For general-purpose transistors, I_C is measured in milliamperes, while I_{CO} is measured in microamperes or nanoamperes. I_{CO}, like I_s for a reverse-biased diode, is temperature sensitive and must be examined carefully when applications of wide temperature ranges are considered. It can severely affect the stability of a system at high temperature if not considered properly. Improvements in construction techniques have resulted in significantly lower levels of I_{CO}, to the point where its effect can often be ignored.

3.4 COMMON-BASE CONFIGURATION

The notation and symbols used in conjunction with the transistor in the majority of texts and manuals published today are indicated in Fig. 3.6 for the common-base configuration with *pnp* and *npn* transistors. The common-base terminology is derived from the fact that the base is common to both the input and output sides of the configuration. In addition, the base is usually the terminal closest to, or at, ground potential. Throughout this book all current directions will refer to conventional (hole) flow rather than electron flow. This choice was based primarily on the fact that the vast amount of literature available at educational and industrial institutions employs conventional flow and the arrows in all electronic symbols have a direction defined by this convention. Recall that the arrow in the diode symbol defined the direction of conduction for conventional current. For the transistor:

The arrow in the graphic symbol defines the direction of emitter current (conventional flow) through the device.

All the current directions appearing in Fig. 3.6 are the actual directions as defined by the choice of conventional flow. Note in each case that $I_E = I_C + I_B$. Note also that the applied biasing (voltage sources) are such as to establish current in the direction indicated for each branch. That is, compare the direction of I_E to the polarity or V_{EE} for each configuration and the direction of I_C to the polarity of V_{CC}.

To fully describe the behavior of a three-terminal device such as the common-base amplifiers of Fig. 3.6 requires two sets of characteristics—one for the *driving point* or *input* parameters and the other for the *output* side. The input set for the common-base amplifier as shown in Fig. 3.7 will relate an input current (I_E) to an input voltage (V_{BE}) for various levels of output voltage (V_{CB}).

The output set will relate an output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E) as shown in Fig. 3.8. The output or *collector* set of characteristics has three basic regions of interest, as indicated in Fig. 3.8: the *active,*

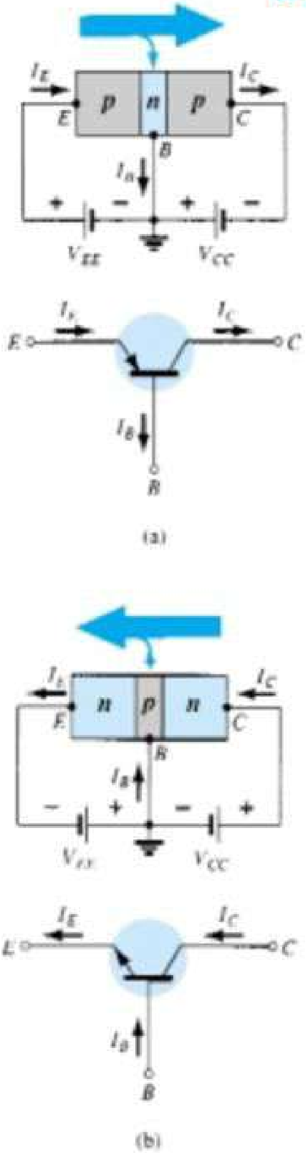

Figure 3.6 Notation and symbols used with the common-base configuration: (a) *pnp* transistor; (b) *npn* transistor.

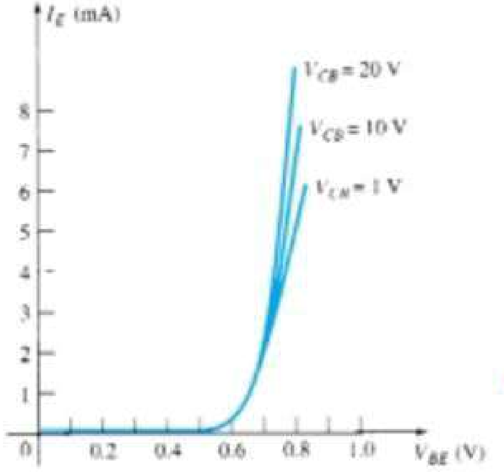

Figure 3.7 Input or driving point characteristics for a common-base silicon transistor amplifier.

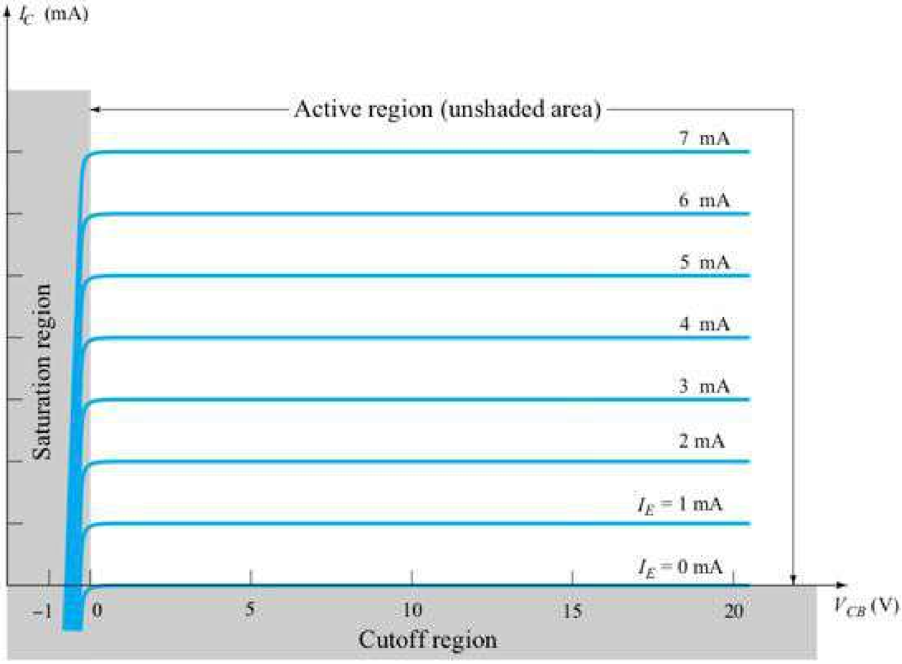

Figure 3.8 Output or collector characteristics for a common-base transistor amplifier.

cutoff, and *saturation* regions. The active region is the region normally employed for linear (undistorted) amplifiers. In particular:

> *In the active region the collector-base junction is reverse-biased, while the base-emitter junction is forward-biased.*

The active region is defined by the biasing arrangements of Fig. 3.6. At the lower end of the active region the emitter current (I_E) is zero, the collector current is simply that due to the reverse saturation current I_{CO}, as indicated in Fig. 3.8. The current I_{CO} is so small (microamperes) in magnitude compared to the vertical scale of I_C (milliamperes) that it appears on virtually the same horizontal line as $I_C = 0$. The circuit conditions that exist when $I_E = 0$ for the common-base configuration are shown in Fig. 3.9. The notation most frequently used for I_{CO} on data and specification sheets is, as indicated in Fig. 3.9, I_{CBO}. Because of improved construction techniques, the level of I_{CBO} for general-purpose transistors (especially silicon) in the low- and mid-power ranges is usually so low that its effect can be ignored. However, for higher power units I_{CBO} will still appear in the microampere range. In addition, keep in mind that I_{CBO}, like I_s, for the diode (both reverse leakage currents) is temperature sensitive. At higher temperatures the effect of I_{CBO} may become an important factor since it increases so rapidly with temperature.

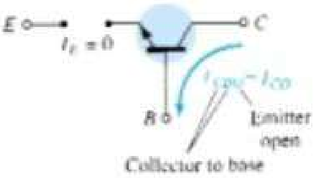

Figure 3.9 Reverse saturation current.

Note in Fig. 3.8 that as the emitter current increases above zero, the collector current increases to a magnitude essentially equal to that of the emitter current as determined by the basic transistor-current relations. Note also the almost negligible effect of V_{CB} on the collector current for the active region. The curves clearly indicate that *a first approximation to the relationship between I_E and I_C in the active region is given by*

$$\boxed{I_C \cong I_E} \qquad (3.3)$$

As inferred by its name, the cutoff region is defined as that region where the collector current is 0 A, as revealed on Fig. 3.8. In addition:

> *In the cutoff region the collector-base and base-emitter junctions of a transistor are both reverse-biased.*

EXAMPLE 3.1

(a) Using the characteristics of Fig. 3.8, determine the resulting collector current if $I_E = 3$ mA and $V_{CB} = 10$ V.
(b) Using the characteristics of Fig. 3.8, determine the resulting collector current if I_E remains at 3 mA but V_{CB} is reduced to 2 V.
(c) Using the characteristics of Figs. 3.7 and 3.8, determine V_{BE} if $I_C = 4$ mA and $V_{CB} = 20$ V.
(d) Repeat part (c) using the characteristics of Figs. 3.8 and 3.10c.

Solution

(a) The characteristics clearly indicate that $I_C \cong I_E =$ **3 mA.**
(b) The effect of changing V_{CB} is negligible and I_C continues to be **3 mA.**
(c) From Fig. 3.8, $I_E \cong I_C = 4$ mA. On Fig. 3.7 the resulting level of V_{BE} is about **0.74 V.**
(d) Again from Fig. 3.8, $I_E \cong I_C = 4$ mA. However, on Fig. 3.10c, V_{BE} is **0.7 V** for any level of emitter current.

Alpha (α)

In the dc mode the levels of I_C and I_E due to the majority carriers are related by a quantity called *alpha* and defined by the following equation:

$$\boxed{\alpha_{\mathrm{dc}} = \frac{I_C}{I_E}} \tag{3.5}$$

where I_C and I_E are the levels of current at the point of operation. Even though the characteristics of Fig. 3.8 would suggest that $\alpha = 1$, for practical devices the level of alpha typically extends from 0.90 to 0.998, with most approaching the high end of the range. Since alpha is defined solely for the majority carriers, Eq. (3.2) becomes

$$\boxed{I_C = \alpha I_E + I_{CBO}} \tag{3.6}$$

For the characteristics of Fig. 3.8 when $I_E = 0$ mA, I_C is therefore equal to I_{CBO}, but as mentioned earlier, the level of I_{CBO} is usually so small that it is virtually undetectable on the graph of Fig. 3.8. In other words, when $I_E = 0$ mA on Fig. 3.8, I_C also appears to be 0 mA for the range of V_{CB} values.

For ac situations where the point of operation moves on the characteristic curve, an ac alpha is defined by

$$\boxed{\alpha_{\mathrm{ac}} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = \text{constant}}} \tag{3.7}$$

The ac alpha is formally called the *common-base, short-circuit, amplification factor,* for reasons that will be more obvious when we examine transistor equivalent circuits in Chapter 7. For the moment, recognize that Eq. (3.7) specifies that a relatively small change in collector current is divided by the corresponding change in I_E with the collector-to-base voltage held constant. For most situations the magnitudes of α_{ac} and α_{dc} are quite close, permitting the use of the magnitude of one for the other. The use of an equation such as (3.7) will be demonstrated in Section 3.6.

Biasing

The proper biasing of the common-base configuration in the active region can be determined quickly using the approximation $I_C \cong I_E$ and assuming for the moment that

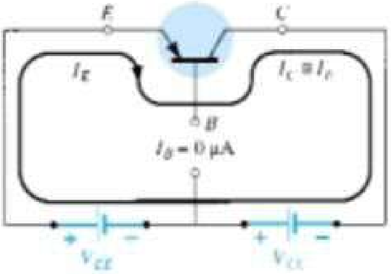

Figure 3.11 Establishing the proper biasing management for a common-base *pnp* transistor in the active region.

$I_B \cong 0\ \mu$A. The result is the configuration of Fig. 3.11 for the *pnp* transistor. The arrow of the symbol defines the direction of conventional flow for $I_E \cong I_C$. The dc supplies are then inserted with a polarity that will support the resulting current direction. For the *npn* transistor the polarities will be reversed.

Some students feel that they can remember whether the arrow of the device symbol in pointing in or out by matching the letters of the transistor type with the appropriate letters of the phrases "pointing in" or "not pointing in." For instance, there is a match between the letters *npn* and the italic letters of *n*ot *p*ointing i*n* and the letters *pnp* with *p*ointi*n*g in.

3.5 TRANSISTOR AMPLIFYING ACTION

Now that the relationship between I_C and I_E has been established in Section 3.4, the basic amplifying action of the transistor can be introduced on a surface level using the network of Fig. 3.12. The dc biasing does not appear in the figure since our interest will be limited to the ac response. For the common-base configuration the ac input resistance determined by the characteristics of Fig. 3.7 is quite small and typically varies from 10 to 100 Ω. The output resistance as determined by the curves of Fig. 3.8 is quite high (the more horizontal the curves the higher the resistance) and typically varies from 50 kΩ to 1 MΩ (100 kΩ for the transistor of Fig. 3.12). The difference in resistance is due to the forward-biased junction at the input (base to emitter) and the reverse-biased junction at the output (base to collector). Using a common value of 20 Ω for the input resistance, we find that

$$I_i = \frac{V_i}{R_i} = \frac{200\ \text{mV}}{20\ \Omega} = \mathbf{10\ mA}$$

If we assume for the moment that $\alpha_{ac} = 1$ ($I_c = I_e$),

$$I_L = I_i = 10\ \text{mA}$$

and

$$\begin{aligned} V_L &= I_L R \\ &= (10\ \text{mA})(5\ \text{k}\Omega) \\ &= \mathbf{50\ V} \end{aligned}$$

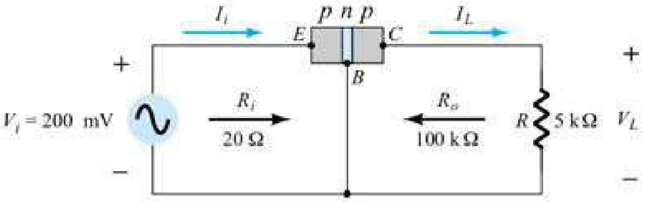

Figure 3.12 Basic voltage amplification action of the common-base configuration.

The voltage amplification is

$$A_v = \frac{V_L}{V_i} = \frac{50\text{ V}}{200\text{ mV}} = \mathbf{250}$$

Typical values of voltage amplification for the common-base configuration vary from 50 to 300. The current amplification (I_C/I_E) is always less than 1 for the common-base configuration. This latter characteristic should be obvious since $I_C = \alpha I_E$ and α is always less than 1.

The basic amplifying action was produced by transferring a current I from a low- to a high-*resistance* circuit. The combination of the two terms in italics results in the label *transistor;* that is,

*tran*sfer + re*sistor* → *transistor*

3.6 COMMON-EMITTER CONFIGURATION

The most frequently encountered transistor configuration appears in Fig. 3.13 for the *pnp* and *npn* transistors. It is called the *common-emitter configuration* since the emitter is common or reference to both the input and output terminals (in this case common to both the base and collector terminals). Two sets of characteristics are again necessary to describe fully the behavior of the common-emitter configuration: one for the *input* or *base-emitter* circuit and one for the *output* or *collector-emitter* circuit. Both are shown in Fig. 3.14.

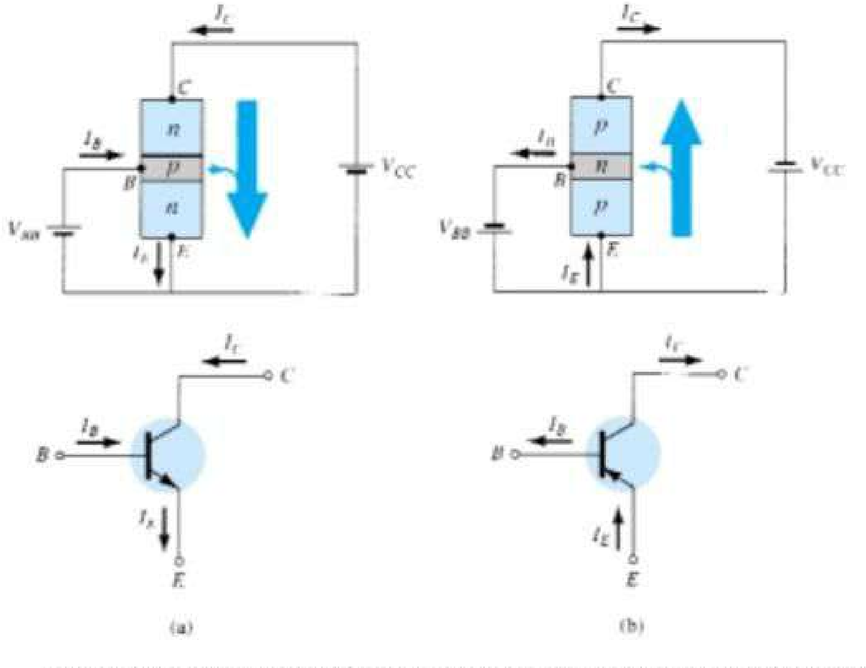

Figure 3.13 Notation and symbols used with the common-emitter configuration: (a) *npn* transistor; (b) *pnp* transistor.

The emitter, collector, and base currents are shown in their actual conventional current direction. Even though the transistor configuration has changed, the current relations developed earlier for the common-base configuration are still applicable. That is, $I_E = I_C + I_B$ and $I_C = \alpha I_E$.

For the common-emitter configuration the output characteristics are a plot of the output current (I_C) versus output voltage (V_{CE}) for a range of values of input current (I_B). The input characteristics are a plot of the input current (I_B) versus the input voltage (V_{BE}) for a range of values of output voltage (V_{CE}).

β

A relationship can be developed between β and α using the basic relationships introduced thus far. Using $\beta = I_C/I_B$ we have $I_B = I_C/\beta$, and from $\alpha = I_C/I_E$ we have $I_E = I_C/\alpha$. Substituting into

$$I_E = I_C + I_B$$

we have
$$\frac{I_C}{\alpha} = I_C + \frac{I_C}{\beta}$$

and dividing both sides of the equation by I_C will result in

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

or
$$\beta = \alpha\beta + \alpha = (\beta + 1)\alpha$$

so that
$$\boxed{\alpha = \frac{\beta}{\beta + 1}} \tag{3.12a}$$

or
$$\boxed{\beta = \frac{\alpha}{1-\alpha}} \tag{3.12b}$$

In addition, recall that

$$I_{CEO} = \frac{I_{CBO}}{1 - \alpha}$$

but using an equivalence of

$$\frac{1}{1 - \alpha} = \beta + 1$$

derived from the above, we find that

$$I_{CEO} = (\beta + 1)I_{CBO}$$

or
$$\boxed{I_{CEO} \cong \beta I_{CBO}} \tag{3.13}$$

as indicated on Fig. 3.14a. Beta is a particularly important parameter because it provides a direct link between current levels of the input and output circuits for a common-emitter configuration. That is,

$$\boxed{I_C = \beta I_B} \tag{31.4}$$

and since
$$\begin{aligned} I_E &= I_C + I_B \\ &= \beta I_B + I_B \end{aligned}$$

we have
$$\boxed{I_E = (\beta + 1)I_B} \tag{3.15}$$

Both of the equations above play a major role in the analysis in Chapter 4.

Biasing

The proper biasing of a common-emitter amplifier can be determined in a manner similar to that introduced for the common-base configuration. Let us assume that we are presented with an *npn* transistor such as shown in Fig. 3.19a and asked to apply the proper biasing to place the device in the active region.

The first step is to indicate the direction of I_E as established by the arrow in the transistor symbol as shown in Fig. 3.19b. Next, the other currents are introduced as

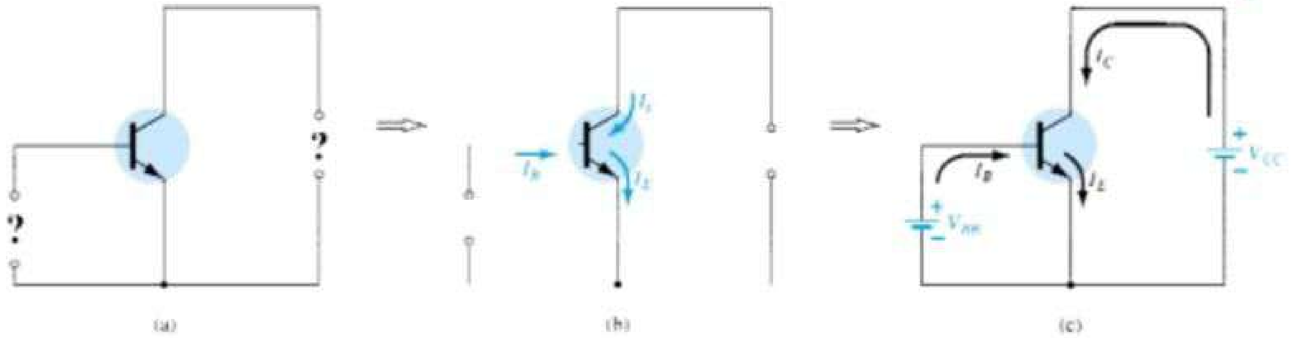

Figure 3.19 Determining the proper biasing arrangement for a common-emitter *npn* transistor configuration.

shown, keeping in mind the Kirchhoff's current law relationship: $I_C + I_B = I_E$. Finally, the supplies are introduced with polarities that will support the resulting directions of I_B and I_C as shown in Fig. 3.19c to complete the picture. The same approach can be applied to *pnp* transistors. If the transistor of Fig. 3.19 was a *pnp* transistor, all the currents and polarities of Fig. 3.19c would be reversed.

3.7 COMMON-COLLECTOR CONFIGURATION

The third and final transistor configuration is the *common-collector configuration,* shown in Fig. 3.20 with the proper current directions and voltage notation. The common-collector configuration is used primarily for impedance-matching purposes since it has a high input impedance and low output impedance, opposite to that of the common-base and common-emitter configurations.

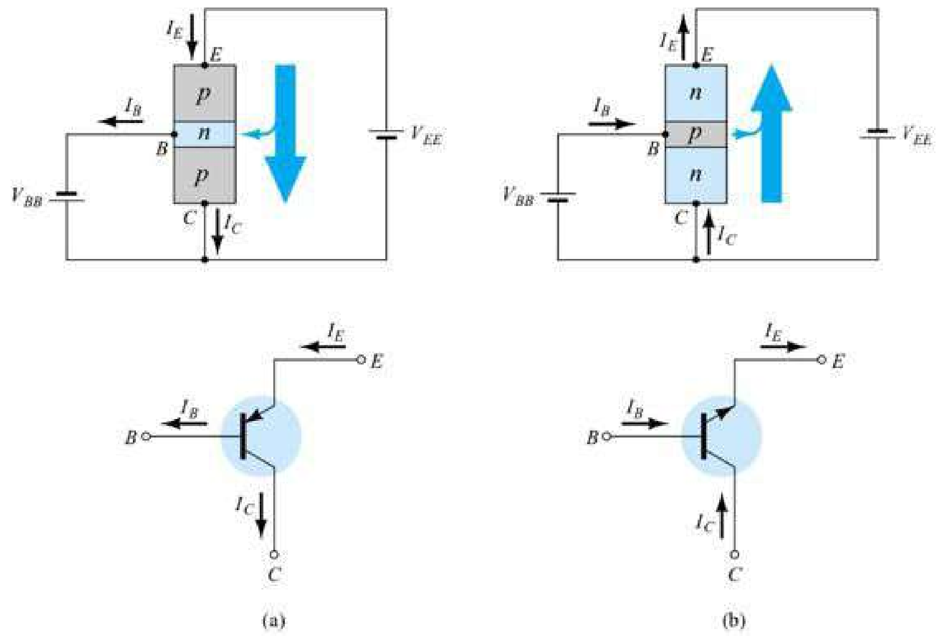

Figure 3.20 Notation and symbols used with the common-collector configuration: (a) *pnp* transistor; (b) *npn* transistor.