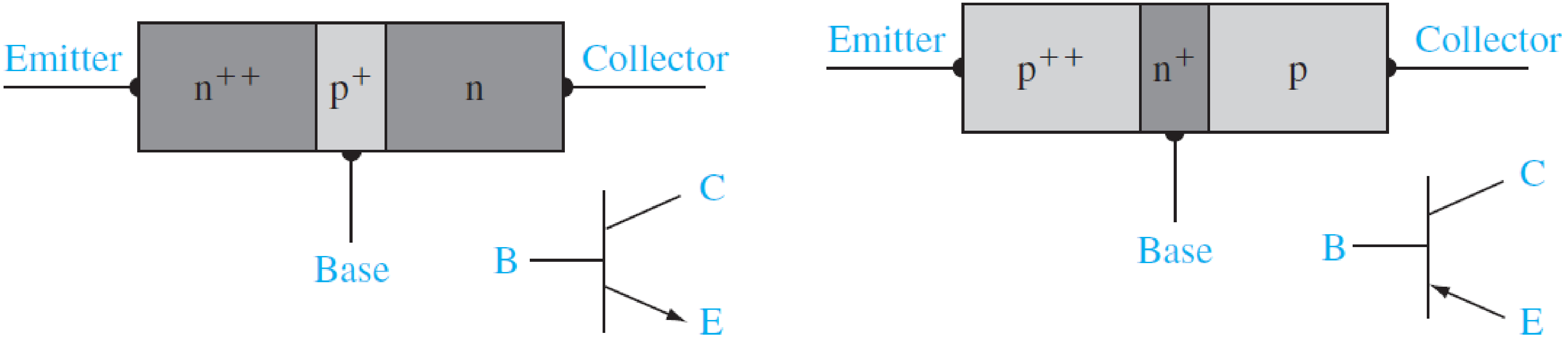
Bipolar Junction Transistor

THE BIPOLAR TRANSISTOR

- The transistor is a multijunction semiconductor device that, in conjunction with other circuit elements, is capable of current gain, voltage gain, and signal power gain.
- The transistor is therefore referred to as an active device, whereas the diode is passive.
- The basic transistor action is the control of current at one terminal by the voltage applied across the other two terminals of the device.
- The Bipolar Junction Transistor (BJT) is one of two major types of transistors.
- The bipolar transistor is used extensively in analog electronic circuits because of its high current gain.
- Two complementary configurations of BJTs, the npn and pnp devices

THE BIPOLAR TRANSISTOR

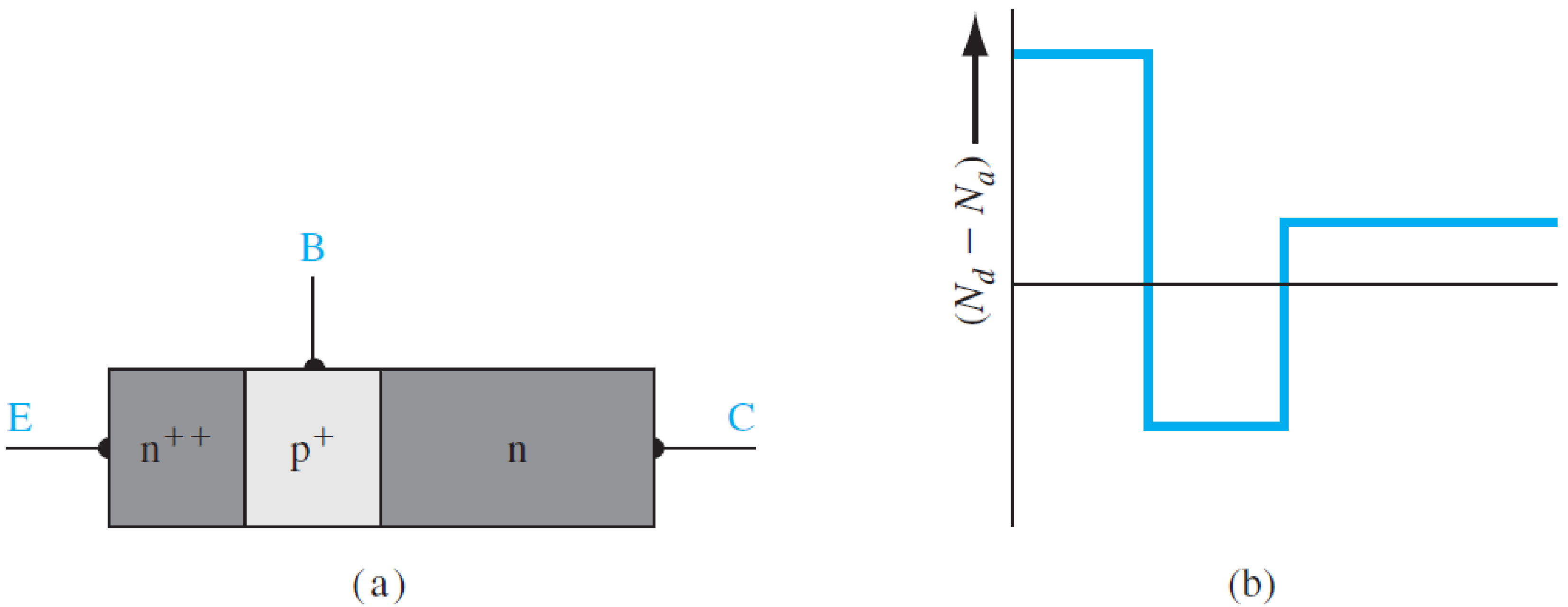


(a) (b)

(a) npn and (b) pnp bipolar transistors

The Basic Principle of Operation

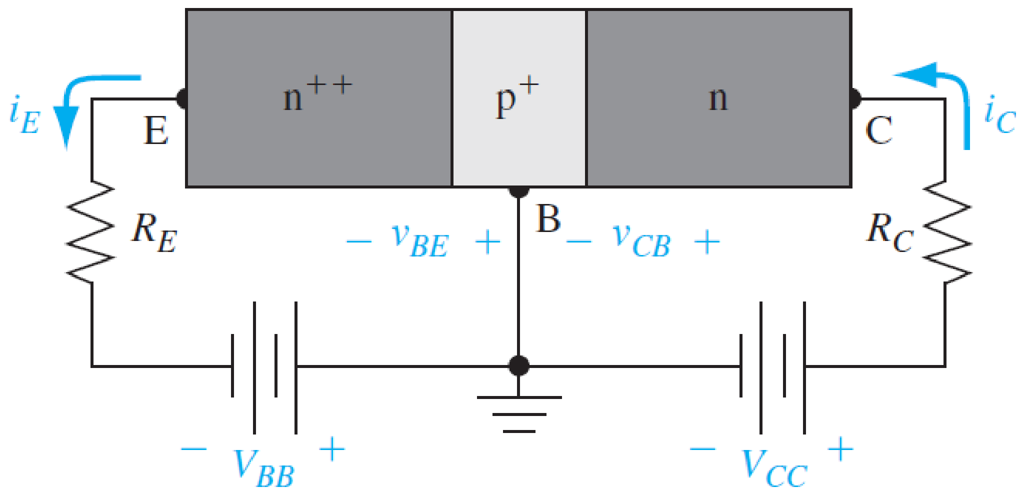
- impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19}, 10^{17}, and 10^{15} cm^{-3},



Idealized doping profile of a uniformly doped npn bipolar transistor

The Basic Principle of Operation

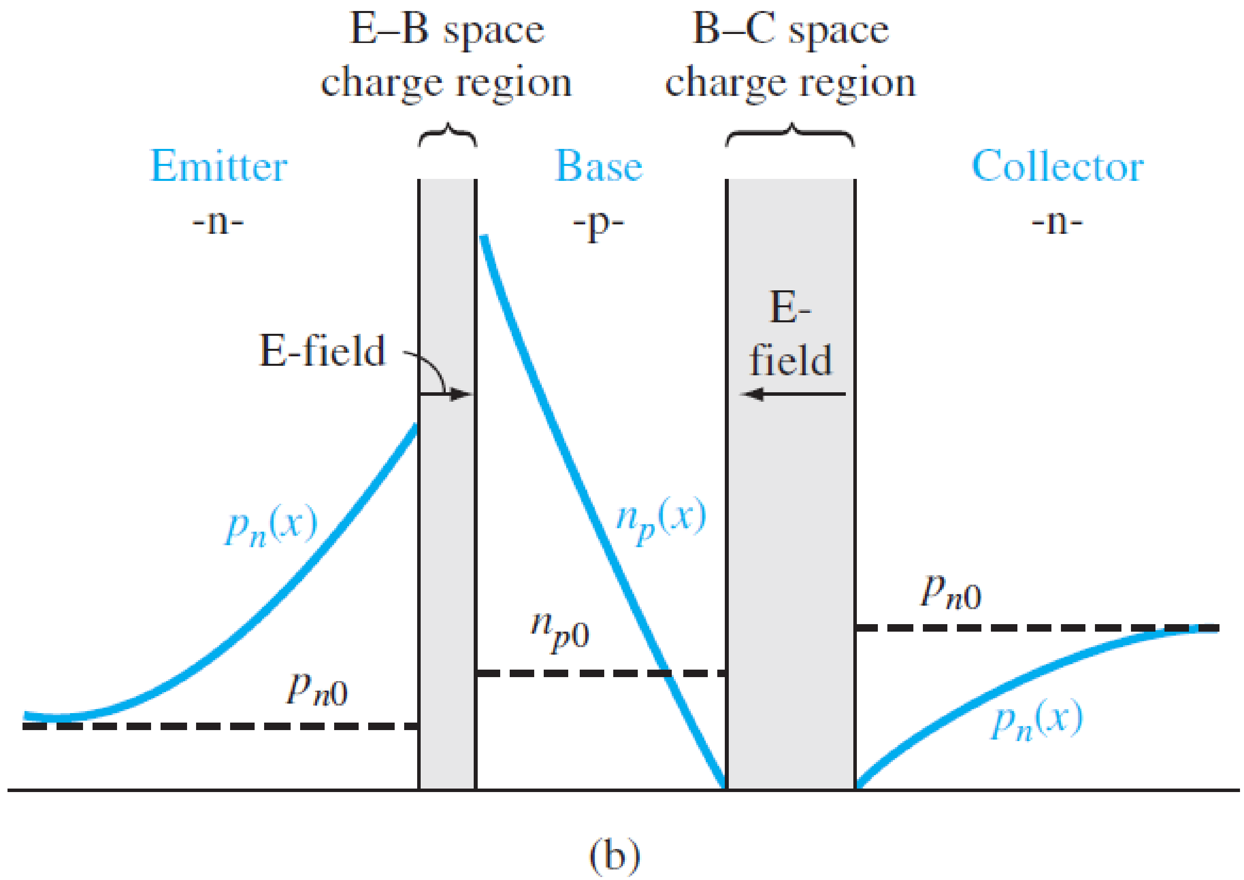
- The base–emitter (B–E) pn junction is forward biased and the base–collector (B–C) pn junction is reverse biased in the normal bias configuration. This configuration is called the *forward-active* operating mode.



(a)

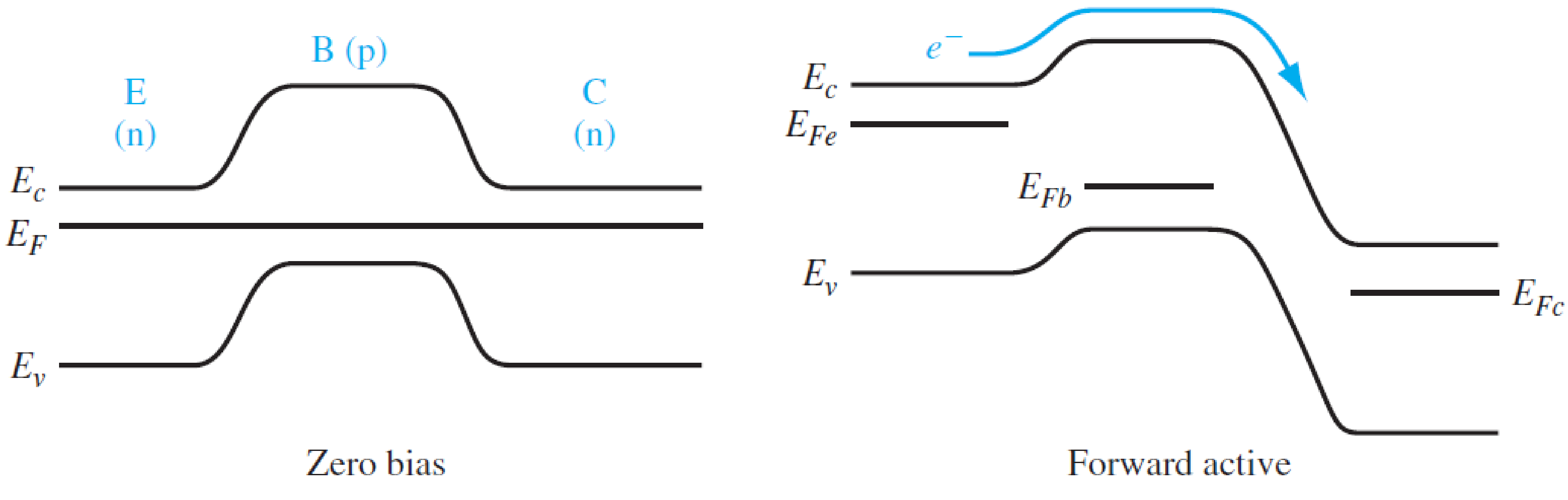
(a) Biasing of an npn bipolar transistor in the forward-active mode

The Basic Principle of Operation



(b) minority carrier distribution in an npn bipolar transistor operating in the forward-active mode

The Basic Principle of Operation



(c)

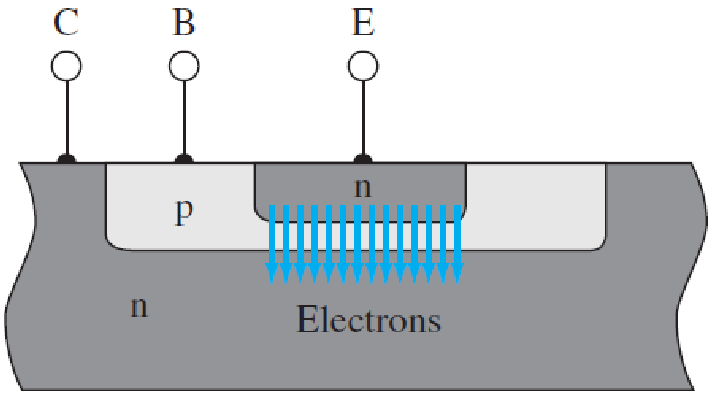
(c) energy-band diagram of the npn bipolar transistor under zero bias and under a forward-active mode bias

The Basic Principle of Operation

- The B–E junction is forward biased so electrons from the emitter are injected across the B–E junction into the base.
- These injected electrons create an excess concentration of minority carriers in the base.
- The B–C junction is reverse biased, so the minority carrier electron concentration at the edge of the B–C junction is ideally zero.
- The large gradient in the electron concentration means that electrons injected from the emitter will diffuse across the base region into the B–C space charge region, where the electric field will sweep the electrons into the collector.

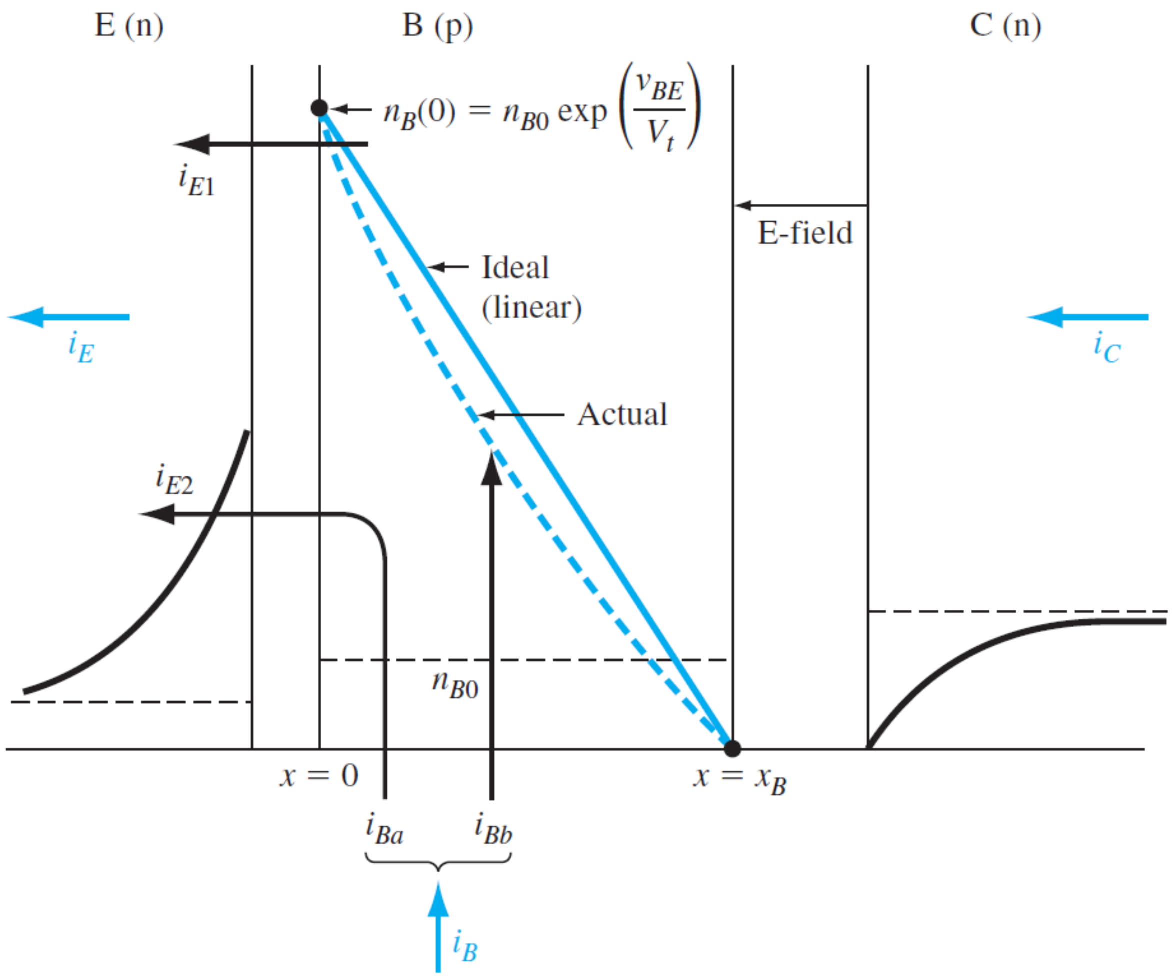
The Basic Principle of Operation

- We want as many electrons as possible to reach the collector without recombining with any majority carrier holes in the base.
- For this reason, the width of the base needs to be small compared with the minority carrier diffusion length.
- If the base width is small, then the minority carrier electron concentration is a function of both the B–E and B–C junction voltages. The two junctions are close enough to be called *interacting* pn junctions



Cross section of an npn bipolar transistor showing the injection and collection of electrons in the forward-active mode.

Simplified Transistor Current Relation



Minority carrier distributions and basic currents in a forward-biased npn bipolar transistor

Collector Current

- Assuming the ideal linear electron distribution in the base, the collector current can be written as a diffusion current given by

$$i_C = eD_n A_{BE} \frac{dn(x)}{dx} = eD_n A_{BE} \left[\frac{n_B(0) - 0}{0 - x_B} \right] = \frac{-eD_n A_{BE}}{x_B} \cdot n_{B0} \exp\left(\frac{v_{BE}}{V_t} \right)$$

- where A_{BE} is the cross-sectional area of the B–E junction, n_{B0} is the thermal equilibrium electron concentration in the base, and V_t is the thermal voltage
- Considering magnitudes only

$$i_C = I_S \exp\left(\frac{v_{BE}}{V_t} \right)$$

- The collector current is controlled by the base–emitter voltage; that is, the current at one terminal of the device is controlled by the voltage applied to the other two terminals of the device

Emitter Current

- One component of emitter current, i_{E1} is due to the flow of electrons injected from the emitter into the base. This current, then, is equal to the collector current. $i_{E1} = i_C$
- Since the base–emitter junction is forward biased, majority carrier holes in the base are injected across the B–E junction into the emitter. These injected holes produce a pn junction current i_{E2}
- This current is only a B–E junction current so this component of emitter current is not part of the collector current. Since i_{E2} is a forward-biased pn junction current, we can write

$$i_{E2} = I_{S2} \exp\left(\frac{v_{BE}}{V_t}\right)$$

- where I_{S2} involves the minority carrier hole parameters in the emitter

Emitter Current

- The total emitter current is the sum of the two components

$$i_E = i_{E1} + i_{E2} = i_C + i_{E2} = I_{SE} \exp\left(\frac{v_{BE}}{V_t}\right)$$

- Since all current components in Equation are functions of exp (V_{BE}/V_t), the ratio of collector current to emitter current is a constant.

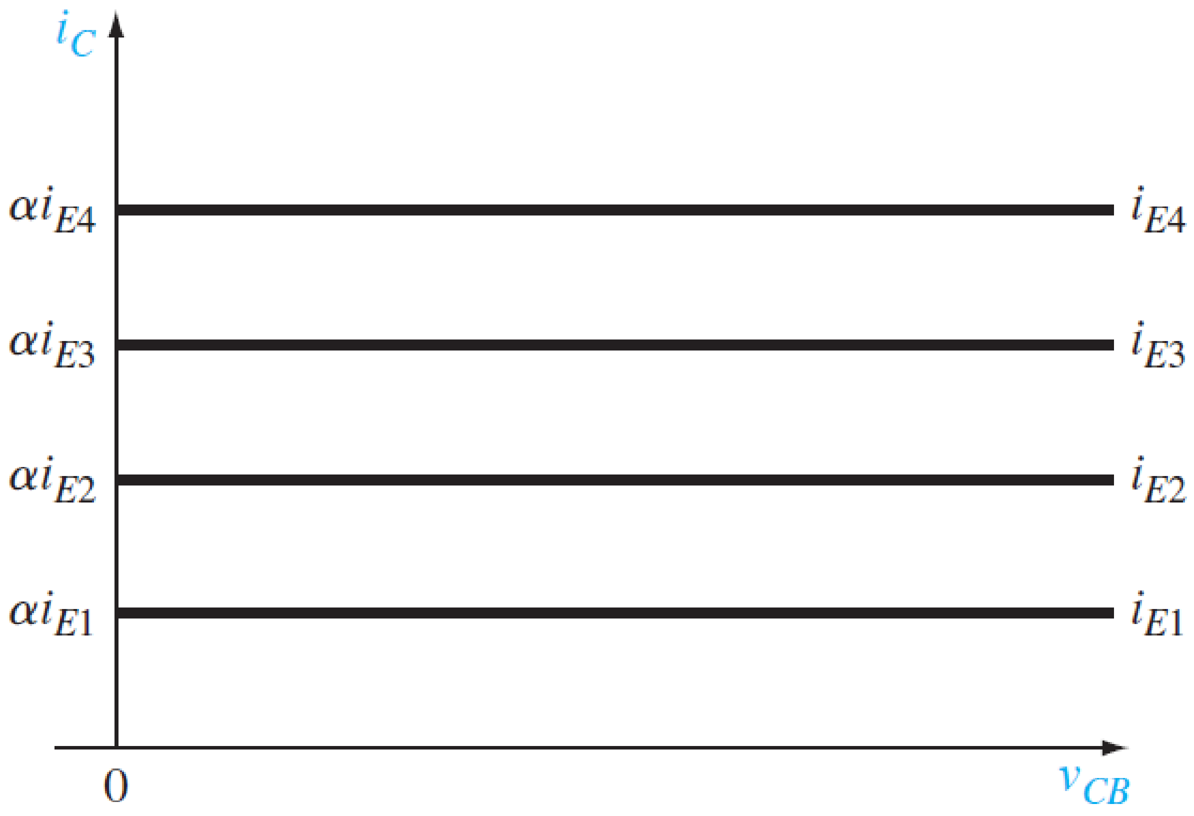
$$\frac{i_C}{i_E} \equiv \alpha$$

- where α is called the *common-base current gain*

$$i_C = \alpha i_E$$

- The bipolar transistor acts like a constant current source

Emitter Current



Ideal bipolar transistor common-base current–voltage characteristics.

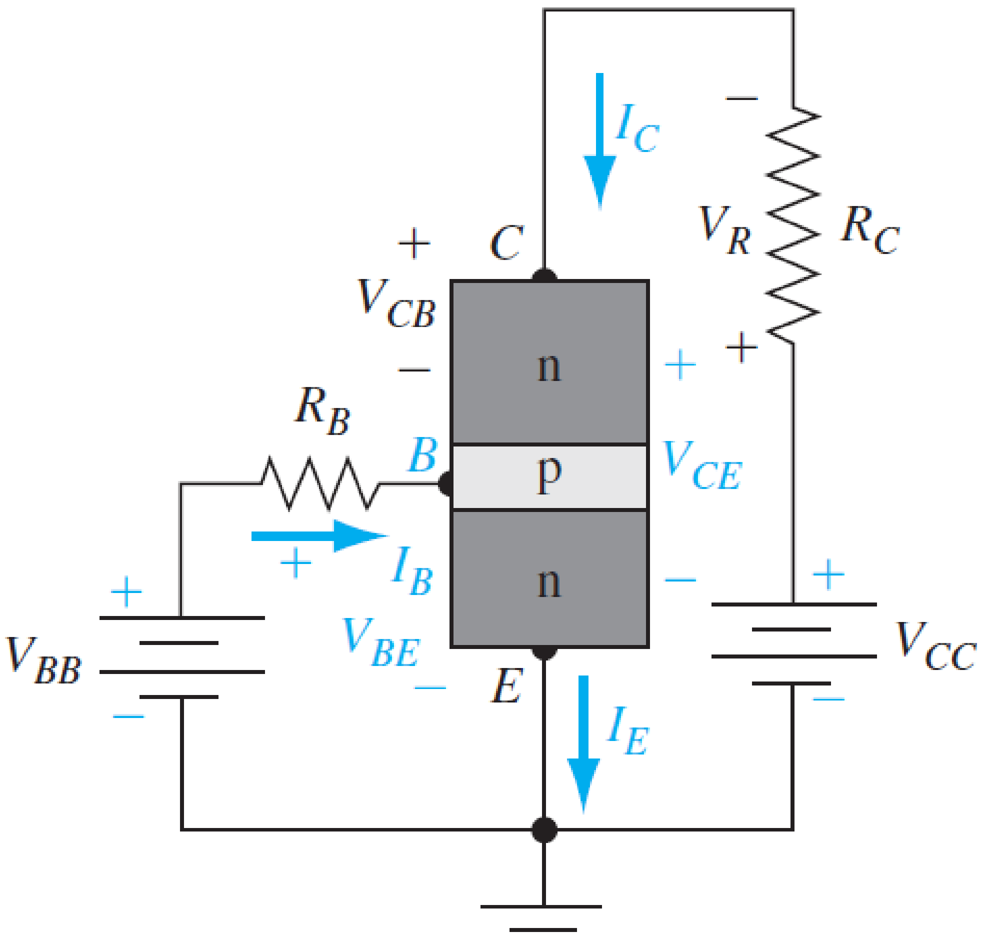
Base Current

- the component of emitter current i_{E2} is a B–E junction current so that this current is also a component of base current shown as i_{Ba}. This component of base current is proportional to $\exp(V_{BE}/V_t)$
- The number of holes per unit time recombining in the base is directly related to the number of minority carrier electrons in the base. Therefore, the current i_{Bb} is also proportional to exp (V_{BE}/V_t).
- The ratio of collector current to base current is a constant since both currents are directly proportional to exp (V_{BE}/V_t).

$$\frac{i_C}{i_B} \equiv \beta$$

- where β is called the *common-emitter current gain.*
- the base current will be relatively small, so that the common-emitter current gain is much larger than unity (on the order of 100 or larger).

The Modes of Operation



An npn bipolar transistor in a common-emitter circuit configuration.

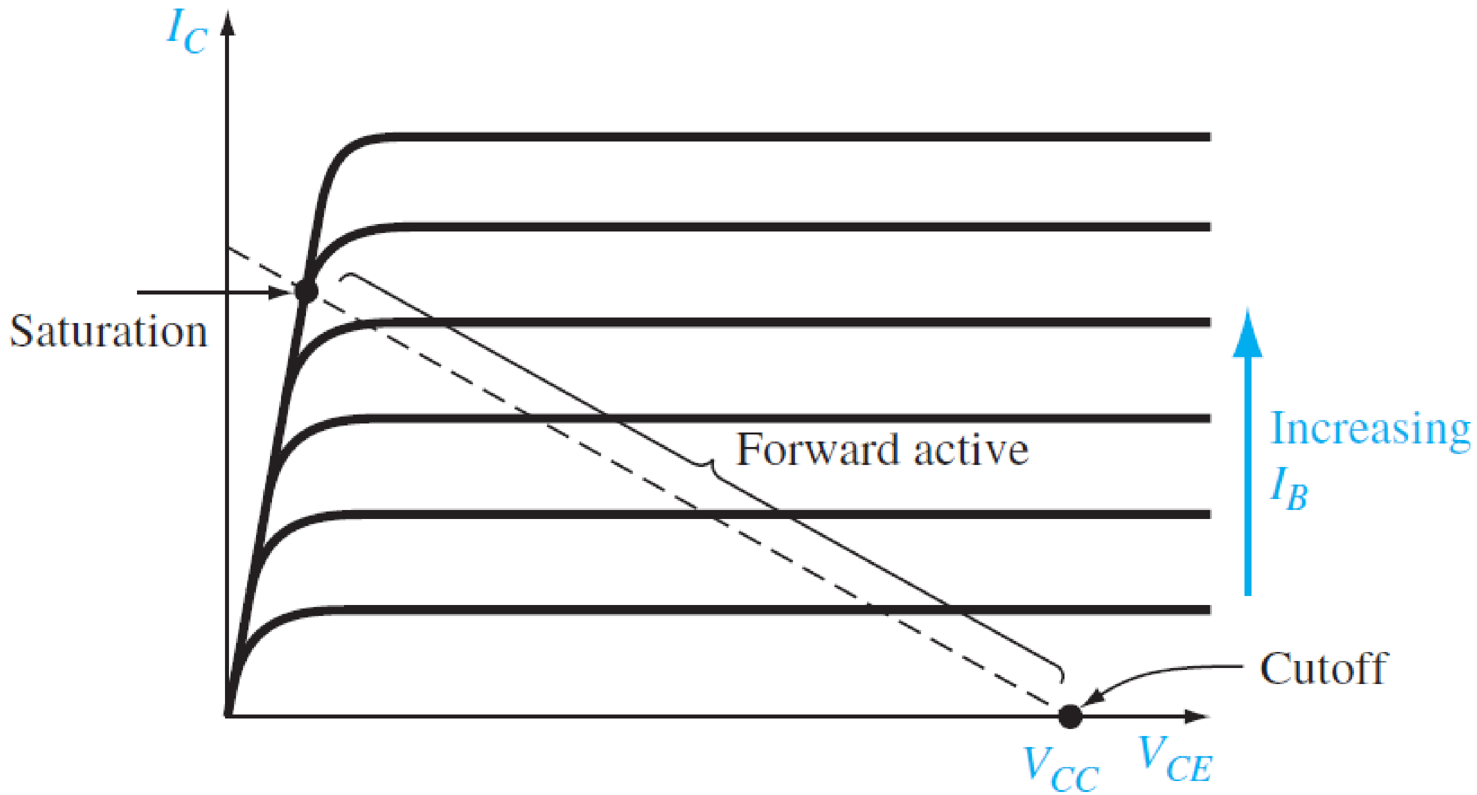
The Modes of Operation

- In this configuration, the transistor may be biased in one of three modes of operation.
- If the B–E voltage is zero or reverse biased (VBE ≤ 0), then majority carrier electrons from the emitter will not be injected into the base. The B–C junction is also reverse biased; thus, the emitter and collector currents will be zero for this case.
- This condition is referred to as **cutoff**—all currents in the transistor are zero.
- When the B–E junction becomes forward biased, an emitter current will be generated and the injection of electrons into the base results in a collector current.
- We may write the KVL equations around the collector–emitter loop as $V_{CC} = I_C R_C + V_{CB} + V_{BE} = V_R + V_{CE}$
- this condition is the **forward-active region** of operation.

The Modes of Operation

- As the forward-biased B–E voltage increases, the collector current and hence V_R will also increase. The increase in V_R means that the reverse-biased C–B voltage decreases, or $|VCB|$ decreases.
- At some point, the collector current may become large enough that the combination of V_R and V_{CC} produces 0 V across the B–C junction.
- A slight increase in *IC* beyond this point will cause a slight increase in *VR* and the B–C junction will become forward biased ($VCB < 0$). This condition is called ***saturation***.
- In the saturation mode of operation, both B–E and B–C junctions are forward biased and the collector current is no longer controlled by the B–E voltage.

Common-Emitter configuration



Bipolar transistor common-emitter current–voltage characteristics with load line superimposed.

Common-Emitter configuration

- When the collector–emitter voltage is large enough so that the base–collector junction is reverse biased, the collector current is a constant.
- For small values of C–E voltage, the base–collector junction becomes forward biased and the collector current decreases to zero for a constant base current.
- Writing a Kirchhoff's voltage equation around the C–E loop

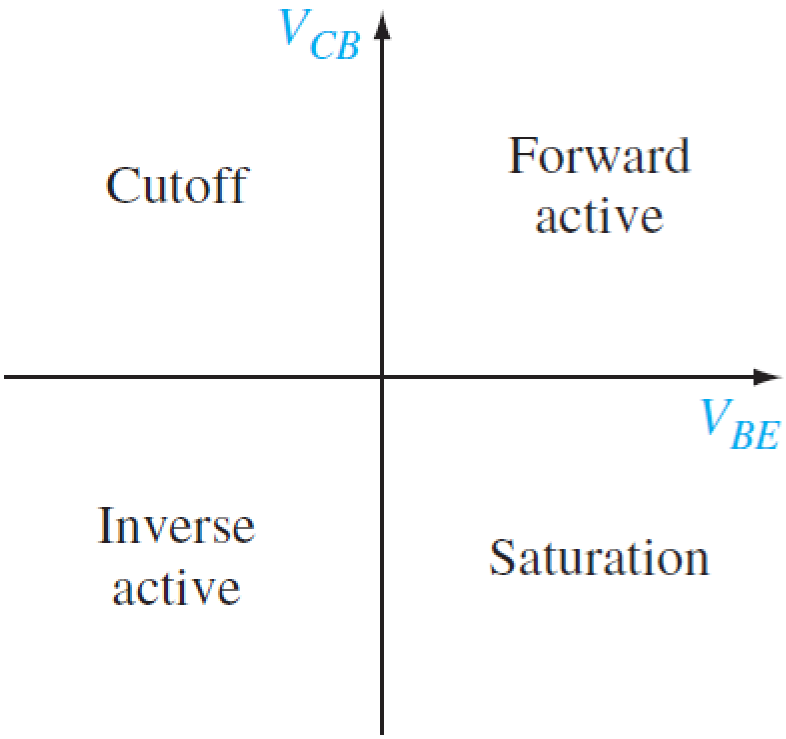
$$V_{CE} = V_{CC} - I_C R_C$$

- Equation shows a linear relation between collector current and collector– emitter voltage. This linear relation is called a *load line* and is plotted in Figure.
- The load line, superimposed on the transistor characteristics, can be used to visualize the bias condition and operating mode of the transistor.

Common-Emitter configuration

- The cutoff mode occurs when $I_C = 0$, saturation occurs when there is no longer a change in collector current for a change in base current, and the forward-active mode occurs when the relation $I_C = \beta I_B$ is valid.
- A fourth mode of operation for the bipolar transistor is possible. This fourth mode, known as *inverse active,* occurs when the B–E junction is reverse biased and the B–C junction is forward biased.
- In this case the transistor is operating "upside down," and the roles of the emitter and collector are reversed.
- the transistor is not a symmetrical device; therefore, the inverse-active characteristics will not be the same as the forward-active characteristics.

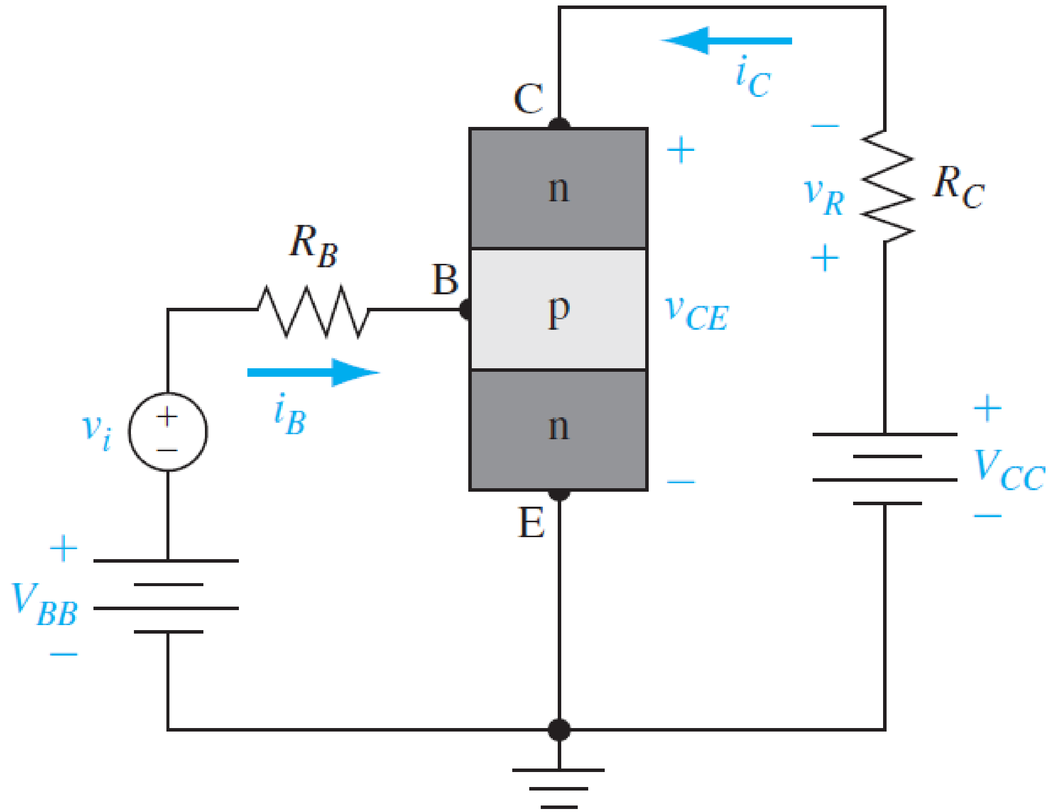
Common-Emitter configuration



Junction voltage conditions for the four operating modes of a bipolar transistor.

Amplification with Bipolar Transistors

- The dc voltage sources, V_{BB} and V_{CC} are used to bias the transistor in the forward-active mode.

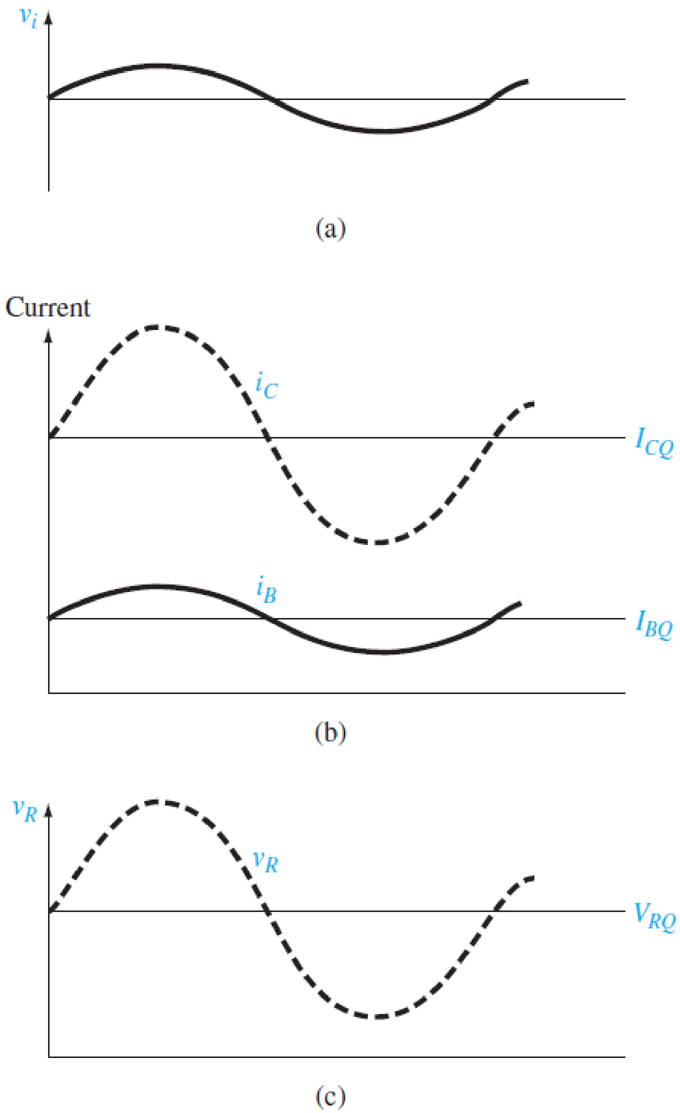


Common-emitter npn bipolar circuit configuration with a time-varying signal voltage v_i included in the base–emitter loop.

Amplification with Bipolar Transistors

- The voltage source v_i represents a time-varying input voltage (such as a signal from a satellite) that needs to be amplified.
- The sinusoidal voltage v_i induces a sinusoidal component of base current superimposed on a dc quiescent value.
- Since $i_C=\beta i_B$, then a relatively large sinusoidal collector current is superimposed on a dc value of collector current.
- The time-varying collector current induces a time varying voltage across the RC resistor which, by Kirchhoff's voltage law, means that a sinusoidal voltage, superimposed on a dc value, exists between the collector and emitter of the bipolar transistor.
- The sinusoidal voltages in the collector–emitter portion of the circuit are larger than the signal input voltage v_i, so that the circuit has produced a *voltage gain* in the time-varying signals. Hence, the circuit is known as a *voltage amplifier.*

Amplification with Bipolar Transistors



(a) Input sinusoidal signal voltage.

(b) Sinusoidal base and collector currents superimposed on the quiescent dc values.

(c) Sinusoidal voltage across the RC resistor super imposed on the quiescent dc value.

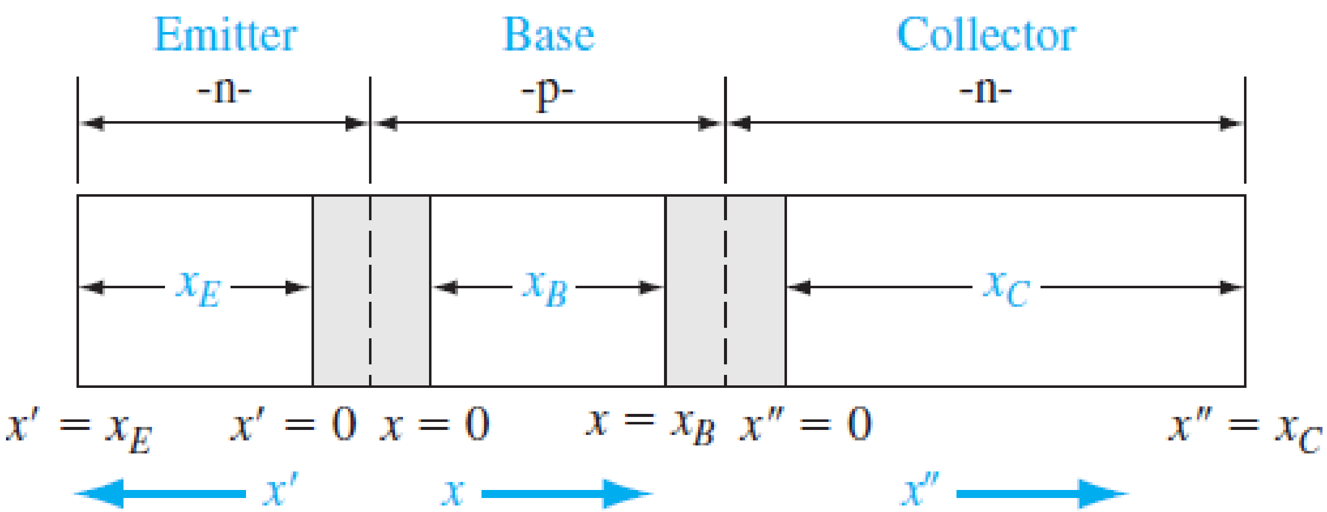
MINORITY CARRIER DISTRIBUTION

Table 12.1 | Notation used in the analysis of the bipolar transistor

Notation	Definition
For both the npn and pnp transistors	
N_E, N_B, N_C	Doping concentrations in the emitter, base, and collector
x_E, x_B, x_C	Widths of neutral emitter, base, and collector regions
D_E, D_B, D_C	*Minority carrier* diffusion coefficients in emitter, base, and collector regions
L_E, L_B, L_C	*Minority carrier* diffusion lengths in emitter, base, and collector regions
τ_{E0}, τ_{B0}, τ_{C0}	*Minority carrier* lifetimes in emitter, base, and collector regions
For the npn	
p_{E0}, n_{B0}, p_{C0}	Thermal-equilibrium *minority carrier* hole, electron, and hole concentrations in the emitter, base, and collector
$p_E(x')$, $n_B(x)$, $p_C(x'')$	Total *minority carrier* hole, electron, and hole concentrations in the emitter, base, and collector
$\delta p_E(x')$, $\delta n_B(x)$, $\delta p_C(x'')$	Excess *minority carrier* hole, electron, and hole concentrations in the emitter, base, and collector
For the pnp	
n_{E0}, p_{B0}, n_{C0}	Thermal-equilibrium *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector
$n_E(x')$, $p_B(x)$, $n_C(x'')$	Total *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector
$\delta n_E(x')$, $\delta p_B(x)$, $\delta n_C(x'')$	Excess *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector

MINORITY CARRIER DISTRIBUTION

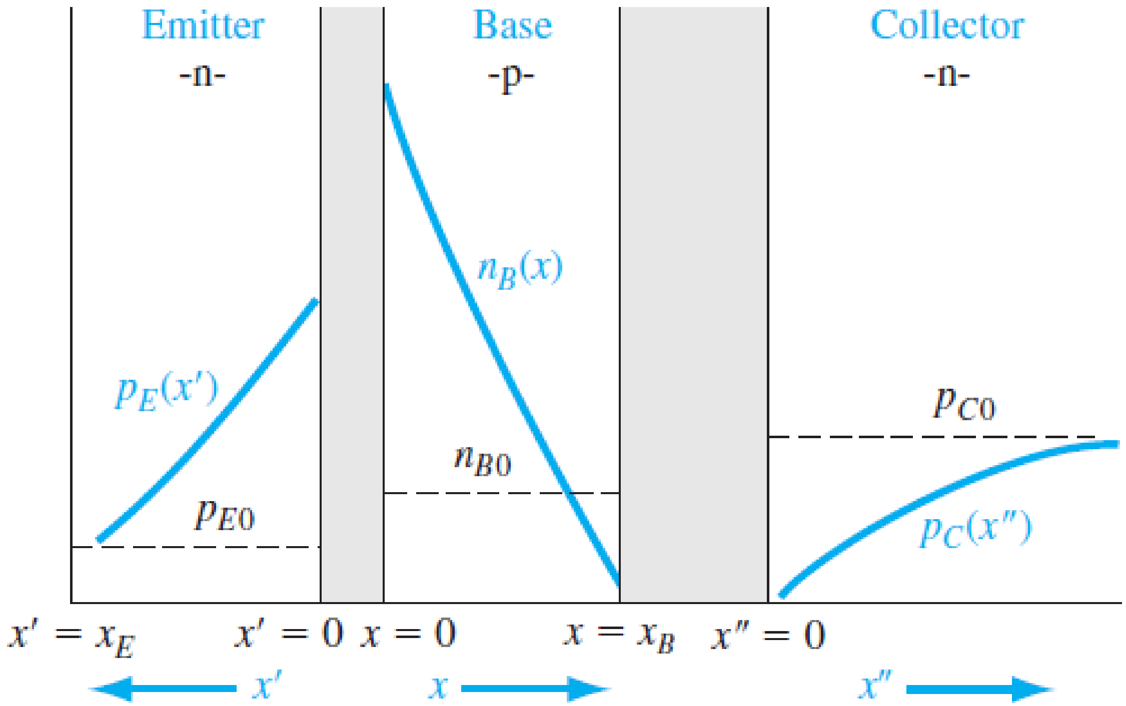
- we must determine the steady-state minority carrier distribution in each of the three transistor regions.
- Consider a uniformly doped npn bipolar transistor



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

Forward-Active Mode

- In the forward-active mode, the B–E junction is forward biased and the B–C is reverse biased.



Minority carrier distribution in an npn bipolar transistor operating in the forward-active mode

Forward-Active Mode

- As there are two n regions, we have minority carrier holes in both emitter and collector.
- The parameters p_{E0}, n_{B0}, and p_{C0} denote the thermal-equilibrium minority carrier concentrations in the emitter, base, and collector, respectively.
- The functions $p_E(x')$, $n_B(x)$, and $p_C(x'')$ denote the steady-state minority carrier concentrations in the emitter, base, and collector, respectively.
- We assume that the neutral collector length x_C is long compared to the minority carrier diffusion length L_C in the collector, but we take into account a finite emitter length x_E.
- If we assume that the surface recombination velocity at $x' = x_E$ is infinite, then the excess minority carrier concentration at $x' = x_E$ is zero, or $pE\ (x'=x_E) = p_{E0}$.
- An infinite surface recombination velocity is a good approximation when an ohmic contact is fabricated at $x' = x_E$.

Base Region

- The steady-state excess minority carrier electron concentration is found from the ambipolar transport equation.
- For a zero electric field in the neutral base region, the ambipolar transport equation in steady state reduces to

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

- 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
- The excess electron concentration is defined as

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

$n_B(x) = n_{B0} + \delta n_B(x)$

- The general solution

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

Base Region

- where L_B is the minority carrier diffusion length in the base, given by $L_B = \sqrt{D_B \tau_{B0}}$.
- The base is of finite width so both exponential terms in Equation must be retained.
- The excess minority carrier electron concentrations at the two boundaries become $\delta n_B(x = 0) \equiv \delta n_B(0) = A + B$

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

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

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

Base Region

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

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

- From the boundary conditions given by above Equations, the coefficients *A* and *B* can be determined

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

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

Base Region

- the excess minority carrier electron concentration in the base region as

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

$x_B < L_B$.

- the excess electron concentration δn_B is approximately a linear function of x through the neutral base region.
- Using the approximation $\sinh(x) \approx x$ for $x \ll 1$

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

Emitter Region

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

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

- 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

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

- The general solution to Equation

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

Emitter Region

- 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 must be retained.
- The excess minority carrier hole concentrations at the two boundaries are

$$\delta p_E(x' = 0) \equiv \delta p_E(0) = C + D$$

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

- the B–E junction is forward biased

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

Emitter Region

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

$$\delta p_E(x_E) = 0$$

- Solving for *C* and *D and* the excess minority carrier hole concentration

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

- This excess concentration will also vary approximately linearly with distance if x_E is small

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

Collector Region

- The excess minority carrier hole concentration in the collector can be determined from the equation

$$D_C \frac{\partial^2[\delta p_C(x'')]}{\partial x''^2} - \frac{\delta p_C(x'')}{\tau_{C0}} = 0$$

- where D_C and τ_{C0} are the minority carrier diffusion coefficient and minority carrier lifetime, respectively, in the collector.
- the excess minority carrier hole concentration in the collector as

$$\delta p_C(x'') = p_C(x'') - p_{C0}$$

- The general solution to Equation

$$\delta p_C(x'') = G \exp\left(\frac{x''}{L_C}\right) + H \exp\left(\frac{-x''}{L_C}\right)$$

Collector Region

- Where $L_C = \sqrt{D_C \tau_{C0}}$

$x'' = \infty \Rightarrow G = 0$

- If we assume that the collector is long, then the coefficient *G* must be zero since the excess concentration must remain finite.
- The second boundary condition gives

$$\delta p_C(x'' = 0) \equiv \delta p_C(0) = p_C(x'' = 0) - p_{C0} = 0 - p_{C0} = -p_{C0}$$

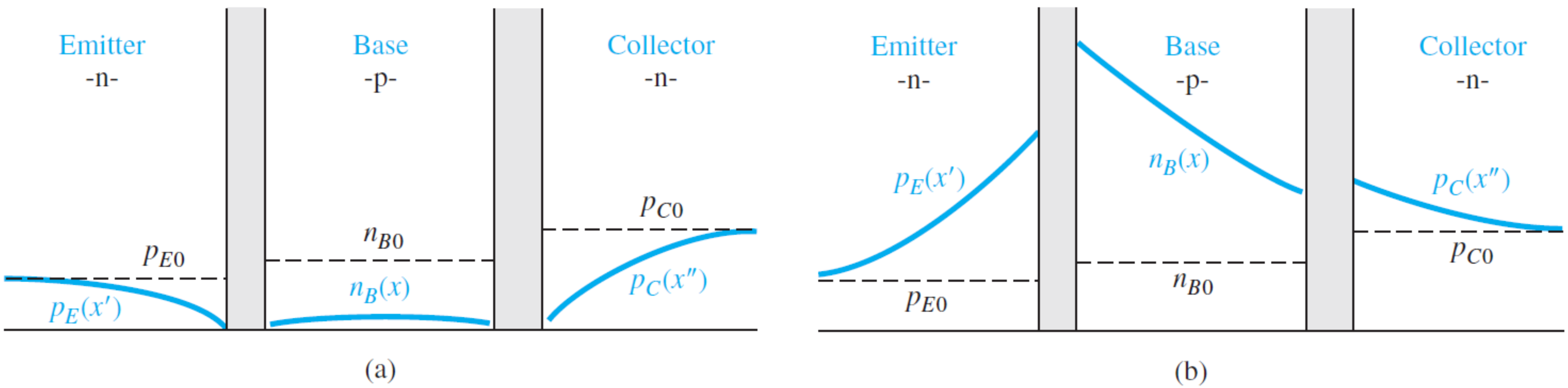
- The excess minority carrier hole concentration in the collector is then given as

$$\delta p_C(x'') = -p_{C0} \exp\left(\frac{-x''}{L_C}\right)$$

- This result is exactly what we expect from the results of a reverse-biased pn junction

Other Modes of Operation

- The bipolar transistor can also operate in the cutoff, saturation, or inverse-active mode.

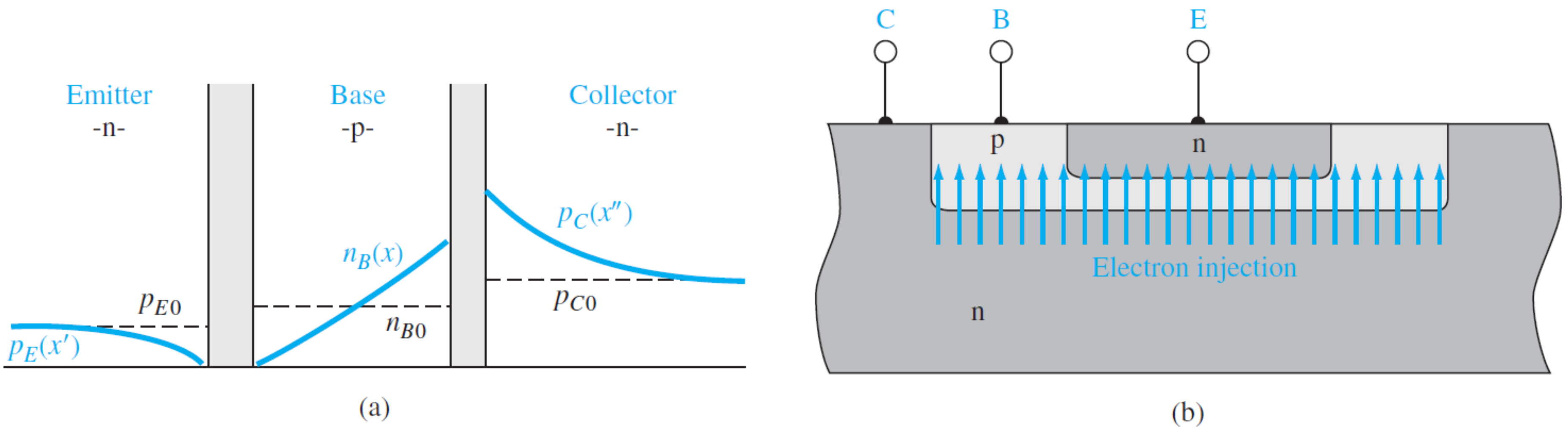


Minority carrier distribution in an npn bipolar transistor operating in (a) cutoff and (b) saturation

Other Modes of Operation

- In **cutoff**, both the B–E and B–C junctions are reverse biased; thus, the minority carrier concentrations are zero at each space charge edge.
- The emitter and collector regions are assumed to be "long" in this figure, while the base is narrow compared with the minority carrier diffusion length.
- Since $x_B << L_B$, essentially all minority carriers are swept out of the base region.
- In **saturation** mode, both the B–E and B–C junctions are forward biased excess minority carriers exist at the edge of each space charge region.
- However, since a collector current still exists when the transistor is in saturation, a gradient will still exist in the minority carrier electron concentration in the base.

Other Modes of Operation



(a) Minority carrier distribution in an npn bipolar transistor operating in the inverse-active mode.
(b) Cross section of an npn bipolar transistor showing the injection and collection of electrons in the inverse-active mode

Other Modes of Operation

- In **inverse-active** mode, the B–E is reverse biased and the B–C is forward biased.
- Electrons from the collector are now injected into the base.
- The gradient in the minority carrier electron concentration in the base is in the opposite direction compared with the forward-active mode, so the emitter and collector currents will change direction.
- Figure shows the injection of electrons from the collector into the base.
- Since the B–C area is normally much larger than the B–E area, not all of the injected electrons will be collected by the emitter.
- The relative doping concentrations in the base and collector are also different compared with those in the base and emitter; thus, we see that the transistor is not symmetrical.

TRANSISTOR CURRENTS AND LOW- FREQUENCY COMMON-BASE CURRENT GAIN

- The basic principle of operation of the bipolar transistor is the control of the collector current by the B–E voltage.
- The collector current is a function of the number of majority carriers reaching the collector after being injected from the emitter across the B–E junction.
- The common-base current gain is defined as the ratio of collector current to emitter current.
- The flow of various charged carriers leads to definitions of particular currents in the device.

Current Gain—Contributing Factors

- The factor J^{-}_{nE} is the electron flux injected from the emitter into the base.
- As the electrons diffuse across the base, a few will recombine with majority carrier holes.
- The majority carrier holes that are lost by recombination must be replenished from the base terminal. This replacement hole fl ux is denoted by J^{+}_{RB}
- The electron flux that reaches the collector is J^{-}_{nC}
- The majority carrier holes from the base that are injected back into the emitter result in a hole flux denoted by J^{+}_{pE}
- Some electrons and holes that are injected into the forward-biased B–E space charge region will recombine in this region. This recombination leads to the electron flux J^{-}_{R} .

Current Gain—Contributing Factors

- Generation of electrons and holes occurs in the reverse-biased B–C junction. This generation yields a hole flux J^{-}_{G}
- Finally, the ideal reverse-saturation current in the B–C junction is denoted by the hole flux J^{+}_{pc0}
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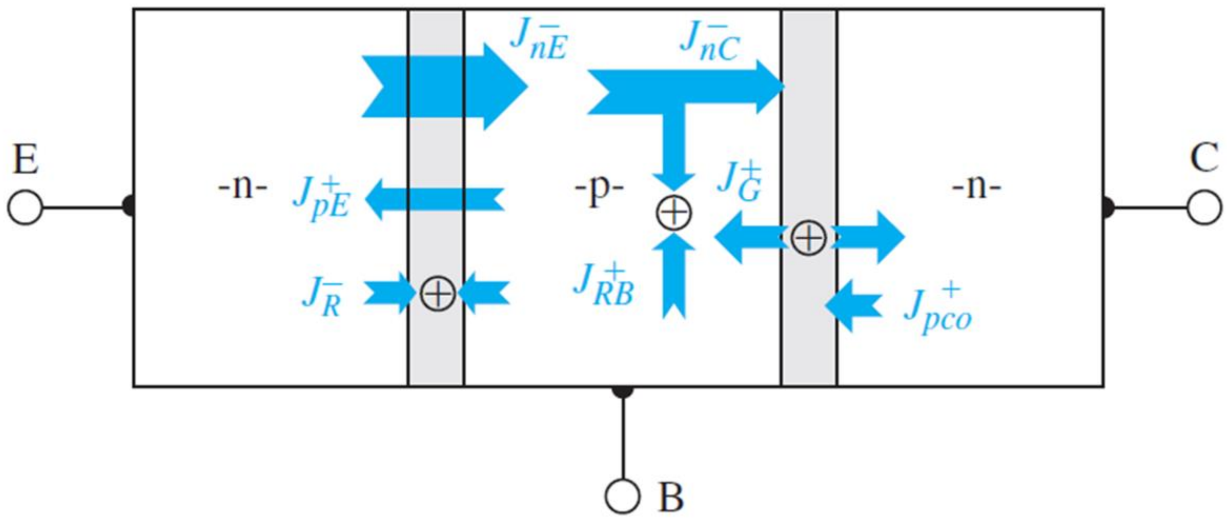
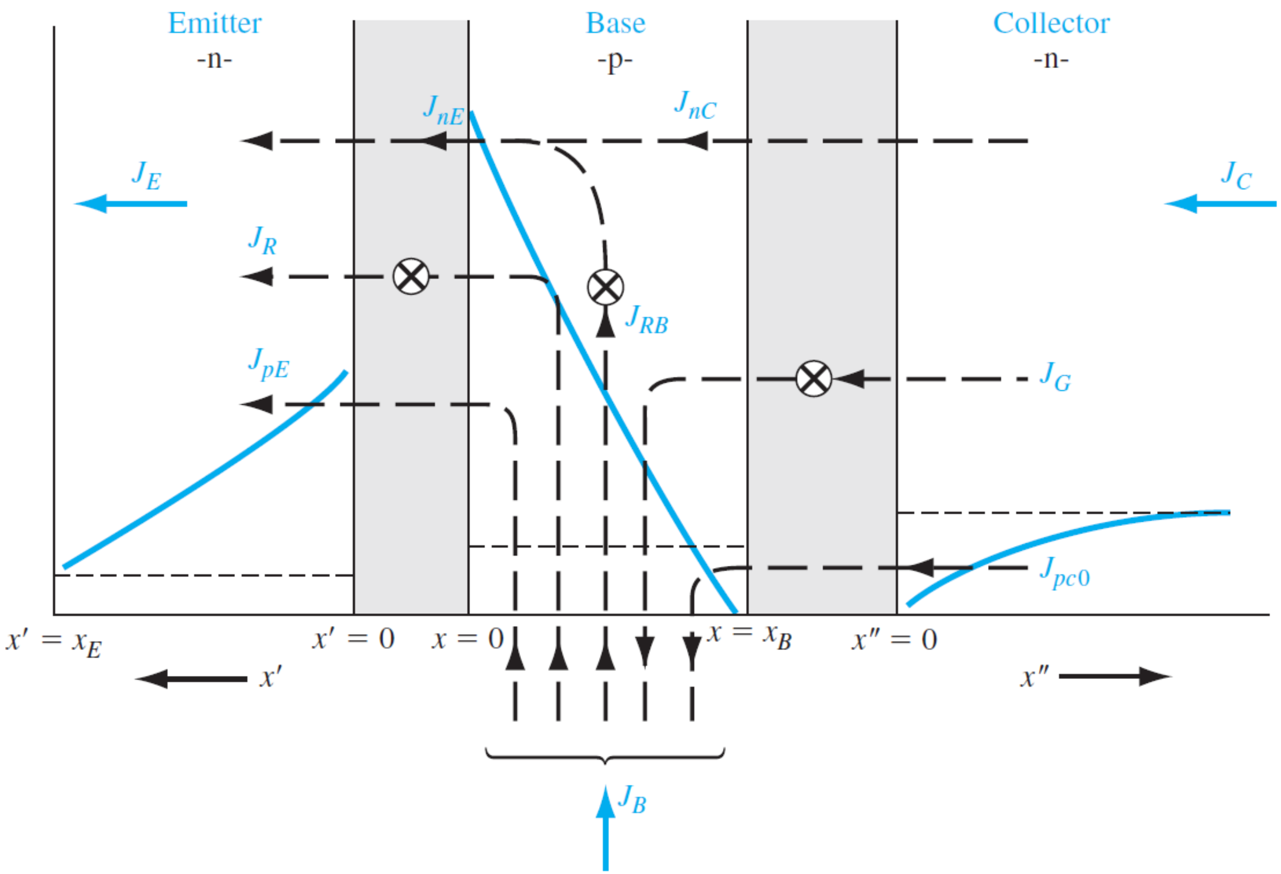


Particle current density or flux components in an npn bipolar transistor operating in the forward-active mode

Current Gain—Contributing Factors



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

Current Gain—Contributing Factors

J_{nE}: Due to the diffusion of minority carrier electrons in the base at $x = 0$.

J_{nC}: Due to the diffusion of minority carrier electrons in the base at $x = x_B$.

J_{RB}: The difference between J_{nE} and J_{nC}, which is due to the recombination of excess minority carrier electrons with majority carrier holes in the base. The J_{RB} current is the flow of holes into the base to replace the holes lost by recombination.

J_{pE}: Due to the diffusion of minority carrier holes in the emitter at $x' = 0$.

J_R: Due to the recombination of carriers in the forward-biased B–E junction.

J_{pc0}: Due to the diffusion of minority carrier holes in the collector at $x'' = 0$.

J_G: Due to the generation of carriers in the reverse-biased B–C junction.

- The currents J_{RB}, J_{pE}, and J_R are B–E junction currents only and do not contribute to the collector current. The currents J_{pc0} and J_G are B–C junction currents only.
- These current components do not contribute to the transistor action or the current gain.

Current Gain—Contributing Factors

$$\alpha = \gamma \alpha_T \delta$$

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

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

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

- The goal is to make as close to unity as possible. To achieve this goal, we must make each term in Equation as close to unity as possible

Current Gain—Contributing Factors

- The emitter injection efficiency factor γ takes into account the minority carrier hole diffusion current in the emitter. This current is part of the emitter current, but does not contribute to the transistor action in that J_{pE} is not part of the collector current.
- The base transport factor α_T takes into account any recombination of excess minority carrier electrons in the base. Ideally, we want no recombination in the base.
- The recombination factor δ takes into account the recombination in the forward- biased B–E junction. The current J_R contributes to the emitter current, but does not contribute to collector current.

Derivation of Transistor Current Components and Current Gain Factors

$$\gamma \approx \frac{1}{1 + \dfrac{N_B}{N_E} \cdot \dfrac{D_E}{D_B} \cdot \dfrac{x_B}{x_E}} \qquad (x_B \ll L_B), (x_E \ll L_E)$$

$$\alpha_T \approx \frac{1}{1 + \dfrac{1}{2}\left(\dfrac{x_B}{L_B}\right)^2} \qquad (x_B \ll L_B)$$

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

Summary

$$\alpha_0 = I_C/I_E \qquad \beta_0 = I_C/I_B$$

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

$$\frac{1}{\alpha_0} = \frac{1}{\beta_0} + 1$$

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

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

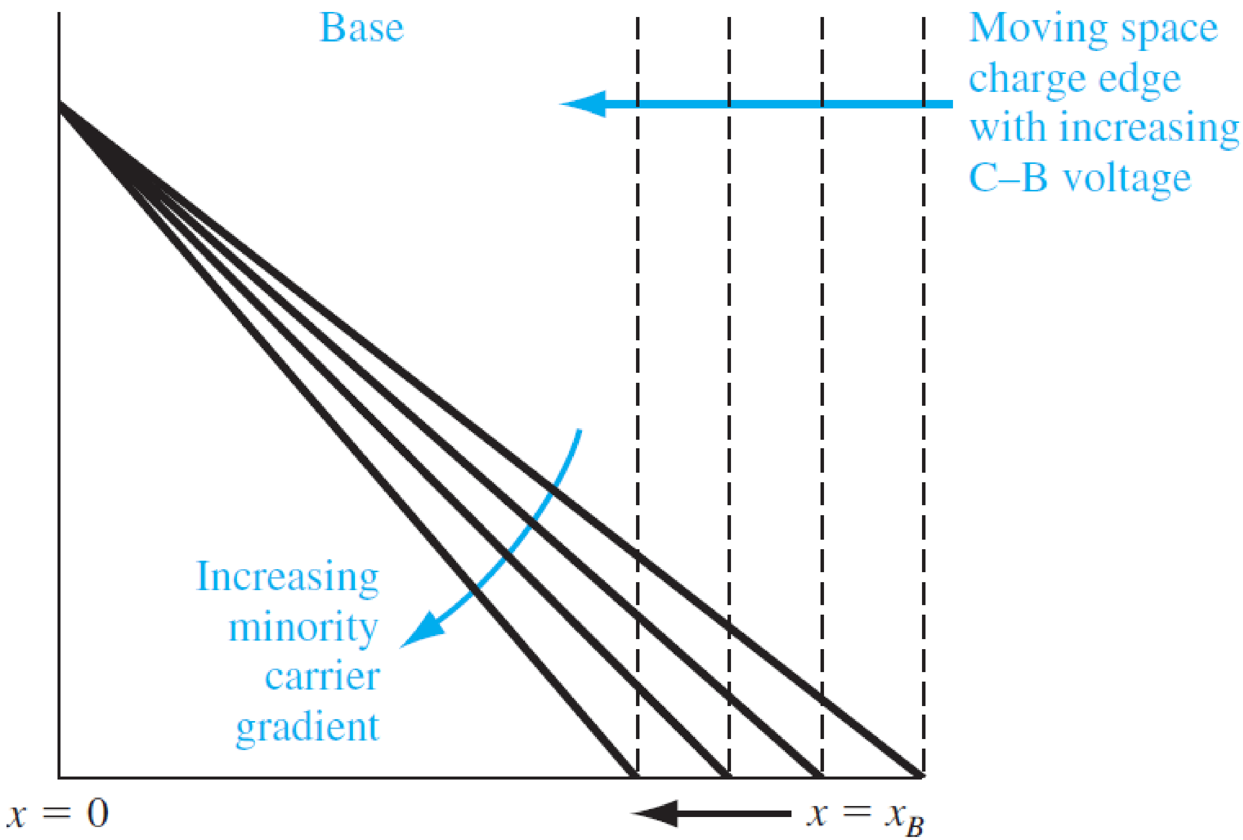
NONIDEAL EFFECTS

- we have considered a transistor with uniformly doped regions, low injection, constant emitter and base widths, an ideal constant energy bandgap, uniform current densities, and junctions that are not in breakdown.
- If any of these ideal conditions is not present, then the transistor properties will deviate from the ideal characteristics

Base Width Modulation

- We have implicitly assumed that the neutral base width x_B is constant.
- This base width is a function of the B–C voltage, since the width of the space charge region extending into the base region varies with B–C voltage.
- As the B–C reverse-biased voltage increases, the B–C space charge region width increases, which reduces x_B.
- A change in the neutral base width will change the collector current as can be observed.
- A reduction in base width will cause the gradient in the minority carrier concentration to increase, which in turn causes an increase in the diffusion current.
- This effect is known as base width modulation; it is also called the Early effect.

Base Width Modulation

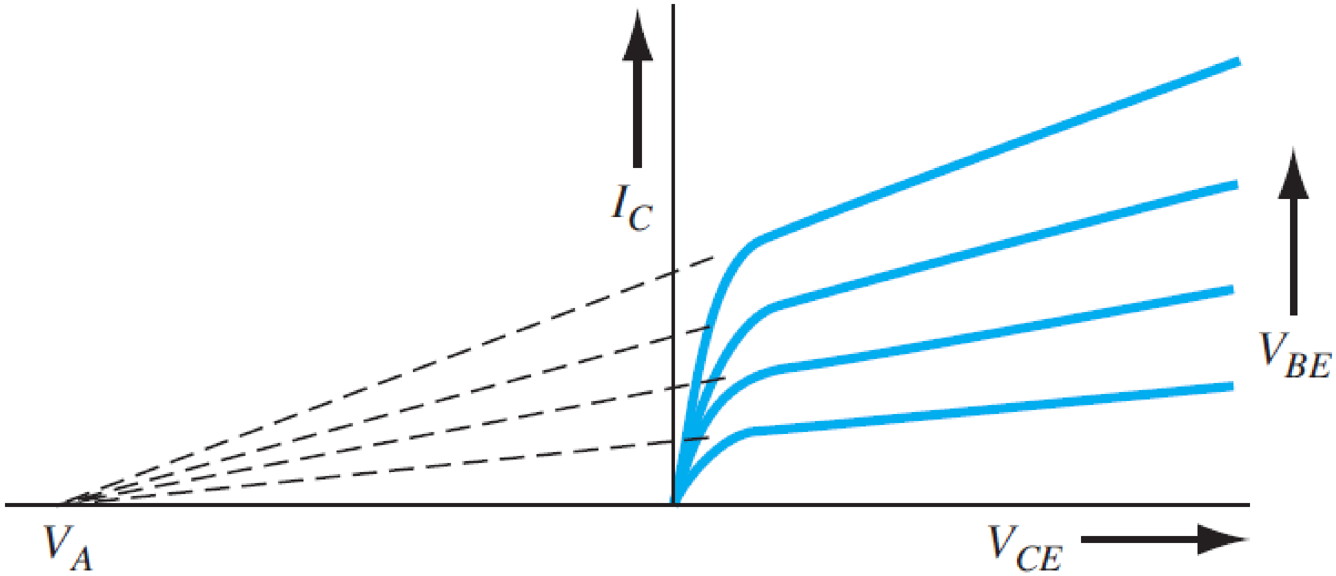


The change in the base width and the change in the minority carrier gradient as the B–C space charge width changes.

Base Width Modulation

- The Early effect can be seen in the current–voltage characteristics shown in Figure.
- In most cases, a constant base current is equivalent to a constant B–E voltage.
- Ideally the collector current is independent of the B–C voltage so that the slope of the curves would be zero; thus, the output conductance of the transistor would be zero.
- However, the base width modulation, or Early effect, produces a nonzero slope and gives rise to a finite output conductance.
- If the collector current characteristics are extrapolated to zero collector current, the curves intersect the voltage axis at a point that is defined as the Early voltage. The Early voltage is considered to be a positive value.

Base Width Modulation



$$\frac{dI_C}{dV_{CE}} \equiv g_o = \frac{I_C}{V_{CE} + V_A} = \frac{1}{r_o}$$

$$I_C = g_o\,(V_{CE} + V_A) = \frac{1}{r_o}(V_{CE} + V_A)$$

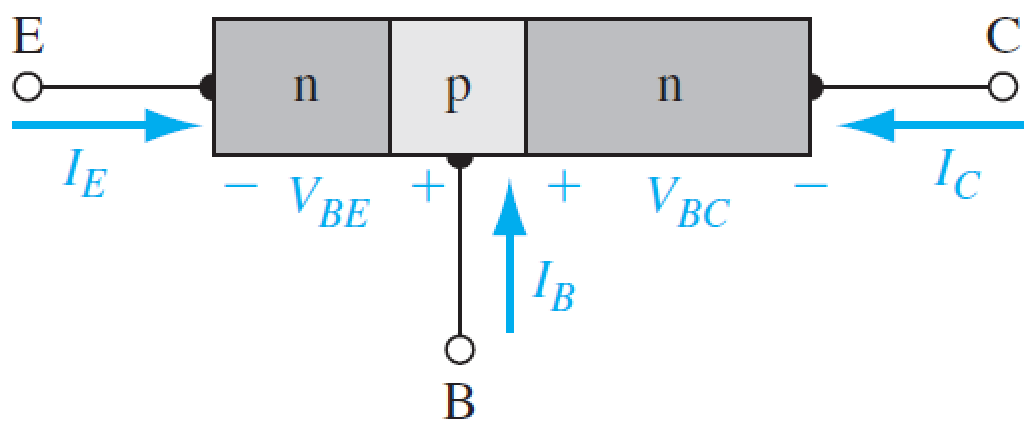
The collector current versus collector– emitter voltage showing the Early effect and Early voltage

EQUIVALENT CIRCUIT MODELS

- In order to analyze a transistor circuit either by hand calculations or using computer codes, one needs a mathematical model, or equivalent circuit, of the transistor.
- It is useful to divide bipolar transistors into two categories—switching and amplification—defined by their use in electronic circuits.
- Switching usually involves turning a transistor from its “off ” state, or cutoff, to its “on” state, either forward active or saturation, and then back to its “off” state.
- Amplification usually involves superimposing sinusoidal signals on dc values so that bias voltages and currents are only perturbed.
- The *Ebers–Moll model* is used in switching applications;
- The *hybrid-pi* model is used in amplification applications.

Ebers–Moll Model

- The Ebers–Moll model, or equivalent circuit, is one of the classic models of the bipolar transistor.
- This particular model is based on the interacting diode junctions and is applicable in any of the transistor operating modes.



Current direction and voltage polarity definitions for the Ebers–Moll model.

Ebers–Moll Model

- The currents are defined as all entering the terminals

$$I_E + I_B + I_C = 0$$

- The collector current can be written in general as

$$I_C = \alpha_F I_F - I_R$$

- Where α_F is the common-base current gain in the forward-active mode.
- In this mode, Equation becomes

$$I_C = \alpha_F I_F + I_{CS}$$

- where the current I_{CS} is the reverse-biased B–C junction current.
- The current I_F is given bv

$$I_F = I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]$$

Ebers–Moll Model

- If the B–C junction becomes forward biased, such as in saturation, then we can write the current I_R as

$$I_R = I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right]$$

- Sub I_F and I_R in I_C

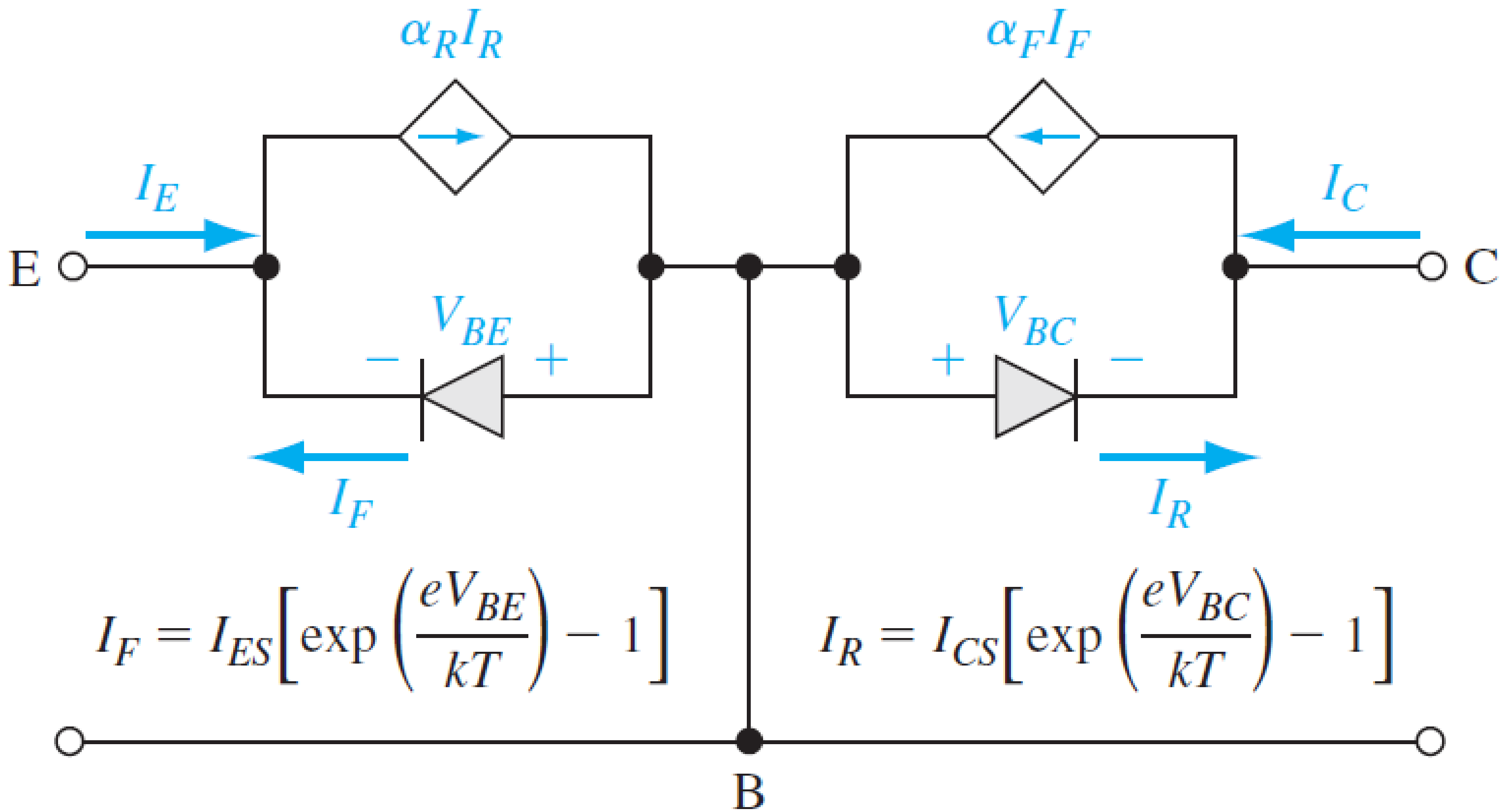
$$I_C = \alpha_F I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] - I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right]$$

$$I_E = \alpha_R I_R - I_F$$

$$I_E = \alpha_R I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right] - I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]$$

- The current I_{ES} is the reverse-biased B–E junction current and α_R is the common-base current gain for the inverse-active mode.
- Equations I_C and I_E are the classic Ebers–Moll equations.

Ebers–Moll Model



Basic Ebers–Moll equivalent circuit

Ebers–Moll Model

- The Ebers–Moll model has four parameters: α_F, α_R, I_{ES}, and I_{CS}.
- However, only three parameters are independent.
- The reciprocity relationship states that

$$\alpha_F I_{ES} = \alpha_R I_{CS}$$

- The Ebers–Moll model is valid in each of the four operating modes
- In the saturation mode, both B–E and B–C junctions are forward biased, so that $V_{BE} > 0$ and $V_{BC} > 0$.
- The B–E voltage will be a known parameter since we will apply a voltage across this junction.
- The forward-biased B–C voltage is a result of driving the transistor into saturation and is the unknown to be determined from the Ebers–Moll equations.

Ebers–Moll Model

- C–E saturation voltage as

$$V_{CE}(\text{sat}) = V_{BE} - V_{BC}$$

$$I_E + I_B + I_C = 0$$

$$-(I_B + I_C) = \alpha_R I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right] - I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]$$

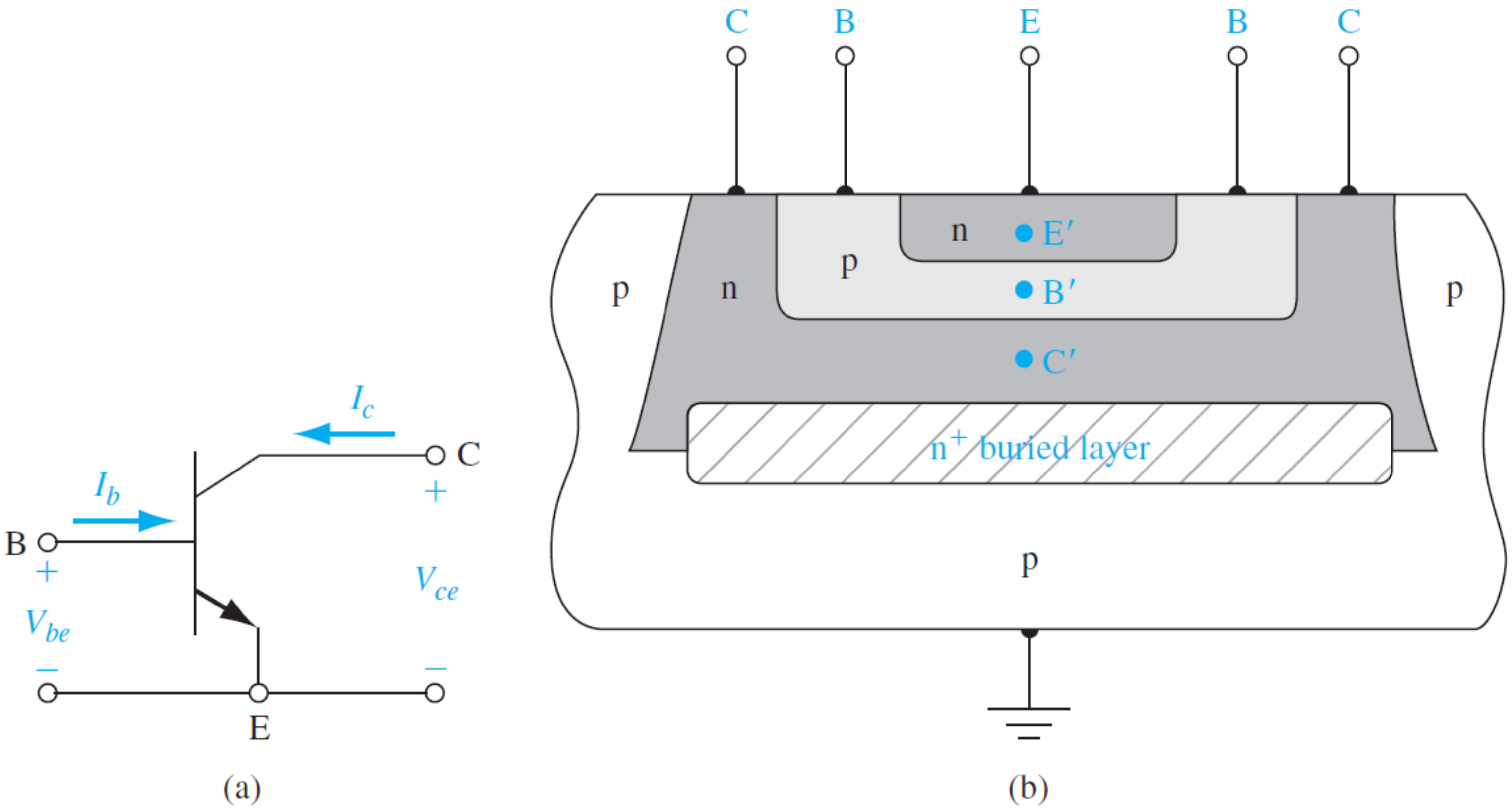
$$V_{BE} = V_t \ln\left[\frac{I_C(1 - \alpha_R) + I_B + I_{ES}(1 - \alpha_F\alpha_R)}{I_{ES}(1 - \alpha_F\alpha_R)}\right]$$

$$V_{BC} = V_t \ln\left[\frac{\alpha_F I_B - (1 - \alpha_F)I_C + I_{CS}(1 - \alpha_F\alpha_R)}{I_{CS}(1 - \alpha_F\alpha_R)}\right]$$

$$V_{CE}(\text{sat}) = V_{BE} - V_{CB} = V_t \ln\left[\frac{I_C(1 - \alpha_R) + I_B}{\alpha_F I_B - (1 - \alpha_F)I_C} \cdot \frac{I_{CS}}{I_{ES}}\right]$$

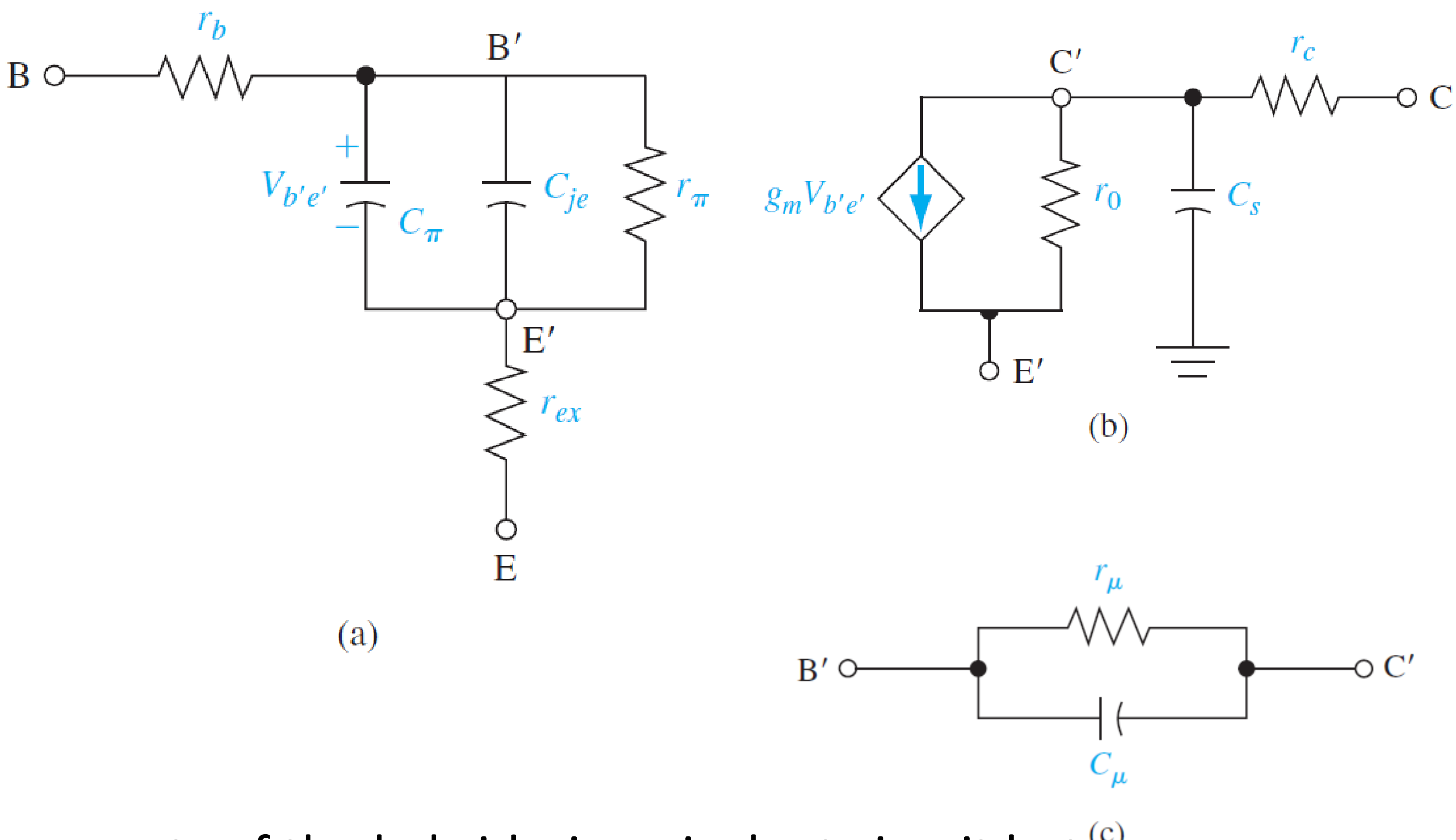
$$V_{CE}(\text{sat}) = V_t \ln\left[\frac{I_C(1 - \alpha_R) + I_B}{\alpha_F I_B - (1 - \alpha_F)I_C} \cdot \frac{\alpha_F}{\alpha_R}\right]$$

Hybrid-Pi Model



(a) Common-emitter npn bipolar transistor with small-signal current and voltages.
(b) Cross section of an npn bipolar transistor for the hybrid-pi model.

Hybrid-Pi Model



Components of the hybrid-pi equivalent circuit between (a) the base and emitter, (b) the collector and emitter, and (c) the base and collector.

Hybrid-Pi Model

- The C, B, and E terminals are the external connections to the transistor, while the C′, B′, and E′ points are the idealized internal collector, base, and emitter regions.
- The resistance r_b is the series resistance in the base between the external base terminal B and the internal base region B′. The B′E′ junction is forward biased, so C_π is the junction diffusion capacitance and r_π is the junction diffusion resistance.
- The diffusion capacitance C_π is the same as the diffusion capacitance C_d
- the diffusion resistance r_π is the same as the diffusion resistance r_d
- The values of both parameters are functions of the junction current.

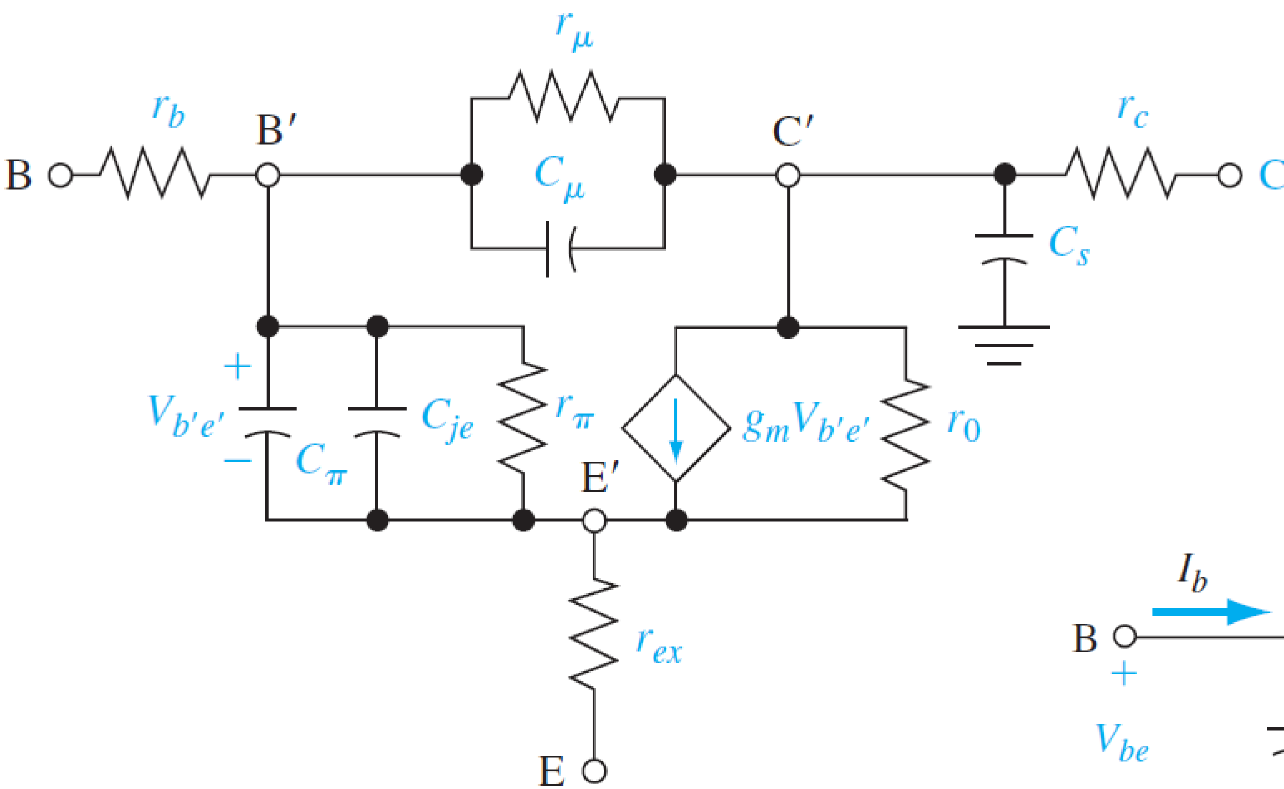
Hybrid-Pi Model

- These two elements are in parallel with the junction capacitance, which is C_{je}.
- Finally, r_{ex} is the series resistance between the external emitter terminal and the internal emitter region. This resistance is usually very small and may be on the order of 1 to 2 Ω.
- The equivalent circuit looking into the collector terminal.
- The r_c resistance is the series resistance between the external and internal collector connections and the capacitance C_s is the junction capacitance of the reverse-biased collector substrate junction.
- The dependent current source, $g_m V_{b'e'}$, is the collector current in the transistor, which is controlled by the internal base–emitter voltage.
- The resistance r_0 is the inverse of the output conductance g_0 and is primarily due to the Early effect.

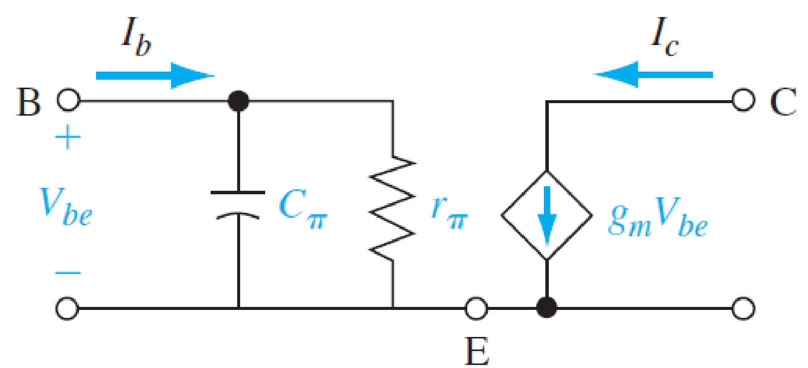
Hybrid-Pi Model

- the equivalent circuit of the reverse-biased B′C′ junction.
- The C_{μ} parameter is the reverse-biased junction capacitance and r_{μ} is the reverse-biased diffusion resistance. Normally, r_{μ} is on the order of megohms and can be neglected.
- The value of C_{μ} is usually much smaller than C but, because of the feedback effect that leads to the Miller effect and Miller capacitance, C_{μ} cannot be ignored in most cases.
- The Miller capacitance is the equivalent capacitance between B′ and E′ due to C_{μ} and the feedback effect, which includes the gain of the transistor.
- The Miller effect also reflects C_{μ} between the C′ and E′ terminals at the output.
- However, the effect on the output characteristics can usually be ignored.

Hybrid-Pi Model



Hybrid-pi equivalent circuit



Simplified hybrid-pi equivalent circuit.