Chapter 1, the switch is the basis for the realization of the logic inverter, the basic element of digital circuits.

The invention of the BJT in 1948 at the Bell Telephone Laboratories ushered in the era of solid-state circuits, which led to electronics changing the way we work, play, and indeed, live. The invention of the BJT also eventually led to the dominance of information technology and the emergence of the knowledge-based economy.

The bipolar transistor enjoyed nearly three decades as the device of choice in the design of both discrete and integrated circuits. Although the MOSFET had been known very early on, it was not until the 1970s and 1980s that it became a serious competitor to the BJT. At the time of this writing (2003), the MOSFET is undoubtedly the most widely used electronic device, and CMOS technology is the technology of choice in the design of integrated circuits. Nevertheless, the BJT remains a significant device that excels in certain applications. For instance, the reliability of BJT circuits under severe environmental conditions makes them the dominant device in automotive electronics, an important and still-growing area.

The BJT remains popular in discrete-circuit design, in which a very wide selection of BJT types are available to the designer. Here we should mention that the characteristics of the bipolar transistor are so well understood that one is able to design transistor circuits whose performance is remarkably predictable and quite insensitive to variations in device parameters.

The BJT is still the preferred device in very demanding analog circuit applications, both integrated and discrete. This is especially true in very-high-frequency applications, such as radio-frequency (RF) circuits for wireless systems. A very-high-speed digital logic-circuit family based on bipolar transistors, namely emitter-coupled logic, is still in use. Finally, bipolar transistors can be combined with MOSFETs to create innovative circuits that take advantage of the high-input-impedance and low-power operation of MOSFETs and the very-high-frequency operation and high-current-driving capability of bipolar transistors. The resulting technology is known as BiMOS or BiCMOS, and it is finding increasingly larger areas of application (see Chapters 6, 7, 9, and 11).

In this chapter, we shall start with a simple description of the physical operation of the BJT. Though simple, this physical description provides considerable insight regarding the performance of the transistor as a circuit element. We then quickly move from describing current flow in terms of electrons and holes to a study of the transistor terminal characteristics. Circuit models for transistor operation in different modes will be developed and utilized in the analysis and design of transistor circuits. The main objective of this chapter is to develop in the reader a high degree of familiarity with the BJT. Thus, by the end of the chapter, the reader should be able to perform rapid first-order analysis of transistor circuits and to design single-stage transistor amplifiers and simple logic inverters.

5.1 DEVICE STRUCTURE AND PHYSICAL OPERATION

5.1.1 Simplified Structure and Modes of Operation

Figure 5.1 shows a simplified structure for the BJT. A practical transistor structure will be shown later (see also Appendix A, which deals with fabrication technology).

As shown in Fig. 5.1, the BJT consists of three semiconductor regions: the emitter region (n type), the base region (p type), and the collector region (n type). Such a transistor is called an *npn* transistor. Another transistor, a dual of the *npn* as shown in Fig. 5.2, has a p-type emitter, an n-type base, and a p-type collector, and is appropriately called a *pnp* transistor.

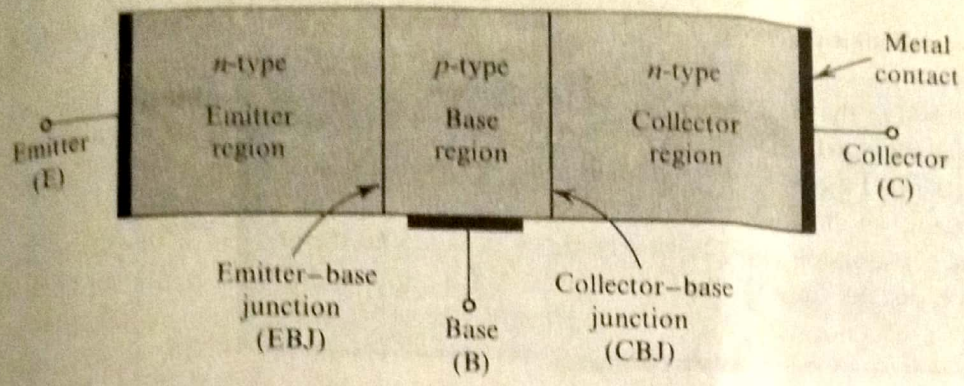

FIGURE 5.1 A simplified structure of the *npn* transistor.

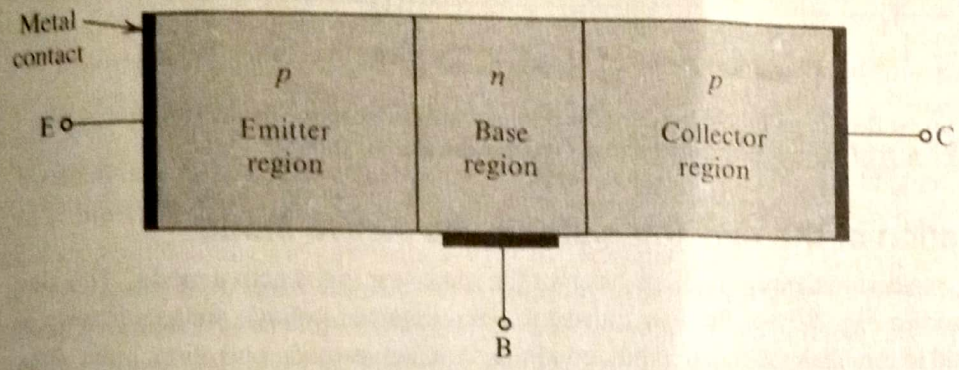

FIGURE 5.2 A simplified structure of the *pnp* transistor.

A terminal is connected to each of the three semiconductor regions of the transistor, with the terminals labeled **emitter** (E), **base** (B), and **collector** (C).

The transistor consists of two *pn* junctions, the **emitter–base junction** (EBJ) and the **collector–base junction** (CBJ). Depending on the bias condition (forward or reverse) of each of these junctions, different modes of operation of the BJT are obtained, as shown in Table 5.1.

The **active mode,** which is also called forward active mode, is the one used if the transistor is to operate as an amplifier. Switching applications (e.g., logic circuits) utilize both the **cutoff mode** and the **saturation mode.** The **reverse active** (or inverse active) mode has very limited application but is conceptually important.

As we will see shortly, charge carriers of both polarities—that is, electrons and holes—participate in the current-conduction process in a bipolar transistor, which is the reason for the name *bipolar*.

TABLE 5.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Reverse active	Reverse	Forward
Saturation	Forward	Forward