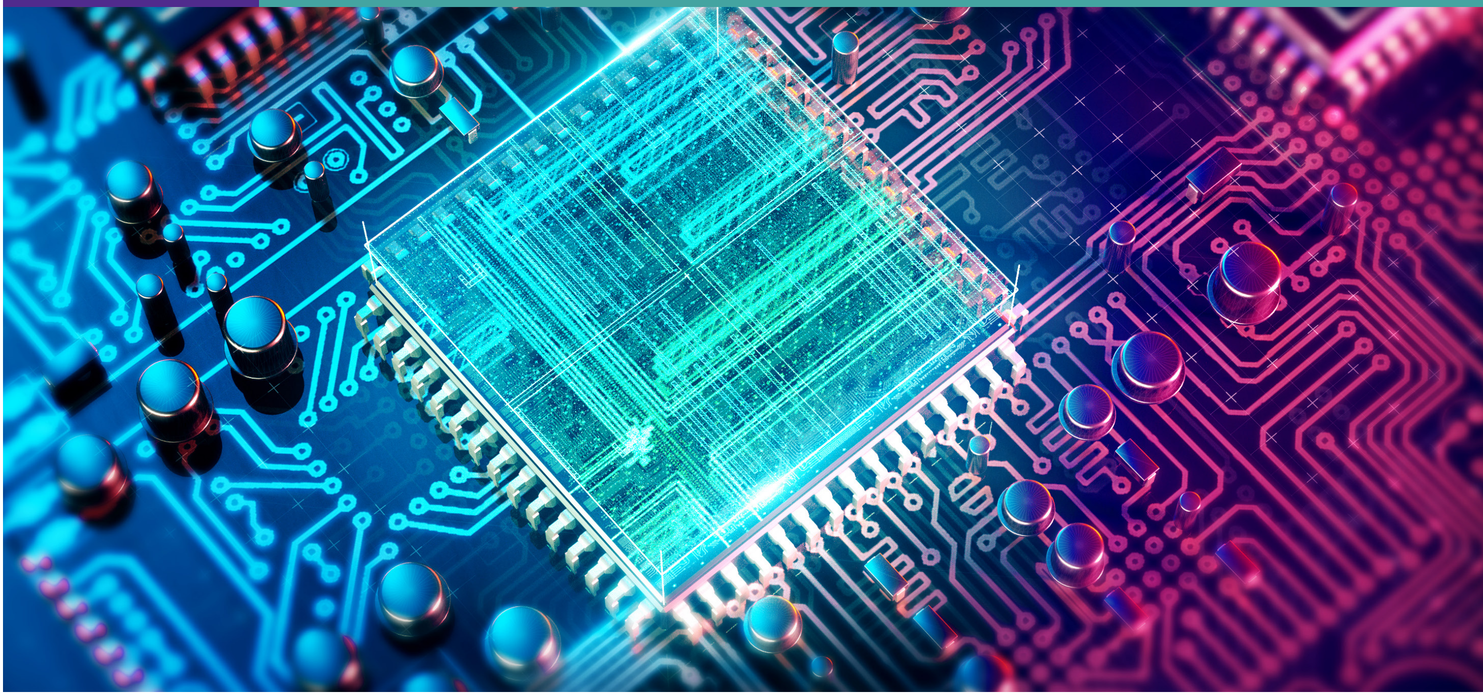
WHITE PAPER

Semiconductors: Status, Challenges, and Trends



Introduction

The small but mighty semiconductor has become an essential part of our high-tech world. Commonly called integrated circuits (ICs) or microchips, semiconductors are used in an ever-growing number of consumer, commercial, and industrial products. A very brief sampling of semiconductor uses includes:

- Personal electronic devices such as computers and tablets, mobile phones, and smart watches
- Household items such as televisions, appliances, LED light bulbs, and heating/cooling equipment
- Commercial and industrial products such as lasers, optical sensors, solar batteries, medical diagnostic equipment, traffic lights, and industrial machinery

The majority of semiconductor demand is driven by products purchased by customers as shown in Table 1.

Table 1. Percent of Semiconductor Demand by End Use, 2019.[1]

Communications	33.0%
PC/Computer	28.5%
Industrial	11.9%
Consumer Electronics	13.3%
Automotive	12.2%
Government	1.3% (includes military)

All of these diverse semiconductor applications share a common thread: the need for electrical properties specific to the application.

A semiconductor is a material that has an intermediate level of electrical conductivity, hence the "semi" prefix. The material is composed of either a single element, typically silicon, or a combination of elements, such as gallium arsenide (GaAs), indium phosphide (InP), and a handful of others.

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The substance most frequently used in semiconductors is the element silicon. Silicon comprises one-quarter of Earth's crust, so it is an abundant resource. It is found in soil, sand, and rock in compound with oxygen, aluminum, and magnesium. For production use, the silicon must be extracted from the compounds and purified to 99.999999999%.

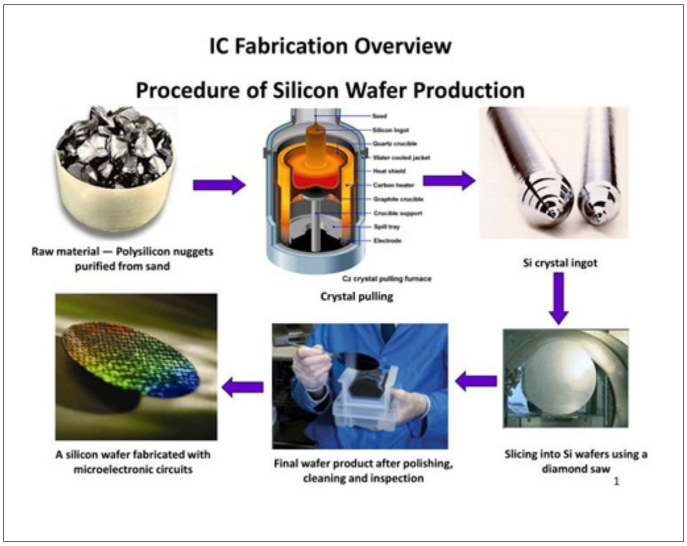

Figure 1. IC fabrication from silicon sand to ingots to wafers with circuitry.

Small amounts of impurities can then be added to change the material's conductivity. This process is called "doping" and can greatly increase the semiconductor's conductivity. Silicon's conductivity also changes based on the ambient temperature, with higher temperatures resulting in higher conductivity.

The great diversity of semiconductor end uses hints at the magnitude of impact the industry has on the global economy. Worldwide semiconductor sales were USD $412.3 billion in 2019. Global semiconductor industry sales are forecast to reach USD $433 billion in 2020.[1]

Global sales of semiconductors were USD $34.4 billion for April 2020, which is a 1.2 percent decrease from March 2020 sales, but a 6.1 percent increase over April 2019 sales. These early 2020 sales indicate minimal impact so far from the novel coronavirus pandemic.[2]

The buyers of semiconductors for electronic equipment manufacturing are distributed around the globe, with the Asia Pacific region purchasing the greatest share:[1]

- Asia Pacific 62.5% (China 35.0%)
- Americas 19.1%
- Europe 9.7%
- Japan 8.7%

Semiconductor Production

Semiconductor production has two primary phases: design and fabrication. Companies that focus solely on design are referred to as fabless firms. Companies that focus only on fabrication are called foundries. Companies that do both the design and the fabrication are called Integrated Device Manufacturers (IDMs).

An overview of the semiconductor production process includes:

Raw Material Processing

- Silicon extraction from raw material
- Purification
- Cylindrical ingot formation, from one to nearly 18 inches (450mm) in diameter, up to 200 pounds each

Research and Development (R&D)

- Semiconductor design
- Process engineering
- Raw and fabrication materials selection
- Quality control (QC) program design

Blank Wafer Production

- Ingots are sliced into 1mm-thick discs or "blank wafers"
- Wafer diameter is adjusted if needed

Wafer Processing

- Multiple layers of transistors and wiring are formed on the wafer surface in an iterative process
- Steps include cleaning, oxidation-diffusion, deposition, photoresist patterning, etching, ion implantation

Wafer Cutting

- Wafer is cut into individual semiconductor units called dies
- Semiconductor chip packaging
- Each finished chip is attached to and encased in protective housing

These main steps are composed of 400 to 600 detailed steps that are typically completed over one to two months.

Challenges

The semiconductor industry has specific needs and faces unique challenges for successful and efficient production.

Detecting Ultra-trace Impurity Levels

Consumers continue to drive the demand for electronic devices that are smaller and lighter without sacrificing speed or reliability. That demand translates to a similar need for smaller and lighter semiconductors that are fast and reliable. The challenge facing fabricators is that the smaller the semiconductor, the more vulnerable it is to interference by chemical and particulate contaminants.

Semiconductor manufacturers need the ability to detect ultra-trace levels of contaminants throughout the fabricating process. Detecting chemical contaminants at the parts per trillion (ppt) level is no longer adequate — parts per quadrillion (ppq) detection limits must now be achieved. Particulates detection must reach nanoparticle size or smaller.

The R&D team must define the purity levels required for each material used in wafer fabrication and packaging:

- Silicon ingots and supplied blank wafers
- Ultrapure water
- Fine chemicals such as acids, bases, solvents
- Inert and specialty gases
- Circuit-building materials such as photoresist material, sputter target, CMP slurry
- Packaging materials such as polymers, resins, dyes, solder, molding compounds, and die attachment materials

R&D identifies the analytical instruments that can achieve the ultra-low detection limits needed for the potential impurities of each material. Sampling and analysis workflows are developed and tested and, once confirmed, implemented for materials receiving and in-process testing.

Maintaining Production Efficiency

There are many opportunities for contaminants or physical defects to be introduced to the wafers as they move through the fabrication process. Such problems can decrease production efficiency or, even worse, cause production delays or product failure. It is crucial, therefore, that a rigorous process QC program be developed, implemented, and maintained. The goal of the program is to catch any problems as early in the workflow as possible to minimize wasted time and materials downstream from the problem.

The R&D team sets the downstream process standards and integrates them into the production workflow design. The process control manager collaborates with the R&D team during design and then implements and monitors the QC program.

Critical monitoring points, materials, and parameters in the production process include:

Blank Wafer Production

- Check for physical deformities and residual particulates after ingot slicing and disc polishing

Clean Room Air

- Airborne molecular contaminants (AMCs) such as volatile and semi-volatile organic compounds (VOCs, SVOCs), metals, acids and bases, and anions
- Airborne particulates
- Air quality parameters such as temperature and humidity

Ultrapure Water

- Contaminants such as anions and cations, silicates, VOCs and SVOCs, organic acids, metals, and total organic carbon (TOC)

Circuit Formation Materials

- Organic and inorganic molecules, ions, acids and bases

Figure 2. Steps of the circuit formation process are repeated to build a multi-layered IC.

To be fully effective at maintaining production efficiency, in-process QC monitoring must be nearly continuous and provide real-time identification of contaminants or specification failures. A high degree of automation minimizes error rates due to manual sampling, and online integration of the monitoring network provides fast turnaround and prompt data reporting.

Regulatory Compliance

Semiconductor manufacturers need to maintain compliance with national, state, and local regulatory requirements. A few nearly universal compliance requirements are considered here.

Permitting

A facility that uses materials that are classified as hazardous will require a permit from national, state, and/or local regulatory agencies to obtain, store, and use those materials. The permit stipulates the types and amounts of materials the facility can obtain, store, and otherwise use in their operations. It also defines the monitoring, record-keeping, and reporting requirements to maintain the permit.

Air permitting is also required for semiconductor production operations. The requirements of the permit will depend on the content of the air emissions and the location of the facility. Air permits stipulate the monitoring, record-keeping, and reporting requirements to maintain the permit.

Employee Health and Safety

Some of the chemicals used in semiconductor production have the potential to release VOCs, SVOCs, and particulate matter to the facility's indoor air. Fabricators need exposure prevention protocols and monitoring programs to confirm compliance with regulatory limits designed to protect employee health.

Some of the components of an effective health and safety program include:

- Personal protective equipment (PPE) requirements
- Target parameters to be monitored
- Sampling and analysis schedule and SOPs
- Analytical sensitivity requirements
- Remedial action alternatives
- Regulatory reporting requirements, schedule, and means
- Record keeping practices
- Other regulatory-specific requirements

A thorough, well-designed health and safety program promotes employee health and safety and helps the company avoid costly regulatory penalties.

Waste Management

Process wastewater and other process wastes are generated by manufacturing facilities of all types. The contents of these and other waste streams produced by semiconductor fabricators depend on the materials and processes used at the facility.

Process wastewater discharge to a treatment facility requires a permit and periodic sampling and analysis. The treatment facility will set the parameters for testing, content limitations, and reporting.

Other process wastes may include off-specification or contaminated materials. Characterization, storage, and transport of the wastes must comply with national, state, and local requirements. A special permit may be required if any wastes are classified as hazardous. The waste disposal or treatment facility will require analytical data on the content of each unique waste stream to ensure their acceptance of the waste complies with the terms of their operating permit.

Minimizing Environmental Impacts

Semiconductor producers, like all manufacturers, must consider the environmental impacts of their operations. In addition to meeting regulatory requirements for emissions and waste disposal, attention to a facility's environmental impacts can help control costs and increase the operational sustainability.

A few practical steps that can move a facility toward these goals are:

- Improving process controls to reduce waste generation and air emissions. This can also increase production efficiency and control costs.
- Using R&D efforts to minimize use of potentially toxic materials in the production process and in the final product. This can reduce costs for waste disposal and the need for special permits or restrictive permit conditions.
- Using R&D efforts to increase the recyclability of electronic waste components. This can improve operational sustainability.

A stormwater pollution prevention plan may be required, depending on the extent of outside storage or operations at the facility. The plan includes sampling and analysis procedures for stormwater discharges, remedial action plans, and record-keeping and reporting procedures.

Trends

There are numerous trends developing in semiconductor design, production, and use. Some have been developing gradually, others are advancing more quickly. The following are a few of the more commonly discussed trends.

Smaller ICs: R&D efforts continue at breakneck pace to further reduce the size of semiconductors. The industry has come a long way from 10 µm technology of the early 1970s to today's 7 nm chips, and industry leaders have even smaller chips in their sights: 5 nm, 3 nm, and beyond. Currently, 7 nm ICs are commonly used, 5 nm ICs are in production, and 3 nm ICs are under development.

Two important goals for 3 nm and smaller chips are to increase performance while decreasing energy use. R&D teams are looking to achieve these advances, in part, by transitioning from finFET to GAAFET technology. As chips reach the 3 nm and smaller sizes, fabricators will also need new equipment and methodologies for lithography, deposition, etching, and QC analytics.[3,4]

Fabless Designers + Independent Foundries: The trend toward more fabless chip design companies continues, and increasing numbers of technology companies are designing their own chips in-house. These trends are driven by the growing need for more specialized, application-specific chips designed for optimization of company-specific software and algorithms.

The fabless design-only and in-house design trends are, in turn, enhancing the need for and success of independent semiconductor foundries. Global expenditures for new foundries are forecast to be USD 50 billion over the next few years. It will be interesting to see how much of the foundry growth is invested in independent foundries.[5,6,7]

Artificial Intelligence (AI): The amount of data processed by AI systems is still increasing rapidly. The semiconductor industry continues to develop new algorithmic-specific chips that provide the processing speed needed for AI data.

Internet of Things (IoT): IoT systems produce tremendous amounts of data that are used to make real-time decisions. The semiconductor industry continues to increase their R&D of new chip architectures, materials, and silicon photonics that will enhance IoT data processing capabilities and stability.

Autonomous Vehicles (AVs): Semiconductors will continue to be a key driver in the successful development of fully autonomous vehicles.

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