Chemical Engineers in Action

INNOVATION

CHEMICAL ENGINEERS IN SEMICONDUCTOR MANUFACTURING

Semiconductor chips are an essential enabling technology for many tools, gadgets, and devices that are a hallmark of modern life and provide inexpensive, fast computing power for electronic devices ranging from children's toys, digital wristwatches, household appliances, mobile phones, and automobiles to complex medical and industrial sensors and sophisticated communication satellites.

Chemical engineers have contributed not only to the invention of semiconductor devices, but also to the ongoing development of advanced materials manufacturing processes to produce such devices as optical lithography techniques, ion implantation, chemical vapor deposition, and dielectric etching. They design and build the complex systems to meet the stringent clean requirements for the commercial-scale production of finished chips.

Thanks to the ingenuity and creativity of chemical engineers, great strides have also been made in the rigorous process control systems and quality control procedures for manufacturing these high-precision devices. The size of semiconductor chips and electronic devices continues to shrink. At the same time, advances in semiconductor design and manufacturing enable the continuous improvement of the data density of modern chips and the diversity and number of functions that the resultant electronic devices can perform. The current generation of semiconductor chips (64 MB) can store 3,355 pages of text on a device that is approximately the size of a dime.

There are about 5,000 semiconductor and electronic components manufacturers in the U.S. as of 2004 generating about $165 billion in annual sales, according to the *U.S. Industry & Market Outlook* by Barnes Reports (Bath, Maine; www.barnesreports.com). This figure, however, represents only a fraction of the overall value of this industry. Today, many other nations such as Israel, Japan, Taiwan, Korea, Singapore, China, and European countries have strong manufacturing capabilities of semiconductor devices.

An ingenious invention

Turning silicon into semiconductor chips is a meticulous undertaking that requires the multidisciplinary expertise of chemical engineers, chemists, material scientists, metallurgists, electronics experts, and many other technical professionals. During the process, a pure monocrystalline ingot of silicon (typically 6 to 12 in. in diameter) is created. The ingot is then sliced into thin wafers (each less than 1/40-in.-thick). The wafers are polished using a specialized technique called chemical-mechanical planarization, which relies on nanoscaled particles of silica, alumina, cerium and other abrasives blended into a polishing slurry.

The highly polished wafers then undergo many successive processing steps. Each step deposits a complex layer of a conductor, semiconductor, or insulating material needed to produce the transistors, resistors, and capacitors that together create integrated circuits. Numerous semiconductor chips (ranging from tens to hundreds) are then created on a single silicon wafer. Eventually, a diamond saw is used to cut the wafer into the individual semiconductor chips.

An industry full of promise

Today's semiconductor industry officially started with the invention of the integrated circuit or "microchip" by Jack Kilby and Robert Noyce who are considered to be among the industry's founding fathers. Kilby devised a promising transistor built on a base made from germanium. The entire device measured just 7/16" by 1/16". (A transistor regulates current or voltage flow acting as a switch or gate for electronic signals and uses a small amount of voltage or electrical current to control a larger change in voltage or current. A series of transistors is joined to make an integrated circuit.)

In 1958, Kilby was an engineer newly employed by Texas Instruments who worked on a problem in circuit design called the "tyranny of numbers." At that time, all the components in an electrical circuit had to be wired and soldered by hand limiting performance, and circuit designers had to accommodate this labor-intensive, error-prone handwork, which increased with every component added to a transistor and every circuit added to a design. Kilby reported to the management that the ability to manufacture the circuit components in a group, using a single piece of semiconductor material, could solve this problem. In 1959, he filed for a patent for a "Solid Circuit Made of Germanium," which became the first integrated circuit. The importance of his contributions to this revolutionary field was recognized as a core recipient of the Nobel Prize in Physics in 2000.

Shortly after Kilby's 1959 breakthrough, Robert Noyce of Fairchild Semiconductor developed a new diffusion-based process called planar technology, which allowed discrete layers to be deposited onto the surface of a silicon wafer. Circuit designers could incorporate the necessary number of transistors with a layer of protective oxide deposited at the junctions, and metal interconnections could be created on the flat transistor surface using chemical engineering techniques. This process replaced the need for hand wiring and soldering. Planar technology used silicon, instead of germanium, as the base material, and opened the door for the first commercial-scale production of integrated circuits. Noyce's system became the industry standard and, as the semiconductor industry in

California grew, spurred the adoption of the name "Silicon Valley," in which many of these early semiconductor manufacturing firms were located.

The roots of the industry can be traced back even further to the invention of the original transistor by John Bardeen, Walter Brattain, and William Shockley in 1947 at Bell Labs. Early transistors built on the pioneering work of Lee De Forest, a Ph.D. physicist, who in 1906 invented the Audion, an early vacuum tube that could amplify a weak electrical signal to create a stronger one. (Prior to the development of transistors, vacuum tubes were the main signal regulator used in electronic equipment, but they had such shortcomings as being bulky, fragile and energy-consuming, and producing considerable heat.) Meanwhile, De Forest's work was built on the pioneering efforts of Thomas Edison who invented the incandescent light bulb in the late 1870s. All these inventions have been essential to the ongoing evolution of the digital revolution.

Material matters

A semiconductor is essentially any material whose ability to conduct electricity lies between that of an insulator and that of a conductor. The conductivity and other electrical properties of semiconductors are determined by the material's electronic band structure, which describes the ranges of energy that an electron is "allowed" or "forbidden" to have. As such, the band structure of amaterial determines the material's electronic and optical properties.

The first materials pursued as possible semiconductors were elements and compounds demonstrating poor electrical conductivity when heated. Early experiments included shining light on the materials, which in some cases generated an electrical current that could pass through them in one direction only.

By 1874, electricity was being used not only to transmit power but also to transport information. The telegraph, the telephone, and later the radio were the earliest devices produced by the as-yet-unnamed electronics industry.

Challenge of scale-up

Once the integrated circuit was discovered and the initial semiconductor materials were identified, the industrial focus shifted to tackling the challenges associated with commercial-scale semiconductor manufacturing. Early on, when the line widths associated with electronic circuits were relatively large (on the order of about 10 microns), purity was not as critical to the manufacturing process as it is today. As relentless pressure to make chips smaller drove technological innovation, the potential for damage from contamination rose sharply. As a result, the standards for clean-room construction and operation have become much more demanding.

Fabricating semiconductor devices involves four basic processing steps: deposition of key active materials onto the underlying silicon wafer; selective removal of unwanted materials; patterning or lithography to alter the shape of the deposited materials (to create the desired connections and circuits); and modification of electrical properties using ion implantation followed by activation and other techniques. The current deposition processes include physical vapor deposition, chemical vapor deposition, electrochemical deposition, molecular beam epitaxy, and atomic layer deposition.

Many common chemical engineering concepts are used during semiconductor manufacturing. For instance, the initial growth of the monocrystalline silicon ingot calls for deep understanding and close control of fluid mechanics, heat and mass transfer, and crystallization. Expertise in kinetics and heat and mass transfer is also required during the deposition and etching processes. Meanwhile, the development of the lithography process would not have been possible without expertise in fluid mechanics, rheology, and evaporation. The ability to understand and manage complex solid-state diffusion issues is critical for the development of various doping processes. (*Doping* refers to the addition of a tiny amount of additives to the crystals.)

As chip makers have crammed more and more transistors on ever-smaller chips of silicon and other semiconducting materials, the purity requirements of the chemicals used to manufacture semiconductor devices have also increased dramatically. Today the strict standards these materials must meet—in terms of acceptable levels of dissolved and particulate contaminants and of trace metals—are in a class by themselves.

For instance, when the circuits on semiconductor chips have line widths measured in micrometers and nanometers, the presence of even tiny impurities in electronics-grade chemicals and gases can ruin individual wafers and severely limit a manufacturing facility’s overall semiconductor production capacity. Unless they are removed by engineered solutions, unwanted impurities can occur in the acids, etchants, solvents, resist strippers, and other chemicals used during the manufacturing process. As a result, suppliers of process chemicals, gases, and equipment constantly pursue advanced technologies and procedures to ensure that these critical process ingredients maintain low residual contaminant levels to be measured in parts per million and parts per trillion.

Various engineering controls are used to control impurity levels in manufacturing, storing, and transporting chemicals, process aids, and ultrapure water, as well as during their use by the semiconductor fabrication facility.

The exacting purity standards of the ultrapure water and electronics-grade chemicals used by today's semiconductor facilities are even more stringent than those used in food processing. To meet the standards, engineers must specify the appropriate combination of purification techniques and select the appropriate construction materials for all vessels, piping, valves, pumps, tanks, and other components that contact the ultrapure water and chemicals to minimize the introduction of dissolved impurities. Fluoropolymers and high-density polyethylene are often selected, because they provide nonreactive solid-liquid interfaces.

Purity measurements during the production and handling of ultrapure electronics-grade chemicals and gases are carried out using such techniques as mass spectroscopy, atomic absorption, and ion chromatography. Meanwhile, because defects and variations across the surface of a wafer can depress efficiency and overall yield, a wide range of monitoring and control techniques are also used to help detect and characterize problems early in the process. These techniques include statistical analytical methods, such advanced sensors as light-scattering techniques, optical imaging sensors, and holography, and advanced process control. Using these tools engineers and operators can take appropriate steps or make process adjustments to reduce the number of semiconductors that might be ruined as a result of unwanted impurities in a tainted batch.

Clean room design

Semiconductor fabrication facilities, known as fabs, rely on clean rooms. These specialized rooms use highly engineered systems that meet rigorous industry standards of an absolute absence of contaminants in the manufacturing environment by removing even the smallest particles on the wafers contributing to defects in semiconductor chips and reducing the overall production yield of the facility. As circuits are increasingly packed onto ever-smaller chips, the line widths used to transmit data are etched so thinly that they can barely be seen by the naked eye. Today, a typical dime-size microprocessor chip contains millions of microscopic transistors. At this scale, even the tiniest speck of dust, which would feel like a dinosaur-sized footprint, could obstruct the chip's many pathways, rendering it unstable. Therefore, acceptable contaminant levels inside semiconductor clean rooms are set in the parts-per-billion range.

Modern clean rooms rely on highly engineered systems to capture, contain, and control airborne particles, aerosol particles, chemical vapors, and microbes to meet acceptable levels of contamination. These levels are typically specified in terms of the number of particles of a given particle size per cubic foot of air. Today's semiconductor-manufacturing facilities are extremely demanding: a modern hospital usually has about 10,000 dust particles per cubic foot of air, while the air inside a so-called class-I clean room allows for no more than one particle of dust per cubic foot of air.

To achieve these results, the complex air-filtration systems in modern clean rooms most often use high-efficiency particulate arrestor (HEPA) filtration systems. They employ ultra- and nanofiltration devices to capture airborne particles of the smallest dimensions, achieving residual particle levels in the parts-per-million to parts-per-trillion range.

Clean rooms are also designed to manage and monitor continuously the direction of air flow, the nature of the air flow (to ensure that air flow remains laminar, which is to say smooth, not turbulent), and the number of air changes per hour.

Strict procedures and protocols such as the use of airlocks and air showers are also followed to control the contamination, which workers may bring into the clean-room environment. Workers are typically required to wear specialized protective clothing such as gowns, caps, masks, gloves, and boots made from specialized lint-free, antistatic materials. This clothing not only protects the technicians from the chemicals and other potentially harmful materials used during the semiconductor manufacturing process, it also protects the manufacturing environment and the semiconductor devices from contamination by human beings.

What does the future hold?

Since its inception in the 1970s, the commercial-scale semiconductor industry has experienced unprecedented growth. In 1965, Gordon Moore, a chemist by training and a cofounder of Intel Corp., predicted that the number of transistors on a chip (and hence the chip's processing power) would double every 18 months or so, which is now known as Moore's law. This prediction has held true since the early 1970s, as computer functionality has become increasingly faster, and computerized devices can carry out more operations of increasing complexity. As the performance demands on today's highly sophisticated semiconductor chips continue to grow, so does the need to manufacture increasingly larger batches of chips with ever-greater precision and -smaller dimensions. Along with these pressures comes the need for expanding chemical engineering expertise and ongoing breakthroughs in this area.

Another area of recent industrial focus has been on "clean manufacturing" (or sustainable manufacturing), which is aimed at applying innovative engineering strategies to maximize the reuse and recycling of all ultrapure chemicals, gases, and water. Such reuse allows semiconductor manufacturers to reduce the volume and toxicity of their waste streams. Recycling helps reduce the use of natural resources and minimize the environmental impact of the process, while reducing the overall manufacturing costs.

Advanced rinsing techniques and purification technologies are needed to treat the recycled water and remove the impurities to meet the rigorous cleanliness standards required in each step of the chip-making process. Efforts to maximize the reuse of ultrapure water during semiconductor manufacturing are ongoing. The SRC Roadmap for Sustainable Manufacturing of Semiconductors has developed a plan for reducing the amount of water used per square inch to make a wafer at a given feature size. Current best practices allow for only 13 gallons of water used to produce each square inch of wafer compared to an average of 23 gallons per square inch in 1999. The required amount of water has been reduced incrementally by applying advanced technology improvements. Additional breakthroughs will be required for further improvements.

Another recent breakthrough is the ability to switch from traditional subtractive processes to new additive processes. Current semiconductor manufacturing processes are subtractive in nature, that is, successive layers of metal are first deposited on the surface of the thin round wafers of silicon crystal to create the desired multilayer electronic circuitry. As each new surface is patterned, the excess or unwanted materials are removed by etching, and the surface is polished to ensure that the finished semiconductor wafer is smooth and free of defects. The new processes, however, require fewer processing steps allowing manufacturers to selectively place metal, silicon, or other materials only where needed to create the desired circuitry on the chip surface. This approach can significantly decrease both the amount of raw materials required and the volume of the waste streams produced during manufacturing. This change will enable the semiconductor manufacturing industry to operate in a more sustainable manner in the future.

During semiconductor manufacturing, only a very small amount of the raw materials end up in a finished chip, so further chemical engineering innovation is needed to enhance the ability to recycle and reuse raw materials, where appropriate.