

metals and nonmetals. A semiconductor can be made to conduct electricity like a metal or to insulate as a nonmetal does. These differing electrical properties can be accurately controlled by mixing the semiconductor with small amounts of other elements. This mixing is called *doping*. A semiconductor can be doped to contain more electrons (N-type) or fewer electrons (P-type). Examples of commonly used semiconductors are silicon and germanium. Phosphorous and boron are two elements that are used to dope N-type and P-type silicon, respectively.

A transistor is constructed by creating a sandwich of differently doped semiconductor layers. The two most common types of transistors, the *bipolar-junction transistor* (BJT) and the *field-effect transistor* (FET) are schematically illustrated in Fig. 2.1. This figure shows both the silicon structures of these elements and their graphical symbolic representation as would be seen in a circuit diagram. The BJT shown is an *NPN* transistor, because it is composed of a sandwich of N-P-N doped silicon. When a small current is injected into the *base* terminal, a larger current is enabled to flow from the *collector* to the *emitter*. The FET shown is an N-channel FET; it is composed of two N-type regions separated by a P-type substrate. When a voltage is applied to the insulated *gate* terminal, a current is enabled to flow from the *drain* to the *source*. It is called N-channel, because the gate voltage induces an N-channel within the substrate, enabling current to flow between the N-regions.

Another basic semiconductor structure shown in Fig. 2.1 is a *diode*, which is formed simply by a junction of N-type and P-type silicon. Diodes act like one-way valves by conducting current only from P to N. Special diodes can be created that emit light when a voltage is applied. Appropriately enough, these components are called *light emitting diodes*, or LEDs. These small lights are manufactured by the millions and are found in diverse applications from telephones to traffic lights.

The resulting small chip of semiconductor material on which a transistor or diode is fabricated can be encased in a small plastic package for protection against damage and contamination from the outside world. Small wires are connected within this package between the semiconductor sandwich and pins that protrude from the package to make electrical contact with other parts of the intended circuit. Once you have several discrete transistors, digital logic can be built by directly wiring these components together. The circuit will function, but any substantial amount of digital logic will be very bulky, because several transistors are required to implement each of the various types of logic gates.

At the time of the invention of the transistor in 1947 by John Bardeen, Walter Brattain, and William Shockley, the only way to assemble multiple transistors into a single circuit was to buy separate discrete transistors and wire them together. In 1959, Jack Kilby and Robert Noyce independently in-

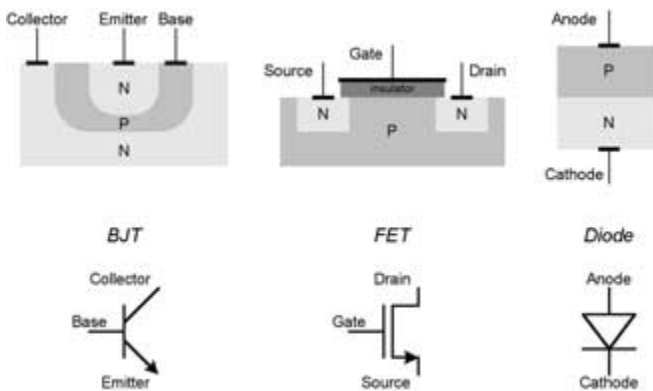


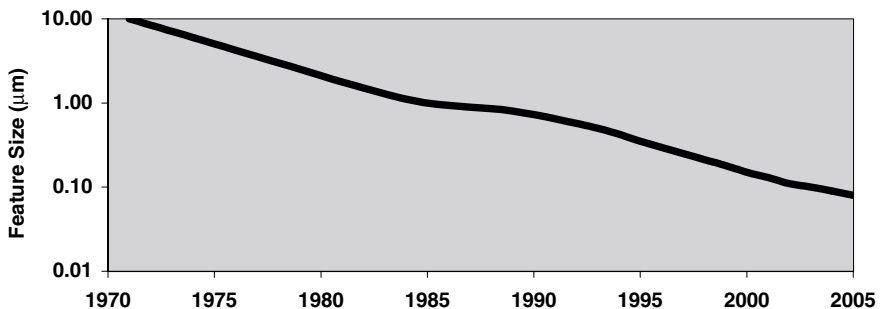
FIGURE 2.1 BJT, FET, and diode structural and symbolic representations.

vented a means of fabricating multiple transistors on a single slab of semiconductor material. Their invention would come to be known as the *integrated circuit*, or IC, which is the foundation of our modern computerized world. An IC is so called because it integrates multiple transistors and diodes onto the same small semiconductor chip. Instead of having to solder individual wires between discrete components, an IC contains many small components that are already wired together in the desired topology to form a circuit.

A typical IC, without its plastic or ceramic package, is a square or rectangular silicon die measuring from 2 to 15 mm on an edge. Depending on the level of technology used to manufacture the IC, there may be anywhere from a dozen to tens of millions of individual transistors on this small chip. This amazing density of electronic components indicates that the transistors and the wires that connect them are extremely small in size. Dimensions on an IC are measured in units of micrometers, with one micrometer ( $1\ \mu\text{m}$ ) being one millionth of a meter. To serve as a reference point, a human hair is roughly  $100\ \mu\text{m}$  in diameter. Some modern ICs contain components and wires that are measured in increments as small as  $0.1\ \mu\text{m}$ ! Each year, researchers and engineers have been finding new ways to steadily reduce these feature sizes to pack more transistors into the same silicon area, as indicated in Fig. 2.2.

Many individual chemical process steps are involved in fabricating an IC. The process begins with a thin, clean, polished semiconductor wafer — most often silicon — that is usually one of three standard diameters: 100, 200, or 300 mm. The circular wafer is cut from a cylindrical ingot of solid silicon that has a perfect crystal structure. This perfect crystal base structure is necessary to promote the formation of other crystals that will be deposited by subsequent processing steps. Many dice are arranged on the wafer in a grid as shown in Fig. 2.3. Each die is an identical copy of a master pattern and will eventually be sliced from the wafer and packaged as an IC. An IC designer determines how different portions of the silicon wafer should be modified to create transistors, diodes, resistors, capacitors, and wires. This IC design layout can then be used to, in effect, draw tiny components onto the surface of the silicon. Sequential drawing steps are able to build sandwiches of differently doped silicon and metal layers.

Engineers realized that light provided the best way to faithfully replicate patterns from a template onto a silicon substrate, similar to what photographers have been doing for years. A photographer takes a picture by briefly exposing film with the desired image and then developing this film into a negative. Once this negative has been created, many identical photographs can be reproduced by briefly exposing the light-sensitive photographic paper to light that is focused through the negative. Portions of the negative that are dark do not allow light to pass, and these corresponding regions of the paper are not exposed. Those areas of the negative that are light allow the paper to be exposed.



**FIGURE 2.2** Decreasing IC feature size over time. (Future data for years 2003 through 2005 compiled from the International Technology Roadmap for Semiconductors, *Semiconductor Industry Association, 2001.*)