Physics of Semiconductor Devices

Lecture 9

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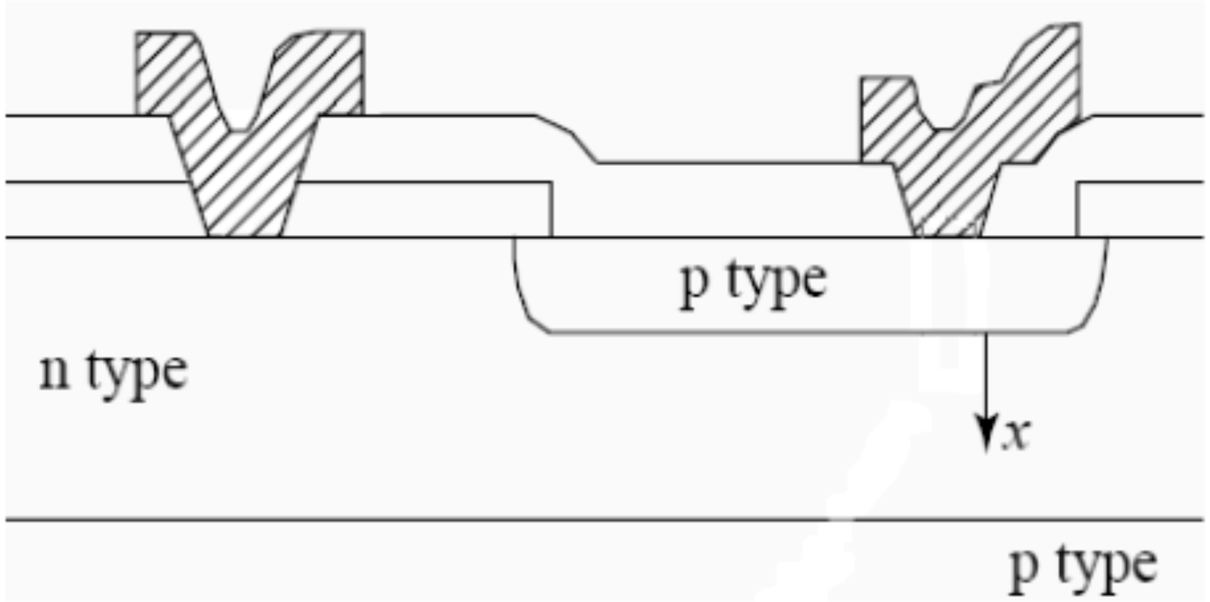
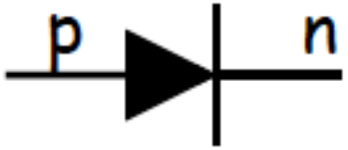
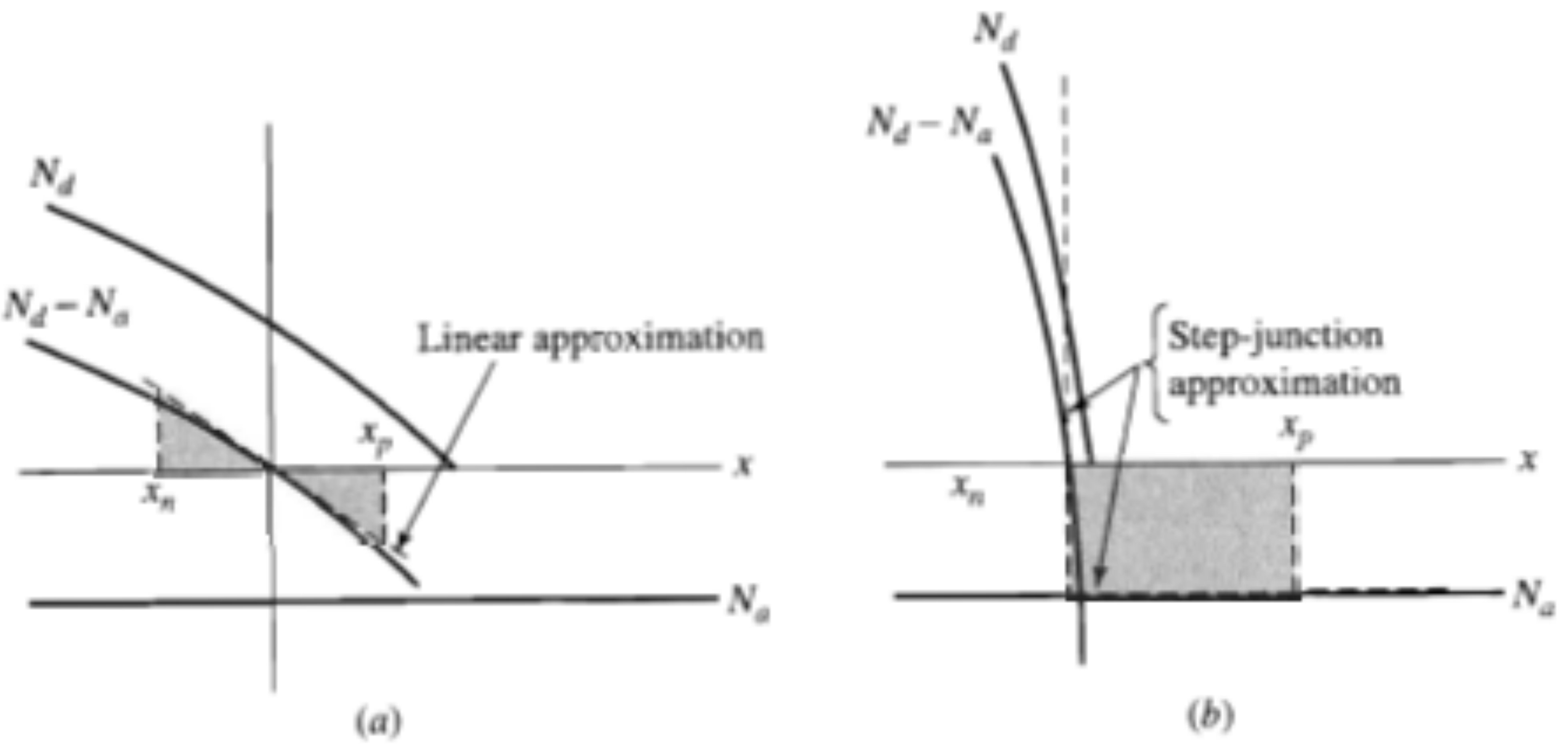
pn junctions

pn junctions are found in:

- diodes
- solar cells
- LEDs
- isolation
- JFETs
- bipolar transistors
- MOSFETs
- solid state lasers






N_d
$N_d - N_a$
Linear approximation
x_p
x
x_n
N_a
(a)
N_d
$N_d - N_a$
Step-junction approximation
x_p
x
x_n
N_a
(b)

7.3 | REVERSE APPLIED BIAS

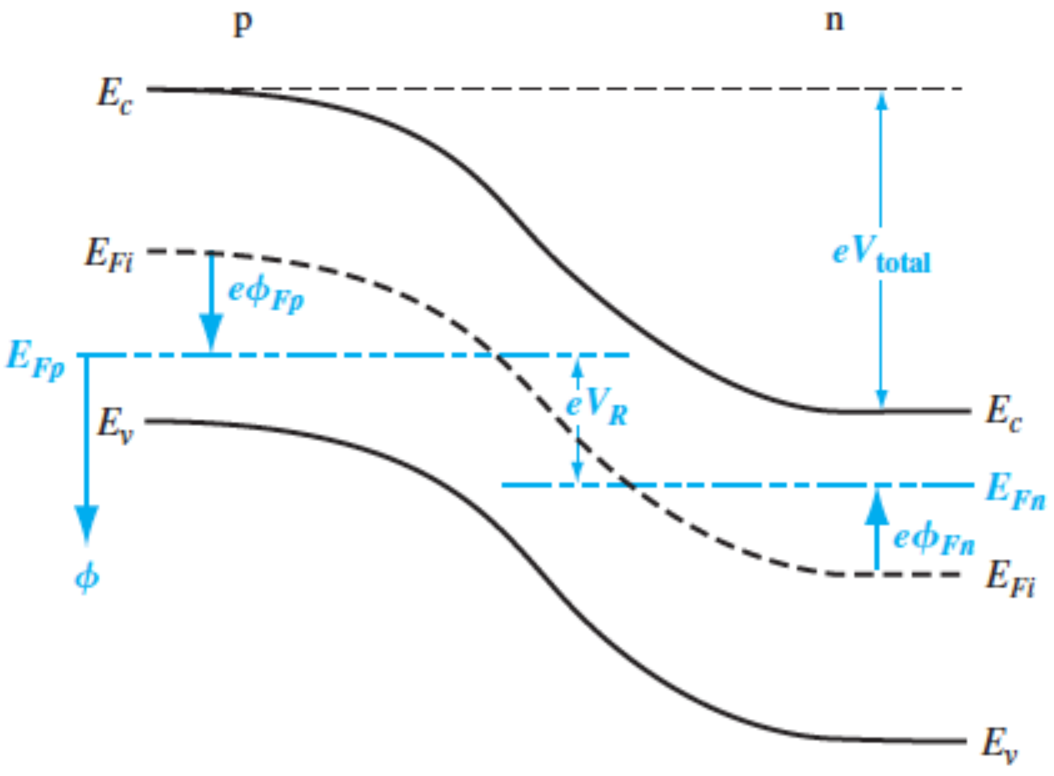


Figure 7.7 | Energy-band diagram of a pn junction under reverse bias.

$$V_{\text{total}} = V_{bi} + V_R$$

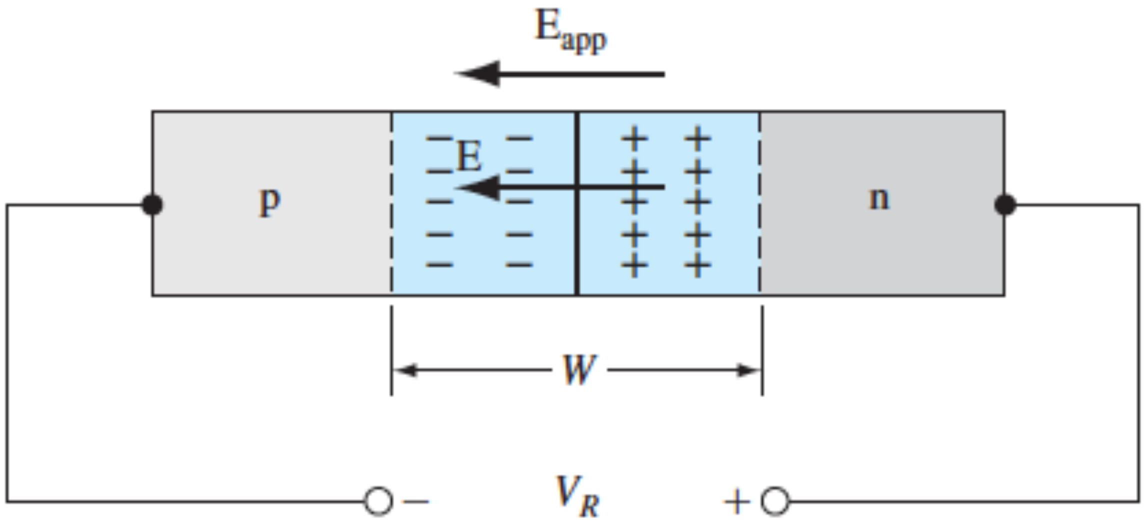


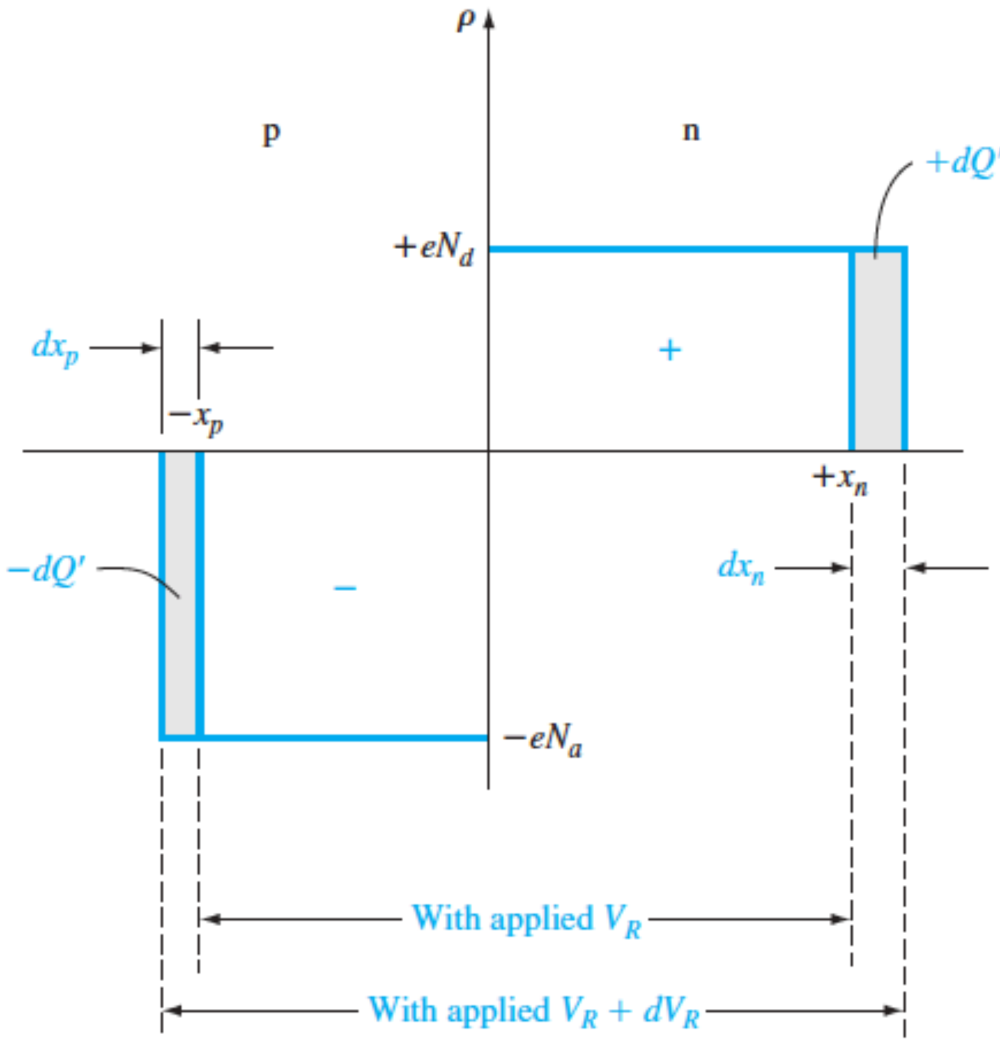
Figure 7.8 | A pn junction, with an applied reverse-biased voltage, showing the directions of the electric field induced by V_R and the space charge electric field.

$$\boxed{W = \left\{ \frac{2\epsilon_s(V_{bi} + V_R)}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}}$$

$$\boxed{\mathrm{E}_{\max} = -\left\{ \frac{2e(V_{bi} + V_R)}{\epsilon_s} \left(\frac{N_a N_d}{N_a + N_d} \right) \right\}^{1/2}}$$

$$\boxed{\mathrm{E}_{\max} = \frac{-2(V_{bi} + V_R)}{W}}$$

7.3.2 Junction Capacitance



$$C' = \frac{dQ'}{dV_R}$$

$$dQ' = eN_d\,dx_n = eN_a\,dx_p$$

For the total potential barrier, Equation (7.28) may be written as

$$x_n = \left\{ \frac{2\epsilon_s(V_{bi} + V_R)}{e} \left[\frac{N_a}{N_d} \right] \left[\frac{1}{N_a + N_d} \right] \right\}^{1/2} \tag{7.40}$$

The junction capacitance can be written as

$$C' = \frac{dQ'}{dV_R} = eN_d \frac{dx_n}{dV_R} \tag{7.41}$$

so that

$$\boxed{C' = \left\{ \frac{e\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2}} \tag{7.42}$$

in the reverse-biased voltage dV_R will uncover additional positive charges in the n region and additional negative charges in the p region. The junction capacitance is defined as

$$C' = \frac{dQ'}{dV_R} \tag{7.38}$$

where

$$dQ' = eN_d\,dx_n = eN_a\,dx_p \tag{7.39}$$

The differential charge dQ' is in units of C/cm^2 so that the capacitance C' is in units of farads per square centimeter F/cm^2), or capacitance per unit area.

For the total potential barrier, Equation (7.28) may be written as

$$x_n = \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{1/2} \tag{7.40}$$

The junction capacitance can be written as

$$C' = \frac{dQ'}{dV_R} = eN_d\frac{dx_n}{dV_R} \tag{7.41}$$

so that

$$\boxed{C' = \left\{\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2}} \tag{7.42}$$

Exactly the same capacitance expression is obtained by considering the space charge region extending into the p region x_p. The junction capacitance is also referred to as the *depletion layer capacitance.*

7.3.3 One-Sided Junctions

Consider a special pn junction called the one-sided junction. If, for example, $N_a \gg N_d$, this junction is referred to as a p^+n junction. The total space charge width, from Equation (7.34), reduces to

$$W \approx \left\{ \frac{2\epsilon_s(V_{bi} + V_R)}{eN_d} \right\}^{1/2} \tag{7.44}$$

Considering the expressions for x_n and x_p, we have for the p^+n junction

$$x_p \ll x_n \tag{7.45}$$

and

$$W \approx x_n \tag{7.46}$$

Almost the entire space charge layer extends into the low-doped region of the junction. This effect can be seen in Figure 7.10.

The junction capacitance of the p^+n junction reduces to

$$C' \approx \left\{ \frac{e\epsilon_s N_d}{2(V_{bi} + V_R)} \right\}^{1/2} \tag{7.47}$$

The depletion layer capacitance of a one-sided junction is a function of the doping concentration in the low-doped region. Equation (7.47) may be manipulated to give

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d} \tag{7.48}$$

which shows that the inverse capacitance squared is a linear function of applied reverse-biased voltage.

$$C' \approx \left\{ \frac{e\epsilon_s N_d}{2(V_{bi} + V_R)} \right\}^{1/2}$$

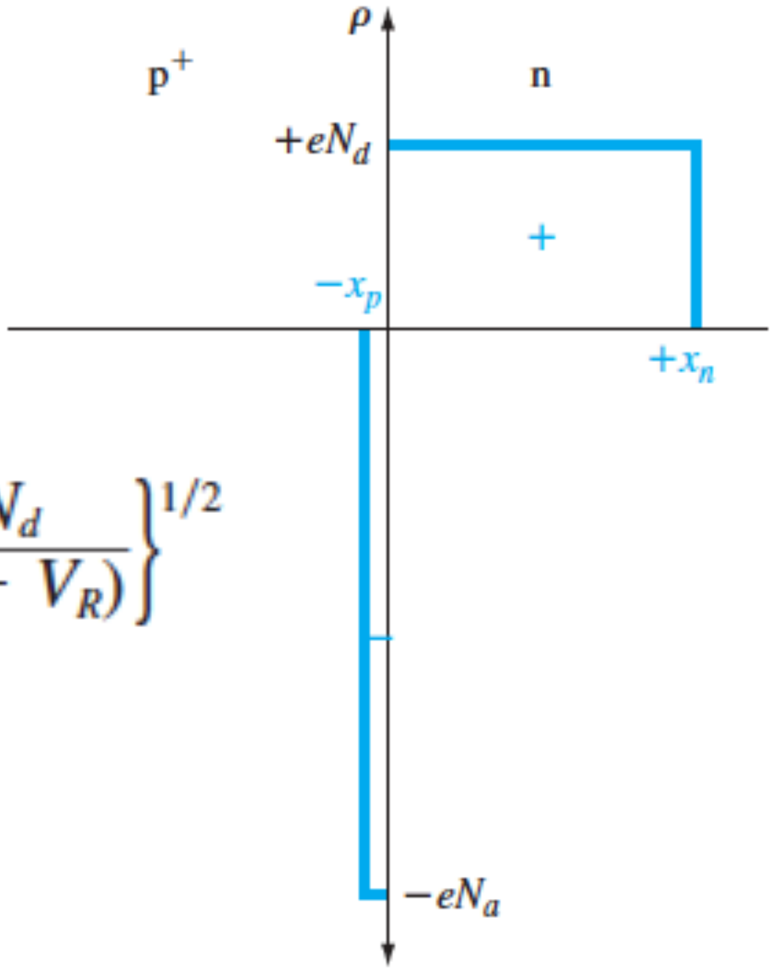


Figure 7.10 | Space charge density of a one-sided p⁻n junction.

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

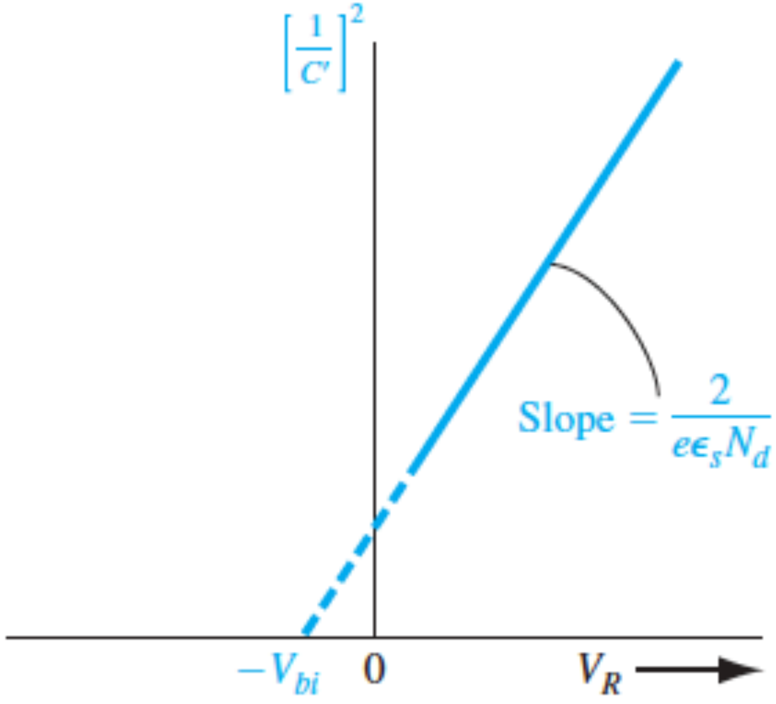


Figure 7.11 | $(1/C')^2$ versus V_R of a uniformly doped pn junction.

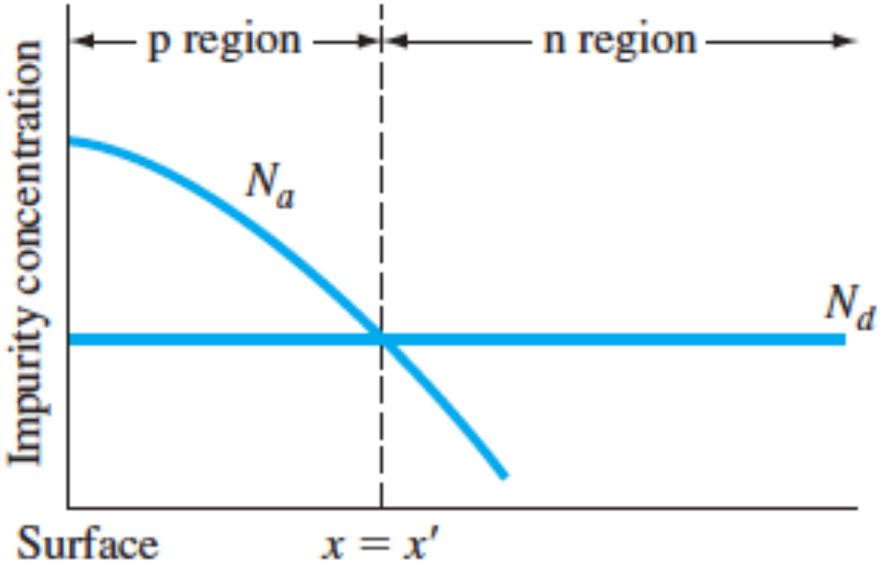


Figure 7.16 | Impurity concentrations of a pn junction with a nonuniformly doped p region.

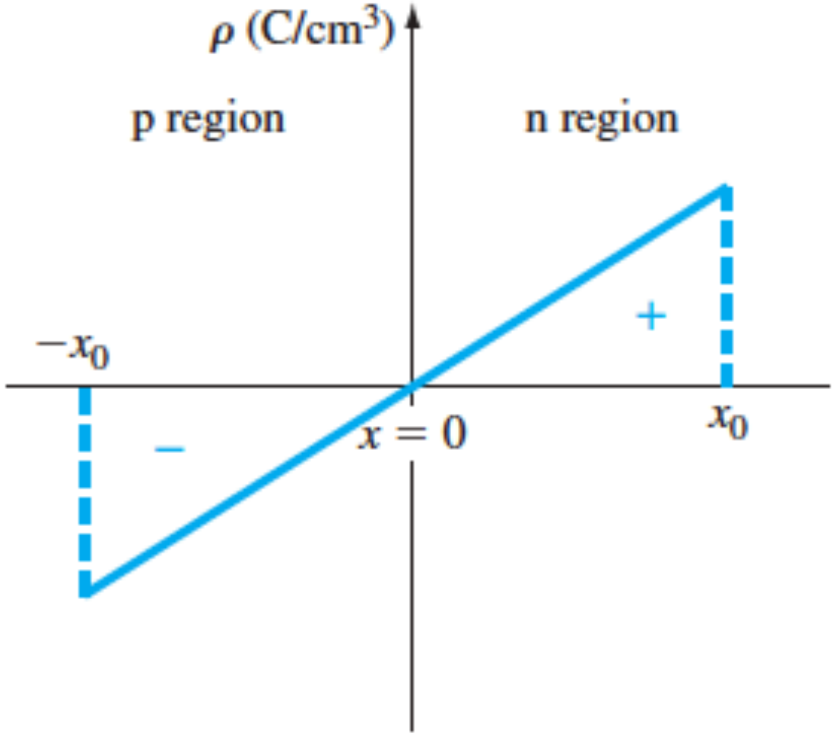


Figure 7.17 | Space charge density in a linearly graded pn junction.

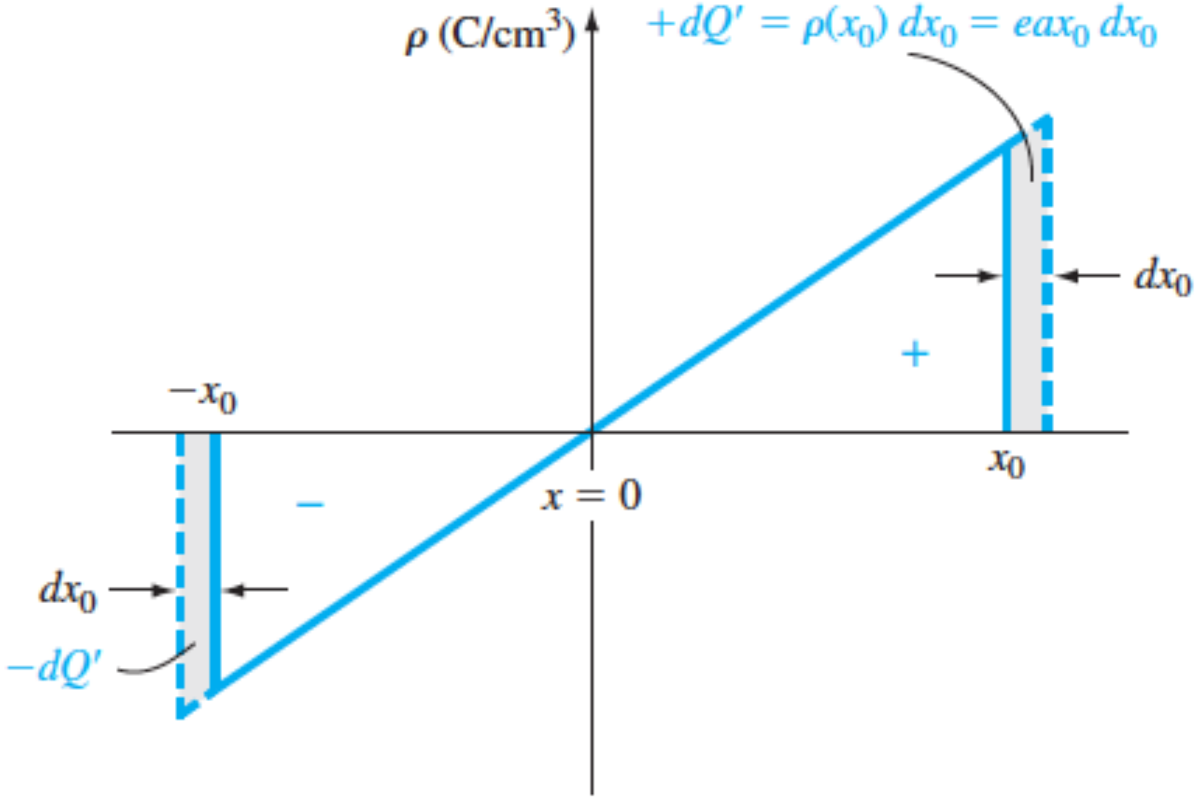


Figure 7.18 | Differential change in space charge width with a differential change in reverse-biased voltage for a linearly graded pn junction.

$$C' = \frac{dQ'}{dV_R} = (eax_0)\frac{dx_0}{dV_R}$$

$$C' = \left\{\frac{ea\epsilon_s^2}{12(V_{bi} + V_R)}\right\}^{1/3}$$

7.4 | JUNCTION BREAKDOWN

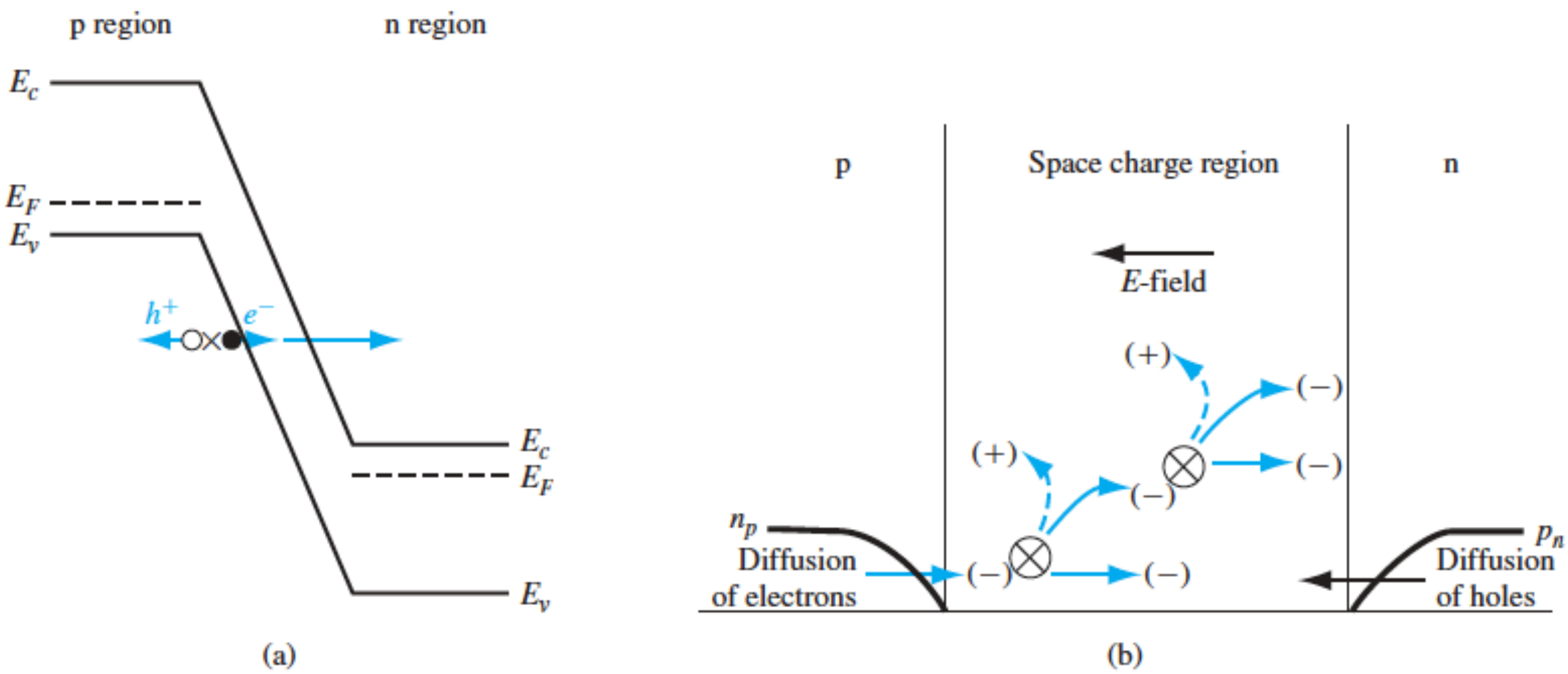


Figure 7.12 | (a) Zener breakdown mechanism in a reverse-biased pn junction; (b) avalanche breakdown process in a reverse-biased pn junction.

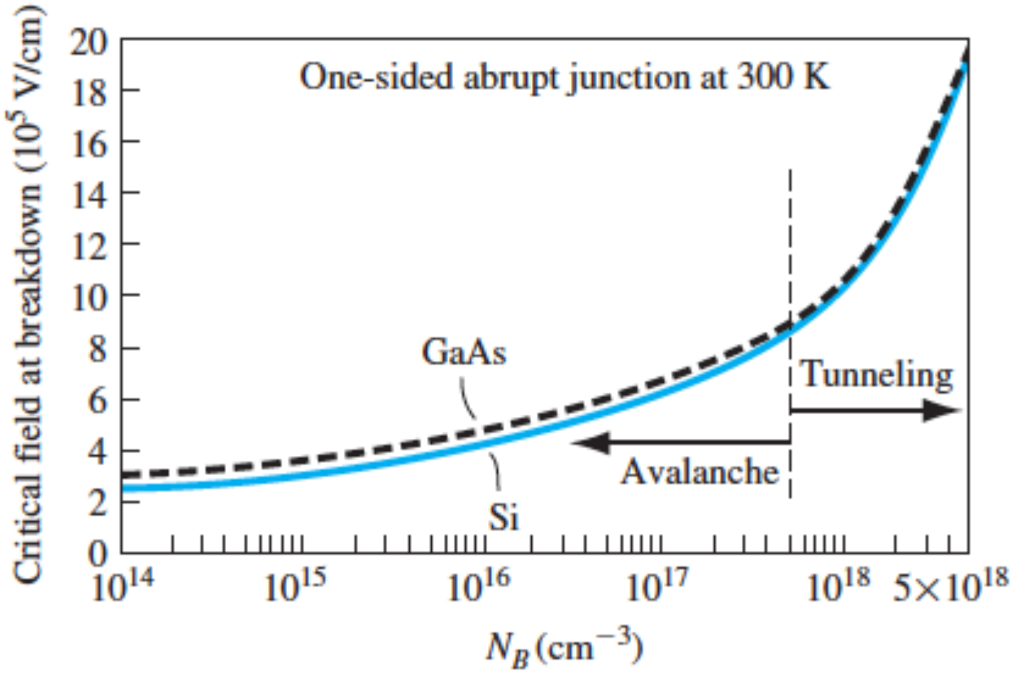


Figure 7.14 | Critical electric field at breakdown in a one-sided junction as a function of impurity doping concentrations. *(From Sze and N_g[14].)*

The depletion width x_n is given approximately as

$$x_n \approx \left\{ \frac{2\epsilon_s V_R}{e} \cdot \frac{1}{N_d} \right\}^{1/2} \tag{7.60}$$

where V_R is the magnitude of the applied reverse-biased voltage. We have neglected the built-in potential V_{bi}.

If we now define V_R to be the breakdown voltage V_B, the maximum electric field, E_{max}, will be defined as a critical electric field, E_{crit}, at breakdown. Combining Equations (7.59) and (7.60), we may write

$$\boxed{V_B = \frac{\epsilon_s \mathrm{E}_{crit}^2}{2eN_B}} \tag{7.61}$$

where N_B is the semiconductor doping in the low-doped region of the one-sided junction. The critical electric field, plotted in Figure 7.14, is a slight function of doping.

PN Diode I-V Relation

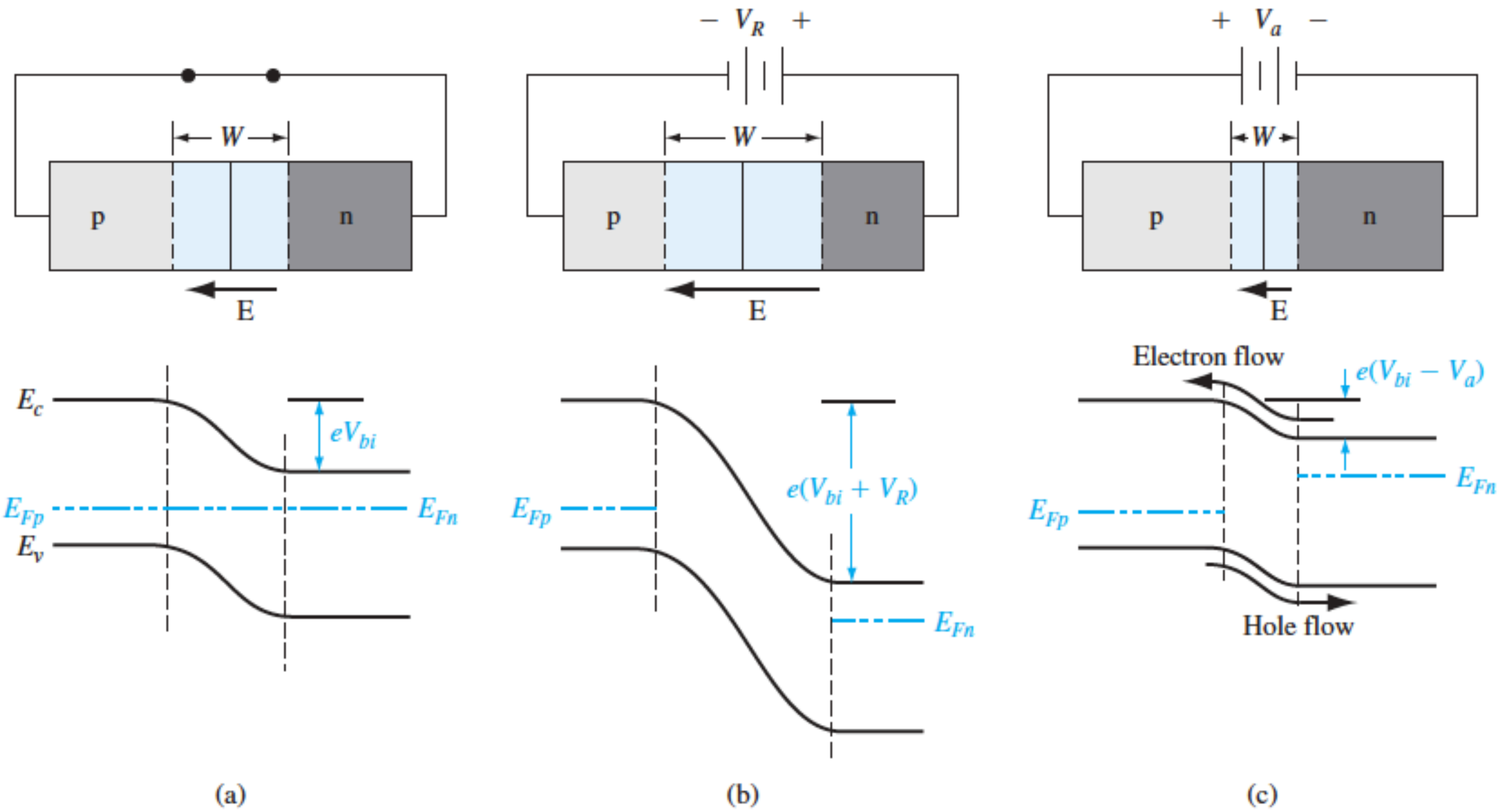


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.

8.1.2 Ideal Current–Voltage Relationship

The ideal current–voltage relationship of a pn junction is derived on the basis of four assumptions. (The last assumption has three parts, but each part deals with current.) They are:

1. The abrupt depletion layer approximation applies. The space charge regions have abrupt boundaries, and the semiconductor is neutral outside of the depletion region.
2. The Maxwell–Boltzmann approximation applies to carrier statistics.
3. The concepts of low injection and complete ionization apply.

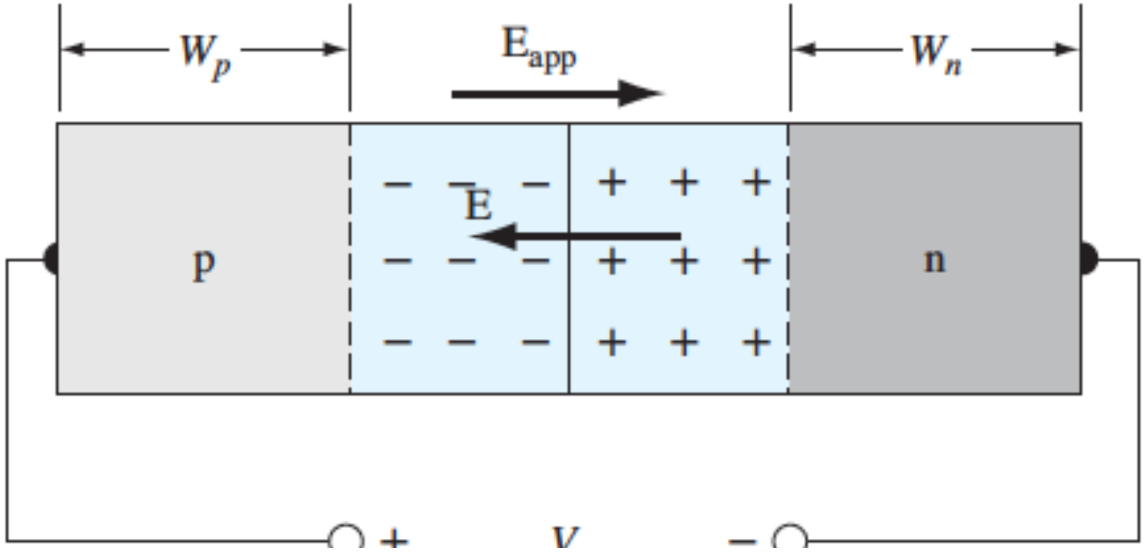
4a. The total current is a constant throughout the entire pn structure.

4b. The individual electron and hole currents are continuous functions through the pn structure.

4c. The individual electron and hole currents are constant throughout the depletion region.

Table 8.1 | Commonly used terms and notation for this chapter

Term	Meaning
N_a	Acceptor concentration in the p region of the pn junction
N_d	Donor concentration in the n region of the pn junction
$n_{n0} = N_d$	Thermal-equilibrium majority carrier electron concentration in the n region
$p_{p0} = N_a$	Thermal-equilibrium majority carrier hole concentration in the p region
$n_{p0} = n_i^2/N_a$	Thermal-equilibrium minority carrier electron concentration in the p region
$p_{n0} = n_i^2/N_d$	Thermal-equilibrium minority carrier hole concentration in the n region
n_p	Total minority carrier electron concentration in the p region
p_n	Total minority carrier hole concentration in the n region
$n_p(-x_p)$	Minority carrier electron concentration in the p region at the space charge edge
$p_n(x_n)$	Minority carrier hole concentration in the n region at the space charge edge
$\delta n_p = n_p - n_{p0}$	Excess minority carrier electron concentration in the p region
$\delta p_n = p_n - p_{n0}$	Excess minority carrier hole concentration in the n region

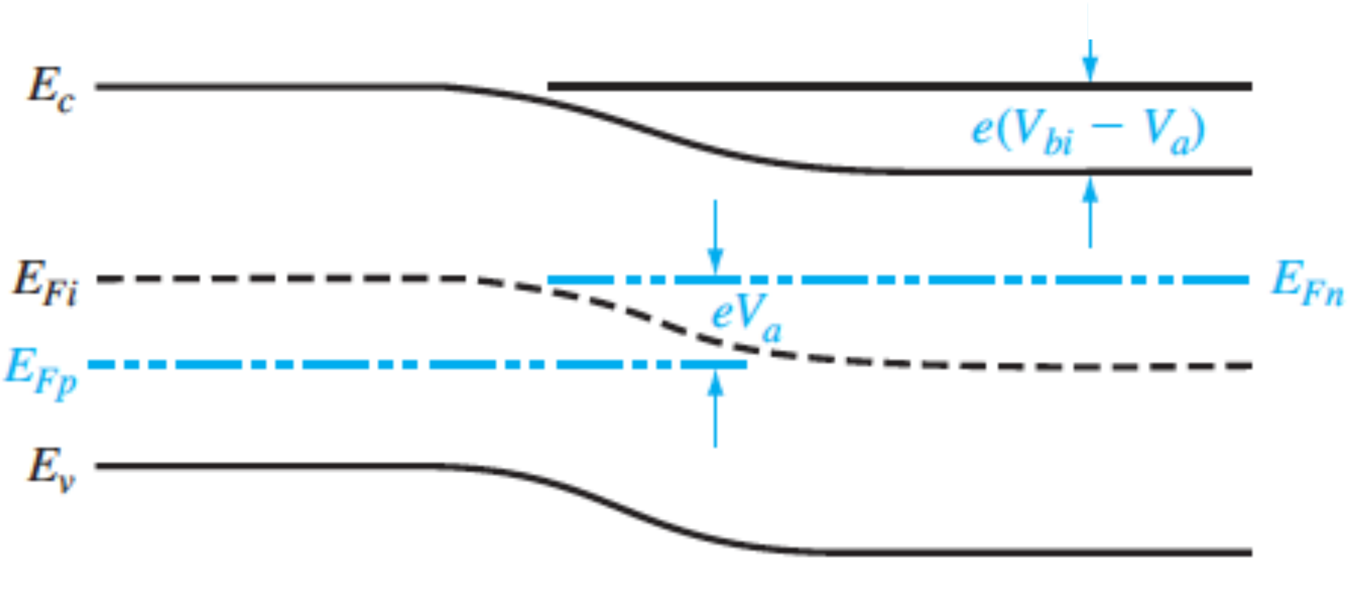


$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \qquad \frac{n_i^2}{N_a N_d} = \exp\left(\frac{-eV_{bi}}{kT}\right)$$

$$n_{n0} \approx N_d \qquad n_{p0} \approx \frac{n_i^2}{N_a}$$

$$n_{p0} = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right)$$

$$n_p = n_{n0} \exp\left(\frac{-e\,(V_{bi} - V_a)}{kT}\right) = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right) \exp\left(\frac{+eV_a}{kT}\right)$$



(b)

$$\boxed{n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)}$$

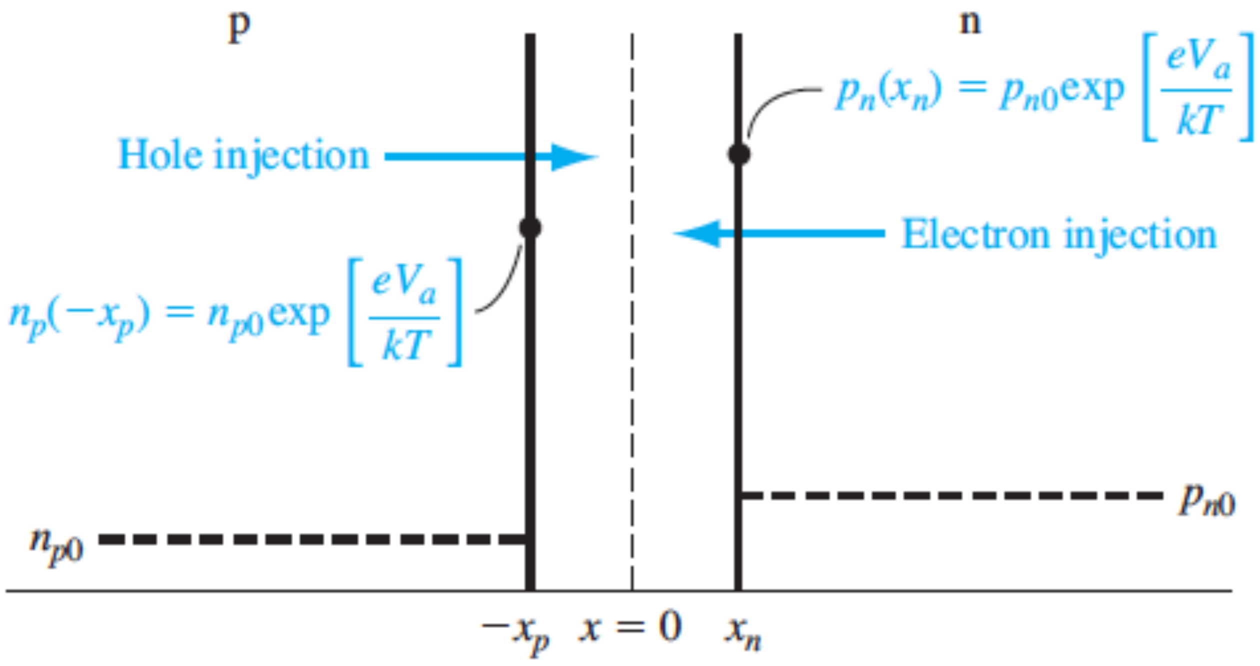


Figure 8.4 | Excess minority carrier concentrations at the space charge edges generated by the forward-bias voltage.

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \qquad (x > x_n)$$

$$\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0 \qquad (x < x_p)$$

The boundary conditions for the total minority carrier concentrations are

$$p_n(x_n) = p_{n0} \exp\left(\frac{eV_a}{kT}\right) \tag{8.11a}$$

$$n_p(-x_p) = n_{p0} \exp\left(\frac{eV_a}{kT}\right) \tag{8.11b}$$

$$p_n(x \to +\infty) = p_{n0} \tag{8.11c}$$

$$n_p(x \to -\infty) = n_{p0} \tag{8.11d}$$

The general solution to Equation (8.9) is

$$\delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \qquad (x \geq x_n) \tag{8.12}$$

and the general solution to Equation (8.10) is

$$\delta n_p(x) = n_p(x) - n_{p0} = Ce^{x/L_n} + De^{-x/L_n} \qquad (x \leq -x_p) \tag{8.13}$$

concentrations are then found to be, for ($x \geq x_n$),

$$\boxed{\delta p_n(x) = p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right)} \qquad (8.14)$$

and, for ($x \leq -x_p$),

$$\boxed{\delta n_p(x) = n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right)} \qquad (8.15)$$

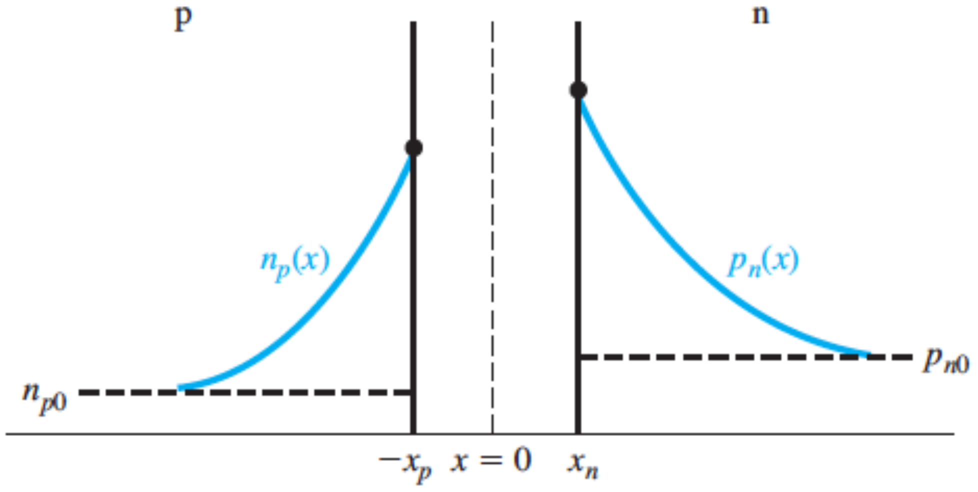


Figure 8.5 | Steady-state minority carrier concentrations in a pn junction under forward bias.

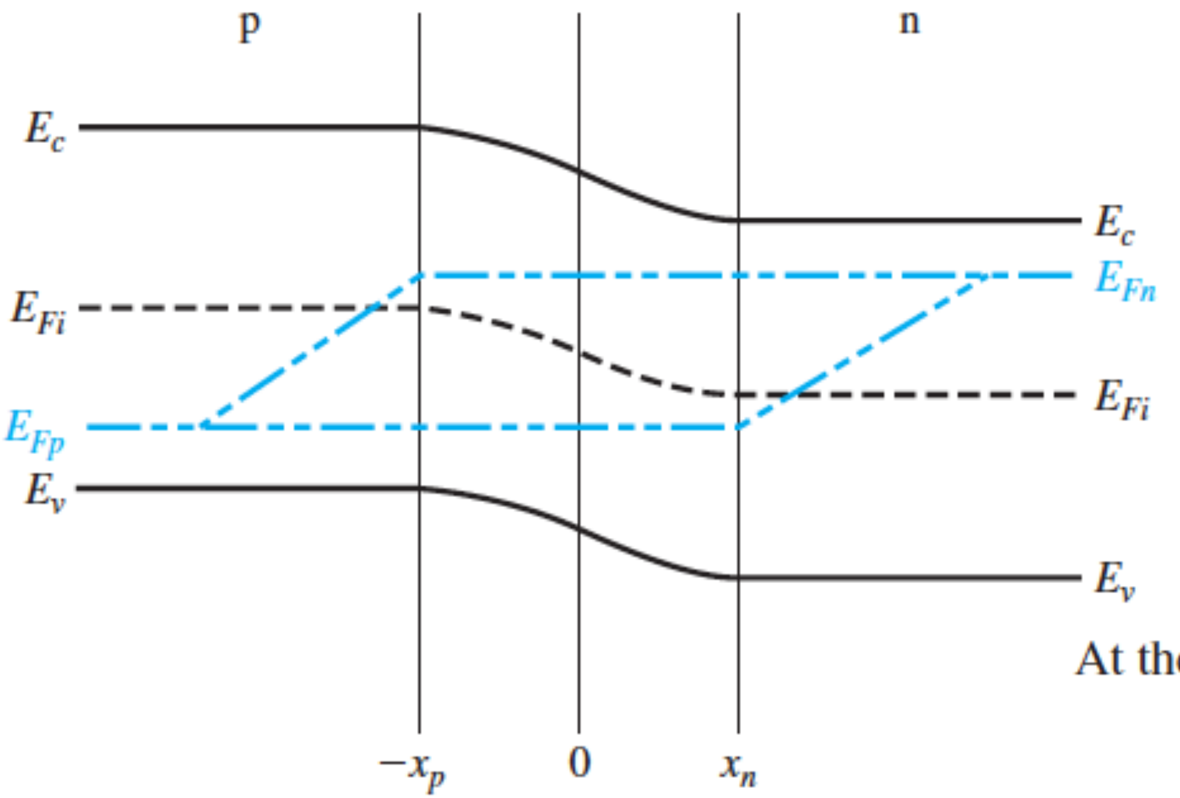


Figure 8.6 | Quasi-Fermi levels through a forward-biased pn junction.

$$p = p_o + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

$$n = n_o + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

At the space charge edge at $x = x_n$, we can write, for low injection

$$n_o p_n(x_n) = n_o p_{no} \exp\left(\frac{V_a}{V_t}\right) = n_i^2 \exp\left(\frac{V_a}{V_t}\right)$$

$$np = n_i^2 \exp\left(\frac{E_{Fn} - E_{Fp}}{kT}\right)$$

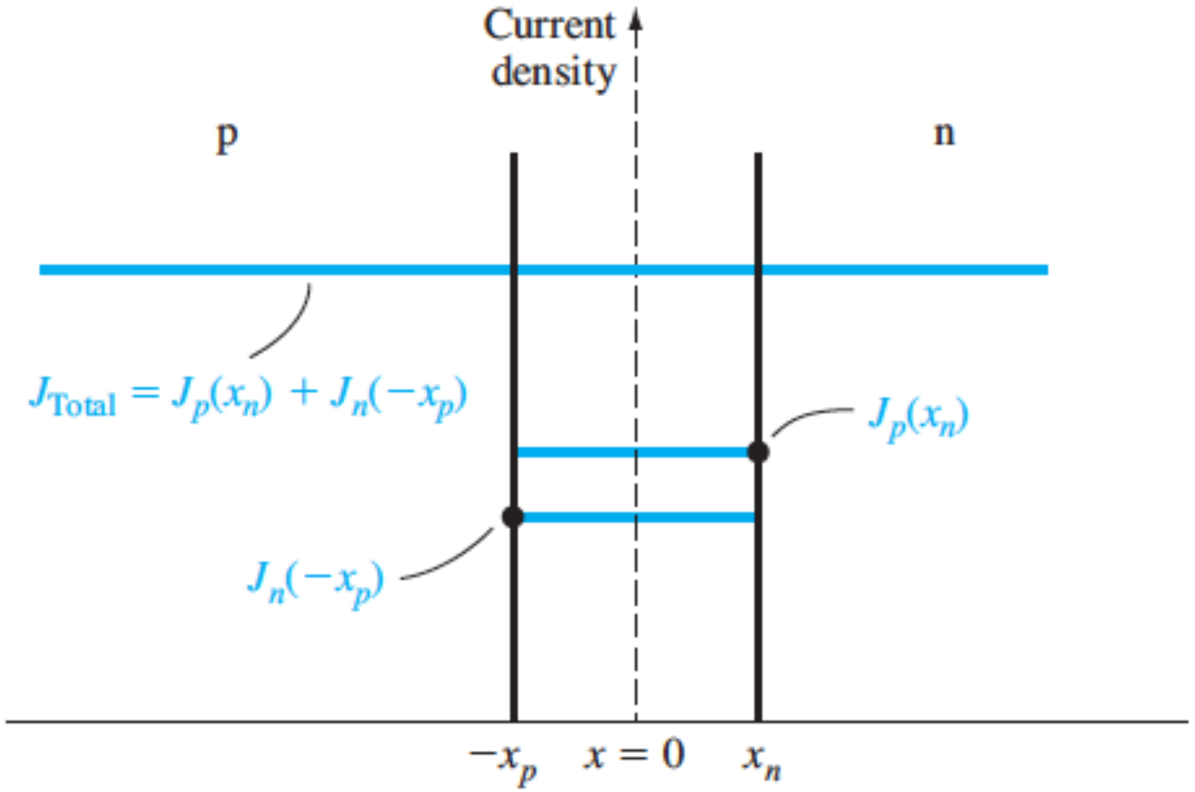


Figure 8.7 | Electron and hole current densities through the space charge region of a pn junction.

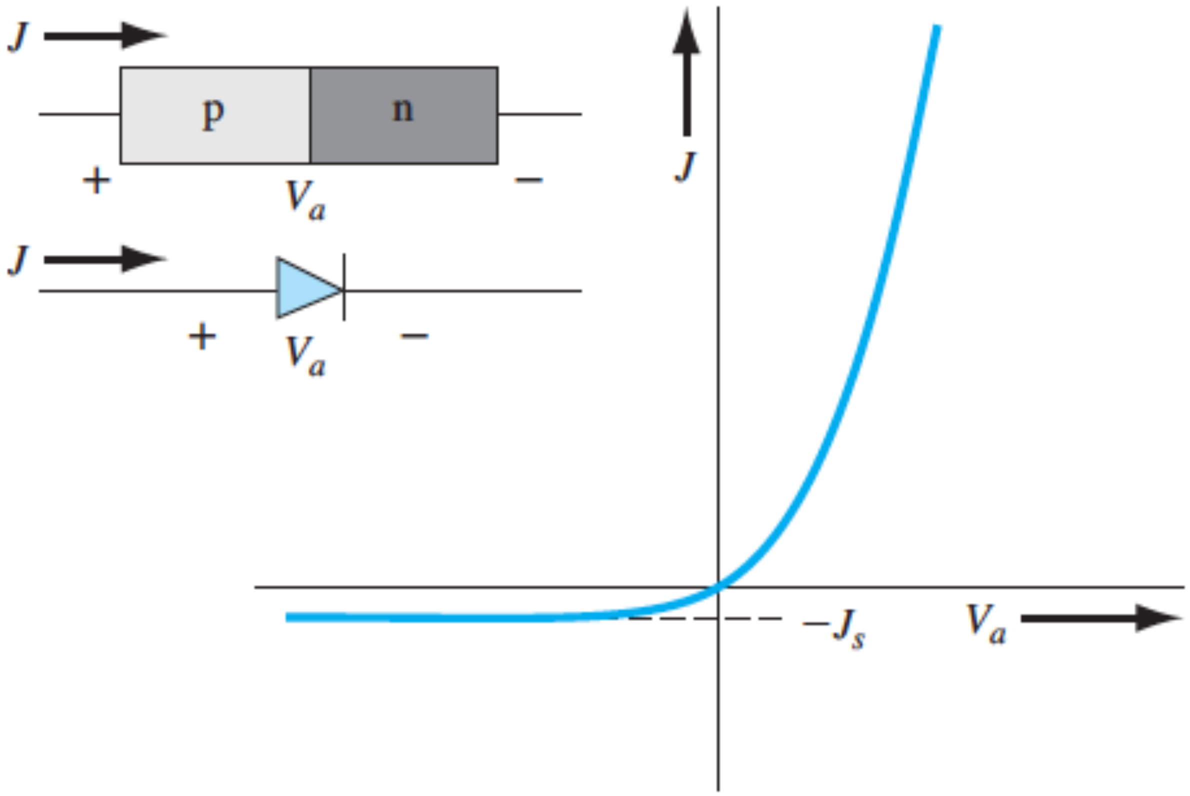
$$J_p(x_n) = -eD_p \left. \frac{d(\delta p_n(x))}{dx} \right|_{x=x_n}$$

$$\boxed{J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

$$J_n(-x_p) = eD_n \left. \frac{d(\delta n_p(x))}{dx} \right|_{x=-x_p}$$

$$\boxed{J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$



$$\boxed{J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]}$$

$$\boxed{J = J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

Figure 8.8 | Ideal *I–V* characteristic of a pn junction diode.

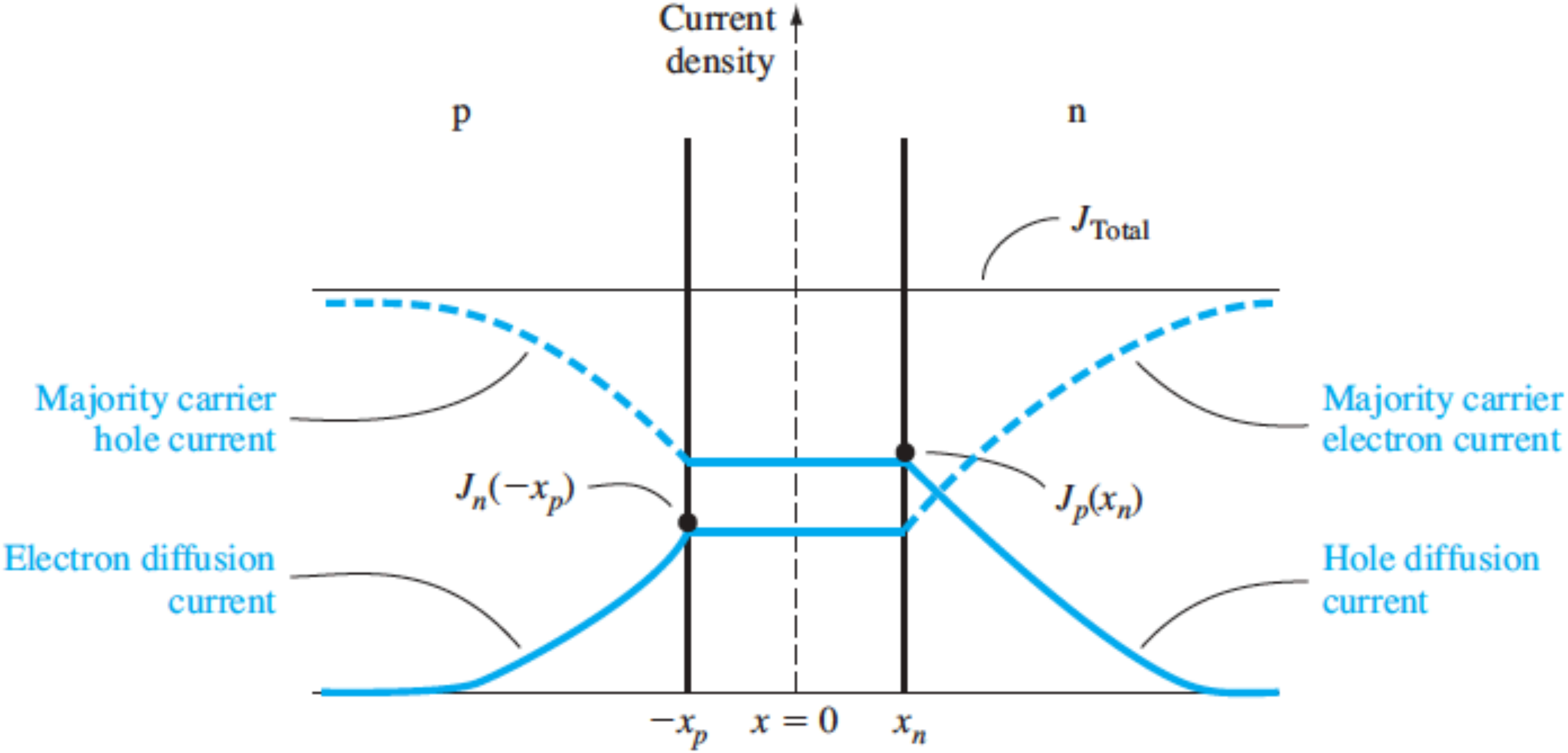


Figure 8.10 | Ideal electron and hole current components through a pn junction under forward bias.