

Topic Hub: Semiconductor Manufacturing Subsection : Operations

Semiconductor manufacturing refers to the series of manufacturing processes which produce packaged integrated circuits (ICs), often referred to as chips or microchips. The industry also produces discrete (or single) semiconductor devices, such as a transistor or diode, that are elements of an integrated circuit.

According to Semiconductor Manufacturing Technology Consortia (SEMATECH) a global industry association working to accelerate technology innovations in semiconductor manufacturing, advanced chips can now contain close to one billion transistors. As transistors, capacitors, and other components shrink in size, and the density of components on a chip increase, new manufacturing materials, tools, and techniques are necessary [1].

The circuit pattern (including transistors, capacitors, and associated components and their interconnections) is designed via computer modeling and tested by simulation. Producing the structure on a silicon wafer requires several hundred separate steps, including in-progress inspections and cleaning. One chip may take a month or more to complete.

The primary production processes are discussed generally below. The discussion excludes crystal growth and wafer production because most fabs obtain single crystal ingots from other firms. These chip production processes are specific to silicon-based chips, which comprises the majority of chips produced.

Note: The information is subject to change because semiconductor products and manufacturing processes evolve fairly rapidly. For instance, the industry converted to 300mm wafer sizes within the past several years, and is currently considering transition to the next wafer size, at 450mm. These industry conversions to larger wafers are challenging but offer definite chip production advantages.

Primary Processes

- Ultrapure water production;
- Chip fabrication;
- Final layering and cleaning; and,
- Assembly and packaging.

Ultrapure Water (UPW) Production

UPW is used in wafer production, standard wet cleans, and other wet processes such as some etch processes, solvent processes and chemical mechanical planarization (CMP), and rinses. The amount of UPW use in a given fab can vary widely and may be an opportunity for pollution prevention. For example, a 2002 study estimated more than 3,000 gallons of UPW are used per 8-inch wafer. However, published data in 2003 suggests UPW consumption per wafer can be up to 80% less [2].

Fabs often produce their own UPW from local feed water. In general, 1,400-1,600 gallons of city water is needed to produce 1,000 gallons of UPW. Purity of UPW is important because even a miniscule contaminant can render a device nonfunctional. Contaminants include particles, organic compounds, dissolved ions, and dissolved gases.

UPW generation process is a series of chemical engineering unit operations designed to remove contaminants from water to achieve an ultrapure level. Production involves pumping feed water, filtration, treating with chemicals and possibly heat, then reverse osmosis with chemical treatment, vacuum degasification, storage, ion exchange, ultraviolet oxidation/sterilization, and finally ultrafilter membrane filtration [3].

Chip Fabrication

Wafers from the wafer production process are coated with photoresist, a substance which becomes soluble when exposed to ultraviolet (UV) light that helps define circuit patterns during chip fabrication.

Sophisticated camera equipment, called microlithography or photolithography, uses masks (like stencils) and UV light to imprint patterns on the resist-coated substrate. Then, etching removes oxide within the developed pattern, and exposes bare silicon. After the etching operation, remaining photoresist is removed, typically by immersion in a stripping solution, and then dried.

The lithography equipment often runs around the clock, for weeks on end. The equipment pushes the state of the art in many different areas - optics, metal work, laser alignment, and climate control. Photolithography is the most crucial



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step in semiconductor manufacturing because incorrect pattern alignments ruin or distort the electrical functions of the semiconductor.

Dopants are applied to the patterned wafer surface, typically using diffusion or ion implantation. Additional layers of silicon or silicon dioxide may also be applied to the wafer using deposition techniques. Other materials used in the circuit manufacturing process as thin films, include aluminum, gallium, gold, beryllium, germanium, magnesium, silicon, tin, and tellurium.

Additional layers are applied sequentially by growing a thin covering of silicon dioxide over the ridges and etched areas of the wafer base, adding polysilicon, and then repeating the above steps to create a new pattern. This creates windows that allow for connections. Etching and cleaning are required with each new layer. The exact number of layers depends on the design but may run as high as 20 layers.

Once the wafer is patterned, the wafer surface is coated with thin layers of metal by metallization. These metal layers perform circuit functions within the finished chip by making contact at any place where bare silicon exposes the circuit device. External connections to the silicon wafer are provided by evaporation of thin metal films onto areas of the semiconductor chip surface in a vacuum.

Final Layering and Cleaning

Passivation reduces chemical reactivity by applying a final coating to seal the circuit and protect it from external influences. The coating may range in thickness from a single layer of silicon dioxide to a relatively thick deposit of special glass. It also insulates the chip from unwanted contact with other external metal contacts.

After all layers have been applied to the wafer, it is typically rinsed in deionized water. The back of the wafer is then mechanically ground (also called lapping or backgrinding) to remove unnecessary material. Testing is conducted to ensure that each chip is performing the operation for which it was designed. The wafer is cleaned again after testing, using solvents such as deionized water, isopropyl alcohol, acetone, and methanol.

Assembly and Packaging

Most packaged ICs are assembled onto printed circuit boards (PCBs) by a separate manufacturer. However, some packaged ICs, such as microprocessor upgrades and memory modules, are used without pre-assembly onto a circuit board.

Semiconductors are typically assembled by mounting chips onto a metal frame, and connecting the chips to metal strips (leads) which provide the connections for the electronic components. Next, the device is enclosed to protect against mechanical shock and the external environment. The device is then mounted and adhered to an "attach pad" with an epoxy material (thermoset plastic) to make the "package."

The combined components are then placed into a molding press, which encases the chip, wire bonds, and portions of the leads in plastic. After the molding compound cures and cools around the package, the package is heated again to ensure that the plastic is completely cured. Final steps in package fabrication include trimming and forming the leads.

The assembly is cleaned and inspected several times during these processes. Even though the chips are produced using the same process, some may function better than others. As a result, final computer tests separate the chips into low- and high-quality circuits. Often, low-quality circuits can still be sold.

Cleanliness Requirements

Cleaning precedes and follows many of the manufacturing process steps. Wet processing, during which semiconductor devices are repeatedly dipped, immersed, or sprayed with solutions, is commonly used to minimize the risk of contamination.

Manufacturing semiconductors requires an ultraclean process to ensure purity. This purity is vital to ensure the semiconductor can act as a circuit at practically the atomic level. The primary reason that semiconductors fail is contamination, particularly the presence of microscopic residue (including chemicals or dust) on the surface of the base material or circuit path. A particle as small as 0.5 microns (as small as a single bacteria cell) can completely



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destroy a circuit.

Cleanrooms are maintained at various levels of cleanliness. Cleanrooms are rated by Class, using the U.S. Federal Standard 209E. A Class 1 clean room has no more than one particle per cubic foot that is larger than 0.5 micron. Class 2 has no more than 2 particles per cubic foot that are larger than 0.5 micron, and so on. Clean rooms may be rated as class 1000, class 100 or class 10 or better, depending on cleanliness requirements.

Inputs and Outputs

Researchers have published several life-cycle analyses of semiconductors. Although some within the industry have now converted to 300mm chips, and this data does not apply directly to 300mm wafers, it still illustrates the amount of resources required to produce chips. One study suggested that producing a 2.0-gram chip requires at least 72 grams of chemicals, and 1.6 kg of fossil fuel for its fabrication [4]. Other studies have shown significantly lower resource intensity. In general, improvements in manufacturing materials / energy consumption occur with each new semiconductor manufacturing generation [2].

Electricity consumed by the U.S. semiconductor industry is estimated at around 13,000 gigawatt-hours per year, about 1.56 percent of total industrial electricity use for all industry sectors in 2002 [5]. Most of the energy is used in (or by) air handling, production tools/equipment, and deionized water and ultrapure water (UPW) production. About 20% of energy use is tied directly or indirectly to pumps that are used in many different aspects of production.

Heating, ventilation, and air-conditioning (HVAC) energy intensities are high in cleanrooms to maintain ultraclean air. Air handling equipment includes fans, vacuums, exhaust systems, makeup and recirculating air systems, compressed air supply, filtration, and chillers. Class 100 clean rooms require ceiling filters covering 100% of the ceiling. The air changed in cleanrooms occurs many times per hour, and fans run 24 hours a day, seven days a week.

A large, modern fab complex can use a few million gallons of water per day [7]. About 70% of the water is deionized and ultrapure water (UPW) for washing and rinsing during manufacturing. These include standard cleans, wet etch, and chemical mechanical planarization (CMP). Wafers must often be cleaned redundantly between processes. Etch processes (which typically use acids), solvent processes, and tool cleaning steps consume the remainder of the UPW. The remainder of industrial water (excluding bathrooms, kitchens, and irrigation) is for cooling.

Water use is inextricably linked to energy use due to pumping water through the plant, producing UPW (which involves UV lamps, filters, pumps, and recirculating systems), and wastewater treatment.

Chip manufacturing primarily uses wet-chemical processing involving hydroxylamines, mineral acids, elemental gases, and organic solvents during the various stages. Some of the bulk carrier gases include argon, carbon dioxide, hydrogen, helium, nitrogen, and oxygen. Additional specialty process gases are also required for current manufacturing processes.

The industry uses several perfluorinated compounds (PFC) as heat transfer fluids and in etching and chemical vapor deposition - that result in potent greenhouse gas emissions. Consumption of these gases has reduced in the last decade, but they remain unsurpassed in their process performance as well as in their low safety and health risks. Member companies of the Semiconductor Industry Association (SIA) forged a voluntary agreement with the US Environmental Protection Agency which enabled the industry to continue its use of PFCs, while committing to a reduction program which targets the reduction of PFC emissions by 2010 to a level 10% below the level of emissions in 1995. Currently, SIA members are working with the Intergovernmental Panel on Climate Change (IPCC) to update the PFC emission inventory process to better reflect methods underway to reduce PFC emissions.

Various metals (received in the form of a "metal target") are oxidized and deposited on the wafer to create thin films and conductivity throughout the processor. Target metals may include aluminum, copper, gallium, gold, beryllium, germanium, magnesium, silicon, tin, and tellurium.

The European Union's Restriction of Hazardous Substances (RoHS) legislation restricts the use of six specific chemicals in electronic components, from July 1, 2006. Of these six, lead is most widely used in semiconductor manufacturing. RoHS allows lead to exist as an impurity below 1000 ppm. Reduction and phaseout efforts are underway by U.S. and international electronics manufacturers. Challenges remain in the quest to completely eliminate lead so it is still used in limited, exempted applications. One such exemption is the use of lead in semiconductors in the first level interconnect ("flipchip" application) which is an exempted application under RoHS



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[8,9].

Additional materials and elements used in the process are listed at [Materials Used in Semiconductor Manufacturing](#).

Semiconductor manufacturing generates a wide variety of waste streams, including solid waste, slurries, spent solutions (e.g., solvents, acids, cleaning solutions, resist material, etchant solutions, electroplating solutions, and developing solutions), wafer rinse waters, spent metal targets, and other wastewater sources such as wet air pollution control and machine cooling lubrication. Effluent discharge monitoring data for SIC 3674 shows a wide variety of pollutants monitored, including nutrients, cyanide, fluoride, metals, solvents, residual chlorine, and hydrogen peroxide [10]. Ultrapure water residuals are often recycled and reused.

Emissions are generated as well. Acidic and volatile organic compound (VOC) emissions are generated during thin film and patterning and photoresist, respectively.

PFC emissions (which are greenhouse gases) result from dielectric wafer etch and chamber cleaning processes. (Per above, the industry has significantly reduced these emissions in the past decade). The US EPA published in 2005 an interim report summarizing the progress made in PFC emissions reductions [11]. Among the key points:

- As advanced 200 mm and 300 mm wafer fabs began ramping in 2001-2004, the normalized rate of emissions (PFC emitted/cm²) decreased, most likely due to the use of NF₃-based chamber clean processes.
- Based on the changes brought about by shifting wafer sizes and the projected acceleration in the transition from old technology to new, there is strong reason to believe the normalized rate of PFC emissions will continue to decline through 2010.
- The U.S. semiconductor industry achieved the 10% reduction goal in 2003 and surpassed the goal in 2004, despite a significant increase in wafer demand over time.

A P2 Challenge

Like other industries driving continuous environmental improvement poses challenges. With many industries, corporate culture can be risk-averse due to high-precision process requirements, safety risks, the high cost of downtime, and extreme competition.

When something works smoothly, such as exceptionally complex wafer fabrication tools made by highly specialized suppliers, or an air handling and recirculation system, or even an entire facility design, it is often copied for future generations. This saves some time and initial cost, yet can hinder improvements outside the clean room, including energy efficiency and water conservation. At the same time, the rapid evolution of manufacturing processes enables the semiconductor industry to implement environmental process improvements more quickly compared to other industries whose processes undergo changes at a much slower pace. The Pollution Prevention Opportunities and Links sections will show some of the advances that have occurred recently to improve environmental performance.

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