. Pattern collapse occurs when the capillary forces created by liquid menisci formed between high aspect ratio features exceed the structural strength of the material forming the walls of the capillary space.	The ability of a non-PFAS alternative to serve effectively as a means of pattern collapse mitigation depends on the particular application. Several different approaches that are in use, or being pursued, as means of mitigating pattern collapse issues that are evolving with increasing use molecular dimension device structures.	**Some PFAS containing formulations used to mitigate pattern collapse may be essential**. Development of new solutions for the evolving pattern collapse issue may be able to avoid the use of fluorinated organics depending on the application specific performance requirements.
Plating and electroplating	Plating and electroless plating utilise surfactants and surface-active materials to: a) Reduce surface tension to improve wetting and access of the plating bath solution to geometric features with high aspect ratios. b) Mitigate the inclusion of hydrogen gas that is generated at electrodes, into the metal deposit. c) Mitigate bubble and/or mist formation. d) Function as a co-reactant to form a deposition conjugate with the plating metal.	a) The surface-active agent must resist decomposition under chemically reactive conditions particularly at plating electrodes; b) Fluorinated surfactants can achieve lower aqueous surface tensions (15 – 20 mN/m) than hydrocarbons (~ 30 mN/m) and other known materials including fluorosilicates; c) Fluoroalkyl acid surfactants have uniquely low pKa values that enable them to remain ionized and hydrophilic even if the pH of the plating solution approaches zero. d) Ability to function as a co-reactant depends on the materials present in the plating operation.	PFAS containing plating mixtures **are critical for some, but not all plating applications**. The requirement for a PFAS is application specific and therefore depends on the materials properties of substance being plated, as well as the dimensions and aspect ratio of the features being plated.

5.3 Environmental Considerations in Wet Chemistries

Semiconductor facilities generate organic and aqueous waste streams which are treated in accordance with local and federal waste and wastewater regulations. Organic waste is typically collected and disposed of as a blended fuel by high temperature incineration or reprocessing.

Historically, the majority of aqueous chemicals employed in fab manufacturing processes are discharged to an industrial wastewater drain system that conveys wastewater for treatment of specific regulated pollutants in accordance with local and federal regulations, and subsequently discharged to a publicly owned treatment works or surface water. Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS. The industry is actively researching PFAS wastewater releases and treatment technologies.

6 FLUOROCARBON USES IN PLASMA ETCH/WAFER CLEAN AND DEPOSITION

Summary: Perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) are essential for semiconductor manufacturing and are used in thin film deposition, plasma etch/wafer clean, and chamber cleaning processes, but are already subject to separate greenhouse gas regulations. The semiconductor industry has a demonstrable history of engineering solutions to reduce both the consumption and emission of HFC/PFC gases in response to environmental concerns. The industry can employ this substantial knowledge base to further improve the performance of abatement systems if exemptions are granted.

PFAS alternatives either do not exist at present, or if they do, they create **PFAS by-products if a carbon containing film is present.** The intrinsic properties of silicon wafers have informed the use of fluorocarbons. Invention is needed to find alternatives because silica compounds (SiO_2, SiN, etc.) are the foundation of semiconductor device structures and tuneable silicon layers require a specific and tuneable ratio of carbon and fluorine to etch.

For chamber cleaning, fluorine ions and radicals are necessary; non-PFAS alternatives are either potent greenhouse gases or extremely reactive and toxic and PFAS by-products are created if residual carbon is present.

A fundamental re-design of semiconductors and the equipment, processes, and chemicals to make them would be needed if HFCs and PFCs are no longer available for plasma etch and chamber cleaning processes. As such the following timelines are estimated (at a minimum) to implement alternatives after a feasible invention is identified:

- Dry etching **more than 15 years** to qualify each specific etch type and **additional implementation time if alternatives are found.**
- Chamber cleans **more than 10 years** for each specific type.

Perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) are critical process gases used within semiconductor manufacturing and have played a critical role in the evolution of semiconductor device technology to its current level of development. PFCs and HFCs are used in dry etching and other process operations due to their chemical stability and as their reactivity in plasma. Table 6-1 below summarises these operations, the current substances used, the status of alternative and the timescale to develop them. Plasmas and other specialised semiconductor process operations can convert stable gases into radicals and ions without the need for reactive gases to be stored and transported within semiconductor manufacturing facilities.

As many of these PFCs and HFCs are greenhouse gases, which are currently subject to separate regulation, the semiconductor industry has worked for over 30 years (and continues to work) to develop best practices to minimise PFC and HFC emissions. However, alternatives to PFCs/HFCs have not yet been found and the search is proving especially challenging for the etching of the insulator in the semiconductor device structure.

6.1 Dry Etching

While wet etches and cleans are used to indiscriminately remove metal, insulators, polymers, or defects; plasma or "dry etching" is used to **remove or chemically change very specific elements on the surface of the wafer**.

In the manufacture of recent logic semiconductor devices, there are more than 100 distinct plasma etching process steps. Many of these process steps use PFAS gases. Some etching processes use PFAS as primary gas(es), whist others use PFAS as an additive. Each of these process steps has a different purpose and different requirements to be achieved, therefore many different combinations of PFAS are used.

Plasma etching is directional, making it possible to target the specific, microscopic features needed to be removed or chemically changed. The desired combination of anisotropic/isotropic etching and protective layer formation can be obtained by using plasma of PFAS gas(es) or a gas mixture containing PFAS gas(es). These etching processes are indispensable steps in the production of semiconductor devices.

In the semiconductor industry today, very high aspect ratios are required to enable increasingly demanding device densities. This means that plasma processes must be able to etch out smaller and smaller gaps. Especially where etching the insulator of the semiconductor device structure, it is important to have the interaction between C/CHF/CF deposition and F etching, when controlling the dissociation ratio of PFAS molecular radicals by plasma. By using directional etching of F while protecting any material that is not intended to be etched or otherwise altered during the etching process, using a deposited layer consisting of C and F, it is possible to etch the intended shape.

The physical and chemical reactions on the wafer are dependent on the type of gases, the flow rate of gases, the chamber pressure, the power, and other highly controlled and highly specialised chemical, and chamber conditions. Changing any one of these parameters can change the overall profile of the device structure being formed by the plasma etch process. The gases used for a specific etch must be selective for the material to be removed or changed. For instance, gases such as CF_4 alone will etch both silicon and silicon dioxide, so CF_4 needs to be combined with other gases (like hydrogen) so that it etches only the silicon dioxide.

6.2 Plasma Cleaning

Even with the highly controlled, selective use of PFCs and HFCs, some by-product deposition or dielectric layers previously deposited may occur on the sidewall of semiconductor equipment chambers. This deposition in both plasma etching and chemical vapour deposition chambers, if not cleaned periodically, can result in contamination of the wafer and the ultimate scrapping of functional semiconductors.

Periodic PFC cleaning and conditioning of chambers is used to optimise product yield. PFCs and HFCs are used due to their relative stability in storage and gas transfer as well as their ion reactivity in plasma. The gases used to clean internal equipment surfaces must be reactive enough to clean the chamber, but not so reactive as to damage it. Common PFAS gases used for plasma cleaning and conditioning include, but are not limited to: C_2F_6, C_3F_8, CF_4, and C_4F_8. In the early 2000's and the implementation of 300mm wafer size and associated tool development, NF_3 chamber cleans were implemented for much of the 300mm semiconductor industry, replacing C_2F_6 and other PFC cleans.

6.3 Chemical Vapour Deposition/Atomic Layer Deposition of Organometallics

Deposition of many metal-containing films (including, but not limited to oxides, nitrides, and pure metals) required for current and future semiconductor process nodes relies on organometallic precursors containing polyfluorinated compounds as ligands. This is especially prevalent in late transition metal deposition precursors. The presence of fluorine in the molecules serves several important roles. First, the presence of fluorine atoms in organometallic compounds reduces the intermolecular dispersion force and thereby increases the volatility (lowers boiling temperature) significantly, allowing the precursor to reach the chamber where it will react to form films containing the metal of interest. The presence of fluorine in these ligands also influences the stability and reactivity of these materials. Fluorine containing ligands have a strong impact on the electron density at the metal centre and can stabilise a molecule sufficiently to allow easy transport to the chamber while leaving the molecule reactive enough to interact with other co-reactants resulting in the film of interest.

6.4 Other critical uses of PFCs and HFCs

Gas-cluster ion beam is a technology used for nano-scale modification of semiconductor surfaces through infusion or deposition. This technology is used to develop the necessary electrical properties of the wafer through surface modification. Current stability gases used in gas-cluster ion beam include, but are not limited to, CF_4 and CF_3.

Assembly, test, and packaging steps connect the semiconductor die to the semiconductor package. These steps include bonding, cleaning, and preparing the package to ensure electrical connectivity. Future advanced assembly, test, and packaging operations (including such processes as through silicon via and wafer stacking) are currently in the invention and research and development phase. PFC and HFC gases, such as but not limited to CF_4, are used, and may be used in next generation assembly, test, and packaging operations.

Table 6-1 Examples of the manufacturing processes using PFC and HFC gases.

Processing need/ function	Example substances	Alternative or replacement status	Timeline to develop
Dry etch	CHF_3; HFC-23; Trifluoromethane; CH_2F_2; CH_3F	There are no viable substitutes for fluorocarbon chemistries at present. These chemistries provide both thermodynamically favourable reactions for patterning silicon and its dielectrics and selectivity to carbon-based masking materials. Attempts to separate these components (e.g., using hydrocarbons and separate fluorine sources) introduce additional safety concerns and likely form PFC by-products. Alternative molecules containing C and F which do not fit into the PFAS definition may have complicating factors such as high global warming potentials and low destruction/removal efficiencies.	15+ years for each specific etch type (for example: oxide etch, nitride etch, silicon etch, hardmask etch, etc.) **with additional time to implement each solution**
	CH_2FCF_3; HFC-134a; 1,1,1,2-tetrafluoroethane		
	C_5F_8; PFC-1418; Octafluorocyclopentene		
	C_4F_8; PFC-318; Octafluoro-2-butene		
	C_4F_6; Hexafluoro-1,3-butadiene		
	C_3F_8; PFC-218; Octafluoropropane		
	CF_4; PFC-14; Carbon tetrafluoride		
Chamber cleans (for deposition and etch chambers)	C_2F_6; PFC-116; C_4F_8; Hexafluoroethane	NF_3 has been implemented as an alternative due to its high utilisation efficiency but can create CF_x by-products when there is residual carbon.	10+ years for each specific cleaning type
	C_3F_8; PFC-218; Octafluoropropane		10+ years[50]

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[50] The alternative would require redesign of tools, existing semiconductor equipment and manufacturing processes which is why such a development timeframe is needed.

Processing need/ function	Example substances	Alternative or replacement status	Timeline to develop
	CF_4; PFC-14; Carbon tetrafluoride		10+ years[50]
Pre-clean/seasoning	CF_4; PFC-14; Carbon tetrafluoride	The process needs exactly the same gas combinations and mix ratio to the etching step following the process.	5 years
	C_4F_6; Hexafluoro-1,3-butadiene		
Assembly test and packaging	CF_4; PFC-14; Carbon tetrafluoride	Replacements investigated, but not viable. Other replacements may be possible but need further investigation.	10+ years
Gas cluster ion beam	CF_4; PFC-14; Carbon tetrafluoride	Replacement may be possible with NF_3, SF_6, O_2, Ar, further investigation needed.	10+ years
	CHF_3; HFC-23; Trifluoromethane		
Organometallic precursors	Metal HFAC Metal TFAC Others	The presence of fluorine in these ligands also influences the stability and reactivity of these materials. Evaluations in progress but do not meet required process performance; further investigation is needed.	Indeterminate
Self-assembled monolayer and small molecule inhibitors[51]	Polyfluorinated hydrocarbons	This is in the research stage. Lack of access to these molecules will limit innovation.	Indeterminate

PFC and HFC gases have been used in the semiconductor industry for decades following many years of intensive development to optimise processes. These gases are and have been a critical component for manufacturing semiconductors due to their relative chemical stability during storage and transfer and relative chemical reactivity during plasma ion generation.

PFC and HFC emission reductions have been a committed goal of the semiconductor industry for over 30 years.[52] PFC and HFC emission reductions have been achieved through the development of industry best practices[53] such as: chemical recipe optimisation, chemical replacements, point of use abatement, and lower emitting remote plasma cleans. Semiconductor manufacturing was one of the first industries to establish global voluntary reduction targets for these PFCs when in 1999 the WSC agreed to reduce absolute PFC emissions by at least 10% by the end of 2010 having as a baseline the 1995 emissions. By 2010, emissions were reduced 32% below the baseline, surpassing the 10% reduction target. The WSC again committed to a voluntary PFC agreement in 2010 with a time horizon up to 2020 and reports on progress publicly in the WSC annual joint statement. However, during these 30 years of investigation,

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[51] This is not discussed previously as it is in the research phase.

[52] World Semiconductor Council (WSC) Joint Statement, April 1999, http://www.semiconductorcouncil.org/wp-content/uploads/2016/04/PFC-Reduction.pdf

[53] World Semiconductor Council (WSC) PFC Best Practices Guidance, September 2012, http://www.semiconductorcouncil.org/wp-content/uploads/2016/07/Final_WSC_Best_Practice_Guidance_26_Sept_2012.pdf

the industry has not identified safe and effective alternatives for all PFC and HFC gas uses. Given this, it is believed the elimination of HFCs and PFCs would require a fundamental re-design of semiconductors to a non-silicon base material as well as redesign of the processes and equipment used to make them. Replacing silicon with another material will not necessarily result in elimination of the need for HFCs and PFCs.

While the use of C_2F_6 in chamber cleaning has been replaced in many applications with NF_3, the semiconductor industry operates a variety of fabs with tools that may not always have the capability to upgrade to an alternative gas. It is important to note that this transition to NF_3 was the result of over 15 years of development which was initiated in 1997 and now has become the industry standard whenever possible. The cost implications of such a transition are high with the costs per chamber ranging from ~$60K to $400K and a semiconductor manufacturing fab containing hundreds of chambers for thin film (etch and deposition) processes.

Even with this transition, PFAS by-products are still produced when carbon containing precursors are used in the dielectric deposition and emitted due to the reaction and recombination of fluorine with carbon and hydrogen to create PFC and HFC by-products. Owing to the resilient nature of many chamber residues, highly reactive fluorine (the most electronegative atom) is required for chamber cleaning which is why alternatives still rely on the inclusion of fluorine. As such, although this does resolve in some ways the reliance on PFAS substances, it still involves PFAS if the end-to-end system is considered.

6.5 Environmental Considerations in PFCs and HFCs

As discussed above, the use of PFCs and HFCs is essential for plasma etching, plasma cleaning, and other low volume critical applications, their uses balance the process need for high chemical and ion reactivity with the need for safe and effective manufacturing. The industry’s commitment to reduce greenhouse gas emissions has successfully reduced PFCs and HFCs emissions through a combination of process optimisation, substitution, and abatement. Implementation has required companies to invest time and funds to identify and research prospective changes to HFC/PFC chemicals, to design, test and implement process and equipment modifications, and to identify, test and design increasingly effective abatement systems. Although this process has proven effective at mitigating the impact of emissions, it has not proven effective in eliminating PFCs and HFCs from the manufacturing process.

The adoption of point of use (POU) technologies on many tools using PFCs and HFCs has reduced the potential hazard exposure risk to employees and has reduced greenhouse gas emissions. With the implementation of WSC PFC best practices in new fabs – including remote plasma clean and POU abatement- many facilities have needed to expand other treatment systems, such as wastewater, fluoride, and exhaust to meet the required standards for wastewater and air toxics. Some POU technologies use fuel-burning processes to abate PFCs and HFCs, creating additional nitrogen oxides, carbon monoxide, and other air pollutants from combustion in exchange for a reduction in PFCs and HFCs. Process and abatement alternatives often require a full safety, health, and environmental impact review to understand additional implications to employee and community safety and health. Viable alternatives often require coordinated efforts between material suppliers, equipment suppliers, device manufacturers, and environmental safety and health professionals to determine the overall environmental impact of even a small change.

7 HEAT TRANSFER FLUID USES

Summary: Two types of fluorinated heat transfer fluids are used in semiconductor manufacturing processes and semiconductor device test applications: liquid fluorinated heat transfer fluids (F-HTFs) and fluorinated refrigerants. These two types of fluorinated heat transfer fluids are used in tandem within corresponding heat transfer fluid (HTF) loops and refrigerant cycles to meet operational temperature requirements in semiconductor manufacturing processes like dry etch or thin film deposition and semiconductor device test applications, of which dry etch is the predominant and most complex use with stringent manufacturing process requirements.

To date, non-PFAS alternatives have not been identified. For F-HTFs the performance characteristics require the material to be electrically non-conductive, to be compatible with all materials of construction including sensitive electrical components, suitable toxicity/flammability, and to not cause catastrophic process contamination issues. Fluorinated refrigerants work in tandem with F-HTFs and must remain in a gaseous or liquid form to remain pumpable and useful for temperature control.

As such, suitable, non-PFAS-containing substitutes for the majority of uses would need to be invented and those invented may not enable ready plug-and-play substitution. When a plug-and-play substitute is not available it would drive a complete redesign of manufacturing and support equipment. New equipment designs may also require invention, may drive additional space and/or facilities that could result in a reduction of available manufacturing space and/or expense, that could impact global competitiveness.

- For the small percentage of applications in which glycol / water alternatives can be substituted and refrigerants within process equipment chillers from **8 to more than 14 years** are required to substitute PFAS in HTF for semiconductor manufacturing processes.
- Where no alternatives have been invented for the remainder of semiconductor manufacturing processes such as dry etch applications (70 – 100% of cases), there is an **unquantifiable time to invent** an alternative, followed by from **5 to more than 15 years** required.
- Invention of a PFAS-free thermal test fluid hasn't started and time to do this cannot be quantified. Once **invented**, it will take from **8 to more than 14 years** to implement and if the thermal test equipment needs redesign to accommodate the new method longer.

Most F-HTF uses involve closed but not hermetically sealed systems where fluorinated long-life seals and optimised equipment minimise evaporative losses during normal operation. Small amounts of emissions are expected from HTF loops during maintenance tasks such as changeout of parts that require replacement, from filling and draining, as well as from any leaks that may occur upon failure of the couplers, seals or gaskets used within the loop systems. Waste is typically collected during operation and end of equipment life for recovery and reuse or thermal destruction.

Heat transfer fluids can be differentiated into two categories based upon their manner of absorption or extraction of heat from the substances to be cooled or heated:

- **Fluorinated heat transfer fluids** (F-HTFs) are used within closed loop systems between specialised semiconductor manufacturing process modules and process equipment temperature control systems that require either heating or cooling to achieve temperature control across a very broad temperature range (-80°C to +125°C) within very tightly controlled setpoints.[54] HTFs remain

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[54] Reference: Tuma, P., & Tousignant, L. (2002). Reducing Emissions of PFC Heat Transfer Fluids. https://multimedia.3m.com/mws/media/122381O/reducing-emissions-of-pfc-heat-transfer-fluids.pdf

in liquid phase in most cases and cool or heat by exchanging heat through use of simple heat exchangers that are part of the closed loop system. Classes of F-HTFs include:

  - Perfluoropolyethers (PFPEs)
  - Perfluorocarbons (PFCs)
  - Hydrofluorocarbons (HFCs)
  - Hydrofluoroethers (HFEs)
  - Hydrofluoroolefins (HFOs)
  - Fluorinated Ketones
  - Other Fluorinated Liquids

- **Fluorinated refrigerants** are used in the refrigeration cycle of process equipment chillers and temperature control units to provide a heat sink often well below ambient temperatures (as low as –80°C). In most cases refrigerants undergo a repeated phase transition from a liquid to a gas and back again with the use of evaporators and condensers integrated into a hermetically sealed cooling loop. [55] Classes of fluorinated refrigerants currently in use within the process equipment chillers used and temperature control units, in support of semiconductor manufacturing include:
  - PFCs
  - HFCs
  - HFOs
  - Fluorinated Ketones
  - Other Fluorinated Liquids

Heat transfer fluids (F-HTFs) fulfil a number of different uses including[56]:

- Manufacturing processes where temperature setpoints must be maintained ranging from -60°C to 125°C and material must remain pumpable across this entire range. For most applications, only one stable temperature set point is required but this must be held within tight tolerances, such as +/- 0.1°C for dry etch, with corresponding cooling capacities of up to several kilowatts.
- Performance and thermal testing at various stages of the semiconductor devices development, to ensure device integrity and to test their ability to effectively operate within the finished electronic end products. Including:
  - Burn-in testing: Burn-in is a part of the end of line test done after package assembly. The part is placed in a socket and an electrical signal is applied to stress and heat up the part. The test is designed to find infancy failures, which are screened out and scrapped.
  - Thermal shock testing: Also known as hermetic seal testing. Parts are shocked at a cold or high temperature to simulate use conditions or shipping, or to accelerate failures that enable better understanding of the longevity of a part in expected use conditions.
  - Device reliability testing: Parts are cycled from low temperature to high temperature to simulate their use in the field, over tens to thousands of cycles. The HTF is required for this to take place in a temperature-controlled environment. Reliability testing is used to certify products for the lifetime use condition of multiple years, through a test protocol that can be achieved over a timeline of a few of weeks or months.

To support the complex requirements of semiconductor manufacturing, specific combinations of physical and chemical properties are required to be met simultaneously from the HTFs. The need to

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[55] ANSI/ASHRAE Standard 34-2019, Designation and Safety Classification of Refrigerants.

[56] https://www.epa.gov/sites/default/files/2016-02/documents/pfc_heat_tranfer_fluid_emission.pdf page 2

meet all requirements at once often requires selection of fluorinated heat transfer fluids, as similar capabilities are not found in non-PFAS alternative fluids. For example and as outlined in Table 7-1 below, certain dry etch processes, which require cooling of an electrostatic chuck very near an active plasma, will need an HTF that possesses a high boiling point, high thermal conductivity, and high resistivity in order to maintain the proper functioning of the wafer chuck, as well as the stability of the plasma. Similarly, an HTF that is used in semiconductor test applications, requires the following: a high boiling point, a low pour-point, low kinematic viscosity at low temperature and high specific heat to enable the test operational temperature range.

The following provides information on specific HTF applications.

Heat Transfer Fluid (F-HTFs) in Process Equipment Chillers: Temperature control for many semiconductor manufacturing steps is achieved through use of individual process equipment chillers which are roughly the size of a small home appliance and are part of the support equipment packages connected to each piece of semiconductor manufacturing equipment in a fab. Process equipment chillers pump HTF through the plumbing loops embedded in the process chambers to either remove or add heat to the system.

A semiconductor manufacturing facility may have well in excess of 1000 process equipment chillers all using PFAS F-HTF[57] which is circulated through the wafer mounts during the process. Through the years of development of semiconductor technology, it was necessary to replace water-based lower boiling point non-F-HTFs with higher boiling point F-HTFs. F-HTFs are capable of achieving all required performance requirements whilst avoiding the generation of imperfections that negatively impact the yield of the semiconductor manufacturing process. They also enable the determination of the appropriate functionality of the semiconductor devices within the conditions expected to be encountered within the end use applications. Part of the drive to convert to F-HTFs was their stability, inertness, reduced flammability risk, lower impact to manufacturing tooling and reduced requirement to replace materials during normal operation.

Dry etch manufacturing equipment: To meet precise temperature requirements within the manufacturing chamber, any alternative would need to avoid interfering with equipment performance or the manufacturing process, while maximising the lifetime of the manufacturing equipment. The process equipment side of the HTF loop usually has mechanical joints for maintenance of process equipment and formation of flammable vapour is possible under fault conditions. The electrical equipment and wiring within the process equipment may need to satisfy electrical design requirement for hazardous (classified) locations, such as NFPA 70.[58] Due to this the development of future non-PFAS utilising systems will likely require significant redesign timelines for development and implementation as outlined in Section 6.1.

Testing applications of semiconductor devices: Precision manufacturing processes necessitate the frequent use of test instrumentation to ensure that these processes are performing as required, and that the final semiconductor devices perform correctly and remain reliable across a range of environmental conditions. In some test applications it is necessary to electrically test a completed semiconductor device over varying conditions to assure that it can perform as required under different temperature conditions.

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[57] Taken from EPA publication “Uses and emissions of liquid pfc heat transfer fluids from the electronics sector” available at Uses and Air Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector | US EPA (1/11/2022)

[58] The US national electrical code, which is the benchmark for safe electrical design, installation, and inspection to protect people and property from electrical hazards.

Certain types of semiconductor device test applications also employ temperature stressing to assure that the different materials of construction are mechanically compatible.

Refrigerants within process equipment chillers: Process equipment chillers currently make use of fluorinated refrigerants within their compressor systems to act as a heat sink and as heat-transfer agents between the manufacturing process and the facility chiller system. Operation of process equipment at the operational temperature set points requires complementary capabilities between the F-HTF in the HTF loop and the refrigerant in the refrigerant cycle. The most critical performance requirement of the refrigerant is to enable the lowest operational setpoint, while avoiding a catastrophic phase shift to solid form (the refrigerant must remain in a gaseous or liquid form to remain pumpable and useful for temperature control). Other performance requirements which need to be optimised include the energy efficiency of the chiller, size of the equipment, and avoiding introducing new safety and worker exposure risks.

It is important to note that **no HTF remains in the finished semiconductor device**. In any case HTFs[42] have the benefits of being odourless, non-flammable, non-explosive, evaporate cleanly and exhibit very low toxicity based on current understanding, which results in easier safe usage and storage. Due to the demanding environments HTF operates in, only specifically tailored fluorinated compounds are able to offer the required performance in many of the applications and there are very few manufacturers of HTFs for semiconductor industry applications.

The following tables shows examples of both types of PFAS HTFs. This table does not exhaustively describe the whole Semiconductor industry as it is limited to information provided by the Semiconductor PFAS consortium members.

Table 7-1 Examples of HTFs utilising PFAS.

PFAS use area	Typical PFAS Used	Role of PFAS	Status of alternatives	Timeline to develop	Concern of alternative
F-HTF in process equipment chillers (except high energy dry etching)	3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6dodeca-fluoro-2-(trifluoromethyl)-hexane, Perfluoroalkanes, perfluoroethers and tertiary perfluoroamines,[59] Perfluorotributylamine, Hydrofluoroolefins[60] such as ethoxytridecafluoroheptene isomers: (Z)-1,1,1,4,4,4-Hexafluoro-2butene, Mixtures of perfluoro-polyethers (PFPEs)[61]	Suitable viscosity at lowest operating temperature, low dielectric constant that supports direct cooling of energised equipment by immersion, low vapour pressure, thermally stable, low toxicity, non-flammable, no affinity for hydrocarbon-based compounds, metal, and plastic compatibility.	In certain applications EG/DI combinations are being investigated.	Invention/Fundamental Research – 2-5+ years, Demonstration – 2 years, Integration – 2 years, HVM – 2-5 years. **Total** from **8 to more than 14 years.**	Materials compatibility and potential corrosion over time.
F-HTF in high energy dry etch manufacturing equipment	Ethoxy-nonafluorobutane CH$_2$FCF$_3$; HFC-134a; 1,1,1,2-tetrafluoroethane	Suitable viscosity (up to -80°C), low dielectric constants that support direct cooling of energised equipment by immersion, high volume resistance, thermally stable for operational temperature range (-50°C to +80°C) for long periods, chemical inertness, low vapour pressure, low toxicity, non-flammability, no affinity for hydrocarbon-based compounds, metal, and plastic compatibility.	Invention is needed for alternative.	Research – unknown, Demonstration – 2+ years; if unsuccessful, return to invention/fundamental research, Integration – 2+ years; if unsuccessful, equipment change may be required (additional 1 year + repeat integration), HVM – 2-5 years. **Total: Invention from 5 to more than 15 years.**	Dielectric property change may affect plasma conditions, which can require extensive process development for each application, followed by adjustment of process conditions. Possible design change of electrode assembly, the chiller and other critical parts of the process chamber may be required. For example, a high flammability alternative would require any equipment used in

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[59] Including 3M™ Novec™ 7XXX series Engineered Fluid range and 3M™ Fluorinert™ Electronic Liquid FC-3283/ FC-40/ FC-43/ FC-70/ FC-770/ FC-7000/ FC-7100/ FC-7200/ FC-7300/ FC-7700

[60] Sold as Chemours Opteon™ SF10.

[61] Including Solvay™ Galden™ range of HTF, including HT 80/ HT-110/ HT-135/ HT-170/ HT-200/ HT-270/ D02-TS, Solvay™ Fomblin™ 14/6 25/6, 16/6.

PFAS use area	Typical PFAS Used	Role of PFAS	Status of alternatives	Timeline to develop	Concern of alternative
					its proximity to meet specialised safety standards such as Class 1 division 2 under NFPA 70.
Testing applications of semiconductor devices	Perfluoroamine,[62] Perfluorotributylamine,[63] PFPE based testing fluids designed for specific test conditions[64]	Suitable viscosity (up to -40°C), low dielectric constants that support direct cooling of energised equipment by immersion, high volume resistance and its long-term stability, thermally stable for the entire operational temperature range (-40°C to +120°C), low toxicity, non-flammability, chemical inertness, low vapour pressure, no affinity for hydrocarbon-based compounds, metal, and plastic compatibility.	Invention is needed for alternative.	Invention/Fundamental Research – 2-5+ years, Demonstration – 2 years, Integration – 2 years, HVM – 2-5 years. **Total: from 8 to more than 14 years.**	Possible design change of tester head assembly, chiller and other critical parts of the process equipment may be required. For example, a high flammability alternative would require any equipment used in its proximity to meet specialised safety standards such as Class 1 division 2 under NFPA 70.
Refrigerants within process equipment chillers	C_2HF_5; HFC-125; Pentafluoroethane[65], CH_2FCF_3; HFC-134°; 1,1,1,2-tetrafluoroethane, $C_3H_3F_5$; HFC 245fa; Pentafluoropropane, R407C	Refrigeration capability that can cool the HTF by heat exchange to lower than -50°C with a cooling capacity of at least 7kW.	CO_2, NH_3 C_3H_8, and Feasibility studies of N_2 chillers required.	Invention/Fundamental Research – 2.5+ years, Demonstration – 2 years, Integration – 2 years, HVM – 2-5 years. **Total: from 8 to more than 14 years.**	CO_2 refrigerant chiller doesn't satisfy cooling capacity, as operational temperature is very close to the triple point. Therefore, a fluctuation of pressure control can result in vapor-solid phase transition (refrigeration failure). NH_3 is flammable and toxic, which requires containment

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[62] Such as 3M™ Fluorinert™ Electronic Liquid FC-3283.

[63] Such as 3M™ Fluorinert™ Electronic Liquid FC-43.

[64] Including , Galden® D02-TS, D02, D03, D05, 3M™ Novec™ 7500/7100 Engineered Fluid and Solvay Galden® PFPE HT-135.

[65] Such as Chemours FE-25™, Fike Ecaro-25®.

PFAS use area	Typical PFAS Used	Role of PFAS	Status of alternatives	Timeline to develop	Concern of alternative
					and exhaust abatement, so cannot be located near the production facility. It also is less efficient at temperatures below -30°C. C_3H_8 is flammable and inefficient at very low temperatures and again cannot be used near the production facility.

7.1 Alternatives

To date, no non-PFAS alternatives have been identified which can be used in dry etch and semiconductor test applications, due to the required performance characteristics of electrical non-conductivity, compatibility with all materials of construction (including sensitive electrical components), non-flammability, all within the operational range that is required for the manufacture and test of semiconductor products.

7.1.1 Alternatives to Liquid HTF

The most promising available non-fluorinated HTFs that have been considered for use in semiconductor manufacturing operations include synthetic hydrocarbon oils, silicone based HTFs and glycol ether and deionised water (EG/DI) combinations.

Synthetic Hydrocarbon Oils

Synthetic hydrocarbon oils have kinematic viscosity values that are much higher than the F-HTFs that are currently in use. This leads to an inability to maintain tight temperature tolerances at the upper operational temperature limit currently required. Residues of these HTFs can cause contamination of the fab environment, leading to a decreased process yield. Flashpoints are also much lower and have the potential to drive significant changes to equipment chiller designs owing to safety requirements.

Silicone-based HTFs

Silicone-based heat transfer fluids are inert and have many unique properties like extreme stability against thermal oxidation, low freezing points, wide operating temperatures, good dielectric strength, favourable environmental properties, and low toxicity. Whilst silicone-based fluids have many advantageous properties for use as an alternative HTF, they are non-viable for use in semiconductor manufacturing processes such as dry etch. This is due to their ability to cause catastrophic contamination issues when they vaporise or to result in residual deposits on surfaces which in turn contaminate the very sensitive processes associated with the semiconductor manufacture.[66] This issue has already been reported in other industries, which have needed to scrap parts that have become contaminated with silicone oil residues.[67] These accidental transfers, in the order of a few drops of fluid, are most likely to occur during the performance of certain maintenance activities like the changeout of replaceable parts connected to the chiller loop. If silicone oils were used to replace the current F-HTFs in dry etch applications, these accidental transfers could result in the need for extensive cleaning and significant downtime in order to complete chamber rebuilds and replace contaminated parts.

Ethylene Glycol and Deionised Water (EG/DI) Combinations

Mixtures of EG/DI are commonly used as HTFs within semiconductor applications. However, where F-HTFs are currently in use, they have been selected because EG/DI is not able to meet boiling point and pour point requirements to support the operational temperature ranges. In addition, EG/DI mixtures have been observed to exhibit a reduction in resistivity during use; this makes the control of the etch and deposition processes increasingly difficult. This can lead to a catastrophic interaction with the plasma or an electrical short circuit due to contact with the wafer chuck. Residues of EG/DI HTFs within the process chamber can cause contamination of the fab environment, leading to decreases in die yield. Use of these HTFs also requires special design considerations to avoid aggressive corrosion of the sensitive semiconductor manufacturing equipment.

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[66] https://www.rdworldonline.com/please-help-us-determine-the-source-of-the-silicone-contamination/

[67] The Removal of Silicone Contaminants from Spacecraft Hardware, 2002, https://apps.dtic.mil/sti/pdfs/ADA410311.pdf

Additional information on alternatives to liquid HTF can be found in the 'PFAS-Containing Heat Transfer Fluids (HTF) used in Semiconductor Manufacturing Whitepaper' outlined in Table 1-2.

7.1.2 Alternatives to Refrigerants

Process equipment chillers currently make use of fluorinated refrigerants within their compressor systems to act as a heat sink and as heat-transfer agents between the manufacturing process and the facility chiller system. Currently available non-fluorinated refrigerants include carbon dioxide and ammonia which have the following concerns:

- Limited operational ranges that do not meet the required operational temperature for dry etch and semiconductor test applications (–60^{o}C).
- Less energy efficient compared to PFAS refrigerants, and in order to provide a similar level of cooling, more chilling capacity would need to be installed, requiring significantly more space and higher energy consumption.
- Ammonia based refrigerant chillers are required by ANSI/ASHRAE Standard 34 safety classification rating of B_2L to be installed in a separate building with ammonia monitoring and other controls, such as a pressure relief valve and associated abatement.

Additional information on alternatives to liquid HTF can be found in the 'PFAS-Containing Heat Transfer Fluids (HTF) used in Semiconductor Manufacturing Whitepaper' outlined in Table 1-2.

7.2 Environmental Considerations for use of F-HTFs

F-HTF is bought by the semiconductor manufacturer when they install and commission the equipment and requires periodic replenishment. As designed, the F-HTFs used within the chiller and test equipment are contained with intent to minimise release during use and are accessed and maintained only by trained and/or certified technicians. Prior to the initiation of maintenance activities, the HTF contents of the chiller and associated equipment is drained into collection containers that are managed either for direct reuse, or for reclaim. If any HTF fluid is required to be managed as a waste, the fluid is incinerated at appropriately certified waste management facilities.

Small amounts of emissions are expected from HTF loops during normal operation of the chillers and heat exchangers, with the exact amount dependent on the process operating temperature. Emissions are also possible during maintenance tasks such as changeout of parts that require replacement, from filling and draining, as well as from any leaks that may occur upon failure of the couplings, seals or gaskets used within the loop systems. Due to the relatively high vapour pressure of the HTFs that are used in semiconductor manufacturing and testing applications, the HTF that escapes containment is released to the air. Overall, the industrial emissions of F-HTF are actively minimised to reduce greenhouse gas emissions and reduce manufacturing costs. Data from the US EPA on emissions across the electronics manufacturing industry from 2014-2021 shows that more than 70% of reporting facilities claimed less than 1 tonne per year of emissions, which is equivalent to less than 2 kilograms of F-HTF per year per piece of equipment (assuming 500 individual closed-loop systems per facility).

8 ASSEMBLY, TEST, PACKAGING AND SUBSTRATE MATERIALS USES

Summary: As packaging becomes more and more complex due to decreasing semiconductor device size, increased processing speed, and/or increased packaging complexity, the combination of material properties required to meeting these challenges are often only found in the fluorinated hydrocarbon family. Changes to assembly packaging materials range in their complexity, but unlike other uses due to their interface with both the silicon die and the end customer product, additional customer product change notification/ requalification processes need to be followed (minimum average product requalification is 1-2 years, with some applications such as aerospace, military, or automotive requiring 6+ years).

The following timelines are estimated to find or implement PFAS free alternatives:

- Packaging fluxes **more than 5 years,** to find and implement alternatives.
- Surfactants from **10 to more than 18 years**, to find and implement alternatives, with many suppliers being single source which may cause suppliers to exit the market.
- For a few older die attach adhesive applications alternatives can be expected in the very near future (1+ year). However, for most adhesives and encapsulants it is expected to take from **10 to more than 13 years** to find and implement alternatives.
- However, for the vast majority of package related uses of adhesives, in MEMS and Thermal Interface Materials System (TIMS), die overcoats, encapsulants and underfills, die passivation and substrate polymer there are no viable alternatives to the PFAS being used. For some of these technologies, alternatives have been sought for 18 years without success. For these uses it is likely that alternatives will take **more than 20 years** to find viable alternative chemistries or technologies and 6 years to implement.

There should be no release of PFAS during normal use of consumer or other end products, for those that include PFAS containing semiconductors. The concentrations of PFAS in assembly, testing, and packaging (ATPS) chemistries are low (parts per billion range) and any releases are anticipated to be minimal and only at the end of the product's useful life, during electronics recycling or disposal. Some of the electronic reclamation processes are thermal and may cause a break-down of PFAS, but this would require further investigation.

A semiconductor package encloses one or more semiconductor devices or integrated circuits protecting the device from the environment. The package connects the semiconductor to the printed circuit board (PCB), dissipates heat and provides protection from the surrounding environment particularly from moisture, shock/vibration, dust, etc. Semiconductor packaging is the process of assembling integrated circuits into final products, individual integrated circuit components are fabricated from semiconductor wafers, and these are then diced into integrated circuit die and tested.

Assembled packages go through multiple package types, to form three dimensional integrated circuits. Older technologies still use subsequent thermal and chemical steps to produce, therefore thermal and chemical stability in the assembled package are important. Semiconductor packaging technology evolves quickly and there are lots of different technology levels on the market at any one time, including dual in-line packaged assembly like wire bond ball-grid assembly and flip-chip technologies as illustrated schematically in Figure 8-1 and Figure 8-2.

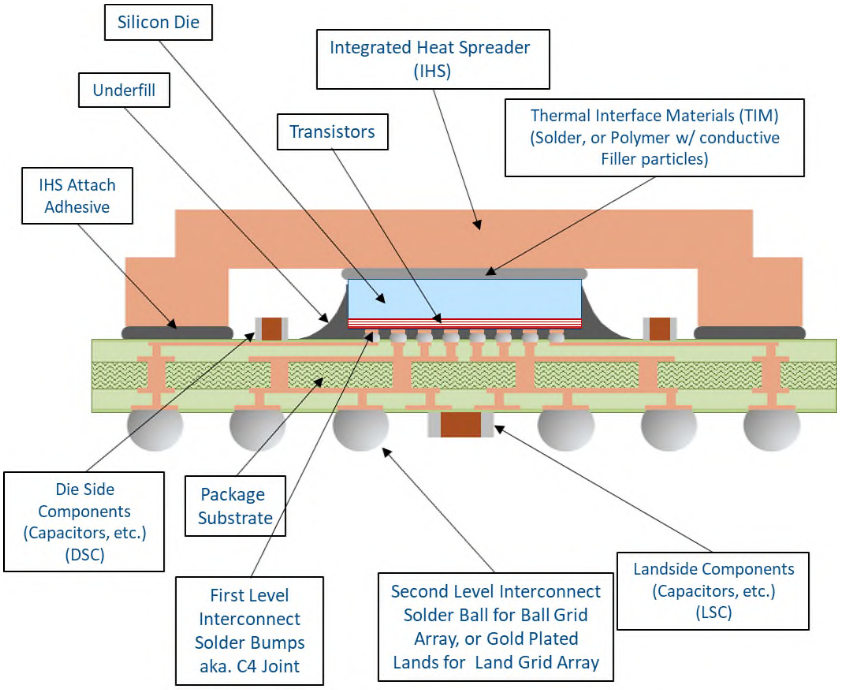


Figure 8-1 An example package, with many other configurations possible.

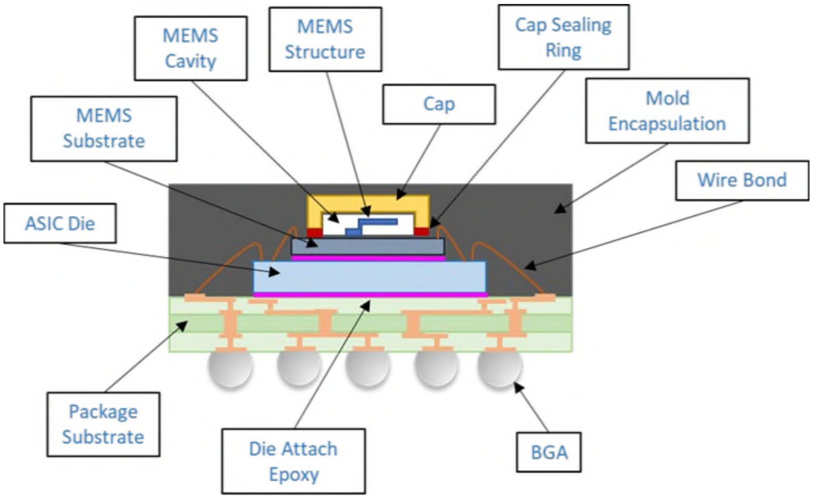
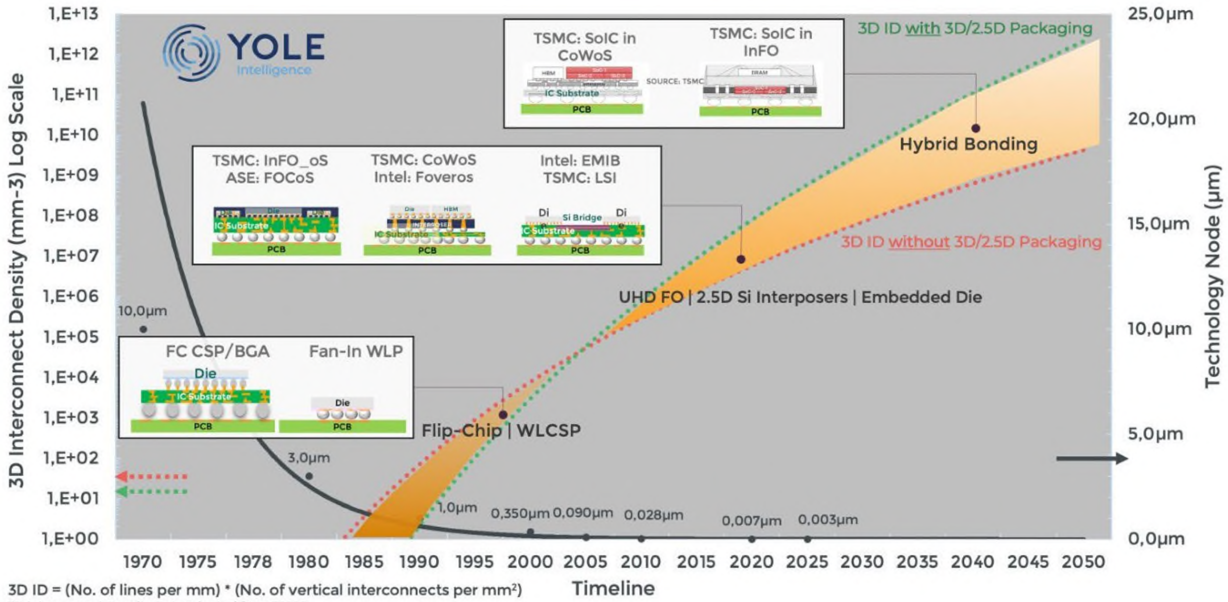


Figure 8-2 An example MEMS package.

Packaging has developed over time, as outlined in Figure 8-3 and Figure 8-4, with all of these packaging types still supported by current manufacturing practices.

SEMICONDUCTOR PACKAGING ROADMAP: COMBINED TIMELINE OF 3D INTERCONNECT DENSITY & TECHNOLOGY NODE

Source: Status of the Advanced Packaging Industry report, Yole Intelligence, 2022



3D ID = (No. of lines per mm) * (No. of vertical interconnects per mm²)
3D Interconnect Density Data adopted from TSMC
Technology Node here refers to front-end node and is based on the expected average value within the industry.

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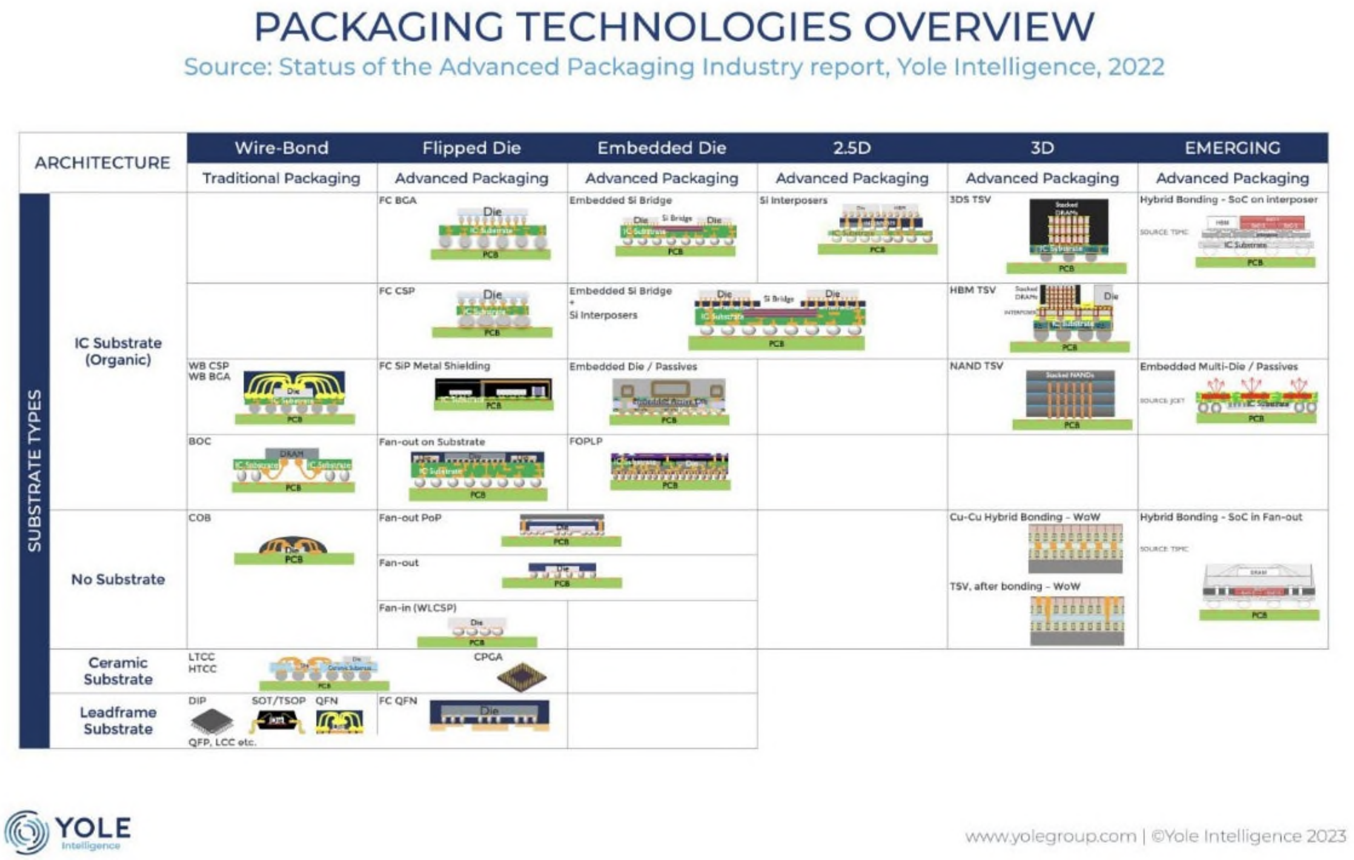
Figure 8-3 Timeline for the semiconductor packaging showing the complexity of packaging increasing over time.



PACKAGING TECHNOLOGIES OVERVIEW

Source: Status of the Advanced Packaging Industry report, Yole Intelligence, 2022

ARCHITECTURE		Wire-Bond	Flipped Die	Embedded Die	2.5D	3D	EMERGING
SUBSTRATE TYPES		Traditional Packaging	Advanced Packaging	Advanced Packaging	Advanced Packaging	Advanced Packaging	Advanced Packaging
	IC Substrate (Organic)		FC BGA	Embedded Si Bridge	Si Interposers	3DS TSV	Hybrid Bonding - SoC on interposer
			FC CSP	Embedded Si Bridge + Si Interposers		HBM TSV	
		WB CSP WB BGA	FC SiP Metal Shielding	Embedded Die / Passives		NAND TSV	Embedded Multi-Die / Passives
		BOC	Fan-out on Substrate	FOPLP			
	No Substrate	COB	Fan-out PoP			Cu-Cu Hybrid Bonding - WoW	Hybrid Bonding - SoC in Fan-out
			Fan-out			TSV, after bonding - WoW	
			Fan-in (WLCSP)				
	Ceramic Substrate	LTCC HTCC	CPGA				
	Leadframe Substrate	DIP SOT/TSOP QFN QFP, LCC etc.	FC QFN				

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Figure 8-4 Status of the Advanced Packaging Industry including multiple types of packaging and materials.

Assembly, Test, Packaging, and Substrate use PFAS in many applications, across multiple process steps, including:

- **Substrate polymers,** including core, build-up, or dielectric materials. These enable high speed signalling between components of a module or an assembly. This is turn enables specific functions within a larger completed package to be met, like on-chip memory, accelerators, controllers, and chip-to-chip interconnections. PFAS provide low dielectric constants, high thermostability, chemical inertness (to acids, bases, and solvents), and low moisture absorption, low electric permittivity / dielectric loss, low water absorption, and low coefficient of thermal expansion (CTE)[68]. These materials are required to be photo-imageable to meet the required high-resolution requirements for chip-to-chip interconnects, PFAS properties typically found in photolithographic chemistries are used and further discussed in Section 4.

  Core dielectrics currently use fully-imidized polyimide and polybenzoxazoles which have to have a pendant PFAS group on the polyimide backbone to be soluble in organic coating solvents. Without the presence of PFAS groups on the polyimide backbone, advances in semiconductor packaging technology will be delayed by decades or never materialise.

- **Assembly materials – coatings**
  - **Die overcoat / adhesive** to provide hermetic sealing for moisture sensitive applications and chemical resistance.
  - **Die attach adhesives** to attach silicon die to packaging substrates or leadframes, while helping to mitigate stress on the die and encapsulant. PFTE/PFAS in the epoxy anti- bleed out agent in die attach glue is important to control the amount of epoxy (adhesive) bleed beyond the peripherals of the die mounted to the frame/substrate.
- **Encapsulants** (hermetic or molding) to provide environmental and mechanical isolation via the following properties: heat conductivity due to a low CTE across a wide temperature range without a glass transition temperature. Electrically insulated, and hydrophobic to avoid void related failures.[69]
- **Underfills** to reduce stress on solder joints and increase the durability and longevity of the assembled package compared to an assembled package without underfill. Underfills must have high mechanical strength, low CTE and generally contain ~50% silica materials with the remainder being polymeric materials such as vinylidene fluoride-propylene hexafluoride copolymer and tetrafluoroethylene-propylene copolymer. The polymer must have high viscosity to ensure homogeneity and low volatility to minimise void formation. Surfactants utilising PFAS are also used to ensure compatibility of the additive with the resin system as well as helping to control resin bleed out.
- **Surfactants** used in defoaming or foam promotion, thin films and spin coating applications require surfactants to adjust the surface energy of the solution the surfactant is added to. They are also used in temporary bonding / mechanical debonding processes. Surfactants can play many rolls within a formulation, such as lowering surface tension, behave as wetting agents, foaming agents,

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[68] These properties are referred to in patents from the University of Electronic Science and Technology of China (CN107474312B), Jiangxi Tieno Technology Co Ltd (CN106604536B, Intel (US 11, 348,897 B2), and Taiwan Semiconductor Manufacturing Company Ltd (TSMC) (US 10,261,248 B2).

[69] A common failure mechanism for encapsulants is void creation caused when water absorbed by the encapsulant expands during heating caused by operation of the semiconductor, as demonstrated by: Thompson, Dane & Tentzeris, Manos & Papapolymerou, John. (2007). Experimental Analysis of the Water Absorption Effects on RF/mm-Wave Active/Passive Circuits Packaged in Multilayer Organic Substrates. Advanced Packaging, IEEE Transactions on. 30. 551 - 557. 10.1109/TADVP.2007.898637.

defoaming agents, or dispersants. Surfactants can be used to improve the coat quality of solution processed films. Surfactants can also be added to cleaning solutions including resist strippers and temporary adhesive cleans to improve the cleaning efficiency.

- **Temporary bonding / mechanical debonding**: an adhesive/release layer pair or single layer material (with appropriate bond strength) providing support to the wafer which is mechanically de-bonded after processing. The release layers for mechanical release typically have very low surface tension. Fluorinated polymers are one class of polymers which fit this description. After debonding the surfaces are cleaned, the cleaner may include a surfactant in its formulation.
- **Laser release layers:** either as a film or mold release sprays use PFAS such as PTFE or ETFE. These provide UV light sensitivity, thermal stability, aid in photoacid generation efficiency and the removal of the adhesive from the wafer or other piece cleanly.
- **Thermal interface material (TIM)** act as a heat conduit between the package (silicon die) and a heat spreader. Good coverage, consistency, and longevity of the material are necessary to withstand high temperatures and multiple thermal cycles.
- **Packaging of microelectromechanical systems (MEMs)** for surface energy modification of MEMS for anti-stiction purposes.
- **Packaging adhesives** (either thermal or UV curable) to improve adhesion between dielectrics and low roughness copper without having to resort to roughening surfaces which introduces low insertion loss. Types of adhesive include paste, film, or wafer.
- **Packaging fluxes** to assist with connecting the die to substrate, with different types of flux used depending on the joining technology in use. With PFAS used as a surfactant in ultra-low residue flux[70] and thermocompression bonding flip chip copper pillar joining, using a specialist copper pillar flip chip flux, but not ball—attach processes or pin attach processes where alternatives to PFAS are routinely used. PFAS-containing surfactants provide heat resistant, void solder resistance[71] and have wetting properties that control spread ensuring package reliability and yield.
- **Memory component packaging** may use PFAS processing steps listed in the manufacture of some products. Additionally, PFAS may be present in manufacturing equipment.
- **Die passivation** as part of the back end of line bumping process[72] in that the photo imageable dielectric is used both to help pattern the bumps and remain on the die to protect the interlayer dielectric (underlying electronics within a die).

As technology is moving to faster signal processing the use of PFAS components is expected to grow, as no other manufacturable material currently exists with the same electrical properties for dielectric constant and insertion loss.

Specifically, as the signalling frequency increases the conductor length becomes even more critical; higher losses require lower insertion loss materials. This is mainly because PCB conductor lengths are long and signal loss increases with longer travel distances. Fluorinated components offer best in class electrical properties for dielectric constant and insertion loss. It may also be the case that in certain packaging applications, where high speed signalling is needed on the core or on package architectures such as package on package or interposers where the material used is a glass reinforced epoxy matrix, PFAS containing components may be needed to mitigate the risk of signal loss.

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[70] As discussed by various patents including KR100985004B1 and IBM's DE2137329A1.

[71] As discussed in Arakawa Chemical Industries Ltd Patent CN101090797B.

[72] Solder bumps deposited on chips pads situated on the top side of a silicon wafer during the final wafer processing step.

8.1 Impact of change

Packaging materials have interactions with both the silicon die and the end customer product, so if substances are changed the following additional steps would be required:

1. Alternative process will require notification of change for each product for each customer. As the assembly process is the interaction between the fab and the end product, it is possible that there could be dies and passivation materials from multiple fabs or multiple motherboards and second level interconnect materials. This creates extensive complexity as a change in one assembly material could require testing across multiple silicon die vendors or multiple second level interconnect vendors/customers. Typical notifications require at least one year prior to any change, due to the contractual requirements and the necessity of the end customer to determine impacts within their processes and/or products, but certain market segments such as aerospace, military, and automotive could require longer change notification or more extensive testing.
2. In some applications, PFAS substances allow for reduced consumption of material (as in coating on a silicon wafer or other substrates). However, if increased volumes of material are needed this will increase cost/wafer and possibly increase waste.
3. In some applications, PFAS substances improve film coating uniformity when coated on a silicon wafer (or other substrates). If the alternative is not able to achieve the same level of uniformity, the process tolerance might suffer. Increased sample volumes may be required during testing or new processes may need to be developed. Ultimately this could lead to loss of yield and scrap.
4. New analytical methods may need to be developed to analyse the presence of alternatives. This will add cost and time to product development. It is also possible that new tooling or methodology developments, will also need to be added.

Table 8-1 indicates the status of alternatives for identified packaging uses and estimated timelines for the development of the alternatives.

Table 8-1 Examples of the packaging products utilising PFAS.

Substance	Function	Quantity	Status of alternative	Concern of alternative	Timeline to develop
PTFE (including versions FEP, PFA, AF, and PTFE 30	Main polymer substrate and build up dielectric material	>0.1%	Replacement known & viable for some formulations but not all. Alternatives are not available in cases where one or more of the functional quality characteristics is not met such as adhesion, dielectric constant, ability to process.	Lower dielectric characteristics, low Coefficient of thermal expansion, low electric permittivity / dielectric loss, and low water absorption. Quality, reliability, form, fit, function in some material changes. Hazards from alternatives.	10+ years depending on chosen replacement technology
Fluorinated-ethylene propylene	TIMs	<0.1%	No viable alternatives have been identified.	Tear resistance, high tensile strength + incorporation of highly thermally conductive fillers such as carbon nano tubes, metals, ceramics into different resin systems may require unique compatibility that only fluorinated-ethylene propylene has.	10+ years
Perfluoroalkyl Alcohols, Fluorine Resins	Additive fluxes	<0.1%	Replacement marketed by flux manufactures in 2020 which needs to be evaluated by manufacturers. After two years of research one candidate flux is now being tested by a chip packaging company, to see if it will perform adequately and has a sufficiently low failure rate.	Quality, reliability, thermal stability, wetting. Some flux alternatives are halogenated and so have other hazards which could prove to be **regrettable substitutions**.	4-5+ years
Fluorinated Pressure Sensitive Adhesives	Additive in adhesive	None as it is a processing aid and not included in the final product	Replacement known & viable for some formulations but not all, with more information outlined below this table.	Difficulties finding a surfactant with low surface energy performance. For one alternative: inadequate chemical resistance, thermal stability. For the other alternative there are the same concerns as well as inadequate photoactive properties.	10-13+ years depending on technical challenges.
Die overcoat / encapsulant		Unknown	No known viable alternative.		15+ years

Substance	Function	Quantity	Status of alternative	Concern of alternative	Timeline to develop
PFH_xA as per relevant dossier presented to ECHA by the European Semiconductor Industry Association 6th September 2021 or perfluoropolyethers	Anti-stiction purposes and surface energy modification in MEMS[73] device	<0.1%. <1kg/year of PFAS in products sold globally.	No known alternative	After >18 years of work, and >$30M, it was determined that non-PFAS alternatives do not exist that meet the performance requirements	20+ years
Adhesive (UV curable adhesives, die attach adhesives) containing PTFE	Surface energy modification in adhesives	<0.1%. <1kg/year of PFAS in products sold globally. In final component PFTE is estimated to range between 0.01 % and 1.4 %	No known alternative	After >18 years of work, and >$30M, it was determined that non-PFAS alternatives do not exist that meet the performance requirements: low dielectric constant; low dielectric loss; high adhesion too low roughness Cu pre and post stress testing [74]	10+ years
PTFE/ Polyvinylidene fluoride (PVDF)/ tooling and fixturing adhesive.	Die attach adhesive and Epoxy Anti Bleed Out agent	None as it is a processing aid and not included in the final product	Testing ongoing. Viable alternative available for all formulations	Time will be required to roll out the alternative technology to all tooling and fixturing uses.	8+ years to develop – 1 year remaining to implement
Trifluoroacetic anhydride in polyimide, polybenzoxazole, and other epoxy-based passivation	Die passivation	In final component the PFAS substance is estimated to be <500 ppm	No known alternative	Non-PFAS alternatives do not exist that meet the performance requirements (Thermal and chemical stability, photo imageable, dielectric, good wetting)	10+ years
Surfactant / defoaming agent		Unknown	Replacement may be possible & plan in place to evaluate	Quality, reliability, form, fit, function.	4+ years
Additive in defoaming agent-PFTE	Underfill	0.01%	Replacement possible, to start the detailed evaluation this year	Quality, reliability, form, fit, function.	4+ years

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[73] MEMs are made up of components between 1 and 100 micrometres in size and usually are made up of a central processor and several components that interact with the surroundings like microsensors. MEMS chips are often packaged together with an application-specific integrated circuit chip stacked together inside the plastic package, so that one package has the sensor and the circuitry, saving space and cost.

[74] A highly accelerated method of electronic component reliability testing using temperature and humidity as the environmental parameters.

Supply chains for some of the specialty chemicals that are of concern, such as low surface energy surfactants, are currently limited to typically just a few, or a single-source supplier, or the end-user actually makes these chemicals themselves. It is expected that once restrictions are in place that suppliers may stop making the intermediates necessary and/or the end product, or they may increase the cost to cover these more limited/restricted materials. For example, Semiconductor PFAS Consortium members purchase a commonly used surfactant, where over the past 10 years the demand from other industries has diminished such that the semi-conductor industry is now the sole user of this surfactant. Research and development efforts to replace the surfactant were not successful.

PTFE is an additive in some die attach adhesives to provide for added specificity in the polymerisation to perform the function of limiting the area of the flow of the adhesive or bleed control. These PTFE “Antibleed agents” control the amount of epoxy bleed beyond the peripherals of the die mounted to the leadframe/substrate. This is important to prevent spread of the epoxy to adjacent critical areas such as wirebond pads which will lead to product failures such as wire non-stick on pad, spread on die top resulting in prevention of mold compound adhesion and subsequent void and delamination on the package. The PTFE also promotes flatness of the die and uniform adhesive thickness. For some specific die attach adhesive applications in packaging, alternatives have been under investigation since 2014 and some appear to work and appear to be viable. For this specific application, the alternative is expected to be used in production in the near future (1 year +).

8.2 Environmental considerations for PFAS packaging materials

There is no foreseeable release of PFAS substances during normal use of consumable products or other end products. Moreover, the concentrations of PFAS in ATPS chemistries are low (parts per billion range) and any release is expected to minimal and only at the end of the product’s useful life. This release would occur only during electronics recycling or disposal. Some of the electronic reclamation processes are thermal and may cause a break-down of PFAS, but this would require further investigation.

There has not been a large-scale investigation in the waste streams across the assembly / test / packaging / substrate supply chain for the broad definition of PFAS that we are using within this paper. As most PFAS materials have not been regulated, there have not been the same tracking of PFAS molecules through manufacturing use to finished semiconductor products as there have been for other regulated or traced ATPS compounds. Further investigation and research in this area will be needed.

9 PUMP FLUIDS & LUBRICANTS USES

Summary: PFAS lubricants are critical for use in semiconductor manufacturing, and currently no viable alternatives are known to exist for many critical applications. As such it is expected that **more than 10 years** would be required to substitute PFAS lubricants in general applications and **more than 25 years** for lubricants used in photolithography.

Potential silicone-based alternatives have a high likelihood of being **unsuitable substitutions** due to the high likelihood for increased failure rates and inability to meet critical performance requirements, like inertness when used in harsh conditions and low off-gassing and particle generation when used in manufacturing areas and processes where maintaining the highest standards of cleanliness is of paramount importance. Also, a switch to a relatively more reactive alternative is likely to result in:

- Mechanical system and seal failures that affect **human health and safety** within the workplace, and environmental releases of toxic/dangerous chemicals from the manufacturing process.
- **Additional energy consumption** of the machinery they are used in would be required due to their decreased performance.
- Reduction in the lifetime of such lubricants so **increased raw material and processing energy** would be required to manufacture additional quantities of lubricants when compared to PFAS lubricant use.

Overall volume of PFAS lubricants used within the semiconductor manufacturing industry is small, with expected minimal impact to human health and safety, and minimal exposure to the environment through reuse, recycling, and proper waste management.

Any substitution effort would require significant resourcing over an extended and indeterminate amount of time, at significant expense that could impact the local (i.e., EU, US, and US States) semiconductor industry's global competitiveness. Some substitutions would require extensive redesign and retrofit of semiconductor manufacturing equipment to an extent that would be cost-prohibitive for semiconductor manufacturers.

Solid and liquid lubricants are used to reduce friction and wear between surfaces and as a sealant to prevent the ingress of foreign materials into the lubrication clearance zone. Semiconductor manufacturing requires high-performance lubricants, many of which are PFAS-based, to prevent the creation of particles within cleanrooms and the extreme physical environments present in the manufacturing environments, as well as remaining inert, non-off gassing, and UV stable. PFAS lubricants are critical for use in semiconductor manufacturing, and currently no viable alternatives are known to exist, alternatives such as silicon-based lubricants do not offer the necessary technical performance.

In many cases the lubricants are exposed to demanding environments for over 10 years, so long term reliability is key. The overall volume of PFAS lubricants used within the semiconductor manufacturing industry is small and no lubricant will ever be on the semiconductor chip. As such the expected environmental exposure is minimal due to lubricant reuse, recycling, and proper waste management.

9.1 Challenges with non-PFAS lubricants

It is important to keep in mind that PFPEs were introduced in semiconductor applications mainly because of safety reasons due to their stability and non-flammability. Any alternative would need to offer these same technical attributes, so as not to decrease the overall safety of these systems potentially causing safety incidents/explosions, injuries, and damage to manufacturing facilities. Specifically, non-PFAS lubricants generate more heat as the lubricant breaks down, which results in lost productivity via indirect routes of increased wear and loss of precision leading to increased defect rates. This has direct implications including reduced productivity and costs through machine downtime for maintenance, cleaning and relubrication activities and replacement of parts.

The production of semiconductors is undertaken in cleanrooms that are thousands of times cleaner than those used for manufacturing of medical devices. Due to this need and the high dimensional tolerances required, all moving mechanisms within manufacturing cleanrooms and within the semiconductor manufacturing equipment itself must be lubricated. Lubricants also ensure that maintenance intervals are minimised, and the lifetime of moving parts is extended to the maximum possible.

PFAS-based lubricants also have negligible evaporation loss which plays an important role in applications such as vacuum applications. Other PFAS-free alternative cannot offer such very low outgassing performance, which would lead to contamination of the semiconductor wafer during production processes and therefore a decrease in yield. In addition, the more an alternative outgasses, the shorter the lifetime of the grease due to its degradation and the increased heat generation and energy consumption. The biggest issue is the potential for generation of particles / contaminants. Any friction arising from insufficient lubrication causes particle generation, and this results in a reduced yield. Each stage in the process must be virtually perfect with yields above 99%, because there may be hundreds of process steps used to manufacture each advanced semiconductor device. Without those very high yields, semiconductor manufacturing would fail to produce functional and economically viable products.

Increased mechanical failures of moving parts, resulting in an increased need for maintenance and shorter lifetimes of semiconductor manufacturing equipment, and a need to update semiconductor manufacturing equipment designs to incorporate additional redundancy and allow access to removable parts. This is due to the fact that all known non-PFAS-containing alternatives would provide lesser performance than the PFAS-containing lubricants currently in use.

The following table provides an overview of PFAS-containing lubricants used in semiconductor manufacturing and support equipment, all of which would require more than **10 to more than 25 years** to develop a PFAS free alternative that meets all technical performance requirements.

Table 9-1 Examples of the products utilising PFAS lubricants.

Substance	Function	Status of alternative	Concern of alternative
PFPE Oil	Very low outgassing properties, and no outgassing of hydrocarbon compounds. Provides a viscous, hydrodynamic film that is sufficient to support the load and separate ball from the raceway in bearing applications, enabling high endurance performance.[75] Any lubricant used within the dry vacuum pump system may mix with the chemically reactive, oxidative process materials and/or corrosive process materials. UV stability for photolithography applications.	Currently, no non-PFAS-based oils and greases are known to be viable for use in dry vacuum pump applications. PFPE is the sole option to be used for the base oil of ferromagnetic fluid used in the ferromagnetic fluid sealed rotation feedthrough.	No known substitute, as all available substitutes are associated with lesser performance, including outgassing, chemical inertness, and thermal stability characteristics. Where PFPE greases are used the components are considered ‘lubricated for life’.

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[75] https://www.dupont.com/molykote/perfluoropolyether-pfpe.html/

Substance	Function	Status of alternative	Concern of alternative
PFPE with PTFE micropowders and/or thickeners, grease	Provides a viscous, hydrodynamic film that is sufficient to support the load and separate ball from the raceway in bearing applications, enabling high endurance performance. Any lubricant used within the dry vacuum pump system may mix with the chemically reactive, oxidative process materials and/or corrosive process materials. Robots for manufacturing use this grease to provide for immediate and accurate responses without jerkiness, as required for high precision, due to performance requirements that include excellent stability and absence of gum formation, a very low coefficient of friction.	The PTFE micropowder is a thickener for which there is no known substitute, as it is a self-lubricating solid that slides against each other with very little friction, without becoming a source of particulate contamination.	No known substitute
Multiple-alkylated cyclopentane based greases with PTFE thickener	Used to lubricate linear guides, slides and ball screws requiring low vapour pressure, non-flammability, and high stability.	No known substitute for PTFE as self-lubricating solids that slide against each other with very little friction/particle generation.	No known substitute
PTFE polymers and polymer plastics with PTFE additives	Solid lubricants utilised in pure polymer form, or additives in polymers and coatings or surface treatments that provide low friction coefficients in applications that require low particle generation, chemical inertness and high stability and excellent stick-slip characteristics	Currently no viable substitutes that have the ability to provide the required lubrication within the semiconductor applications that require use of these solids	No viable substitutes, as available solid lubricant alternatives require very dry conditions that are not provided within semiconductor manufacturing environments

The amount of any of the above listed substances in the manufacturing equipment is not known but estimated to be <0.1% w/w in most instances. In the worst-case applications such as ferromagnetic fluid sealing applications and certain dry vacuum pumps, there could be a maximum of 5% w/w in the manufacturing equipment.

The best potential PFAS-free alternatives are believed to be silicone-based oils and lubricants, however these have a limited temperature range when compared to PFAS alternatives, they are prone to off gassing, and have compatibility issues with some elastomers. As such, this is limited in the applications they can be used in. Silicone based alternatives also have the disadvantage of producing lens contamination in lithography as they decompose under UV irradiation and form a film on optical components particularly lenses. This leads to significant loss in optical transmission which severely lowers the productivity (by 10%) within a few weeks of use and increases the number of scrap wafers. Such a productivity loss has a negative impact to overall manufacturing production and reduces competitiveness in the global marketplace.

It is also worthwhile noting that D4-, D5-, and D6-ring siloxanes could be included in those silicones, which are classified as SVHC under the REACH Regulation due to their classification as Persistent, Bio accumulative and Toxic-substances. A change from PFAS-based lubricants to silicone might therefore be considered a **regrettable substitution**. Moreover, the increase in expected failures and the number of scheduled maintenance processes is likely to subject operators to a higher probability of exposure to the lubricant used.

As yet a PFAS-free viable alternative does not yet exist, and so a fundamental technology development would be needed in either the lubricant-containing equipment and/or lubricant itself. This is especially true of the lubricants used in photolithography as a fundamental change in the airborne molecular contamination load would be required. This change would require several years and significant expense to complete fundamental research, to qualify new designs, and to implement the use of non-PFAS lubricants. Once a promising alternative is invented/identified, the estimated timeline of qualification is expected to be at least 10 years but in the majority of applications 25+ years. For the more technically demanding applications, such as lubricants used in high vacuum applications with elevated temperatures, or reactive chemical/gas processes a fundamental technological development would need to occur within the advised timelines so there is some uncertainty with these estimates. It is possible that in some applications all PFAS-free alternatives will only offer reduced technical performance and increased environmental impacts and increased maintenance would always be observed if an alternative is used.

The overall mass quantity of PFAS-containing lubricants used within the semiconductor manufacturing process is very small. Semiconductor PFAS Consortium members estimate that on average 200ml of lubricant/oil per pump, and 100 g of grease per tool per year is used. However, this is not localised but rather virtually all contact points between moving parts make use of PFAS-containing lubricants and therefore the number of uses is estimated to be in the many tens of thousands within a semiconductor fabrication facility. Even if a number of these uses are less technically demanding and therefore a non-PFAS containing substitute may be possible, the reliability of such uses still needs to be ensured as it could result in catastrophic manufacturing losses.

The process of substituting lubricant would potentially require extensive cleaning with special solvents and the rebuild of up to 3000 pieces of complex machinery in each fabrication facility. It is also expected to significantly increase the requirement for maintenance activities, estimated to be a 3-fold increase or more.[76] As such, the resulting increase in waste would be expected to rise by a similar amount. Due to the increase in maintenance requirements, a higher proportion of down time for semiconductor manufacturing equipment is expected which against the backdrop of increasing demand would not be acceptable. The only way to maintain the same production volume would be to increase the quantity of production equipment and clean rooms, which in turn uses more energy, utilities etc. and the CO_2 emission per semiconductor device would then be higher.

9.2 Environmental Considerations in Lubricants

Liquid PFAS lubricants are only used in closed systems and do not need to be replenished as often as other lubricants as they are designed to be long-lasting. There are instances, such as PFPE greases where the lubricant does not need to be replaced throughout the life of the equipment. As such the potential exposures for most lubricants are limited to product damage, or at end-of-life.

There are some liquid lubricant uses which require changing periodically, with some being between 1-2 years but others only after 10 years+. During oil change, the liquids are pumped via a closed system into a tote/drum with negligible emissions. Liquid wastes are collected and sent for recycling. All PFAS

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[76] Based on estimations made by Semiconductor PFAS Consortium membership.

containing solid wastes involving lubricants are treated by incineration at specialist facilities capable of dealing with halogens and destroying PFAS.

Relative impact of alternatives

Based on the currently available alternatives discussed above, even in the limited applications where PFAS-free alternatives could be used, it is expected that **additional energy consumption** of the machinery they are used in would be required due to their decreased performance. There is also the consideration that the lifetime of such lubricants is also generally decreased, so **increased raw material and processing energy** would be required to manufacture additional quantities of lubricants when compared to PFAS lubricant use.

It is also worthwhile highlighting that thanks to their stability, all of the PFPE oils can be easily recycled and reused (reducing almost to zero emission into the environment). There are in fact readily available market options which provide a recycling service for PFAS pump oils, with progressive research into improvements in the quality of the recycled products.

10 ARTICLE USES

Summary: The PFAS substances most commonly present within articles used within the semiconductor industry are PVDF, PTFE, FKM, FFKM, PCTFE, ETFE, PFA, and PFA-CF.[77] As the number of applications that use fluoropolymer articles are myriad, a more detailed review is outlined in the PFAS Consortium whitepaper "PFAS-Containing Articles used in Semiconductor Manufacturing" outlined in Table 1-2.

The semiconductor manufacturing process is unique in several ways. It is making the smallest dimension objects ever attempted by humans, using some of the most exacting chemical processes to build features 5 nm (5 billionths of a meter) in "width". The feature size of device elements in turn demands the lowest possible organic, inorganic, metallic or particulate contamination from the environment in which wafers and devices are processed. Semiconductor manufacturing and related equipment (SMRE) is equipment used to manufacture, measure, assemble, or test semiconductor products. Many individual component parts in SMRE, facilities equipment, and infrastructure are dependent on PFAS-containing articles to provide the required cleanliness and purity; chemical & permeation resistance; compatibility; inertness; temperature stability; low coefficient of friction; non-flammability; optical, mechanical and electrical properties; processibility; and bacterial growth resistance to manufacture semiconductor devices as listed in Table 10-1.

For most uses, **invention is required to develop suitable replacement materials**. A timeline cannot be assigned to the invention process; however, once potential replacements are identified, some may take up to **15 years or more to evaluate**, demonstrate, qualify, and implement in the full supply chain. Applications such as transport of ozonated ultrapure water (UPW), tubing used to transport chemicals, fittings, O-rings, valve seals, process chambers and tanks, pump wetted parts, filters and scrubbers, and various applications in electronics all fit into this category as an alternative has not been invented which is suited to the use. It is not a given that non-PFAS alternatives that have all the salient properties of PFAS would be found.

This section covers known fluoropolymers present in articles required for semiconductor manufacturing which are components of SMRE and semiconductor manufacturing facility equipment and infrastructure. SMRE are enormously complicated with a large, international supply chain.

The current leading-edge photolithography exposure tool as shown in Figure 10-1, is described by Dario Gil, a senior vice president at IBM, as "…definitely the most complicated machine humans have built."[78] The EUV tool, manufactured by Dutch firm ASML, contains 100,000 parts and two kilometres of cabling. A single fabrication facility (fab) manufacturing leading edge chips has multiple EUV tools as well as dozens of deep UV exposure tools. There are challenges in identifying which components contain fluoropolymers as the information may be held within the supply chain of Consortium members which can be many layers deep. Consortium members are starting to obtain information from their supply chain, but the depth and complexity of the supply chain, and a lack of disclosure requirements, hinder information gathering.

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[77] Fluoroelastomers (FKM), perfluoroelastomers (FFKM), polychlorotrifluoroethylene (PCTFE), ethylene tetrafluoroethylene (ETFE), perfluoroalkoxy alkanes (PFA), and perfluoroalkoxyperfluoropropyl vinyl ether with carbon fibre filler (PFA-CF).

[78] The Tech Cold War's 'Most Complicated Machine' That's Out of China's Reach - The New York Times (nytimes.com)

Figure 10-1 ASML Latest Extreme Ultraviolet Photolithography Exposure Tool.[79]

Fluoropolymer and other PFAS-containing articles are found in a wide variety of articles used by the semiconductor industry for the manufacture of semiconductors, examples of which are listed in Table 10-1. A more detailed review is outlined in the PFAS Consortium whitepaper "PFAS-Containing Articles used in Semiconductor Manufacturing" outlined in Table 1-2.

10.1 Required Characteristics

Fluoropolymers have multiple useful characteristics, but it is the simultaneous achievement of these properties that makes these materials critical for the safe and efficient manufacture of semiconductors. The following is a list of fluoropolymer properties which are important for semiconductor manufacturing:

- Purity
- Chemical and permeation resistance
- Temperature stability
- Coefficient of friction
- Non-flammability
- Optical properties
- Mechanical properties
- Contamination control
- Electrical properties
- Processability
- Bacterial Growth Resistance

One example is the use of perfluoroelastomers in high performance fluoroelastomer seals in semiconductor manufacturing equipment in gaps between mating surfaces to prevent contamination. These polymers are required to be resistant to a broad range of chemicals and high temperatures, as many of the seals are exposed to O_2 plasma, fluorine (F_2) plasma and/or O_2/F_2 mix plasma at temperatures of 200°C and higher. Technological advancements in semiconductor device

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[79] Photo courtesy of ASML.

manufacturing have only been made possible by utilising these and other highly reactive species, often at high temperatures. Fluoroelastomer seals also do not outgas even at these conditions and equipment cleanliness is maintained. Seals such as these are only used where necessary as these technical characteristics come with an associated increase in cost when compared to non-PFAS alternatives. Fluoroelastomer seals also are necessary to maintain the vacuum within semiconductor manufacturing equipment, which ensures safe removal of harsh chemicals and worker protection. Therefore, any potential alternative needs to be able to operate in such an environment without degradation, erosion, or loss of elastomeric properties over a reasonable interval of time to be considered a realistic alternative. Very few polymers are able to operate in these environments.

Another example is the use of PFA and PTFE in chemical tanks used in wet cleans and wet etch processing equipment. The manufacture of integrated circuits requires contamination removal and surface preparation to enable high yields. Aggressive chemicals, sometimes at high temperature are used in wet cleaning and etching. PFA and PTFE are used because they do not react with the chemicals, do not leach contaminants that can negatively impact yield, and are stable under process conditions including elevated temperature. The material must be compatible with the continual exposure of aggressive chemicals and not contaminate the system with particles, metals, or dissolved organics, during the life of the equipment. PTFE may be used in tubing, valves, spray nozzles and other components that contact the chemicals to prevent contamination and ensure chemical compatibility. In addition, PFA tubing is highly flexible and can be easily bent and routed, making it easier to design and implement in wet etch processing equipment.

Fire/explosion, fluid leakage and critical service interruption are the primary threats to safe and continuous fab operations according to FM Global, a leading insurer of semiconductor facilities world-wide.[80] Fluoropolymers used to meet technical performance requirements such as chemical compatibility while also mitigating fire and release risks. SEMI S14[81] and FM 7-7 are used by the semiconductor industry to mitigate fire risk. These standards reference other standards such as FM4910 and UL 94 to assess smoke generation and/or fire propagation. Examples where fluoropolymers are used for technical performance requirements and fire protection include:

- Ultrapure water (UPW) piping and tubing
- Wet bench construction materials.
- Fluoropolymer insulated wire and cable.
- Fluoropolymer and fluoropolymer-coated ductwork.
- Ultra-high purity (UHP) chemical distribution
- Process liquid heating systems.
- Valve manifold boxes.
- Hazardous production chemical liquid storage.

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[80] As noted in FM7-7, “Fire and explosion hazards include combustible plastic construction materials (tools, ducts, and scrubbers)...”.

[81] SEMI S14 - Safety Guideline for Fire Risk Assessment and Mitigation for Semiconductor Manufacturing Equipment, S01400 - SEMI S14 - Safety Guideline for Fire Risk Assessment and Miti

Table 10-1 Examples of articles utilising PFAS where no alternatives have been identified to date.

Substance	Function	Concern of alternative[82]	Timeline to develop
PVDF	In Lithium batteries: provide a thermal and electrochemical stability as a barrier. Excellent electrochemical stability, good wettability with electrolyte and acceptable binding ability between active materials and current collectors.	Information should be sought from lithium battery manufacturers; expected concerns include chemical resistance, heat resistance, and non-flammability.	Unknown
PTFE	In bearings: provide lubricity, chemical resistance, thermal resistance.	Chemical resistance, heat resistance, and cleanliness.	Unknown
PFAs or PTFE	Wet cleans and etch processing equipment such as tubing and fittings, Purity via low particle shed, surface smoothness, chemical resistance, thermal resistance.	Whether they can be maintained and if they will gain the necessary safety approvals.	>15 years
FKM, FFKM and PTFE	In wire insulation, O-rings, valve seal, abatement seals, sealing tape: elasticity, chemical inertness, resistance properties against power, dampness, temperature, heat, UV, and corrosion.	Chemical resistance, heat resistance, and non-flammability.	>15 years
PVDF, PTFE, PFA	In chemical storage and transportation (tanks, pumps, pipes, seal, gaskets etc), ultra-pure water systems including pumps and filters provides purity via low particle shed, surface smoothness, and is chemically resistant.	Chemical resistance and cleanliness.	>15 years
PTFE	In exhaust abatement / scrubber: chemical inertness, non-flammable.	Chemical resistance and heat resistance.	>15 years
PTFE/PFA/PCTFE, ETFE, PFA-CF, PTFE/PFA/PVDF	In Chemical dispense arm/nozzle assembly, wafer spin chuck, wafer splash guard, reclaim tank, IPA tank, solvent supply/measuring tank, chemical mixing tank, air/liquid separation box chemical mixing box wafer handling and effector coatings, valves, control, switching, regulating monitoring systems low pressure chamber, robot hand, lifters piping, automated material handling systems wafer carriers, UPW & Chemical Filters/housings; Purity via low particle shed, surface smoothness, chemical resistance, thermal resistance, resistance to permeation of chemical resistance and gasses.	Reduced durability and component lifetimes resulting in a significant increase in waste.	5-15+ years depending on the application
PTFE	In potentiometer shims provides smooth motion. In potentiometer resistive inks: presumed to provide long term wear. In SMD tantalum capacitors provides a special mechanical/chemical barrier on the magnesium electrode. In liquid dielectric capacitors as dielectric films and electrolyte constituents provides long term chemical stability.	Information should be sought from potentiometer and capacitor manufacturers.	Unknown

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[82] Properties where it may be difficult to find an equivalent alternative, or factors that will increase development times, or possible consequences of an alternative.

If the technical characteristics of a proposed alternative do not strongly align with the PFAS substance it is intended to replace, the requalification time is anticipated to be much longer; moreover, the replacement may fail entirely.

10.2 Alternatives

The specific application of the article informs the necessary technical requirements, which in turn inform the viability of potential alternatives. The following are key themes relating to technical performance that alternatives need to meet:

- **Cleanliness:** Alternative materials must offer the same level of cleanliness with specifications such as SEMI F57[83] outlining requirements. For example, ultra-pure water (UPW) systems need to operate to demanding specifications which include metals <0.05ppb, low ion contaminants (>19 Mohm/cm resistivity), total organic carbon <1.0 ppb, dissolved oxygen of <5 ppb, low particulate matter with no particles greater in size than 0.2 microns, and <10 particles/ml of particles greater than 10 nm diameter. The historic move from PVC to PVDF to meet these criteria took 47 years to fully complete (1948-1995).
- **High chemical resistance** as otherwise this could lead to chemical leakage, chemical damage to equipment and in operating conditions pose safety concerns for workers. For example, replacing PFA and FFKM seals would require a redesign of the tool which would either need to include a seal, where this would be exposed to the plasma, or would need to shield the seal from plasma exposure.
- **Heat resistance** as otherwise this could lead to piping components melting or deforming, resulting in chemical leakage and fire, e.g., silicon rubber replacing PTFE gaskets in turbo pumps could result in failure due to decreased heat resistance.

Replacing with PFAS-free alternatives is often incredibly challenging as often potential alternatives require more frequent replacement. For example, data collected by Consortium members has highlighted that the degradation of O-rings consisting of PFAS- free alternatives is higher than the currently used PFAS material. The use of such alternatives would result in increased waste generation, equipment downtime, and maintenance worker exposure to potential hazards. There is also the environmental concern related to any failures of the materials in service, resulting in a higher likelihood of negative environmental impacts and worker exposure due to unplanned releases of process chemicals.

In order for PFAS-free alternatives to be incorporated in semiconductor equipment, and especially fabs, it is important that the initial qualification is undertaken by the many layers of the supply chain. Although there may be PFAS-free alternatives advertised, until they have been evaluated in semiconductor applications described in this report, they cannot be determined to be viable alternatives. Extensive test data would be required to understand the impacts of material changes on the safe use, degradation potential and useful life of any articles. Without the development timescales outlined in Table 10-1, there is a greater probability of an alternative material failing whilst in use, which could have serious health and safety implications. Alternatively, if the replacement part is for a key piece of equipment in the device manufacturing process, it could impede the availability of many thousand end-use devices (chips) per day.

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[83] F05700 - SEMI F57 - Specification for High Purity Polymer Materials an – semi.org

10.2.1 Examples of unsuccessful PFAS-free article trials

The following are some examples of PFAS-free alternatives that have been researched and evaluated but do not offer suitable performance in the applications in which they were assessed, grouped by the failure type.

Decreased Cleanliness

- Sulfuric acid container made from high-density polyethylene (HDPE) leached particles over time, resulting in wasted chemical and product failure. PFA/PTFE lined containers eliminated the leached particle issue.
- IPA container made from HDPE leached high molecular weight organics into IPA causing a process issue and contaminating the tubing and process chamber.
- Polyvinylchloride (PVC) has been shown to shed particles, so is not suitable for use in SMRE.[84]
- One of the major properties of fluoropolymers is their low outgassing, which contribute to the clean environment required during photolithography. Without PFAS materials impurities are deposited on mirrors used during the processing of semiconductors. Only fluor- and silicon-based materials are able to meet the critical requirements necessary for these applications.[85]

Increased Failure/Safety Concerns

- PVC filter housing for the dilution of copper water increased failures by a factor of 2.5. Changed to PFA and zero failure rate was achieved with removal of the risk of chemical spill and safety concerns for the workers.
- Stainless steel was used for level indicator of ammonia waste transmitters, but this had a high corrosion rate, resulting in the overflow of the tank due to failure of the component. The part was substituted by a PFAS, and the failure rate was greatly reduced.
- The design of piping system to deliver organic amines was trialled however PFA was the only material that showed compatibility with organic amines and achieved zero failure rate.
- HDPE was investigated as a possible replacement for PTFE in tanks, tubing, and containers, however after 6 months it was found to start decomposing in 70% nitric acid, which leads to chemical leakage and an increased replacement rate.
- Pulse dampeners using nitrile or EPDM (ethylene propylene diene monomer) elastomers failed because of chemical breaching the diaphragm. By using fluoropolymers, i.e., PTFE, PVDF or PFA in the diaphragm the failure rate has been zero, eliminating both a contamination and failure mechanism.
- Non-PFAS elastomers have been used as O-rings and seals, by mistake, within mechanical and chemical/gas delivery systems. In some cases, these seals failed almost immediately and caused leaks due to their incompatibility with the gases and chemistries running through the lines. This has resulted in the requirement to disassemble the system and replace the O-rings, result in >10 days of lost production time to replace and requalify the system.

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[84] Burkhart, Marty, Martin Bittner, Casey Williamson, and Andrea Ulrich, "A Scientific Look at Lab Quality Deionized Water Piping Materials", Ultrapure Water, Nov 2003, p 36-41.

[85] Based on information on outgassing complied by NASA in relation to O-rings and gaskets. Outgassing Data for Selecting Spacecraft Materials Online | Outgassing (nasa.gov)

Each of the above examples indicate that replacement can increase product safety risk and, more importantly, a risk to workers and the manufacturing facility. As such each use meets a safety need in production. For example, if the alternative non-PFAS substance used is combustible or does not have the appropriate heat resistance it will result in an unacceptable fire risk.

10.3 Environmental Considerations for Articles

Potential environmental impacts associated with articles occur primarily during the manufacture of raw materials, which is upstream of the semiconductor devices manufacture. There are also environmental impacts associated with the end of life of articles. Articles are reused and recycled when possible. In some instances, articles are contaminated during use with hazardous chemicals and, therefore, require management according to specific regulatory obligations. The industry will continue to act responsibly by taking advantage of circular economy opportunities as they arise.

11 ENVIRONMENTAL IMPACT, END OF LIFE AND WASTE CONSIDERATIONS

The semiconductor industry works to understand the environmental impact of its manufacturing process and employs wherever possible appropriate engineering controls, abatement, and treatment systems to minimise emissions. In addition, the semiconductor industry undertakes process optimisation to reduce the amount of waste generated and disposed of at a regulated waste disposal facility.

The semiconductor industry has implemented where possible control and treatment technologies to reduce emissions and discharges of chemicals, including PFAS, used in semiconductor manufacturing processes. Typical environmental releases include emissions to air and water and disposal of hazardous or non-hazardous waste. Some PFAS-containing materials are sent off-site for treatment, such as incineration, or disposal in regulated solid waste disposal facilities. Semiconductor manufacturing facilities also have on-site abatement systems for air emissions and wastewater pre-treatment or treatment systems prior to discharging wastewater. The semiconductor industry continues to actively identify, test, and implement wherever possible improved process controls that reduce PFAS releases to the environment.

11.1 Air Emissions Control and Abatement

Manufacturing facility exhaust systems are designed to remove chemical vapours or gases and heat from equipment. The use of PFCs and HFCs is essential for plasma etching, plasma cleaning, and other low volume but critical applications, as their uses balance the process need for high chemical and ion reactivity with the need for safe and effective manufacturing. The chemistries used in photolithography have relatively low vapour pressure and as outlined in Section 4.6 the quantities of emissions from photolithography are extremely small.

The semiconductor industry has a history of commitment to reducing greenhouse gases and has successfully reduced PFCs and HFCs emissions through a combination of process optimisation, substitution, and abatement. The use of POU technologies on many tools using PFCs and HFCs has reduced the potential hazard of exposure to employees and has reduced greenhouse gas emissions. With the implementation of WSC PFC best practices in new fabs - including remote plasma clean and POU abatement- many facilities have needed to expand other treatment systems, such as wastewater, fluoride, and exhaust to meet the required standards for wastewater and air toxics.

Some POU technologies use fuel-burning processes to abate PFCs and HFCs, creating additional nitrogen oxides, carbon monoxide, and other air pollutants from combustion in exchange for a reduction in PFCs and HFCs. It is therefore especially important that process and abatement alternatives undertake a full safety, health, and environmental impact review to understand additional implications to employee and community safety and health.

In addition, tool PFCs and HFCs, F-HTF are also a potential small source of PFAS emissions to air. The F-HTFs used within chillers and test equipment are contained with intent to minimise release during use. Prior to any maintenance activities, F-HTF in the equipment is drained into collection containers that are typically managed for direct use or reclaim at the location of the F-HTF supplier. If any of the F-HTF fluid is required to be managed as waste, the fluid is typically managed for destruction by incineration or thermal destruction by certified waste management facilities. However, during this activity it is possible that small quantities of the F-HTF can be released into the air.

11.2 Wastewater Treatment

Semiconductor manufacturing facilities generate organic and aqueous waste streams which are treated in accordance with local and federal waste and wastewater regulations. Historically, the majority of aqueous chemicals employed in fab manufacturing processes are discharged to an industrial wastewater drain system that conveys wastewater for treatment of specific regulated pollutants in accordance with local and federal regulations, and subsequently discharged to a publicly owned treatment works or surface water. Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS. The industry is actively researching PFAS wastewater releases and treatment technologies.

Conventional precipitation-coagulation-clarification treatment processes that are typically used to remove dissolved metals and fluoride from semiconductor wastewater would not be expected to exert a high removal efficiency for soluble PFAS. However, partitioning of some PFAS to the biological waste solids can be anticipated, and may represent a significant opportunity for PFAS migration in the treatment processes. In general, the state of technology for PFAS wastewater treatment is immature, with significant improvements needed to increase the number and types of PFAS that can be cost effectively removed from wastewater.

11.3 Waste Disposal

Organic waste, including organic liquids containing PFAS, is typically segregated, collected, and containerised to be treated at an offsite licensed treatment and disposal facility, as a blended fuel by high temperature incineration or reprocessing.

Liquid PFAS lubricants are only used in closed systems and do not need to be replenished as often as other lubricants as they are designed to be long-lasting. As such the potential exposures for most lubricants are limited to product damage, or at end-of-life. For lubricants requiring replenishment, during oil change, the liquids are pumped via a closed system into a collection container with negligible emissions. Typically, liquid PFAS lubricant wastes are collected and sent for recycling so are not expected to enter waste disposal streams.

For articles and packaging, there should be minimal or no release of PFAS during normal use of the end product containing semiconductors. At the end-of-life of the product containing the semiconductor, or any parts replaced during the manufacture of semiconductors, would enter waste disposal streams where any PFAS contained therein could enter the environment. Articles are reused and recycled when possible. In some instances, articles replaced during the manufacture of semiconductors are contaminated with hazardous chemicals and, therefore, require management according to specific regulatory obligations so would not enter general waste disposal streams.

11.4 Environmental Impacts of Non-PFAS Use

It is worthwhile noting that if PFAS-based materials are substituted, there are some broad potential adverse environmental implications which are as outlined:

- If alternatives **decrease yield** even by very small percentages significant increases are required in semiconductor manufacturing facility size resulting in correspondingly increased chemical, water, and energy consumption, as well as waste generation.
- **Decrease in PFAS-free alternative performance would increase the consumption of parts and waste generation** for some uses. For example, some PFAS-free articles have an increased risk of

release to air and water due to early article failure, increasing the number of leaks and the consumption of articles, as they need replacing more often. This loss of process integrity also results in process safety concerns due to loss of containment.

12 SUMMARY OF FINDINGS

RINA has undertaken a process of data collection and analysis based on a survey of Semiconductor PFAS Consortium members and subsequent discussion and technical feedback. The evidence provided can be summarised as follows.

PFAS are used in chemical formulations, components of manufacturing process tools, facilities infrastructure, and packaging used to make the semiconductor devices that are integral to the modern world. The current semiconductor state of the art is critically reliant on the use of PFAS chemistry owing to the particular properties that these substances provide to enable the extremely demanding performance requirements of semiconductor devices to be realised. **Given their unique properties, it is going to be extremely difficult, if not impossible in some instances, to find viable alternatives without stepping back decades in technological advancement.** There are also environmental impacts with not using PFAS, such as the potential for decrease in yield and therefore and increase in chemical, water, energy consumption and waste generation. In addition, there is the potential for the decrease in performance of some PFAS-free articles to result in increased waste.

The following highlights key uses of PFAS and the estimated time to identify PFAS-free alternatives in each area. More detailed technical information can be found in the respective white papers and case study reports written by the Semiconductor PFAS Consortium (listed in Table 1-2).

- **Photolithography** – PFAS has been an enabling technology in the development of ever smaller semiconductors through cutting edge lithographic developments. PFAS are used in multiple processing steps including photoacid generators (PAG), antireflective coatings (TARCS), surfactants, and barrier layers. For each use type, there are significant technical challenges, many of which will require a new technological development to enable any alternatives to even be potentially viable.

  All successfully demonstrated PAGs are fluorinated and there are no universally applicable viable fluorine free alternatives for a vast array of lithographic materials. Current PAGs have been in development for 25 years, and alternatives are expected to take from **15 to more than 20 years** to reach production.

  TARCs previously used PFOS and PFOA, which industry moved away from to shorter chain PFAS when regulators identified them as a safer alternative. A high fluorine content is needed to achieve the low refractive index required for TARCs to work, so an **alternative solution needs to be identified**, after which qualification activities can start.

  There is a similar need for the invention of new materials offering the necessary technical parameters for immersion barriers and dielectric materials.

  It may be possible to find non-PFAS alternatives for less advanced surfactant applications using current known potential alternatives, however, for most advanced applications, a new material would need to be invented to meet the necessary technical requirements.

  Although each PFAS use has its own challenges and timelines for development, most uses are expected to take between from **10 to more than 13 years** to develop and qualify a PFAS-free alternative, with the exception of PAG's.

  Alternative solutions will not only have to offer highly demanding technical performance for their intended use, but also not affect subsequent processing steps. A further complicating consideration is that a one-for-one replacement in many of the PFAS uses is not deemed to be technically viable due to the changing technological challenges as the node size decreases. As such, qualification activities are likely to be limited to certain node sizes, with particular challenges at the smaller node sizes.

- **Wet Chemistry** – There are application-specific performance requirements, which may be product or company specific and essential applications which are not universally used by all manufacturers, fabs or products. PFAS are used in several types of formulations of photodevelopers, and etchants, at different steps in the semiconductor manufacturing process. The timeline needed to develop, qualify, and implement alternatives falls into the following four broad categories:
    - **3 to 4 years**: If an existing non-PFAS alternative is available and can be demonstrated to provide adequate performance for a specific application.
    - **3 to more than 15 years**: In some applications where existing non-PFAS alternative may be viable but requires tooling and/or process changes before it can be successfully introduced into HVM.
    - **Successful invention required (from 5 to more than 25 years**): where the invention of new chemicals, and/or development of alternative approaches to manufacturing the device are required, with no guarantee of success.
    - **No alternative achievable**: In some cases, it may ultimately be found that a non-PFAS alternative is not capable of providing the required chemical function and therefore an alternative semiconductor device structure would be required.
- **Fluorocarbon uses in plasma (or “dry”) etch / wafer clean and deposition**– PFC and HFC are used in plasma (or dry) etch/wafer clean, deposition chamber clean, and organometallic precursors and cannot be substituted as extreme cleanliness is necessary to anisotropically etch features without damage. PFC and HFC emission reductions have been a committed goal of the semiconductor industry for over 30 years. However, cutting-edge semiconductor technology only exists because of the unique properties of these gases to perform specifically as intended in this environment. **Fundamental changes in semiconductor materials, device design and manufacturing processes are required for alternatives to be feasible. For the vast majority of uses 10-15 years after invention of new semiconductor materials, designs and processes** would be required to substitute **for each specific type** of PFC and HFC use.
- **Heat Transfer Fluids (HTF)** - Fluorinated HTFs are used as liquid fluorinated heat transfer fluids (F-HTFs) and fluorinated refrigerants which are used in tandem within HTF loops and refrigerant cycles to meet operational temperature requirements in semiconductor manufacturing processes like dry etch, thin film deposition and semiconductor device test applications. Similarly performing non-PFAS do not exist for most heat-transfer applications, due to differing working temperature ranges, viscosity, and dielectric properties.

  There are some PFAS-free HTF, such as glycol / water alternatives which can be used in a limited number of applications. However, it would require from **8 to more than 14 years** to substitute due to the need for equipment redesigns to ensure the ongoing safety of equipment making use of the HTF. A similar timeline from **8 to more than 14 years** is also required for the substitution of refrigerants within process equipment chillers. For over 70% of applications there is no currently viable alternative, so **an alternative would need to be invented**, after which from **5 to more than 15 years** would be required to implement this and ramp up to HVM.

  There are very few companies which manufacture thermal test fluids, which are manufactured to extremely high specifications. Invention of a PFAS-free thermal test method has not started and the time to do this cannot be quantified. However once invented, it will take from **8 to more than 14 years** to implement, or considerably longer if the thermal test equipment needs redesign to accommodate the new method.

- **Assembly, Test, & Packaging Materials** - As packaging becomes more and more complex due to decreased size, increased processing speed, and/or increased packaging complexity, the combination of properties required are often only found in the fluorinated hydrocarbon family. Changes to assembly package materials range in their complexity, but unlike other uses, due to their interactions with both the silicon die and the end customer product, additional customer product change notification/approval steps are required (average 1-2 years, with some applications requiring 6+ years). The following timelines are estimated to implement PFAS free alternatives: **Packaging fluxes 5+ years**, **surfactants 18+ years**, with many suppliers being single source which may cause suppliers to exit the market, **encapsulants 13**+ **years**, and **adhesives and certain MEMS anti-stiction agents 20+ years** as alternatives have been sought for 18 years without success.

  It is important to keep in mind that the use of PFAS underpins fast signal processing requirements, so the need for PFAS components is expected to grow to limit signal losses; so additional PFAS uses are expected to be required to enable key technology developments within the semiconductor industry.

- **Pump Fluids & Lubricants** - PFAS lubricants are critical for use in semiconductor manufacturing, and currently no viable alternatives are known to exist. As such it is expected that **more than 10 years** would be required to substitute PFAS lubricants in general applications and **more than 25 years** for lubricants used in photolithography. Potential silicon-based alternatives have a high likelihood for increased failure rates and an inability to meet critical performance requirements, like inertness when used in harsh conditions and low off-gassing and particle generation when used in clean manufacturing environments. A more reactive lubricant is also likely to result in system and seal failures, ultimately resulting in health and environmental impacts as a result of, increased energy consumption of the machinery, and the more frequent replacement of the lubricant.

- **Articles** - Very many individual component parts in semiconductor manufacturing equipment are dependent on these substances to provide the compatible, inert, clean, temperature tolerant environment needed for the fluids used in the equipment. Fluoropolymer articles are key in supporting billion-dollar EUV semiconductor lithography machinery, plasma chambers, ultra-pure water system piping, and the multitude of electronic equipment and tools that support a manufacturing facility.

  Alternatives typically take **more than 15 years** to substitute, and it is not guaranteed that a non-PFAS alternative will be able to offer all the salient properties of PFAS.

It is worthwhile noting that the timelines outlined above have a significant degree of uncertainty. For many of the substances there are no alternative theoretical material chemistries to use as a basis for invention and a whole new area of chemistry and/or technology will be required. There are also concerns that a change process as large as designing out all PFAS has never taken place and the timelines are based on the time to undertake a single change. As highlighted above, there may be interactions between multiple stages in processing which will need to be explored. There will also be limitations on how many suitably knowledgeable people are available given the magnitude and complexity of the task at hand. As such, the timelines could easily be much longer than those estimated.

The semiconductor industry has, where possible, implemented control and treatment technologies to reduce emissions and discharges of chemicals, including PFAS, used in semiconductor manufacturing processes. Typical environmental releases include emissions to air and water and disposal of hazardous or non-hazardous waste. Some PFAS-containing materials are sent off-site for treatment, such as incineration, or disposal in regulated solid waste disposal facilities. Semiconductor manufacturing facilities also have on-site abatement systems for air emissions and wastewater pre-treatment or treatment systems prior to discharging wastewater. In addition, the semiconductor industry undertakes process optimisation to reduce the amount of waste generated and disposed of at a regulated waste disposal facility.

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Sent: Tuesday, October 31, 2023 5:26:16 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
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Subject: Micron DEIS Scoping Comments

To: OCIDA

On behalf of the following individuals and myself working together as the CNY Sustainability Coalition, and who have signed the attached memorandum on behalf of our respective organizations, I am submitting the attached comments and supporting 4 attachments (A1-A4) pursuant to the public comment period for the Micron project SEQRA DEIS scoping. Please do not hesitate to contact me if you have any questions. Thank you for the opportunity to comment on this important document and for allowing an extension of time for filing this.

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Thank you again. We look forward to working with you as this project moves forward.

John Przepiora

Vice-President & Director

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…Advocating for sustainable communities

to the benefit of local economies and environments.

To: Onondaga County Industrial Development Agency (OCIDA)

From: The undersigned individuals and representatives of environmental and sustainability organizations of Central New York, aka, “CNY Sustainability Coalition”

RE: Comments on the **DRAFT SEQRA SCOPE OF WORK (**draft Scoping Document or draft scope**),** dated September 12, 2023 for the proposed **MICRON SEMICONDUCTOR FABRICATION plant in** Clay, NY.

The SEQR Handbook, 4th Edition, dated 2020, states: “A written scope of issues developed through a public scoping process benefits the lead agency and the sponsor by providing explicit guidance as to what criteria will be used to determine whether a submitted draft EIS is adequate. The written scope provides a means of ensuring that significant topics have not been missed and that the level of analysis in the EIS satisfies standards established during the scoping process.”

While the draft Scoping Document offers a reasonable approach to defining significant environmental impacts in certain areas, we believe it is inadequate in other areas, especially ith respect to chemicals and energy usage. We offer the following comments:"

4.3 ALTERNATIVES TO BE ANALYZED IN THE DEIS

The SEQR Handbook stipulates (p 100) the scoping process should “Define reasonable alternatives for avoiding specific impacts which must be included in the EIS, either as individual scenarios or a range of alternatives.”

Two “build” alternatives are presented in the draft scope:

1) Full construction and operation of four fabs over an approximately 20-year period
2) Reduced Scale: construction and operation of two fabs over a shorter period.

This analysis is too limited. It does not address a proper range of alternatives. For example, the impacts on Greenhouse Gas Emissions and Climate Change will vary tremendously depending on the amount of renewable energy that Micron is able to procure. Micron has expressed a desire to achieve 100% renewable energy for electricity, but that may be unrealistic for the construction timeframes that are envisioned. Micron’s electricity demands are projected to be very large (7.15 billion kWh/year for Phase 1; 16.17 billion kWh/year for Phase 2), so it would be far more realistic to evaluate a range of alternatives which take into account the time needed to construct a supply of renewable energy sources (wind, solar, and hydropower). The evaluation must assess the feasibility of achieving 100% of electricity from renewable sources for each Phase of the project.

It has been estimated (Plumley, pers. communication) that it would take 1200 3MW wind turbines to generate the power needed for Phase 2.

It would also be useful to consider alternatives with different phasing such as construction of a single fab followed by a reassessment of impacts prior to construction of a second fab. In a

multi-phase approach, lengthening the time frame may be an appropriate way to manage the community impacts while allowing for the potential for technological changes that may affect chip fabrication or building and/or transportation improvements which may reduce impacts. A long term approach may allow the community to adjust to the growth and assimilate it with less adversity.

5 ANALYSIS FRAMEWORK

Preparation of the DEIS must conform to 6 NYCRR Part 617.9(b). The DEC's SEQR Handbook asserts that "An Environmental Impact Statement (EIS) is a document that impartially analyzes the full range of potential significant adverse environmental impacts of a proposed action and how those impacts can be avoided or minimized."

Section 5.1 of the draft scope states: "The Proposed Project will be evaluated for potential significant adverse effects to the Project Site and **applicable study areas** for all relevant environmental technical categories in accordance with applicable SEQRA requirements."

'Applicable study areas' is a vague phrase which needs to be better defined specifically in an overarching, comprehensive manner. Answers to questions are directly related to the question asked; asking the wrong question leads to wrong answers. We recognize that each of the sub-sections in 5.3.1 may define study area specific to the particular analysis and that may be appropriate, however, we believe that the final scope document should include a stand alone section devoted to defining the study area clearly in order to convey the breadth with which the impacts of this project will be manifest and establish the full areal extent of the analytical framework.

This project requires an ecosystem approach that considers the regional impacts on the environment, the economy and society. The impacts must be determined and assessed for their equitable distribution and for their adverse impacts that are detrimental to the region's short and long term sustainability. This is not a typical project. It is enormous in scale, unprecedented for the region and with potential for egregious environmental impacts. It has been suggested by Onondaga county officials that the Onondaga County population may increase by 25% or 125,000 over the full build-out period (estimates of regional growth are unknown to this reviewer). The scale of the environmental review process, and the expertise required to carry it out, must rival the project's enormity.

OCIDA must assure that the final scope for each of the technical sections of the DEIS is specified with rigor, that the appropriate and necessary expertise is utilized in the writing of each scope item, that the study areas are broad enough and that each analysis is based on not only the current standards, but also reasonably presumed standards that will be in force throughout the build out and operational period of the proposed project.

Finally, The SEQR Handbook requires the following in the scoping of the identified reasonably expected impacts:

- Describe the extent and quality of information needed;
- List available sources of information;
- Specify study methods or models to be used to generate new information, including criteria or assumptions underlying any models, and define nature and presentation of the data to be generated by those studies and models.

In many of the areas included in section 5.3 the standards for information and methods appear to be inadequate. The scoping document must require high standards be applied to the analysis and specify information and methods to be utilized. To do less shortchanges the community and can lead to disastrous and unanticipated consequences.

The biggest challenge presented by this project is the enormity of it; in order to fulfill the dreams which this project offers in a just, equitable, economically and environmentally sustainable manner, the review process must be equally enormous, impartial and thorough.

5.3 **METHODOLOGIES FOR TECHNICAL ANALYSES**

Comments on specific sections are listed below.

Many of the methodologies outlined in Chapter 5, Analysis Framework, are very comprehensive and appropriate for a project of this size. We fully support the inclusion of each of these categories. However, we have noted certain areas where the level of detail and intent seems inadequate as follows.

5.3.1 TECHNICAL STUDIES

- LAND USE, ZONING, AND PUBLIC POLICY

  COMMENT: Why isn’t the city of Syracuse explicitly included here? Seems to be a major omission.

- COMMUNITY FACILITIES/OPEN SPACE AND RECREATION

  COMMENT: Here is an assessment of impacts on community emergency services, fire safety requirements included in building code and site access requirements of the emergency service providers.

  Lumped in is assessment of growth impacts on educational facilities and parks and recreational facilities. The study area seems ill defined and critical to this analysis. Some reference to Towns of Clay and Cicero seems to limit the study area to these two towns; is that what is intended? If so, it is probably too narrow an area particularly when the cumulative and indirect impacts are considered.

  This section is poorly organized and deserves to be rewritten to define more clearly what are the parameters to be studied and analyzed relevant to police, fire and other emergency services; schools; parks and rec facilities. Absent from the community facilities most notably is the health care and hospital system.

- SOCIO-ECONOMIC CONDITIONS

  COMMENT: The study area is defined better here and seems appropriate. It is necessary to assess the way benefits and adverse impacts are distributed. There is no specified time horizon for this analysis and little specificity regarding the analytical standards, tools and techniques that will be employed. If OCIDA is ill equipped to specify generally accepted standards for such an analysis it is incumbent tha OCIDA obtain the expertise required to specify how this must be done.

- VISUAL IMPACTS AND COMMUNITY CHARACTER

  COMMENT: This project has the potential to significantly alter the character of the community—not only the locale surrounding the immediate project location, but the wider Syracuse and Onondaga County as well as portions of Oswego County as population growth and housing development is induced. The DEIS should include an analysis of the potential for growth-induced changes in the community that this project will induce.

- GEOLOGY, SOILS, AND TOPOGRAPHY

  COMMENT: Reference is made to 'property survey' as a data source but later the 'geotechnical investigation' is mentioned but not included in the sentence describing the analysis. Is this an oversight that should be corrected? Certainly the geotechnical survey will provide valuable information to confirm or modify the USGS soil survey data.

- NATURAL RESOURCES

  COMMENT: This seems to prioritize wildlife and overlook the categorization of existing vegetation. Is that what is intended? The EAF mentioned the undertaking of detailed field studies of land coverage and natural resource conditions on or near the Micron Campus. Will a detailed land cover field study be done? It should be included.

  Little detail is included about the hydrology and wetlands evaluations that will be necessary. Standards, tools and analytical techniques required to be employed must be specified. If OCIDA lacks the expertise to properly specify this analysis they must obtain that expertise from involved agencies or consultants that can properly specify the scope and requirements of this work.

- SOLID WASTE & HAZARDOUS MATERIALS

  "This analysis will describe the proposed generation of solid waste by the Proposed Project and how that material will be handled, stored, and transported. This analysis will describe Micron's proposed measures to reduce generation of solid waste through reuse or recycling."

  COMMENT: It is appropriate for Micron to identify the quantities and types of solid waste that are likely to be generated at their facilities. The applicant estimates the generation of 45,000 tons per year of solid waste, which represents an additional 15% of waste generated in Onondaga County. All solid waste in Onondaga County is burned in an incinerator. What impacts will the solid wastes disposed of through the OCRRA system have on air quality? The fiscal implications for the OCRRA must also be assessed. The indirect, long term and cumulative impacts of the use and disposal of both solid and hazardous waste materials must be included in the analysis.

  The applicant is proposing to take measures to reduce the generation of solid waste. What is under consideration?
  Strangely, the same level of investigation is not described for hazardous wastes, which constitute a far greater threat to employees, the community, and the environment.

The text reads that the DEIS “will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect against releases to the environment.”

It is imperative that the DEIS identify ways to reduce and eliminate the generation of hazardous waste through reuse and recycling. Hazardous waste is best eliminated by using non-hazardous substances in the fabrication process. In the event that hazardous substances must be used in the fabrication process, methods to completely contain those substances, and/or ultimately destroy them, must be considered.

Of particular concern are perfluorinated alkyl substances (PFAS), otherwise known as “forever” chemicals because of their long lifetimes in the environment and in organisms. These chemicals are of great concern due to their high levels of toxicity. The semiconductor industry uses PFAS extensively (Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P) The DEIS must address the use of these chemicals and alternative chemicals that could be used as substitutes.

The attached memorandum from Lenny Siegel, Center for Public Environmental Oversight, provides additional details regarding the problems posed by PFAS and other hazardous chemicals. The authors of a recent paper on use of PFAS in the semiconductor industry note that: “ the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in ***strong resistance toward physical, chemical, and biological degradation***. Due to this strong resistance to degradation, PFAS compounds in general ***are extremely stable in the environment.*** In addition, such compounds have been found to be bioaccumulative. Extensive literature exists describing the detection of a number of PFAS compounds in drinking water.” (emphasis added) The authors also note “there is a strong societal interest in eliminating their use, and “essential use” is a stopgap situation in which replacements are actively sought.” https://www.spiedigitallibrary.org/journals/journal-of-micro-nanopatterning-materials-and-metrology/volume-21/issue-01/010901/Review-of-essential-use-of-fluorochemicals-in-lithographic-patterning-and/10.1117/1.JMM.21.1.010901.full?SSO=1

Enhesa (formerly Chemical Watch) is an industry trade organization that provides regulatory guidance to industry. They note that: “The use of PFAS is a major focus for regulatory authorities worldwide right now. In Europe, the REACH restriction proposal aims to place limits on all uses of more than 10,000 per- and polyfluoroalkyl substances. Meanwhile, in the US, restrictions are high on the agenda in several states.

In late September 2023 the European Parliament voted overwhelmingly in support of a parliamentary report backing the first revision of the Urban Wastewater Treatment Directive (UWWTD) in 30 years. The revision proposal would introduce new limit values and treatment requirements for micropollutants in wastewater, including per- and polyfluoroalkyl substances (PFASs) and microplastics.

The hazardous materials component is a significant component of the EIS. It deserves its own chapter. As written, there is no reference to worker safety; but of course OSHA rules apply as well as other laws when the use, storage and transport of Hazardous Materials (HazMat) is considered. The DEIS should be required to include information about this issue as 9,000 workers will potentially interact with these materials, and the community in general is potentially being put at risk. HazMat emergency response and potential risks to the community must also be fully considered and described. The DEIS must include a full disclosure of HazMat risks related to the manufacture of chips including supply chain, transport, storage, security, air quality, spill/release response and disposal. Cradle to grave analysis must be provided to decision makers being asked to permit this endeavor, as well as community members who are being asked to assume these risks. Additionally, we believe alternative production processes should be evaluated to determine whether the objective production can be realized without the utilization of hazardous materials.

- TRANSPORTATION:

  The only mitigation measures mentioned in this section are improvements to roadways. It is imperative that the utilization of public transportation, including mass transit by bus and light rail, be considered.

- UTILITIES & INFRASTRUCTURE:

  COMMENT: The potential impacts on infrastructure (water, stormwater, sanitary sewer, electrical and telecommunications) will be assessed. The scope of this assessment is ill defined here and needs to be specified in greater detail. The DEIS needs to address parameters such as system capacity, level of service changes, fiscal implications for the community and impacts on water bodies.

  The city of Syracuse should be considered an interested agency for this (as well as other aspects of this project) as it relies on a connection to the OCWA for a portion of its water supply needs.

  It is noted elsewhere in project documents that a 16” natural gas main will be extended to the plant, yet it isn’t mentioned in this section; Shouldn’t impacts associated with the area’s gas supply and the construction of this line be included here?

- USE AND CONSUMPTION OF ENERGY

  The Scoping Document simply states: “This analysis will describe the Proposed Project’s use and consumption of energy and measures that Micron intends to pursue to reduce energy consumption and use of renewable sources.”

  COMMENT: The anticipated energy needs of this project are enormous. Much greater detail is warranted, as discussed below. Local as well as regional and statewide impacts must be considered. Further, this section is related to other sections such as transportation, air quality, and climate change.

Electricity: Electrical consumption is anticipated to be 16 billion kilowatt-hours of electricity per year, when fully built. (Phase 2, Envir. Assessment Form, Part 1, Section K) To put this in perspective, this is equivalent to all of the electricity consumed by the states of New Hampshire and Vermont, combined. The entire state of New York used 143 billion kWh of energy in 2022. Micron will increase demand in NY by 11%. The Scoping Document clearly needs to provide greater details about:

- How will the EIS consider the various sources of electricity which are currently available, and which may become available as the plant is constructed?
- The EIS must evaluate the ability of current power lines owned and operated by National Grid to deliver the required power.
- Micron has stated its goal "to achieve 100% renewable energy for existing U.S. operations by the end of 2025." (Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology) Does Micron plan to achieve this goal for the proposed facility in Clay?
- The Scoping Document should state that the EIS will examine:
    - power purchase agreements with suppliers of solar power, wind power and hydropower.
    - on-site production of electricity from solar and/or wind generation

Natural Gas: National Grid is proposing to build approximately 2.5 miles of 124-psig,12" natural gas distribution main to the new Micron facility. (Exhibit G, Micron Term Sheet, signed Sept. 22, 2022). The DEIS needs to address these topics:

- How much natural gas will the facility need, and for what purpose?
- The use of natural gas seems inconsistent with New York state's CLCPA, which calls for a 40% reduction of greenhouse gas (GHG) emissions 2030, and then an 85% reduction of GHG (below 1990 levels) by 2050. Combustion of natural gas releases CO_2 which is the primary driver of climate change.
- The use of natural gas also seems incompatible with Micron's global target to achieve a 42% reduction in GHG emissions from operations ("scope 1") by 2030 and net-zero emissions from operations and purchased energy ("scope 1 & 2") by 2050, supporting the objectives of the Paris Agreement. (Source: Micron website: https://www.micron.com/ny/fact-sheet)

Related energy usage: The use of energy for construction, facility operations and the ancillary increases in energy consumption related to transportation needs the project will generate should also be investigated. It may not be unreasonable to consider the increase in energy consumption from the induced community growth which this project will generate as described in the chapters on indirect and cumulative impacts and the growth inducing aspects of the project.

- INDIRECT AND CUMULATIVE IMPACTS:

COMMENT: The use of the word 'summarize' to describe the scope of this Chapter is insufficient. This Chapter must assess indirect and cumulative impacts of the proposed project for each of the technical areas included in the DEIS. If these effects are included elsewhere it may be appropriate to summarize them here. Let's be clear about exactly what is required to be included in the DEIS

- GROWTH INDUCING ASPECTS OF THE PROPOSED PROJECT:

  COMMENT: This section relates to perhaps the most significant aspects of this project. While jobs and employment and economic growth will be created, the population growth of the region has the potential to produce significant adverse environmental and economic impacts as well which must be considered. While this section overlaps with other sections of the proposed DEIS scope, it is important to not forget that there will be significant impacts on the community. Such effects as rising housing costs could disproportionately impact the impoverished and increase the potential for a rise in homelessness. The DEIS must not overlook this and other issues relating to population growth of Syracuse, Onondaga County and the surrounding area.

- IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

  COMMENT: Aside from building materials and energy, resources consumed in the manufacturing process, as well as the land devoted to this project, the water consumed and the changes to water and air quality (eg., compounds such as “forever chemicals” which could be discharged into water bodies and the air) should be included in this analysis. The community should, and must know, the sustainability aspects of this venture as it decides to permit its development.

- MITIGATION:
  The SEQR Handbook suggests, “ Specify possible measures for mitigating potential impacts that must be discussed in the EIS, to the extent that they can be identified at the time of scoping.”

  In addition to those listed in this draft scope, others that should be listed are:
    - Public transportation (various options such as fixed route bus, demand activated bus service, light rail),
    - Building design features such as those proscribed in LEED building standards that reduce energy consumption, or production of renewable energy (geothermal or other water-source heat pumps) or
    - Mitigate habitat loss with green roofs or parking area reductions via public transportation options for employees
    - Alternative production processes that can minimize use of hazardous materials, energy use, etc.

Respectfully submitted by the following, on behalf of their respective organizations.

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LIST OF ATTACHMENTS

1. Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P

2. Memorandum from Lenny Siegel, Center for Public Environmental Oversight

3. Christopher K. Ober ,* Florian Käfer , and Jingyuan Deng. "Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing,"Journal of Micro/Nanopatterning, Materials, and Metrology, Vol. 21, Issue 1, 010901 (March 2022). https://doi.org/10.1117/1.JMM.21.1.010901

4. Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology

More Domestic Chip-Making Means More ‘Forever Chemicals’

by Amy Feldman, Forbes Staff, October 5, 2033

https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821

Mark Newman, CEO of Chemours, the only American PFA manufacturer, says the company is ramping up production to meet the demands of reshored semiconductor fabrication.

“I brought some show-and-tell,” Mark Newman, CEO of chemical maker Chemours, told *Forbes* during a recent interview in a midtown Manhattan conference room. He pulled a valve assembly out of a bag. The innocuous piece of plastic, he explained, is made of fluoropolymer known as PFA — a type of controversial “forever chemical” and an essential tool in the production of semiconductors.

"You cannot make chips without a whole PFA infrastructure," he said. "We estimate that in a modern-day fab, there's a half-kilo of PFA in every square foot. So in a 400,000- to 600,000-square-foot fab, that's 200 to 300 metric tons of this stuff."

It's not just valves, of course, but all types of pipes, tubes and pumps in semiconductor equipment. Fluoropolymers are particularly key for filtering out small particles from fluids during chip production. Few factories need to be as clean as chip fabs, where particles as tiny as human skin cells can contaminate production. Chemours' PFA is in much of that equipment and material, providing a big, and largely unseen, part of a semiconductor fab's processes.

Wilmington, Delaware-based Chemours, a spinout of DuPont, is the only U.S. manufacturer of PFA. For Chemours, advanced materials including fluoropolymers represent roughly one-quarter of its total $6.3 billion (latest 12-months revenue) business, with refrigerants and titanium dioxide, used in paints and aerospace coatings, making up the bulk of the rest. Within that, semiconductors are part of its performance-solutions segment, which accounted for $493 million in sales for 2022, up 53% from $322 million in 2020. On its website, Chemours says flat-out that "without PFA, domestic semiconductor manufacturing would not be possible."

Last year, President Biden signed into law the CHIPS Act, which provides $52 billion in funding to spur domestic semiconductor manufacturing with a goal of improving national security by decreasing reliance on nations like China for critical technology. Chips are essential not just for our phones and computers, but also for medical devices and fighter jets. "Geopolitics has been defined by oil over the last 50 years," Intel CEO Pat Gelsinger said at an MIT event earlier this year. "Technology supply chains are more important for a digital future than oil for the next 50 years."

But our insatiable desire for electronic devices and American policymakers' push for more domestic manufacturing of semiconductors relies on the industry's access to large amounts of "forever chemicals."

Ongoing Litigation

Forever chemicals, or PFAS, comprise thousands of synthetic chemicals. They're long-lasting and resistant to heat, corrosion and moisture, making them popular for a variety of products that include nonstick pans, stain-resistant upholstery, firefighting foam — and semiconductor production. Studies, however, have linked PFAS to a variety of diseases, including cancers and reduced immune system response, as well as to contaminated groundwater, air and soil that can lead to a host of health problems. PFAS are an enormous category. Fluoropolymers, like those that Chemours manufactures for industrial uses, are just one class.

Litigation over their impact is ongoing. In June, Chemours, along with DuPont and another spinoff, Corteva, reached a $1.2 billion settlement with public water systems. Meanwhile, legislators and regulators have been cracking down on the chemicals' use, particularly in consumer products such as clothing, furniture and textiles, where they can be more easily replaced. Minneapolis-based 3M, which in 2018 agreed to pay $850 million for damaging drinking water and natural resources in the Twin Cities area, announced that it would cease production of PFAS by the end of 2025.

The semiconductor industry has pushed back against regulations here and in Europe, where regulators had proposed a ban on PFAS. When the U.S. Environmental Protection Agency asked for comments on tightened oversight on PFAS earlier this year by revoking certain low-volume exemptions, the microelectronics trade group SEMI called it "catastrophic" for domestic chip manufacturing. In a letter to the EPA, it said that such a rule "would significantly hamper the domestic semiconductor industry despite express goals of the Administration to the contrary and to the detriment of the U.S. economy."

Doubling Down

In this landscape, Chemours' Newman is doubling down. In a wide-ranging interview with *Forbes* during a trip to New York for Climate Week, Newman said that the $4 billion

(market cap) company was expanding production of fluoropolymers, driven by the critical need for the chemicals in semiconductors and electric vehicles. Further, he said, such production could be done safely with investments that his company is making. It has, for example, invested more than $100 million in emissions control technology at its Fayetteville, North Carolina plant.

“We’re currently sold out and working to expand capacity here in the United States,” Newman said. Chemours plans to enlarge its West Virginia production facility, he said. Located just across the river from Ohio, the factory is well positioned to supply Intel’s giant chip fab near Columbus, now under construction. “Imagine making something for the semiconductor industry in what people think of as coal country,” Newman said. All told, the company is investing up to $1 billion in fluoropolymers, including those for use in semiconductors.

The combination of reshoring and PFAS is “a very complicated discussion,” said Zhanyun Wang, a scientist and PFAS researcher with EMPA-Swiss Federal Laboratories for Materials Testing and Research. “There’s a lot of resistance from the industry because, of course, if we want to do the change, it costs.” That’s especially problematic if the United States and the European Union impose regulations and other parts of the world do not. However, he said, such regulations could be designed to spur new innovations. “The semiconductor industry has a lot of R&D power,” he said.

In July 2015, when industrial giant DuPont spun off its performance chemicals division and named it Chemours for “chemistry” plus the “Nemours” part of DuPont’s full name, the new company was saddled with debt and potentially toxic assets. “I think investors were worried if we were going to be solvent,” then-CEO Mark Vergnano told *Fortune* in 2016. “Were we going to make it through this or not?” Vergnano proceeded to pull off a dramatic turnaround by slashing costs, selling off non-essential businesses and gaining market share for its refrigerants business.

Big Expense

Newman, who had been the company's chief financial officer during those years and is one of the country's top Black executives, became CEO in 2021. The company's revenue ballooned to a peak of $6.8 billion in 2022, driven by strong pricing. Its advanced performance materials business, which includes the Teflon lineup of fluorine chemicals, gained price increases of 18% and reached total sales of $1.6 billion as it focused on high-tech markets including advanced electronics and clean energy.

The semiconductor industry "didn't want to use fluoropolymers, not because they were concerned about them, but because fluoropolymers are expensive," said Gerardo Familiar, president of Chemours' Advanced Performance Materials division, which includes fluorine chemicals. But alternatives have been scarce because of fluoropolymers' resistance to corrosion and ability to work at high temperatures and to last for a long time. He said that fluoropolymers like PFA are "substances of low concern," and that they should be considered differently than PFAS. "Those materials last a very, very, very long time, but they make your manufacturing very, very, very safe for the people who are there because you don't have an issue with corrosion," he said. The conundrum, he said, is how to manufacture them responsibly and what to do with the materials at the end of their life.

Some smaller companies are working on replacing PFAS in electronics manufacturing. Danvers, Massachusetts-based Transene, a privately held business founded in 1965, partnered with Toxics Use Reduction Institute (TURI) researchers at University of Massachusetts Lowell to develop alternatives for its etching solutions used in the semiconductor industry. The vast majority of customers have made the switch, and others are working through their qualification process. "You keep hearing from the industry, 'We need 10 or 15 years to make a change,'" said Greg Morose, research professor at UMass Lowell and research manager at TURI, who worked with Transene. "We basically did the research in 18 months, which is really rapid."

Phasing Out PFAS

But that’s just one small company, and one use of PFAS within a semiconductor fab. David Zamarin, founder of venture-backed DetraPel, which works on sustainable coatings for food packaging and textiles, said he received inquiries from semiconductor and electronics manufacturers, but that the cost and time didn’t make it economically viable. In the electronics industry, even companies that have set goals of getting rid of PFAS are moving slowly. Apple, for example, has promised to “thoughtfully phase out PFAS in a way that does not result in regrettable substitutions.”

Newman said that fluorine chemicals can be made responsibly. Chemours has committed to eliminating at least 99% of PFAS air and water emissions from its manufacturing processes by 2030. Chemours is also working on sustainable technologies, he said, such as renewable membranes for green hydrogen production marketed under the Nafion brand name and low-global-warming refrigerants for heating and cooling buildings.

“We felt because of our legacy we needed to lean into this mantra of being a different kind of chemistry company and showcasing the fact that we could be a leader in emissions reduction,” Newman said. “Our chemistry really enables a lot of the future economy.”

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TO: Micron Project, Office of Economic Development, Onondaga County
FROM: Lenny Siegel, Center for Public Environmental Oversight
DATE: October 30, 2023
SUBJECT: SEQRA Scope of Work for Micron Semiconductor Fabrication

Thank you for the opportunity to comment on the September 12, 2023 Draft SEQRA Scope of Work for Micron Semiconductor Fabrication. I have been asked by residents of Onondoga County to offer my comments.

I have nearly five decades of experience monitoring and influencing the worker health and environmental impacts of the semiconductor industry, through the Pacific Studies Center, the Project on Health and Safety in Electronics, the Silicon Valley Toxics Coalition, and the Center for Public Environmental Oversight, as well as my service as Council Member and Mayor of Mountain View, the birthplace of the commercial semiconductor industry.

The semiconductor industry produces remarkable products that we all use. Unfortunately, its environmental and workplace health record is less than remarkable. The MEW Superfund Area here in Mountain View was the home of some of the earliest successful integrated circuit manufacturers. The wafer fabs are gone, but despite the scores (hundreds?) of millions of dollars spent thus far on subsurface remediation, the contamination—including the risk of public exposure—will remain for decades more, if not longer. The same is true at other Silicon Valley sites.

The SEQRA process provides an opportunity to identify and minimize, in advance, the environmental hazards of semiconductor production. By doing so, it can lead to appropriate regulation, research on waste management and pollution prevention, and investments in safer facilities.

Semiconductor production is essentially a series of chemical processes that use a wide variety of hazardous substances. The industry explains, “While in the 1980s semiconductor fabs used

fewer than 20 elements, today they are using over 50% of the nonradioactive elements in the periodic table."[1] Those include toxic heavy metals. The industry is a major user of Per- and Polyfluorinated Substances (PFAS), also known as "Forever Chemicals" because they persist and bioaccumulate in the environment and even human bloodstreams. As New York state agencies are well aware, these compounds are toxic, even at extremely low exposure concentrations, through multiple pathways. But industry has become reliant on PFAS without first examining the human and environmental risks. It explains, "Without PFAS, the ability to produce semiconductors (and the facilities and equipment related to and supporting semiconductor manufacturing) would be put at risk."[2]

Use and release of the industry's hazardous building blocks are regulated by both state and federal statutes and regulations, but the public is generally unaware of the series of upcoming permit applications that Micron is expecting to make. The SEQRA review should list **all** anticipated permitting processes, with the anticipated schedule of public comment periods, and it should require public notification to interested parties of each permit application as it is submitted.

It should also identify hazardous substances, whether or not they currently have promulgated exposure standards. For example, the industry reports, "Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS."[3]

Furthermore, potential workplace exposures should not be ignored because exposures are below the Occupational Exposure Level (OEL) or even a fraction of the OEL, as industry suggests.[4] In most cases OELs, such as the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limits (PELs), are orders of magnitude above what the science—including U.S. EPA studies—dictates.

While the draft Scope of Work proposes many useful Technical Chapters, there is room for more specificity. I focus on the use and release of hazardous substances.

For **Solid Wastes and Hazardous Materials**, the Scope of Work states, "The chapter will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect

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[1] "Background on Semiconductor Manufacturing and PFAS," Semiconductor Association (SIA) PFAS Consortium, May 17, 2023, p. 54. The SIA PFAS Consortium is made up of chipmakers and their suppliers of equipment and materials. To sign up to receive their technical papers, go to https://www.semiconductors.org/pfas/ . I am attaching this document.

[2] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3. I am also attaching this document.

[3] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3

[4] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 25.

against releases to the environment. Any warranted remedial approaches for addressing identified or potential contaminated materials would be described." I suggest that the Review describe any permitting required for the Treatment, Storage, and Disposal of hazardous materials and solid wastes, and that it list the storage requirements, such as double-walled tanks and piping, necessary to prevent environmental releases. Furthermore, how will employees be educated about the risk from leaks and spills, as well as what to do when they occur?

To what degree will disposal—including landfilling and incineration—create off-site hazards? Industry reports, "Organic waste, including organic liquids containing PFAS, is typically segregated, collected, and containerized to be treated at an offsite licensed treatment and disposal facility, as a blended fuel by high temperature incineration or reprocessing."[5] Perfluorinated compounds are particularly difficult to destroy using incineration. Furthermore, even when permitted by regulatory agencies, incineration may release products of incomplete combustion into the atmosphere.

For **Air Quality**, the Scope of Work barely mentions the potential emissions of highly toxic air contaminants. Historically the industry has used lethal gases such as arsine and phosphine, as well as toxic gases such as hydrogen chloride (the gaseous form of hydrochloric acid). Micron should identify plans to notify first responders and public of any toxic air releases, and first responders should be provided in advance with training and equipment to respond safely to such releases. Employees should be warned about the toxicity of gases used by the industry and trained to protect themselves from potential releases, both at low levels associated with chronic toxicity as well as higher levels with acute toxicity.

I am surprised and disappointed that no chapter is listed for **Wastewater and Stormwater**. The release of toxic contaminants through water pathways is one of the most serious threats of semiconductor productions. Releases of certain contaminants in wastewater could compromise the operations of the Oak Orchard Wastewater Treatment Plant, even undermining compliance with its discharge permit. The draft Scope of Work mentions industrial pre-treatment. Not only should that be described in an environmental review chapter, but the review should identify ways to pre-treat hazardous chemicals, perhaps even reusing some, before comingling with other wastes. This is particularly important for PFAS, because in the future more PFAS compounds are likely to be subjected to enforceable environmental standards, many at very low concentrations.

In fact, given the vast number of PFAS used by the semiconductor industry, the Review should identify methods for sampling total organic fluorine, not just targeted compounds. "At present, only a small percentage of PFAS compounds within typical semiconductor wastewater are detectable and quantifiable using conventional U.S. EPA analytical methods for PFAS-containing

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[5] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 30.

materials."[6] However, U.S. EPA has a draft method (1621) for measuring total organic fluorine.[7] Furthermore, academic researchers are finding that failure to measure total fluorine misses discharges of significant quantities of PFAS pollutants. "[B]ecause many studies of total organic fluorine have shown that total PFAS concentrations are at least 10 times higher than the sum of target PFASs. However, this does reinforce the idea that PFAS monitoring should incorporate complementary target and nontarget analyses or otherwise include measures of total organic fluorine to accurately assess PFAS abundance and potential environmental impacts."[8]

Furthermore, there should be a chapter on **Life-Cycle Environmental Impacts.** What hazardous substances remain in the finished semiconductor products, including packaging. At the end-of-life, are there mechanisms for preventing the environmental release of semiconductor hazardous substances? Industry's PFAS Consortium reports, "At the end-of-life of the product containing the semiconductor, or any parts replaced during the manufacture of semiconductors, would enter waste disposal streams where any PFAS contained therein could enter the environment."[9] Are manufacturers responsible for end-of-life pollution?

Finally, there are those who argue that a thorough environmental review, as I have suggested, would unnecessarily delay the operation of new, advanced wafer fabrication plants. I find it hard to believe that documenting potential hazardous substance and waste impacts in advance would hamper the construction of a factory that is not expected to begin production until 2032. Micron—indeed, all semiconductor manufacturers—**should** already know what hazardous substances it uses and releases. Shouldn't the public also know? The semiconductor and computer manufacturing industry, such as IBM's complex in Endicott, New York, has a long history of causing pollution that threatens public health and the environment. An industry that claims that PFAS—chemicals that are persistent, bioaccumulative, and extremely toxic in low concentrations—are essential to its operations should be required to **come clean** about its environmental and public health hazards.

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[6] "PFOS and PFOA Conversion to Short-Chain PFAS-Containing Materials Used in Semiconductor Manufacturing," SIA PFAS Consortium, June 5, 2023, p. 11.

[7] Draft Method 1621: Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (CIC), U.S. EPA, April 2022, https://www.epa.gov/system/files/documents/2022-04/draft-method-1621-for-screening-aof-in-aqueous-matrices-by-cic_0.pdf

[8] Paige Jacob, Kristas Barzen-Hanson, and Damian Helbling, "Target and Nontarget Analysis of Per- and Polyfluoralkyl Substances in Wastewater from Electronics Fabrication Facilities," *Environmental Science & Technology,* February 16, 2021, p. 2353. https://pubs.acs.org/doi/10.1021/acs.est.0c06690

[9] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 90,

Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing

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Abstract. We identify and describe categories of fluorochemicals used to produce advanced semiconductors within the lithographic patterning manufacturing processes. Topics discussed include the per- and polyfluoroalkyl substance (PFAS) materials used and their necessary attributes for successful semiconductor manufacturing, consisting of photoacid generators, fluorinated polyimides, poly(benzoxazole)s, antireflection coatings, topcoats, and embedded barrier layers, fluorinated surfactants, and materials for nanoimprint lithography. In particular, an explanation is given of the particular function that these PFAS materials contribute. It is noted that in almost all cases fluorine-free alternatives are very unlikely to provide the essential properties present in PFAS systems. Nonfluorinated alternative compounds are discussed where available. Finally, a summary table is provided listing the families of materials discussed, the critical purpose served, what the PFAS compound provides, and the prospects for alternatives. [DOI: 10.1117/1.JMM.21.1.010901]

Keywords: fluorochemicals; per- and polyfluoroalkyl substance; photolithography; semiconductor processing.

Paper 22003V received Jan. 21, 2022; accepted for publication Mar. 3, 2022; published online Mar. 31, 2022.

1 Introduction

The use of fluorochemicals in lithography and semiconductor patterning plays a critical role in the success of semiconductor technology. The addition of small quantities of fluorinated materials enables patterning capabilities that are otherwise not possible to achieve, and this leads to superior device performance. The compact size of the fluorine atom and its strong electron-withdrawing characteristics make it stand out in the periodic table and gives fluorocarbon materials unique properties, unmatched by other chemical compounds. Fluorochemicals have found use in semiconductor processing for good technical reasons.

1. The presence of fluorine near acidic groups can convert them from an acid to a superacid, an essential characteristic for photoacid generators (PAGs) needed in advanced photoresists.
2. Fluorocarbon materials have low surface energy characteristics and act as superior barrier layers (including water repellence), which provide useful properties in photoresists and in antireflection coatings used in immersion lithography while also providing excellent release properties because they do not adhere strongly to other materials.
3. Fluorinated materials have unique solubility characteristics and can prevent intermixing between layers in a complex system such as an antireflection coating. Fluorinated materials are both hydrophobic and oleophobic and thus have reduced or no miscibility with essentially all fluorine-free classes of polymers.
4. Fluoropolymers have a low refractive index compared with any material except air and provide useful optical properties in photoresists and antireflection coatings.
5. They possess low dielectric constant and are especially good electrical insulators, an important feature when polyimides are patterned and retained in the final device.

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> This document provides a systematic overview of the photolithography process and key fluorinated materials involved, provides insight into performance requirements, and describes why fluorinated chemicals help achieve needed characteristics.

Photolithography, a critical process step in the production of a semiconductor, uses a photoresist to transfer a pattern. The primary component of a photoresist is a photopolymer whose solubility will be changed upon exposure to short wavelength radiation. In addition, the photoresist contains a deposition solvent and several small-molecule compounds. The desired solubility change must be great enough that a developer (a solvent that removes the unwanted region of a resist pattern) does not swell the remaining photoresist. The development process must be able to discriminate between exposed and unexposed regions as small as a few nanometers in size. The unremoved photoresist must protect the underlying substrate from the next process steps in semiconductor manufacturing. Each stage in the process must be virtually perfect with yields well above 99%, because there may be hundreds of process steps used to manufacture each advanced semiconductor device. Without those very high yields, semiconductor manufacturing would fail.

The basic lithography process used globally today for advanced semiconductor manufacturing and the foreseeable future employs chemically amplified photoresists. Chemical amplification was a key invention needed to overcome the challenge of limited light sources but was also found to provide superior patterning performance. In such resist systems a photopolymer that contains acid cleavable protecting groups is combined with a photoactive compound, such as a PAG. In its native state, the photoresist polymer with protecting groups is soluble in organic solvents. Upon exposure to UV radiation, the PAG releases acid. Frequently, a subsequent post-exposure bake (PEB) step leads to the acid-catalyzed removal of protecting groups, thereby transforming the hydrophobic photopolymer into one that is soluble in an aqueous base developer. The single photon of light needed to release one acidic proton is “amplified” by the more efficient acid-catalyzed deprotection process. By transforming the solubility of the photoresist, a high contrast patterning process needed in semiconductor manufacturing becomes possible. The combination of photoresist polymer and PAG to make the photoresist system is an essential part of this process and fluorination in the PAG provides the high acidity necessary for chemical amplification to work and will be described subsequently.

The lithographic process is a complex series of steps requiring, at times, several complex properties in a single material or other cases combination of different materials used in the same process step. An example of the latter can be represented by the use of an antireflective coating in combination with a photoresist. An antireflection coating (ARC) is important to prevent light reflected from the semiconductor substrate, which would otherwise alter the very precise molecular scale patterns required for today’s semiconductor devices. An ARC does this by minimizing the refractive index difference across each interface of all layers in the system. As an example, a top ARC (TARC) is a layer that sits on top of the already complex photoresist. It must not intermix with the photoresist, and it can also serve as a protective layer for this complex, multilayer lithographic system. Finally, it must be easily removed. Only a fluorinated material has a significantly lower refractive index and fluorination also provides these additional properties. More details for ARCs will be discussed below.

Additional uses of fluorochemicals in photolithography processes are also discussed in this paper. It is worth noting that while there are many types of fluorochemicals, our survey of the technical literature reveals that there are several specific examples of fluorocompounds that are currently in use by the semiconductor industry in the lithography process including (1) perfluoroalkyl acid compounds (C4 or less), used in PAGs; (2) hexafluoroisopropanol, fluorotelomers, and fluoroacrylate side-chain units may be used in photoresists to incorporate specific functionalities including barrier properties and low surface energy; (3) hexafluoropropyl units are used in sub-units of some classes of polyimides for thermal stability and low dielectric constant; (4) specialized per- and polyfluoroalkyl substances (PFAS) are used in ARCs; (5) PFAS are also include surfactants (used as coating leveling agents) to improve coating uniformity in a number of products used in lithographic processes. A key feature of the addition of a fluorinated component is that its addition provides a necessary additional characteristic to the material while minimally compromising its other critical properties. Examples of these materials and uses are tabulated in

the Appendix. This paper discusses current PFAS use in the field of photolithography, explains why certain materials are used, reviews in part the current understanding of PFAS degradation during processing, and where possible, identifies alternative materials.

One of the special features of the C─F bond is its strength compared with the C─C bond due to the electron-withdrawing power of the fluorine atom. This attribute is the basis of many of the technical benefits of fluorinated materials in semiconductor processing but leads to its chemical stability and environmental persistence. Fluorination brings specific improvement in performance, and its targeted incorporation can minimize the quantities of material needed to achieve that performance. Such aspects are discussed in the context of PAGs. Thus, despite the remarkable performance improvement in many aspects of the lithographic process provided by fluorochemicals (PFAS) that makes possible the semiconductor revolution with its benefit to society, the large and growing environmental and societal concerns surrounding PFAS may counterbalance the positive technological benefits of these materials. The reader is referred to a discussion of such PFAS concerns in a well-written review article, but photolithography chemicals are largely glossed over.[1] Going forward, due to environmental and regulatory concerns, performance equivalent alternatives for many of these applications still need to be identified and this will be a major research challenge.

This paper presents a detailed discussion of the different types of PFAS used in advanced lithographic patterning and semiconductor manufacturing paying specific attention to the unique physical-chemical attributes of these chemistries that make them essential for semiconductor manufacturing. Specifically, we break the PFAS used in semiconductor manufacturing into six main categories of fluorochemicals used in photolithography and semiconductor patterning. For each category, we discuss the critical function served by the fluorochemicals and why the specific fluorocompounds are used, based on the unique properties provided by the chemical. However, it is worth noting that there are required processes in the semiconductor manufactory using per-fluorinated compounds such as etch gases for metal etching, wet cleaning chemicals to clean and condition substrate, and other minor processes that are not covered further in this paper.

Based on concerns regarding the high persistence, bioaccumulation potential, and potential toxicity of PFAS studied to date, it has been suggested that the use of PFAS be limited to essential uses only.

We discuss whether viable alternatives exist for each of these applications and the characteristics that must be achieved to find an alternative compound where none currently exists. Finally, we apply the essential use concept described by Cousins et al.[2] to show that these compounds should be considered essential for certain processes in semiconductor manufacturing (i.e., photolithography and patterning) because they provide for vital functions and are currently without established alternatives. The prior paper did an excellent job of discussing different aspects of PFAS use. In this paper, we focus our discussion of essential use as “necessary for highly important purposes in semiconductor manufacturing for which alternatives are not yet established.” We describe the many uses and unique properties of PFAS chemicals, which in our opinion justifies their current use as essential in microelectronics manufacturing and for which alternatives have not yet been adequately identified. This paper is not intended to be an extensive listing of every example of fluorochemical used in photolithography but does attempt to explain strategies and classes of material used in the manufacturing of semiconductors.

2 Photoacid Generators

PAGs are photoactive compounds that generate acids upon exposure to high-energy light [deep ultraviolet (DUV) or extreme ultraviolet (EUV)]. These photoactive compounds were originally used for applications in photopolymerization in the early 1960s.[3] After the introduction of chemically amplified resists (CARs) in the 1980s, they have been used in semiconductor manufacturing as key components in advanced photoresists. It is important to understand that the process of chemical amplification requires a very strong acid in the PAG to function well. PAGs are now highly evolved with over 40 years of in-depth research and development for photoresist applications. A positive tone resist polymer after deprotection, for example, contains

weak acid groups that will act to buffer (weaken) the acidity of the deprotection process. Without the presence of the strong fluorosulfonic (or stronger) acid, the catalyzed deprotection process will be less efficient or may not even occur. Sulfonate anions without fluorination have repeatedly been shown to be inadequate for use ineffective 193 nm chemically amplified photoresists and this is well known in the photoresist community. The unique characteristics of fluorine (noted below), which lead to very strong proton donation by fluorinated sulfonic acids, are essential in CARs. This intrinsic benefit of fluorinated acids makes it extremely difficult to eliminate the use of fluorinated acids whilst retaining the key performance characteristics of CARs needed for advanced photolithography in microelectronics manufacturing. Other attributes of a PAG that depend less on the acid and more on the chromophore include quantum yield at the wavelength of use, the sensitivity of the overall resist formulation (e.g., 15 to 60 $\mathrm{mJ/cm^2}$), miscibility in the resist matrix, thermal and hydrolytic stability and shelf life of the photoresist, solubility in aqueous base developer for positive tone develop or organic solvent for negative tone development followed by removal in the resist strip operation. In general, PAGs are divided into two categories: either ionic or covalent (nonionic) structures. As the name suggests, ionic PAGs consist of two portions: a cation and an anion. In addition, covalent PAGs are uncharged, nonpolar compounds that are constructed of covalent bonds but are generally less sensitive and therefore less effective than ionic PAGs. The availability of both ionic and covalent PAGs offers process flexibility. In some cases, the presence of ionic groups may lead to storage instability of the photoresist mixture or the inhomogeneous distribution of photoactive compounds in the photoresist, thus making a nonionic PAG necessary. However, most photoresist compositions that are used in semiconductor manufacturing employ ionic PAGs because of their greater sensitivity. Examples of PAGs are shown in Figs. 1 (ionic) and (covalent).

In either case, a fluorinated sulfonic acid would be used to make an effective PAG. The photoefficiency difference between ionic and covalent PAGs, which leads to higher quantum yields in the ionic PAG is controlled by the cation.[4] The low diffusivity and high strength of the acid resulting from the photolysis of the cation are controlled by the resulting accompanying fluorosulfonate anion. These anions are used in virtually all current commercial photoresists. Limited diffusivity is important to achieving high-resolution patterns because excess diffusion of the PAG has been shown to limit the resolution of the images produced in a CAR. While aromatic sulfonic esters are shown in some nonionic PAGs described in Fig. 2, the strength of the resulting sulfonic acid after photolysis is not as high as the ionic PAGs with fluorinated sulfonate anions.

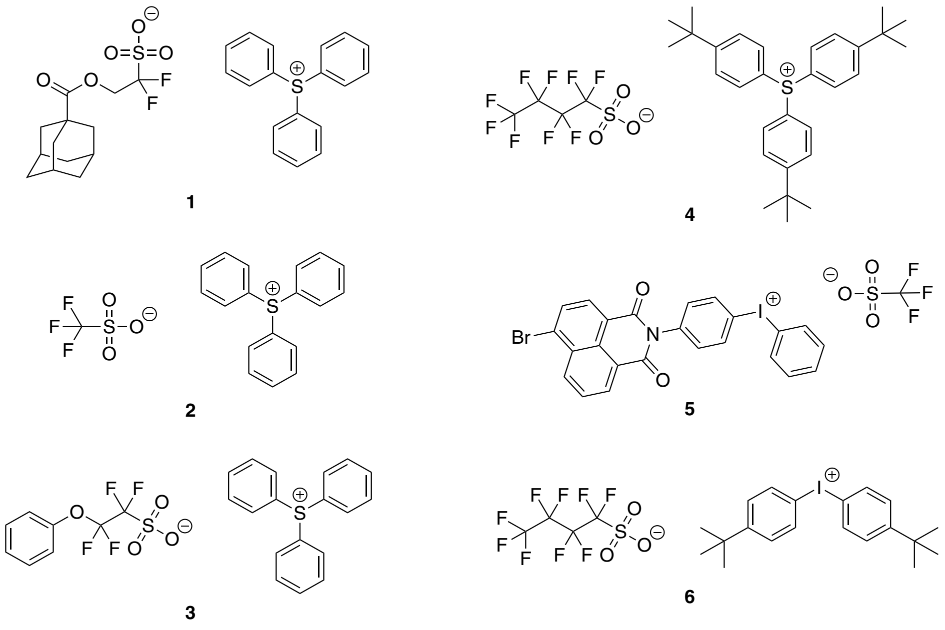
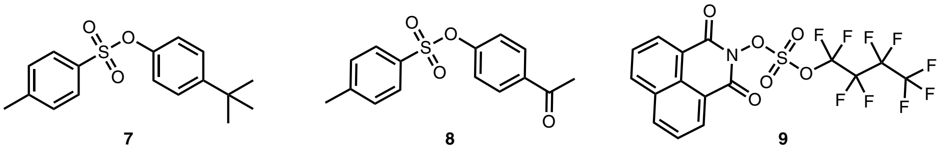


Fig. 1 Representative ionic PAGs: 1,2,3,4 Sulfonium PAG and 5,6 Iodonium PAG.



7 8 9

Fig. 2 Representative nonionic covalent PAGs.

Covalent PAGs do not suffer from the sorts of phase separation, low miscibility, and dark loss (the dissolution of unexposed photoresist) issues that may occur in ionic PAG-containing resist formulations, but the quantum yield of photoacid generation is generally lower for covalent PAGs so this and other factors drive the ultimate choice of PAG.[5] In order to increase the acidity of the photoacid, perfluorinated methylene units may be placed next to the sulfonate group in both ionic and covalent PAGs. The polarization present in the C—F bond due to the electron-withdrawing character of fluorine stabilizes the acid anion and makes the acid stronger. A sulfonic acid such as methane sulfonic acid has a pK_a of −2 (already a strong acid) but trifluoromethyl sulfonic acid (triflic acid) has a pK_a of −14. Any induction effect is significantly smaller after two or three CF_2 units, so the relative benefit of fluorination is significantly reduced as the neighboring CF_2 units are further away from the acid group. The original choice of longer sequence perfluorinated sulfonates (six or more) has not been explained in patents or the literature but was likely due to the effectiveness of the resulting PAG, the reduced diffusivity because it is a larger molecule, its availability, and the lack of volatility in this material. For example, the volatility of the small triflate anion limits its use in a production photoresist PAG because the resulting concentration gradients in such photoresist films harm performance. However, shorter CF_2 segments (1 or 2) next to the anion and connected to other units of higher mass have been shown to make effective PAGs (see Sec. 2.3).[6] Finally, the diffusivity of the PAG will affect pattern resolution (less diffusion enhances resolution) and can be addressed by the use of a higher molar mass PAG/acid and even covalent attachment of the PAG to the photoresist polymer itself (see Sec. 2.4). Although actively used in some applications, triflic acid is not always a useful component in a PAG since it may have significant deficiencies when used in a very high-resolution CAR system; it is volatile and may evaporate during the PEB step leading to composition gradients that are detrimental to image resolution and it readily diffuses during annealing, which may, in turn, lead to pattern degradation from deprotection chemistry occurring in unexposed areas, effectively reducing image contrast and disrupting pattern formation.

2.1 *Ionic PAGs and Their Photochemistry*

Most ionic PAGs used in lithography are onium salt derivatives. Such ionic compounds consist of an onium moiety as the cation and sulfonate groups as the anion.[4] Upon exposure, photolysis occurs and photoacid is formed. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. Returning to Fig. 1, ionic PAGs are generally composed of either diaryliodonium or triarylsulfonium photoactive units to form a salt with an appropriate anion. Triarylsulfonium PAGs usually have longer shelf life compared with diaryliodonium salt. However, a diaryliodonium salt has higher absorptivity in particular for next-generation 13.5-nm wavelength EUV photons. The mechanism of photolysis of diaryliodonium salt[4] and triarylsulfonium salts[7,8] has been studied extensively. Reported photolysis mechanisms for diaryliodonium salt and triarylsulfonium salts are shown in Figs. 3 and 4, respectively. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. In Fig. 3, the energy required to cleave the aromatic C (sp^2) and iodine bond is somewhat higher compared with the energy required to promote bond cleavage between the aromatic C (sp^2) and sulfur bond (Fig. 4).

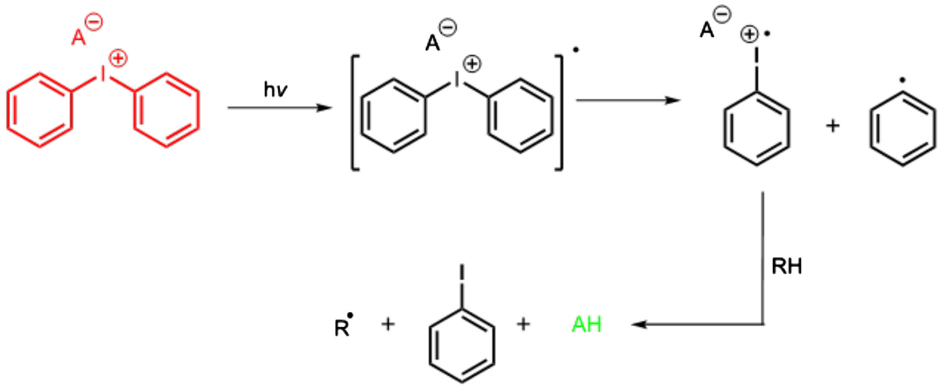


Fig. 3 Proposed photolysis mechanism for diaryliodonium salt under DUV exposure. Reproduced from Ref. 8.

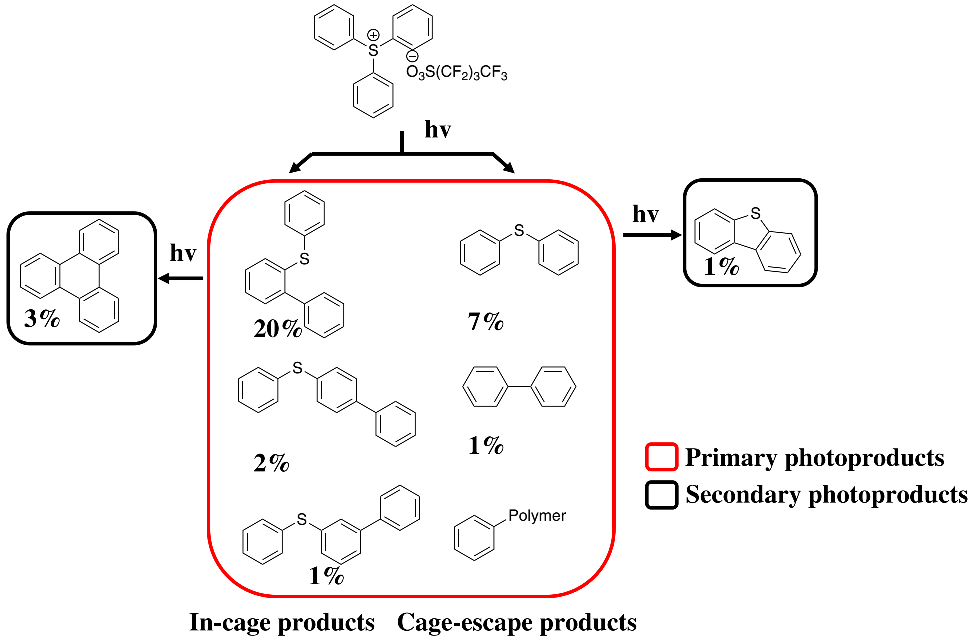


Fig. 4 Proposed photolysis mechanism for triarylsulfonium salt in solid poly(methyl methacrylate) matrix exposed to 266-nm irradiation (2631 mJ · cm^{-2}). Reproduced from Ref. 9.

Generally, the sulfonium PAG family is more widely used than iodonium PAGs considering its greater sensitivity and longer shelf life when used in either DUV or EUV lithography. Reference 8 reports solution results for exposure of the triphenylsulfonium cation. More recent results of solid-state polymer matrix results are shown in Fig. 4.[9] Solid-state studies at 193, 248, and 266 nm exposures reveal additional products including in all cases, two previously unreported Triphenyl sulfonium photoproducts, triphenylene, and dibenzothiophene.

2.2 *Nonionic Covalent PAGs and Their Photochemistry*

Although ionic PAGs have higher sensitivity in lithographic applications, they may be less soluble and more prone to phase separation in photoresist formulations. It is worth recalling that the PAG is needed to generate acid in the exposed regions to deprotect the photoresist and thereby change its solubility. Uniform distribution of a PAG is an essential attribute to excellent performance in a photoresist. Detrimental interaction between ionic structures in a photoresist and an ionic PAG may also occur in future resist materials.[10] To overcome such issues, covalent PAGs

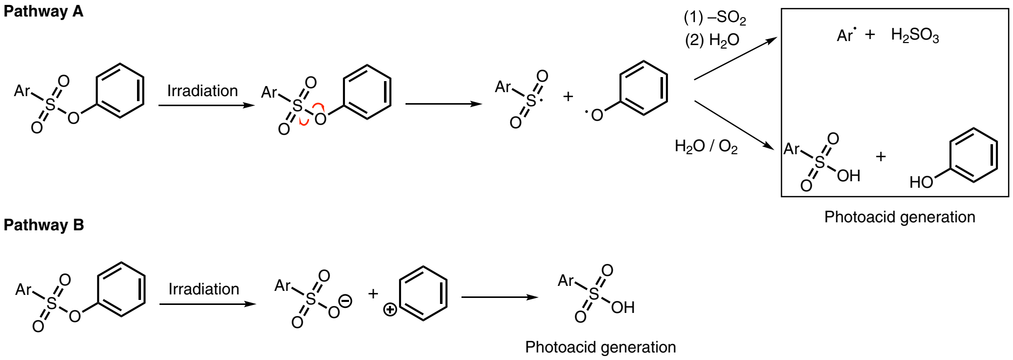


Fig. 5 Photoacid generation mechanism for arylsulfonate esters.

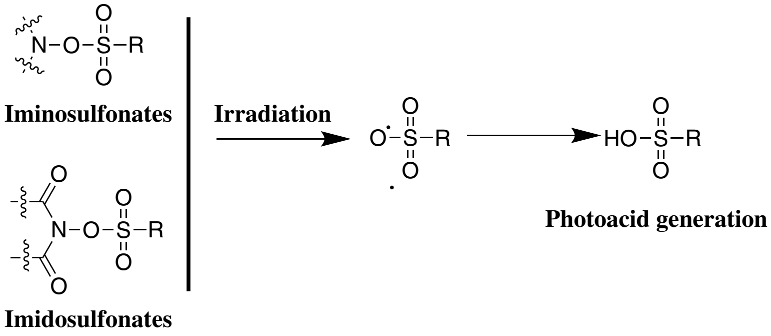


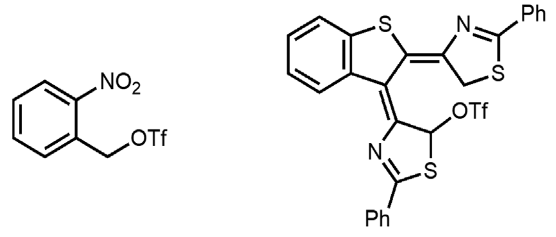
Fig. 6 Photoacid generation mechanism for iminosulfonates and imidosulfonates.

may be attractive alternatives.[4] In general, covalent PAGs are derivatives of arylsulfonates,[11] iminosulfonates,[12] and imidosulfonates.[13] Arylsulfonate esters can be easily synthesized from phenol and sulfonyl chlorides. A similar effort to create fluorinated sulfonate ester-containing covalent PAGs has not taken place because such PAGs have not been as effective in photoresist applications. The photoacid generation mechanism is proposed based on the nonfries photolytic ArO─S bond cleavage (pathway A) or pseudofries rearrangement (pathway B), which is more likely to occur for electron-rich aryl sulfonates as shown in Fig. 5.[14,15]

It is worth noting that in pathway A, in the presence of oxygen and water, stronger sulfonic acid is generated. In the absence of oxygen, weaker sulfurous acid is produced. Iminosulfonates and imidosulfonates have similar chemical structures with the N─O bond undergoing homolytic cleavage upon irradiation to generate sulfonyloxy radicals, which subsequently capture hydrogens from nearby molecules to afford the corresponding sulfonic acid as shown in Fig. 6.

2.3 *Alternatives to Current PAGs*

PAGs other than iodonium and sulfonium units as well as those that do not contain traditional PFAS have also been studied for use in photolithography. To be used successfully in a CAR photoresist, the resulting acid must be as acidic as a perfluorosulfonic acid, lack volatility so that it does not evaporate during the PEB step, and in the next generation photoresists possess minimum diffusivity (to enable high-resolution pattern formation). The PAG-resist combination should have a sensitivity in the range between 10 and 75 $\mathrm{mJ/cm^2}$ under exposure conditions i.e., the source wavelength and tool-specific settings. Some new photoresists attach the PAG directly to the photopolymer chain to both limit diffusion and deal with issues of stochastic variations that may be present in photoresists consisting of mixtures of polymer and photoactive molecules. Nontraditional PFAS Covalent PAGs: Nitrobenzyl esters have found some application in DUVL and may be extendable to EUV lithography.[10] Such molecules can generate photoacid



(a) (b)

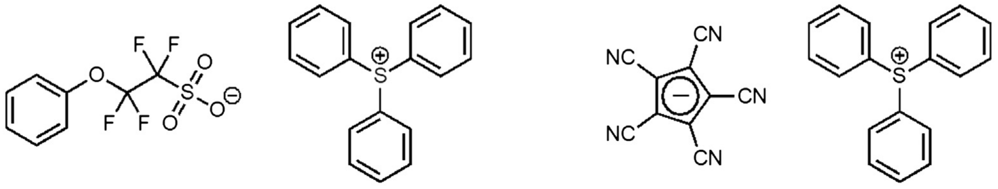
Fig. 7 Chemical structure for non-PFAS covalent PAGs: (a) nitrobenzyl ester and (b) terarylene backbone-based PAG.

upon irradiation through *o*-nitrobenzyl rearrangement to generate nitrobenzaldehyde and a sulfonic acid such as triflic acid shown in Fig. 7.

The chemical structure is shown in Fig. 7(a). The terarylene skeleton-based self-contained PAG is another potential candidate for some applications. The photoacid generation is triggered by the 6π-electro-cyclization reaction of photochromic triangular terarylenes.[16] The chemical structure is shown in Fig. 7(b). Similarly, a triflate ester is used in the reported structure to release triflic acid upon exposure. While these and other structures can be used to demonstrate PAG concepts, they are unlikely to be as useful in new high-resolution photoresist systems because they use triflate groups. Alternative acids may be used to make more suitable PAGs from the moieties in Fig. 7. Should a useful PAG be produced from these types of photoactive structures the resulting sulfonic acid will need to be less volatile and less mobile in the polymer film? A higher molar mass, much less volatile, lower diffusivity anion might work well with these materials in a functioning photoresist system. Nontraditional PFAS Ionic PAGs: Ionic PAGs derived from 2-phenoxytetrafluoroethane sulfonate were introduced by Ober and coworkers in 2007.[17] This PAG was tested under e-beam and EUV radiation and showed high sensitivity, resolution, and acceptably low line edge deviations. The use of such a fluorosulfonic acid has the advantage that it limits fluorine content yet produces a very strong acid with both limited volatility and diffusivity by placing a CF_2 group next to the acid group. Such an approach (discussed more below) can be used to minimize fluorine incorporation while placing this structure where it is most valuable. Its chemical structure is shown in Fig. 8(a). This PAG was tested for its environmental degradation and its effect on bacterial populations when first reported and found to be benign under the rules of that time.

The good lithographic results suggest that shorter fluorinated segments (two or possibly one CF_2 unit adjacent to the sulfonic acid) may make useful ionic PAGs. It should be noted that the building blocks for sulfonic acids with one CF_2 are the subject of experimental studies. The pentacyanocyclopentadienide PAG is another potential ionic PAG candidate in some applications. Its lithographic performance was demonstrated by Varanasi and coworkers in 2010, and it stands out for the amount of publicity it received.[18] The chemical structure is shown in Fig. 8(b).

While announced in 2010 as part of IBM's efforts to reduce Perfluorooctanoic acid (PFOA) in its manufacturing process, to the best of our knowledge, this PAG was not commercialized.



(a) (b)

Fig. 8 Chemical structure of untraditional ionic PAGs: (a) 2-phenoxytetrafluoroethane sulfonate PAG and (b) pentacyanocyclopentadienide PAGs.

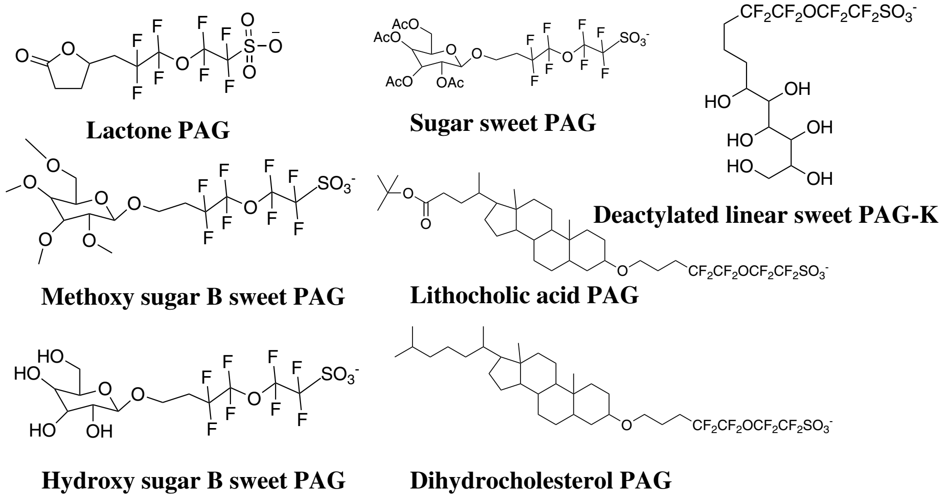


Fig. 9 Chemical structures for natural products-based PAGs.

Finally, PAGs based on glucose or other natural products have been explored. These PAGs were demonstrated to be functional materials for some high-resolution photoresist applications enabling sub-100nm features using ArF laser and e-beam lithography. Moreover, these PAGs showed successful microbial degradation to smaller molecular units under aerobic conditions. The chemical structures are shown in Fig. 9.

Such studies revealed the successful biodegradation of these PFAS units to smaller oxidized components as well as low bacterial cytotoxicity[19,20] of the photoactive sulfonium subunit. In general, the anionic units underwent biodegradation using sludge from a local municipal wastewater treatment plant. The sugar or cholesterol groups appeared to degrade easily leaving only a short, fluorinated acid residue. An advantage of these structures is that the residues retain polar functional groups and are therefore more hydrophilic than PFOS/PFAS units. This makes them less likely to accumulate in fatty tissues, but further studies are needed to identify any bioaccumulation characteristics. The photoactive cation unit but not the fluorinated anion was generally found to be cytotoxic to the bacteria. Importantly, the short, fluorinated segment enabled the formation of a high-performance PAG that could be subjected to successful biological degradation.

More recently, patents have appeared that describe a number of related chemical structures, the goal of which is intended to deliver strong PAG performance and minimize the size of the fluorinated unit in the fluorosulfonic acid or eliminate it entirely. These patents claim excellent lithographic performance.[21] These and other patents describe PAGs with shorter fluorinated segments,[22] some of which are designed to fall into small molecular pieces.[23] To assess their viability as alternative PAGs their performance characteristics (sensitivity, acid strength, and diffusivity) and environmental characteristics (fluorine content, degradation products, and toxicity) will need to be assessed.

2.4 *Polymer-Bound PAGs*

One approach to increasing the resolution to photolithography is to employ PAG that is incorporated into the photoresist polymer structure.[24] It has the advantage of making the distribution more uniform and at the same time limits the diffusivity of the sulfonate anion since it is bound to the photoresist polymer. Resolution is set in part by the diffusivity of the PAG in the photoresist formulation, which is associated with the size of the molecule. The smaller the anion, the farther the photogenerated proton can diffuse in a given time. If the PAG acid diffuses too broadly then deprotection of the photoresist takes place in unwanted regions and makes the pattern larger, less precise, and "blurry." These pattern irregularities are characterized in terms of line edge roughness, line width roughness, and critical dimension uniformity. Examples of bound-PAG structures have been reported and two are described below shown in Fig. 10.

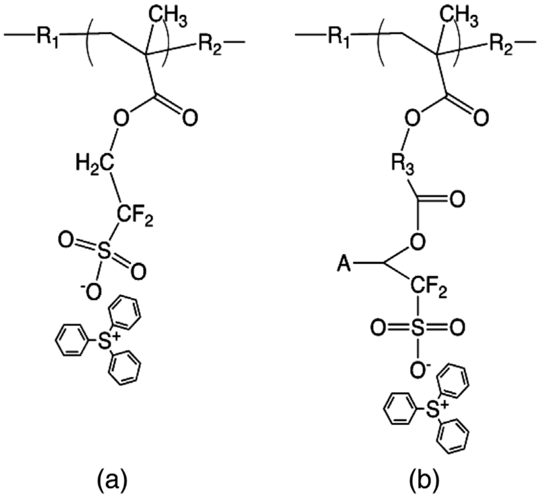


Fig. 10 Examples of polymer-bound PAGs. (a) Single CF_2 unit next to sulfonate[21] and (b) single CF_2 unit next to sulfonate in a structure that falls apart on exposure; groups (R1, and R2) not specified groups while R3 is a linking group.[20]

This strategy also lowers concerns about "stochastics," i.e., the chemical heterogeneity of a photoresist mixture at the dimensions of the pattern are thought to also contribute to the limit of resolution of today's most advanced lithographic processes. Upon exposure, the fluorosulfonate group becomes protonated, catalyzes deprotection of the rest of the photoresist chain, but the strongly acidic proton cannot diffuse broadly because it remains near the anion bound to the polymer chain and thereby forms higher resolution patterns. By attaching the same number of PAG units to each polymer chain, then the PAG is uniformly distributed throughout the photoresist film. This strategy is being seriously considered for future generations of photoresists, particularly for use in EUV lithography.[25] These examples share several common features, including the attachment of the anion to the polymer backbone. Since many CAR photoresists are based on (meth) acrylates, examples reported for 193 nm (DUV) resists [shown in Figs. 10(a) and 10(b)] possess a sulfonate anion and an adjacent CF_2 unit, which then is connected to the methacrylate monomer through an ester linkage. While it has not been established if one or two CF_2 units are needed to produce sufficiently strong anion, this example demonstrates one approach and good prospects for polymer-bound PAGs.

3 Fluorinated Polyimides

In an increasing number of applications, the photopatterned polymer is not removed but is retained as part of the device, even though the lithographic requirements are not as stringent as the high-resolution photoresist systems discussed above. Their use ranges from semiconductor packaging to lithographic insulation patterns for integrated circuits. Under these circumstances a completely different photopolymer must be used and have properties of very high thermal stability, strong mechanical properties (high Young's modulus, good fracture toughness), low dielectric constant (be an insulator), and moisture resistance.[26] In this highly demanding application only a few polymers can provide this complex set of properties and, among them, polyimides have been found to provide the best trade-off between processing and performance. Polyimides themselves bring many of these necessary attributes but the introduction of fluorinated groups is used to incorporate a chemical function capable of withstanding high process temperature, making the final material more moisture resistant and providing a lower dielectric constant than otherwise possible without compromise to other necessary properties.

The technical literature reveals that polyimides are used in a number of processes and applications in photolithography.[27] Polyimides are a family of polymers characterized by high thermal

stability, excellent thin film mechanical properties, good adhesion properties, and a low dielectric constant and dissipation factor. In particular, rigid functional groups such as phenylene- and less polar functional groups provide low dielectric constant (Δk) and good mechanical toughness (resistance to tearing). Polyimides are unique as a family of polymers because they have among the highest glass transition (softening) temperatures known in a polymer (>200°C) and they are thermally stable because the polymer chain consists of interconnected aromatic rings. These properties make polyimides able to withstand the high-temperature processing used in semiconductor manufacturing. Like all polymers, they can be etched with the right etchants and therefore patterned, they are amorphous and transparent so they can be used to guide light and they have a lower dielectric constant than many other components in a device so they can be insulators, but unlike other polymers they come with the ability to withstand very high-temperature processing without physical softening and deformation. They often remain in the semiconductor device, unlike most other photolithographic layers.

Photopatternable polyimides are generally made from a poly(amic acid) precursor such as one made from oxydianiline (ODA) (Y═O) and a dianhydride (such as pyromellitic dianhydride), which can be spin coated onto a substrate (see Fig. 11).

However, photocrosslinkable acrylate (or similar) groups are incorporated in the soluble poly(amic acid). A photoradical initiator is used to crosslink the acrylate groups and the pattern is developed in this negative tone system. Then a high-temperature bake step is used to transform the poly(amic acid) to the polyimide (with loss of the acrylate groups) to form its final high thermal stability, patterned and insoluble polyimide form. Any component in the final polyimide must withstand this high-temperature bake step.

Among the applications of polyimides in microelectronics processing, they find use as thick film photoresist, sacrificial layers, and structural layers. It is notable that the structure of a fluorinated unit, when incorporated into the polyimide, largely employs the identical hexafluoroisopropyl unit regardless of the application.[28–30] Hence, in the most common examples, the polyimides consist of tetracarboxylic acid anhydride derivatives and aromatic diamines, as shown in Fig. 11. The polyimide polymer itself has a softening temperature too high for melt processing, but this group of polymers offers processing through its poly(amide) intermediate. The intermediate is soluble, can be coated in a thin or thick film, and after patterning is converted to the polyimide through the heating step making it an ideal material for integration with semiconductor manufacturing. The soluble intermediate can be made into a polymer that is directly photo-patternable as shown in the poly(amide) in Fig. 11. The acrylate modified poly(amide) is photo-crosslinked upon exposure to UV radiation in the presence of a photoradical generator and then a pattern is formed. After development, the patterned polymer is subsequently transformed to the final polyimide by thermal processing. It is known in the art that the insertion of the fluorinated hexafluoroisopropyl functional group into the backbone provides a combination of better solubility in processing solvents, lower dielectric constant (more insulating), and provides higher thermal and thermooxidative stability compared with other alternate chemical functions.[31]

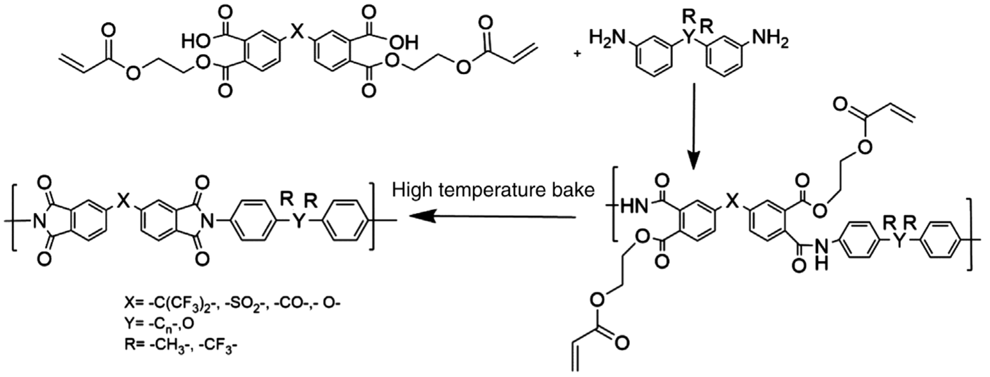


Fig. 11 Synthesis and structure of polyimides for photolithographic processes.

It must be noted that similar insulator properties have been claimed for the targeted optimization of a polyimide chemical structure without the presence of fluorinated residues such as CF_3- and others, which has been successfully demonstrated in at least one scientific study.[32] Araki et al.[32] recently described the synthesis of a novel low dielectric constant (Δk) and low dissipation factor (Δf) polyimides suitable for insulator of redistribution layers used as an interposer layer in wafer-level packaging. However, this polyimide replaces the thermally stable aromatic structure with a silicone segment (chemically identical to bathtub caulk) to achieve the insulating properties. While this new polyimide has good dielectric properties, unmentioned in the report is the fact it undoubtedly has poor mechanical properties, thermal stability and introduces a softening temperature well below materials used in this semiconductor manufacturing application. To demonstrate equivalence to the fluorinated polyimides, it would be necessary to evaluate these new polymers in a series of comparative studies. It is likely that the lower glass transition temperature and the higher associated thermal expansion changes of the silicone-based system would lead to mechanical stresses that severely limit its use outside of simple packaging applications.

No literature was found on the in-process or environmental degradation of these fluorinated polyimides.

4 Fluorinated Polybenzoxazoles

Building on the properties described for fluorinated polyimides, the industry has requested materials with similar properties, which could be patterned using the more generally acceptable aqueous tetramethylammonium hydroxide based developers. One way to achieve this end was to replace the polyamic acid derivative precursors with polyhydroxyamide precursors to polybenzoxazole, which could, after patterning and cyclization, yield a polybenzoxazole (Fig. 12).

The phenolic group allows for development by aqueous base, whereas use of classical diazonaphthoquinone (DNQ) photoactive units to modify the base solubility as in positive-tone photoresists allows for the needed selective patterning (Fig. 13).[4]

Alternatively, other protective groups such as acid-labile ethers and a PAG can also be used, as are common in advanced positive tone photoresists. These materials provide properties similar to polyimides, including thermal stability, tensile strength, and transparency as polyimides while also allowing easier processing. The incorporation of a hexafluoroisopropylidene containing monomer again confers the needed properties of transparency in 365 nm applications, good moisture resistance, thermal stability, reduced darkening after cure, and the correct solubility in aqueous development. Other additives are used to further control base solubility.[33–36] The DNQ PAC may either be added to the formulation or incorporated into the polymer backbone as shown below.

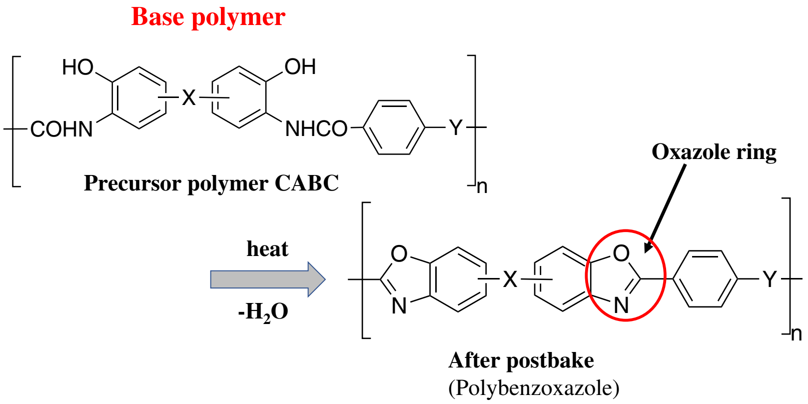


Fig. 12 Figure showing ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

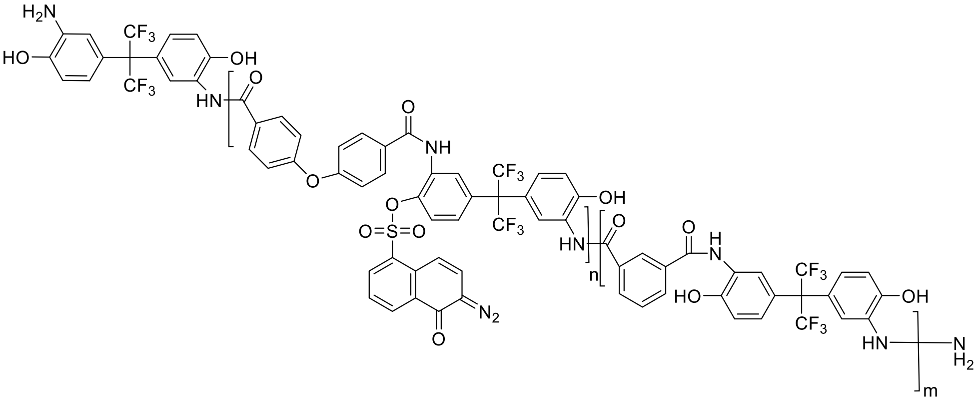


Fig. 13 Ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

5 Antireflection Coatings and Topcoats

The purpose of an antireflection coating (ARC) is to prevent reflection of the imaging radiation from interface layers that produce unwanted exposure effects including standing waves. An important attribute of an ARC is to tune the refractive index difference across each interface, and reflection from the many interfaces between layers is suppressed. A difference in refractive index is essential in preventing unwanted reflection of imaging radiation, which otherwise has a detrimental effect on pattern exposures. Fluorinated materials are important because they have a lower refractive index than virtually any other material category. For example, the refractive index of poly(trifluoroethyl methacrylate) is 1.418 compared with a polymer chemically similar to photoresist materials, poly(2-methoxy styrene) with its refractive index of 1.585, a significant and critical difference for an antireflection coating. Ideally a TARC, e.g., should have an RI value of ∼1.3 and even with fluorinated materials, a good TARC refractive index is currently between 1.4 and 1.45. In addition to their optical properties, ARCs must not intermix with the photoresist as the different layers are deposited, and fluorination helps make that possible. Important requirements for ARCs also include ease of etching, their adhesion to a substrate, and precise thickness deposition.[37–39] Bottom ARCs (BARCs) are also used to form a level surface for a photoresist. Processing of ARC and topcoat materials depend very much on where they sit in the lithographic stack (on top or on the bottom) and a combination of etch, rinse and/or development steps are used in processing. This paper does not detail these differences. TARC materials require first and foremost controlled and reduced refractive index (RI), good mechanical properties for film formation as well as excellent etch characteristics (faster etching than the photoresist). The low RI properties and immiscibility (by being both nonpolar and oleophobic) with the photoresist are mainly achieved by the incorporation of short, fluorinated groups such as CF_3- and C_2F_4- units in the TARC, although longer fluorinated segments have been used. An example of a generic chemical structure of an ARC is shown in Fig. 14 in which a base soluble fluoropolymer is displayed.[40]

It is also possible to achieve immiscibility between ARC and resist using cyclic perfluorinated ether units in the ARC[41] Finally, fluorinated surfactants have also been used to improve ARC coating quality, and more is discussed about such surfactants below. There are two possible geometries that work to limit reflection: TARC and BARC antireflection coating materials. The name specifies wherein the multilayer stack the ARC is located. Figure 15 shows the arrangement of the silicon substrate, the photoresist, and a TARC.[42]

The radiation path is different in the air, the TARC, and the photoresist since each has a different refractive index. By using a low RI TARC (due to its fluorination) and by finding the

$$\left[\mathrm{CF_2{-}CF_2} \right]_n \left[\mathrm{CF_2\,CF(OCF_2CF_2COOH)} \right]_m$$

Fig. 14 Composition of a commercial ARC; $n = m$.[40]

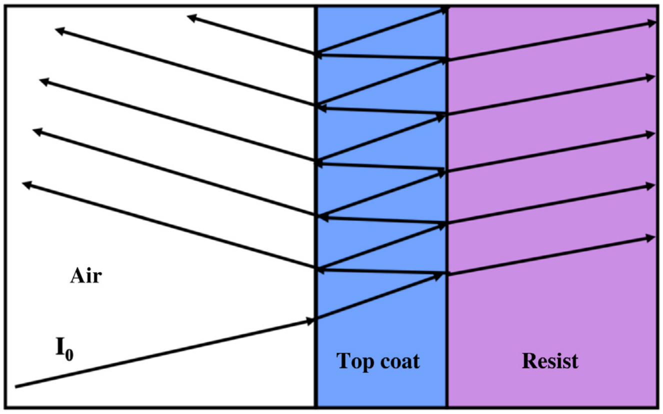


Fig. 15 Light path of top coat/antireflective coating and resist film stack.[43]

optimal TARC film thickness reflection can be minimized.[44–47] Both the phase match and intensity match conditions must be satisfied. This follows Airy's original 19th-century derivation. If both conditions are met perfectly, the reflection amplitude is zero and all light is coupled into the film. This added ARC layer of lower RI results in a superior pattern with higher resolution.

5.1 *Bottom Antireflective Coatings*

Some fluorine-containing acrylate and methacrylate-based copolymers may be used as components in BARC antireflection coating materials (as shown in Fig. 16).

BARC materials used for 193-nm lithography include copolymers of acrylates/methacrylates/alicyclic units as well as bis(benzocyclobutene) and fluorinated arylene ethers.[31] Besides the use of acrylate-based copolymers, it has been reported that perfluoroalkyl silanes (shown in Fig. 13) and poly(ethoxy siloxanes) (not shown) are used as BARC materials. In all these materials the fluorinated component aids in preventing intermixing between the antireflection coating and the photoresist. If mixing were to occur then the performance of the ARC (top or bottom) and the photoresist will be greatly diminished, because the thin photoresist layers will no longer be optically uniform. It should also be noted that fluorine "free" alternative BARCs are known, and they similarly must prevent mixing between ARC layers and photoresists without fluorination. Material suppliers have shown fast etching BARCs for 193-nm lithography. Such materials were targeted for first and second reflectivity minima thickness, are immiscible with photoresists (by being crosslinked), and are not affected by base developers, see Fig. 17.

However, these materials were introduced before the advent of 193-nm immersion lithography. In addition, disposal of hydrophilic ARCs is complicated when ARC and resist disposal cannot be disposed of via the same waste system.

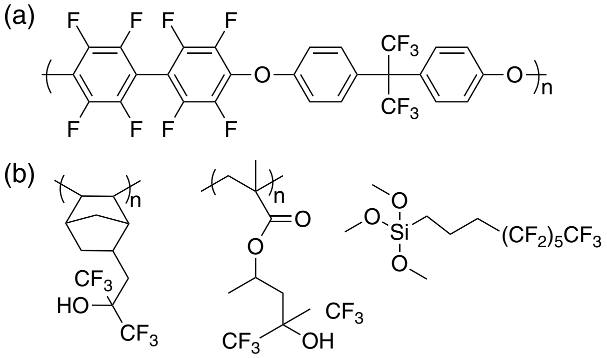


Fig. 16 (a) Fluorinated arylene ethers and (b) acrylate/methacrylate perfluoroalkyl silane-based BARC and TARC materials.

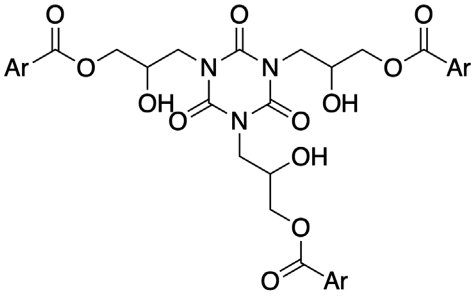


Fig. 17 Representative BARC material.[52]

5.2 *Top Antireflective Coatings*

Antireflective coatings may also be placed on top of a photoresist stack to reduce optical issues. The comments related to BARCs above about refractive index and miscibility are relevant to TARC materials as well. Issues of wetting and interactions with water arise when 193-nm immersion lithography is used. In this variation of high-resolution lithography, a droplet of water is placed between the photoresist stack surface and the stepper (exposure) lens. As the wafer is patterned, the water film must not wet the wafer surface, or else the patterning process will fail since the rapid movement of the stepper would rapidly lead to the breakdown of the immersion layer. A very hydrophobic, nonwetting surface makes the immersion process work well and prevents leaching of the photoactive component. For immersion lithography, control of substrate reflectivity is critical and for this reason immersion, BARCs are favored over TARC when using this process.

Similar chemical strategies have been used to make fluorinated TARCs and topcoats (below), where fluorinated acrylate- and methacrylate-based copolymers are used, but they are optimized for different property sets.[48] Jung et al.[49] showed a TARC material based on these components, which are easily developable but possess a relatively low refractive index of 1.55. Furthermore, by increasing the fluorine content of the TARC material, a high dissolution rate and receding contact angles >70 deg could be achieved.

5.3 *Topcoats*

Sanders wrote an extensive review of resist systems for 193-nm immersion lithography and discussed the need for topcoats.[41] These are materials used as the upper layer in the resist stack that was optimized for the purpose of preventing immersion liquid (water) from leaching photoactive materials from the photoresist during the patterning process and for base development. In that report, he describes several compositions that work well as topcoats. These include perfluoro ethers as well as polymers with hexafluoroisopropanol units and those with short-chain perfluoroalkyl units. All approaches reported function well as barrier materials. In addition to immersion topcoats, which are directly coated on the resist, material suppliers have also developed highly functionalized fluorinated amphiphilic molecular structures, which provide the same properties as a topcoat. The advantage of this approach is that the material, known as an embedded barrier layer (EBL), is formulated directly in the resist, and no separate topcoat coating step is required. Such photoresists are known as topcoat-free resists.[50] Such EBL materials may have similar fluorinated components as those found in fluorinated topcoats and fluorinated ARCs, but their application and processing are different.

Other approaches to low RI materials include the incorporation of air pockets using silica nanoparticles. However, this approach did not gain industry acceptance, because it was not possible to implement with the necessary process reliability and reproducibility. In addition, dyed TARCs (limited by the availability of appropriate chromophores) have been developed that reduce the need for fluorination using anomalous dispersion optical effects but do not eliminate the need for fluorinated components for performance reasons discussed above.

Finally, the only molecular unit that comes close to fluorochemicals in low surface energy are silicones, but they have the disadvantage that they have low softening temperatures and are very

oxygen plasma etch-resistant. Where ARCs need to be removed using such etch methods, alternative structures with silicones do not provide needed properties.

6 Fluorinated Surfactants and Surface Leveling Agents

Surfactants in general are "surface-active agents" that consists of a hydrophobic segment and a hydrophilic unit. Surfactants can be used in a variety of coating applications for improving film quality, changing surface interaction,[51] and wetting characteristics, and component mixing. The hydrophobic portion of a surfactant can consist of such moieties as hydrocarbon, silicone, or perfluorocarbon segments while the hydrophilic portion of a surfactant can be charged or neutral. Specific performance advantage of fluorinated surfactants is that the surface activity is much higher than equivalent hydrocarbon or silicone surfactants as indicated by the requirement for less surfactant material in a formulation to achieve its critical micelle concentration.

Fluorinated surfactants may be used in several applications in photoresist processing. For example, they can be used to improve photoresist deposition and eliminate defects during photoresist coating. Fluorinated surfactants have been used to improve the development process of an exposed photoresist. They are used to improve the uniformity of an ARC coating process and are especially effective when fluorinated ARCs are involved. Thick film photoresists benefit from surfactants in the formulation to achieve good coating uniformity. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality to reduce layer contamination and increase process yield) and the surface activity of fluorocarbon surfactants makes them readily useable with other ARCs and photoresist materials.

Fluorinated nonionic surfactants have been used in a wide range of lithographic processes due to their very low surface energy, thermal-and mechanical stability, and low refractive index. Nanoimprint lithography (below) is making use of fluorinated surfactants to reduce defects caused by the removal of the template in the patterning process.[53,54] Lin et al.[55] demonstrated the use of methyl perfluorooctanoate to significantly reduce defects of printed patterns. Another example was shown by Zelsmann et al.[56] applying perfluorooctyl-triethoxysilane and perfluorooctyl-trimethoxysilane. Besides use in nanoimprint lithography, fluorosurfactant-assisted photolithography was demonstrated by Sakanoue et al. using commercial polymeric fluorosurfactants, such as Surflon S-386, S-651 (AGC) and Novec FC-4432 (3M).[57] It should be noted that, due to the unique properties of fluorinated surfactants, examples of nonfluorinated surfactants with equivalent characteristics to those of fluorinated surfactants are limited and have been used in few resist formulations.

7 Nanoimprint Lithography

While nanoimprint lithography is not today a mainstream patterning technology, it has the potential to be introduced soon for specific patterning applications. A mold with nm-scale features is used to imprint polymer or a photopolymerizable monomer mixture to form the pattern in the transparent mold.[58,59] In the former case, many polymers have been explored for nanoimprinting but a mold release agent such as a poly(perfluoroether) is usually added to the surface of the mold. In the latter case, fluorochemical units such as those used in BARCs and ARCs including perfluoralkyl segments or hexafluoroisopropanol groups have been used.[60] In all cases, removal of the polymer from the mold is an important step in the production of the pattern and for this reason, fluoropolymers are frequently used. It is worth being aware of this approach to high-resolution pattern formation because some early attempts at process development depend on the use of fluorinated photoresists. The fluoropolymer has, in addition to excellent release properties, the advantage that air, which can be trapped in the process, is easily dissolved in the fluoropolymer thereby eliminating trapped bubbles and does not seem to affect pattern formation. Therefore, fluoropolymers are often preferred in this process. This technology area is new enough that little or no reported work has been carried out on the environmental fate of such materials.

Alternate materials for this process include silicones that can be used for their mold release properties.[61] This area is attracting strong interest and demonstrates that nonfluorinated materials

perform well, but at this time it has not been established if silicone materials are superior in performance. Etch characteristics and wear properties are of course different between fluoropolymers and silicones.

8 PFOS/PFAS Remediation

As noted above, the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in strong resistance toward physical, chemical, and biological degradation. Due to this strong resistance to degradation, PFAS compounds in general are extremely stable in the environment. In addition, such compounds have been found to be bioaccumulative.[62] Extensive literature exists describing the detection of a number of PFAS compounds in drinking water.[63] Postuse PFAS waste treatment methods including advanced oxidation processes,[64] reductive decomposition processes (aqueous electrons, hydrated electrons, etc.), and incineration have been developed for mitigation purposes.[59] Among these methods, advanced oxidation processes do not show high efficacy for PFAS degradation due to the high electronegativity of the fluorine atoms. More work will need to be done to assess the relevance to the kinds of fluorinated materials discussed in this paper.

Recent actions by the EPA include interim recommendations for addressing groundwater contaminated with PFOA and PFOS, published method 533 for detection of PFAS compounds in drinking water, an updated list of 172 PFAS chemicals subject to toxics release inventory reporting, a proposal to regulate PFOA and PFOS in drinking water and significant new use rule for certain PFAS in manufactured products.[65] Significant data gaps presently exist in dealing with PFAS and PFOS materials. The EPA is also leading a national effort to understand PFAS and reduce PFAS risks to the public through the implementation of its PFAS action plan and through active engagement and partnership with other government agencies and constituencies.[66]

9 Summary

Fluorinated materials play a useful and often essential role in many aspects of semiconductor processing. In our review of the technical literature, we have examined six major applications of fluorochemicals in photolithography and semiconductor processing and identified an emerging technology, nanoimprint lithography, see Table 1. These fluorochemicals are employed as components of PAGs, as components of photoresists, as elements of high-temperature polymers, and as ingredients in ARCs, BARCs, and as topcoats, frequently satisfying the "essential use" criterion. However, there is a strong societal interest in eliminating their use, and "essential use" is a stopgap situation in which replacements are actively sought. The "essential use" concept expects that PFAS uses considered essential today should be continually reviewed for potential removal or replacement by new technologies and be targeted by innovation toward alternatives. The concept does not support long-term and large-scale remediation technologies to justify the ongoing use of PFAS chemicals.

Thus, the challenges going forward are to find a means to replace PFAS components that achieve or surpass today's current performance characteristics in the following current and possible future lithography systems.

1. The use of fluorination in PAGs is to enhance the acidity (make $pK_a \ll 1$) of the acid produced in the region of exposure of a photoresist. The formation of acid to induce a solubility change is the critical step in today's chemically amplified photoresists, the workhorse family of photoresists that enable the production of the vast majority of semiconductors. The presence of a fluorinated unit adjacent to the sulfonic acid gives the acid its ability to efficiently release a proton that reacts with the resist polymer to create a solubility switch. Subsequent development forms a pattern in the photoresist. Today there is no effective alternative to a fluorinated sulfonic acid and this situation applies to chemically amplified photoresists across all wavelengths of lithography from 248 nm to EUV. Efforts to reduce the amount of fluorination in a PAG molecule have been demonstrated, but a survey of the current literature has not shown that complete elimination of

fluorination has produced a successful alternative. However, it is very likely that fluorine-free alternatives, which perform equally well and can easily take the place of the fluorinated compounds used today, will be more widely used, and developed in the coming years. Fluorinated polyimides use the presence of a fluorinated unit to improve the dielectric constant of the material and make it a better insulator while retaining excellent thermal stability. This combination of characteristics has not been effectively achieved by alternate means.

2. Other materials like poly(benzoxazole)s also receive an important performance boost from the incorporation of a fluorinated unit.
3. Antireflection coatings (ARC, BARC, and TARC) and other coatings such as topcoats or EBL use fluorinated components to limit the miscibility of this added layer with a photoresist or other organic layer in the semiconductor manufacturing process. As surface layers, they also provide barrier properties and when used as a topcoat act to protect the photoresist from interactions with the immersion fluid (currently water) used in 193-nm lithography. However, while these features can in part be replicated by other systems the necessary combination of properties (immiscibility, surface wetting properties, barrier properties, low refractive index) has not been successfully achieved.
4. Fluorinated surfactants provide a specific performance advantage since their surface energy is much lower than hydrocarbon or silicone surfactants resulting in the need for less surfactant material in formulations. Additionally, properties including very low surface energy, thermal and mechanical stability, and low refractive index provide benefits to coating and etching processes. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality), and the surface activity of fluorocarbon surfactants makes them readily useable with ARCs and photoresist materials.
5. Nanoimprint lithography may become an important technology for some specialized forms of nanopatterning, and there is interest in the use of fluoromaterials in nanoimprint lithography. Current studies have not yet fully demonstrated that fluorine-free alternatives are successful in producing fine-featured patterns in a production capable system.

Appendix

Table 1 summarizes the function of the fluorinated compounds required for the main lithographic processes. In addition, non-fluorinated alternatives and their current feasibility are shown.

Table 1 Purpose, properties of fluorocompounds for lithographic patterning and semiconductor processing.

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
PAGs	Generation of strong acid upon exposure to UV light, when fluorination acid groups. Control of location and distribution of generated acids, especially in high-resolution applications	Fluorinated sulfonium- and iodonium-acid salts/ strong electronegativity of F atom—creates superacid material capable of mixing with photoresist	All successfully demonstrated alternatives have fluorinated segments —some down to one CF_2 unit	Not yet demonstrated in completely fluorine-free materials
Antireflection coatings (top and bottom versions have different requirements)	Low refractive index, low surface energy, and good barrier properties	Largely fluorinated units in acrylate/ methacrylate/ styrene-based copolymers, very low refractive index, and excellent barrier properties	Fluorine-free alternatives known. But necessary properties not yet broadly demonstrated in 193 immersion	ARC requirements different in 193- and 193-nm immersion lithography—fluorine-free systems not fully demonstrated

Table 1 (*Continued*).

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
Topcoat (for 193-nm immersion photoresist)	Provides barrier layer for 193-nm immersion photoresists applied on top of photoresist and prevents leaching of photoactive components. Protects the photoresist from contact with immersion liquid (water)	Largely fluorinated acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
EBL (for 193-nm immersion photoresist)	Forms a protective surface layer for 193-nm immersion photoresists and prevents leaching of photoactive components. Incorporated as part of photoresist and segregates to film surface during the coating process. Protects the photoresist from contact with immersion liquid (water)	Largely acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
Polyimides (photopatternable)	Required stress buffer coat between chip and package to prevent premature device failure; especially good electrical insulating characteristics	Tetracarboxylic acid anhydride derivatives and aromatic diamines/solubility in organic solvents, low dielectric constants, and high thermal and thermooxidative stability; requires negative tone solvent to develop	Novel polyimides—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Polybenzoxazoles (photopatternable)	Stress buffer coat to prevent premature device failure; high-temperature stability and good insulating characteristics	Low dielectric constants, and high thermal and thermooxidative stability; processed using positive resist developer	Novel polybenzoxazoles—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Nanoimprint Lithography fluoropolymers	Excellent release characteristics; low surface energy and fluoromonomers reported to dissolve trapped air making them ideal for filling the micromolds of nanoimprint lithography	Fluoropolymers/low surface adherence	Silicone-based release agents	Potentially good but not yet established
Nonionic fluorinated surfactants	Improve coat quality in thin lithographic films (e.g., photoresists and BARCs); compatibility with photoresists and TARC/BARC structures; high efficiency of fluorinated surfactants requires very little additive and enables better performance	Nonionic fluorinated segments with water-soluble units	For a number of applications, alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials

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Christopher K. Ober is the Francis Bard professor of materials engineering at Cornell University. He has pioneered new materials for photolithography and studies the biology-materials interface. He received his BSc degree in honors chemistry (Co-op) from the University of Waterloo, Ontario, Canada, in 1978 and his MS and PhD degrees in polymer science and engineering from the University of Massachusetts (Amherst) in 1982. From 1982 to

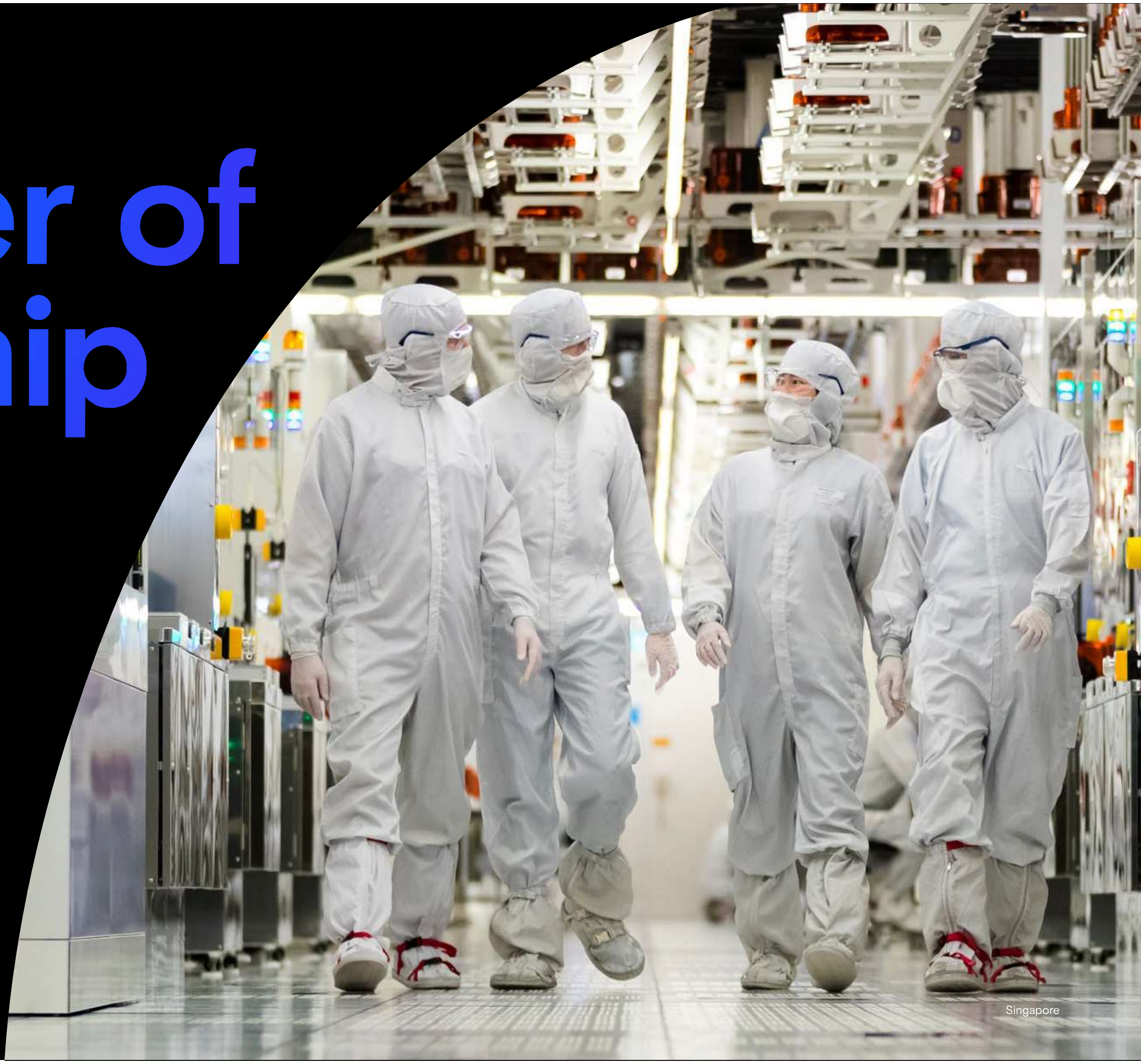
1986, he was a senior member of the research staff at the Xerox Research Centre of Canada, where he worked on marking materials. He joined Cornell University in the Department of Materials Science and Engineering in 1986. Recently, he served as interim dean of the College of Engineering. Currently, he is a director of the Cornell Nanoscale Facility. From 2014 to 2021, he served on the executive committee (its governing group) of The International Union of Pure and Applied Chemistry (IUPAC). He is a fellow of the ACS (2009), APS (2014), and AAAS (2014). He is a SPIE Senior Member (2018). He received his ACS Award in applied polymer science in 2006, the Gutenberg Research Award in 2009, the Society of Polymer Science Japan (SPSJ) International Prize in 2013, and the Japan Photopolymer Science and Technology Outstanding Achievement Award in 2015.

Florian Käfer received his PhD from the University of Bayreuth, Germany, in 2019. Throughout his PhD thesis he focused on the synthesis of new thermoresponsive polymers and their applications. Since 2018, he is a postdoctoral fellow in the Department of Materials Science and Engineering at Cornell University, supervised by professor Christopher Ober. Thereby, he is focused on the synthesis of polymer-grafted nanoparticles as well as the design and synthesis of sequence-controlled small molecules as future photoresist materials for extreme ultraviolet (EUV) photolithography.

Jingyuan Deng graduated from Nagoya University in 2016 with a BEng in applied chemistry and the University of Tokyo in 2018 with an MEng in chemistry and biotechnology. He is currently pursuing his PhD in materials chemistry under the supervision of professor Christopher Ober at Cornell University. His current research focuses on the development of novel photoresist materials for EUV lithography.

The power of partnership

Micron sustainability report 2023


Singapore

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A message from our CEO

More than ever before, the world is recognizing the importance of semiconductors — not only to our economic health and advancement, but to every aspect of modern life, from education to entertainment. Micron's vision is to transform how the world uses information to enrich life *for all*, and the solutions we make are becoming increasingly important as we move into the age of ubiquitous artificial intelligence systems powered by fast data.

In the pages of these reports, you'll see that sustainability is not just central to Micron's vision, mission and values, it is also integral to our long-term strategic plans. We believe we also have a responsibility to help lead sustainability improvements across our industry. None of these goals are possible without strong partnerships. We actively work with industry peers, suppliers and customers worldwide to set new standards for the sustainability of semiconductor production.

Manufacturing semiconductor products is a resource- and power- intensive business, and careful management and planning are required to ensure efficient production. In 2022, Micron announced several critical expansions that will be central to the company's future, including investments in Boise, Idaho, and Clay, New York. Both projects are pivotal to Micron's manufacturing strategy to meet DRAM demand over the decades ahead. With the support of the CHIPS and Science Act, these projects stand to make a significant impact on U.S. semiconductor manufacturing leadership. Each will also demonstrate leadership techniques for energy conservation and sustainability. We are also making significant investments in community and education around these expansions. These investments will help us create sustainable growth and train the workforce we need to drive advanced semiconductor manufacturing.

Our aim with this report is to provide a detailed accounting of our progress toward our sustainability goals and note specific contributions over the past year. It also shares our vision for sustainable development in the years ahead. Below are a few highlights.

Environment

- Emissions: We expanded our climate initiative goals early last year, working toward targets to reach net zero greenhouse gas emissions in our operations (scope 1) and purchased energy (scope 2) by 2050, with a 2030 milestone to reduce scope 1 emissions from our 2020 baseline by 42%. These complement our existing goal to achieve 100% renewable energy for existing U.S. operations by the end of 2025.
- Energy, water and waste: We continue to make our operations more efficient and sustainable, with aspirational targets of 100% renewable energy, 100% water conservation, and zero waste to landfill. This report outlines our participation in alternative energy facilities, as well as water conservation and river restoration projects in our communities.
- Sustainable financing: Micron continues to lead in sustainable financing. We have executed $3.7 billion in credit facilities linked to our sustainability performance and achieved our 2022 performance metrics in connection with this credit. The $1 billion green bond we issued in November 2021 supports Micron's commitments to environmental performance and LEED-certified buildings.

Social

- Equity and representation: We continue to maintain global pay equity for women and people with disabilities globally, as well as across race/ethnicity and veteran status in the U.S. and race/ethnicity for Malays in Singapore. We actively promote a culture of inclusion and focus our educational outreach on bringing more women and underrepresented groups into semiconductor fields.
- Team engagement: We grew participation in employee resource groups to 39% of our workforce, a nearly 50% increase from fiscal year 2021 (FY21). Micron is in a leadership position in this metric.
- Diverse suppliers: Our spend with diverse suppliers is growing. In FY22, we achieved $454 million in spend with diverse suppliers, exceeding our goal of $404 million.
- Diverse financial institutions: In FY22, we achieved our goal to have $500 million in cash investments managed by underrepresented financial firms.

Governance

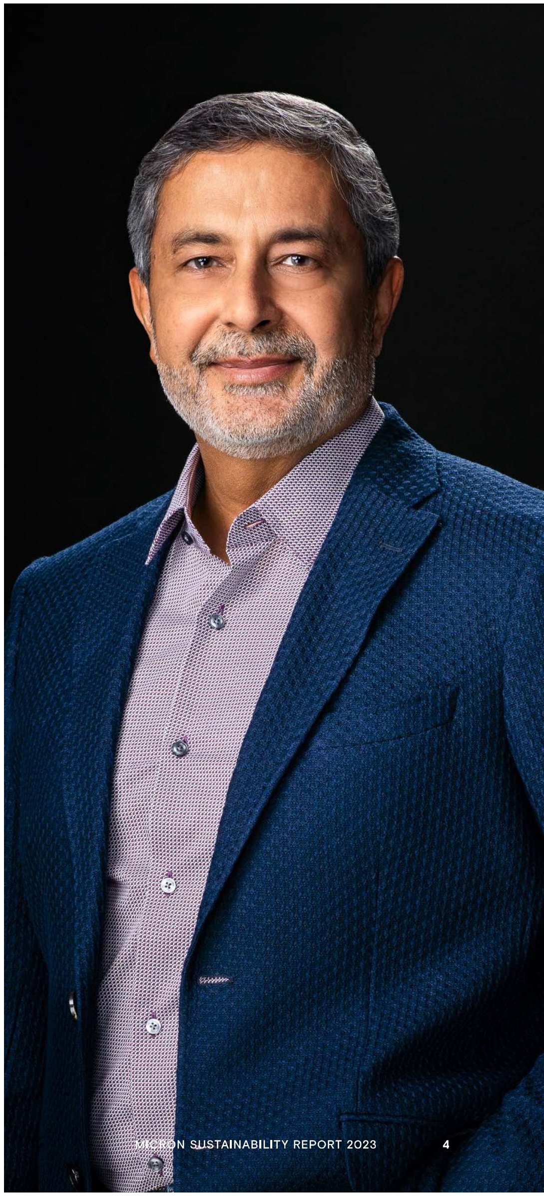
- Ethics: I personally place a high emphasis on integrity with our team, and we institute regular training so that every team member understands and adheres to our code of conduct and related policies.
- Responsible sourcing: We have a number of programs focusing on responsible minerals sourcing, in addition to supplier diversity, environmental performance and human and labor rights.

Micron continues to make strong progress toward our sustainability, community and governance goals, and I'm proud of the work represented in these pages.

I hope you enjoy reading our 2023 sustainability report and progress summary, and we invite your feedback. You can reach us by emailing sustainability@micron.com.

Sanjay

Sanjay Mehrotra
President and CEO, Micron Technology



From: Balduzzi, Kevin M (DEC) <kevin.balduzzi@dec.ny.gov>
Sent: Tuesday, October 31, 2023 6:59:34 PM (UTC+00:00) Monrovia, Reykjavik
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Subject: NYSDEC Micron White Pine Draft Scope Response

Good afternoon Director Petrovitch

Attached are DEC’s comments on the Draft Scope for the Micron Semiconductor Fabrication Draft Environmental Impact Statement.

Thank you.

Kevin M. Balduzzi

Regional Permit Administrator, Division of Environmental Permits

New York State Department of Environmental Conservation, Region 7

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NEW YORK STATE | Department of Environmental Conservation

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October 31, 2023

Robert Petrovitch-Director
Onondaga County Industrial Development Agency
335 Montgomery Street, 2nd floor
Syracuse, NY 13202

RE: SEQR Draft EIS Scoping Comments-Micron Semiconductor Fabrication
White Pine Industrial Park, Town of Clay, Onondaga County
DEC ID 7-3124-00575

Dear Mr. Petrovitch:

The New York State Department of Environmental Conservation (DEC) reviewed the "Draft SEQRA Scope of Work" and Full Environmental Assessment Form (EAF) documents, received on September 25, 2023, associated with the State Environmental Quality Review (SEQR) for the proposed Micron Semiconductor Fabrication project (Proposed Project) proposed at the White Pine Industrial Park in the Town of Clay. Based on current information, DEC's expected jurisdiction(s) under the Environmental Conservation Law (ECL) are listed in Attachment A. Please note that DEC may identify additional jurisdictions as information becomes available.

DEC offers the following comments on the draft scope for consideration in the preparation of the final scope for the Draft Environmental Impact Statement (DEIS).

General Comments

1. Section 5.3.1 outlines technical studies to be performed for the DEIS. Both the "Geology, Soils, and Topography" and "Utilities & Infrastructure" sections briefly address stormwater, but do not include a specific heading for stormwater management. A separate chapter should be included for an evaluation of stormwater runoff (industrial and construction) and water quality. This section should identify the current requirements of DEC's State Pollutant Discharge Elimination System (SPDES) Permits, including the Construction General Permit (GP-0-20-001) and Multi-Sector General Permit (GP-0-23-001). The DEIS should evaluate how these requirements will be met. Sufficient information should be developed to identify the approximate size and location of necessary stormwater management measures and outfalls during and after construction. In addition, due to the scale of the project and the anticipated need to have large areas of soil exposed at any given time, the DEIS should evaluate the soil characteristics that may cause or contribute to erosion on site. A reference should be developed to identify any supporting information or reports that will be included as an

appendix. The Stormwater Pollution Prevention Plan (SWPPP) needs to address hydraulic changes pre- and post-construction, and all changes to hydrology from filling in any wetlands, streams, and drainageways on site. It is important to note that while DEC's Region 7 Division of Water and the Town of Clay will jointly evaluate the required SWPPP prepared by the Applicant, responsibility for the approval of the SWPPP lies with the Town of Clay as per the municipal separate stormwater sewer systems (MS4) General Permit (currently GP 0-15-003).

When considering an overall approach to stormwater management at the Micron site, the DEIS should pay particular attention to Chapter 3 of the New York State Stormwater Management Design Manual (SMDM). This chapter focuses on Stormwater Management Planning. The SMDM requires a specific planning process when addressing stormwater management on a project site and guides the planner through steps to maintain pre-development natural hydrologic conditions of the site by application of environmentally sound development principles, such as green infrastructure, as well as treatment and control of runoff discharges from the site.

Chapter 2 Project Alternatives and Description of the Proposed Project

2. The scoping documents only consider two development alternatives: build and reduced-scale. DEC recommends identifying additional potential development alternatives considering design and configuration changes to avoid or minimize potential impacts to wetlands, streams, and other sensitive natural resources. The area east of Burnett Road contains a large, forested wetland complex and portions of Youngs Creek; additional consideration should be given to avoiding development in this area.

3. Please include a discussion of potential alternatives and mitigation that could reduce energy and fuel demands during construction and the long-term operation of the facility, including renewable energy sources.

Chapter 10 Natural Resources

In addition to the details in Section 5.3.1 Technical Studies-Natural Resources, DEC believe the following items should be evaluated:

4. The Utilities & Infrastructures narrative states that substantial off-site infrastructure improvements are required to support the Proposed Project. To the extent they can be included, natural resource impacts associated with these projects should be evaluated and described in the DEIS. The DEIS should also assess the presence of, and impacts to, wetlands, waterbodies, and threatened and endangered species for all linear utility construction projects, new infrastructure such as pump stations, and the expansion of existing infrastructure such as the Oak Orchard Wastewater Treatment Plant and the Lake Ontario water filtration plant. For linear pipeline construction projects, DEC recommends

considering and discussing horizontal directional drilling (HDD) pipelines under streams and wetlands to the greatest extent practicable.

5. The DEIS should include a table summarizing the amounts and types of wetlands, streams, and other waterbodies on the Proposed Project site, and those associated with the previous comment. The table should also quantify the impacts on these resources for phases 1 and 2, and the cumulative of both phases.

6. The natural resource section states that potential adverse wetlands impacts will be assessed, and potential mitigation identified. The DEIS should also include a complete discussion on the avoidance and minimization of wetlands impacts, which are the first two analyses required prior to considering wetland mitigation under implementing regulatory programs for Section 404 of the Clean Water Act and Article 24 of the New York State Environmental Conservation Law.

7. The on-site and off-site wetland mitigation is described as “enhancement” in this section. The DEIS should include and discuss wetland creation and restoration prior to consideration of enhancement. Please see attachment B, which discusses DEC wetland mitigation requirements. This information should be discussed in the DEIS.

8. To the extent it is available, the DEIS should include the Proposed Project’s onsite wetland delineation and compensatory mitigation package being developed by Micron and its consultants.

9. The DEIS should address and discuss stream mitigation that will be completed to offset impacts to waterbodies on the Proposed Project site.

10. The DEIS should include an assessment of the functions and benefits of all the streams and wetlands on the Proposed Project site.

11. The Acoustic Bat Survey Report and the Grassland Breeding Bird Survey Report, prepared for Micron New York by AKRF Inc., should be discussed and appended to the DEIS. Additionally, DEC's "Grass Land Bird Mitigation Requirements" is included as attachment C to this document, and the DEIS should reference these requirements in the mitigation discussion for grassland bird habitat impacts.

12. The natural resource analysis of the Proposed Project should also include details on wildlife that likely use the site based on habitat types and any ancillary observations made by on-site natural resource consultants. Additionally, the DEIS should discuss the impacts on the species associated with converting these habitats to an industrial site.

13. The C-Class Youngs Creek (Water Index Number ONT-66-11-14), located east of Burnett Road, is continuously connected to the Oneida River (Water Index Number ONT-66-11). with no known impassable barrier The site plan OCIDA included with the draft scope show portions of the Proposed Project filling

Youngs Creek. The DEIS should include information on any portions of Youngs Creek being filled or "culverted" and discuss how water in the stream will be managed. In addition, a biological survey of the stream on the Proposed Project site should be completed to assess fish species composition in this stream. The DEIS should also detail the effects on these species associated with any impact on the stream from the Proposed Project. This analysis should consider upstream and downstream impacts, as well. The DEIS should evaluate upstream and downstream instream habitat enhancement projects to mitigate potential onsite impacts.

14. The DEIS should include further details to identify how surface and subsurface water resources will be evaluated. The DEIS should address potential on-site and off-site flooding and impacts to surface and groundwater. This section should include an evaluation of impacts on surface water volume, including streams, wetlands, and drainageways, and groundwater elevations during and after construction. Additionally, it should detail impacts on groundwater levels, quantity, and quality from filling any wetlands on site. The analysis should include a groundwater hydrologic and hydraulic analysis of the impacts of placing fill in watersheds contributing to the project area. Special consideration should be given to filling wetlands, drainage areas, Youngs Creek, and its tributaries, including unmapped streams, and evaluate how fill may affect the surface and subsurface water flow and drainage patterns in the area and surrounding properties. The DEIS should also consider factors such as increased surface runoff, potential water flow redirection, and impacts on nearby waterbodies or stormwater management systems. Portions of this information are also needed as part of the SWPPP review. In the hydrologic/hydraulic analysis, please consider:
    a. Pre- and post-construction design points (i.e., receiving waterbodies).
    b. Wetland cover types.
    c. Pre- and post-construction ordinary water levels in streams and wetlands.
    d. Hydraulic modeling to simulate the effects of cut and fill on water flow, flood levels, and drainage patterns. The modeling should include all the surrounding areas that will be affected by this development.

15. The DEIS should discuss how drainage will be maintained and how potential flooding would be mitigated.

16. DEC supports documenting floodplains and recommends re-evaluating and updating floodplain mapping for any significant grade changes.

17. Dewatering of groundwater during construction should be discussed including best management practices that may be employed to avoid and mitigate impacts to the resource.

Chapter 11 Solid & Hazardous Waste

18. The DEIS should evaluate the impact potential population growth associated with this development will have on the management of solid waste and recyclables,

as well as the anticipated amount of waste and recyclable material generated by Micron. Onondaga County law requires that waste generated within the County be disposed of at the Onondaga County Resource Recovery Waste to Energy Facility. This evaluation should consider the existing waste management network's capacity, its ability to accept increased volumes associated with the Proposed Project, and the potential for population growth. If the evaluation includes an expansion of any waste or recycling facilities or the use of the Onondaga County landfill, approximate dates of the expansion(s) should be included that correspond with Micron's expected buildout.

19. The DEIS should include a discussion of hazardous waste, listed in 6 NYCRR Part 371.4, that the Proposed Project may generate. Details should include the type of hazardous waste anticipated to be generated, approximate volumes, storage methods, disposal options, and how the facility will operate following hazardous waste regulations found at 6 NYCRR Part 370-373.

20. Mitigation considerations for solid waste should include an evaluation of processing methods and chemicals used in the manufacturing process to determine if alternative methods could reduce the generation of hazardous waste.

Chapter 13 Air Quality

21. DEC offers the following regarding comments the air quality modeling and impact assessment that will be prepared to support the air pollution control permit:
    a. The air quality modeling included in the DEIS should include an air quality impact evaluation or dispersion modeling analysis for a variety of emission sources including major sources, air toxic sources, and any sources that appear likely to contravene an applicable ambient air quality standard. DEC developed the DAR-10 guidance document, *NYSDEC Guidelines on Dispersion Modeling Procedures for Air Quality Impact Analysis*, found at https://www.dec.ny.gov/docs/air_pdf/dar10.pdf, which details the recommended procedures for conducting ambient air quality impact analyses. The applicant should submit a modeling protocol to DEC for approval prior to performing any dispersion modeling analyses.
    b. If the impact assessment includes a private, pre-construction, on-site air quality monitoring network, the plan will need prior DEC approval. Guidance for the establishment, maintenance, and reporting requirements of private air monitoring networks can be found in DAR-2, 6 NYCRR Part 231-12.3 and Appendix B to 40 CFR Part 58.
    c. If one or more applicable requirements or proposed compliance certification sections require the use of a continuous emissions monitoring (CEM) system, the analysis should develop and include a continuous emissions monitoring plan.
    d. The analysis should include applicable RACT/BACT/LAER demonstrations, as well as Appropriate Emission Reduction Credit (ERCs) demonstrations and analysis

    e. The analysis should include, as applicable, a Toxic Impact Assessment and Environmental Rating Demonstration pursuant to the requirements of 6 NYCRR Part 212. DEC developed DAR-1: *Guidelines for the Evaluation and Control of Ambient Air Contaminants Under Part 212* found at https://www.dec.ny.gov/docs/air_pdf/dar1proposed.pdf for reference.

22. DEC recommends that a copy of the Air Title V permit application and supporting information be appended to the DEIS to the extent it is available.

Chapter 14 Greenhouse Gas and Climate Change

23. The Proposed Project is subject to the mandates of the Climate Leadership and Community Protection Act (CLCPA) and therefore requires an analysis pursuant to Section 7(2) of CLCPA. Please see DEC Program Policy DAR-21 for guidance on preparing the CLCPA analysis. DAR-21: https://www.dec.ny.gov/docs/air_pdf/dar21.pdf.

24. DEC recommends evaluating and quantifying GHG and co-pollutants of mobile emissions sources during construction and when the plant is in operation. Additionally, alternatives and mitigation that reduce GHG and co-pollutants from mobile emission sources must be considered.

25. Among other CLCPA requirements, the Proposed Project will result in an actual increase in greenhouse gas (GHG) emissions, including both direct and indirect GHG emissions. Therefore, the DEIS should include a discussion of the justification for the Proposed Project, along with the technical and economic feasibility of any alternatives or GHG mitigation measures to address the increase. Any such mitigation should take place at the New York facility or in the immediate area, rather than in other cities or out of state. DEC offers the following details and illustrative examples regarding potential alternatives and mitigation the DEIS could consider:
    a. Given the large site footprint, the facility should explore geothermal heating and cooling. Further details about the plant's operating profiles (MW) and the annual heating/cooling loads (MWh) would help determine the balance of heating and cooling and how much of the thermal process loads could be efficiently supported by a ground loop heat exchanger (geothermal). This would require information about the size of the manufacturing plant, including its thermal load profiles, peak loads, and annual loads.
    b. Installation of solar arrays to provide power directly to the facility and minimize energy demands for facility operation.
    c. Assessment of mobile source emissions consistent with guidance from the New York State Department of Transportation (NYSDOT).
    d. Use of electric powered alternatives wherever fossil fuels are typically utilized.
    e. Discuss of the use of bus or light rail connecting residences in the Syracuse metropolitan area.

Chapter 16 Utilities and Infrastructure

26. DEC's comment 4 noted the DEIS should include a discussion of discuss natural resource impacts for constructing utility connections, such as clean water, wastewater, electric, gas, telecommunications, and roadway expansions. The information in the Natural Resource chapter relevant to the Utilities and Infrastructure should also be referenced in this section of the DEIS.

27. DEC recommends developing a phasing plan, which coincides with Micron's incremental expansion, for the buildout and expansion of all utility upgrades required to meet the Proposed Project's anticipated demands. The phasing plan should include sewer extensions, pumping systems, new clean water source(s) and distribution systems, wastewater plant upgrades, and gas and electricity distribution infrastructure.

28. The DEIS should also provide adequate information to demonstrate that all utility upgrades will be constructed, operational, and sufficient to accept waste from or provide service to the Proposed Project. Please see Attachment D, which lists the typical details DEC reviews for a sewer extension and force main approvals.

29. The DEIS should provide adequate details on the Proposed Project's wastewater loading, flow, and discuss the on-site wastewater pretreatments.

30. As stated in the section 1.1.2 Project Description Water Supply, the Proposed Project has an anticipated total future demand of approximately 48 million gallons per day (MGD). Withdrawals of this scale have the potential to impact fisheries resources through impingement and entrainment. The DEIS should provide details on the design specification of the new lake water intake structure and intake screening and assess potential fish impingement mortality and entrainment. Any additional measures to avoid and minimize fish impingement and entrainment should also be discussed (e.g., variable speed pumps, water reuse/conservation, etc.).

31. The DEIS should consider and include details and a summary of water conservation and reuse practices to mitigate water demands.

32. The DEIS should include a summary of any investigated and considered alternative water sources.

33. Water withdrawals within the Great Lakes Basin are subject to the requirements and provisions of the Great Lakes-St. Lawrence River Basin Water Resource Compact, found at the link below. The DEIS should discuss and address how the proposed water withdrawal and use is consistent with the Compact and all state, local, and federal laws.
    https://www.glslcompactcouncil.org/media/nmzfv5jq/great_lakes-st_lawrence_river_basin_water_resources_compact.pdf

Chapter 17-Use and Consumption of Energy

34. DEC recommends renaming this chapter as “Use and Conservation of Energy.”

35. The DEIS should contain a description of energy sources to be used during both construction and operational phases of a project. Anticipated levels of demand or consumption should be quantified or estimated as accurately as possible given available information. In addition, the DEIS should discuss alternatives and mitigation that could reduce energy and fuel demands during construction and long-term operation. The 2018 amendments to SEQR regulations require all New York State agencies to evaluate such GHG impacts in a new section specifically dedicated to climate change and its impacts. Proposed energy conservation measures that go beyond the minimum requirements of the State Energy Conservation Construction Code (9 NYCRR Parts 7810 through 7816) should be specifically identified, such as LEED or Energy Star. Please refer to Chapter 5, Section C, Item 44 on page 123 in DEC’s SEQR Handbook, found at https://www.dec.ny.gov/docs/permits_ej_operations_pdf/seqrhandbook.pdf. The information and energy conservation measures discussed in this section may be applicable and cross-referenced to the Greenhouse Gas Emissions and Climate Change chapter.

Thank you for the opportunity to provide written comments on the DEIS for the Micron project. DEC hopes that OCIDA will find the information helpful in the preparation of the DEIS for this Proposed Project. If you have any questions on the information provided in this letter, you may call me at 315-426-7493, or email me at kevin.balduzzi@dec.ny.gov

Sincerely,

Kevin M. Balduzzi

Digitally signed by Kevin M.
Balduzzi
Date: 2023.10.31 14:49:35
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Kevin M. Balduzzi
Regional Permit Administrator
Division of Environmental Permits

Cc Thomas Berkman, DEC Deputy Commissioner and General Counsel
Katharine Petronis, DEC Deputy Commissioner
Dereth Glance, DEC Regional Director, Region 7
Daniel Whitehead, DEC Division of Environmental Permit, Director
Margaret Sheen, DEC Regional Attorney, Region 7
Scott Sheeley, DEC Chief Permit Administrator

Att. Attachment A- NYSDEC’s Jurisdictions Associated with Micron-White Pine Development.
Attachment B- Proposed Project Wetland Mitigation Requirements
Attachment C- Grassland Bird Mitigation Requirements
Attachment D- Proposed Project Wastewater Sewer Extension Information

Attachment A

NYSDEC's Jurisdictions Associated with Micron-White Pine Development

- Water Quality Certifications (401 certifications), Section 401 of the Clean Water Act, U.S. Public Law 95-217, and 33 USC 1341 (see section 608.9[c] of this Title) (implemented by 6 NYCRR Part 608): for projects which impact federally regulated waters of the US require Federal approval under Section 404 of the Clean Water Act.
- Use and Protection of Water, ECL article 15, title 5 (implemented by 6 NYCRR Part 608)
- State Pollutant Discharge Elimination System (SPDES), ECL article 17 titles 7 and 8, (implemented by 6 NYCRR Part 750), General Permit for Stormwater Discharges from Construction Activities (GP-0-20-001) and Multi-Sector General Permit for Stormwater Discharges Associated with Industrial Activity (GP-0-23-001).
- Air Pollution Control, ECL article 19, (implemented by 6 NYCRR Parts 201 and 231): including construction and operation of a new emission source or a modification to an existing emission source of air contamination, and construction of indirect sources of air contamination.
- Endangered and Threatened Species of Fish and Wildlife; Species of Special Concern; Incidental Take Permits, ECL article 11, (implemented by 6 NYCRR Part 182) for the take of state-listed, endangered bird species occupied habitat.
- Water withdrawals, ECL article 15, title 15 (implemented by 6 NYCRR Parts 601 and 602).
- Freshwater Wetlands, ECL article 24, (implemented by 6 NYCRR Parts 662-663).
- Solid Waste Management, ECL article 27 title 7, (implemented by 6 NYCRR Part 360).
- Industrial Hazardous Waste Management, ECL article 27 title 9, (implemented by 6 NYCRR Part 373).

Attachment B

Proposed Project Wetland Mitigation Requirements

Mitigation proposals should be based on plans containing clear and specific details, short and long-term goals and measurable performance criteria. Wetland design must provide for persistence of the wetlands over time with the capacity to successfully adapt to changing conditions.

The plan must include but is not limited to:

- Acreage of proposed mitigation at the DEC-accepted, replacement ratios which may vary dependent on wetland cover types and lost functions and values.
- Location of mitigation site(s), including such information as site descriptions, topography, and proximity to DEC mapped Freshwater Wetlands. Mitigation sites should be located as close as possible to the impacted wetlands. Explore all possible locations within the Hydrologic Unit Code (HUC) 12 watershed areas first. After exhausting all potential mitigation sites near the impacted areas, the search may be expanded beyond the HUC 12.
- Analysis of lost functions and values (ECL § 24-0105) and how mitigation plans will compensate for these losses.
- A plan to create wetland hydrology at the mitigation site for each cover type, including water source, water budget and monitoring plan.
- The mitigation plan must provide for a proportional replacement for all cover types lost; forested, shrub/scrub, emergent marsh open water wetland and wet meadow with native wetland herbaceous and woody plant species
- A Planting Plan consisting of a site plan showing the locations of plantings/seedings, the source of plant materials, a species list, and performance criteria used to measure success. The Monitoring Plan must include a description of annual monitoring, the duration of which is dependent on the cover type must be described. For example, forested wetlands must be monitored for successful replacement for a minimum of 10 years. Corrective actions, including re-planting, to achieve sustainable hydrology and control of invasive species must be taken promptly until the mitigation goals are met. Annual monitoring reports will include observed percent coverage of the planned vegetation cover type, hydroperiod, percent coverage of invasive species, and an analysis of any deficiencies, along with corrective actions to achieve the goals of the mitigation plan.

Attachment C
Grassland Bird Mitigation Requirements

The primary threat to grassland bird species in New York is habitat loss. As a result, the best mitigation method is habitat creation, habitat enhancement, and habitat management. Field size is a significant predictor of use by listed grassland birds.

For this reason, acceptable habitat mitigation should include fields of similar size to those taken, with all fields used for mitigation being at least 25 acres in size. A large field of 100 acres or more is generally preferred over several fields meeting the minimum size criteria. The benefits of mitigation are quantified based on the total acreage proposed for mitigation, the conservation plan proposed for those acres, and the length of time that the conservation plan will be implemented. Although parcels may include wetlands, wetland acres are not credited for grassland or species mitigation as they are already protected through Article 24 or their own mitigation process.

Mitigation actions must be either completed before initiation of construction of the project in the occupied habitat or an implementation agreement must be in place that demonstrates Micron has fully funded the proposed mitigation plan, and all entities responsible for its implementation sign off that they can ensure the work is implemented.

Approvable mitigation strategies must demonstrate that they will accomplish a net conservation benefit to the species impacted, such that the affected species is better off after the completion of the project than if the Micron development had not been implemented. Baseline mitigation ratios are 3:1 for impacts to breeding habitat and 1:1 for wintering habitat, based on the assumption that habitat mitigation will employ management practices that will result in better habitat than the habitat being taken. Ratios may be reduced if the applicant can demonstrate that their proposed management will demonstrably improve the status of the impacted species. Factors that can potentially decrease the ratio of breeding habitat required for mitigation include the following:

1. At least one proposed mitigation area is a larger contiguous grassland than the largest field taken by the project.
2. At least one mitigation parcel is greater than 100 acres of contiguous habitat.
3. The proposed mitigation areas are immediately adjacent to other protected grassland habitats that are at least 25 acres in size.
4. Proposed mitigation will result in the removal of known threats from parcels of known occupied habitat of the species being taken similar in size to those taken (>25 acres).
5. Proposed mitigation lands are within recognized important landscapes for grassland birds (e.g., Grassland Focus Area, Important Bird Area, Raptor Concentration Area).

6. The proposed mitigation area can be protected and managed for a period of time that extends beyond the 30-year life of the facility (e.g., 40 years, 50 years, or in perpetuity).

Attachment D
Proposed Project Wastewater Sewer Extension Information

Please provide the following information regarding the proposed facilities' wastewater sewer extension:

1. Conveyances
    - Confirmation from Onondaga County that its facility can accept the expected additional flows and organic loadings from the extension.
    - Location of the proposed sewer extension.
    - Expected hydraulic flows (gpd) and organic loadings (lb/d) in the proposed flow.
    - Design plans and specifications stamped and signed by a Professional Engineer licensed in the State of New York. Design plans must include plan and profile views of the proposed extension. These must be submitted in hardcopy.
    - Plan indicating the downstream routing of the sewer to the Oak Orchard WWTP detailing all sewer diameters, theoretical capacities and actual capacities during peak flows.
    - Design plans indicating lots served, property lines, existing and proposed streets (if applicable), storm drainage, existing and proposed utilities and easements, direction of flow, contour lines, placement of manholes, rim and invert elevations for pipes and type of pipe selected, and special construction (i.e. drop manholes, crossing of waterways).
    - Design capacity and how this capacity was determined.
    - Detailed drawings and specifications for manholes, pipe bedding and construction, leakage testing, deflection testing, notes indicating sewer and waterline separation distances.
2. Pump stations
    - Type of pump station (wet well/dry well); package or built-in-place; number and type of pumps chosen (submersible or suction lift).
    - Maximum flow expected and how this was calculated.
    - Provide pump curves and head calculations.
    - Accessibility of pump station for maintenance and protections for personnel, including ventilation.
    - Provisions which consider buoyance of the station and its structures.
    - Chemical storage and pumps (if applicable).
    - Detail of bar rack (if applicable).
    - Corrosion prevention considerations.
    - Location of all valves and control systems.
    - Provisions for alarm systems and emergency operation.
    - Bypass plan (if applicable).

- Design plans (with requirements as noted above).
- Design specifications covering all equipment and appurtenances, construction procedures, testing of piping and equipment
- Design plans and specifications stamped and signed by a Professional Engineer licensed in the State of New York. Design plans must include plan and profile views of the proposed extension. These must be submitted in hardcopy.

From: Don Hughes <dhughes171@gmail.com>
Sent: Wednesday, November 1, 2023 3:03:40 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Fwd: Micron DEIS Scoping Comments

To: Onondaga County Industrial Development Agency
ATTN: Micron Project
335 Montgomery Street, 2nd Floor
Syracuse, New York 13202

From: Donald Hughes,
Conservation Chair, Central & Northern New York Sierra Club Group

Re: Draft Scoping Document for the proposed Micron Semiconductor Fabrication facility in Clay, NY

I wish to submit, on behalf of the approximately 3000 members of Sierra Club who reside in our territory, the attached comments. You should have received the same documents from John Przepiora earlier today. Would you kindly confirm receipt of these comments with four supporting attachments?

thank you,
DH

Donald J. Hughes, P.E., Ph.D.
dhughes171@gmail.com
315.214.4060
=============================
Hughes Environmental Consulting

157 Strong Ave,
Syracuse, NY 13210
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"*dans les champs de l'observation, le hasard ne favorise que les esprits préparés*" ("In the field of observation, chance favors only the prepared mind") **Louis Pasteur,** French chemist and microbiologist (1822 -1895)

To: OCIDA

On behalf of the following individuals and myself working together as the CNY Sustainability Coalition, and who have signed the attached memorandum on behalf of our respective organizations, I am submitting the attached comments and supporting 4 attachments (A1-A4) pursuant to the public comment period for the Micron project SEQRA DEIS scoping. Please do not hesitate to contact me if you have any questions. Thank you for the opportunity to comment on this important document and for allowing an extension of time for filing this.

Donald Hughes

Conservation Chair, Sierra Club Central & Northern NY Group

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Thank you again. We look forward to working with you as this project moves forward.

John Przepiora

Vice-President & Director

GreeningUSA, Inc.

(315) 382-3829

…Advocating for sustainable communities

to the benefit of local economies and environments.

To: Onondaga County Industrial Development Agency (OCIDA)

From: The undersigned individuals and representatives of environmental and sustainability organizations of Central New York, aka, "CNY Sustainability Coalition"

RE: Comments on the **DRAFT SEQRA SCOPE OF WORK (**draft Scoping Document or draft scope**),** dated September 12, 2023 for the proposed **MICRON SEMICONDUCTOR FABRICATION plant in** Clay, NY.

The SEQR Handbook, 4th Edition, dated 2020, states: "A written scope of issues developed through a public scoping process benefits the lead agency and the sponsor by providing explicit guidance as to what criteria will be used to determine whether a submitted draft EIS is adequate. The written scope provides a means of ensuring that significant topics have not been missed and that the level of analysis in the EIS satisfies standards established during the scoping process."

While the draft Scoping Document offers a reasonable approach to defining significant environmental impacts in certain areas, we believe it is inadequate in other areas, especially ith respect to chemicals and energy usage. We offer the following comments:"

4.3 ALTERNATIVES TO BE ANALYZED IN THE DEIS

The SEQR Handbook stipulates (p 100) the scoping process should "Define reasonable alternatives for avoiding specific impacts which must be included in the EIS, either as individual scenarios or a range of alternatives."

Two "build" alternatives are presented in the draft scope:

1) Full construction and operation of four fabs over an approximately 20-year period
2) Reduced Scale: construction and operation of two fabs over a shorter period.

This analysis is too limited. It does not address a proper range of alternatives. For example, the impacts on Greenhouse Gas Emissions and Climate Change will vary tremendously depending on the amount of renewable energy that Micron is able to procure. Micron has expressed a desire to achieve 100% renewable energy for electricity, but that may be unrealistic for the construction timeframes that are envisioned. Micron's electricity demands are projected to be very large (7.15 billion kWh/year for Phase 1; 16.17 billion kWh/year for Phase 2), so it would be far more realistic to evaluate a range of alternatives which take into account the time needed to construct a supply of renewable energy sources (wind, solar, and hydropower). The evaluation must assess the feasibility of achieving 100% of electricity from renewable sources for each Phase of the project.

It has been estimated (Plumley, pers. communication) that it would take 1200 3MW wind turbines to generate the power needed for Phase 2.

It would also be useful to consider alternatives with different phasing such as construction of a single fab followed by a reassessment of impacts prior to construction of a second fab. In a

multi-phase approach, lengthening the time frame may be an appropriate way to manage the community impacts while allowing for the potential for technological changes that may affect chip fabrication or building and/or transportation improvements which may reduce impacts. A long term approach may allow the community to adjust to the growth and assimilate it with less adversity.

5 ANALYSIS FRAMEWORK

Preparation of the DEIS must conform to 6 NYCRR Part 617.9(b). The DEC's SEQR Handbook asserts that "An Environmental Impact Statement (EIS) is a document that impartially analyzes the full range of potential significant adverse environmental impacts of a proposed action and how those impacts can be avoided or minimized."

Section 5.1 of the draft scope states: "The Proposed Project will be evaluated for potential significant adverse effects to the Project Site and **applicable study areas** for all relevant environmental technical categories in accordance with applicable SEQRA requirements."

'Applicable study areas' is a vague phrase which needs to be better defined specifically in an overarching, comprehensive manner. Answers to questions are directly related to the question asked; asking the wrong question leads to wrong answers. We recognize that each of the sub-sections in 5.3.1 may define study area specific to the particular analysis and that may be appropriate, however, we believe that the final scope document should include a stand alone section devoted to defining the study area clearly in order to convey the breadth with which the impacts of this project will be manifest and establish the full areal extent of the analytical framework.

This project requires an ecosystem approach that considers the regional impacts on the environment, the economy and society. The impacts must be determined and assessed for their equitable distribution and for their adverse impacts that are detrimental to the region's short and long term sustainability. This is not a typical project. It is enormous in scale, unprecedented for the region and with potential for egregious environmental impacts. It has been suggested by Onondaga county officials that the Onondaga County population may increase by 25% or 125,000 over the full build-out period (estimates of regional growth are unknown to this reviewer). The scale of the environmental review process, and the expertise required to carry it out, must rival the project's enormity.

OCIDA must assure that the final scope for each of the technical sections of the DEIS is specified with rigor, that the appropriate and necessary expertise is utilized in the writing of each scope item, that the study areas are broad enough and that each analysis is based on not only the current standards, but also reasonably presumed standards that will be in force throughout the build out and operational period of the proposed project.

Finally, The SEQR Handbook requires the following in the scoping of the identified reasonably expected impacts:

- Describe the extent and quality of information needed;
- List available sources of information;
- Specify study methods or models to be used to generate new information, including criteria or assumptions underlying any models, and define nature and presentation of the data to be generated by those studies and models.

In many of the areas included in section 5.3 the standards for information and methods appear to be inadequate. The scoping document must require high standards be applied to the analysis and specify information and methods to be utilized. To do less shortchanges the community and can lead to disastrous and unanticipated consequences.

The biggest challenge presented by this project is the enormity of it; in order to fulfill the dreams which this project offers in a just, equitable, economically and environmentally sustainable manner, the review process must be equally enormous, impartial and thorough.

5.3 **METHODOLOGIES FOR TECHNICAL ANALYSES**

Comments on specific sections are listed below.

Many of the methodologies outlined in Chapter 5, Analysis Framework, are very comprehensive and appropriate for a project of this size. We fully support the inclusion of each of these categories. However, we have noted certain areas where the level of detail and intent seems inadequate as follows.

5.3.1 TECHNICAL STUDIES

- LAND USE, ZONING, AND PUBLIC POLICY

  COMMENT: Why isn't the city of Syracuse explicitly included here? Seems to be a major omission.

- COMMUNITY FACILITIES/OPEN SPACE AND RECREATION

  COMMENT: Here is an assessment of impacts on community emergency services, fire safety requirements included in building code and site access requirements of the emergency service providers.

  Lumped in is assessment of growth impacts on educational facilities and parks and recreational facilities. The study area seems ill defined and critical to this analysis. Some reference to Towns of Clay and Cicero seems to limit the study area to these two towns; is that what is intended? If so, it is probably too narrow an area particularly when the cumulative and indirect impacts are considered.

  This section is poorly organized and deserves to be rewritten to define more clearly what are the parameters to be studied and analyzed relevant to police, fire and other emergency services; schools; parks and rec facilities. Absent from the community facilities most notably is the health care and hospital system.

- SOCIO-ECONOMIC CONDITIONS

  COMMENT: The study area is defined better here and seems appropriate. It is necessary to assess the way benefits and adverse impacts are distributed. There is no specified time horizon for this analysis and little specificity regarding the analytical standards, tools and techniques that will be employed. If OCIDA is ill equipped to specify generally accepted standards for such an analysis it is incumbent tha OCIDA obtain the expertise required to specify how this must be done.

- VISUAL IMPACTS AND COMMUNITY CHARACTER

  COMMENT: This project has the potential to significantly alter the character of the community—not only the locale surrounding the immediate project location, but the wider Syracuse and Onondaga County as well as portions of Oswego County as population growth and housing development is induced. The DEIS should include an analysis of the potential for growth-induced changes in the community that this project will induce.

- GEOLOGY, SOILS, AND TOPOGRAPHY

  COMMENT: Reference is made to 'property survey' as a data source but later the 'geotechnical investigation' is mentioned but not included in the sentence describing the analysis. Is this an oversight that should be corrected? Certainly the geotechnical survey will provide valuable information to confirm or modify the USGS soil survey data.

- NATURAL RESOURCES

  COMMENT: This seems to prioritize wildlife and overlook the categorization of existing vegetation. Is that what is intended? The EAF mentioned the undertaking of detailed field studies of land coverage and natural resource conditions on or near the Micron Campus. Will a detailed land cover field study be done? It should be included.

  Little detail is included about the hydrology and wetlands evaluations that will be necessary. Standards, tools and analytical techniques required to be employed must be specified. If OCIDA lacks the expertise to properly specify this analysis they must obtain that expertise from involved agencies or consultants that can properly specify the scope and requirements of this work.

- SOLID WASTE & HAZARDOUS MATERIALS

  "This analysis will describe the proposed generation of solid waste by the Proposed Project and how that material will be handled, stored, and transported. This analysis will describe Micron's proposed measures to reduce generation of solid waste through reuse or recycling."

  COMMENT: It is appropriate for Micron to identify the quantities and types of solid waste that are likely to be generated at their facilities. The applicant estimates the generation of 45,000 tons per year of solid waste, which represents an additional 15% of waste generated in Onondaga County. All solid waste in Onondaga County is burned in an incinerator. What impacts will the solid wastes disposed of through the OCRRA system have on air quality? The fiscal implications for the OCRRA must also be assessed. The indirect, long term and cumulative impacts of the use and disposal of both solid and hazardous waste materials must be included in the analysis.

  The applicant is proposing to take measures to reduce the generation of solid waste. What is under consideration?
  Strangely, the same level of investigation is not described for hazardous wastes, which constitute a far greater threat to employees, the community, and the environment.

The text reads that the DEIS "will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect against releases to the environment."

It is imperative that the DEIS identify ways to reduce and eliminate the generation of hazardous waste through reuse and recycling. Hazardous waste is best eliminated by using non-hazardous substances in the fabrication process. In the event that hazardous substances must be used in the fabrication process, methods to completely contain those substances, and/or ultimately destroy them, must be considered.

Of particular concern are perfluorinated alkyl substances (PFAS), otherwise known as "forever" chemicals because of their long lifetimes in the environment and in organisms. These chemicals are of great concern due to their high levels of toxicity. The semiconductor industry uses PFAS extensively (Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P) The DEIS must address the use of these chemicals and alternative chemicals that could be used as substitutes.

The attached memorandum from Lenny Siegel, Center for Public Environmental Oversight, provides additional details regarding the problems posed by PFAS and other hazardous chemicals. The authors of a recent paper on use of PFAS in the semiconductor industry note that: " the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in ***strong resistance toward physical, chemical, and biological degradation***. Due to this strong resistance to degradation, PFAS compounds in general ***are extremely stable in the environment.*** In addition, such compounds have been found to be bioaccumulative. Extensive literature exists describing the detection of a number of PFAS compounds in drinking water." (emphasis added) The authors also note "there is a strong societal interest in eliminating their use, and "essential use" is a stopgap situation in which replacements are actively sought." https://www.spiedigitallibrary.org/journals/journal-of-micro-nanopatterning-materials-and-metrology/volume-21/issue-01/010901/Review-of-essential-use-of-fluorochemicals-in-lithographic-patterning-and/10.1117/1.JMM.21.1.010901.full?SSO=1

Enhesa (formerly Chemical Watch) is an industry trade organization that provides regulatory guidance to industry. They note that: "The use of PFAS is a major focus for regulatory authorities worldwide right now. In Europe, the REACH restriction proposal aims to place limits on all uses of more than 10,000 per- and polyfluoroalkyl substances. Meanwhile, in the US, restrictions are high on the agenda in several states.

In late September 2023 the European Parliament voted overwhelmingly in support of a parliamentary report backing the first revision of the Urban Wastewater Treatment Directive (UWWTD) in 30 years. The revision proposal would introduce new limit values and treatment requirements for micropollutants in wastewater, including per- and polyfluoroalkyl substances (PFASs) and microplastics.

The hazardous materials component is a significant component of the EIS. It deserves its own chapter. As written, there is no reference to worker safety; but of course OSHA rules apply as well as other laws when the use, storage and transport of Hazardous Materials (HazMat) is considered. The DEIS should be required to include information about this issue as 9,000 workers will potentially interact with these materials, and the community in general is potentially being put at risk. HazMat emergency response and potential risks to the community must also be fully considered and described. The DEIS must include a full disclosure of HazMat risks related to the manufacture of chips including supply chain, transport, storage, security, air quality, spill/release response and disposal. Cradle to grave analysis must be provided to decision makers being asked to permit this endeavor, as well as community members who are being asked to assume these risks. Additionally, we believe alternative production processes should be evaluated to determine whether the objective production can be realized without the utilization of hazardous materials.

- TRANSPORTATION:

  The only mitigation measures mentioned in this section are improvements to roadways. It is imperative that the utilization of public transportation, including mass transit by bus and light rail, be considered.

- UTILITIES & INFRASTRUCTURE:

  COMMENT: The potential impacts on infrastructure (water, stormwater, sanitary sewer, electrical and telecommunications) will be assessed. The scope of this assessment is ill defined here and needs to be specified in greater detail. The DEIS needs to address parameters such as system capacity, level of service changes, fiscal implications for the community and impacts on water bodies.

  The city of Syracuse should be considered an interested agency for this (as well as other aspects of this project) as it relies on a connection to the OCWA for a portion of its water supply needs.

  It is noted elsewhere in project documents that a 16” natural gas main will be extended to the plant, yet it isn’t mentioned in this section; Shouldn’t impacts associated with the area’s gas supply and the construction of this line be included here?

- USE AND CONSUMPTION OF ENERGY

  The Scoping Document simply states: “This analysis will describe the Proposed Project’s use and consumption of energy and measures that Micron intends to pursue to reduce energy consumption and use of renewable sources.”

  COMMENT: The anticipated energy needs of this project are enormous. Much greater detail is warranted, as discussed below. Local as well as regional and statewide impacts must be considered. Further, this section is related to other sections such as transportation, air quality, and climate change.

Electricity: Electrical consumption is anticipated to be 16 billion kilowatt-hours of electricity per year, when fully built. (Phase 2, Envir. Assessment Form, Part 1, Section K) To put this in perspective, this is equivalent to all of the electricity consumed by the states of New Hampshire and Vermont, combined. The entire state of New York used 143 billion kWh of energy in 2022. Micron will increase demand in NY by 11%. The Scoping Document clearly needs to provide greater details about:

- How will the EIS consider the various sources of electricity which are currently available, and which may become available as the plant is constructed?
- The EIS must evaluate the ability of current power lines owned and operated by National Grid to deliver the required power.
- Micron has stated its goal "to achieve 100% renewable energy for existing U.S. operations by the end of 2025." (Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology) Does Micron plan to achieve this goal for the proposed facility in Clay?
- The Scoping Document should state that the EIS will examine:
    - power purchase agreements with suppliers of solar power, wind power and hydropower.
    - on-site production of electricity from solar and/or wind generation

Natural Gas: National Grid is proposing to build approximately 2.5 miles of 124-psig,12" natural gas distribution main to the new Micron facility. (Exhibit G, Micron Term Sheet, signed Sept. 22, 2022). The DEIS needs to address these topics:

- How much natural gas will the facility need, and for what purpose?
- The use of natural gas seems inconsistent with New York state's CLCPA, which calls for a 40% reduction of greenhouse gas (GHG) emissions 2030, and then an 85% reduction of GHG (below 1990 levels) by 2050. Combustion of natural gas releases CO_2 which is the primary driver of climate change.
- The use of natural gas also seems incompatible with Micron's global target to achieve a 42% reduction in GHG emissions from operations ("scope 1") by 2030 and net-zero emissions from operations and purchased energy ("scope 1 & 2") by 2050, supporting the objectives of the Paris Agreement. (Source: Micron website: https://www.micron.com/ny/fact-sheet)

Related energy usage: The use of energy for construction, facility operations and the ancillary increases in energy consumption related to transportation needs the project will generate should also be investigated. It may not be unreasonable to consider the increase in energy consumption from the induced community growth which this project will generate as described in the chapters on indirect and cumulative impacts and the growth inducing aspects of the project.

- INDIRECT AND CUMULATIVE IMPACTS:

COMMENT: The use of the word 'summarize' to describe the scope of this Chapter is insufficient. This Chapter must assess indirect and cumulative impacts of the proposed project for each of the technical areas included in the DEIS. If these effects are included elsewhere it may be appropriate to summarize them here. Let's be clear about exactly what is required to be included in the DEIS

- GROWTH INDUCING ASPECTS OF THE PROPOSED PROJECT:

  COMMENT: This section relates to perhaps the most significant aspects of this project. While jobs and employment and economic growth will be created, the population growth of the region has the potential to produce significant adverse environmental and economic impacts as well which must be considered. While this section overlaps with other sections of the proposed DEIS scope, it is important to not forget that there will be significant impacts on the community. Such effects as rising housing costs could disproportionately impact the impoverished and increase the potential for a rise in homelessness. The DEIS must not overlook this and other issues relating to population growth of Syracuse, Onondaga County and the surrounding area.

- IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

  COMMENT: Aside from building materials and energy, resources consumed in the manufacturing process, as well as the land devoted to this project, the water consumed and the changes to water and air quality (eg., compounds such as "forever chemicals" which could be discharged into water bodies and the air) should be included in this analysis. The community should, and must know, the sustainability aspects of this venture as it decides to permit its development.

- MITIGATION:
  The SEQR Handbook suggests, " Specify possible measures for mitigating potential impacts that must be discussed in the EIS, to the extent that they can be identified at the time of scoping."

  In addition to those listed in this draft scope, others that should be listed are:
    - Public transportation (various options such as fixed route bus, demand activated bus service, light rail),
    - Building design features such as those proscribed in LEED building standards that reduce energy consumption, or production of renewable energy (geothermal or other water-source heat pumps) or
    - Mitigate habitat loss with green roofs or parking area reductions via public transportation options for employees
    - Alternative production processes that can minimize use of hazardous materials, energy use, etc.

Respectfully submitted by the following, on behalf of their respective organizations.

Donald Hughes
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LIST OF ATTACHMENTS

1. Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P

2. Memorandum from Lenny Siegel, Center for Public Environmental Oversight

3. Christopher K. Ober ,* Florian Käfer , and Jingyuan Deng. "Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing,"Journal of Micro/Nanopatterning, Materials, and Metrology, Vol. 21, Issue 1, 010901 (March 2022). https://doi.org/10.1117/1.JMM.21.1.010901

4. Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology

More Domestic Chip-Making Means More ‘Forever Chemicals’

by Amy Feldman, Forbes Staff, October 5, 2033

https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821

Mark Newman, CEO of Chemours, the only American PFA manufacturer, says the company is ramping up production to meet the demands of reshored semiconductor fabrication.

“I brought some show-and-tell,” Mark Newman, CEO of chemical maker Chemours, told *Forbes* during a recent interview in a midtown Manhattan conference room. He pulled a valve assembly out of a bag. The innocuous piece of plastic, he explained, is made of fluoropolymer known as PFA — a type of controversial “forever chemical” and an essential tool in the production of semiconductors.

“You cannot make chips without a whole PFA infrastructure,” he said. “We estimate that in a modern-day fab, there’s a half-kilo of PFA in every square foot. So in a 400,000- to 600,000-square-foot fab, that’s 200 to 300 metric tons of this stuff.”

It’s not just valves, of course, but all types of pipes, tubes and pumps in semiconductor equipment. Fluoropolymers are particularly key for filtering out small particles from fluids during chip production. Few factories need to be as clean as chip fabs, where particles as tiny as human skin cells can contaminate production. Chemours’ PFA is in much of that equipment and material, providing a big, and largely unseen, part of a semiconductor fab’s processes.

Wilmington, Delaware-based Chemours, a spinout of DuPont, is the only U.S. manufacturer of PFA. For Chemours, advanced materials including fluoropolymers represent roughly one-quarter of its total $6.3 billion (latest 12-months revenue) business, with refrigerants and titanium dioxide, used in paints and aerospace coatings, making up the bulk of the rest. Within that, semiconductors are part of its performance-solutions segment, which accounted for $493 million in sales for 2022, up 53% from $322 million in 2020. On its website, Chemours says flat-out that “without PFA, domestic semiconductor manufacturing would not be possible.”

Last year, President Biden signed into law the CHIPS Act, which provides $52 billion in funding to spur domestic semiconductor manufacturing with a goal of improving national security by decreasing reliance on nations like China for critical technology. Chips are essential not just for our phones and computers, but also for medical devices and fighter jets. “Geopolitics has been defined by oil over the last 50 years,” Intel CEO Pat Gelsinger said at an MIT event earlier this year. “Technology supply chains are more important for a digital future than oil for the next 50 years.”

But our insatiable desire for electronic devices and American policymakers’ push for more domestic manufacturing of semiconductors relies on the industry’s access to large amounts of “forever chemicals.”

Ongoing Litigation

Forever chemicals, or PFAS, comprise thousands of synthetic chemicals. They're long-lasting and resistant to heat, corrosion and moisture, making them popular for a variety of products that include nonstick pans, stain-resistant upholstery, firefighting foam — and semiconductor production. Studies, however, have linked PFAS to a variety of diseases, including cancers and reduced immune system response, as well as to contaminated groundwater, air and soil that can lead to a host of health problems. PFAS are an enormous category. Fluoropolymers, like those that Chemours manufactures for industrial uses, are just one class.

Litigation over their impact is ongoing. In June, Chemours, along with DuPont and another spinoff, Corteva, reached a $1.2 billion settlement with public water systems. Meanwhile, legislators and regulators have been cracking down on the chemicals' use, particularly in consumer products such as clothing, furniture and textiles, where they can be more easily replaced. Minneapolis-based 3M, which in 2018 agreed to pay $850 million for damaging drinking water and natural resources in the Twin Cities area, announced that it would cease production of PFAS by the end of 2025.

The semiconductor industry has pushed back against regulations here and in Europe, where regulators had proposed a ban on PFAS. When the U.S. Environmental Protection Agency asked for comments on tightened oversight on PFAS earlier this year by revoking certain low-volume exemptions, the microelectronics trade group SEMI called it "catastrophic" for domestic chip manufacturing. In a letter to the EPA, it said that such a rule "would significantly hamper the domestic semiconductor industry despite express goals of the Administration to the contrary and to the detriment of the U.S. economy."

Doubling Down

In this landscape, Chemours' Newman is doubling down. In a wide-ranging interview with *Forbes* during a trip to New York for Climate Week, Newman said that the $4 billion

(market cap) company was expanding production of fluoropolymers, driven by the critical need for the chemicals in semiconductors and electric vehicles. Further, he said, such production could be done safely with investments that his company is making. It has, for example, invested more than $100 million in emissions control technology at its Fayetteville, North Carolina plant.

“We’re currently sold out and working to expand capacity here in the United States,” Newman said. Chemours plans to enlarge its West Virginia production facility, he said. Located just across the river from Ohio, the factory is well positioned to supply Intel’s giant chip fab near Columbus, now under construction. “Imagine making something for the semiconductor industry in what people think of as coal country,” Newman said. All told, the company is investing up to $1 billion in fluoropolymers, including those for use in semiconductors.

The combination of reshoring and PFAS is “a very complicated discussion,” said Zhanyun Wang, a scientist and PFAS researcher with EMPA-Swiss Federal Laboratories for Materials Testing and Research. “There’s a lot of resistance from the industry because, of course, if we want to do the change, it costs.” That’s especially problematic if the United States and the European Union impose regulations and other parts of the world do not. However, he said, such regulations could be designed to spur new innovations. “The semiconductor industry has a lot of R&D power,” he said.

In July 2015, when industrial giant DuPont spun off its performance chemicals division and named it Chemours for “chemistry” plus the “Nemours” part of DuPont’s full name, the new company was saddled with debt and potentially toxic assets. “I think investors were worried if we were going to be solvent,” then-CEO Mark Vergnano told *Fortune* in 2016. “Were we going to make it through this or not?” Vergnano proceeded to pull off a dramatic turnaround by slashing costs, selling off non-essential businesses and gaining market share for its refrigerants business.

Big Expense

Newman, who had been the company's chief financial officer during those years and is one of the country's top Black executives, became CEO in 2021. The company's revenue ballooned to a peak of $6.8 billion in 2022, driven by strong pricing. Its advanced performance materials business, which includes the Teflon lineup of fluorine chemicals, gained price increases of 18% and reached total sales of $1.6 billion as it focused on high-tech markets including advanced electronics and clean energy.

The semiconductor industry "didn't want to use fluoropolymers, not because they were concerned about them, but because fluoropolymers are expensive," said Gerardo Familiar, president of Chemours' Advanced Performance Materials division, which includes fluorine chemicals. But alternatives have been scarce because of fluoropolymers' resistance to corrosion and ability to work at high temperatures and to last for a long time. He said that fluoropolymers like PFA are "substances of low concern," and that they should be considered differently than PFAS. "Those materials last a very, very, very long time, but they make your manufacturing very, very, very safe for the people who are there because you don't have an issue with corrosion," he said. The conundrum, he said, is how to manufacture them responsibly and what to do with the materials at the end of their life.

Some smaller companies are working on replacing PFAS in electronics manufacturing. Danvers, Massachusetts-based Transene, a privately held business founded in 1965, partnered with Toxics Use Reduction Institute (TURI) researchers at University of Massachusetts Lowell to develop alternatives for its etching solutions used in the semiconductor industry. The vast majority of customers have made the switch, and others are working through their qualification process. "You keep hearing from the industry, 'We need 10 or 15 years to make a change,'" said Greg Morose, research professor at UMass Lowell and research manager at TURI, who worked with Transene. "We basically did the research in 18 months, which is really rapid."

Phasing Out PFAS

But that’s just one small company, and one use of PFAS within a semiconductor fab. David Zamarin, founder of venture-backed DetraPel, which works on sustainable coatings for food packaging and textiles, said he received inquiries from semiconductor and electronics manufacturers, but that the cost and time didn’t make it economically viable. In the electronics industry, even companies that have set goals of getting rid of PFAS are moving slowly. Apple, for example, has promised to “thoughtfully phase out PFAS in a way that does not result in regrettable substitutions.”

Newman said that fluorine chemicals can be made responsibly. Chemours has committed to eliminating at least 99% of PFAS air and water emissions from its manufacturing processes by 2030. Chemours is also working on sustainable technologies, he said, such as renewable membranes for green hydrogen production marketed under the Nafion brand name and low-global-warming refrigerants for heating and cooling buildings.

“We felt because of our legacy we needed to lean into this mantra of being a different kind of chemistry company and showcasing the fact that we could be a leader in emissions reduction,” Newman said. “Our chemistry really enables a lot of the future economy.”

CENTER FOR PUBLIC ENVIRONMENTAL OVERSIGHT
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TO: Micron Project, Office of Economic Development, Onondaga County
FROM: Lenny Siegel, Center for Public Environmental Oversight
DATE: October 30, 2023
SUBJECT: SEQRA Scope of Work for Micron Semiconductor Fabrication

Thank you for the opportunity to comment on the September 12, 2023 Draft SEQRA Scope of Work for Micron Semiconductor Fabrication. I have been asked by residents of Onondoga County to offer my comments.

I have nearly five decades of experience monitoring and influencing the worker health and environmental impacts of the semiconductor industry, through the Pacific Studies Center, the Project on Health and Safety in Electronics, the Silicon Valley Toxics Coalition, and the Center for Public Environmental Oversight, as well as my service as Council Member and Mayor of Mountain View, the birthplace of the commercial semiconductor industry.

The semiconductor industry produces remarkable products that we all use. Unfortunately, its environmental and workplace health record is less than remarkable. The MEW Superfund Area here in Mountain View was the home of some of the earliest successful integrated circuit manufacturers. The wafer fabs are gone, but despite the scores (hundreds?) of millions of dollars spent thus far on subsurface remediation, the contamination—including the risk of public exposure—will remain for decades more, if not longer. The same is true at other Silicon Valley sites.

The SEQRA process provides an opportunity to identify and minimize, in advance, the environmental hazards of semiconductor production. By doing so, it can lead to appropriate regulation, research on waste management and pollution prevention, and investments in safer facilities.

Semiconductor production is essentially a series of chemical processes that use a wide variety of hazardous substances. The industry explains, “While in the 1980s semiconductor fabs used

fewer than 20 elements, today they are using over 50% of the nonradioactive elements in the periodic table."[1] Those include toxic heavy metals. The industry is a major user of Per- and Polyfluorinated Substances (PFAS), also known as "Forever Chemicals" because they persist and bioaccumulate in the environment and even human bloodstreams. As New York state agencies are well aware, these compounds are toxic, even at extremely low exposure concentrations, through multiple pathways. But industry has become reliant on PFAS without first examining the human and environmental risks. It explains, "Without PFAS, the ability to produce semiconductors (and the facilities and equipment related to and supporting semiconductor manufacturing) would be put at risk."[2]

Use and release of the industry's hazardous building blocks are regulated by both state and federal statutes and regulations, but the public is generally unaware of the series of upcoming permit applications that Micron is expecting to make. The SEQRA review should list **all** anticipated permitting processes, with the anticipated schedule of public comment periods, and it should require public notification to interested parties of each permit application as it is submitted.

It should also identify hazardous substances, whether or not they currently have promulgated exposure standards. For example, the industry reports, "Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS."[3]

Furthermore, potential workplace exposures should not be ignored because exposures are below the Occupational Exposure Level (OEL) or even a fraction of the OEL, as industry suggests.[4] In most cases OELs, such as the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limits (PELs), are orders of magnitude above what the science—including U.S. EPA studies—dictates.

While the draft Scope of Work proposes many useful Technical Chapters, there is room for more specificity. I focus on the use and release of hazardous substances.

For **Solid Wastes and Hazardous Materials**, the Scope of Work states, "The chapter will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect

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[1] "Background on Semiconductor Manufacturing and PFAS," Semiconductor Association (SIA) PFAS Consortium, May 17, 2023, p. 54. The SIA PFAS Consortium is made up of chipmakers and their suppliers of equipment and materials. To sign up to receive their technical papers, go to https://www.semiconductors.org/pfas/ . I am attaching this document.

[2] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3. I am also attaching this document.

[3] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3

[4] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 25.

against releases to the environment. Any warranted remedial approaches for addressing identified or potential contaminated materials would be described." I suggest that the Review describe any permitting required for the Treatment, Storage, and Disposal of hazardous materials and solid wastes, and that it list the storage requirements, such as double-walled tanks and piping, necessary to prevent environmental releases. Furthermore, how will employees be educated about the risk from leaks and spills, as well as what to do when they occur?

To what degree will disposal—including landfilling and incineration—create off-site hazards? Industry reports, "Organic waste, including organic liquids containing PFAS, is typically segregated, collected, and containerized to be treated at an offsite licensed treatment and disposal facility, as a blended fuel by high temperature incineration or reprocessing."[5] Perfluorinated compounds are particularly difficult to destroy using incineration. Furthermore, even when permitted by regulatory agencies, incineration may release products of incomplete combustion into the atmosphere.

For **Air Quality**, the Scope of Work barely mentions the potential emissions of highly toxic air contaminants. Historically the industry has used lethal gases such as arsine and phosphine, as well as toxic gases such as hydrogen chloride (the gaseous form of hydrochloric acid). Micron should identify plans to notify first responders and public of any toxic air releases, and first responders should be provided in advance with training and equipment to respond safely to such releases. Employees should be warned about the toxicity of gases used by the industry and trained to protect themselves from potential releases, both at low levels associated with chronic toxicity as well as higher levels with acute toxicity.

I am surprised and disappointed that no chapter is listed for **Wastewater and Stormwater**. The release of toxic contaminants through water pathways is one of the most serious threats of semiconductor productions. Releases of certain contaminants in wastewater could compromise the operations of the Oak Orchard Wastewater Treatment Plant, even undermining compliance with its discharge permit. The draft Scope of Work mentions industrial pre-treatment. Not only should that be described in an environmental review chapter, but the review should identify ways to pre-treat hazardous chemicals, perhaps even reusing some, before comingling with other wastes. This is particularly important for PFAS, because in the future more PFAS compounds are likely to be subjected to enforceable environmental standards, many at very low concentrations.

In fact, given the vast number of PFAS used by the semiconductor industry, the Review should identify methods for sampling total organic fluorine, not just targeted compounds. "At present, only a small percentage of PFAS compounds within typical semiconductor wastewater are detectable and quantifiable using conventional U.S. EPA analytical methods for PFAS-containing

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[5] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 30.

materials."[6] However, U.S. EPA has a draft method (1621) for measuring total organic fluorine.[7] Furthermore, academic researchers are finding that failure to measure total fluorine misses discharges of significant quantities of PFAS pollutants. "[B]ecause many studies of total organic fluorine have shown that total PFAS concentrations are at least 10 times higher than the sum of target PFASs. However, this does reinforce the idea that PFAS monitoring should incorporate complementary target and nontarget analyses or otherwise include measures of total organic fluorine to accurately assess PFAS abundance and potential environmental impacts."[8]

Furthermore, there should be a chapter on **Life-Cycle Environmental Impacts.** What hazardous substances remain in the finished semiconductor products, including packaging. At the end-of-life, are there mechanisms for preventing the environmental release of semiconductor hazardous substances? Industry's PFAS Consortium reports, "At the end-of-life of the product containing the semiconductor, or any parts replaced during the manufacture of semiconductors, would enter waste disposal streams where any PFAS contained therein could enter the environment."[9] Are manufacturers responsible for end-of-life pollution?

Finally, there are those who argue that a thorough environmental review, as I have suggested, would unnecessarily delay the operation of new, advanced wafer fabrication plants. I find it hard to believe that documenting potential hazardous substance and waste impacts in advance would hamper the construction of a factory that is not expected to begin production until 2032. Micron—indeed, all semiconductor manufacturers—**should** already know what hazardous substances it uses and releases. Shouldn't the public also know? The semiconductor and computer manufacturing industry, such as IBM's complex in Endicott, New York, has a long history of causing pollution that threatens public health and the environment. An industry that claims that PFAS—chemicals that are persistent, bioaccumulative, and extremely toxic in low concentrations—are essential to its operations should be required to **come clean** about its environmental and public health hazards.

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[6] "PFOS and PFOA Conversion to Short-Chain PFAS-Containing Materials Used in Semiconductor Manufacturing," SIA PFAS Consortium, June 5, 2023, p. 11.

[7] Draft Method 1621: Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (CIC), U.S. EPA, April 2022, https://www.epa.gov/system/files/documents/2022-04/draft-method-1621-for-screening-aof-in-aqueous-matrices-by-cic_0.pdf

[8] Paige Jacob, Kristas Barzen-Hanson, and Damian Helbling, "Target and Nontarget Analysis of Per- and Polyfluoralkyl Substances in Wastewater from Electronics Fabrication Facilities," *Environmental Science & Technology,* February 16, 2021, p. 2353. https://pubs.acs.org/doi/10.1021/acs.est.0c06690

[9] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 90,

Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing

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Abstract. We identify and describe categories of fluorochemicals used to produce advanced semiconductors within the lithographic patterning manufacturing processes. Topics discussed include the per- and polyfluoroalkyl substance (PFAS) materials used and their necessary attributes for successful semiconductor manufacturing, consisting of photoacid generators, fluorinated polyimides, poly(benzoxazole)s, antireflection coatings, topcoats, and embedded barrier layers, fluorinated surfactants, and materials for nanoimprint lithography. In particular, an explanation is given of the particular function that these PFAS materials contribute. It is noted that in almost all cases fluorine-free alternatives are very unlikely to provide the essential properties present in PFAS systems. Nonfluorinated alternative compounds are discussed where available. Finally, a summary table is provided listing the families of materials discussed, the critical purpose served, what the PFAS compound provides, and the prospects for alternatives. [DOI: 10.1117/1.JMM.21.1.010901]

Keywords: fluorochemicals; per- and polyfluoroalkyl substance; photolithography; semiconductor processing.

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1 Introduction

The use of fluorochemicals in lithography and semiconductor patterning plays a critical role in the success of semiconductor technology. The addition of small quantities of fluorinated materials enables patterning capabilities that are otherwise not possible to achieve, and this leads to superior device performance. The compact size of the fluorine atom and its strong electron-withdrawing characteristics make it stand out in the periodic table and gives fluorocarbon materials unique properties, unmatched by other chemical compounds. Fluorochemicals have found use in semiconductor processing for good technical reasons.

1. The presence of fluorine near acidic groups can convert them from an acid to a superacid, an essential characteristic for photoacid generators (PAGs) needed in advanced photoresists.
2. Fluorocarbon materials have low surface energy characteristics and act as superior barrier layers (including water repellence), which provide useful properties in photoresists and in antireflection coatings used in immersion lithography while also providing excellent release properties because they do not adhere strongly to other materials.
3. Fluorinated materials have unique solubility characteristics and can prevent intermixing between layers in a complex system such as an antireflection coating. Fluorinated materials are both hydrophobic and oleophobic and thus have reduced or no miscibility with essentially all fluorine-free classes of polymers.
4. Fluoropolymers have a low refractive index compared with any material except air and provide useful optical properties in photoresists and antireflection coatings.
5. They possess low dielectric constant and are especially good electrical insulators, an important feature when polyimides are patterned and retained in the final device.

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> This document provides a systematic overview of the photolithography process and key fluorinated materials involved, provides insight into performance requirements, and describes why fluorinated chemicals help achieve needed characteristics.

Photolithography, a critical process step in the production of a semiconductor, uses a photoresist to transfer a pattern. The primary component of a photoresist is a photopolymer whose solubility will be changed upon exposure to short wavelength radiation. In addition, the photoresist contains a deposition solvent and several small-molecule compounds. The desired solubility change must be great enough that a developer (a solvent that removes the unwanted region of a resist pattern) does not swell the remaining photoresist. The development process must be able to discriminate between exposed and unexposed regions as small as a few nanometers in size. The unremoved photoresist must protect the underlying substrate from the next process steps in semiconductor manufacturing. Each stage in the process must be virtually perfect with yields well above 99%, because there may be hundreds of process steps used to manufacture each advanced semiconductor device. Without those very high yields, semiconductor manufacturing would fail.

The basic lithography process used globally today for advanced semiconductor manufacturing and the foreseeable future employs chemically amplified photoresists. Chemical amplification was a key invention needed to overcome the challenge of limited light sources but was also found to provide superior patterning performance. In such resist systems a photopolymer that contains acid cleavable protecting groups is combined with a photoactive compound, such as a PAG. In its native state, the photoresist polymer with protecting groups is soluble in organic solvents. Upon exposure to UV radiation, the PAG releases acid. Frequently, a subsequent post-exposure bake (PEB) step leads to the acid-catalyzed removal of protecting groups, thereby transforming the hydrophobic photopolymer into one that is soluble in an aqueous base developer. The single photon of light needed to release one acidic proton is "amplified" by the more efficient acid-catalyzed deprotection process. By transforming the solubility of the photoresist, a high contrast patterning process needed in semiconductor manufacturing becomes possible. The combination of photoresist polymer and PAG to make the photoresist system is an essential part of this process and fluorination in the PAG provides the high acidity necessary for chemical amplification to work and will be described subsequently.

The lithographic process is a complex series of steps requiring, at times, several complex properties in a single material or other cases combination of different materials used in the same process step. An example of the latter can be represented by the use of an antireflective coating in combination with a photoresist. An antireflection coating (ARC) is important to prevent light reflected from the semiconductor substrate, which would otherwise alter the very precise molecular scale patterns required for today's semiconductor devices. An ARC does this by minimizing the refractive index difference across each interface of all layers in the system. As an example, a top ARC (TARC) is a layer that sits on top of the already complex photoresist. It must not intermix with the photoresist, and it can also serve as a protective layer for this complex, multilayer lithographic system. Finally, it must be easily removed. Only a fluorinated material has a significantly lower refractive index and fluorination also provides these additional properties. More details for ARCs will be discussed below.

Additional uses of fluorochemicals in photolithography processes are also discussed in this paper. It is worth noting that while there are many types of fluorochemicals, our survey of the technical literature reveals that there are several specific examples of fluorocompounds that are currently in use by the semiconductor industry in the lithography process including (1) perfluoroalkyl acid compounds (C4 or less), used in PAGs; (2) hexafluoroisopropanol, fluorotelomers, and fluoroacrylate side-chain units may be used in photoresists to incorporate specific functionalities including barrier properties and low surface energy; (3) hexafluoropropyl units are used in sub-units of some classes of polyimides for thermal stability and low dielectric constant; (4) specialized per- and polyfluoroalkyl substances (PFAS) are used in ARCs; (5) PFAS are also include surfactants (used as coating leveling agents) to improve coating uniformity in a number of products used in lithographic processes. A key feature of the addition of a fluorinated component is that its addition provides a necessary additional characteristic to the material while minimally compromising its other critical properties. Examples of these materials and uses are tabulated in

the Appendix. This paper discusses current PFAS use in the field of photolithography, explains why certain materials are used, reviews in part the current understanding of PFAS degradation during processing, and where possible, identifies alternative materials.

One of the special features of the C─F bond is its strength compared with the C─C bond due to the electron-withdrawing power of the fluorine atom. This attribute is the basis of many of the technical benefits of fluorinated materials in semiconductor processing but leads to its chemical stability and environmental persistence. Fluorination brings specific improvement in performance, and its targeted incorporation can minimize the quantities of material needed to achieve that performance. Such aspects are discussed in the context of PAGs. Thus, despite the remarkable performance improvement in many aspects of the lithographic process provided by fluorochemicals (PFAS) that makes possible the semiconductor revolution with its benefit to society, the large and growing environmental and societal concerns surrounding PFAS may counterbalance the positive technological benefits of these materials. The reader is referred to a discussion of such PFAS concerns in a well-written review article, but photolithography chemicals are largely glossed over.[1] Going forward, due to environmental and regulatory concerns, performance equivalent alternatives for many of these applications still need to be identified and this will be a major research challenge.

This paper presents a detailed discussion of the different types of PFAS used in advanced lithographic patterning and semiconductor manufacturing paying specific attention to the unique physical-chemical attributes of these chemistries that make them essential for semiconductor manufacturing. Specifically, we break the PFAS used in semiconductor manufacturing into six main categories of fluorochemicals used in photolithography and semiconductor patterning. For each category, we discuss the critical function served by the fluorochemicals and why the specific fluorocompounds are used, based on the unique properties provided by the chemical. However, it is worth noting that there are required processes in the semiconductor manufactory using per-fluorinated compounds such as etch gases for metal etching, wet cleaning chemicals to clean and condition substrate, and other minor processes that are not covered further in this paper.

Based on concerns regarding the high persistence, bioaccumulation potential, and potential toxicity of PFAS studied to date, it has been suggested that the use of PFAS be limited to essential uses only.

We discuss whether viable alternatives exist for each of these applications and the characteristics that must be achieved to find an alternative compound where none currently exists. Finally, we apply the essential use concept described by Cousins et al.[2] to show that these compounds should be considered essential for certain processes in semiconductor manufacturing (i.e., photolithography and patterning) because they provide for vital functions and are currently without established alternatives. The prior paper did an excellent job of discussing different aspects of PFAS use. In this paper, we focus our discussion of essential use as "necessary for highly important purposes in semiconductor manufacturing for which alternatives are not yet established." We describe the many uses and unique properties of PFAS chemicals, which in our opinion justifies their current use as essential in microelectronics manufacturing and for which alternatives have not yet been adequately identified. This paper is not intended to be an extensive listing of every example of fluorochemical used in photolithography but does attempt to explain strategies and classes of material used in the manufacturing of semiconductors.

2 Photoacid Generators

PAGs are photoactive compounds that generate acids upon exposure to high-energy light [deep ultraviolet (DUV) or extreme ultraviolet (EUV)]. These photoactive compounds were originally used for applications in photopolymerization in the early 1960s.[3] After the introduction of chemically amplified resists (CARs) in the 1980s, they have been used in semiconductor manufacturing as key components in advanced photoresists. It is important to understand that the process of chemical amplification requires a very strong acid in the PAG to function well. PAGs are now highly evolved with over 40 years of in-depth research and development for photoresist applications. A positive tone resist polymer after deprotection, for example, contains

weak acid groups that will act to buffer (weaken) the acidity of the deprotection process. Without the presence of the strong fluorosulfonic (or stronger) acid, the catalyzed deprotection process will be less efficient or may not even occur. Sulfonate anions without fluorination have repeatedly been shown to be inadequate for use ineffective 193 nm chemically amplified photoresists and this is well known in the photoresist community. The unique characteristics of fluorine (noted below), which lead to very strong proton donation by fluorinated sulfonic acids, are essential in CARs. This intrinsic benefit of fluorinated acids makes it extremely difficult to eliminate the use of fluorinated acids whilst retaining the key performance characteristics of CARs needed for advanced photolithography in microelectronics manufacturing. Other attributes of a PAG that depend less on the acid and more on the chromophore include quantum yield at the wavelength of use, the sensitivity of the overall resist formulation (e.g., 15 to 60 $\mathrm{mJ/cm^2}$), miscibility in the resist matrix, thermal and hydrolytic stability and shelf life of the photoresist, solubility in aqueous base developer for positive tone develop or organic solvent for negative tone development followed by removal in the resist strip operation. In general, PAGs are divided into two categories: either ionic or covalent (nonionic) structures. As the name suggests, ionic PAGs consist of two portions: a cation and an anion. In addition, covalent PAGs are uncharged, nonpolar compounds that are constructed of covalent bonds but are generally less sensitive and therefore less effective than ionic PAGs. The availability of both ionic and covalent PAGs offers process flexibility. In some cases, the presence of ionic groups may lead to storage instability of the photoresist mixture or the inhomogeneous distribution of photoactive compounds in the photoresist, thus making a nonionic PAG necessary. However, most photoresist compositions that are used in semiconductor manufacturing employ ionic PAGs because of their greater sensitivity. Examples of PAGs are shown in Figs. 1 (ionic) and (covalent).

In either case, a fluorinated sulfonic acid would be used to make an effective PAG. The photoefficiency difference between ionic and covalent PAGs, which leads to higher quantum yields in the ionic PAG is controlled by the cation.[4] The low diffusivity and high strength of the acid resulting from the photolysis of the cation are controlled by the resulting accompanying fluorosulfonate anion. These anions are used in virtually all current commercial photoresists. Limited diffusivity is important to achieving high-resolution patterns because excess diffusion of the PAG has been shown to limit the resolution of the images produced in a CAR. While aromatic sulfonic esters are shown in some nonionic PAGs described in Fig. 2, the strength of the resulting sulfonic acid after photolysis is not as high as the ionic PAGs with fluorinated sulfonate anions.

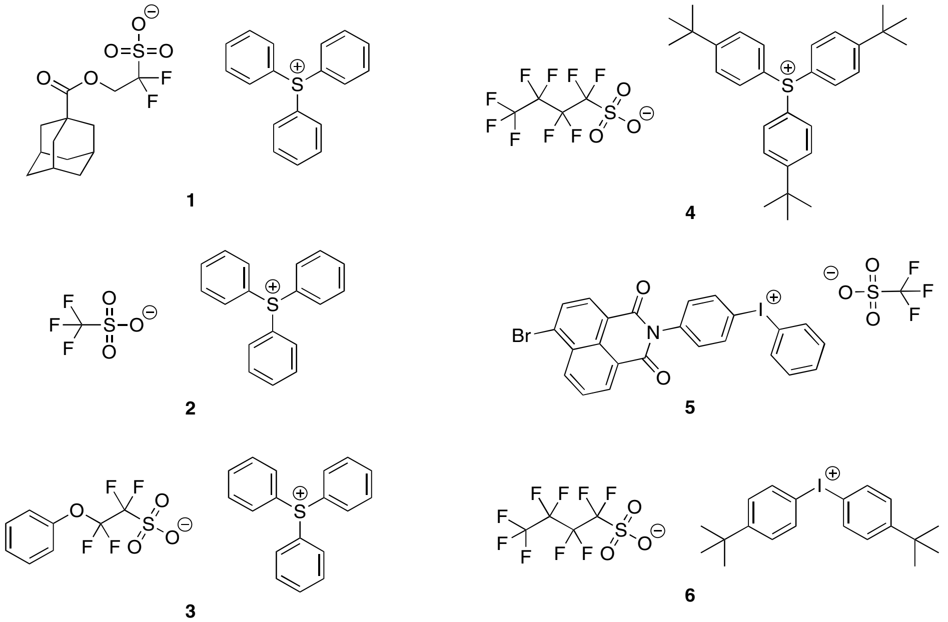

Fig. 1 Representative ionic PAGs: 1,2,3,4 Sulfonium PAG and 5,6 Iodonium PAG.

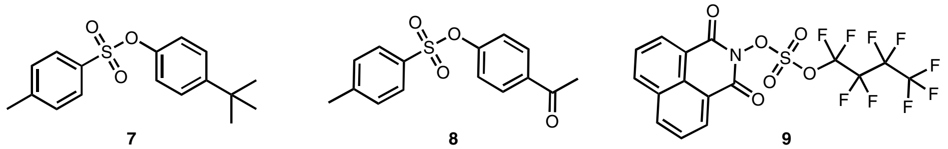
7 8 9

Fig. 2 Representative nonionic covalent PAGs.

Covalent PAGs do not suffer from the sorts of phase separation, low miscibility, and dark loss (the dissolution of unexposed photoresist) issues that may occur in ionic PAG-containing resist formulations, but the quantum yield of photoacid generation is generally lower for covalent PAGs so this and other factors drive the ultimate choice of PAG.[5] In order to increase the acidity of the photoacid, perfluorinated methylene units may be placed next to the sulfonate group in both ionic and covalent PAGs. The polarization present in the C─F bond due to the electron-withdrawing character of fluorine stabilizes the acid anion and makes the acid stronger. A sulfonic acid such as methane sulfonic acid has a pK_a of −2 (already a strong acid) but trifluoromethyl sulfonic acid (triflic acid) has a pK_a of −14. Any induction effect is significantly smaller after two or three CF_2 units, so the relative benefit of fluorination is significantly reduced as the neighboring CF_2 units are further away from the acid group. The original choice of longer sequence perfluorinated sulfonates (six or more) has not been explained in patents or the literature but was likely due to the effectiveness of the resulting PAG, the reduced diffusivity because it is a larger molecule, its availability, and the lack of volatility in this material. For example, the volatility of the small triflate anion limits its use in a production photoresist PAG because the resulting concentration gradients in such photoresist films harm performance. However, shorter CF_2 segments (1 or 2) next to the anion and connected to other units of higher mass have been shown to make effective PAGs (see Sec. 2.3).[6] Finally, the diffusivity of the PAG will affect pattern resolution (less diffusion enhances resolution) and can be addressed by the use of a higher molar mass PAG/acid and even covalent attachment of the PAG to the photoresist polymer itself (see Sec. 2.4). Although actively used in some applications, triflic acid is not always a useful component in a PAG since it may have significant deficiencies when used in a very high-resolution CAR system; it is volatile and may evaporate during the PEB step leading to composition gradients that are detrimental to image resolution and it readily diffuses during annealing, which may, in turn, lead to pattern degradation from deprotection chemistry occurring in unexposed areas, effectively reducing image contrast and disrupting pattern formation.

2.1 *Ionic PAGs and Their Photochemistry*

Most ionic PAGs used in lithography are onium salt derivatives. Such ionic compounds consist of an onium moiety as the cation and sulfonate groups as the anion.[4] Upon exposure, photolysis occurs and photoacid is formed. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. Returning to Fig. 1, ionic PAGs are generally composed of either diaryliodonium or triarylsulfonium photoactive units to form a salt with an appropriate anion. Triarylsulfonium PAGs usually have longer shelf life compared with diaryliodonium salt. However, a diaryliodonium salt has higher absorptivity in particular for next-generation 13.5-nm wavelength EUV photons. The mechanism of photolysis of diaryliodonium salt[4] and triarylsulfonium salts[7,8] has been studied extensively. Reported photolysis mechanisms for diaryliodonium salt and triarylsulfonium salts are shown in Figs. 3 and 4, respectively. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. In Fig. 3, the energy required to cleave the aromatic C (sp^2) and iodine bond is somewhat higher compared with the energy required to promote bond cleavage between the aromatic C (sp^2) and sulfur bond (Fig. 4).

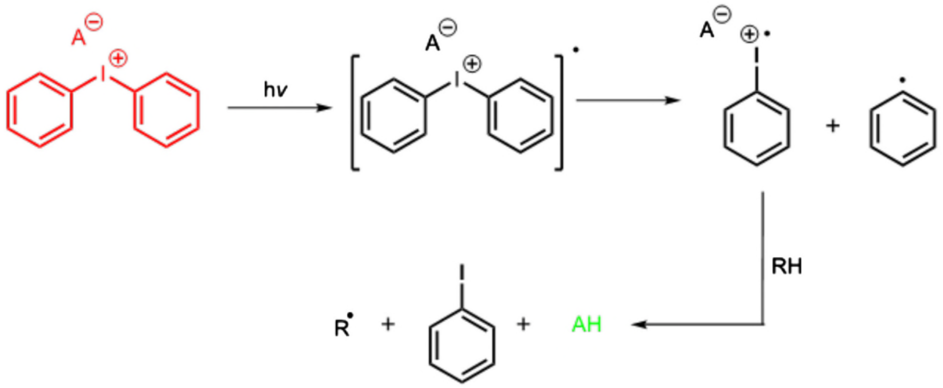

Fig. 3 Proposed photolysis mechanism for diaryliodonium salt under DUV exposure. Reproduced from Ref. 8.

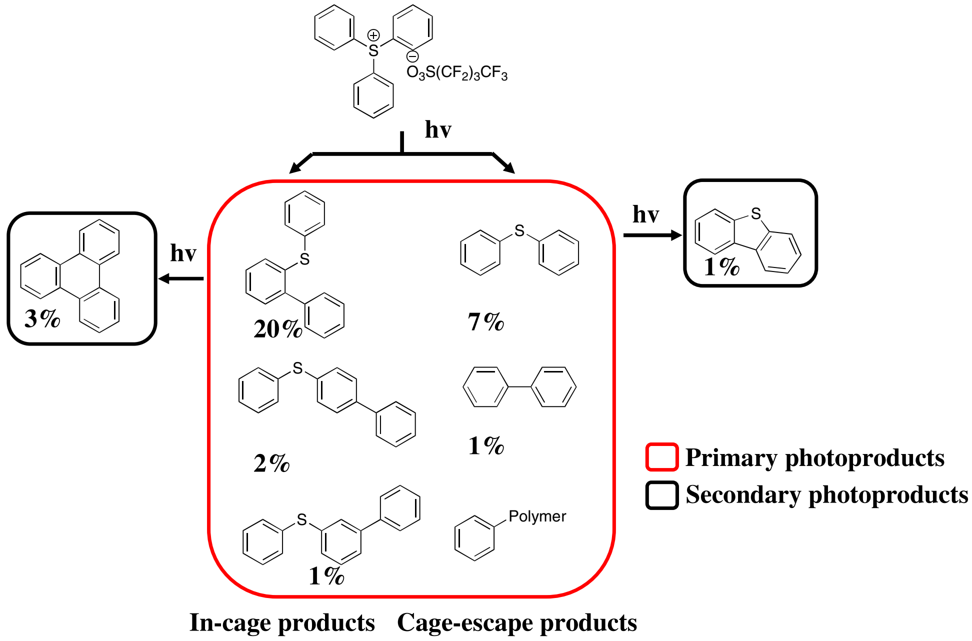

Fig. 4 Proposed photolysis mechanism for triarylsulfonium salt in solid poly(methyl methacrylate) matrix exposed to 266-nm irradiation (2631 mJ · cm^{-2}). Reproduced from Ref. 9.

Generally, the sulfonium PAG family is more widely used than iodonium PAGs considering its greater sensitivity and longer shelf life when used in either DUV or EUV lithography. Reference 8 reports solution results for exposure of the triphenylsulfonium cation. More recent results of solid-state polymer matrix results are shown in Fig. 4.[9] Solid-state studies at 193, 248, and 266 nm exposures reveal additional products including in all cases, two previously unreported Triphenyl sulfonium photoproducts, triphenylene, and dibenzothiophene.

2.2 *Nonionic Covalent PAGs and Their Photochemistry*

Although ionic PAGs have higher sensitivity in lithographic applications, they may be less soluble and more prone to phase separation in photoresist formulations. It is worth recalling that the PAG is needed to generate acid in the exposed regions to deprotect the photoresist and thereby change its solubility. Uniform distribution of a PAG is an essential attribute to excellent performance in a photoresist. Detrimental interaction between ionic structures in a photoresist and an ionic PAG may also occur in future resist materials.[10] To overcome such issues, covalent PAGs

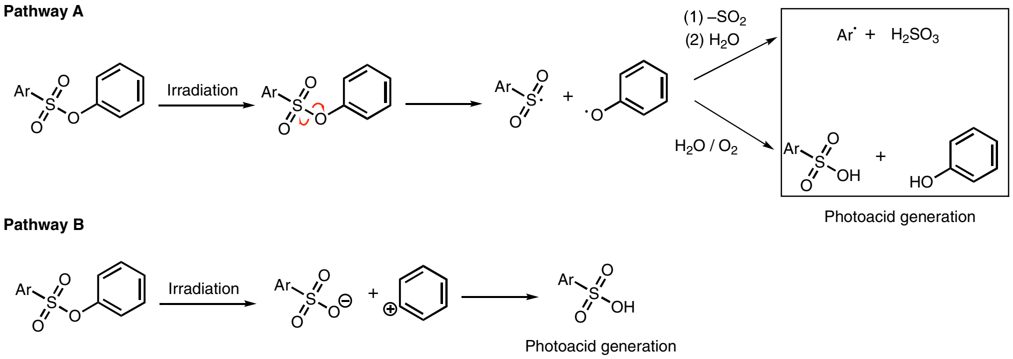

Fig. 5 Photoacid generation mechanism for arylsulfonate esters.

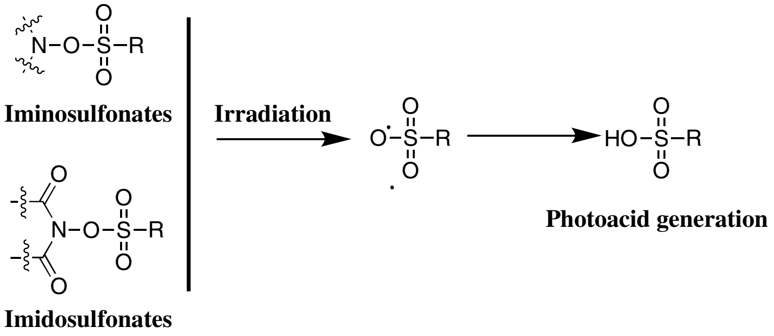

Fig. 6 Photoacid generation mechanism for iminosulfonates and imidosulfonates.

may be attractive alternatives.[4] In general, covalent PAGs are derivatives of arylsulfonates,[11] iminosulfonates,[12] and imidosulfonates.[13] Arylsulfonate esters can be easily synthesized from phenol and sulfonyl chlorides. A similar effort to create fluorinated sulfonate ester-containing covalent PAGs has not taken place because such PAGs have not been as effective in photoresist applications. The photoacid generation mechanism is proposed based on the nonfries photolytic ArO─S bond cleavage (pathway A) or pseudofries rearrangement (pathway B), which is more likely to occur for electron-rich aryl sulfonates as shown in Fig. 5.[14,15]

It is worth noting that in pathway A, in the presence of oxygen and water, stronger sulfonic acid is generated. In the absence of oxygen, weaker sulfurous acid is produced. Iminosulfonates and imidosulfonates have similar chemical structures with the N─O bond undergoing homolytic cleavage upon irradiation to generate sulfonyloxy radicals, which subsequently capture hydrogens from nearby molecules to afford the corresponding sulfonic acid as shown in Fig. 6.

2.3 *Alternatives to Current PAGs*

PAGs other than iodonium and sulfonium units as well as those that do not contain traditional PFAS have also been studied for use in photolithography. To be used successfully in a CAR photoresist, the resulting acid must be as acidic as a perfluorosulfonic acid, lack volatility so that it does not evaporate during the PEB step, and in the next generation photoresists possess minimum diffusivity (to enable high-resolution pattern formation). The PAG-resist combination should have a sensitivity in the range between 10 and 75 $\mathrm{mJ/cm^2}$ under exposure conditions i.e., the source wavelength and tool-specific settings. Some new photoresists attach the PAG directly to the photopolymer chain to both limit diffusion and deal with issues of stochastic variations that may be present in photoresists consisting of mixtures of polymer and photoactive molecules. Nontraditional PFAS Covalent PAGs: Nitrobenzyl esters have found some application in DUVL and may be extendable to EUV lithography.[10] Such molecules can generate photoacid

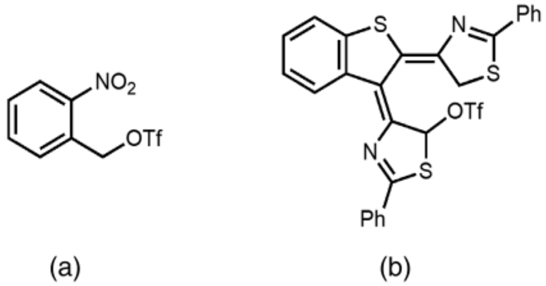

Fig. 7 Chemical structure for non-PFAS covalent PAGs: (a) nitrobenzyl ester and (b) terarylene backbone-based PAG.

upon irradiation through *o*-nitrobenzyl rearrangement to generate nitrobenzaldehyde and a sulfonic acid such as triflic acid shown in Fig. 7.

The chemical structure is shown in Fig. 7(a). The terarylene skeleton-based self-contained PAG is another potential candidate for some applications. The photoacid generation is triggered by the 6π-electro-cyclization reaction of photochromic triangular terarylenes.[16] The chemical structure is shown in Fig. 7(b). Similarly, a triflate ester is used in the reported structure to release triflic acid upon exposure. While these and other structures can be used to demonstrate PAG concepts, they are unlikely to be as useful in new high-resolution photoresist systems because they use triflate groups. Alternative acids may be used to make more suitable PAGs from the moieties in Fig. 7. Should a useful PAG be produced from these types of photoactive structures the resulting sulfonic acid will need to be less volatile and less mobile in the polymer film? A higher molar mass, much less volatile, lower diffusivity anion might work well with these materials in a functioning photoresist system. Nontraditional PFAS Ionic PAGs: Ionic PAGs derived from 2-phenoxytetrafluoroethane sulfonate were introduced by Ober and coworkers in 2007.[17] This PAG was tested under e-beam and EUV radiation and showed high sensitivity, resolution, and acceptably low line edge deviations. The use of such a fluorosulfonic acid has the advantage that it limits fluorine content yet produces a very strong acid with both limited volatility and diffusivity by placing a CF_2 group next to the acid group. Such an approach (discussed more below) can be used to minimize fluorine incorporation while placing this structure where it is most valuable. Its chemical structure is shown in Fig. 8(a). This PAG was tested for its environmental degradation and its effect on bacterial populations when first reported and found to be benign under the rules of that time.

The good lithographic results suggest that shorter fluorinated segments (two or possibly one CF_2 unit adjacent to the sulfonic acid) may make useful ionic PAGs. It should be noted that the building blocks for sulfonic acids with one CF_2 are the subject of experimental studies. The pentacyanocyclopentadienide PAG is another potential ionic PAG candidate in some applications. Its lithographic performance was demonstrated by Varanasi and coworkers in 2010, and it stands out for the amount of publicity it received.[18] The chemical structure is shown in Fig. 8(b).

While announced in 2010 as part of IBM's efforts to reduce Perfluorooctanoic acid (PFOA) in its manufacturing process, to the best of our knowledge, this PAG was not commercialized.

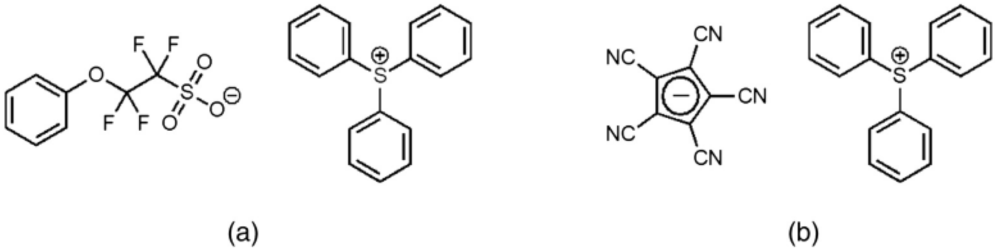

Fig. 8 Chemical structure of untraditional ionic PAGs: (a) 2-phenoxytetrafluoroethane sulfonate PAG and (b) pentacyanocyclopentadienide PAGs.

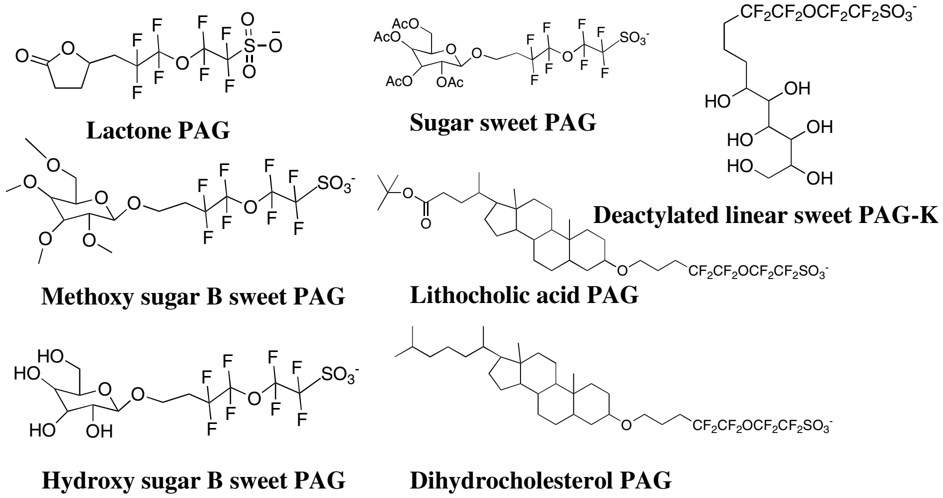

Fig. 9 Chemical structures for natural products-based PAGs.

Finally, PAGs based on glucose or other natural products have been explored. These PAGs were demonstrated to be functional materials for some high-resolution photoresist applications enabling sub-100nm features using ArF laser and e-beam lithography. Moreover, these PAGs showed successful microbial degradation to smaller molecular units under aerobic conditions. The chemical structures are shown in Fig. 9.

Such studies revealed the successful biodegradation of these PFAS units to smaller oxidized components as well as low bacterial cytotoxicity[19,20] of the photoactive sulfonium subunit. In general, the anionic units underwent biodegradation using sludge from a local municipal wastewater treatment plant. The sugar or cholesterol groups appeared to degrade easily leaving only a short, fluorinated acid residue. An advantage of these structures is that the residues retain polar functional groups and are therefore more hydrophilic than PFOS/PFAS units. This makes them less likely to accumulate in fatty tissues, but further studies are needed to identify any bioaccumulation characteristics. The photoactive cation unit but not the fluorinated anion was generally found to be cytotoxic to the bacteria. Importantly, the short, fluorinated segment enabled the formation of a high-performance PAG that could be subjected to successful biological degradation.

More recently, patents have appeared that describe a number of related chemical structures, the goal of which is intended to deliver strong PAG performance and minimize the size of the fluorinated unit in the fluorosulfonic acid or eliminate it entirely. These patents claim excellent lithographic performance.[21] These and other patents describe PAGs with shorter fluorinated segments,[22] some of which are designed to fall into small molecular pieces.[23] To assess their viability as alternative PAGs their performance characteristics (sensitivity, acid strength, and diffusivity) and environmental characteristics (fluorine content, degradation products, and toxicity) will need to be assessed.

2.4 *Polymer-Bound PAGs*

One approach to increasing the resolution to photolithography is to employ PAG that is incorporated into the photoresist polymer structure.[24] It has the advantage of making the distribution more uniform and at the same time limits the diffusivity of the sulfonate anion since it is bound to the photoresist polymer. Resolution is set in part by the diffusivity of the PAG in the photoresist formulation, which is associated with the size of the molecule. The smaller the anion, the farther the photogenerated proton can diffuse in a given time. If the PAG acid diffuses too broadly then deprotection of the photoresist takes place in unwanted regions and makes the pattern larger, less precise, and "blurry." These pattern irregularities are characterized in terms of line edge roughness, line width roughness, and critical dimension uniformity. Examples of bound-PAG structures have been reported and two are described below shown in Fig. 10.

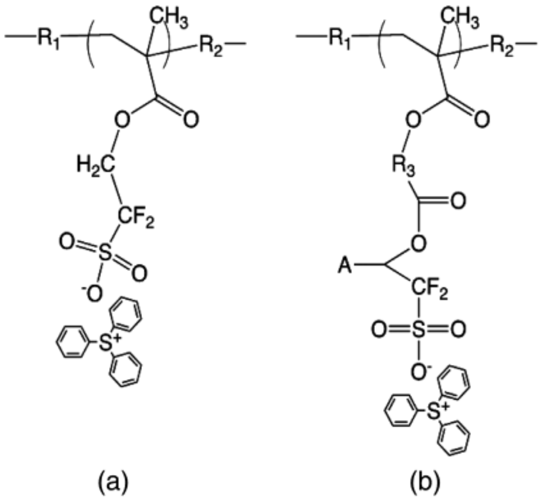

Fig. 10 Examples of polymer-bound PAGs. (a) Single CF_2 unit next to sulfonate[21] and (b) single CF_2 unit next to sulfonate in a structure that falls apart on exposure; groups (R1, and R2) not specified groups while R3 is a linking group.[20]

This strategy also lowers concerns about "stochastics," i.e., the chemical heterogeneity of a photoresist mixture at the dimensions of the pattern are thought to also contribute to the limit of resolution of today's most advanced lithographic processes. Upon exposure, the fluorosulfonate group becomes protonated, catalyzes deprotection of the rest of the photoresist chain, but the strongly acidic proton cannot diffuse broadly because it remains near the anion bound to the polymer chain and thereby forms higher resolution patterns. By attaching the same number of PAG units to each polymer chain, then the PAG is uniformly distributed throughout the photoresist film. This strategy is being seriously considered for future generations of photoresists, particularly for use in EUV lithography.[25] These examples share several common features, including the attachment of the anion to the polymer backbone. Since many CAR photoresists are based on (meth) acrylates, examples reported for 193 nm (DUV) resists [shown in Figs. 10(a) and 10(b)] possess a sulfonate anion and an adjacent CF_2 unit, which then is connected to the methacrylate monomer through an ester linkage. While it has not been established if one or two CF_2 units are needed to produce sufficiently strong anion, this example demonstrates one approach and good prospects for polymer-bound PAGs.

3 Fluorinated Polyimides

In an increasing number of applications, the photopatterned polymer is not removed but is retained as part of the device, even though the lithographic requirements are not as stringent as the high-resolution photoresist systems discussed above. Their use ranges from semiconductor packaging to lithographic insulation patterns for integrated circuits. Under these circumstances a completely different photopolymer must be used and have properties of very high thermal stability, strong mechanical properties (high Young's modulus, good fracture toughness), low dielectric constant (be an insulator), and moisture resistance.[26] In this highly demanding application only a few polymers can provide this complex set of properties and, among them, polyimides have been found to provide the best trade-off between processing and performance. Polyimides themselves bring many of these necessary attributes but the introduction of fluorinated groups is used to incorporate a chemical function capable of withstanding high process temperature, making the final material more moisture resistant and providing a lower dielectric constant than otherwise possible without compromise to other necessary properties.

The technical literature reveals that polyimides are used in a number of processes and applications in photolithography.[27] Polyimides are a family of polymers characterized by high thermal

stability, excellent thin film mechanical properties, good adhesion properties, and a low dielectric constant and dissipation factor. In particular, rigid functional groups such as phenylene- and less polar functional groups provide low dielectric constant (Δk) and good mechanical toughness (resistance to tearing). Polyimides are unique as a family of polymers because they have among the highest glass transition (softening) temperatures known in a polymer (>200°C) and they are thermally stable because the polymer chain consists of interconnected aromatic rings. These properties make polyimides able to withstand the high-temperature processing used in semiconductor manufacturing. Like all polymers, they can be etched with the right etchants and therefore patterned, they are amorphous and transparent so they can be used to guide light and they have a lower dielectric constant than many other components in a device so they can be insulators, but unlike other polymers they come with the ability to withstand very high-temperature processing without physical softening and deformation. They often remain in the semiconductor device, unlike most other photolithographic layers.

Photopatternable polyimides are generally made from a poly(amic acid) precursor such as one made from oxydianiline (ODA) (Y═O) and a dianhydride (such as pyromellitic dianhydride), which can be spin coated onto a substrate (see Fig. 11).

However, photocrosslinkable acrylate (or similar) groups are incorporated in the soluble poly(amic acid). A photoradical initiator is used to crosslink the acrylate groups and the pattern is developed in this negative tone system. Then a high-temperature bake step is used to transform the poly(amic acid) to the polyimide (with loss of the acrylate groups) to form its final high thermal stability, patterned and insoluble polyimide form. Any component in the final polyimide must withstand this high-temperature bake step.

Among the applications of polyimides in microelectronics processing, they find use as thick film photoresist, sacrificial layers, and structural layers. It is notable that the structure of a fluorinated unit, when incorporated into the polyimide, largely employs the identical hexafluoroisopropyl unit regardless of the application.[28–30] Hence, in the most common examples, the polyimides consist of tetracarboxylic acid anhydride derivatives and aromatic diamines, as shown in Fig. 11. The polyimide polymer itself has a softening temperature too high for melt processing, but this group of polymers offers processing through its poly(amide) intermediate. The intermediate is soluble, can be coated in a thin or thick film, and after patterning is converted to the polyimide through the heating step making it an ideal material for integration with semiconductor manufacturing. The soluble intermediate can be made into a polymer that is directly photo-patternable as shown in the poly(amide) in Fig. 11. The acrylate modified poly(amide) is photo-crosslinked upon exposure to UV radiation in the presence of a photoradical generator and then a pattern is formed. After development, the patterned polymer is subsequently transformed to the final polyimide by thermal processing. It is known in the art that the insertion of the fluorinated hexafluoroisopropyl functional group into the backbone provides a combination of better solubility in processing solvents, lower dielectric constant (more insulating), and provides higher thermal and thermooxidative stability compared with other alternate chemical functions.[31]

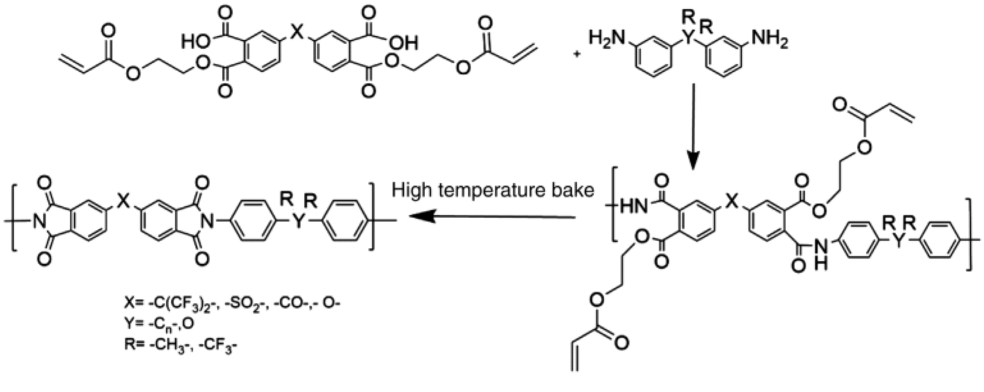

Fig. 11 Synthesis and structure of polyimides for photolithographic processes.

It must be noted that similar insulator properties have been claimed for the targeted optimization of a polyimide chemical structure without the presence of fluorinated residues such as CF_3- and others, which has been successfully demonstrated in at least one scientific study.[32] Araki et al.[32] recently described the synthesis of a novel low dielectric constant (Δk) and low dissipation factor (Δf) polyimides suitable for insulator of redistribution layers used as an interposer layer in wafer-level packaging. However, this polyimide replaces the thermally stable aromatic structure with a silicone segment (chemically identical to bathtub caulk) to achieve the insulating properties. While this new polyimide has good dielectric properties, unmentioned in the report is the fact it undoubtedly has poor mechanical properties, thermal stability and introduces a softening temperature well below materials used in this semiconductor manufacturing application. To demonstrate equivalence to the fluorinated polyimides, it would be necessary to evaluate these new polymers in a series of comparative studies. It is likely that the lower glass transition temperature and the higher associated thermal expansion changes of the silicone-based system would lead to mechanical stresses that severely limit its use outside of simple packaging applications.

No literature was found on the in-process or environmental degradation of these fluorinated polyimides.

4 Fluorinated Polybenzoxazoles

Building on the properties described for fluorinated polyimides, the industry has requested materials with similar properties, which could be patterned using the more generally acceptable aqueous tetramethylammonium hydroxide based developers. One way to achieve this end was to replace the polyamic acid derivative precursors with polyhydroxyamide precursors to polybenzoxazole, which could, after patterning and cyclization, yield a polybenzoxazole (Fig. 12).

The phenolic group allows for development by aqueous base, whereas use of classical diazonaphthoquinone (DNQ) photoactive units to modify the base solubility as in positive-tone photoresists allows for the needed selective patterning (Fig. 13).[4]

Alternatively, other protective groups such as acid-labile ethers and a PAG can also be used, as are common in advanced positive tone photoresists. These materials provide properties similar to polyimides, including thermal stability, tensile strength, and transparency as polyimides while also allowing easier processing. The incorporation of a hexafluoroisopropylidene containing monomer again confers the needed properties of transparency in 365 nm applications, good moisture resistance, thermal stability, reduced darkening after cure, and the correct solubility in aqueous development. Other additives are used to further control base solubility.[33–36] The DNQ PAC may either be added to the formulation or incorporated into the polymer backbone as shown below.

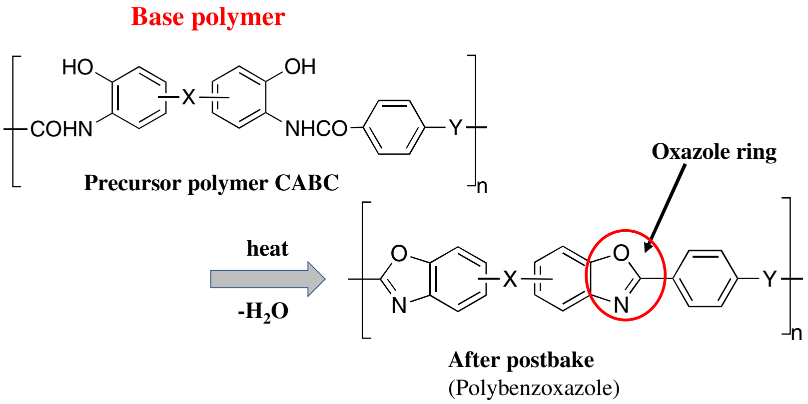

Fig. 12 Figure showing ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

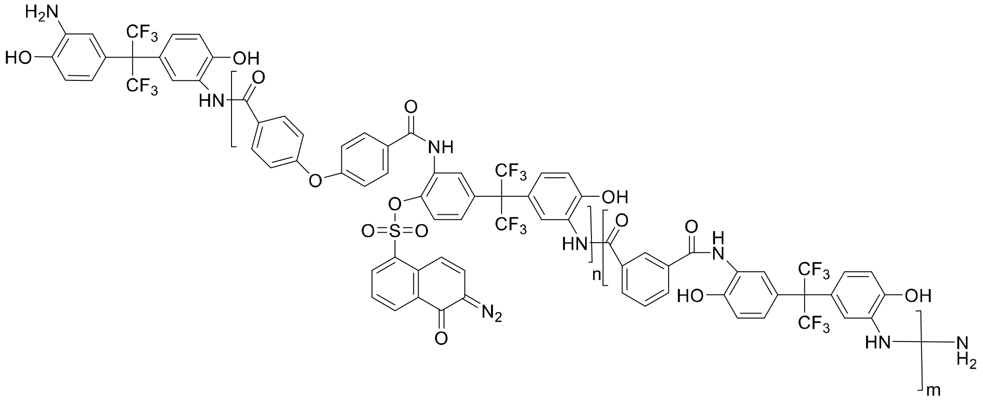

Fig. 13 Ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

5 Antireflection Coatings and Topcoats

The purpose of an antireflection coating (ARC) is to prevent reflection of the imaging radiation from interface layers that produce unwanted exposure effects including standing waves. An important attribute of an ARC is to tune the refractive index difference across each interface, and reflection from the many interfaces between layers is suppressed. A difference in refractive index is essential in preventing unwanted reflection of imaging radiation, which otherwise has a detrimental effect on pattern exposures. Fluorinated materials are important because they have a lower refractive index than virtually any other material category. For example, the refractive index of poly(trifluoroethyl methacrylate) is 1.418 compared with a polymer chemically similar to photoresist materials, poly(2-methoxy styrene) with its refractive index of 1.585, a significant and critical difference for an antireflection coating. Ideally a TARC, e.g., should have an RI value of ~1.3 and even with fluorinated materials, a good TARC refractive index is currently between 1.4 and 1.45. In addition to their optical properties, ARCs must not intermix with the photoresist as the different layers are deposited, and fluorination helps make that possible. Important requirements for ARCs also include ease of etching, their adhesion to a substrate, and precise thickness deposition.[37–39] Bottom ARCs (BARCs) are also used to form a level surface for a photoresist. Processing of ARC and topcoat materials depend very much on where they sit in the lithographic stack (on top or on the bottom) and a combination of etch, rinse and/or development steps are used in processing. This paper does not detail these differences. TARC materials require first and foremost controlled and reduced refractive index (RI), good mechanical properties for film formation as well as excellent etch characteristics (faster etching than the photoresist). The low RI properties and immiscibility (by being both nonpolar and oleophobic) with the photoresist are mainly achieved by the incorporation of short, fluorinated groups such as CF_3- and C_2F_4- units in the TARC, although longer fluorinated segments have been used. An example of a generic chemical structure of an ARC is shown in Fig. 14 in which a base soluble fluoropolymer is displayed.[40]

It is also possible to achieve immiscibility between ARC and resist using cyclic perfluorinated ether units in the ARC[41] Finally, fluorinated surfactants have also been used to improve ARC coating quality, and more is discussed about such surfactants below. There are two possible geometries that work to limit reflection: TARC and BARC antireflection coating materials. The name specifies wherein the multilayer stack the ARC is located. Figure 15 shows the arrangement of the silicon substrate, the photoresist, and a TARC.[42]

The radiation path is different in the air, the TARC, and the photoresist since each has a different refractive index. By using a low RI TARC (due to its fluorination) and by finding the

$$\left[CF_2-CF_2 \right]_n \left[CF_2\,CF(OCF_2CF_2COOH) \right]_m$$

Fig. 14 Composition of a commercial ARC; $n = m$.[40]

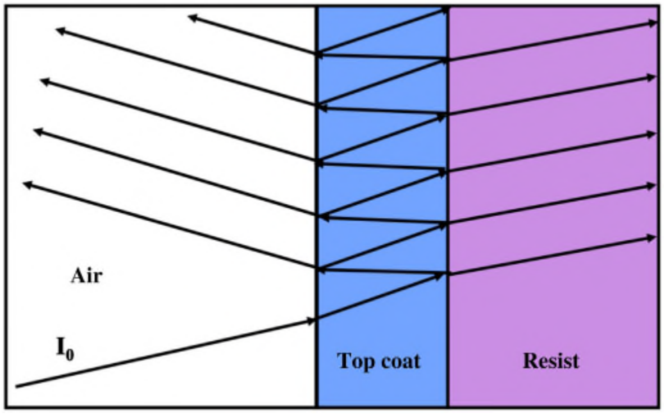

Fig. 15 Light path of top coat/antireflective coating and resist film stack.[43]

optimal TARC film thickness reflection can be minimized.[44–47] Both the phase match and intensity match conditions must be satisfied. This follows Airy's original 19th-century derivation. If both conditions are met perfectly, the reflection amplitude is zero and all light is coupled into the film. This added ARC layer of lower RI results in a superior pattern with higher resolution.

5.1 *Bottom Antireflective Coatings*

Some fluorine-containing acrylate and methacrylate-based copolymers may be used as components in BARC antireflection coating materials (as shown in Fig. 16).

BARC materials used for 193-nm lithography include copolymers of acrylates/methacrylates/alicyclic units as well as bis(benzocyclobutene) and fluorinated arylene ethers.[31] Besides the use of acrylate-based copolymers, it has been reported that perfluoroalkyl silanes (shown in Fig. 13) and poly(ethoxy siloxanes) (not shown) are used as BARC materials. In all these materials the fluorinated component aids in preventing intermixing between the antireflection coating and the photoresist. If mixing were to occur then the performance of the ARC (top or bottom) and the photoresist will be greatly diminished, because the thin photoresist layers will no longer be optically uniform. It should also be noted that fluorine "free" alternative BARCs are known, and they similarly must prevent mixing between ARC layers and photoresists without fluorination. Material suppliers have shown fast etching BARCs for 193-nm lithography. Such materials were targeted for first and second reflectivity minima thickness, are immiscible with photoresists (by being crosslinked), and are not affected by base developers, see Fig. 17.

However, these materials were introduced before the advent of 193-nm immersion lithography. In addition, disposal of hydrophilic ARCs is complicated when ARC and resist disposal cannot be disposed of via the same waste system.

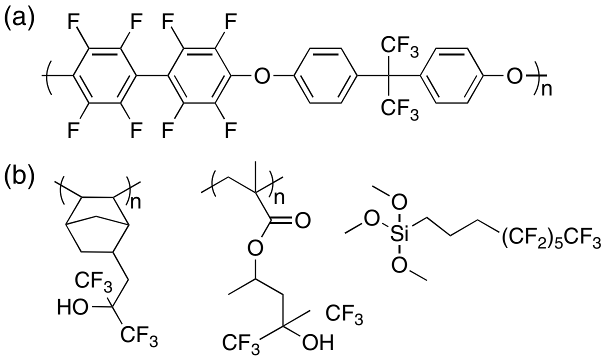

Fig. 16 (a) Fluorinated arylene ethers and (b) acrylate/methacrylate perfluoroalkyl silane-based BARC and TARC materials.

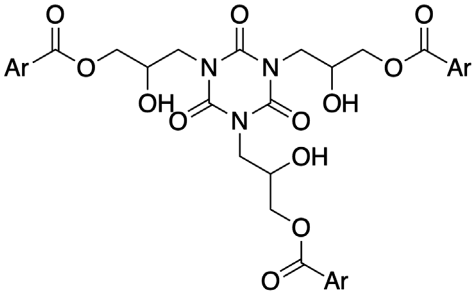

Fig. 17 Representative BARC material.[52]

5.2 *Top Antireflective Coatings*

Antireflective coatings may also be placed on top of a photoresist stack to reduce optical issues. The comments related to BARCs above about refractive index and miscibility are relevant to TARC materials as well. Issues of wetting and interactions with water arise when 193-nm immersion lithography is used. In this variation of high-resolution lithography, a droplet of water is placed between the photoresist stack surface and the stepper (exposure) lens. As the wafer is patterned, the water film must not wet the wafer surface, or else the patterning process will fail since the rapid movement of the stepper would rapidly lead to the breakdown of the immersion layer. A very hydrophobic, nonwetting surface makes the immersion process work well and prevents leaching of the photoactive component. For immersion lithography, control of substrate reflectivity is critical and for this reason immersion, BARCs are favored over TARC when using this process.

Similar chemical strategies have been used to make fluorinated TARCs and topcoats (below), where fluorinated acrylate- and methacrylate-based copolymers are used, but they are optimized for different property sets.[48] Jung et al.[49] showed a TARC material based on these components, which are easily developable but possess a relatively low refractive index of 1.55. Furthermore, by increasing the fluorine content of the TARC material, a high dissolution rate and receding contact angles >70 deg could be achieved.

5.3 *Topcoats*

Sanders wrote an extensive review of resist systems for 193-nm immersion lithography and discussed the need for topcoats.[41] These are materials used as the upper layer in the resist stack that was optimized for the purpose of preventing immersion liquid (water) from leaching photoactive materials from the photoresist during the patterning process and for base development. In that report, he describes several compositions that work well as topcoats. These include perfluoro ethers as well as polymers with hexafluoroisopropanol units and those with short-chain perfluoroalkyl units. All approaches reported function well as barrier materials. In addition to immersion topcoats, which are directly coated on the resist, material suppliers have also developed highly functionalized fluorinated amphiphilic molecular structures, which provide the same properties as a topcoat. The advantage of this approach is that the material, known as an embedded barrier layer (EBL), is formulated directly in the resist, and no separate topcoat coating step is required. Such photoresists are known as topcoat-free resists.[50] Such EBL materials may have similar fluorinated components as those found in fluorinated topcoats and fluorinated ARCs, but their application and processing are different.

Other approaches to low RI materials include the incorporation of air pockets using silica nanoparticles. However, this approach did not gain industry acceptance, because it was not possible to implement with the necessary process reliability and reproducibility. In addition, dyed TARCs (limited by the availability of appropriate chromophores) have been developed that reduce the need for fluorination using anomalous dispersion optical effects but do not eliminate the need for fluorinated components for performance reasons discussed above.

Finally, the only molecular unit that comes close to fluorochemicals in low surface energy are silicones, but they have the disadvantage that they have low softening temperatures and are very

oxygen plasma etch-resistant. Where ARCs need to be removed using such etch methods, alternative structures with silicones do not provide needed properties.

6 Fluorinated Surfactants and Surface Leveling Agents

Surfactants in general are "surface-active agents" that consists of a hydrophobic segment and a hydrophilic unit. Surfactants can be used in a variety of coating applications for improving film quality, changing surface interaction,[51] and wetting characteristics, and component mixing. The hydrophobic portion of a surfactant can consist of such moieties as hydrocarbon, silicone, or perfluorocarbon segments while the hydrophilic portion of a surfactant can be charged or neutral. Specific performance advantage of fluorinated surfactants is that the surface activity is much higher than equivalent hydrocarbon or silicone surfactants as indicated by the requirement for less surfactant material in a formulation to achieve its critical micelle concentration.

Fluorinated surfactants may be used in several applications in photoresist processing. For example, they can be used to improve photoresist deposition and eliminate defects during photoresist coating. Fluorinated surfactants have been used to improve the development process of an exposed photoresist. They are used to improve the uniformity of an ARC coating process and are especially effective when fluorinated ARCs are involved. Thick film photoresists benefit from surfactants in the formulation to achieve good coating uniformity. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality to reduce layer contamination and increase process yield) and the surface activity of fluorocarbon surfactants makes them readily useable with other ARCs and photoresist materials.

Fluorinated nonionic surfactants have been used in a wide range of lithographic processes due to their very low surface energy, thermal-and mechanical stability, and low refractive index. Nanoimprint lithography (below) is making use of fluorinated surfactants to reduce defects caused by the removal of the template in the patterning process.[53,54] Lin et al.[55] demonstrated the use of methyl perfluorooctanoate to significantly reduce defects of printed patterns. Another example was shown by Zelsmann et al.[56] applying perfluorooctyl-triethoxysilane and perfluorooctyl-trimethoxysilane. Besides use in nanoimprint lithography, fluorosurfactant-assisted photolithography was demonstrated by Sakanoue et al. using commercial polymeric fluorosurfactants, such as Surflon S-386, S-651 (AGC) and Novec FC-4432 (3M).[57] It should be noted that, due to the unique properties of fluorinated surfactants, examples of nonfluorinated surfactants with equivalent characteristics to those of fluorinated surfactants are limited and have been used in few resist formulations.

7 Nanoimprint Lithography

While nanoimprint lithography is not today a mainstream patterning technology, it has the potential to be introduced soon for specific patterning applications. A mold with nm-scale features is used to imprint polymer or a photopolymerizable monomer mixture to form the pattern in the transparent mold.[58,59] In the former case, many polymers have been explored for nanoimprinting but a mold release agent such as a poly(perfluoroether) is usually added to the surface of the mold. In the latter case, fluorochemical units such as those used in BARCs and ARCs including perfluoralkyl segments or hexafluoroisopropanol groups have been used.[60] In all cases, removal of the polymer from the mold is an important step in the production of the pattern and for this reason, fluoropolymers are frequently used. It is worth being aware of this approach to high-resolution pattern formation because some early attempts at process development depend on the use of fluorinated photoresists. The fluoropolymer has, in addition to excellent release properties, the advantage that air, which can be trapped in the process, is easily dissolved in the fluoropolymer thereby eliminating trapped bubbles and does not seem to affect pattern formation. Therefore, fluoropolymers are often preferred in this process. This technology area is new enough that little or no reported work has been carried out on the environmental fate of such materials.

Alternate materials for this process include silicones that can be used for their mold release properties.[61] This area is attracting strong interest and demonstrates that nonfluorinated materials

perform well, but at this time it has not been established if silicone materials are superior in performance. Etch characteristics and wear properties are of course different between fluoropolymers and silicones.

8 PFOS/PFAS Remediation

As noted above, the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in strong resistance toward physical, chemical, and biological degradation. Due to this strong resistance to degradation, PFAS compounds in general are extremely stable in the environment. In addition, such compounds have been found to be bioaccumulative.[62] Extensive literature exists describing the detection of a number of PFAS compounds in drinking water.[63] Postuse PFAS waste treatment methods including advanced oxidation processes,[64] reductive decomposition processes (aqueous electrons, hydrated electrons, etc.), and incineration have been developed for mitigation purposes.[59] Among these methods, advanced oxidation processes do not show high efficacy for PFAS degradation due to the high electronegativity of the fluorine atoms. More work will need to be done to assess the relevance to the kinds of fluorinated materials discussed in this paper.

Recent actions by the EPA include interim recommendations for addressing groundwater contaminated with PFOA and PFOS, published method 533 for detection of PFAS compounds in drinking water, an updated list of 172 PFAS chemicals subject to toxics release inventory reporting, a proposal to regulate PFOA and PFOS in drinking water and significant new use rule for certain PFAS in manufactured products.[65] Significant data gaps presently exist in dealing with PFAS and PFOS materials. The EPA is also leading a national effort to understand PFAS and reduce PFAS risks to the public through the implementation of its PFAS action plan and through active engagement and partnership with other government agencies and constituencies.[66]

9 Summary

Fluorinated materials play a useful and often essential role in many aspects of semiconductor processing. In our review of the technical literature, we have examined six major applications of fluorochemicals in photolithography and semiconductor processing and identified an emerging technology, nanoimprint lithography, see Table 1. These fluorochemicals are employed as components of PAGs, as components of photoresists, as elements of high-temperature polymers, and as ingredients in ARCs, BARCs, and as topcoats, frequently satisfying the "essential use" criterion. However, there is a strong societal interest in eliminating their use, and "essential use" is a stopgap situation in which replacements are actively sought. The "essential use" concept expects that PFAS uses considered essential today should be continually reviewed for potential removal or replacement by new technologies and be targeted by innovation toward alternatives. The concept does not support long-term and large-scale remediation technologies to justify the ongoing use of PFAS chemicals.

Thus, the challenges going forward are to find a means to replace PFAS components that achieve or surpass today's current performance characteristics in the following current and possible future lithography systems.

1. The use of fluorination in PAGs is to enhance the acidity (make $\mathrm{p}K_\mathrm{a} \ll 1$) of the acid produced in the region of exposure of a photoresist. The formation of acid to induce a solubility change is the critical step in today's chemically amplified photoresists, the workhorse family of photoresists that enable the production of the vast majority of semiconductors. The presence of a fluorinated unit adjacent to the sulfonic acid gives the acid its ability to efficiently release a proton that reacts with the resist polymer to create a solubility switch. Subsequent development forms a pattern in the photoresist. Today there is no effective alternative to a fluorinated sulfonic acid and this situation applies to chemically amplified photoresists across all wavelengths of lithography from 248 nm to EUV. Efforts to reduce the amount of fluorination in a PAG molecule have been demonstrated, but a survey of the current literature has not shown that complete elimination of

fluorination has produced a successful alternative. However, it is very likely that fluorine-free alternatives, which perform equally well and can easily take the place of the fluorinated compounds used today, will be more widely used, and developed in the coming years. Fluorinated polyimides use the presence of a fluorinated unit to improve the dielectric constant of the material and make it a better insulator while retaining excellent thermal stability. This combination of characteristics has not been effectively achieved by alternate means.

2. Other materials like poly(benzoxazole)s also receive an important performance boost from the incorporation of a fluorinated unit.
3. Antireflection coatings (ARC, BARC, and TARC) and other coatings such as topcoats or EBL use fluorinated components to limit the miscibility of this added layer with a photoresist or other organic layer in the semiconductor manufacturing process. As surface layers, they also provide barrier properties and when used as a topcoat act to protect the photoresist from interactions with the immersion fluid (currently water) used in 193-nm lithography. However, while these features can in part be replicated by other systems the necessary combination of properties (immiscibility, surface wetting properties, barrier properties, low refractive index) has not been successfully achieved.
4. Fluorinated surfactants provide a specific performance advantage since their surface energy is much lower than hydrocarbon or silicone surfactants resulting in the need for less surfactant material in formulations. Additionally, properties including very low surface energy, thermal and mechanical stability, and low refractive index provide benefits to coating and etching processes. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality), and the surface activity of fluorocarbon surfactants makes them readily useable with ARCs and photoresist materials.
5. Nanoimprint lithography may become an important technology for some specialized forms of nanopatterning, and there is interest in the use of fluoromaterials in nanoimprint lithography. Current studies have not yet fully demonstrated that fluorine-free alternatives are successful in producing fine-featured patterns in a production capable system.

Appendix

Table 1 summarizes the function of the fluorinated compounds required for the main lithographic processes. In addition, non-fluorinated alternatives and their current feasibility are shown.

Table 1 Purpose, properties of fluorocompounds for lithographic patterning and semiconductor processing.

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
PAGs	Generation of strong acid upon exposure to UV light, when fluorination acid groups. Control of location and distribution of generated acids, especially in high-resolution applications	Fluorinated sulfonium- and iodonium-acid salts/ strong electronegativity of F atom—creates superacid material capable of mixing with photoresist	All successfully demonstrated alternatives have fluorinated segments—some down to one CF_2 unit	Not yet demonstrated in completely fluorine-free materials
Antireflection coatings (top and bottom versions have different requirements)	Low refractive index, low surface energy, and good barrier properties	Largely fluorinated units in acrylate/ methacrylate/ styrene-based copolymers, very low refractive index, and excellent barrier properties	Fluorine-free alternatives known. But necessary properties not yet broadly demonstrated in 193 immersion	ARC requirements different in 193- and 193-nm immersion lithography—fluorine-free systems not fully demonstrated

Table 1 (*Continued*).

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
Topcoat (for 193-nm immersion photoresist)	Provides barrier layer for 193-nm immersion photoresists applied on top of photoresist and prevents leaching of photoactive components. Protects the photoresist from contact with immersion liquid (water)	Largely fluorinated acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
EBL (for 193-nm immersion photoresist)	Forms a protective surface layer for 193-nm immersion photoresists and prevents leaching of photoactive components. Incorporated as part of photoresist and segregates to film surface during the coating process. Protects the photoresist from contact with immersion liquid (water)	Largely acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
Polyimides (photopatternable)	Required stress buffer coat between chip and package to prevent premature device failure; especially good electrical insulating characteristics	Tetracarboxylic acid anhydride derivatives and aromatic diamines/solubility in organic solvents, low dielectric constants, and high thermal and thermooxidative stability; requires negative tone solvent to develop	Novel polyimides—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Polybenzoxazoles (photopatternable)	Stress buffer coat to prevent premature device failure; high-temperature stability and good insulating characteristics	Low dielectric constants, and high thermal and thermooxidative stability; processed using positive resist developer	Novel polybenzoxazoles—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Nanoimprint Lithography fluoropolymers	Excellent release characteristics; low surface energy and fluoromonomers reported to dissolve trapped air making them ideal for filling the micromolds of nanoimprint lithography	Fluoropolymers/low surface adherence	Silicone-based release agents	Potentially good but not yet established
Nonionic fluorinated surfactants	Improve coat quality in thin lithographic films (e.g., photoresists and BARCs); compatibility with photoresists and TARC/BARC structures; high efficiency of fluorinated surfactants requires very little additive and enables better performance	Nonionic fluorinated segments with water-soluble units	For a number of applications, alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials

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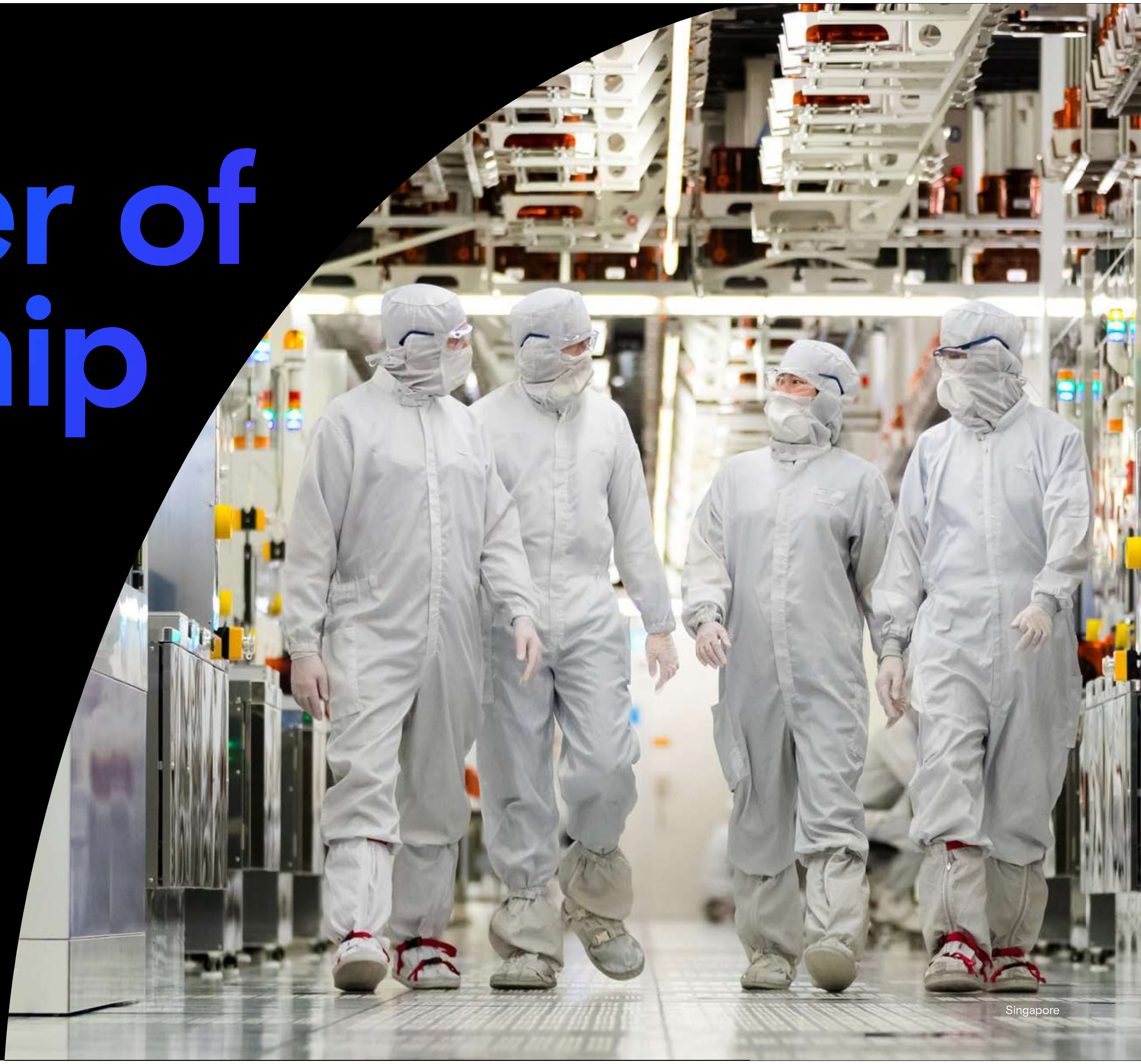
The power of partnership

Micron sustainability report 2023



Singapore

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A message from our CEO

More than ever before, the world is recognizing the importance of semiconductors — not only to our economic health and advancement, but to every aspect of modern life, from education to entertainment. Micron's vision is to transform how the world uses information to enrich life *for all*, and the solutions we make are becoming increasingly important as we move into the age of ubiquitous artificial intelligence systems powered by fast data.

In the pages of these reports, you'll see that sustainability is not just central to Micron's vision, mission and values, it is also integral to our long-term strategic plans. We believe we also have a responsibility to help lead sustainability improvements across our industry. None of these goals are possible without strong partnerships. We actively work with industry peers, suppliers and customers worldwide to set new standards for the sustainability of semiconductor production.

Manufacturing semiconductor products is a resource- and power- intensive business, and careful management and planning are required to ensure efficient production. In 2022, Micron announced several critical expansions that will be central to the company's future, including investments in Boise, Idaho, and Clay, New York. Both projects are pivotal to Micron's manufacturing strategy to meet DRAM demand over the decades ahead. With the support of the CHIPS and Science Act, these projects stand to make a significant impact on U.S. semiconductor manufacturing leadership. Each will also demonstrate leadership techniques for energy conservation and sustainability. We are also making significant investments in community and education around these expansions. These investments will help us create sustainable growth and train the workforce we need to drive advanced semiconductor manufacturing.

Our aim with this report is to provide a detailed accounting of our progress toward our sustainability goals and note specific contributions over the past year. It also shares our vision for sustainable development in the years ahead. Below are a few highlights.

Environment

- Emissions: We expanded our climate initiative goals early last year, working toward targets to reach net zero greenhouse gas emissions in our operations (scope 1) and purchased energy (scope 2) by 2050, with a 2030 milestone to reduce scope 1 emissions from our 2020 baseline by 42%. These complement our existing goal to achieve 100% renewable energy for existing U.S. operations by the end of 2025.
- Energy, water and waste: We continue to make our operations more efficient and sustainable, with aspirational targets of 100% renewable energy, 100% water conservation, and zero waste to landfill. This report outlines our participation in alternative energy facilities, as well as water conservation and river restoration projects in our communities.
- Sustainable financing: Micron continues to lead in sustainable financing. We have executed $3.7 billion in credit facilities linked to our sustainability performance and achieved our 2022 performance metrics in connection with this credit. The $1 billion green bond we issued in November 2021 supports Micron's commitments to environmental performance and LEED-certified buildings.

Social

- Equity and representation: We continue to maintain global pay equity for women and people with disabilities globally, as well as across race/ethnicity and veteran status in the U.S. and race/ethnicity for Malays in Singapore. We actively promote a culture of inclusion and focus our educational outreach on bringing more women and underrepresented groups into semiconductor fields.
- Team engagement: We grew participation in employee resource groups to 39% of our workforce, a nearly 50% increase from fiscal year 2021 (FY21). Micron is in a leadership position in this metric.
- Diverse suppliers: Our spend with diverse suppliers is growing. In FY22, we achieved $454 million in spend with diverse suppliers, exceeding our goal of $404 million.
- Diverse financial institutions: In FY22, we achieved our goal to have $500 million in cash investments managed by underrepresented financial firms.

Governance

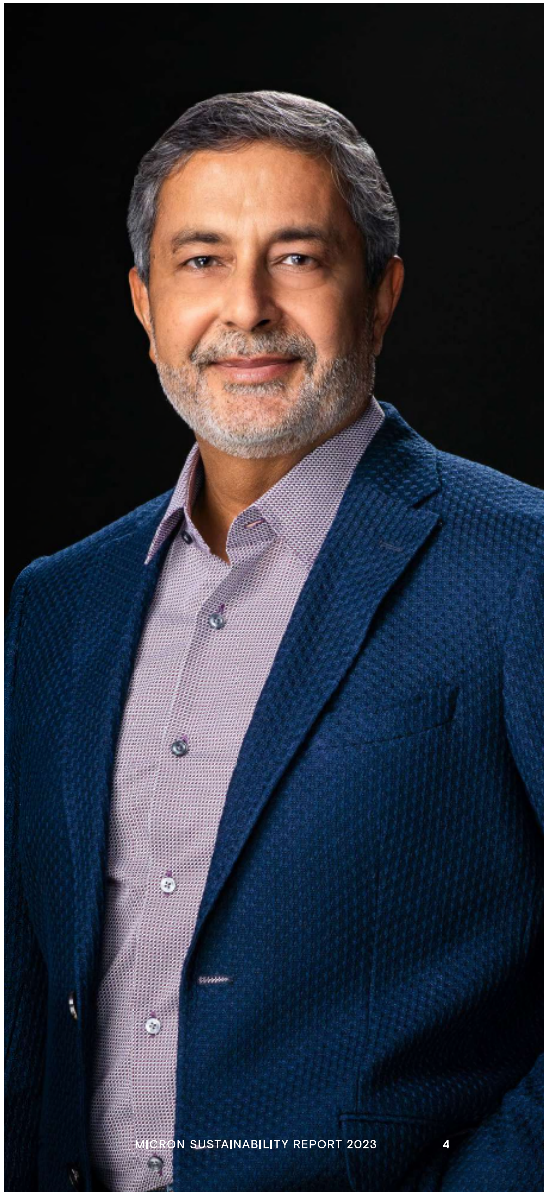
- Ethics: I personally place a high emphasis on integrity with our team, and we institute regular training so that every team member understands and adheres to our code of conduct and related policies.
- Responsible sourcing: We have a number of programs focusing on responsible minerals sourcing, in addition to supplier diversity, environmental performance and human and labor rights.

Micron continues to make strong progress toward our sustainability, community and governance goals, and I'm proud of the work represented in these pages.

I hope you enjoy reading our 2023 sustainability report and progress summary, and we invite your feedback. You can reach us by emailing sustainability@micron.com.

Sanjay

Sanjay Mehrotra
President and CEO, Micron Technology



From: Don Hughes <dhughes171@gmail.com>
Sent: Wednesday, November 1, 2023 3:03:40 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Fwd: Micron DEIS Scoping Comments

To: Onondaga County Industrial Development Agency
ATTN: Micron Project
335 Montgomery Street, 2nd Floor
Syracuse, New York 13202

From: Donald Hughes,
Conservation Chair, Central & Northern New York Sierra Club Group

Re: Draft Scoping Document for the proposed Micron Semiconductor Fabrication facility in Clay, NY

I wish to submit, on behalf of the approximately 3000 members of Sierra Club who reside in our territory, the attached comments. You should have received the same documents from John Przepiora earlier today. Would you kindly confirm receipt of these comments with four supporting attachments?

thank you,
DH

Donald J. Hughes, P.E., Ph.D.
dhughes171@gmail.com
315.214.4060
=============================
Hughes Environmental Consulting

157 Strong Ave,
Syracuse, NY 13210
==============================

"*dans les champs de l'observation, le hasard ne favorise que les esprits préparés*" ("In the field of observation, chance favors only the prepared mind") **Louis Pasteur,** French chemist and microbiologist (1822 -1895)

To: OCIDA

On behalf of the following individuals and myself working together as the CNY Sustainability Coalition, and who have signed the attached memorandum on behalf of our respective organizations, I am submitting the attached comments and supporting 4 attachments (A1-A4) pursuant to the public comment period for the Micron project SEQRA DEIS scoping. Please do not hesitate to contact me if you have any questions. Thank you for the opportunity to comment on this important document and for allowing an extension of time for filing this.

Donald Hughes

Conservation Chair, Sierra Club Central & Northern NY Group

Syracuse, NY

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Tylah Worrell

Exec. Director,

Urban Jobs Task Force of Syracuse

Syracuse, NY

t.worrell@ujtfs.org

Thank you again. We look forward to working with you as this project moves forward.

John Przepiora

Vice-President & Director

GreeningUSA, Inc.

(315) 382-3829

…Advocating for sustainable communities

to the benefit of local economies and environments.

To: Onondaga County Industrial Development Agency (OCIDA)

From: The undersigned individuals and representatives of environmental and sustainability organizations of Central New York, aka, “CNY Sustainability Coalition”

RE: Comments on the **DRAFT SEQRA SCOPE OF WORK (**draft Scoping Document or draft scope**),** dated September 12, 2023 for the proposed **MICRON SEMICONDUCTOR FABRICATION plant in** Clay, NY.

The SEQR Handbook, 4th Edition, dated 2020, states: “A written scope of issues developed through a public scoping process benefits the lead agency and the sponsor by providing explicit guidance as to what criteria will be used to determine whether a submitted draft EIS is adequate. The written scope provides a means of ensuring that significant topics have not been missed and that the level of analysis in the EIS satisfies standards established during the scoping process.”

While the draft Scoping Document offers a reasonable approach to defining significant environmental impacts in certain areas, we believe it is inadequate in other areas, especially ith respect to chemicals and energy usage. We offer the following comments:"

4.3 ALTERNATIVES TO BE ANALYZED IN THE DEIS

The SEQR Handbook stipulates (p 100) the scoping process should “Define reasonable alternatives for avoiding specific impacts which must be included in the EIS, either as individual scenarios or a range of alternatives.”

Two “build” alternatives are presented in the draft scope:

1) Full construction and operation of four fabs over an approximately 20-year period
2) Reduced Scale: construction and operation of two fabs over a shorter period.

This analysis is too limited. It does not address a proper range of alternatives. For example, the impacts on Greenhouse Gas Emissions and Climate Change will vary tremendously depending on the amount of renewable energy that Micron is able to procure. Micron has expressed a desire to achieve 100% renewable energy for electricity, but that may be unrealistic for the construction timeframes that are envisioned. Micron’s electricity demands are projected to be very large (7.15 billion kWh/year for Phase 1; 16.17 billion kWh/year for Phase 2), so it would be far more realistic to evaluate a range of alternatives which take into account the time needed to construct a supply of renewable energy sources (wind, solar, and hydropower). The evaluation must assess the feasibility of achieving 100% of electricity from renewable sources for each Phase of the project.

It has been estimated (Plumley, pers. communication) that it would take 1200 3MW wind turbines to generate the power needed for Phase 2.

It would also be useful to consider alternatives with different phasing such as construction of a single fab followed by a reassessment of impacts prior to construction of a second fab. In a

multi-phase approach, lengthening the time frame may be an appropriate way to manage the community impacts while allowing for the potential for technological changes that may affect chip fabrication or building and/or transportation improvements which may reduce impacts. A long term approach may allow the community to adjust to the growth and assimilate it with less adversity.

5 ANALYSIS FRAMEWORK

Preparation of the DEIS must conform to 6 NYCRR Part 617.9(b). The DEC's SEQR Handbook asserts that "An Environmental Impact Statement (EIS) is a document that impartially analyzes the full range of potential significant adverse environmental impacts of a proposed action and how those impacts can be avoided or minimized."

Section 5.1 of the draft scope states: "The Proposed Project will be evaluated for potential significant adverse effects to the Project Site and **applicable study areas** for all relevant environmental technical categories in accordance with applicable SEQRA requirements."

'Applicable study areas' is a vague phrase which needs to be better defined specifically in an overarching, comprehensive manner. Answers to questions are directly related to the question asked; asking the wrong question leads to wrong answers. We recognize that each of the sub-sections in 5.3.1 may define study area specific to the particular analysis and that may be appropriate, however, we believe that the final scope document should include a stand alone section devoted to defining the study area clearly in order to convey the breadth with which the impacts of this project will be manifest and establish the full areal extent of the analytical framework.

This project requires an ecosystem approach that considers the regional impacts on the environment, the economy and society. The impacts must be determined and assessed for their equitable distribution and for their adverse impacts that are detrimental to the region's short and long term sustainability. This is not a typical project. It is enormous in scale, unprecedented for the region and with potential for egregious environmental impacts. It has been suggested by Onondaga county officials that the Onondaga County population may increase by 25% or 125,000 over the full build-out period (estimates of regional growth are unknown to this reviewer). The scale of the environmental review process, and the expertise required to carry it out, must rival the project's enormity.

OCIDA must assure that the final scope for each of the technical sections of the DEIS is specified with rigor, that the appropriate and necessary expertise is utilized in the writing of each scope item, that the study areas are broad enough and that each analysis is based on not only the current standards, but also reasonably presumed standards that will be in force throughout the build out and operational period of the proposed project.

Finally, The SEQR Handbook requires the following in the scoping of the identified reasonably expected impacts:

- Describe the extent and quality of information needed;
- List available sources of information;
- Specify study methods or models to be used to generate new information, including criteria or assumptions underlying any models, and define nature and presentation of the data to be generated by those studies and models.

In many of the areas included in section 5.3 the standards for information and methods appear to be inadequate. The scoping document must require high standards be applied to the analysis and specify information and methods to be utilized. To do less shortchanges the community and can lead to disastrous and unanticipated consequences.

The biggest challenge presented by this project is the enormity of it; in order to fulfill the dreams which this project offers in a just, equitable, economically and environmentally sustainable manner, the review process must be equally enormous, impartial and thorough.

5.3 **METHODOLOGIES FOR TECHNICAL ANALYSES**

Comments on specific sections are listed below.

Many of the methodologies outlined in Chapter 5, Analysis Framework, are very comprehensive and appropriate for a project of this size. We fully support the inclusion of each of these categories. However, we have noted certain areas where the level of detail and intent seems inadequate as follows.

5.3.1 TECHNICAL STUDIES

- LAND USE, ZONING, AND PUBLIC POLICY

  COMMENT: Why isn't the city of Syracuse explicitly included here? Seems to be a major omission.

- COMMUNITY FACILITIES/OPEN SPACE AND RECREATION

  COMMENT: Here is an assessment of impacts on community emergency services, fire safety requirements included in building code and site access requirements of the emergency service providers.

  Lumped in is assessment of growth impacts on educational facilities and parks and recreational facilities. The study area seems ill defined and critical to this analysis. Some reference to Towns of Clay and Cicero seems to limit the study area to these two towns; is that what is intended? If so, it is probably too narrow an area particularly when the cumulative and indirect impacts are considered.

  This section is poorly organized and deserves to be rewritten to define more clearly what are the parameters to be studied and analyzed relevant to police, fire and other emergency services; schools; parks and rec facilities. Absent from the community facilities most notably is the health care and hospital system.

- SOCIO-ECONOMIC CONDITIONS

  COMMENT: The study area is defined better here and seems appropriate. It is necessary to assess the way benefits and adverse impacts are distributed. There is no specified time horizon for this analysis and little specificity regarding the analytical standards, tools and techniques that will be employed. If OCIDA is ill equipped to specify generally accepted standards for such an analysis it is incumbent tha OCIDA obtain the expertise required to specify how this must be done.

- VISUAL IMPACTS AND COMMUNITY CHARACTER

  COMMENT: This project has the potential to significantly alter the character of the community—not only the locale surrounding the immediate project location, but the wider Syracuse and Onondaga County as well as portions of Oswego County as population growth and housing development is induced. The DEIS should include an analysis of the potential for growth-induced changes in the community that this project will induce.

- GEOLOGY, SOILS, AND TOPOGRAPHY

  COMMENT: Reference is made to 'property survey' as a data source but later the 'geotechnical investigation' is mentioned but not included in the sentence describing the analysis. Is this an oversight that should be corrected? Certainly the geotechnical survey will provide valuable information to confirm or modify the USGS soil survey data.

- NATURAL RESOURCES

  COMMENT: This seems to prioritize wildlife and overlook the categorization of existing vegetation. Is that what is intended? The EAF mentioned the undertaking of detailed field studies of land coverage and natural resource conditions on or near the Micron Campus. Will a detailed land cover field study be done? It should be included.

  Little detail is included about the hydrology and wetlands evaluations that will be necessary. Standards, tools and analytical techniques required to be employed must be specified. If OCIDA lacks the expertise to properly specify this analysis they must obtain that expertise from involved agencies or consultants that can properly specify the scope and requirements of this work.

- SOLID WASTE & HAZARDOUS MATERIALS

  "This analysis will describe the proposed generation of solid waste by the Proposed Project and how that material will be handled, stored, and transported. This analysis will describe Micron's proposed measures to reduce generation of solid waste through reuse or recycling."

  COMMENT: It is appropriate for Micron to identify the quantities and types of solid waste that are likely to be generated at their facilities. The applicant estimates the generation of 45,000 tons per year of solid waste, which represents an additional 15% of waste generated in Onondaga County. All solid waste in Onondaga County is burned in an incinerator. What impacts will the solid wastes disposed of through the OCRRA system have on air quality? The fiscal implications for the OCRRA must also be assessed. The indirect, long term and cumulative impacts of the use and disposal of both solid and hazardous waste materials must be included in the analysis.

  The applicant is proposing to take measures to reduce the generation of solid waste. What is under consideration?
  Strangely, the same level of investigation is not described for hazardous wastes, which constitute a far greater threat to employees, the community, and the environment.

The text reads that the DEIS "will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect against releases to the environment."

It is imperative that the DEIS identify ways to reduce and eliminate the generation of hazardous waste through reuse and recycling. Hazardous waste is best eliminated by using non-hazardous substances in the fabrication process. In the event that hazardous substances must be used in the fabrication process, methods to completely contain those substances, and/or ultimately destroy them, must be considered.

Of particular concern are perfluorinated alkyl substances (PFAS), otherwise known as "forever" chemicals because of their long lifetimes in the environment and in organisms. These chemicals are of great concern due to their high levels of toxicity. The semiconductor industry uses PFAS extensively (Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P) The DEIS must address the use of these chemicals and alternative chemicals that could be used as substitutes.

The attached memorandum from Lenny Siegel, Center for Public Environmental Oversight, provides additional details regarding the problems posed by PFAS and other hazardous chemicals. The authors of a recent paper on use of PFAS in the semiconductor industry note that: " the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in ***strong resistance toward physical, chemical, and biological degradation***. Due to this strong resistance to degradation, PFAS compounds in general ***are extremely stable in the environment.*** In addition, such compounds have been found to be bioaccumulative. Extensive literature exists describing the detection of a number of PFAS compounds in drinking water." (emphasis added) The authors also note "there is a strong societal interest in eliminating their use, and "essential use" is a stopgap situation in which replacements are actively sought."
https://www.spiedigitallibrary.org/journals/journal-of-micro-nanopatterning-materials-and-metrology/volume-21/issue-01/010901/Review-of-essential-use-of-fluorochemicals-in-lithographic-patterning-and/10.1117/1.JMM.21.1.010901.full?SSO=1

Enhesa (formerly Chemical Watch) is an industry trade organization that provides regulatory guidance to industry. They note that: "The use of PFAS is a major focus for regulatory authorities worldwide right now. In Europe, the REACH restriction proposal aims to place limits on all uses of more than 10,000 per- and polyfluoroalkyl substances. Meanwhile, in the US, restrictions are high on the agenda in several states.

In late September 2023 the European Parliament voted overwhelmingly in support of a parliamentary report backing the first revision of the Urban Wastewater Treatment Directive (UWWTD) in 30 years. The revision proposal would introduce new limit values and treatment requirements for micropollutants in wastewater, including per- and polyfluoroalkyl substances (PFASs) and microplastics.

The hazardous materials component is a significant component of the EIS. It deserves its own chapter. As written, there is no reference to worker safety; but of course OSHA rules apply as well as other laws when the use, storage and transport of Hazardous Materials (HazMat) is considered. The DEIS should be required to include information about this issue as 9,000 workers will potentially interact with these materials, and the community in general is potentially being put at risk. HazMat emergency response and potential risks to the community must also be fully considered and described. The DEIS must include a full disclosure of HazMat risks related to the manufacture of chips including supply chain, transport, storage, security, air quality, spill/release response and disposal. Cradle to grave analysis must be provided to decision makers being asked to permit this endeavor, as well as community members who are being asked to assume these risks. Additionally, we believe alternative production processes should be evaluated to determine whether the objective production can be realized without the utilization of hazardous materials.

- TRANSPORTATION:

  The only mitigation measures mentioned in this section are improvements to roadways. It is imperative that the utilization of public transportation, including mass transit by bus and light rail, be considered.

- UTILITIES & INFRASTRUCTURE:

  COMMENT: The potential impacts on infrastructure (water, stormwater, sanitary sewer, electrical and telecommunications) will be assessed. The scope of this assessment is ill defined here and needs to be specified in greater detail. The DEIS needs to address parameters such as system capacity, level of service changes, fiscal implications for the community and impacts on water bodies.

  The city of Syracuse should be considered an interested agency for this (as well as other aspects of this project) as it relies on a connection to the OCWA for a portion of its water supply needs.

  It is noted elsewhere in project documents that a 16” natural gas main will be extended to the plant, yet it isn’t mentioned in this section; Shouldn’t impacts associated with the area’s gas supply and the construction of this line be included here?

- USE AND CONSUMPTION OF ENERGY

  The Scoping Document simply states: “This analysis will describe the Proposed Project’s use and consumption of energy and measures that Micron intends to pursue to reduce energy consumption and use of renewable sources.”

  COMMENT: The anticipated energy needs of this project are enormous. Much greater detail is warranted, as discussed below. Local as well as regional and statewide impacts must be considered. Further, this section is related to other sections such as transportation, air quality, and climate change.

Electricity: Electrical consumption is anticipated to be 16 billion kilowatt-hours of electricity per year, when fully built. (Phase 2, Envir. Assessment Form, Part 1, Section K) To put this in perspective, this is equivalent to all of the electricity consumed by the states of New Hampshire and Vermont, combined. The entire state of New York used 143 billion kWh of energy in 2022. Micron will increase demand in NY by 11%. The Scoping Document clearly needs to provide greater details about:

- How will the EIS consider the various sources of electricity which are currently available, and which may become available as the plant is constructed?
- The EIS must evaluate the ability of current power lines owned and operated by National Grid to deliver the required power.
- Micron has stated its goal "to achieve 100% renewable energy for existing U.S. operations by the end of 2025." (Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology) Does Micron plan to achieve this goal for the proposed facility in Clay?
- The Scoping Document should state that the EIS will examine:
    - power purchase agreements with suppliers of solar power, wind power and hydropower.
    - on-site production of electricity from solar and/or wind generation

Natural Gas: National Grid is proposing to build approximately 2.5 miles of 124-psig,12" natural gas distribution main to the new Micron facility. (Exhibit G, Micron Term Sheet, signed Sept. 22, 2022). The DEIS needs to address these topics:

- How much natural gas will the facility need, and for what purpose?
- The use of natural gas seems inconsistent with New York state's CLCPA, which calls for a 40% reduction of greenhouse gas (GHG) emissions 2030, and then an 85% reduction of GHG (below 1990 levels) by 2050. Combustion of natural gas releases CO_2 which is the primary driver of climate change.
- The use of natural gas also seems incompatible with Micron's global target to achieve a 42% reduction in GHG emissions from operations ("scope 1") by 2030 and net-zero emissions from operations and purchased energy ("scope 1 & 2") by 2050, supporting the objectives of the Paris Agreement. (Source: Micron website: https://www.micron.com/ny/fact-sheet)

Related energy usage: The use of energy for construction, facility operations and the ancillary increases in energy consumption related to transportation needs the project will generate should also be investigated. It may not be unreasonable to consider the increase in energy consumption from the induced community growth which this project will generate as described in the chapters on indirect and cumulative impacts and the growth inducing aspects of the project.

- INDIRECT AND CUMULATIVE IMPACTS:

COMMENT: The use of the word 'summarize' to describe the scope of this Chapter is insufficient. This Chapter must assess indirect and cumulative impacts of the proposed project for each of the technical areas included in the DEIS. If these effects are included elsewhere it may be appropriate to summarize them here. Let's be clear about exactly what is required to be included in the DEIS

- GROWTH INDUCING ASPECTS OF THE PROPOSED PROJECT:

  COMMENT: This section relates to perhaps the most significant aspects of this project. While jobs and employment and economic growth will be created, the population growth of the region has the potential to produce significant adverse environmental and economic impacts as well which must be considered. While this section overlaps with other sections of the proposed DEIS scope, it is important to not forget that there will be significant impacts on the community. Such effects as rising housing costs could disproportionately impact the impoverished and increase the potential for a rise in homelessness. The DEIS must not overlook this and other issues relating to population growth of Syracuse, Onondaga County and the surrounding area.

- IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

  COMMENT: Aside from building materials and energy, resources consumed in the manufacturing process, as well as the land devoted to this project, the water consumed and the changes to water and air quality (eg., compounds such as "forever chemicals" which could be discharged into water bodies and the air) should be included in this analysis. The community should, and must know, the sustainability aspects of this venture as it decides to permit its development.

- MITIGATION:
  The SEQR Handbook suggests, " Specify possible measures for mitigating potential impacts that must be discussed in the EIS, to the extent that they can be identified at the time of scoping."

  In addition to those listed in this draft scope, others that should be listed are:
    - Public transportation (various options such as fixed route bus, demand activated bus service, light rail),
    - Building design features such as those proscribed in LEED building standards that reduce energy consumption, or production of renewable energy (geothermal or other water-source heat pumps) or
    - Mitigate habitat loss with green roofs or parking area reductions via public transportation options for employees
    - Alternative production processes that can minimize use of hazardous materials, energy use, etc.

Respectfully submitted by the following, on behalf of their respective organizations.

Donald Hughes
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Tylah Worrell
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Urban Jobs Task Force of Syracuse
Syracuse, NY
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LIST OF ATTACHMENTS

1. Forbes magazine, Oct. 5 , 2023; https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821P

2. Memorandum from Lenny Siegel, Center for Public Environmental Oversight

3. Christopher K. Ober ,* Florian Käfer , and Jingyuan Deng. "Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing,"Journal of Micro/Nanopatterning, Materials, and Metrology, Vol. 21, Issue 1, 010901 (March 2022). https://doi.org/10.1117/1.JMM.21.1.010901

4. Micron sustainability progress summary 2023: Message from Sanjay Mehrotra President and CEO, Micron Technology

More Domestic Chip-Making Means More ‘Forever Chemicals’

by Amy Feldman, Forbes Staff, October 5, 2033

https://www.forbes.com/sites/amyfeldman/2023/10/05/more-domestic-chip-making-means-more-forever-chemicals/?sh=2d10b08c7821

Mark Newman, CEO of Chemours, the only American PFA manufacturer, says the company is ramping up production to meet the demands of reshored semiconductor fabrication.

“I brought some show-and-tell,” Mark Newman, CEO of chemical maker Chemours, told *Forbes* during a recent interview in a midtown Manhattan conference room. He pulled a valve assembly out of a bag. The innocuous piece of plastic, he explained, is made of fluoropolymer known as PFA — a type of controversial “forever chemical” and an essential tool in the production of semiconductors.

“You cannot make chips without a whole PFA infrastructure,” he said. “We estimate that in a modern-day fab, there’s a half-kilo of PFA in every square foot. So in a 400,000- to 600,000-square-foot fab, that’s 200 to 300 metric tons of this stuff.”

It’s not just valves, of course, but all types of pipes, tubes and pumps in semiconductor equipment. Fluoropolymers are particularly key for filtering out small particles from fluids during chip production. Few factories need to be as clean as chip fabs, where particles as tiny as human skin cells can contaminate production. Chemours’ PFA is in much of that equipment and material, providing a big, and largely unseen, part of a semiconductor fab’s processes.

Wilmington, Delaware-based Chemours, a spinout of DuPont, is the only U.S. manufacturer of PFA. For Chemours, advanced materials including fluoropolymers represent roughly one-quarter of its total $6.3 billion (latest 12-months revenue) business, with refrigerants and titanium dioxide, used in paints and aerospace coatings, making up the bulk of the rest. Within that, semiconductors are part of its performance-solutions segment, which accounted for $493 million in sales for 2022, up 53% from $322 million in 2020. On its website, Chemours says flat-out that “without PFA, domestic semiconductor manufacturing would not be possible.”

Last year, President Biden signed into law the CHIPS Act, which provides $52 billion in funding to spur domestic semiconductor manufacturing with a goal of improving national security by decreasing reliance on nations like China for critical technology. Chips are essential not just for our phones and computers, but also for medical devices and fighter jets. “Geopolitics has been defined by oil over the last 50 years,” Intel CEO Pat Gelsinger said at an MIT event earlier this year. “Technology supply chains are more important for a digital future than oil for the next 50 years.”

But our insatiable desire for electronic devices and American policymakers’ push for more domestic manufacturing of semiconductors relies on the industry’s access to large amounts of “forever chemicals.”

Ongoing Litigation

Forever chemicals, or PFAS, comprise thousands of synthetic chemicals. They're long-lasting and resistant to heat, corrosion and moisture, making them popular for a variety of products that include nonstick pans, stain-resistant upholstery, firefighting foam — and semiconductor production. Studies, however, have linked PFAS to a variety of diseases, including cancers and reduced immune system response, as well as to contaminated groundwater, air and soil that can lead to a host of health problems. PFAS are an enormous category. Fluoropolymers, like those that Chemours manufactures for industrial uses, are just one class.

Litigation over their impact is ongoing. In June, Chemours, along with DuPont and another spinoff, Corteva, reached a $1.2 billion settlement with public water systems. Meanwhile, legislators and regulators have been cracking down on the chemicals' use, particularly in consumer products such as clothing, furniture and textiles, where they can be more easily replaced. Minneapolis-based 3M, which in 2018 agreed to pay $850 million for damaging drinking water and natural resources in the Twin Cities area, announced that it would cease production of PFAS by the end of 2025.

The semiconductor industry has pushed back against regulations here and in Europe, where regulators had proposed a ban on PFAS. When the U.S. Environmental Protection Agency asked for comments on tightened oversight on PFAS earlier this year by revoking certain low-volume exemptions, the microelectronics trade group SEMI called it "catastrophic" for domestic chip manufacturing. In a letter to the EPA, it said that such a rule "would significantly hamper the domestic semiconductor industry despite express goals of the Administration to the contrary and to the detriment of the U.S. economy."

Doubling Down

In this landscape, Chemours' Newman is doubling down. In a wide-ranging interview with *Forbes* during a trip to New York for Climate Week, Newman said that the $4 billion

(market cap) company was expanding production of fluoropolymers, driven by the critical need for the chemicals in semiconductors and electric vehicles. Further, he said, such production could be done safely with investments that his company is making. It has, for example, invested more than $100 million in emissions control technology at its Fayetteville, North Carolina plant.

"We're currently sold out and working to expand capacity here in the United States," Newman said. Chemours plans to enlarge its West Virginia production facility, he said. Located just across the river from Ohio, the factory is well positioned to supply Intel's giant chip fab near Columbus, now under construction. "Imagine making something for the semiconductor industry in what people think of as coal country," Newman said. All told, the company is investing up to $1 billion in fluoropolymers, including those for use in semiconductors.

The combination of reshoring and PFAS is "a very complicated discussion," said Zhanyun Wang, a scientist and PFAS researcher with EMPA-Swiss Federal Laboratories for Materials Testing and Research. "There's a lot of resistance from the industry because, of course, if we want to do the change, it costs." That's especially problematic if the United States and the European Union impose regulations and other parts of the world do not. However, he said, such regulations could be designed to spur new innovations. "The semiconductor industry has a lot of R&D power," he said.

In July 2015, when industrial giant DuPont spun off its performance chemicals division and named it Chemours for "chemistry" plus the "Nemours" part of DuPont's full name, the new company was saddled with debt and potentially toxic assets. "I think investors were worried if we were going to be solvent," then-CEO Mark Vergnano told *Fortune* in 2016. "Were we going to make it through this or not?" Vergnano proceeded to pull off a dramatic turnaround by slashing costs, selling off non-essential businesses and gaining market share for its refrigerants business.

Big Expense

Newman, who had been the company's chief financial officer during those years and is one of the country's top Black executives, became CEO in 2021. The company's revenue ballooned to a peak of $6.8 billion in 2022, driven by strong pricing. Its advanced performance materials business, which includes the Teflon lineup of fluorine chemicals, gained price increases of 18% and reached total sales of $1.6 billion as it focused on high-tech markets including advanced electronics and clean energy.

The semiconductor industry "didn't want to use fluoropolymers, not because they were concerned about them, but because fluoropolymers are expensive," said Gerardo Familiar, president of Chemours' Advanced Performance Materials division, which includes fluorine chemicals. But alternatives have been scarce because of fluoropolymers' resistance to corrosion and ability to work at high temperatures and to last for a long time. He said that fluoropolymers like PFA are "substances of low concern," and that they should be considered differently than PFAS. "Those materials last a very, very, very long time, but they make your manufacturing very, very, very safe for the people who are there because you don't have an issue with corrosion," he said. The conundrum, he said, is how to manufacture them responsibly and what to do with the materials at the end of their life.

Some smaller companies are working on replacing PFAS in electronics manufacturing. Danvers, Massachusetts-based Transene, a privately held business founded in 1965, partnered with Toxics Use Reduction Institute (TURI) researchers at University of Massachusetts Lowell to develop alternatives for its etching solutions used in the semiconductor industry. The vast majority of customers have made the switch, and others are working through their qualification process. "You keep hearing from the industry, 'We need 10 or 15 years to make a change,'" said Greg Morose, research professor at UMass Lowell and research manager at TURI, who worked with Transene. "We basically did the research in 18 months, which is really rapid."

Phasing Out PFAS

But that's just one small company, and one use of PFAS within a semiconductor fab. David Zamarin, founder of venture-backed DetraPel, which works on sustainable coatings for food packaging and textiles, said he received inquiries from semiconductor and electronics manufacturers, but that the cost and time didn't make it economically viable. In the electronics industry, even companies that have set goals of getting rid of PFAS are moving slowly. Apple, for example, has promised to "thoughtfully phase out PFAS in a way that does not result in regrettable substitutions."

Newman said that fluorine chemicals can be made responsibly. Chemours has committed to eliminating at least 99% of PFAS air and water emissions from its manufacturing processes by 2030. Chemours is also working on sustainable technologies, he said, such as renewable membranes for green hydrogen production marketed under the Nafion brand name and low-global-warming refrigerants for heating and cooling buildings.

"We felt because of our legacy we needed to lean into this mantra of being a different kind of chemistry company and showcasing the fact that we could be a leader in emissions reduction," Newman said. "Our chemistry really enables a lot of the future economy."

CENTER FOR PUBLIC ENVIRONMENTAL OVERSIGHT
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TO: Micron Project, Office of Economic Development, Onondaga County
FROM: Lenny Siegel, Center for Public Environmental Oversight
DATE: October 30, 2023
SUBJECT: SEQRA Scope of Work for Micron Semiconductor Fabrication

Thank you for the opportunity to comment on the September 12, 2023 Draft SEQRA Scope of Work for Micron Semiconductor Fabrication. I have been asked by residents of Onondoga County to offer my comments.

I have nearly five decades of experience monitoring and influencing the worker health and environmental impacts of the semiconductor industry, through the Pacific Studies Center, the Project on Health and Safety in Electronics, the Silicon Valley Toxics Coalition, and the Center for Public Environmental Oversight, as well as my service as Council Member and Mayor of Mountain View, the birthplace of the commercial semiconductor industry.

The semiconductor industry produces remarkable products that we all use. Unfortunately, its environmental and workplace health record is less than remarkable. The MEW Superfund Area here in Mountain View was the home of some of the earliest successful integrated circuit manufacturers. The wafer fabs are gone, but despite the scores (hundreds?) of millions of dollars spent thus far on subsurface remediation, the contamination—including the risk of public exposure—will remain for decades more, if not longer. The same is true at other Silicon Valley sites.

The SEQRA process provides an opportunity to identify and minimize, in advance, the environmental hazards of semiconductor production. By doing so, it can lead to appropriate regulation, research on waste management and pollution prevention, and investments in safer facilities.

Semiconductor production is essentially a series of chemical processes that use a wide variety of hazardous substances. The industry explains, “While in the 1980s semiconductor fabs used

fewer than 20 elements, today they are using over 50% of the nonradioactive elements in the periodic table."[1] Those include toxic heavy metals. The industry is a major user of Per- and Polyfluorinated Substances (PFAS), also known as "Forever Chemicals" because they persist and bioaccumulate in the environment and even human bloodstreams. As New York state agencies are well aware, these compounds are toxic, even at extremely low exposure concentrations, through multiple pathways. But industry has become reliant on PFAS without first examining the human and environmental risks. It explains, "Without PFAS, the ability to produce semiconductors (and the facilities and equipment related to and supporting semiconductor manufacturing) would be put at risk."[2]

Use and release of the industry's hazardous building blocks are regulated by both state and federal statutes and regulations, but the public is generally unaware of the series of upcoming permit applications that Micron is expecting to make. The SEQRA review should list **all** anticipated permitting processes, with the anticipated schedule of public comment periods, and it should require public notification to interested parties of each permit application as it is submitted.

It should also identify hazardous substances, whether or not they currently have promulgated exposure standards. For example, the industry reports, "Most PFAS are not regulated pollutants and therefore unless company specific provisions are in place, the wastewater from processes that use aqueous wet chemical formulations that contain PFAS would likely be discharged to the publicly owned treatment works without substantive removal of the PFAS."[3]

Furthermore, potential workplace exposures should not be ignored because exposures are below the Occupational Exposure Level (OEL) or even a fraction of the OEL, as industry suggests.[4] In most cases OELs, such as the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limits (PELs), are orders of magnitude above what the science—including U.S. EPA studies—dictates.

While the draft Scope of Work proposes many useful Technical Chapters, there is room for more specificity. I focus on the use and release of hazardous substances.

For **Solid Wastes and Hazardous Materials**, the Scope of Work states, "The chapter will identify any hazardous materials (including any chemical or petroleum bulk storage) that would be used, stored, transported, or generated by the Proposed Project and measures to protect

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[1] "Background on Semiconductor Manufacturing and PFAS," Semiconductor Association (SIA) PFAS Consortium, May 17, 2023, p. 54. The SIA PFAS Consortium is made up of chipmakers and their suppliers of equipment and materials. To sign up to receive their technical papers, go to https://www.semiconductors.org/pfas/ . I am attaching this document.

[2] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3. I am also attaching this document.

[3] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 3

[4] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 25.

against releases to the environment. Any warranted remedial approaches for addressing identified or potential contaminated materials would be described." I suggest that the Review describe any permitting required for the Treatment, Storage, and Disposal of hazardous materials and solid wastes, and that it list the storage requirements, such as double-walled tanks and piping, necessary to prevent environmental releases. Furthermore, how will employees be educated about the risk from leaks and spills, as well as what to do when they occur?

To what degree will disposal—including landfilling and incineration—create off-site hazards? Industry reports, "Organic waste, including organic liquids containing PFAS, is typically segregated, collected, and containerized to be treated at an offsite licensed treatment and disposal facility, as a blended fuel by high temperature incineration or reprocessing."[5] Perfluorinated compounds are particularly difficult to destroy using incineration. Furthermore, even when permitted by regulatory agencies, incineration may release products of incomplete combustion into the atmosphere.

For **Air Quality**, the Scope of Work barely mentions the potential emissions of highly toxic air contaminants. Historically the industry has used lethal gases such as arsine and phosphine, as well as toxic gases such as hydrogen chloride (the gaseous form of hydrochloric acid). Micron should identify plans to notify first responders and public of any toxic air releases, and first responders should be provided in advance with training and equipment to respond safely to such releases. Employees should be warned about the toxicity of gases used by the industry and trained to protect themselves from potential releases, both at low levels associated with chronic toxicity as well as higher levels with acute toxicity.

I am surprised and disappointed that no chapter is listed for **Wastewater and Stormwater**. The release of toxic contaminants through water pathways is one of the most serious threats of semiconductor productions. Releases of certain contaminants in wastewater could compromise the operations of the Oak Orchard Wastewater Treatment Plant, even undermining compliance with its discharge permit. The draft Scope of Work mentions industrial pre-treatment. Not only should that be described in an environmental review chapter, but the review should identify ways to pre-treat hazardous chemicals, perhaps even reusing some, before comingling with other wastes. This is particularly important for PFAS, because in the future more PFAS compounds are likely to be subjected to enforceable environmental standards, many at very low concentrations.

In fact, given the vast number of PFAS used by the semiconductor industry, the Review should identify methods for sampling total organic fluorine, not just targeted compounds. "At present, only a small percentage of PFAS compounds within typical semiconductor wastewater are detectable and quantifiable using conventional U.S. EPA analytical methods for PFAS-containing

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[5] "Background on Semiconductor Manufacturing and PFAS," SIA PFAS Consortium, May 17, 2023, p. 30.

materials."[6] However, U.S. EPA has a draft method (1621) for measuring total organic fluorine.[7] Furthermore, academic researchers are finding that failure to measure total fluorine misses discharges of significant quantities of PFAS pollutants. "[B]ecause many studies of total organic fluorine have shown that total PFAS concentrations are at least 10 times higher than the sum of target PFASs. However, this does reinforce the idea that PFAS monitoring should incorporate complementary target and nontarget analyses or otherwise include measures of total organic fluorine to accurately assess PFAS abundance and potential environmental impacts."[8]

Furthermore, there should be a chapter on **Life-Cycle Environmental Impacts.** What hazardous substances remain in the finished semiconductor products, including packaging. At the end-of-life, are there mechanisms for preventing the environmental release of semiconductor hazardous substances? Industry's PFAS Consortium reports, "At the end-of-life of the product containing the semiconductor, or any parts replaced during the manufacture of semiconductors, would enter waste disposal streams where any PFAS contained therein could enter the environment."[9] Are manufacturers responsible for end-of-life pollution?

Finally, there are those who argue that a thorough environmental review, as I have suggested, would unnecessarily delay the operation of new, advanced wafer fabrication plants. I find it hard to believe that documenting potential hazardous substance and waste impacts in advance would hamper the construction of a factory that is not expected to begin production until 2032. Micron—indeed, all semiconductor manufacturers—**should** already know what hazardous substances it uses and releases. Shouldn't the public also know? The semiconductor and computer manufacturing industry, such as IBM's complex in Endicott, New York, has a long history of causing pollution that threatens public health and the environment. An industry that claims that PFAS—chemicals that are persistent, bioaccumulative, and extremely toxic in low concentrations—are essential to its operations should be required to **come clean** about its environmental and public health hazards.

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[6] "PFOS and PFOA Conversion to Short-Chain PFAS-Containing Materials Used in Semiconductor Manufacturing," SIA PFAS Consortium, June 5, 2023, p. 11.

[7] Draft Method 1621: Screening Method for the Determination of Adsorbable Organic Fluorine (AOF) in Aqueous Matrices by Combustion Ion Chromatography (CIC), U.S. EPA, April 2022, https://www.epa.gov/system/files/documents/2022-04/draft-method-1621-for-screening-aof-in-aqueous-matrices-by-cic_0.pdf

[8] Paige Jacob, Kristas Barzen-Hanson, and Damian Helbling, "Target and Nontarget Analysis of Per- and Polyfluoralkyl Substances in Wastewater from Electronics Fabrication Facilities," *Environmental Science & Technology,* February 16, 2021, p. 2353. https://pubs.acs.org/doi/10.1021/acs.est.0c06690

[9] "The Impact of a Potential PFAS Restriction on the Semiconductor Sector," SIA PFAS Consortium, April 13, 2023, p. 90,

Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing

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Abstract. We identify and describe categories of fluorochemicals used to produce advanced semiconductors within the lithographic patterning manufacturing processes. Topics discussed include the per- and polyfluoroalkyl substance (PFAS) materials used and their necessary attributes for successful semiconductor manufacturing, consisting of photoacid generators, fluorinated polyimides, poly(benzoxazole)s, antireflection coatings, topcoats, and embedded barrier layers, fluorinated surfactants, and materials for nanoimprint lithography. In particular, an explanation is given of the particular function that these PFAS materials contribute. It is noted that in almost all cases fluorine-free alternatives are very unlikely to provide the essential properties present in PFAS systems. Nonfluorinated alternative compounds are discussed where available. Finally, a summary table is provided listing the families of materials discussed, the critical purpose served, what the PFAS compound provides, and the prospects for alternatives. [DOI: 10.1117/1.JMM.21.1.010901]

Keywords: fluorochemicals; per- and polyfluoroalkyl substance; photolithography; semiconductor processing.

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1 Introduction

The use of fluorochemicals in lithography and semiconductor patterning plays a critical role in the success of semiconductor technology. The addition of small quantities of fluorinated materials enables patterning capabilities that are otherwise not possible to achieve, and this leads to superior device performance. The compact size of the fluorine atom and its strong electron-withdrawing characteristics make it stand out in the periodic table and gives fluorocarbon materials unique properties, unmatched by other chemical compounds. Fluorochemicals have found use in semiconductor processing for good technical reasons.

1. The presence of fluorine near acidic groups can convert them from an acid to a superacid, an essential characteristic for photoacid generators (PAGs) needed in advanced photoresists.
2. Fluorocarbon materials have low surface energy characteristics and act as superior barrier layers (including water repellence), which provide useful properties in photoresists and in antireflection coatings used in immersion lithography while also providing excellent release properties because they do not adhere strongly to other materials.
3. Fluorinated materials have unique solubility characteristics and can prevent intermixing between layers in a complex system such as an antireflection coating. Fluorinated materials are both hydrophobic and oleophobic and thus have reduced or no miscibility with essentially all fluorine-free classes of polymers.
4. Fluoropolymers have a low refractive index compared with any material except air and provide useful optical properties in photoresists and antireflection coatings.
5. They possess low dielectric constant and are especially good electrical insulators, an important feature when polyimides are patterned and retained in the final device.

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> This document provides a systematic overview of the photolithography process and key fluorinated materials involved, provides insight into performance requirements, and describes why fluorinated chemicals help achieve needed characteristics.

Photolithography, a critical process step in the production of a semiconductor, uses a photoresist to transfer a pattern. The primary component of a photoresist is a photopolymer whose solubility will be changed upon exposure to short wavelength radiation. In addition, the photoresist contains a deposition solvent and several small-molecule compounds. The desired solubility change must be great enough that a developer (a solvent that removes the unwanted region of a resist pattern) does not swell the remaining photoresist. The development process must be able to discriminate between exposed and unexposed regions as small as a few nanometers in size. The unremoved photoresist must protect the underlying substrate from the next process steps in semiconductor manufacturing. Each stage in the process must be virtually perfect with yields well above 99%, because there may be hundreds of process steps used to manufacture each advanced semiconductor device. Without those very high yields, semiconductor manufacturing would fail.

The basic lithography process used globally today for advanced semiconductor manufacturing and the foreseeable future employs chemically amplified photoresists. Chemical amplification was a key invention needed to overcome the challenge of limited light sources but was also found to provide superior patterning performance. In such resist systems a photopolymer that contains acid cleavable protecting groups is combined with a photoactive compound, such as a PAG. In its native state, the photoresist polymer with protecting groups is soluble in organic solvents. Upon exposure to UV radiation, the PAG releases acid. Frequently, a subsequent post-exposure bake (PEB) step leads to the acid-catalyzed removal of protecting groups, thereby transforming the hydrophobic photopolymer into one that is soluble in an aqueous base developer. The single photon of light needed to release one acidic proton is "amplified" by the more efficient acid-catalyzed deprotection process. By transforming the solubility of the photoresist, a high contrast patterning process needed in semiconductor manufacturing becomes possible. The combination of photoresist polymer and PAG to make the photoresist system is an essential part of this process and fluorination in the PAG provides the high acidity necessary for chemical amplification to work and will be described subsequently.

The lithographic process is a complex series of steps requiring, at times, several complex properties in a single material or other cases combination of different materials used in the same process step. An example of the latter can be represented by the use of an antireflective coating in combination with a photoresist. An antireflection coating (ARC) is important to prevent light reflected from the semiconductor substrate, which would otherwise alter the very precise molecular scale patterns required for today's semiconductor devices. An ARC does this by minimizing the refractive index difference across each interface of all layers in the system. As an example, a top ARC (TARC) is a layer that sits on top of the already complex photoresist. It must not intermix with the photoresist, and it can also serve as a protective layer for this complex, multilayer lithographic system. Finally, it must be easily removed. Only a fluorinated material has a significantly lower refractive index and fluorination also provides these additional properties. More details for ARCs will be discussed below.

Additional uses of fluorochemicals in photolithography processes are also discussed in this paper. It is worth noting that while there are many types of fluorochemicals, our survey of the technical literature reveals that there are several specific examples of fluorocompounds that are currently in use by the semiconductor industry in the lithography process including (1) perfluoroalkyl acid compounds (C4 or less), used in PAGs; (2) hexafluoroisopropanol, fluorotelomers, and fluoroacrylate side-chain units may be used in photoresists to incorporate specific functionalities including barrier properties and low surface energy; (3) hexafluoropropyl units are used in sub-units of some classes of polyimides for thermal stability and low dielectric constant; (4) specialized per- and polyfluoroalkyl substances (PFAS) are used in ARCs; (5) PFAS are also include surfactants (used as coating leveling agents) to improve coating uniformity in a number of products used in lithographic processes. A key feature of the addition of a fluorinated component is that its addition provides a necessary additional characteristic to the material while minimally compromising its other critical properties. Examples of these materials and uses are tabulated in

the Appendix. This paper discusses current PFAS use in the field of photolithography, explains why certain materials are used, reviews in part the current understanding of PFAS degradation during processing, and where possible, identifies alternative materials.

One of the special features of the C─F bond is its strength compared with the C─C bond due to the electron-withdrawing power of the fluorine atom. This attribute is the basis of many of the technical benefits of fluorinated materials in semiconductor processing but leads to its chemical stability and environmental persistence. Fluorination brings specific improvement in performance, and its targeted incorporation can minimize the quantities of material needed to achieve that performance. Such aspects are discussed in the context of PAGs. Thus, despite the remarkable performance improvement in many aspects of the lithographic process provided by fluorochemicals (PFAS) that makes possible the semiconductor revolution with its benefit to society, the large and growing environmental and societal concerns surrounding PFAS may counterbalance the positive technological benefits of these materials. The reader is referred to a discussion of such PFAS concerns in a well-written review article, but photolithography chemicals are largely glossed over.[1] Going forward, due to environmental and regulatory concerns, performance equivalent alternatives for many of these applications still need to be identified and this will be a major research challenge.

This paper presents a detailed discussion of the different types of PFAS used in advanced lithographic patterning and semiconductor manufacturing paying specific attention to the unique physical-chemical attributes of these chemistries that make them essential for semiconductor manufacturing. Specifically, we break the PFAS used in semiconductor manufacturing into six main categories of fluorochemicals used in photolithography and semiconductor patterning. For each category, we discuss the critical function served by the fluorochemicals and why the specific fluorocompounds are used, based on the unique properties provided by the chemical. However, it is worth noting that there are required processes in the semiconductor manufactory using per-fluorinated compounds such as etch gases for metal etching, wet cleaning chemicals to clean and condition substrate, and other minor processes that are not covered further in this paper.

Based on concerns regarding the high persistence, bioaccumulation potential, and potential toxicity of PFAS studied to date, it has been suggested that the use of PFAS be limited to essential uses only.

We discuss whether viable alternatives exist for each of these applications and the characteristics that must be achieved to find an alternative compound where none currently exists. Finally, we apply the essential use concept described by Cousins et al.[2] to show that these compounds should be considered essential for certain processes in semiconductor manufacturing (i.e., photolithography and patterning) because they provide for vital functions and are currently without established alternatives. The prior paper did an excellent job of discussing different aspects of PFAS use. In this paper, we focus our discussion of essential use as “necessary for highly important purposes in semiconductor manufacturing for which alternatives are not yet established.” We describe the many uses and unique properties of PFAS chemicals, which in our opinion justifies their current use as essential in microelectronics manufacturing and for which alternatives have not yet been adequately identified. This paper is not intended to be an extensive listing of every example of fluorochemical used in photolithography but does attempt to explain strategies and classes of material used in the manufacturing of semiconductors.

2 Photoacid Generators

PAGs are photoactive compounds that generate acids upon exposure to high-energy light [deep ultraviolet (DUV) or extreme ultraviolet (EUV)]. These photoactive compounds were originally used for applications in photopolymerization in the early 1960s.[3] After the introduction of chemically amplified resists (CARs) in the 1980s, they have been used in semiconductor manufacturing as key components in advanced photoresists. It is important to understand that the process of chemical amplification requires a very strong acid in the PAG to function well. PAGs are now highly evolved with over 40 years of in-depth research and development for photoresist applications. A positive tone resist polymer after deprotection, for example, contains

weak acid groups that will act to buffer (weaken) the acidity of the deprotection process. Without the presence of the strong fluorosulfonic (or stronger) acid, the catalyzed deprotection process will be less efficient or may not even occur. Sulfonate anions without fluorination have repeatedly been shown to be inadequate for use ineffective 193 nm chemically amplified photoresists and this is well known in the photoresist community. The unique characteristics of fluorine (noted below), which lead to very strong proton donation by fluorinated sulfonic acids, are essential in CARs. This intrinsic benefit of fluorinated acids makes it extremely difficult to eliminate the use of fluorinated acids whilst retaining the key performance characteristics of CARs needed for advanced photolithography in microelectronics manufacturing. Other attributes of a PAG that depend less on the acid and more on the chromophore include quantum yield at the wavelength of use, the sensitivity of the overall resist formulation (e.g., 15 to 60 $\mathrm{mJ/cm^2}$), miscibility in the resist matrix, thermal and hydrolytic stability and shelf life of the photoresist, solubility in aqueous base developer for positive tone develop or organic solvent for negative tone development followed by removal in the resist strip operation. In general, PAGs are divided into two categories: either ionic or covalent (nonionic) structures. As the name suggests, ionic PAGs consist of two portions: a cation and an anion. In addition, covalent PAGs are uncharged, nonpolar compounds that are constructed of covalent bonds but are generally less sensitive and therefore less effective than ionic PAGs. The availability of both ionic and covalent PAGs offers process flexibility. In some cases, the presence of ionic groups may lead to storage instability of the photoresist mixture or the inhomogeneous distribution of photoactive compounds in the photoresist, thus making a nonionic PAG necessary. However, most photoresist compositions that are used in semiconductor manufacturing employ ionic PAGs because of their greater sensitivity. Examples of PAGs are shown in Figs. 1 (ionic) and (covalent).

In either case, a fluorinated sulfonic acid would be used to make an effective PAG. The photoefficiency difference between ionic and covalent PAGs, which leads to higher quantum yields in the ionic PAG is controlled by the cation.[4] The low diffusivity and high strength of the acid resulting from the photolysis of the cation are controlled by the resulting accompanying fluorosulfonate anion. These anions are used in virtually all current commercial photoresists. Limited diffusivity is important to achieving high-resolution patterns because excess diffusion of the PAG has been shown to limit the resolution of the images produced in a CAR. While aromatic sulfonic esters are shown in some nonionic PAGs described in Fig. 2, the strength of the resulting sulfonic acid after photolysis is not as high as the ionic PAGs with fluorinated sulfonate anions.

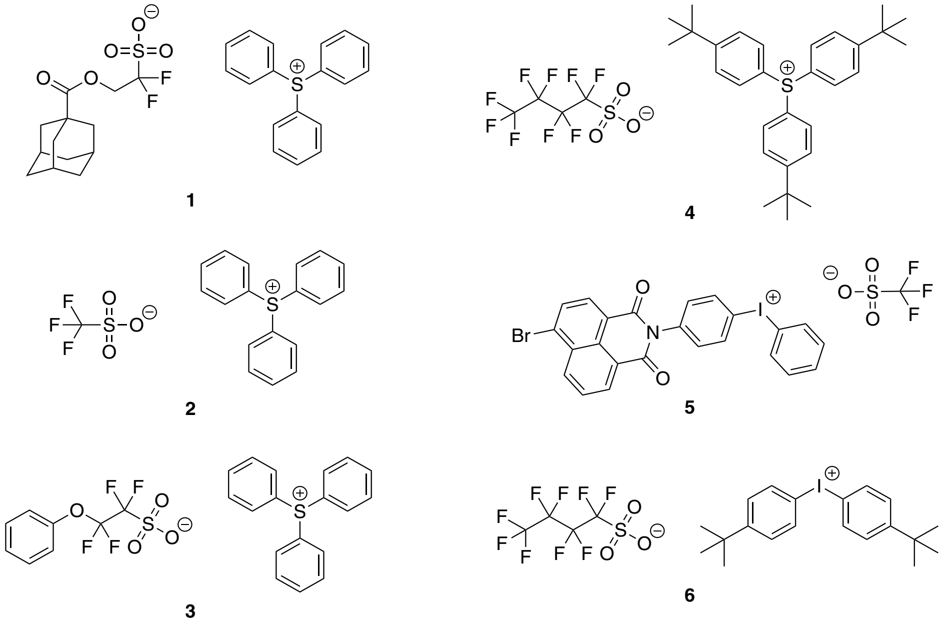
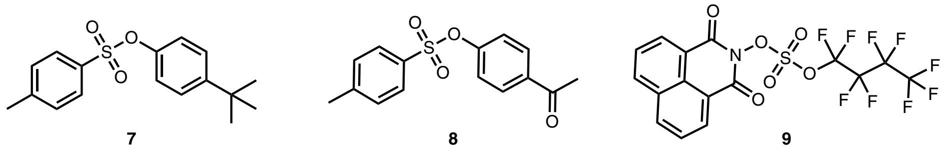


Fig. 1 Representative ionic PAGs: 1,2,3,4 Sulfonium PAG and 5,6 Iodonium PAG.



7 **8** **9**

Fig. 2 Representative nonionic covalent PAGs.

Covalent PAGs do not suffer from the sorts of phase separation, low miscibility, and dark loss (the dissolution of unexposed photoresist) issues that may occur in ionic PAG-containing resist formulations, but the quantum yield of photoacid generation is generally lower for covalent PAGs so this and other factors drive the ultimate choice of PAG.[5] In order to increase the acidity of the photoacid, perfluorinated methylene units may be placed next to the sulfonate group in both ionic and covalent PAGs. The polarization present in the C—F bond due to the electron-withdrawing character of fluorine stabilizes the acid anion and makes the acid stronger. A sulfonic acid such as methane sulfonic acid has a pK_a of −2 (already a strong acid) but trifluoromethyl sulfonic acid (triflic acid) has a pK_a of −14. Any induction effect is significantly smaller after two or three CF_2 units, so the relative benefit of fluorination is significantly reduced as the neighboring CF_2 units are further away from the acid group. The original choice of longer sequence perfluorinated sulfonates (six or more) has not been explained in patents or the literature but was likely due to the effectiveness of the resulting PAG, the reduced diffusivity because it is a larger molecule, its availability, and the lack of volatility in this material. For example, the volatility of the small triflate anion limits its use in a production photoresist PAG because the resulting concentration gradients in such photoresist films harm performance. However, shorter CF_2 segments (1 or 2) next to the anion and connected to other units of higher mass have been shown to make effective PAGs (see Sec. 2.3).[6] Finally, the diffusivity of the PAG will affect pattern resolution (less diffusion enhances resolution) and can be addressed by the use of a higher molar mass PAG/acid and even covalent attachment of the PAG to the photoresist polymer itself (see Sec. 2.4). Although actively used in some applications, triflic acid is not always a useful component in a PAG since it may have significant deficiencies when used in a very high-resolution CAR system; it is volatile and may evaporate during the PEB step leading to composition gradients that are detrimental to image resolution and it readily diffuses during annealing, which may, in turn, lead to pattern degradation from deprotection chemistry occurring in unexposed areas, effectively reducing image contrast and disrupting pattern formation.

2.1 *Ionic PAGs and Their Photochemistry*

Most ionic PAGs used in lithography are onium salt derivatives. Such ionic compounds consist of an onium moiety as the cation and sulfonate groups as the anion.[4] Upon exposure, photolysis occurs and photoacid is formed. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. Returning to Fig. 1, ionic PAGs are generally composed of either diaryliodonium or triarylsulfonium photoactive units to form a salt with an appropriate anion. Triarylsulfonium PAGs usually have longer shelf life compared with diaryliodonium salt. However, a diaryliodonium salt has higher absorptivity in particular for next-generation 13.5-nm wavelength EUV photons. The mechanism of photolysis of diaryliodonium salt[4] and triarylsulfonium salts[7,8] has been studied extensively. Reported photolysis mechanisms for diaryliodonium salt and triarylsulfonium salts are shown in Figs. 3 and 4, respectively. The quantum yield of the photoacid is directly impacted by the cation fragment. The acidity of the generated photoacid as noted above is controlled by the anionic fragment in the PAG (usually a fluorinated sulfonic acid). The rate of photoacid release is controlled by both cation and anion. In Fig. 3, the energy required to cleave the aromatic C (sp^2) and iodine bond is somewhat higher compared with the energy required to promote bond cleavage between the aromatic C (sp^2) and sulfur bond (Fig. 4).

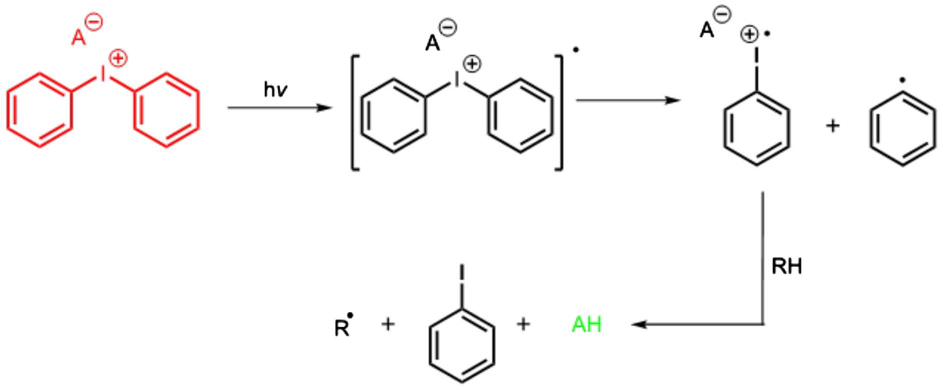


Fig. 3 Proposed photolysis mechanism for diaryliodonium salt under DUV exposure. Reproduced from Ref. 8.

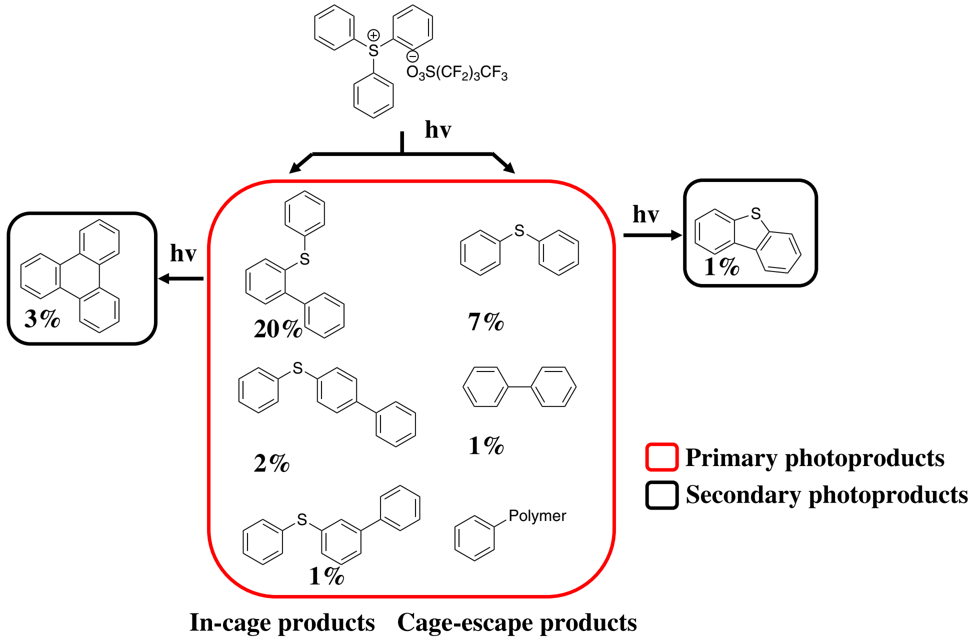


Fig. 4 Proposed photolysis mechanism for triarylsulfonium salt in solid poly(methyl methacrylate) matrix exposed to 266-nm irradiation (2631 mJ · cm^{-2}). Reproduced from Ref. 9.

Generally, the sulfonium PAG family is more widely used than iodonium PAGs considering its greater sensitivity and longer shelf life when used in either DUV or EUV lithography. Reference 8 reports solution results for exposure of the triphenylsulfonium cation. More recent results of solid-state polymer matrix results are shown in Fig. 4.[9] Solid-state studies at 193, 248, and 266 nm exposures reveal additional products including in all cases, two previously unreported Triphenyl sulfonium photoproducts, triphenylene, and dibenzothiophene.

2.2 *Nonionic Covalent PAGs and Their Photochemistry*

Although ionic PAGs have higher sensitivity in lithographic applications, they may be less soluble and more prone to phase separation in photoresist formulations. It is worth recalling that the PAG is needed to generate acid in the exposed regions to deprotect the photoresist and thereby change its solubility. Uniform distribution of a PAG is an essential attribute to excellent performance in a photoresist. Detrimental interaction between ionic structures in a photoresist and an ionic PAG may also occur in future resist materials.[10] To overcome such issues, covalent PAGs

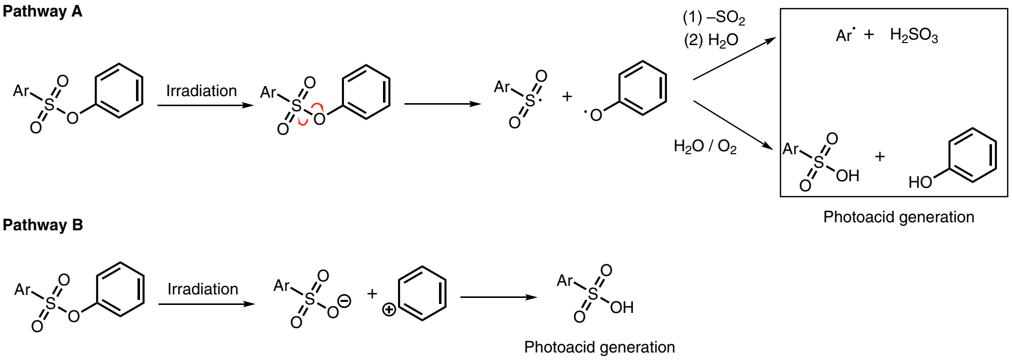


Fig. 5 Photoacid generation mechanism for arylsulfonate esters.

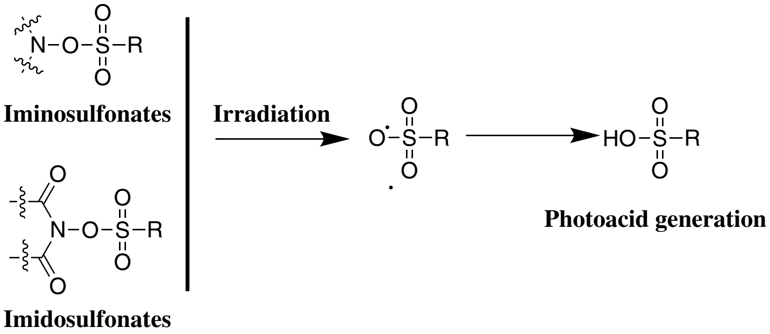


Fig. 6 Photoacid generation mechanism for iminosulfonates and imidosulfonates.

may be attractive alternatives.[4] In general, covalent PAGs are derivatives of arylsulfonates,[11] iminosulfonates,[12] and imidosulfonates.[13] Arylsulfonate esters can be easily synthesized from phenol and sulfonyl chlorides. A similar effort to create fluorinated sulfonate ester-containing covalent PAGs has not taken place because such PAGs have not been as effective in photoresist applications. The photoacid generation mechanism is proposed based on the nonfries photolytic ArO─S bond cleavage (pathway A) or pseudofries rearrangement (pathway B), which is more likely to occur for electron-rich aryl sulfonates as shown in Fig. 5.[14,15]

It is worth noting that in pathway A, in the presence of oxygen and water, stronger sulfonic acid is generated. In the absence of oxygen, weaker sulfurous acid is produced. Iminosulfonates and imidosulfonates have similar chemical structures with the N─O bond undergoing homolytic cleavage upon irradiation to generate sulfonyloxy radicals, which subsequently capture hydrogens from nearby molecules to afford the corresponding sulfonic acid as shown in Fig. 6.

2.3 *Alternatives to Current PAGs*

PAGs other than iodonium and sulfonium units as well as those that do not contain traditional PFAS have also been studied for use in photolithography. To be used successfully in a CAR photoresist, the resulting acid must be as acidic as a perfluorosulfonic acid, lack volatility so that it does not evaporate during the PEB step, and in the next generation photoresists possess minimum diffusivity (to enable high-resolution pattern formation). The PAG-resist combination should have a sensitivity in the range between 10 and 75 $\mathrm{mJ/cm^2}$ under exposure conditions i.e., the source wavelength and tool-specific settings. Some new photoresists attach the PAG directly to the photopolymer chain to both limit diffusion and deal with issues of stochastic variations that may be present in photoresists consisting of mixtures of polymer and photoactive molecules. Nontraditional PFAS Covalent PAGs: Nitrobenzyl esters have found some application in DUVL and may be extendable to EUV lithography.[10] Such molecules can generate photoacid

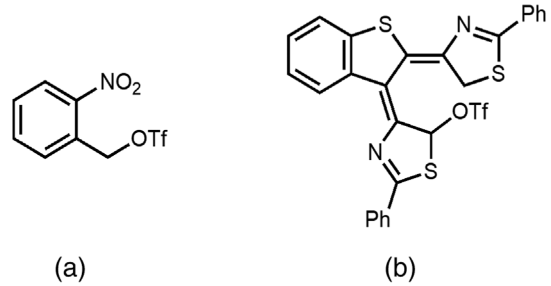


Fig. 7 Chemical structure for non-PFAS covalent PAGs: (a) nitrobenzyl ester and (b) terarylene backbone-based PAG.

upon irradiation through *o*-nitrobenzyl rearrangement to generate nitrobenzaldehyde and a sulfonic acid such as triflic acid shown in Fig. 7.

The chemical structure is shown in Fig. 7(a). The terarylene skeleton-based self-contained PAG is another potential candidate for some applications. The photoacid generation is triggered by the 6π-electro-cyclization reaction of photochromic triangular terarylenes.[16] The chemical structure is shown in Fig. 7(b). Similarly, a triflate ester is used in the reported structure to release triflic acid upon exposure. While these and other structures can be used to demonstrate PAG concepts, they are unlikely to be as useful in new high-resolution photoresist systems because they use triflate groups. Alternative acids may be used to make more suitable PAGs from the moieties in Fig. 7. Should a useful PAG be produced from these types of photoactive structures the resulting sulfonic acid will need to be less volatile and less mobile in the polymer film? A higher molar mass, much less volatile, lower diffusivity anion might work well with these materials in a functioning photoresist system. Nontraditional PFAS Ionic PAGs: Ionic PAGs derived from 2-phenoxytetrafluoroethane sulfonate were introduced by Ober and coworkers in 2007.[17] This PAG was tested under e-beam and EUV radiation and showed high sensitivity, resolution, and acceptably low line edge deviations. The use of such a fluorosulfonic acid has the advantage that it limits fluorine content yet produces a very strong acid with both limited volatility and diffusivity by placing a CF_2 group next to the acid group. Such an approach (discussed more below) can be used to minimize fluorine incorporation while placing this structure where it is most valuable. Its chemical structure is shown in Fig. 8(a). This PAG was tested for its environmental degradation and its effect on bacterial populations when first reported and found to be benign under the rules of that time.

The good lithographic results suggest that shorter fluorinated segments (two or possibly one CF_2 unit adjacent to the sulfonic acid) may make useful ionic PAGs. It should be noted that the building blocks for sulfonic acids with one CF_2 are the subject of experimental studies. The pentacyanocyclopentadienide PAG is another potential ionic PAG candidate in some applications. Its lithographic performance was demonstrated by Varanasi and coworkers in 2010, and it stands out for the amount of publicity it received.[18] The chemical structure is shown in Fig. 8(b).

While announced in 2010 as part of IBM's efforts to reduce Perfluorooctanoic acid (PFOA) in its manufacturing process, to the best of our knowledge, this PAG was not commercialized.

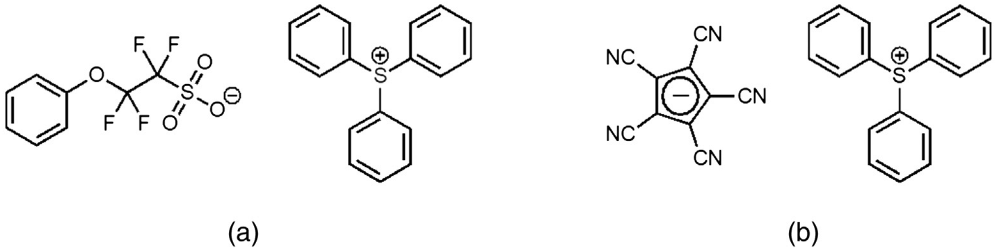


Fig. 8 Chemical structure of untraditional ionic PAGs: (a) 2-phenoxytetrafluoroethane sulfonate PAG and (b) pentacyanocyclopentadienide PAGs.

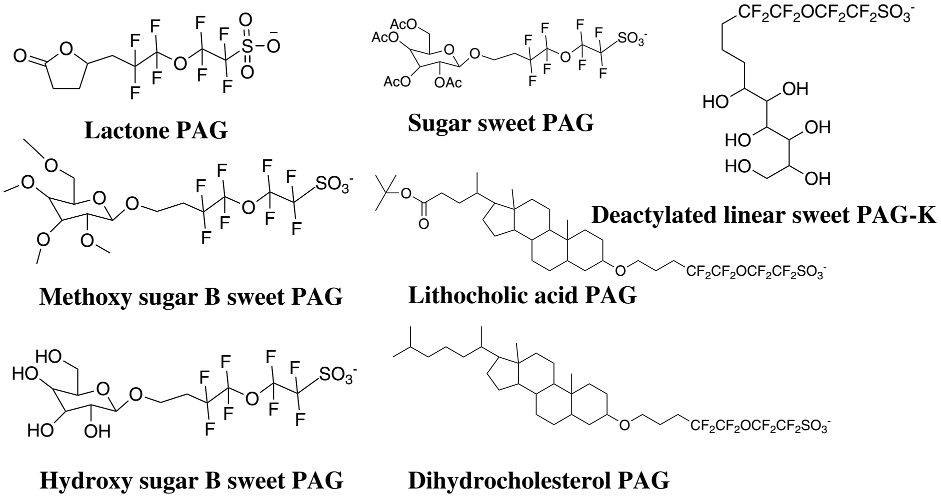


Fig. 9 Chemical structures for natural products-based PAGs.

Finally, PAGs based on glucose or other natural products have been explored. These PAGs were demonstrated to be functional materials for some high-resolution photoresist applications enabling sub-100nm features using ArF laser and e-beam lithography. Moreover, these PAGs showed successful microbial degradation to smaller molecular units under aerobic conditions. The chemical structures are shown in Fig. 9.

Such studies revealed the successful biodegradation of these PFAS units to smaller oxidized components as well as low bacterial cytotoxicity[19,20] of the photoactive sulfonium subunit. In general, the anionic units underwent biodegradation using sludge from a local municipal wastewater treatment plant. The sugar or cholesterol groups appeared to degrade easily leaving only a short, fluorinated acid residue. An advantage of these structures is that the residues retain polar functional groups and are therefore more hydrophilic than PFOS/PFAS units. This makes them less likely to accumulate in fatty tissues, but further studies are needed to identify any bioaccumulation characteristics. The photoactive cation unit but not the fluorinated anion was generally found to be cytotoxic to the bacteria. Importantly, the short, fluorinated segment enabled the formation of a high-performance PAG that could be subjected to successful biological degradation.

More recently, patents have appeared that describe a number of related chemical structures, the goal of which is intended to deliver strong PAG performance and minimize the size of the fluorinated unit in the fluorosulfonic acid or eliminate it entirely. These patents claim excellent lithographic performance.[21] These and other patents describe PAGs with shorter fluorinated segments,[22] some of which are designed to fall into small molecular pieces.[23] To assess their viability as alternative PAGs their performance characteristics (sensitivity, acid strength, and diffusivity) and environmental characteristics (fluorine content, degradation products, and toxicity) will need to be assessed.

2.4 *Polymer-Bound PAGs*

One approach to increasing the resolution to photolithography is to employ PAG that is incorporated into the photoresist polymer structure.[24] It has the advantage of making the distribution more uniform and at the same time limits the diffusivity of the sulfonate anion since it is bound to the photoresist polymer. Resolution is set in part by the diffusivity of the PAG in the photoresist formulation, which is associated with the size of the molecule. The smaller the anion, the farther the photogenerated proton can diffuse in a given time. If the PAG acid diffuses too broadly then deprotection of the photoresist takes place in unwanted regions and makes the pattern larger, less precise, and "blurry." These pattern irregularities are characterized in terms of line edge roughness, line width roughness, and critical dimension uniformity. Examples of bound-PAG structures have been reported and two are described below shown in Fig. 10.

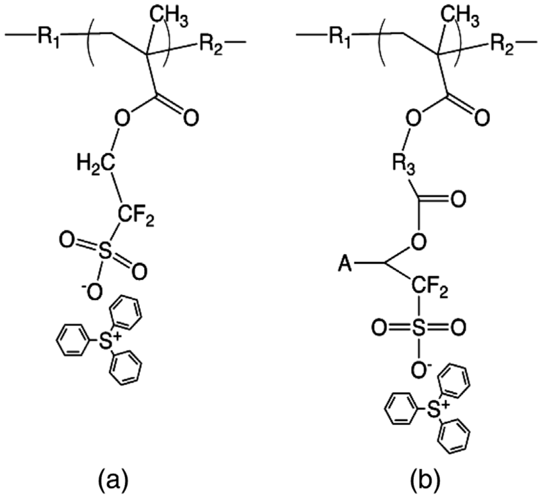


Fig. 10 Examples of polymer-bound PAGs. (a) Single CF_2 unit next to sulfonate[21] and (b) single CF_2 unit next to sulfonate in a structure that falls apart on exposure; groups (R1, and R2) not specified groups while R3 is a linking group.[20]

This strategy also lowers concerns about "stochastics," i.e., the chemical heterogeneity of a photoresist mixture at the dimensions of the pattern are thought to also contribute to the limit of resolution of today's most advanced lithographic processes. Upon exposure, the fluorosulfonate group becomes protonated, catalyzes deprotection of the rest of the photoresist chain, but the strongly acidic proton cannot diffuse broadly because it remains near the anion bound to the polymer chain and thereby forms higher resolution patterns. By attaching the same number of PAG units to each polymer chain, then the PAG is uniformly distributed throughout the photoresist film. This strategy is being seriously considered for future generations of photoresists, particularly for use in EUV lithography.[25] These examples share several common features, including the attachment of the anion to the polymer backbone. Since many CAR photoresists are based on (meth) acrylates, examples reported for 193 nm (DUV) resists [shown in Figs. 10(a) and 10(b)] possess a sulfonate anion and an adjacent CF_2 unit, which then is connected to the methacrylate monomer through an ester linkage. While it has not been established if one or two CF_2 units are needed to produce sufficiently strong anion, this example demonstrates one approach and good prospects for polymer-bound PAGs.

3 Fluorinated Polyimides

In an increasing number of applications, the photopatterned polymer is not removed but is retained as part of the device, even though the lithographic requirements are not as stringent as the high-resolution photoresist systems discussed above. Their use ranges from semiconductor packaging to lithographic insulation patterns for integrated circuits. Under these circumstances a completely different photopolymer must be used and have properties of very high thermal stability, strong mechanical properties (high Young's modulus, good fracture toughness), low dielectric constant (be an insulator), and moisture resistance.[26] In this highly demanding application only a few polymers can provide this complex set of properties and, among them, polyimides have been found to provide the best trade-off between processing and performance. Polyimides themselves bring many of these necessary attributes but the introduction of fluorinated groups is used to incorporate a chemical function capable of withstanding high process temperature, making the final material more moisture resistant and providing a lower dielectric constant than otherwise possible without compromise to other necessary properties.

The technical literature reveals that polyimides are used in a number of processes and applications in photolithography.[27] Polyimides are a family of polymers characterized by high thermal

stability, excellent thin film mechanical properties, good adhesion properties, and a low dielectric constant and dissipation factor. In particular, rigid functional groups such as phenylene- and less polar functional groups provide low dielectric constant (Δk) and good mechanical toughness (resistance to tearing). Polyimides are unique as a family of polymers because they have among the highest glass transition (softening) temperatures known in a polymer (>200°C) and they are thermally stable because the polymer chain consists of interconnected aromatic rings. These properties make polyimides able to withstand the high-temperature processing used in semiconductor manufacturing. Like all polymers, they can be etched with the right etchants and therefore patterned, they are amorphous and transparent so they can be used to guide light and they have a lower dielectric constant than many other components in a device so they can be insulators, but unlike other polymers they come with the ability to withstand very high-temperature processing without physical softening and deformation. They often remain in the semiconductor device, unlike most other photolithographic layers.

Photopatternable polyimides are generally made from a poly(amic acid) precursor such as one made from oxydianiline (ODA) (Y═O) and a dianhydride (such as pyromellitic dianhydride), which can be spin coated onto a substrate (see Fig. 11).

However, photocrosslinkable acrylate (or similar) groups are incorporated in the soluble poly(amic acid). A photoradical initiator is used to crosslink the acrylate groups and the pattern is developed in this negative tone system. Then a high-temperature bake step is used to transform the poly(amic acid) to the polyimide (with loss of the acrylate groups) to form its final high thermal stability, patterned and insoluble polyimide form. Any component in the final polyimide must withstand this high-temperature bake step.

Among the applications of polyimides in microelectronics processing, they find use as thick film photoresist, sacrificial layers, and structural layers. It is notable that the structure of a fluorinated unit, when incorporated into the polyimide, largely employs the identical hexafluoroisopropyl unit regardless of the application.[28–30] Hence, in the most common examples, the polyimides consist of tetracarboxylic acid anhydride derivatives and aromatic diamines, as shown in Fig. 11. The polyimide polymer itself has a softening temperature too high for melt processing, but this group of polymers offers processing through its poly(amide) intermediate. The intermediate is soluble, can be coated in a thin or thick film, and after patterning is converted to the polyimide through the heating step making it an ideal material for integration with semiconductor manufacturing. The soluble intermediate can be made into a polymer that is directly photo-patternable as shown in the poly(amide) in Fig. 11. The acrylate modified poly(amide) is photo-crosslinked upon exposure to UV radiation in the presence of a photoradical generator and then a pattern is formed. After development, the patterned polymer is subsequently transformed to the final polyimide by thermal processing. It is known in the art that the insertion of the fluorinated hexafluoroisopropyl functional group into the backbone provides a combination of better solubility in processing solvents, lower dielectric constant (more insulating), and provides higher thermal and thermooxidative stability compared with other alternate chemical functions.[31]

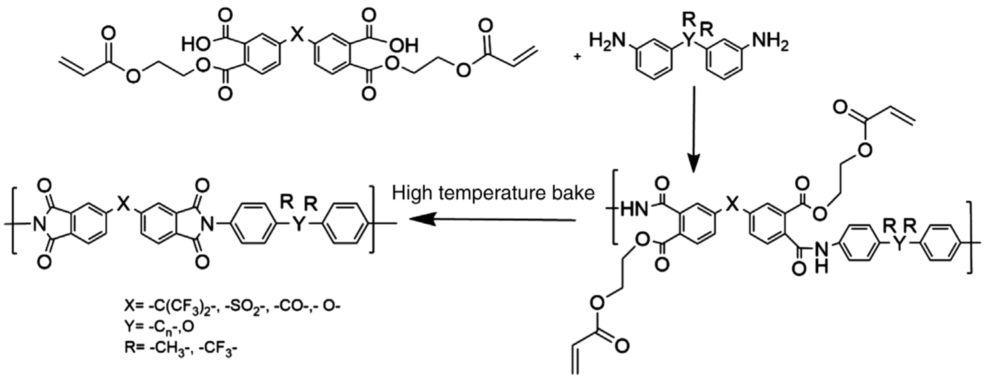


Fig. 11 Synthesis and structure of polyimides for photolithographic processes.

It must be noted that similar insulator properties have been claimed for the targeted optimization of a polyimide chemical structure without the presence of fluorinated residues such as CF_3- and others, which has been successfully demonstrated in at least one scientific study.[32] Araki et al.[32] recently described the synthesis of a novel low dielectric constant (Δk) and low dissipation factor (Δf) polyimides suitable for insulator of redistribution layers used as an interposer layer in wafer-level packaging. However, this polyimide replaces the thermally stable aromatic structure with a silicone segment (chemically identical to bathtub caulk) to achieve the insulating properties. While this new polyimide has good dielectric properties, unmentioned in the report is the fact it undoubtedly has poor mechanical properties, thermal stability and introduces a softening temperature well below materials used in this semiconductor manufacturing application. To demonstrate equivalence to the fluorinated polyimides, it would be necessary to evaluate these new polymers in a series of comparative studies. It is likely that the lower glass transition temperature and the higher associated thermal expansion changes of the silicone-based system would lead to mechanical stresses that severely limit its use outside of simple packaging applications.

No literature was found on the in-process or environmental degradation of these fluorinated polyimides.

4 Fluorinated Polybenzoxazoles

Building on the properties described for fluorinated polyimides, the industry has requested materials with similar properties, which could be patterned using the more generally acceptable aqueous tetramethylammonium hydroxide based developers. One way to achieve this end was to replace the polyamic acid derivative precursors with polyhydroxyamide precursors to polybenzoxazole, which could, after patterning and cyclization, yield a polybenzoxazole (Fig. 12).

The phenolic group allows for development by aqueous base, whereas use of classical diazonaphthoquinone (DNQ) photoactive units to modify the base solubility as in positive-tone photoresists allows for the needed selective patterning (Fig. 13).[4]

Alternatively, other protective groups such as acid-labile ethers and a PAG can also be used, as are common in advanced positive tone photoresists. These materials provide properties similar to polyimides, including thermal stability, tensile strength, and transparency as polyimides while also allowing easier processing. The incorporation of a hexafluoroisopropylidene containing monomer again confers the needed properties of transparency in 365 nm applications, good moisture resistance, thermal stability, reduced darkening after cure, and the correct solubility in aqueous development. Other additives are used to further control base solubility.[33–36] The DNQ PAC may either be added to the formulation or incorporated into the polymer backbone as shown below.

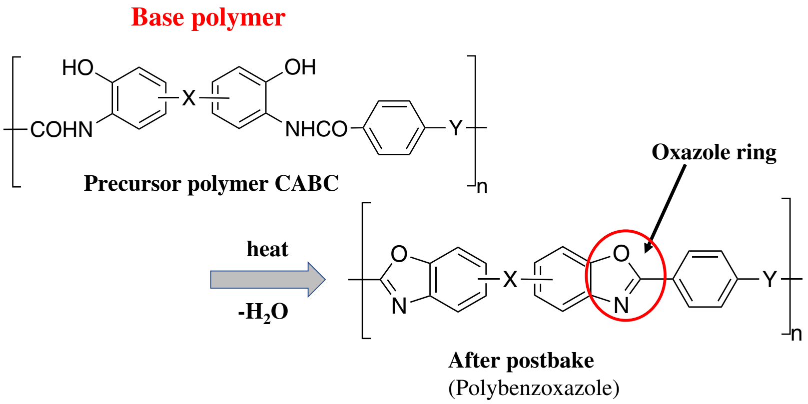


Fig. 12 Figure showing ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

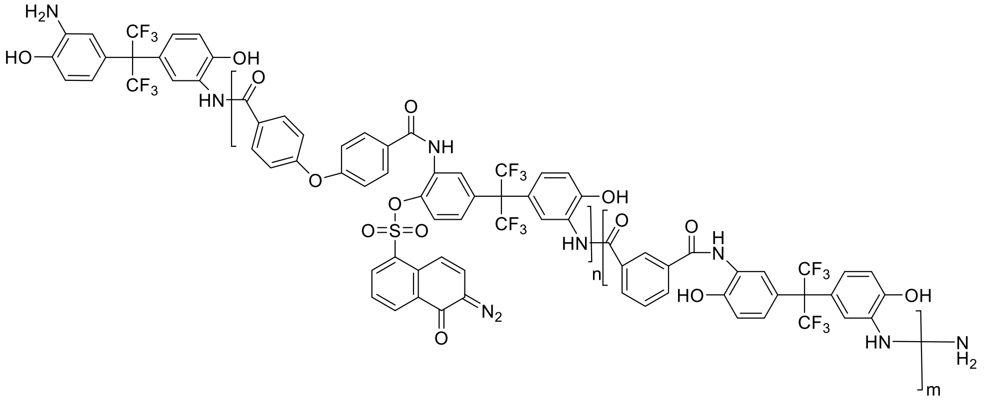


Fig. 13 Ring closure of precursor polymer to form polybenzoxazole polymer after thermal treatment.

5 Antireflection Coatings and Topcoats

The purpose of an antireflection coating (ARC) is to prevent reflection of the imaging radiation from interface layers that produce unwanted exposure effects including standing waves. An important attribute of an ARC is to tune the refractive index difference across each interface, and reflection from the many interfaces between layers is suppressed. A difference in refractive index is essential in preventing unwanted reflection of imaging radiation, which otherwise has a detrimental effect on pattern exposures. Fluorinated materials are important because they have a lower refractive index than virtually any other material category. For example, the refractive index of poly(trifluoroethyl methacrylate) is 1.418 compared with a polymer chemically similar to photoresist materials, poly(2-methoxy styrene) with its refractive index of 1.585, a significant and critical difference for an antireflection coating. Ideally a TARC, e.g., should have an RI value of ∼1.3 and even with fluorinated materials, a good TARC refractive index is currently between 1.4 and 1.45. In addition to their optical properties, ARCs must not intermix with the photoresist as the different layers are deposited, and fluorination helps make that possible. Important requirements for ARCs also include ease of etching, their adhesion to a substrate, and precise thickness deposition.[37–39] Bottom ARCs (BARCs) are also used to form a level surface for a photoresist. Processing of ARC and topcoat materials depend very much on where they sit in the lithographic stack (on top or on the bottom) and a combination of etch, rinse and/or development steps are used in processing. This paper does not detail these differences. TARC materials require first and foremost controlled and reduced refractive index (RI), good mechanical properties for film formation as well as excellent etch characteristics (faster etching than the photoresist). The low RI properties and immiscibility (by being both nonpolar and oleophobic) with the photoresist are mainly achieved by the incorporation of short, fluorinated groups such as CF_3- and C_2F_4- units in the TARC, although longer fluorinated segments have been used. An example of a generic chemical structure of an ARC is shown in Fig. 14 in which a base soluble fluoropolymer is displayed.[40]

It is also possible to achieve immiscibility between ARC and resist using cyclic perfluorinated ether units in the ARC[41] Finally, fluorinated surfactants have also been used to improve ARC coating quality, and more is discussed about such surfactants below. There are two possible geometries that work to limit reflection: TARC and BARC antireflection coating materials. The name specifies wherein the multilayer stack the ARC is located. Figure 15 shows the arrangement of the silicon substrate, the photoresist, and a TARC.[42]

The radiation path is different in the air, the TARC, and the photoresist since each has a different refractive index. By using a low RI TARC (due to its fluorination) and by finding the

$$\left[CF_2-CF_2 \right]_n \left[CF_2\;CF(OCF_2CF_2COOH) \right]_m$$

Fig. 14 Composition of a commercial ARC; $n = m$.[40]

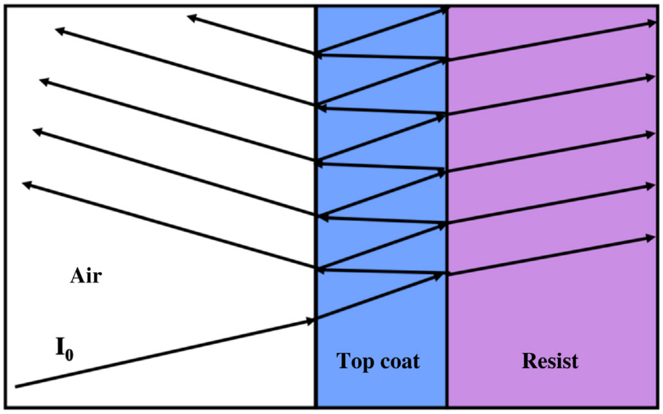


Fig. 15 Light path of top coat/antireflective coating and resist film stack.[43]

optimal TARC film thickness reflection can be minimized.[44–47] Both the phase match and intensity match conditions must be satisfied. This follows Airy's original 19th-century derivation. If both conditions are met perfectly, the reflection amplitude is zero and all light is coupled into the film. This added ARC layer of lower RI results in a superior pattern with higher resolution.

5.1 *Bottom Antireflective Coatings*

Some fluorine-containing acrylate and methacrylate-based copolymers may be used as components in BARC antireflection coating materials (as shown in Fig. 16).

BARC materials used for 193-nm lithography include copolymers of acrylates/methacrylates/alicyclic units as well as bis(benzocyclobutene) and fluorinated arylene ethers.[31] Besides the use of acrylate-based copolymers, it has been reported that perfluoroalkyl silanes (shown in Fig. 13) and poly(ethoxy siloxanes) (not shown) are used as BARC materials. In all these materials the fluorinated component aids in preventing intermixing between the antireflection coating and the photoresist. If mixing were to occur then the performance of the ARC (top or bottom) and the photoresist will be greatly diminished, because the thin photoresist layers will no longer be optically uniform. It should also be noted that fluorine "free" alternative BARCs are known, and they similarly must prevent mixing between ARC layers and photoresists without fluorination. Material suppliers have shown fast etching BARCs for 193-nm lithography. Such materials were targeted for first and second reflectivity minima thickness, are immiscible with photoresists (by being crosslinked), and are not affected by base developers, see Fig. 17.

However, these materials were introduced before the advent of 193-nm immersion lithography. In addition, disposal of hydrophilic ARCs is complicated when ARC and resist disposal cannot be disposed of via the same waste system.

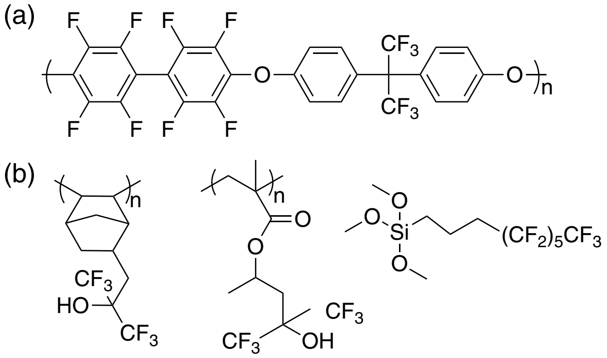


Fig. 16 (a) Fluorinated arylene ethers and (b) acrylate/methacrylate perfluoroalkyl silane-based BARC and TARC materials.

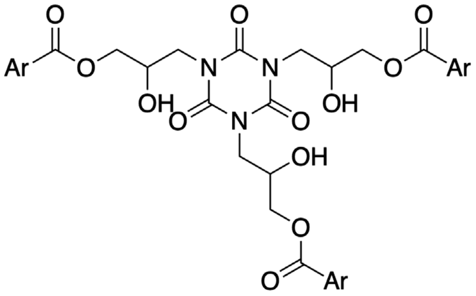


Fig. 17 Representative BARC material.[52]

5.2 *Top Antireflective Coatings*

Antireflective coatings may also be placed on top of a photoresist stack to reduce optical issues. The comments related to BARCs above about refractive index and miscibility are relevant to TARC materials as well. Issues of wetting and interactions with water arise when 193-nm immersion lithography is used. In this variation of high-resolution lithography, a droplet of water is placed between the photoresist stack surface and the stepper (exposure) lens. As the wafer is patterned, the water film must not wet the wafer surface, or else the patterning process will fail since the rapid movement of the stepper would rapidly lead to the breakdown of the immersion layer. A very hydrophobic, nonwetting surface makes the immersion process work well and prevents leaching of the photoactive component. For immersion lithography, control of substrate reflectivity is critical and for this reason immersion, BARCs are favored over TARC when using this process.

Similar chemical strategies have been used to make fluorinated TARCs and topcoats (below), where fluorinated acrylate- and methacrylate-based copolymers are used, but they are optimized for different property sets.[48] Jung et al.[49] showed a TARC material based on these components, which are easily developable but possess a relatively low refractive index of 1.55. Furthermore, by increasing the fluorine content of the TARC material, a high dissolution rate and receding contact angles >70 deg could be achieved.

5.3 *Topcoats*

Sanders wrote an extensive review of resist systems for 193-nm immersion lithography and discussed the need for topcoats.[41] These are materials used as the upper layer in the resist stack that was optimized for the purpose of preventing immersion liquid (water) from leaching photoactive materials from the photoresist during the patterning process and for base development. In that report, he describes several compositions that work well as topcoats. These include perfluoro ethers as well as polymers with hexafluoroisopropanol units and those with short-chain perfluoroalkyl units. All approaches reported function well as barrier materials. In addition to immersion topcoats, which are directly coated on the resist, material suppliers have also developed highly functionalized fluorinated amphiphilic molecular structures, which provide the same properties as a topcoat. The advantage of this approach is that the material, known as an embedded barrier layer (EBL), is formulated directly in the resist, and no separate topcoat coating step is required. Such photoresists are known as topcoat-free resists.[50] Such EBL materials may have similar fluorinated components as those found in fluorinated topcoats and fluorinated ARCs, but their application and processing are different.

Other approaches to low RI materials include the incorporation of air pockets using silica nanoparticles. However, this approach did not gain industry acceptance, because it was not possible to implement with the necessary process reliability and reproducibility. In addition, dyed TARCs (limited by the availability of appropriate chromophores) have been developed that reduce the need for fluorination using anomalous dispersion optical effects but do not eliminate the need for fluorinated components for performance reasons discussed above.

Finally, the only molecular unit that comes close to fluorochemicals in low surface energy are silicones, but they have the disadvantage that they have low softening temperatures and are very

oxygen plasma etch-resistant. Where ARCs need to be removed using such etch methods, alternative structures with silicones do not provide needed properties.

6 Fluorinated Surfactants and Surface Leveling Agents

Surfactants in general are "surface-active agents" that consists of a hydrophobic segment and a hydrophilic unit. Surfactants can be used in a variety of coating applications for improving film quality, changing surface interaction,[51] and wetting characteristics, and component mixing. The hydrophobic portion of a surfactant can consist of such moieties as hydrocarbon, silicone, or perfluorocarbon segments while the hydrophilic portion of a surfactant can be charged or neutral. Specific performance advantage of fluorinated surfactants is that the surface activity is much higher than equivalent hydrocarbon or silicone surfactants as indicated by the requirement for less surfactant material in a formulation to achieve its critical micelle concentration.

Fluorinated surfactants may be used in several applications in photoresist processing. For example, they can be used to improve photoresist deposition and eliminate defects during photoresist coating. Fluorinated surfactants have been used to improve the development process of an exposed photoresist. They are used to improve the uniformity of an ARC coating process and are especially effective when fluorinated ARCs are involved. Thick film photoresists benefit from surfactants in the formulation to achieve good coating uniformity. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality to reduce layer contamination and increase process yield) and the surface activity of fluorocarbon surfactants makes them readily useable with other ARCs and photoresist materials.

Fluorinated nonionic surfactants have been used in a wide range of lithographic processes due to their very low surface energy, thermal-and mechanical stability, and low refractive index. Nanoimprint lithography (below) is making use of fluorinated surfactants to reduce defects caused by the removal of the template in the patterning process.[53,54] Lin et al.[55] demonstrated the use of methyl perfluorooctanoate to significantly reduce defects of printed patterns. Another example was shown by Zelsmann et al.[56] applying perfluorooctyl-triethoxysilane and perfluorooctyl-trimethoxysilane. Besides use in nanoimprint lithography, fluorosurfactant-assisted photolithography was demonstrated by Sakanoue et al. using commercial polymeric fluorosurfactants, such as Surflon S-386, S-651 (AGC) and Novec FC-4432 (3M).[57] It should be noted that, due to the unique properties of fluorinated surfactants, examples of nonfluorinated surfactants with equivalent characteristics to those of fluorinated surfactants are limited and have been used in few resist formulations.

7 Nanoimprint Lithography

While nanoimprint lithography is not today a mainstream patterning technology, it has the potential to be introduced soon for specific patterning applications. A mold with nm-scale features is used to imprint polymer or a photopolymerizable monomer mixture to form the pattern in the transparent mold.[58,59] In the former case, many polymers have been explored for nanoimprinting but a mold release agent such as a poly(perfluoroether) is usually added to the surface of the mold. In the latter case, fluorochemical units such as those used in BARCs and ARCs including perfluoralkyl segments or hexafluoroisopropanol groups have been used.[60] In all cases, removal of the polymer from the mold is an important step in the production of the pattern and for this reason, fluoropolymers are frequently used. It is worth being aware of this approach to high-resolution pattern formation because some early attempts at process development depend on the use of fluorinated photoresists. The fluoropolymer has, in addition to excellent release properties, the advantage that air, which can be trapped in the process, is easily dissolved in the fluoropolymer thereby eliminating trapped bubbles and does not seem to affect pattern formation. Therefore, fluoropolymers are often preferred in this process. This technology area is new enough that little or no reported work has been carried out on the environmental fate of such materials.

Alternate materials for this process include silicones that can be used for their mold release properties.[61] This area is attracting strong interest and demonstrates that nonfluorinated materials

perform well, but at this time it has not been established if silicone materials are superior in performance. Etch characteristics and wear properties are of course different between fluoropolymers and silicones.

8 PFOS/PFAS Remediation

As noted above, the strength of the C─F bond creates materials with unique and technologically useful properties in semiconductor processing. That same bond strength also results in strong resistance toward physical, chemical, and biological degradation. Due to this strong resistance to degradation, PFAS compounds in general are extremely stable in the environment. In addition, such compounds have been found to be bioaccumulative.[62] Extensive literature exists describing the detection of a number of PFAS compounds in drinking water.[63] Postuse PFAS waste treatment methods including advanced oxidation processes,[64] reductive decomposition processes (aqueous electrons, hydrated electrons, etc.), and incineration have been developed for mitigation purposes.[59] Among these methods, advanced oxidation processes do not show high efficacy for PFAS degradation due to the high electronegativity of the fluorine atoms. More work will need to be done to assess the relevance to the kinds of fluorinated materials discussed in this paper.

Recent actions by the EPA include interim recommendations for addressing groundwater contaminated with PFOA and PFOS, published method 533 for detection of PFAS compounds in drinking water, an updated list of 172 PFAS chemicals subject to toxics release inventory reporting, a proposal to regulate PFOA and PFOS in drinking water and significant new use rule for certain PFAS in manufactured products.[65] Significant data gaps presently exist in dealing with PFAS and PFOS materials. The EPA is also leading a national effort to understand PFAS and reduce PFAS risks to the public through the implementation of its PFAS action plan and through active engagement and partnership with other government agencies and constituencies.[66]

9 Summary

Fluorinated materials play a useful and often essential role in many aspects of semiconductor processing. In our review of the technical literature, we have examined six major applications of fluorochemicals in photolithography and semiconductor processing and identified an emerging technology, nanoimprint lithography, see Table 1. These fluorochemicals are employed as components of PAGs, as components of photoresists, as elements of high-temperature polymers, and as ingredients in ARCs, BARCs, and as topcoats, frequently satisfying the "essential use" criterion. However, there is a strong societal interest in eliminating their use, and "essential use" is a stopgap situation in which replacements are actively sought. The "essential use" concept expects that PFAS uses considered essential today should be continually reviewed for potential removal or replacement by new technologies and be targeted by innovation toward alternatives. The concept does not support long-term and large-scale remediation technologies to justify the ongoing use of PFAS chemicals.

Thus, the challenges going forward are to find a means to replace PFAS components that achieve or surpass today's current performance characteristics in the following current and possible future lithography systems.

1. The use of fluorination in PAGs is to enhance the acidity (make $\mathrm{p}K_\mathrm{a} \ll 1$) of the acid produced in the region of exposure of a photoresist. The formation of acid to induce a solubility change is the critical step in today's chemically amplified photoresists, the workhorse family of photoresists that enable the production of the vast majority of semiconductors. The presence of a fluorinated unit adjacent to the sulfonic acid gives the acid its ability to efficiently release a proton that reacts with the resist polymer to create a solubility switch. Subsequent development forms a pattern in the photoresist. Today there is no effective alternative to a fluorinated sulfonic acid and this situation applies to chemically amplified photoresists across all wavelengths of lithography from 248 nm to EUV. Efforts to reduce the amount of fluorination in a PAG molecule have been demonstrated, but a survey of the current literature has not shown that complete elimination of

fluorination has produced a successful alternative. However, it is very likely that fluorine-free alternatives, which perform equally well and can easily take the place of the fluorinated compounds used today, will be more widely used, and developed in the coming years. Fluorinated polyimides use the presence of a fluorinated unit to improve the dielectric constant of the material and make it a better insulator while retaining excellent thermal stability. This combination of characteristics has not been effectively achieved by alternate means.

2. Other materials like poly(benzoxazole)s also receive an important performance boost from the incorporation of a fluorinated unit.
3. Antireflection coatings (ARC, BARC, and TARC) and other coatings such as topcoats or EBL use fluorinated components to limit the miscibility of this added layer with a photoresist or other organic layer in the semiconductor manufacturing process. As surface layers, they also provide barrier properties and when used as a topcoat act to protect the photoresist from interactions with the immersion fluid (currently water) used in 193-nm lithography. However, while these features can in part be replicated by other systems the necessary combination of properties (immiscibility, surface wetting properties, barrier properties, low refractive index) has not been successfully achieved.
4. Fluorinated surfactants provide a specific performance advantage since their surface energy is much lower than hydrocarbon or silicone surfactants resulting in the need for less surfactant material in formulations. Additionally, properties including very low surface energy, thermal and mechanical stability, and low refractive index provide benefits to coating and etching processes. Fluorocarbon surfactants are more easily etched than silicone surfactants in oxygen plasma (a desirable quality), and the surface activity of fluorocarbon surfactants makes them readily useable with ARCs and photoresist materials.
5. Nanoimprint lithography may become an important technology for some specialized forms of nanopatterning, and there is interest in the use of fluoromaterials in nanoimprint lithography. Current studies have not yet fully demonstrated that fluorine-free alternatives are successful in producing fine-featured patterns in a production capable system.

Appendix

Table 1 summarizes the function of the fluorinated compounds required for the main lithographic processes. In addition, non-fluorinated alternatives and their current feasibility are shown.

Table 1 Purpose, properties of fluorocompounds for lithographic patterning and semiconductor processing.

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
PAGs	Generation of strong acid upon exposure to UV light, when fluorination acid groups. Control of location and distribution of generated acids, especially in high-resolution applications	Fluorinated sulfonium- and iodonium-acid salts/ strong electronegativity of F atom—creates superacid material capable of mixing with photoresist	All successfully demonstrated alternatives have fluorinated segments —some down to one CF_2 unit	Not yet demonstrated in completely fluorine-free materials
Antireflection coatings (top and bottom versions have different requirements)	Low refractive index, low surface energy, and good barrier properties	Largely fluorinated units in acrylate/ methacrylate/ styrene-based copolymers, very low refractive index, and excellent barrier properties	Fluorine-free alternatives known. But necessary properties not yet broadly demonstrated in 193 immersion	ARC requirements different in 193- and 193-nm immersion lithography—fluorine-free systems not fully demonstrated

Table 1 (*Continued*).

Lithographic processing need	Critical purpose served	Fluorocompound(s) in use/unique properties provided	Known or potential nonfluorine-containing alternatives	Current viability of alternative
Topcoat (for 193-nm immersion photoresist)	Provides barrier layer for 193-nm immersion photoresists applied on top of photoresist and prevents leaching of photoactive components. Protects the photoresist from contact with immersion liquid (water)	Largely fluorinated acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
EBL (for 193-nm immersion photoresist)	Forms a protective surface layer for 193-nm immersion photoresists and prevents leaching of photoactive components. Incorporated as part of photoresist and segregates to film surface during the coating process. Protects the photoresist from contact with immersion liquid (water)	Largely acrylate/methacrylate/styrene-based copolymers, excellent barrier properties with fluorinated components	Lacking satisfactory options	Not yet demonstrated in fluorine-free materials
Polyimides (photopatternable)	Required stress buffer coat between chip and package to prevent premature device failure; especially good electrical insulating characteristics	Tetracarboxylic acid anhydride derivatives and aromatic diamines/solubility in organic solvents, low dielectric constants, and high thermal and thermooxidative stability; requires negative tone solvent to develop	Novel polyimides—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Polybenzoxazoles (photopatternable)	Stress buffer coat to prevent premature device failure; high-temperature stability and good insulating characteristics	Low dielectric constants, and high thermal and thermooxidative stability; processed using positive resist developer	Novel polybenzoxazoles—suitable fluorine-free alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials
Nanoimprint Lithography fluoropolymers	Excellent release characteristics; low surface energy and fluoromonomers reported to dissolve trapped air making them ideal for filling the micromolds of nanoimprint lithography	Fluoropolymers/low surface adherence	Silicone-based release agents	Potentially good but not yet established
Nonionic fluorinated surfactants	Improve coat quality in thin lithographic films (e.g., photoresists and BARCs); compatibility with photoresists and TARC/BARC structures; high efficiency of fluorinated surfactants requires very little additive and enables better performance	Nonionic fluorinated segments with water-soluble units	For a number of applications, alternatives have not demonstrated equal performance	Not yet demonstrated in fluorine-free materials

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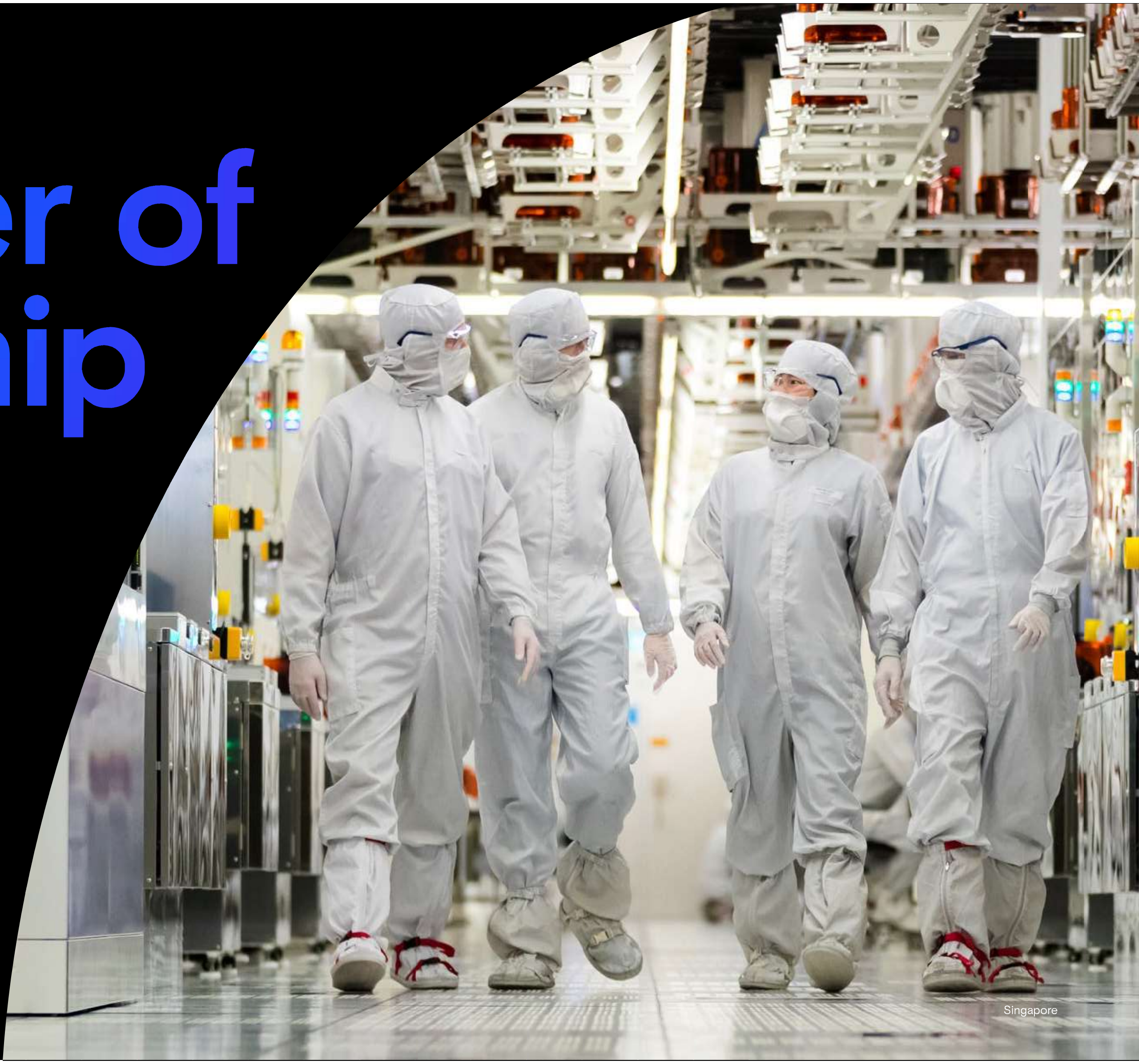
The power of partnership

Micron sustainability report 2023



Singapore

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A message from our CEO

More than ever before, the world is recognizing the importance of semiconductors — not only to our economic health and advancement, but to every aspect of modern life, from education to entertainment. Micron's vision is to transform how the world uses information to enrich life *for all*, and the solutions we make are becoming increasingly important as we move into the age of ubiquitous artificial intelligence systems powered by fast data.

In the pages of these reports, you'll see that sustainability is not just central to Micron's vision, mission and values, it is also integral to our long-term strategic plans. We believe we also have a responsibility to help lead sustainability improvements across our industry. None of these goals are possible without strong partnerships. We actively work with industry peers, suppliers and customers worldwide to set new standards for the sustainability of semiconductor production.

Manufacturing semiconductor products is a resource- and power- intensive business, and careful management and planning are required to ensure efficient production. In 2022, Micron announced several critical expansions that will be central to the company's future, including investments in Boise, Idaho, and Clay, New York. Both projects are pivotal to Micron's manufacturing strategy to meet DRAM demand over the decades ahead. With the support of the CHIPS and Science Act, these projects stand to make a significant impact on U.S. semiconductor manufacturing leadership. Each will also demonstrate leadership techniques for energy conservation and sustainability. We are also making significant investments in community and education around these expansions. These investments will help us create sustainable growth and train the workforce we need to drive advanced semiconductor manufacturing.

Our aim with this report is to provide a detailed accounting of our progress toward our sustainability goals and note specific contributions over the past year. It also shares our vision for sustainable development in the years ahead. Below are a few highlights.

Environment

- Emissions: We expanded our climate initiative goals early last year, working toward targets to reach net zero greenhouse gas emissions in our operations (scope 1) and purchased energy (scope 2) by 2050, with a 2030 milestone to reduce scope 1 emissions from our 2020 baseline by 42%. These complement our existing goal to achieve 100% renewable energy for existing U.S. operations by the end of 2025.
- Energy, water and waste: We continue to make our operations more efficient and sustainable, with aspirational targets of 100% renewable energy, 100% water conservation, and zero waste to landfill. This report outlines our participation in alternative energy facilities, as well as water conservation and river restoration projects in our communities.
- Sustainable financing: Micron continues to lead in sustainable financing. We have executed $3.7 billion in credit facilities linked to our sustainability performance and achieved our 2022 performance metrics in connection with this credit. The $1 billion green bond we issued in November 2021 supports Micron's commitments to environmental performance and LEED-certified buildings.

Social

- Equity and representation: We continue to maintain global pay equity for women and people with disabilities globally, as well as across race/ethnicity and veteran status in the U.S. and race/ethnicity for Malays in Singapore. We actively promote a culture of inclusion and focus our educational outreach on bringing more women and underrepresented groups into semiconductor fields.
- Team engagement: We grew participation in employee resource groups to 39% of our workforce, a nearly 50% increase from fiscal year 2021 (FY21). Micron is in a leadership position in this metric.
- Diverse suppliers: Our spend with diverse suppliers is growing. In FY22, we achieved $454 million in spend with diverse suppliers, exceeding our goal of $404 million.
- Diverse financial institutions: In FY22, we achieved our goal to have $500 million in cash investments managed by underrepresented financial firms.

Governance

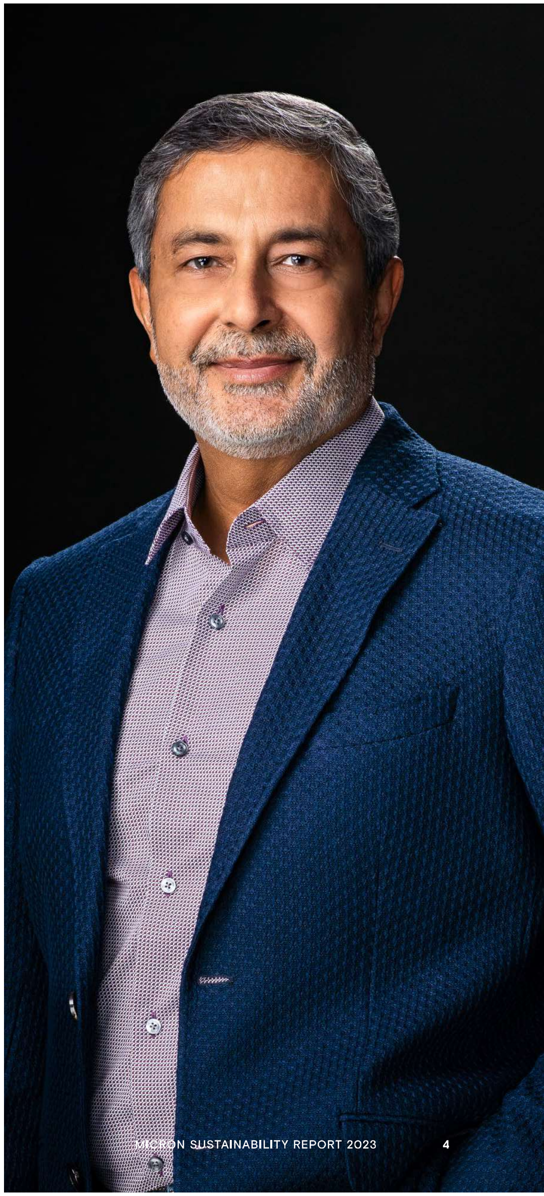
- Ethics: I personally place a high emphasis on integrity with our team, and we institute regular training so that every team member understands and adheres to our code of conduct and related policies.
- Responsible sourcing: We have a number of programs focusing on responsible minerals sourcing, in addition to supplier diversity, environmental performance and human and labor rights.

Micron continues to make strong progress toward our sustainability, community and governance goals, and I'm proud of the work represented in these pages.

I hope you enjoy reading our 2023 sustainability report and progress summary, and we invite your feedback. You can reach us by emailing sustainability@micron.com.

Sanjay

Sanjay Mehrotra
President and CEO, Micron Technology



From: Sara Pieklik <sarapieklik@gmail.com>
Sent: Tuesday, October 31, 2023 6:28:58 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron
Subject: Community input - Micron

To whom it may concern:

We have an opportunity, and Micron has the monetary means, to lead by example. I have two young boys that thrive outdoors, and whose mental health visibly suffers when we spend too much time inside. As a mom, it is difficult to find places to take my toddlers where they can be in a natural environment without it being a “trip” to get there. As a teacher, I have taught hundreds of middle schoolers and know the importance of mental health and how being outside can positively affect mental health, demeanor, attitude, and outlook. Please consider letting part of Micron’s investment in our community be one with POSITIVE LASTING impacts on the small part of our world around us.

Please consider the following ideas, and dream even bigger, push this company to make our community BETTER for generations to come. Learn from our local history of the travesty of what was once a thriving Onondaga Lake, and what industry turned it into, and not only mitigate the environmental impact of the Micron plant, but use their investment as an opportunity to not just preserve but build up our environment and natural spaces.

I want my kids, all the kids I will teach, all the kids in our community, to know and be able to access nature regularly. I don’t want to have to take my children on a trip, outside of our local community, to go be in nature. A natural environment should be the norm, not a “field trip.”

Suggestions:

Donating enough money to the CNY Land Trust to create public green spaces that exceeds the footprint of their facilities and the support infrastructure. I would like to see 6,000+ acres preserved.

Donate enough money to the Onondaga Earth Corps to exceed their annual funding needs. This organization helps teach young people about ecology and fits in with Micron’s STEM education mission goal.

Demand that new housing have walkable community parks that exceed the WHO recommendation of green space per person, and demand current brownfield sites be priority of new development.

Completely utilize their rooftop space and parking areas for solar PV generation.

Ensure the out-going water is potable and free of whatever chemicals are added to it through their processes and that they recycle the water they use on site to reduce demand from our surrounding ecosystems.

Demand outdoor lighting be minimal and not face upward or outward if possible.

Create a transportation plan that prioritizes walk-ability, bicycling and mass transit over automobiles.

Sincerely,
Sara Pieklik
Mom of 2 toddlers
Teacher of middle school math
Facilitator at Micron’s Liverpool Chip Camp Concerned community member Liverpool, NY

Sent from my iPhone

From: Gonzalez-Trelles, Melissa D <melissa_gonzalez-trelles@fws.gov>
Sent: Tuesday, October 31, 2023 8:43:02 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Cc: Sullivan, Tim R <tim_r_sullivan@fws.gov>; dep.r7@dec.ny.gov <dep.r7@dec.ny.gov>; dep.r4@dec.ny.gov <dep.r4@dec.ny.gov>; Margaret Crawford <Margaret.A.Crawford@usace.army.mil>
Subject: Micron Semiconductor Manufacturing Campus, Town of Clay

Good Afternoon,

This responds to the Onondaga County's Notice of Positive Declaration, Availability of Draft Scope and Public Scoping Session issued by the Onondaga County Industrial Development Authority (IDA) pursuant to the State Environmental Quality Review Act (SEQRA) for the proposed Micron Semiconductor Fabrication Project to be located in the Town of Clay, Onondaga County, New York.

Regards,

Melissa Gonzalez-Trelles (she/they)

Secretary

US Fish & Wildlife Service

Ecological Services

New York Field Office

3817 Luker Road

Cortland, NY 13045

(607)299-0624

United States Department of the Interior

FISH AND WILDLIFE SERVICE
3817 Luker Road
Cortland, New York 13045

October 31, 2023

Mr. Robert Petrovich
Executive Director
Onondaga County Industrial Development Authority
335 Montgomery Street
Syracuse, NY 13202

Dear Mr. Petrovich:

This responds to the Onondaga County's Notice of Positive Declaration, Availability of Draft Scope and Public Scoping Session issued by the Onondaga County Industrial Development Authority (IDA) pursuant to the State Environmental Quality Review Act (SEQRA) for the proposed Micron Semiconductor Fabrication Project to be located in the Town of Clay, Onondaga County, New York. Thank you for including the U.S. Fish and Wildlife Service (Service) as an interested agency for the SEQRA process.

Supporting documents issued by the IDA include the Environmental Assessment Form and Addendum dated September 12, 2023, and application for funding dated July 14, 2023. The Draft Scope of Work (DSOW) was updated on September 20, 2023, and includes the areas to be studied and documented in a Draft Environmental Impact Statement (DEIS) Report. The DSOW was received in our office on September 25, 2023, and the IDA is accepting our comments until October 31, 2023.

We understand the US Department of Commerce (DOC) is the lead federal agency for the project and the U.S. Army Corps of Engineers (Corps) will be involved with the project through permitting pursuant to Section 404 of the Clean Water Act. As you may be aware, federal agencies, such as the DOC and Corps, have responsibilities under Section 7 of the Endangered Species Act (ESA) (87 Stat. 884, as amended; 16 U.S.C. 1531 *et seq.*) to consult with the Service regarding projects that may affect federally listed species or designated critical habitat, and confer with the Service regarding projects that are likely to jeopardize federally proposed species and/or adversely modify proposed critical habitat.

Project Description

The Micron Corporation proposes to construct four fabrication (Fab) facilities in two phases on an approximately 1,400-acre area currently owned by the IDA. Two Fabs would be built together in Phase 1 and two would be bult 10 years later in Phase 2. The SEQRA review and DSOW will encompass the full build out of four Fabs. Each Fab will be approximately 1.2 million square feet in size and require additional utility, warehouse and testing space. This will encompass an additional approximately 870,000 square feet of space for each set of Fabs.

A facility of this size will require extensive infrastructure work to support the manufacturing facilities. For example, a new or upgraded interchange on Interstate 81will be needed in Clay. Utility work will include new power lines and substations, natural gas pipelines, water and sewer treatment facilities and lines and industrial gas storage. These improvements will be required both on and off site. A modification to an existing rail line will also be implemented to facilitate cargo delivery. In addition, access roads, parking lots, storm water detention basins and wastewater pretreatment and storage will be built on site.

The Micron site was formerly named the White Pine Commerce Park and has been studied for industrial use since 1991. Onondaga County originally purchased 340 acres of property and this area was the focus of a Generic Environmental Impact Statement (GEIS) Report completed in 2002. Most of the current 1,400-acre site was reviewed in a Supplemental GEIS in 2021.

Draft Scope of Work

The DSOW contains the areas to be studied and documented in the DEIS. This includes applicable social and natural resources affected by the project on site and in the larger central New York region. Section five of the DSOW provides general topics and specific technical studies proposed to inform the DEIS. We note that while the list of resources includes wetlands, floodplains, and vegetated habitat, there is no mention of an analysis of the project's effects on wildlife. The DSOW should be amended to include literature review and field observations of wildlife using the site at all times of the year, including winter and migration seasons. Potential impacts to wildlife that should be considered in the DEIS include, but are not limited to, noise, lighting, pollution, human activity and traffic. Potential loss of habitat and fragmentation appear to be substantial and will negatively affect many species. This information should be included in the DSOW and documented in the DEIS.

In regard to site vegetation, the DSOW should include mapping of vegetation communities, surveys to document endemic plants and identification of rare species and communities as well as invasive plant species. Information should also be provided on the present and future threats of spreading invasive plants to and from the site. An invasive species management plan should be developed for the site in consultation with the New York State Department of Environmental Conservation (NYSDEC).

Micron and its consultants have gathered information on federally listed species using the Service's Information, Planning and Consultation (IPaC) system. This information should be included in the DEIS along with a description of studies completed thus far. For example, the

Service and the Micron team, along with staff from the NYSDEC, have discussed studies of two endangered bat species believed to be using the site.

Based on information in IPaC, the project is within the range of the federally listed endangered Indiana bat (*Myotis sodalis*) and the federally listed endangered northern long-eared bat (*Myotis septentrionalis*). Accordingly, Micron initiated acoustic surveys of these species at sample locations on the site. A summary of the survey results should be included in the DEIS. The documented call locations should be analyzed in regard to tree removal and habitat modification. This information should inform what the potential effects to these listed species may be and what, if any, measures could be implemented to mitigate adverse effects. The Service will continue to work with Micron and other partners in evaluating the project's effects on federally listed species. Since federal agencies will be funding, permitting and/or approving aspects of the project, section 7 consultation under the ESA will be required. More information about the process can be found here: https://www.fws.gov/service/esa-section-7-consultation.

The DSOW indicates that wetlands will be identified and delineated in consultation with the US Army Corps of Engineers. We understand that most of that field work has been completed. However, the DSOW does not indicate if or how wetland functions and services will be evaluated and reported. This information is important in understanding the habitat and social values (flood flow attenuation, sediment and nutrient retention, pollution abatement, etc.) these areas provide. Documentation in the DEIS is also important to understand what is being potentially lost from the project and what mitigation is required of Micron to replace these functions and services. In line with section 404 of the Clean Water Act, the project design must avoid, minimize, and mitigate potential impacts to aquatic resources to the greatest extent practicable. This review approach should be added to the DSOW.

Wetland mitigation is mentioned in the DSOW as potentially occurring on and off site. While the extent of potential wetland impacts is not yet known, it appears to be a substantial amount based upon the extent of wetlands found on the 1400-acre site. Mitigation for unavoidable impacts should occur within the same watershed (as defined by the 8-digit hydrologic code) and be as close to the impacted wetlands as practicable. Micron has inquired about mitigation options including the purchase of credits at third party wetland mitigation banks or in-lieu fee sites. The Service does not support the complete purchase of available credits for the Micron project as that reduces the effectiveness of the mitigation program.

We note that the DSOW does not mention stream impacts or mitigation. As proposed, it appears that the Micron facility will result in the loss of hundreds to thousands of feet of perennial and intermittent stream habitat. This issue should be added to the DSOW and a thorough evaluation provided in the DEIS. If there are no existing data for Youngs Creek, then Micron should perform field studies to gather information on the physical, biological and chemical characteristics of streams on the site. The completed Environmental Assessment Form for the project indicates that approximately 48 million gallons of water will be needed per day to operate the Fabs. The DSOW should identify where the discharge point(s) of effluent will be located and the potential effect these discharges will have on local surface waters. Also, the DEIS should include an analysis of the impacts to aquatic life because of the discharges.

The DSOW briefly addresses the topics of indirect and cumulative impacts as well as growth inducing aspects associated with secondary development (i.e. new housing and commercial construction). However, the text indicates that these topics will be evaluated in terms of human health and the built environment and not the natural environment. Secondary growth impacts of the Micron project have the potential to be wide ranging and substantial. We encourage the IDA to closely work with experts in planning, academia as well as agencies such as the Service and the NYSDEC to identify potential impacts of growth on the region's habitat and associated wildlife species. A thorough analysis of secondary and cumulative impacts in the DEIS should follow the recommendations of the Council of Environmental Quality's National Environmental Policy Act Handbook found at:
https://ceq.doe.gov/publications/NEPA-CEQA_Handbook.html.

Summary

The proposed Micron project has the potential to cause substantial if not significant environmental impacts to a wide range of natural resources. Not only will the 1,400-acre Micron site be affected but numerous other areas will be developed to support the facility. The Onondaga County IDA has the responsibility to adequately document and evaluate the potential effects to the resources. We have concerns about potential near term and long-term effects to federally listed species, aquatic resources such as streams and wetlands, invasive species, native wildlife, and existing habitat. A concerted effort should be made to account for all foreseeable regional development that will be attributed to the Micron project. This information is essential to avoiding, minimizing, and mitigating impacts as required by SEQRA and federal laws.

Thank you for your coordination and consideration of these comments. If you require additional information, please contact Tim Sullivan at 607-753-9334 or tim_r_sullivan@fws.gov. Future correspondence with us on this project should reference project file 2024-0005791.

Sincerely,

IAN DREW
Digitally signed by IAN DREW
Date: 2023.10.31 15:48:39 -04'00'

Ian Drew
Field Supervisor

cc: NYSDEC, Syracuse, NY (K. Balduzzi)
NYSDEC, Albany, NY (D. Roesenblatt)
USACOE, Auburn, NY (M. Crawford)

From: Michael Wolfson <mwolf122@aol.com>
Sent: Wednesday, November 1, 2023 3:58:33 AM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: MICRON SCOPING COMMENTS

Chairman Pat Hogan, OCIDA, enclosed are my scoping comments

Michael A. Wolfson, MD

MICRON SCOPING COMMENTS
Michael A. Wolfson, MD

1) Much more detail is needed by members of the public than what was provided on the OCIDA website in the New York State Environmental Assessment Forms (EAFs), Parts 1-3. The proposed Micron plant will not be a "reinvention of the wheel". Micron has been operating similar or identical plants for years at other locations including Boise, Idaho. Therefore, details of the types and amounts of pollutants (air, water, and solid waste) are already known based on the same industrial processes used at other Micron plants. Although information on exact amounts of various pollutants expected to be produced or released at the proposed plant may not be exact, the specific identification, character, and expected estimates of amounts must be provided to the public now. One way that this can be accomplished is the disclosure of this information by Micron to OCIDA and the public from already existing Micron manufacturing plants. A comparison between the existing information and estimates of pollutants, water use, waste water, etc. can be based on a comparison of the industrial processes proposed for the Clay plant and the known throughput of Micron products from current plants.

2) The public has been misled regarding the amount of water use proposed or predicted for the Clay Micron plant in a variety of public statements in the news. The EAFs on the OCIDA sight indicate that Micro will be using 48,000,000 gallons of Onondaga County/Lake Ontario (Onondaga County Water Authority - OCWA) water per day. This huge volume of fresh water needed is one-third greater than the entire amount of water that OCWA has reported is used by all its commercial and industrial customers in its five-county service area of approximately 36,000,000 gallons per day. Information provided to the public to date has not contradicted this huge volume of water use. Also, to date, the amount (or percentage of fresh water used daily) of water which can and will be recycled by Micron, reducing the requirement for fresh water supply, has been a moving target as well. This information must be provided to the public now while the environmental assessment proceeds, long before any Environmental Impact Statement (EIS) is produced.

3) In addition to the above concerns about the massive use of Lake Ontario water, the public must be assured with irreversible documentation that the public water drinking supply will never be compromised to accommodate water use by the Micron plant. Any contracts with Micron must include guarantees to the public that the drinking water supply will always be primary. Also, news reports have indicated that Micron has not committed to the huge expense of building a second water supply system from Lake Ontario in order to serve its industrial needs. The taxpayers of Onondaga County should not pay for this water supply system. This new system amounts to a dedicated supply for the Clay Micron plant.

4) The OCIDA EAFs include no details regarding the discharge of wastewater from the Micron plant into the Oneida River. The volume of water and the contents of wastewater including, but not limited to known hazardous waste products/chemicals must be identified now. At the very least, the various expected contents of the water must be specified, including hazardous materials, even if the weights and the volumes are not known.

5) In addition to water pollutants to be identified now, the public must be informed now regarding the amounts and types of air pollutants released by current Micron industrial facilities and expected to be released/emitted by the proposed Clay plant. A detailed assessment of the expected numbers of cancers and other pollutant-related illnesses based on air emissions, water discharge, and hazardous solid waste from the plant must be identified as part of the EIS and such assessment must be released to the public long before the EIS is completed.

6) Air pollutants including, but not limited to, particulate matter (PM2.5 and PM 10.0, etc.) from truck and other transportation traffic serving the plant must be identified now. The designation of hazardous air pollutants (HAPs), water and solid waste pollutants, in addition to the transportation air pollutants, need to be known now. The use of the acronym TBD ("to be determined") used in the OCIDA EAFs is not acceptable

7) The disposal, including methods of on-site storage or transportation to off-site storage, must be identified. Will the plant use current landfill sites now utilized by Onondaga County for any types of waste? How will wastewater be treated, i.e. where (on the plant grounds? at Onondaga County facilities?) and what types of upgrades and cost will be needed for current or proposed county facilities. Does Micron propose to send solid waste to the Onondaga County solid waste incinerator on Rock Cut Road? Are other incineration sites proposed? What volume and types of waste are proposed for incineration? What air,water, and soil pollutant will result from waste disposal or incineration? What are the expected health effects of such waste product treatments?

8) What is the identity of individuals and/or consulting firms proposed for the development of an EIS? The names of individuals and their professional credentials, methods of contact by phone or electronic means, and vetting of such consultants for conflicts of interest between the citizens of Onondaga County must be identified now. The public may and should demand that consultants independent of OCIDA and Micron be engaged to produce an environmental assessment of the proposed plant under the aegis of an independent group of professionals from the county or vicinity whose only interest is the protection of the public health and the environment with no financial conflict of interest.

9) Onondaga County health care facilities, in particular our hospitals, were short-staffed even before the Coronavirus pandemic. Waiting times and bed shortages were unfortunately highlighted by Covid-19 cases and have continued. What improvements in the healthcare system are proposed to remedy these shortcomings in view of the expectation of potentially thousands of new residents to work at and/or serve the Micron plant.

10) These are not the only issues that need to be addressed, and, in my opinion, the SEQURA process and the EAFs referred to above do not adequately address the myriad potential environmental and public health issues and problems posed by Clay Micron plant.

Michael A. Wolfson, MD, MPH, MS
Onondaga County Resident

From: straussnyc@verizon.net <straussnyc@verizon.net>
Sent: Wednesday, November 1, 2023 8:19:04 PM (UTC+00:00) Monrovia, Reykjavik
To: ED-Micron <micron@ongov.net>
Subject: Micron Project EIS

Dear Onondaga County IDA:

I know that I missed the deadline for providing specific comments on the Draft Scoping document for the EIS. Nevertheless, the Empire State Passengers Association would like encourage the Onondaga County IDA to consider the opportunity to mitigate transportation impacts of the Micron plant via improvements to freight and passenger rail access to Syracuse. ESPA was pleased to learn that Micron proposes to construct a freight rail line extension for the delivery of construction material to the site. As important is the question of how raw materials and completed products will move to and from the Micron plant. Truck only solutions would be undesirable for the Syracuse area and might not comply with the NY Climate Act. Similarly, the Micron plant will generate additional traffic from suppliers and other ancillary businesses in addition to the traffic volumes created by just the Micron plant. Improving passenger rail service to and from Syracuse can be part of the traffic management plan.

New York State has a new plan for improving intercity passenger rail service in upstate New York and advancing the construction of some of the Syracuse elements is highly recommended. You may read more about the Plan here: Empire Corridor Tier One EIS - Empire State Passenger Association (esparail.org) Appendix H provides the best project details chronologically. This could be part of the traffic mitigation and growth management plan for the project.

Please add my name to the e-mailing list for the environmental review. Thanks.

Steve Strauss

Executive Director

Empire State Passengers Association

www.esparail.org

646-334-4214