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Emerging Trends in Wastewater Treatment of Semiconductor Industry: A Review

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ABSTRACT

The semiconductor industry produces a lot of wastewater. These wastewaters can affect the environment if they are not treated. As a result, one of the semiconductor industry's primary concerns and duties is the treatment and disposal of wastewater from the industry. Many processes, including electrocoagulation, electro-adsorption, and coagulation-flocculation using both natural and synthetic coagulants, have been invented over the years for purifying semiconductor effluent. The long-term viability of this system is unknown although it generates solid by-products (sludge) and requires routine sludge disposal, both of which raise the operational expenses of effluent treatment. Thus, a sustainable alternative method of removing contaminants from the semiconductor industry is needed to advance toward pollution prevention and green innovation. The hydrodynamic cavitation technique has improved over time and is useful for treating water and wastewater. This article gives an insight into different wastewater technologies, so proper technology must be chosen.

INTRODUCTION

One of the quickly expanding economic sectors is the semiconductor industry, which is anticipated to experience increased expansion in the future (Eng et al. 2019). High-quality semiconductor wafers must be produced using intricate and delicate processes such as wafer back polishing, cutting, device connection, wire bonding, encapsulating, cutting, shape, and labeling (Hollingsworth et al. 2005, Lai & Lin 200, Sun & Tay 2004). In these processes, there are more than 200 different kinds of natural and synthetic substances. Water is also essential for the fabrication of thin films, in addition to elements and materials that are manmade and natural. Investigation shows that the manufacturing processes for semiconductor wafers utilize about 60% of the water from the tap and 40% of ultra-pure water, which is then wasted (Drouiche et al. 2007). In the electronics sector, back grinding and chemical mechanical polishing (CMP) are the two main producers of wastewater (Teow et al. 2022, Lin & Yang 2004). CMP wastewater is produced when wafers are cleaned after a CMP operation when tiny surface particles mix with CMP slurry (Huang et al. 2011). The resulting effluent is dark in color and has a high level of turbidity in contrast to wastewater, which is created from back grinding operations where synthetic particles combine with cleaning water (Yang et al. 2012). Chemicals and by-products from the semiconductor industry, including acidic, basic ions, volatile compounds, trace metals, minute scattered ionic compounds, and organic materials, are frequently found in the effluent (Eng et al. 2019). The semiconductor sector creates more wastewater due to the rising demand for semiconductor wafers. As a result, one of the semiconductor industry's primary concerns and duties is managing and disposing of wastewater from manufacturing. There have been a number of processes that have evolved for treating electronic effluent, namely electrocoagulation, electro-adsorption, and coagulation-flocculation using both natural and synthetic coagulants. (Mousazadeh et al. 2021). It is uncertain if this system will be financially feasible in the long term, although it generates solid by-products (sludge) and requires frequent scheduled disposal of the sludge. Therefore, a sustainable choice of treating wastewater from the electronic sector is required to move toward ecological safety and green manufacturing. One of the semiconductor industry's most water and energy-consuming processes is copper chemical mechanical planarization (Cu-CMP). Around 30 to 40 percent of the water utilized during the entire semiconductor production process is used in this phase alone, according to estimates (Golden et al. 2000). The wastewater produced contains a lot of copper, usually

Table 1: Characteristics of metal plating industrial wastewater.

Characteristics	Units	Value
pH	-	2.0
Electric Conductivity	$mS.cm^{-1}$	560
Zinc	$mg.L^{-1}$	25
Copper	$mg.L^{-1}$	30
DO	$mg.L^{-1}$	4
Turbidity	(NTU)	256
TDS	$mg.L^{-1}$	1180
TSS	$mg.L^{-1}$	100
TOC	$mg.L^{-1}$	370
COD	$mg.L^{-1}$	1430

between 5 and 100 $mg.L^{-1}$ of soluble copper (Maag et al. 2000). Semiconductor wastewater is distinguished by its strenuously dark color, high turbidity, high chemical oxygen demand (COD) concentration, non - biodegradable, and presence of both inorganic and organic pollutants. It may also contain a variety of solvents, acids, bases, salts, and fine oxide particles. Hussein and Abdel-Shafy (2022) collected samples from a plating industry and analyzed them for the metals shown in Table 1.

Many methods have been used to treat organics and heavy metals like Cu; the methodology selected will primarily depend on the characteristics of the influent being treated and the intended effluent properties. Considering the characteristics of the wastewater, it is possible to apply both physical-chemical and biological treatments.

PHYSICO-CHEMICAL TREATMENT OF CMP EFFLUENTS

Cu-CMP wastewater treatment in the semiconductor sector involves a variety of physico-chemical techniques, most frequently utilizing coagulation and flocculation for wastewater preprocessing, led by micro or ultrafiltration, and then cation exchange for the removal of copper (Golden et al. 2000, Mendicino & Brown 1998).

The production of huge quantities of metal-bearing sludges or brines during the physico-chemical treatment of metals is one of the primary issues with this process and could lead to their eventual dumping in unsafe discarded locations (Golden et al. 2000).

Chemical Coagulation-Flocculation

Chemical coagulation can remove heavy metals above 90% (Alazaiza et al. 2022). Research on electrocoagulation demonstrates excellent outcomes in eliminating copper ions and floating fragments (99% clearance) (Lai & Lin 2003).

Sun et al. (2020) produced a new dual-functional chitosan flocculant CMCTS-g-P(AM-CA) for the flocculation removal of heavy metal using UV-induced graft copolymerization using AM, CMCTS, and ammonium di-thio-carbamate as reaction monomers.

Chemical Precipitation

Chemical precipitation is one way to remove the most frequently utilized heavy metals (Pohl 2020, Yan et al. 2020).

Precipitation With Hydroxides

Precipitation with hydroxides is one of the most common techniques due to its low cost and very simple control by altering pH (Bilal et al. 2013, Veeken et al. 2003). The precipitate from hydroxide precipitation is a gelatinous sludge that is challenging to dewater, one of its main drawbacks (Pohl 2020). One major problem with chemical precipitation is that it lacks selection. Thus, even if pH is only raised, many metal hydroxides may precipitate at once (Bilal et al. 2013), making the resulting sludge useless for metal recovery (Veeken et al. 2003).

Precipitation With Sulfides

The most significant benefits of employing sulfide as a ligand to precipitate heavy metals over hydroxide precipitation are greater removal efficiency and reduced reliance on chelating chemicals found in contaminated water (Prokkola et al. 2020). In reality, sulfide precipitation is an extra costly practice (in terms of chemical expenses), and too much sulfide in the effluent could cause hazardous and corrosion issues preventing it from being widely used as a physico-chemical approach, however (Kaksonen 2004).

Ion Exchange

Unfavorable metal ions are exchanged for secure, environmentally beneficial ones using the ion exchange method, which employs a reversible chemical reaction. A heavy metal ion is removed from a wastewater solution by attaching it to an immobile solid particle and then replacing it with the solid particle cation. According to Bisht & Agarwal (2017), the ion-exchange approach may eliminate target (all or some) heavy metal ions from wastewater, including lead, mercury, cadmium, nickel, chromium, copper, and zinc. According to Zhang et al. (2021), when comparing SiAcyl resin to other commercially available resins, it showed good stability, reusability, and cost-effectiveness for potential use in industrial applications.

BIOLOGICAL APPROACHES

Microbial processes usually focus on immobilization strategies to remove metals from aqueous streams, the more prominently biosorption by microorganisms; metal reduction to less soluble forms; and chemical precipitation with biogenic products, such as oxalates, phosphates, or sulfides (Schiewer & Volesky 2000, White et al. 1995, Gadd 2000). There haven't been many attempts to use biological methods to treat CMP wastewater.

Biosorption

In research to eradicate cadmium from wastewater by the blue-green alga, Abdel et al. (2013) achieved high biosorption. By partially or completely esterifying the carboxylic sites on its cell wall, sargassum biomass was found to be able to biosorbent cadmium and lead cations (Abdi & Kazemi 2015).

RECENT TRENDS IN WASTEWATER TREATMENT

Membrane Technology

Ahmed and Yossor (2016) found that industrial effluent containing nickel, lead, and copper ions can be effectively treated using reverse osmosis (RO) membrane technologies to save water and protect the environment. The outcomes demonstrated that the RO process could efficiently remove heavy metals, with removal efficiencies for Ni(II), Pb(II), and Cu(II) ions of 98.5%, 97.5%, and 96%, respectively. Teow et al. (2022) evaluated the performance of commercial ultrafiltration (UF) ceramic and polymeric membranes when treating three different types of wastewater from the semiconductor industry: diluted back grinding wastewater (DBGW), diluted chemical mechanical polishing wastewater (DCMPW), and collection tank wastewater. In this study, two types of polymeric membranes and one type of ceramic membrane were assessed. Due to its high porosity, hydrophilicity, and permeability, the ceramic membrane produced the maximum permeate flux (131.23-308.98 $L.m^{-2}h^{-1}$) for all three types of wastewaters and was least prone to fouling, as seen by the lowest relative flux reduction (RFR) (8.22-57.59%).

Advanced Oxidation Process

In advanced treatment methods, degrading promising intractable components with membrane and bioremediation is difficult. Owing to its capacity to decompose a variety of natural micro-pollutants, the advanced oxidation process (AOP) has drawn a lot of interest in solving this issue (Sievers 2010, Bethi et al. 2016).

Photocatalysis

Some semiconductors for purifying water are $_{TiO2,}$ ZnO, Fe_2O_3, CdS, and ZnS (Diya'Uddeen et al. 2011, Hasan et al. 2012). To detect and adsorb heavy metal ions in water, a unique titania nanomaterial was modified with a sulfhydryl group (nano TiO_2-SH) and properly quantified the adsorption process utilizing Surface-Enhanced Raman Spectroscopy (SERS) and other useful testing methods by Chen et al. (2023). For the three heavy metal ions, Hg^{2+}, Cd^{2+}, and Pb^{2+}, the maximum adsorption efficiency of nano TiO_2-SH was 98.3%, 98.4%, and 98.4%, respectively. Furthermore, the adsorption efficiency of nano TiO_2-SH for these three metal ions remains above 96% after five adsorption and desorption cycles. These findings demonstrated the nano TiO_2-SH adsorbent's considerable potential for removing water pollutants in real-world applications.

GAPS OR LIMITATIONS IDENTIFIED

Removing nutrients from wastewater is commonly acknowledged as an affordable and practical procedure called biological treatment. However, due to the high amount of hazardous chemicals in semiconductor wastewater, which can prevent microbe movement in the organic handling procedure, biological procedures may not be practical for the treatment of semiconductor wastewater (Kim et al. 2009). Although the electro-dialytic approach may effectively remove fluoride from an aqueous solution (Keri et al. 2011), it is challenging to apply this technology to the management of semiconductor effluent owing to the difficulty of wastewater. The effluent from semiconductor manufacturing is frequently treated alternatively by precipitation using calcium salts. However, the presence of PO_4^{-3}, SO_4^{-2}, and NH^{4+} in the wastewater fast prevents this procedure from removing the TAN and PO_4^{-3} concurrently, which lowers the recapture issue of CaF_2 for a variety of manufacturing uses (Aldaco et al. 2007).

Furthermore, flocculants like polyferric sulfate and polyaluminum chloride must speed up the solid separation process since the chemical precipitation creates extremely small CaF_2 precipitates (Liu & Liu, 2016). Copper concentrations in semiconductor effluent can reach 100 $mg.L^{-1}$ (Lai & Lin 2004). Cu^{2+} can now be detached through a range of techniques and technologies, as well as chemical precipitation, ion exchange, sorption, membrane filtering, and electrochemical treatment (Awual 2015). Copper removal from the trash from semiconductors using the coagulation-flocculation method followed by sedimentation is one of them. The generation of excessive mud and/or the use of copious quantities of coagulants and/or coagulant aids

Table 2: Identified drawbacks in the treatment of semiconductor wastewater.

Sr. No.	Treatment	Limitations/Drawbacks Identified	Reference
1.	Biological Process	Inhibit the Microorganisms' activity in a biological system	Kim et al. (2001)
2.	Eletrodialetic Method	Difficult to apply to Semiconductor Wastewater due to the complexity of wastewater	Keri et al. (2011)
3.	Precipitation Process	This process can not eliminate the TAN & Po4 Since it is quickly intercepted by the presence of PO_3, SO_4 & NH_4	Aldaco et al. (2007)
4.	Coagulation – Flocculation Process	Creation of surplus sludge and use of huge amounts of coagulation or conjugate aids	Awual (2015)
5.	Ion Exchange	Require Regular regeneration, and hence treatment cost increases	Fang et al. (2010)
6.	Adsorption	Requires regular regeneration and hence difficult to recover chemicals from Waste.	Crini (2005)
7.	Physico-Chemical Treatment of CMP Effluents	Large-scale production of metal-containing sludges that would need to be disposed of in hazardous waste sites in the future	Golden et al. (2000)
8.	Hydroxide precipitation	Gelatinous mud, which is not easy to get rid of water	Lanouette (1977)
9.	Sulfide precipitation	It is a more expensive process (chemical costs), and too much sulfide in the effluent can cause toxicity and corrosion issues.	Kaksonen (2004), Humberto et al. (2021), and Veeken et al. (2003)
10.	Biosorption	The price of supplying nutrition and the harm that heavy metals do to living cells	Schiewer and Volesky (2000)
11.	Dissolved air flotation	High initial energy and capital costs. High costs for operations and maintenance.	Chuang et al. (2002)
12.	Membrane filtration, Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF) Reverse osmosis, Dialysis Electrodialysis (ED) Electro-electrodialysis (EED) Emulsion liquid membranes (ELM)	For small and medium-sized businesses, investment expenses are frequently too expensive, and they have large energy needs. Membrane filtering system designs can vary significantly. High operating and maintenance costs rapidly clog membranes (fouling with high concentrations). Little throughput, Restricted flow rates Low solute feed concentrations are uninteresting. The particular application determines the membrane choice.	Sharma & Sanghi (2012) Sonawane and Ghate (2004)
13.	Advanced oxidation processes (AOP) Photolysis	Laboratory scale Insufficiently profitable for small and medium-sized businesses	Parsons (2004) Sharma (2015)
14.	Electrochemical reduction	Passivation of the anode and sludge buildup on the electrodes can prevent the electrolytic process from running continuously.	Chen (2004)

are the process's main downsides, though. Ion exchange and sorption are now regarded as efficient and affordable approaches. However, regeneration is necessary to have a repeatable response using this strategy after equilibrium is reached. Chemical coagulation, electrocoagulation, flotation, membrane filtering, and adsorption are traditional methods for removing silica particles from CMP or BG wastewater (Fang et al. 2010). Adsorption technologies are possibly the most alluring of the previously discussed treatment methods because of their effectiveness, affordability, and ease of use (Crini 2005). Table 2 gives the different wastewater treatment technologies and identified drawbacks.

COMMENTS ON THE TREATMENT MODALITIES AND PROSPECTIVE OUTCOMES

The information above shows that any technique used to remove metal ions is not universally favorite and has pros and cons. Adsorption has received the greatest attention recently among all approaches. It demonstrated simple to use, low expense, and a large sorption capacity. The present study trend is to create affordable, eco-friendly adsorbents from the garbage. To reduce environmental concerns, disposing of such adsorbents after the adsorption process is a significant task.

Membrane techniques are important in the treatment of wastewater and are now seen as a more viable solution. Some separation applications, like desalination, already suit them the best. High effectiveness in the extraction of metal ions is a characteristic of membrane processes. Membrane fouling and biofouling, low recovery for the volume of feed wastewater, process complexity, pre-treatment, frequent membrane cleaning, and high cost are further downsides of this strategy. Future industrial wastewater treatment requires the growth of innovative membrane resources with improved thermal and chemical stability to achieve superior anti-fouling capabilities and increase membrane selectivity for the target metals. The autonomous operation of industrial facilities requires more implementation and development for both adsorption and membrane techniques. Chemical-based separations have been used widely for heavy metal removal due to their simplicity and low cost. However, chemicals are used to adjust pH levels and improve ion accumulation. There is a huge amount of sludge created that desires additional action.

The electrochemical treatment benefits from being quick, and well-controlled sludge removal is made simple, and there are fewer chemicals used. However, the main issues with this approach are the high cost of anodes and cathodes, low throughput, and excessive energy consumption. To solve this problem, combining several electrochemical treatment techniques powered by renewable energy sources may be effective. Aerated electrochemical oxidation (EC) and electrochemical oxidation technologies were the best choices to be integrated with other approaches since they can remove both organic and inorganic contaminants from wastewater.

Small sludge is formed by the flotation method. Therefore, this technique is a great candidate to be incorporated into creating a successful and affordable electrochemical treatment system.

The stability and reusability issues with the ion exchange method are comparable to those with adsorption techniques, where further research may be necessary. With minimal chemical use and no sludge generation, the photocatalyst approach enables straightforward treatment. It is still being researched, is pH-dependent, has low throughput, and is useless when different metals are present.

CONCLUSION

The most effective way to remove heavy ions from sewage depends on a number of important criteria, including the cost of operation, the metal ions' initial concentration, the effect on the environment, the pH levels, the chemicals used, the effectiveness of the removal, and the viability from an economic standpoint. These procedures can be broken down into four groups: adsorption treatments (using different adsorbents, including carbon-based, carbon-composites, minerals, CS, magnetic, biosorbents, and MOFs), membrane treatments (such as UF, nanofiltration, microfiltration, reverse osmosis, and electrodialysis), chemical treatments (such as chemical precipitation, coagulation-flocculation, and flotation), and electric treatments.

Adsorption is the most promising technology for removing heavy metal ions from wastewater that has undergone substantial research because of its simple operation, broad applicability, high removal rate, and economical reusability. Nevertheless, the key factors influencing this desire are the choice of inexpensive materials, high uptake, and effective regeneration procedures.

Technically sophisticated and useful are the chemical-based approaches, particularly chemical precipitation. They are also regarded as economical techniques. They depend on the chemical consumed, as opposed to the electrochemical technique, which also depends on electrodes, electrical energy, and other fixed expenditures. However, they produce a lot of sludge and require sedimentation separation.

Because electrodes are passivated, and a lot of electrical energy is used during the electrochemical process, it is a relatively costly technology. In addition, electric approaches are the least developed compared to photocatalytic ones. The photocatalytic process has the advantage of being ecologically friendly because it utilizes fewer chemicals and generates less sludge.

Because the majority of research used synthetic wastewater that contained just one or a small number of metal types, it has been noted that there is a glaring information gap about the effectiveness of treatment strategies for the removal of heavy metal ions from actual wastewater. Therefore, more studies on treating different toxins should be conducted using actual wastewater. The development of low-cost components and methods for heavy metal removal from wastewater should be further researched. The pilot-scale procedure should be the focus of future research as well. Future research should consider the best techniques for obtaining effective metal recovery with minimal environmental harm and at a reasonable cost.

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