8

Bipolar Transistor

CHAPTER OBJECTIVES

This chapter introduces the bipolar junction transistor (BJT) operation and then presents the theory of the bipolar transistor I-V characteristics, current gain, and output conductance. High-level injection and heavy doping induced band narrowing are introduced. SiGe transistor, transit time, and cutoff frequency are explained. Several bipolar transistor models are introduced, i.e., Ebers–Moll model, small-signal model, and charge control model. Each model has its own areas of applications.

The **bipolar junction transistor** or **BJT** was invented in 1948 at Bell Telephone Laboratories, New Jersey, USA. It was the first mass produced transistor, ahead of the MOS field-effect transistor (MOSFET) by a decade. After the introduction of metal-oxide-semiconductor (MOS) ICs around 1968, the high-density and low-power advantages of the MOS technology steadily eroded the BJT's early dominance. BJTs are still preferred in some high-frequency and analog applications because of their high speed, low noise, and high output power advantages such as in some cell phone amplifier circuits. When they are used, a small number of BJTs are integrated into a high-density complementary MOS (CMOS) chip. Integration of BJT and CMOS is known as the **BiCMOS technology**.

The term **bipolar** refers to the fact that both electrons and holes are involved in the operation of a BJT. In fact, minority carrier diffusion plays the leading role just as in the PN junction diode. The word **junction** refers to the fact that PN junctions are critical to the operation of the BJT. BJTs are also simply known as **bipolar transistors**.

8.1 ● INTRODUCTION TO THE BJT ●

A BJT is made of a heavily doped **emitter** (see Fig. 8–1a), a P-type **base**, and an N-type **collector**. This device is an **NPN** BJT. (A **PNP** BJT would have a P^+ emitter, N-type base, and P-type collector.) NPN transistors exhibit higher transconductance and

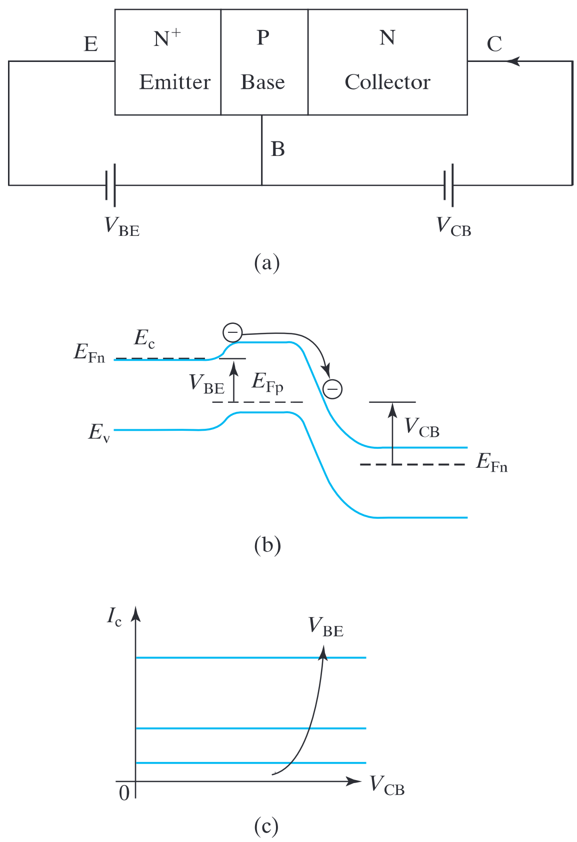

FIGURE 8–1 (a) Schematic NPN BJT and normal voltage polarities; (b) electron injection from emitter into base produces and determines I_C; and (c) I_C is basically determined by V_{BE} and is insensitive to V_{CB}.

speed than PNP transistors because the electron mobility is larger than the hole mobility. BJTs are almost exclusively of the NPN type since high performance is BJTs' competitive edge over MOSFETs.

Figure 8–1b shows that when the base–emitter junction is forward biased, electrons are injected into the more lightly doped base. They diffuse across the base to the reverse-biased base–collector junction (edge of the depletion layer) and get swept into the collector. This produces a **collector current**, I_C. I_C is independent of V_{CB} as long as V_{CB} is a reverse bias (or a small forward bias, as explained in Section 8.6). Rather, I_C is determined by the rate of electron injection from the emitter into the base, i.e., determined by V_{BE}. You may recall from the PN diode theory that the rate of injection is proportional to $e^{qV_{BE}/kT}$. These facts are obvious in Fig. 8–1c.

Figure 8–2a shows that the emitter is often connected to ground. (The emitter and collector are the equivalents of source and drain of a MOSFET. The base is the equivalent of the gate.) Therefore, the I_C curve is usually plotted against V_{CE} as shown in Fig. 8–2b. For V_{CE} higher than about 0.3 V, Fig. 8–2b is identical to Fig. 8–1c but with a shift to the right because $V_{CE} = V_{CB} + V_{BE}$. Below $V_{CE} \approx 0.3$ V,

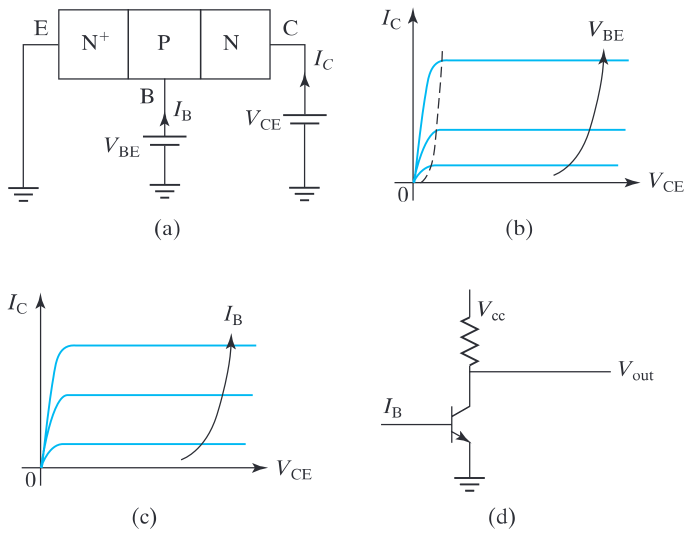

FIGURE 8–2 (a) Common-emitter convention; (b) I_C vs. V_{CE}; (c) I_B may be used as the parameter instead of V_{BE}; and (d) circuit symbol of an NPN BJT and an inverter circuit.

the base–collector junction is strongly forward biased and I_C decreases as explained in Section 8.6. Because of the parasitic IR drops, it is difficult to accurately ascertain the true base–emitter junction voltage. For this reason, the easily measurable base current, I_B, is commonly used as the variable parameter in lieu of V_{BE} (as shown in Fig. 8–2c). We will see later that I_C is proportional to I_B.

8.2 • COLLECTOR CURRENT •

The collector current is the output current of a BJT. Applying the electron diffusion equation [Eq. (4.7.7)] to the base region,

$$\frac{d^2 n'}{dx^2} = \frac{n'}{L_B^2} \tag{8.2.1}$$

$$L_B \equiv \sqrt{\tau_B D_B} \tag{8.2.2}$$

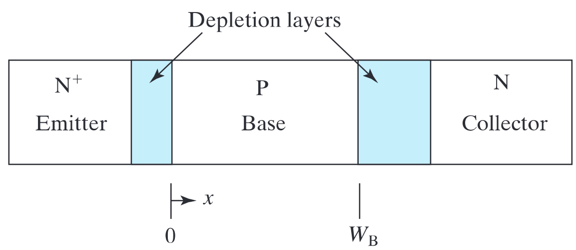

FIGURE 8–3 $x = 0$ is the edge of the BE junction depletion layer. W_B is the width of the base neutral region.