Physics of Semiconductor Devices

Lecture 14-16

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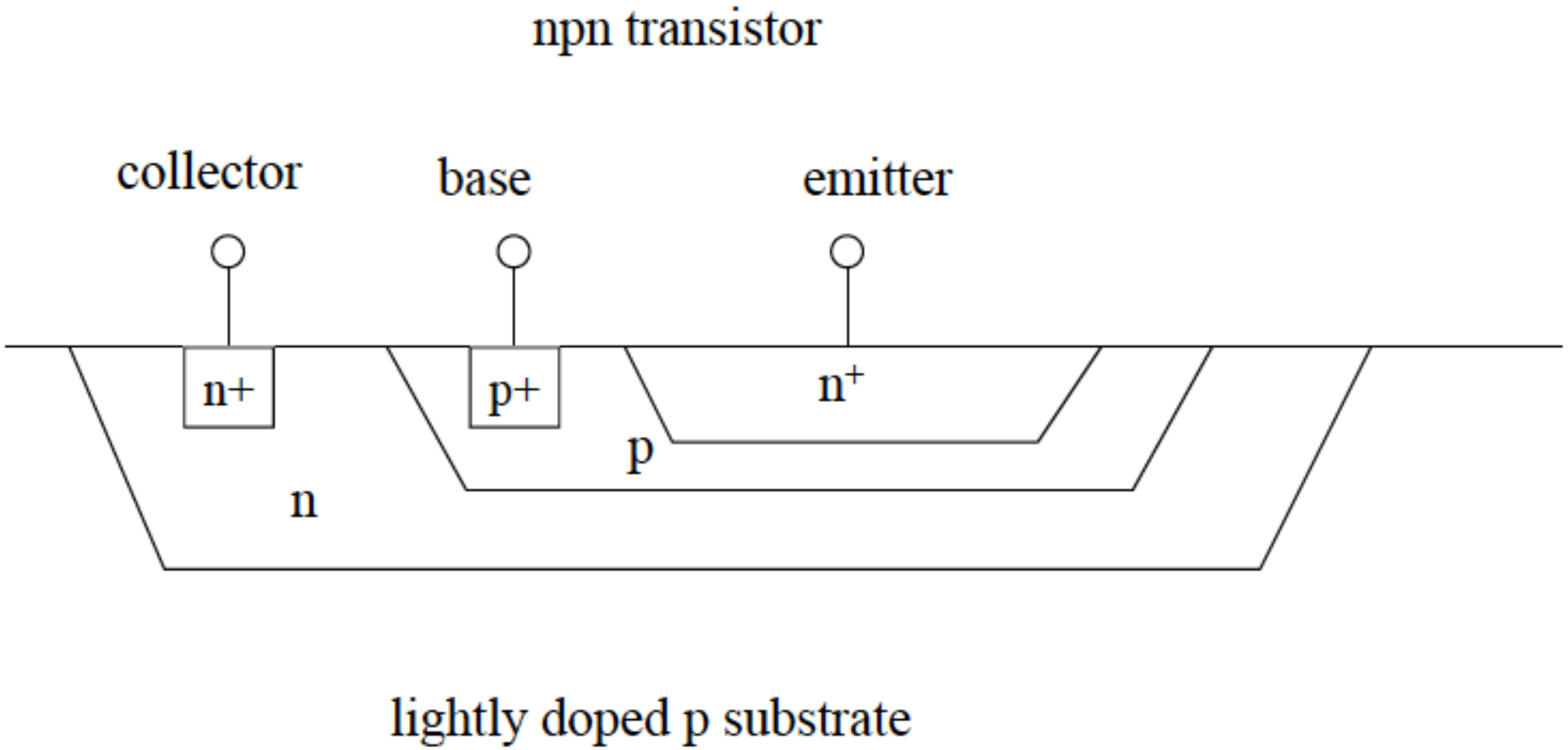
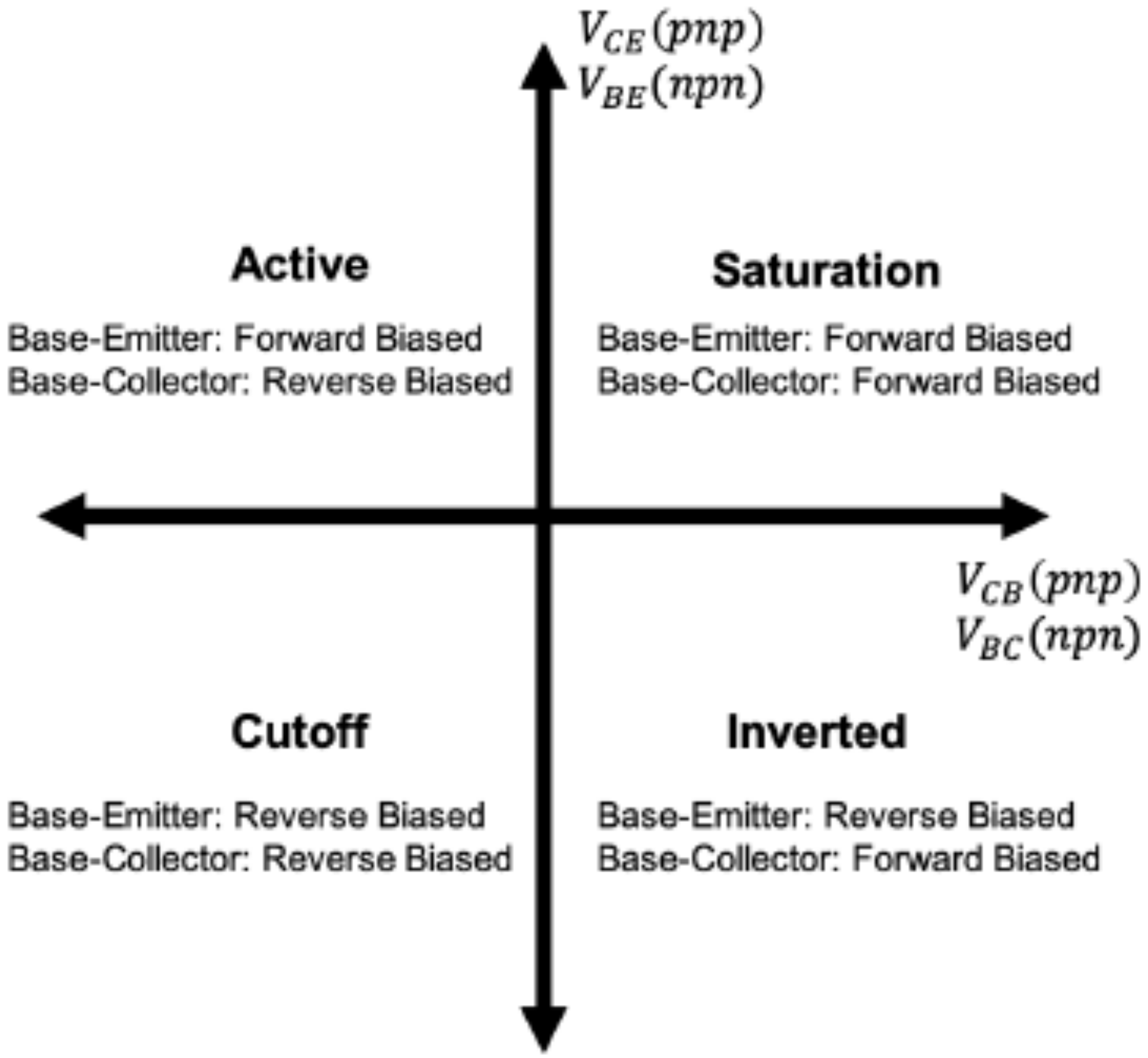
bipolar transistors

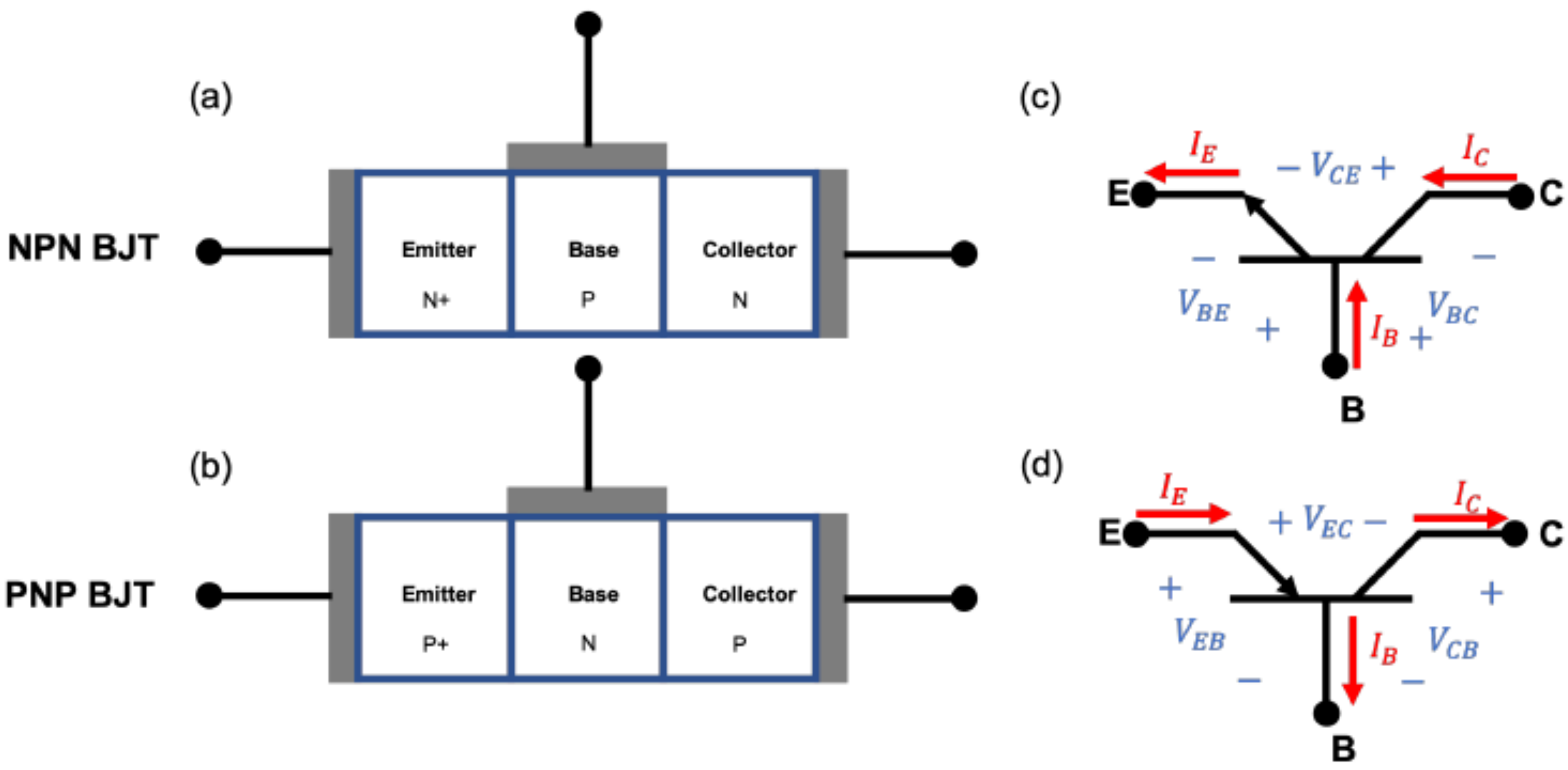


Used in front-end high-frequency receivers (mobile telephones).


$V_{CE}(pnp)$
$V_{BE}(npn)$
Active
Base-Emitter: Forward Biased
Base-Collector: Reverse Biased
Saturation
Base-Emitter: Forward Biased
Base-Collector: Forward Biased
$V_{CB}(pnp)$
$V_{BC}(npn)$
Cutoff
Base-Emitter: Reverse Biased
Base-Collector: Reverse Biased
Inverted
Base-Emitter: Reverse Biased
Base-Collector: Forward Biased

Schematic Representation

Circuit Symbol



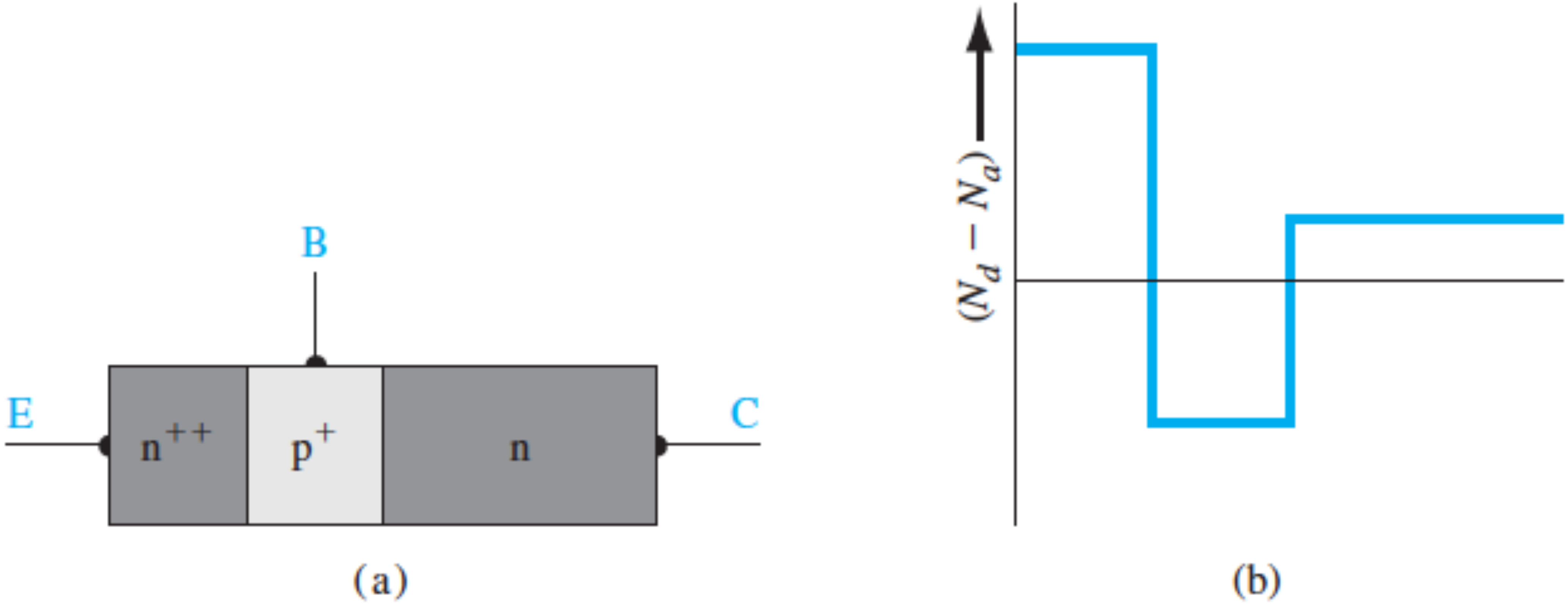


Figure 12.3 | Idealized doping profile of a uniformly doped npn bipolar transistor.

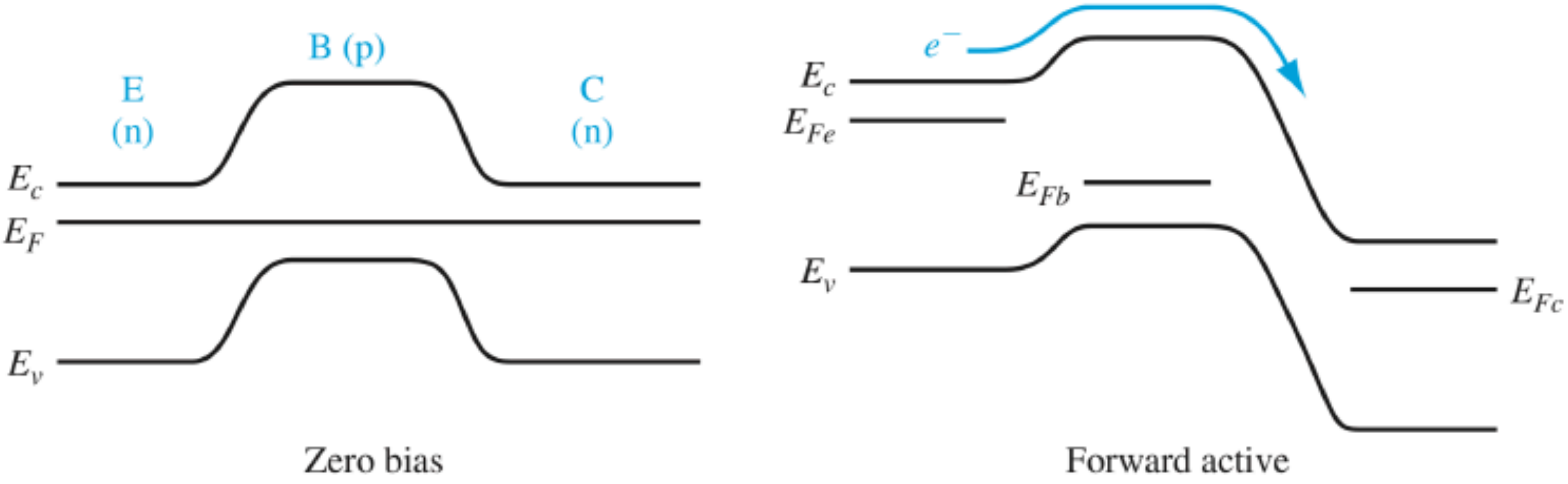


Figure 5: (left) Equilibrium and (right) forward active band diagrams of an npn BJT

BJT as a Voltage-Controlled Current Source

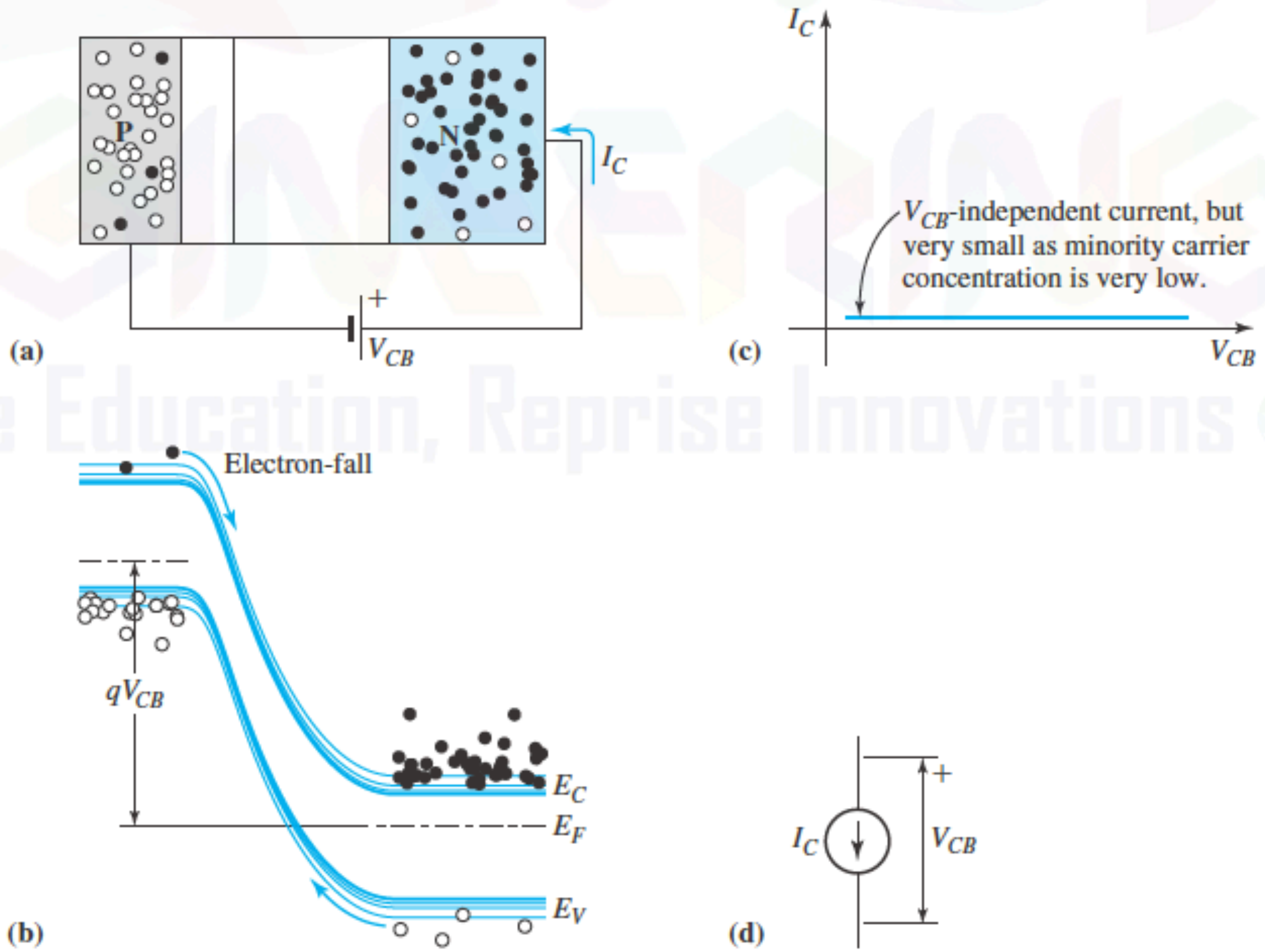


Figure 9.1 Reverse-biased P–N junction as a current source. (a) Cross section. (b) Energy-band diagram. (c) *I–V* characteristic. (d) Current-source symbol.

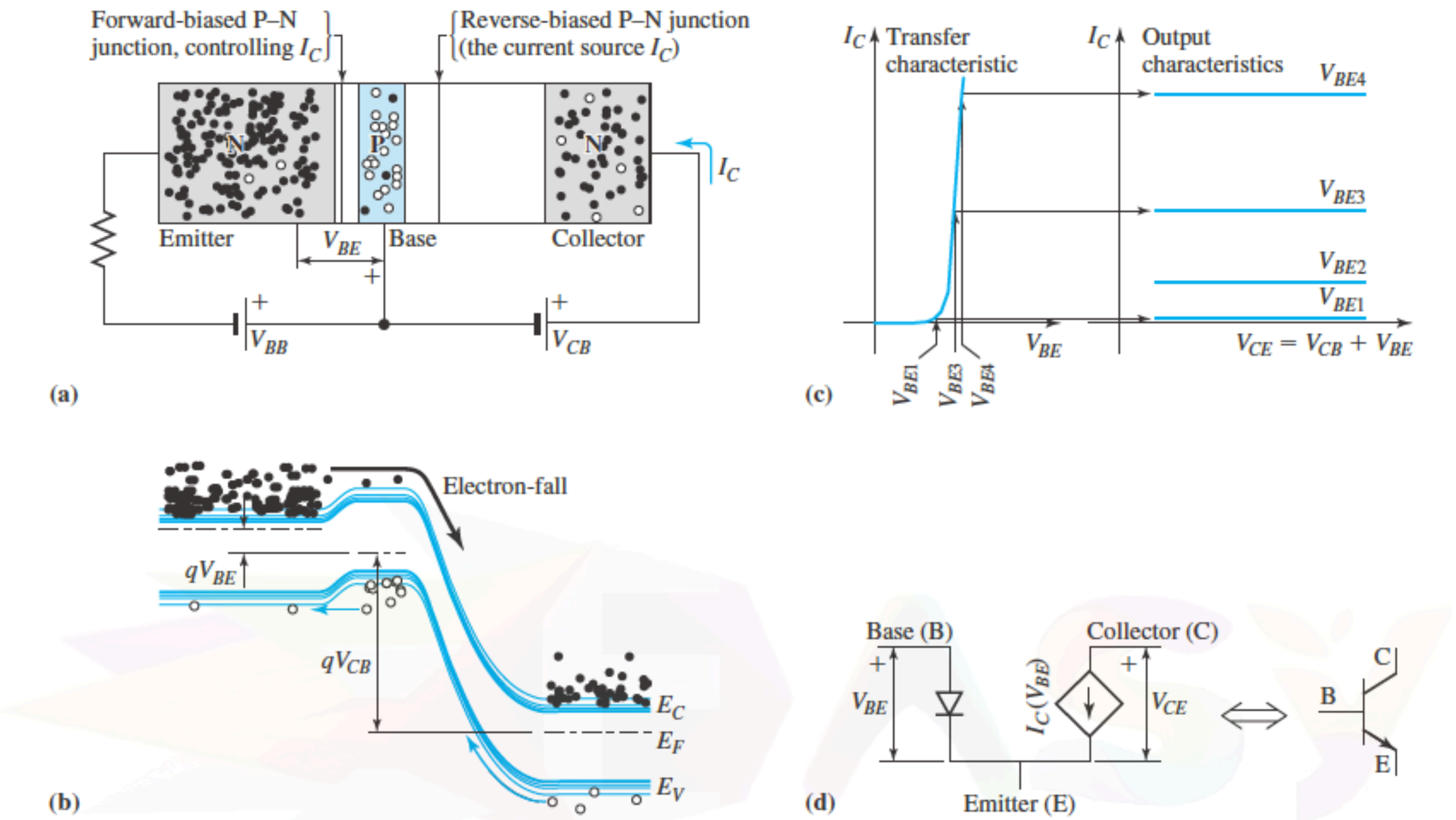


Figure 9.2 Summary of NPN BJT operation as a voltage-controlled current source. (a) Cross section showing the three regions, their names, the two junctions, and the biasing arrangement. (b) Energy-band model. (c) Main current–voltage characteristics. (d) An equivalent circuit (left) and the symbol (right).

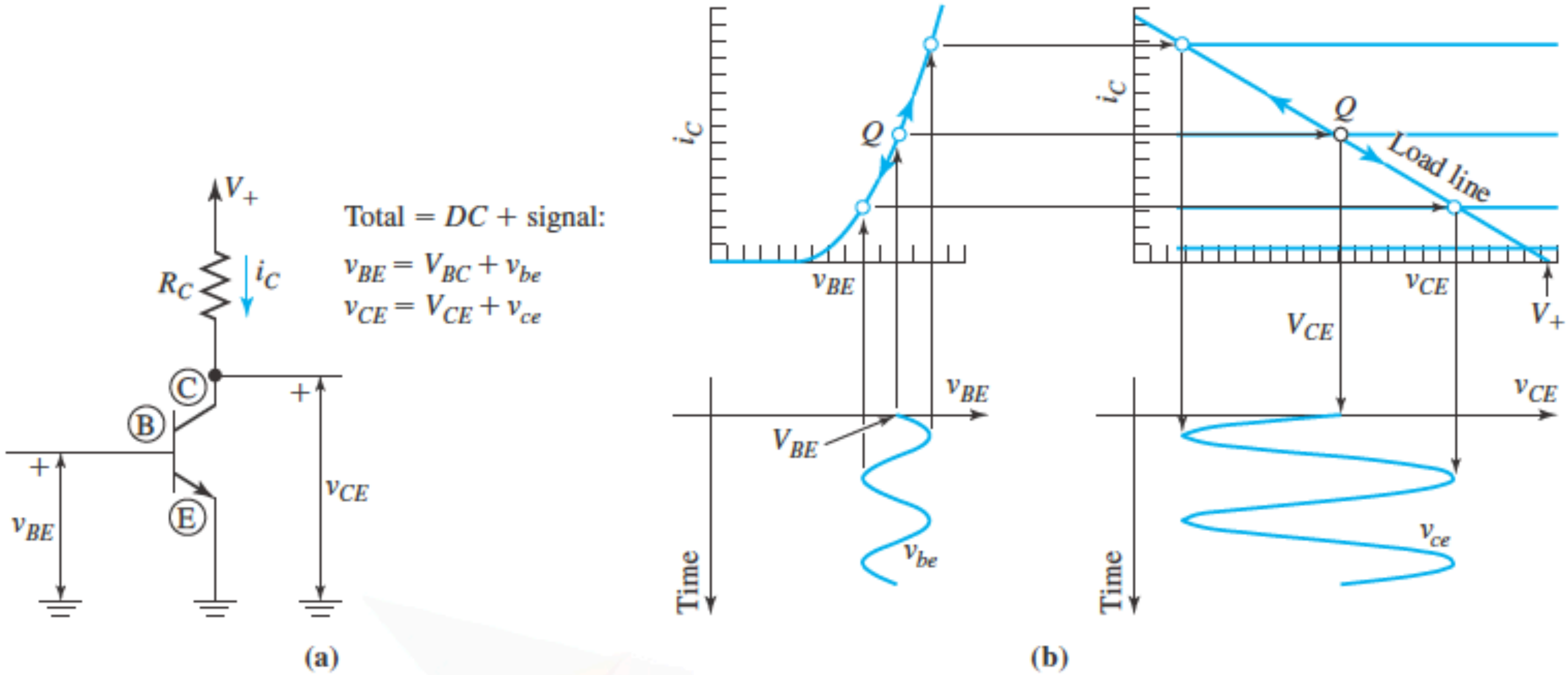
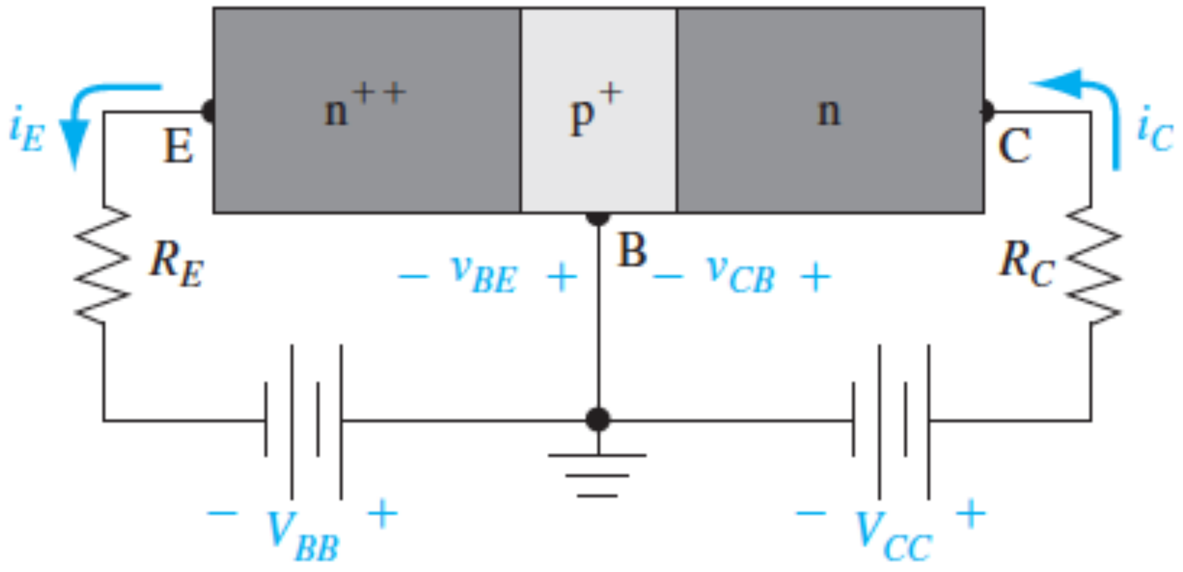
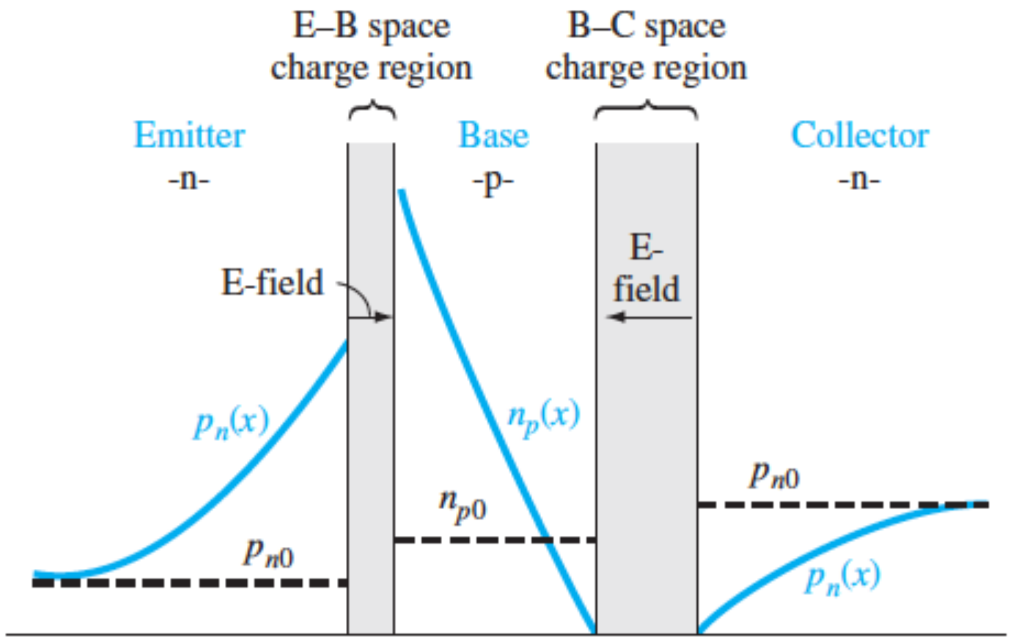


Figure 9.3 Principles of voltage amplification by a voltage-controlled current source. (a) A BJT is connected to a DC power supply through a loading resistor to create the principal amplifier circuit. (b) Graphic analysis of the amplifier circuit.



n^{++}
p^{+}
n
i_E
E
i_C
C
B
R_E
R_C
$-\ v_{BE}\ +$
$-\ v_{CB}\ +$
$-\ V_{BB}\ +$
$-\ V_{CC}\ +$

(a)



E–B space charge region
B–C space charge region
Emitter
-n-
Base
-p-
Collector
-n-
E-field
E-field
$p_n(x)$
$n_p(x)$
$p_n(x)$
p_{n0}
n_{p0}
p_{n0}

(b)

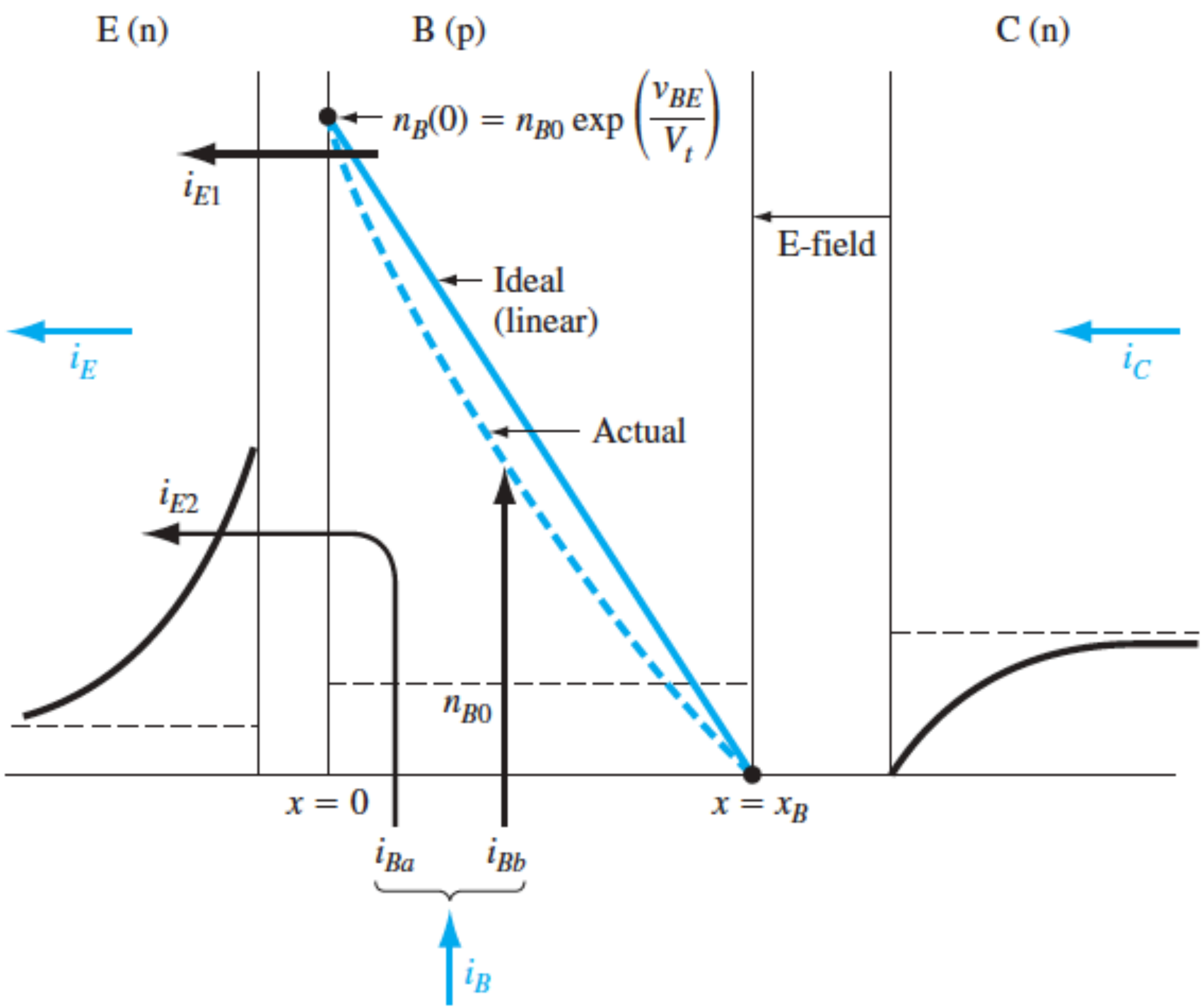


Figure 12.6 | Minority carrier distributions and basic currents in a forward-biased npn bipolar transistor.

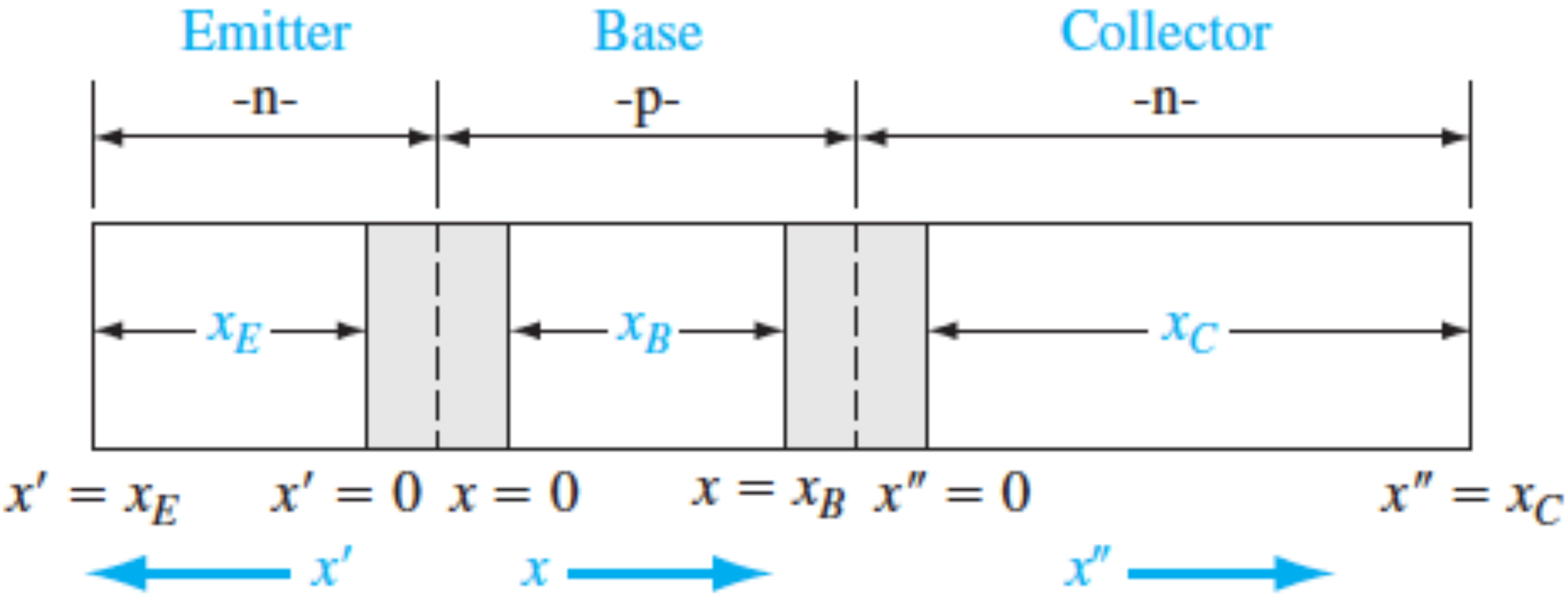


Figure 12.13 | Geometry of the npn bipolar transistor used to calculate the minority carrier distribution.

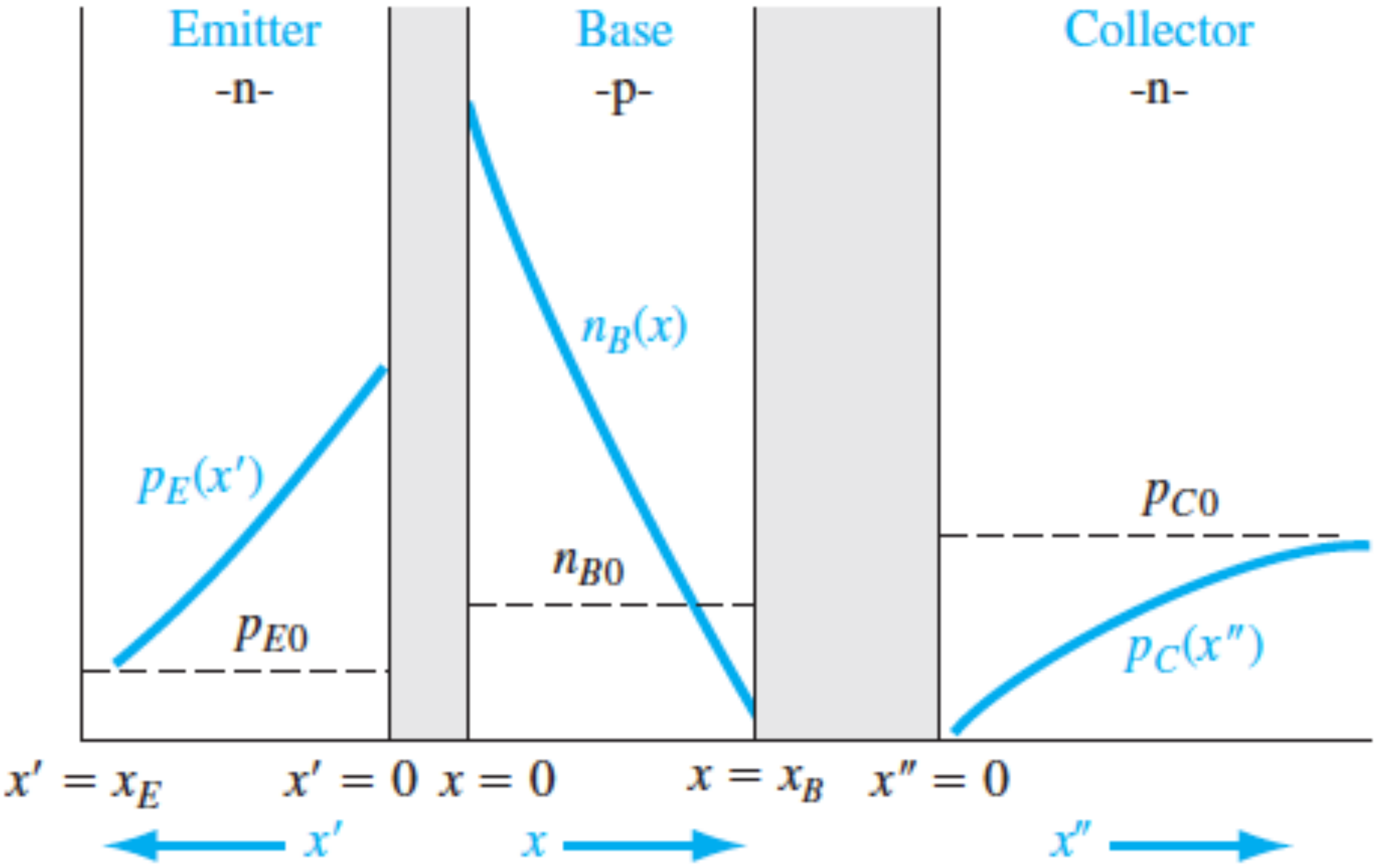


Figure 12.14 | Minority carrier distribution in an npn bipolar transistor operating in the forward-active mode.

Base Region The steady-state excess minority carrier electron concentration is found from the ambipolar transport equation, which we discussed in detail in Chapter 6. For a zero electric field in the neutral base region, the ambipolar transport equation in steady state reduces to

$$D_B \frac{\partial^2(\delta n_B(x))}{\partial x^2} - \frac{\delta n_B(x)}{\tau_{B0}} = 0 \tag{12.9}$$

where δn_B is the excess minority carrier electron concentration, and D_B and τ_{B0} are the minority carrier diffusion coefficient and lifetime in the base region, respectively. The excess electron concentration is defined as

$$\delta n_B(x) = n_B(x) - n_{B0} \tag{12.10}$$

The general solution to Equation (12.9) can be written as

$$\delta n_B(x) = A \exp\left(\frac{+x}{L_B}\right) + B \exp\left(\frac{-x}{L_B}\right) \tag{12.11}$$

The excess minority carrier electron concentrations at the two boundaries become

$$\delta n_B(x = 0) \equiv \delta n_B(0) = A + B \tag{12.12a}$$

and

$$\delta n_B(x = x_B) \equiv \delta n_B(x_B) = A \exp\left(\frac{+x_B}{L_B}\right) + B \exp\left(\frac{-x_B}{L_B}\right) \tag{12.12b}$$

The B–E junction is forward biased, so the boundary condition at $x = 0$ is

$$\delta n_B(0) = n_B(x = 0) - n_{B0} = n_{B0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] \tag{12.13a}$$

The B–C junction is reverse biased, so the second boundary condition at $x = x_B$ is

$$\delta n_B(x_B) = n_B(x = x_B) - n_{B0} = 0 - n_{B0} = -n_{B0} \tag{12.13b}$$

From the boundary conditions given by Equations (12.13a) and (12.13b), the coefficients A and B from Equations (12.12a) and (12.12b) can be determined. The results are

$$A = \frac{-n_{B0} - n_{B0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]\exp\left(\frac{-x_B}{L_B}\right)}{2\sinh\left(\frac{x_B}{L_B}\right)} \tag{12.14a}$$

and

$$B = \frac{n_{B0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]\exp\left(\frac{x_B}{L_B}\right) + n_{B0}}{2\sinh\left(\frac{x_B}{L_B}\right)} \tag{12.14b}$$

Then, substituting Equations (12.14a) and (12.14b) into Equation (12.9), we can write the excess minority carrier electron concentration in the base region as

$$\boxed{\delta n_B(x) = \frac{n_{B0}\left\{\left[\exp\left(\dfrac{eV_{BE}}{kT}\right) - 1\right]\sinh\left(\dfrac{x_B - x}{L_B}\right) - \sinh\left(\dfrac{x}{L_B}\right)\right\}}{\sinh\left(\dfrac{x_B}{L_B}\right)}} \quad (12.15a)$$

Using the approximation that $\sinh(x) \approx x$ for $x \ll 1$, the excess electron concentration in the base is given by

$$\boxed{\delta n_B(x) \approx \frac{n_{B0}}{x_B}\left\{\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right](x_B - x) - x\right\}} \quad (12.15b)$$

Emitter Region Consider, now, the minority carrier hole concentration in the emitter. The steady-state excess hole concentration is determined from the equation

$$D_E \frac{\partial^2[\delta p_E(x')]}{\partial x'^2} - \frac{\delta p_E(x')}{\tau_{E0}} = 0 \tag{12.16}$$

where D_E and τ_{E0} are the minority carrier diffusion coefficient and minority carrier lifetime, respectively, in the emitter. The excess hole concentration is given by

$$\delta p_E(x') = p_E(x') - p_{E0} \tag{12.17}$$

The general solution to Equation (12.16) can be written as

$$\delta p_E(x') = C \exp\left(\frac{+x'}{L_E}\right) + D \exp\left(\frac{-x'}{L_E}\right) \tag{12.18}$$

where $L_E = \sqrt{D_E \tau_{E0}}$. If we assume the neutral emitter length x_E is not necessarily long compared to L_E, then both exponential terms in Equation (12.18) must be retained.

The excess minority carrier hole concentrations at the two boundaries are

$$\delta p_E(x' = 0) \equiv \delta p_E(0) = C + D \tag{12.19a}$$

and

$$\delta p_E(x' = x_E) \equiv \delta p_E(x_E) = C \exp\left(\frac{x_E}{L_E}\right) + D \exp\left(\frac{-x_E}{L_E}\right) \tag{12.19b}$$

Again, the B–E junction is forward biased, so

$$\delta p_E(0) = p_E(x' = 0) - p_{E0} = p_{E0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] \tag{12.20a}$$

An infinite surface recombination velocity at $x' = x_E$ implies that

$$\delta p_E(x_E) = 0 \tag{12.20b}$$

Solving for C and D using Equations (12.19) and (12.20) yields the excess minority carrier hole concentration in Equation (12.18):

$$\boxed{\delta p_E(x') = \frac{p_{E0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]\sinh\left(\frac{x_E - x'}{L_E}\right)}{\sinh\left(\frac{x_E}{L_E}\right)}} \tag{12.21a}$$

This excess concentration will also vary approximately linearly with distance if x_E is small. We find

$$\boxed{\delta p_E(x') \approx \frac{p_{E0}}{x_E}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right](x_E - x')} \tag{12.21b}$$

If x_E is comparable to L_E, then $\delta p_E(x')$ shows an exponential dependence on x_E.

12.3.1 Current Gain—Contributing Factors

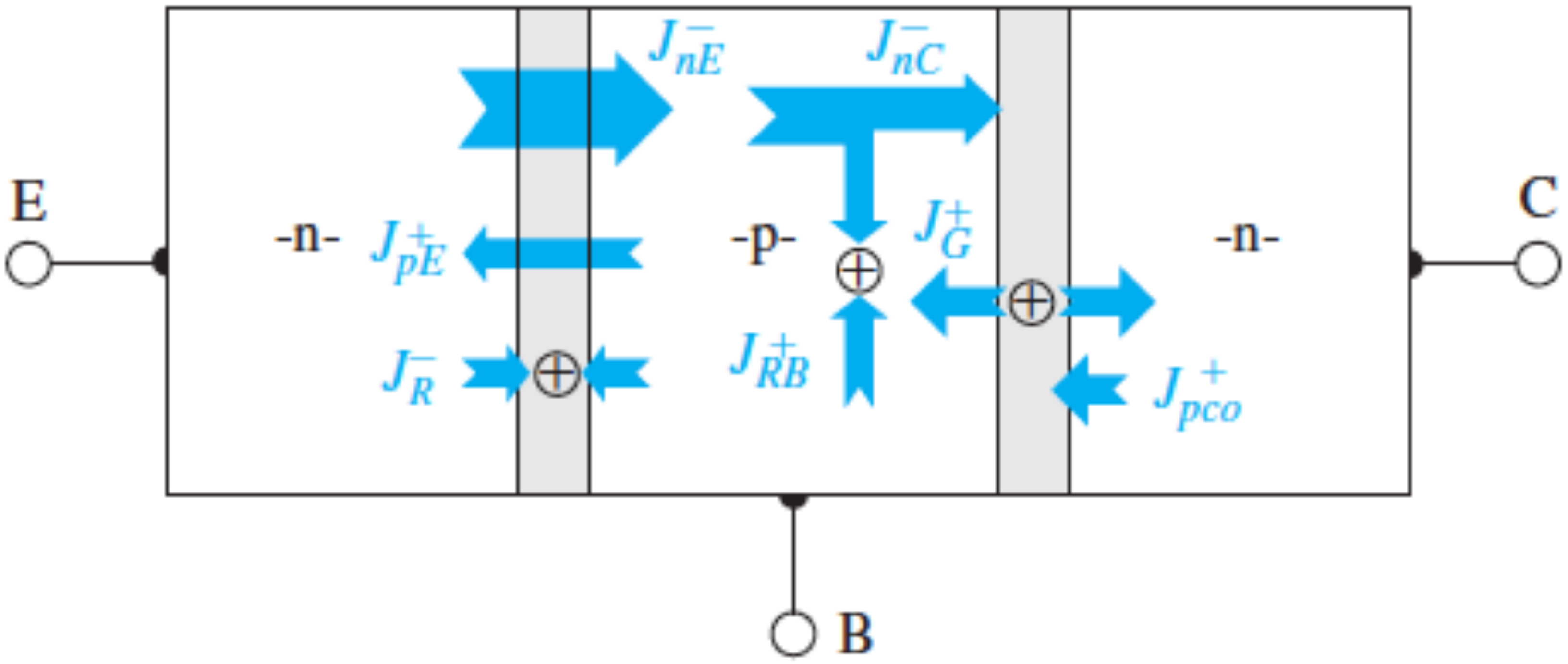


Figure 12.18 | Particle current density or flux components in an npn bipolar transistor operating in the forward-active mode.

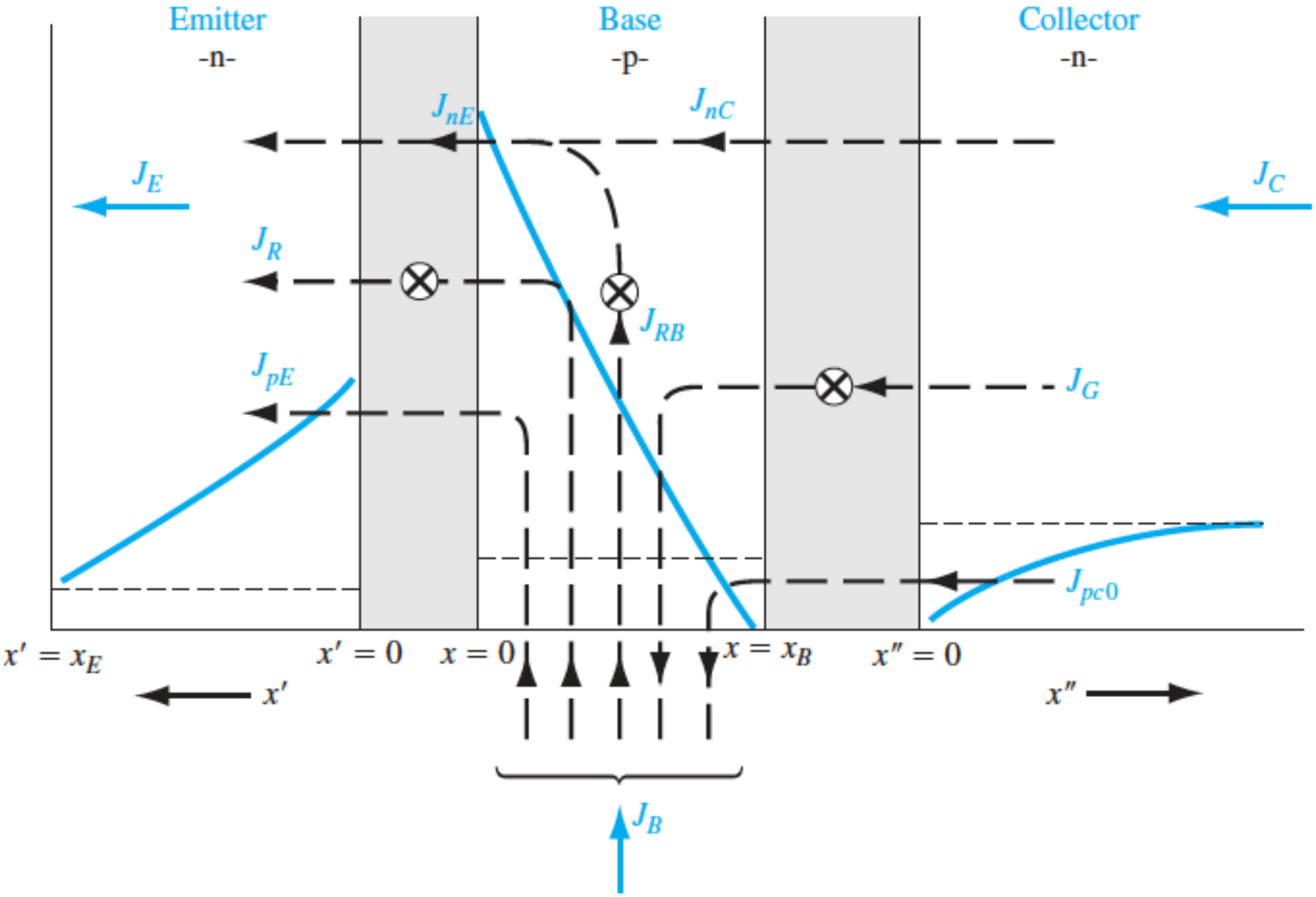


Figure 12.19 | Current density components in an npn bipolar transistor operating in the forward-active mode.

The dc common-base current gain is defined as

$$\alpha_0 = \frac{I_C}{I_E} \tag{12.27}$$

If we assume that the active cross-sectional area is the same for the collector and emitter, then we can write the current gain in terms of the current densities, or

$$\alpha_0 = \frac{J_C}{J_E} = \frac{J_{nC} + J_G + J_{pc0}}{J_{nE} + J_R + J_{pE}} \tag{12.28}$$

We are primarily interested in determining how the collector current will change with a change in emitter current. The small-signal, or sinusoidal, common-base current gain is defined as

$$\alpha = \frac{\partial J_C}{\partial J_E} = \frac{J_{nC}}{J_{nE} + J_R + J_{pE}} \tag{12.29}$$

We can rewrite Equation (12.29) in the form

$$\alpha = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right)\left(\frac{J_{nC}}{J_{nE}}\right)\left(\frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}}\right) \tag{12.30a}$$

or

$$\alpha = \gamma \alpha_T \delta \tag{12.30b}$$

The factors in Equation (12.30b) are defined as:

$$\gamma = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right) \equiv \text{emitter injection efficiency factor} \tag{12.31a}$$

$$\alpha_T = \left(\frac{J_{nC}}{J_{nE}}\right) \equiv \text{base transport factor} \tag{12.31b}$$

$$\delta = \frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}} \equiv \text{recombination factor} \tag{12.31c}$$

Emitter Injection Efficiency Factor Consider, initially, the emitter injection efficiency factor. We have from Equation (12.31a)

$$\gamma = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right) = \frac{1}{\left(1 + \frac{J_{pE}}{J_{nE}}\right)} \tag{12.32}$$

We derived the minority carrier distribution functions for the forward-active mode in Section 12.2.1. Noting that J_{nE}, as defined in Figure 12.19, is in the negative x direction, we can write the current densities as

$$J_{pE} = -eD_E \left.\frac{d[\delta p_E(x')]}{dx'}\right|_{x'=0} \tag{12.33a}$$

and

$$J_{nE} = (-)eD_B \left.\frac{d[\delta n_B(x)]}{dx}\right|_{x=0} \tag{12.33b}$$

where $\delta p_E(x')$ and $\delta n_B(x)$ are given by Equations (12.21) and (12.15), respectively.

Taking the appropriate derivatives of $\delta p_E(x')$ and $\delta n_B(x)$, we obtain

$$J_{pE} = \frac{eD_E p_{E0}}{L_E}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] \cdot \frac{1}{\tanh\,(x_E/L_E)} \tag{12.34a}$$

and

$$J_{nE} = \frac{eD_B n_{B0}}{L_B}\left\{\frac{1}{\sinh\,(x_B/L_B)} + \frac{[\exp\,(eV_{BE}/kT) - 1]}{\tanh\,(x_B/L_B)}\right\} \tag{12.34b}$$

Positive J_{pE} and J_{nE} values imply that the currents are in the directions shown in Figure 12.19. If we assume that the B–E junction is biased sufficiently far in the forward bias so that $V_{BE} \gg kT/e$, then

$$\exp\left(\frac{eV_{BE}}{kT}\right) \gg 1$$

and also

$$\frac{\exp\,(eV_{BE}/kT)}{\tanh\,(x_B/L_B)} \gg \frac{1}{\sinh\,(x_B/L_B)}$$

The emitter injection efficiency, from Equation (12.32), then becomes

$$\boxed{\gamma = \frac{1}{1 + \dfrac{p_{E0} D_E L_B}{n_{B0} D_B L_E} \cdot \dfrac{\tanh (x_B/L_B)}{\tanh (x_E/L_E)}}} \tag{12.35a}$$

If we assume that all the parameters in Equation (12.35a) except p_{E0} and n_{B0} are fixed, then in order for $\gamma \approx 1$, we must have $p_{E0} \ll n_{B0}$. We can write

$$p_{E0} = \frac{n_i^2}{N_E} \qquad \text{and} \qquad n_{B0} = \frac{n_i^2}{N_B}$$

where N_E and N_B are the impurity doping concentrations in the emitter and base, respectively. Then the condition that $p_{E0} \ll n_{B0}$ implies that $N_E \gg N_B$. For the emitter injection efficiency to be close to unity, the emitter doping must be large compared to the base doping. This condition means that many more electrons from the n-type emitter than holes from the p-type base will be injected across the B–E space charge region. If both $x_B \ll L_B$ and $x_E \ll L_E$, then the emitter injection efficiency can be written as

$$\boxed{\gamma \approx \frac{1}{1 + \dfrac{N_B}{N_E} \cdot \dfrac{D_E}{D_B} \cdot \dfrac{x_B}{x_E}}} \tag{12.35b}$$

Base Transport Factor The next term to consider is the base transport factor, given by Equation (12.31b) as $\alpha_T = J_{nC}/J_{nE}$. From the definitions of the current directions shown in Figure 12.19, we can write

$$J_{nC} = (-)eD_B \left.\frac{d[\delta n_B(x)]}{dx}\right|_{x=x_B} \tag{12.36a}$$

and

$$J_{nE} = (-)eD_B \left.\frac{d[\delta n_B(x)]}{dx}\right|_{x=0} \tag{12.36b}$$

Using the expression for $\delta n_B(x)$ given in Equation (12.15), we find that

$$J_{nC} = \frac{eD_B n_{B0}}{L_B}\left\{\frac{[\exp(eV_{BE}/kT) - 1]}{\sinh(x_B/L_B)} + \frac{1}{\tanh(x_B/L_B)}\right\} \tag{12.37}$$

The expression for J_{nE} is given in Equation (12.34a).

If we again assume that the B–E junction is biased sufficiently far in the forward bias so that $V_{BE} \gg kT/e$, then $\exp(eV_{BE}/kT) \gg 1$. Substituting Equations (12.37) and (12.34b) into Equation (12.31b), we have

$$\alpha_T = \frac{J_{nC}}{J_{nE}} \approx \frac{\exp(eV_{BE}/kT) + \cosh(x_B/L_B)}{1 + \exp(eV_{BE}/kT)\cosh(x_B/L_B)} \tag{12.38}$$

In order for α_T to be close to unity, the neutral base width x_B must be much smaller than the minority carrier diffusion length in the base L_B. If $x_B \ll L_B$, then $\cosh(x_B/L_B)$ will be just slightly greater than unity. In addition, if $\exp(eV_{BE}/kT) \gg 1$, then the base transport factor is approximately

$$\boxed{\alpha_T \approx \frac{1}{\cosh(x_B/L_B)}} \tag{12.39a}$$

For $x_B \ll L_B$, we may expand the cosh function in a Taylor series, so that

$$\boxed{\alpha_T \approx \frac{1}{\cosh(x_B/L_B)} \approx \frac{1}{1 + \frac{1}{2}(x_B/L_B)^2} \approx 1 - \frac{1}{2}(x_B/L_B)^2} \qquad (12.39b)$$

The base transport factor α_T will be close to one if $x_B \ll L_B$. We can now see why we indicated earlier that the neutral base width x_B would be less than L_B.

Recombination Factor The recombination factor is given by Equation (12.31c). We can write

$$\delta = \frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}} \approx \frac{J_{nE}}{J_{nE} + J_R} = \frac{1}{1 + J_R/J_{nE}} \tag{12.40}$$

We have assumed in Equation (12.40) that $J_{pE} \ll J_{nE}$. The recombination current density, due to the recombination in a forward-biased pn junction, was discussed in Chapter 8 and can be written as

$$J_R = \frac{e x_{BE} n_i}{2\tau_0} \exp\left(\frac{eV_{BE}}{2kT}\right) = J_{r0} \exp\left(\frac{eV_{BE}}{2kT}\right) \tag{12.41}$$

where x_{BE} is the B–E space charge width.

The current J_{nE} from Equation (12.34b) can be approximated as

$$J_{nE} = J_{s0} \exp\left(\frac{eV_{BE}}{kT}\right) \tag{12.42}$$

where

$$J_{s0} = \frac{eD_B n_{B0}}{L_B \tanh(x_B/L_B)} \tag{12.43}$$

The recombination factor, from Equation (12.40), can then be written as

$$\boxed{\delta = \frac{1}{1 + \dfrac{J_{r0}}{J_{s0}} \exp\left(\dfrac{-eV_{BE}}{2kT}\right)}} \tag{12.44}$$

The recombination factor is a function of the B–E voltage. As V_{BE} increases, the recombination current becomes less dominant and the recombination factor approaches unity.