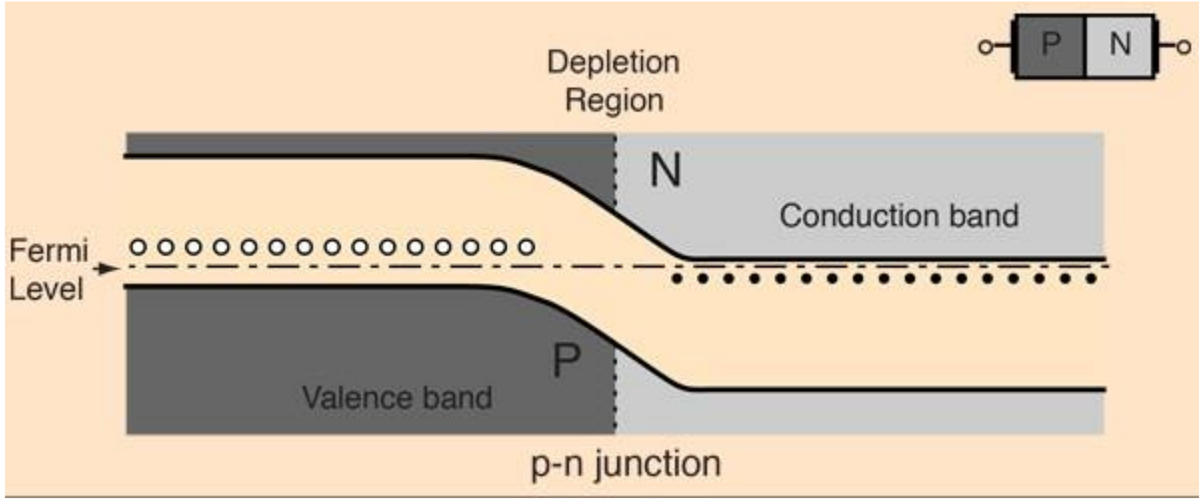
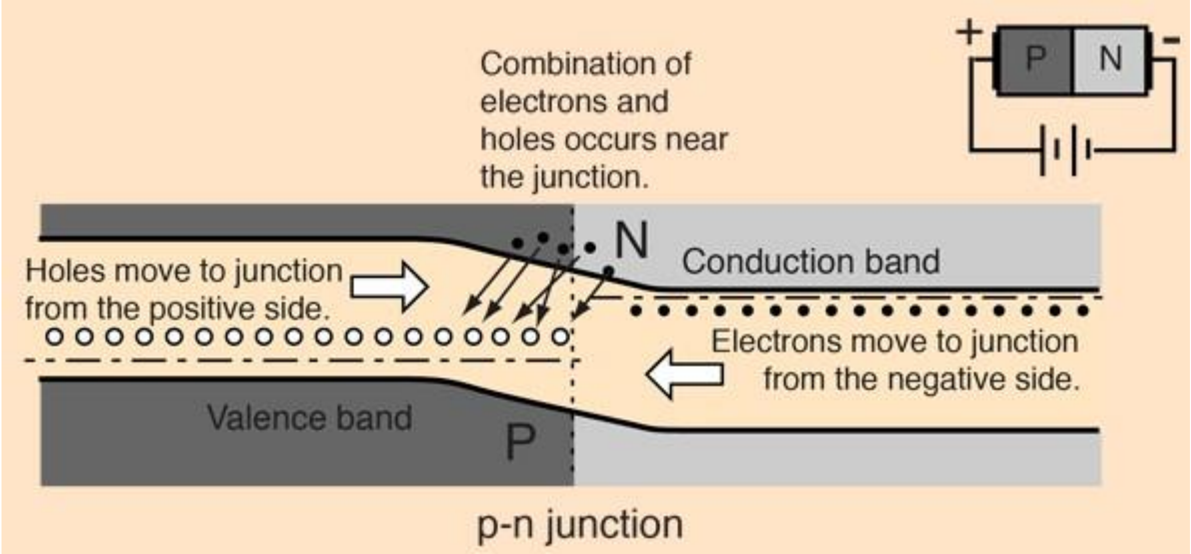
Forward bias	Reverse bias
1. The electrostatic potential barrier at the junction is lowered by a forward bias V_f from the equilibrium contact potential V_0 to the smaller value V_0 - V_f . 2. This lowering of the potential barrier occurs because a forward bias (p positive with respect to n) raises the electrostatic potential on the p side relative to the n side. 3. The electric field decreases with forward bias, since the applied electric field opposes the built-in field. 4. The space chare region width W will decrease under forward bias. 5. The height of the electron energy barrier is [q(V0 - Vf)] under forward bias than at equilibrium. 6. The electron diffusion current can be quite large with forward bias.	1. The electrostatic potential of the p side is depressed relative to the n side, and the potential barrier at the junction becomes larger (V_0 + V_r). 2. The electric field at the junction is increased by the applied field, which is in the same direction as the equilibrium field. 3. The space chare region width W will increase under forward bias. 4. The height of the electron energy barrier is [q(V0 + Vr)]. 5. The diffusion current is usually negligible for reverse bias.

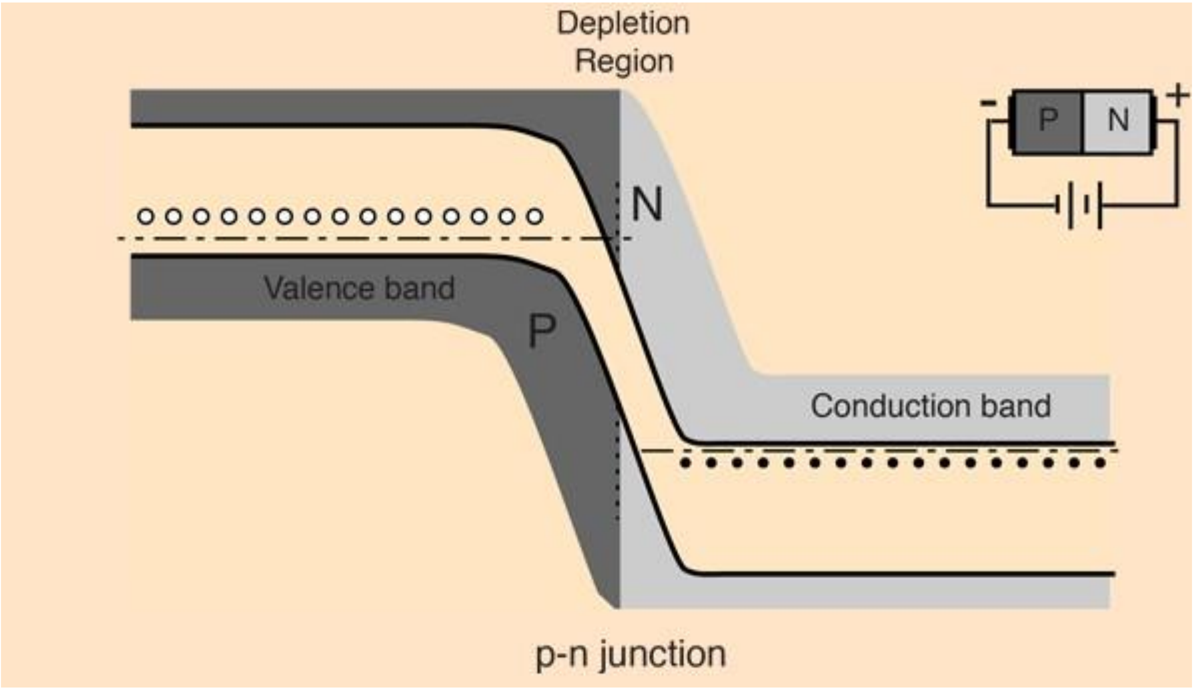
Energy band diagram of pn junction

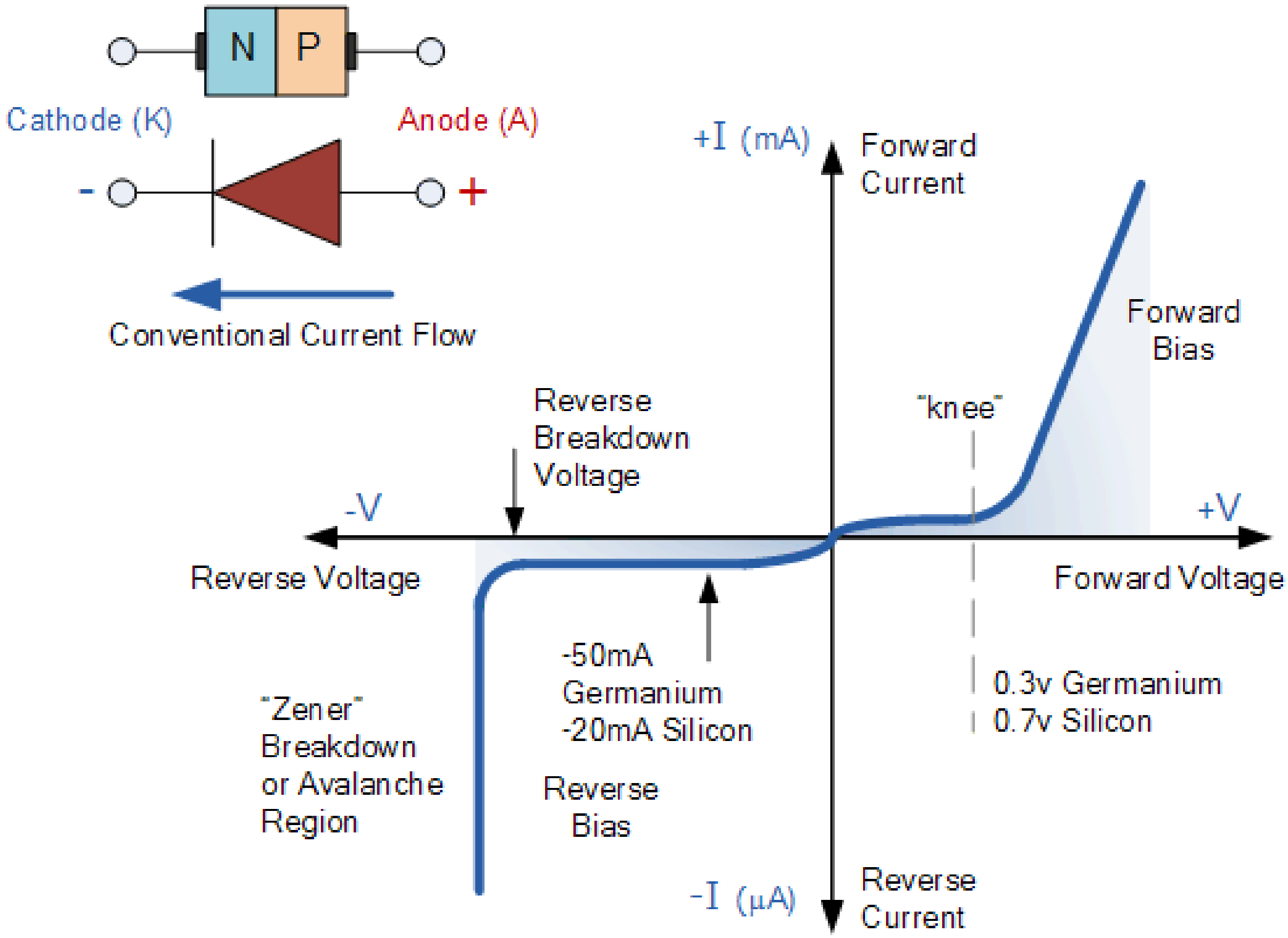
- **Down Hill –** The word "downhill" refers to the way the electron flows through the PN junction under forward bias conditions where the p side is made more positive.
- **Up Hill –** Under reverse bias condition of PN junction, the p side of the junction is made more negative which makes the electrons to cross the junction in upward direction refers to term "uphill".





V-I characteristics





Breakdown processes

- At some particular voltage, the reverse-biased current will increase rapidly. The applied voltage at this point is called the breakdown voltage.
- Two physical mechanisms give rise to the reverse-biased breakdown in a pn junction:
  - the Zener effect and the avalanche effect.
- **Zener breakdown** occurs in highly doped pn junctions through a tunneling mechanism.
- The **avalanche breakdown** process occurs when electrons and/or holes, moving across the space charge region, acquire sufficient energy from the electric field to create electron–hole pairs by colliding with atomic electrons within the depletion region.

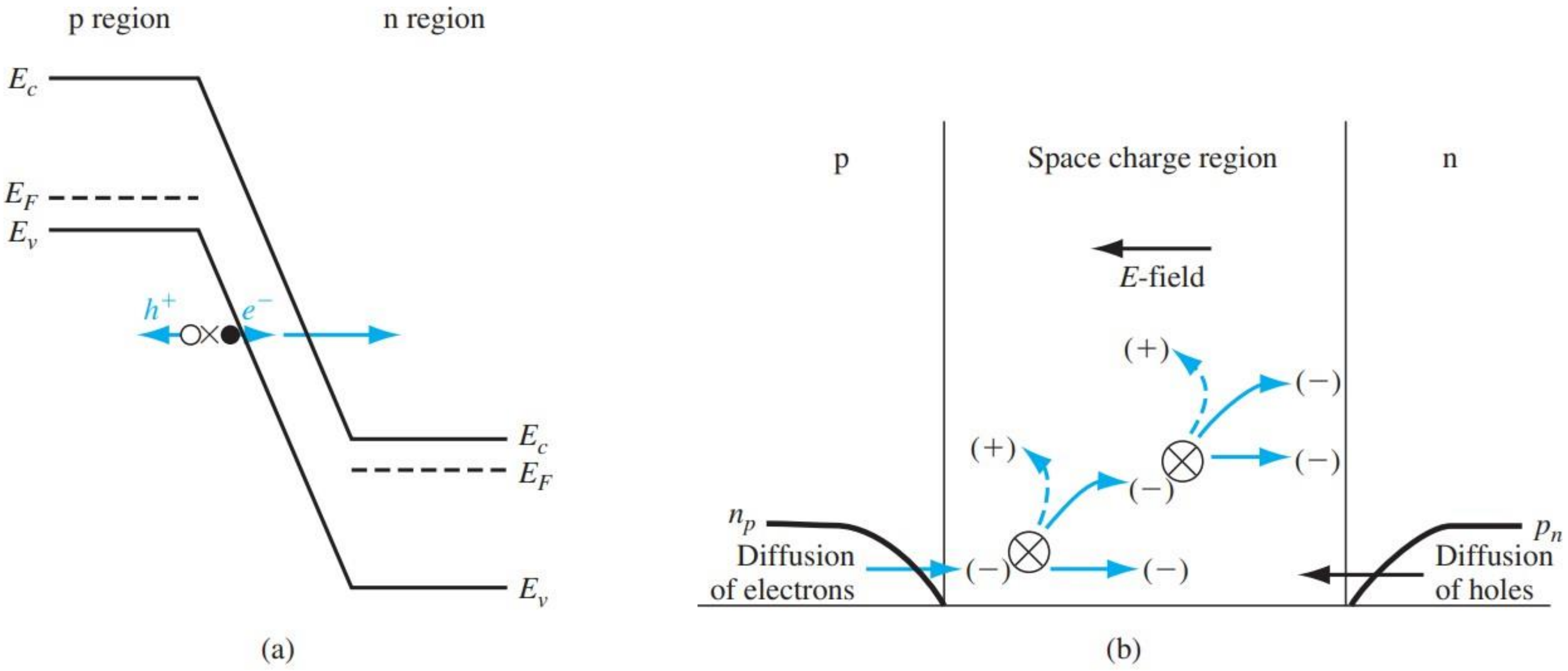


Figure 7.12 | (a) Zener breakdown mechanism in a reverse-biased pn junction; (b) avalanche breakdown process in a reverse-biased pn junction.

Ideal pn junction current

- As long as the bias V_a is applied, the injection of carriers across the space charge region continues and a current is created in the pn junction. This bias condition is known as forward bias;
- The total current in the junction is the sum of the individual electron and hole currents that are constant through the depletion region.
- Since the electron and hole currents are continuous functions through the pn junction, the total pn junction current will be the minority carrier hole diffusion current at $x = x_n$ plus the minority carrier electron diffusion current at $x=-x_p$.
- The gradients in the minority carrier concentrations produce diffusion currents, and since we are assuming the electric field to be zero at the space charge edges, we can neglect any minority carrier drift current component.

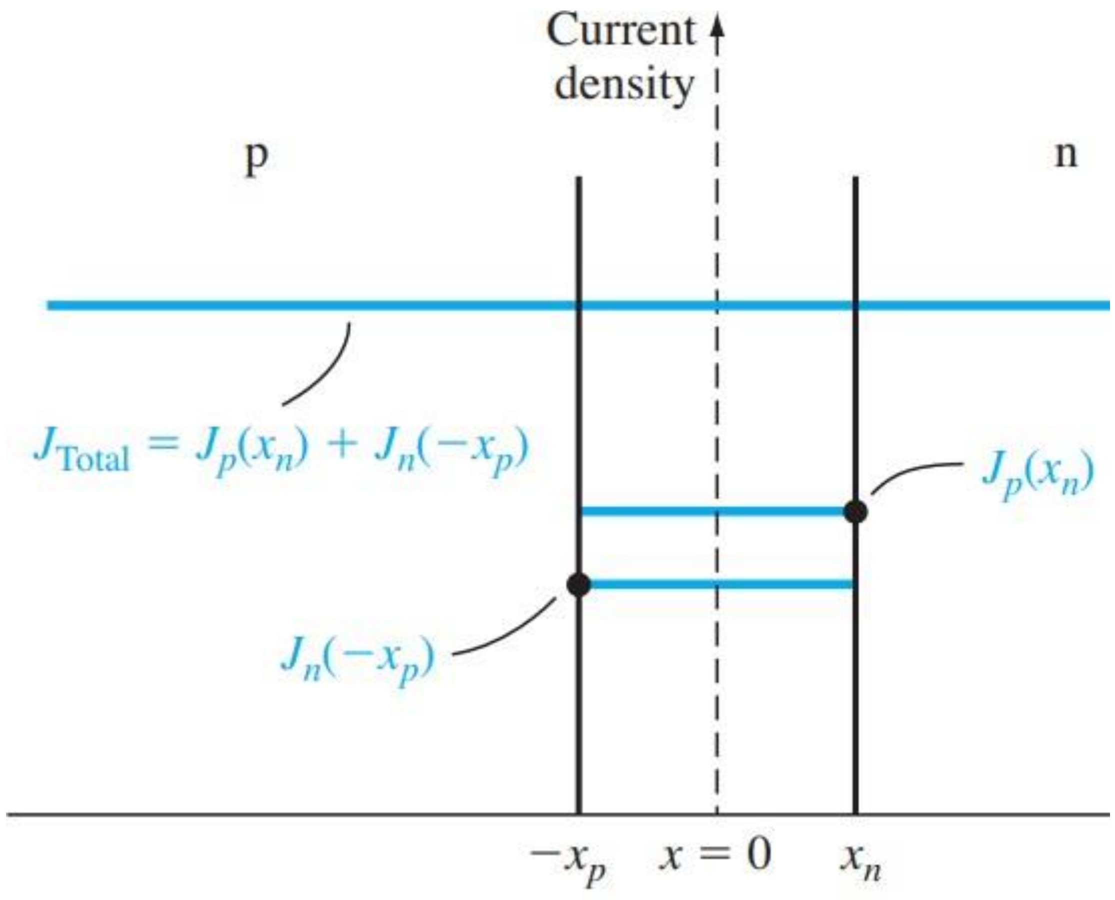


Figure 8.7 | Electron and hole current densities through the space charge region of a pn junction.

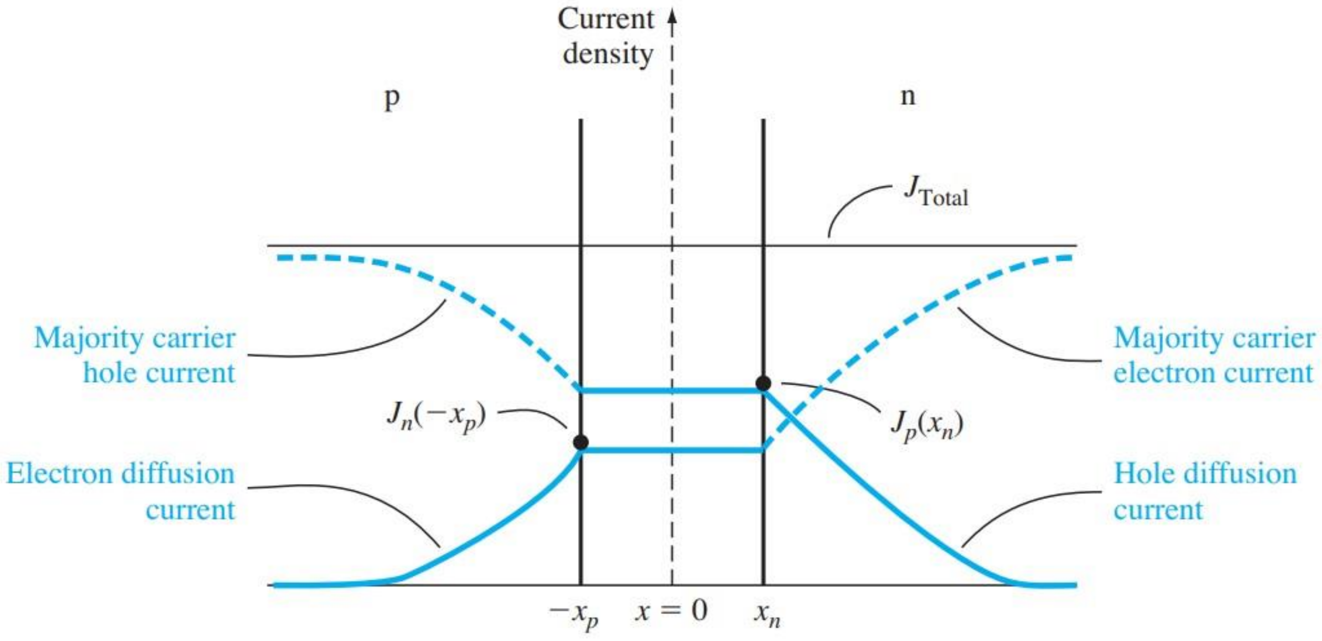


Figure 8.10 | Ideal electron and hole current components through a pn junction under forward bias.

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

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

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

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

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

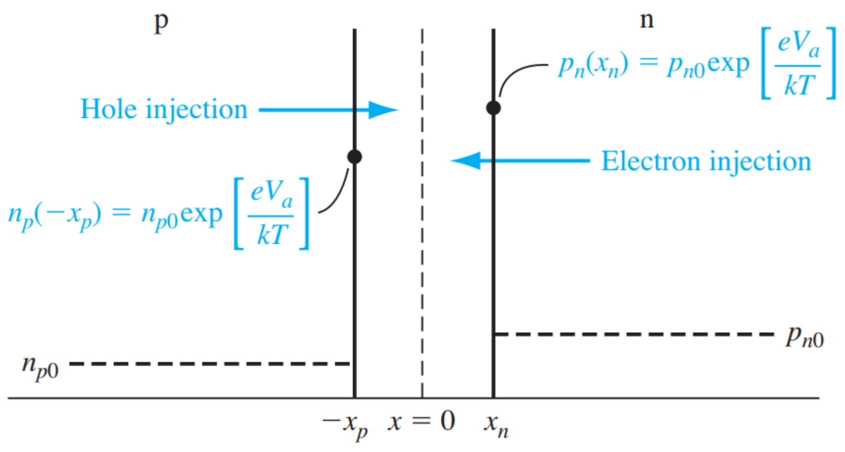


Figure 8.4 | Excess minority carrier concentrations at the space charge edges generated by the forward-bias voltage.

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

$$\boxed{p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)}$$

We can calculate the minority carrier hole diffusion current density at $x = x_n$ from the relation

$$J_p(x_n) = -eD_p \left.\frac{dp_n(x)}{dx}\right|_{x=x_n} \tag{8.20}$$

Since we are assuming uniformly doped regions, the thermal-equilibrium carrier concentration is constant, so the hole diffusion current density may be written as

$$J_p(x_n) = -eD_p \left.\frac{d(\delta p_n(x))}{dx}\right|_{x=x_n} \tag{8.21}$$

Taking the derivative of Equation (8.14) and substituting into Equation (8.21), we obtain

$$\boxed{J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{8.22}$$

The hole current density for this forward-bias condition is in the $+x$ direction, which is from the p to the n region.

Similarly, we may calculate the electron diffusion current density at $x = -x_p$. This may be written as

$$J_n(-x_p) = eD_n \left.\frac{d(\delta n_p(x))}{dx}\right|_{x=-x_p} \tag{8.23}$$

Using Equation (8.15), we obtain

$$\boxed{J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{8.24}$$

Applying the boundary conditions from Equations (8.11c) and (8.11d), the coefficients A and D must be zero. The coefficients B and C may be determined from the boundary conditions given by Equations (8.11a) and (8.11b). The excess carrier concentrations are then found to be, for $(x \geq x_n)$,

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

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

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

$$\boxed{J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{8.22}$$

The hole current density for this forward-bias condition is in the $+x$ direction, which is from the p to the n region.

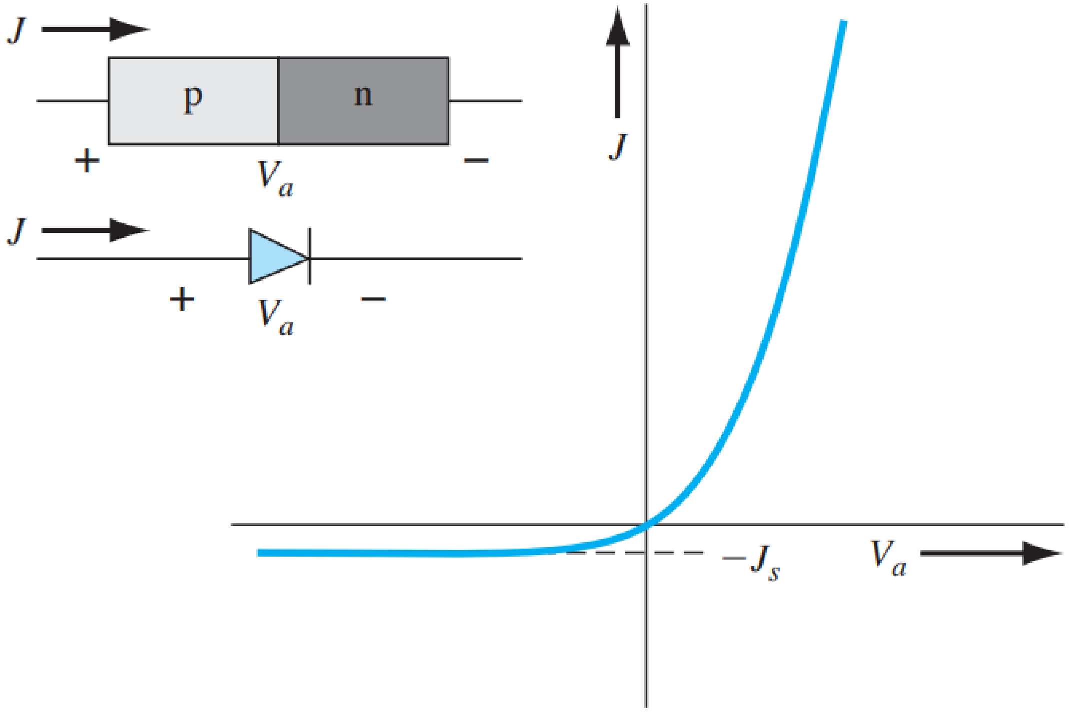
$$\boxed{J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

The electron current density is also in the $+x$ direction.

The total current density in the pn junction is then

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \tag{8.25}$$

Equation (8.25) is the ideal current–voltage relationship of a pn junction.



The forward-bias current–voltage relation is given by

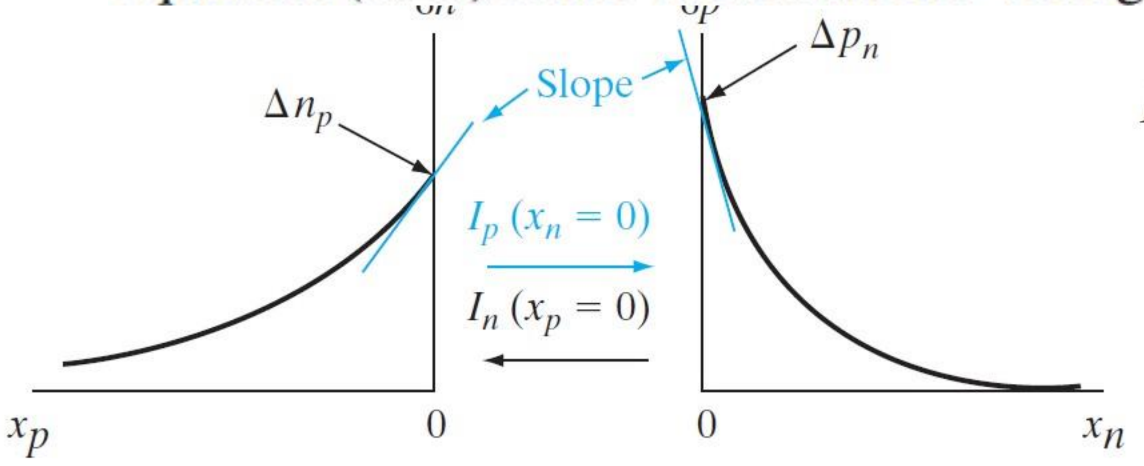
$$J = J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

- As temperature increases, less forward-bias voltage is required to obtain the same diode current.
- If the voltage is held constant, the diode current will increase as temperature increases.
- The change in forward-bias current with temperature is less sensitive than the reverse-saturation current.
- The ideal reverse-saturation current density J_s, is a function of the thermal-equilibrium minority carrier concentrations n_{p0} and p_{n0} which are proportional to n_i^2.

The total current density in the pn junction is then

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad (8.25)$$

Equation (8.25) is the ideal current–voltage relationship of a pn junction.



$$I = I_p(x_n = 0) - I_n(x_p = 0) = qA\left(\frac{D_p}{L_p}\,\Delta p_n + \frac{D_n}{L_n}\,\Delta n_p\right)$$

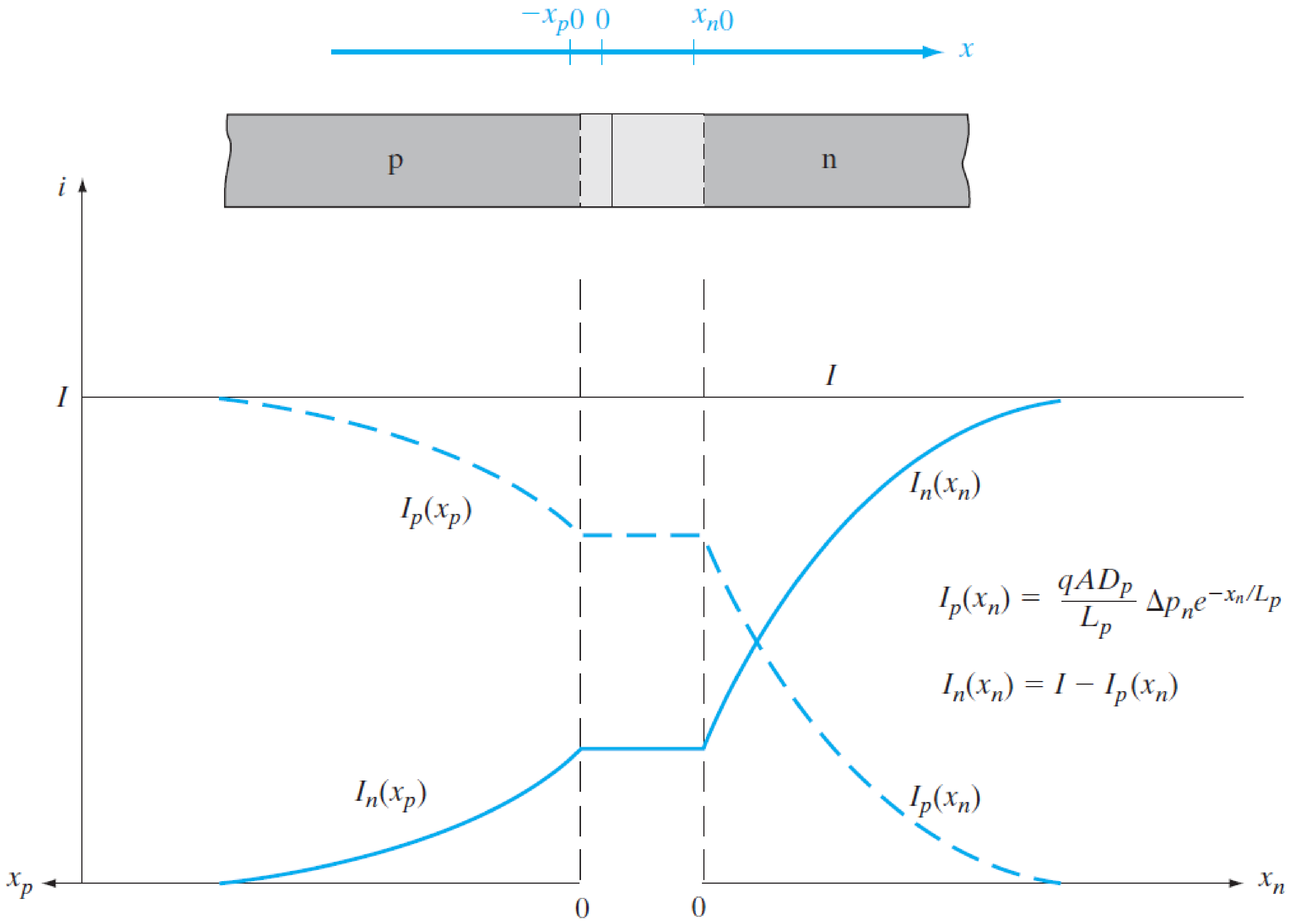
$$= qA\left(\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right)\left(e^{qV/kT} - 1\right)$$

$$I_n(x_p = 0) = qAD_n \left.\frac{d\delta n}{dx_p}\right|_{x_p = 0}$$

$$= -qA\,\frac{D_n}{L_n}\,\Delta n_p$$

$$I_p(x_n = 0) = -qAD_p \left.\frac{d\delta p}{dx_n}\right|_{x_n = 0}$$

$$= qA\,\frac{D_p}{L_p}\,\Delta p_n$$



$-x_{p0}$ 0 x_{n0}
x
p
n
i
I
I
$I_p(x_p)$
$I_n(x_n)$
$I_p(x_n) = \frac{qAD_p}{L_p}\Delta p_n e^{-x_n/L_p}$
$I_n(x_n) = I - I_p(x_n)$
$I_n(x_p)$
$I_p(x_n)$
x_p
0
0
x_n

Objective: Determine the ideal reverse-saturation current density in a silicon pn junction at $T = 300$ K.

Consider the following parameters in a silicon pn junction:

$$N_a = N_d = 10^{16}\ \text{cm}^{-3} \qquad n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$$

$$D_n = 25\ \text{cm}^2/\text{s} \qquad \tau_{p0} = \tau_{n0} = 5 \times 10^{-7}\ \text{s}$$

$$D_p = 10\ \text{cm}^2/\text{s} \qquad \epsilon_r = 11.7$$

■ Solution

The ideal reverse-saturation current density is given by

$$J_s = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p}$$

which may be rewritten as

$$J_s = en_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}}\right)$$

Then

$$J_s = (1.6 \times 10^{-19})(1.5 \times 10^{10})^2\left(\frac{1}{10^{16}}\sqrt{\frac{25}{5 \times 10^{-7}}} + \frac{1}{10^{16}}\sqrt{\frac{10}{5 \times 10^{-7}}}\right)$$

or $\quad J_s = 4.16 \times 10^{-11}\ \text{A/cm}^2$

■ Comment

The ideal reverse-biased saturation current density is very small. If the pn junction cross-sectional area were $A = 10^{-4}\ \text{cm}^2$, for example, then the ideal reverse-biased diode current would be $I_s = 4.15 \times 10^{-15}$ A.

Objective: Calculate the minority carrier concentrations at the edge of the space charge regions in a forward-biased pn junction.

Consider a silicon pn junction at $T = 300$ K. Assume the doping concentration in the n region is $N_d = 10^{16}\ \text{cm}^{-3}$ and the doping concentration in the p region is $N_a = 6 \times 10^{15}\ \text{cm}^{-3}$, and assume that a forward bias of 0.60 V is applied to the pn junction.

$$n_p(-x_p) = n_{po} \exp\left(\frac{eV_a}{kT}\right) \quad \text{and} \quad p_n(x_n) = p_{no} \exp\left(\frac{eV_a}{kT}\right)$$

$$n_{po} = \frac{n_i^2}{N_a} \qquad n_p(-x_p) = 3.75 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 4.31 \times 10^{14}\ \text{cm}^{-3}$$

$$p_{no} = \frac{n_i^2}{N_d} \qquad p_n(x_n) = 2.25 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 2.59 \times 10^{14}\ \text{cm}^{-3}$$

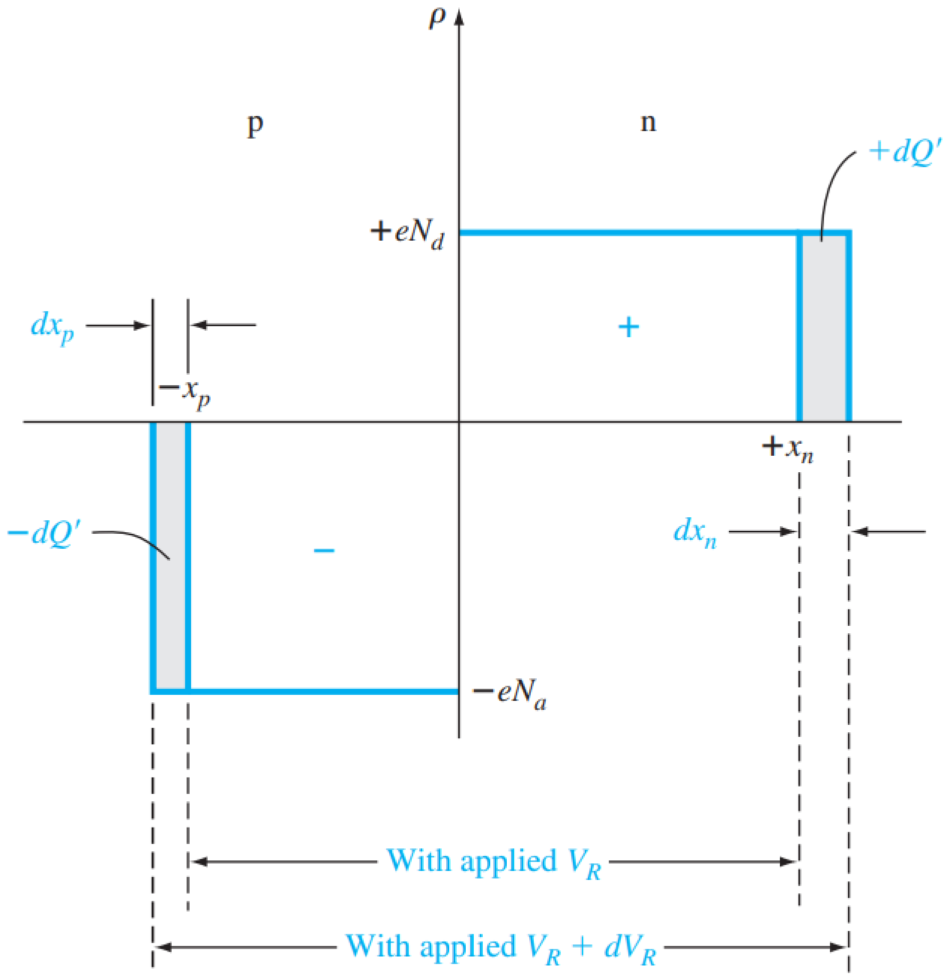


Figure 7.9 | Differential change in the space charge width with a differential change in reverse-biased voltage for a uniformly doped pn junction.

Junction capacitance

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

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

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

The junction capacitance can be written as

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

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

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

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

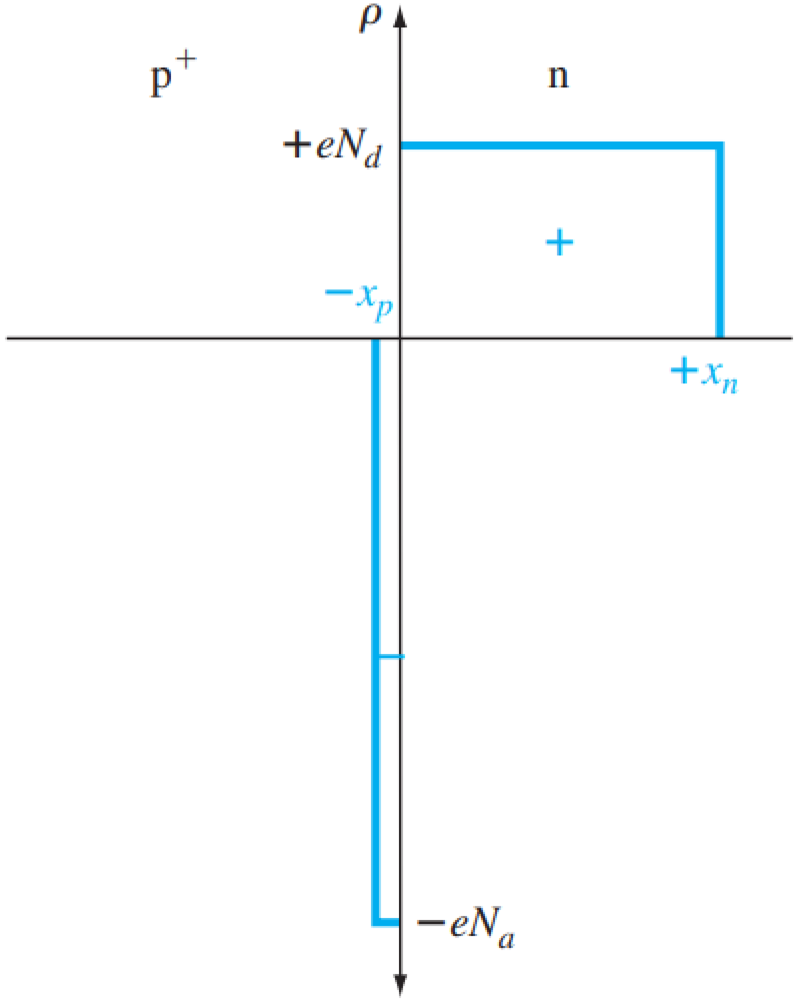


Figure 7.10 | Space charge density of a one-sided p^-n junction.

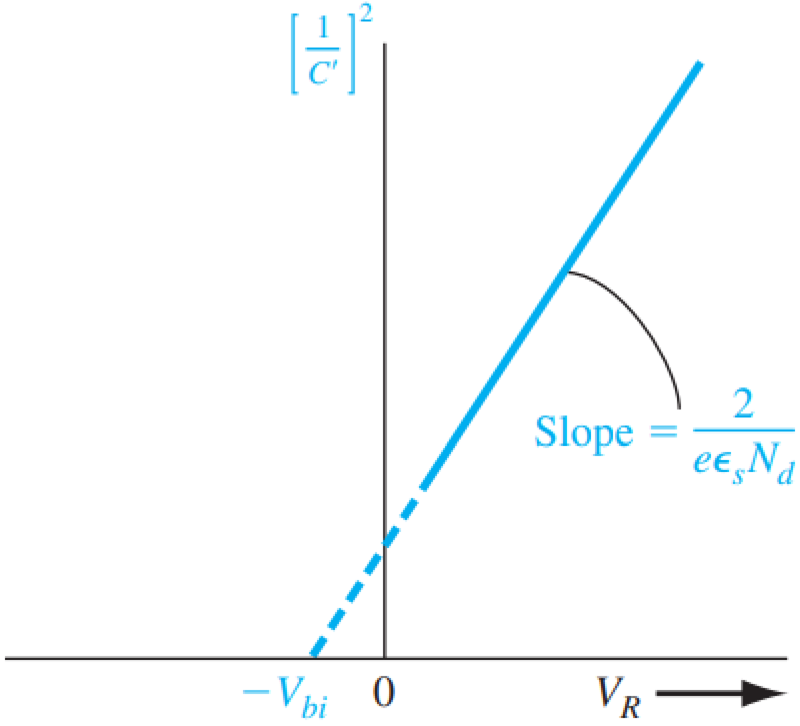


Figure 7.11 | $(1/C')^2$ versus V_R of a uniformly doped pn junction.

$$x_p \ll x_n$$

$$W \approx x_n$$

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

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

- There are basically two types of capacitance associated with a junction:

(1)the *junction capacitance* *due to the dipole in the transition region*

(2)the *charge storage capacitance* *arising from the lagging behind of voltage* as current changes, due to charge storage effects

Junction capacitance	Diffusion capacitance
1. The junction capacitance dominates the reactance of a p-n junction under reverse bias. 2. It occurs in long diode. $$C_j = \left\| \frac{dQ}{d(V_0 - V)} \right\| = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2}$$	1. for forward bias, however, the charge storage, or diffusion capacitance, Cs becomes dominant. 2. It occurs in short diode. $$C_s = \frac{dQ_p}{dV} = \frac{1}{3}\frac{q^2}{kT}Acp_n e^{qV/kT}$$

Diffusion capacitance

- The *Q charge is alternately being charged and discharged* through the junction as the voltage across the junction changes.
- The change in the stored minority carrier charge as a function of the change in voltage is the diffusion capacitance, C_d.

$$\boxed{C_d = \left(\frac{1}{2V_t}\right)(I_{p0}\tau_{p0} + I_{n0}\tau_{n0})}$$

Non-uniformly doped junctions

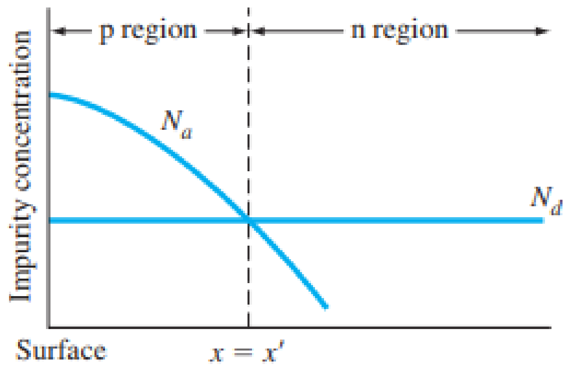


Figure 7.16 | Impurity concentrations of a pn junction with a nonuniformly doped p region.

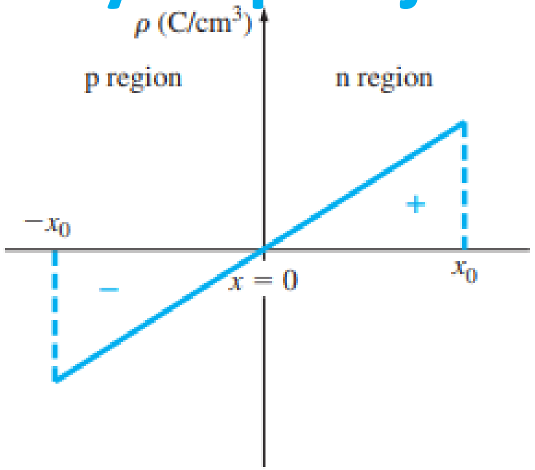


Figure 7.17 | Space charge density in a linearly graded pn junction.

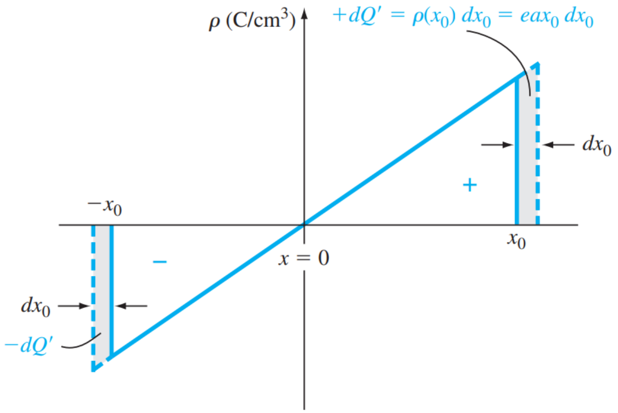


Figure 7.18 | Differential change in space charge width with a differential change in reverse-biased voltage for a linearly graded pn junction.

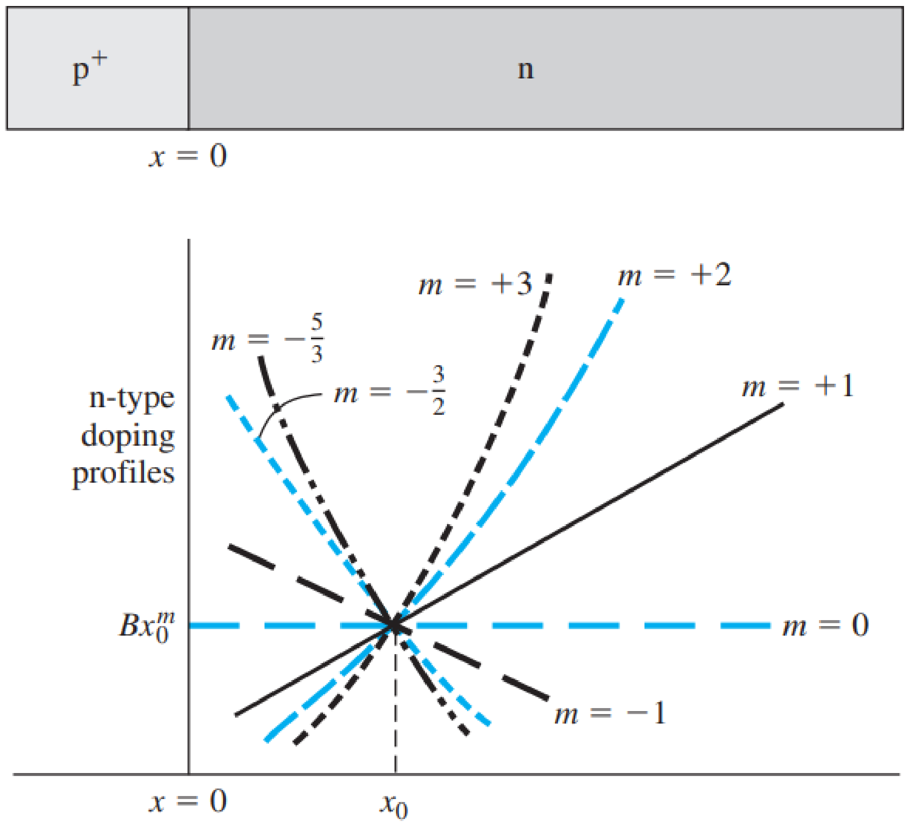


Figure 7.19 | Generalized doping profiles of a one-sided p$^+$n junction.
(From Sze [14].)

$$N = Bx^m$$

- m =0 corresponds to the uniformly doped junction
- m =+1 corresponds to the linearly graded junction
- m =+2 and m =+3, fairly low-doped epitaxial n-type layer grown on a much more heavily doped n+ substrate layer
- m is negative, we have what is referred to as a hyperabrupt junction. In this case, the n-type doping is larger near the metallurgical junction than in the bulk semiconductor

Transient analysis

- The pn junction is typically used as an electrical switch.
- In forward bias, referred to as the on state, a relatively large current can be produced by a small applied voltage;
- In reverse bias, referred to as the off state, only a very small current will exist.
- While changing the bias conditions, the diode undergoes a **transient response**.
- The response of a system to any sudden change from an equilibrium position is called as transient response.

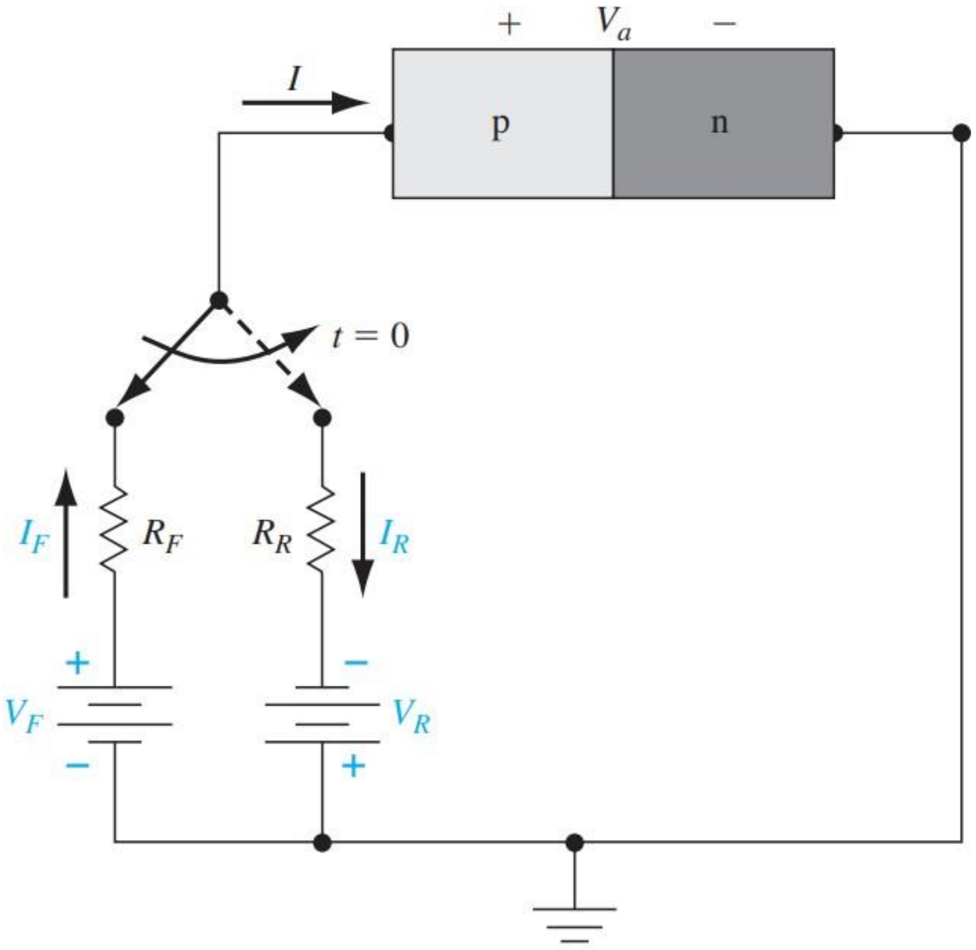


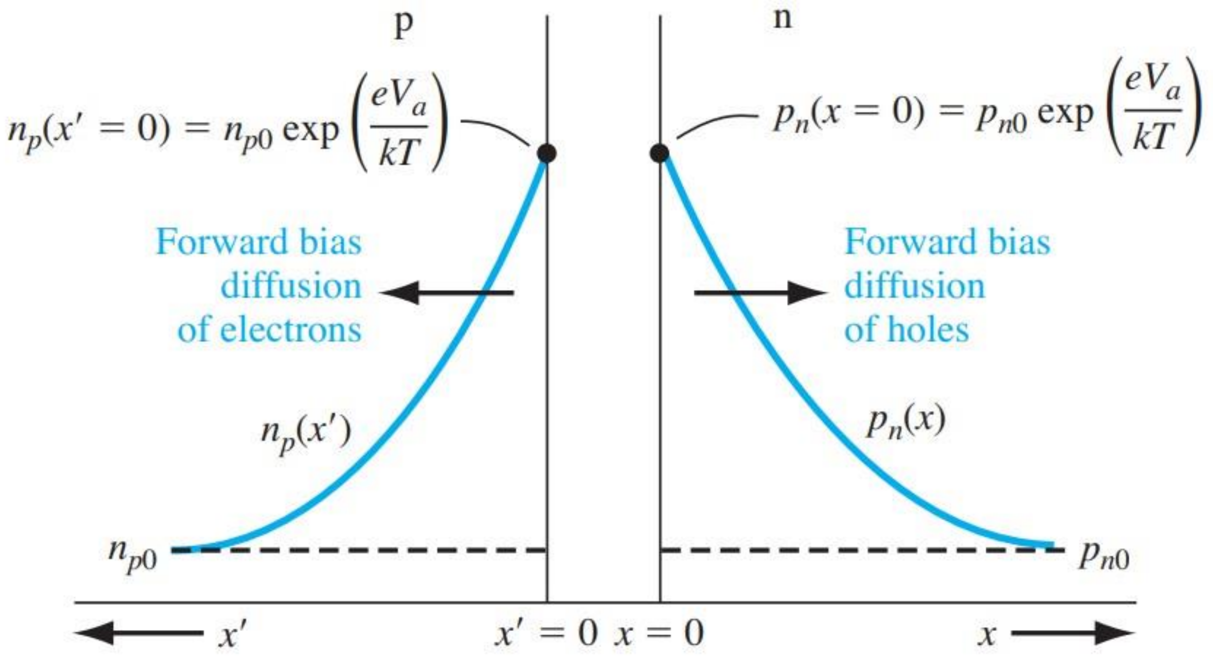
Figure 8.24 | Simple circuit for switching a diode from forward to reverse bias.

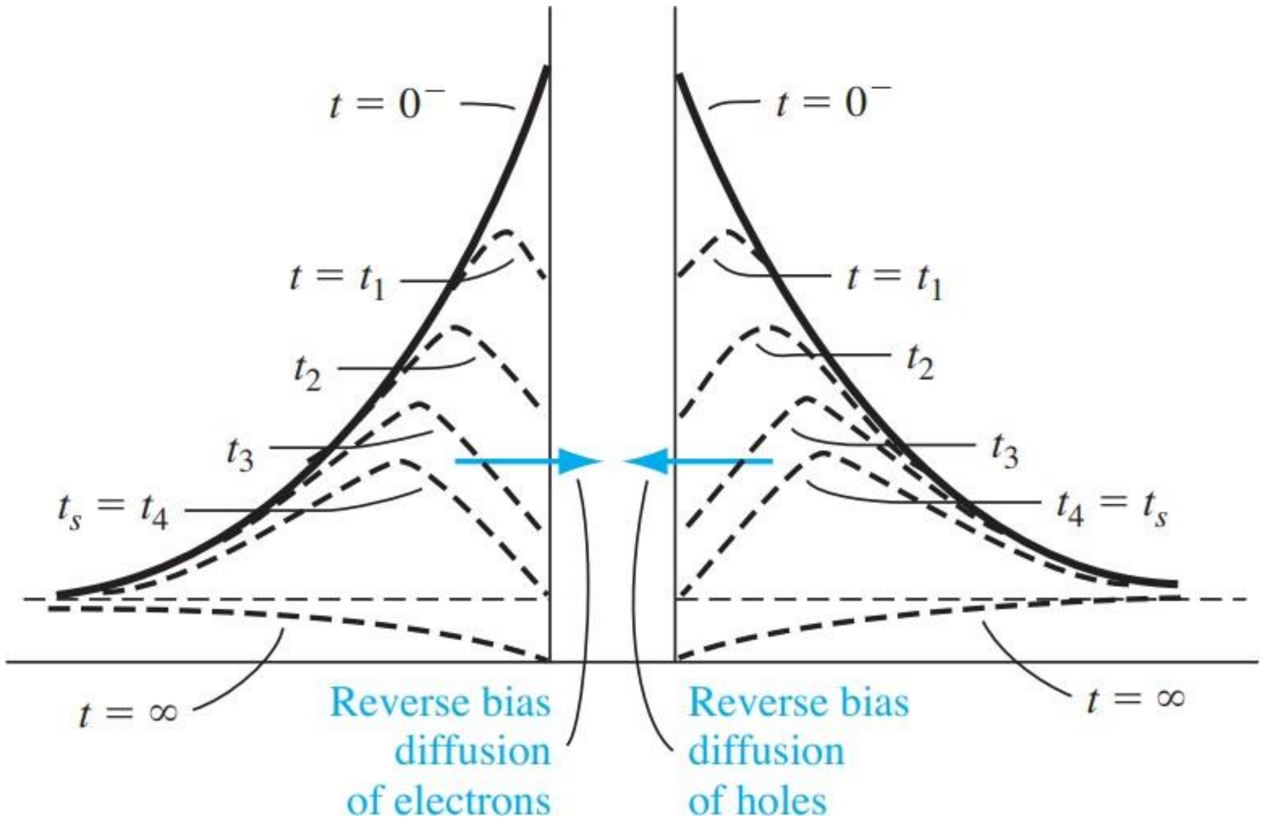
Turn-off transient

- Switching of the diode from the forward bias on state to the reverse biased off state.
- There is excess minority carrier charge stored in both the p and n regions of the diode. The excess minority carrier concentrations at the space charge edges are supported by the forward-bias junction voltage Va.
- When the voltage is switched from the forward- to the reverse-biased state, the excess minority carrier concentrations at the space charge edges can no longer be supported and they start to decrease.
- The collapse of the minority carrier concentrations at the edges of the space charge region leads to large concentration gradients and diffusion currents in the reverse-biased direction.
- This reverse current IR will be approximately constant for $0<t<t_s$, where t_s is called the storage time.
- The storage time is the length of time required for the minority carrier concentrations at the space charge edge to reach the thermal-equilibrium values.

Turn-on transient

- The turn-on transient occurs when the diode is switched from its "off" state into the forward-bias "on" state.
- The turn-on can be accomplished by applying a forward bias current pulse.
- The first stage of turn-on occurs very quickly and is the length of time required to narrow the space charge width from the reverse-biased value to its thermal-equilibrium value when Va=0.
- During this time, ionized donors and acceptors are neutralized as the space charge width narrows.
- The second stage of the turn-on process is the time required to establish the minority carrier distributions. During this time the voltage across the junction is increasing toward its steady-state value.
- A small turn-on time is achieved if the minority carrier lifetime is small and if the forward-bias current is small.


p
n
$n_p(x' = 0) = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$
$p_n(x = 0) = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$
Forward bias diffusion of electrons
Forward bias diffusion of holes
$n_p(x')$
$p_n(x)$
n_{p0}
p_{n0}
x'
$x' = 0$
$x = 0$
x


$t = 0^-$
$t = 0^-$
$t = t_1$
$t = t_1$
t_2
t_2
t_3
t_3
$t_s = t_4$
$t_4 = t_s$
$t = \infty$
$t = \infty$
Reverse bias diffusion of electrons
Reverse bias diffusion of holes

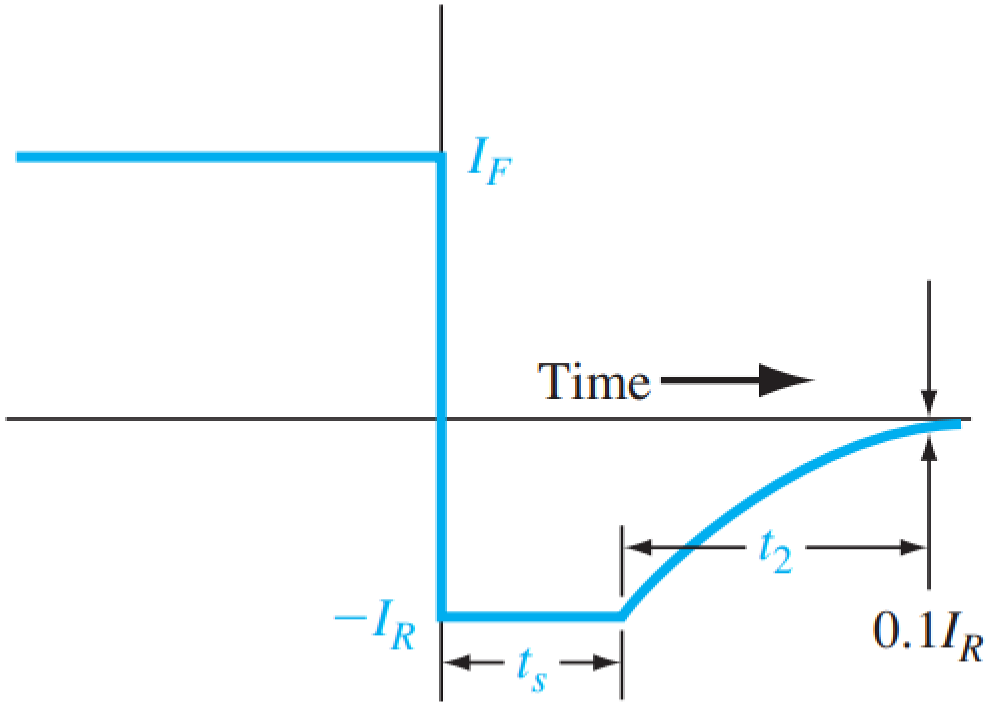


Figure 8.26 | Current characteristic versus time during diode switching.

$$t_s \approx \tau_{p0} \ln\left(1 + \frac{I_F}{I_R}\right)$$

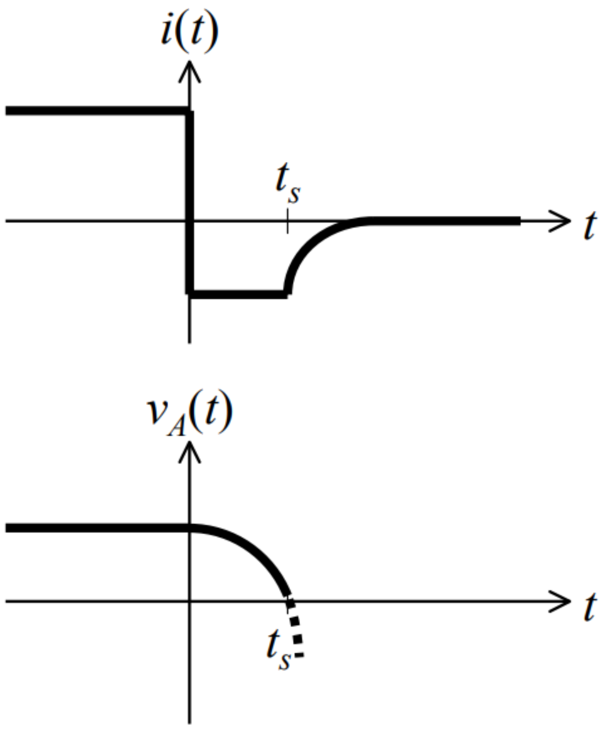
For $t < 0$, the forward-bias current is

$$I = I_F = \frac{V_F - V_a}{R_F}$$

$$I = -I_R \approx \frac{-V_R}{R_R}$$

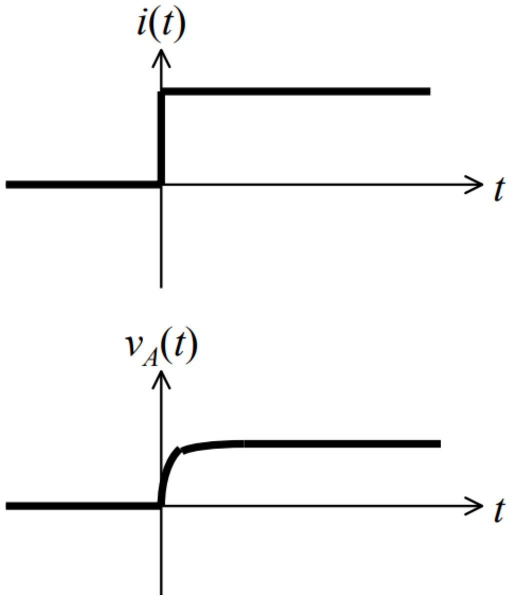
- The collapse of the minority carrier concentrations at the edges of the space charge region leads to large concentration gradients and diffusion currents in the reverse-biased direction.
- The total turn-off time is the sum of t_s and t_2.

Turn OFF transient



For t > 0: $\left.\dfrac{dp_n}{dx}\right|_{x=x_n} = -\dfrac{i}{qAD_p} > 0$

Turn ON transient



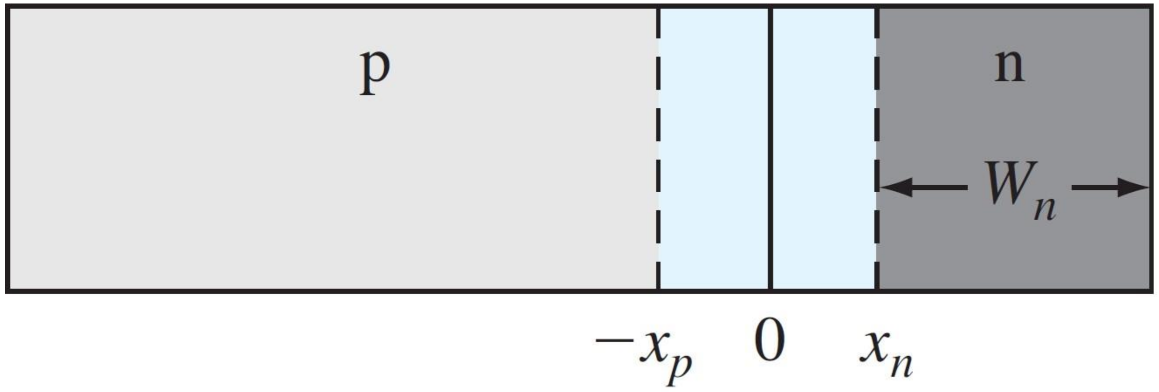
For t > 0: $\left.\dfrac{dp_n}{dx}\right|_{x=x_n} = -\dfrac{i}{qAD_p} < 0$

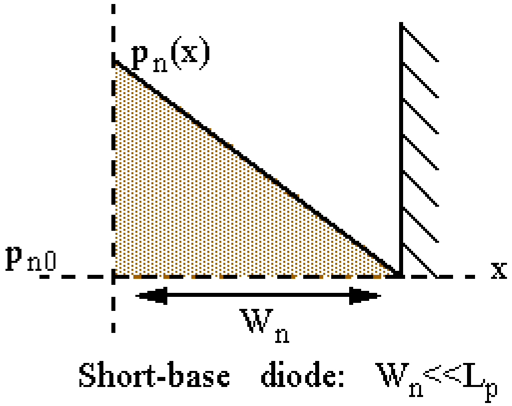
$$v_A(t) = \frac{kT}{q}\ln\left[1 + \frac{I_F}{I_0}\left(1 - e^{-t/\tau_p}\right)\right]$$

- If a junction diode is to be used to switch rapidly from the conducting to the nonconducting state and back again, special consideration must be given to its charge control properties.
- must either store very little charge in the neutral regions for steady forward currents or have a very short carrier lifetime, or both.

1. improve the switching speed of a diode by **adding efficient recombination centers** to the bulk material
2. A second approach to improving the diode switching time is to make the **lightly doped neutral region shorter than a minority carrier diffusion length**. This is the *narrow base diode.*

The Short Diode





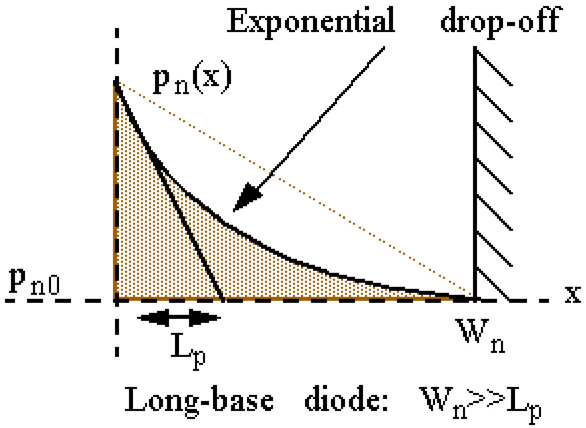


Figure 8.11 | Geometry of a "short" diode

so that in the short n region, we have

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

- The minority carrier hole diffusion current density now contains the length W_n *in the* denominator, rather than the diffusion length L_p.
- *The diffusion current density is larger* for a short diode than for a long diode since $W_n < L_p$.
- *In addition, since the minority* carrier concentration is approximately a linear function of distance through the n region, the minority carrier diffusion current density is a constant.
- This constant current implies that there is no recombination of minority carriers in the short region.

Diode current equation

The recombination rate of excess electrons and holes, given by the Shockley–Read–Hall recombination theory, was written as

$$R = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n + n') + C_p(p + p')} \tag{8.35}$$

The parameters n and p are, as usual, the concentrations of electrons and holes, respectively.

Reverse-Biased Generation Current For a pn junction under reverse bias, we have argued that the mobile electrons and holes have essentially been swept out of the space charge region. Accordingly, within the space charge region, $n \approx p \approx 0$. The recombination rate from Equation (8.35) becomes

$$R = \frac{-C_n C_p N_t n_i^2}{C_n n' + C_p p'} \tag{8.36}$$

- As electrons and holes are generated, they are swept out of the space charge region by the electric field.
- The flow of charge is in the direction of a reverse-biased current.
- This reverse-biased generation current, caused by the generation of electrons and holes in the space charge region, is in addition to the ideal reverse-biased saturation current.

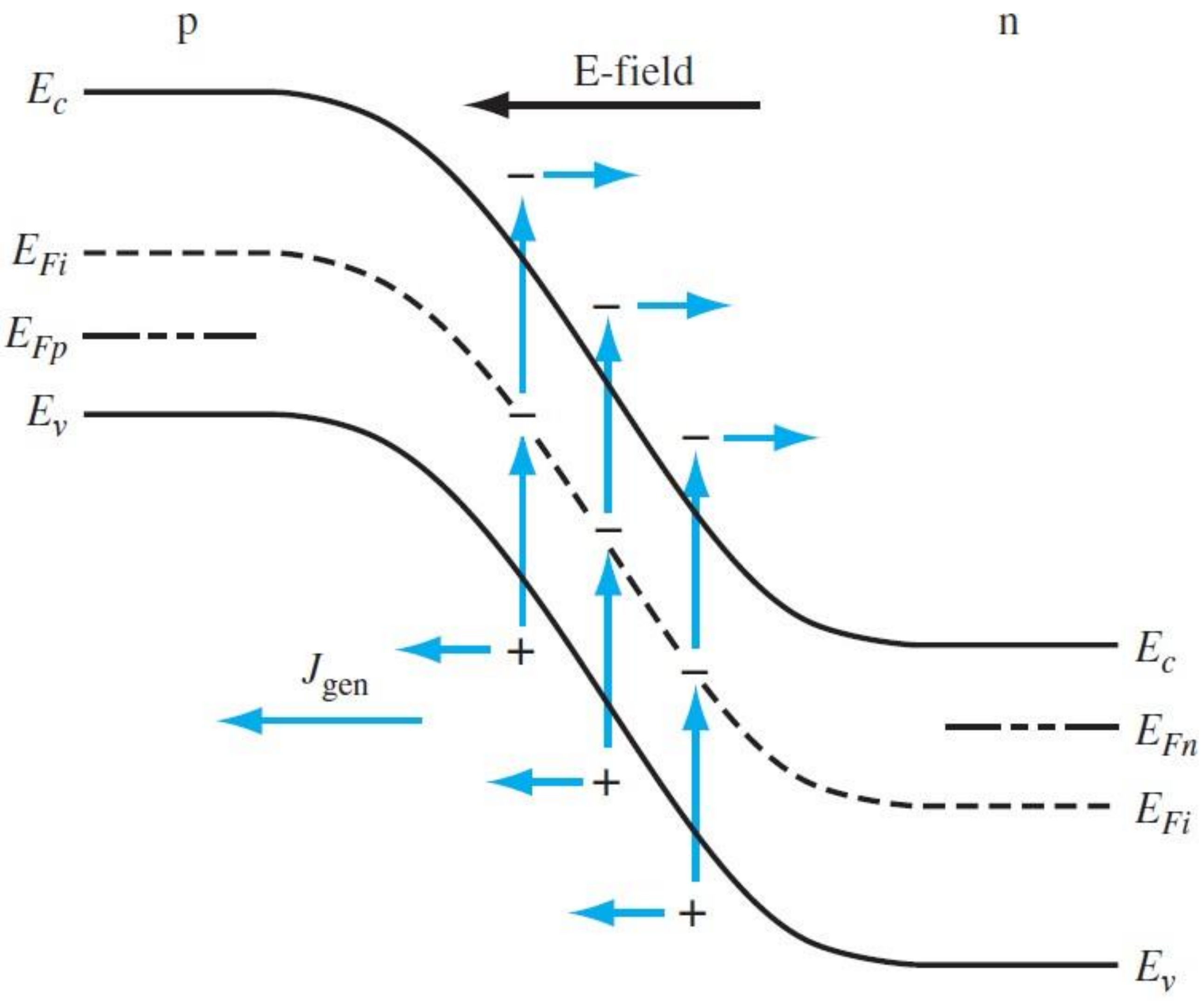


Figure 8.12 | Generation process in a reverse-biased pn junction.

$$R = \frac{-n_i}{\dfrac{1}{N_t C_p} + \dfrac{1}{N_t C_n}} \tag{8.37}$$

Using the definitions of lifetimes from Equations (6.103) and (6.104), we may write Equation (8.37) as

$$R = \frac{-n_i}{\tau_{p0} + \tau_{n0}} \tag{8.38}$$

If we define a new lifetime as the average of τ_{p0} and τ_{n0}, or

$$\tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2} \tag{8.39}$$

then the recombination rate can be written as

$$R = \frac{-n_i}{2\tau_0} \equiv -G \tag{8.40}$$

The negative recombination rate implies a generation rate, so G is the generation rate of electrons and holes in the space charge region.

Forward bias

The generation current density may be determined from

$$J_{\text{gen}} = \int_0^W e\,G dx \tag{8.41}$$

where the integral is over the space charge region. If we assume that the generation rate is constant throughout the space charge region, then we obtain

$$\boxed{J_{\text{gen}} = \frac{en_i W}{2\tau_0}} \tag{8.42}$$

The total reverse-biased current density is the sum of the ideal reverse saturation current density and the generation current density, or

$$J_R = J_s + J_{\text{gen}} \tag{8.43}$$

The ideal reverse-saturation current density J_s is independent of the reverse-biased voltage. However, J_{gen} is a function of the depletion width W, which in turn is a function of the reverse-biased voltage. The actual reverse-biased current density, then, is no longer independent of the reverse-biased voltage.

$$R_{\max} = \frac{n_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) \tag{8.52}$$

The recombination current density may be calculated from

$$J_{\text{rec}} = \int_0^W eR\,dx \tag{8.53}$$

where again the integral is over the entire space charge region. In this case, however, the recombination rate is not a constant through the space charge region. We have calculated the maximum recombination rate at the center of the space charge region, so we may write

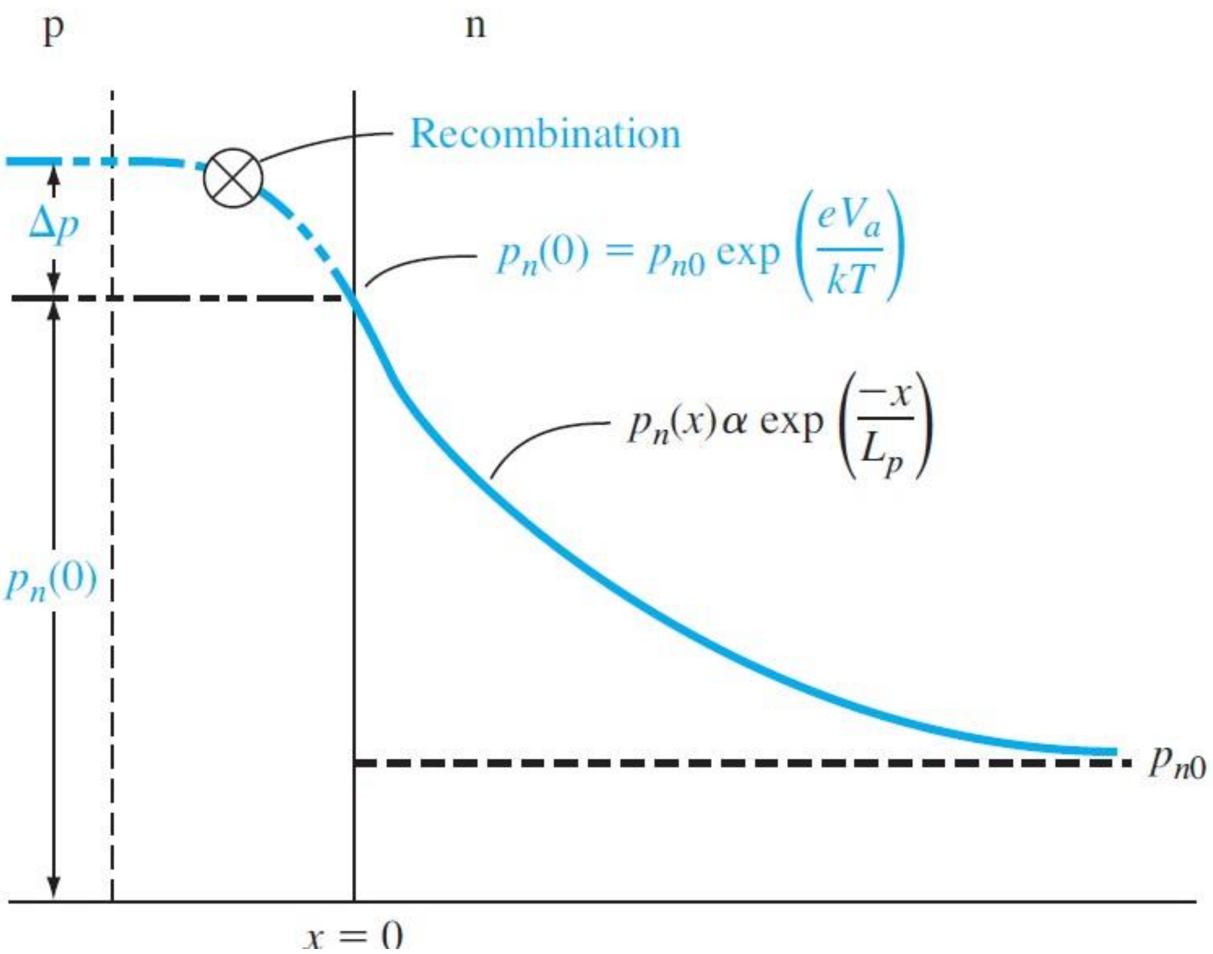
$$J_{\text{rec}} = ex' \frac{n_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) \tag{8.54}$$

where x' is a length over which the maximum recombination rate is effective. However, since τ_0 may not be a well-defined or known parameter, it is customary to write

$$\boxed{J_{\text{rec}} = \frac{eWn_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) = J_{r0} \exp\left(\frac{eV_a}{2kT}\right)} \tag{8.55}$$

where W is the space charge width.

Total Forward-Bias Current The total forward-bias current density in the pn junction is the sum of the recombination and the ideal diffusion current densities. Figure 8.15 shows a plot of the minority carrier hole concentration in the neutral



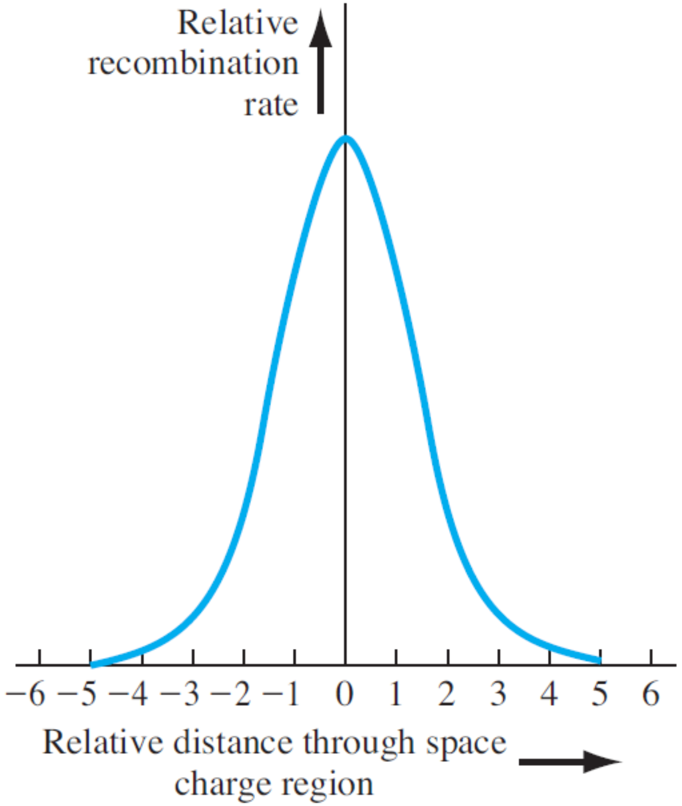


Figure 8.14 | Relative magnitude of the recombination rate through the space charge region of a forward-biased pn junction.

The total forward-bias current density is the sum of the recombination and the ideal diffusion current densities, so we can write

$$J = J_{\text{rec}} + J_D \tag{8.56}$$

where J_{rec} is given by Equation (8.55) and J_D is given by

$$J_D = J_s \exp\left(\frac{eV_a}{kT}\right) \tag{8.57}$$

In general, the diode current–voltage relationship may be written as

$$\boxed{I = I_s\left[\exp\left(\frac{eV_a}{nkT}\right) - 1\right]} \tag{8.59}$$

where the parameter n is called the *ideality factor*. For a large forward-bias voltage, $n \approx 1$ when diffusion dominates, and for low forward-bias voltage, $n \approx 2$ when recombination dominates. There is a transition region where $1 < n < 2$.

DC and AC characteristics of diode

- Assume that the diode is forward-biased with a dc voltage *V0 producing a dc* diode current I_{DQ}.
- *If we now superimpose a small, low-frequency* sinusoidal *voltage*, then a small sinusoidal current will be produced, superimposed on the dc current.
- The ratio of sinusoidal current to sinusoidal voltage is called the incremental conductance.
- In the limit of a very small sinusoidal current and voltage, the small-signal incremental conductance is just the slope of the dc current–voltage curve.

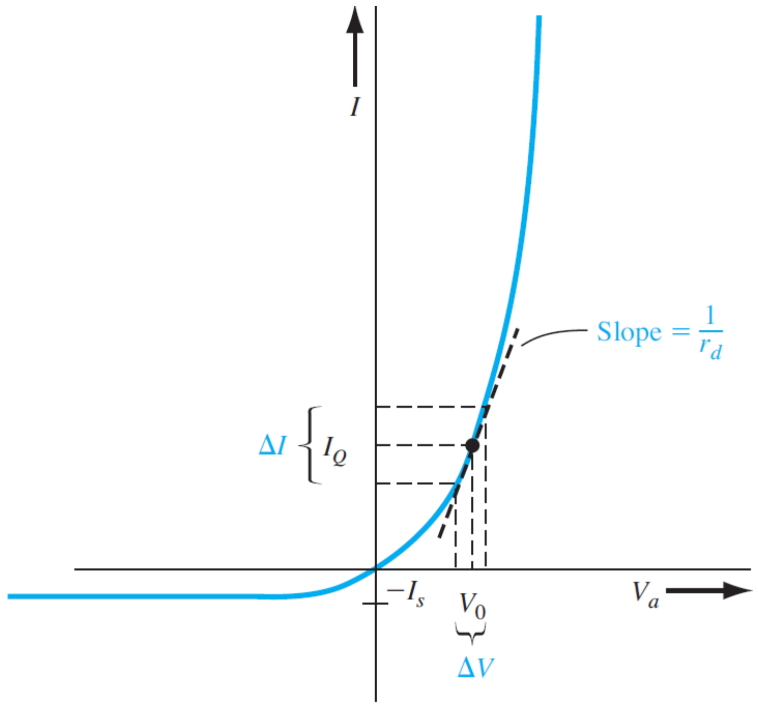


Figure 8.18 | Curve showing the concept of the small-signal diffusion resistance.

$$g_d = \left.\frac{dI_D}{dV_a}\right|_{V_a=V_0} \tag{8.65}$$

The reciprocal of the incremental conductance is the incremental resistance, defined as

$$r_d = \left.\frac{dV_a}{dI_D}\right|_{I_D=I_{DQ}} \tag{8.66}$$

where I_{DQ} is the dc quiescent diode current.

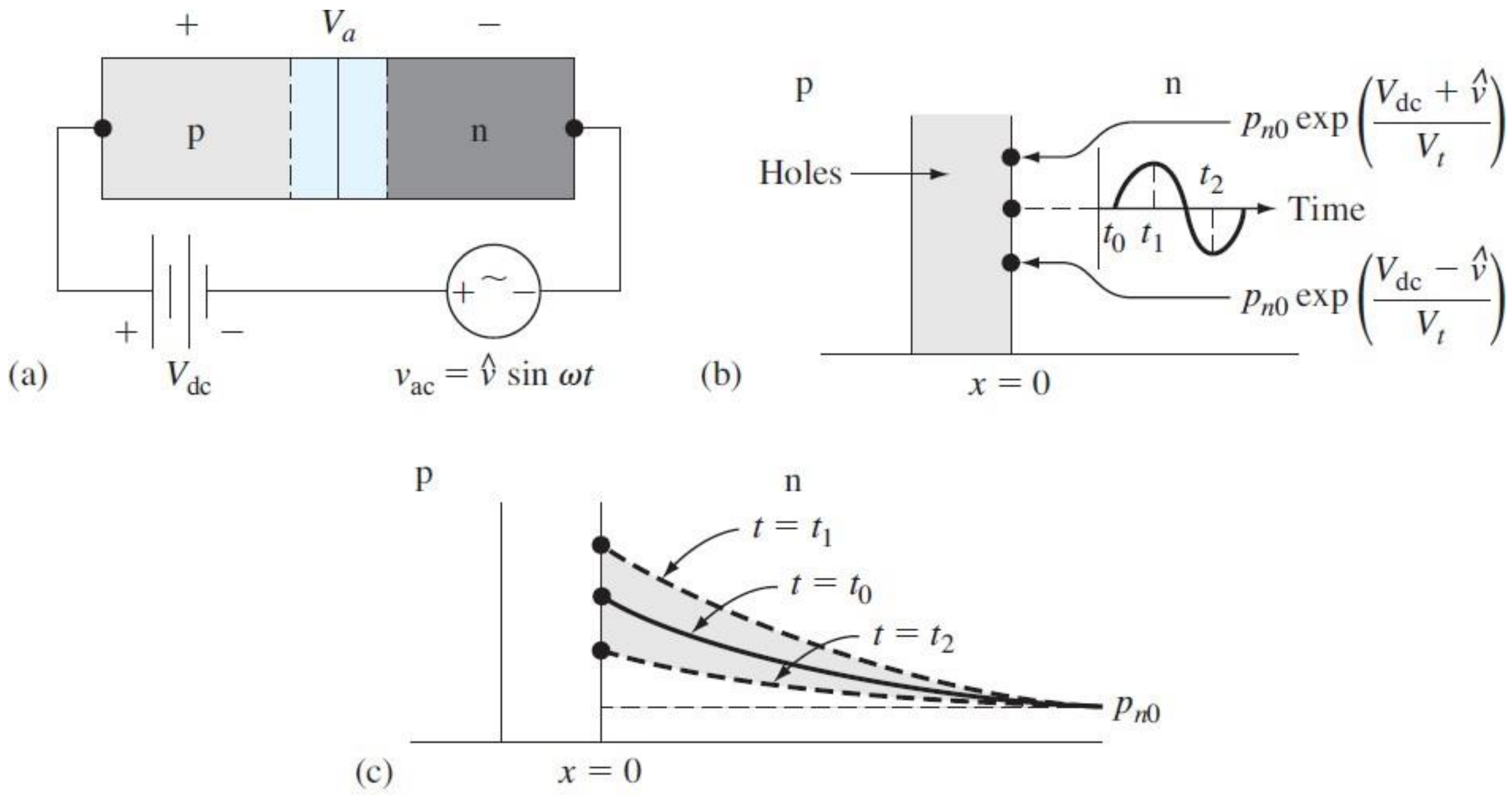


Figure 8.19 | (a) A pn junction with an ac voltage superimposed on a forward-biased dc value; (b) the hole concentration versus time at the space charge edge; (c) the hole concentration versus distance in the n region at three different times.

- The small-signal equivalent circuit of the forward-biased pn junction involves the junction capacitance, which will be in parallel with the diffusion resistance and diffusion capacitance.
- The last element we add, to complete the equivalent circuit, is a series resistance. The neutral n and p regions have finite resistances so the actual pn junction will include a series resistance.

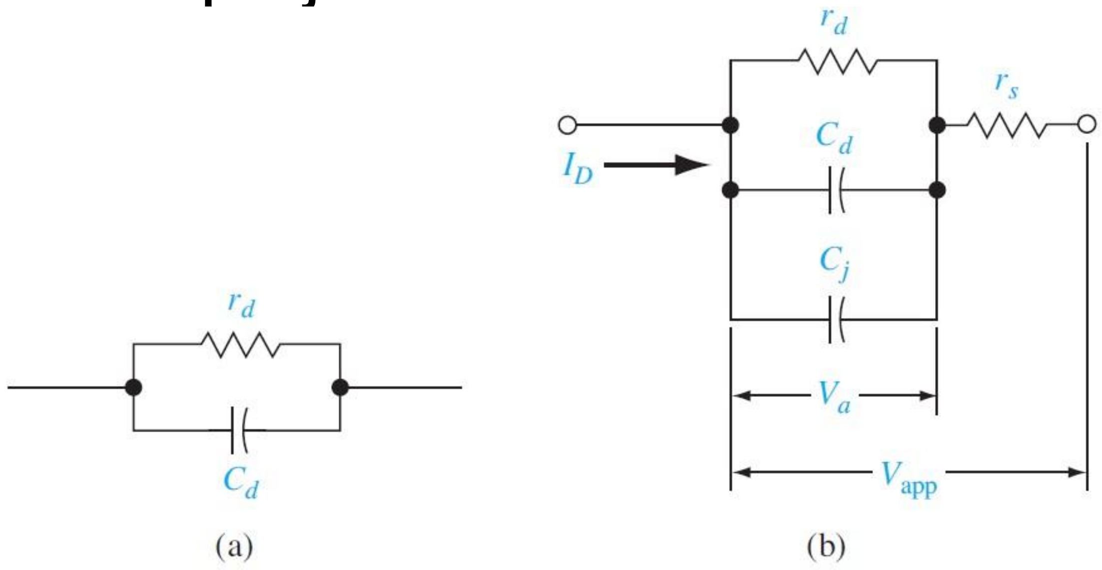
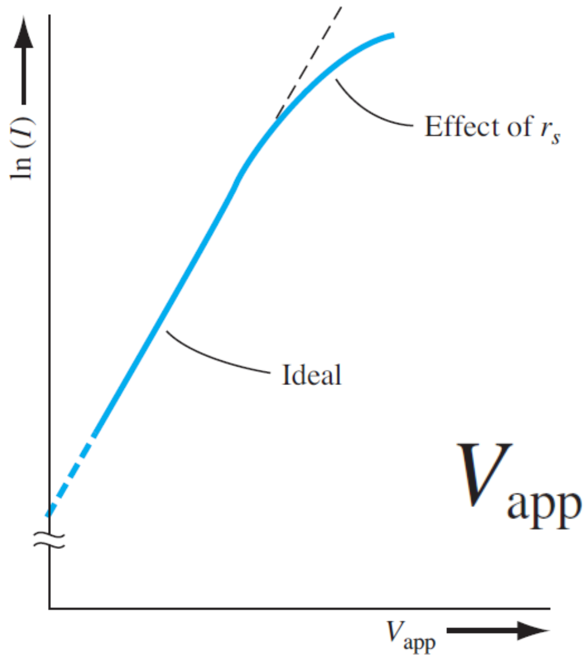


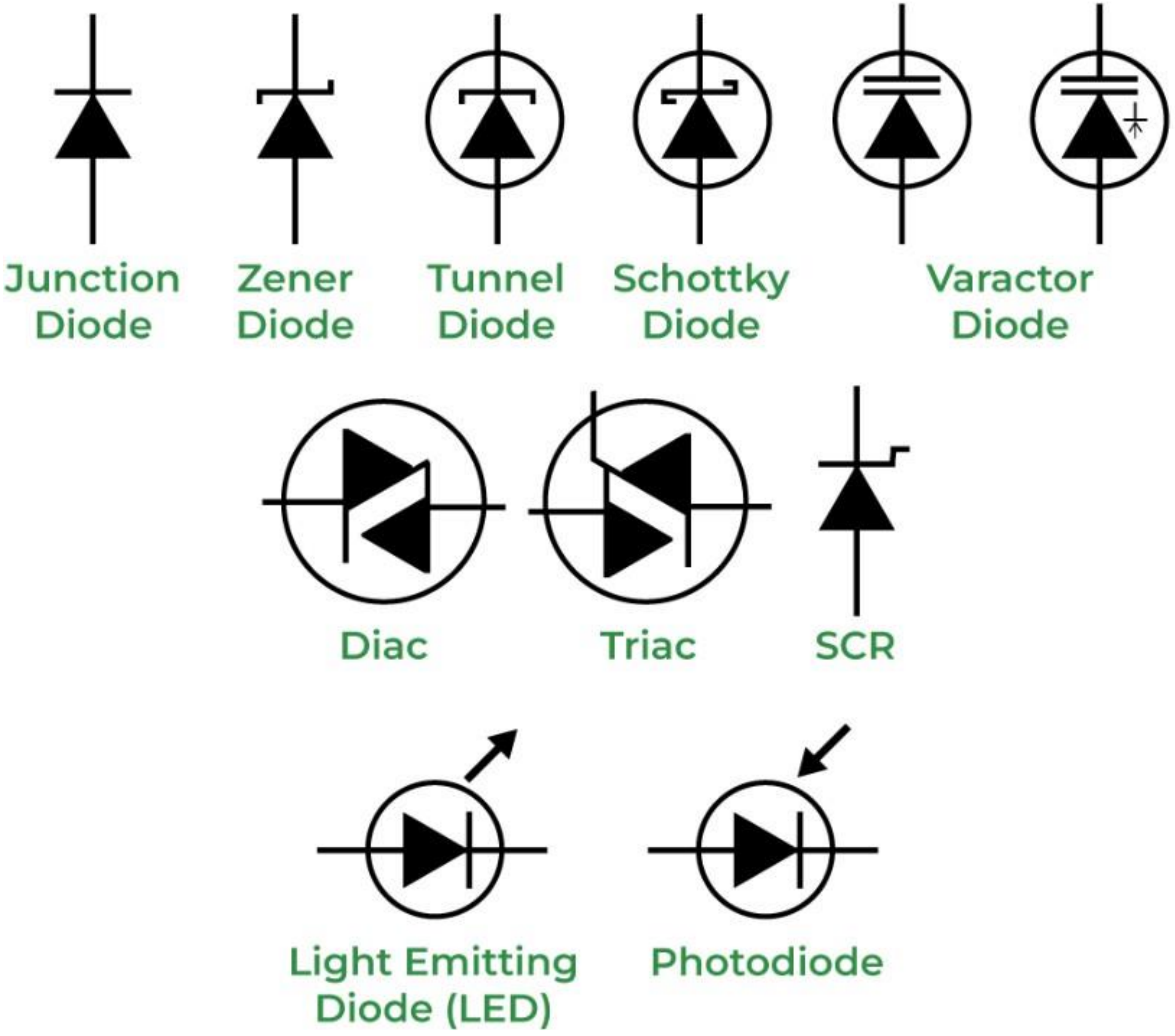
Figure 8.22 | (a) Small-signal equivalent circuit of ideal forward-biased pn junction diode; (b) complete small-signal equivalent circuit of pn junction.



$$V_{app} = V_a + Ir_s$$

Figure 8.23 | Forward-biased I–V characteristics of a pn junction diode showing the effect of series resistance.

Types and applications of diode



- Rectifiers
- Clipper Circuits
- Clamping Circuits
- Reverse Current Protection Circuits
- In Logic Gates
- Voltage Multipliers

Rectifiers

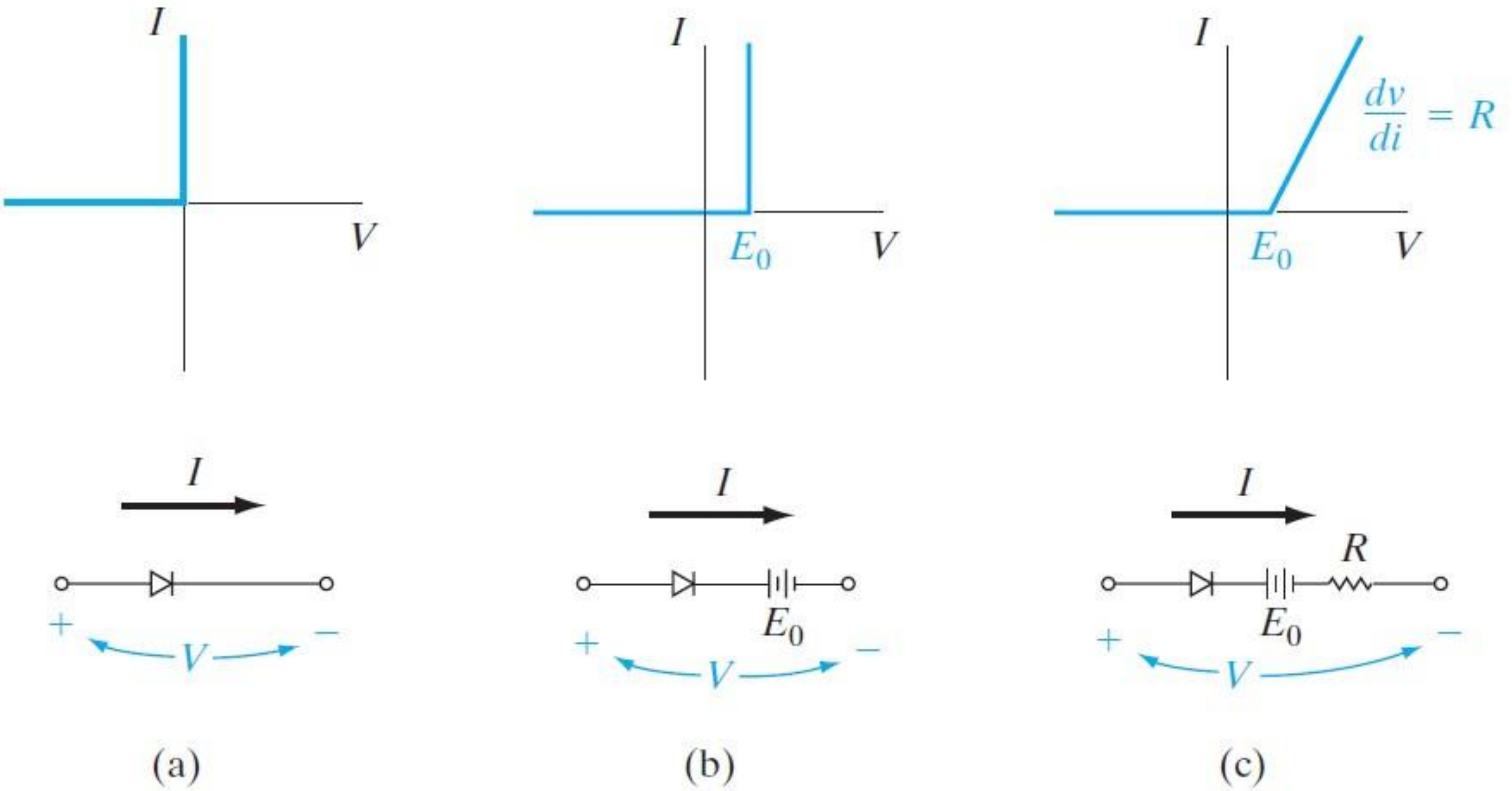


Figure 5–23
Piecewise-linear approximations of junction diode characteristics: (a) the ideal diode; (b) ideal diode with an offset voltage; (c) ideal diode with an offset voltage and a resistance to account for slope in the forward characteristic.

- An **ideal diode can be placed in series with an a-c voltage source** to provide *rectification of the signal. Since current can flow only in the forward* direction through the diode, only the positive half-cycles of the input sine wave are passed.
- The output voltage is a *half-rectified sine wave. Whereas the* input sinusoid has zero average value, the rectified signal has a positive average value and therefore contains a d-c component.
- By appropriate filtering, this d-c level can be extracted from the rectified signal.
- The **unilateral nature of diodes** is useful for many other circuit applications that require ***waveshaping***. *This involves alteration of a-c signals by* passing only certain portions of the signal while blocking other portions.
- Junction diodes designed for use as **rectifiers should have *I–V characteristics* as close as possible to that of the ideal diode.**
- The **reverse current** should be **negligible**, and the forward current should exhibit little voltage dependence (negligible *forward resistance R).*
- *The reverse breakdown voltage* should be large, and the offset voltage *E0 in the forward direction should* be small.

Zener diode

- By **varying the doping** we can fabricate diodes with specific breakdown voltages ranging from less than one volt to several hundred volts.
- If the junction is well designed, the breakdown will be sharp and the current after breakdown will be essentially independent of voltage.
- When a **diode is designed for a specific breakdown voltage**, it is called a *breakdown diode. Such diodes are also called Zener diodes, despite the fact that the* actual breakdown mechanism is usually the avalanche effect.
- Breakdown diodes can be used as *voltage regulators in circuits with* varying inputs.

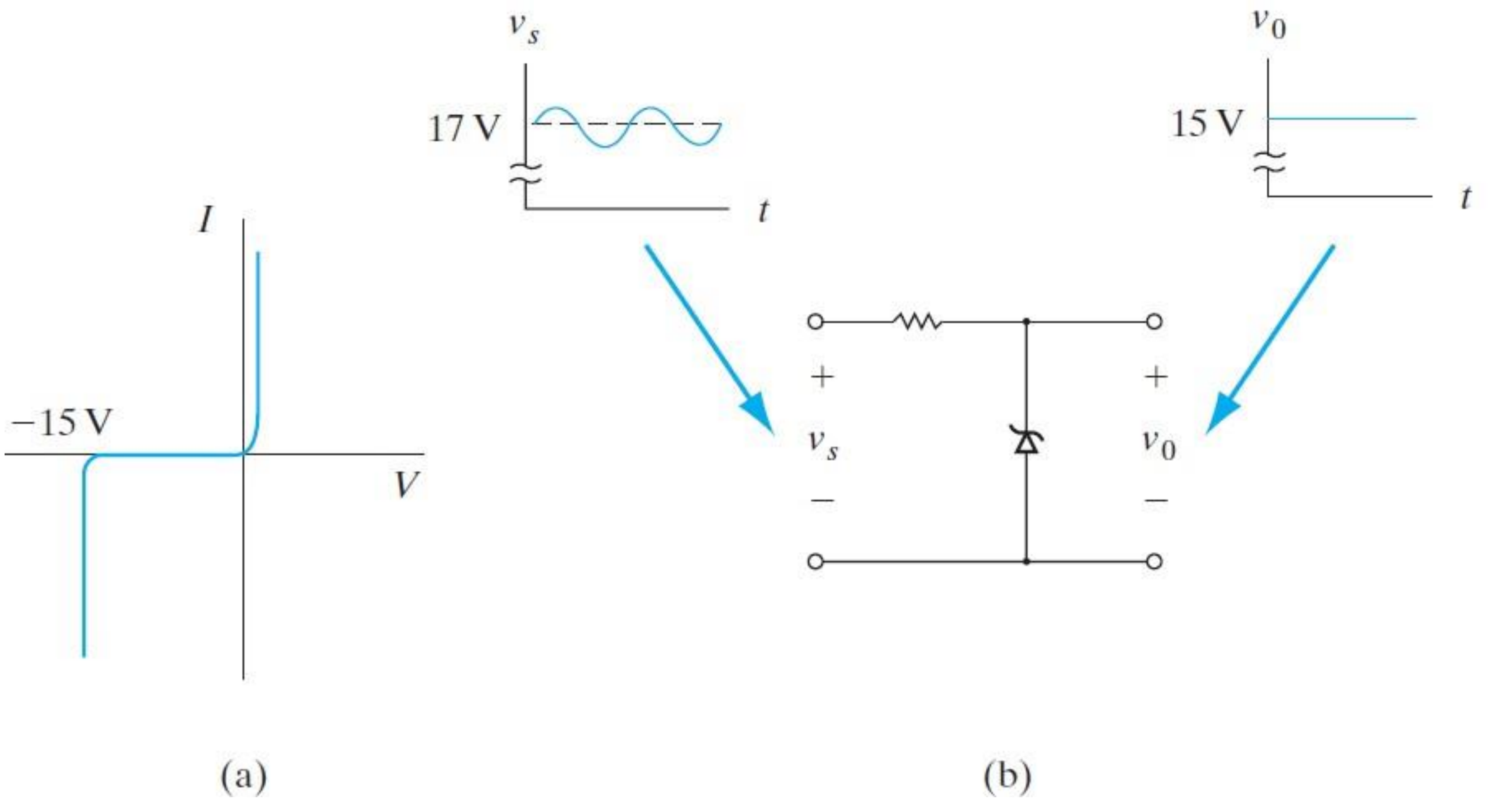


Figure 5–26
A breakdown diode: (a) *I–V* characteristic; (b) application as a voltage regulator.

Objective: Calculate the built-in potential barrier in a pn junction.

Consider a silicon pn junction at $T = 300$ K with doping concentrations of $N_a = 2 \times 10^{17}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}.

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$= (0.0259) \ln\left[\frac{(2 \times 10^{17})(10^{15})}{(1.5 \times 10^{10})^2}\right] = 0.713 \text{ V}$$

(a) Calculate the built-in potential barrier in a silicon pn junction at $T = 300$ K for (i) $N_a = 5 \times 10^{15}\ \text{cm}^{-3}$, $N_d = 10^{17}\ \text{cm}^{-3}$ and (ii) $N_a = 2 \times 10^{16}\ \text{cm}^{-3}$, $N_d = 2 \times 10^{15}\ \text{cm}^{-3}$.

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

(i) 0.736 V, (ii) 0.671 V

Metal semiconductor junction

Metal semiconductor diode is also called as point contact diode or schottky barrier diode.

This is made by touching a metallic whisker to an exposed semiconductor surface.

These metal–semiconductor diodes were not easily reproduced or mechanically reliable and were replaced by the pn junction in the 1950s.

However, **semiconductor and vacuum technology** is now used to fabricate reproducible and reliable metal–semiconductor contacts.

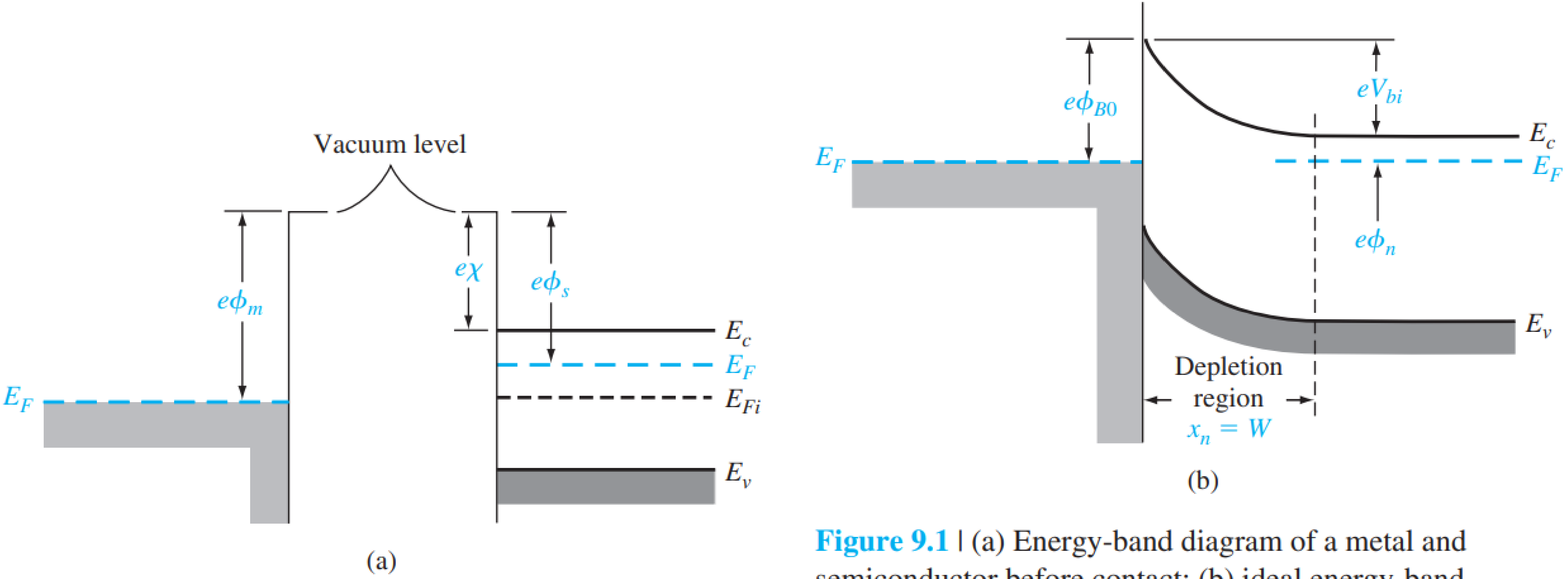


Figure 9.1 | (a) Energy-band diagram of a metal and semiconductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$.

$$V_{bi} = \phi_{B0} - \phi_n$$

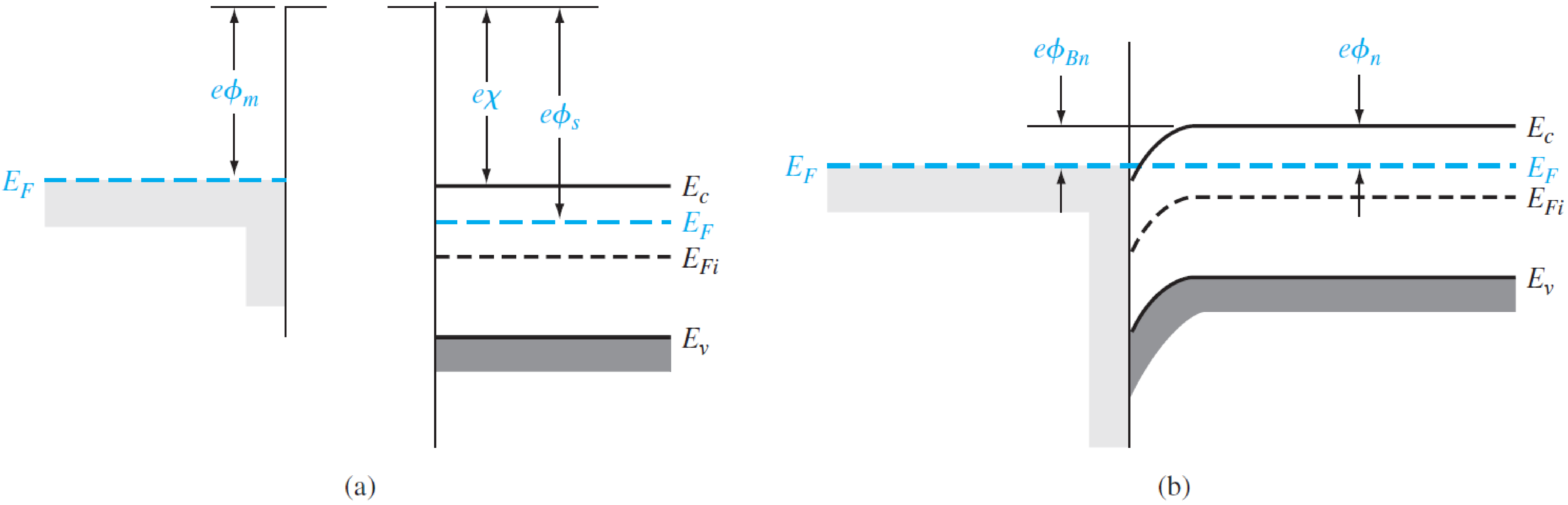


Figure 9.11 | Ideal energy-band diagram (a) before contact and (b) after contact for a metal-n-type semiconductor junction for $\phi_m < \phi_s$.

The parameter ϕ_{B0} is the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor. This barrier is known as the *Schottky barrier* and is given, ideally, by

$$\boxed{\phi_{B0} = (\phi_m - \chi)} \tag{9.1}$$

A junction capacitance can also be determined in the same way as we do for the pn junction. We have that

$$C' = eN_d \frac{dx_n}{dV_R} = \left[\frac{e\epsilon_s N_d}{2\,(V_{bi} + V_R)}\right]^{1/2} \tag{9.8}$$

where C' is the capacitance per unit area. If we square the reciprocal of Equation (9.8), we obtain

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d} \tag{9.9}$$

Forward and reverse bias

If we apply a positive voltage to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases, while Φ_{B0} remains constant in this idealized case. This bias condition is the **reverse bias.**

If a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier V_{bi} is reduced while Φ_{B0} again remains essentially constant.

In this situation, electrons can more easily flow from the semiconductor into the metal since the barrier has been reduced. This bias condition is the **forward bias.**

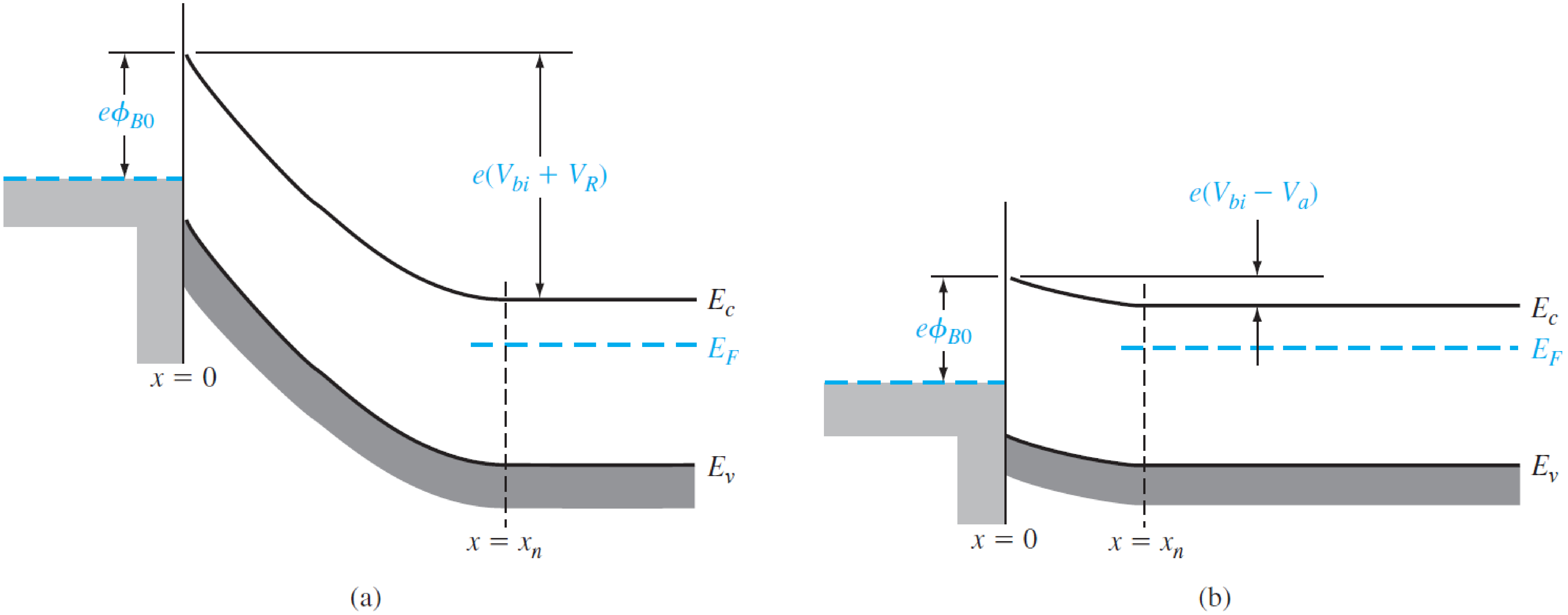


Figure 9.2 | Ideal energy-band diagram of a metal–semiconductor junction (a) under reverse bias and (b) under forward bias.

The electric field can then be written as

$$\mathrm{E} = -\frac{eN_d}{\epsilon_s}(x_n - x) \tag{9.6}$$

which is a linear function of distance, for the uniformly doped semiconductor, and reaches a peak value at the metal–semiconductor interface. Since the E-field is zero inside the metal, a negative surface charge must exist in the metal at the metal–semiconductor junction.

The space charge region width, W, may be calculated as we do for the pn junction. The result is identical to that of a one-sided p^+n junction. For the uniformly doped semiconductor, we have

$$\boxed{W = x_n = \left[\frac{2\epsilon_s(V_{bi} + V_R)}{eN_d}\right]^{1/2}} \tag{9.7}$$

where V_R is the magnitude of the applied reverse-biased voltage. We are again as-

The current mechanism here, however, is due to the flow of majority carrier electrons.

In forward bias, the barrier seen by the electrons in the semiconductor is reduced, so majority carrier electrons flow more easily from the semiconductor into the metal.

The forward-bias current is in the direction from metal to semiconductor: It is an exponential function of the forward-bias voltage.

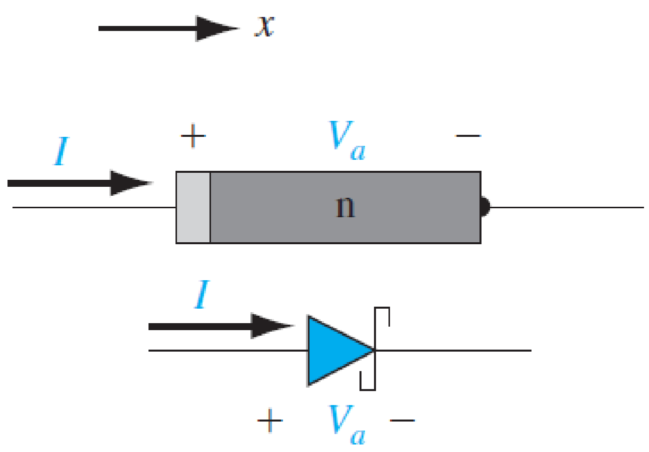
The reverse-saturation current density of the Schottky barrier diode was given by Equation (9.26) and is

$$J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

The ideal reverse-saturation current density of the pn junction diode can be written as

$$J_s = \frac{eD_n n_{po}}{L_n} + \frac{eD_p p_{no}}{L_p} \tag{9.28}$$

I-V characteristics



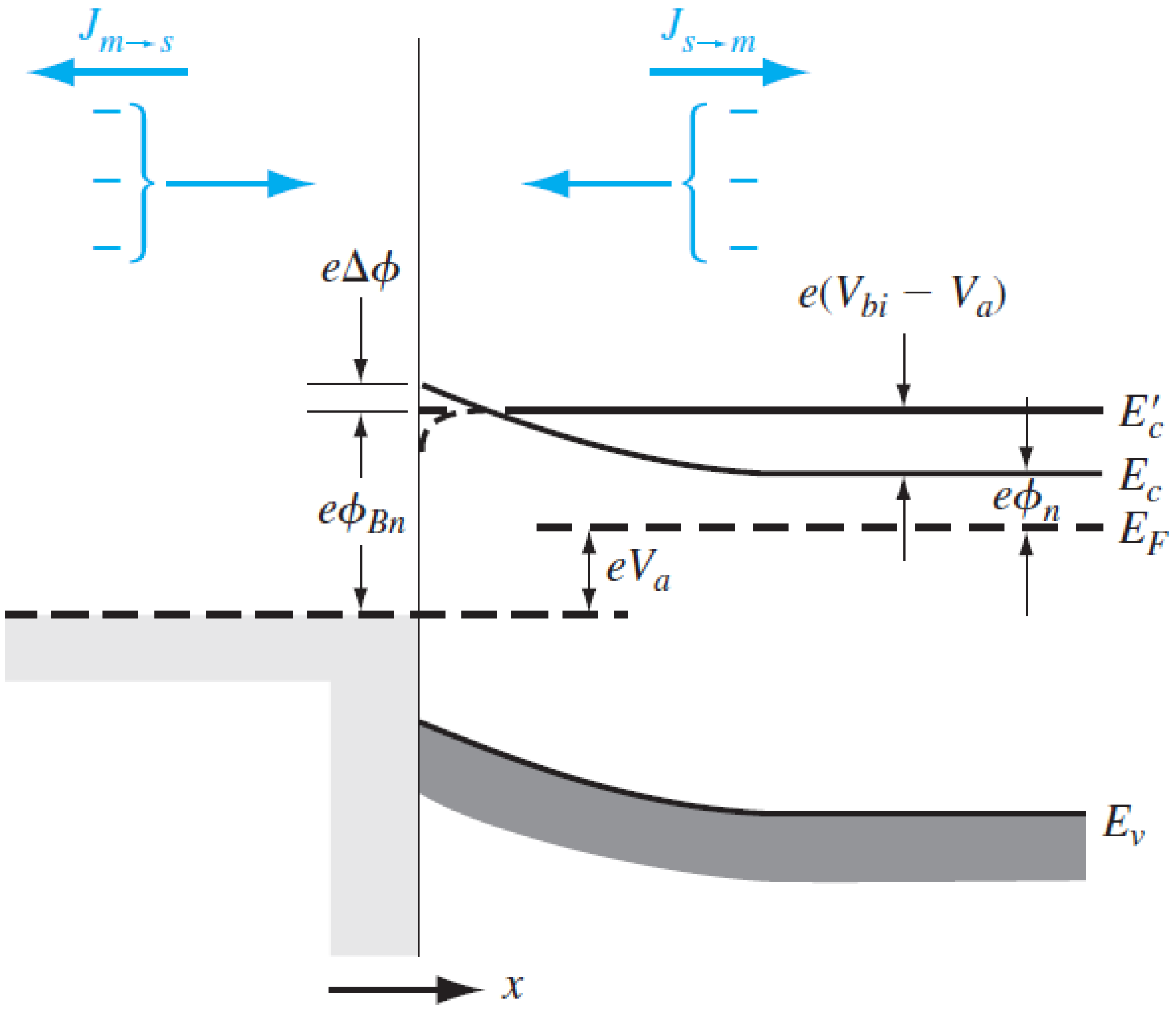


Figure 9.7 | Energy-band diagram of a forward-biased metal–semiconductor junction including the image lowering effect.

The net current density in the metal-to-semiconductor junction can be written as

$$J = J_{s \to m} - J_{m \to s} \tag{9.22}$$

which is defined to be positive in the direction from the metal to the semiconductor. We find that

$$\boxed{J = \left[A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{9.23}$$

where

$$\boxed{A^* \equiv \frac{4\pi e m_n^* k^2}{h^3}} \tag{9.24}$$

The parameter A^* is called the effective Richardson constant for thermionic emission.

Equation (9.23) can be written in the usual diode form as

$$\boxed{J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{9.25}$$

where J_{sT} is the reverse-saturation current density and is given by

$$\boxed{J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)} \tag{9.26}$$

Comparison of Schottky barrier and pn diode

The first is in the magnitudes of the reverse-saturation current densities and the second is in the switching characteristics.

The current in a pn junction is determined by the **diffusion of minority carriers** while the current in a Schottky barrier diode is determined by **thermionic emission of majority carriers** over a potential barrier.

The effective turn-on voltage of the Schottky diode is less than that of the pn junction diode.

The reverse-biased current in a silicon pn junction diode is dominated by the generation current. A generation current also exists in the reverse-biased Schottky barrier diode; however, the generation current is negligible compared with the J_{sT} value.

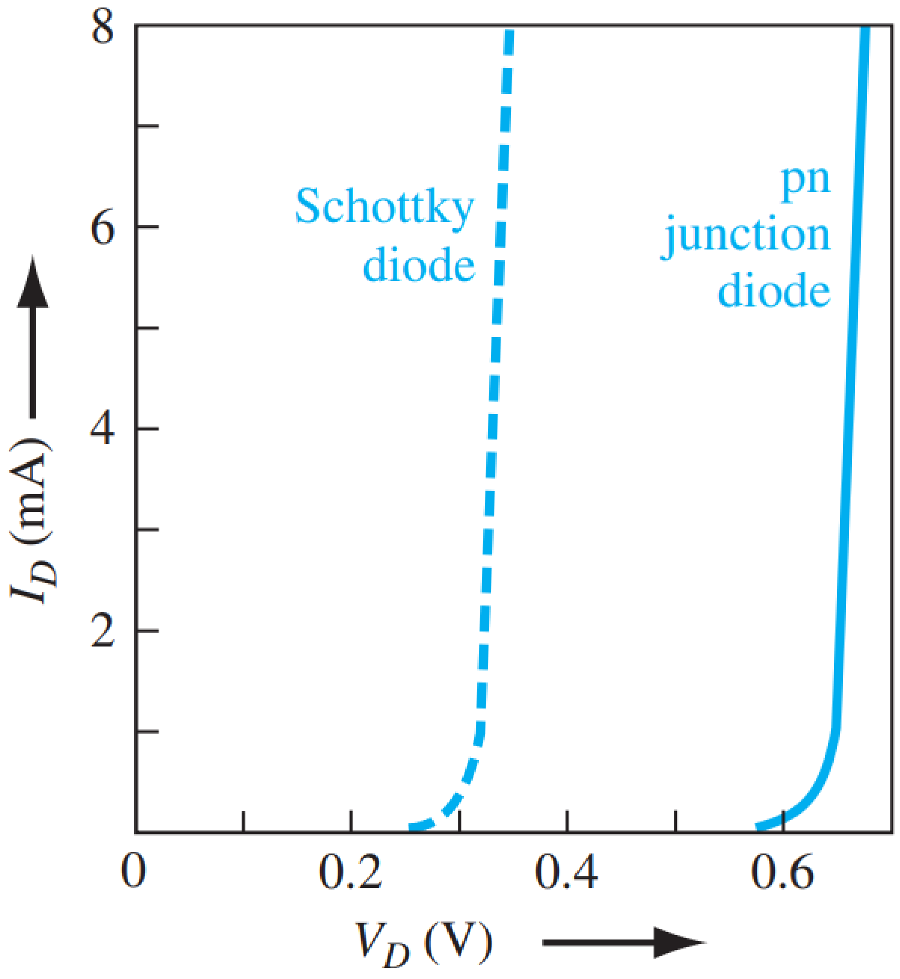


Figure 9.10 | Comparison of forward-bias I–V characteristics between a Schottky diode and a pn junction diode.

when switching a Schottky diode from forward to reverse bias, there is no minority carrier stored charge to remove, as is the case in the pn junction diode.

Since there is no minority carrier storage time, the Schottky diodes can be used in fast-switching applications.

A typical switching time for a Schottky diode is in the picosecond range, while for a pn junction it is normally in the nanosecond range.

Heterojunctions

we assumed that the semiconductor material is homogeneous throughout the structure. This type of junction is called a *homojunction.*

When two different semiconductor materials are used to form a junction, the junction is called a *semiconductor heterojunction.*

There are four basic types of heterojunction.

Those in which the dopant type changes at the junction are called ***anisotype.*** *We can form nP or Np junctions, where* the capital letter indicates the larger-bandgap material.

Heterojunctions with the same dopant type on either side of the junction are called ***isotype***. *We can form nN* and pP isotype heterojunctions.

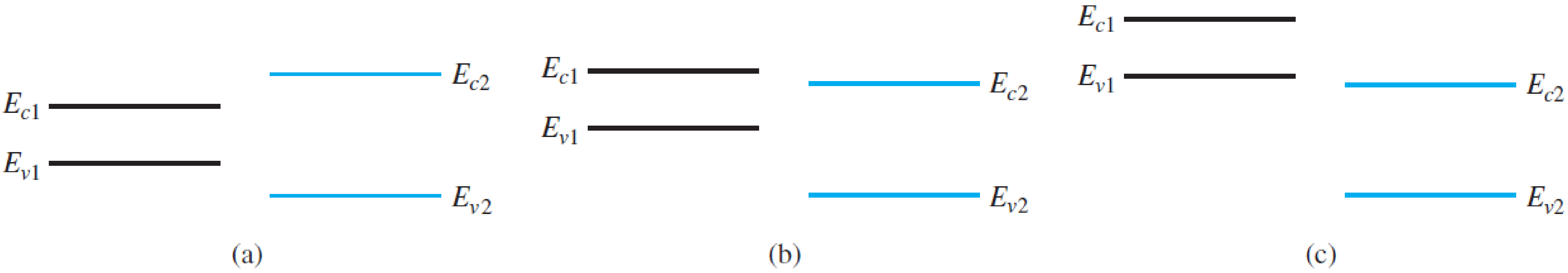


Figure 9.16 | Relation between narrow-bandgap and wide-bandgap energies: (a) straddling, (b) staggered, and (c) broken gap.

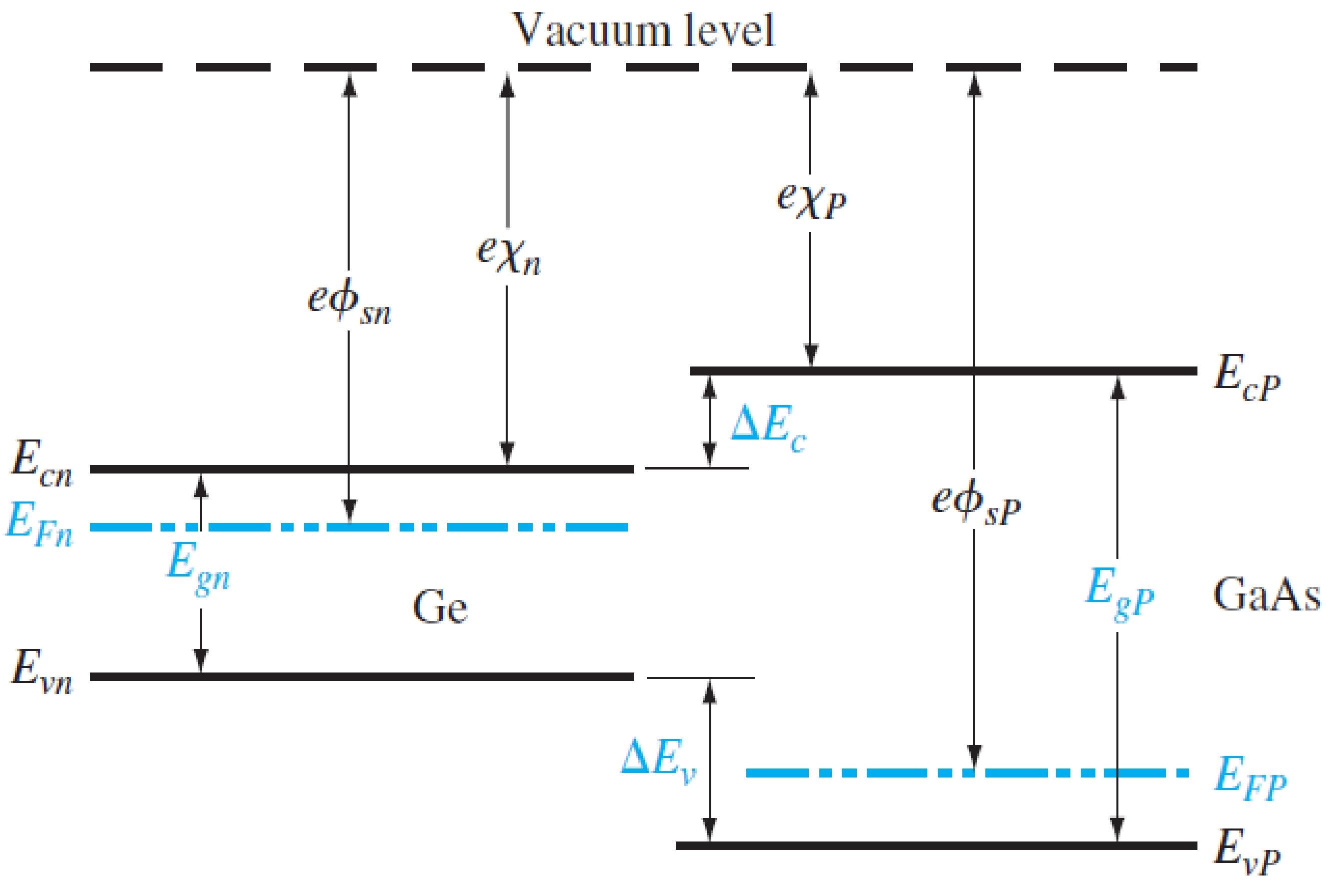


Figure 9.17 | Energy-band diagrams of a narrow-bandgap and a wide-bandgap material before contact.

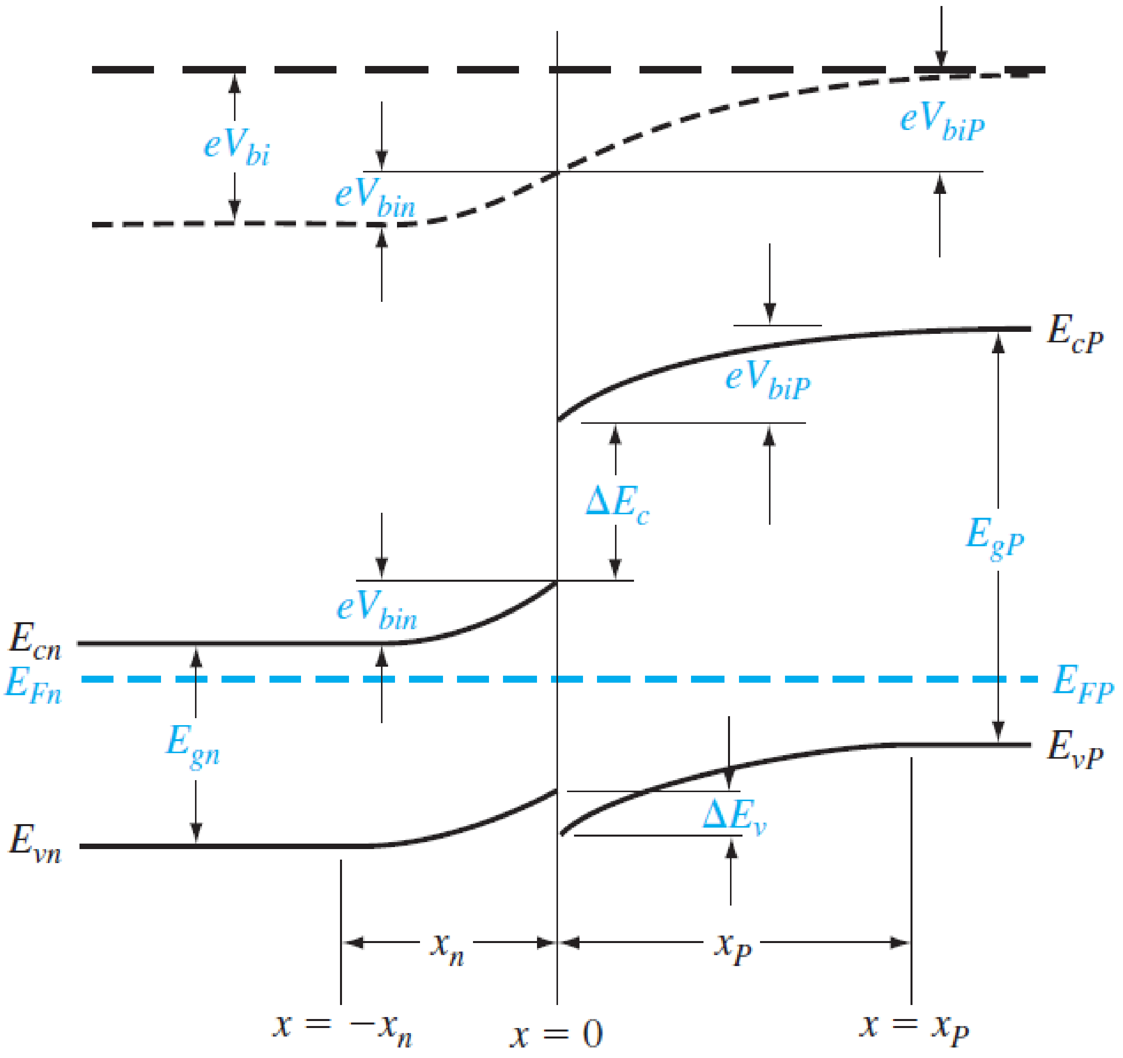


Figure 9.18 | Ideal energy-band diagram of an nP heterojunction in thermal equilibrium.