PFASware: Quantifying the Environmental Impact of Per- and Polyfluoroalkyl Substances (PFAS) in Computing Systems

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***Abstract*—PFAS (per- and poly-fluoroalkyl substances), also known as forever chemicals, are widely used in electronics and semiconductor manufacturing. PFAS are environmentally persistent and bioaccumulative synthetic chemicals, which have recently received considerable regulatory attention. Manufacturing semiconductors and electronics, including integrated circuits (IC), batteries, displays, etc., currently accounts for a staggering 10% of the total PFAS-containing fluoropolymers used in Europe alone. Now, computer system designers have an opportunity to reduce the use of PFAS in semiconductors and electronics at the design phase. In this work, we quantify the environmental impact of PFAS in computing systems, and outline how designers can optimize their designs to use less PFAS. We show that manufacturing an IC design at a 7 nm technology node using Extreme Ultraviolet (EUV) lithography uses 20% less volume of PFAS-containing chemicals versus manufacturing the same design at a 7 nm node using Deep Ultraviolet (DUV) immersion lithography (instead of EUV). We also show that manufacturing an IC design at a 16 nm technology node results in 15% less volume of PFAS than manufacturing the same design at a 28 nm node due to its smaller area.**

***Index Terms*—PFAS, forever chemicals, semiconductor manufacturing, lithography**

I. Introduction and Background

The environmental impact of computing systems extends beyond their carbon emissions and water usage. PFAS, per- and poly-fluoroalkyl substances, are a class of over 16,000 synthetic chemicals used in manufacturing across global industries for their heat-resistant, water-resistant, and chemical stability properties [1]. PFAS are physiochemically diverse chemicals containing one or more fully fluorinated methyl (3 carbon-fluorine bonds) or ethylene (2 carbon-fluorine bonds) carbon atoms [2]. Due to their bioaccumulation, human toxicity, and environmental impact, PFAS have been under extensive public, scientific, and regulatory action globally [2]–[4]. Across the electronics and semiconductor industry, PFAS are widely used including in manufacturing computing ICs, displays, batteries, and cooling liquids for thermal management in datacenters [1], [5]. Figure 1(a) shows that the electronics and semiconductor industry was the *third largest consumer of fluoropolymers* in 2020 in Europe. With the rising proliferation of electronics and computing chips, PFAS use in electronics is expected to grow 10% annually, primarily driven by semiconductor manufacturing and production [4].

As humanity builds more fabrication facilities globally, the rise of PFAS use in manufacturing and PFAS contaminants [6], through wastewater, emissions, and e-waste, is a pressing environmental issue for the semiconductor and computing communities. Figure 1(b) shows that the majority of PFAS used in chip manufacturing is incinerated or disposed in wastewater, signifying major opportunities to reduce PFAS. In this work, we take a data-driven approach toward studying PFAS in ICs manufacturing, and discuss design optimization trade-offs between PFAS use and conventional design metrics (e.g. performance).

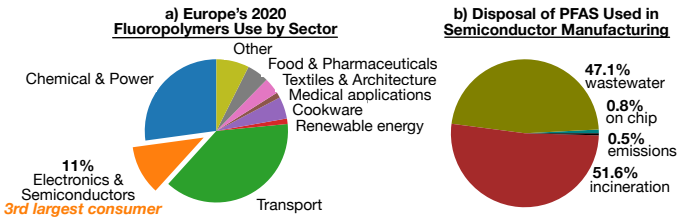

Fig. 1. (a) Electronic and semiconductor industries are the third largest consumer of fluoropolymers across sectors in Europe in 2020 [1]. (b) The majority of PFAS used in semiconductor manufacturing is either incinerated or goes to wastewater [6], signifying major opportunities for computer designers and researchers to reduce PFAS at the design phase.

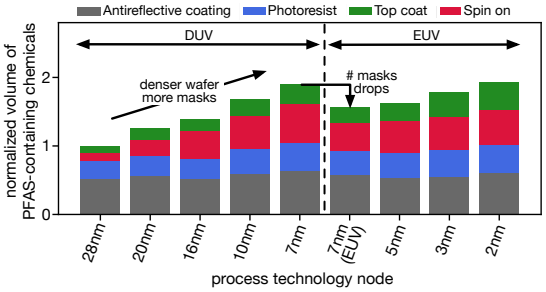

Fig. 2. Quantifying PFAS-containing chemicals in integrated circuit (IC) manufacturing [8]. The volume of PFAS containing chemicals varies with process technology node in semiconductor manufacturing, depending on the design's metal stack, lithography steps, and patterning complexity.

II. PFAS in Semiconductor Manufacturing

A major use of PFAS in semiconductor manufacturing is in lithography. Figure 2 shows the breakdown of PFAS volumes used across four semiconductor manufacturing process steps at varying technology nodes: antireflective coating (i.e., a thin layer of dielectric), photoresist for lithography and patterning, top coat to protect from leaching and water uptake, and spin-on dielectrics. Among these four manufacturing processes, antireflective coating requires the highest amount of PFAS-containing chemicals: up to 52% of total PFAS-containing chemicals used for a 28 nm technology node [8]. At more advanced process technology nodes, however, top coat and spin-on dielectrics are the manufacturing processes that primarily contribute to increasing use of PFAS-chemicals: up to 4.18× in volume (top coat) and 4.36× in volume (spin-on) for a 2 nm technology node. Yield also impacts the amount of PFAS used in manufacturing. Higher chip yield leads to lower PFAS.

Figure 2 shows that manufacturing an IC design at a 7 nm node that comprises four EUV-patterned metal layers, as described in [9], uses 20% less volume of PFAS-containing chemicals, compared to manufacturing the same design in a 7 nm node that instead uses Deep Ultraviolet (DUV) immersion lithography (193 nm wavelength) to pattern these same four layers (also described in [9]). This is because direct EUV helps reduce the number of manufacturing steps, including lithography, deposition and etching. One direct EUV mask can

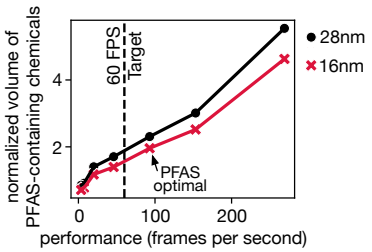

Fig. 3. We compute the normalized volume of PFAS-containing chemicals versus performance for NVIDIA's NVDLA AI accelerator for Int8 ResNet-50 inference [11]. The NVDLA IC design manufactured at a 16 nm node, with 60 FPS Quality-of-Service constraint, uses less volume of PFAS-containing chemicals versus the design manufactured at a 28 nm node due to area savings.

replace up to five immersion DUV masks, with better yield and fabrication time. As an example, 7 nm nodes using immersion 193 nm (DUV) instead of EUV lithography require *additional* PFAS-containing topcoats to prevent immersion water from leaching into the photoresist during multiple patterning [10]. As feature sizes get smaller, the number of lithography steps (and number of masks) increases due to the rising patterning complexity. This results in an increasing trend for volume of PFAS-containing chemicals for 5 nm nodes and beyond.

III. PFAS-Performance-Area Analysis

As computer architects and designers, we have an opportunity to design systems that have smaller environmental footprint, including lower PFAS. Figure 3 shows the trade-off between normalized volumes of PFAS-containing chemicals (y-axis) versus the performance of a range of NVIDIA Deep Learning Accelerators (NVDLA) manufactured in 28 nm and 16 nm technology nodes [11]. The NVDLA accelerators range from 32 to 2,048 Multiply-Accumulate (MAC) units and 128 KB to 512 KB buffer size for on-chip SRAM. The NVDLA accelerator achieves better performance and energy efficiency when implemented at the more advanced process technology node, and also uses less volume of PFAS-containing chemicals during manufacturing due to area savings.

We illustrate an example for designing an NVDLA to meet Quality-of-Service (QoS) constraints for image processing (e.g. frame rate of 60 frames-per-second or FPS), while minimizing PFAS-containing chemicals in manufacturing. The 512-MAC design manufactured at a 16 nm node incurs 15% less volume of PFAS-containing chemicals during manufacturing versus the 512-MAC design at a 28 nm node with similar QoS. This is because the 28 nm node design has 1.64× higher area than the design manufactured at the 16 nm node (considering yield, using a Murphy yield model).

IV. Conclusion and Call to Action

The environmental impact of computing systems includes carbon footprint, water consumption, and PFAS. Manufacturing semiconductors and electronics relies heavily on the pervasive use of PFAS-containing chemicals, which poses uncertain bioaccumulation and human health concerns. As computer designers and architects, we can help address the environmental impact of our computing systems, including PFAS, *at the design phase*. We outline potential steps to minimize PFAS use and enable holistic sustainable computing system design:

- **Better and standardized PFAS quantification methods.** The environmental impact of PFAS in computing is complex and understudied. Quantifying PFAS is a two-step process. (1) Environmental scientists must be able to *detect* PFAS. (2) They must be able to *measure* PFAS. Unlike carbon footprint, which can be measured and converted to units of carbon dioxide equivalent (CO_2e), measuring PFAS is more challenging. Given the range of PFAS chain lengths (i.e., number of perfluorinated carbon), simply measuring PFAS concentration (in units of parts-per-trillion or μg/L) may not be a sufficient indicator for PFAS impact. Alternatively, referring to the amount of PFAS in fluorine basis, such as the number of perfluorinated carbon chains [12] or molarity equivalence, will enable more accurate comparisons between different PFAS. For example, a PFAS with 1 perfluorinated carbon is referred to as C1, another with 8 perfluorinated carbons is referred to as C8.
- **Minimizing use of PFAS-containing chemicals in manufacturing.** A few technology companies, such as Apple [7], have announced the phasing out of PFAS in their products. Technology companies can benefit from investing in research and infrastructure to: (1) find PFAS-free alternatives in products, and (2) safely dispose of PFAS-containing e-waste.
- **Designing systems with lower PFAS-containing chemicals.** Researchers and designers across the computing stack have an opportunity to identify trade-offs and incorporate optimizations for lower environmental impacts of PFAS at the design phase. This is especially important given the current lack of PFAS-free alternatives in IC manufacturing.
- **Designing hardware for longer use, and repurposing hardware to minimize e-waste.** By extending the lifetime and hardware use, we can minimize the amount of e-waste sent to landfills and incineration sites, resulting in less PFAS polluting the atmosphere or leaching into the soil and aqueous streams.

Please refer to [13] for the extended version of this work.

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