RESEARCH REPORT

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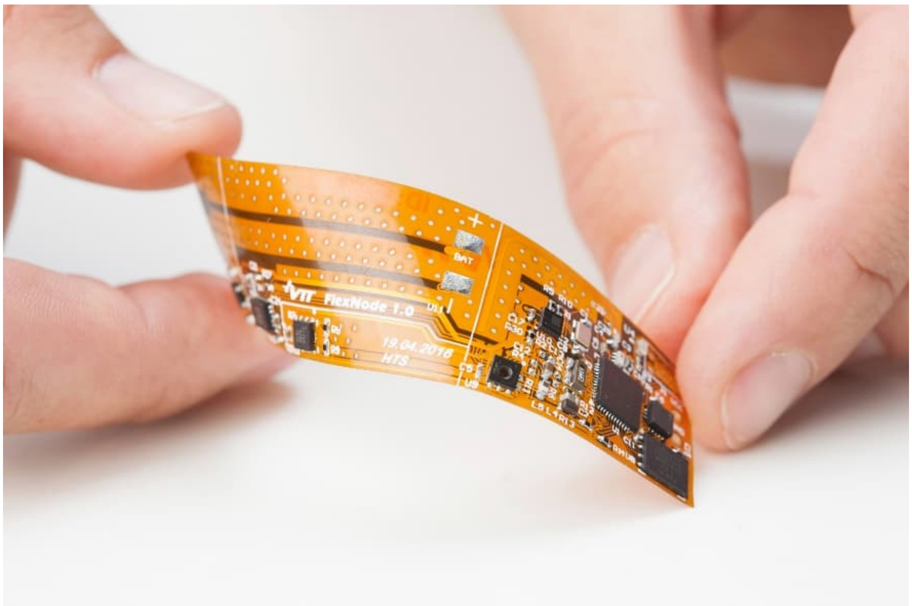

Material recovery in semiconductor fabrication

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beyond the obvious

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Summary

Semiconductors are a cornerstone of the green transition, enabling energy efficiency, electrification, digitalisation, and advanced technologies across multiple sectors. At the same time, semiconductor fabrication is itself a resource-intensive industry, characterised by high energy and water demand, extensive use of ultra-pure chemicals, and reliance on critical and precious materials. While significant progress has been made in improving energy and water efficiency, material circularity in semiconductor manufacturing remains limited. This is largely due to stringent purity requirements, complex material flows, low concentrations of recoverable substances, and economic constraints.

This report reviews the current state of material recovery, recycling, and reuse in semiconductor fabrication, with a particular focus on high-value, noble, and critical materials as well as mineral nanomaterials. The analysis combines a review of sustainability reports from major semiconductor companies, a systematic literature review, and an extensive patent landscape analysis covering developments since the year 2000. In addition, insights from industry discussions and technology providers complement the documented sources.

The review shows that existing circularity practices in the industry predominantly focus on packaging materials, solvents, acids, and water recycling. Recovery of metals and other valuable input materials is implemented selectively, often via off-site refining, and is typically limited to cases where economic value and purity requirements justify the effort. Precious metals such as copper, gold, silver, palladium, and platinum are most commonly recovered, particularly from CMP slurries, plating baths, etching processes, wastewater streams, and silicon sludge. Recovery methods include electrochemical processes, membrane filtration, adsorption, precipitation, and thermal or chemical treatment.

Wastewater is a major secondary source of recoverable materials, although metal concentrations are generally low compared to electronic waste. Point-of-source treatment is increasingly recognised as critical for improving recovery efficiency and material quality before dilution and contamination occur. Advanced electrochemical and membrane-based technologies show promise for recovering metals while simultaneously meeting discharge limits.

Chemical Mechanical Polishing (CMP) emerges as one of the most intensively studied process steps from a circularity perspective. CMP generates large volumes of slurry waste containing abrasives, metals, and chemicals. The patent landscape reveals numerous approaches for recycling CMP slurries, recovering abrasive particles, and regenerating slurry for reuse. In addition to conventional filtration and sedimentation, newer concepts include magnetic abrasives, selective separation, and design-for-recycling approaches that address fundamental limitations of downstream treatment.

Beyond liquids and slurries, the report covers recovery strategies for wafers and silicon, acids and solvents, deposition precursors, and process gases. Wafer reclaiming and dry recovery methods have advanced in recent years, reducing chemical consumption and environmental impact. Acid, solvent, and gas recycling

technologies are comparatively mature, often achieving purity levels suitable for reuse in semiconductor fabrication. However, these practices are not yet uniformly adopted across the industry.

Examples from major semiconductor manufacturers demonstrate that material recovery is increasingly integrated into sustainability strategies, although the level of detail and ambition varies. While most companies report high waste diversion rates, only a few explicitly articulate long-term, quantitative goals for material recovery or closed-loop reuse of specific materials. Technology providers and comparable industries, such as optics, catalysis, and environmental remediation, offer additional insights into recovery pathways that could be adapted to semiconductor manufacturing.

Overall, the findings indicate that a wide range of technically feasible recovery solutions exists, but large-scale implementation remains uneven. Economic viability, process integration, and assurance of material quality are key barriers that continue to limit broader uptake.

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1. Introduction

Semiconductors form an essential part of the societies' green transition. At the same time, the industry itself faces challenges with several sustainability related issues, like high demand of energy and water and the need for critical materials in their manufacturing. While the industry already has taken important stepping stones toward efficient energy and water use, the level of circularity, i.e. material recycling and reuse remains still low. Though closing material loops can bring environmental benefits and increase the resilience of manufacturing, technical factors such as generally low material flow and high requirement on absolute purity of the raw materials used in the processes have contributed to the slow development.

This report addresses the low degree of circularity in the industry and provides a background for developing new strategies and solutions for material recovery, recycling and industrial reuse. Focus is on high value, noble and critical materials and mineral nanomaterial foremost in semiconductor fabrication. In addition, the review includes examples of recycling and reuse concepts developed for other relevant industrial processes where similar materials are used. These are e.g. the optical industry and catalytic materials production.

2. Resource efficiency in semiconductor fabrication

Advanced and new materials and components are often highlighted as the key enablers for solving many of the challenges related to green transition - climate change and transformation to a sustainable society. The manufacturing of advanced and new materials must, of course, like any other manufacturing process, also be both sustainable and competitive. However, current fabrication processes are not always designed with a sustainability focus, often consuming large amounts of energy and using environmentally harmful chemicals. Product development in the sector is very fast, sometimes described with the Moore's law, which indicate that number of transistors on an integrated circuit doubles approximately every two years, resulting in a corresponding increase in computing power and decrease in cost. Simultaneously the size of the semiconductors is continuously decreasing. However, this development is found to correlate with an increasing climate impact as depicted in Figure 1.

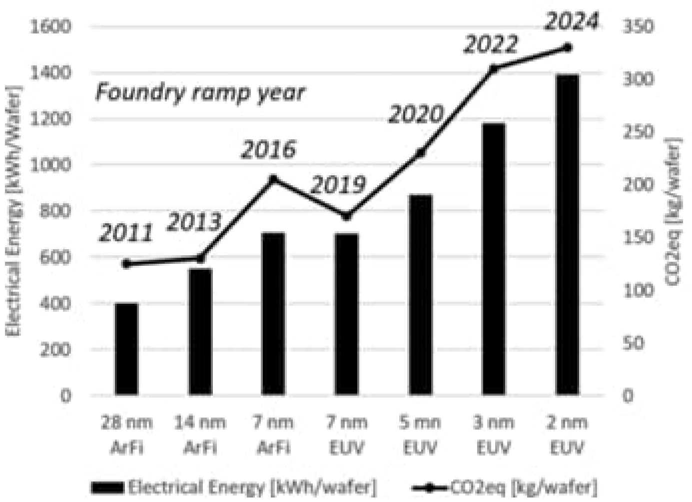

Figure 1. Climate impact of Moore's law (Pedersen et al. 2021)

Further development is needed toward achieving more energy- and material-efficient processes. To do so, the full lifecycle of processes and products must be considered, from design to end of life. While the largest footprint of a semiconductor - up to 95% - is generated in the product's usage phase (Heger 2025), 80 % is said to be defined already in the design phase (Westrich, 2025).

While a major part of industrial actions for increased resource efficiency concentrates on mitigating energy and water consumption, some circularity processes are also in use. Semiconductor fabs often run multimillion-dollar tools for 10–20+ years, making refurbishment economically attractive. Typical examples include photolithography steppers and scanners, which are commonly refurbished for use in mature-node fabs producing power devices, sensors, and automotive chips; etch and deposition tools such as plasma etchers, PECVD, LPCVD, and PVD tools. Usual actions include cleaning chambers, replacing seals and pumps, updating electronics, and modernizing control software. Moreover, ion implanters are frequently overhauled by OEMs or third-party specialists, replacing beamline components, vacuum systems, and control units.

Also, specific subsystems can be remanufactured, such as vacuum pumps, robotics and wafer-handling modules, and process chambers. For instance, Infineon Technologies uses refurbished lithography steppers and for power electronics and automotive chips. They also run programs for remanufactured vacuum pumps and refurbished wafer-handling robots. Again, Global Foundries integrates refurbished ion implanters and CMP modules and employs third-party European firms to remanufacture chillers, scrubbers, and fan filter units.

3. Methodology and limitations

In order to get a picture of current recycling processes, the sustainability reports of major semiconductor companies (Table 1) were analysed (cf Harju et al, 2026). The considered sustainability reports were from year 2025, representing the performance in year 2024. This was complemented with a literature search in Web of Science and eKnowledge Search (VTT internal search machine) using a combination of the following search words*: nanoparticles, nano-scale, nano, thin film,* Atomic Layer Deposition *(ALD), deposition, wide band gap, wafer processing, semiconductor, semiconductor industry, glass polishing, lens polishing, optical, optics, noble metal, precious metal, CMP slurry, critical raw material, recycling, recovery, metal recovery, material recovery, material efficiency, circularity.* The literature search focused on semiconductor industry, whereby CMP slurry was frequently highlighted. Examples from the glass polishing industry were also reviewed, since the polishing processes applied are similar to the CMP process.

Table 1. Semiconductor companies whose sustainability reports were analysed.

Company	Abbreviation
Taiwan Semiconductor Manufacturing Company Limited	TSMC
Intel Corporation	Intel
Samsung	-
Micron Technology	Micron
GlobalFoundries	GF
Texas Instruments	TI
STMicroelectronics	ST
Applied materials	AMAT
Infineon Technologies	Infineon

In addition, 10 patent searches in Patbase were done using a combination of keywords:

- nano-Pd/-Pl/-Ag/-Au/-Ce etc
- reuse/recovery/recycling
- CMP /chemical mechanical polishing
- ALD /Atomic Layer Deposition
- semiconductor

The patent searches resulted in total 1653 patents out of which 127 were manually selected for further analysis. Patents that were older than from the year 2000, were not analysed further. 19 patents concerned the recycling of various process gases, and seven wafer regeneration. Though the focus of the study laid primarily on noble and critical minerals, these patents have also been summarised in this report. Moreover, eight patents about recycling of CMP slurry were added based on the patent landscape analysis commissioned by Sofi Filtration (Leitzinger, 2025).

The focus was on material flows in semiconductor fabrication processes and with minor weight put on end-of-life processes for electronic goods. For those a vast number of recovery processes has already been established, supported among others by the WEEE directive and similar regulations.

Industrial offerings and pilot cases related to material recovery were pursued by company discussions during the Semicon Europa fair in Munich November 2025. The event gathered +100 semiconductor manufacturing companies and technology/service providers in addition to technical sessions, such as the Tech Arena Sustainable Future Fabs

4. Innovations in material recovery and recycling

Semiconductor fabrication is the characterised by high precision nanoscale processes. Though the materials handled are per se precious (e.g. Au, Pt, Cu) and /or critical (e.g. Ce, Li, Rh) the total low recoverable amount and challenges related to the economy of reuse processes have until now given little incentives to develop circular economy concepts around the inputs. According to the sustainability reports by major semiconductor companies, material recycling processes have mostly focussed on the recycling of packaging material and (hazardous) solvents. Recycling of residual input raw material and auxiliaries are rare with little incentives. However, scientific literature provides some examples of research and development of the recovery of noble metals, recovered either directly from the manufacturing process or from the wastewater. Moreover, LCA studies, such as that by Vauche et al. (2024) who in their LCA study on manufacturing of 200 nm wafers, have pointed out that from the environmental point of view, some metals such as gold used for the wafer manufacturing should at a minimum, be recovered from the processing, and substitution materials should be preferred.

This chapter contains the findings from the literature research and the upscaling of these innovations into market ready solutions have not been confirmed. The motivation is to show the variety of approaches as a source of inspiration for future endeavours for material recovery.

Several approaches (Kim et al., 2021; Oestreicher et al., 2019; Liu et al., 2010, Luty-Błocho et al.' 2024) have been developed to recover residual (or waste) materials from semiconductor fabrication, and this is a well-established practice, though what can be recovered and how economically viable it is depends on the material and process step. Copper (Cu) – from electroplating baths, CMP slurries, rinse waters, Gold (Au) –

from bonding, plating, and etching processes, Silver (Ag), Platinum (Pt), Palladium (Pd) – from specialty deposition steps and Cobalt (Co), Nickel (Ni), Tungsten (W) – from advanced interconnect processes are routinely reclaimed because of their high cost and purity requirements. Recovery methods include electrochemical recovery, ion exchange and selective precipitation and most commonly, by off-site metal refiners. Purity, cost, and yield dictate feasibility.

Kim et al. (2021) proposed an approach to substrate recycling in epitaxial processes involving thin films and nanomaterials. In conventional use of epitaxial layers, the underlying substrates are typically disposed of after growth or permanently integrated as base substrates in devices. Because substrate costs take up a significant portion of overall device manufacturing expenses, substrate recycling can be easily justified. Kim et al. (2021) demonstrated the reuse of graphene as a growth template for single-crystalline ZnO nanowires through hydrothermal synthesis combined with chemical wet etching. They showed that the chemical robustness of graphene enables repeated cycles of ZnO nanowire growth without noticeable degradation in graphene quality. The authors concluded that this template-assisted synthesis strategy, based on CVD-grown graphene and its recyclability, presents a viable pathway for employing graphitic materials as reusable growth substrates in manufacturing and industrial applications.

Liu et al. (2010) reported on a method to treat Cr(VI)-containing nanowastes via the growth of nanomaterial to larger particles by adding a carbonate solution and heat. The generated particles could then be separated and utilised e.g. as crystal glaze. While this approach enables the recovery of Cr, another important benefit is to mitigate the toxicity of nanomaterial. Though the authors' case relates to Cr use in chlorate plants, similar approaches can be applied in semiconductor industry.

Oestreicher et al. (2019) separated gold nanoparticles by mixing the suspension with HCl and recovered after settling the sediment. The sediment was then oxidized by mixing with HCl and H2O2 to form HAuCl4. The recovered Au solution could be used as a part of a growth solution to obtain uniform spherical AuNPs with diameters 30-60 nm using a seed-mediated approach. The approach was developed for laboratory waste, but the authors argued that their one-pot methodology, because of its simplicity, may also find applications at the industrial level. Moreover, it could also be expanded to other noble metals by controlling the reduction potential of the reducing agents.

Luty-Błocho et al. (2024) took the recovered product as a starting point and developed a method for creating Pd and Pt catalysts from dilute aqueous waste solutions containing these metals. Their approach included the adsorption on activated carbon with addition of hydrochloric acid.

Recycling of (nano)metals:

The patent search identified several patents related to the recovery nano-silver and nano-gold (Table 2). Nano-silver is recovered by physical separation via centrifuge, ultrasonic dispersion and drying (#1, #3, #4), but also by using chemical processing, like ammonia treatment, nitric acid dissolution and reduction reactions (#2, #3, #4, #5). Nano-silver is recovered from waste liquid streams using physical and chemical separation techniques, such as freeze-drying (#1), ultrasonic treatment (#3), centrifugation (#4) and reduction reactions (#2, #5), although also biological approach with microbial flocculants (#2) is used.

Most patents describe the recovery of nano-gold from liquid waste streams. These recovery methods include liquid-phase extraction and separation using, e.g. electrocoagulation (#6), filtration (#8, #9) and multi-stage adsorption towers (#9). One patent, #7 describes the extraction of nano-gold from waste Printed Circuit Boards (PCBs). In this case, the PCBs are immersed into a dissolving solution releasing nano-gold particles for recovery. However, with respect to possible reuse in semiconductor manufacturing, the patents do not provide claims on the quality of the recovered particles (purity or particle size).

Table 2. Patents related to the recovery of nano-silver and nano-gold. The ID number is used to refer to the patents in the text.

Waste stream	Recycled material	Method	Patent application year	Publication no.	ID no.
Waste liquid	Nano-silver	Crushing and stirring of nano-silver waste liquid, freeze-drying and vacuum sublimation to remove water from nano-silver particles	2025	CN119979892 A	#1
Sewage	Nano-silver	Microbial flocculant adsorption under UV condition, reduction of heavy metal silver ions, preparation of nano-silver	2024	CN118005158 A	#2
Silver nanowire waste	Nano-silver	Pure water ultrasonic treatment of silver nanowires, drying, nitric acid dissolution, heating and vacuumizing, purification and separation	2021	CN112939057 A	#3
Nano-silver particle waste liquid	Nano-silver	Centrifugation, ammonia treatment, standing, centrifugation, drying, grinding	2018	CN108480647 B	#4
Nano silver-nickel/nano carbon tube catalyst	Nano silver-nickel / nanocarbon tube catalyst	Acid activation of carbon nanotubes, metal salt deposition, reduction with ascorbic acid, separation, washing, drying	2008	CN101502799 A	#5
Aqueous solution	Nano-gold	Electrocoagulation extraction, pickling and liquefaction, nanofiltration separation	2022	WO20240009 70A1	#6
Waste PCBs	Nano-gold	A device handles PCBs mechanically so that they are lowered into a dissolving solution inside a U-shaped net frame, where nano-gold particles are released	2021	CN216107132 U	#7
Nano-gold dispersion waste	Nano-gold	Chemical destabilization, filtration, drying, dissolution in aqua regia, reduction with potassium borohydride (KBH_4) and polyvinylpyrrolidone (PVP), regeneration of nano-gold dispersion	2019	CN110791655 A	#8
Gold-containing wastewater	Nano-gold	Filtration, liquid separation, multi-stage adsorption towers	2019	CN21097412 0U	#9

Waste stream	Recycled material	Method	Patent application year	Publication no.	ID no.
		to capture gold from the liquid stream			

Table 3 summarizes the patents regarding the recovery of other residual metals. Noble metals are recovered from semiconductor waste by thermal treatment combined with chemical reaction using reactive gases (#10). The patents on recovery of precious metals target for example platinum and palladium (#11, #12). Patent #11 recovers precious metals from electronic waste by tin stripping, processing of substrate and electronic components, resin powder treatment and finally treating the metal powder. Patent #12 focuses on recovering precious metals from waste catalyst with oxygen pressure acid leaching, chemical separation, and reduction and precipitation. In patent #13, Group IIIA metals[1] are recovered from semiconductor wafer waste by high-temperature pyrolysis, followed by gas extraction and condensation for by-products.

Moreover, patent #16 about the recovery of metal sludge from semiconductor wastewater uses mechanical filtration and patent #15 about metal layer recovery from semiconductor structures utilizes adhesive film attachment and controlled gas pressure differential to peel and transfer metals. Additionally, patent (#14) focusing on the recovery of nanometals from waste liquid uses alkaline treatment to break polyvinylpyrrolidone structure to obtain agglomerates, after which the nanomaterial recyclate is washed, dried and optionally pulverized. Three patents (#17-#19) focused on recovering heavy metals from semiconductor wastewaters. These use photocatalytic reduction and electrochemical deposition, while one patent (#17) also includes the additional steps mechanical filtration and adsorption.

[1] Group IIIA elements (also known as the Boron Group) include Boron (B), Aluminum (Al), Gallium (Ga), Indium (In), Thallium (Tl), and Nihonium (Nh).

Table 3. Patents related to the recovery of other residual metals. The ID number is used to refer to the patents in the text.

Waste stream	Recycled material	Method	Application year	Publication no.	ID no.
Semiconductor waste	Noble metals	Thermal treatment combined with chemical reaction using reactive gases in a controlled reaction chamber	2023	TWM645401U	#10
Electronic waste	Precious metals	Tin stripping process, substrate and electronic component treatment, resin powder treatment, metal powder treatment	2022	CN115841257A	#11
Waste catalyst	Precious metals	Pretreatment, oxygen pressure acid leaching, chemical separation, reduction and precipitation	2013	CN103451433B	#12
Semiconductor wafer waste	Group IIIA metals	High-temperature pyrolysis under inert gas in a reaction chamber, followed by gas extraction and condensation for by-products	2021	TWM619529U	#13
Waste liquid	Nanometals	Alkaline treatment to obtain agglomerates, washing, drying, optionally pulverizing the nanomaterial recyclate	2021	CN114752765A	#14
Semiconductor structure	Metal layer	Adhesive film attachment, controlled gas pressure differential to detach metal layer	2015	TWI672727B	#15
Semiconductor treatment liquid	Metal sludge	Mechanical filtration, collection in a recovery cage	2016	TW201727731A	#16
Semiconductor wastewater	Heavy metal ions	Photocatalytic reduction, electrochemical deposition, mechanical filtration, adsorption	2018	TWI690493B	#17
Semiconductor wastewater	Heavy metals	Photocatalytic reduction using semiconductor-coated conductors under light irradiation, combined with electrochemical deposition	2018	CN110318071A	#18
Semiconductor wastewater	Heavy metals	Photocatalytic reduction using semiconductor-coated conductors under light irradiation, combined with electrochemical deposition.	2018	TW201942070A	#19

Moreover, Table 4 lists some innovations for recovering other relevant substrates such as lithium cobaltate (#20) and silicon (#21). High purity silicon is recovered from residual silicon (e.g. saw dust from semiconductor manufacturing) with direct chlorination so that unreacted silicon can be captured and recycled, while also silicon tetrachloride ($SiCl_4$) and solid chlorides are separated and reused. Lithium cobaltate is recovered by acid leaching, filtration, phosphate precipitation (#20). Sapphire substrates are recovered from intact epitaxial wafers by baking and acid rinsing in high temperatures (#22). Chemical etchant can be regenerated for the etching process by adding reagents and adjusting pH (#23). Patent #24 addresses semiconductor wastewater recycling and tail gas treatment by filtration, oxidation, chemical treatment and ion exchange.

Table 4. Patents related to the recovery of other residuals. The ID number is used to refer to the patents in the text.

Waste stream	Recycled material	Method	Applicati on year	Publication no.	ID no.
Waste lithium cobaltate	Lithium cobalt phosphate	Acid leaching, filtration, phosphate precipitation, mixing filter residue lithium and carbon sources to form powder, calcination of the powder, and final crushing, screening and removal of iron	2022	CN11440039 5B	#20
Residual silicon	High purity silicon	Direct chlorination in a fluidized bed reactor, capturing and recycling unreacted silicon, separation and reuse of $SiCl_4$ and solid chlorides	2008	TW20090035 2A	#21
Intact epitaxial wafer	Sapphire substrate	Baking and acid rinsing in high temperature to remove epitaxial layers and contaminants	2017	US1028334 6B2	#22
Etching process	Chemical etchant	Peroxide-based etchant is regenerated by adding reagents, like hydrogen peroxide, water, metal chelate and pH adjuster, then reintroduced into the wet chemical etch chamber for reuse	2010	TWI417421 B	#23
Semiconducto r wastewater	Wastewater recycling and process tail gas treatment	Filtration, oxidation (ozone, catalyst, UV), chemical treatment, ion exchange, storage, reuse	2007	TW200829 520A	#24

While the patents listed above concentrate on the recycling and recovery processes, little is said about where the recovered materials can be used. Against that background Table 5 lists nine patents describing the use of (recycled/recovered) (nano)materials which are also typical inputs in the semiconductor industry. Nanoparticles (without further specification) together with powder recovered from circuit boards were used as composite material for glass-fibre-reinforced epoxy resin (#31). Additionally, spent chemical-mechanical polishing sludge, disposed calcium fluoride sludge, nano silica, nano cerium oxide and perfluorinated organic waste from semiconductor industry are used in the recycling of concrete and the production of eco-cement (#25-#28). Moreover, nano cerium oxide is used in recycled asphalt (#29, #30). Nanogold and nanosilver can find further use in medical care (#32, #33). However, it should be noted that the patents do not specify whether nanoparticles from primary or secondary sources are used, or if recovered nanoparticles from semiconductor industry would be usable. The purpose of this patent search was to find potential use cases for recovered nanoparticles from semiconductor industry.

Table 5. Summary of patents related to the application of (nano)materials relevant to semiconductor industry in other applications. The ID number is used to refer to the patents in the text.

Used (nano)material	Invention utilising the recovered material	Application year	Publication no.	ID nb.
Nano-silica, nano cerium oxide	High-strength recycled concrete	2023	CN116143478A	#25
Chemical-mechanical polishing sludge	Reuse of hazardous waste in cement concrete	2011	TWI422555B	#26
Disposed calcium fluoride sludge	Recycled premixed concrete	2008	TW201016627A	#27
Mixed waste, including semiconductor perfluorinated organic waste gas	Eco-cement	2007	TW200902470A	#28
Nano cerium oxide	Emulsified asphalt cold-recycled mixture	2024	CN118851636A	#29
Nano cerium oxide	Asphalt recycling additive suitable for microwave heating	2015	CN105176113A	#30
Circuit board recovered powder and nanoparticles	Glass-fibre-reinforced epoxy resin composite material	2011	CN102226034B	#31
Nano gold	Pharmaceutical application in cancer drug delivery	2019	IDP000082037B	#32
Nano silver	Ceramic dental restoration components	2005	KR1020060111042A	#33

In line with the growing focus on the supply of critical raw materials, interest in recovering metals from semiconductor wastewater has also increased. A review of the literature reveals several studies exploring novel processes for metal recovery. However, compared to wastewater generated from the treatment of various types of electronic waste, semiconductor wastewater typically contains target metals at concentrations 2–40 times lower (Lee et al., 2024). This significantly affects the economic feasibility of recovery processes and necessitates careful evaluation.

High-value metals such as Au and Ag are generally the primary targets for recovery. In addition, silicon (Si) residues are recovered from microelectronics wastewater and recycled into new products in major semiconductor fabrication plants (Noman et al., 2024).

Conventional wastewater treatment for semiconductor industry effluents typically relies on coagulation and flocculation processes (Ang et al., 2024). While effective, these approaches require the addition of chemical reagents. Alternative treatment strategies for semiconductor wastewater are electrocoagulation, simultaneous coagulation–flocculation, and membrane technologies. Electrocoagulation applies an electric current in conjunction with sacrificial electrodes to generate coagulants in situ, thereby promoting the aggregation and precipitation of pollutants for subsequent separation. Simultaneous coagulation–flocculation employs anionic and cationic polyelectrolytes to remove suspended solids, organic matter, and cationic species 10] However, all approaches present limitations, including continued chemical consumption, increased operating costs associated with high electricity demand, and the inability to address the recovery of silica particles (ibid.).

Sadafale and Gaikwad (2023) pointed out in their overview of different wastewater technologies that could be used in semiconductor industry to remove contaminants, such as metal, that the majority of research has used synthetic wastewater that contained just one or a small number of metal types, whereby there is an information gap about the effectiveness of treatment strategies for the removal and recovery of heavy metal ions from actual wastewater. On industrial scale, treatment of the wastewater generated from CMP and dilute metal waste streams often involves processes that are incapable of recovering metals on site due to the complex nature of the water matrix, opting instead for technologies that can remove metals from the wastewater without recovery taking place. These streams can contain various levels of organics, TSS, and metal chelators making removal treatment solutions such as ion-exchange and chemical coagulation the preferred options, even if valuable metals are lost in the process (Lippert et al. 2025). For instance, acidic copper concentrates produced from wet etching and electroplating operations are often transported offsite for treatment and disposal due to the challenges associated with hydrogen peroxide, elevated copper concentrations, and high acidity (Wismer and Woodling 2005). In this context, Lippert et al. (2025) developed a selective electrochemical cell method able to remove copper to below the industry's discharge limits across a wide range of wastewater streams while also recovering the copper as high purity metal sheets as a value-added product. Each process produces a different type of wastewater with different characteristics, and the authors emphasised the advantages of point of source treatment, enabled by the compact equipment size, thereby treating the wastewater before it mixes with other streams and the wastewater matrix becomes more complex and diluted. The importance of a point-of-source strategy was further highlighted in an interview with a German abatement and water technology provider, with particular reference to burn-wet abatement and GaN recovery.

4.1 Recycling and reuse of CMP Chemical Mechanical Polishing (CMP) slurries

Typically, CMP slurries are composed of abrasive particles, chemical additives, and ultrapure water. The production of CMP slurries has a notable environmental footprint, largely due to their complex formulations and the energy-intensive processes required in their manufacture (Venkataswamy et al. 2024). In the CMP process, the primary consumables are slurries and pads.

According to Datta et al's estimations (2022) CMP consumes around 40% of the total water consumption in the semiconductor industry. Additionally, CMP produces 30 to 50 litres of waste slurry per 200 mm wafer. Lee et al. (2014) evaluated environmental impact caused by CMP based on kinematic models. According to Lee, the slurry consumption strongly impacts the carbon footprint of the CMP process though electricity consumption increases with lower CMP flows. To address this issue, researchers have explored various methods to effectively recover and reuse CMP slurries, including, chemical adjustments, and chemical coagulation to recover and reuse CMP slurries (Seo et al, 2024). These methods can separate slurries into different components or component matrices and restore their properties for reuse.

The patent search of recycling and reusing CMP related waste streams resulted in 20 patents which are summarized in Table 6. The studied patents generally aim at treating the CMP slurry in such way that it can be recycled back to the CMP process, although there are few examples where valuable metals, abrasive particles and water are recovered separately. The recovery methods for valuable particles, such as copper and abrasive particles mainly included filtration and washing (#38-#40)), distillation and acid leaching (#34), wind separation (#35), UV irradiation (#36) and electrostatic separation (#37). One of the main methods used to recycle or remediate CMP slurry is filtration (#42, #44, #45, #47, #49-#52), which can be combined with other treatment methods, like UV activation/irradiation, heat treatment, ion exchange, and finally adjusting the concentration and pH. Additionally, mixing spent slurry with fresh one (#45, #46), gravity sedimentation (#41), dispersion with ultrasonic irradiation (#49) and dewatering (#43) were used to treat the spent slurry. Another way to remediate CMP slurry is to remove coarse particles, while maintaining the concentration of copper ion and metal ion concentrations (#48). Patents #52 and #53 primarily focused on purifying the slurry, although #52 included optional measurements to determine the recyclability of the slurry.

Table 6. Summary of patents related to the recycling and recovery of CMP waste streams. The ID number is used to refer to the patents in the text.

Purpose	Method	Application year	Publication no.	ID nb.
Recovery of copper and water from CMP waste stream for reuse	Distillation, drying and sintering the sludge, acid leaching, separation of solids, copper sulphate solution recovery	2023	TW202402685 A	#34
Recovery of valuable metals (e.g. Cu) from polishing waste	Wind separation by applying centrifugal force	2014	JP6271392B2	#35
Recycling copper from Cu-CMP waste liquid	Photocatalyst assisted UV irradiation to deposit Cu onto the catalyst surface	2003	TW200502177 A	#36
Recycling grinded nanoparticles for cleaning applications and water for reuse from used CMP waste liquid	Electrostatic separation of nanoparticles and water	2005	TWI288053B	#37
Recovery of abrasive particles[1]	Slurry collection, filtration, advanced membrane separation, washing and concentration adjustment of concentrated slurry	2000	JP2002011664 A	#38
Abrasive collection[1]	Filtration, membrane separation, washing with water, concentration adjustment	2000	JP2002075931 A	#39
Collection of polishing material[1]	Centrifugal separation, microfiltration, washing	2000	JP2001225070 A	#40
Recycling CMP slurry for reuse	Gravity sedimentation, separation of solids, washing, pH adjustment	2013	KR102013011 6188A	#41
Recycling CMP slurry-containing wastewater	Continuous ultrafiltration and adjustment of concentration and pH	2010	JP5873020B2	#42

Purpose	Method	Application year	Publication no.	ID nb.
CMP slurry recycling[1]	Slurry collection, dewatering, drying	2022	KR20230105065A	#43
CMP slurry recycling[1]	Circulation of recovered slurry from a blending tank to ultrafiltration, optional removal of specific ions and pH adjustment	2010	KR20130093112A	#44
CMP slurry recycling[1]	Filtration, heat treatment, blending with stock slurry	2004	KR20050078723A	#45
CMP slurry recycling[1]	Mixing of disposed and previously ground slurry, quality monitored and slurry directed to waste treatment when quality no longer reached	2010	TW201208815A	#46
Regeneration of CMP slurry[1]	Membrane filtration, pH adjustment to dissolve silica, repeated cycles of dilution and concentration to selectively recover ceria	2022	JP2024053779A	#47
Regeneration of CMP slurry	Removal of coarse particles, maintaining copper ion and metal ion concentration	2009	TWI438252B	#48
Regeneration of griding slurry containing colloidal silica	Dispersion with ultrasonic irradiation, filtration	2008	TWI388653B	#49
Regeneration of CMP slurry	Filtration, ultrafiltration, dilution, addition of metal chelating and oxidizing agents, composition adjustment	2000	JP4585100B2	#50
Remediation of Cu-CMP waste	Photocatalyst assisted UV irradiation, copper deposition, organic deposition, optional oxidation and second irradiation	2003	TWI227216B	#51
Treatment of CMP effluents	Oxidation, UV activation, organoclay filtration, activated carbon filtration, ion exchange, optional measurement to determine the recyclability of the waste fluid	2007	US7947170B2	#52
Cleaning CMP	Chelate-based metal ion removal	2002	JP2004075859A	#53

[1]*Patent originates from a patent landscape analysis commissioned by Sofi Filtration (Leitzinger 2025).*

Direct utilisation of CMP sludge:

While the refences in Table 6 deal with recovery of valorisable material in the CMP sludge, Qui et al. (2022) proposed a function for the overall sludge. One major concern in the semiconductor industry is the generation of fluoride containing waste water, produced as a consequence of the significant use of fluoride-based acid in etching processes. Therefore, the fluoride-containing wastewater mainly contains high fluoride concentration varying from 250 to 1500 mg/L, while different environmental agencies globally limit their respective fluoride emission discharge standards to a median value of 15 mg/L. For the coagulation-ultrafiltration treatment of this wastewater flow Qui et al. (2022) proposed to substitute conventional coagulant/flocculant directly with CMP wastewater. Their results showed that conventional coagulant could be substituted by CMP wastewater to accelerate CaF2 particles settling through electrostatic interaction. Compared with conventional coagulant, the proposed coagulation process presented superior turbidity and fluoride removal efficiencies at defined molar ratio of SiO2 CMP wastewater as coagulant for fluoride removal from wastewater:

CMP design for recycling:

Targeting continuous recovery and reuse of the abrasives, Seo et al. (2024) developed an abrasive introducing magnetite (Fe_3O_4) particles coated with SiO_2 layers and tested it on the polishing of tungsten (W) CVD -coated wafers. The abrasives could be selectively recovered with magnetic separation and reused. They concluded that slurries containing Fe_3O_4@SiO2 particles could improve tungsten -removal rates and surface smoothness compared to conventional slurries, attributed to the optimal mechanical properties. Moreover, the magnetite core facilitates the magnetic separation and recovery of used particles from spent slurries. With their Design for Recycling (DfR) approach they tackled the challenges with the commonly applied recycling by ultrafiltration, i.e. ultrafiltration may not effectively remove all types of contaminants, especially those of similar size to the desired particles and that chemical adjustments and chemical coagulation can irreversibly alter slurry properties.

4.2 Resource efficient CVD and ALD processes

Several CVD (Chemical Vapour Deposition) processes transform only a small fraction of the precursors supplied into the CVD reactor into the intended film. For instance, Wang et al. (2014) showed in their study on LP-CVD of TiO2 from titanium isopropoxide and water that the precursor utilization efficiency was less than 1%. Standard sequential ALD is generally estimated to waste 50-90% of the entrained precursor during sequential precursor saturation pulses (Pedersen et al. 2021, Yuan et al. 2012).

However, impact assessments (e.g. Zieminska-Stolarska et al. 2022) have shown that the main impact of ALD is related to electricity, whereas the impact produced by the material is of minor importance. Based on an assessment of transparent conductive oxide layer (TCO) deposition, films deposited by CVD and ALD, the main impact is related to energy or nitrogen consumption, whereas for PVD (physical vapor deposition) to energy and raw material of TCO (Zieminska-Stolarska et al. 2022).

In single wafer CVD processes, the gas mixture is generally flown through the reactor without recirculation, and the molecules, typically, only get one chance to react with a given surface before they are pumped out. However, a technology has been developed for recycling ruthenium carbonyl precursors to be recaptured and reconstituted from a reaction byproduct in a Ru CVD process used in the semiconductor process (Suzuki et al. 2006).

Pedersen et al. (2021) suggested more careful design and modelling of precursor molecules to render a more efficient CVD chemistry where a larger fraction of the supplied precursor concentration is incorporated into the target film, and the precursors can be supplied closer to the same stoichiometric ratio as the atoms in the film. Such modelling and experimental work has been performed e.g. for CVD of SiC.

Patents related to deposition processes are summarized in Table 7. In general, the patents focused on recycling precursors and reaction residues, recovering metals and minimizing liquid discharge. Metal halides and hydrogen sulphides can be recovered from harmful reaction residues of the atomic layer deposition of metal sulphide (#54). Unreacted precursor chemicals can be reused in ALD/CVD deposition by trapping these chemicals in cold/cryogenic traps after which they can be released under controlled conditions (#55). Cold trapping is also used for effluent abatement from multi-component metal oxides deposited in CVD along with other methods, like adsorption on activated carbon and metal trapping (#60). Moreover, metallic precursor can be converted into a semiconducting layer with a recovery of chalcogen by thermal treatment in a multi-zone furnace (#56). Additionally, metals can be captured from ALD exhaust gas by cooling-based condensation (#57).

Two patents (#58, #59) disclose a method for fabricating a first substrate and recycling a second substrate during the fabrication of the first substrate. The second substrate is prepared by depositing a buffer layer on it, which helps in the formation of the semiconductor material layer on top of it and serves as a strip layer. Then, the strip layer is etched with etching liquid to separate the second substrate for recovery from the semiconductor material layer.

A “zero liquid discharge” method is intended to treat waste generated from semiconductor manufacturing operations, like PVD (#59). The method is a multi-stage process including ion exchange, activated carbon, selective ion exchange, reverse osmosis/electrodeionization/nanofilter membranes, advanced oxidation treatment, chemical dehydration, thermal vacuum distillation, and crystallization.

Table 7. Summary of patents related to deposition processes. The ID number is used to refer to the patents in the text. PVD: physical vapor deposition.

Purpose	Method	Application year	Publication no.	ID no.
Recycling of reaction residues from ALD of metal sulphide	Condensation and adsorption of metal halides, neutralization, drying, filtration and storage	2023	CN116145107 A	#54
Reclaiming unreacted precursor chemicals	Trap unreacted precursor in cold/cryogenic traps, release under controlled conditions, reuse in ALD/CVD deposition	2008	US201000750 37A1	#55
Thermal conversion of metallic precursor layers on flat substrates into semiconducting layers with a recovery of chalcogen	Thermal treatment in a multi-zone furnace with controlled introduction of oxygen group element vapor (selenium/sulphur) and carrier gas	2010	TW201038770 A	#56
Metal capture from ALD exhaust gas	Cooling-based condensation on a refrigerant-cooled capturing plate placed in the exhaust path of ALD equipment	2010	US201100417 67A1	#57
Effluent abatement from multi-component metal oxides deposited by CVD	Adsorption on activated carbon/alumina, metal trapping, cold trapping, regeneration of adsorbent bed, recovery via heat/vacuum, distillation or condensation for reuse	2000	TW544722B	#58
Zero liquid discharge recycling for waste from processes, e.g. PVD	Ion exchange, activated carbon, selective ion exchange, RO/EDI/NF membranes, AOP, chemical dehydration, thermal vacuum distillation, crystallization	2021	TW202229175 A	#59

4.3 Recycling of wafers and silicon

Silicon is the most used element in semiconductor devices such as in microelectronics and photovoltaic devices. Silicon is used as the substrate, active semiconductor, doped medium, oxide former, and manufacturing backbone. At the same time, the production process of silicon is energy-intensive and complex, factors which could form the basis for recycling activities. Moreover, the rate of rejected wafers before the dicing process can be high, which calls for relevant methods to recycle / restore / regenerate / reclaim wafers so that the material losses can be minimized.

In practice, recycling silicon from electronic devices has remained limited due to the increasingly small and complex chip designs, high costs, and technological challenges involved in the process. Key obstacles include separating silicon from other materials, the energy-intensive nature of recycling operations, the need for specialized equipment, and difficulties in maintaining the high purity required for recovered silicon.

Currently, most recycling efforts in the semiconductor industry focus on retrieving silicon from photovoltaic devices, while other semiconductor components such as integrated circuits (ICs) remain harder to reuse due to their continuously shrinking size.

The patent search resulted in seven patents with the focus on recycling or reclaiming wafers (Table 8). Wafers are generally defective or rejected and in order to be able to use them again for semiconductor manufacturing, the methods mainly include variations of wet processes where some layers are removed from the wafer surface (#62- #66). The newest patents (#60 and #61) both use dry wafer recovery methods that avoid liquids, which reduces environmental impact and costs. Patent #60 relies on soft elastic carriers with hard particles to polish the wafer surface, while patent #61 uses a scanning recovery beam to remove attachments without damaging wafers made of materials such as silicon, germanium, selenium, or gallium arsenide.

Table 8. Summary of patents related to the recycling/reclaim of wafers. The ID number is used to refer to the patents in the text.

Purpose	Method	Application year	Publication no.	ID no.
Regenerating (removing, polishing) or thinning the surface and thickness of a silicon wafer	Dry surface treatment with a composition that contains a mixture of soft elastic carrier and hard particles can effectively remove coating or metal layer. The used composition is reusable/ recyclable	2020	TWI768329B	#60
Restore the surface of a wafer to enable reuse in the semiconductor manufacturing after chemical-mechanical polishing	Equipment for dry wafer recycling including a platform for carrying a wafer with attachments on a surface of the wafer and a transmitter emitting a recovery beam that scans the attachments and moves them away from the wafer to restore the surface	2019	TWI825194B	#61
Manufacturing a reclaimed semiconductor wafer or substrate	Removal of a metal wiring and an insulating film on the wafer surface by wet etching, followed by wet chemical-mechanical polishing using a polishing pad with fixed abrasive grains	2009	TW201034066 A	#62
Reclaiming, reworking and/or reusing rejected microelectronic device structure	Removing material layer(s) (e.g. photoresist, metal stack material, barrier layer material) from the structure using a “removal composition” comprising e.g. hydrofluoric acid, surfactant, organic solvent and water	2008	TW200908148 A	#63
Reclaiming, reworking and/or reusing rejected microelectronic device structure (SiC)	Removing material layer(s) (e.g. photoresist, metal stack material, barrier layer material) from the structure using a “removal composition” comprising e.g. hydrofluoric acid, mineral acid, etchant, oxidizing agent and water	2008	WO20081573 45A2	#64
Recycling or reusing wafer structure	Removing low-k dielectric materials, etch stop materials, and/or metal stack materials from defective microelectronic device structure using a removal composition	2006	TWI513799B	#65

Purpose	Method	Application year	Publication no.	ID no.
Reclaiming silicon wafers with reduced process steps and chemical use	The first and second conductive layers (titanium and aluminium) are removed with an acid solution, then the wafer is cleaned with a pure liquid so that wafer promotes the quality of the deposition process	2004	TWI245317B	#66

4.4 Acid and solvent recycling

Semiconductor fabrication consumes acids and solvents in huge volumes. As these chemicals need to be of ultra-pure quality, their use is connected to significant costs, further augmented by associated waste management costs. Recycling can provide a way to mitigate the costs. Commonly used acids are HF, HCl, H_2SO_4 and H_3PO_4, whereby solvents include IPA, acetone, NMP, and PGMEA. These chemicals are used for wafer cleaning, photoresist stripping, etching and surface preparation.

Table 9 gives a list of patents on acids and solvents recycling. All the recycling methods achieve high purity level for the recycled acids and solvents so that they can be used again in the semiconductor industry. Typically, the recycling methods are multistage processes including various filtration processes, distillation, and ion exchange. Additionally for sulphuric acid recycling, catalytic UV treatment (#67), thermal decomposition (#67, #68) and infrared heating and concentration method (#69) are used. Citric acid is recycled only by a two-stage filtration process (#70). Patent #71 has a different approach to recycle hydrofluoric acid and nitric acid by using azeotrope-breaking additives, vacuum rectification, mist removal, purification and condensation. Besides distillation, filtration and ion exchange, phosphoric acid-based etchant undergoes chemical treatment, electrochemical activation and activated carbon treatment (#72). While the recycling of organic solvents (#73) goes only through a combination of filtration, distillation and ion exchange, Recycling of isopropanol (#74) additionally includes thin-film pervaporation for water removal.

Table 9. Patents related to the recycling of solvent and acids. The ID number is used to refer to the patents in the text.

Recycled material	Method	Application year	Publication no.	ID no.
Sulphuric acid	Filtration, catalytic UV treatment, vacuum distillation, thermal decomposition, catalytic conversion, absorption and purification	2022	TWI859653B	#67
Sulphuric acid	Thermal decomposition, catalytic conversion, absorption, thin-film distillation, filtration, final absorption and filtration	2015	TWI585035B	#68
Sulphuric acid and hydrogen peroxide	Infrared heating and concentration method, condensation, nano-scale ceramic membrane filtration, ion exchange purification and concentration adjustment	2015	TW201637997 A	#69
Citric acid	Two-step filtration process to remove calcium and magnesium ions	2021	TW202346249 A	#70
Hydrofluoric acid and nitric acid	Using azeotrope-breaking additives, vacuum rectification, mist removal, purification and condensation	2021	TWI782757B	#71
Phosphoric acid-based etchant	Vacuum distillation, dilution, chemical treatment, multi-stage filtration, electrochemical activation, ion exchange, activated carbon treatment, final distillation and reconstitution for reuse	2005	TW200600451 A	#72
Isopropanol	Particle filtration, ion exchange, supergravity distillation, light and heavy boiler distillation, thin-film pervaporation for water removal, and final impurity removal	2022	TWM630268U	#73
Organic solvent	Distillation, ion exchange, particle removal filtration before and after ion exchange	2021	TW202146365 A	#74

4.5 Recycling of process gases

In the search for cost reduction and emission mitigation the interest in recycling of process gases has also emerged. Several process gases are costly, energy intensively produced, and in addition, typically only a small fraction of the used gas is consumed in the fab processes.

Based on the patent search, the most common gases to be recovered are hydrogen and ammonia (patents #75-#88) (Table 11, Appendix A). Other recovered gases include helium (#93), nitrogen (#91), HF/HCl-containing etching tail gas (#92) and elemental fluorine (#94). Gas recycling has also been coupled with solids recovery, such as, rare earth metallic particles (#89), elemental metals (90#) and graphene (#91).

Hydrogen is typically separated from the exhaust gas using membranes, commonly made of palladium alloy. Membrane separation is also applied to other gases, like PFCs, but using different membrane materials. Ammonia is typically separated and recovered from mixed gases by liquification through pressurizing and cooling whereas other components (H2, N2) remain gaseous. Generally, Pressure Swing Adsorption (PSA) is applied in the purification processes of gases. Patent #95 focuses on treating flue gas by molecular adsorbent and molecular sieve to remove mercury and to denitrificate the gas.

5. Practical applications in the industry

Though not receiving as high attention as the reduction of greenhouse gas emission and water consumption, waste reduction and recycling efforts have been noted in major chip manufacturers' sustainability goals. TSMC and Samsung, for example, aim for waste diversion rates of 99% and improvements in recycling rates to 99.5% by 2025, respectively (Venkataswamy et al. 2024).

Focussing on Samsung's achievements, Baek et al. (2024) outlined methods and applications of green chemistry and sustainable engineering in chemical vapor deposition (CVD) for semiconductor mass production. The green CVD methods included sustainable chemical processes, efficient equipment designs and hibernation operation.

Ruberti (2023) analysed and assessed the environmental impacts and the eco-efficiency of the world's leading semiconductor foundries by calculating and analysing various key environmental performance indicators (KEPIs) from the data of the fabs CSR reports. The aim was to highlight the relations between company size, technological capacity and environmental impact. He later used the data to quantify the environmental performance of these leading semiconductor foundries (Ruberti 2024).

5.1 Reported recycling activities in major s companies

Table 10 summarises the circularity related goals and those materials that the studied companies are said to recover in their sustainability reports 2023-2025. While most of the companies recycle water to be reused in internal processes, the focus of this analysis lies on other materials, especially on critical raw materials and precious metals. In general, TSMC, Intel, Micron and Samsung have announced tangible long-term goals that they want to achieve by 2030 or 2050. AMAT, GF, TI, Infineon and ST, on the other hand, only have annual goals or they have not publicly defined any timeframe for their targets.

Table 10. Summary of circularity goals and recovered materials by the companies studied.

Companies	Reported goals for circular materials[1]	Recovered materials
Taiwan Semiconductor Manufacturing Company Limited	100% waste recycling, 70% in-house recycling rate, reduce waste treatment related CO_2 emissions to 2020 levels by 2030, reduce waste generation per wafer in Taiwan and in overseas subsidiaries.	Copper, cobalt, different chemicals and solvents
Intel Corporation	Zero waste to landfill and implement circular strategies for at least 60% of manufacturing waste streams by 2030.	Chemicals, solvents and precious metals
Samsung[2,3]	99.9% waste recycling for Korean manufacturing sites of DS division by 2030.	Precious metals (e.g. Cu), ventilation absorbents, CMP pads, CMP retainer rings, wafer trays
Micron Technology	95% of waste reused, recycled and recovered, no hazardous waste to landfill by 2030.	Chemicals
GlobalFoundries	Reduce hazardous and non-hazardous waste from 2020 levels by 16% and 19% by 2025.[4]	Not specified
Texas Instruments	Annual goal to divert 90% of materials from landfills.	Metals
STMicroelectronics[3]	Annual landfill waste rate below 5%[5]. Reuse, recycle and recover 95% of waste annually.	Metals, precious metals (e.g. Pd, Au, Cu), solvents, chemicals, silicon wafer scrap, sludge waste
Applied materials	Committed to reducing waste e.g. by eliminating non-recyclable landfill-bound waste	Not specified
Infineon Technologies	Increase the amount of solvent recovered, with the aim of reusing 700 tons of solvents in manufacturing	Solvents (e.g. CPT, PGMEA), precious metals (e.g. Pd), sludge

1) *Aspects related to water are excluded.*
2) *Only Samsung's DS Division was considered, which consists of business units that are responsible for producing and selling semiconductor components.*
3) *For recovered materials, also the sustainability report of 2023 performance was considered because it mentioned the recycling of critical raw materials and precious metals.*
4) *The goal for 2024 included also 90% diversion of total waste from landfill, which was achieved.*
5) *The goal for annual landfill waste rate increased from the previous year when it was 3%.*

TSMC, Intel and Micron have quantitative targets promoting circular thinking aiming for recycling and reuse materials. Samsung's sustainability report is divided between DX and DS divisions, of which the DS division refers to business units responsible for producing and selling semiconductor components. When focusing solely on the DS division, Samsung's goal is to achieve 99,9% recycling for its Korean manufacturing facilities. GF and TI also have quantitative targets, but their approach is more waste management focused than circularity centred as both are aiming to divert waste from landfills, while GF also works toward reducing their total waste amount. Infineon is the only one of the studied companies that defines an annual recovery goal for a specific waste stream, solvents. Moreover, Infineon claims contributing to circular economy through product design and by exploring how their products could help enabling circular economy. AMAT and ST both are focused on waste reduction, reuse, recycling and other circularity related actions, but they both lack long-term quantitative goals so that their improvement over the years could be tracked.

Although the recovery of materials is not specifically highlighted in the circularity goals of the studied companies, all the companies state applying the recovery and recycling of materials in their circularity aligned actions. Nevertheless, there are differences in how detailed the recovered materials or their targeted reuse is described. TSMC, Intel, Samsung, ST and Infineon share in more detail the waste fractions that are recovered for reuse or recycling, covering e.g. several chemicals, solvents, precious metals and other types of metals.

ST is the only company that shares in greater detail their process of recovering precious metals, such as copper, palladium, silver and gold. They have partnered with an external company specializing in the recovery of precious metals through several thermal, chemical and electrochemical processes, and have achieved a recovery rate up to 99%. The resulting recycled materials are said to be of high quality with similar characteristics as virgin materials, so they can be reused in the semiconductor industry. In addition, ST recycles sludge waste into raw materials and building materials. They also mention recycling metals (without specifications) from dismantled electronic waste as well as from scrapped devices. Other circular economy related actions of ST include using silicon wafer scrap for aluminium production (e.g. in automotive industry), distilling solvents either to be reused or incinerated for energy recovery and recovering sulphuric acids to be used for recycling batteries.

Infineon recovers solvents, such as cyclopentanone (CPT) and propylene glycol methyl ether acetate (PGMEA), that are purified and processed in close co-operation with suppliers so that they can be reused in production. In addition, they recover precious metals, like palladium, from silicon sludge, or alternatively recycle the silicon sludge produced during wafer slicing, polishing and other silicon-based manufacturing by using it in cement kilns.

TSMC classifies liquid waste into 38 different types, for which there are 13 types of waste treatment available so that finally eight different products, including copper, ammonium sulphate, sulphuric acid and silicon aluminium oxide, can be recycled and used internally or by other industries. For instance, through collaboration with a supplier, TSMC could recycle TMAH waste into electronic-grade products for reuse in its own facilities.

Samsung recovers precious metals for recycling from wafer polishing consumables containing hazardous materials, although they do not specify which metals are recovered. Samsung also recycles wafer trays and recovers absorbents used in air pollutant abatement equipment, which are regenerated. Moreover, they recover CMP pads, which are regenerated and used for wafer polishing. Samsung also recovers CMP retainer rings to avoid their incineration, and they are regenerated through separation, sorting, cleaning, melting and palletisation. Moreover, Samsung applies recycled aluminium to Portable Solid State Drive (SSD) T7 Shield product case, which has received recycled material certification from TÜV.

TI reports recovering metals from solids, liquids, scrap wafers and other material, without stating which metals are targeted. For Intel, the material recovery focus is on chemicals and solvents as they recover e.g. sulphuric acid, ammonium sulphate and cyclohexanone. Micron also recovers chemicals but without elaborating further which ones and for which purpose.

5.2 Recovery projects by technology providers

Interviews with a couple of European environmental technology and services providers indicate that during the last five years, while not being the mainstream yet in a semiconductor fabrication environment, material recovery is becoming an important complement to waste reduction and cost control with a clear customer demand. In the following, some examples of material recovery are given by companies operating as technology and service providers within the semiconductor industry.

Germanium recovery from backgrinding

The German company DAF Engineering has developed several applications for metal recovery from semiconductor fabrication. One example is the recovery of germanium from the wet backgrinding process. During this step, process water contains fine germanium particles that would traditionally be lost with the wastewater stream. By applying dead-end microfiltration using hollow-fibre membranes (0.2 µm), these particles can be effectively captured. Periodic backflushing, combined with optimised chemical dosing, concentrates germanium into a manageable slurry. This concentrated stream is then sent to an external chemical refiner, such as Umicore or Kite Metals Sarl, where the material can be further purified and reintroduced into the value chain.

Gallium recovery from wet abatement systems

A similar recovery approach by DAF is applied to gallium, particularly from wet abatement systems treating exhaust gases from gallium nitride (GaN) processes. As GaN is increasingly used in advanced semiconductor products, the value of gallium recovery continues to rise. In this case, a combination of dead-end hollow-fibre membrane separation, ultrafiltration, and ion exchange is employed, again achieving effective retention down to approximately 0.2 µm. Recovery is preferably performed directly at the gas treatment unit, where gallium species are still relatively pure and have not yet been diluted or contaminated by other process streams, such as isopropyl alcohol. By targeting recovery at this early stage, both efficiency and material quality are significantly improved.

Lithium tantalate recovery from wastewater

Fäth Group reported on the development of a lithium tantalate ($LiTaO_3$) recovery project in France, which originated from the need to reduce wastewater volumes generated during the grinding process. The initial objective was to remove particulate matter from $LiTaO_3$–containing wastewater in order to minimise disposal and enable water reuse, thus mitigating high discharge costs.

An outside-in ultrafiltration (UF) system with hollow-fibre membranes was selected as primary treatment. When suspended solids concentrations were below approximately 300 mg/l, outside-in filtration enabled up to 80% wastewater recycling; at higher concentrations, cross-flow filtration was considered more efficient. Solid metal particles were retained in the reject stream and managed through back-flushing, decantation, and precipitation. For removal of smaller dissolved contaminants, nanofiltration or reverse osmosis (RO) could be applied in downstream.

As the project evolved, its scope expanded to include systematic water reuse. The UF permeate was redirected to ultrapure water (UPW) production upstream of RO, resulting in a closed-loop water-recycling concept that is now implemented at an industrial plant in France. A remaining challenge concerned the treatment of the reject stream containing concentrated solids. Separation trials, including centrifugation using a partner's technology, reduced waste volumes but failed to achieve the solids concentration required by the $LiTaO_3$ supplier for material recovery. Additional investigations are currently being conducted by FÄTH in Munich using the 360 RF system. Thermal treatment of the solids-containing rejects has not yet been evaluated, as it lies outside the current technology portfolio.

Recovery of metals from sputtering

Several companies, such as Materion, Tanaka Precious Metals, PhotonExport provide services for the recycling of sputter targets so that the sputter targets bought from them can be returned to them for recycling. To succeed, this process should be made simple and involving minimal administrative burden (e.g. shipping, waste transfer regulations).

Tanaka Precious Metals' Tanaka Green Shield, process, involves removing nickel plating from adhesion-preventing plates on specific components to which sputtered films can adhere. These films may contain platinum group metals (PGMs, platinum and palladium), which the Tanaka Green Shield process can detach from the plates. After detaching sputtered films adhering to components, mainly made of stainless steel, used in vacuum film formation equipment such as sputtering and vacuum deposition systems, the recovered precious metals are refined and returned to the customer along with the precision-cleaned components. According to Tanaka, applying nickel plating to the adhesion-preventing plate allows PGM sputtered films to be removed through chemical treatment without damaging the base material (Taylor, 2024).

Sindlhauser Materials from Germany suggests lining the interior of the sputtering device with a special removable sheet which can then easily be detached and sent to the material recycling process. Sindlhauser Materials also provides services for precious material recovery from sputtering equipment (Konrad, 2025).

5.3 Examples from comparable industries

5.3.1 Optical industry

Ceria polishing is also applied in the glass polishing industry and circularity strategies applied for the CMP treatment in that sector can find a foothold also in semiconductor fabrication. In this growing industry, similar CMP slurry is used for polishing in high precision manufacturing precise optics and other branches of the glass industry. The literature review identified a handful of studies on recycling strategies.

Janoš et al. (2015) developed several procedures for the recovery of rare earth elements (REEs) from spent polishing sludges. Cerium oxide was digested in a mixture of a strong mineral acid and a reducing agent, such as hydrochloric acid with potassium iodide or nitric acid and hydrogen peroxide. After filtering out glass particles, cerium was precipitated from the solution as cerous carbonate and then converted into cerium oxide by annealing in a rotary kiln. The study demonstrated that cerium oxide prepared by thermal decomposition of cerous carbonate may serve as an effective reactive sorbent capable of destroying highly toxic organophosphate compounds. However, the degradation efficiency of the recovered cerium oxide towards toxic organophosphates was somewhat lower in comparison with that of the pure cerium oxide prepared in a similar way, probably because of the presence of impurities originating from the polishing slurry. They hypothesized that nonlanthanide elements, although present in minor amounts (Ca, Si), could have an adverse effect on the degradation efficiency.

Lee et al. (2019) studied the recycling of both cerium and lanthanum from glass polishing sludge. Two major methods were used, namely leaching and precipitation on spent sludge containing 12% of La and 24% of Ce. The sludge was leached in concentrated hydrochloric acid at a temperature of 70°C for 3 h to obtain a 100% leaching recovery of La and Ce. After pH adjustment and a simultaneous addition of H_2O_2 the dissolved Ce could be precipitated out with 66 % recovery. On the other hand, La was not precipitated. The results obtained in this study reveal that leaching and pH adjustment method could be used to recover Ce from glass polishing sludge.

Lin et al. (2021) provided an example of utilising silicon containing sludge for the production of a high value humidity control material suitable for indoor environments. By combining two abundant waste streams; silicon carbon (SiC) sludge from photovoltaic manufacturing and residual granite sludge from construction stone polishing, they prepared a mesoporous silica nanomaterial by alkali fusion and hydrothermal treatment. The researchers concluded that the recycling of SiC sludge and granite sludge generated in industrial processes can effectively replace chemicals and can also be used as a new application.

Zhu et al. (2025) reported on a study aimed at both efficient waste treatment and comprehensive utilization of rare earth resources. They used a simple direct and low-cost gravity settling-hydrofluoric acid (HF) leaching process to regenerate rare earth polishing powder from the glass polishing waste. After diluting and stirring the waste slurry evenly the following gravity settling step removed most of the large impurity particles, and the acid-leaching process restored the aggregated polishing powder particles to their original size while removing the SiO2 impurities to obtain the regenerated polishing powder. The regenerated powder reached a rare earth content of 95 % which could be directly used for glass polishing. Particularly, ultra-precision surface roughness was achieved, and the materials removal rate was actually better (ca 120 %) than that of the pristine polishing powder. The authors also proposed a regeneration mechanism of the HF leaching process. The material flow and mass balance of the products obtained during the regenerating process indicate that the recycling of 1000 kg rare earth polishing powder waste slurry yielded approximately 658 kg regenerated polishing powder providing a total economic value of ca 2400 $US in the regenerating process.

5.3.2 Catalysts

Nanomaterial-based catalysts are usually heterogeneous catalysts based upon metal nanoparticles. Metal nanoparticles have high surface area, which can increase catalytic activity.

Bhattacharya et al. (2020) reviewed technologies and the economy of using waste materials as raw material for catalyst production. Applied technology routes include ball milling, magnetic separation, and thermal/chemical processing employed on e.g. e-waste, red mud, and rust waste. Individual economic analysis on such processes (e-waste -> nano-FEO3) (Fu et al. 2011) point at poor competitiveness compared to using "virgin" metal powder. Important factors are the energy consumption and investments needed to achieve necessary quality. In this respect, the use of relatively clean and micronic semiconductor derived materials may be advantageous considering the overall monetary cost of obtaining nanomaterials from waste sources and considerations of nanomaterial purity. Other key determining factor in increasing the utilization of sidestreams/wastes are the consistency of the output, and the scalability of the process, the latter being a clear challenge with respect to the relatively small volumes which can be recovered in the fablabs.

Tan et al. (2019) presented a novel approach to recycle heavy metal-contaminated sewage sludge into an energy storage material. They designed a flocculant to remove toxic Cu(II) from wastewater and subsequently produced a Cu-doped carbon electrode for supercapacitor applications. While lab tests indicated the electrode's suitability as a supercapacitor electrode, it was found that a better specific capacitance can only be achieved at the expense of poor removal efficiency which thus partly limits the invention's applicability.

Luty-Błocho et al. (2024) developed an efficient and cheap method for metal ion removal from waste solution and processing of material into a catalyst. Synthetic waste solutions with low content of metals (Pd and Pt) or their mixture were performed and activated carbon was used as an adsorbent of metal ions and as catalyst carrier. According to the authors, the obtained results were promising in the context of waste-for-product concept development. Recovered PGM, due to their unique chemical properties, can be treated again as input material for, e.g., catalytic purposes.

6. Advancing circularity and resilience

The semiconductor industry is evolving toward more sustainable practices that emphasize waste reduction and resource efficiency. Achieving meaningful progress, however, requires strategies that extend beyond isolated initiatives and address sustainability across the entire product portfolio. While many currently reported actions focus on end-of-life solutions, these measures represent only one stage of a much broader system. Greater long-term impact can be realized by adopting strategies that consider the full product life cycle and the entire value chain—from raw material sourcing and manufacturing processes to product design, use, and eventual recovery or reuse. A comprehensive life-cycle perspective enables the industry to move beyond reactive waste management and toward proactive design and operational decisions that reduce environmental impacts at every stage.

Advancing circularity and resilience in semiconductor manufacturing calls for a fundamental rethinking of how materials, processes, and partnerships are designed and managed. Rather than treating waste as an inevitable by-product to be handled downstream, the industry is beginning to recognize circularity as a design principle—one that must be embedded from the earliest stages of innovation and carried through the entire value chain.

A transformation starts with a decisive shift from waste management to design-for-circularity. In semiconductor fabrication, where processes are highly complex and materials are often difficult to separate, the greatest gains come from upstream decisions. By designing process chemistries, selecting materials, and engineering equipment with recovery in mind, manufacturers can reduce the difficulty and cost of reclaiming valuable inputs. Approaches such as design-for-recycling and design-for-recovery ensure that materials remain accessible and reusable, turning what was once waste into a viable resource stream.

Building on this foundation, the industry must prioritise point-of-source recovery solutions. Recovering materials as close as possible to where waste is generated—within individual process steps or tools—offers clear technical advantages, which also can be translated into economic gains. At this stage, materials are more concentrated, less contaminated, and therefore easier to reclaim at high purity. The deployment of compact, modular recovery technologies directly at the fab level enables more efficient capture of valuable substances, reducing losses and minimizing the need for energy-intensive downstream processing.

However, circularity driven innovations and technologies cannot succeed in isolation. Strengthened collaboration across the value chain is essential to unlocking circularity at scale. Semiconductor manufacturing depends on an interconnected – though typically geographically fragmented - ecosystem that includes fabs, equipment suppliers, chemical producers, recyclers, and technology developers. Coordinated action—through shared responsibility models, aligned contractual frameworks, and long-term partnerships—helps overcome fragmented incentives and distributes both risk and value more equitably. In this collaborative model, circularity becomes a shared objective rather than an individual burden.

To move from concept to reality, the sector need to support pilot projects and scale-up pathways. While many recovery technologies have demonstrated technical feasibility in laboratories and controlled environments, they often lack validation under full industrial conditions, much due to the sector's high requirement on speed and efficiency, and thereby economic risks involved with testing new solutions. Targeted pilot initiatives, backed by public funding and policy incentives, play a critical role in bridging this gap. They provide the data, confidence, and operational experience needed to scale solutions across fabs and regions, accelerating adoption while reducing uncertainty.

At a broader level, aligning material recovery with strategic resource security goals reframes circularity as not only an environmental imperative but also a geopolitical and economic one. Semiconductor production relies on a range of critical raw materials, many of which are subject to supply constraints and geopolitical risk. By integrating recovery into industrial and innovation strategies—particularly within Europe—policymakers can strengthen supply resilience, reduce external dependencies, and support the development of a more self-sufficient semiconductor ecosystem.

At a certain level, progress can be accelerated by leveraging cross-industry knowledge transfer. Other sectors—such as mining, chemicals, and electronics recycling—have already developed and implemented recovery-based value chains. By actively promoting knowledge exchange and adopting proven practices, semiconductor stakeholders can possibly shorten development timelines, avoid common pitfalls, and reduce the risks associated with scaling new solutions.

Taken together, these elements form a coherent pathway toward a more circular and resilient semiconductor industry. It is a shift from linear to regenerative thinking, from isolated optimisation to system-wide coordination, and from short-term efficiency to long-term stability. In this emerging model, circularity is not just about reducing waste—it is about securing the future of semiconductor manufacturing in an increasingly resource-constrained and uncertain world.

7. Conclusions

The semiconductor industry is gradually moving toward more sustainable manufacturing practices, but material circularity remains at an early stage compared to energy and water efficiency. This review demonstrates that recovery and recycling of valuable materials is technically possible across many process steps, including wastewater treatment, CMP, deposition processes, wafer fabrication, and chemical management. In several cases, recovery rates and material qualities comparable to virgin inputs have already been achieved.

However, the adoption of these solutions is constrained by structural and economic factors. Low material concentrations, complex and variable waste streams, high purity requirements, and the long lifetime of fabrication equipment reduce incentives for rapid change. As a result, material recovery is often treated as a waste-management or compliance issue rather than a core element of process design and optimisation.

To advance circularity, the industry would benefit from a stronger shift toward design-for-recycling and design-for-recovery principles. This includes considering recoverability already at the stage of process chemistry, material selection, and equipment design, as well as favouring point-of-source recovery solutions that preserve material value. Greater transparency and harmonisation in sustainability reporting would also improve comparability and enable tracking of progress over time.

Collaboration across the value chain is essential. Equipment suppliers, chemical providers, fabs, and recyclers all play a role in enabling closed-loop solutions. In addition, lessons from adjacent industries demonstrate that secondary materials can find high-value applications if quality, consistency, and logistics are properly managed.

In conclusion, while material recovery is not yet a central pillar of semiconductor sustainability strategies, it represents a significant opportunity to reduce environmental impacts, improve resource security, and enhance industrial resilience. Continued research, targeted pilot projects, and integration of circularity into long-term strategic planning will be critical to unlocking this potential and moving the industry toward a more circular and sustainable future.

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Appendix A Recycling of process gases

Table 11. Summary of patents related to the recycling of process gases. The ID number is used to refer to the patents in the text.

Recycled/recovered material	Method	Application year	Publication no.	ID no.
Hydrogen	Exhaust gas collection, separation and purification of gas into monohydrogen gas (H2) and nitrogen gas (N2), mixing hydrogen with natural gas to form a storage gas	2024	TWM668378U	#75
Hydrogen	Pretreatment, temperature swing adsorption roughing, chemical adsorption fine stripping process, pressure swing adsorption purification, hydrogen purification	2019	TWI691359B	#76
Hydrogen	Catalytic combustion, spray washing, water-gas separation, adsorption and purification, pressure swing adsorption and hydrogen gas purification	2018	CN108529559A	#77
Hydrogen	Exhausted gas condensation with chlorosilanes recovery, residual impurities abatement treatment, final purification preferably via a Pd membrane unit	2009	EP2233195A1	#78
Hydrogen and nitrogen mixed tail gas	Feed gas pretreatment, refining and impurity removal, low-temperature pressure swing adsorption (LPSA) and low-temperature fractionation	2019	CN110040700A	#79
Hydrogen, ammonia	Organic metal compound removal, ammonia decomposition, hydrogen recovery, ammonia liquefaction and separation	2015	US9815707B2	#80
Ammonia and hydrogen	Ammonia is liquefied and separated from the exhaust gas with a heat pump by pressurizing and cooling. Treatment is repeated for the remaining gas to separate hydrogen, which is further purified with palladium alloy membrane	2013	JP6101958B2	#81

Recycled/recovered material	Method	Application year	Publication no.	ID no.
Ammonia and hydrogen	Ammonia is liquefied and separated from the exhaust gas with a heat pump by pressurizing and cooling. Pressurized gas is brought in contact with palladium alloy membrane to recover hydrogen	2012	JP6082915 B2	#85
Ammonia and hydrogen	Ammonia is liquefied and separated from the exhaust gas with a heat pump by pressurizing and cooling. Hydrogen is collected by pressure swing adsorption	2012	JP2014124584A	#86
Ammonia	Ammonia is adsorbed by a porous coordination polymer from ammonia-containing liquid or gas	2022	TW202310911A	#80
Ammonia	Pretreatment, medium-shallow temperature PSA concentration, condensation and freezing, liquid ammonia vaporization, PSA ammonia extraction, and ammonia gas purification	2019	US20190366260A1	#87
Ammonia	Solid compound removal, ammonia liquefaction, combination with hydrogen, nitrogen separation	2013	TWI495502 B	#88
Ammonia	Hydrogen is removed from the exhaust gas by membrane separation (Pd alloy), then gas is cooled to liquefy it and recover ammonia from it	2012	JP2014118309A	#89
Ammonia	Ammonia gas is separated from organic metals and dust using an alkaline solution to clean the gas	2011	TW201302285A	#90
Rare earth metallic particles, ammonia, hydrogen	Rare earth metallic particles are recovered from the exhaust gas by precision filtering, then ammonia is recovered from the gas by compression and cooling, lastly hydrogen is recovered by Pd tube purifier	2012	CN203150595U	#91
Elemental metal	Decompose trichlorosilane to form polysilicon and $SiCl_4$, react $SiCl_4$ with elemental metal to produce polysilicon and metal chloride, recover metal from metal chloride via hydrogenation or silicon reaction	2013	TW201406966A	#92
Graphene, hydrogen-nitrogen mixed tail gas	Pretreatment of hydrogen-nitrogen mixed gas, refining and impurity removal, graphene membrane separation from the gas mix	2019	CN109970028B	#93
HF/HCl-containing etching tail gas	Pretreatment, chlorosilane/HCl spray absorption, medium temperature pressure swing adsorption, HF rectification, multi-stage evaporation/ compression/ condensation, HCl	2021	WO2022127019A1	#94

Recycled/recovered material	Method	Application year	Publication no.	ID no.
	refining, shallow cooling rectification in chlorosilane, tail gas absorption			
Helium	Process gas delivery, first film separation stage, second film separation stage, PSA, recirculation of the second permeate stream and purging gas to the first film separation stage	2016	TW201729885A	#95
Elemental fluorine	Waste gases are reacted with a metal or metal compound to form manganese tetrafluoride to bind fluoride, which can be decomposed by heating to release elemental fluoride for reuse	2008	TW200932340A	#96
Flue gas cleaning	Catalytic adsorbent, molecular sieve	2021	CN116059961B	#97

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