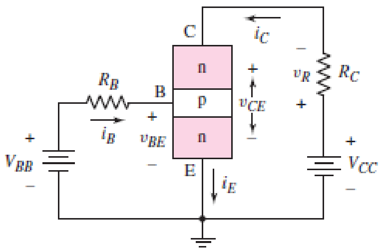
Figure 5.6 shows an npn bipolar transistor in a circuit. Because the emitter is the common connection, this circuit is referred to as a **common-emitter configuration.** When the transistor is biased in the forward-active mode, the B–E junction is forward



Draw ckt (CE configuration) as is it

Figure 5.6 An npn transistor circuit in the common-emitter configuration. Shown are the current directions and voltage polarities for the transistor biased in the forward-active mode.

biased and the B–C junction is reverse biased. Using the piecewise linear model of a pn junction, we assume that the B–E voltage is equal to $V_{BE}(\text{on})$, the junction turn-on voltage. Since $V_{CC} = v_{CE} + i_C R_C$, the power supply voltage must be sufficiently large to keep the B–C junction reverse biased. The base current is established by V_{BB} and R_B, and the resulting collector current is $i_C = \beta i_B$.

If we set $V_{BB} = 0$, the B–E junction will have zero applied volts; therefore, $i_B = 0$, which implies that $i_C = 0$. This condition is called **cutoff.**

Current Relationships

If we treat the bipolar transistor as a single node, then, by Kirchhoff's current law, we have

$$i_E = i_C + i_B \tag{5.7}$$

If the transistor is biased in the forward-active mode, then

$$i_C = \beta i_B \tag{5.8}$$

Substituting Equation (5.8) into (5.7), we obtain the following relationship between the emitter and base currents:

$$i_E = (1 + \beta) i_B \tag{5.9}$$

Solving for i_B in Equation (5.8) and substituting into Equation (5.9), we obtain a relationship between the collector and emitter currents, as follows:

$$i_C = \left(\frac{\beta}{1+\beta}\right) i_E \tag{5.10}$$

We can write $i_C = \alpha i_E$ so

$$\alpha = \frac{\beta}{1+\beta} \tag{5.11}$$

The parameter α is called the common-base current gain and is always slightly less than 1. We may note that if $\beta = 100$, then $\alpha = 0.99$, so α is indeed close to 1. From Equation (5.11), we can state the common-emitter current gain in terms of the common-base current gain:

$$\beta = \frac{\alpha}{1-\alpha} \tag{5.12}$$

5.1.3 pnp Transistor: Forward-Active Mode Operation

We have discussed the basic operation of the npn bipolar transistor. The complementary device is the pnp transistor. Figure 5.7 shows the flow of holes and electrons in a pnp device biased in the forward-active mode. Since the B–E junction is forward biased, the p-type emitter is positive with respect to the n-type base, holes flow from the emitter into the base, the holes diffuse across the base, and they are swept into the collector. The collector current is a result of this flow of holes.

Again, since the B–E junction is forward biased, the emitter current is an exponential function of the B–E voltage. Noting the direction of emitter current and the polarity of the foward-biased B–E voltage, we can write

$$i_E = I_{EO}e^{v_{EB}/V_T} \tag{5.13}$$

where v_{EB} is the voltage between the emitter and base, and now implies that the emitter is positive with respect to the base. We are again assuming the -1 term in the ideal diode equation is negligible.

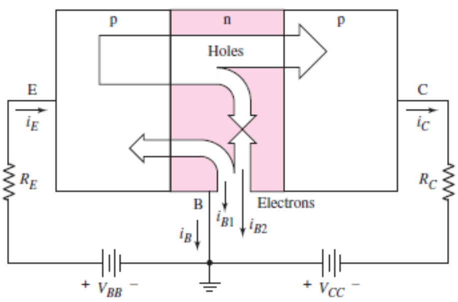


Figure 5.7 Electron and hole currents in a pnp bipolar transistor biased in the forward-active mode. Emitter, base, and collector currents are proportional to e^{v_{EB}/V_T}.

The collector current is an exponential function of the E–B voltage, and the direction is out of the collector terminal, which is opposite to that in the npn device. We can now write

$$i_C = \alpha i_E = I_S e^{v_{EB}/V_T} \tag{5.14}$$

where α is again the common-base current gain.

The base current in a pnp device is the sum of two components. The first component, i_{B1}, comes from electrons flowing from the base into the emitter as a result of the forward-biased E–B junction. We can then write $i_{B1} \propto \exp(v_{EB}/V_T)$. The second component, i_{B2}, comes from the flow of electrons supplied through the base terminal to replace those lost by recombination with the minority carrier holes injected into the base from the emitter. This component is proportional to the number of holes injected into the base, so $i_{B2} \propto \exp(v_{EB}/V_T)$. Therefore the total base current is $i_B = i_{B1} + i_{B2} \propto \exp(v_{EB}/V_T)$. The direction of the base current is out of the base terminal. Since the total base current in the pnp device is an exponential function of the E–B voltage, we can write

$$i_B = I_{BO}e^{v_{EB}/V_T} = \frac{i_C}{\beta} = \frac{I_S}{\beta}e^{v_{EB}/V_T} \tag{5.15}$$

The parameter β is also the common-emitter current gain of the pnp bipolar transistor.

The relationships between the terminal currents of the pnp transistor are exactly the same as those of the npn transistor and are summarized in Table 5.1 in the next section. Also the relationships between β and α are the same as given in Equations (5.11) and (5.12).

5.1.4 Circuit Symbols and Conventions

The block diagram and conventional circuit symbol of an npn bipolar transistor are shown in Figures 5.8(a) and 5.8(b). The arrowhead in the circuit symbol is always placed on the emitter terminal, and it indicates the direction of the emitter current. For the npn device, this direction is out of the emitter. The simplified block diagram and conventional circuit symbol of a pnp bipolar transistor are shown in Figures 5.9(a) and 5.9(b). Here, the arrowhead on the emitter terminal indicates that the direction of the emitter current is into the emitter.

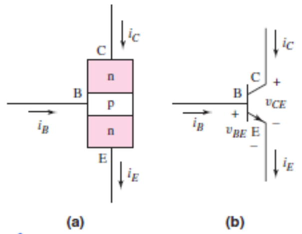


Figure 5.8 npn bipolar transistor: (a) simple block diagram and (b) circuit symbol. Arrow is on the emitter terminal and indicates the direction of emitter current (out of emitter terminal for the npn device).

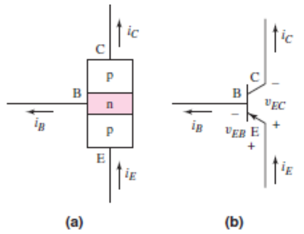


Figure 5.9 pnp bipolar transistor: (a) simple block diagram and (b) circuit symbol. Arrow is on the emitter terminal and indicates the direction of emitter current (into emitter terminal for the pnp device).

Table 5.1 Summary of the bipolar current–voltage relationships in the active region

npn	pnp
$i_C = I_S e^{v_{BE}/V_T}$	$i_C = I_S e^{v_{EB}/V_T}$
$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$	$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$
$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$	$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$
For both transistors	
$i_E = i_C + i_B$	$i_C = \beta i_B$
$i_E = (1+\beta) i_B$	$i_C = \alpha i_E = \left(\frac{\beta}{1+\beta}\right) i_E$
$\alpha = \frac{\beta}{1+\beta}$	$\beta = \frac{\alpha}{1-\alpha}$

Referring to the circuit symbols given for the npn (Figure 5.8(b)) and pnp (Figure 5.9(b)) transistors showing current directions and voltage polarities, we can summarize the current–voltage relationships as given in Table 5.1.

Figure 5.10(a) shows a common-emitter circuit with an npn transistor. The figure includes the transistor currents, and the base-emitter (B–E) and collector–emitter

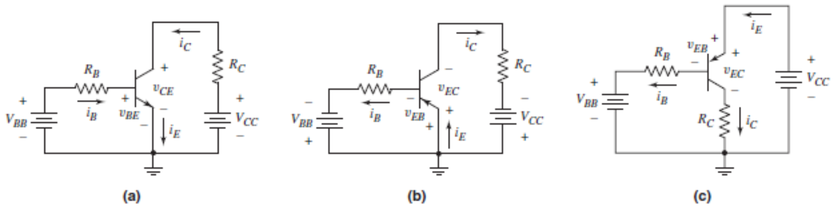


Figure 5.10 Common-emitter circuits: (a) with an npn transistor, (b) with a pnp transistor, and (c) with a pnp transistor biased with a positive voltage source

(C–E) voltages. Figure 5.10(b) shows a common-emitter circuit with a pnp bipolar transistor. Note the different current directions and voltage polarities in the two circuits. A more usual circuit configuration using the pnp transistor is shown in Figure 5.10(c). This circuit allows positive voltage supplies to be used.

5.1.5 Current–Voltage Characteristics

Figures 5.11(a) and 5.11(b) are **common-base circuit configurations** for an npn and a pnp bipolar transistor, respectively. The current sources provide the emitter current. Previously, we stated that the collector current i_C was nearly independent of the C–B voltage as long as the B–C junction was reverse biased. When the B–C junction becomes forward biased, the transistor is no longer in the forward-active mode, and the collector and emitter currents are no longer related by $i_C = \alpha i_E$.

Figure 5.12 shows the typical common-base current–voltage characteristics. When the collector–base junction is reverse biased, then for constant values of emitter

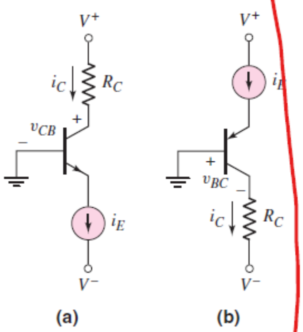


Figure 5.11 Common-base circuit configuration with constant current source biasing: (a) an npn transistor and (b) a pnp transistor

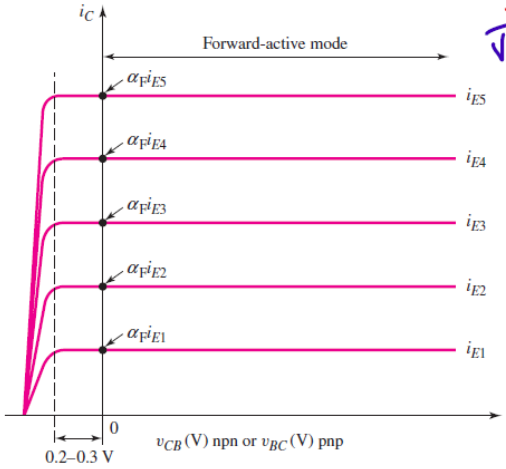
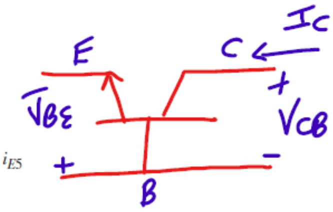


Figure 5.12 Transistor current–voltage characteristics of the common-base circuit



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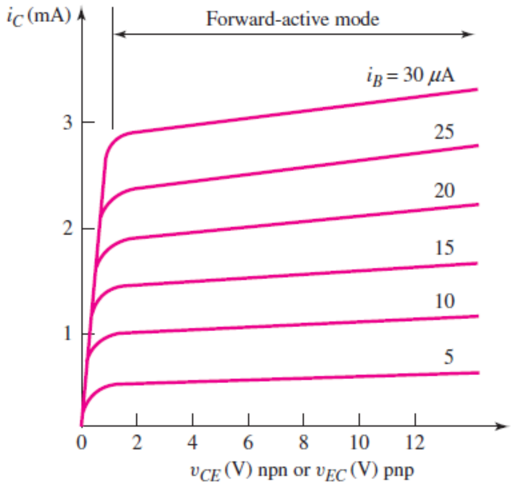
$\boxed{i_E = \alpha\, i_C}$

current, the collector current is nearly equal to i_E. These characteristics show that the common-base device is nearly an ideal constant-current source.

The C–B voltage can be varied by changing the V^+ voltage (Figure 5.11(a)) or the V^- voltage (Figure 5.11(b)). When the collector–base junction becomes forward biased in the range of 0.2 and 0.3 V, the collector current i_C is still essentially equal to the emitter current i_E. In this case, the transistor is still basically biased in the forward-active mode. However, as the forward-bias C–B voltage increases, the linear relationship between the collector and emitter currents is no longer valid, and the collector current very quickly drops to zero.

The common-emitter circuit configuration provides a slightly different set of current–voltage characteristics, as shown in Figure 5.13. For these curves, the collector current is plotted against the collector–emitter voltage, for various constant values of the base current. These curves are generated from the common-emitter circuits shown in Figure 5.10. In this circuit, the V_{BB} source forward biases the B–E junction and controls the base current i_B. The C–E voltage can be varied by changing V_{CC}.



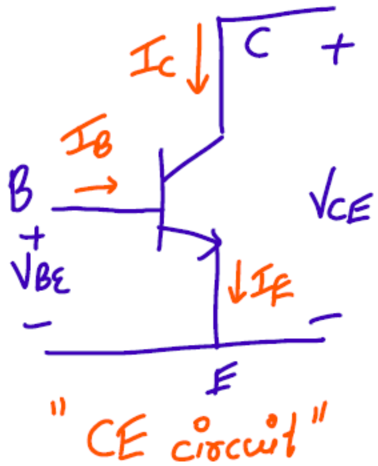


Figure 5.13 Transistor current–voltage characteristics of the common-emitter circuit

In the npn device, in order for the transistor to be biased in the forward-active mode, the B–C junction must be zero or reverse biased, which means that V_{CE} must be greater than approximately $V_{BE}(\text{on})$.[5] For $V_{CE} > V_{BE}(\text{on})$, there is a finite slope to the curves. If, however, $V_{CE} < V_{BE}(\text{on})$, the B–C junction becomes forward biased, the transistor is no longer in the forward-active mode, and the collector current very quickly drops to zero.

Figure 5.14 shows an exaggerated view of the current–voltage characteristics plotted for constant values of the B–E voltage. The curves are theoretically linear with respect to the C–E voltage in the forward-active mode. The slope in these characteristics is due to an effect called base-width modulation that was first analyzed by J. M. Early. The phenomenon is generally called the *Early effect*. When the curves are extrapolated to zero current, they meet at a point on the negative voltage axis, at $v_{CE} = -V_A$. The voltage V_A is a positive quantity called the **Early voltage.** Typical

[5] Even though the collector current is essentially equal to the emitter current when the B–C junction becomes slightly forward biased, as was shown in Figure 5.12, the transistor is said to be biased in the forward-active mode when the B–C junction is zero or reverse biased.

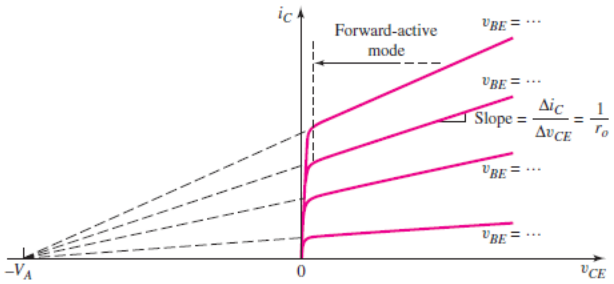


Figure 5.14 Current-voltage characteristics for the common-emitter circuit, showing the Early voltage and the finite output resistance, r_o, of the transistor

values of V_A are in the range $50 < V_A < 300$ V. For a pnp transistor, this same effect is true except the voltage axis is v_{EC}.

For a given value of v_{BE} in an npn transistor, if v_{CE} increases, the reverse-bias voltage on the collector–base junction increases, which means that the width of the B–C space-charge region also increases. This in turn reduces the neutral base width W (see Figure 5.4). A decrease in the base width causes the gradient in the minority carrier concentration to increase, which increases the diffusion current through the base. The collector current then increases as the C–E voltage increases.

The linear dependence of i_C versus v_{CE} in the forward-active mode can be described by

$$i_C = I_S(e^{v_{BE}/V_T}) \cdot \left(1 + \frac{v_{CE}}{V_A}\right) \tag{5.16}$$

where I_S is assumed to be constant.

In Figure 5.14, the nonzero slope of the curves indicates that the **output resistance** r_o looking into the collector is finite. This output resistance is determined from

$$\frac{1}{r_o} = \left.\frac{\partial i_C}{\partial v_{CE}}\right|_{v_{BE}=\text{const.}} \tag{5.17}$$

Using Equation (5.16), we can show that

$$r_o \cong \frac{V_A}{I_C} \tag{5.18}$$

where I_C is the quiescent collector current when v_{BE} is a constant and v_{CE} is small compared to V_A.