SIM ***5.60** For the devices in the circuit of Fig. P5.60, $|V_t| = 1$ V, $\lambda = 0$, $\mu_n C_{ox} = 50\ \mu\text{A/V}^2$, $L = 1\ \mu$m, and $W = 10\ \mu$m. Find V_2 and I_2. How do these values change if Q_3 and Q_4 are made to have $W = 100\ \mu$m?

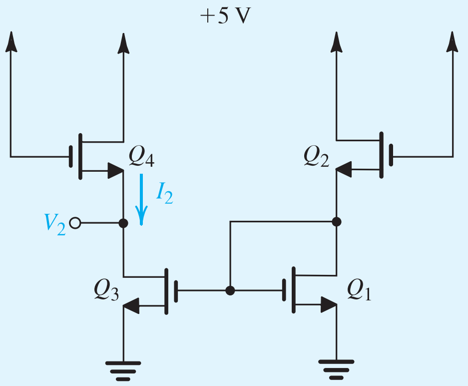

Figure P5.60

5.61 In the circuit of Fig. P5.61, transistors Q_1 and Q_2 have $V_t = 0.7$ V, and the process transconductance parameter $k_n' = 125\ \mu\text{A/V}^2$. Find V_1, V_2, and V_3 for each of the following cases:

(a) $(W/L)_1 = (W/L)_2 = 20$
(b) $(W/L)_1 = 1.5(W/L)_2 = 20$

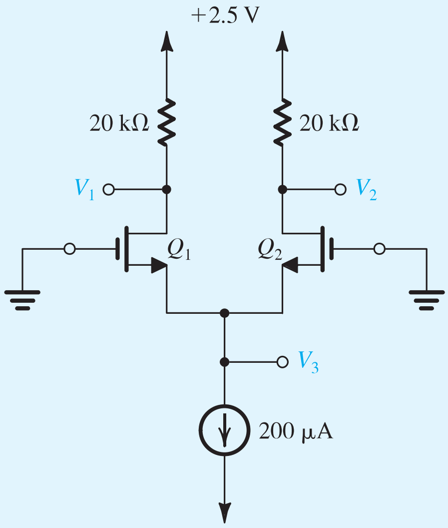

Figure P5.61

Section 5.4: The Body Effect and Other Topics

5.62 In a particular application, an n-channel MOSFET operates with V_{SB} in the range 0 V to 4 V. If V_{t0} is nominally 1.0 V, find the range of V_t that results if $\gamma = 0.5\ \text{V}^{1/2}$ and $2\phi_f = 0.6$ V. If the gate oxide thickness is increased by a factor of 4, what does the threshold voltage become?

5.63 A p-channel transistor operates in saturation with its source voltage 3 V lower than its substrate. For $\gamma = 0.5\ \text{V}^{1/2}$, $2\phi_f = 0.75$ V, and $V_{t0} = -0.7$ V, find V_t.

***5.64** (a) Using the expression for i_D in saturation and neglecting the channel-length modulation effect (i.e., let $\lambda = 0$), derive an expression for the per unit change in i_D per °C $\left[(\partial i_D/i_D)/\partial T\right]$ in terms of the per unit change in k_n' per °C $\left[(\partial k_n'/k_n')/\partial T\right]$, the temperature coefficient of V_t in V/°C $(\partial V_t/\partial T)$, and V_{GS} and V_t.
(b) If V_t decreases by 2 mV for every °C rise in temperature, find the temperature coefficient of k_n' that results in i_D decreasing by 0.2%/°C when the NMOS transistor with $V_t = 1$ V is operated at $V_{GS} = 5$ V.

5.65 A depletion-type n-channel MOSFET with $k_n'W/L = 2\ \text{mA/V}^2$ and $V_t = -3$ V has its source and gate grounded. Find the region of operation and the drain current for $v_D = 0.1$ V, 1 V, 3 V, and 5 V. Neglect the channel-length-modulation effect.

5.66 For a particular depletion-mode NMOS device, $V_t = -2$ V, $k_n'W/L = 200\ \mu\text{A/V}^2$, and $\lambda = 0.02\ \text{V}^{-1}$. When operated at $v_{GS} = 0$, what is the drain current that flows for $v_{DS} = 1$ V, 2 V, 3 V, and 10 V? What does each of these currents become if the device width is doubled with L the same? With L also doubled?

***5.67** Neglecting the channel-length-modulation effect, show that for the depletion-type NMOS transistor of Fig. P5.67, the i–v relationship is given by

$$i = \frac{1}{2}k_n'(W/L)\left(v^2 - 2V_t v\right) \qquad \text{for } v \geq V_t$$
$$i = -\frac{1}{2}k_n'(W/L)V_t^2 \qquad \text{for } v \leq V_t$$

(Recall that V_t is negative.) Sketch the i–v relationship for the case: $V_t = -2$ V and $k_n'(W/L) = 2\ \text{mA/V}^2$.

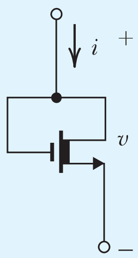

Figure P5.67

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

CHAPTER 6

Bipolar Junction Transistors (BJTs)

IN THIS CHAPTER YOU WILL LEARN

1. The physical structure of the bipolar transistor and how it works.

2. How the voltage between two terminals of the transistor controls the current that flows through the third terminal, and the equations that describe these current–voltage characteristics.

3. How to analyze and design circuits that contain bipolar transistors, resistors, and dc sources.

Introduction

In this chapter, we study the other major three-terminal device: the bipolar junction transistor (BJT). The presentation of the material in this chapter parallels but does not rely on that for the MOSFET in Chapter 5; thus, if desired, the BJT can be studied before the MOSFET.

Three-terminal devices are far more useful than two-terminal ones, such as the diodes studied in Chapter 4, because they can be used in a multitude of applications, ranging from signal amplification to the design of digital logic and memory circuits. The basic principle involved is the use of the voltage between two terminals to control the current flowing in the third terminal. In this way, a three-terminal device can be used to realize a controlled source, which as we learned in Chapter 1 is the basis for amplifier design. Also, in the extreme, the control signal can be used to cause the current in the third terminal to change from zero to a large value, thus allowing the device to act as a switch. 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. The result was not just the replacement of vacuum tubes by transistors in radios and television sets but the eruption of an electronics revolution that led to major changes in the way we work, play, and indeed, live. The invention of the transistor 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. By 2014, the MOSFET was undoubtedly the most widely used electronic device, and CMOS technology the technology of choice in the design of integrated circuits. Nevertheless, the BJT remains a significant device that excels in certain applications.

The BJT remains popular in discrete-circuit design, where it is used together with other discrete components such as resistors and capacitors to implement circuits that are assembled on printed-circuit boards (PCBs). Here we note the availability of a very wide selection of BJT types that fit nearly every conceivable application. As well, the BJT is still the preferred device in some very demanding analog and digital integrated-circuit applications. This is especially true in very-high-frequency and high-speed circuits. In particular, a very-high-speed digital logic-circuit family based on bipolar transistors, namely, emitter-coupled logic, is still in use (Chapter 15). 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 BiCMOS, and it is finding increasingly larger areas of application (see Chapters 8, 9, 13, and 15).

In this chapter, we shall start with a 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, it lays the foundation for the use of the BJT in amplifier design (Chapter 7).

6.1 Device Structure and Physical Operation

6.1.1 Simplified Structure and Modes of Operation

Figure 6.1 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. 6.1, 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. 6.2, has a *p*-type emitter, an *n*-type base, and a *p*-type collector, and is appropriately called a *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 6.1. The **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**. As the name implies, in the cutoff mode no current flows because both junctions are reverse biased.

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*.[1]

[1]This should be contrasted with the situation in the MOSFET, where current is conducted by charge carriers of one type only: electrons in *n*-channel devices or holes in *p*-channel devices. In earlier days, some referred to FETs as unipolar devices.

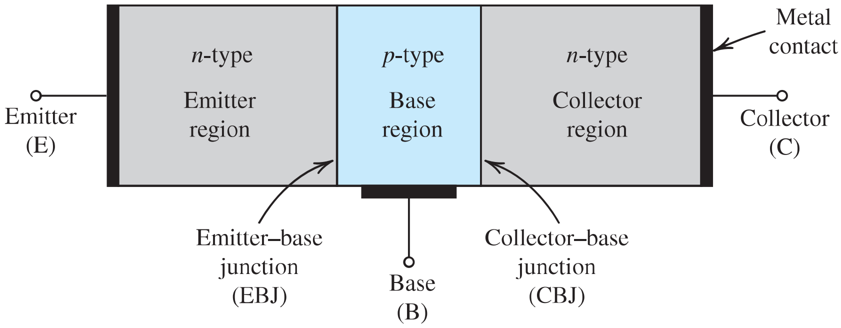

Figure 6.1 A simplified structure of the *npn* transistor.

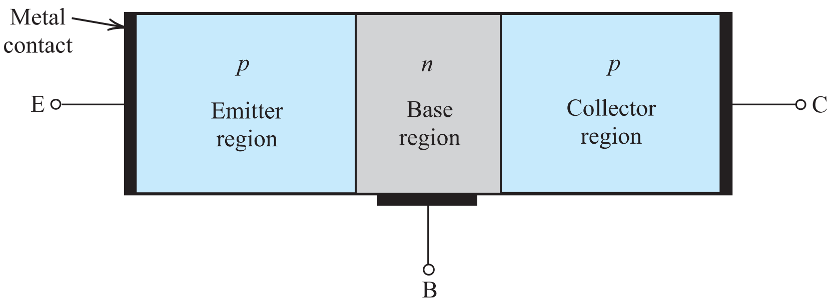

Figure 6.2 A simplified structure of the *pnp* transistor.

Table 6.1 BJT Modes of Operation

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

6.1.2 Operation of the *npn* Transistor in the Active Mode

Of the three modes of operation of the BJT, the active mode is the most important. Therefore, we begin our study of the BJT by considering its physical operation in the active mode.[2] This situation is illustrated in Fig. 6.3 for the *npn* transistor. Two external voltage sources (shown as batteries) are used to establish the required bias conditions for active-mode operation. The voltage V_{BE} causes the *p*-type base to be higher in potential than the *n*-type emitter, thus forward biasing the emitter–base junction. The collector–base voltage V_{CB} causes the *n*-type collector to be at a higher potential than the *p*-type base, thus reverse biasing the collector–base junction.

[2]The material in this section assumes that the reader is familiar with the operation of the *pn* junction under forward-bias conditions (Section 3.5).

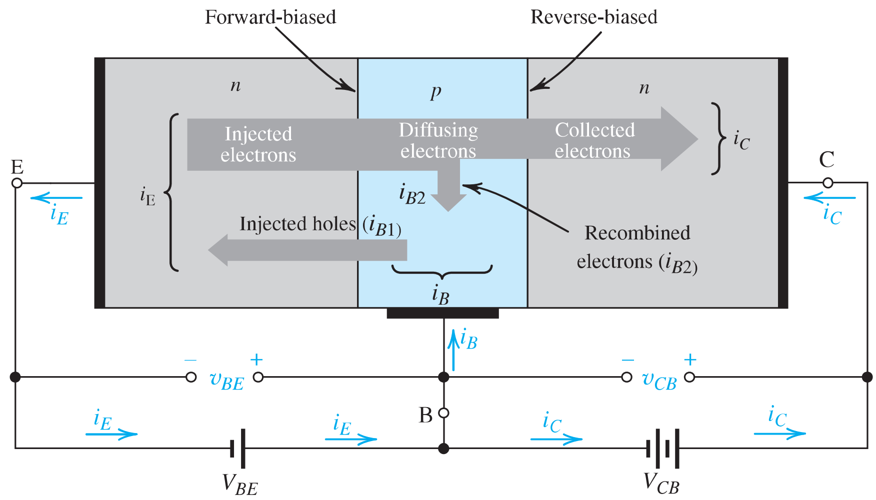

Figure 6.3 Current flow in an *npn* transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)

Current Flow The forward bias on the emitter–base junction will cause current to flow across this junction. Current will consist of two components: electrons injected from the emitter into the base, and holes injected from the base into the emitter. As will become apparent shortly, it is highly desirable to have the first component (electrons from emitter to base) be much larger than the second component (holes from base to emitter). This can be accomplished by fabricating the device with a heavily doped emitter and a lightly doped base; that is, the device is designed to have a high density of electrons in the emitter and a low density of holes in the base.

The current that flows across the emitter–base junction will constitute the emitter current i_E, as indicated in Fig. 6.3. The direction of i_E is "out of" the emitter lead, which, following the usual conventions, is in the direction of the positive-charge flow (hole current) and opposite to the direction of the negative-charge flow (electron current), with the emitter current i_E being equal to the sum of these two components. However, since the electron component is much larger than the hole component, the emitter current will be dominated by the electron component.

From our study in Section 3.5 of the current flow across a forward-biased *pn* junction, we know that the magnitude of both the electron component and the hole component of i_E will be proportional to e^{v_{BE}/V_T}, where v_{BE} is the forward voltage across the base–emitter junction and V_T is the thermal voltage (approximately 25 mV at room temperature).

Let's now focus our attention on the first current component, namely, that carried by electrons injected from the emitter into the base. These electrons will be **minority carriers** in the *p*-type base region. Because their concentration will be highest at the emitter side of the base, the injected electrons will diffuse through the base region toward the collector. In their journey across the base, some of the electrons will combine with holes, which are majority carriers in the base. However, since the base is usually very thin and, as mentioned earlier, lightly doped, the proportion of electrons that are "lost" through this **recombination process** will be quite small. Thus, most of the diffusing electrons will reach the boundary of the collector–base depletion region. Because the collector is more positive than the base (by the reverse-bias voltage v_{CB}), these successful electrons will be swept across the CBJ depletion region into the collector. They will thus get collected and constitute the collector current i_C.

The Collector Current From the foregoing statements, we see that the collector current is carried by the electrons that reach the collector region. Its direction will be opposite to that of the flow of electrons, and thus into the collector terminal. Its magnitude will be proportional to e^{v_{BE}/V_T}, thus

$$i_C = I_S e^{v_{BE}/V_T} \tag{6.1}$$

where the constant of proportionality I_S, as in the case of the diode, is called the **saturation current** and is a transistor parameter. We will have more to say about I_S shortly.

An important observation to make here is that i_C is independent of the value of v_{CB}. That is, as long as the collector is positive with respect to the base, the electrons that reach the collector side of the base region will be swept into the collector and will register as collector current.

The Base Current Reference to Fig. 6.3 shows that the base current i_B is composed of two components. The first component i_{B1} is due to the holes injected from the base region into the emitter region. This current component is proportional to e^{v_{BE}/V_T}. The second component of base current, i_{B2}, is due to holes that have to be supplied by the external circuit in order to replace the holes lost from the base through the recombination process. Because i_{B2} is proportional to the number of electrons injected into the base, it also will be proportional to e^{v_{BE}/V_T}. Thus the total base current, $i_B = i_{B1} + i_{B2}$, will be proportional to e^{v_{BE}/V_T}, and can be expressed as a fraction of the collector current i_C as follows:

$$i_B = \frac{i_C}{\beta} \tag{6.2}$$

That is,

$$i_B = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T} \tag{6.3}$$

where β is a transistor parameter.

For modern *npn* transistors, β is in the range 50 to 200, but it can be as high as 1000 for special devices. For reasons that will become clear later, the parameter β is called the **common-emitter current gain**.

The above description indicates that the value of β is highly influenced by two factors: the width of the base region, W, and the relative dopings of the base region and the emitter region, N_A/N_D. To obtain a high β (which is highly desirable since β represents a gain parameter) the base should be thin (W small) and lightly doped and the emitter heavily doped (making N_A/N_D small). For modern integrated circuit fabrication technologies, W is in the nanometer range.

The Emitter Current Since the current that enters a transistor must leave it, it can be seen from Fig. 6.3 that the emitter current i_E is equal to the sum of the collector current i_C and the base current i_B; that is,

$$i_E = i_C + i_B \tag{6.4}$$

Use of Eqs. (6.2) and (6.4) gives

$$i_E = \frac{\beta + 1}{\beta} i_C \tag{6.5}$$

That is,

$$i_E = \frac{\beta + 1}{\beta} I_S e^{v_{BE}/V_T} \tag{6.6}$$

Alternatively, we can express Eq. (6.5) in the form

$$i_C = \alpha i_E \tag{6.7}$$

where the constant α is related to β by

$$\alpha = \frac{\beta}{\beta + 1} \tag{6.8}$$

Thus the emitter current in Eq. (6.6) can be written

$$i_E = (I_S/\alpha) e^{v_{BE}/V_T} \tag{6.9}$$

Finally, we can use Eq. (6.8) to express β in terms of α, that is,

$$\beta = \frac{\alpha}{1 - \alpha} \tag{6.10}$$

It can be seen from Eq. (6.8) that α is a constant (for a particular transistor) that is less than but very close to unity. For instance, if $\beta = 100$, then $\alpha \simeq 0.99$. Equation (6.10) reveals an important fact: Small changes in α correspond to very large changes in β. This mathematical observation manifests itself physically, with the result that transistors of the same type may have widely different values of β. For reasons that will become apparent later, α is called the **common-base current gain**.

Minority-Carrier Distribution Our understanding of the physical operation of the BJT can be enhanced by considering the distribution of minority charge carriers in the base and the emitter. Figure 6.4 shows the profiles of the concentration of electrons in the base and holes in the emitter of an *npn* transistor operating in the active mode. Observe that since the doping concentration in the emitter, N_D, is much higher than the doping concentration in the base, N_A, the concentration of electrons injected from emitter to base, $n_p(0)$, is much higher than the concentration of holes injected from the base to the emitter, $p_n(0)$. Both quantities are proportional to e^{v_{BE}/V_T}, thus

$$n_p(0) = n_{p0} e^{v_{BE}/V_T} \tag{6.11}$$

where n_{p0} is the thermal-equilibrium value of the minority-carrier (electron) concentration in the base region.

Next, observe that because the base is very thin, the concentration of excess electrons decays almost linearly (as opposed to the usual exponential decay, as observed for the excess holes in the emitter region). Furthermore, the reverse bias on the collector–base junction causes the concentration of excess electrons at the collector side of the base to be zero. (Recall that electrons that reach that point are swept into the collector.)

The tapered minority-carrier concentration profile (Fig. 6.4) causes the electrons injected into the base to diffuse through the base region toward the collector. This electron diffusion