4

BIPOLAR JUNCTION TRANSISTORS (BJTs)

INTRODUCTION

The transistor was invented by a team of three men at Bell Laboratories in 1947. Although this first transistor was not a bipolar junction device, it was the beginning of a technological revolution that is still continuing. All of the complex electronic devices and systems today are an outgrowth of early developments in semiconductor transistors.

Two basic types of transistors are the bipolar junction transistor (BJT), which we will begin to study in this chapter, and the field-effect transistor (FET), which we will cover in later chapters. The BJT is used in two broad areas—as a linear amplifier to boost or amplify an electrical signal and as an electronic switch. Both of these applications are introduced in this chapter.

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe the basic structure of the BJT (bipolar junction transistor)
- Explain how a transistor is biased and discuss the transistor currents and their relationships
- Discuss transistor parameters and characteristics and use these to analyze a transistor circuit
- Discuss how a transistor is used as a voltage amplifier
- Discuss how a transistor is used as an electronic switch
- Identify various types of transistor package configurations
- Troubleshoot various faults in transistor circuits

KEY TERMS

BJT (bipolar junction transistor)
Emitter
Base
Collector
Bias
Beta
Gain
Saturation
Linear
Cutoff
Amplification

■■■ SYSTEM APPLICATION PREVIEW

Suppose you work for a company that makes a security alarm system for protecting homes and places of business against illegal entry. You are given the responsibility for final development and for testing each system before it goes to the customer's location. The first step in your assignment is to learn all you can about transistor operation. You will then apply your knowledge to the system application at the end of the chapter.

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4–1 TRANSISTOR STRUCTURE

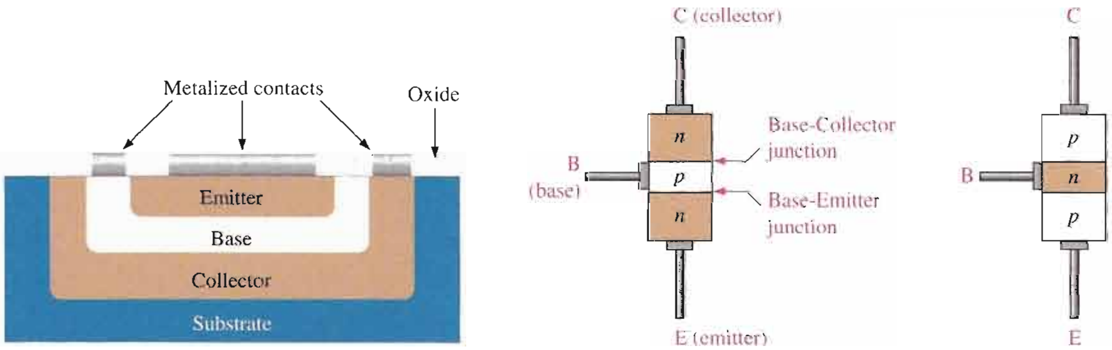
The basic structure of the bipolar junction transistor (BJT) determines its operating characteristics. In this section, you will see how semiconductive materials are used to form a transistor, and you will learn the standard transistor symbols.

After completing this section, you should be able to

- **Describe the basic structure of the BJT (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 **BJT (bipolar junction transistor)** 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 BJTs 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 type 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 *pn* 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. 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.)



(a) Basic epitaxial planar structure (b) *npn* (c) *pnp*

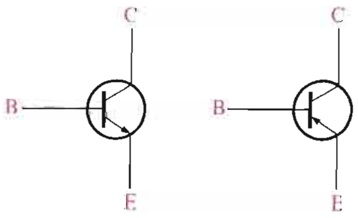
▲ FIGURE 4–1

Basic BJT construction.

Figure 4–2 shows the schematic symbols for the *npn* and *pnp* bipolar junction transistors. The term **bipolar** refers to the use of both holes and electrons as carriers in the transistor structure.

▶ FIGURE 4–2

Standard BJT (bipolar junction transistor) symbols.



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

SECTION 4-1 REVIEW

Answers are at the end of the chapter.

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

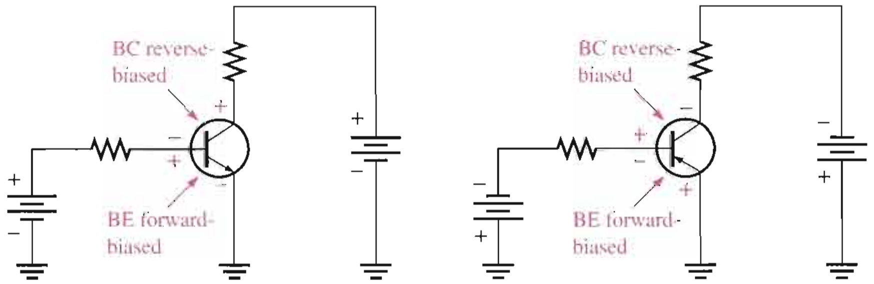
4-2 BASIC TRANSISTOR OPERATION

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.



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

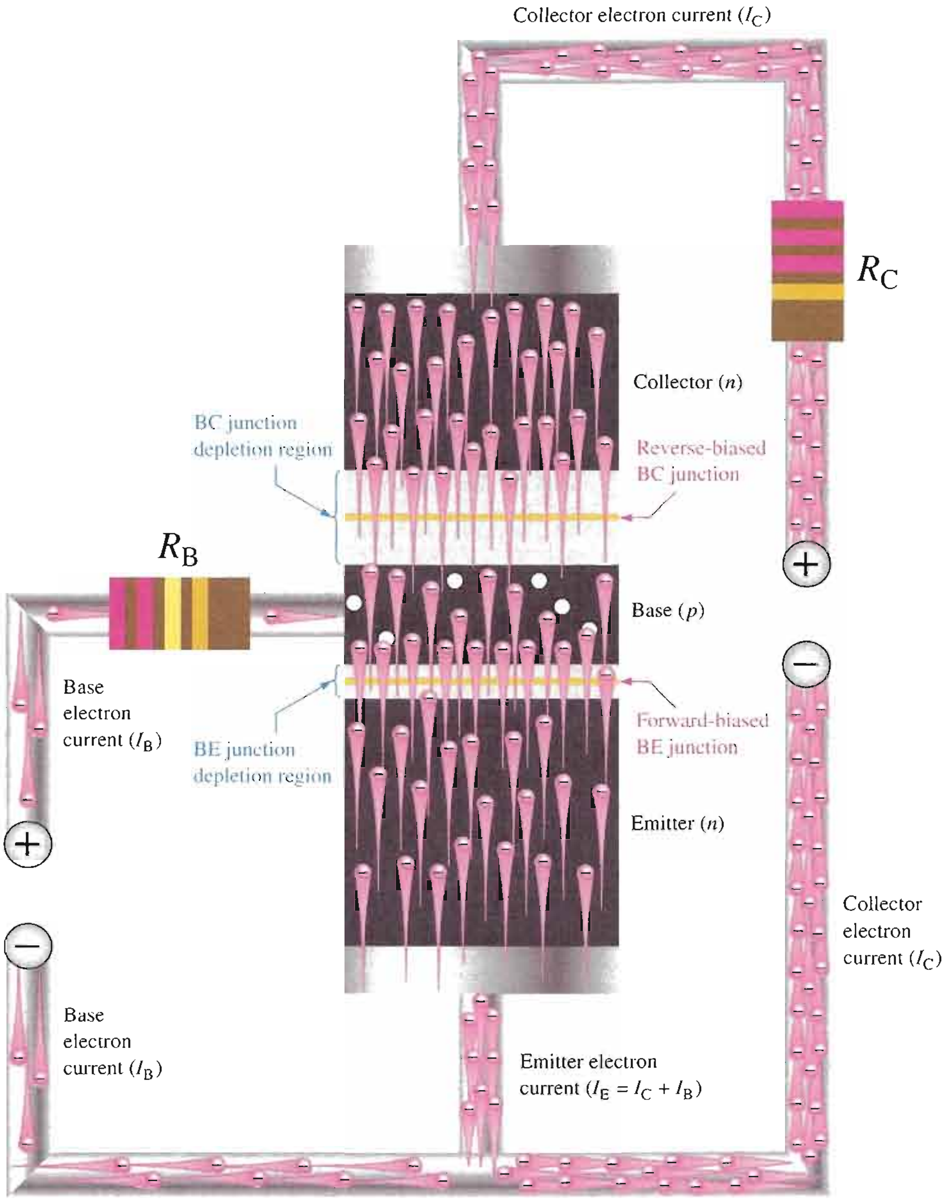
FIGURE 4–3

Forward-reverse bias of a BJT.

To illustrate transistor action, let's examine what happens inside the *npn* transistor. 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-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 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.

FIGURE 4–4

Illustration of BJT action.



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 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. The collector current is much larger than the base current. This is the reason transistors exhibit current gain.

Transistor Currents

The directions of the currents in an *npn* transistor and its schematic symbol are as shown in Figure 4–5(a); those for a *pnp* transistor are shown in Figure 4–5(b). Notice that the arrow on the emitter of the transistor symbols points in the direction of conventional current.

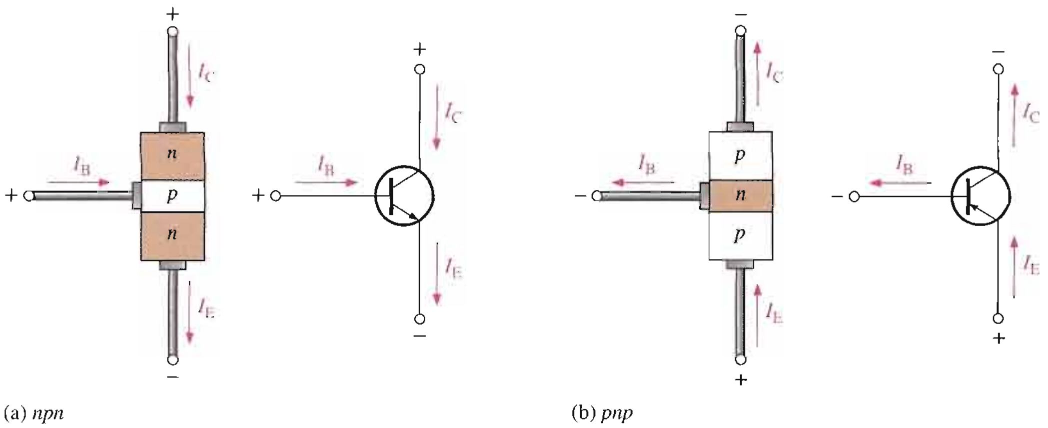


FIGURE 4–5

Transistor currents.

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:

$$I_E = I_C + I_B$$

Equation 4–1

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

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

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

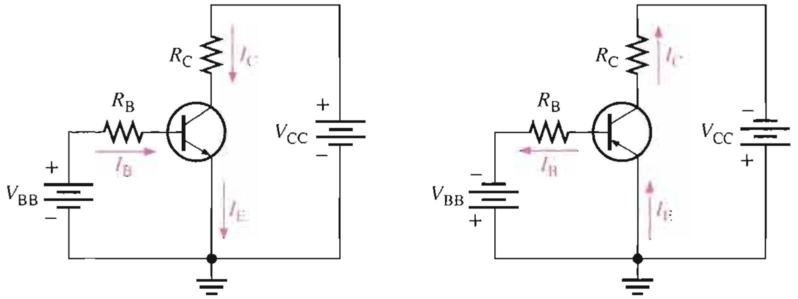
- **Discuss transistor parameters and characteristics and use these to analyze a transistor circuit**
- Define dc *beta* (β_{DC})
- Define dc *alpha* (α_{DC})
- Identify all currents and voltages in a transistor circuit

- 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

As discussed in the last section, when a transistor is connected to dc 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 often derived from a dc power supply. For example, V_{CC} is normally taken directly from the power supply output and V_{BB} (which is smaller) can be produced with a voltage divider. Bias circuits are examined thoroughly in Chapter 5.

FIGURE 4–6

Transistor dc bias circuits.



(a) *npn*

(b) *pnp*

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

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

Equation 4–2

$$\beta_{DC} = \frac{I_C}{I_B}$$

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designated as an equivalent hybrid (h) parameter, h_{FE}, on transistor data sheets. h-parameters are covered in Chapter 6. All you need to know now is that

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

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc **alpha** (α_{DC}). The alpha is a less-used parameter than beta in transistor circuits.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

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 α_{DC} = 0.99.

EXAMPLE 4–1

Determine β_{DC} and I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

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

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

Related Problem* A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current.

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*Answers are at the end of the chapter.

Current and Voltage Analysis

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

I_B: dc base current

I_E: dc emitter current

I_C: dc collector current

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

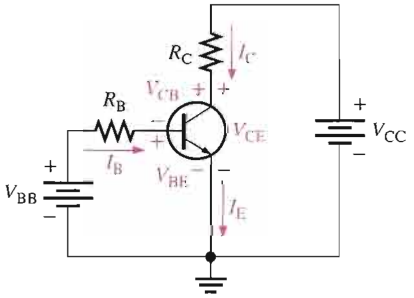


FIGURE 4–7

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 nominal forward voltage drop of

$$V_{BE} \cong 0.7\text{ V}$$ **Equation 4–3**

Although in an actual transistor V_{BE} can be as high as 0.9 V and is dependent on current, we will use 0.7 V throughout this text in order to simplify the analysis of the basic concepts.

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,

Equation 4–4

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

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

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

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

the voltage at the collector can be written as

Equation 4–5

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

where $I_C = \beta_{DC} I_B$.

The voltage across the reverse-biased collector-base junction is

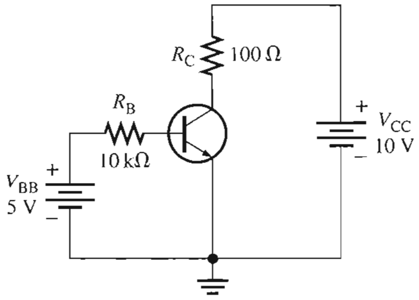
Equation 4–6

$$V_{CB} = V_{CE} - V_{BE}$$

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 4–3, $V_{BE} \cong$ **0.7 V**. Calculate the base, collector, and emitter currents as follows:

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

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

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

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

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

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

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

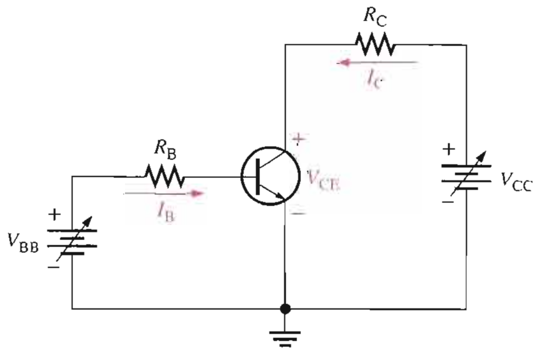
Related Problem Determine I_B, I_C, I_E, V_{CE}, and V_{CB} in Figure 4–8 for the following values: $R_B = 22\text{ k}\Omega$, $R_C = 220\ \Omega$, $V_{BB} = 6\text{ V}$, $V_{CC} = 9\text{ V}$, and $\beta_{DC} = 90$.

Open the Multisim file E04-02 in the Examples folder on your CD-ROM. Measure each current and voltage and compare with the calculated values.

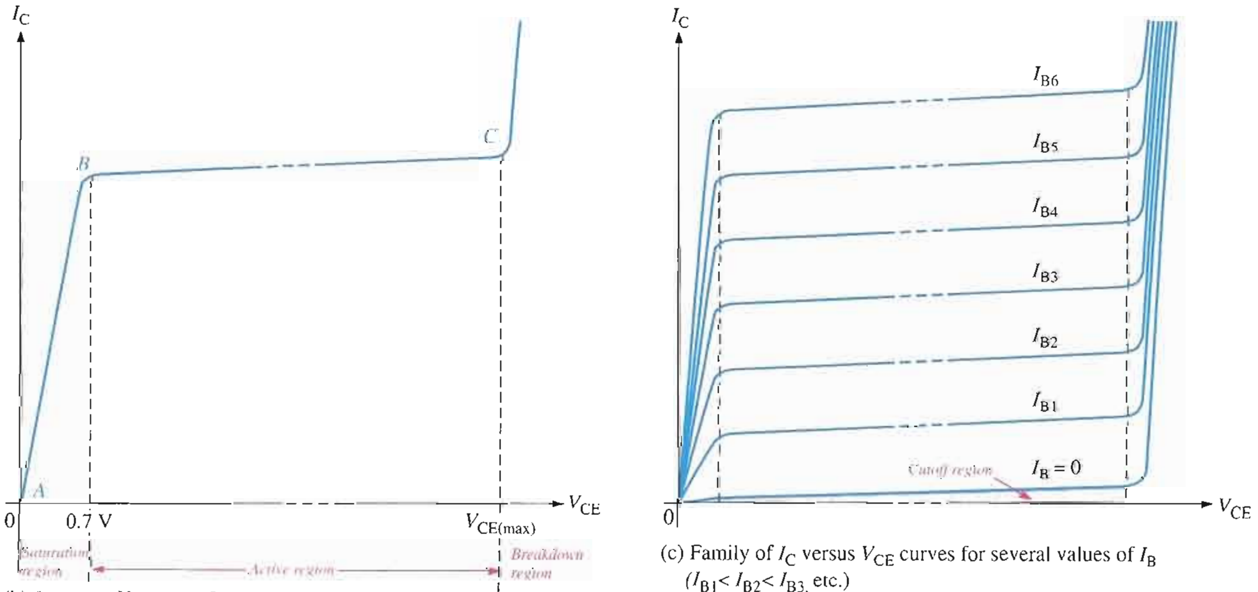
Collector Characteristic Curves

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



(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.

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.

Ideally, 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 $I_C = \beta_{DC}I_B$.

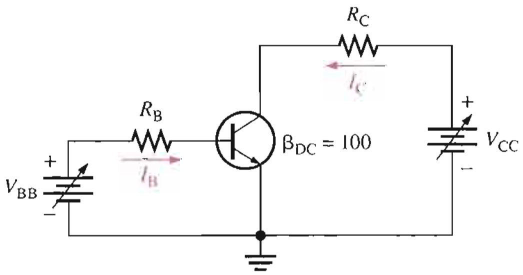
When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly as indicated by the part of the curve to the right of point *C* in Figure 4–9(b). A transistor should never be operated in this breakdown region.

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 illustration.

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

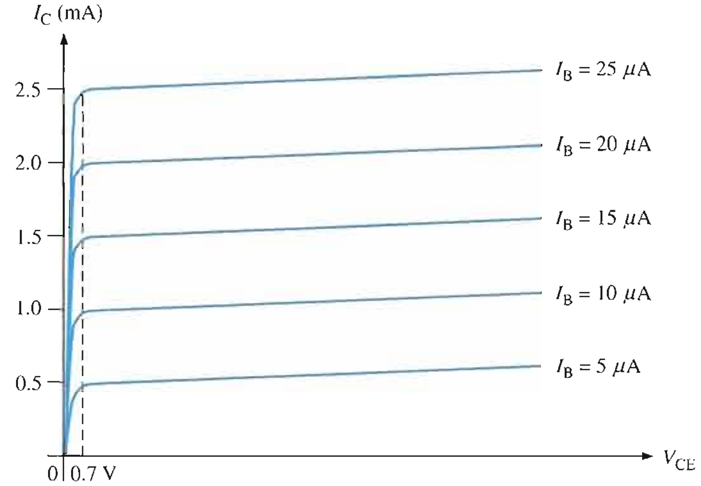


Solution Using the relationship $I_C = \beta_{DC}I_B$, values of I_C are calculated and tabulated in Table 4–1. The resulting curves are plotted in Figure 4–11. These are ideal curves because the slight increase in I_C for a given value of I_B as V_{CE} increases in the active region is neglected.

► 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 Problem 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.

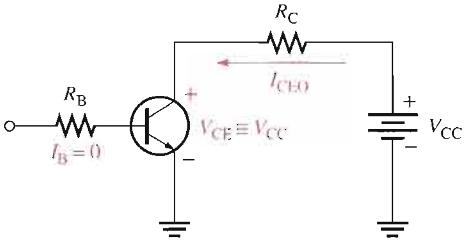


FIGURE 4–12

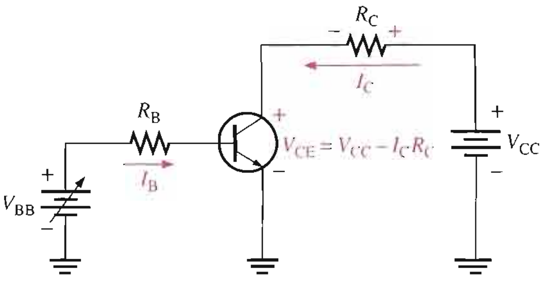
Cutoff: Collector leakage current (I_{CEO}) is extremely small and is usually neglected. Base-emitter and base-collector junctions are reverse-biased.

Saturation

When the base-emitter junction becomes forward-biased and the base current 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

Saturation: 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. When the transistor reaches saturation, I_C can increase no further regardless of further increase in I_B. Base-emitter and base-collector junctions are forward-biased.

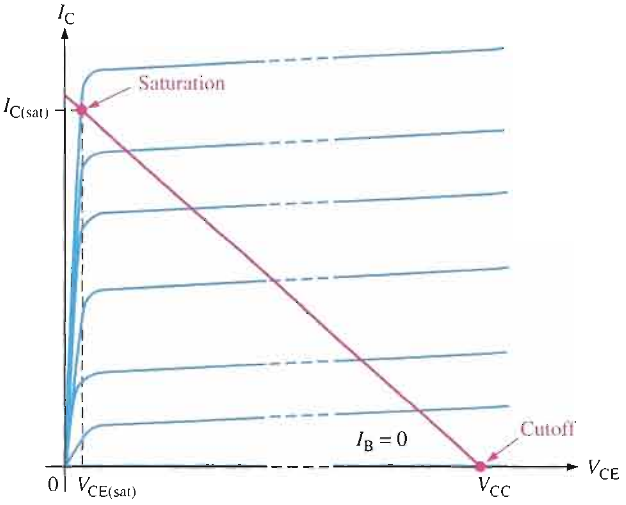


DC Load Line

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 Chapter 5.

FIGURE 4–14

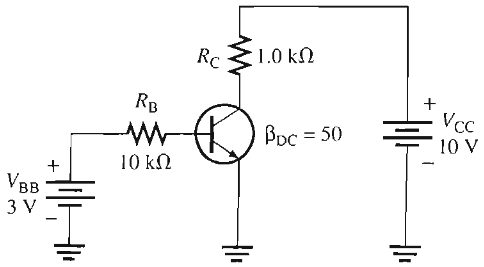
DC load line on a family of collector characteristic curves illustrating the cutoff and saturation conditions.



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 $I_{C(sat)}$.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\text{ V} - 0.2\text{ V}}{1.0\text{ k}\Omega} = \frac{9.8\text{ V}}{1.0\text{ k}\Omega} = 9.8\text{ mA}$$

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 Problem 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.

Open the Multisim file E04-04 in the Examples folder on your CD-ROM. Determine if the transistor is in saturation and explain how you did this.

More About β_{DC}

The β_{DC} or h_{FE} is an 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.

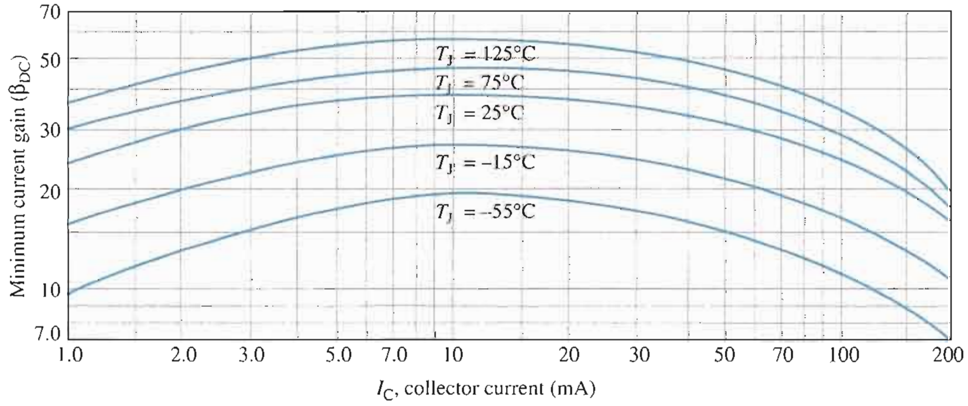


FIGURE 4–16

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

A 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

Equation 4–7

$$I_C = \frac{P_{D(max)}}{V_{CE}}$$

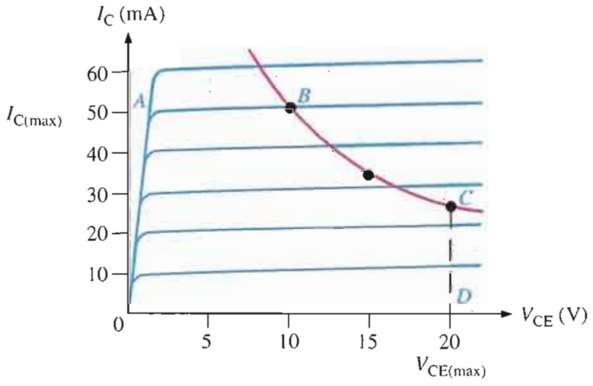
If I_C is maximum, V_{CE} can be calculated by rearranging Equation 4–7 as follows:

$$V_{CE} = \frac{P_{D(max)}}{I_C}$$

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 *B* and *C*, and $V_{CE(max)}$ is the limiting rating between points *C* and *D*.

FIGURE 4–17

Maximum power dissipation curve and tabulated values.



(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)

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

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

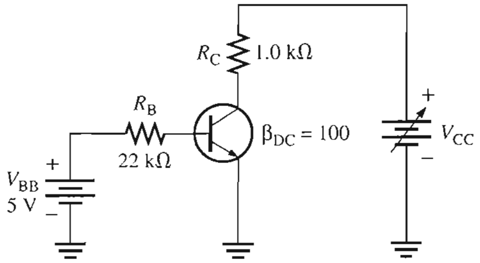
Remember that this is not necessarily the maximum I_C. The transistor can handle more collector current if V_{CE} is reduced, as long as $P_{D(max)}$ is not exceeded.

Related Problem 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

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1.0\text{ k}\Omega) = 19.5\text{ V}$$

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,

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

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 first** because the entire supply voltage, V_{CC}, will be dropped across the transistor.

Related Problem 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 degree centigrade 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

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

Related Problem 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 CEO 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 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?

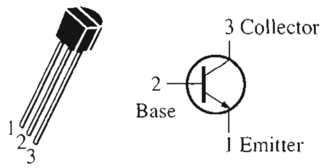
4–4 THE TRANSISTOR AS AN AMPLIFIER

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, a 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

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 ($I_C = 10\ \mu$A dc, $I_E = 0$)		$V_{(BR)CBO}$	60	–	V dc
Emitter-Base breakdown voltage ($I_E = 10\ \mu$A 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.

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.

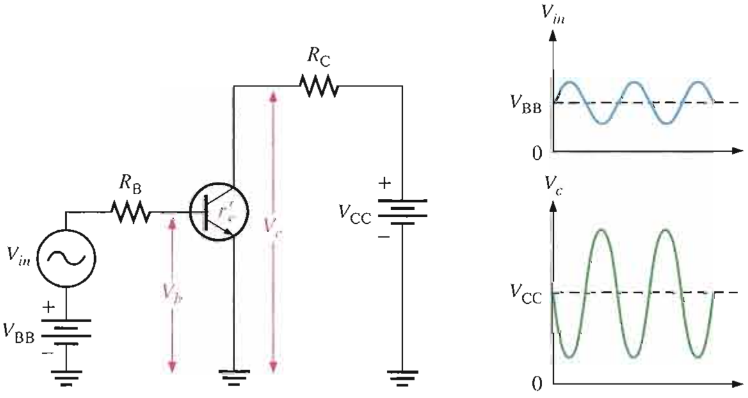
Transistor Amplification

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}.

FIGURE 4–20

Basic transistor amplifier circuit.



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

(b) Waveforms

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 amplified, but inverted, reproduction of the ac input voltage in the active region of operation, as illustrated in Figure 4–20(b).

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(a), the ac emitter current is

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

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 $I_e R_C$ for V_c and $I_e r'_e$ for V_b yields

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

The I_e terms cancel; therefore,

$$A_v \cong \frac{R_C}{r'_e}$$

Equation 4–8

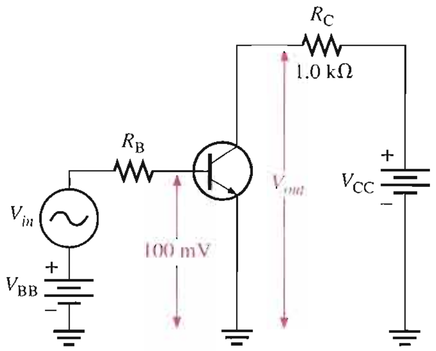
Equation 4–8 shows that the transistor in Figure 4–20 provides amplification in the form of voltage gain, which is dependent on the values of R_C and r'_e.

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

$$A_v \cong \frac{R_C}{r'_e} = \frac{1.0\ \text{k}\Omega}{50\ \Omega} = \mathbf{20}$$

Therefore, the ac output voltage is

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

Related Problem 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 Ω, what is the voltage gain?

4–5 THE TRANSISTOR AS A SWITCH

In the previous section, you saw how the transistor can be used 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. Digital circuits make use of the switching characteristics of transistors.

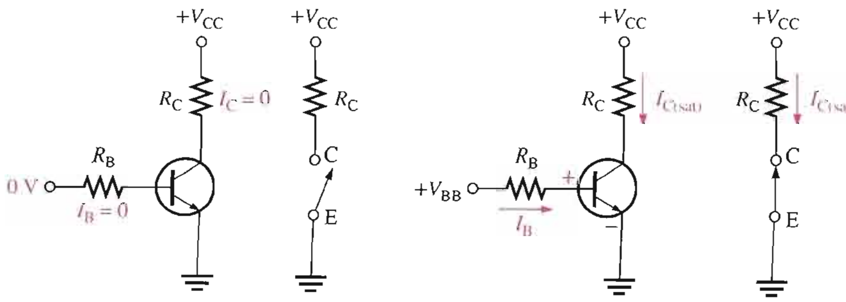
After completing this section, you should be able to

- **Discuss how a transistor is used as an electronic switch**
- Analyze a transistor switching circuit for cutoff and saturation
- Describe the conditions that produce cutoff
- Describe the conditions that produce 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 indicated by the switch equivalent. Actually, a voltage drop of up to a few tenths of a volt normally occurs, which is the saturation voltage, $V_{CE(sat)}$.

FIGURE 4–22

Ideal switching action of a transistor.



(a) Cutoff — open switch

(b) Saturation — closed switch

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}.

$$V_{CE(cutoff)} = V_{CC}$$

Equation 4–9

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

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

Equation 4–10

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

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}}$$

Equation 4–11

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

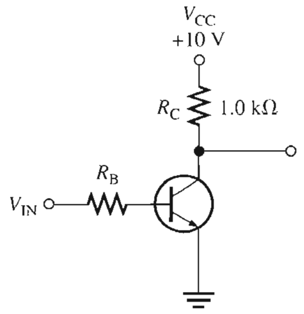
EXAMPLE 4–9

(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



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

$$V_{CE} = V_{CC} = \mathbf{10\ V}$$

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

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{10\text{ V}}{1.0\text{ k}\Omega} = 10\text{ mA}$$

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

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, $V_{BE} \cong 0.7$ V. The voltage across R_B is

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

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

$$R_{B(max)} = \frac{V_{R_B}}{I_{B(min)}} = \frac{4.3\text{ V}}{50\ \mu\text{A}} = \mathbf{86\ k\Omega}$$

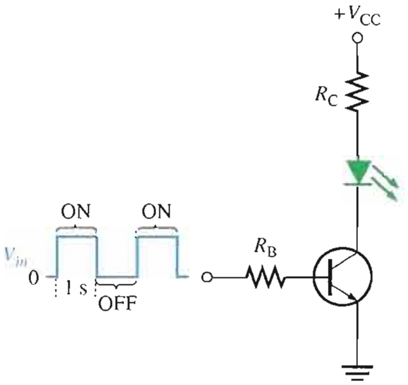
Related Problem Determine the minimum value of I_B required to saturate the transistor in Figure 4–23 if β_{DC} is 125 and $V_{CE(sat)}$ is 0.2 V.

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. Thus, the LED is on for 1 s and off for 1 s.

FIGURE 4–24

A transistor used to switch an LED on and off.



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, $R_C = 270\ \Omega$, $R_B = 3.3$ kΩ, 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 is 1.29 mA. Use the formula for I_B to solve for V_{in}.

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

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

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

Related Problem 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).

Open the Multisim file E04-10 in the Examples folder on your CD-ROM. Using a 0.5 Hz square wave input with the calculated amplitude, verify that the transistor is switching between cutoff and saturation and that the LED is alternately turning on and off.

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?

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-power 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.

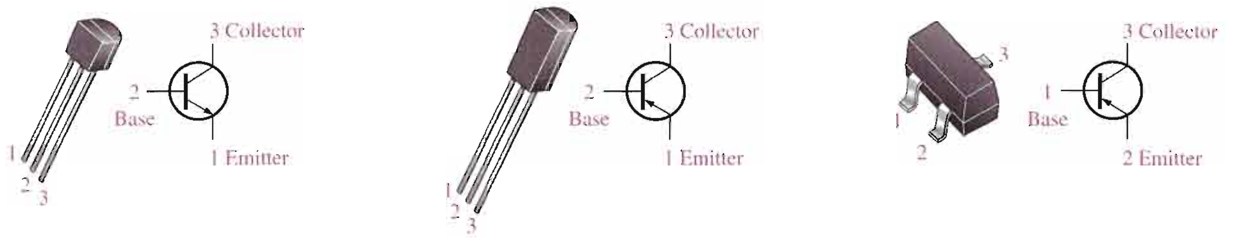
After completing this section, you should be able to

- **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. Let's 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.

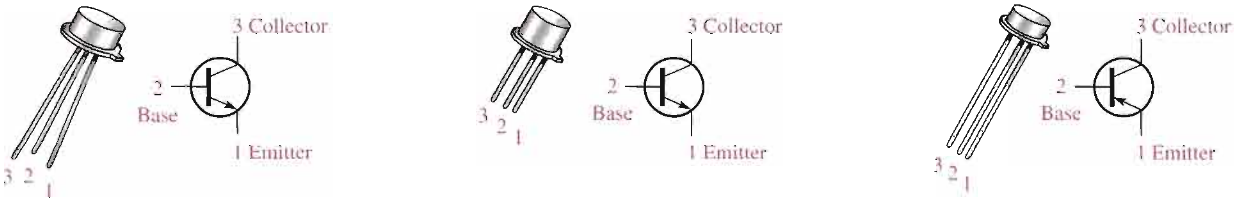
General-Purpose/Small-Signal Transistors General-purpose/small-signal transistors are generally used for low- or medium-power amplifiers or switching circuits. The packages are either plastic or metal cases. Certain types of packages contain multiple transistors. Figure 4–25 illustrates common plastic 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.



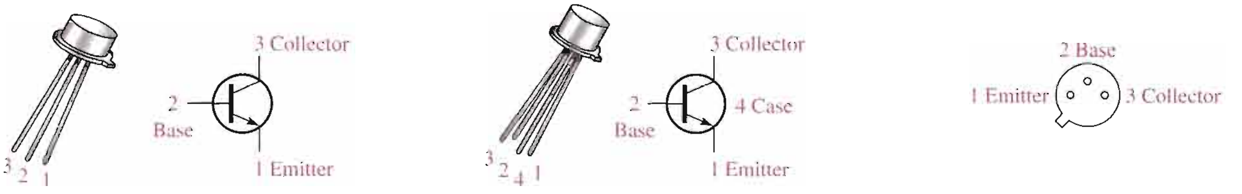
(a) TO-92 or TO-226AA (b) TO-92 or TO-226AE (c) SOT-23 or TO-236AB

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.



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

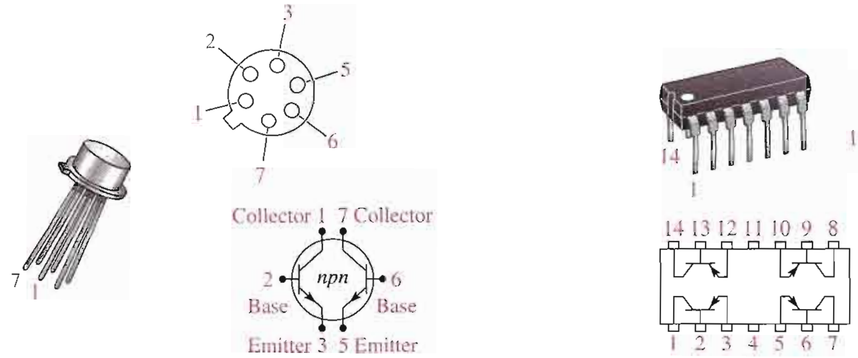


(d) TO-52 or TO-206AC (e) TO-72 or TO-206AF (f) Pin configuration (bottom view). Emitter is closest to tab.

FIGURE 4–26

Metal cases for general-purpose/small-signal transistors.

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.



(a) Dual metal can

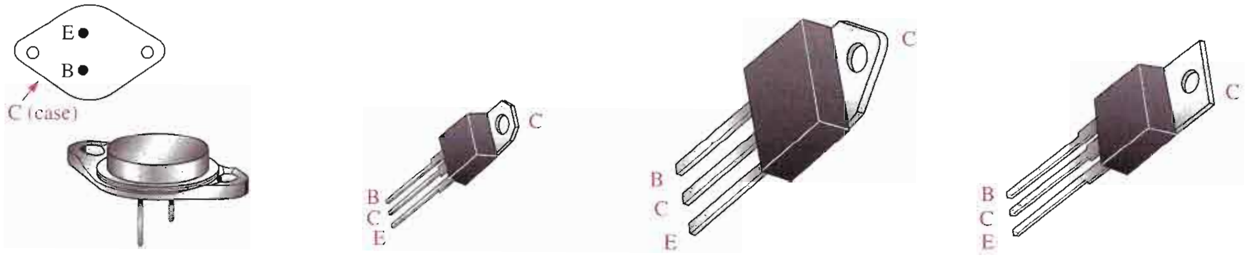
(b) Quad dual in-line (DIP) and quad flat-pack. Dot indicates pin 1.

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

(d) Dual ceramic flat-pack

FIGURE 4–27

Typical multiple-transistor packages.

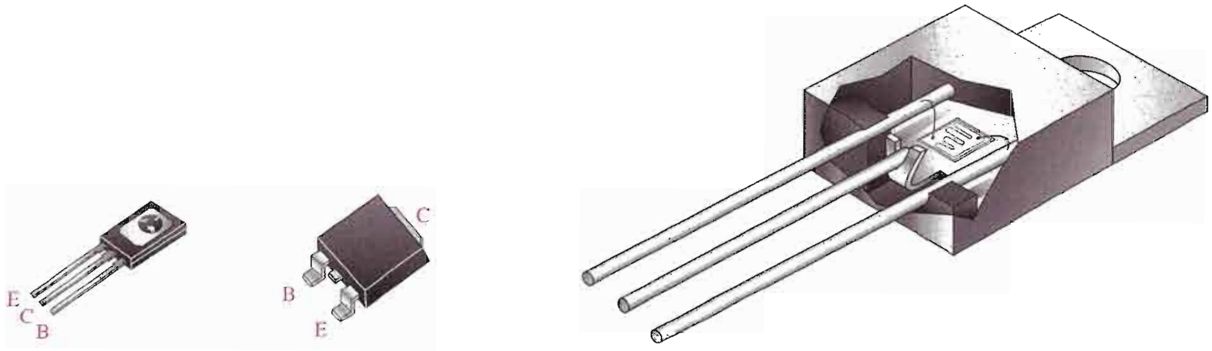


(a) TO-3 or TO-204AE

(b) TO-218

(c) TO-218AC

(d) TO-220AB



(e) TO-225AA

(f) Surface-mount technology

(g) Greatly enlarged cutaway view of tiny transistor chip mounted in the encapsulated package

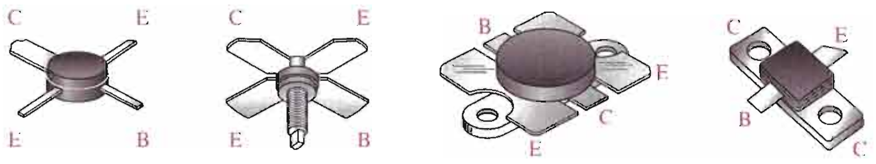
FIGURE 4–28

Typical power transistors.

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.

FIGURE 4–29

Examples of RF transistors.



(a) (b) (c) (d)

SECTION 4–6 REVIEW

1. List the three broad categories of bipolar junction transistors.
2. In Figure 4–26, how is the emitter identified?
3. In power transistors, the metal mounting tab or case is connected to which transistor region?

4–7 TROUBLESHOOTING

As you already know, a critical skill in electronics work is the ability to identify a circuit malfunction and to isolate the failure to a single component if necessary. In this section, the basics of troubleshooting transistor bias circuits and testing individual transistors are covered.

After completing this section, you should be able to

- **Troubleshoot various faults in transistor circuits**
- Explain floating point measurement
- Use voltage measurements to identify a fault in a transistor circuit
- Use a DMM to test a transistor
- Explain how a transistor can be viewed in terms of a diode equivalent
- Discuss in-circuit and out-of-circuit testing
- Discuss point-of-measurement in troubleshooting
- Discuss leakage and gain measurements

Troubleshooting a Biased Transistor

Several faults can occur in a simple transistor bias circuit. Possible faults are open bias resistors, open or resistive connections, shorted connections, and opens or shorts internal to the transistor itself. Figure 4–30 is a basic transistor bias circuit with all voltages referenced to ground. The two bias voltages are $V_{BB} = 3$ V and $V_{CC} = 9$ V. The correct voltage measurements at the base and collector are shown. Analytically, these voltages are verified as follows. A $\beta_{DC} = 200$ is taken as midway between the minimum and maximum values of h_{FE} given on the data sheet for the 2N3904 in Figure 4–19. A different h_{FE} (β_{DC}), of course, will produce different results for the given circuit.

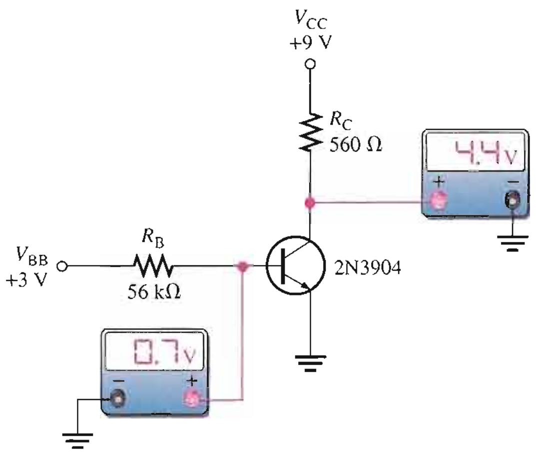


FIGURE 4–30

A basic transistor bias circuit.

$$V_B = V_{BE} = 0.7\text{ V}$$

$$I_B = \frac{V_{BB} - 0.7\text{ V}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{56\text{ k}\Omega} = \frac{2.3\text{ V}}{56\text{ k}\Omega} = 41.1\ \mu\text{A}$$

$$I_C = \beta_{DC}I_B = 200(41.1\ \mu\text{A}) = 8.2\text{ mA}$$

$$V_C = 9\text{ V} - I_CR_C = 9\text{ V} - (8.2\text{ mA})(560\ \Omega) = 4.4\text{ V}$$

Several faults that can occur in the circuit and the accompanying symptoms are illustrated in Figure 4–31. Symptoms are shown in terms of measured voltages that are incorrect. The term **floating point** refers to a point in the circuit that is not electrically connected to ground or a "solid" voltage. Normally, very small and sometimes fluctuating voltages in the μV to low mV range are generally measured at floating points. The faults in Figure 4–31 are typical but do not represent all possible faults that may occur.

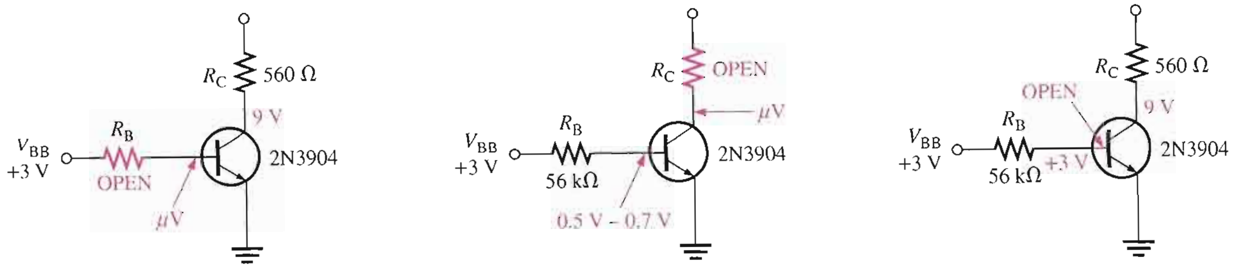
Testing a Transistor with a DMM

A digital multimeter can be used as a fast and simple way to check a transistor for open or shorted junctions. For this test, you can view the transistor as two diodes connected as shown in Figure 4–32 for both *npn* and *pnp* transistors. The base-collector junction is one diode and the base-emitter junction is the other.

Recall that a good diode will show an extremely high resistance (or open) with reverse bias and a very low resistance with forward bias. A defective open diode will show an extremely high resistance (or open) for both forward and reverse bias. A defective shorted or resistive diode will show zero or a very low resistance for both forward and reverse bias. An open diode is the most common type of failure. Since the transistor *pn* junctions are, in effect diodes, the same basic characteristics apply.

The DMM Diode Test Position Many digital multimeters (DMMs) have a *diode test* position that provides a convenient way to test a transistor. A typical DMM, as shown in Figure 4–33, has a small diode symbol to mark the position of the function switch. When set to diode test, the meter provides an internal voltage sufficient to forward-bias and reverse-bias a transistor junction. This internal voltage may vary among different makes of DMM, but 2.5 V to 3.5 V is a typical range of values. The meter provides a voltage reading to indicate the condition of the transistor junction under test.

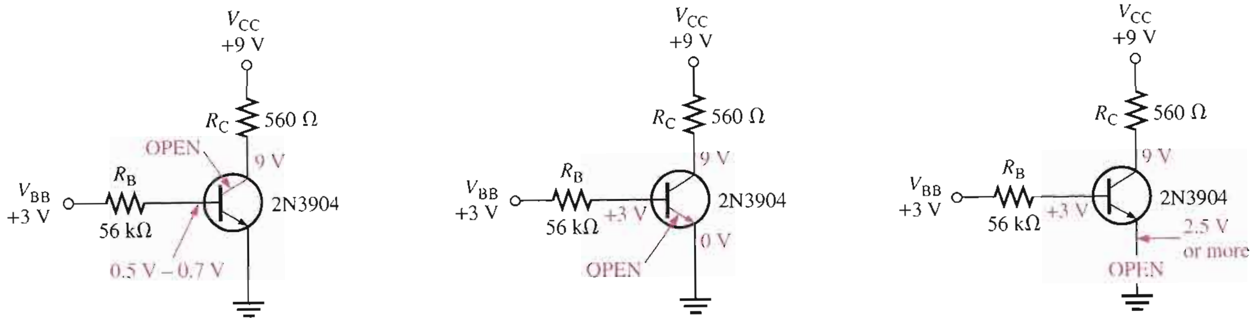
When the Transistor Is Not Defective In Figure 4–33(a), the red (positive) lead of the meter is connected to the base of an *npn* transistor and the black (negative) lead is connected to the emitter to forward-bias the base-emitter junction. If the junction is good, you will get a reading of between 0.5 V and 0.9 V, with 0.7 V being typical for forward bias.



(a) ***Fault:*** Open base resistor.
Symptoms: Readings from μV to a few mV at base due to floating point. 9 V at collector because transistor is in cutoff.

(b) ***Fault:*** Open collector resistor.
Symptoms: Readings from μV to a few mV at collector due to floating point. 0.5 V – 0.7 V at base due to forward voltage drop across the base-emitter junction.

(c) ***Fault:*** Base internally open.
Symptoms: 3 V at base lead. 9 V at collector because transistor is in cutoff.



(d) ***Fault:*** Collector internally open.
Symptoms: 0.5 V – 0.7 V at base lead due to forward voltage drop across base-emitter junction. 9 V at collector because the open prevents collector current.

(e) ***Fault:*** Emitter internally open.
Symptoms: 3 V at base lead. 9 V at collector because there is no collector current. 0 V at the emitter as normal.

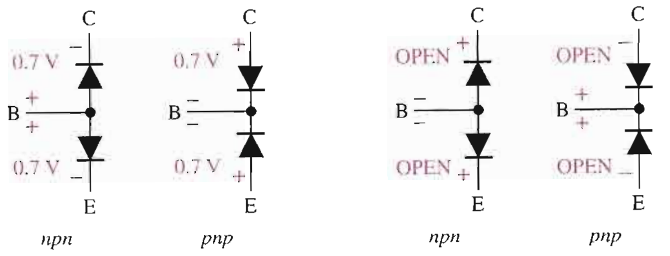
(f) ***Fault:*** Open ground connection.
Symptoms: 3 V at base lead. 9 V at collector because there is no collector current. 2.5 V or more at the emitter due to the forward voltage drop across the base-emitter junction. The measuring voltmeter provides a forward current path through its internal resistance.

▲ FIGURE 4–31

Typical faults and symptoms in the basic transistor bias circuit.

▶ FIGURE 4–32

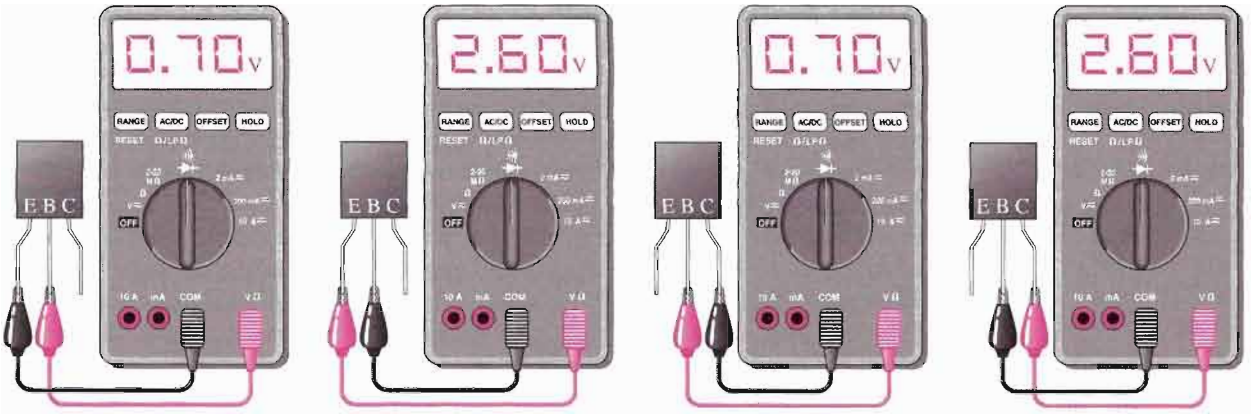
A transistor viewed as two diodes.



(a) Both junctions should read 0.7 V ± 0.2 V when forward-biased.

(b) Both junctions should ideally read OPEN when reverse-biased.

In Figure 4–33(b), the leads are switched to reverse-bias the base-emitter junction, as shown. If the transistor is working properly, you will get a voltage reading based on the meter's internal voltage source. The 2.6 V shown in the figure represents a typical value and indicates that the junction has an extremely high reverse resistance with essentially all of the internal voltage appearing across it.



(a) Forward-bias test of BE junction

(b) Reverse-bias test of BE junction

(c) Forward-bias test of BC junction

(d) Reverse-bias test of BC junction

FIGURE 4–33

Typical DMM test of a properly functioning *npn* transistor. Leads are reversed for a *pnp* transistor.

The process just described is repeated for the base-collector junction as shown in Figure 4–33(c) and (d). For a *pnp* transistor, the polarity of the meter leads are reversed for each test.

When the Transistor Is Defective When a transistor has failed with an open junction or internal connection, you get an open circuit voltage reading (2.6 V is typical for many DMMs) for both the forward-bias and the reverse-bias conditions for that junction, as illustrated in Figure 4–34(a). If a junction is shorted, the meter reads 0 V in both forward-and reverse-bias tests, as indicated in part (b). Sometimes, a failed junction may exhibit a small resistance for both bias conditions rather than a pure short. In this case, the meter will show a small voltage much less than the correct open voltage. For example, a resistive junction may result in a reading of 1.1 V in both directions rather than the correct readings of 0.7 V for forward bias and 2.6 V for reverse bias.

Some DMMs provide a test socket on their front panel for testing a transistor for the h_{FE} (β_{DC}) value. If the transistor is inserted improperly in the socket or if it is not functioning properly due to a faulty junction or internal connection, a typical meter will flash a 1 or display a 0. If a value of β_{DC} within the normal range for the specific transistor is displayed, the device is functioning properly. The normal range of β_{DC} can be determined from the data sheet.

(a) Forward-bias test and reverse-bias test give the same reading (2.60 V is typical) for an open BC junction.

(b) Forward- and reverse-bias tests for a shorted junction give the same 0 V reading. If the junction is resistive, the reading is less than 2.6 V.

FIGURE 4–34

Testing a defective *npn* transistor. Leads are reversed for a *pnp* transistor.

Checking a Transistor with the OHMs Function DMMs that do not have a diode test position or an h_{FE} socket can be used to test a transistor for open or shorted junctions by setting the function switch to an OHMs range. For the forward-bias check of a good transistor *pn* junction, you will get a resistance reading that can vary depending on the meter's internal battery. Many DMMs do not have sufficient voltage on the OHMs range to fully forward-bias a junction, and you may get a reading of from several hundred to several thousand ohms.

For the reverse-bias check of a good transistor, you will get an out-of-range indication on most DMMs because the reverse resistance is too high to measure. An out-of-range indication may be a flashing 1 or a display of dashes, depending on the particular DMM.

Even though you may not get accurate forward and reverse resistance readings on a DMM, the relative readings are sufficient to indicate a properly functioning transistor *pn* junction. The out-of-range indication shows that the reverse resistance is very high, as you expect. The reading of a few hundred to a few thousand ohms for forward bias indicates that the forward resistance is small compared to the reverse resistance, as you expect.

Transistor Testers

An individual transistor can be tested either in-circuit or out-of-circuit with a transistor tester. For example, let's say that an amplifier on a particular printed circuit (PC) board has malfunctioned. Good troubleshooting practice dictates that you do not unsolder a component from a circuit board unless you are reasonably sure that it is bad or you simply cannot isolate the problem down to a single component. When components are removed, there is a risk of damage to the PC board contacts and traces.

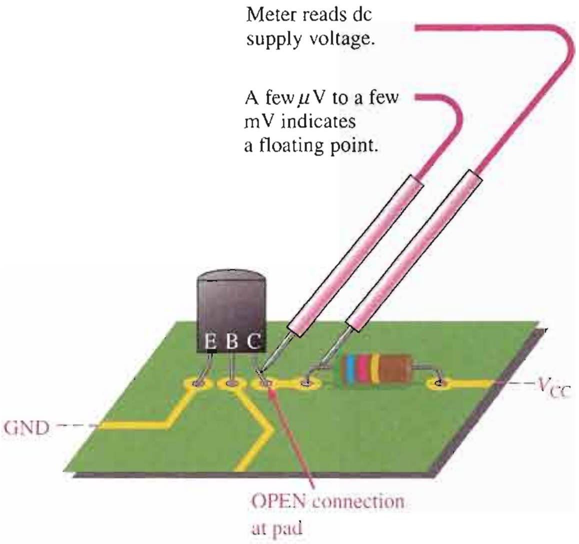
The first step is to do an in-circuit check of the transistor using a transistor tester similar to the one shown in Figure 4–35. The three clip-leads are connected to the transistor terminals and the tester gives a positive indication if the transistor is good.

FIGURE 4–35

Transistor tester (courtesy of B+K Precision).

Case 1 If the transistor tests defective, it should be carefully removed and replaced with a known good one. An out-of-circuit check of the replacement device is usually a good idea, just to make sure it is OK. The transistor is plugged into the socket on the transistor tester for out-of-circuit tests.

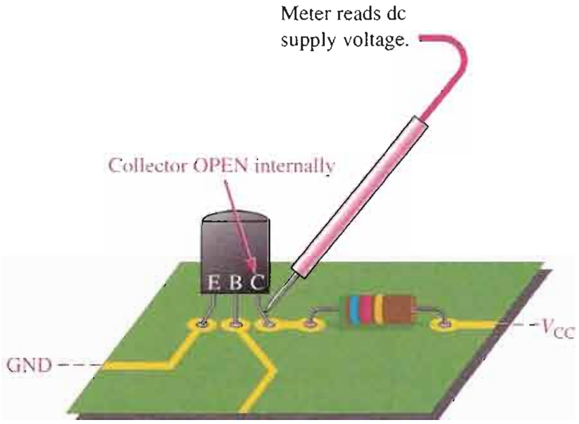
Case 2 If the transistor tests good in-circuit but the circuit is not working properly, examine the circuit board for a poor connection at the collector pad or for a break in the connecting trace. A poor solder joint often results in an open or a highly resistive contact. The physical point at which you actually measure the voltage is very important in this case. For example, if you measure on the collector lead when there is an external open at the collector pad, you will measure a floating point. If you measure on the connecting trace or on the R_C lead, you will read V_{CC}. This situation is illustrated in Figure 4–36.



◄ **FIGURE 4–36**

The indication of an open, when it is in the circuit external to the transistor, depends on where you measure.

Importance of Point-of-Measurement in Troubleshooting In case 2, if you had taken the initial measurement on the transistor lead itself and the open were *internal* to the transistor as shown in Figure 4–37, you would have measured V_{CC}. This would have indicated a defective transistor even before the tester was used. This simple concept emphasizes the importance of point-of-measurement in certain troubleshooting situations.



◄ **FIGURE 4–37**

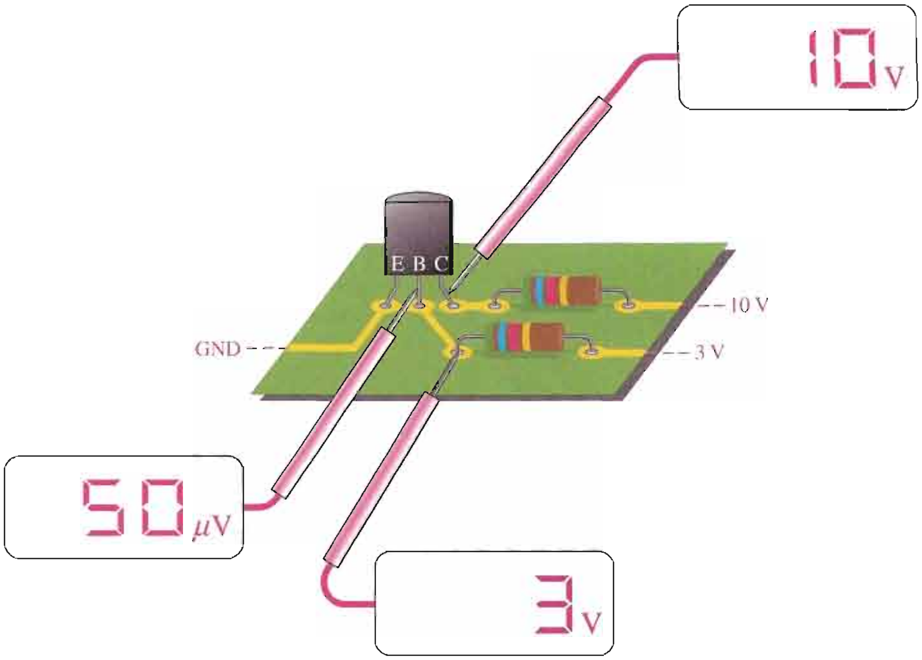
Illustration of an internal open. Compare with Figure 4–36.

EXAMPLE 4–11

What fault do the measurements in Figure 4–38 indicate?

Solution The transistor is in cutoff, as indicated by the 10 V measurement on the collector lead. The base bias voltage of 3 V appears on the PC board contact but not on the transistor lead, as

FIGURE 4–38



indicated by the floating point measurement. This shows that there is an open external to the transistor between the two measured base points. Check the solder joint at the base contact on the PC board. If the open were internal, there would be 3 V on the base lead.

Related Problem If the meter in Figure 4–38 that now reads 3 V indicates a floating point when touching the circuit board pad, what is the most likely fault?

Leakage Measurement

Very small leakage currents exist in all transistors and in most cases are small enough to neglect (usually nA). When a transistor is connected with the base open ($I_B = 0$), it is in cutoff. Ideally $I_C = 0$; but actually there is a small current from collector to emitter, as mentioned earlier, called I_{CEO} (collector-to-emitter current with base open). This leakage current is usually in the nA range for silicon. A faulty transistor will often have excessive leakage current and can be checked in a transistor tester. Another leakage current in transistors is the reverse collector-to-base current, I_{CBO}. This is measured with the emitter open. If it is excessive, a shorted collector-base junction is likely.

Gain Measurement

In addition to leakage tests, the typical transistor tester also checks the β_{DC}. A known value of I_B is applied, and the resulting I_C is measured. The reading will indicate the value of the I_C/I_B ratio, although in some units only a relative indication is given. Most testers provide for an in-circuit β_{DC} check, so that a suspected device does not have to be removed from the circuit for testing.

Curve Tracers

A *curve tracer* is an oscilloscope type of instrument that can display transistor characteristics such as a family of collector curves. In addition to the measurement and display of various transistor characteristics, diode curves can also be displayed.

Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on your CD-ROM.

1. Open file TSE04-01. Determine if the circuit is working properly and, if not, determine the fault.
2. Open file TSE04-02. Determine if the circuit is working properly and, if not, determine the fault.
3. Open file TSE04-03. Determine if the circuit is working properly and, if not, determine the fault.

SECTION 4–7 REVIEW

1. If a transistor on a circuit board is suspected of being faulty, what should you do?
2. In a transistor bias circuit, such as the one in Figure 4–30, what happens if R_B opens?
3. In a circuit such as the one in Figure 4–30, what are the base and collector voltages if there is an external open between the emitter and ground?

SYSTEM APPLICATION

You have been assigned to work on an electronic security alarm system. This system has several parts, but you will concentrate on the transistor circuits that detect a break (open) in the loops containing remote sensors for windows and doors. In this particular application, the transistors are used as switching devices. You will apply the knowledge you have gained in this chapter to complete your assignment.

The Security Alarm System

The block diagram for a three-zone security alarm system is shown in Figure 4–39. A detail of the circuit board containing the zone-monitoring circuits is included because this is the part of the system that is the focus of this assignment.

Two of the zones contain conductive loops with several magnetic switches that protect the windows and doors in that particular zone. The third zone protects the main entry door.

When an intrusion occurs, a magnetic switch at that point of entry breaks contact and opens the zone loop. This causes the input to the monitoring circuit for that zone to go to a 0 V level, activating the circuit which, in turn, energizes the relay. The closure of the relay contacts sets off the audible alarm (siren) and/or initiates an automatic telephone dialing sequence. The monitoring circuits for either zone 1 or zone 2 can energize the common relay.

For zone 3, which is the main entry, the output of the monitoring circuit goes to the time-delay circuit to allow time for keying in an entry code that will disarm the system. If, after a preset time interval, no code or an incorrect code has been entered, the time-delay circuit will set off the alarm and/or the telephone dialing sequence.

There are many features in a typical security system, and systems can range from very simple to very complex. For this assignment, you will concentrate on the zone-monitoring circuits board.

The Zone-Monitoring Circuits

There are three identical transistor monitoring circuits, one for each zone. The magnetic switches in the zone loop are normally closed and open only when there is an intrusion (a window or door opened). Because the magnetic switches are in series, the entire loop is open when one switch is open.

The circuit for one zone consists of two transistors and is shown in Figure 4–40. Transistor Q_1 detects when one of the remote magnetic switches is open, and transistor Q_2 drives the relay that activates the alarm. The transistors operate only in cutoff or saturation.

The zone loop is normally closed, keeping the input to R_1 at 12 V and transistor Q_1 in saturation. Since Q_1 is operating in saturation, its collector voltage (with respect to ground) is no more than 0.2 V. This keeps transistor Q_2 in cutoff; and since there is no Q_2 collector current through the relay coil, the system is unactivated.

When a magnetic switch in the zone loop opens, the 12 V at the input is removed and transistor Q_1 switches to cutoff because R_2 pulls the base to ground. When Q_1 goes into cutoff, Q_2 is biased into saturation by the 12 V and the base current through R_3 and R_4. The resulting Q_2 collector current through the relay coil energizes the normally open relay and causes the contact to close; this activates the alarm. Diode D_1 across the relay coil suppresses the induced transient voltage when the relay is deactivated.

The Components

- *The transistors* The transistors are 2N3947s.
- *The resistors* Determine the minimum power rating for each of the resistors in the circuit and specify a standard rating.
- *The relay* Based on the applicable transistor ratings and parameters and on the power supply voltage, select one of the following relays:

Relay A: coil voltage, 12 V;
coil resistance, 55 Ω;
turn-on current, 0.2 A;
holding current, 0.15 A
Relay B: coil voltage, 12 V;
coil resistance, 95 Ω;
turn-on current, 0.5 A;
holding current, 0.4 A
Relay C: coil voltage, 24 V;
coil resistance, 150 Ω;
turn-on current, 0.75 A;
holding current, 0.5 A

- *The diode* Select a diode with a PIV rating of at least 100 V.

Analysis of the Circuit

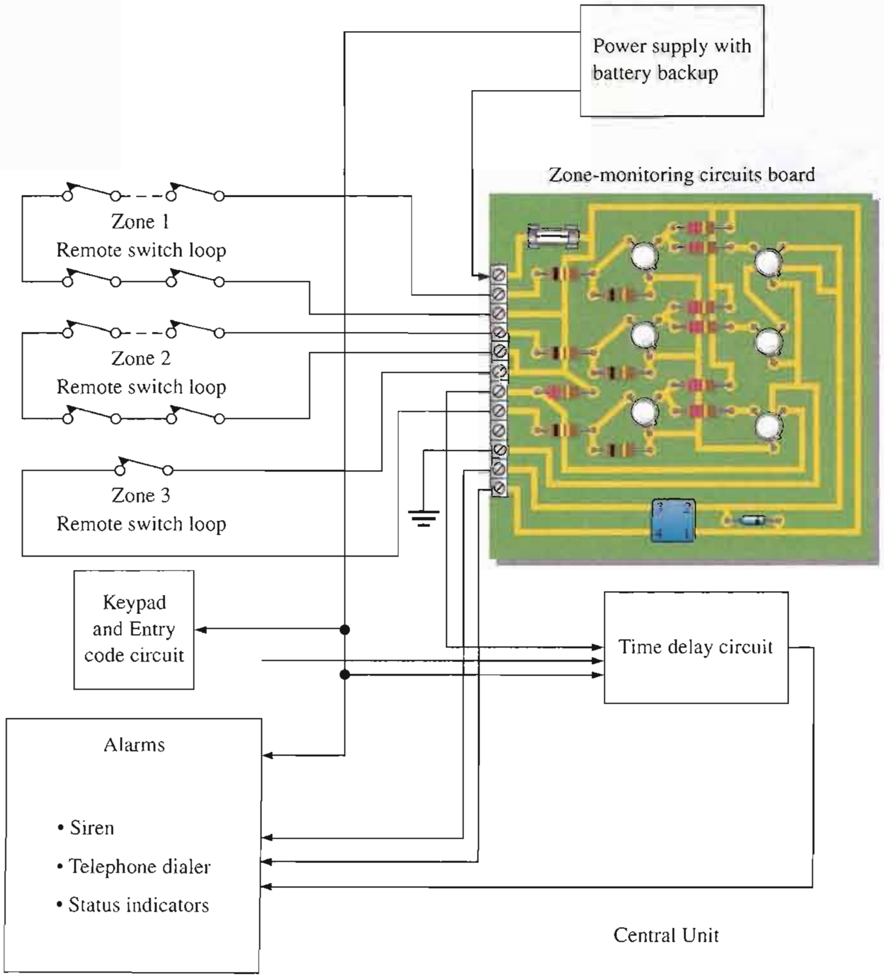
Verify that the resistors in Figure 4–40 have values that produce adequate currents for the transistors to operate in cutoff and saturation and to drive the selected relay. Refer to the transistor data sheet in Figure 4–41.

The Printed Circuit Board

- Using the complete zone-monitoring circuits schematic in Figure 4–42(b), check out the printed circuit board in Figure 4–42(a) to verify that it is correct.
- Label a copy of the board with the component and input/output

FIGURE 4–39

Basic block diagram of the security alarm system.



designations in agreement with the schematic.

A Test Procedure

- Develop a step-by-step set of instructions on how to completely check the zone-monitoring circuits board for proper operation using the test points (circled numbers) and connector terminals indicated in the test bench setup of Figure 4–43 on page 202. The zone loop for each circuit is simulated with a single SPST switch.
- Specify voltage values and/or resistance for all the measurements to be made. Provide a fault analysis for all possible component failures.

Troubleshooting

Three boards in the initial manufacturing run have been found to be defective. You must troubleshoot to determine the problems.

The test results are shown in Figure 4–44 on page 203. Based on the sequence of measurements and the loop switch configuration for each defective board, determine the most likely fault(s) in each case.

The red circled numbers indicate test points on the circuit board, and the black numbers in squares are for connector terminals on the circuit board. The DMM function setting is indicated below the display.

Final Report (Optional)

Submit a final written report on the zone-monitoring circuits board using an organized format that includes the following:

1. A physical description of the circuits.
2. A discussion of the operation of each circuit.
3. A list of the specifications.
4. A list of parts with part numbers if available.
5. A list of the types of problems on the three defective circuit boards.
6. A complete description of how you determined the problem on each of the three defective boards.

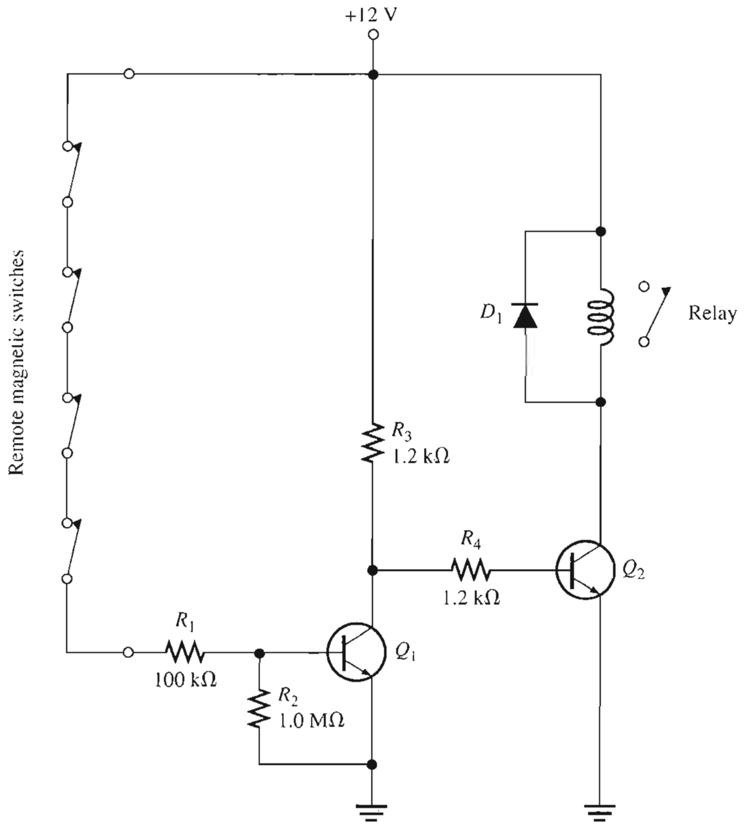
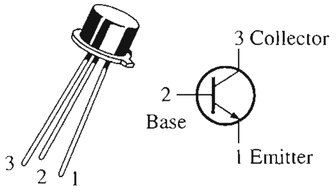


FIGURE 4–40

Zone-monitoring circuit. All three circuits are identical with the exception that the zone 3 circuit has a collector resistor instead of the relay.

2N3946
2N3947



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	0.36 2.06	Watts mW/°C
Total device dissipation @ T_C = 25°C Derate above 25°C	P_D	1.2 6.9	Watts mW/°C
Operating and storage junction Temperature range	T_J, T_{stg}	–65 to +200	°C

Thermal Characteristics

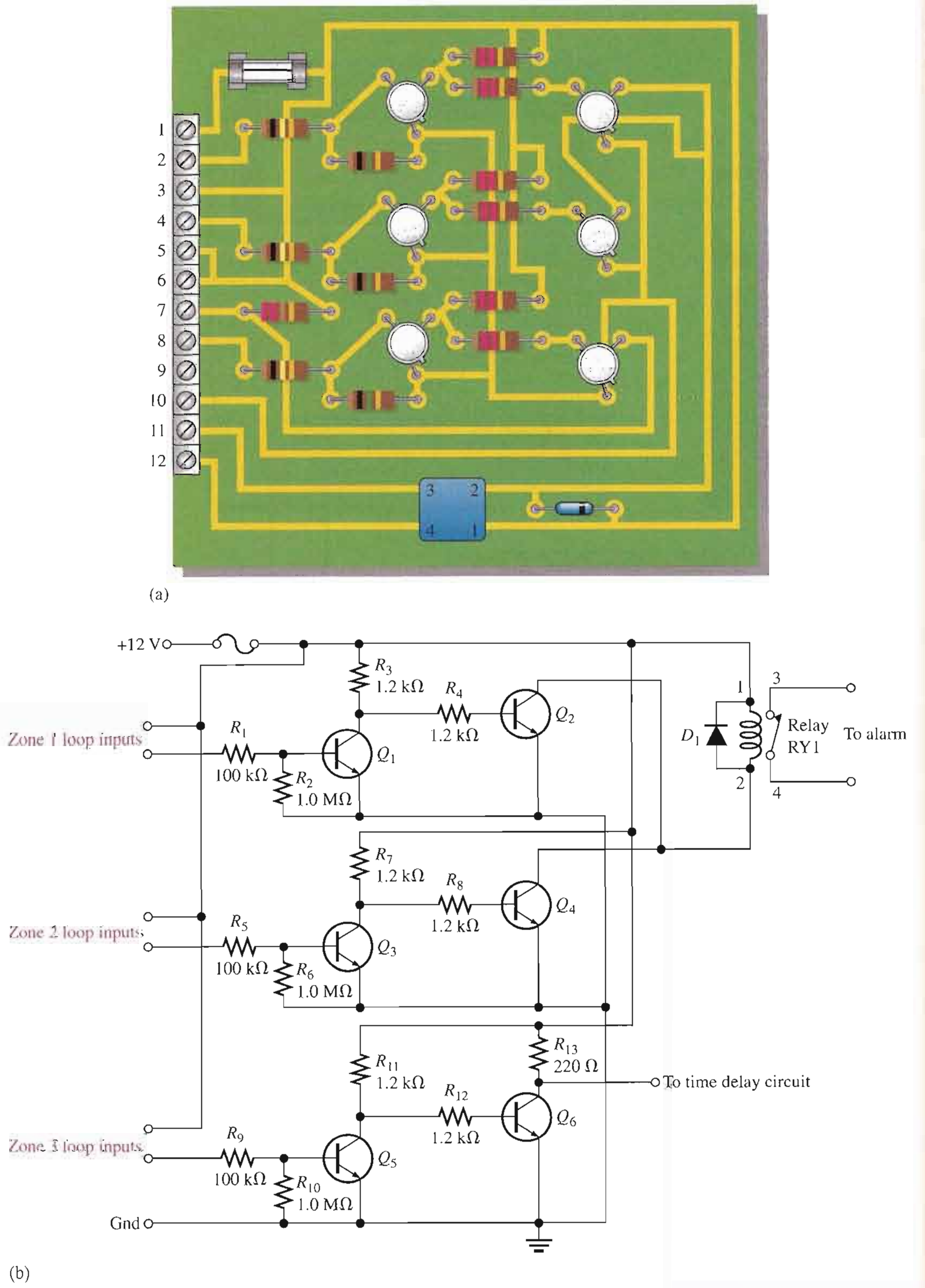
Characteristic	Symbol	Max	Unit
Thermal resistance, junction to case	$R_{\theta JC}$	0.15	°C/mW
Thermal resistance, junction to ambient	$R_{\theta JA}$	0.49	°C/mW

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

Characteristic	Symbol	Min	Max	Unit
OFF Characteristics				
Collector-Emitter breakdown voltage (I_C = 10 mA dc)	$V_{(BR)CEO}$	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
Collector cutoff current (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc) (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc, T_A = 150°C)	I_{CEX}	 – –	 0.010 15	μA dc
Base cutoff current (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc)	I_{BL}	–	.025	μA dc
ON Characteristics				
DC current gain	h_{FE}			–
(I_C = 0.1 mA dc, V_{CE} = 1.0 V dc) 2N3946 2N3947		30 60	– –	
(I_C = 1.0 mA dc, V_{CE} = 1.0 V dc) 2N3946 2N3947		45 90	– –	
(I_C = 10 mA dc, V_{CE} = 1.0 V dc) 2N3946 2N3947		50 100	150 300	
(I_C = 50 mA dc, V_{CE} = 1.0 V dc) 2N3946 2N3947		20 40	– –	
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)	$V_{BE(sat)}$	 0.6 –	 0.9 1.0	V dc
Small-Signal Characteristics				
Current gain — Bandwidth product (I_C = 10 mA dc, V_{CE} = 20 V dc, f = 100 MHz) 2N3946 2N3947	f_T	 250 300	 – –	MHz
Output capacitance (V_{CB} = 10 V dc, I_E = 0, f = 100 kHz)	C_{obo}	–	4.0	pF

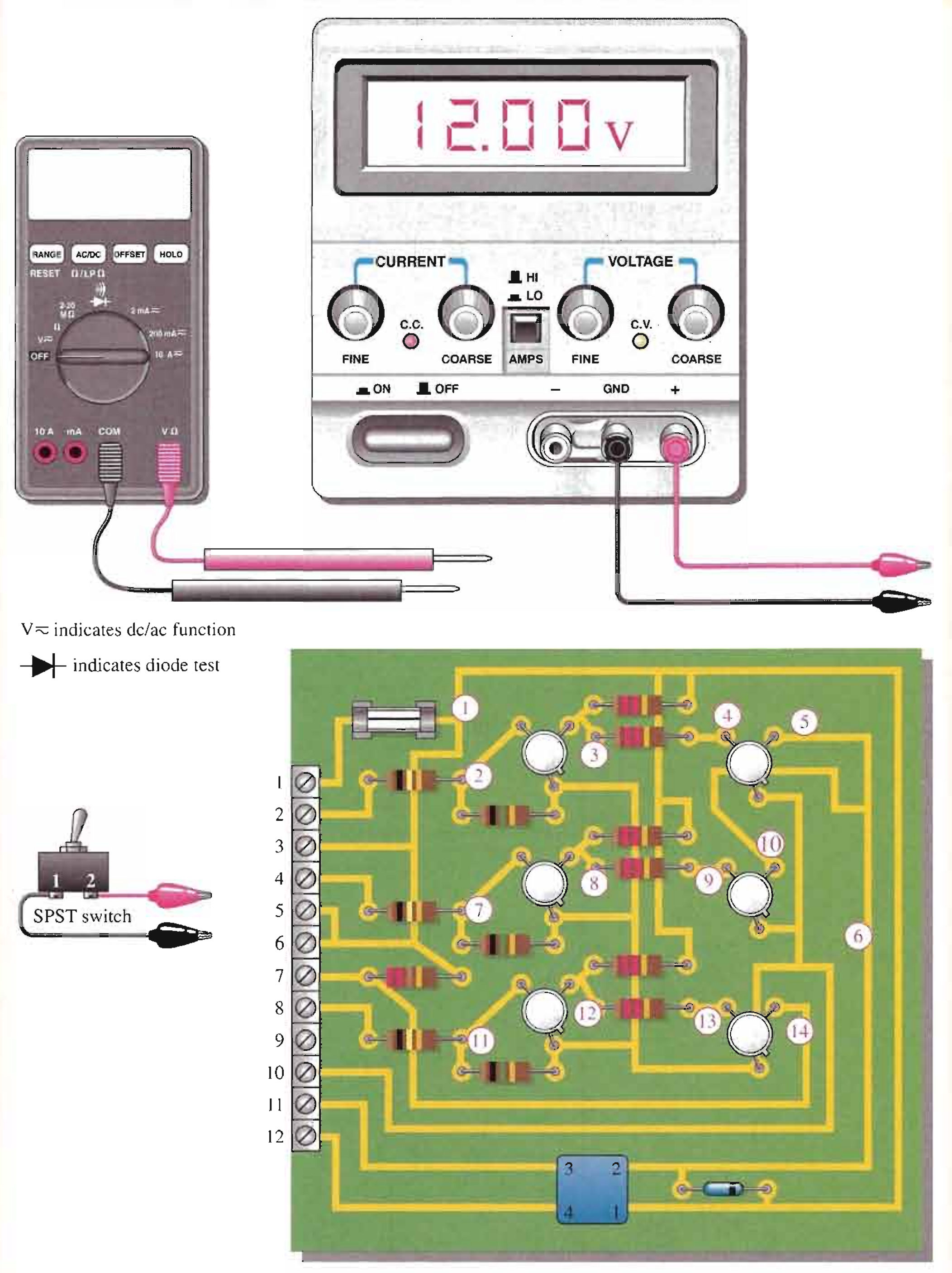
FIGURE 4–41

Partial data sheet for the 2N3947 *npn* transistor.



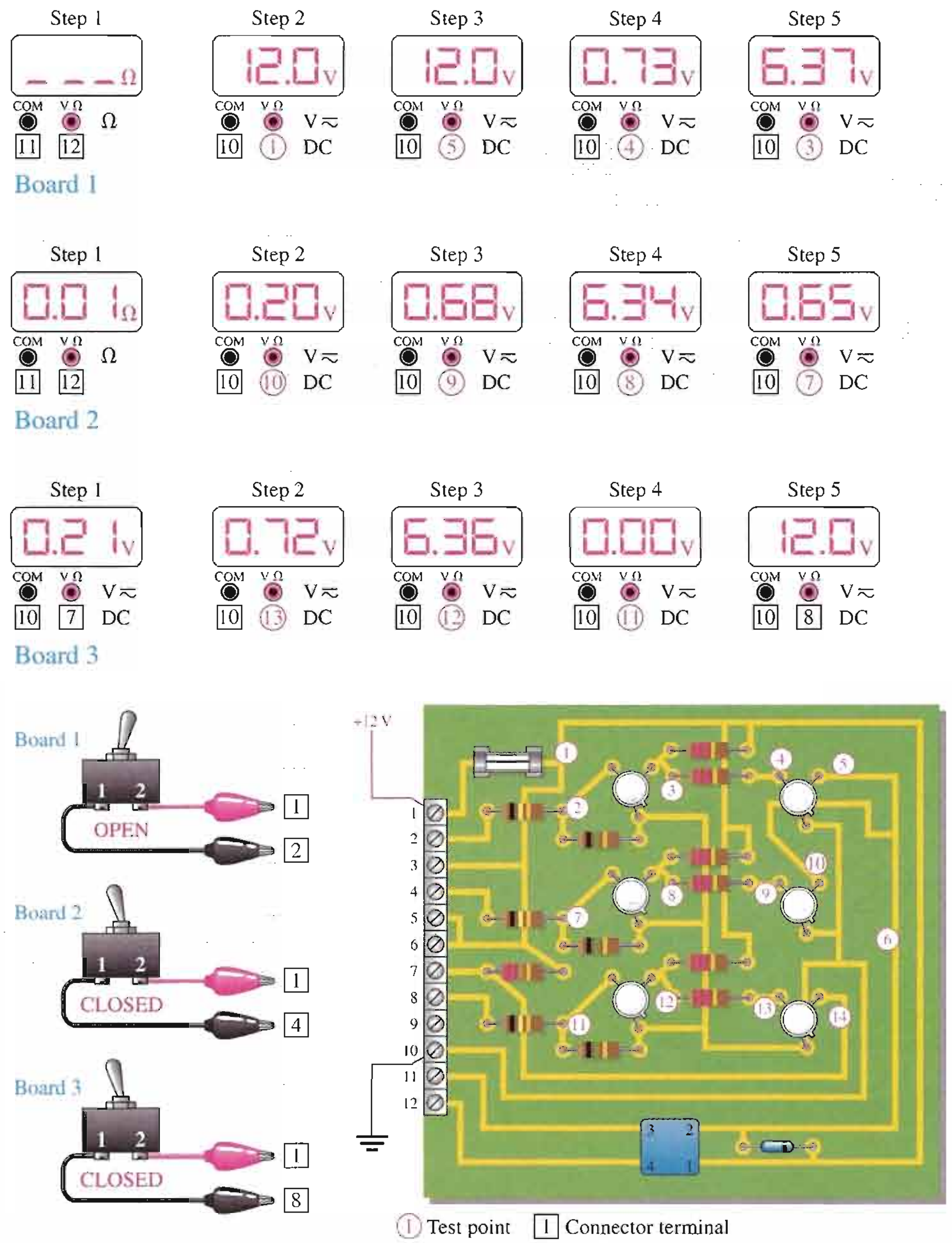
▲ **FIGURE 4–42**

Zone-monitoring circuits schematic and printed circuit board.



▲ FIGURE 4–43

Zone-monitoring circuits board test bench.

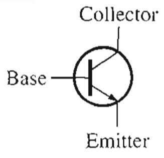


▲ **FIGURE 4–44**

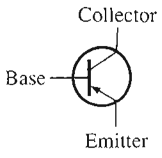
Test results for the three defective circuit boards.

SUMMARY OF BIPOLAR JUNCTION TRANSISTORS

SYMBOLS

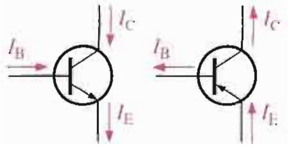


npn

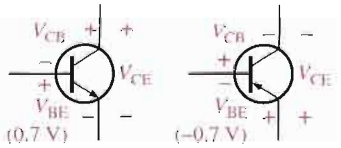


pnp

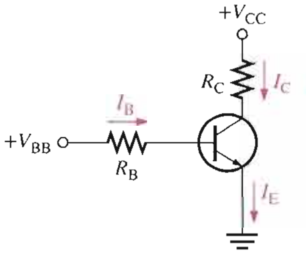
CURRENTS AND VOLTAGES



$I_E = I_C + I_B$



AMPLIFICATION

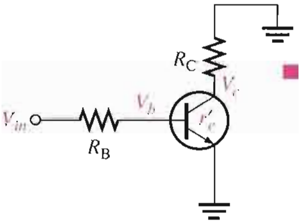


- DC current gain

$I_C = \beta_{DC} I_B$

DC circuit

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

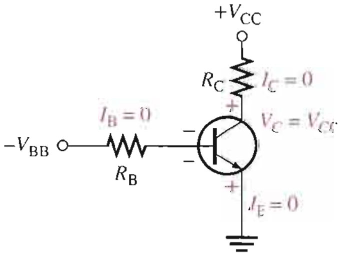


- AC voltage gain

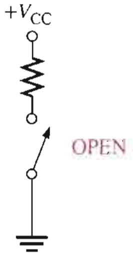
$$A_v = \frac{V_c}{V_b} = \frac{R_C}{r'_e}$$

AC equivalent circuit

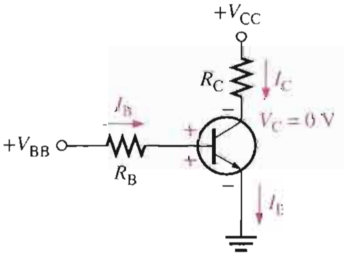
CUTOFF AND SATURATION



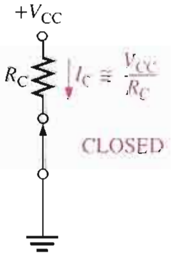
Cutoff: BE junction reverse-biased
BC junction reverse-biased



Ideal switch equivalent for cutoff



Saturation: BE junction forward-biased
BC junction forward-biased



Ideal switch equivalent for saturation

CHAPTER SUMMARY

- The BJT (bipolar junction transistor) is constructed with three regions: base, collector, and emitter.
- The BJT has two *pn* junctions, the base-emitter junction and the base-collector junction.
- Current in a BJT consists of both free electrons and holes, thus the term *bipolar*.
- The base region is very thin and lightly doped compared to the collector and emitter regions.
- The two types of bipolar junction transistor are the *npn* and the *pnp*.

- To operate as an amplifier, the base-emitter junction must be forward-biased and the base-collector junction must be reverse-biased. This is called *forward-reverse bias.*
- The three currents in the transistor are the base current (I_B), emitter current (I_E), and collector current (I_C).
- I_B is very small compared to I_C and I_E.
- The dc current gain of a transistor is the ratio of I_C to I_B and is designated β_{DC}. Values typically range from less than 20 to several hundred.
- β_{DC} is usually referred to as h_{FE} on transistor data sheets.
- The ratio of I_C to I_E is called α_{DC}. Values typically range from 0.95 to 0.99.
- When a transistor is forward-reverse biased, the voltage gain depends on the internal emitter resistance and the external collector resistance.
- A transistor can be operated as an electronic switch in cutoff and saturation.
- In cutoff, both *pn* junctions are reverse-biased and there is essentially no collector current. The transistor ideally behaves like an open switch between collector and emitter.
- In saturation, both *pn* junctions are forward-biased and the collector current is maximum. The transistor ideally behaves like a closed switch between collector and emitter.
- There is a variation in β_{DC} over temperature and also from one transistor to another of the same type.
- There are many types of transistor packages using plastic, metal, or ceramic.
- It is best to check a transistor in-circuit before removing it.
- Common faults are open junctions, low β_{DC}, excessive leakage currents, and external opens and shorts on the circuit board.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Amplification The process of increasing the power, voltage, or current by electronic means.

Base One of the semiconductor regions in a BJT. The base is very thin and lightly doped compared to the other regions.

Beta (β) The ratio of dc collector current to dc base current in a BJT; current gain from base to collector.

Bias The necessary application of a dc voltage to a transistor or other device to produce a desired mode of operation.

BJT (bipolar junction transistor) A transistor constructed with three doped semiconductor regions separated by two *pn* junctions.

Collector The largest of the three semiconductor regions of a BJT.

Cutoff The nonconducting state of a transistor.

Emitter The most heavily doped of the three semiconductor regions of a BJT.

Gain The amount by which an electrical signal is increased or amplified.

Linear Characterized by a straight-line relationship.

Saturation The state of a BJT in which the collector current has reached a maximum and is independent of the base current.

KEY FORMULAS

4–1	$I_E = I_C + I_B$	Transistor currents
4–2	$\beta_{DC} = \dfrac{I_C}{I_B}$	DC current gain
4–3	$V_{BE} \cong 0.7\text{ V}$	Base-to-emitter voltage (silicon)
4–4	$I_B = \dfrac{V_{BB} - V_{BE}}{R_B}$	Base current

4–5	$V_{CE} = V_{CC} - I_C R_C$	Collector-to-emitter voltage (common-emitter)
4–6	$V_{CB} = V_{CE} - V_{BE}$	Collector-to-base voltage
4–7	$I_C = \dfrac{P_{D(max)}}{V_{CE}}$	Maximum I_C for given V_{CE}
4–8	$A_v \cong \dfrac{R_C}{r'_e}$	Approximate ac voltage gain
4–9	$V_{CE(cutoff)} = V_{CC}$	Cutoff condition
4–10	$I_{C(sat)} = \dfrac{V_{CC} - V_{CE(sat)}}{R_C}$	Collector saturation current
4–11	$I_{B(min)} = \dfrac{I_{C(sat)}}{\beta_{DC}}$	Minimum base current for saturation

CIRCUIT-ACTION QUIZ

Answers are at the end of the chapter.

1. If a transistor with a higher β_{DC} is used in Figure 4–8, the collector current will
   (a) increase (b) decrease (c) not change
2. If a transistor with a higher β_{DC} is used in Figure 4–8, the emitter current will
   (a) increase (b) decrease (c) not change
3. If a transistor with a higher β_{DC} is used in Figure 4–8, the base current will
   (a) increase (b) decrease (c) not change
4. If V_{BB} is reduced in Figure 4–15, the collector current will
   (a) increase (b) decrease (c) not change
5. If V_{CC} in Figure 4–15 is increased, the base current will
   (a) increase (b) decrease (c) not change
6. If the amplitude of V_{in} in Figure 4–21 is decreased, the ac output voltage amplitude will
   (a) increase (b) decrease (c) not change
7. If the transistor in Figure 4–23 is saturated and the base current is increased, the collector current will
   (a) increase (b) decrease (c) not change
8. If R_C in Figure 4–23 is reduced in value, the value of $I_{C(sat)}$ will
   (a) increase (b) decrease (c) not change
9. If the transistor in Figure 4–30 is open from collector to emitter, the voltage across R_C will
   (a) increase (b) decrease (c) not change
10. If the transistor in Figure 4–30 is open from collector to emitter, the collector voltage will
    (a) increase (b) decrease (c) not change
11. If the base resistor in Figure 4–30 is open, the transistor collector voltage will
    (a) increase (b) decrease (c) not change
12. If the emitter in Figure 4–30 becomes disconnected from ground, the collector voltage will
    (a) increase (b) decrease (c) not change

SELF-TEST

Answers are at the end of the chapter.

1. The three terminals of a bipolar junction transistor are called
   (a) *p, n, p* (b) *n, p, n* (c) input, output, ground (d) base, emitter, collector
2. In a *pnp* transistor, the *p* regions are
   (a) base and emitter (b) base and collector (c) emitter and collector

3. For operation as an amplifier, the base of an *npn* transistor must be
   (a) positive with respect to the emitter **(b)** negative with respect to the emitter
   (c) positive with respect to the collector **(d)** 0 V
4. The emitter current is always
   (a) greater than the base current **(b)** less than the collector current
   (c) greater than the collector current **(d)** answers (a) and (c)
5. The β_{DC} of a transistor is its
   (a) current gain **(b)** voltage gain **(c)** power gain **(d)** internal resistance
6. If I_C is 50 times larger than I_B, then β_{DC} is
   (a) 0.02 **(b)** 100 **(c)** 50 **(d)** 500
7. The approximate voltage across the forward-biased base-emitter junction of a silicon BJT is
   (a) 0 V **(b)** 0.7 V **(c)** 0.3 V **(d)** V_{BB}
8. The bias condition for a transistor to be used as a linear amplifier is called
   (a) forward-reverse **(b)** forward-forward **(c)** reverse-reverse **(d)** collector bias
9. If the output of a transistor amplifier is 5 V rms and the input is 100 mV rms, the voltage gain is
   (a) 5 **(b)** 500 **(c)** 50 **(d)** 100
10. When operated in cutoff and saturation, the transistor acts like a
    (a) linear amplifier **(b)** switch **(c)** variable capacitor **(d)** variable resistor
11. In cutoff, V_{CE} is
    (a) 0 V **(b)** minimum **(c)** maximum
    (d) equal to V_{CC} **(e)** answers (a) and (b) **(f)** answers (c) and (d)
12. In saturation, V_{CE} is
    (a) 0.7 V **(b)** equal to V_{CC} **(c)** minimum **(d)** maximum
13. To saturate a BJT,
    (a) $I_B = I_{C(sat)}$ **(b)** $I_B > I_{C(sat)}/\beta_{DC}$
    (c) V_{CC} must be at least 10 V **(d)** the emitter must be grounded
14. Once in saturation, a further increase in base current will
    (a) cause the collector current to increase
    (b) not affect the collector current
    (c) cause the collector current to decrease
    (d) turn the transistor off
15. If the base-emitter junction is open, the collector voltage is
    (a) V_{CC} **(b)** 0 V **(c)** floating **(d)** 0.2 V

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

SECTION 4–1 Transistor Structure

1. What are the majority carriers in the base region of an *npn* transistor called?
2. Explain the purpose of a thin, lightly doped base region.

SECTION 4–2 Basic Transistor Operation

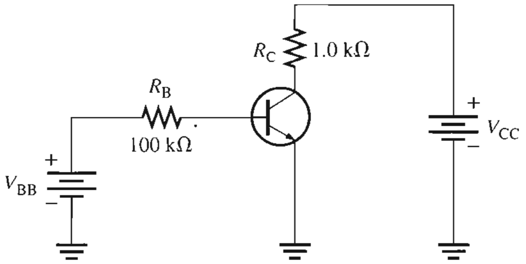
3. Why is the base current in a transistor so much less than the collector current?
4. In a certain transistor circuit, the base current is 2 percent of the 30 mA emitter current. Determine the collector current.

5. For normal operation of a *pnp* transistor, the base must be (+ or −) with respect to the emitter, and (+ or −) with respect to the collector.
6. What is the value of I_C for $I_E = 5.34$ mA and $I_B = 475\ \mu$A?

SECTION 4–3 Transistor Characteristics and Parameters

7. What is the α_{DC} when $I_C = 8.23$ mA and $I_E = 8.69$ mA?
8. A certain transistor has an $I_C = 25$ mA and an $I_B = 200\ \mu$A. Determine the β_{DC}.
9. What is the β_{DC} of a transistor if $I_C = 20.5$ mA and $I_E = 20.3$ mA?
10. What is the α_{DC} if $I_C = 5.35$ mA and $I_B = 50\ \mu$A?
11. A certain transistor exhibits an α_{DC} of 0.96. Determine I_C when $I_E = 9.35$ mA.
12. A base current of 50 μA is applied to the transistor in Figure 4–45, and a voltage of 5 V is dropped across R_C. Determine the β_{DC} of the transistor.

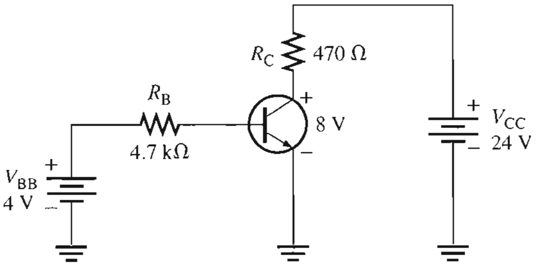
FIGURE 4–45



13. Calculate α_{DC} for the transistor in Problem 12.
14. Determine each current in Figure 4–46. What is the β_{DC}?

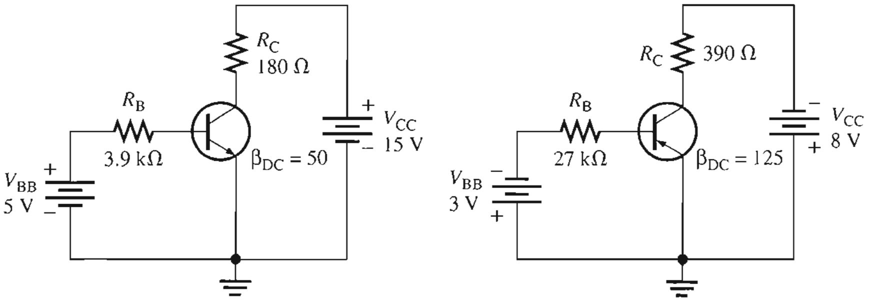
FIGURE 4–46

Multisim file circuits are identified with a CD logo and are in the Problems folder on your CD-ROM. Filenames correspond to figure numbers (e.g., F04–46).



15. Find V_{CE}, V_{BE}, and V_{CB} in both circuits of Figure 4–47.

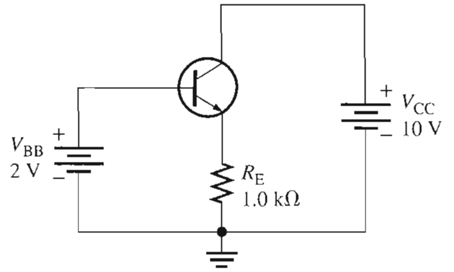
FIGURE 4–47



(a) (b)

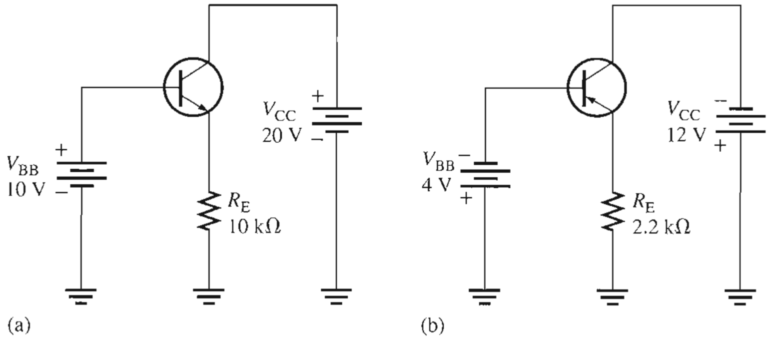
16. Determine whether or not the transistors in Figure 4–47 are saturated.
17. Find I_B, I_E, and I_C in Figure 4–48. $\alpha_{DC} = 0.98$.

FIGURE 4–48



18. Determine the terminal voltages of each transistor with respect to ground for each circuit in Figure 4–49. Also determine V_{CE}, V_{BE}, and V_{CB}.

FIGURE 4–49



19. If the β_{DC} in Figure 4–49(a) changes from 100 to 150 due to a temperature increase, what is the change in collector current?
20. A certain transistor is to be operated at a collector current of 50 mA. How high can V_{CE} go without exceeding a $P_{D(max)}$ of 1.2 W?
21. The power dissipation derating factor for a certain transistor is 1 mW/°C. The $P_{D(max)}$ is 0.5 W at 25°C. What is $P_{D(max)}$ at 100°C?

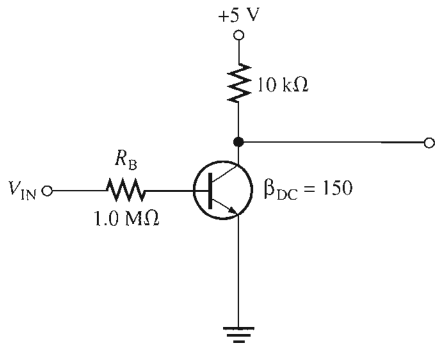
SECTION 4–4 The Transistor as an Amplifier

22. A transistor amplifier has a voltage gain of 50. What is the output voltage when the input voltage is 100 mV?
23. To achieve an output of 10 V with an input of 300 mV, what voltage gain is required?
24. A 50 mV signal is applied to the base of a properly biased transistor with $r'_e = 10$ and $R_C =$ 560 Ω. Determine the signal voltage at the collector.

SECTION 4–5 The Transistor as a Switch

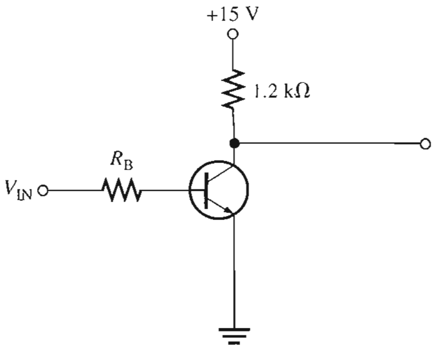
25. Determine $I_{C(sat)}$ for the transistor in Figure 4–50. What is the value of I_B necessary to produce saturation? What minimum value of V_{IN} is necessary for saturation? Assume $V_{CE(sat)} = 0$ V.

FIGURE 4–50



26. The transistor in Figure 4–51 has a β_{DC} of 50. Determine the value of R_B required to ensure saturation when V_{IN} is 5 V. What must V_{IN} be to cut off the transistor? Assume $V_{CE(sat)} = 0$ V.

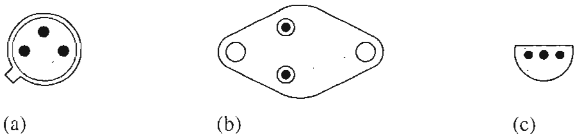
► FIGURE 4–51



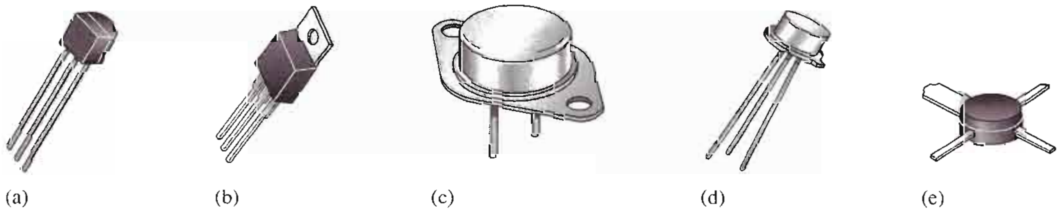
SECTION 4–6 Transistor Packages and Terminal Identification

27. Identify the leads on the transistors in Figure 4–52. Bottom views are shown.

► FIGURE 4–52



28. What is the most probable category of each transistor in Figure 4–53?



▲ FIGURE 4–53

TROUBLESHOOTING PROBLEMS

SECTION 4–7 Troubleshooting

29. In an out-of-circuit test of a good *npn* transistor, what should an analog ohmmeter indicate when its positive probe is touching the emitter and the negative probe is touching the base? When its positive probe is touching the base and the negative probe is touching the collector?

30. What is the most likely problem, if any, in each circuit of Figure 4–54? Assume a β_{DC} of 75.

31. What is the value of the β_{DC} of each transistor in Figure 4–55?

SYSTEM APPLICATION PROBLEMS

32. This problem relates to the circuit board and schematic in Figure 4–42. A remote switch loop is connected between pins 2 and 3. When the remote switches are closed, the relay (RY1) contacts between pin 11 and pin 12 are normally open. When a remote switch is opened, the relay contacts do not close. Determine the possible causes of this malfunction.

33. This problem relates to Figure 4–42. The relay contact remains closed between pins 11 and 12 of the circuit board no matter what any of the inputs are. This means that the relay is energized continuously. What are the possible faults?

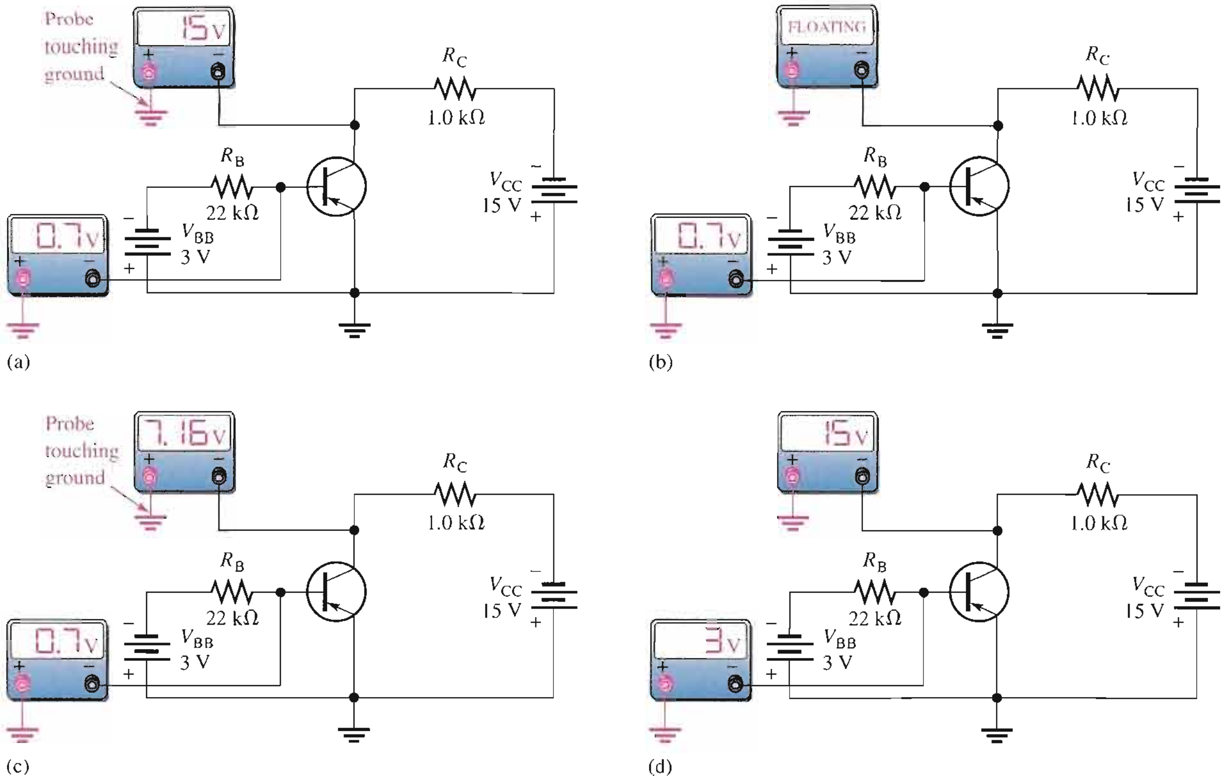


FIGURE 4–54

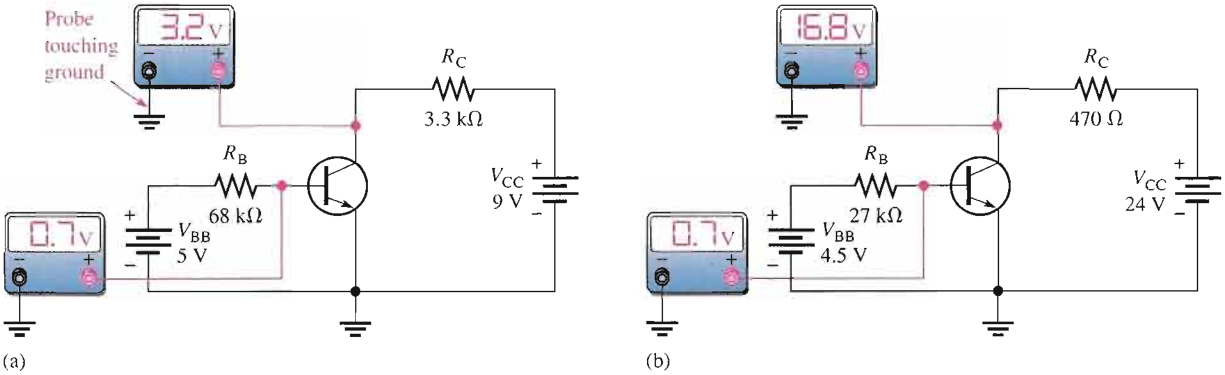


FIGURE 4–55

34. This problem relates to Figure 4–42. Pin 7 stays at approximately 0.1 V, regardless of the input at pin 8. What do you think is wrong? What would you check first?

DATA SHEET PROBLEMS

35. Refer to the partial transistor data sheet in Figure 4–19.

(a) What is the maximum collector-to-emitter voltage for a 2N3903?

(b) How much dc collector current can the 2N3904 handle?

(c) How much power can a 2N3903 dissipate if the surrounding air is at a temperature of 25°C?

(d) How much power can a 2N3904 dissipate if the case is at a temperature of 25°C?

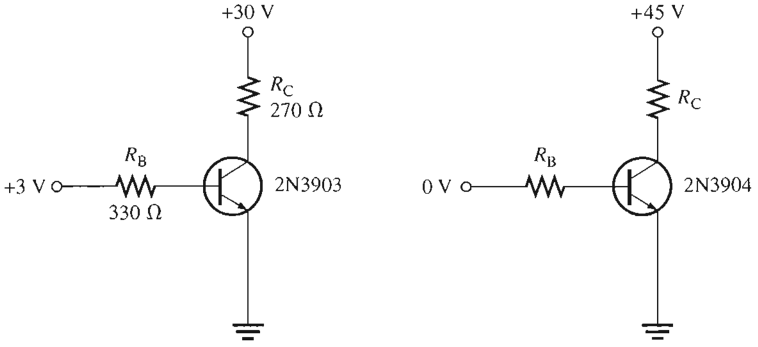
(e) What is the minimum h_{FE} of a 2N3903 if the collector current is 1 mA?

36. Refer to the transistor data sheet in Figure 4–19. A 2N3904 is operating in an environment where the ambient temperature is 65°C. What is the most power that it can dissipate?

37. Refer to the transistor data sheet in Figure 4–19. A 2N3903 is operating with a case temperature of 45°C. What is the most power that it can dissipate?

38. Refer to the transistor data sheet in Figure 4–19. Determine if any rating is exceeded in each circuit of Figure 4–56 based on minimum specified values.

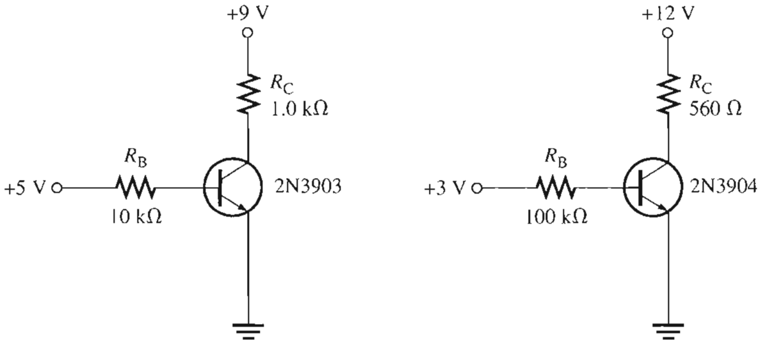
FIGURE 4–56



(a) $T_A = 50°C$ (b) $T_A = 25°C$

39. Refer to the transistor data sheet in Figure 4–19. Determine whether or not the transistor is saturated in each circuit of Figure 4–57 based on the maximum specified value of h_{FE}.

FIGURE 4–57

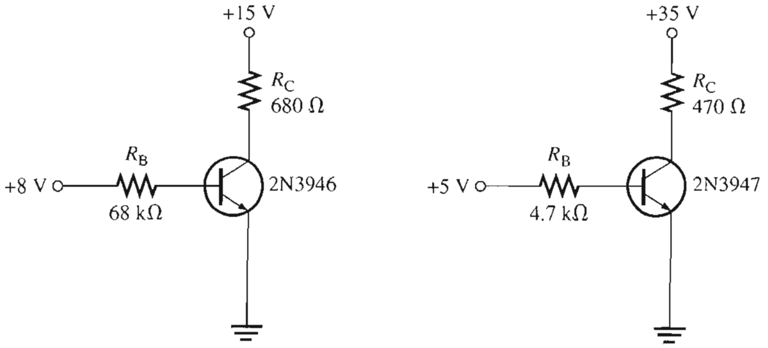


(a) (b)

40. Refer to the partial transistor data sheet in Figure 4–41. Determine the minimum and maximum base currents required to produce a collector current of 10 mA in a 2N3946. Assume that the transistor is not in saturation and $V_{CE} = 1$ V.

41. For each of the circuits in Figure 4–58, determine if there is a problem based on the data sheet information in Figure 4–41. Use the maximum specified h_{FE}.

FIGURE 4–58



(a) $T_A = 40°C$ (b) $T_A = 25°C$

ADVANCED PROBLEMS

42. Derive a formula for α_{DC} in terms of β_{DC}.

43. A certain 2N3904 dc bias circuit with the following values is in saturation. $I_B = 500\ \mu A$, $V_{CC} = 10$ V, and $R_C = 180\ \Omega$, $h_{FE} = 150$. If you increase V_{CC} to 15 V, does the transistor come out of saturation? If so, what is the collector-to-emitter voltage and the collector current?

44. Design a dc bias circuit for a 2N3904 operating from a collector supply voltage of 9 V and a base-bias voltage of 3 V that will supply 150 mA to a resistive load that acts as the collector resistor. The circuit must not be in saturation. Assume the minimum specified β_{DC} from the data sheet.

45. Modify the design in Problem 44 to use a single 9 V dc source rather than two different sources. Other requirements remain the same.

46. Design a dc bias circuit for an amplifier in which the voltage gain is to be a minimum of 50 and the output signal voltage is to be "riding" on a dc level of 5 V. The maximum input signal voltage at the base is 10 mV rms. $V_{CC} = 12$ V, and $V_{BB} = 4$ V. Assume $r'_e = 8\ \Omega$.

MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on your CD-ROM.

47. Open file TSP04-47 and determine the fault.

48. Open file TSP04-48 and determine the fault.

49. Open file TSP04-49 and determine the fault.

50. Open file TSP04-50 and determine the fault.

51. Open file TSP04-51 and determine the fault.

52. Open file TSP04-52 and determine the fault.

53. Open file TSP04-53 and determine the fault.

54. Open file TSP04-54 and determine the fault.

ANSWERS

SECTION REVIEWS

SECTION 4–1 Transistor Structure

1. The two types of BJTs are *npn* and *pnp*.
2. The terminals of a BJT are base, collector, and emitter.
3. The three regions of a BJT are separated by two *pn* junctions.

SECTION 4–2 Basic Transistor Operation

1. To operate as an amplifier, the base-emitter is forward-biased and the base-collector is reverse-biased.
2. The emitter current is the largest.
3. The base current is much smaller than the emitter current.
4. The base region is very narrow compared to the other two regions.
5. $I_E = 1\text{ mA} + 10\ \mu\text{A} = 1.01\text{ mA}$

SECTION 4–3 Transistor Characteristics and Parameters

1. $\beta_{DC} = I_C/I_B$; $\alpha_{DC} = I_C/I_E$; h_{FE} is β_{DC}.
2. $\beta_{DC} = 100$; $\alpha_{DC} = 100/(100 + 1) = 0.99$
3. I_C is plotted versus V_{CE}.
4. Forward-reverse bias is required for amplifier operation.

5. β_{DC} increases with temperature.
6. No. β_{DC} generally varies some from one device to the next for a given type.

SECTION 4–4 The Transistor as an Amplifier

1. Amplification is the process where a smaller signal is used to produce a larger identical signal.
2. Voltage gain is the ratio of output voltage to input voltage.
3. R_C and r'_e determine the voltage gain.
4. $A_v = 5\text{ V}/250\text{ mV} = 20$
5. $A_v = 1200\ \Omega/20\ \Omega = 60$

SECTION 4–5 The Transistor as a Switch

1. A transistor switch operates in cutoff and saturation.
2. The collector current is maximum in saturation.
3. The collector current is approximately zero in cutoff.
4. $V_{CE} = V_{CC}$ in cutoff.
5. V_{CE} is minimum in saturation.

SECTION 4–6 Transistor Packages and Terminal Identification

1. Three categories of BJTs are small signal/general purpose, power, and RF.
2. Emitter is the lead closest to the tab.
3. The metal mounting tab or case in power transistors is the collector.

SECTION 4–7 Troubleshooting

1. First, test it in-circuit.
2. If R_B opens, the transistor is in cutoff.
3. The base voltage is +3 V and the collector voltage is +9 V.

RELATED PROBLEMS FOR EXAMPLES

4–1	10 mA
4–2	$I_B = 241\ \mu A$; $I_C = 21.7$ mA; $I_E = 21.94$ mA; $V_{CE} = 4.23$ V; $V_{CB} = 3.53$ V
4–3	Along the horizontal axis
4–4	Not saturated
4–5	10 V
4–6	$V_{CC(max)} = 44.5$ V; $V_{CE(max)}$ is exceeded first.
4–7	4.55 W
4–8	2.5 kΩ
4–9	78.4 μA
4–10	Reduce R_C to 160 Ω and R_B to 2.2 kΩ.
4–11	R_B open

CIRCUIT-ACTION QUIZ

1. (a) **2.** (a) **3.** (c) **4.** (b) **5.** (c) **6.** (b) **7.** (c) **8.** (a)
9. (b) **10.** (a) **11.** (a) **12.** (a)

SELF-TEST

1. (d) **2.** (c) **3.** (a) **4.** (d) **5.** (a) **6.** (c) **7.** (b) **8.** (a) **9.** (c)
10. (b) **11.** (f) **12.** (c) **13.** (b) **14.** (b) **15.** (a)