Chapter 8

The pn Junction

Outline

8.1 pn Junction Current

8.2 Generation–Recombination Currents and High-Injection Levels

8.3 Small-Signal Model of the pn Junction

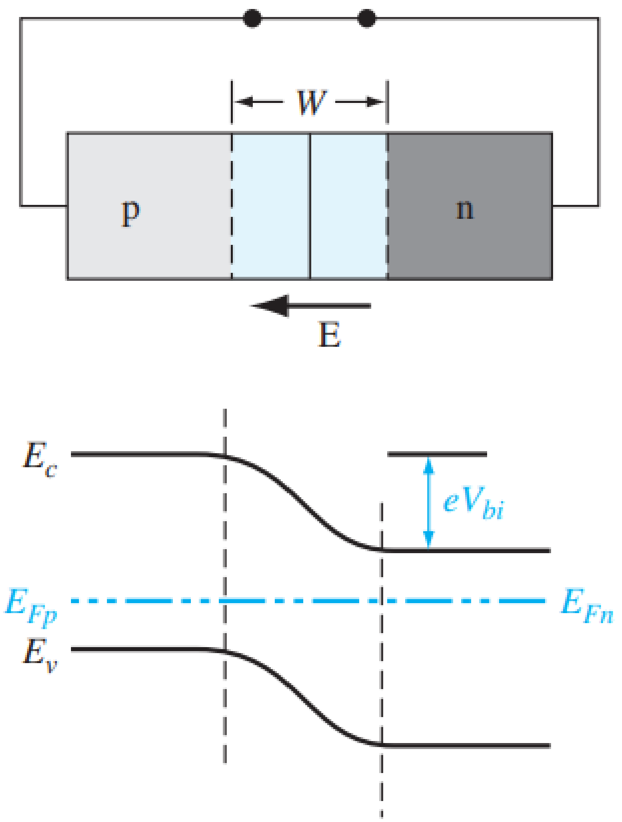
8.4 Charge Storage and Diode Transients

8.5 The Tunnel Diode

8.1pn JUNCTION CURRENT

- When a forward-bias voltage is applied to a pn junction, a current will be induced in the device.

- 8.1.1 Qualitative Description of Charge Flow in a pn Junction
- Fig.1a, **no current** flows due to the potential barrier and maintain thermal equilibrium under **zero bias**.



(a)

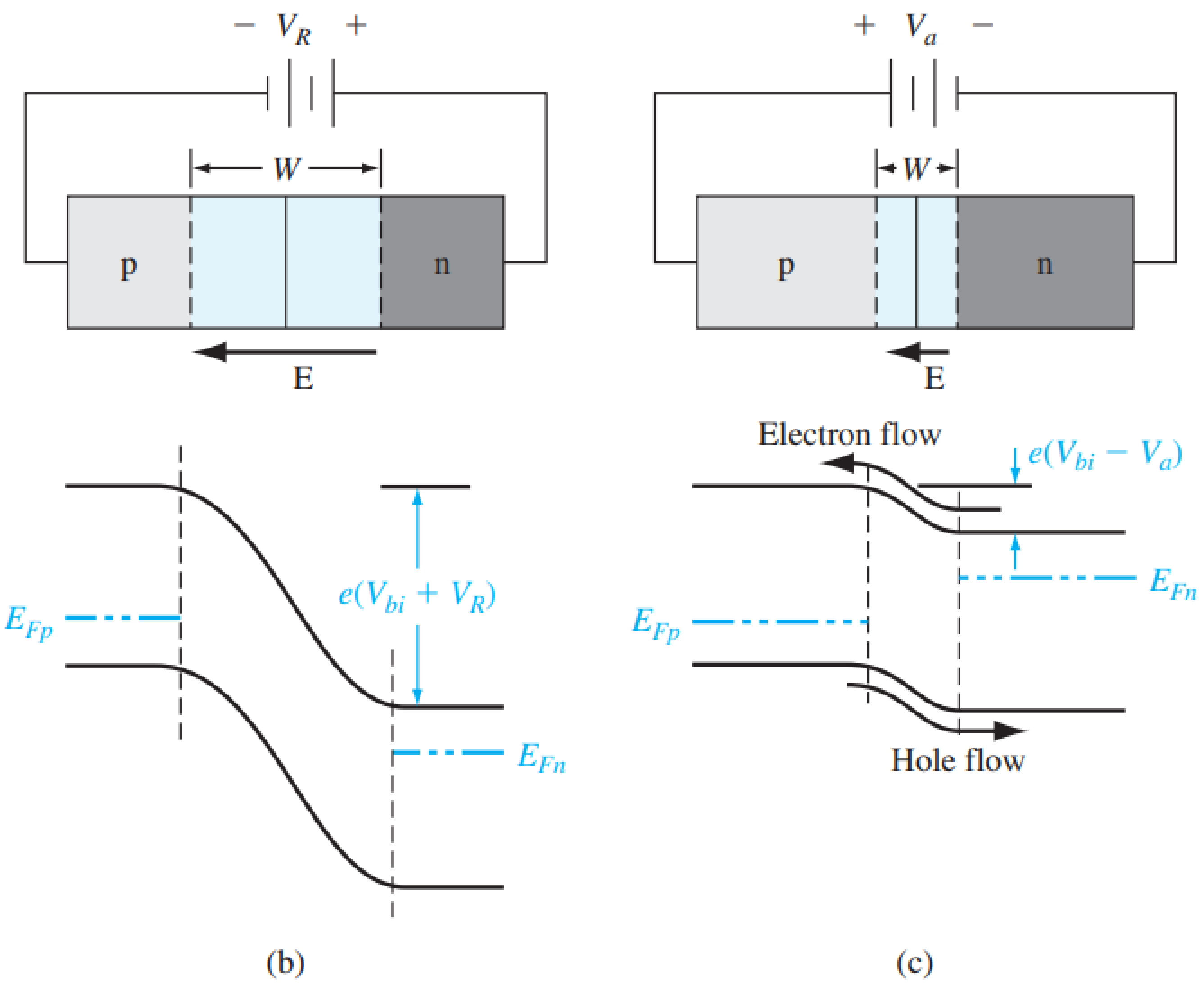
pn JUNCTION CURRENT

Figure 8.1b

- The potential of the n region is positive with respect to the p region
- there is still essentially no charge flow and hence essentially no current

Figure 8.1c

- Figure 8.1c the total potential barrier is now rhargeduced
- The flow of ce generates a current through the pn junction
- There will be diffusion as well as recombination of excess carriers in these regions



Ideal Current–Voltage Relationship

- 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
- The concepts of low injection and complete ionization apply
- 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

Commonly used terms and notation

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

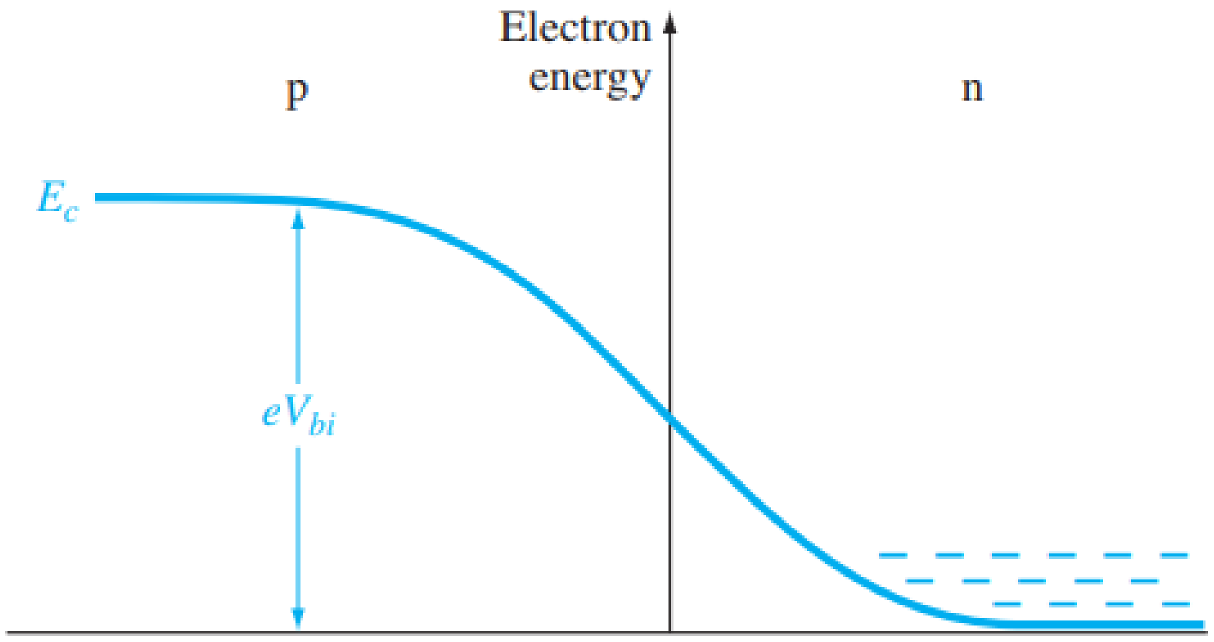
Boundary Conditions

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \text{divide } V_t = kT/e$$

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

Assume $n_{n0} \approx N_d$

In p-region $n_{p0} \approx \dfrac{n_i^2}{N_a} = n_{n0} \exp\left(\dfrac{-eV_{bi}}{kT}\right)$

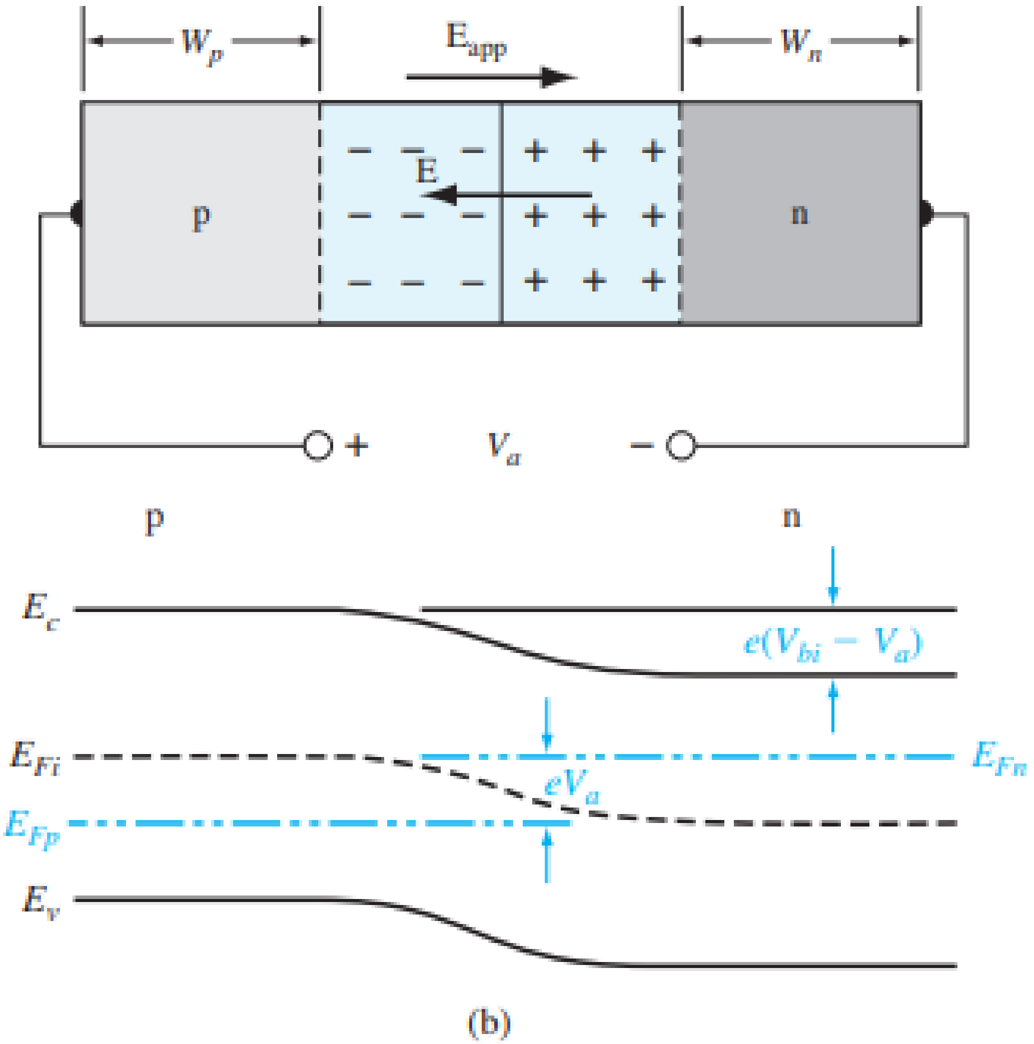


Boundary Conditions of forward bias

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

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

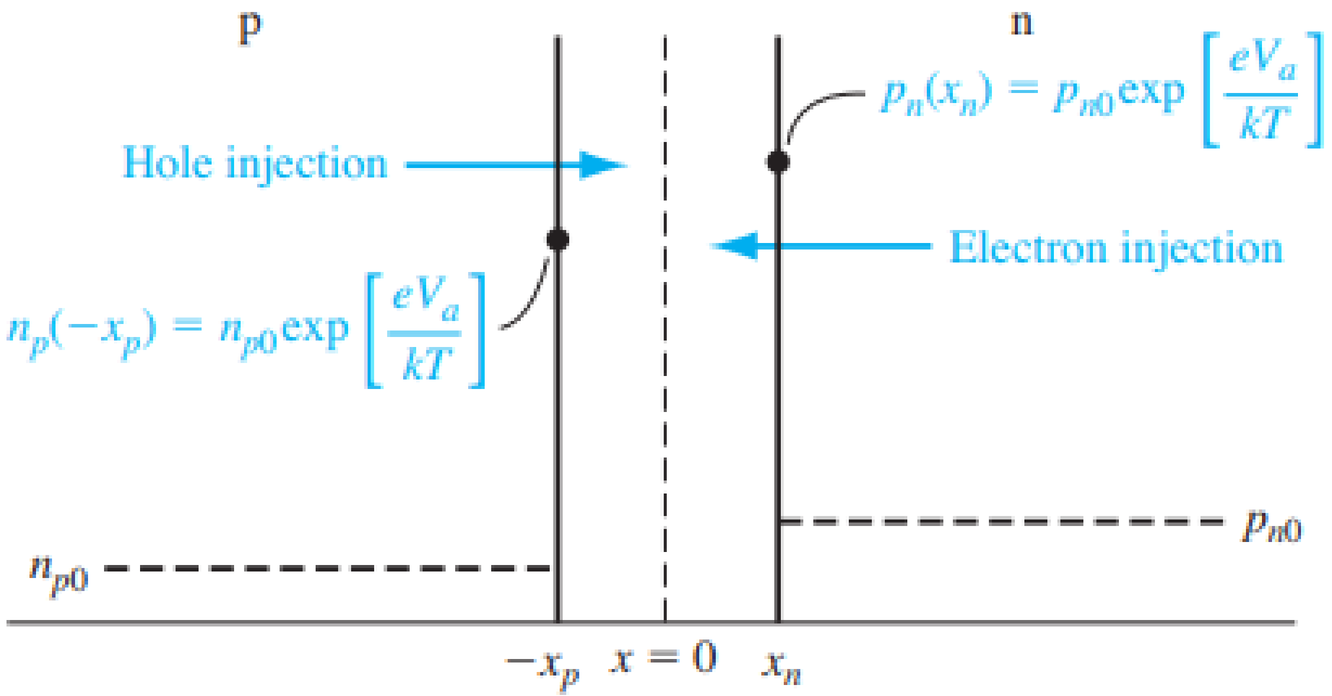
$$= n_{p0}\exp\left(\frac{eV_a}{kT}\right)$$



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

Excess minority carrier concentrations at the space charge edges

When the electrons are injected into the p region, these excess carriers are subject to the diffusion and recombination processes



$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right) \qquad p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

EXAMPLE 8.1

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

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

$$n_{po} = \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{6 \times 10^{15}} = 3.75 \times 10^4\ \text{cm}^{-3}$$

$$p_{no} = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4\ \text{cm}^{-3}$$

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

$$p_n(x_n) = 2.25 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 2.59 \times 10^{14}\ \text{cm}^{-3}$$

Minority Carrier Distribution

$$D_p \frac{\partial^2 (\delta p_n)}{\partial x^2} - \mu_p E \frac{\partial (\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{p0}} = \frac{\partial (\delta p_n)}{\partial t} \qquad ; \delta p_n = p_n - p_{n0}$$

we assume that the electric field is zero in both the neutral p and n regions∞

In the n region for x > x_n, we have E =0 and g′=0. With steady state $\partial(\delta p_n)/\partial t = 0$

$$\frac{d^2 (\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \left(x > x_n \right) \text{ where } L_p^2 = D_p \tau_{p0}$$

For same condition

$$\frac{d^2 (\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0 \left(x < x_p \right) \text{ where } L_n^2 = D_n \tau_{n0}$$

Minority Carrier Distribution

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0\left(x > x_n\right) \text{ where } L_p^2 = D_p \tau_{p0}$$

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

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

Boundary condtion:

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

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

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

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

$$\boxed{\begin{aligned} \delta p_n(x) = p_n(x) - p_{n0} &= p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right)\left(x \geq x_n\right) \\ \delta n_p(x) = n_p(x) - n_{p0} &= n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right)\left(x \leq -x_p\right) \end{aligned}}$$

Minority Carrier Distribution

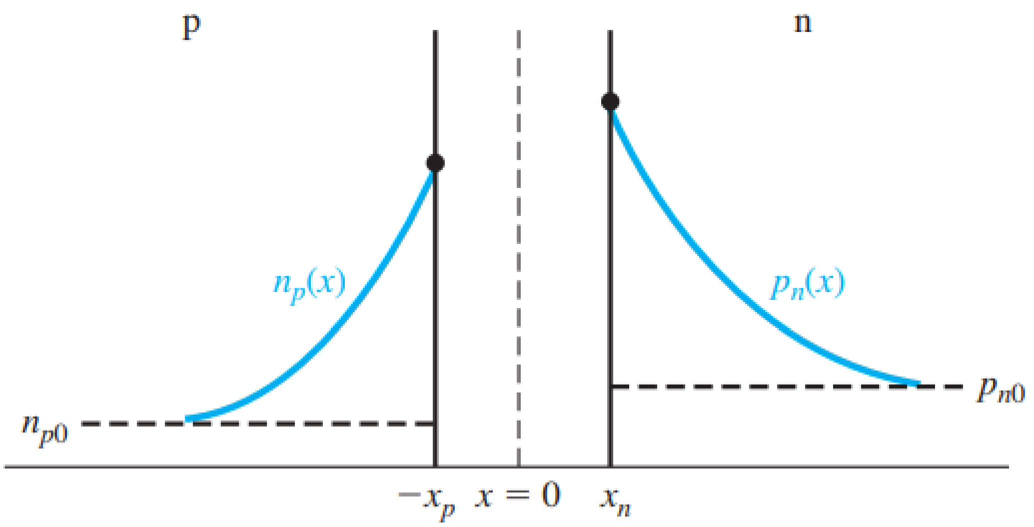

Figure 8.5 | Steady-state minority carrier concentrations in a pn junction under forward bias.

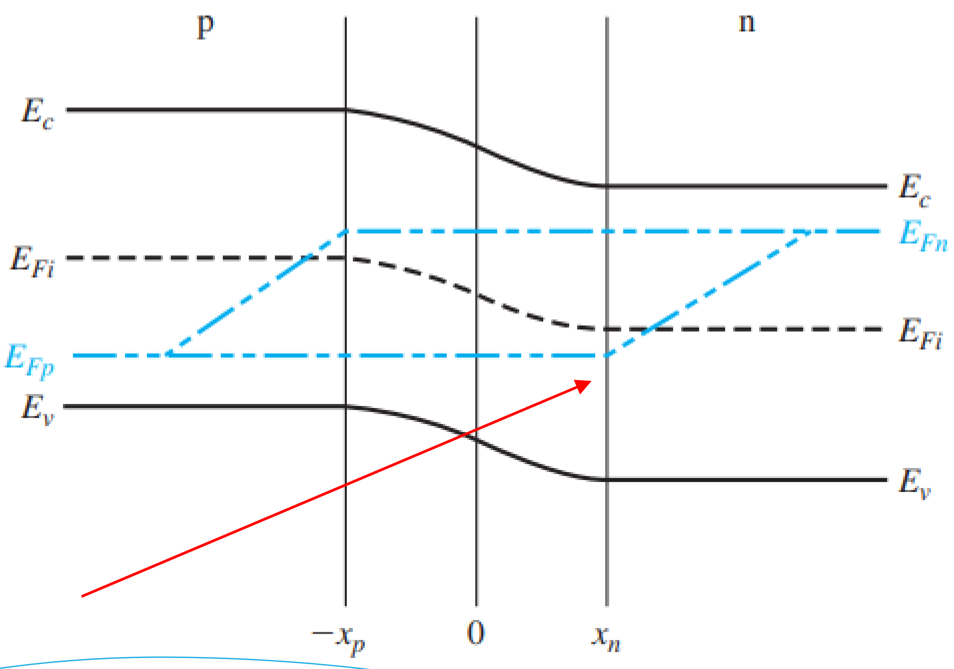

Figure 8.6 | Quasi-Fermi levels through a forward-biased pn junction.

linear

$$p = p_0 + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

$$n = n_0 + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

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

$$\delta p_n(x) = p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_P}\right) \quad (x \geq x_n)$$

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

Ideal pn Junction Current

$$J_p(x_n) = -eD_p \frac{dp_n(x)}{dx}\bigg|_{x=x_n} = -eD_p \frac{d(\delta p_n(x))}{dx}\bigg|_{x=x_n} = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right)-1\right]$$

$$J_n(-x_p) = eD_n \frac{dn_p(x)}{dx}\bigg|_{x=-x_p} = eD_n \frac{d(\delta n_p(x))}{dx}\bigg|_{x=-x_p} = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right)-1\right]$$

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

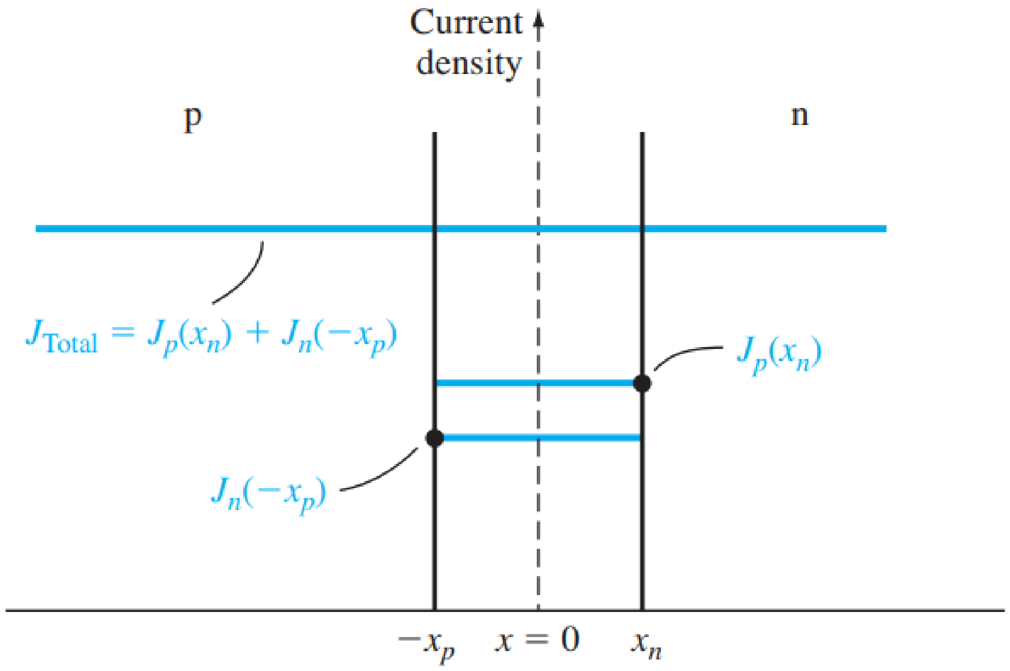

Figure 8.7 | Electron and hole current densities through the space charge region of a pn junction.

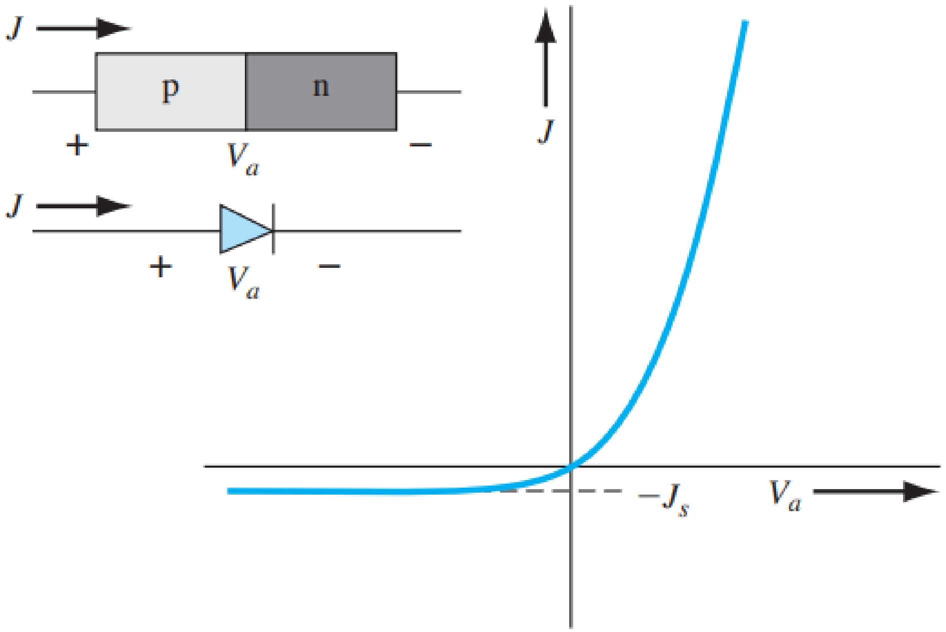

Figure 8.8 | Ideal I–V characteristic of a pn junction diode.

EXAMPLE 8.2

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:

$$N_a = N_d = 10^{16}\ \text{cm}^{-3} \qquad n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$$
$$D_n = 25\ \text{cm}^2/\text{s} \qquad \tau_{p0} = \tau_{n0} = 5 \times 10^{-7}\ \text{s}$$
$$D_p = 10\ \text{cm}^2/\text{s} \qquad \epsilon_r = 11.7$$

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

The ideal reverse-saturation current density is given by

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

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

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

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

Ideal I–V characteristic of a pn junction

- If the forward-bias voltage in Equation (8.27) is positive by more than a few kT/eV, , then the -1 term in Equation (8.27) becomes negligible

$$J = J_p(x_n) + J_n(-x_p)$$
$$= J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

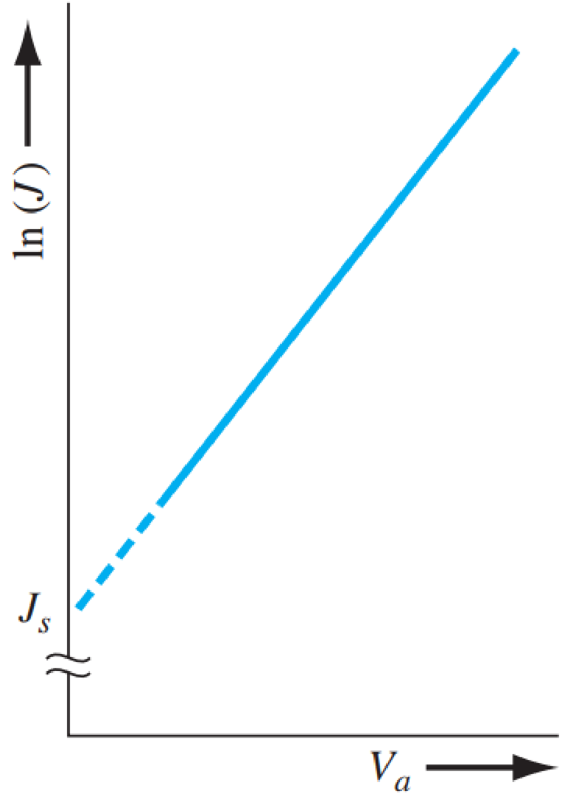

Figure 8.9 | Ideal *I–V* characteristic of a pn junction diode with the current plotted on a log scale.

EXAMPLE 8.3

Objective: Design a pn junction diode to produce particular electron and hole current densities at a given forward-bias voltage.

Consider a silicon pn junction diode at $T = 300$ K. Design the diode such that $J_n = 20$ A/cm^2 and $J_p = 5$ A/cm^2 at $V_a = 0.65$ V. Assume the remaining semiconductor parameters are as given in Example 8.2.

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$$J_n = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] = e\sqrt{\frac{D_n}{\tau_{n0}}} \cdot \frac{n_i^2}{N_a}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$20 = (1.6 \times 10^{-19})\sqrt{\frac{25}{5 \times 10^{-7}}} \cdot \frac{(1.5 \times 10^{10})^2}{N_a}\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right] \longrightarrow N_a = 1.01 \times 10^{15}\ \text{cm}^{-3}$$

$$J_p = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] = e\sqrt{\frac{D_p}{\tau_{p0}}} \cdot \frac{n_i^2}{N_d}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$5 = (1.6 \times 10^{-19})\sqrt{\frac{10}{5 \times 10^{-7}}} \cdot \frac{(1.5 \times 10^{10})^2}{N_d}\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right] \longrightarrow N_d = 2.55 \times 10^{15}\ \text{cm}^{-3}$$

Summary of Physics

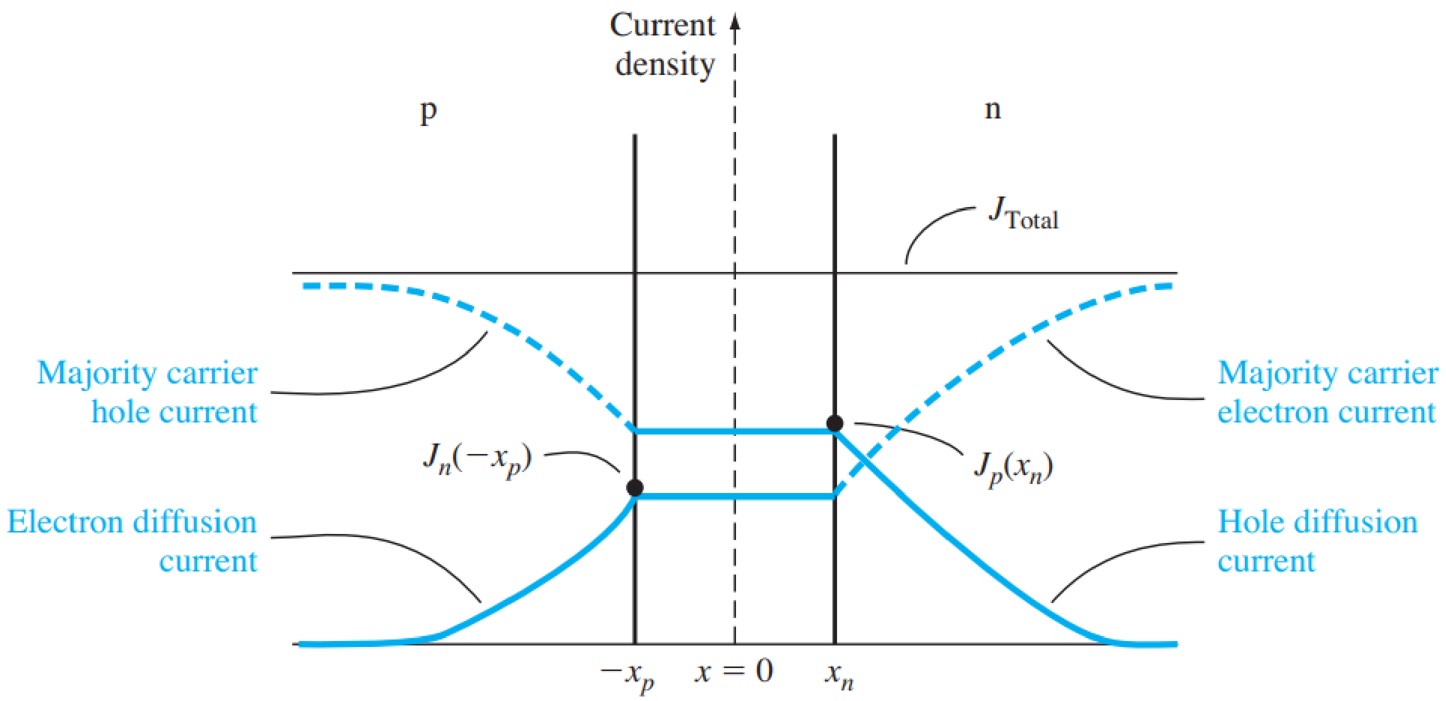

Figure 8.10 | Ideal electron and hole current components through a pn junction under forward bias.

$$J_p(x_n) = -eD_p \frac{dp_n(x)}{dx}\bigg|_{x=x_n} = -eD_p \frac{d(\delta p_n(x))}{dx}\bigg|_{x=x_n} = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right)-1\right]$$

$$J_n(-x_p) = eD_n \frac{dn_p(x)}{dx}\bigg|_{x=-x_p} = eD_n \frac{d(\delta n_p(x))}{dx}\bigg|_{x=-x_p} = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right)-1\right]$$

EXAMPLE 8.4

Objective: Calculate the electric field in a neutral region of a silicon diode to produce a given majority carrier drift current density.

Consider a silicon pn junction at $T = 300$ K with the parameters given in Example 8.2 and with an applied forward-bias voltage $V_a = 0.65$ V.

EXAMPLE 8.4

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Consider a silicon pn junction at $T = 300$ K with the parameters given in Example 8.2 and with an applied forward-bias voltage $V_a = 0.65$ V.

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

We determined the reverse-saturation current density in Example 8.2, so we can write

$$J = (4.155 \times 10^{-11})\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right] = 3.295 \text{ A/cm}^2$$

The total current far from the junction in the n region will be majority carrier electron drift current, so we can write $J = J_n \approx e\mu_n N_d \mathrm{E}$

$N_d = 10^{16}$ cm^{-3} $\quad \mu_n = 1350$ cm^2/V-s

$$\mathrm{E} = \frac{J_n}{e\mu_n N_d} = \frac{3.295}{(1.6 \times 10^{-19})(1350)(10^{16})} = 1.525 \text{ V/cm}$$

Temperature Effects

- $J_s = [\frac{eD_p p_{no}}{L_p} + \frac{eD_n n_{po}}{L_n}]$, where p_{no} and n_{po} are proportional to n_i^2, which is a very strong function of temperature.
- For a silicon pn junction, a factor of **4** for every **10˚C** increase in temperature.
- $\mathrm{J} = J_s[\exp\left(\frac{eV_a}{kT}\right) - 1]$, where $\exp\left(\frac{eV_a}{kT}\right)$ is a function of temperature also.
- As temperature increases, **less** forward-bias voltage is required to obtain the same diode current.
- The change in forward-bias current with temperature is **less sensitive** than the reverse-saturation current.

EXAMPLE 8.5

Objective: Determine the change in the forward-bias voltage on a pn junction with a change in temperature to maintain a constant diode current.

Consider a silicon pn junction initially biased at 0.60 V at $T = 300$ K. Assume the temperature increases to $T = 310$ K. Calculate the change in the forward-bias voltage required to maintain a constant current through the junction.

EXAMPLE 8.5

Objective: Determine the change in the forward-bias voltage on a pn junction with a change in temperature to maintain a constant diode current.

Consider a silicon pn junction initially biased at 0.60 V at $T = 300$ K. Assume the temperature increases to $T = 310$ K. Calculate the change in the forward-bias voltage required to maintain a constant current through the junction.

$$J \propto \exp\left(\frac{-E_g}{kT}\right)\exp\left(\frac{eV_a}{kT}\right) \longrightarrow \frac{J_2}{J_1} = \frac{\exp(-E_g/kT_2)\exp(eV_{a2}/kT_2)}{\exp(-E_g/kT_1)\exp(eV_{a1}/kT_1)}$$

If current is to be held constant, then $J_1 = J_2$, and we must have

$$\frac{E_g - eV_{a2}}{kT_2} = \frac{E_g - eV_{a1}}{kT_1}$$

For $T_1 = 300$ K, $T_2 = 310$ K, $E_g = 1.12$ eV, and $V_{a1} = 0.60$ V. We then find

$$\frac{1.12 - V_{a2}}{310} = \frac{1.12 - 0.60}{300} \longrightarrow V_{a2} = 0.5827 \text{ V}$$

The “Short” Diode

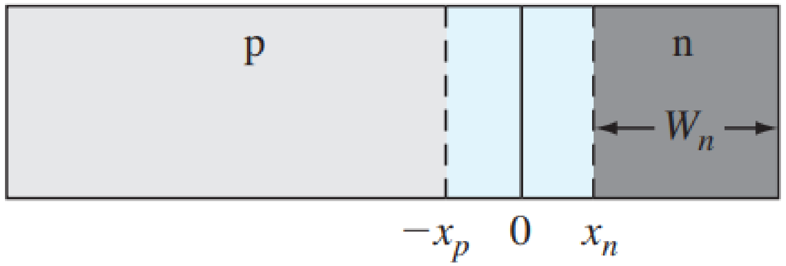

Figure 8.11 | Geometry of a “short” diode.

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0\left(x > x_n\right) \text{ where } L_p^2 = D_p \tau_{p0}$$

$$\downarrow$$

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

Boundary condtion:

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

$$\boxed{p_n\left(x = x_n + W_n\right) = p_{n0}}$$

$$\delta p_n(x) = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \frac{\sinh\left[\left(x_n + W_n - x\right)/L_p\right]}{\sinh\left[W_n / L_p\right]}$$

$W_n \gg L_p$ back to original form

$W_n \ll L_p$ $\sinh\left(\frac{x_n + W_n - x}{L_p}\right) \approx \frac{x_n + W_n - x}{L_p}$ and

$$\sinh\left(\frac{W_n}{L_p}\right) \approx \frac{W_n}{L_p}$$

then

$$\delta p_n(x) = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\left(\frac{x_n + W_n - x}{W_n}\right)$$

so that in the short n region:

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

8.2GENERATION–RECOMBINATION CURRENTS AND HIGH-INJECTION LEVELS

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

n: electron concentrations

p: hole concentrations

N_t: total concentration of trapping centers

C_n:constant proportional to electron-capture cross section

C_p:constant proportional to hole-capture cross section

n': trap density of electron

p': trap density of hole

Reverse-Biased Generation Current

$n \approx p \approx 0$ in depletion region

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

- The negative sign implies a negative recombination rate; hence, we are really generating electron–hole pairs within the reverse-biased space charge region
- electrons and holes are being generated via the trap level to also try to reestablish thermal equilibrium

Reverse-Biased Generation Current

- If we make a simplifying assumption and let the trap level be at the intrinsic Fermi level then $n' = p' = n_i$

$$R = \frac{-n_i}{\frac{1}{N_t C_p} + \frac{1}{N_t C_n}} = \frac{-n_i}{\tau_{p0} + \tau_{n0}}$$

Define $\tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2}$ then $R = \frac{-n_i}{2\tau_0} = -G$

$$J_{gen} = \int_0^W eG\,dx = \frac{en_i W}{2\tau_0}$$

$$J_R = J_s + J_{gen}$$

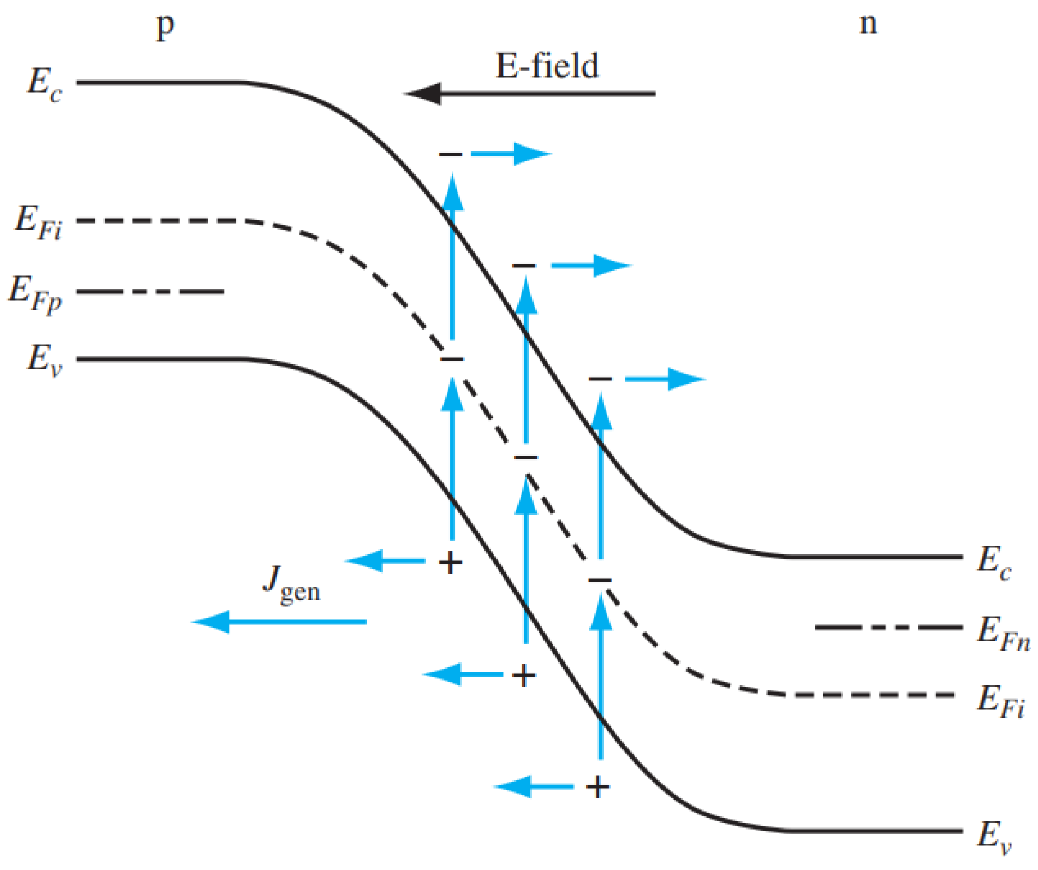

Figure 8.12 | Generation process in a reverse-biased pn junction.

EXAMPLE 8.6

Objective: Determine the relative magnitudes of the ideal reverse-saturation current density and the generation current density in a reverse-biased pn junction.

Consider a silicon pn junction at $T = 300$ K with parameters $D_n = 25\ \text{cm}^2/\text{s}$, $D_p = 10\ \text{cm}^2/\text{s}$, $N_a = N_d = 10^{16}\ \text{cm}^{-3}$, and $\tau_0 = \tau_{n0} = \tau_{p0} = 5 \times 10^{-7}$ s. Assume the diode is reverse biased at $V_R = 5$ V.

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already known from ex8.2 that $J_s = 4.155\times10^{-11}\ A/cm^2$

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.0259\ln\left[\frac{(10^{16})(10^{16})}{(1.5\times10^{10})^2}\right] = 0.695\text{V}$$

$$W = \left\{\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\left(\frac{N_a+N_d}{N_aN_d}\right)\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{2(11.7)(8.85\times10^{-14})(0.695+5)}{1.6\times10^{-19}}\left[\frac{10^{16}+10^{16}}{(10^{16})(10^{16})}\right]\right\}^{1/2} = 1.214\times10^{-4}\ cm$$

$$J_{gen} = \frac{en_iW}{2\tau_0}$$

$$= \frac{(1.6\times10^{-19})(1.5\times10^{10})(1.214\times10^{-4})}{2(5\times10^{-7})}$$

$$\boxed{\frac{J_{gen}}{J_s} = \frac{2.914\times10^{-7}}{4.155\times10^{-11}} \cong 7\times10^3}$$

Forward-Bias Recombination Current

$$R = \frac{C_n C_p N_t \left(np - n_i^2\right)}{C_n\left(n+n'\right)+C_p\left(p+p'\right)} = \frac{np-n_i^2}{\tau_{p0}\left(n+n'\right)+\tau_{n0}\left(p+p'\right)}$$

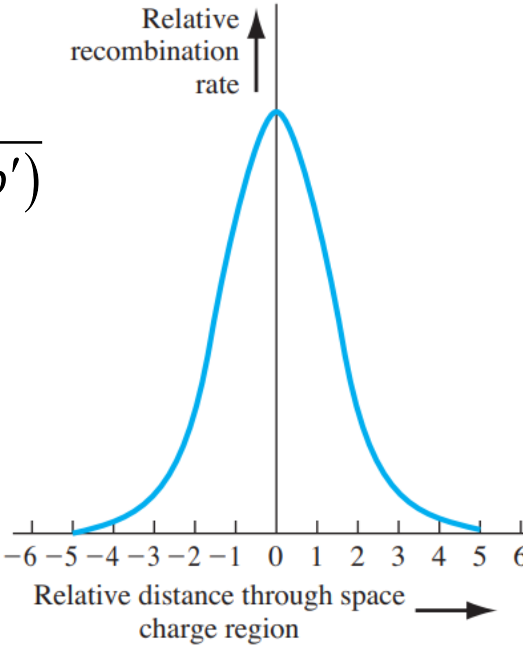
$$p = n_i \exp\left(\frac{E_{Fi}-E_{Fp}}{kT}\right) = n_i \exp\left(\frac{eV_a}{2kT}\right)$$

$$n = n_i \exp\left(\frac{E_{Fn}-E_{Fi}}{kT}\right) = n_i \exp\left(\frac{eV_a}{2kT}\right)$$

assuming $n' = p' = n_i$ and $\tau_{n0} = \tau_{p0} = \tau_0$

$$R_{\max} = \frac{n_i}{2\tau_0}\frac{\left[\exp\left(eV_a/kT\right)-1\right]}{\left[\exp\left(eV_a/2kT\right)+1\right]} \approx \frac{n_i}{2\tau_0}\exp\left(eV_a/2kT\right)$$

$$J_{rec} = \int_0^W eR\,dx = \frac{eWn_i}{2\tau_0}\exp\left(eV_a/2kT\right) = J_{r0}\exp\left(eV_a/2kT\right)$$



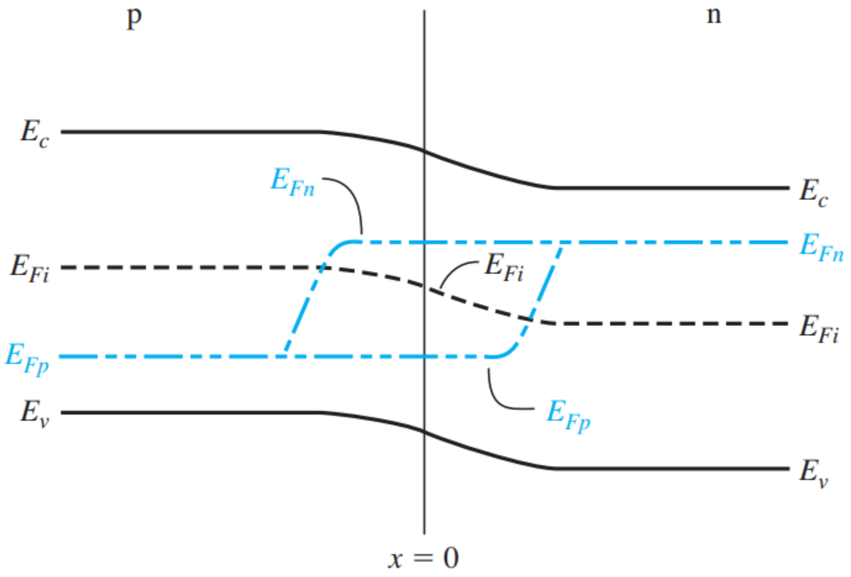


Figure 8.13 | Energy-band diagram of a forward-biased pn junction including quasi-Fermi levels.

Total Forward-Bias Current

$$J = J_{rec} + J_D = J_{r0}\exp\left(eV_a/2kT\right) + J_s \exp\left(\frac{eV_a}{kT}\right)$$

- The total forward-bias current density in the pn junction is the sum of the recombination and the ideal diffusion current densities
- The distribution is established as a result of holes being injected across the space charge region
- some of the injected holes in the space charge region are lost due to recombination, then additional holes must be injected from the p region to make up for this loss

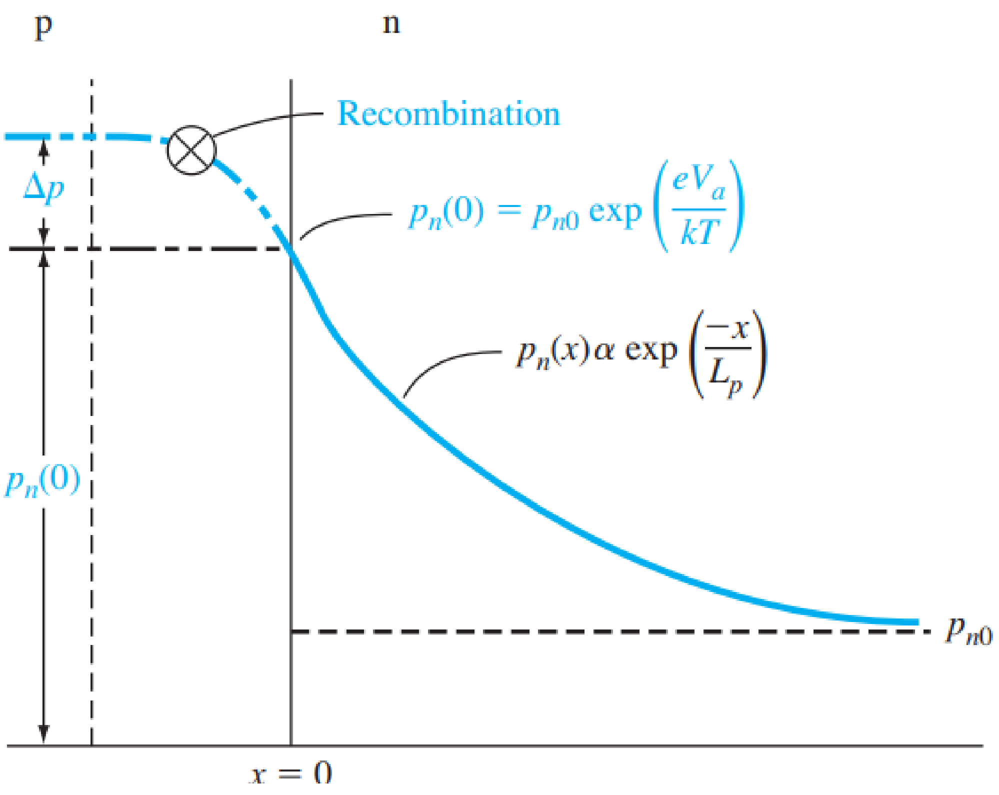


Figure 8.15 | Because of recombination, additional holes from the p region must be injected into the space charge region to establish the minority carrier hole concentration in the n region.

Ideal diffusion, recombination, and total current in a forward-biased pn junction

$$\ln J_{rec} = \ln J_{r0} + \frac{eV_a}{2kT} = \ln J_{r0} + \frac{V_a}{2V_t}$$

$$\ln J_D = \ln J_s + \frac{eV_a}{kT} = \ln J_s + \frac{V_a}{V_t}$$

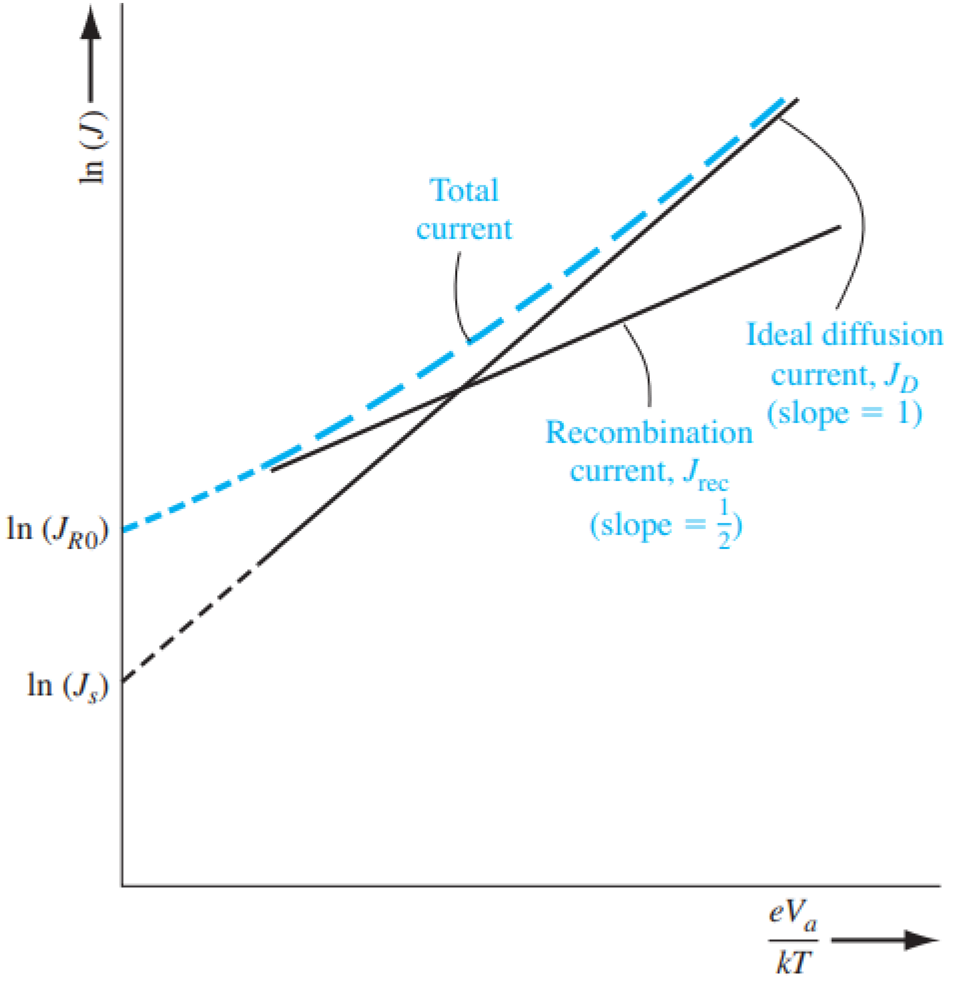


Figure 8.16 | Ideal diffusion, recombination, and total current in a forward-biased pn junction.

High-Level Injection

$$np = n_i^2 \exp\left(\frac{V_a}{V_t}\right)$$

$$(n_0 + \delta n)(p_0 + \delta p) = n_i^2 \exp\left(\frac{V_a}{V_t}\right)$$

under high-level $\delta n > n_0, \delta p > p_0$ then

$$\delta n \delta p \approx n_i^2 \exp\left(\frac{V_a}{V_t}\right)$$

since $\delta n = \delta p$

$$\delta n = \delta p \approx n_i \exp\left(\frac{V_a}{2V_t}\right)$$

$$I \propto \exp\left(\frac{V_a}{2V_t}\right)$$

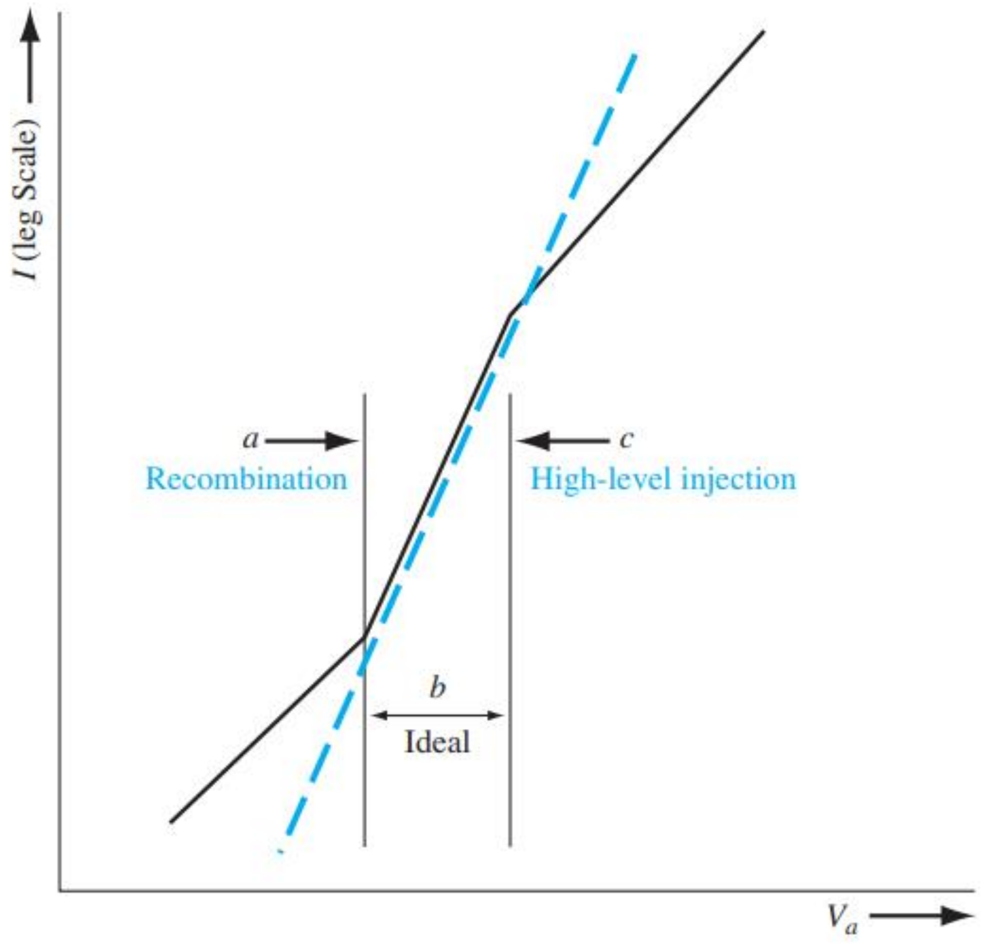


Figure 8.17 | Forward-bias current versus voltage from low forward bias to high forward bias.

8.3SMALL-SIGNAL MODEL OF THE pn JUNCTION-Diffusion Resistance(補)

Ideal current-voltage relationship:

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

- If we now superimpose a small, low-frequency sinusoidal voltage as shown in Figure 8.18
- 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

$$g_d = \frac{dI_D}{dV_a}\bigg|_{V_a=V_0} = \frac{e}{kT} I_s \exp\left(\frac{eV_0}{kT}\right) - \cancel{1} \approx \frac{I_{DQ}}{V_t} \text{(conductance)}$$

$$r_d = \frac{dV_a}{dI_D}\bigg|_{I_D=I_{DQ}} \text{(resistance)}$$

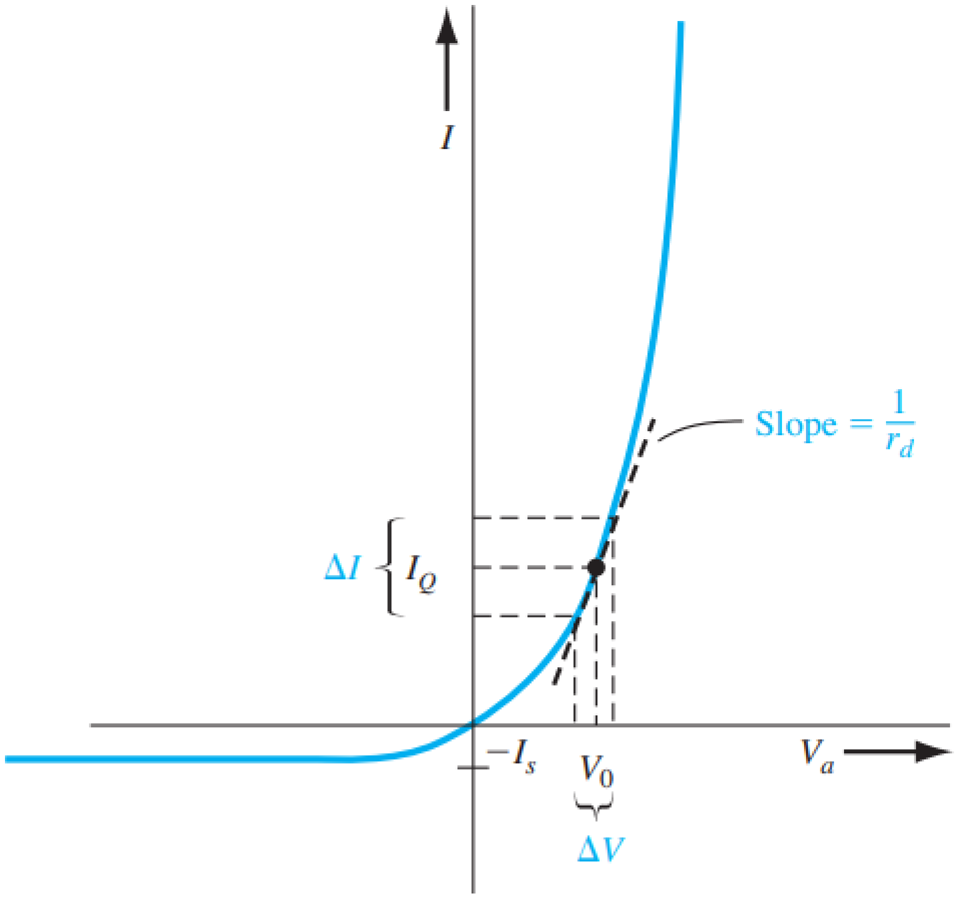
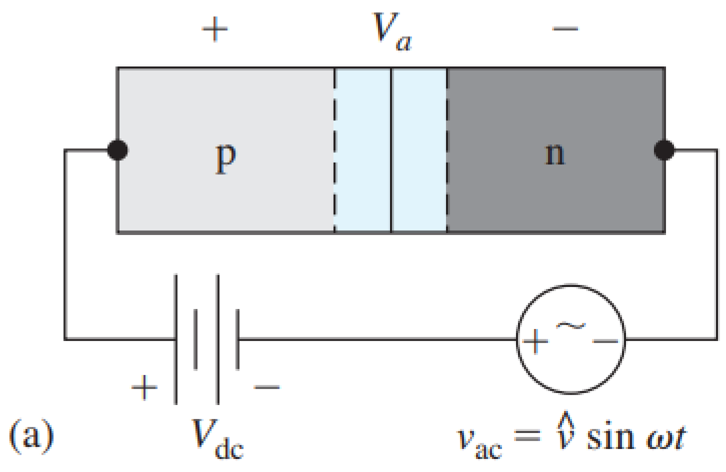
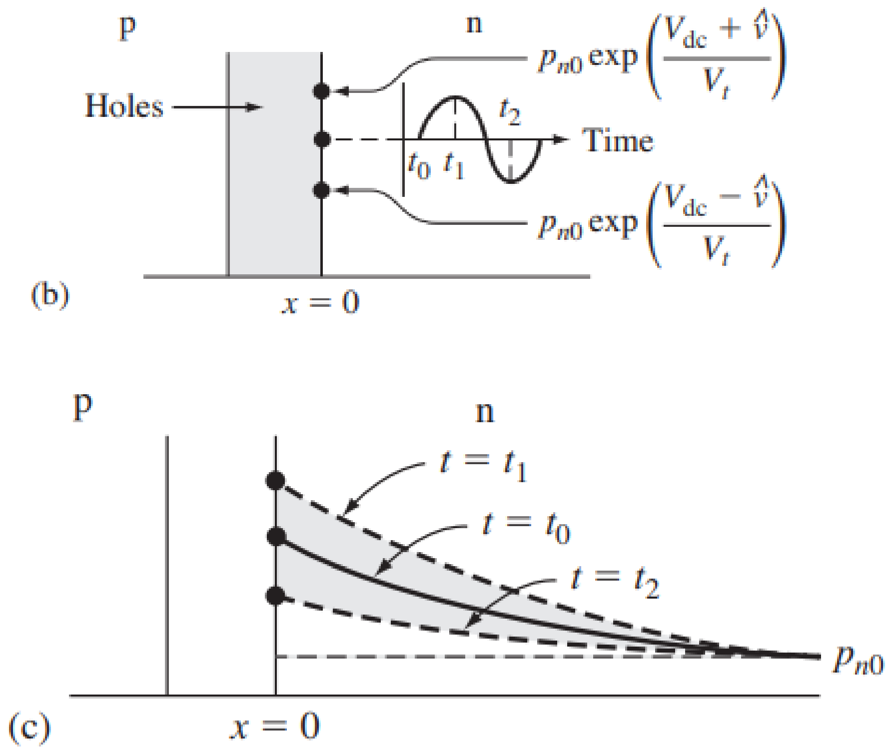


Figure 8.18 | Curve showing the concept of the small-signal diffusion resistance.

Small-Signal Admittance(Qualitative Analysis)



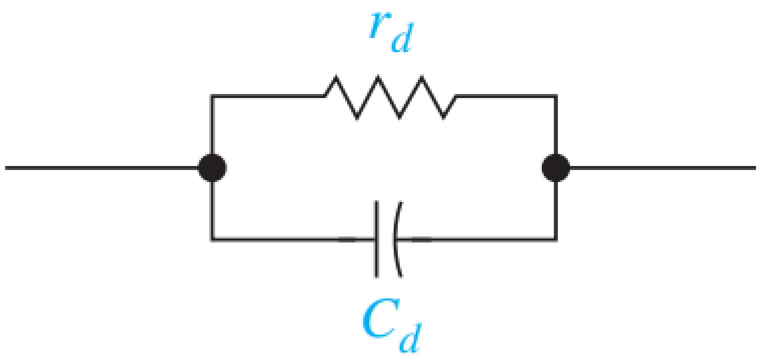


- the total forward-biased voltage can be written as

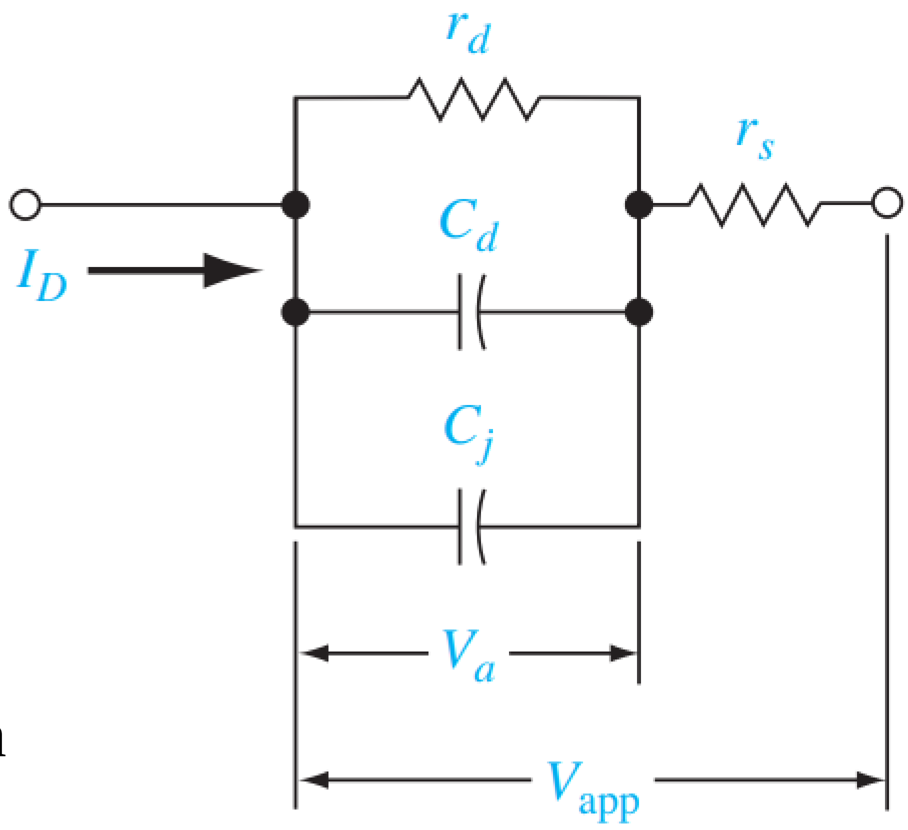
$$V_a = V_{dc} + \hat{v} \sin \omega t$$

- The shaded areas represents the charge ΔQ that is alternately charged and discharged during the ac voltage cycle

Equivalent Circuit



(a)
ideal case of small signal



(b)
real case of small signal

- We need to add the junction capacitance, which will be in parallel with the diffusion resistance and diffusion capacitance
- The neutral n and p regions have finite resistances so the actual pn junction will include a series resistance

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

Forward-biased I–V with series resistance

- A larger applied voltage is required to achieve the same current value when a series resistance is included
- In some semiconductor devices with pn junctions, however, the series resistance will be in a feedback loop

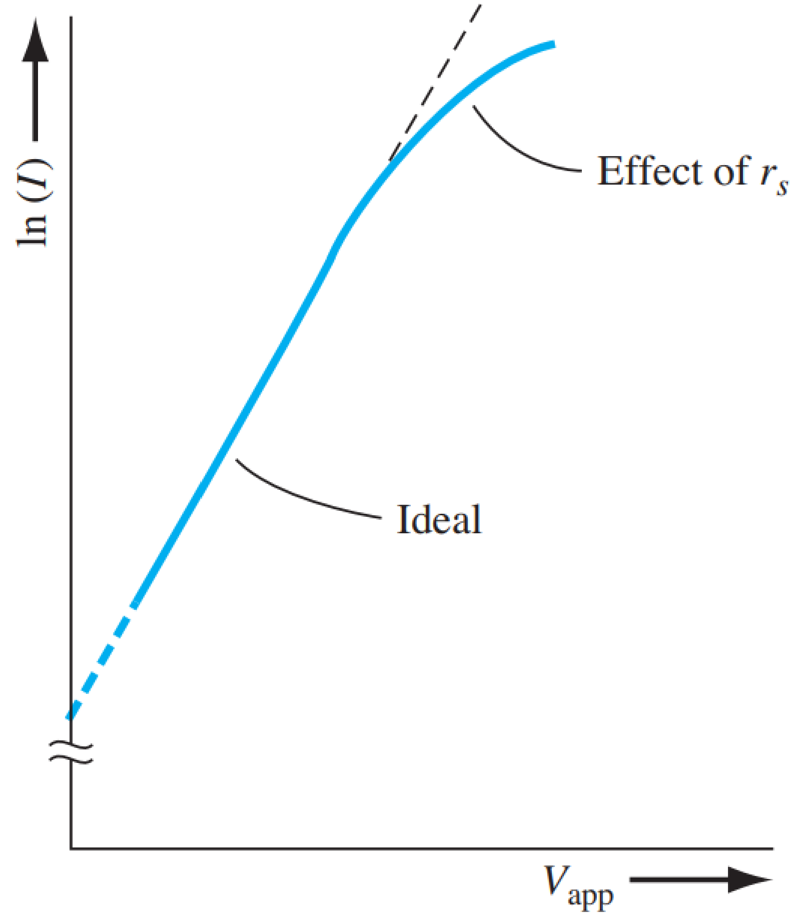


Figure 8.23 | Forward-biased I–V characteristics of a pn junction diode showing the effect of series resistance.

8.4CHARGE STORAGE AND DIODE TRANSIENTS

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

- The excess minority carrier concentrations at the space charge edges are supported by the forward-bias junction voltage
- 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

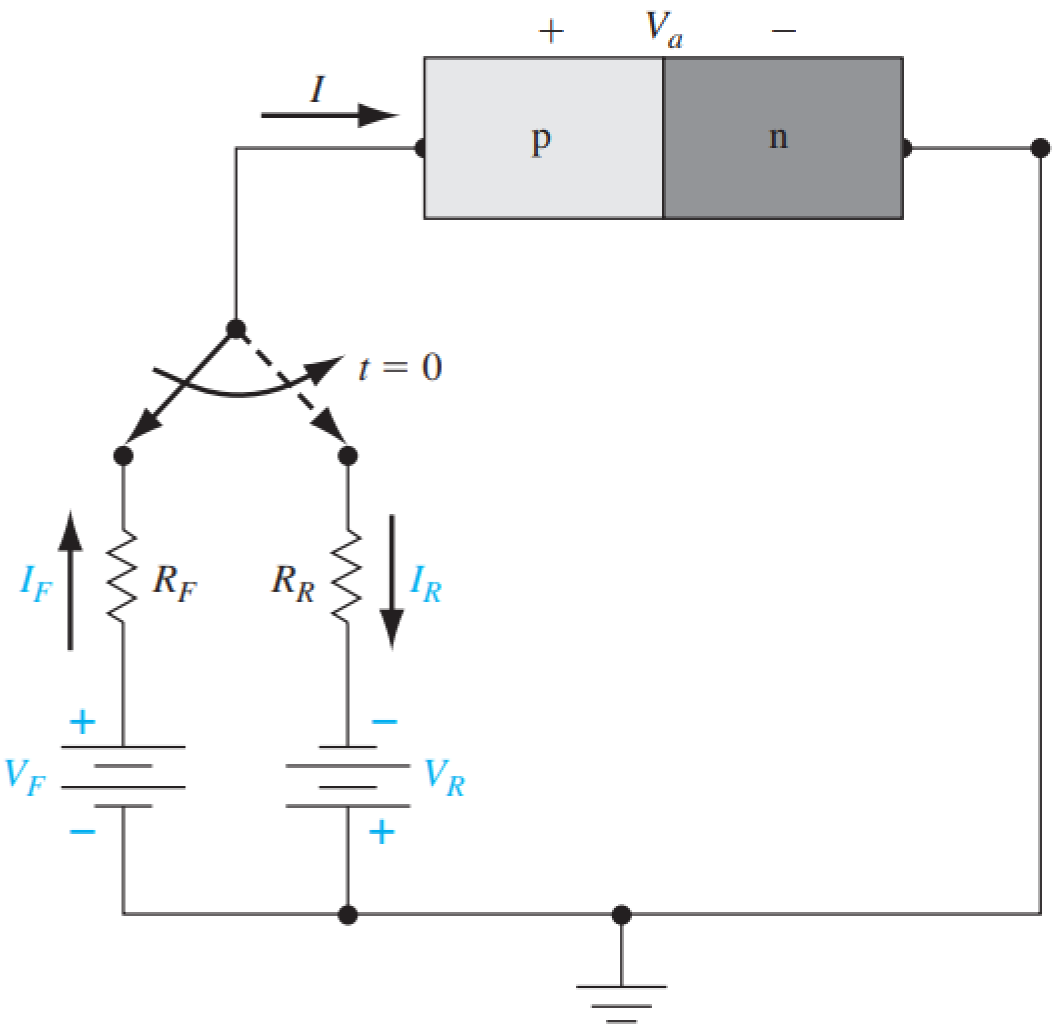
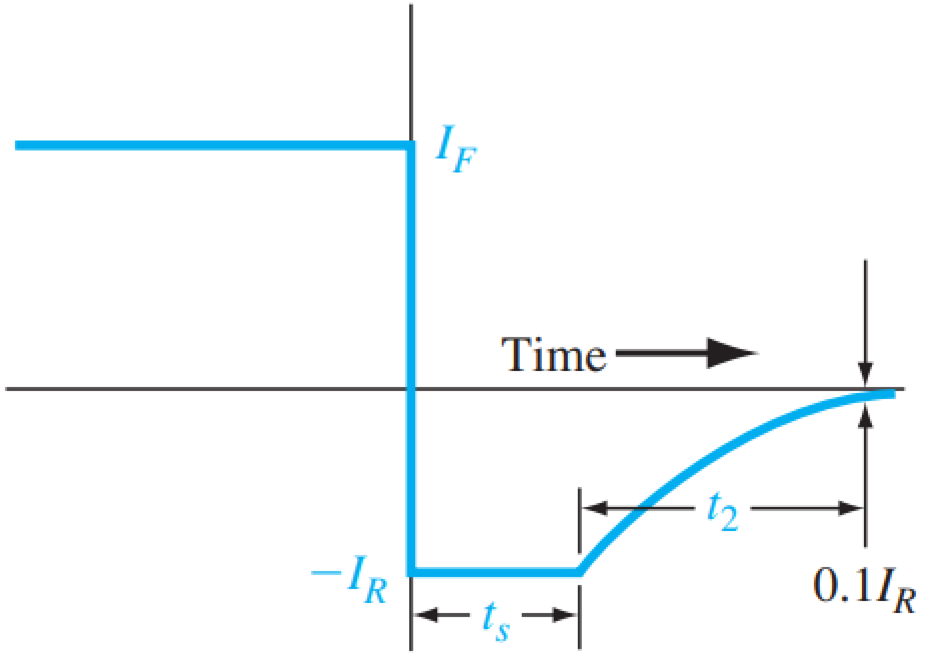


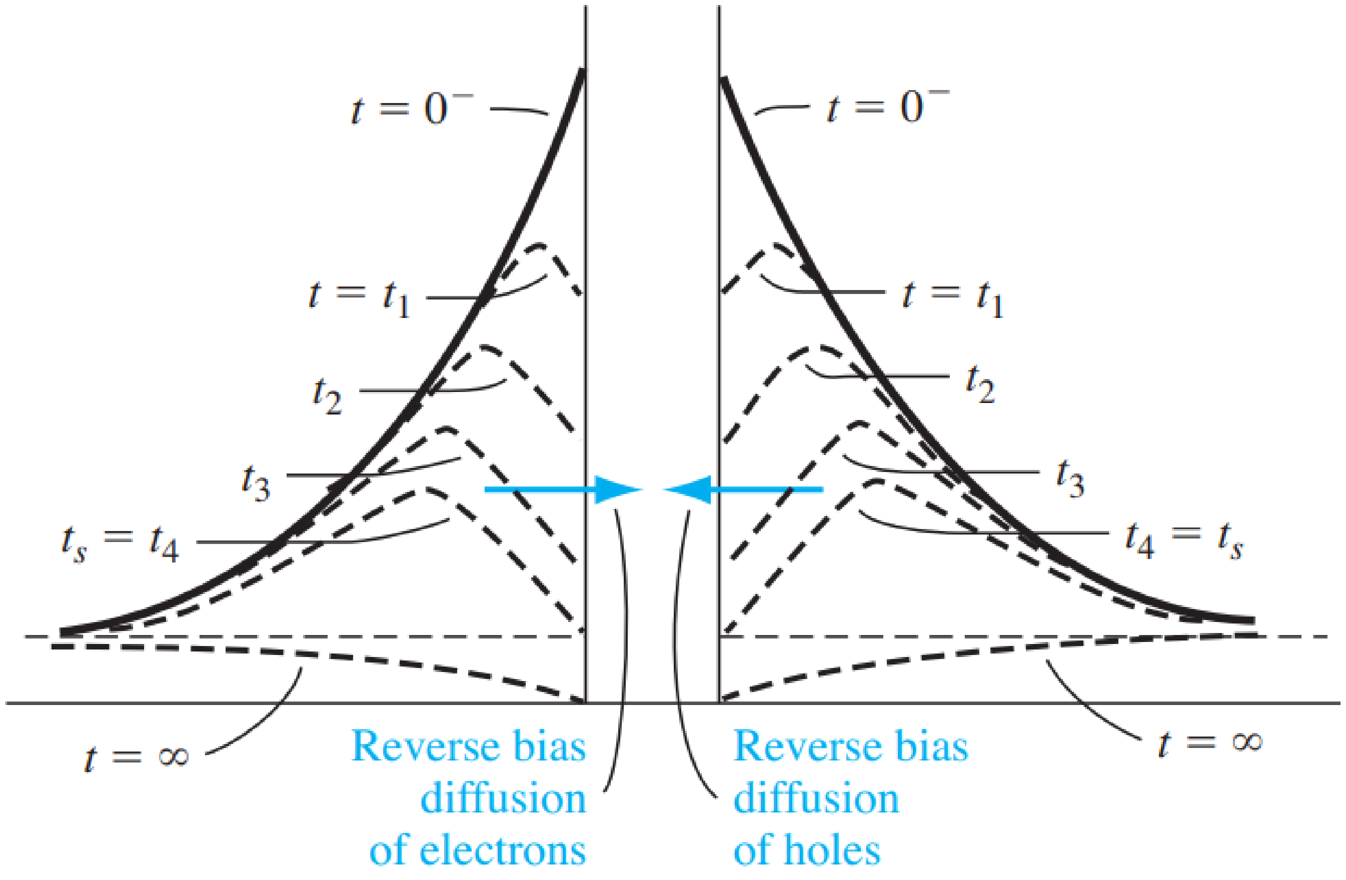
Figure 8.24 | Simple circuit for switching a diode from forward to reverse bias.

The Turn-off Transient

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

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

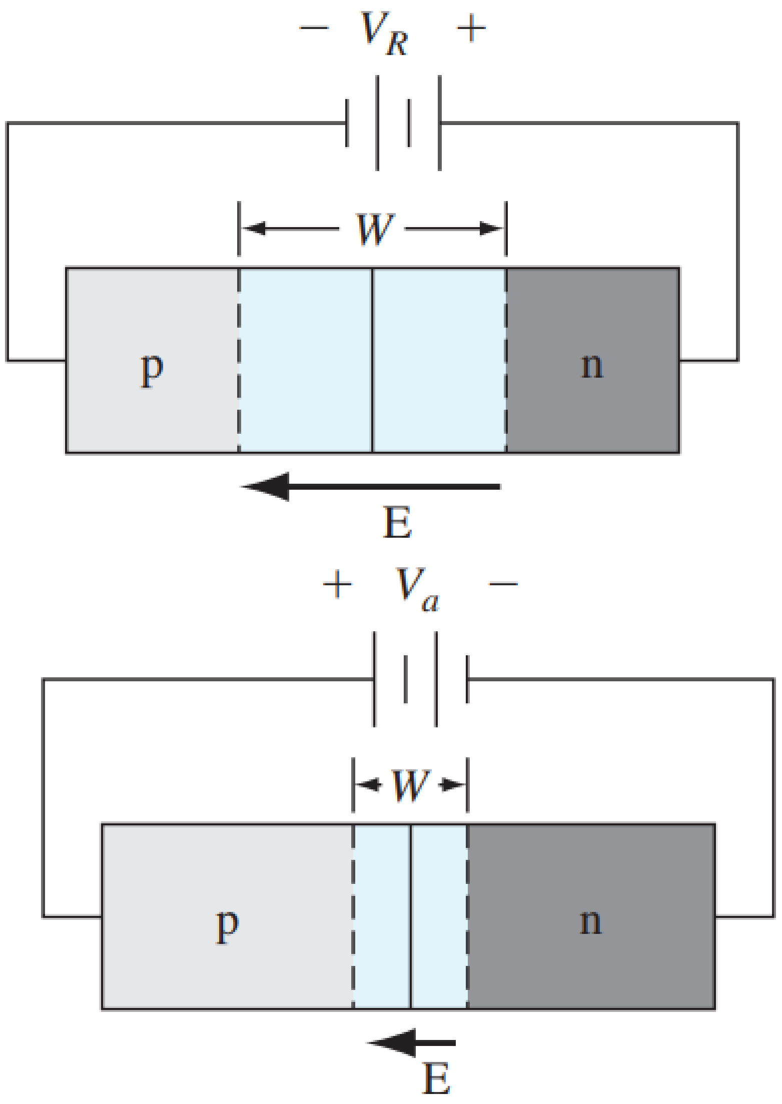




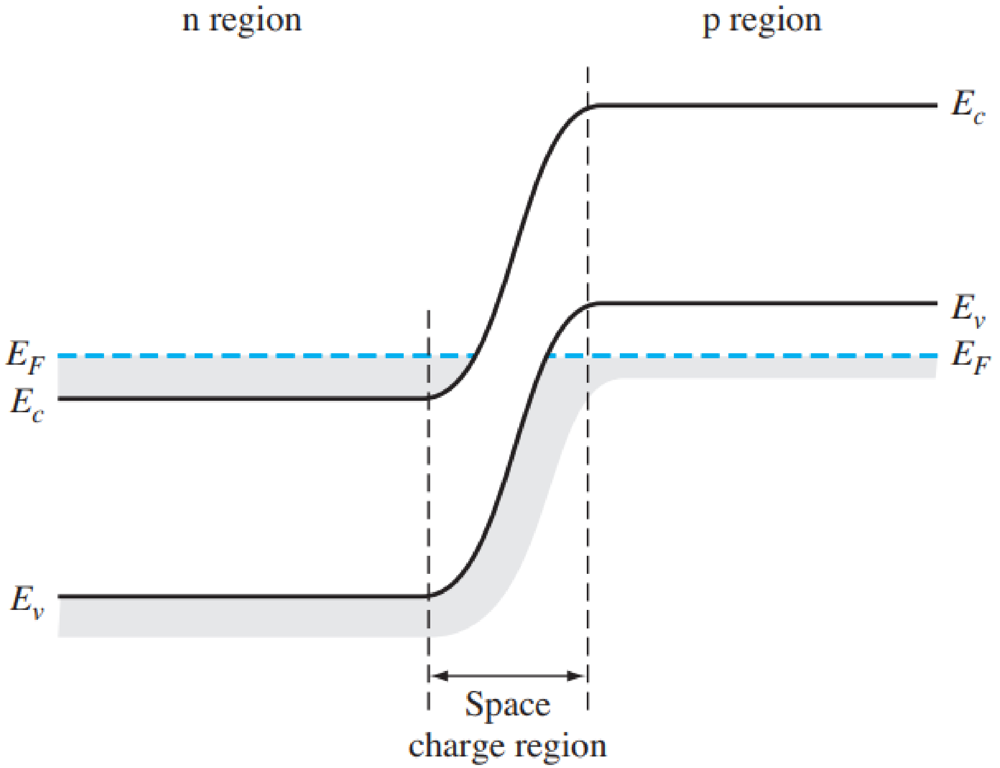
(b)

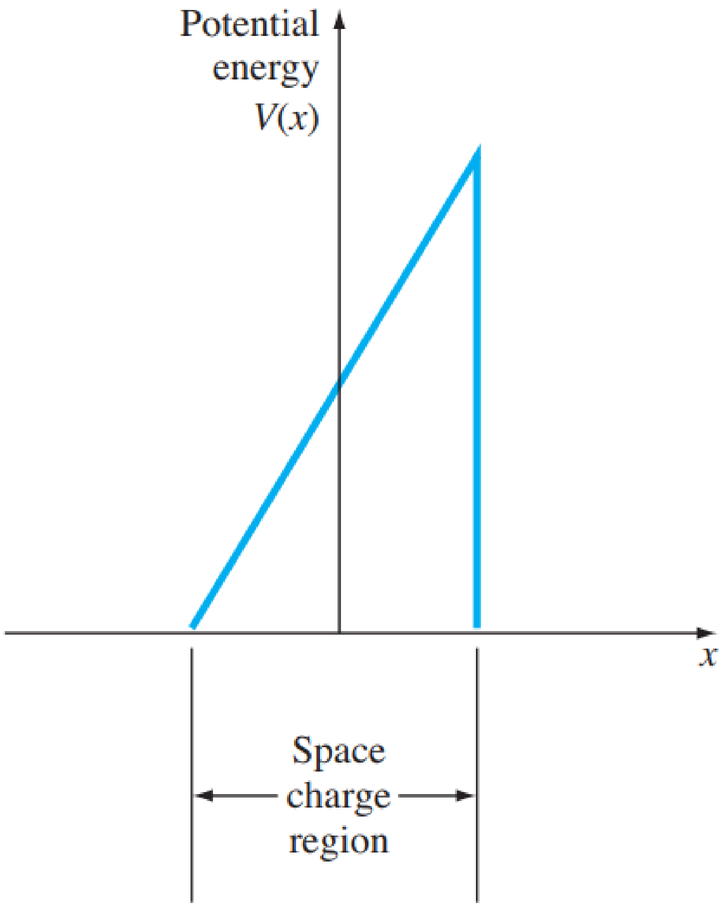
The Turn-on Transient

- The turn-on transient occurs when the diode is switched from its “off” state into the forward-bias “on” state
- 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
- The second stage of the turn-on process is the time required to establish the minority carrier distributions



8.5THE TUNNEL DIODE

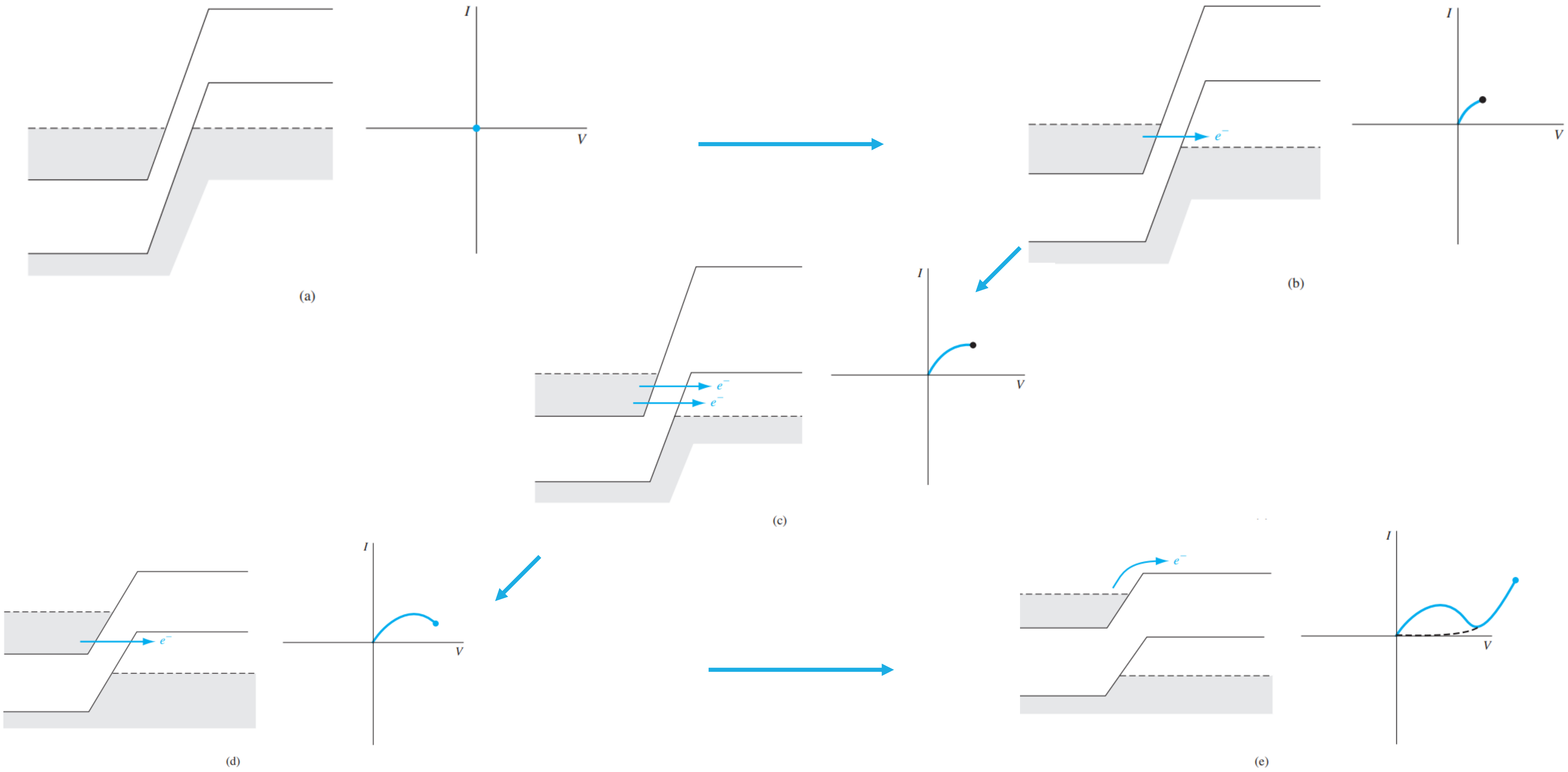




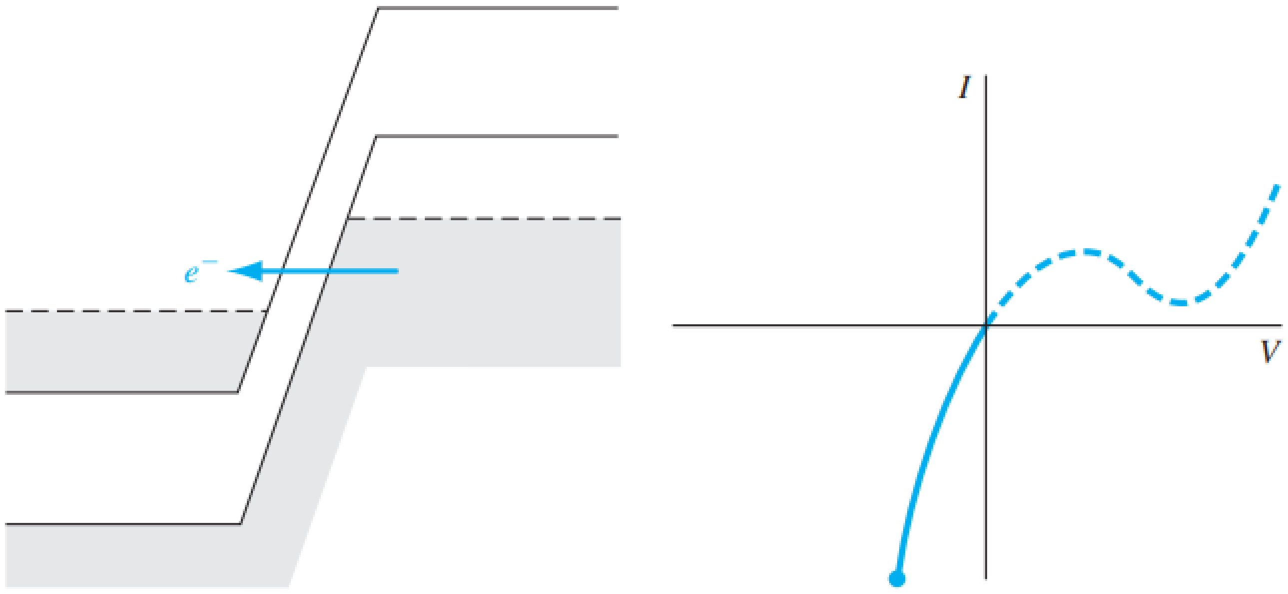
- The tunnel diode is a pn junction in which both the n and p regions are degenerately doped
- The depletion region width decreases as the doping increases and may be on the order of approximately 100 Å

- The barrier width is small and the electric field in the space charge region is quite large

THE TUNNEL DIODE WITH FORWARD BIAS



THE TUNNEL DIODE WITH REVERSED BIAS



(a) (b)