Semiconductor Industry Waste Valorization for Recovery of Gallium

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Focus Area: The focus of this paper is on advancing energy-efficient industrial water reuse while recovering gallium (Ga), a critical mineral that can be found in semiconductor wastewater streams. Semiconductor fabrication industry is among the most water and energy intensive manufacturing processes, generating large volumes of wastewater that contain strategically important metals, such as Ga. The urgency of this effort is also underscored by the escalating water shortages in leading semiconductor manufacturing regions where industrial expansion increasingly competes with municipal and ecological water needs. Thus, there is a need for a cost-effective and eco-friendly water management strategy that could benefit all the stakeholders. The dual optimization of energy consumption in water treatment and critical-material recovery efficiency through an energy extensive advanced nanofiltration based separation process can be a viable option. Advanced nanofiltration can minimize the energy footprint of semiconductor wastewater treatment and offers economic and strategic incentives through securing water reuse and Ga recovery.

Background and Existing challenge: The semiconductor industry forms a technological cornerstone of modern society enabling advances in computing, communication, healthcare and clean energy (1). Fueled by advances in artificial intelligence, 5G connectivity, electric vehicles and data intensive applications, the global semiconductor industry sales amounted is expected to reach USD 1 trillion by the year 2030 (2-4). This rapid growth, however, has magnified the industry's energy and water footprint. Each fabrication facilities require of 5–10 million gallons of ultrapure water (UPW) per day – equivalent to the water use of 33,000 households (5, 6). Producing this UPW is energy-intensive, involving processes like reverse osmosis, ion exchange, and UV oxidation and ~1,500 gallons of municipal water to yield 1,000 gallons of UPW (6). At the back end, the manufacturing process generates large volumes of wastewater contaminated with critical metals, such as copper, arsenic (As), and Ga (5-7). Treating or reusing these streams demands 0.5–2 $kWhm^{-3}$ of energy which can rise sharply for complex industrial effluents (8). The environmental impact of not treating these streams is severe: if heavy metals like Ga (and often co-occurring As in GaAs processes) are released, they pose toxic risks to ecosystems and public health (6). Thus, fabs face a unique challenge at the nexus of energy, water, and materials –consume energy to purify and treat water, compete for limited water resources, and lose critical materials in the process. Without effective recovery and treatment, the discharge of Ga and co-occurring As possess environmental and public health risks. The growing overlap of water stress and manufacturing intensity makes addressing this interconnected energy for water an urgent priority.

The urgency of addressing these challenges is magnified by the regional water scarcity in several parts of the United States. Many leading U.S. semiconductor manufacturing hubs

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are in water-stressed areas. Arizona, for instance, has attracted over USD 100 billion in new semiconductor investments from companies such as TSMC, Intel, etc., but the area is grappling with historic drought. Colorado river, source of about one-third of Arizona's water, is in shortage, and the state's desert climate forces strict limits on water use (5). Industrial users have thus far been spared severe cuts (only ~3% reductions so far) in part because chipmakers are implementing aggressive water recycling and conservation measures (5). TSMC's new Phoenix fab plans to reclaim ~65% of its water on-site, and Intel's facilities in Chandler are partnering on a reclaimed water project to restore 2.2 billion gallons per year to the region (5, 6).

Coupled with intensifying water scarcity, the constrained and geographically concentrated availability of critical materials renders this challenge particularly urgent. The U.S. Department of the Energy and USGS have identified Ga as a critical metal (which is available in the semiconductor waste stream) with one of the highest supply risk profiles (9). The U.S. relies almost entirely on imported Ga, with China historically supplying ~84% of the world's demand (9). Ensuring a sustainable Ga recovery and reuse is, therefore, essential to strengthen domestic resilience and supporting U.S. clean energy and manufacturing initiatives.

Ironically, even as Ga is in short supply, substantial quantities are wasted in the semiconductor fabrication process. Ga is used in many chip manufacturing processes (particularly for GaAs/ GaN wafer production and in certain deposition or etching steps), and a considerable portion of the material is lost to waste streams. An estimated ~120 tons of Ga per year is lost during the production of Ga-containing products (integrated circuits, LEDs, magnet alloys, etc. globally. (10). Typical concentrations of Ga in semiconductor effluent can be as high as 35 mg/L (11). These concentrations, while low in absolute terms, represent a significant cumulative mass of Ga, given the large volumes of water used in the processing. Present capture technologies are inefficient, cost-prohibitive, and generate secondary waste at low concentrations of target metals, restricting their application in industry (12, 13). Moreover, they lack economic incentives, making DOE investments crucial to demonstrate scalable low energy alternatives.

We envision that with the right technological inputs, the semiconductor industry could valorize the critical materials from the waste stream, serving as additional revenue, compensating the wastewater treatment and reusing the purified water back into the fabrication process for further use.

Near-Term Opportunity; Nanofiltration Membranes for Gallium Recovery: The near-term opportunity lies in transforming semiconductor wastewater from an environmental liability into a recoverable resource through integrated, low energy separation processes. These separation processes could supplement already existing wastewater treatment infrastructure and the same energy used in compliance-driven treatment can be redirected towards value creation- enabling water recovery and reuse as well as Ga reclamation. The emphasis is not only on water recycling but on developing self-sustaining industrial water loops that minimize freshwater intake and reduce energy intensity of ultrapure water. This approach improves the system level resilience by closing internal reuse cycles while parallelly recovering Ga from dilute effluents enhancing domestic supply chain stability and offsetting costs associated with wastewater management. The economic opportunity extends beyond metal value, encompassing reduced water needs, lower waste handling costs and improved sustainability cumulatively amounting to conserve billions of gallons of water annually.

One of the most promising and practical approaches for the aforementioned challenge is to use membrane technologies, specifically nanofiltration membranes. Nanofiltration is a pressure-driven membrane process with pore sizes in the sub-nanometer range, allowing it to selectively reject larger ions with steric hinderance and charge interaction (14). In the context of Ga recovery, nanofiltration can be used to concentrate Ga (III) ions (often present as Ga^{3+} or gallate complexes in slightly basic streams) from a large volume of water and separate them from other ions into a smaller concentrate stream (15). Moreover, nanofiltration operates at ambient temperature and can be retrofitted into existing water treatment trains with relative ease (in many cases, semiconductor wastewater facilities already use reverse osmosis or ultrafiltration for water recycling – adding a nanofiltration module for targeted metal removal is a logical extension). Standard nanofiltration membranes alone may not distinguish Ga from other multivalent ions very selectively (Ga might be accompanied by other metals like copper, nickel, or aluminum in waste streams) (16). There is a need for development of Ga specific binding sites in these nanofiltration membranes for the effective valorization of Ga (17, 18).

Figure 1. Waste water treatment in wafer-fab by UV-oxidation[1]

Success Measure: From a societal perspective, success should be measured by the technological contribution to sustainable manufacturing- reducing industrial freshwater consumption, mitigating waste and securing domestic supply for critical materials. These societal outcomes will be governed by quantifiable technical performance metrics to ensure measurable impact and scalability. Technical success of this process should be gauged by the demonstration of an integrated, energy-efficient membrane platform capable of simultaneously recovering Ga and enabling water reuse from semiconductor wastewater. The key metric will be the quantifiable recovery of Ga from dilute waste streams at < 3 kWh m^{-3} energy input, directly offsetting both material loss and water-treatment costs. The effort should prioritize validation using real or simulated fab effluents to establish scalability and techno-economic feasibility. In addition to recovery efficiency, the percentage of Ga reused within domestic supply chains will be a direct indicator of impact toward the Department of Energy's circular-manufacturing and critical-material-security goals. Early-stage (low-TRL) success should encompass development of these nanofiltration membranes with quantifiable % recovery of Ga from these waste streams and the waste stream purity. These outcomes should enable a path to pilot-scale demonstrations and quantifiable energy, water, and materials benefits aligned with WPTO's industrial-water-recovery mission.

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