5

BIPOLAR JUNCTION TRANSISTORS

5–1

TRANSISTOR CONSTRUCTION

The bipolar junction transistor is constructed with *three* doped semiconductor regions separated by *two* pn junctions. The three regions are called *emitter, base,* and *collector.* The two types of bipolar transistors are shown in Figure 5–1. One type consists of two n regions separated by a p region (npn), and the other consists of two p regions separated by an n region (pnp).

The pn junction joining the base region and the emitter region is called the *base-emitter* junction. The junction joining the base region and the collector region is called the *base-collector* junction, as indicated. 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 material is lightly doped and very narrow compared to the heavily doped emitter and collector materials. The reason for this is discussed in the next section.

Figure 5–2 shows the schematic symbols for the npn and pnp bipolar transistors. The term *bipolar* refers to the use of both *holes* and *electrons* as carriers in the transistor structure.

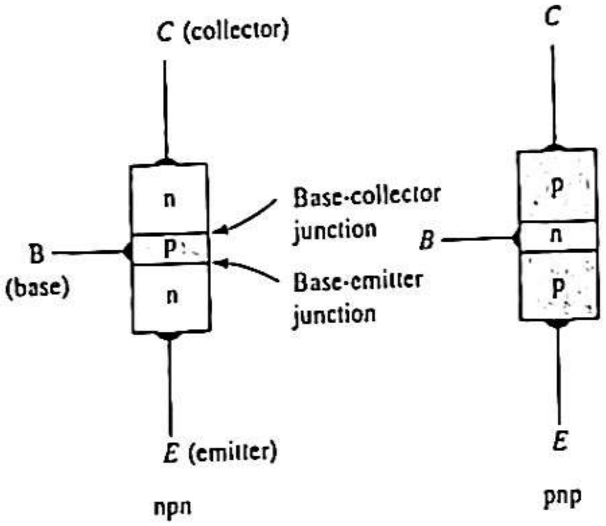


FIGURE 5–1 *Bipolar transistor construction.*

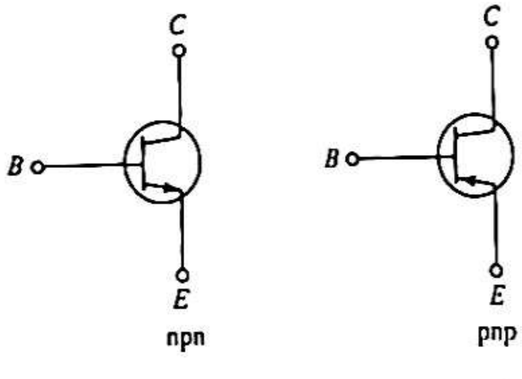


FIGURE 5–2 *Standard transistor symbols.*

Review for 5–1

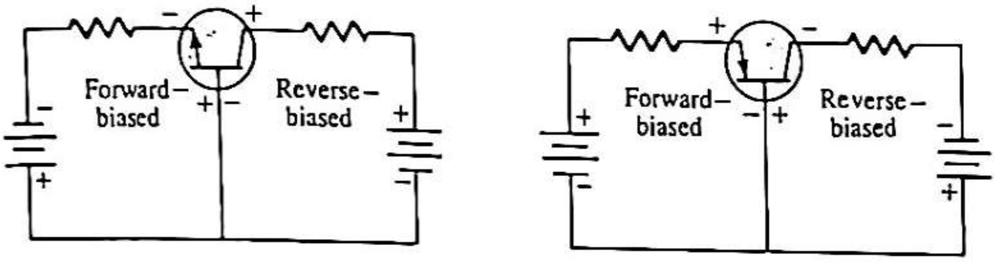
1. Name the two types of bipolar transistors according to the construction.
2. The transistor is a three-terminal device. Name the three terminals.

5–2

BASIC TRANSISTOR OPERATION

In order for the transistor to operate properly as an amplifier, the two pn junctions must be correctly *biased* with external voltages.

In our discussion, the npn transistor is used for the purpose of 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. Figure 5–3 shows the proper bias arrangement for both npn and pnp transistors. 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

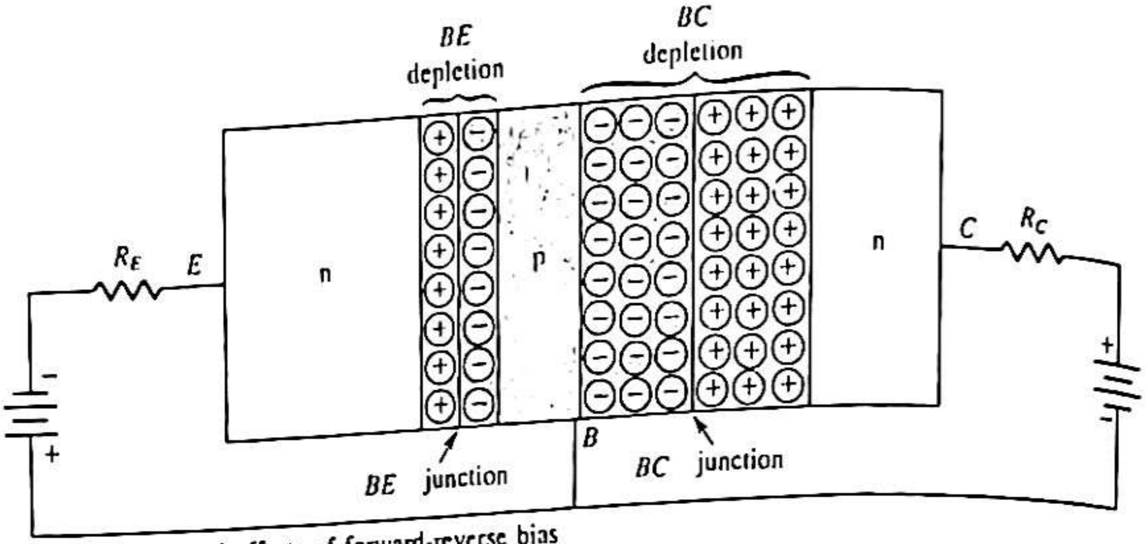
FIGURE 5–3 *Transistor forward-reverse bias.*

Now, let's examine what happens inside the transistor when it is forward-reverse biased. The forward bias from base to emitter *narrows* the *BE* depletion layer, and the reverse bias from base to collector *widens* the *BC* depletion layer, as depicted in Figure 5–4A.

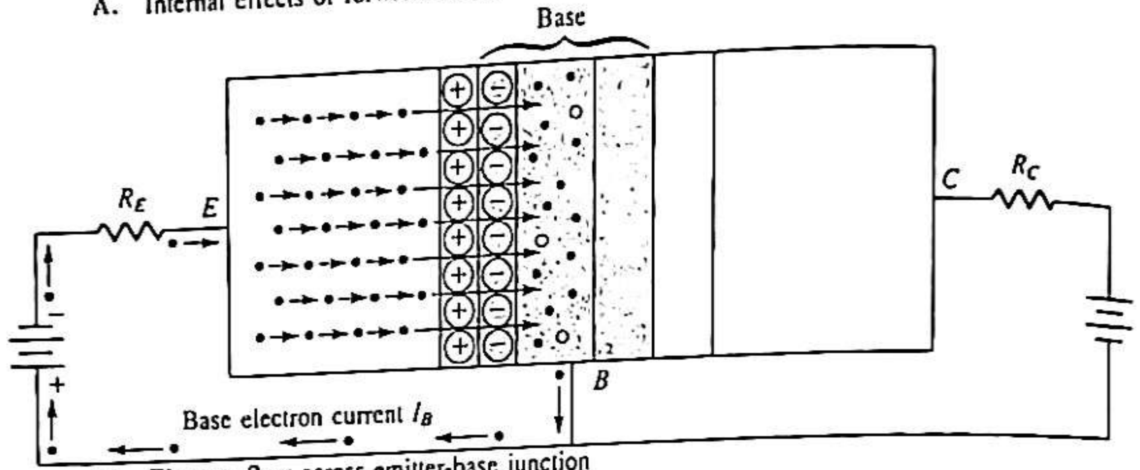
The n-type emitter region is teeming with conduction-band (free) electrons which easily diffuse across the *BE* junction into the p-type base region, just as in a forward-biased diode.

The base region is lightly doped and very thin so that it has a very limited number of holes. Thus, only a small percentage of all the electrons flowing across the *BE* junction combine with the available holes. These relatively few recombined electrons flow out of the base lead as valence electrons, forming the small base current, I_B, as shown in Figure 5–4B.

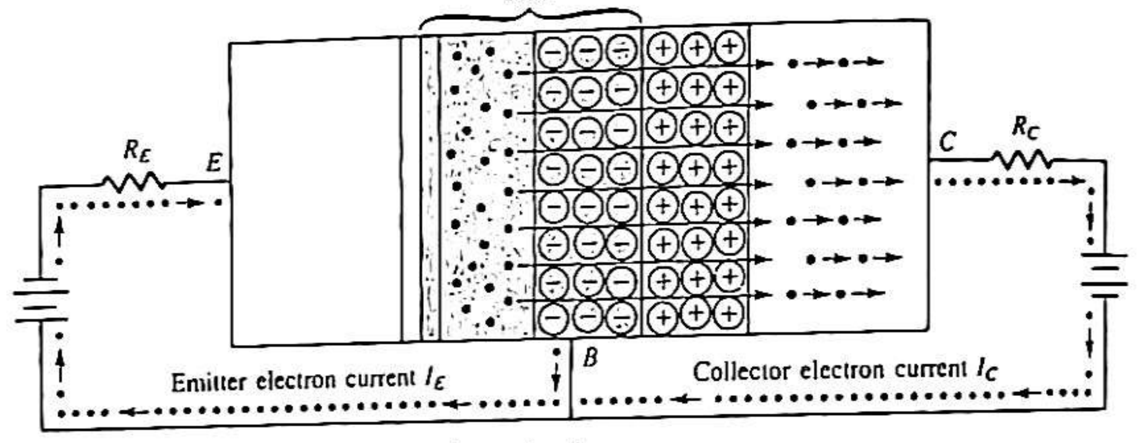
Most of the electrons flowing from the emitter into the base region diffuse into the *BC* depletion layer. Once in this layer they are pulled across the *BC* junction by the depletion layer field set up by the force of attraction between the positive and negative ions. Actually, you can think of the electrons as being pulled across the reverse-biased *BC* junction by the attraction of the positive ions on the other side. This is illustrated in part C.



A. Internal effects of forward-reverse bias



B. Electron flow across emitter-base junction



C. Electron flow across base-collector junction

FIGURE 5–4 *Transistor action.*

The electrons now move through the collector region, out through the collector lead, and into the positive terminal of the external dc source. This forms the collector current, I_C, as shown. The amount of collector current depends directly on the amount of base current and is essentially independent of the dc collector voltage.

Transistor Currents

The directions of conventional current in an npn transistor are as shown in Figure 5–5A, and those for a pnp are shown in Figure 5–5B. The currents are indicated

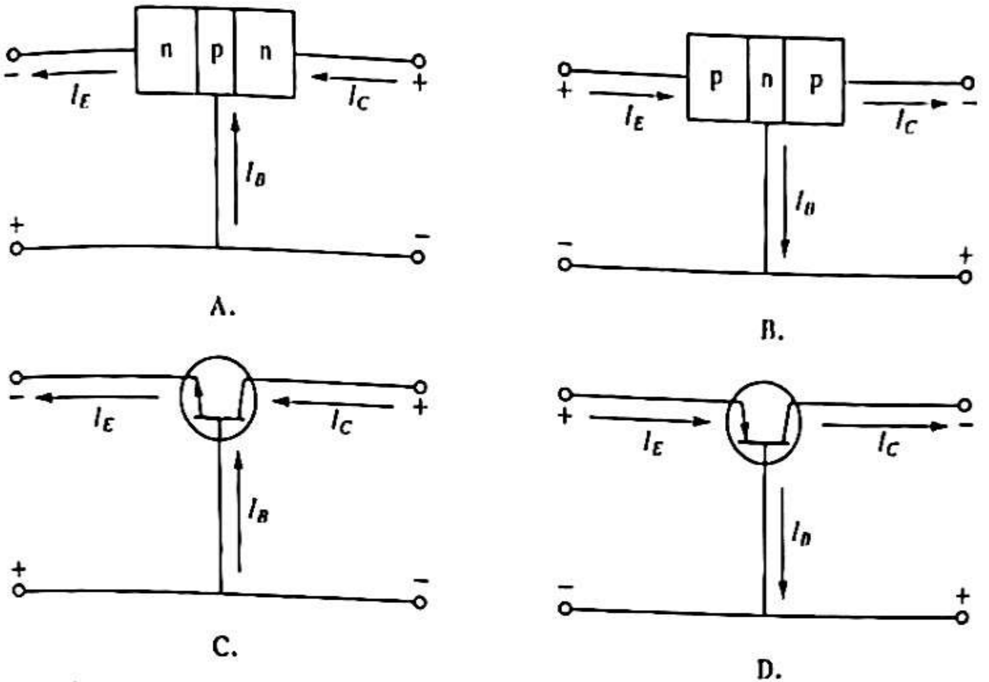


FIGURE 5–5 *Transistor conventional current directions.*

on the corresponding schematic symbols in parts C and D of the figure. Notice that the arrow on the emitter of the transistor symbols points in the direction of *conventional* current.

An examination of these diagrams shows that the emitter current is the *sum* of the collector and base currents, expressed as follows.

$$I_E = I_C + I_B \tag{5-1}$$

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

Review for 5–2

1. For proper amplifier operation, the *BE* junction must be ________ biased, and the *BC* junction must be ________ biased.
2. A certain transistor has a collector current of 1 mA and a base current of 1 μA. Determine the emitter current.

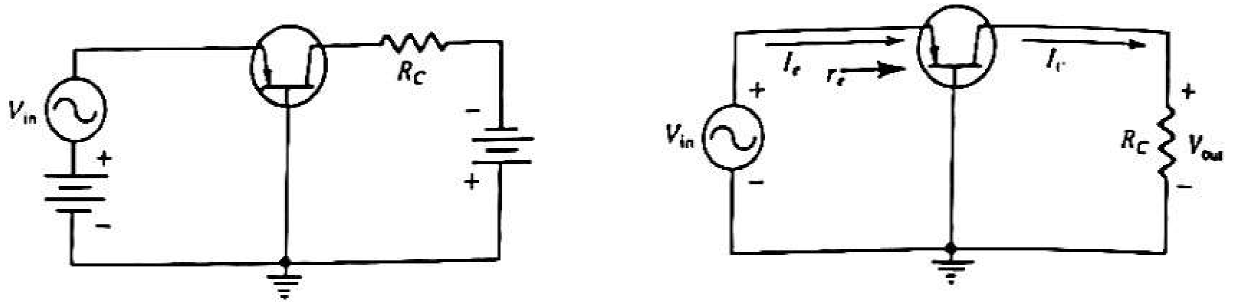
5–3
AMPLIFICATION

Amplification is the process of increasing the amplitude of an electrical signal and is one of the major properties of a transistor.

When a transistor is biased as described in the last section, the *BE* junction has a *low resistance* due to forward bias and the *BC* junction has a *high resistance* due to reverse bias.

Since I_B is extremely small, I_C is approximately equal to I_E. Actually, I_C is always slightly less than I_E. Therefore, equation (5–1) can be restated as an approximation, as follows.

$$I_E \cong I_C \tag{5–2}$$



A. ac input and bias

B. ac equivalent circuit

FIGURE 5–6 *Biased transistor with ac input signal.*

With this in mind, let's consider the transistor in Figure 5–6A with an ac input voltage, V_{in}, applied in series with the *BE* bias voltage and with an external resistor, R_C, connected in series with the *BC* bias voltage. Because the dc sources appear ideally as shorts to the ac voltage, the *ac equivalent* circuit is as shown in Figure 5–6B.

The forward-biased base-emitter junction appears as a *low resistance* to the ac signal. This ac emitter resistance is called r_e. The ac emitter current in Figure 5–6B is

$$I_e = \frac{V_{in}}{r_e}$$

Since $I_c \cong I_e$, the output voltage developed across R_C is

$$V_{out} \cong I_e R_C$$

The ratio of V_{out} to V_{in} is called the ac *voltage gain* (A_v) and is expressed as follows:

$$A_v = \frac{V_{out}}{V_{in}} \tag{5–3}$$

Substituting, we get

$$A_v = \frac{V_{out}}{V_{in}} \cong \frac{I_e R_C}{I_e r_e}$$

$$A_v \cong \frac{R_C}{r_e} \tag{5–4}$$

This shows that the transistor circuit in Figure 5–7 provides amplification or voltage gain, dependent on the value of R_C and r_e. Remember that lower-case subscripts indicate ac quantities.

Example 5–1

Determine the voltage gain and output voltage in Figure 5–7 if $r_e = 50\ \Omega$.

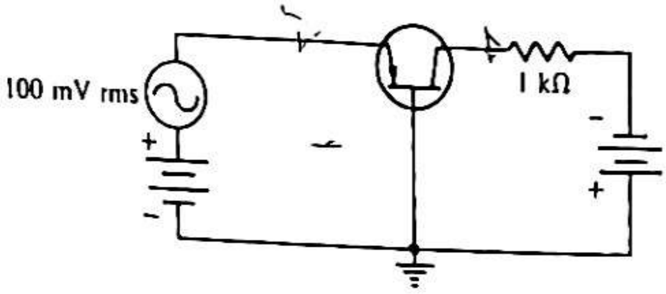


FIGURE 5–7

Solution:

The voltage gain is

$$A_v \cong \frac{R_C}{r_e} = \frac{1\ \text{k}\Omega}{50\ \Omega} = 20$$

Therefore, the output voltage is

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

Review for 5–3

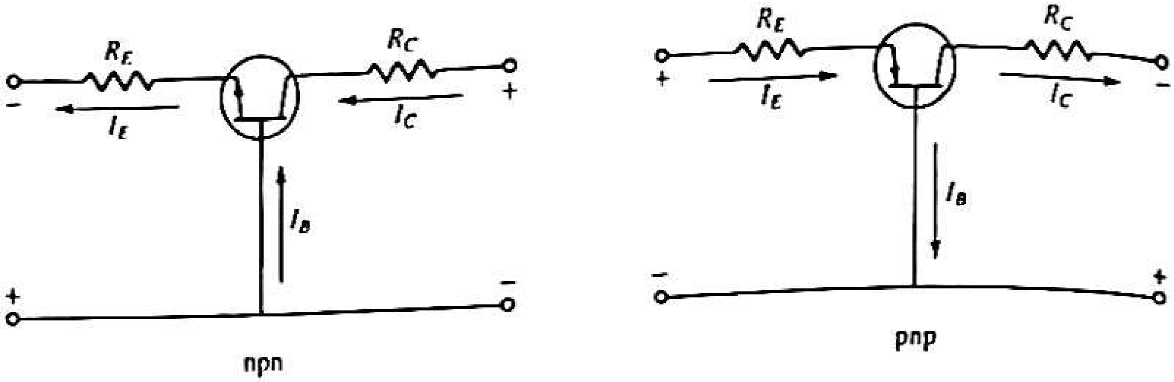
1. Define *amplification.*
2. A certain transistor circuit has an output voltage of 5 V rms and an input of 250 mV rms. What is the voltage gain?
3. A transistor connected as in Figure 5–7 has an $r_e = 20\ \Omega$. If R_C is 1200 Ω, what is the voltage gain?

5–4

COMMON-BASE (CB) CONFIGURATION

When a transistor is connected with the *base* as the common or grounded terminal, it is called a *common-base* connection. This is the type used in the last two sections for describing transistor action.

Common-base connections for both npn and pnp transistors are shown in Figure 5–8, with conventional current directions indicated.



npn

pnp

FIGURE 5–8 *Common-base configuration.*

Current Gain

In this configuration the *input* is at the emitter, the *output* at the collector, and the base is grounded.

Since I_E is the input current and I_C is the output current, the *current gain* is I_C/I_E. This ratio is the dc alpha (α_{dc}) of the transistor. It is often called the *static forward current transfer ratio* for common-base and is usually designated h_{FB} on transistor data sheets.

$$\alpha_{dc} = \frac{I_C}{I_E} \tag{5–5}$$

Because $I_C \cong I_E$, the value of α_{dc} is near unity. Actual values range from about 0.95 to 0.99 or greater.

Example 5–2

For the common-base circuit in Figure 5–9, determine α_{dc}.

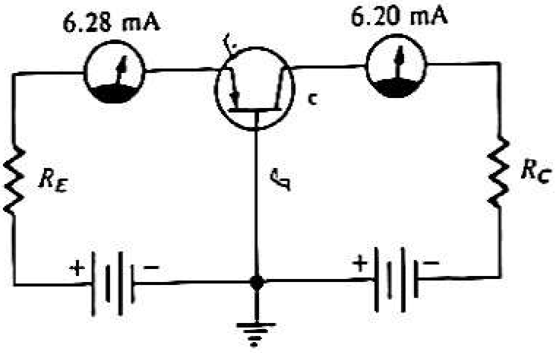


FIGURE 5–9

Solution:

$$\alpha_{dc} = \frac{I_C}{I_E} = \frac{6.20 \text{ mA}}{6.28 \text{ mA}} = 0.987$$

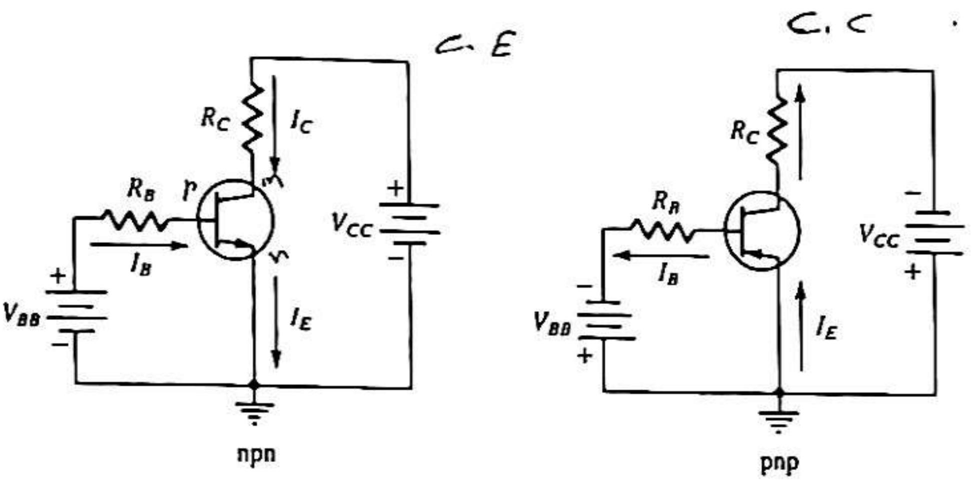
Review for 5–4

1. $I_E = 10$ mA and $I_C = 9.67$ mA. Determine α_{dc}.
2. The input terminal of a common-base connection is the ________, and the output is the ________.

5–5

COMMON-EMITTER (CE) CONFIGURATION

When a transistor is connected with the *emitter* as the common or grounded terminal, it is called a *common-emitter* connection. Common-emitter connections for both npn and pnp transistors are shown in Figure 5–10.



npn   pnp

FIGURE 5–10 *Common-emitter configuration.*

Basic transistor action is the same as with the common-base connection. V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. The conventional current directions are indicated in the figure. The input voltage is applied at the base, and the output voltage is taken at the collector with respect to ground.

Current Gain

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

$$\beta_{dc} = \frac{I_C}{I_B} \qquad (5\text{–}6)$$

Typical values of β_{dc} range from 20 to 200 or higher. β_{dc} is often called the *static forward current transfer ratio* for the common-emitter configuration and is usually designated as h_{FE} on transistor data sheets.

Relationship of α_{dc} and β_{dc}

Starting with the current formula $I_E = I_C + I_B$ and dividing by I_C, we get

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

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

[illegible]

Since $\beta_{dc} = I_C/I_B$ and $\alpha_{dc} = I_C/I_E$, the equation becomes

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

Rearranging, we get

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

$$\boxed{\alpha_{dc} = \frac{\beta_{dc}}{\beta_{dc} + 1}} \qquad (5\text{–}7)$$

Equation (5–7) allows us to calculate α_{dc} if we know β_{dc}. By simple algebra, a formula for β_{dc} in terms of α_{dc} is derived as follows from equation (5–7).

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

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

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

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

$$\boxed{\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}} \qquad (5\text{–}8)$$

Example 5–3

Determine β_{dc} and α_{dc} for a transistor connected in a common-emitter configuration where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution:

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

$$\alpha_{dc} = \frac{\beta_{dc}}{\beta_{dc} + 1} = \frac{73}{74} = 0.986$$

dc Analysis

Consider the common-emitter configuration in Figure 5–11. There are three transistor currents and three voltages: I_B, I_E, I_C, V_{BE}, V_{CB}, and V_{CE}.

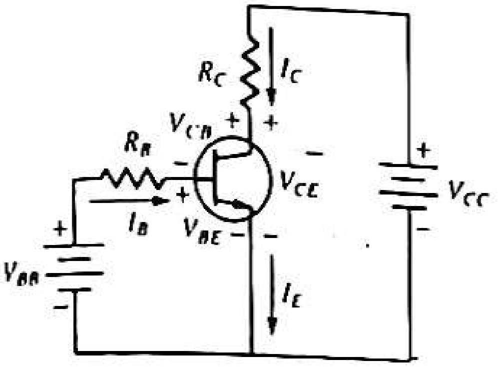


FIGURE 5–11 *Common-emitter currents and voltages.*

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

$$V_{BE} = 0.7\ \text{V} \tag{5-9}$$

The voltage across R_B is

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

$$\text{and } V_{R_B} = I_B R_B$$

$$\text{Substituting, } I_B R_B = V_{BB} - V_{BE}$$

$$\text{and } I_B = \frac{V_{BB} - V_{BE}}{R_B} \tag{5-10}$$

From equation (5–5), the expression for I_E is

$$I_E = \frac{I_C}{\alpha_{\text{dc}}}$$

From equation (5–6), the collector current is

$$I_C = \beta_{\text{dc}} I_B$$

The drop across R_C is

$$V_{R_C} = I_C R_C$$

The voltage at the collector with respect to the emitter (ground) is

$$V_{CE} = V_{CC} - I_C R_C \tag{5-11}$$

The voltage between the base and collector is

$$V_{CB} = V_{CE} - V_{BE} \tag{5-12}$$

Example 5–4

Determine I_B, I_C, I_E, α_{dc}, V_{CE}, and V_{CB} in the circuit of Figure 5–12. The transistor has a $\beta_{\text{dc}} = 150$.