UNIT 4

BIPOLAR JUNCTION TRANSISTORS

4–1 ■ TRANSISTOR CONSTRUCTION

The basic structure of the bipolar junction transistor (BJT) determines its operating characteristics. In this section, you will see how semiconductor materials are used to form a transistor, and you will learn the standard transistor symbols.

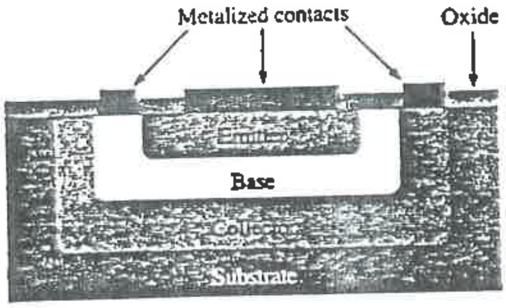
After completing this section, you should be able to

- **Describe the basic structure of the bipolar junction transistor**
  - ☐ **Explain the difference between the structure of an *npn* and a *pnp* transistor**
  - ☐ **Identify the symbols for *npn* and *pnp* transistors**
  - ☐ **Name the three regions of a BJT and their labels**

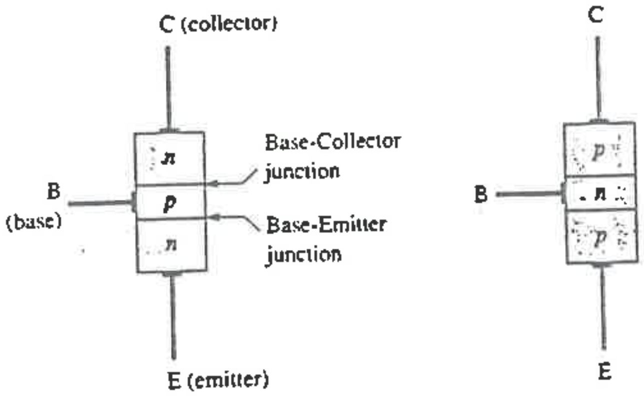
The bipolar junction transistor (BJT) is constructed with three doped semiconductor regions separated by two *pn* junctions, as shown in the epitaxial planar structure in Figure 4–1(a). The three regions are called emitter, base, and collector. Physical representations of the two types of bipolar transistors are shown in Figure 4–1(b) and (c). One type consists of two *n* regions separated by a *p* region (*npn*), and the other consists of two *p* regions separated by an *n* region (*pnp*).

The *pn* junction joining the base region and the emitter region is called the *base-emitter junction*. The junction joining the base region and the collector region is called the *base-collector junction*, as indicated in Figure 4–1(b). A wire lead connects to each of the three regions, as shown. These leads are labeled E, B, and C for emitter, base, and collector, respectively.

FIGURE 4–1
Basic bipolar transistor construction.



(a) Basic epitaxial planar structure

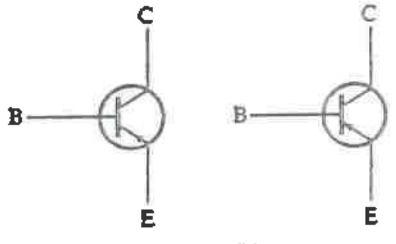


(b) *npn*

(c) *pnp*

The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions. (The reason for this is discussed in the next section.) Figure 4–2 shows the schematic symbols for the *npn* and *pnp* bipolar transistors. The term **bipolar** refers to the use of both holes and electrons as carriers in the transistor structure.

FIGURE 4–2
Standard bipolar junction transistor (BJT) symbols.



(a) *npn* (b) *pnp*

SECTION 4–1 REVIEW

1. Name the two types of BJTs according to their construction.
2. The BJT is a three-terminal device. Name the three terminals.
3. What separates the three regions in a BJT?

4–2 ■ BASIC TRANSISTOR OPERATION

In order for the transistor to operate properly as an amplifier, the two pn junctions must be correctly biased with external dc voltages. In this section, we use the npn transistor for illustration. The operation of the pnp is the same as for the npn except that the roles of the electrons and holes, the bias voltage polarities, and the current directions are all reversed.

After completing this section, you should be able to

- **Explain how a transistor is biased and discuss the transistor currents and their relationships**
  - ☐ Describe forward-reverse bias
  - ☐ Show how to connect a transistor to the bias-voltage sources
  - ☐ Describe the basic internal operation of a transistor
  - ☐ State the formula relating the collector, emitter, and base currents in a transistor

---

Figure 4–3 shows the proper **bias** arrangement for both *npn* and *pnp* transistors for active operation as an amplifier. Notice that in both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased.

To illustrate transistor action let's examine what happens inside the *npn* transistor when the junctions are forward-reverse biased. The forward bias from base to emitter narrows the BE depletion region, and the reverse bias from base to collector widens the BC depletion region, as depicted in Figure 4–4. The heavily doped *n*-type emitter region is teeming with conduction-band (free) electrons that easily diffuse through the forward-

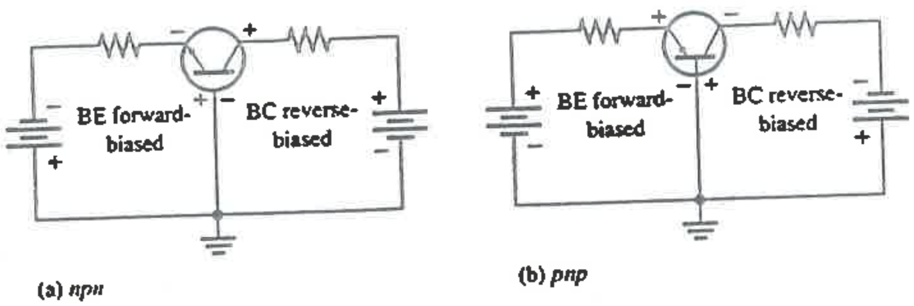


FIGURE 4–3
Forward-reverse bias of a bipolar transistor.

biased BE junction into the *p*-type base region where they become minority carriers, just as in a forward-biased diode. The base region is lightly doped and very thin so that it has a very limited number of holes. Thus, only a small percentage of all the electrons flowing through the BE junction can combine with the available holes in the base. These relatively few recombined electrons flow out of the base lead as valence electrons, forming the small base electron current, as shown in Figure 4–4.

Most of the electrons flowing from the emitter into the thin, lightly doped base region do not recombine but diffuse into the BC depletion region. Once in this region they are pulled through the reverse-biased BC junction by the electric field set up by the force of attraction between the positive and negative ions. Actually, you can think of the electrons as being pulled across the reverse-biased BC junction by the attraction of the collector supply voltage. The electrons now move through the collector region, out

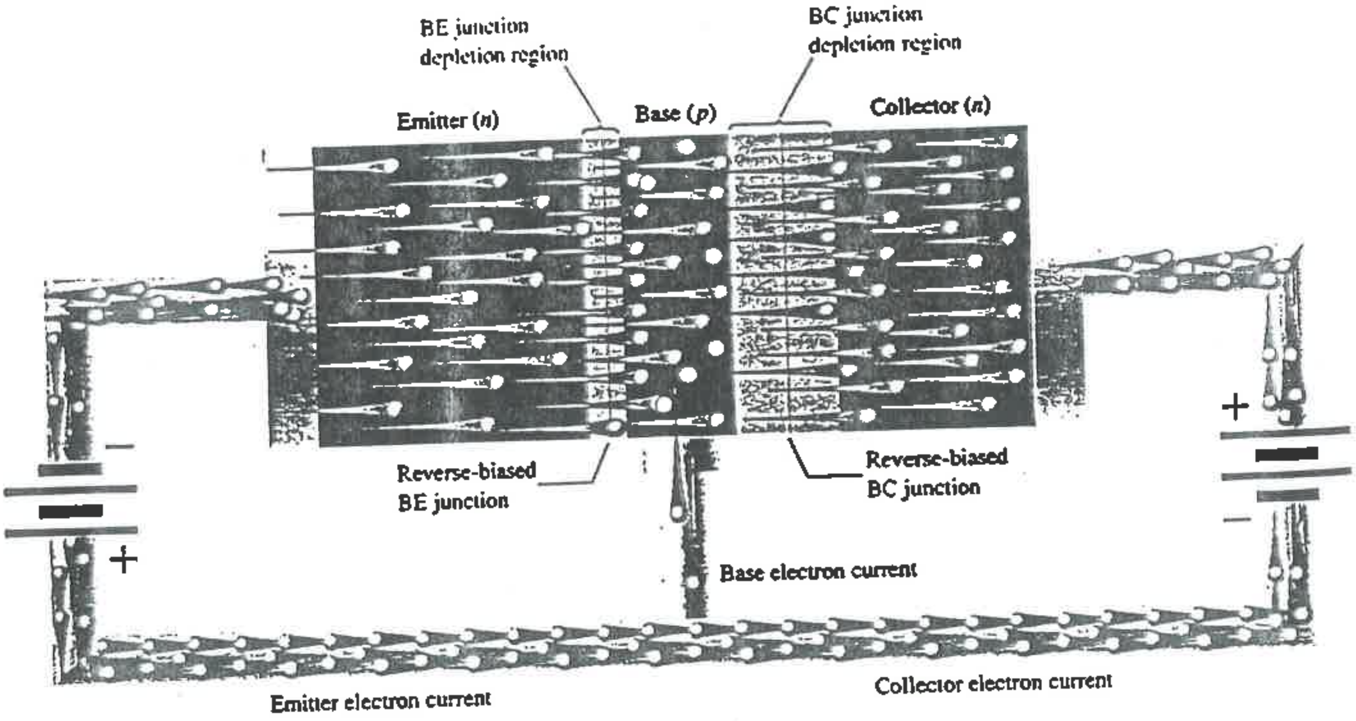


FIGURE 4–4
Illustration of BJT action.

through the collector lead, and into the positive terminal of the collector voltage source. This forms the collector electron current, as shown in Figure 4–4.

Transistor Currents

The directions of the currents in an *npn* transistor are as shown in Figure 4–5(a), and those for a *pnp* are shown in Figure 4–5(b). The currents are indicated on the corresponding schematic symbols in parts (c) and (d) of the figure. Notice that the arrow on the emitter of the transistor symbols points in the direction of conventional current. These diagrams show that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

$$I_E = I_C + I_B \tag{4–1}$$

As mentioned before, I_B is very small compared to I_E or I_C. The uppercase subscripts indicate dc values.

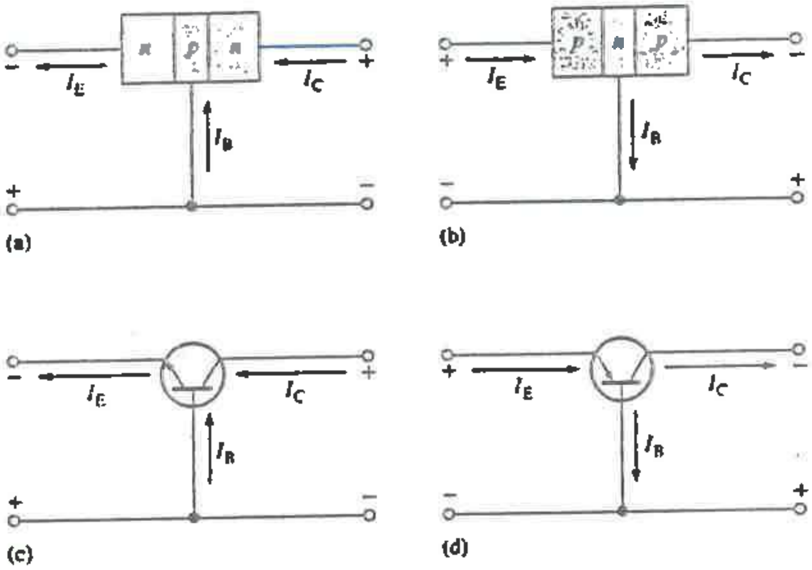


FIGURE 4–5
Transistor currents.

SECTION 4–2 REVIEW

1. What are the bias conditions of the base-emitter and base-collector junctions for a transistor to operate as an amplifier?
2. Which is the largest of the three transistor currents?
3. Is the base current smaller or larger than the emitter current?
4. Is the base region much thinner or much wider than the collector and emitter regions?
5. If the collector current is 1 mA and the base current is 10 µA, what is the emitter current?

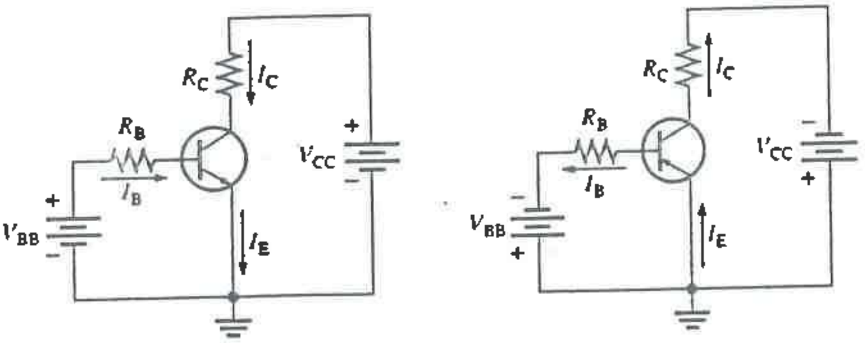
4–3 ■ TRANSISTOR CHARACTERISTICS AND PARAMETERS

In this section, you will first learn how to set up a dc circuit to properly bias a transistor. Two important parameters, β_{DC} (dc current gain) and α_{DC} are introduced and used to analyze a transistor circuit. Also, transistor characteristic curves are covered, and you will learn how a transistor's operation can be determined from these curves. Finally, maximum ratings of a transistor are discussed.

After completing this section, you should be able to

- ■ **Discuss transistor parameters and characteristics and use these to analyze a transistor circuit**
  - ☐ Define dc *beta* (β_{DC})
  - ☐ Define dc *alpha* (α_{DC})
  - ☐ State the mathematical relationship between β_{DC} and α_{DC}
  - ☐ Identify all currents and voltages in a transistor circuit
  - ☐ Analyze a basic transistor dc circuit
  - ☐ Interpret collector characteristic curves and use a dc load line
  - ☐ Describe how β_{DC} varies with temperature and collector current
  - ☐ Discuss and apply maximum transistor ratings
  - ☐ Derate a transistor for power dissipation
  - ☐ Interpret a transistor data sheet

When a transistor is connected to bias voltages, as shown in Figure 4–6 for both *npn* and *pnp* types, V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. Although in this chapter we are using battery symbols to represent the bias voltages, in practice the voltages are usually derived from a dc power supply. For example, V_{CC} is usually taken directly from the power supply output and V_{BB} (which is smaller) can be produced with a voltage divider. Bias arrangements are examined thoroughly in Chapter 5.



(a) *npn*

(b) *pnp*

FIGURE 4–6

Transistor dc bias circuits.

DC Beta (β_{DC}) and DC Alpha (α_{DC})

The ratio of the collector current I_C to the base current I_B is the dc beta (β_{DC}), which is the dc current gain of a transistor.

$$\beta_{DC} = \frac{I_C}{I_B} \tag{4–2}$$

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designated as h_{FE} on transistor data sheets.

$$h_{FE} = \beta_{DC}$$

The ratio of the collector current I_C to the emitter current I_E is the dc **alpha** (α_{DC}).

$$\alpha_{DC} = \frac{I_C}{I_E} \tag{4–3}$$

Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1. The reason is that I_C is always slightly less than I_E by the amount of I_B. For example, if $I_E = 100$ mA and $I_B = 1$ mA, then $I_C = 99$ mA and $\alpha_{DC} = 0.99$.

Relationship of β_{DC} and α_{DC}

Let's start with the current formula $I_E = I_C + I_B$ and divide each current by I_C:

$$\frac{I_E}{I_C} = \frac{I_C}{I_C} + \frac{I_B}{I_C} = 1 + \frac{I_B}{I_C}$$

Since $\beta_{DC} = I_C/I_B$ and $\alpha_{DC} = I_C/I_E$, we can substitute the reciprocals into the equation:

$$\frac{1}{\alpha_{DC}} = 1 + \frac{1}{\beta_{DC}}$$

By rearranging and solving for β_{DC}, we get

$$\frac{1}{\alpha_{DC}} = \frac{\beta_{DC} + 1}{\beta_{DC}}$$

$$\beta_{DC} = \alpha_{DC}(\beta_{DC} + 1)$$

$$\beta_{DC} = \alpha_{DC}\beta_{DC} + \alpha_{DC}$$

$$\beta_{DC} - \alpha_{DC}\beta_{DC} = \alpha_{DC}$$

$$\beta_{DC}(1 - \alpha_{DC}) = \alpha_{DC}$$

$$\beta_{DC} = \frac{\alpha_{DC}}{1 - \alpha_{DC}} \tag{4–4}$$

Equation (4–4) shows that the closer α_{DC} is to 1, the higher the value of β_{DC}.

EXAMPLE 4–1 Determine β_{DC}, I_E, and α_{DC} for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = 73$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = 3.70\text{ mA}$$

$$\alpha_{DC} = \frac{I_C}{I_E} = \frac{3.65\text{ mA}}{3.70\text{ mA}} = 0.986$$

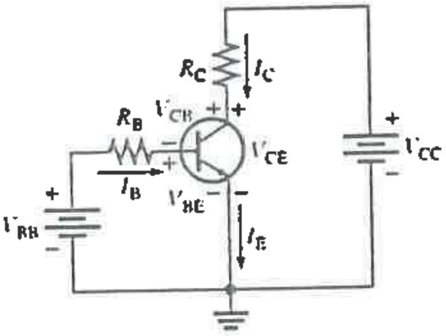
Related Exercise A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current. What is α_{DC}?

Current and Voltage Analysis

Consider the circuit configuration in Figure 4–7. Three transistor currents and three dc voltages can be identified.

I_B: base current (dc)
I_E: emitter current (dc)
I_C: collector current (dc)
V_{BE}: dc voltage at base with respect to emitter
V_{CB}: dc voltage at collector with respect to base
V_{CE}: dc voltage at collector with respect to emitter

FIGURE 4–7
Transistor currents and voltages.



V_{BB} forward-biases the base-emitter junction and V_{CC} reverse-biases the base-collector junction. When the base-emitter junction is forward-biased, it is like a forward-biased diode and has a forward voltage drop of

$$V_{BE} \cong 0.7\text{ V} \tag{4–5}$$

Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{R_B} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

$$I_B R_B = V_{BB} - V_{BE}$$

Solving for I_B, you get

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \quad (4\text{–}6)$$

The drop across R_C is

$$V_{R_C} = I_C R_C$$

The voltage at the collector with respect to the emitter, which is grounded, is

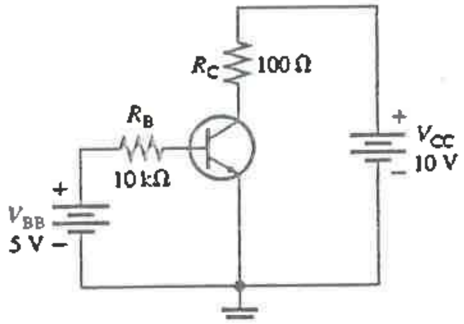
$$V_{CE} = V_{CC} - I_C R_C \quad (4\text{–}7)$$

where $I_C = \beta_{DC} I_B$. The voltage across the reverse-biased collector-base junction is

$$V_{CB} = V_{CE} - V_{BE} \quad (4\text{–}8)$$

EXAMPLE 4–2 Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–8. The transistor has a $\beta_{DC} = 150$.

FIGURE 4–8



Solution From Equation (4–5) $V_{BE} = 0.7$ V. Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 430\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = 64.5\text{ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = 64.9\text{ mA}$$

Solve for V_{CE} and V_{CB}:

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega)$$
$$= 10\text{ V} - 6.45\text{ V} = 3.55\text{ V}$$
$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = 2.85\text{ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

Related Exercise Determine I_B, I_C, I_E, V_{CE}, and V_{CB} in Figure 4–8 for the following values: $R_B = 22\text{ k}\Omega$, $R_C = 220\ \Omega$, $V_{BB} = 6$ V, $V_{CC} = 9$ V, and $\beta_{DC} = 90$.

Collector Characteristic Curves

Using a circuit like that shown in Figure 4–9(a), you can generate a set of collector characteristic curves that show how the collector current, I_C, varies with the collector-to-emitter voltage, V_{CE}, for specified values of base current, I_B. Notice in the circuit diagram that both V_{BB} and V_{CC} are variable sources of voltage.

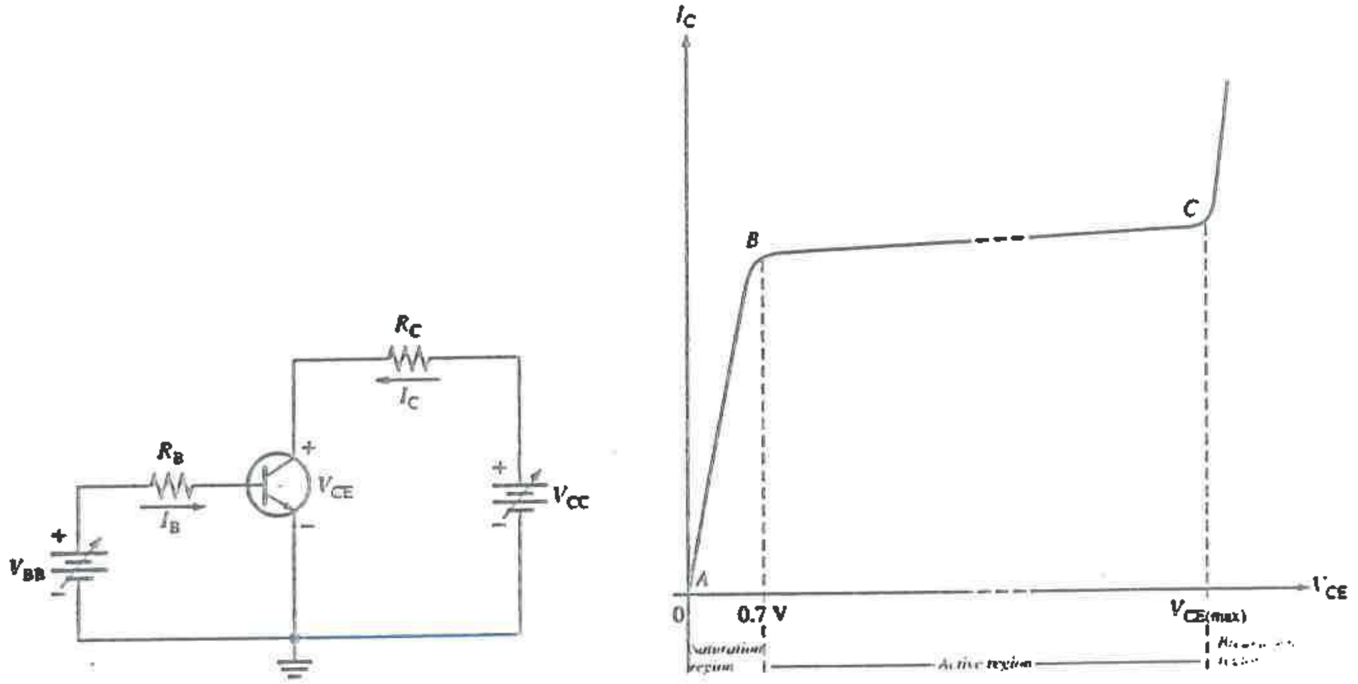
Assume that V_{BB} is set to produce a certain value of I_B and V_{CC} is zero. For this condition, both the base-emitter junction and the base-collector junction are forward-biased because the base is at approximately 0.7 V while the emitter and the collector are at 0 V. The base current is through the base-emitter junction because of the low impedance path to ground and, therefore, I_C is zero. When both junctions are forward-biased, the transistor is in the **saturation** region of its operation.

As V_{CC} is increased, V_{CE} increases gradually as the collector current increases. This is indicated by the portion of the characteristic curve between points A and B in Figure 4–9(b). I_C increases as V_{CC} is increased because V_{CE} remains less than 0.7 V due to the forward-biased base-collector junction.

When V_{CE} exceeds 0.7 V, the base-collector junction becomes reverse-biased and the transistor goes into the *active* or linear region of its operation. Once the base-collector junction is reverse-biased, I_C levels off and remains essentially constant for a given value of I_B as V_{CE} continues to increase. Actually, I_C increases very slightly as V_{CE} increases due to widening of the base-collector depletion region. This results in fewer holes for recombination in the base region which effectively causes a slight increase in β_{DC}. This is shown by the portion of the characteristic curve between points B and C in Figure 4–9(b). For this portion of the characteristic curve, the value of I_C is determined only by the relationship expressed as $I_C = \beta_{DC} I_B$.

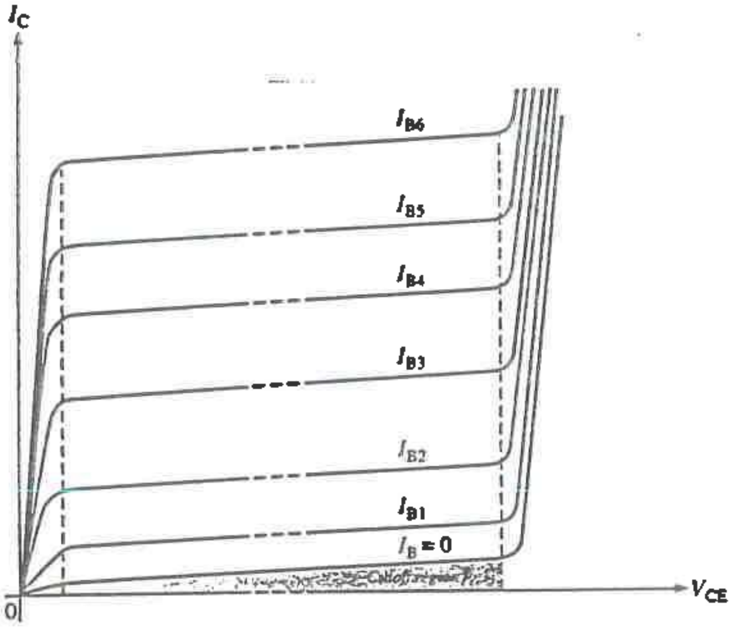
When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly as indicated by the part of the curve to the right of point C in Figure 4–9(b). A transistor should never be operated in this breakdown region.

A family of collector characteristic curves is produced when I_C versus V_{CE} is plotted for several values of I_B, as illustrated in Figure 4–9(c). When $I_B = 0$, the transistor is in the cutoff region although there is a very small collector leakage current as indicated. The amount of collector leakage current for $I_B = 0$ is exaggerated on the graph for purposes of illustration.



(a) Circuit

(b) I_C versus V_{CE} curve for one value of I_B



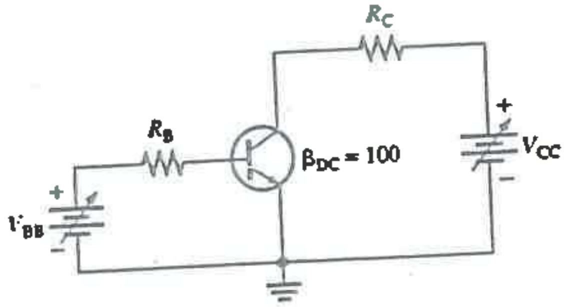
(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

FIGURE 4–9
Collector characteristic curves.

EXAMPLE 4–3

Sketch an ideal family of collector curves for the circuit in Figure 4–10 for $I_B = 5\ \mu A$ to $25\ \mu A$ in $5\ \mu A$ increments. Assume $\beta_{DC} = 100$ and that V_{CE} does not exceed breakdown.

FIGURE 4–10

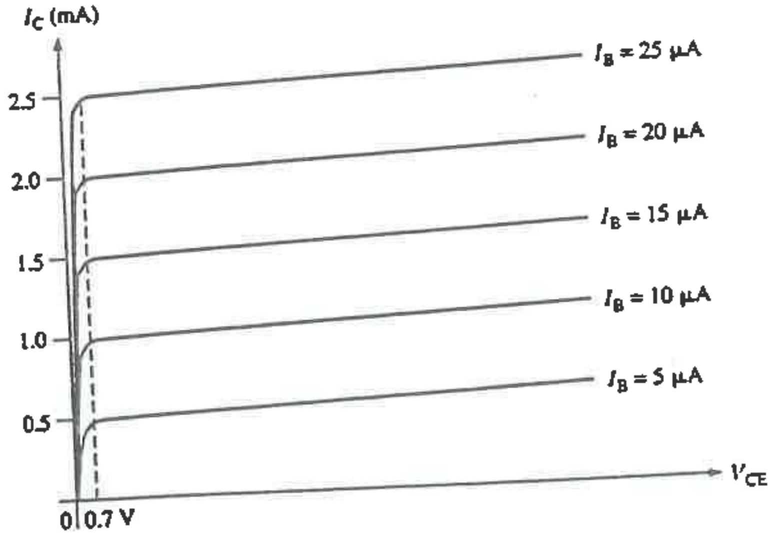


Solution Using the relationship $I_C = \beta_{DC} I_B$, values of I_C are calculated and tabulated in Table 4–1. The resulting curves are plotted in Figure 4–11. These are ideal curves because the slight increase in I_C for a given value of I_B as V_{CE} increases in the active region is neglected.

TABLE 4–1

I_B	I_C
5 µA	0.5 mA
10 µA	1.0 mA
15 µA	1.5 mA
20 µA	2.0 mA
25 µA	2.5 mA

FIGURE 4–11

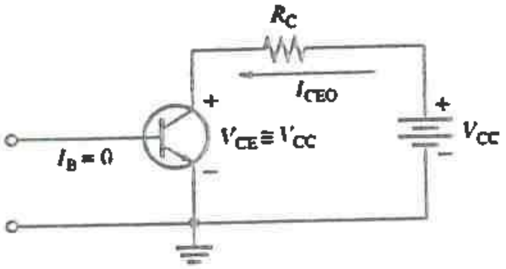


Related Exercise Where would the curve for $I_B = 0$ appear on the graph in Figure 4–11, neglecting collector leakage current?

Cutoff

As previously mentioned, when $I_B = 0$, the transistor is in the cutoff region of its operation. This is shown in Figure 4–12 with the base lead open, resulting in a base current of zero. Under this condition, there is a very small amount of collector leakage current, I_{CEO}, due mainly to thermally produced carriers. Because I_{CEO} is extremely small, it will usually be neglected in circuit analysis so that $V_{CE} = V_{CC}$. In cutoff, both the base-emitter and the base-collector junctions are reverse-biased.

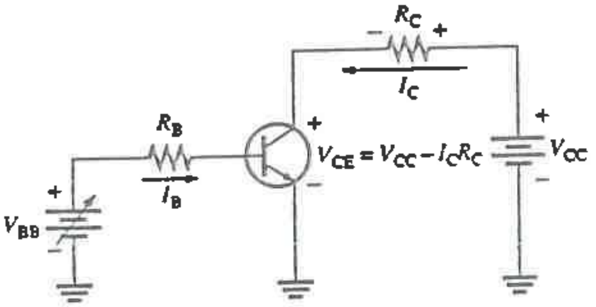
FIGURE 4-12
Collector leakage current (I_{CEO}) in cutoff.



Saturation

When the base current in Figure 4–13(a) is increased, the collector current also increases ($I_C = \beta_{DC}I_B$) and V_{CE} decreases as a result of more drop across the collector resistor ($V_{CE} = V_{CC} - I_CR_C$). This is illustrated in Figure 4–13. When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased and I_C can increase no further even with a continued increase in I_B. At the point of saturation, the relation $I_C = \beta_{DC}I_B$ is no longer valid. $V_{CE(sat)}$ for a transistor occurs somewhere below the knee of the collector curves, and it is usually only a few tenths of a volt for silicon transistors.

FIGURE 4–13
As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across R_C.



DC Load Line

Cutoff and saturation can be illustrated in relation to the collector characteristic curves by the use of a load line. Figure 4–14 shows a dc load line drawn on a family of curves connecting the cutoff point and the saturation point. The bottom of the load line is at ideal cutoff where $I_C = 0$ and $V_{CE} = V_{CC}$. The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$. In between cutoff and saturation along the load line is the active region of the transistor's operation. Load line operation is discussed more in a later chapter.

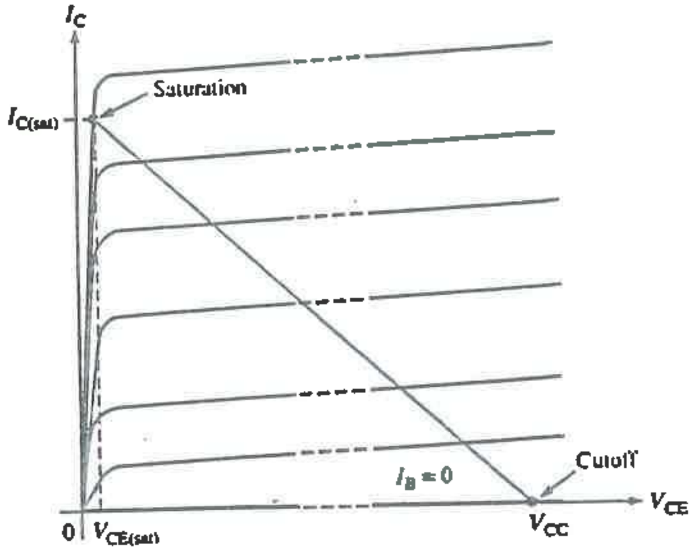
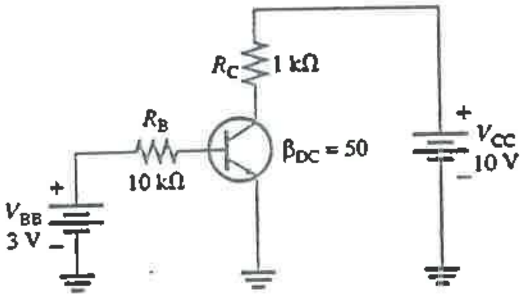


FIGURE 4–14
DC load line on a family of collector characteristic curves illustrating the cutoff and saturation conditions.

EXAMPLE 4–4 Determine whether or not the transistor in Figure 4–15 is in saturation. Assume $V_{CE(sat)} = 0.2$ V.

FIGURE 4–15



Solution First, determine $I_{C(sat)}$.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\text{ V} - 0.2\text{ V}}{1\text{ k}\Omega} = \frac{9.8\text{ V}}{1\text{ k}\Omega} = 9.8\text{ mA}$$

Now, see if I_B is large enough to produce $I_{C(sat)}$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$$

$$I_C = \beta_{DC} I_B = (50)(0.23\text{ mA}) = 11.5\text{ mA}$$

This shows that with the specified β_{DC}, this base current is capable of producing an I_C greater than $I_{C(sat)}$. Therefore, the transistor is saturated, and the collector current value of 11.5 mA is never reached. If you further increase I_B, the collector current remains at its saturation value.

Related Exercise Determine whether or not the transistor in Figure 4–15 is saturated for the following values: $\beta_{DC} = 125$, $V_{BB} = 1.5$ V, $R_B = 6.8$ kΩ, $R_C = 180$ Ω, and $V_{CC} = 12$ V.

More About β_{DC}

The β_{DC} or h_{FE} is a very important bipolar junction transistor parameter that we need to examine further. β_{DC} is not truly constant but varies with both collector current and with temperature. Keeping the junction temperature constant and increasing I_C causes β_{DC} to increase to a maximum. A further increase in I_C beyond this maximum point causes β_{DC} to decrease. If I_C is held constant and the temperature is varied, β_{DC} changes directly with the temperature. If the temperature goes up, β_{DC} goes up and vice versa. Figure 4–16 shows the variation of β_{DC} with I_C and junction temperature (T_J) for a typical transistor.

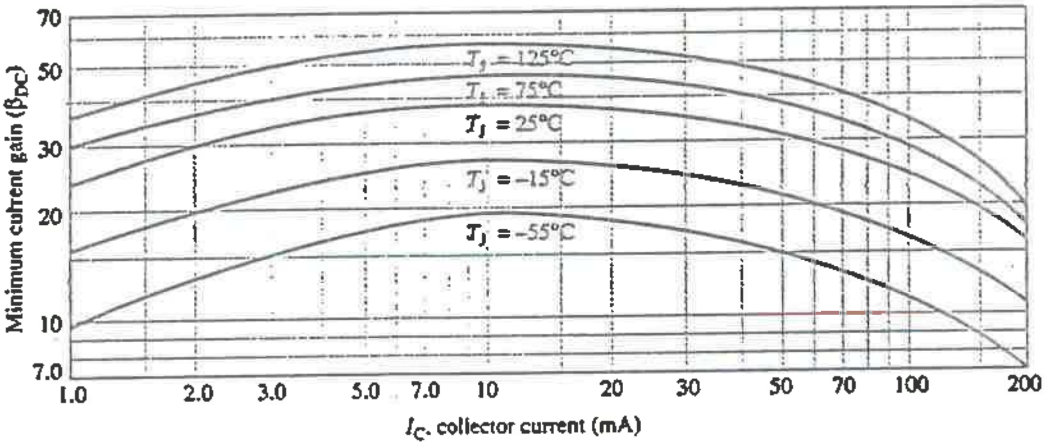


FIGURE 4–16

Variation of β_{DC} with I_C for several temperatures.

A transistor data sheet usually specifies β_{DC} (h_{FE}) at specific I_C values. Even at fixed values of I_C and temperature, β_{DC} varies from device to device for a given transistor due to inconsistencies in the manufacturing process that are unavoidable. The β_{DC} specified at a certain value of I_C is usually the minimum value, $\beta_{DC(min)}$, although the maximum and typical values are also sometimes specified.

Maximum Transistor Ratings

The transistor, like any other electronic device, has limitations on its operation. These limitations are stated in the form of maximum ratings and are normally specified on the manufacturer's data sheet. Typically, maximum ratings are given for collector-to-base voltage, collector-to-emitter voltage, emitter-to-base voltage, collector current, and power dissipation.

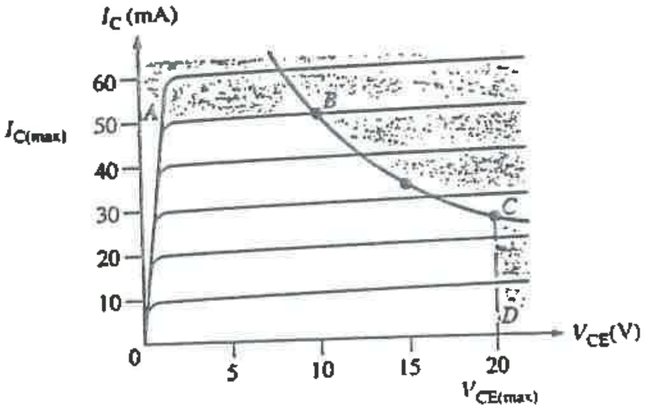
The product of V_{CE} and I_C must not exceed the maximum power dissipation. Both V_{CE} and I_C cannot be maximum at the same time. If V_{CE} is maximum, I_C can be calculated as

$$I_C = \frac{P_{D(max)}}{V_{CE}} \tag{4–9}$$

If I_C is maximum, V_{CE} can be calculated by rearranging Equation (4–9) as follows:

$$V_{CE} = \frac{P_{D(max)}}{I_C} \tag{4–10}$$

For any given transistor, a maximum power dissipation curve can be plotted on the collector characteristic curves, as shown in Figure 4–17(a). These values are tabulated in Figure 4–17(b). Assume $P_{D(max)}$ is 500 mW, $V_{CE(max)}$ is 20 V, and $I_{C(max)}$ is 50 mA. The curve shows that this particular transistor cannot be operated in the shaded portion of the graph. $I_{C(max)}$ is the limiting rating between points A and B, $P_{D(max)}$ is the limiting rating between points C and D.



(a)

$P_{D(max)}$	V_{CE}	I_C
500 mW	5 V	100 mA
500 mW	10 V	50 mA
500 mW	15 V	33 mA
500 mW	20 V	25 mA

(b)

FIGURE 4–17
Maximum power dissipation curve.

EXAMPLE 4–5

A certain transistor is to be operated with $V_{CE} = 6$ V. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

Solution

$$I_C = \frac{P_{D(max)}}{V_{CE}} = \frac{250\text{ mW}}{6\text{ V}} = 41.7\text{ mA}$$

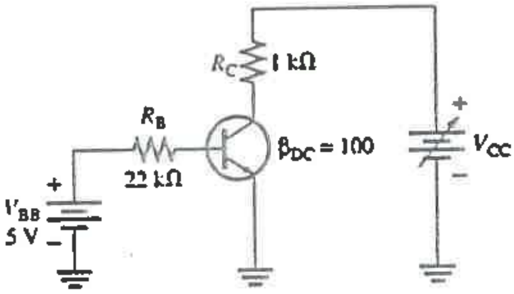
Remember that this is not necessarily the maximum I_C. The transistor can handle more collector current if V_{CE} is reduced, as long as $P_{D(max)}$ is not exceeded.

Related Exercise If $P_{D(max)} = 1$ W, how much voltage is allowed from collector to emitter if the transistor is operating with $I_C = 100$ mA?

EXAMPLE 4–6

The transistor in Figure 4–18 has the following maximum ratings: $P_{D(max)} = 800$ mW, $V_{CE(max)} = 15$ V, and $I_{C(max)} = 100$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

FIGURE 4–18



Solution First, find I_B so that you can determine I_C.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 195\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (100)(195\ \mu\text{A}) = 19.5\text{ mA}$$

I_C is much less than $I_{C(max)}$ and will not change with V_{CC}. It is determined only by I_B and β_{DC}.

The voltage drop across R_C is

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1\text{ k}\Omega) = 19.5\text{ V}$$

Now you can determine the value of V_{CC} when $V_{CE} = V_{CE(max)} = 15$ V.

$$V_{R_C} = V_{CC} - V_{CE}$$

So,

$$V_{CC(max)} = V_{CE(max)} + V_{R_C} = 15\text{ V} + 19.5\text{ V} = 34.5\text{ V}$$

V_{CC} can be increased to 34.5 V, under the existing conditions, before $V_{CE(max)}$ is exceeded. However, at this point it is not known whether or not $P_{D(max)}$ has been exceeded.

$$P_D = V_{CE(max)} I_C = (15\text{ V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(max)}$ is 800 mW, it is *not* exceeded when $V_{CC} = 34.5$ V. So, $V_{CE(max)} = 15$ V is the limiting rating in this case. If the base current is removed causing the transistor to turn off, $V_{CE(max)}$ will be exceeded because the entire supply voltage, V_{CC}, will be dropped across the transistor.

Related Exercise The transistor in Figure 4–18 has the following maximum ratings: $P_{D(max)} = 500$ mW, $V_{CE(max)} = 25$ V, and $I_{C(max)} = 200$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

Derating $P_{D(max)}$

$P_{D(max)}$ is usually specified at 25°C. For higher temperatures, $P_{D(max)}$ is less. Data sheets often give derating factors for determining $P_{D(max)}$ at any temperature above 25°C. For example, a derating factor of 2 mW/C° indicates that the maximum power dissipation is reduced 2 mW for each Centigrade degree increase in temperature.

EXAMPLE 4–7

A certain transistor has a $P_{D(max)}$ of 1 W at 25°C. The derating factor is 5 mW/C°. What is the $P_{D(max)}$ at a temperature of 70°C?

Solution The change (reduction) in $P_{D(max)}$ is

$$\Delta P_{D(max)} = (5\text{ mW/C°})(70\text{°C} - 25\text{°C}) = (5\text{ mW/C°})(45\text{ C°}) = 225\text{ mW}$$

Therefore, the $P_{D(max)}$ at 70°C is

$$1\text{ W} - 225\text{ mW} = 775\text{ mW}$$

Related Exercise A transistor has a $P_{D(max)} = 5$ W at 25°C. The derating factor is 10 mW/C°. What is the $P_{D(max)}$ at 70°C?

Transistor Data Sheet

A partial data sheet for the 2N3903 and 2N3904 *npn* transistors is shown in Figure 4–19. Notice that the maximum collector-emitter voltage (V_{CEO}) is 40 V. The "O" in the subscript indicates that the voltage is measured from collector (C) to emitter (E) with the base open (O). In the text, we use $V_{CE(max)}$ for purposes of clarity. Also notice that the maximum collector current is 200 mA.

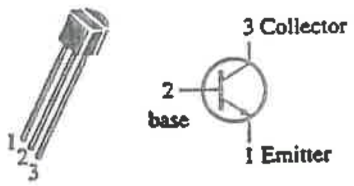
The β_{DC} (h_{FE}) is specified for several values of I_C and, as you can see, h_{FE} varies with I_C as we previously discussed.

The collector-emitter saturation voltage, $V_{CE(sat)}$ is 0.2 V maximum for $I_{C(sat)}$ = 10 mA and increases with the current.

SECTION 4–3 REVIEW

1. Define β_{DC} and α_{DC}. What is h_{FE}?
2. If the dc current gain of a transistor is 100, determine β_{DC} and α_{DC}.
3. What two variables are plotted on a collector characteristic curve?
4. What bias conditions must exist for a transistor to operate as an amplifier?
5. Does β_{DC} increase or decrease with temperature?
6. For a given type of transistor, can β_{DC} be considered to be a constant?

2N3903
2N3904



General Purpose
Transistors

NPN Silicon

Maximum Ratings

Rating	Symbol	Value	Unit
Collector-Emitter voltage	V_{CEO}	40	V dc
Collector-Base voltage	V_{CBO}	60	V dc
Emitter-Base voltage	V_{EBO}	6.0	V dc
Collector current — continuous	I_C	200	mA dc
Total device dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	625 5.0	mW mW/C°
Total device dissipation @ $T_C = 25°C$ Derate above 25°C	P_D	1.5 12	Watts mW/C°
Operating and storage junction Temperature range	T_J, T_{stg}	−55 to +150	°C

Thermal Characteristics

Characteristic	Symbol	Max	Unit
Thermal resistance, junction to case	$R_{\theta JC}$	83.3	C°/W
Thermal resistance, junction to ambient	$R_{\theta JA}$	200	C°/W

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted.)

Characteristic		Symbol	Min	Max	Unit
OFF Characteristics					
Collector-Emitter breakdown voltage ($I_C = 1.0$ mA dc, $I_B = 0$)		$V_{(BR)CEO}$	40	–	V dc
Collector-Base breakdown voltage ($I_C = 10$ µA dc, $I_E = 0$)		$V_{(BR)CBO}$	60	–	V dc
Emitter-Base breakdown voltage ($I_E = 10$ µA dc, $I_C = 0$)		$V_{(BR)EBO}$	6.0	–	V dc
Base cutoff current ($V_{CE} = 30$ V dc, $V_{EB} = 3.0$ V dc)		I_{BL}	–	50	nA dc
Collector cutoff current ($V_{CE} = 30$ V dc, $V_{EB} = 3.0$ V dc)		I_{CEX}	–	50	nA dc
ON Characteristics					
DC current gain ($I_C = 0.1$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904	h_{FE}	20 40	– –	–
($I_C = 1.0$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		35 70	– –	
($I_C = 10$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		50 100	150 300	
($I_C = 50$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		30 60	– –	
($I_C = 100$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		15 30	– –	
Collector-Emitter saturation voltage ($I_C = 10$ mA dc, $I_B = 1.0$ mA dc) ($I_C = 50$ mA dc, $I_B = 5.0$ mA dc)		$V_{CE(sat)}$	– –	0.2 0.3	V dc
Base-Emitter saturation voltage ($I_C = 10$ mA dc, $I_B = 1.0$ mA dc) ($I_C = 50$ mA dc, $I_B = 5.0$ mA dc)		$V_{BE(sat)}$	0.65 –	0.85 0.95	V dc

FIGURE 4–19
Partial transistor data sheet.

4–4 ■ THE TRANSISTOR AS AN AMPLIFIER

Amplification is the process of linearly increasing the amplitude of an electrical signal and is one of the major properties of a transistor. As you learned, the transistor exhibits current gain (called β). When a transistor is biased in the active (or linear) region, as previously described, the BE junction has a low resistance due to forward bias and the BC junction has a high resistance due to reverse bias.

After completing this section, you should be able to

- ■ **Discuss how a transistor is used as a voltage amplifier**
  - ☐ **Describe amplification**
  - ☐ **Develop the ac equivalent circuit for a basic transistor amplifier**
  - ☐ **Determine the voltage gain of a basic transistor amplifier**

DC and AC Quantities

Before introducing the concept of transistor amplification, the designations that we will use for the circuit quantities of current, voltage, and resistance must be explained because amplifier circuits have both dc and ac quantities.

In this text, italic capital letters are used for both dc and ac currents (I) and voltages (V). This rule applies to rms, average, peak, and peak-to-peak ac values. AC current and voltage values are always rms unless stated otherwise. Although some texts use lowercase i and v for ac current and voltage, we reserve the use of lowercase i and v only for instantaneous values, as you learned in your dc/ac circuits course. In this text, the distinction between a dc current or voltage and an ac current or voltage is in the subscript.

DC quantities always carry an uppercase roman (nonitalic) subscript. For example, I_{B}, I_{C}, and I_{E} are the dc transistor currents. V_{BE}, V_{CB}, and V_{CE} are the dc voltages from one transistor terminal to another. Single subscripted voltages such as V_{B}, V_{C}, and V_{E} are dc voltages from the transistor terminals to ground.

AC and all time-varying quantities always carry a lowercase italic subscript. For example, I_b, I_c, and I_e are the ac transistor currents. V_{be}, V_{cb}, and V_{ce} are the ac voltages from one transistor terminal to another. Single subscripted voltages such as V_b, V_c, and V_e are ac voltages from the transistor terminals to ground.

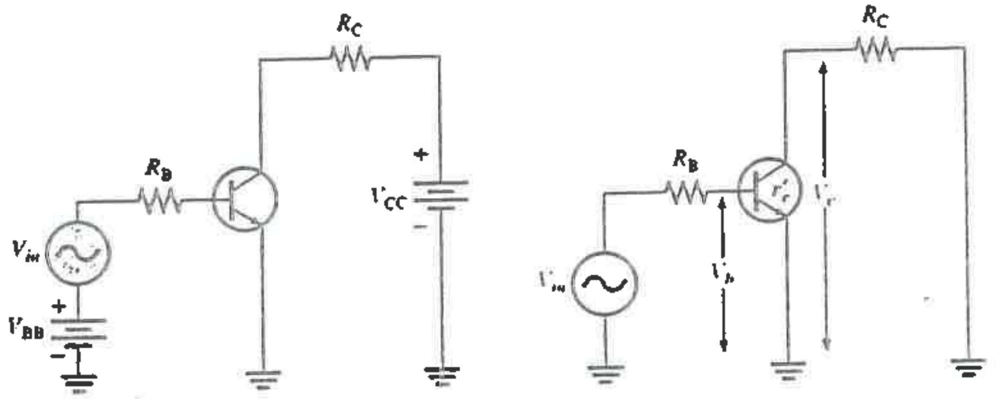
The rule is different for *internal* transistor resistances. As you will see later, transistors have internal ac resistances that are designated by lowercase r' with an appropriate subscript. For example, the internal ac emitter resistance is designated as r'_e.

Circuit resistances external to the transistor itself use the standard italic capital R with a subscript that identifies the resistance as dc or ac (when applicable), just as for current and voltage. For example R_{E} is an external dc emitter resistance and R_e is an external ac emitter resistance.

Transistor Amplification

As you have learned, a transistor amplifies current because the collector current is equal to the base current multiplied by the current gain, β. The base current in a transistor is very small compared to the collector and emitter currents. Because of this, the collector current is approximately equal to the emitter current.

With this in mind, let's look at the circuit in Figure 4–20(a). An ac voltage, V_{in} is superimposed on the dc bias voltage V_{BB} by connecting them in series with the base resistor, R_B, as shown. The dc bias voltage V_{CC} is connected to the collector through the collector resistor, R_C.



(a) Circuit with ac input voltage V_{in} and dc bias voltage superimposed

(b) AC equivalent circuit

FIGURE 4–20
Basic transistor amplifier circuit.

The ac input voltage produces an ac base current, which results in a much larger ac collector current. The ac collector current produces an ac voltage across R_C, thus producing an apparent amplified reproduction of the ac input voltage in the active region of operation.

The AC Equivalent Circuit The dc bias sources ideally appear as shorts to the ac voltage. Therefore, the ac equivalent circuit can be represented as shown in Figure 4–20(b) with V_{CC} and V_{BB} replaced by shorts.

The forward-biased base-emitter junction presents a very low resistance to the ac signal. This internal ac emitter resistance is designated r'_e. In Figure 4–20(b), the ac emitter current is

$$I_e \cong \frac{V_b}{r'_e}$$

The ac collector voltage, V_c, equals the ac voltage drop across R_C:

$$V_c = I_c R_C$$

Since $I_c \cong I_e$, the ac collector voltage is

$$V_c \cong I_e R_C$$

V_b can be considered the transistor ac input voltage where $V_b = V_{in} - I_b R_B$. V_c can be considered the transistor ac output voltage. The ratio of V_c to V_b is the ac voltage gain, A_v, of the transistor circuit:

$$A_v = \frac{V_c}{V_b}$$

Substituting I_eR_C for V_c and $I_er'_e$ for V_b, we get

$$A_v = \frac{V_c}{V_b} \cong \frac{I_eR_C}{I_er'_e}$$

The I_e terms cancel; therefore,

$$A_v \cong \frac{R_C}{r'_e} \qquad (4\text{–}11)$$

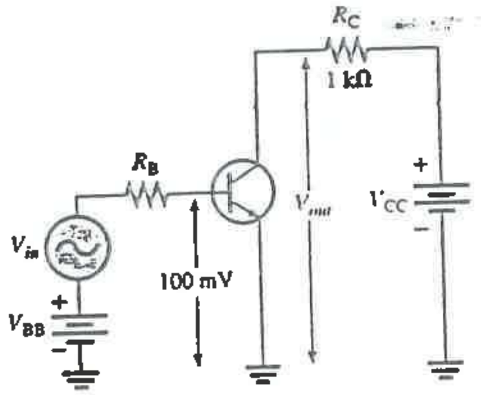
Equation (4–11) shows that the transistor in Figure 4–20 provides amplification or voltage gain dependent on the value of R_C and r'_e.

Since R_C is always considerably larger in value than r'_e, the output voltage is always greater than the input voltage. Various types of amplifiers are covered in detail in later chapters.

EXAMPLE 4–8

Determine the voltage gain and the ac output voltage in Figure 4–21 if $r'_e = 50\ \Omega$.

FIGURE 4–21



Solution The voltage gain is

$$A_v \cong \frac{R_C}{r'_e} = \frac{1\ \text{k}\Omega}{50\ \Omega} = 20$$

Therefore, the ac output voltage is

$$V_{out} = A_vV_b = (20)(100\text{ mV}) = 2\text{ V rms}$$

Related Exercise What value of R_C in Figure 4–21 will it take to have a voltage gain of 50?

SECTION 4–4 REVIEW

1. What is amplification?
2. How is voltage gain defined?
3. Name two factors that determine the voltage gain of an amplifier.
4. What is the voltage gain of a transistor amplifier that has an output of 5 V rms and an input of 250 mV rms?
5. A transistor connected as in Figure 4–21 has an $r'_e = 20\ \Omega$. If R_C is $1200\ \Omega$, what is the voltage gain?

4–5 ■ THE TRANSISTOR AS A SWITCH

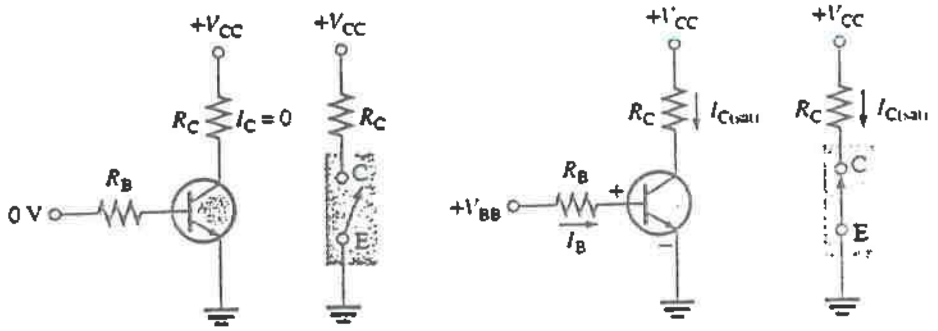
In the previous section, we discussed the transistor as a linear amplifier. The second major application area is switching applications. When used as an electronic switch, a transistor is normally operated alternately in cutoff and saturation.

After completing this section, you should be able to

- Discuss how a transistor is used as an electronic switch
  - ☐ Define *cutoff* and *saturation*
  - ☐ Describe the conditions that produce cutoff
  - ☐ Describe the conditions that produce saturation
  - ☐ Analyze a transistor switching circuit for cutoff and saturation
  - ☐ Discuss a basic application of a transistor switching circuit

---

Figure 4–22 illustrates the basic operation of the transistor as a switching device. In part (a), the transistor is in the cutoff region because the base-emitter junction is not forward-biased. In this condition, there is, ideally, an *open* between collector and emitter as indicated by the switch equivalent. In part (b), the transistor is in the saturation region because the base-emitter junction and the base-collector junction are forward-biased and the base current is made large enough to cause the collector current to reach its saturation value. In this condition, there is, ideally, a *short* between collector and emitter as indi-



(a) Cutoff — open switch

(b) Saturation — closed switch

FIGURE 4–22
Ideal switching action of a transistor.

cated by the switch equivalent. Actually, a voltage drop of up to a few tenths of a volt normally occurs, which is the saturation voltage, $V_{CE(sat)}$.

Conditions in Cutoff

As mentioned before, a transistor is in the cutoff region when the base-emitter junction is *not* forward-biased. Neglecting leakage current, all of the currents are zero, and V_{CE} is equal to V_{CC}.

$$V_{CE(cutoff)} = V_{CC} \tag{4–12}$$

Conditions in Saturation

As you have learned, when the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is saturated. The formula for collector saturation current is

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} \tag{4–13}$$

Since $V_{CE(sat)}$ is very small compared to V_{CC}, it can usually be neglected.

The minimum value of base current needed to produce saturation is

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} \tag{4–14}$$

I_B should be significantly greater than $I_{B(min)}$ to keep the transistor well into saturation.

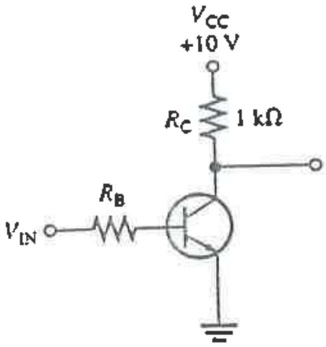
EXAMPLE 4–9

(a) For the transistor circuit in Figure 4–23, what is V_{CE} when $V_{IN} = 0$ V?

(b) What minimum value of I_B is required to saturate this transistor if β_{DC} is 200? Neglect $V_{CE(sat)}$.

(c) Calculate the maximum value of R_B when $V_{IN} = 5$ V.

FIGURE 4–23



-104-

Solution

(a) When $V_{IN} = 0$ V, the transistor is in cutoff (acts like an open switch) and $V_{CE} = V_{CC} = 10$ V.

(b) Since $V_{CE(sat)}$ is neglected (0 V),

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

$$I_B = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{10\text{ mA}}{200} = 50\ \mu\text{A}$$

This is the value of I_B necessary to drive the transistor to the point of saturation. Any further increase in I_B will drive the transistor deeper into saturation but will not increase I_C.

(c) When the transistor is on, $V_{BE} = 0.7$ V. The voltage across R_B is

$$V_{R_B} = V_{IN} - V_{BE} = 5\text{ V} - 0.7\text{ V} = 4.3\text{ V}$$

Calculate the maximum value of R_B needed to allow a minimum I_B of 50 μA by Ohm's law as follows:

$$R_B = \frac{V_{R_B}}{I_B} = \frac{4.3\text{ V}}{50\ \mu\text{A}} = 86\text{ k}\Omega$$

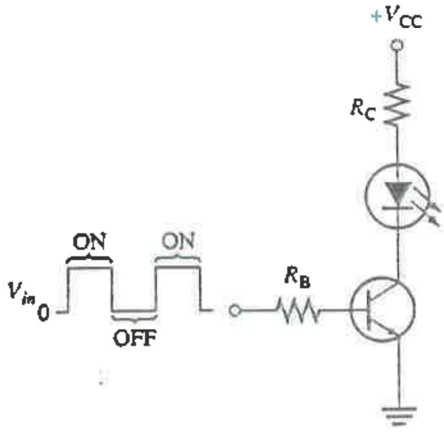
Related Exercise Determine the minimum value of I_B required to saturate the transistor in Figure 4–23 if β_{DC} is 125 and $V_{CE(sat)}$ is 0.2 V.

A Simple Application of a Transistor Switch

The transistor in Figure 4–24 is used as a switch to turn the LED on and off. For example, a square wave input voltage with a period of 2 s is applied to the input as indicated. When the square wave is at 0 V, the transistor is in cutoff and, since there is no collector current, the LED does not emit light. When the square wave goes to its high level, the transistor saturates. This forward-biases the LED, and the resulting collector current through the LED causes it to emit light. So, we have a blinking LED that is on for 1 s and off for 1 s.

FIGURE 4–24

A transistor used to switch an LED on and off.



-105-

EXAMPLE 4–10

The LED in Figure 4–24 requires 30 mA to emit a sufficient level of light. Therefore, the collector current should be approximately 30 mA. For the following circuit values, determine the amplitude of the square wave input voltage necessary to make sure that the transistor saturates. Use double the minimum value of base current as a safety margin to ensure saturation. $V_{CC} = 9$ V, $V_{CE(sat)} = 0.3$ V, $R_C = 270\ \Omega$, $R_B = 3.3\ \text{k}\Omega$, and $\beta_{DC} = 50$.

Solution

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{9\text{ V} - 0.3\text{ V}}{270\ \Omega} = 32.2\text{ mA}$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{32.2\text{ mA}}{50} = 644\ \mu\text{A}$$

To ensure saturation, use twice the value of $I_{B(min)}$, which gives 1.29 mA. Then

$$I_B = \frac{V_{R_B}}{R_B} = \frac{V_{in} - V_{BE}}{R_B} = \frac{V_{in} - 0.7\text{ V}}{3.3\text{ k}\Omega}$$

Solve for the voltage amplitude of the square wave input V_{in}:

$$V_{in} - 0.7\text{ V} = 2I_{B(min)}R_B = (1.29\text{ mA})(3.3\text{ k}\Omega)$$

$$V_{in} = (1.29\text{ mA})(3.3\text{ k}\Omega) + 0.7\text{ V} = 4.96\text{ V}$$

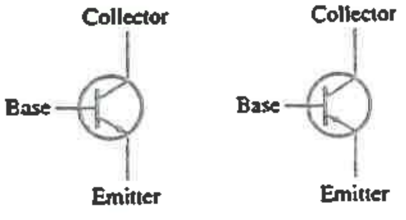
Related Exercise If you change the LED in Figure 4–24 to one that requires 50 mA for a specified light emission and you can't increase the input amplitude above 5 V or V_{CC} above 9 V, how would you modify the circuit? Specify the component(s) to be changed and the value(s).

SECTION 4–5 REVIEW

1. When a transistor is used as a switch, in what two states is it operated?
2. When is the collector current maximum?
3. When is the collector current approximately zero?
4. Under what condition is $V_{CE} = V_{CC}$?
5. When is V_{CE} minimum?

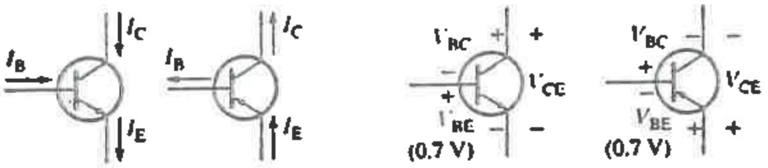
SUMMARY OF BIPOLAR JUNCTION TRANSISTORS

SYMBOLS



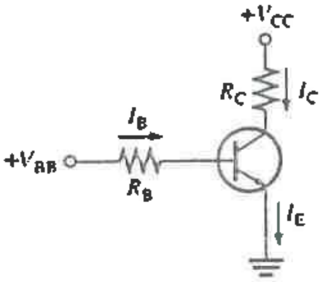
npn pnp

CURRENTS AND VOLTAGES



$I_E = I_C + I_B$

AMPLIFICATION

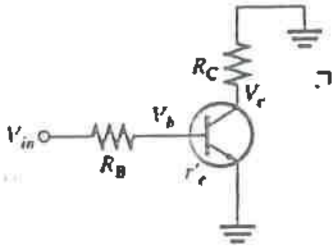


DC current gain

$I_C = \beta_{DC} I_B$

DC circuit

Cutoff: BE junction forward-biased
BC junction reverse-biased



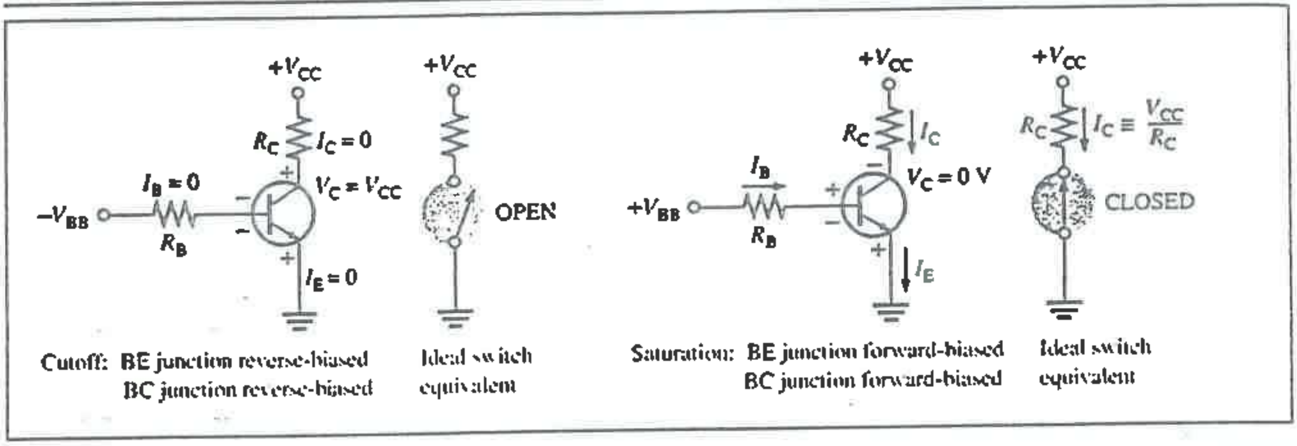
AC voltage gain

$A_v = \frac{V_c}{V_b} = \frac{R_C}{r'_e}$

AC equivalent circuit

SUMMARY OF BIPOLAR JUNCTION TRANSISTORS, *continued*

CUTOFF AND SATURATION



4-6 ■ TRANSISTOR PACKAGES AND TERMINAL IDENTIFICATION

Transistors are available in a wide range of package types for various applications. Those with mounting studs or heat sinks are usually power transistors. Low and medium power transistors are usually found in smaller metal or plastic cases. Still another package classification is for high-frequency devices. You should be familiar with common transistor packages and be able to identify the emitter, base, and collector terminals. This section is about transistor packages and terminal identification.

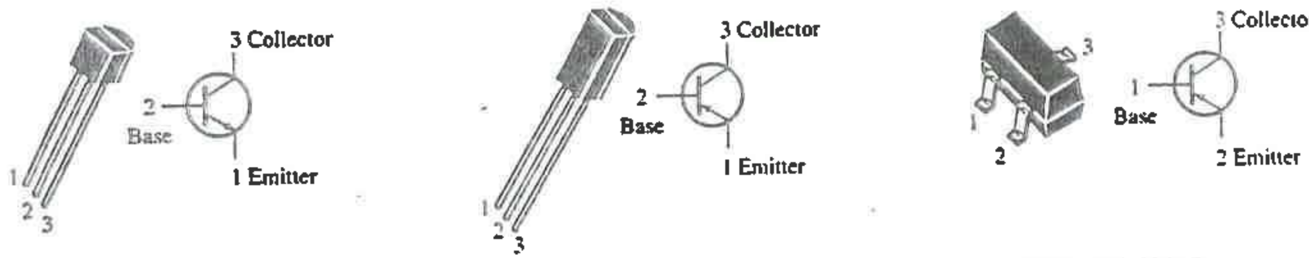
After completing this section, you should be able to

- Identify various types of transistor package configurations
  - ☐ List three broad categories of transistors
  - ☐ Recognize various types of cases and identify the pin configurations

Transistor Categories

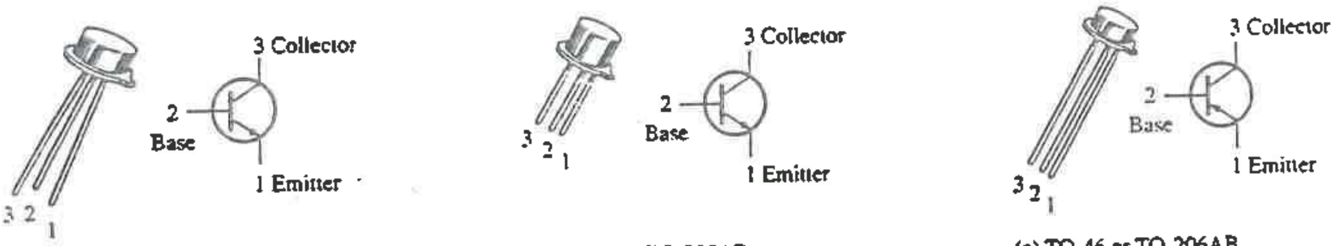
Manufacturers generally classify their bipolar junction transistors into three broad categories: general-purpose/small-signal devices, power devices, and RF (radio frequency/microwave) devices. Although each of these categories, to a large degree, has its own unique package types, you will find certain types of packages used in more than one device category. While keeping in mind there is some overlap, we will look at transistor packages for each of the three categories, so that you will be able to recognize a transistor when you see one on a circuit board and have a good idea of what general category it is in.

General-Purpose/Small-Signal Transistors General-purpose/small-signal transistors are generally used for low or medium power amplifiers or switching circuits. The packages are either plastic or metal cases. Certain types of packages contain multiple transistors. Figure 4–25 illustrates common plastic cases, Figure 4–26 shows packages called *metal cans*, and Figure 4–27 shows multiple-transistor packages. Some of the multiple-transistor packages such as the dual-in-line (DIP) and the small-outline (SO) are the same as those used for many integrated circuits. Typical pin connections are shown so you can identify the emitter, base, and collector.

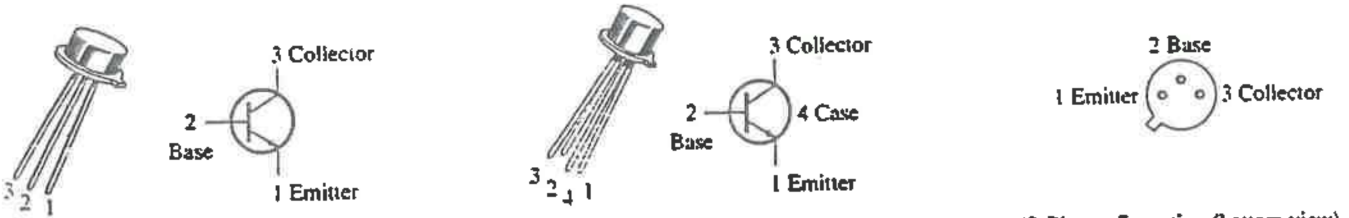


(a) TO-92 or TO-226AA (b) TO-92 or TO-226AE (c) SOT-23 or TO-236AB

FIGURE 4–25
Plastic cases for general-purpose/small-signal transistors. Both old and new JEDEC TO numbers are given. Pin configurations may vary. Always check the data sheet. (Copyright of Motorola, Inc. Used by permission.)

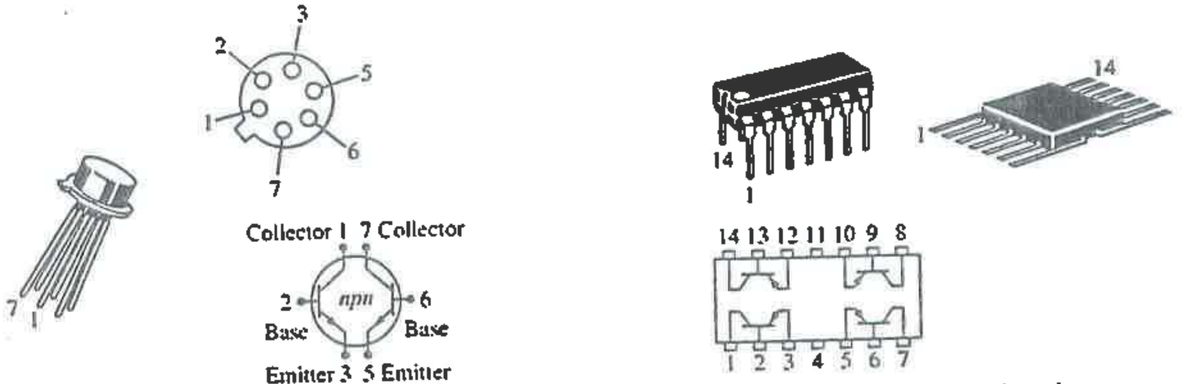


(a) TO-18 or TO-206AA (b) TO-39 or TO-205AD (c) TO-46 or TO-206AB



(d) TO-52 or TO-206AC (e) TO-72 or TO-206AF (f) Pin configuration (bottom view). Emitter is closest to tab.

FIGURE 4–26
Metal cases for general-purpose/small-signal transistors (copyright of Motorola, Inc. Used by permission).



(a) Dual metal can

(b) Quad dual in-line (DIP) and quad flat-pack. Dot indicates pin 1.

(c) Quad small outline (SO) package for surface-mount technology

(d) Dual ceramic flat-pack

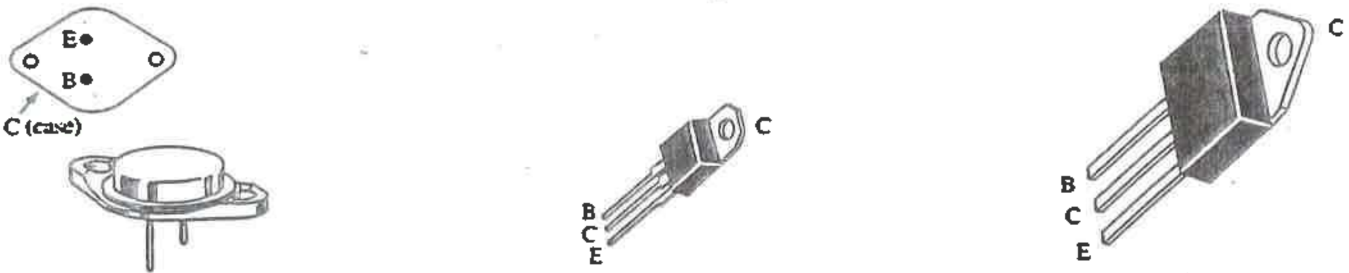
FIGURE 4–27
Typical multiple-transistor packages (copyright of Motorola, Inc. Used by permission).

Power Transistors Power transistors are used to handle large currents (typically more than 1 A) and/or large voltages. For example, the final audio stage in a stereo system uses a power transistor amplifier to drive the speakers. Figure 4–28 shows some common package configurations. In most applications, the metal tab or the metal case is common to the collector and is thermally connected to a heat sink for heat dissipation. Notice in part (g) how the small transistor chip is mounted inside the much larger package.

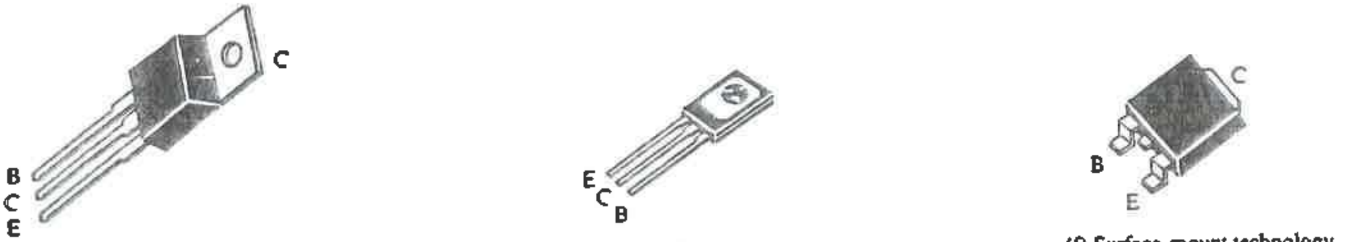
RF Transistors RF transistors are designed to operate at extremely high frequencies and are commonly used for various purposes in communications systems and other high-frequency applications. Their unusual shapes and lead configurations are designed to optimize certain high-frequency parameters. Figure 4–29 shows some examples.

SECTION 4–6 REVIEW

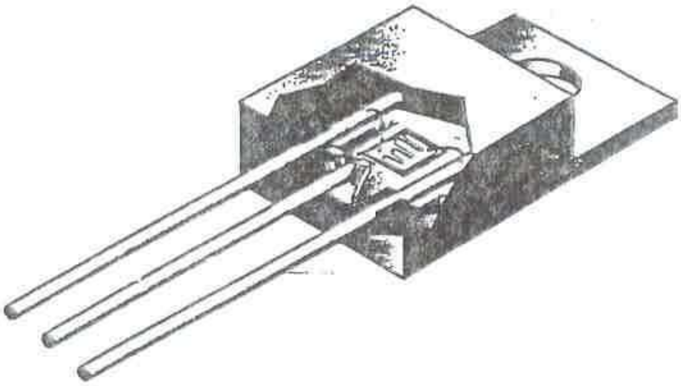
1. List the three broad categories of bipolar junction transistors.
2. In a single-transistor metal case, how do you identify the leads?
3. In power transistors, the metal mounting tab or case is connected to which transistor region?



(a) TO-3 or TO-204AE (b) TO-218 (c) TO-218AC



(d) TO-220AB (e) TO-225AA (f) Surface-mount technology



(g) Cutaway view of tiny transistor chip mounted in the encapsulated package

FIGURE 4–28
Typical power transistors (copyright of Motorola, Inc. Used by permission).

FIGURE 4–29
Examples of RF transistors (copyright of Motorola, Inc. Used by permission).