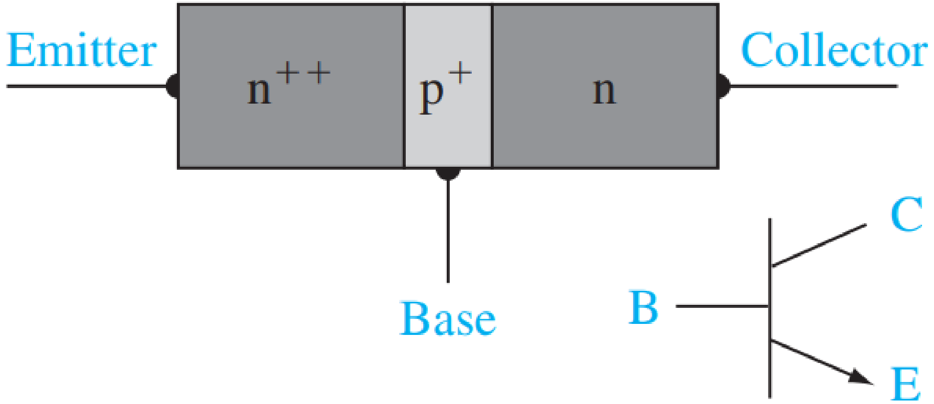
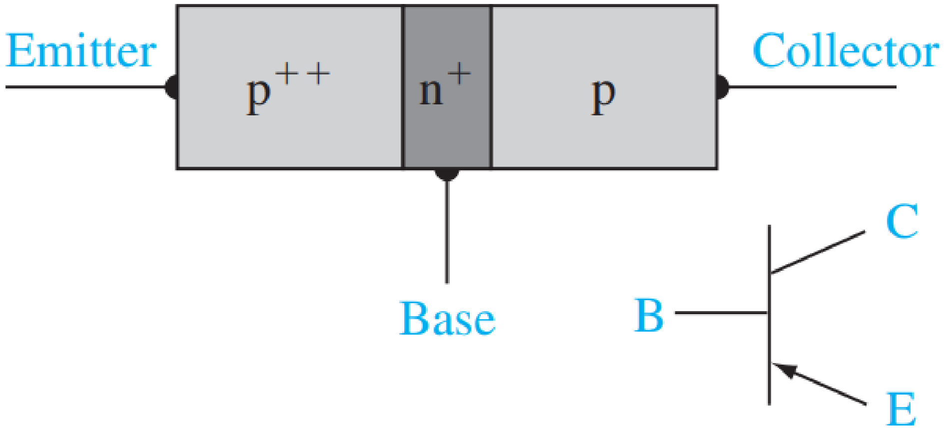
Bipolar junction transistors (L4+T1)

- Fundamentals and characteristics
- Biasing
- Switching
- Modelling of BJT

Field Effect Transistors (L10+T3)

- JEFT, MESFET, MOSFET, HEMT
- MOS capacitor
- MOSFET – device physics, operation, characteristics and modelling


Emitter
n++
p+
n
Collector
Base
B
C
E


Emitter
p++
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Collector
Base
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C
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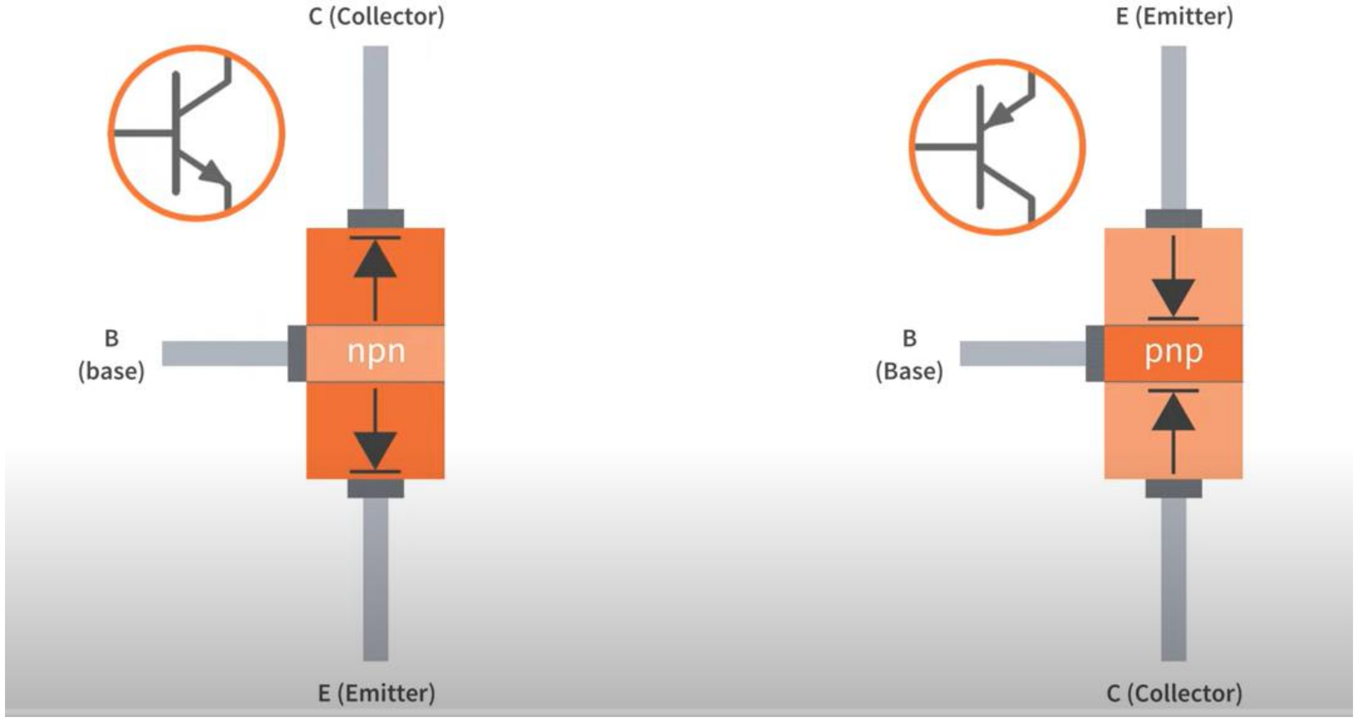

C (Collector)
B
(base)
npn
E (Emitter)
E (Emitter)
B
(Base)
pnp
C (Collector)

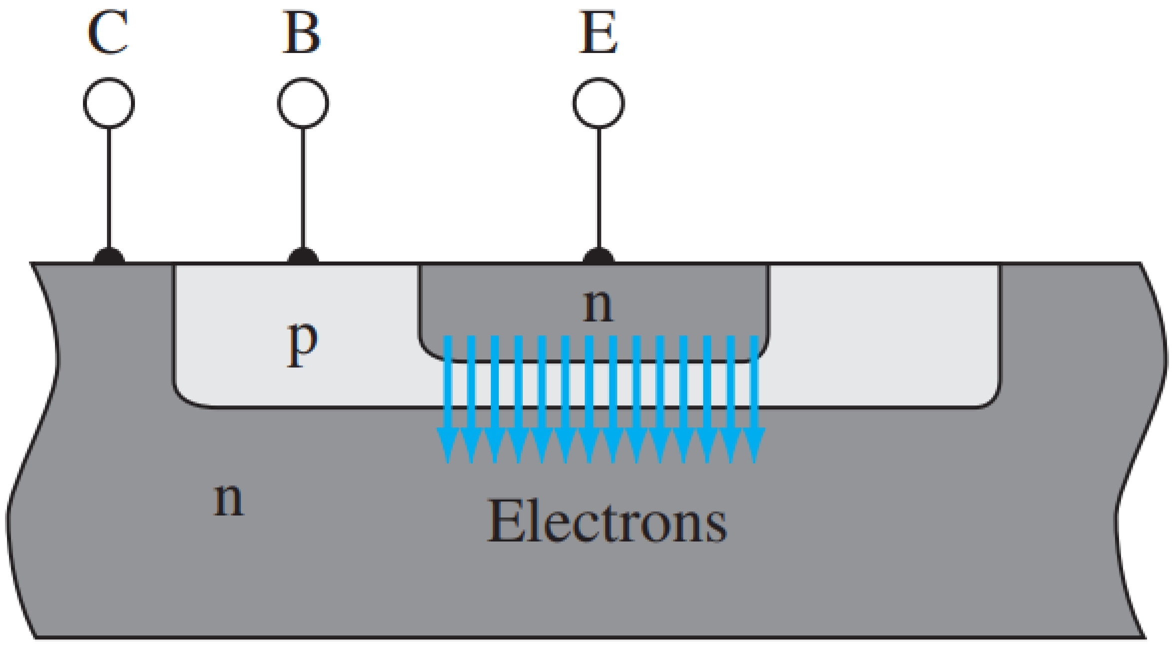
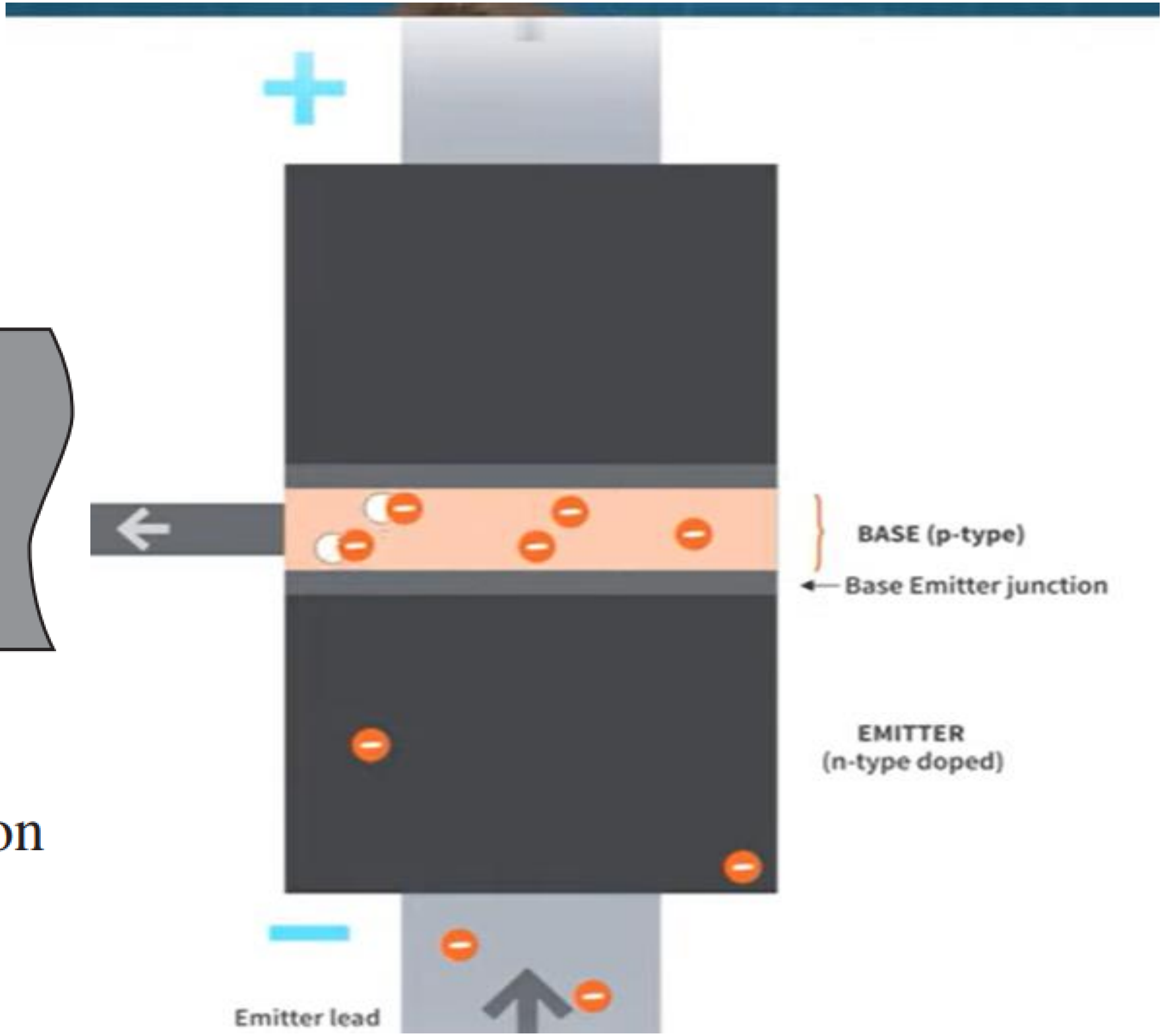
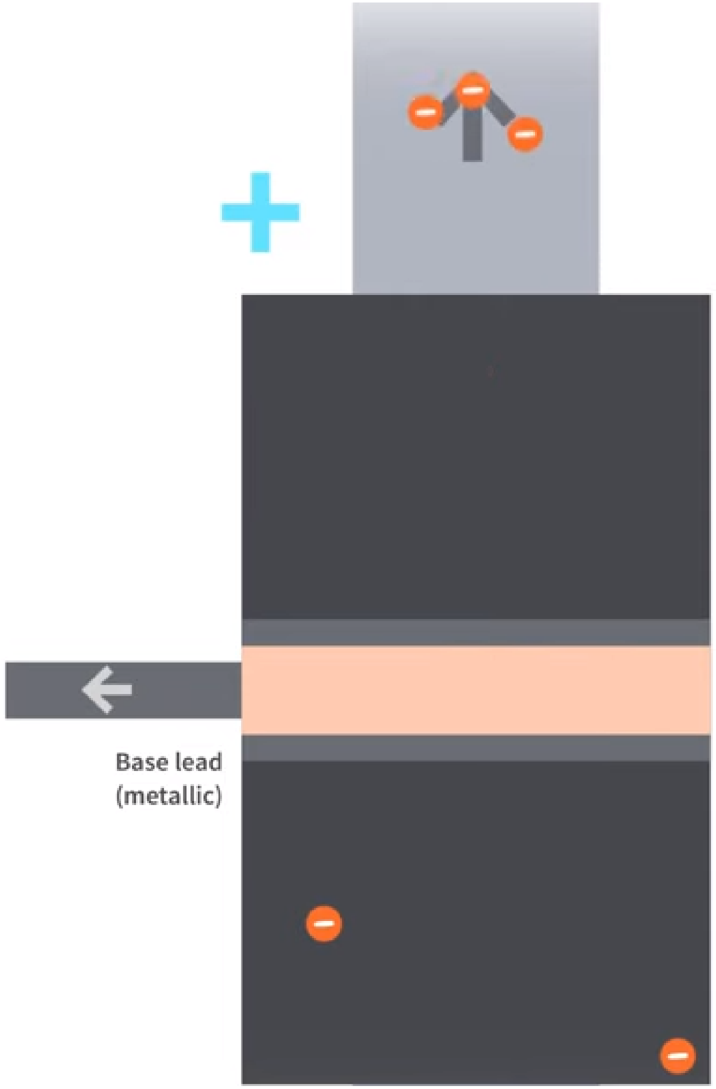
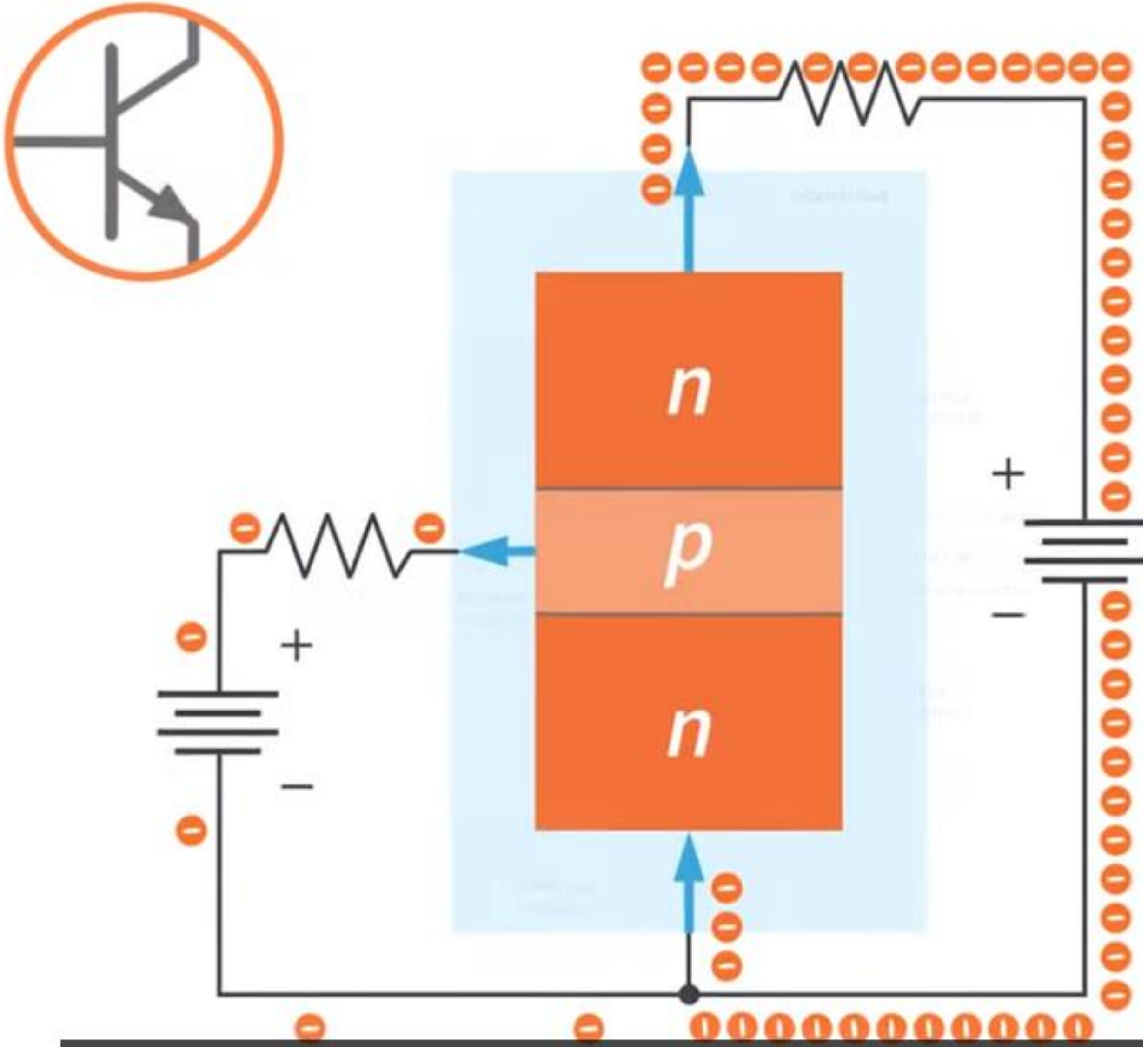


Figure 12.5 | Cross section of an npn bipolar transistor showing the injection and collection of electrons in the forward-active mode.





COLLECTOR
(n-type doped)
Base Collector Junction
BASE (p-type)
Base Emitter junction
Base lead
(metallic)
EMITTER
(n-type doped)



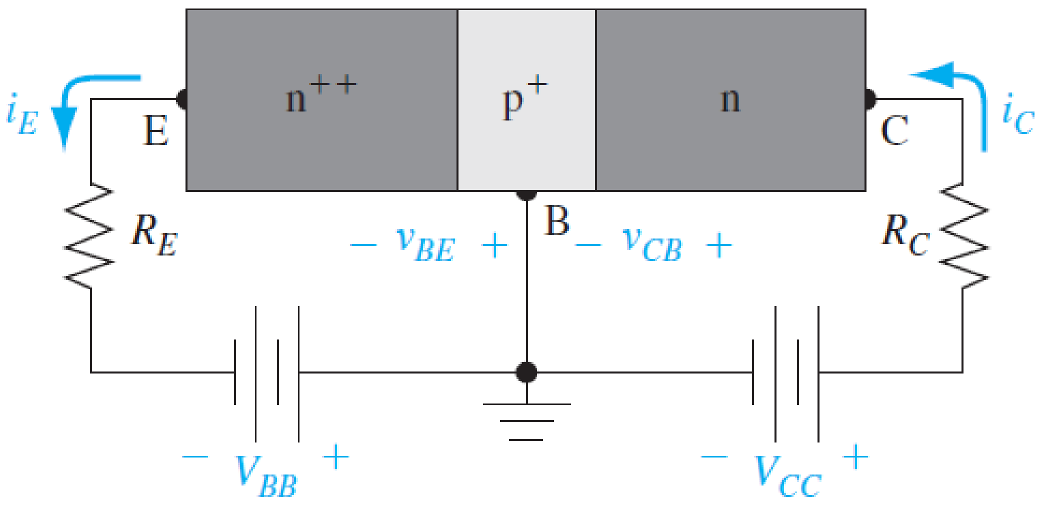
n
p
n
+
−
+
−

Fundamentals and characteristics

- The emitter region has the largest doping concentration; the collector region has the smallest.
- Typical impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19}, 10^{17}, and 10^{15} cm^{-3}, respectively.
- 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.
- **forward-active operating mode:** 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.

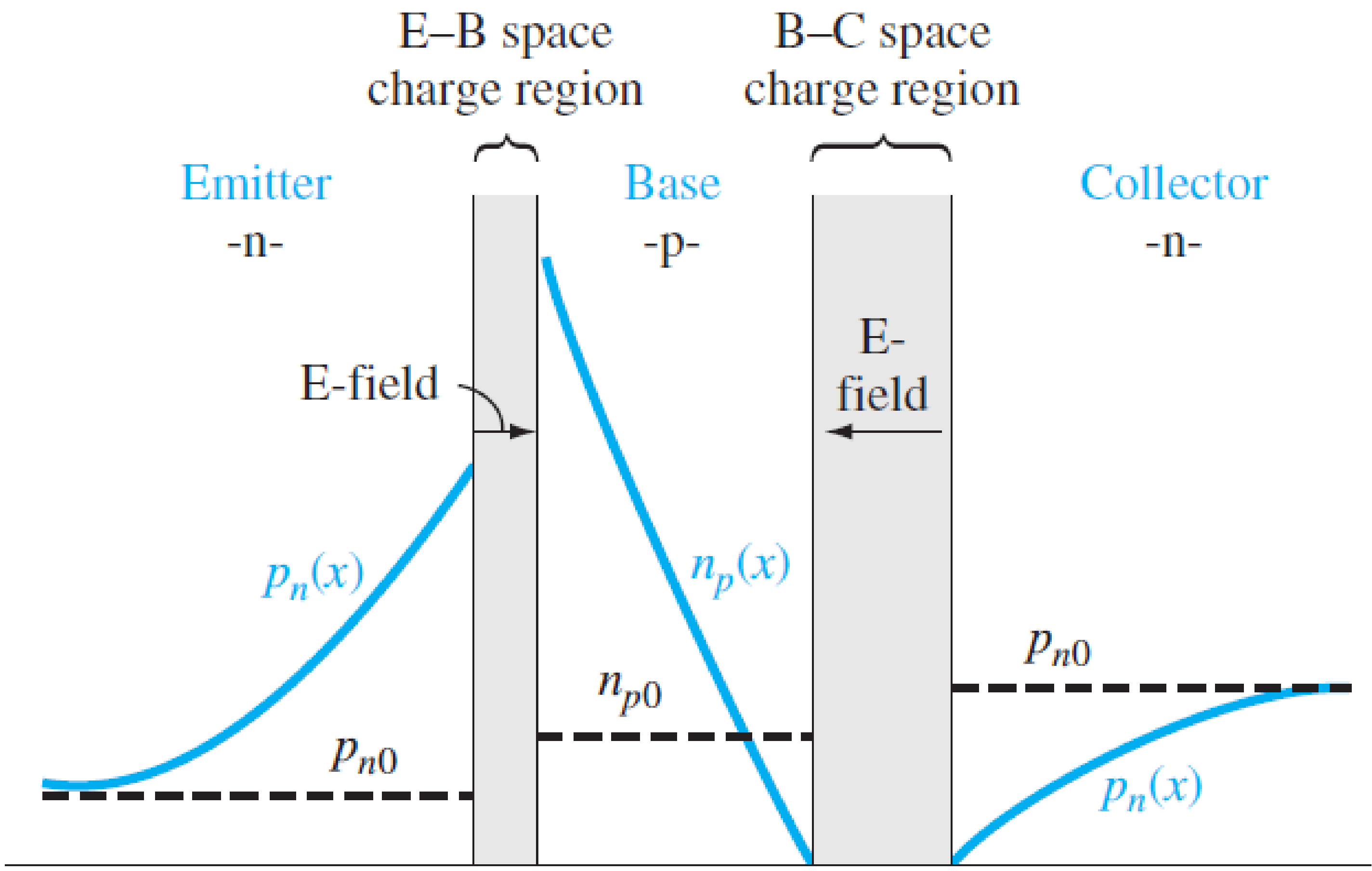
- The large gradient in the electron concentration means that electrons injected from the emitter will diffuse across the base region into the B–C space charge region, where the electric field will sweep the electrons into the collector.
- We want as many electrons as possible to reach the collector 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.**

Biasing



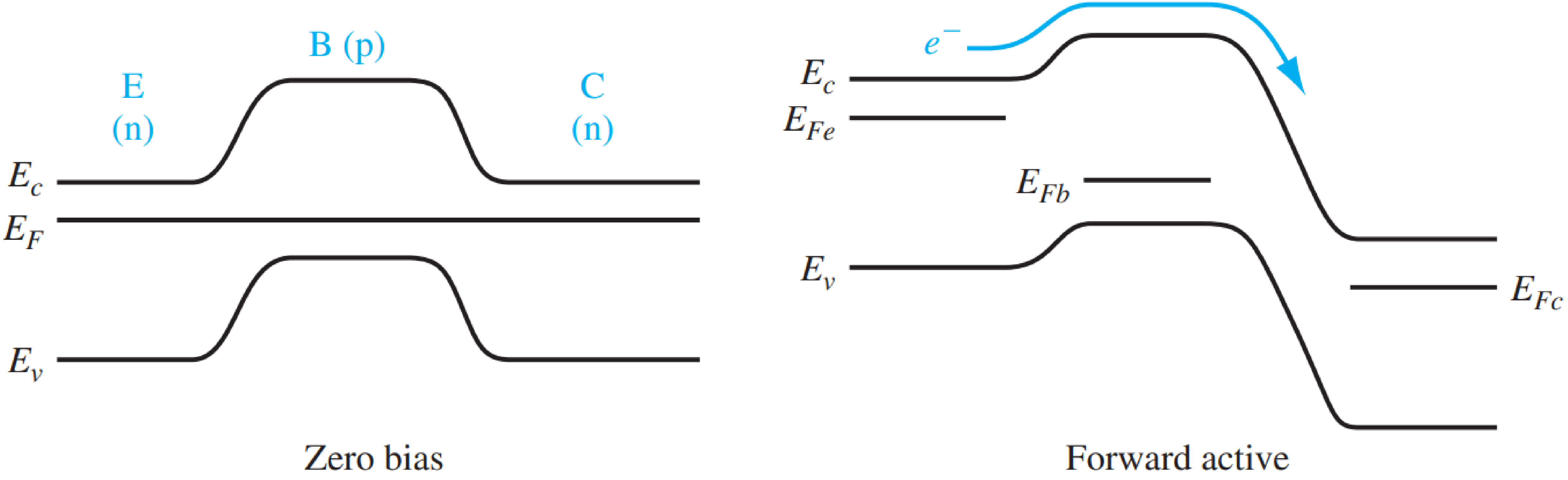
i_E
E
n^{++}
p^{+}
n
C
i_C
R_E
$-\ v_{BE}\ +$
B
$-\ v_{CB}\ +$
R_C
$-\ V_{BB}\ +$
$-\ V_{CC}\ +$

(a)

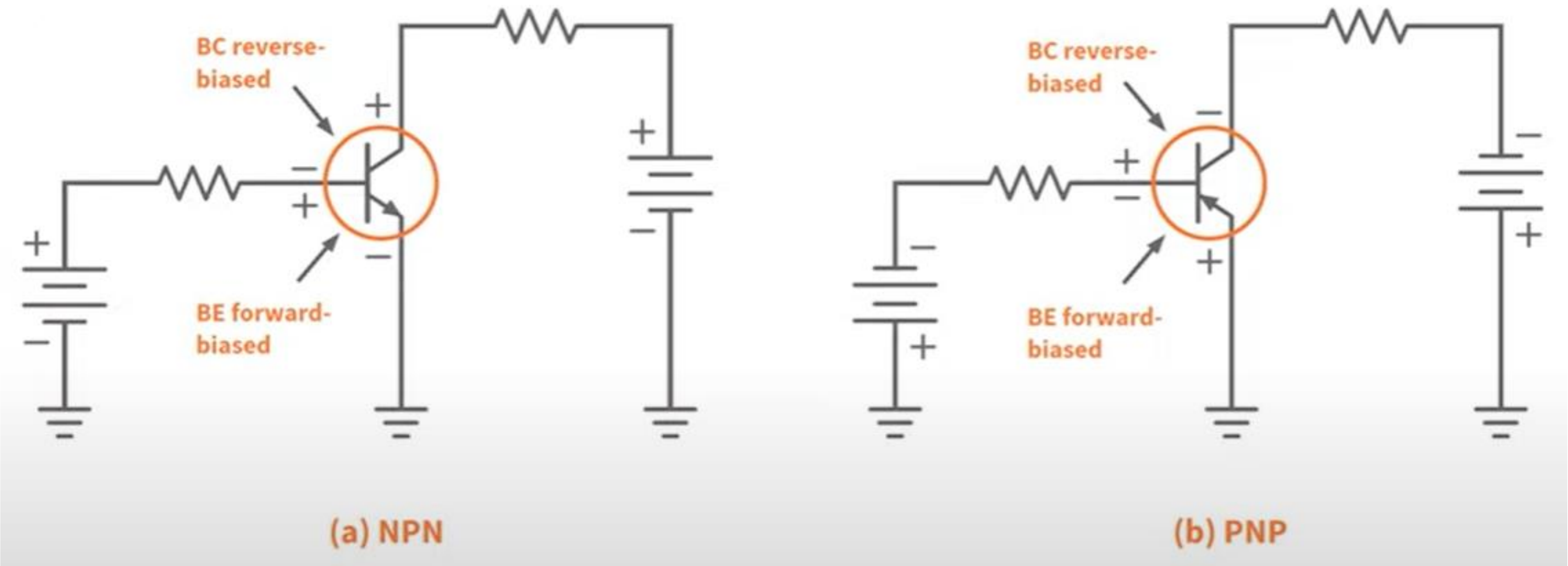


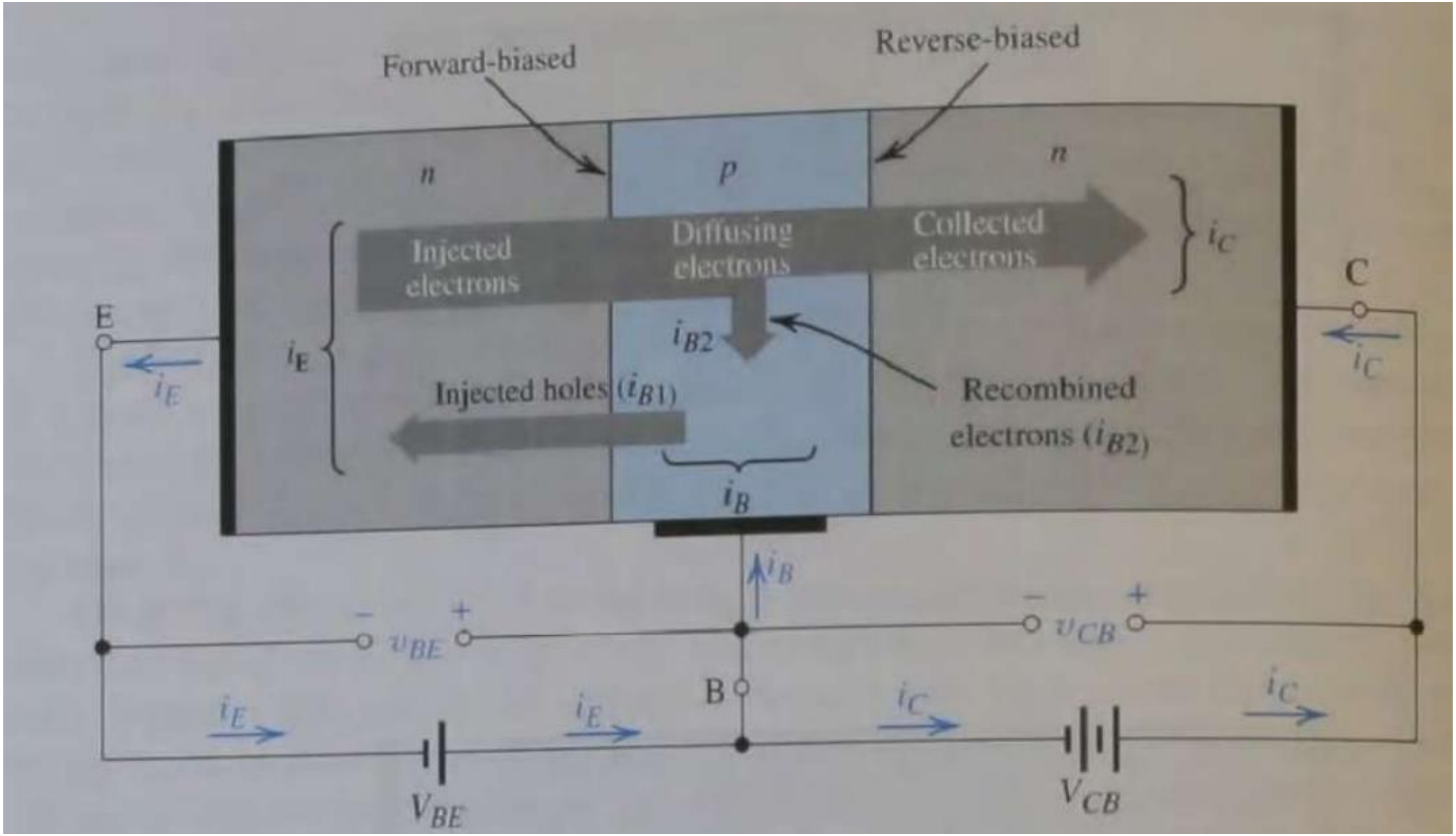
E–B space charge region
B–C space charge region
Emitter
-n-
Base
-p-
Collector
-n-
E-field
E-field
$p_n(x)$
$n_p(x)$
p_{n0}
n_{p0}
p_{n0}
$p_n(x)$

(b)

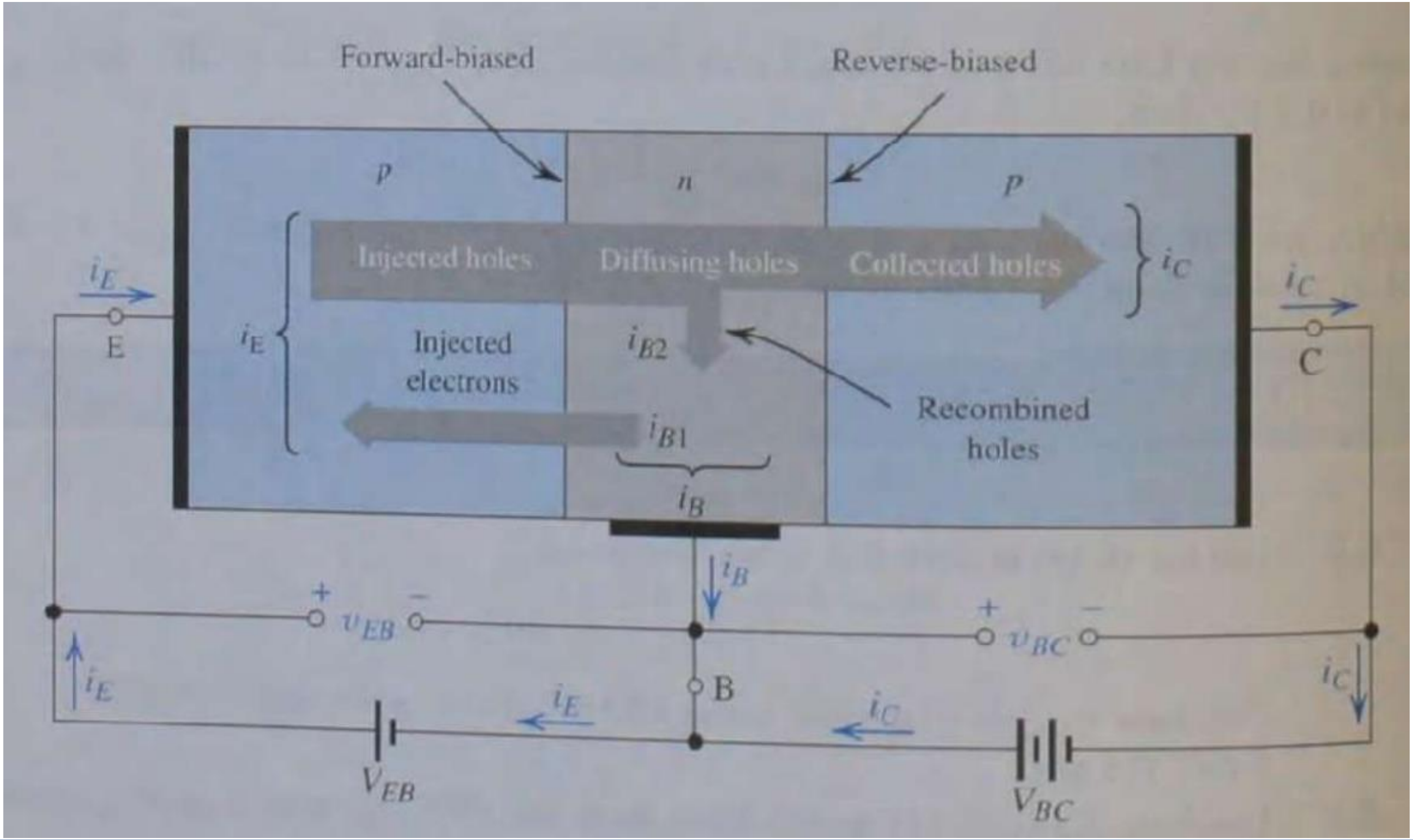


E
(n)
B (p)
C
(n)
E_c
E_F
E_v
Zero bias
e^-
E_c
E_{Fe}
E_{Fb}
E_v
E_{Fc}
Forward active


BC reverse-biased
BE forward-biased
(a) NPN
BC reverse-biased
BE forward-biased
(b) PNP



Forward-biased
Reverse-biased
n
p
n
Injected electrons
Diffusing electrons
Collected electrons
i_C
C
E
i_E
i_{B2}
i_E
i_C
Injected holes (i_{B1})
Recombined electrons (i_{B2})
i_B
i_B
v_{BE}
v_{CB}
B
i_E
i_E
i_C
i_C
V_{BE}
V_{CB}


Forward-biased
Reverse-biased
p
n
p
Injected holes
Diffusing holes
Collected holes
i_C
i_E
i_E
E
Injected electrons
i_{B2}
Recombined holes
i_{B1}
i_B
i_C
C
i_B
+
v_{EB}
−
+
v_{BC}
−
i_E
B
i_E
i_C
i_C
V_{EB}
V_{BC}

Transistor Current Relation

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

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

where the **saturation current** I_S is given by

$$I_S = A_E q D_n n_{p0} / W$$

Substituting $n_{p0} = n_i^2/N_A$, where n_i is the intrinsic carrier density and N_A is the doping concentration in the base, we can express I_S as

$$I_S = \frac{A_E q D_n n_i^2}{N_A W} \tag{6.4}$$

Emitter current:

where I_{S2} involves the minority carrier hole parameters in the emitter. The total emitter current is the sum of the two components, or

$$i_E = i_{E1} + i_{E2} = i_C + i_{E2} = I_{SE} \exp\left(\frac{v_{BE}}{V_t}\right) \tag{12.4}$$

All current components are functions of exp (V_{BE}/V_t), the ratio of collector current to emitter current is a constant which is called as **common base current gain.**

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

[see Equation (6.13)]. Therefore, the current i_{Bb} is also proportional to $\exp(v_{BE}/V_t)$. The total base current is the sum of i_{Ba} and i_{Bb} and is 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 $\exp(v_{BE}/V_t)$. We can then write

$$\frac{i_C}{i_B} \equiv \beta \qquad (12.6)$$

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

$\beta = \alpha/1-\alpha$

- Generally, β is in the range of 50 to 200.
- β is highly influenced by two factors:
  - Width of the base region
  - Relative doping of the base and emitter region N_A/N_D

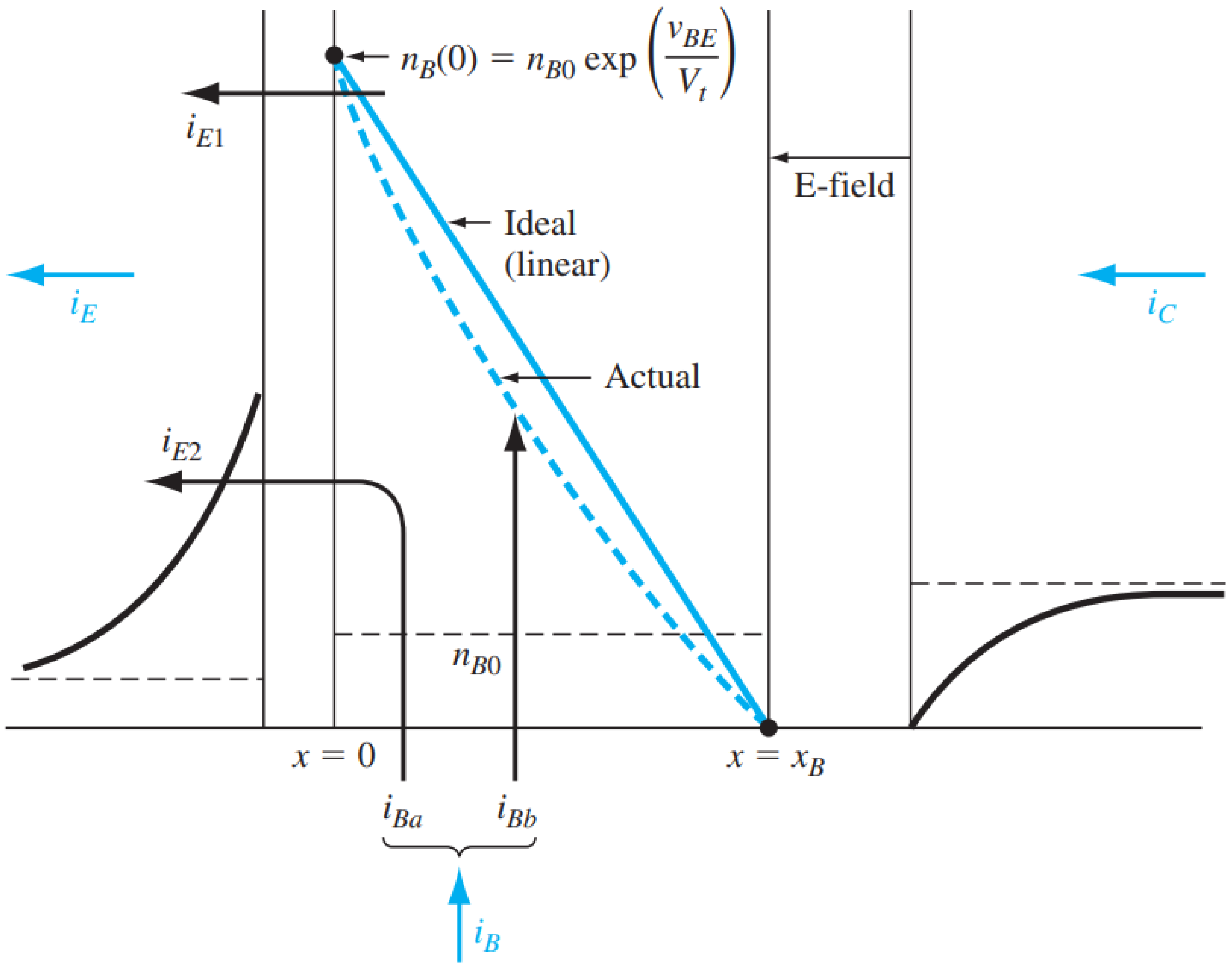


Figure 12.6 | Minority carrier distributions and basic currents in a forward-biased npn bipolar transistor.

Modes of operation

- If the B–E voltage is zero or reverse biased ($V_{BE} \leq 0$), 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, If V_{CC} is large enough and if V_R is small enough, then $V_{CB} > 0$, which means that the B–C junction is reverse biased for this npn transistor. Again, this condition is the **forward-active region** of operation.

- As the forward-biased B–E voltage increases, the collector current and hence VR will also increase.
- The increase in V_R means that the reverse-biased C–B voltage decreases, or V_{CB} 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 V_R and the B–C junction will become forward biased (V_{CB}<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.

- Fourth mode of operation is **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.

Mode of operation	**Biasing condition**
Forward active	• B-E junction is forward biased and B-C junction is reverse biased.
Saturation	• B-E and B-C junctions are forward biased • I_c is not dependent on V_{BE}
Cut off	• B-E and B-C junctions are reverse biased • All currents in transistor are zero.
Inverse active	• B-E junction is reverse biased and B-C junction is forward biased.

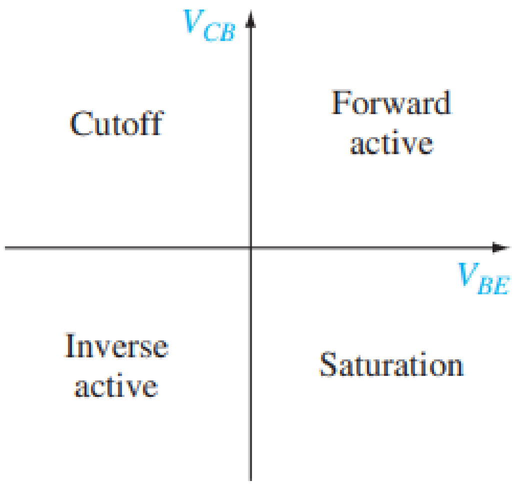


Figure 12.10 | Junction voltage conditions for the four operating modes of a bipolar transistor.

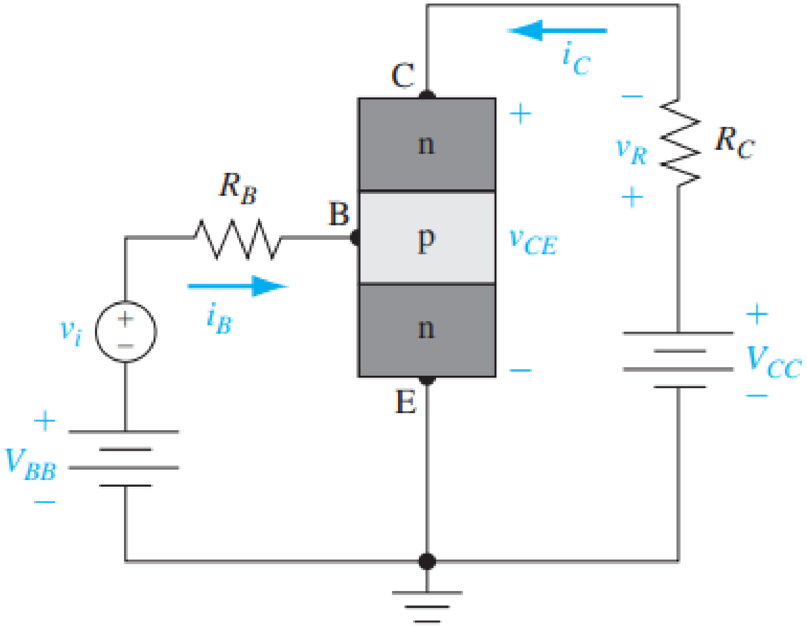
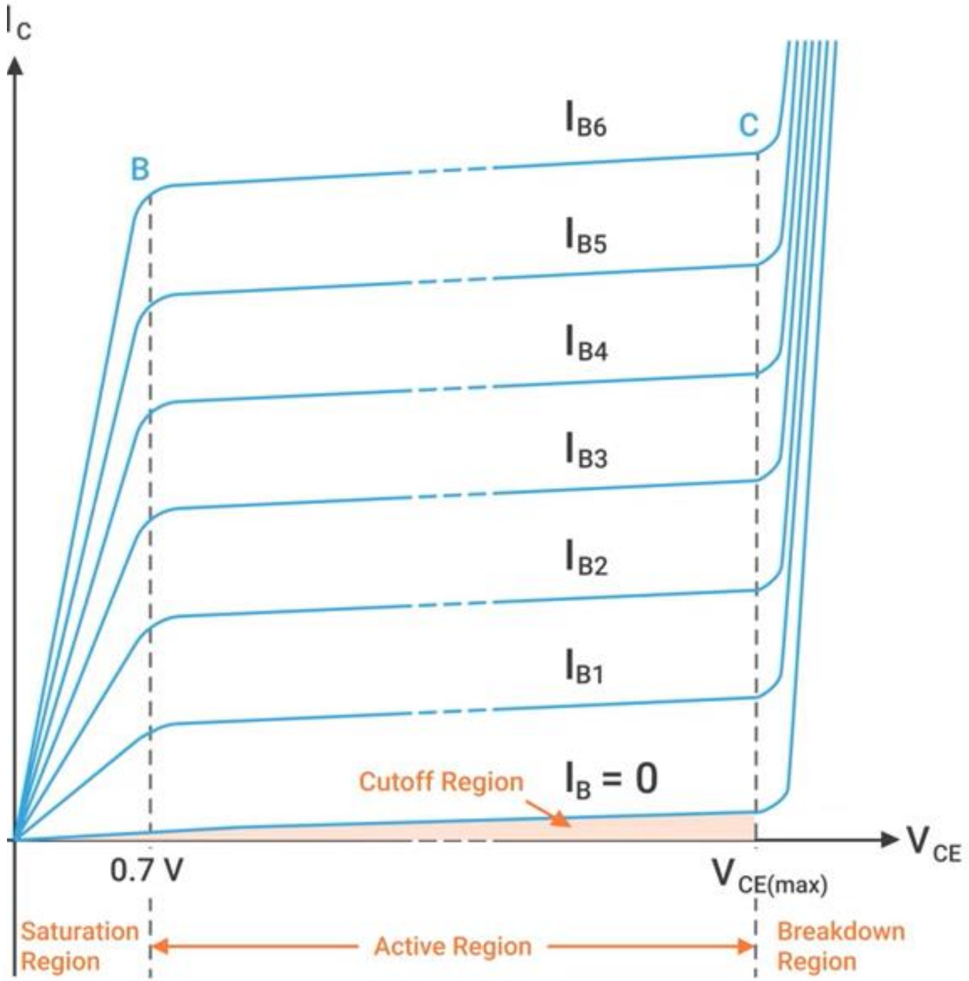
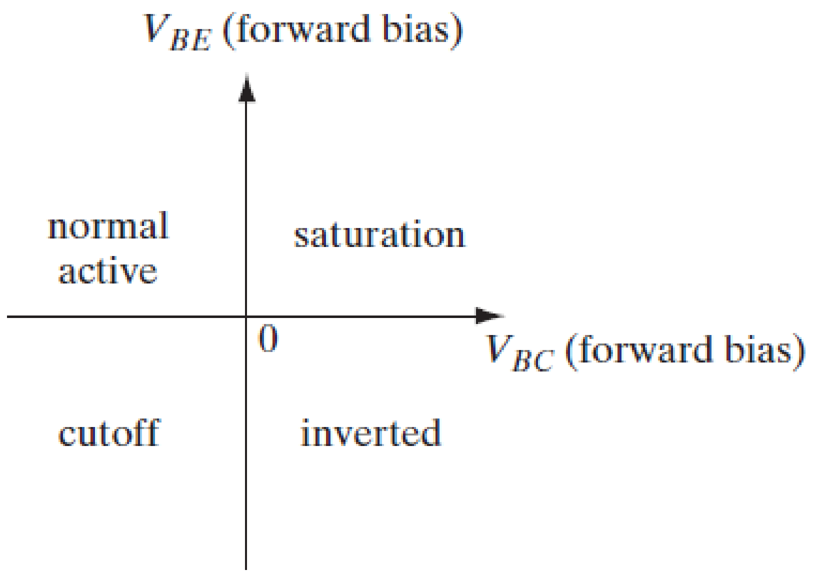


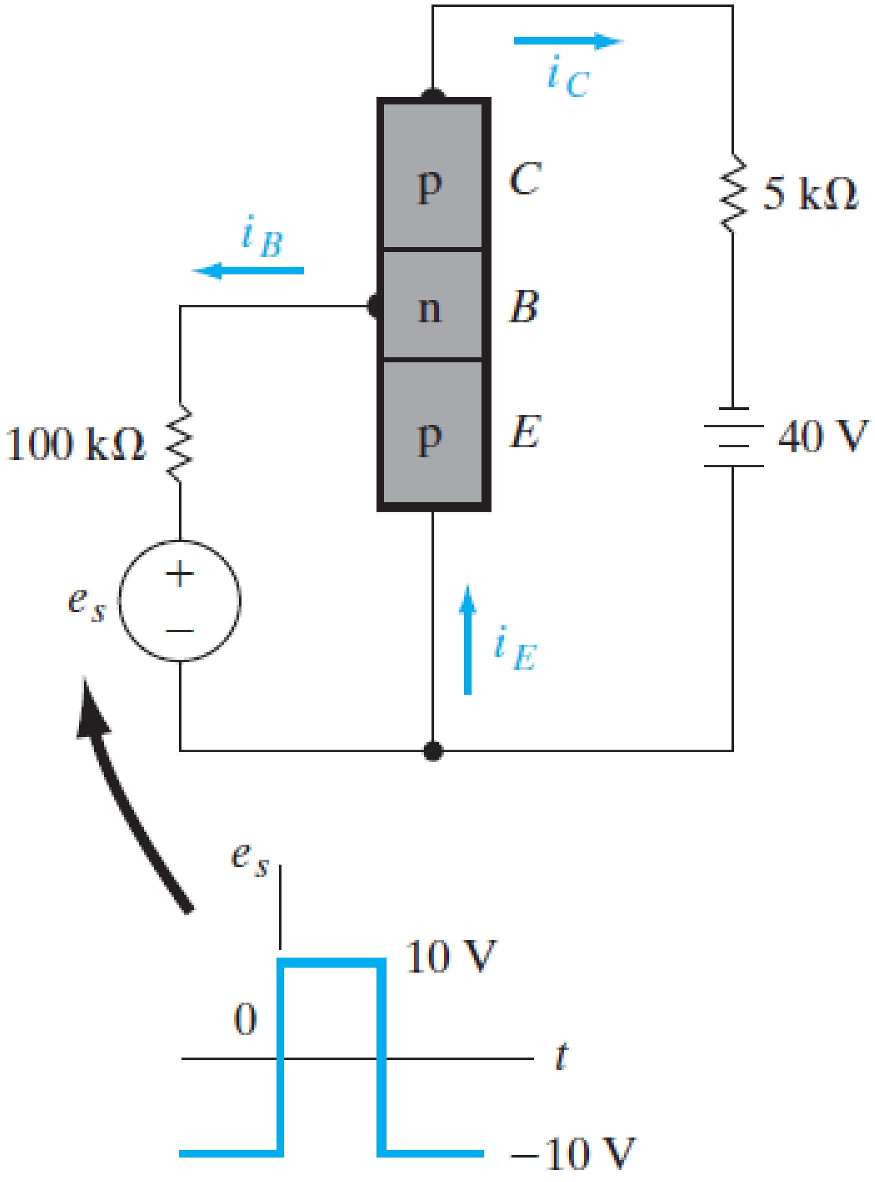
Figure 12.11 | Common-emitter npn bipolar circuit configuration with a time-varying signal voltage v_i included in the base–emitter loop.



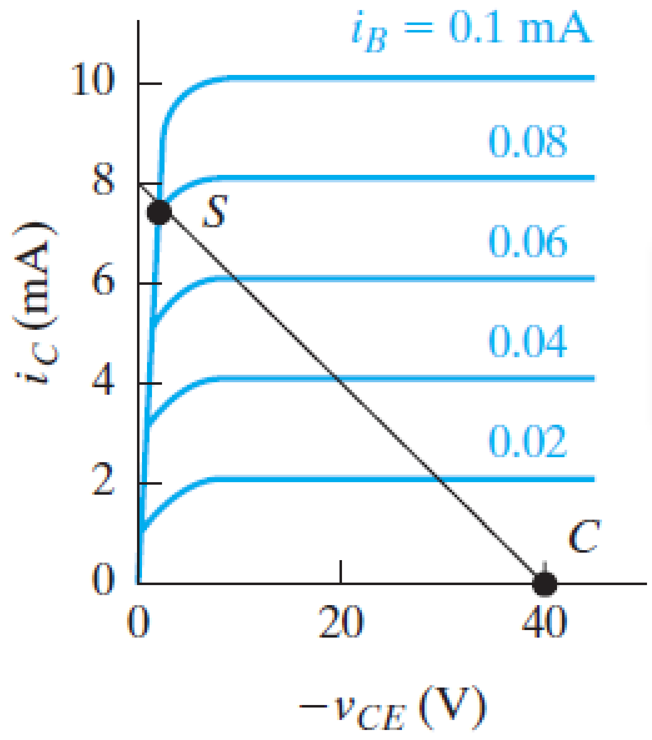


V_{BE} (forward bias)
normal active
saturation
0
V_{BC} (forward bias)
cutoff
inverted

(c)



i_C
p
C
5 kΩ
i_B
n
B
100 kΩ
p
E
40 V
e_s
+
−
i_E
e_s
10 V
0
t
−10 V



i_B = 0.1 mA
10
0.08
8
S
6
0.06
0.04
4
2
0.02
0
C
0
20
40
i_C (mA)
$-v_{CE}$ (V)

Current-voltage relationship of BJT in active mode

$$i_C = I_s e^{v_{BE}/V_T}$$

$$i_B = \frac{i_C}{\beta} = \left(\frac{I_s}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_s}{\alpha}\right) e^{v_{BE}/V_T}$$

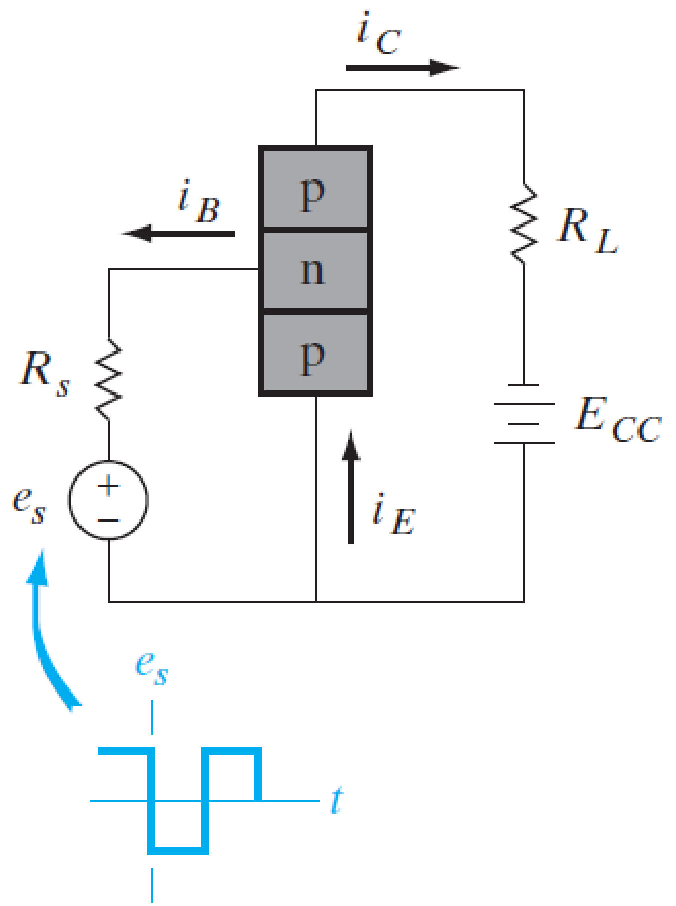
$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta + 1}$$

$$i_C = \beta i_B \qquad i_E = (\beta + 1) i_B$$

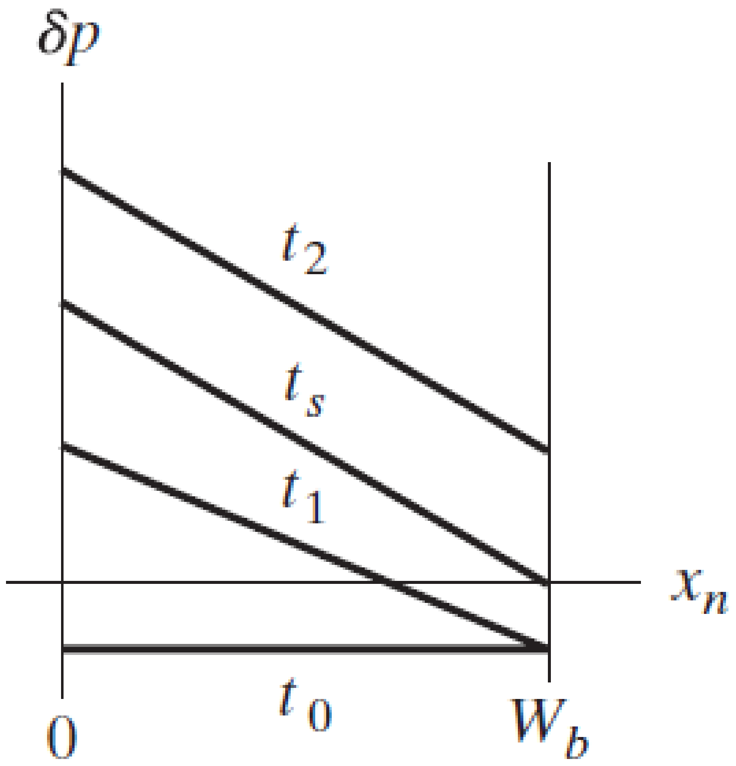
$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta + 1}$$

- For pnp transistor, replace V_{BE} with V_{EB}

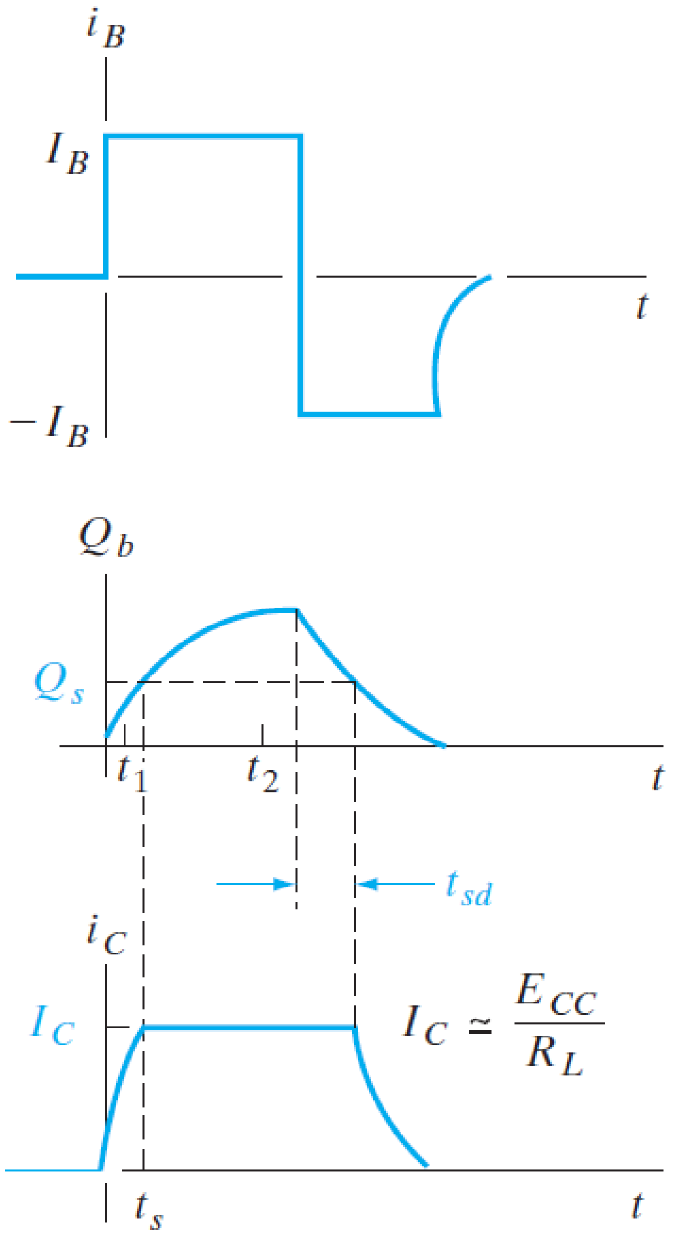
Switching cycle



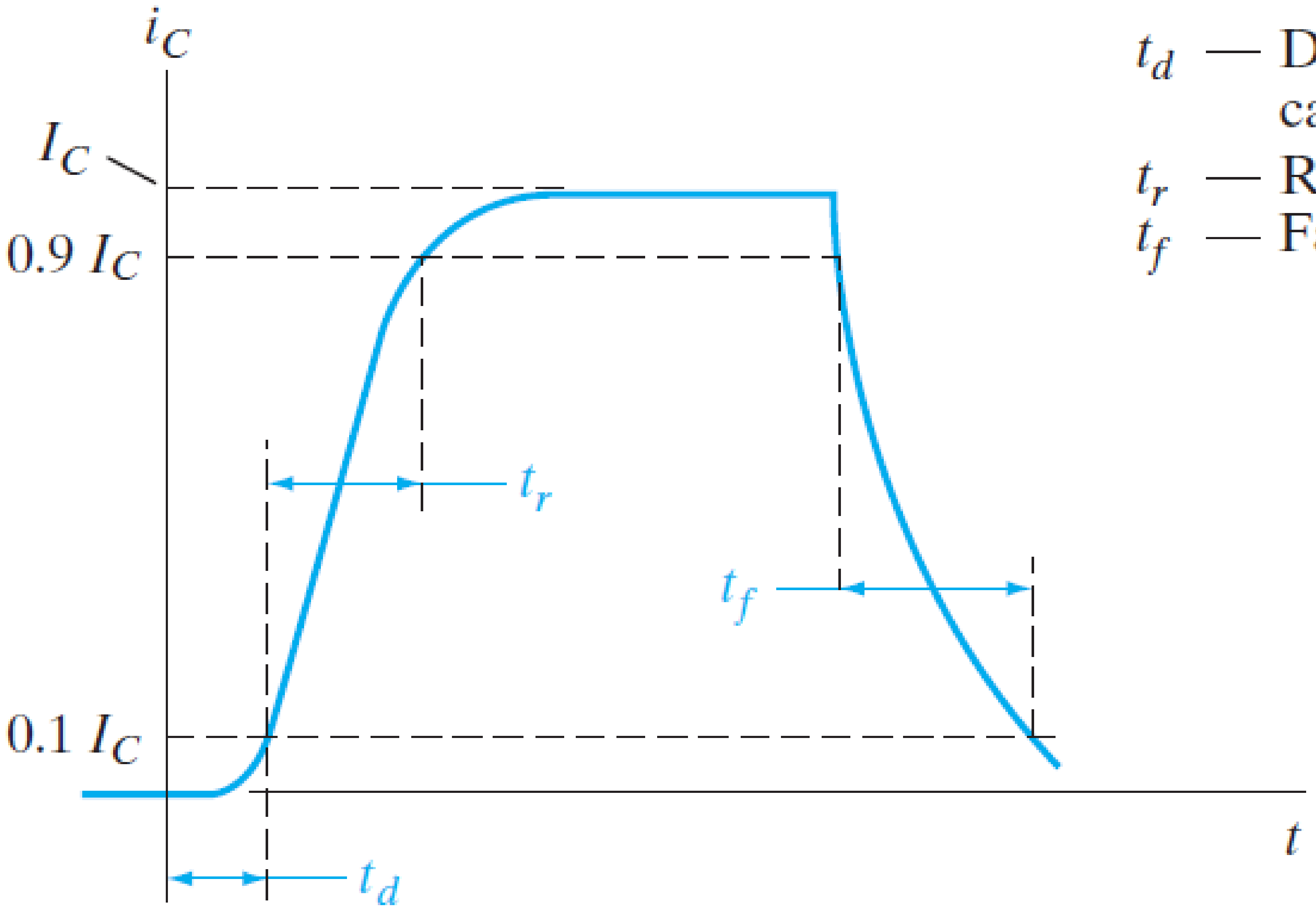
(a)



t_0 — Cutoff
t_1 — Normal active region
t_s — Beginning of saturation
t_2 — Final saturated state



- If the device is originally in the cutoff condition, a step increase of base current to I_B causes the hole distribution to increase approximately.
- At time t_s the device enters saturation, and the hole distribution reaches its final state at t_2.
- As the stored charge in the base Q_b increases, there is an increase in the collector current I_C.
- The collector current does not increase beyond its value at the beginning of saturation t_s, however, We can approximate this saturated collector current as $I_C \simeq E_{CC} > R_L$, where E_{CC} is the value of the collector circuit battery and R_L is the load resistor



t_d — Delay time while junction capacitance is charging
t_r — Rise time from $0.1-0.9\ I_C$
t_f — Fall time from $0.9-0.1\ I_C$

Secondary effects

- Effects of non-uniform doping in the base region of the transistor
  - graded doping can lead to a drift component of charge transport across the base, adding to the diffusion of carriers from emitter to collector.
- Effects of large reverse bias on the collector junction
  - widening the space charge region about the junction and avalanche multiplication.
- Transistor parameters are affected at high current levels by the degree of injection and by heating effects.
- Several structural effects that are important in practical devices, such as **asymmetry** in the areas of the emitter and collector junctions, **series resistance** between the base contact and the active part of the base region, and **non-uniformity of injection** at the emitter junction.

Several nonideal effects are considered:

1. Base width modulation, or Early effect—the change in the neutral base width with a change in B–C voltage, producing a change in collector current with a change in B–C or C–E voltage.
2. High-injection effects that cause the collector current to increase at a slower rate with base–emitter voltage.
3. Emitter bandgap narrowing that produces a smaller emitter injection efficiency because of a very large emitter region doping concentration.
4. Current crowding effects that produce a larger current density at the emitter edge than in the center of the emitter.
5. A nonuniform base doping concentration that induces an electric field in the base region, which aids the flow of minority carriers across the base.
6. Two breakdown voltage mechanisms—punch-through and avalanche.

Base width modulation or Early effect

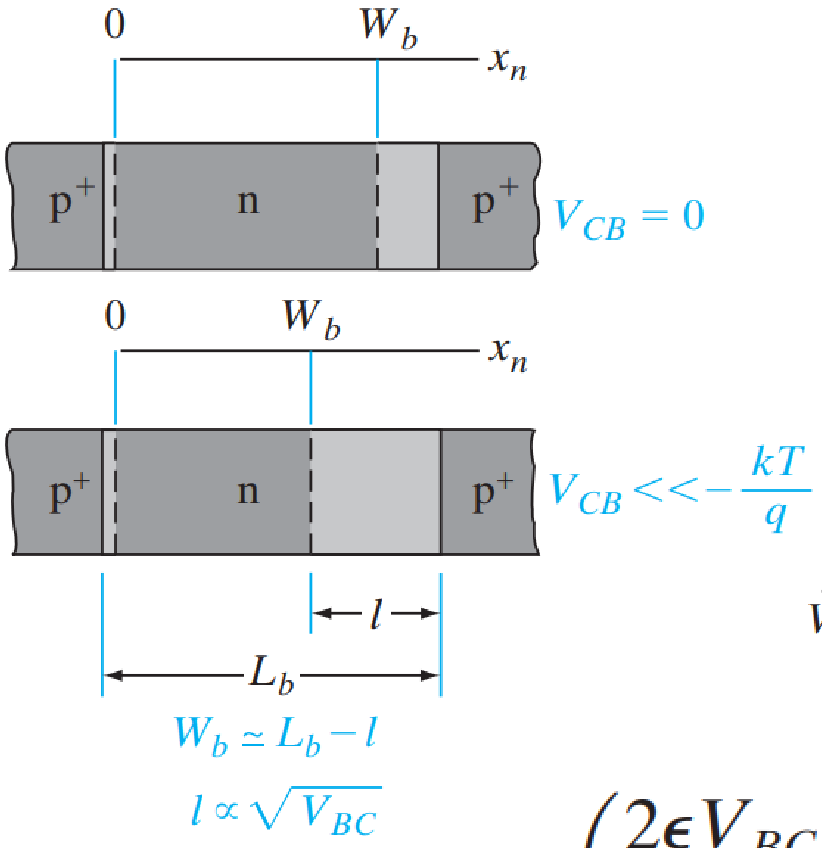
- A reduction in base width will cause the gradient in the minority carrier concentration to increase, which in turn causes an increase in the diffusion current. This effect is known as base width modulation; it is also called the Early effect.

$$I_C = g_o (V_{CE} + V_A) = \frac{1}{r_o}(V_{CE} + V_A) \quad (12.45b)$$

showing that the collector current is now an explicit function of the collector–emitter voltage or the collector–base voltage.

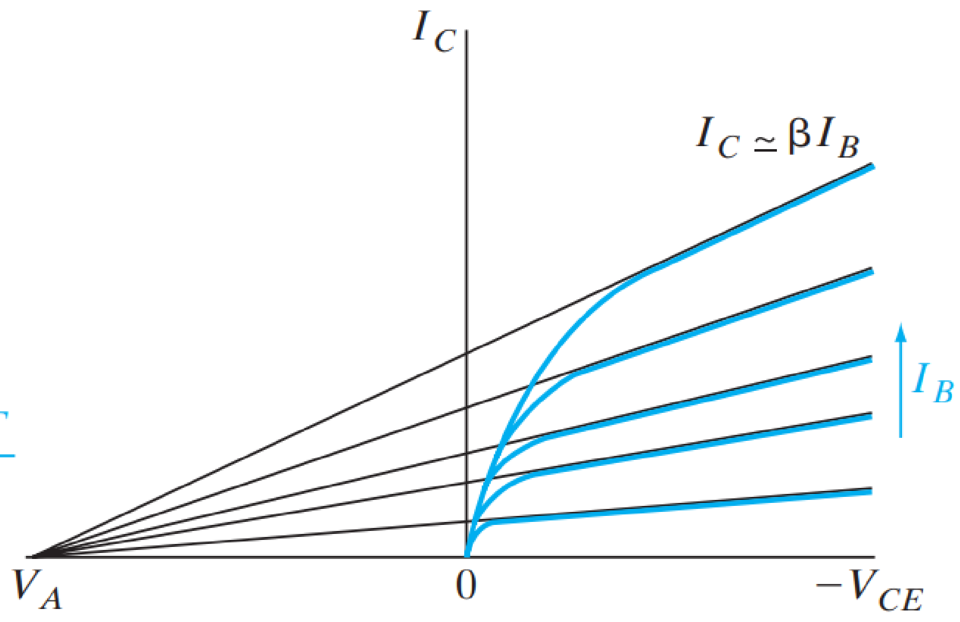
Punch through and Avalanche breakdown

- If the reverse bias on the collector junction is increased far enough, it is possible to decrease W_b to the extent that the collector depletion region essentially fills the entire base.
- In this punch-through condition **holes are swept directly from the emitter region to the collector**, and transistor action is lost.
- In most cases, however, avalanche breakdown of the collector junction occurs before punch-through is reached.
- As the reverse-biased B–C voltage increases, the B–C space charge region widens and extends farther into the neutral base. It is possible for the B–C depletion region to penetrate completely through the base and reach the B–E space charge region, the effect called **punch-through.**



(a)

$$l = \left(\frac{2\epsilon V_{BC}}{qN_d}\right)^{1/2}$$



(b)

Figure 7–18

The effects of base narrowing on the characteristics ot a p^+-n-p^+ transistor: (a) decrease in the effective base width as the reverse bias on the collector junction is increased; (b) common-emitter characteristics showing the increase in I_C with increased collector voltage. The black lines in (b) indicate the extrapolation of the curves to the Early voltage V_A.

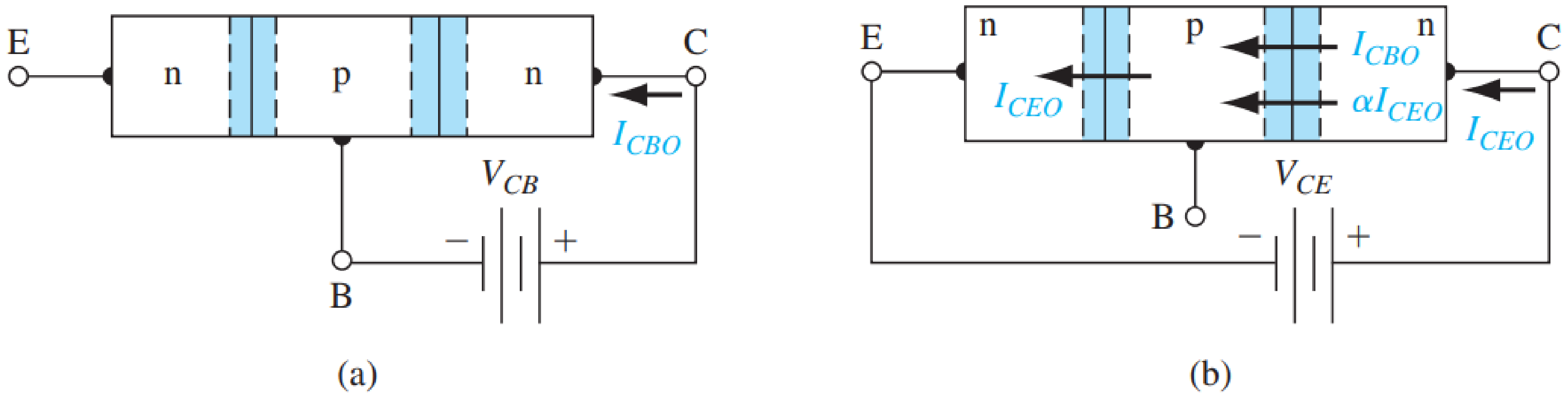


Figure 12.34 | (a) Open-emitter configuration with saturation current I_{CBO}: (b) Open-base configuration with saturation current I_{CEO}.

When the transistor is biased in the open-emitter configuration as in Figure 12.34a, the current I_{CBO} at breakdown becomes $I_{CBO} \rightarrow MI_{CBO}$, where M is the multiplication factor. An empirical approximation for the multiplication factor is usually written as

$$M = \frac{1}{1 - (V_{CB}/BV_{CBO})^n} \tag{12.56}$$

where n is an empirical constant, usually between 3 and 6, and BV_{CBO} is the B–C breakdown voltage with the emitter left open.

Emitter bandgap narrowing

- As the emitter doping concentration increases, E_g increases;
- Thus, p_{E0} does not continue to decrease with increasing emitter doping NE.
- If p_{E0} starts to increase because of the bandgap narrowing, the emitter injection efficiency begins to fall off instead of continuing to increase with increased emitter doping.

High injection

- The excess minority carrier concentration in the base, and hence the **collector current, will increase at a slower rate** with B–E voltage in high injection than low injection.
- The high-injection effect is very similar to the effect of a series resistance in a pn junction diode.

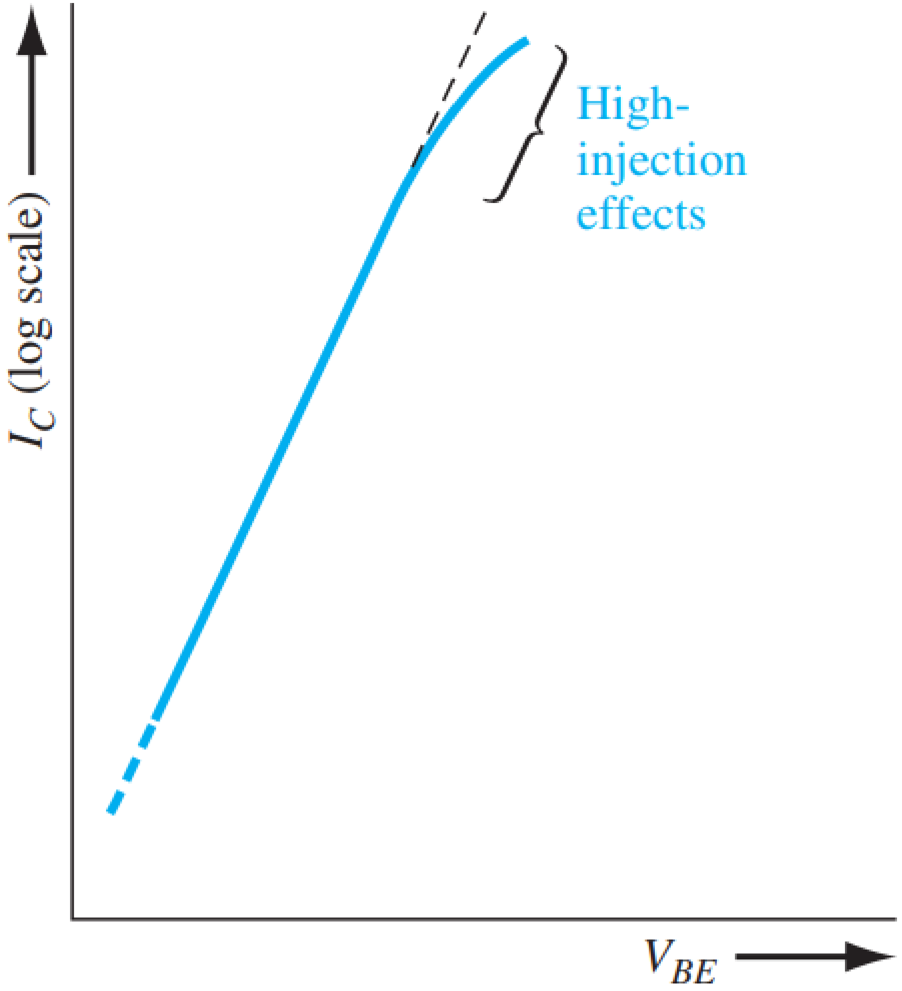


Figure 12.25 | Collector current versus base–emitter voltage showing high-injection effects.

- The first effect is a reduction in emitter injection efficiency.
- Since the majority carrier hole concentration at $x = 0$ increases with high injection, more holes are injected back into the emitter because of the forward-biased B–E voltage.
- An increase in the hole injection causes an increase in the J_{pE} current and an increase in J_{pE} reduces the emitter injection efficiency.
- The common-emitter current gain decreases, then, with high injection.
- The low gain at low currents is due to the small recombination factor and the drop-off at the high current is due to the high-injection effect.

Current crowding

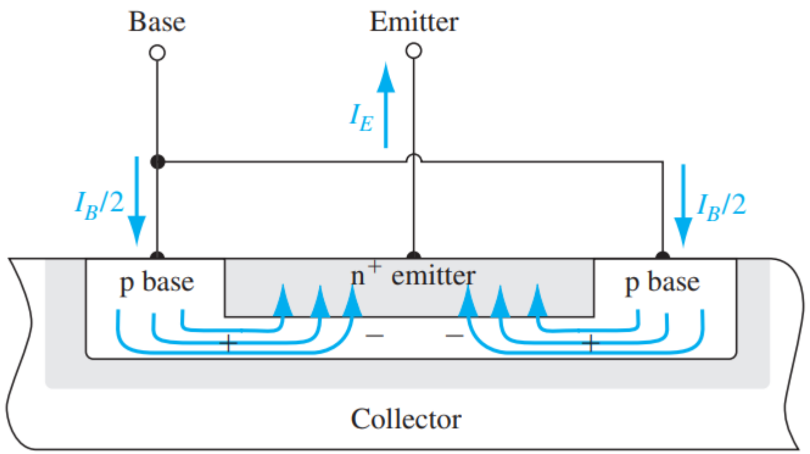


Figure 12.27 | Cross section of an npn bipolar transistor showing the base current distribution and the lateral potential drop in the base region.

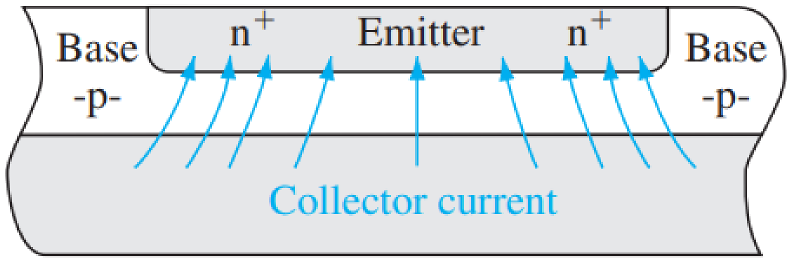


Figure 12.28 | Cross section of an npn bipolar transistor showing the emitter current crowding effect.

- The number of electrons from the emitter injected into the base is exponentially dependent on the B–E voltage.
- With the lateral voltage drop in the base between the edge and center of the emitter, more electrons will be injected near the emitter edges than in the center, causing the **emitter current to be crowded** toward the edges.
- The larger current density near the emitter edge may cause localized **heating effects** as well as **localized high-injection** effects.
- To avoid the current crowding effect, these transistors are usually designed with **narrow emitter widths**.

Table 12.3 | Summary of limiting factors

Emitter injection efficiency

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

Base transport factor

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

Recombination factor

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

Common-base current gain

$$\alpha = \gamma\alpha_T\delta \approx \frac{1}{1 + \frac{N_B}{N_E} \cdot \frac{D_E}{D_B} \cdot \frac{x_B}{x_E} + \frac{1}{2}\left(\frac{x_B}{L_B}\right)^2 + \frac{J_{r0}}{J_{s0}} \exp\left(\frac{-eV_{BE}}{2kT}\right)}$$

Common-emitter current gain

$$\beta = \frac{\alpha}{1-\alpha} \approx \frac{1}{\frac{N_B}{N_E} \cdot \frac{D_E}{D_B} \cdot \frac{x_B}{x_E} + \frac{1}{2}\left(\frac{x_B}{L_B}\right)^2 + \frac{J_{r0}}{J_{s0}} \exp\left(\frac{-eV_{BE}}{2kT}\right)}$$

- Three equivalent circuits or mathematical models of the transistor are considered.
- **Ebers–Moll model** and equivalent circuit are applicable in any of the transistor operating modes.
- The **Gummel–Poon model** is convenient to use when nonuniform doping exists in the transistor.
- The **small-signal hybrid-pi model** applies to transistors operating in the forward-active mode in linear amplifier circuits.