American Chemistry Council

CHEMISTRY CREATES AMERICA COMPETES™

REPORT

Chemistry in Semiconductors and Electronics

KEY FINDINGS

Chemistry makes modern living enabled by electronics (mobile phones, computers, EVs, medical equipment, defense equipment, gaming systems) possible.

Without chemistry, electronics production would be impossible.

Chemistry is a critical part of the semiconductor manufacturing supply chain: 500 different process chemicals are required to manufacture a single semiconductor chip.

The CHIPS Act is incentivizing semiconductor manufacturing back to US, and with it, capacity for the highly specialized chemistries.

Policymakers must support producing these chemistries in the U.S.

Introduction

Chemistry plays an essential role in the manufacturing of semiconductors, printed circuit boards, display materials, and other electronic components. These components go into the devices and equipment that make modern living possible. In addition to laptops, mobile phones, gaming systems, and increasingly automobiles, electronics power life-saving medical equipment, sophisticated systems for national defense, and the servers that run the global financial system. None of these advances would be possible without the chemistry that creates these devices.

Over the past several decades, electronics manufacturing has migrated to countries with lower labor costs, mostly in Asia. According to SEMI, around 70% of global semiconductor capacity is in South Korea, Taiwan, and China. The U.S. is the fifth largest after Japan. The COVID-19 pandemic highlighted the vulnerabilities of long supply chains. Recognizing the importance of a robust and resilient semiconductor supply chain in the U.S., Congress passed the Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act in 2021. The Act authorized $52.7 billion in spending to promote the research, development, and manufacture of semiconductors in the U.S. These incentives have leveraged substantial investment in the semiconductor supply chain to the U.S. in recent years. Those investments include materials and chemicals to supply growing domestic demand for the suite of high-purity chemistries needed for semiconductor manufacturing.

In addition to government incentives to promote semiconductor manufacturing in the U.S., demand for chips is growing with the build out of generative artificial intelligence (AI). Generative AI applications (e.g. ChatGPT) will drive demand for more computational power and electronics, which in turn will drive increased demand for the chemistries that enable them.

Electronics Manufacturing in the U.S.

The broader electronics manufacturing industry[1] employs nearly 1.1 million people in the United States producing the technology products that support our modern lifestyle, including laptops, mobile phones, flat panel displays, instruments, and automobiles and the semiconductors and other electronic components that make them work. While electronics products are manufactured in every state, electronics manufacturing is concentrated in several states. The top five states are California, Texas, New York, Massachusetts, and Florida. Together these states represent just over 50% of total electronics manufacturing employment.

Chemistry in Electronics

The production of electronics would be impossible without chemistry. As detailed below, an enormous and diverse portfolio of basic and specialty chemistries are required to transform sand and other basic materials into laptop, mobile phone, or other electronic equipment. Globally, these materials represent a nearly $50 billion business that is expected to grow around 5% per year to supply the world's growing output of electronic products. Even more chemistry is contained in equipment housings, wiring, protective covers, and batteries.

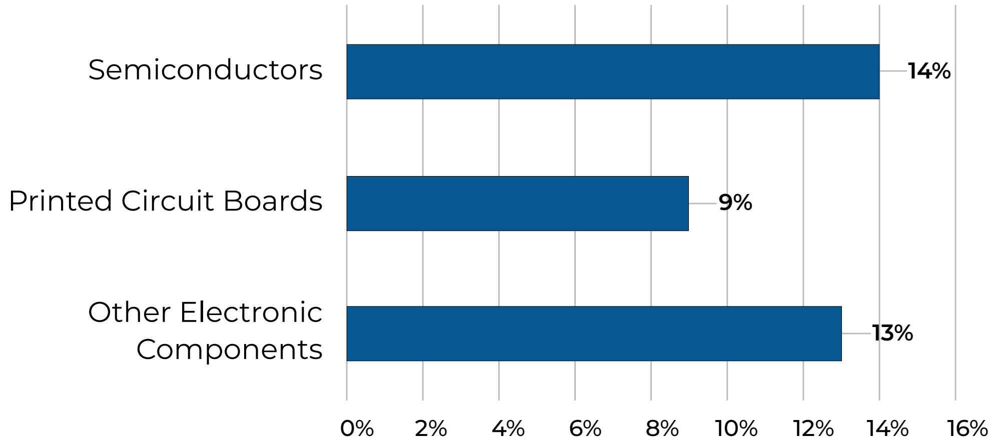
With the resurgence of electronics manufacturing in the U.S., production of electronic chemicals is set to expand. The U.S. currently accounts for less than 10% of the global electronic chemicals and materials market, but that share is set to increase in the coming years. New chemical capacity is being built to support the growing semiconductor capacity across America.

1 NAICS (North American Industry Classification System) code #334
https://www.census.gov/naics/?input=334&chart=2017&details=334

CHEMISTRY CONTENT OF ELECTRONIC PRODUCTS

An analysis of input-output data from the Bureau of Economic Analysis suggests that production of semiconductors, printed circuit boards, and other electronic components is chemistry-intensive. Chemistry products represent an estimated 9–14% of all materials[2] purchased to manufacture electronic device components.

Chemistry Content as a Share of Total Materials



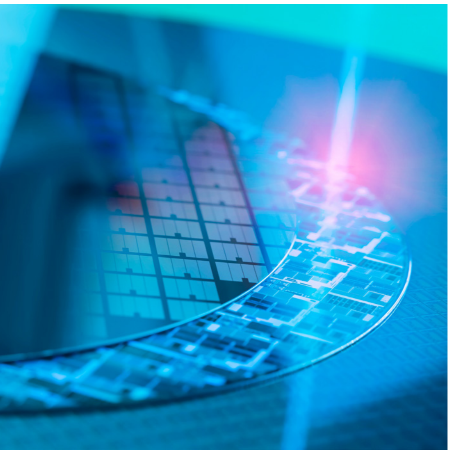
Semiconductors

SEMI notes that 500 different process chemicals are required to manufacture a single semiconductor chip[3]. These materials are typically used in the manufacturing process and do not remain in the final chips. Chemistry is used in each of the multiple steps of the semiconductor manufacturing process including the making of the silicon crystals, cutting and polishing wafers, etching complex circuitry, and improving semiconductor performance.

2 Materials include products of the agriculture, mining, and manufacturing sectors.

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

WAFER PROCESSING



The base material of most semiconductor chips is silicon. While silicon is the second most abundant element in the earth's crust, it is generally found as silicon dioxide in sand or quartz, not as pure silicon. So the first step is to create metallurgical silicon. This is done in a furnace where the silicon dioxide-containing mineral is combined with carbon to separate the silicon[4]. Trace elements of aluminum, calcium, and other impurities are removed using various chemical processes to produce solar-grade polysilicon which is 99.999999% pure (aka "six nines"). To make semiconductors, however, the silicon must be further purified to 99.999999999% pure ("nine nines").

Ingots of single crystal silicon called boules are drawn from molten silicon in an oxygen-free (using high-purity nitrogen or argon gas) environment into cylinders (called boules). The silicon boules are ground to a uniform diameter (up to 12 inches in diameter) and then cut into wafers of about 0.75 mm thickness. Wafers are sliced using a thin wire (often impregnated with synthetic diamonds) passed through an abrasive slurry (containing silicon carbide, boron carbide, aluminum oxide, or other hard abrasive materials).

Dopants (usually inorganic elements or compounds)[5] are introduced into the silicon crystal lattice in controlled amounts to alter its electrical properties to certain specifications. This allows for a very precise configuration of electrical and optical properties (including light emitting diodes (LEDs) and quantum dots).

The rough wafers are then ground to a specific thickness and evenness using abrasive slurries (containing aluminum oxide and other abrasive materials). Surface defects are removed using solvents. The wafers are then polished using abrasive chemical mechanical planarization (CMP) slurries. Slurries are formulated

4 $SiO_2 + 2C \rightarrow Si + 2CO$

5 Phosphorous, boron, arsenic, antimony, and bismuth are among conventional doping materials, though many others exist

for specific surfaces and include abrasive and corrosive chemicals, such as colloidal silica, cerium oxide, alumina abrasives, potassium hydroxide, and ammonium hydroxide. Pads made of polyurethane are used for polishing. Ultrasonic sound waves are very commonly used to remove ultra fine particles from these processes.

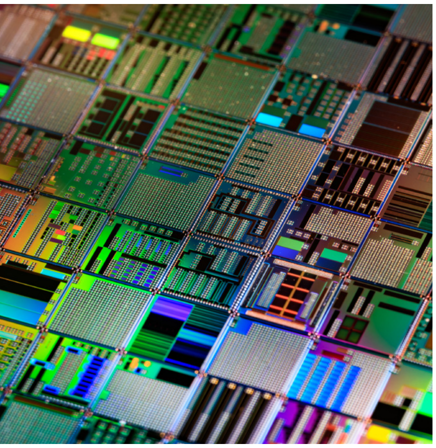
CLEANING

At each step in the manufacturing process, silicon wafers need to be extremely clean to prevent contamination that could affect the performance of the devices. Chemical cleaning processes involving acids, bases, and solvents are employed to achieve this extremely high degree of cleanliness. Examples of chemicals used in cleaning include, isopropanol, propylene glycol ethers, acetone, methylethylketone, n-butyl acetate, 1,1,1-trichloroethane, n-methyl pyrrolidone, sulfuric acid, ammonia, hydrogen peroxide, and hydrofluoric acid.

PHOTOLITHOGRAPHY

Chemicals known as photoresists are used in photolithography to transfer circuit patterns onto the silicon wafer. Photoresist materials undergo chemical changes when exposed to light, allowing for precise patterning of the semiconductor layers. Chemicals used in photoresists include: cyclic polyisoprene resins, glycidyl methacrylate, ethyl acrylate, acetoxystyrene, bisarylazides, diazonaphthoquinones. Additional chemistries are used during photolithography including developers, primers, photoresist strippers. Some chemicals in this category include: tetramethylammonium hydroxide, n-methyl pyrrolidone, hydroxylamine and ethanolamine, diethylene glycol monobutyl ether, propylene glycol monomethyl ether acetate, hexamethyldisilazane. Deep UV gases used during lithography include mixtures of argon, fluorine, neon and krypton.

DEPOSITION



Once the wafers are manufactured, the next step is building the complex circuitry. Layers of various materials (metals, insulators, semiconductors) are deposited onto the silicon wafer surface to build up the desired circuitry. This is accomplished by chemical vapor deposition (CVD) requiring specialty gases in highly controlled environments. In some places on the wafer, the silicon is exposed to oxygen to create a thin film of silicon dioxide to protect certain sections from etching.

ETCHING

Circuits are also etched onto wafers by selectively removing layers of silicon dioxide or other materials deposited on the silicon wafer. Etching can be accomplished using wet or dry processes. Wet processes involve submersing wafers in acids, including hydrochloric acid, sulfuric acid, ammonium hydroxide, tetramethylammonium hydroxide, ammonium fluoride and hydrofluoric acid. Dry etching is used to create patterns on wafers using specialty gases, such as silane, phosphine, tungsten hexafluoride, arsine, carbon monoxide, fluorocarbons, sulfur hexafluoride, and nitrogen trifluoride.

PLATING AND OTHER PROCESSING

Some silicon wafers are further treated to impart specific dielectric, efficiency or other performance characteristics. Additional processes include annelaling, epitaxal layering (using tetrachloride or trichlorosilane gas), insulating (using a thin layer of silicon dioxide), and ion implantation. Some dielectric materials include trimethylcyclotetrasiloxane, octamethylcyclotetrasiloxane, dimethyldimethoxysilane, diethoxydimethylsilane, oxynitride, hafnium silicate, hafnium silicon oxynitride, zirconium tetrachloride, hafnium tetrachloride and oxides of tantalum, hafnium, and zirconium.

Metals can be applied to specific locations on the wafer in order to create transistors. Metallic compounds such as copper sulfate, aluminum oxide, titanium oxide and nickel compounds are used to impart these compounds onto wafer surfaces.

INDUSTRIAL GASES

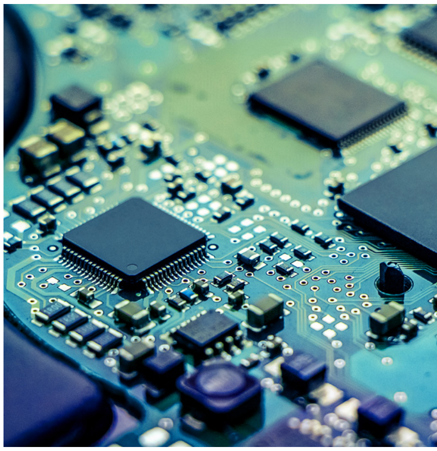
Throughout these processes, large quantities of high-purity industrial and specialty gases are used to create controlled environments. These gases include nitrogen, argon, oxygen, helium and hydrogen.

SEMICONDUCTOR MANUFACTURING EQUIPMENT

In addition to the vast array of chemistries used to produce semiconductor chips, there is also chemistry used in the highly sophisticated equipment. Fluoropolymers are used to protect semiconductor manufacturing equipment to protect process vessels, pipes, and valves from high-purity fluids to prevent corrosion and contamination.

Printed Circuit Boards

Printed circuit boards (PCBs) are the backbone of electronic devices. PCBs are like a roadmap that help electronic components (semiconductors, resistors, capacitors, etc.) work together. They are made of non-conductive base materials with pathways and connections etched or printed onto their surface using conductive materials, including copper.



The base of many rigid circuit boards is often a fiberglass mat or copper foil laminated with plastic resins, such as epoxy, bismaleimide, phenolics or polytetrafluoroethylene (PTFE). Flexible PCBs can use polyester or polyamide films as a base.

After being treated with formaldehyde to create a uniform, smooth surface, a copper layer is added to define the circuits

using copper salts and other plating chemicals. A solder mask (made of acrylic, polyurethane, or epoxy in combination with hardening agents and photoinitiators) is applied to insulate the copper and protect it from coming into contact with other materials. The solder mask is what gives PCBs their distinctive green color. Multiple layers can be constructed with epoxy laminate separating the layers.

Etching is also performed on PCBs to remove copper in certain places. Etchants for PCB manufacturing include cupric chloride, sulfuric acid, and hydrogen peroxide.

As with semiconductor manufacturing, cleanliness is critical during production of PCBs. A number of solvents and other cleaners are used to remove residue during PCB manufacturing, including acetone, isopropanol, 1-bromopropane, and cupric chloride.

Finally, a silkscreen layer is added to print labels and codes onto PCBs using specialty inks.

Specialty solder and adhesive pastes are used to attach electronic components, connectors, etc. to PCBs. Epoxy resins are used to encapsulate semiconductor packages and electronic components. Silicones are used as buffer materials in semiconductor packages.

Plastics, such as polymethyl methacrylate, ABS, and nylon are used connectors and sockets on PCBs. These housings provide mechanical support and insulation for electrical contacts, ensuring reliable connection and preventing damage to the PCB and other components.

In recent years, the entire process to fabricate PCBs has become fully automated. Throughout the PCB manufacturing process, chemistry is integrated into various steps to control material properties, facilitate precise patterning, promote adhesion, and ensure the overall functionality and reliability of the finished circuit boards.

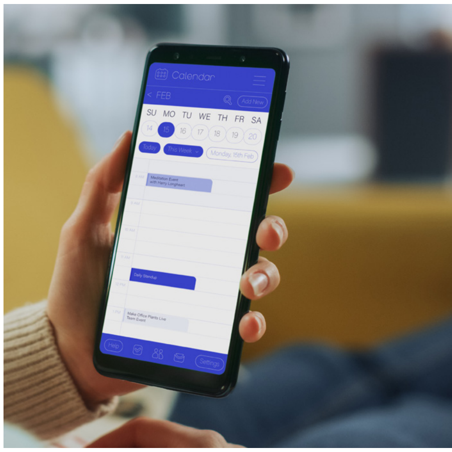
Electronics Display Materials

Computer monitors, televisions, instrument displays, and mobile phones use a variety of display materials supported by chemistry. Electronic displays involve multiple layers of specialty films and the application of metallic layers. The two primary technologies for electronic displays are light-emitting diode (LED) and liquid crystal display (LCD).

LEDs use an array of semiconductor materials that emit light when electric current passes through it in combination with additive color mixing. LCDs contain a layer of liquid crystals, chemicals with unique properties that manipulate light passed through it to create images. In addition to the primary image generating technology, LEDs and LCDs include insulating layers (including silicon nitride), an electrode layer (including indium tin oxide) and color filters.

Putting it All Together

Finished electronic devices combine semiconductors, printed circuit boards, and other electronic components inside a housing, often with a display.



The outer shell of most electronic devices includes durable, lightweight plastics. In addition to protecting sensitive electronic components, plastics are inherently insulating and also allow for an almost infinite number of shapes and designs. Plastics are also used in keyboards, computer mouses, game controllers, etc. They’re also used in fan assemblies to cool electronic devices.

Housings for consumer electronics like laptops and cell phones use a variety of materials, including acrylonitrile butadiene styrene (ABS) and polycarbonate.

Electrical connectors join current-carrying devices. Nylon and polybutylene terephthalate are popular materials for electrical connectors. Other materials include polycarbonate, sulfone polymers, silicones, polypropylene, and PTFE.

Wires conduct electricity to and through electronic devices, but those wires must be insulated to reduce the risk of short circuits, electric shock, and fires. Wire insulation also protects the wire and resists electrical leakage. Many materials are used in wire insulation, with the most common being polyvinyl chloride (PVC). Other resins used in wire insulation include chlorinated PVC, polyethylene, polypropylene, polyurethane, nylon, and fluoropolymers (including PTFE and polyvinylidene fluoride (PVDF)).

Elastomers, including silicones and thermoplastic polyurethanes are used as sealing materials inside electronic devices and to provide shock absorption. In addition, elastomers may be added to device housings (including mobile phone cases) to provide grip.

To reduce the risk of fire, flame retardant chemicals are often added to wire insulation, laminate resins, housings, etc.

Conclusion

Chemistry is foundational to the manufacture of the electronics that power modern living today. With the evolution of generative AI and the wave of investment in semiconductor supply chains, more chemistry will be needed to supply the return of electronics manufacturing to the U.S., including existing chemistries and chemistries that are on the cutting edge of innovation. The U.S. must not fumble the opportunity to become a world leader in advanced electronics production. Policymakers must support producing these chemistries in the U.S.

DISCLAIMER

Appendix – The ABCs of Chemistry in Semiconductors & Electronics

A list of selected chemistries used in semiconductor and electronics manufacturing.

CHEMICAL	CATEGORY	USE
Acetone	Cleaning Solvent	Removing residues during PCB manufacturing.
Acrylic	Solder Mask Material	Insulating copper tracks on PCBs and protecting them.
Aluminum Oxide	CMP Slurries	Polishing and planarizing silicon wafers.
Aluminum Sulfate	Cleaning Agent	Cleaning and etching PCBs.
Ammonia	Cleaning Agent	Cleaning and etching PCBs.
Ammonium Fluoride	Etching Chemical	Selective removal of materials to create circuit patterns on PCBs.
Ammonium Hydroxide	CMP Slurries, Etching Chemical	Polishing and planarizing silicon wafers; cleaning and etching PCBs.
Argon	Industrial Gas	Creating controlled environments during semiconductor manufacturing processes.
Arsine	Dry Etching Gas	Creating patterns on wafers in semiconductor manufacturing.
Boron Carbide	CMP Slurries	Polishing and planarizing silicon wafers.
Boron Nitride	Insulating Material	Thermal management in electronics.
Carbon Monoxide	Dry Etching Gas	Creating patterns on wafers in semiconductor manufacturing.
Cerium Oxide	CMP Slurries	Polishing and planarizing silicon wafers.
Chlorinated PVC	Wire Insulation	Insulating wires in electronics to prevent short circuits and electric shocks.

CHEMICAL	CATEGORY	USE
Colloidal Silica	CMP Slurries	Polishing and planarizing silicon wafers.
Copper Sulfate	PCB Plating Chemical	Depositing conductive layers on PCB surfaces.
Cyclohexanone	Cleaning Solvent	Cleaning residues in semiconductor manufacturing.
Diethylene Glycol Monobutyl Ether	Photoresist Chemical	Developing semiconductor layers in photolithography.
Dimethyl Sulfoxide	Cleaning Solvent	Removing residues in semiconductor manufacturing.
Ethyl Acrylate	Photoresist Chemical	Patterning circuit patterns onto silicon wafers in photolithography.
Fluorocarbons	Dry Etching Gas	Creating patterns on wafers in semiconductor manufacturing.
Glycidyl Methacrylate	Photoresist Chemical	Patterning circuit patterns onto silicon wafers in photolithography.
Hydrochloric Acid	Etching Chemical	Selective removal of materials to create circuit patterns on PCBs.
Hydrofluoric Acid	Etching Chemical	Selective removal of materials to create circuit patterns on PCBs.
Methanol	Cleaning Solvent	Cleaning residues in semiconductor manufacturing.
Methylethylketone	Cleaning Solvent	Cleaning residues in semiconductor manufacturing.
Nitrogen	Industrial Gas	Creating controlled environments during semiconductor manufacturing processes.
Phenolics	PCB Base Material	Providing mechanical strength and insulation for PCBs.
Polybutylene Terephthalate (PBT)	Electrical Connector Material	Used for electrical connectors in electronics.

Polycarbonate	Housing Material	Used for housings of electronic devices due to durability and impact resistance.
Polyethylene	Wire Insulation	Insulating wires in electronics to prevent short circuits and electric shocks.
Polypropylene	Wire Insulation, Housing Material	Insulating wires and providing mechanical support in electronics.
Polytetrafluoroethylene (PTFE)	Housing Material, Wire Insulation	Used for housings and wire insulation in electronics due to its non-stick and high-temperature resistance properties.
Potassium Hydroxide	CMP Slurries	Polishing and planarizing silicon wafers.
Propylene Glycol Monomethyl Ether Acetate	Photoresist Chemical	Patterning semiconductor layers in photolithography.
Silicon Dioxide	Insulating Material	Used in various forms such as silicon nitride for insulating layers in electronics.
Sulfuric Acid	Etching Chemical	Selective removal of materials to create circuit patterns on PCBs.
Tetramethylammonium Hydroxide	Etching Chemical	Selective removal of materials to create circuit patterns on PCBs.
Tungsten Hexafluoride	Dry Etching Gas	Creating patterns on wafers in semiconductor manufacturing.
Vinyl Acetate	Solder Mask Material	Insulating copper tracks on PCBs and protecting them.

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