Appendix A
Current Microelectronics Technology

This appendix provides general background information about microelectronics technology, the roots of which extend back to the early part of this century. Today, a vast assortment of integrated circuits (ICs) and other miniature electronic devices are on the market. All of these components pass through complex design and fabrication processes before reaching consumers.

Electronics Technology From Vacuum Tubes to Integrated Circuits

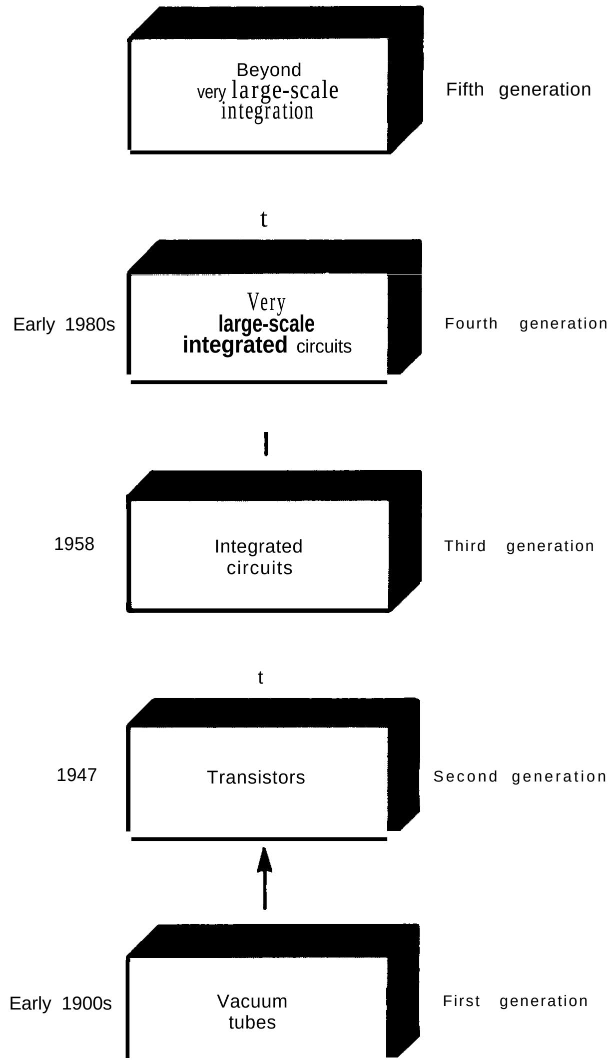
Electronics technology over the last century has advanced in a series of dramatic breakthroughs: the vacuum tube, the transistor, and the integrated circuit. These are often used to designate different generations of technology, as shown in figure A-1.

The history of electronic devices began in the early 1900s with the invention of vacuum tubes, the first devices to reach major use in manipulating and amplifying electrical currents. This technology is limited by several related features. Vacuum tubes require high voltages and, by microelectronics standards, a great deal of power.

The invention of the transistor in 1947 marked the beginning of a new generation in electronics. The inventors fabricated the device from a crystal of semiconductor material to which they added controlled quantities of different impurities. The transistor had three points of electrical contact, or terminals. Like a vacuum tube, it could amplify an electrical signal, but at room temperature, and it required only a small fraction of the power, voltage, and space that tubes demand. The transistor rapidly became the central component in circuits for a variety of applications.

By the late 1950s, transistor-based circuits dominated early computers and military systems. But the drive for increasingly complex circuitry encountered some difficult barriers. Millions of connections were required to turn the hundreds of thousands of components into a functioning circuit—a labor-intensive process with unreliable results. Further complicating things, the total circuit size was growing unmanageable, although the individual components were quite small. The equipment in which electronic devices were used

Figure A-1 .—Generations of Electronics Technology



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demanded smaller, faster circuits that would consume less power and could be fabricated reliably.

The next major breakthrough in electronics was the invention of the integrated circuit in 1958. Until this time, all electrical circuits consisted of separate components-transistors, diodes, resistors, capacitors—connected by wires. The inventors of the IC recognized that the wires and other components could also be fabricated from or on the same semiconductor material that was used to make transistors.[1] In this way, they made an entire circuit on a single piece, or chip, of the material. Using this technique, engineers were able to make connections and components by etching the semiconductor and depositing metals and insulators in patterns on the chip. The new process eliminated many of the problems associated with producing highly complex circuits. Because the huge number of connections no longer had to be made by soldering wires together, the IC technique was more reliable and less labor-intensive. The individual components could now be smaller since they would not need to be handled by people. This shrinkage yielded circuits that operated at higher frequencies and consumed less power.

Progress in microelectronics over the last 25 years has been based on further shrinkage of the circuitry etched onto chips. The number of components per chip has, on average, almost doubled every year, Today, up to 1 million transistors and other components are fabricated on a single chip that may have an area of less than 1 square centimeter.

Microelectronic Devices

In this background paper, the term "microelectronics" is used to refer to miniature electronic devices in general. Figure A-2 shows the types of microelectronic devices on the market today. The most numerous and widely used of these are standard ICs made of silicon. Other semiconductor devices, such as optoelectronic and microwave products and discrete devices, are also part of microelectronics technology. Additionally, a few examples exist of miniature devices made from materials other than semiconductors (e.g., magnetic bubble storage devices), but these fall outside the scope of this paper.

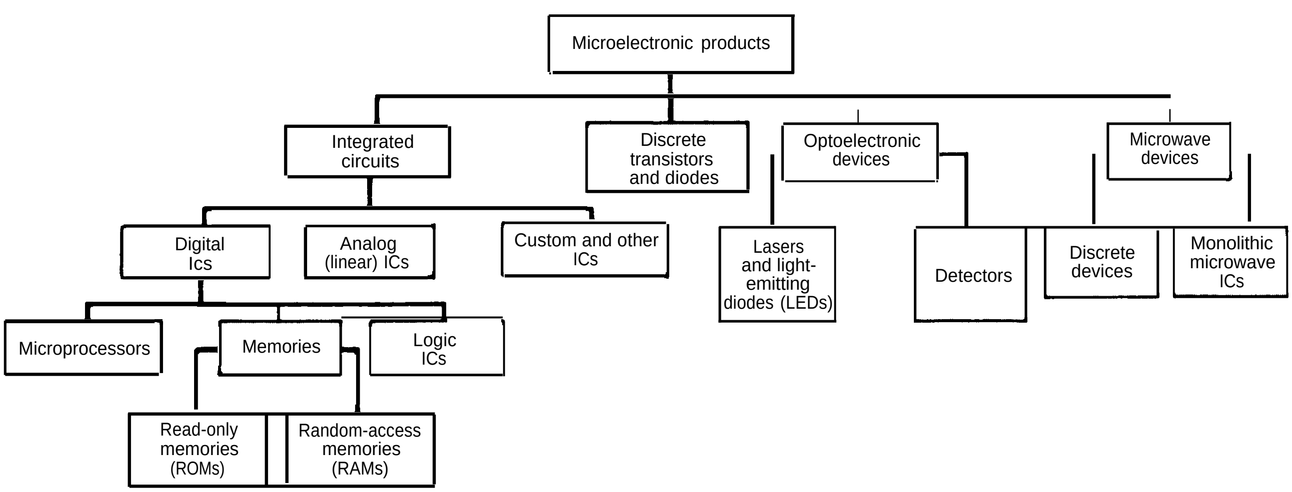
Types of Integrated Circuits

Integrated circuits are commonly classified in a variety of ways and referred to with an impressive number of acronyms. They may be categorized by function, by the level of integration (number of components), by the type of transistors used in the circuitry, or by the underlying material (or substrate) on which they are fabricated.

Types of Functions.–Integrated circuits may be either digital or analog (also called linear). In general, a digital circuit switches or stores voltages that represent discrete values. For example, O volts and 5 volts may represent the values O and 1, respectively. An analog circuit, in contrast, amplifies or otherwise modifies voltages of any value within a given range (e.g., any voltage between O and 5 volts). Some integrated circuits are designed to convert signals from analog form to digital form (A-to-D converters) or vice versa (D-to-A converters). Custom chips can combine the various functions. Currently, the majority of ICs are digi-

[1]For an account of the invention of the integrated circuit, see T. Il. Reid, 'The Chip," Science 85, February 1985, p. 32, excerpted from T.R. Reid, *The Chip: The Microelectronics Revolution and the Men Who Made It* (New York: Simon & Schuster, 1985).

Figure A-2.—Types of Microelectronic Products



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tal; computers, the major use of ICs, are based on digital integrated circuits.

The major product categories in digital integrated circuits are logic circuits, memories, and microprocessors. All three handle information in the form of electrical signals: logic circuits process the signals, memories store them, and microprocessors combine the two functions.

Logic circuits carry out the operations required to manipulate data in binary digital form. They perform mathematical functions. Logic ICs are typically classified according to the type of transistors used to make them.

Semiconductor memories are microelectronic circuits designed to store information. They fall into two groups: read/write memories and read-only memories (ROMs). Although both groups consist primarily of memories that can be accessed randomly (i.e., any storage location can be accessed in the same amount of time), the term "random-access memory" (RAM) usually refers only to read/write memories. A computer can store a datum in a location within a read/write memory and later retrieve it or store a new datum there. However, the computer can only *retrieve* information that is already stored (by some external means) in a ROM. Thus, a ROM may be used to store unchanging information or instructions that the computer needs regularly, while read/write memories are used to store data as they come into the computer and as they are processed.

Read/write memories may be labeled "static" or "dynamic" depending on the design of the circuits that make up the RAM. Dynamic RAMs (DRAMs) store data in the form of charge on capacitors, and so require that the capacitors be recharged regularly-every few milliseconds. Static RAMs (SRAMs), on the other hand, store data by changing the state of transistors in the storage element, a technique that requires a constant flow of power rather than intermittent recharging to maintain accurate storage. Both static and dynamic read/write memories need a constant supply of power to the circuit as a whole to operate.

Designers can program information into read-only memories in different ways. They may put the information in the physical chip design; this type is known as a mask-programmable ROM. Alternatively, chip manufacturers fabricate ROMs that users can program themselves (programmable ROMs, or PROMs)–a much more versatile product. Some varieties of these PROMS can be erased and reprogrammed using light or electrical signals (erasable PROMS, or EPROMs). EPROMs differ from read/write memories in two ways: they typically cannot be reprogrammed by the computer itself, but they need no power source to retain information.

The capacity of a semiconductor memory is determined by the number of bits that it can store. The maximum capacity available in the early 1970s was 1,024 bits, commonly called a kilobit or kbit. Today, 262,144-bit (256 -kbit) RAMs are on the market, and l,048,676-bit (l-megabit) RAMs are just around the corner. Prices for memories have dropped as dramatically as their capacity has risen: memory costs approximately one-thousandth of a cent per bit today.

Because a microprocessor is a complete computer processing unit on a single IC, it can process data expressed in a series of binary digits or bits (ones or zeroes). The number of bits used in the series determines the precision of the datum's digital representation; precision increases with the number of bits. The original microprocessor, made in 1970 at Intel Corp., was designed to handle four bits. The industry introduced 8- and 16-bit microprocessors by the end of that decade and 32-bit microprocessors within the last few years.

Levels of Integration.—The level of integration of an integrated circuit refers to the number of components packed on the chip. The progress in integration since the invention of the IC is shown in table A-1. Figure A-3 shows how a transistor on an IC compares in size with some other microscopic items.

Types of Transistors. -An integrated circuit may also be classified according to the kind of transis-

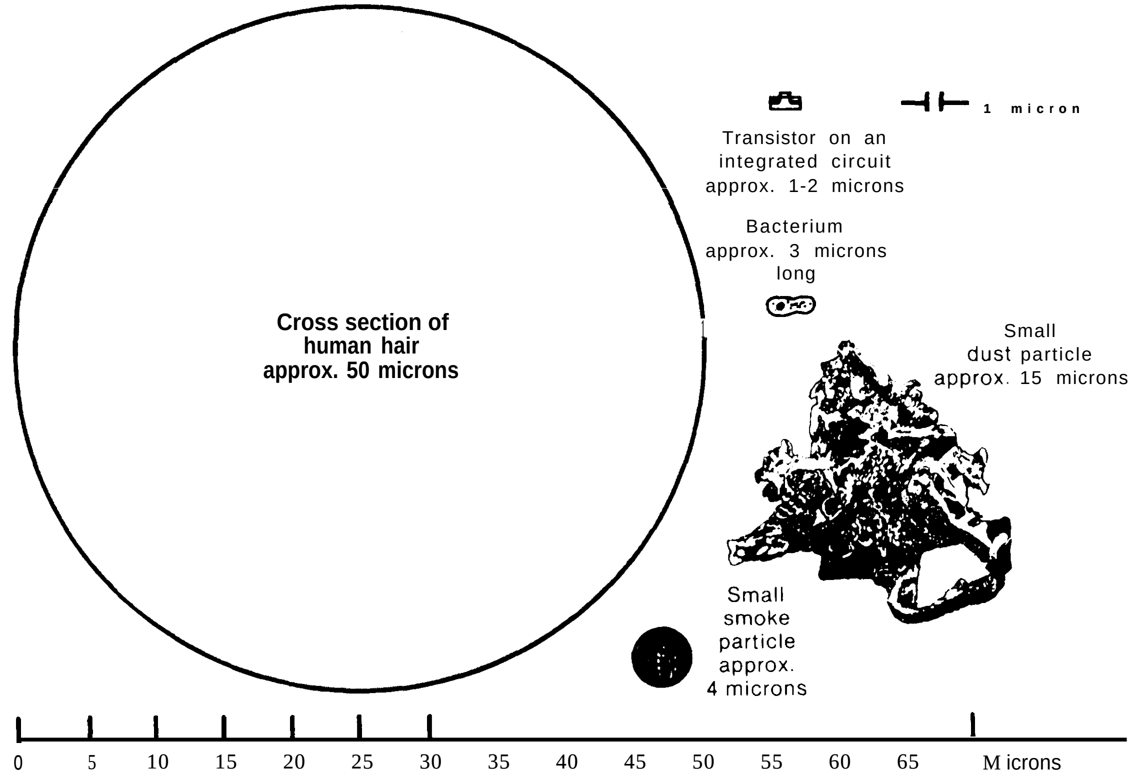
Table A-1 .—Levels of Integration

Level of integration	Design rule (microns)	Number of transistors	Approximate years
Scale-scale integration (SSI)	30-20	2 to 64	1960-65
Medium-scale integration (MSI)	20-10	64 to 2,000	1965-70
Large-scale integration (LSI)	10-3½	2,000 to 64,000	1970-78
Very large-scale integration (VLSI)	3½ -1 1/4	64,000 to 2 million	1978-86
Ultra large-scale integration (ULSI)	<1 l/4	>2 million	after 1986

NOTE The numbers in this table are approximate No standard definition exists for the different integration levels

SOURCE Adapted from James M Early and Bruce E Deal Fairchild Research Center and C Gordon Bell Encore Computer Corp

Figure A-3. —Microscopic Sizes



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tor used in its design. For silicon ICs, two types of transistors are used: bipolar transistors and metal-oxide-semiconductor field-effect transistors (MOSFETs). These are further subdivided to describe the specific structure of the device and the design of the surrounding circuit. The most common bipolar designations are ECL (emitter-coupled logic) and TTL (transistor-transistor logic); the most common types of MOSFETS are NMOS (n-channel MOS) and CMOS (complementary MOS). (See the discussion of chip fabrication in this appendix for some additional details.)

The primary differences between bipolar and MOS technologies are speed (bipolar transistors are faster); power (MOS circuits require less power); and ease of manufacture (MOS circuits have higher yield). Because the yield determines, in large part, the cost of the chip, bipolar chips are typically more expensive. However, the advantage of higher speed is worth the extra cost and power requirements for bipolar ICs in some applications. For example, most makers of large computers use bipolar ICs for the central components in their machines because they are the only chips capable of the high speeds that are required. On the other hand, personal computer vendors tend to base their products on MOS chips, because cost is generally a bigger concern than speed.

Types of Materials.–Virtually all integrated circuits on the market today are made on substrates of the same material that was the base for the first IC: silicon. The longevity of silicon is due to its physical properties as well as to practical economic considerations. Silicon IC technology is more easily executed than is the technology of compound semiconductors, which have more than one element, because the chemistry of a material made of a single element is innately simpler. Furthermore, once silicon technology was established, economic factors dictated that any replacement be far superior to silicon to be worth the large costs of converting to a new system. And since silicon technology has never stopped progressing-or even slowed significantly-attempts to replace it have been shooting at a moving target. The recent decline of Josephson junction technology (which is based on superconductors) for computers has largely been attributed to this problem.

Despite its great usefulness, however, silicon cannot satisfy all demands of microelectronics. Since transistors made from gallium arsenide (GaAs) can be faster and more impervious to radiation damage than silicon transistors, several companies are trying to introduce GaAs integrated circuits. These ICs are particularly attractive for some military applications (e.g., space-based circuitry), and they may also find standard commercial applications. However, they cannot currently compete with silicon technology for standard functions. For example, a fully operational 1,024-bit GaAs RAM is still in the laboratory phase, while silicon RAMs with over 250 times the capacity have been on the market for some time already, (See ch, 3 for a more detailed description of current R&D activities in this area.)

Other Semiconductor Devices

Semiconductor materials are also used to make a host of individual microelectronic devices, as distinguished from standard silicon integrated circuits. These include discrete transistors and diodes, optoelectronic devices, and microwave devices.

Discrete Transistors and Diodes.—Electronic instruments, including radios, televisions, and control instruments, use not only ICs but also individual transistors and diodes. (Diodes are two-terminal devices that allow current flow in only one direction.) These components are typically made from silicon, The transistors may be bipolar or field-effect transistors.

Optoelectronic Devices. -Semiconductors such as gallium arsenide (GaAs), iridium phosphide (InP), cadmium telluride (CdTe), and mercury telluride (HgTe) are the bases for a range of other microelectronic devices that require properties that silicon lacks—the ability to interact efficiently with light and the ability to operate at extremely high speeds or frequencies.

Optoelectronic devices depend on the first of these properties. Optoelectronics includes light-emitting diodes (LEDs) and lasers, which convert electrical signals to light signals, and photodetectors, which convert light signals into electrical signals. The two major applications for these devices are fiber optic communications and long-wavelength infrared light detection.

Fiber optic or lightwave communications systems use glass fibers to transmit light signals from one point to another; the fibers can replace metal wires that carry electrical signals. Semiconductor lasers or LEDs generate the light signals, and semiconductor photodetectors convert the received light signals back to electrical signals. These devices are most commonly made from layers of GaAs and aluminum gallium arsenide (AIGaAs) on a substrate of GaAs, or, more recently, from layers of iridium gallium arsenide phosphide (InGaAsP) and iridium gallium arsenide (InGaAs) on a substrate of InP. The quaternary materials-different compositions of InGaAsP-can generate and detect the wavelengths of light that travel along the glass fibers with the least distortion (wavelength of 1.3 microns) and fading (wavelength of 1.55 microns).

The primary purpose of long-wavelength infrared (IR) detection is to “see” living or hot objects in the dark. The Department of Defense has spearheaded work on IR sensors, since their potential military uses are many. Typically, the devices are made from alloys of HgTe and CdTe, because these materials can be adjusted to detect the appropriate wavelengths of light (3 to 5 microns and 8 to 14 microns). Special types of silicon diodes can also act as IR sensors in some of these wavelength ranges.

Microwave Devices.-Microwave (high-frequency) devices take advantage of the intrinsic high speed of gallium arsenide. They generate, amplify, switch, and receive microwave signals with frequencies from approximately 1 to 60 gigahertz (1 gigahertz is 1 billion cycles per second). Radar systems and transmission systems for telephone, television, and telegraph signals, which operate at these frequencies, as well as military systems, depend on these microwave devices. This technology is at present progressing to monolithic microwave integrated circuits (MM ICs), in which microwave circuits are fabricated on a single substrate, typically gallium arsenide.

Technologies To Produce Semiconductor Microelectronics

Numerous steps are involved in making any microelectronic device. Integrated circuits are the most complex in this respect. The process can be separated into two parts: circuit design and chip fabrication.

Circuit Design

Once the application for a new integrated circuit is established, the first step in making the chip is the design of the circuit. The use of a wide variety of computer-aided design (CAD) tools has facilitated all parts of the design process for large ICs tremendously. For a digital IC, the overall circuit will typically be a combination of logic functions and storage functions. The designer determines the layout of the subcircuits that carry out each of these functions and the connections between the subcircuits. Also in this initial stage, the chip designer must establish mechanisms for bringing the external signals and power to the various subcircuits. Each subcircuit may itself be composed of smaller, interconnected cells of circuitry. The fundamental units for the designer are the individual components, such as transistors, diodes, resistors, and capacitors, and the connections between them.

Because the process of designing circuits has grown so complex over the years, now involving over 100,000 components on a chip, design software is a major research area which is as important to progress in microelectronics technology as advancements in chip fabrication. As the capabilities of design tools grow, they provide increasingly greater flexibility for different chip architectures, and therefore open the door to using IC technology in completely new ways to fabricate specialized circuits.

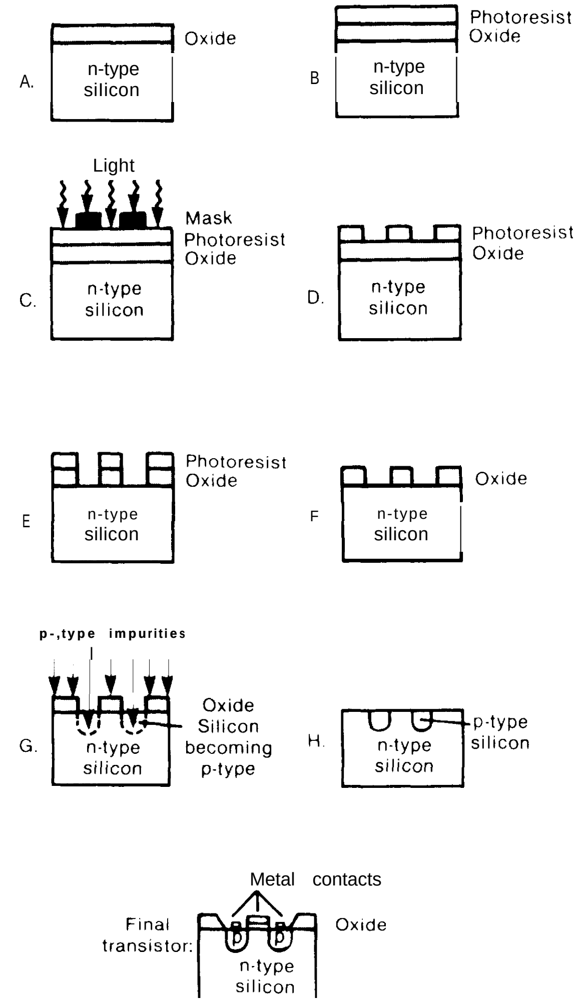
Chip Fabrication

Chip fabrication includes making the circuitry and packaging the completed chip.

The first step of the process is transferring the circuit designers' layout onto the semiconductor chip. The substrate onto which the circuits are transferred is a wafer, or thin slice, of a single crystal of the semiconductor. Currently, a typical wafer is several inches in diameter, so many chips can be made on a single wafer and separated after circuit fabrication. The circuit is created by depositing thin layers of metals, insulators, and perhaps additional semiconductor materials on the wafer; adding n-type impurity atoms (negative charge contributors) or p-type impurity atoms (positive charge contributors) to the semiconductor; and etching away precisely defined portions of the various layers with chemicals or ions.

Illustrating a simplified example of one part of this process, figure A-4 shows the steps in the first phase of the fabrication of a single transistor-an n-channel MOSFET—on a silicon substrate. The objective of this first phase is to add p-type impurity atoms in two small selected regions near the surface of the chip, thereby forming "p-wells." The first six steps of this phase (which constitute lithography) leave a layer of silicon dioxide (SiO_2), with small holes etched in it, on top of the substrate. This layer serves as a stencil for the p-type impurities to which the chip is then exposed: only the portions that are not covered with SiO_2 become p-type.

Figure A-4.– First of Four Mask Processes To Make an N-channel MOSFET



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This process is accomplished as follows. The starting material is a wafer of silicon to which n-type impurities were added during growth. The first step is to grow a thin layer of silicon dioxide on the surface of this substrate, either by exposing the surface to the proper chemicals, or by heating the wafer in a furnace with water vapor (step A in figure A-4). Next, a layer of light-sensitive material called photoresist coats the oxide (step B). The portions of the photoresist that are exposed when the surface is irradiated with light through a glass mask (step C) undergo a chemical change. These parts of the photoresist do not wash away when the chip is rinsed in the chemical developer, but the unexposed portions do (step D). Now, the chip is placed in a bath of chemicals that etch away silicon dioxide, but leave the photoresist and silicon intact (step E). Since the portions of the oxide that are below the photoresist are not etched, this procedure opens windows in the oxide layer. A different chemical bath removes the remaining photoresist without damaging the oxide regions (step F). The chip is now ready for exposure to the p-type impurities, which are driven into the chip either from a piece of source material in a furnace or by accelerating impurity ions into the material (step G). When the number of p-type impurities exceeds the number of n-type impurities that were there originally, the wells will exhibit p-type behavior. Finally, when the p-wells have been formed, the remaining SiO_2 can be chemically removed (step H).

After three more mask cycles, the completed device is composed of regions of semiconductor with p- and n-type impurities; silicon dioxide, which acts as an electrical insulator; and aluminum electrical contacts. In present-day chips, the physical separation between the regions with p-type impurities may be less than 1 micron, and the entire transistor is invisible to the naked eye. Furthermore, the number of impurities must be controlled to within a few parts per billion in some regions of the device.

Fabricating an entire integrated circuit is significantly more complicated because a larger number of much more complex masks are necessary. Chips now also require extremely sophisticated techniques for selective etching of materials, photoresist exposure, and other parts of the process. All of these processing steps must be carried out in an environment completely free of particulate —clean-room facilities. Thus, it is not surprising that the trend in chip fabrication has consistently been towards greater automation of the processes, which reduces the chances of contamination or human error. Today, most machines used in chip fabrication can handle cassettes containing many large wafers of silicon, minimizing the need for humans to handle the delicate circuitry.

When the final lithographic procedures are complete, the large silicon wafer is tested and diced to separate the individual chips. The good chips are then assembled in packages appropriate for their particular applications. Packaging technology is a crucial part of the production of ICs. Proper packaging techniques can shield the chip from physical damage and some forms of radiation damage, For commodity ICs that are sold to a variety of end users, standard packaging systems are necessary to ensure that chips are interchangeable. On the other hand, chips designed and used for high-speed computation require special custom packages that maximize the speed with which signals enter and leave the chip, since standard packaging schemes could obliterate the special speed advantage of the chip by itself.