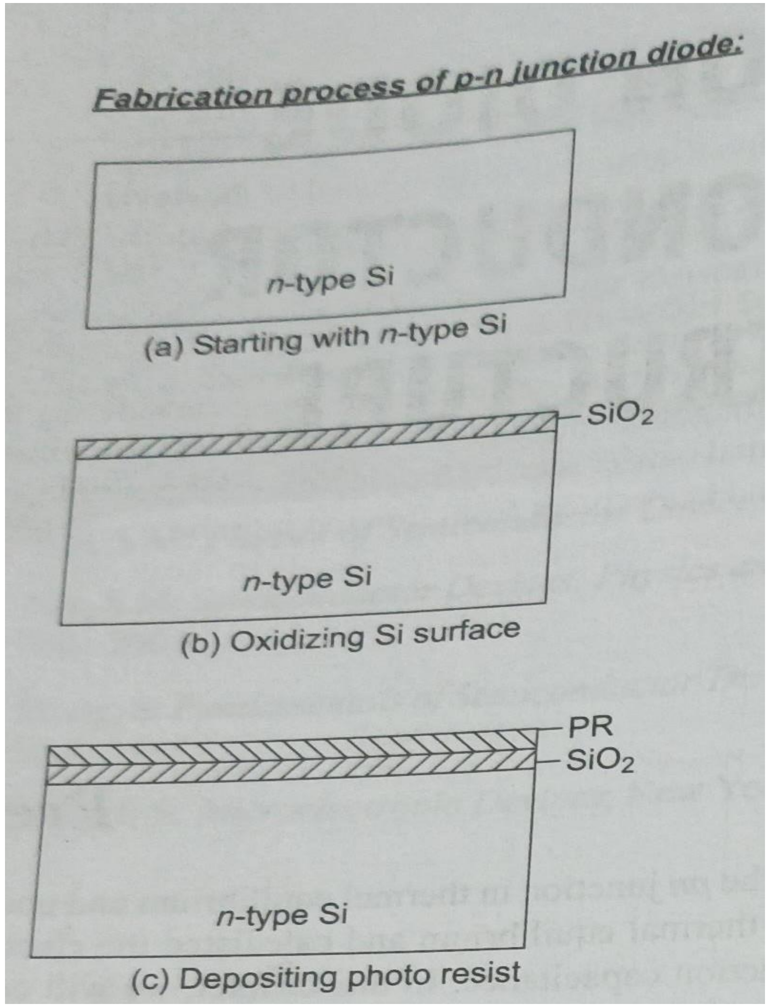
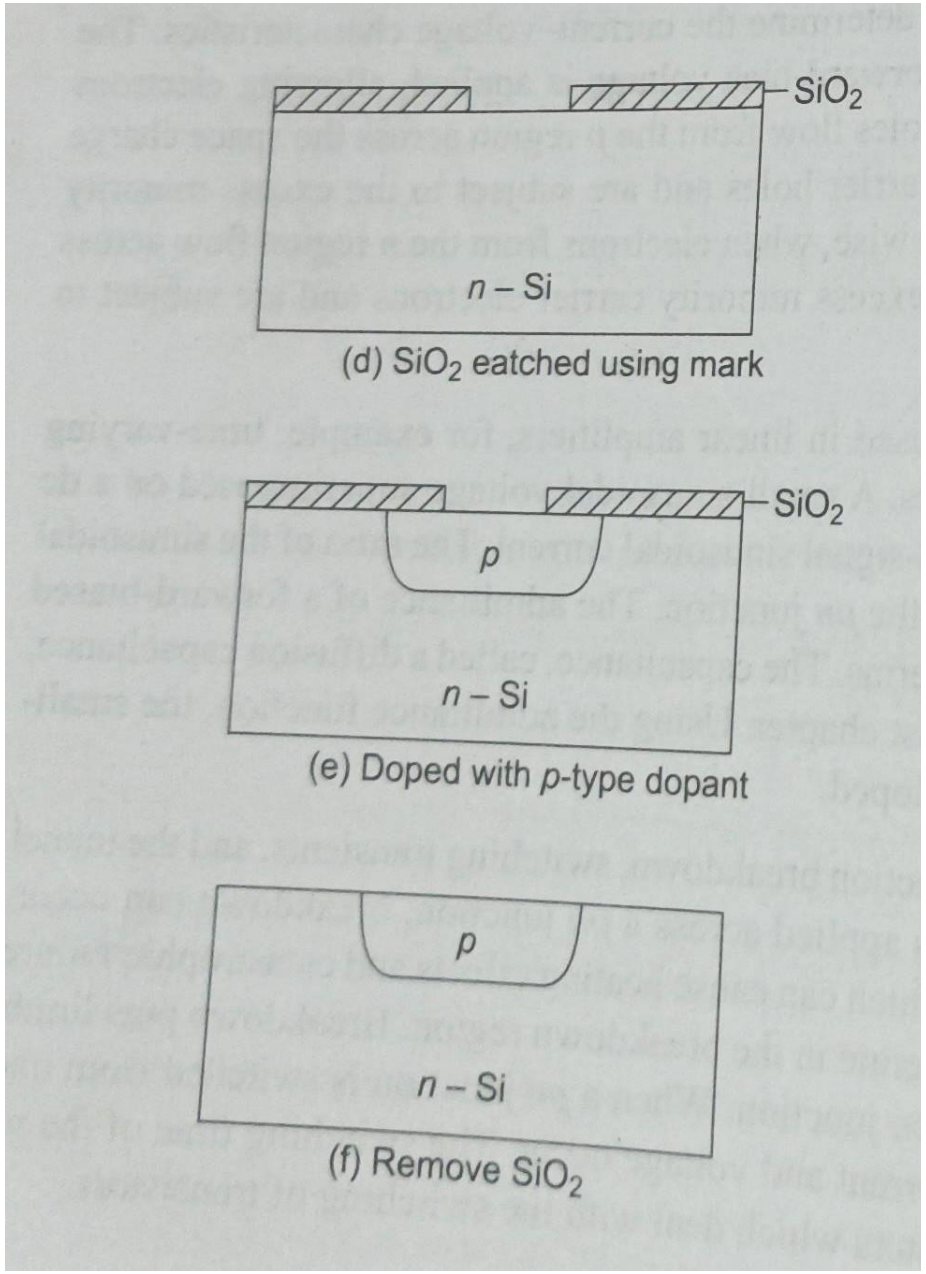
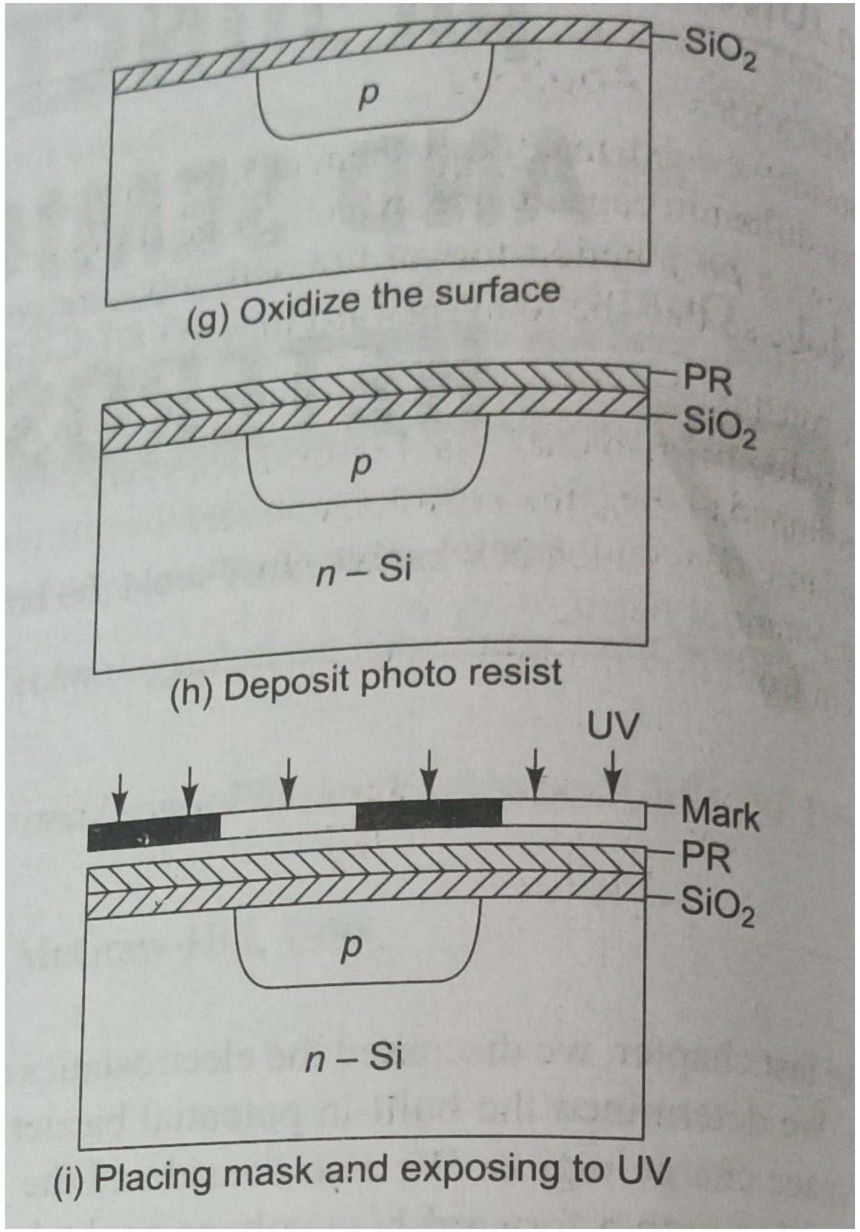
pn junction (L9+T3)

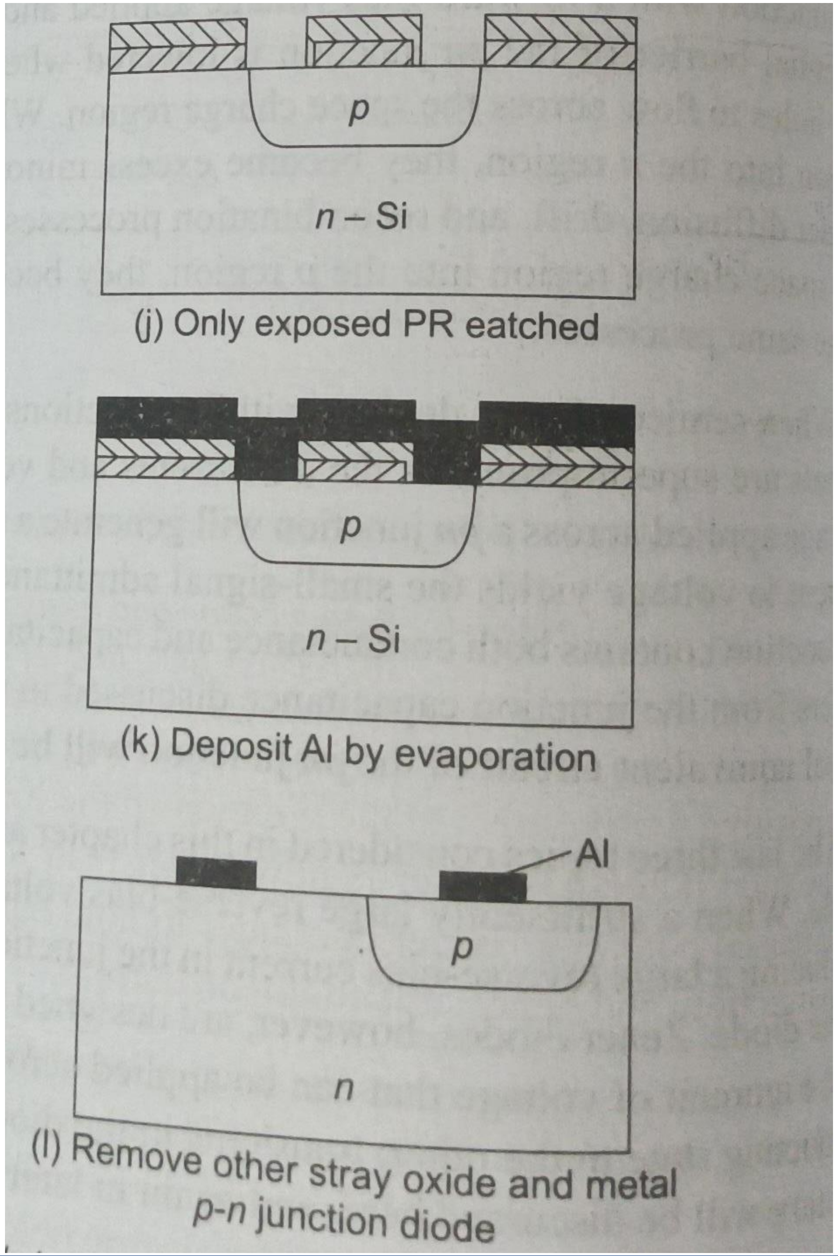
- Derivation of dc and ac characteristics
- Forward and reverse biasing
- Static analysis
- Breakdown processes
- Transient analysis
- Metal semiconductor junction
- Modelling of p-n junction.

pn junction diode fabrication






SiO2
p
(g) Oxidize the surface
PR
SiO2
p
n – Si
(h) Deposit photo resist
UV
Mark
PR
SiO2
p
n – Si
(i) Placing mask and exposing to UV


p
n – Si
(j) Only exposed PR eatched
p
n – Si
(k) Deposit Al by evaporation
Al
p
n
(l) Remove other stray oxide and metal
p-n junction diode

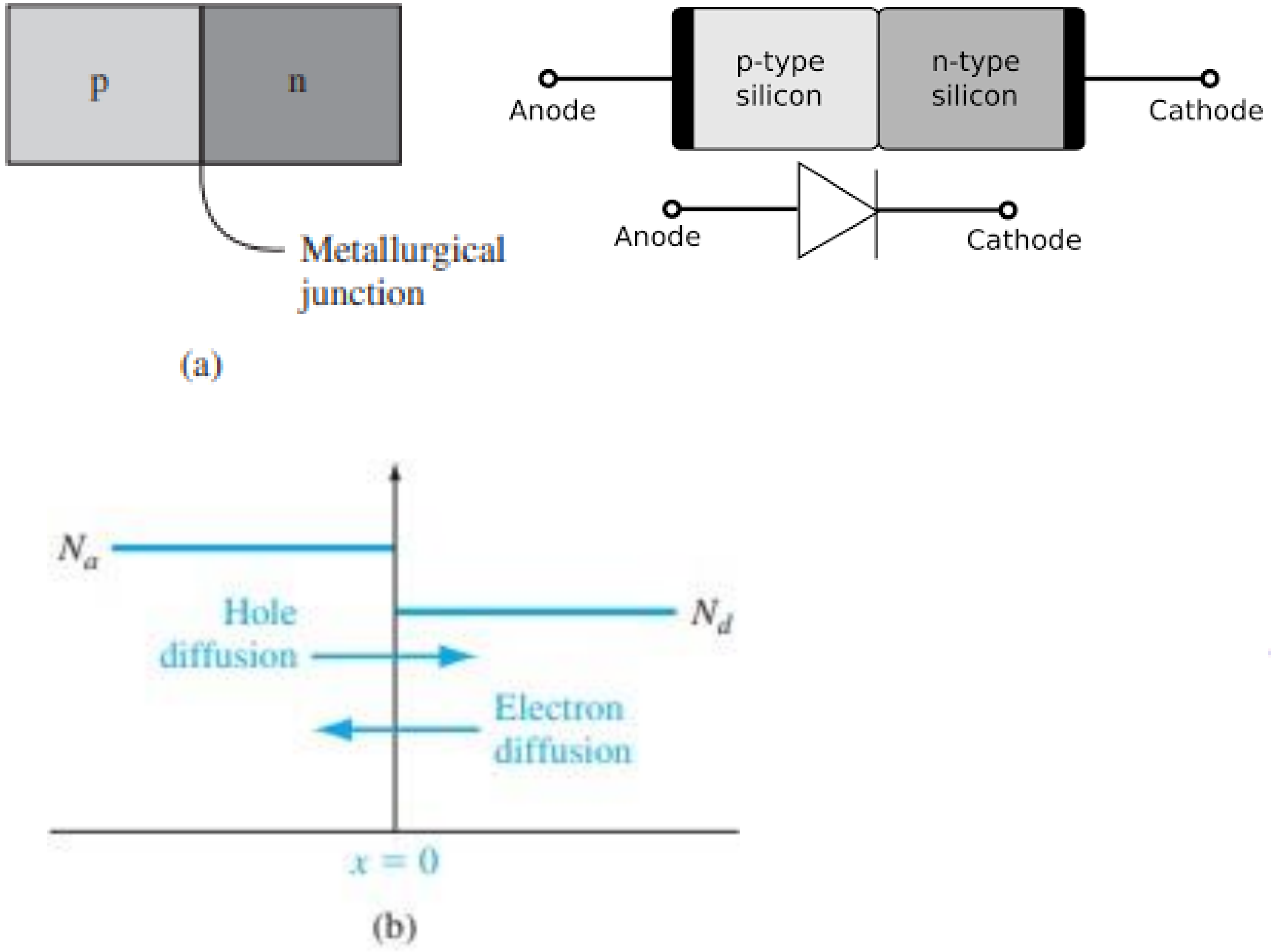


Figure 7.1 | (a) Simplified geometry of a pn junction; (b) doping profile of an ideal uniformly doped pn junction.

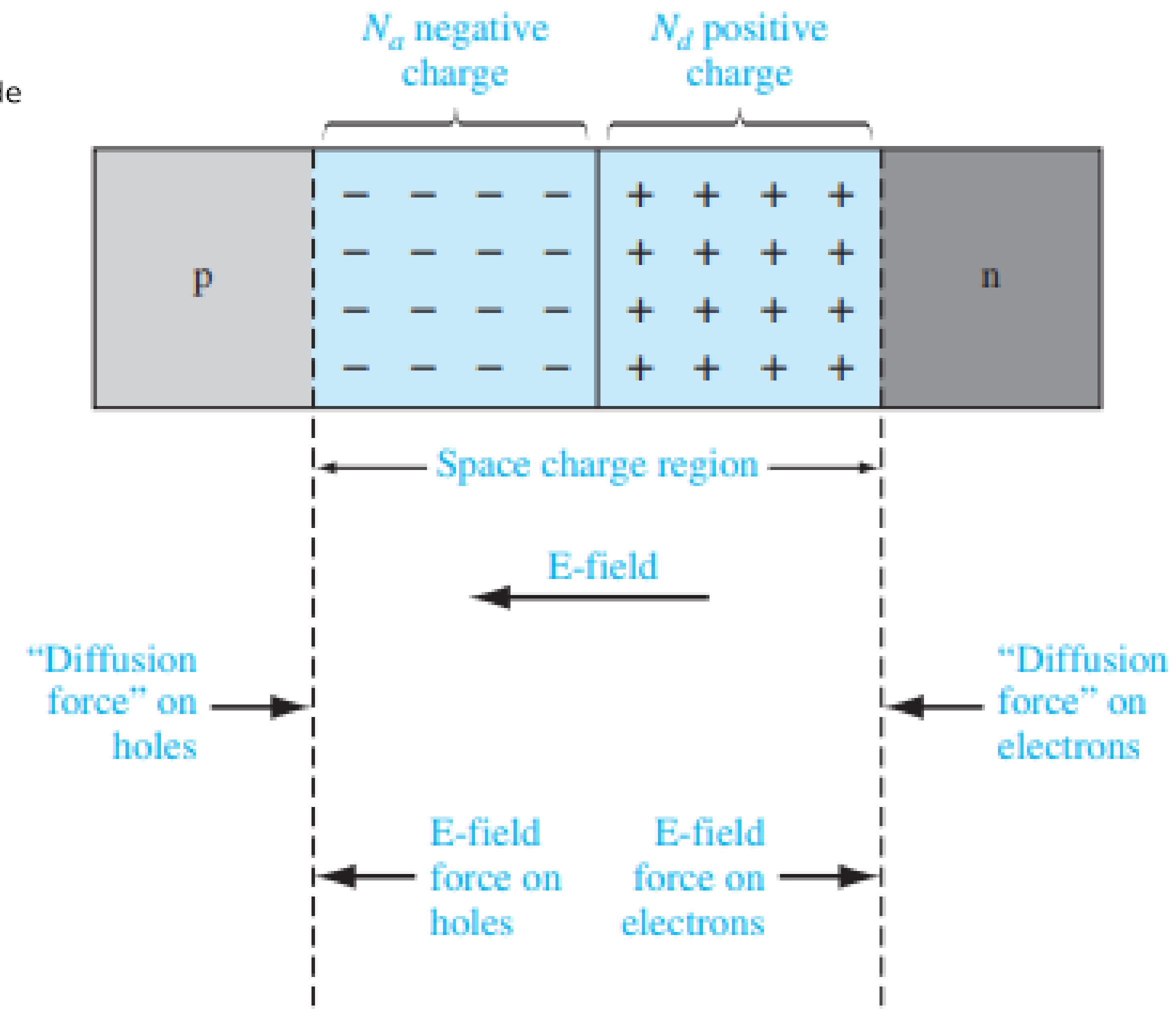


Figure 7.2 | The space charge region, the electric field, and the forces acting on the charged carriers.

ZERO APPLIED BIAS

The properties of the step junction in thermal equilibrium is investigated to determine

- space charge width
- electric field
- built in potential

- The first assumption is that the Boltzmann approximation is valid, which means that each semiconductor region is non-degenerately doped.
- The second assumption is that complete ionization exists, which means that the temperature of the pn junction is not “too low.”

- Electrons in the conduction band of the n region see a potential barrier in trying to move into the conduction band of the p region. This potential barrier is referred to as the built-in potential barrier and is denoted by V_{bi}.
- The built-in potential barrier can be determined as the difference between the intrinsic Fermi levels in the p and n regions.

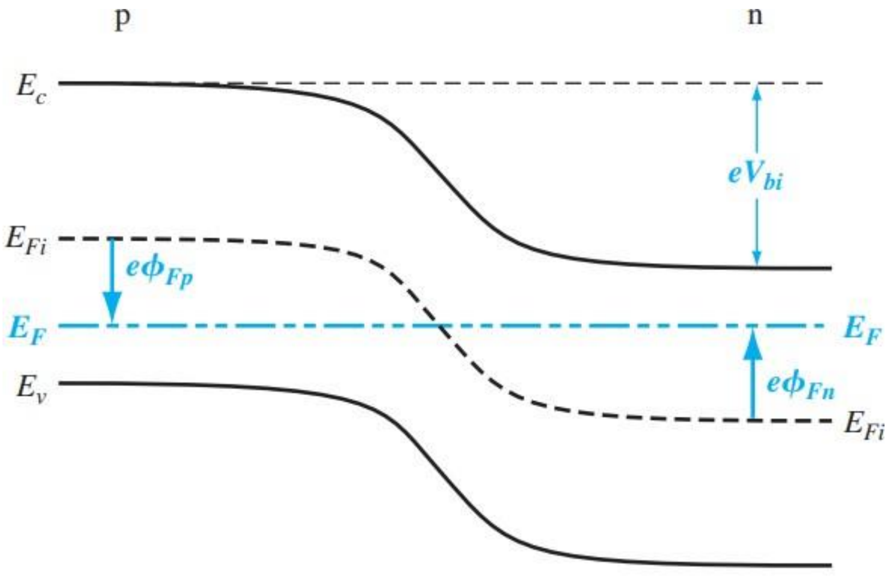


Figure 7.3 | Energy-band diagram of a pn junction in thermal equilibrium.

$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$p_0 = N_a = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right]$$

$$e\phi_{Fn} = E_{Fi} - E_F$$

$$e\phi_{Fp} = E_{Fi} - E_F$$

$$n_0 = n_i \exp\left[\frac{-(e\phi_{Fn})}{kT}\right]$$

$$\phi_{Fp} = +\frac{kT}{e} \ln\left(\frac{N_a}{n_i}\right)$$

$$\phi_{Fn} = \frac{-kT}{e} \ln\left(\frac{N_d}{n_i}\right)$$

$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

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

Thermal voltage, $V_t = kT/e$

where

k, Boltzmann constant = 1.381×10^{-23} J/K

T, Temperature = 300 K

e or (q), charge of an electron = 1.6×10^{-19} C

$V_t = (1.381 \times 10^{-23} \times 300)/(1.6 \times 10^{-19})$

$= 0.02589$ V

Electric Field

- An electric field is created in the depletion region by the separation of positive and negative space charge densities.

The electric field is determined from Poisson's equation, which, for a one-dimensional analysis, is

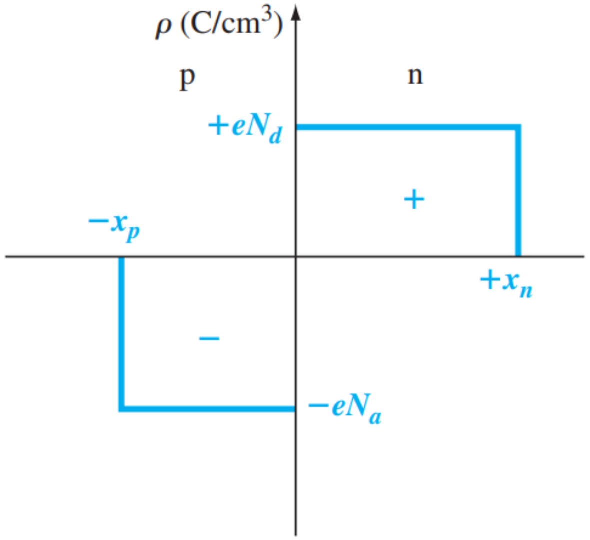


Figure 7.4 | The space charge density in a uniformly doped pn junction assuming the abrupt junction approximation.

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = -\frac{d\mathrm{E}(x)}{dx} \tag{7.11}$$

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

$$\rho(x) = eN_d \qquad 0 < x < x_n$$

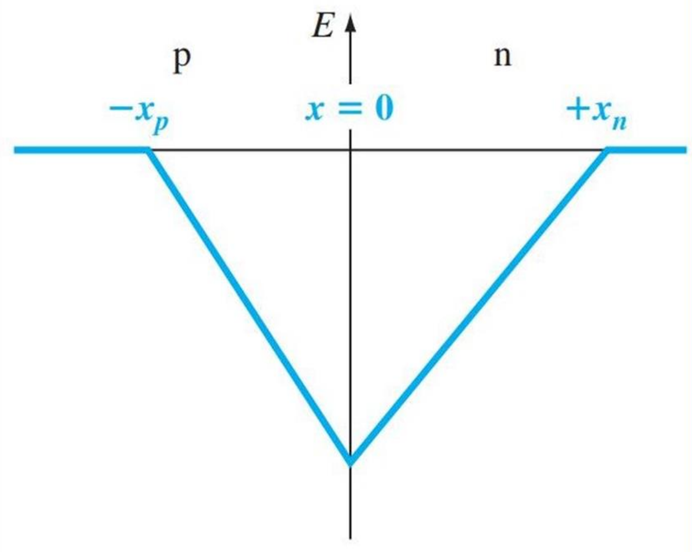


Figure 7.5 | Electric field in the space charge region of a uniformly doped pn junction.

$$\mathrm{E} = \int \frac{\rho(x)}{\epsilon_s}\,dx = -\int \frac{eN_a}{\epsilon_s}\,dx = \frac{-eN_a}{\epsilon_s}x + C_1$$

field is a continuous function. The constant of integration is determined by setting $\mathrm{E} = 0$ at $x = -x_p$. The electric field in the p region is then given by

$$\mathrm{E} = \frac{-eN_a}{\epsilon_s}(x + x_p) \qquad -x_p \le x \le 0 \tag{7.14}$$

In the n region, the electric field is determined from

$$\mathrm{E} = \int \frac{(eN_d)}{\epsilon_s}\,dx = \frac{eN_d}{\epsilon_s}x + C_2 \tag{7.15}$$

where C_2 is again a constant of integration and is determined by setting $\mathrm{E} = 0$ at $x = x_n$, since the E-field is assumed to be zero in the n region and is a continuous function. Then

$$\mathrm{E} = \frac{-eN_d}{\epsilon_s}(x_n - x) \qquad 0 \le x \le x_n \tag{7.16}$$

The potential in the junction is found by integrating the electric field. In the p region then, we have

$$\phi(x) = -\int E(x)dx = \int \frac{eN_a}{\epsilon_s}(x + x_p)dx \qquad (7.18)$$

$$\phi(x) = \frac{eN_a}{\epsilon_s}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_1'$$

$$C_1' = \frac{eN_a}{2\epsilon_s}x_p^2$$

so that the potential in the p region can now be written as

$$\phi(x) = \frac{eN_a}{2\epsilon_s}(x + x_p)^2 \qquad (-x_p \le x \le 0)$$

The potential in the n region is determined by integrating the electric field in the n region, or

$$\phi(x) = \int \frac{eN_d}{\epsilon_s}(x_n - x)dx \tag{7.22}$$

Then

$$\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + C_2' \tag{7.23}$$

where C_2' is another constant of integration. The potential is a continuous function, so setting Equation (7.21) equal to Equation (7.23) at the metallurgical junction, or at $x = 0$, gives

$$C_2' = \frac{eN_a}{2\epsilon_s} x_p^2 \tag{7.24}$$

The potential in the n region can thus be written as

$$\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + \frac{eN_a}{2\epsilon_s} x_p^2 \qquad (0 \le x \le x_n) \tag{7.25}$$

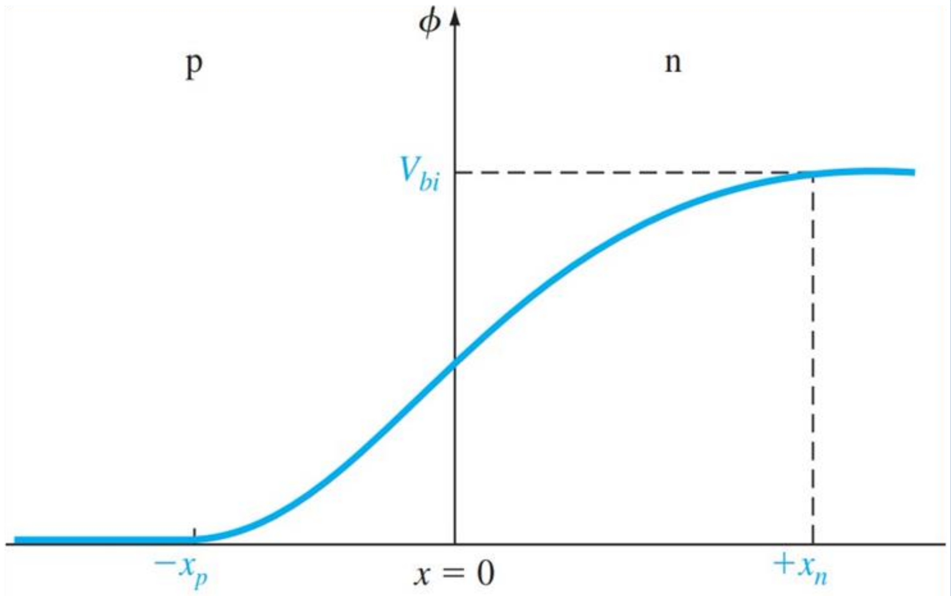


Figure 7.6 | Electric potential through the space charge region of a uniformly doped pn junction.

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

Space charge width

- The distance that the space charge region extends into the p and n regions from the metallurgical junction. This distance is known as the space charge width.

$$x_p = \frac{N_d x_n}{N_a}$$

$$W = x_n + x_p$$

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

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

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

Built-in barrier potential:

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

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

Electric field:

$$\boxed{\mathrm{E} = \int \frac{\rho(x)}{\epsilon_s}\,dx = -\int \frac{eN_a}{\epsilon_s}\,dx} \qquad \boxed{\mathrm{E} = \int \frac{(eN_d)}{\epsilon_s}\,dx}$$

Space charge width:

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

A silicon pn junction at $T = 300$ K with zero applied bias has doping concentrations of $N_d = 5 \times 10^{16}$ cm^{-3} and $N_a = 5 \times 10^{15}$ cm^{-3}. Determine x_n, x_p, W, and $|E_{max}|$.

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

$$= (0.0259)\ln\left[\frac{(5\times10^{16})(5\times10^{15})}{(1.5\times10^{10})^2}\right]$$

$$= 0.7184 \text{ V}$$

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

$$= \left\{\frac{2(11.7)(8.85\times10^{-14})(0.7184)}{(1.6\times10^{-19})}\right.$$

$$\left.\times\left(\frac{5\times10^{15}}{5\times10^{16}}\right)\left(\frac{1}{5\times10^{15}+5\times10^{16}}\right)\right\}^{1/2}$$

$$\Rightarrow x_n = 4.11\times10^{-6} \text{ cm}$$

$$x_p = \left\{\frac{2(11.7)(8.85\times10^{-14})(0.7184)}{(1.6\times10^{-19})}\right.$$

$$\left.\times\left(\frac{5\times10^{16}}{5\times10^{15}}\right)\left(\frac{1}{5\times10^{15}+5\times10^{16}}\right)\right\}^{1/2}$$

$$\Rightarrow x_p = 4.11\times10^{-5} \text{ cm}$$

Now

$$W = x_n + x_p = 4.11\times10^{-6} + 4.11\times10^{-5}$$

$$= 4.52\times10^{-5} \text{ cm}$$

$$|E_{max}| = \frac{eN_d x_n}{\in_s}$$

$$= \frac{(1.6\times10^{-19})(5\times10^{16})(4.11\times10^{-6})}{(11.7)(8.85\times10^{-14})}$$

$$= 3.18\times10^4 \text{ V/cm}$$

Reverse bias

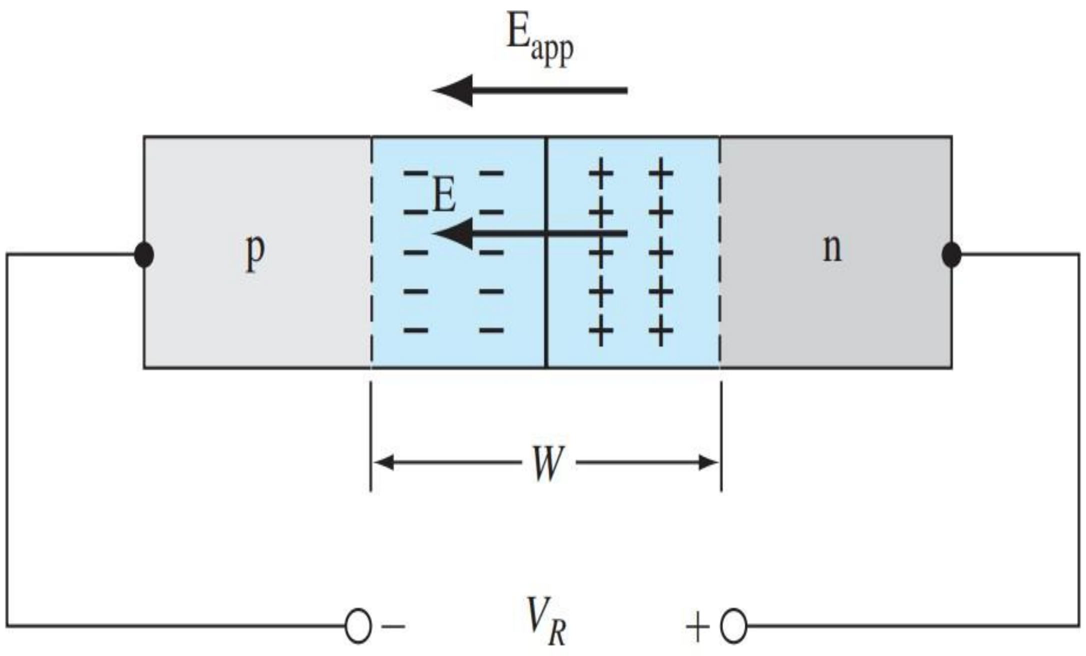
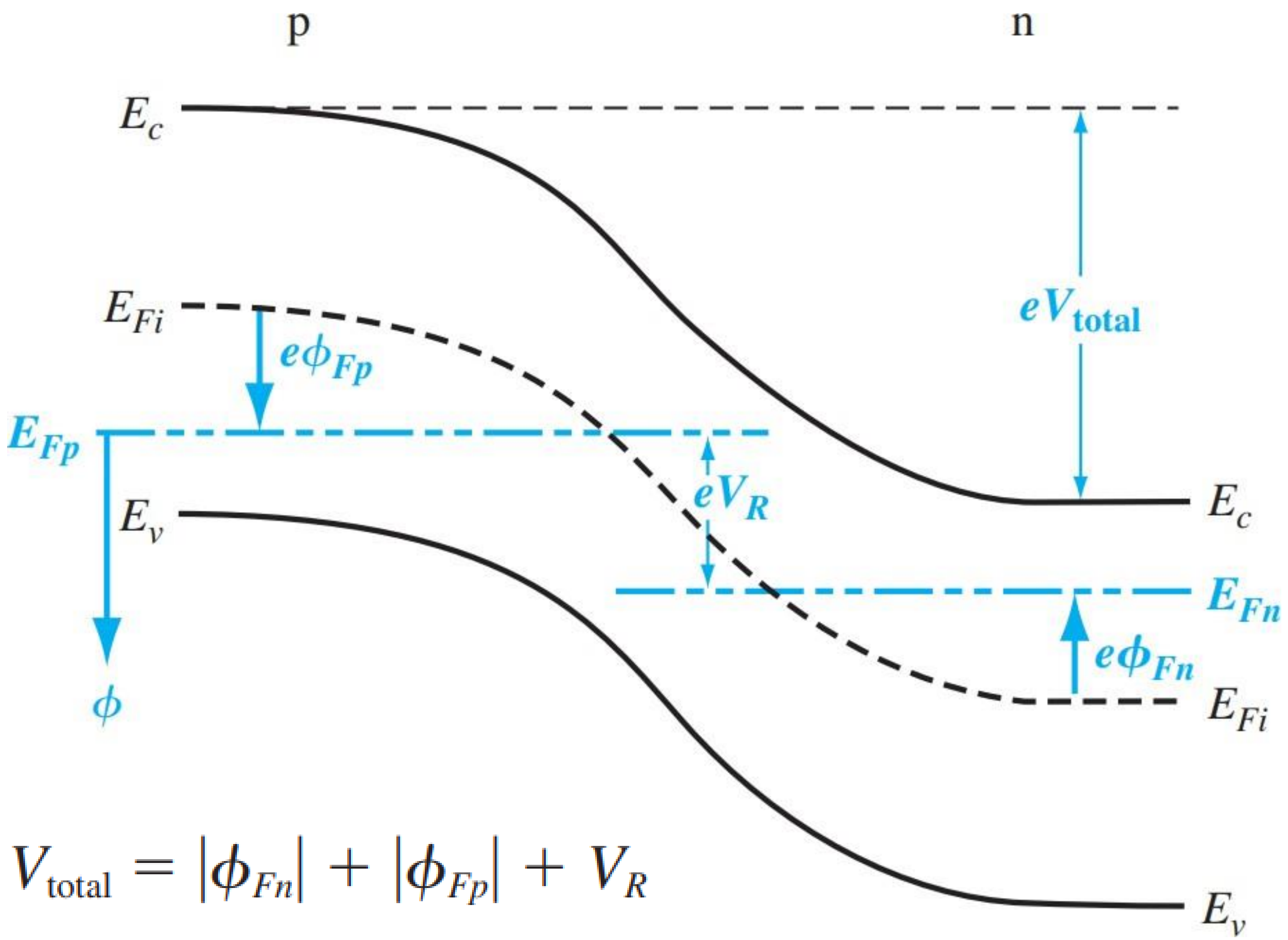


Figure 7.8 | A pn junction, with an applied reverse-biased voltage, showing the directions of the electric field induced by V_R and the space charge electric field.



$$V_{\text{total}} = |\phi_{Fn}| + |\phi_{Fp}| + V_R$$

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

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

The maximum electric field at the metallurgical junction, from Equations (7.14) and (7.16), is

$$E_{\max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-eN_a x_p}{\epsilon_s} \tag{7.35}$$

If we use either Equation (7.28) or (7.29) in conjunction with the total potential barrier, $V_{bi} + V_R$, then

$$\boxed{E_{\max} = -\left\{ \frac{2e(V_{bi} + V_R)}{\epsilon_s} \left(\frac{N_a N_d}{N_a + N_d} \right) \right\}^{1/2}} \tag{7.36}$$

We can show that the maximum electric field in the pn junction can also be written as

$$\boxed{E_{\max} = \frac{-2(V_{bi} + V_R)}{W}} \tag{7.37}$$

where W is the total space charge width.

The maximum electric field in a reverse-biased GaAs pn junction at $T = 300$ K is to be limited to $|E_{max}| = 7.2 \times 10^4$ V/cm. The doping concentrations are $N_d = 5 \times 10^{15}$ cm^{-3} and $N_a = 3 \times 10^{16}$ cm^{-3}. Determine the maximum reverse-biased voltage that can be applied.

$$|E_{max}| = \left\{ \frac{2e(V_{bi} + V_R)}{\epsilon_s} \left(\frac{N_a N_d}{N_a + N_d} \right) \right\}^{1/2}$$

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

$$= (0.0259) \ln\left[\frac{(5 \times 10^{15})(3 \times 10^{16})}{(1.8 \times 10^6)^2} \right]$$

$$= 1.173 \text{ V}$$

Now $(7.2 \times 10^4)^2 = \left\{ \frac{2(1.6 \times 10^{-19})(V_{bi} + V_R)}{(13.1)(8.85 \times 10^{-14})} \times \left[\frac{(5 \times 10^{15})(3 \times 10^{16})}{5 \times 10^{15} + 3 \times 10^{16}} \right] \right\}$

$$5.184 \times 10^9 = 1.1829 \times 10^9 (V_{bi} + V_R)$$

$$V_{bi} + V_R = 1.173 + V_R = 4.382$$

Then $V_R = 3.21$ V

Forward and Reverse biasing

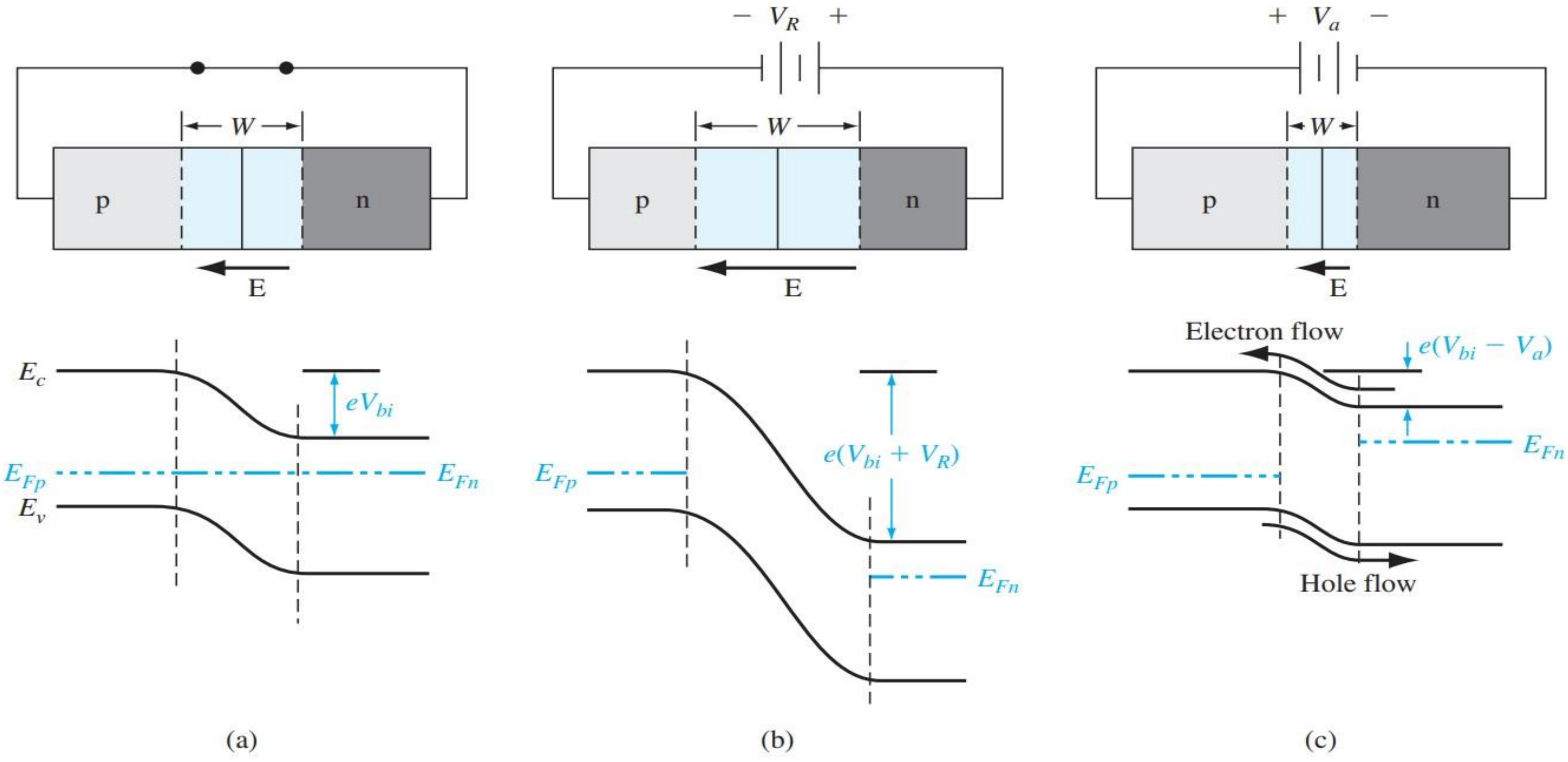


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.