Semiconductor Devices

Chapter 7
The pn Junction

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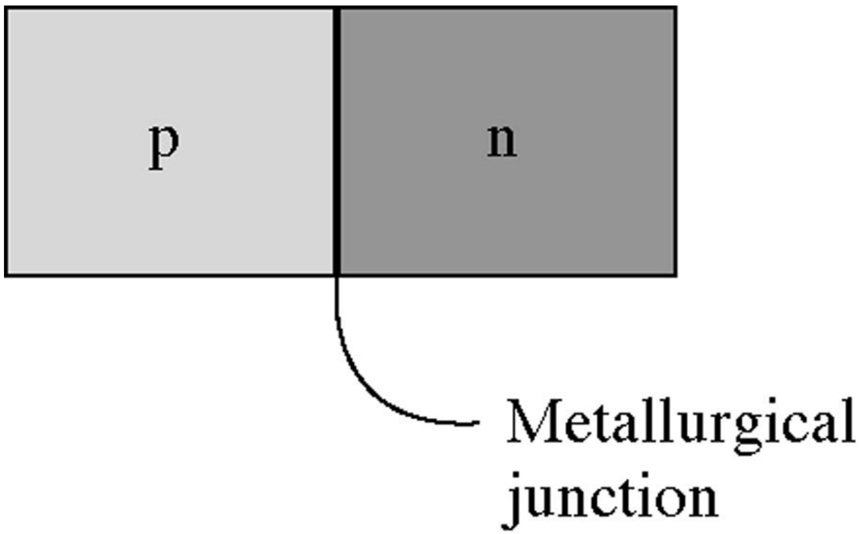
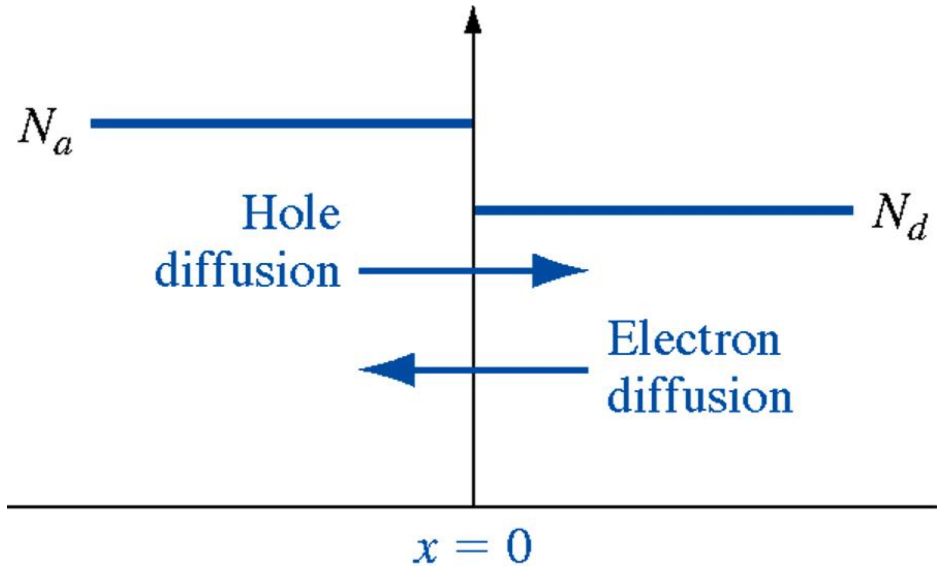
Basic Structure of PN Junction

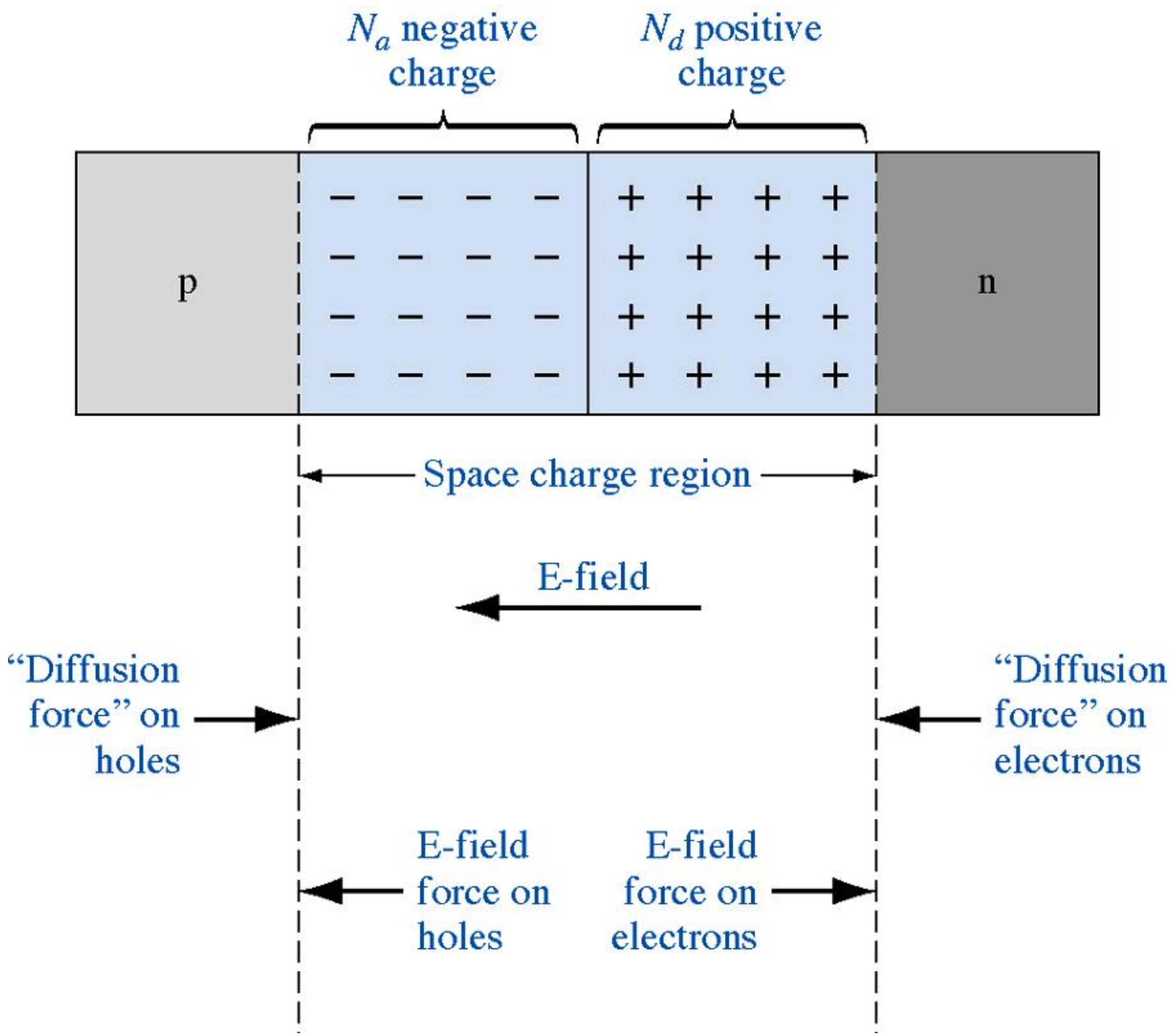


(a)

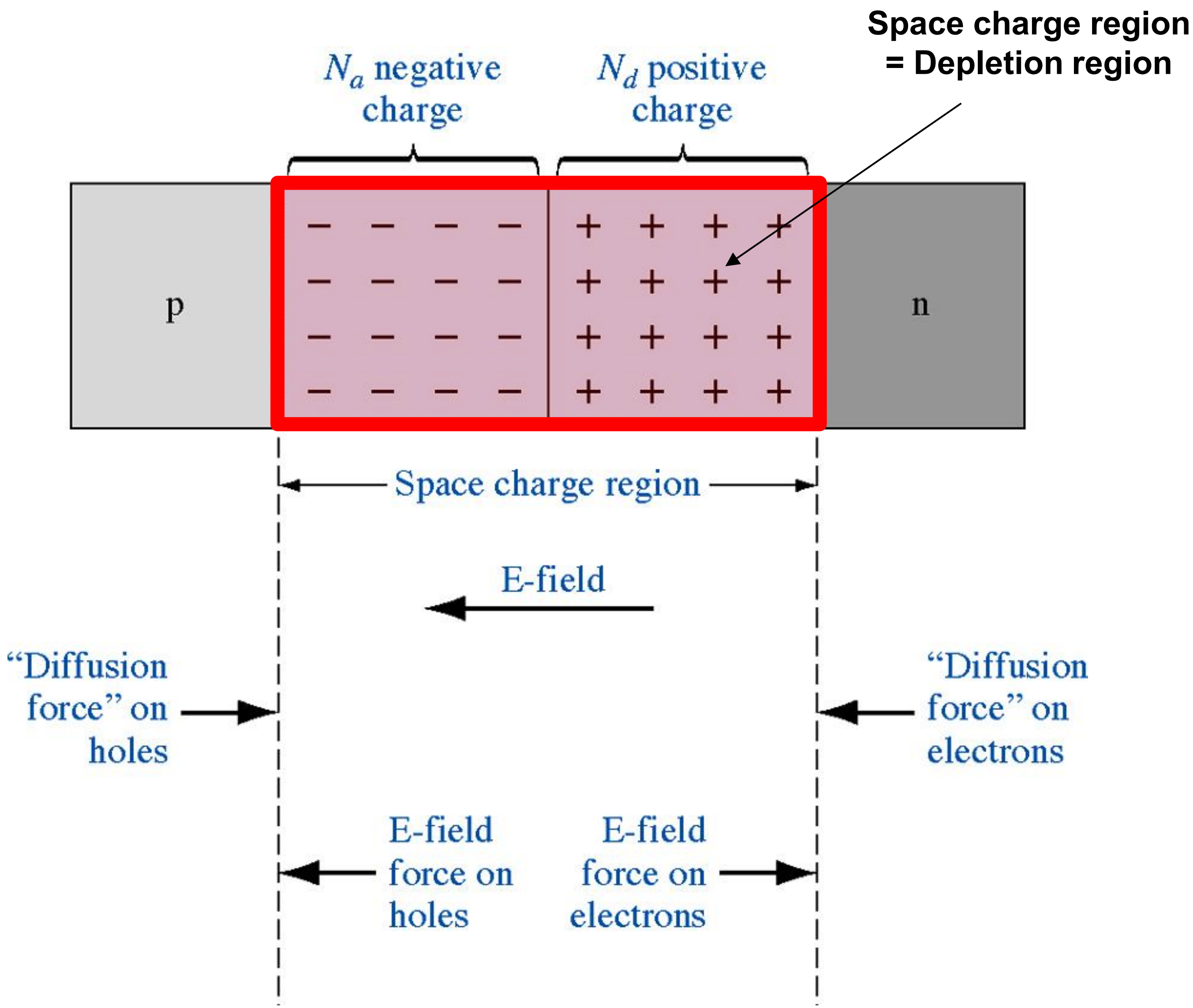


(b)

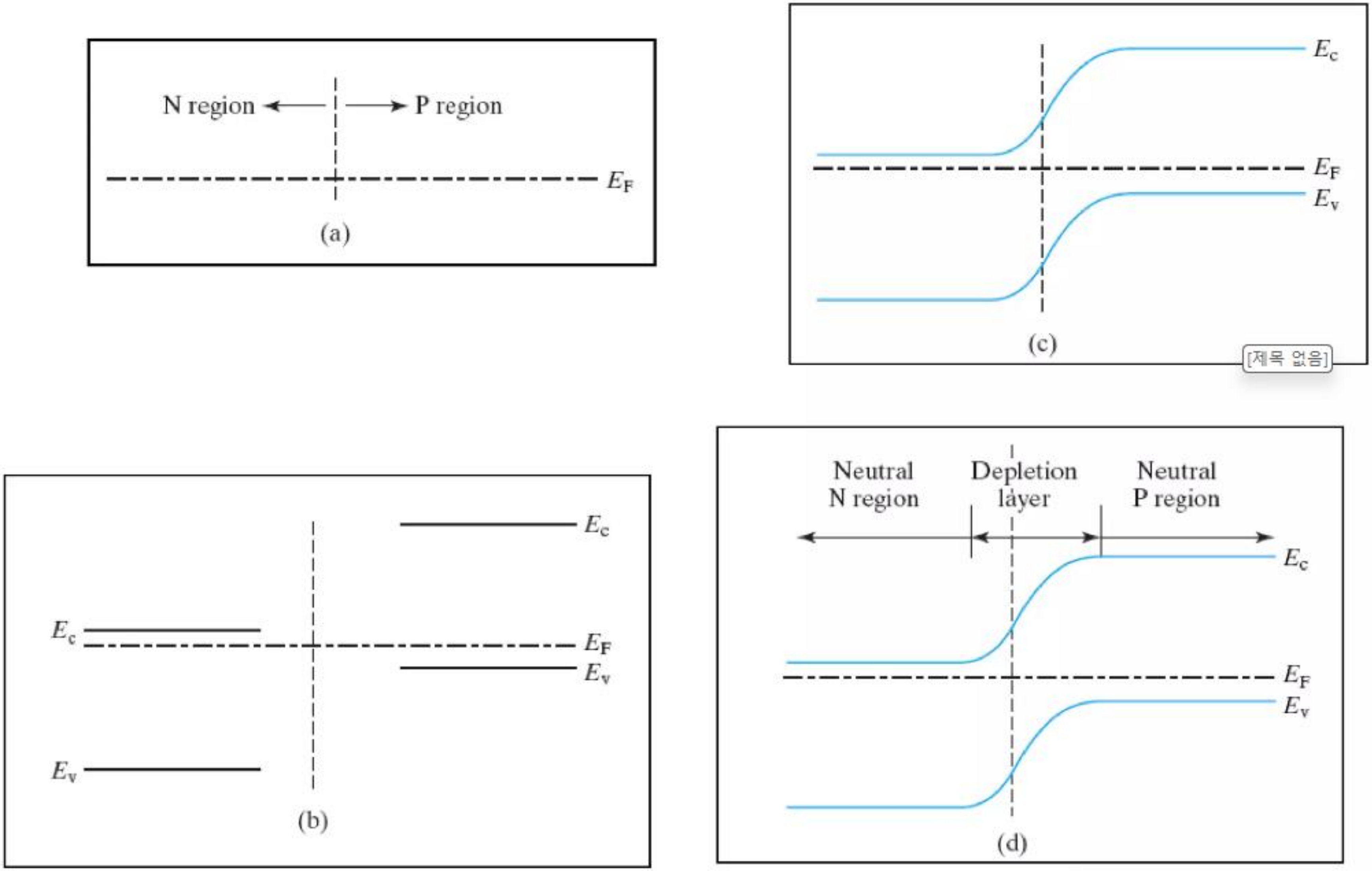
Basic Structure of PN Junction



Basic Structure of PN Junction



PN Junction Band Diagram

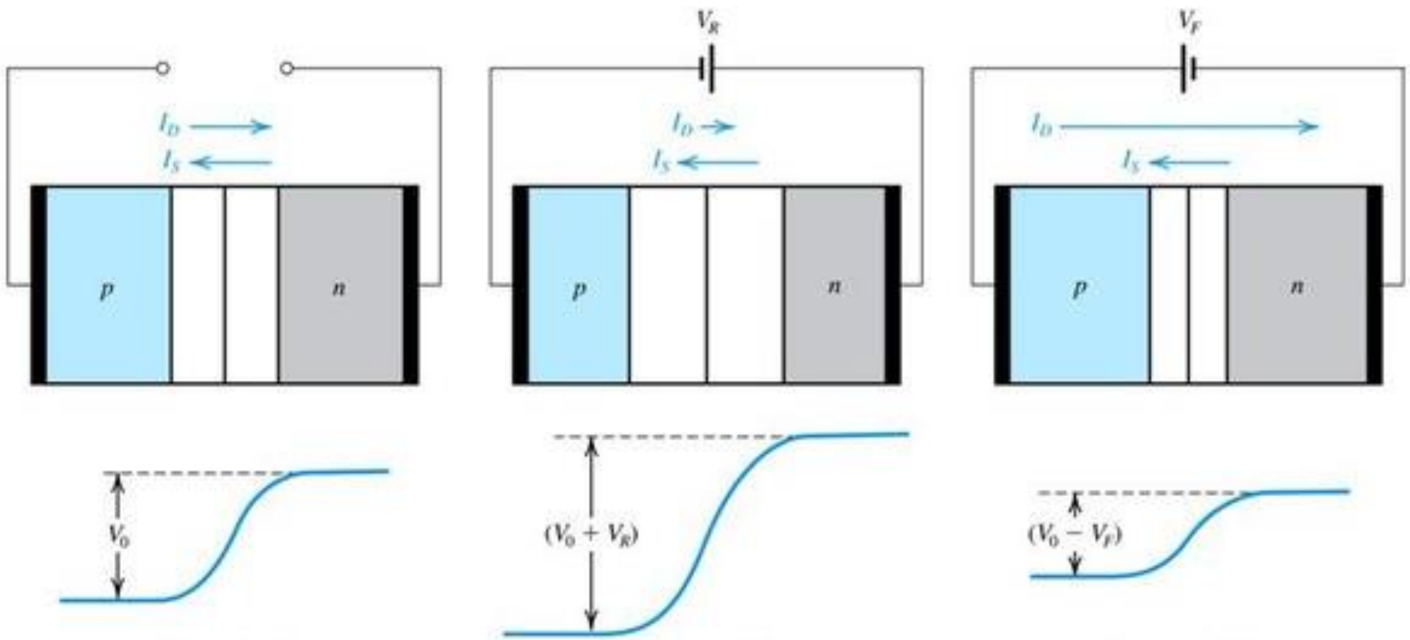


Voltage Bias

- Zero Bias (Equilibrium)

- Reverse Bias

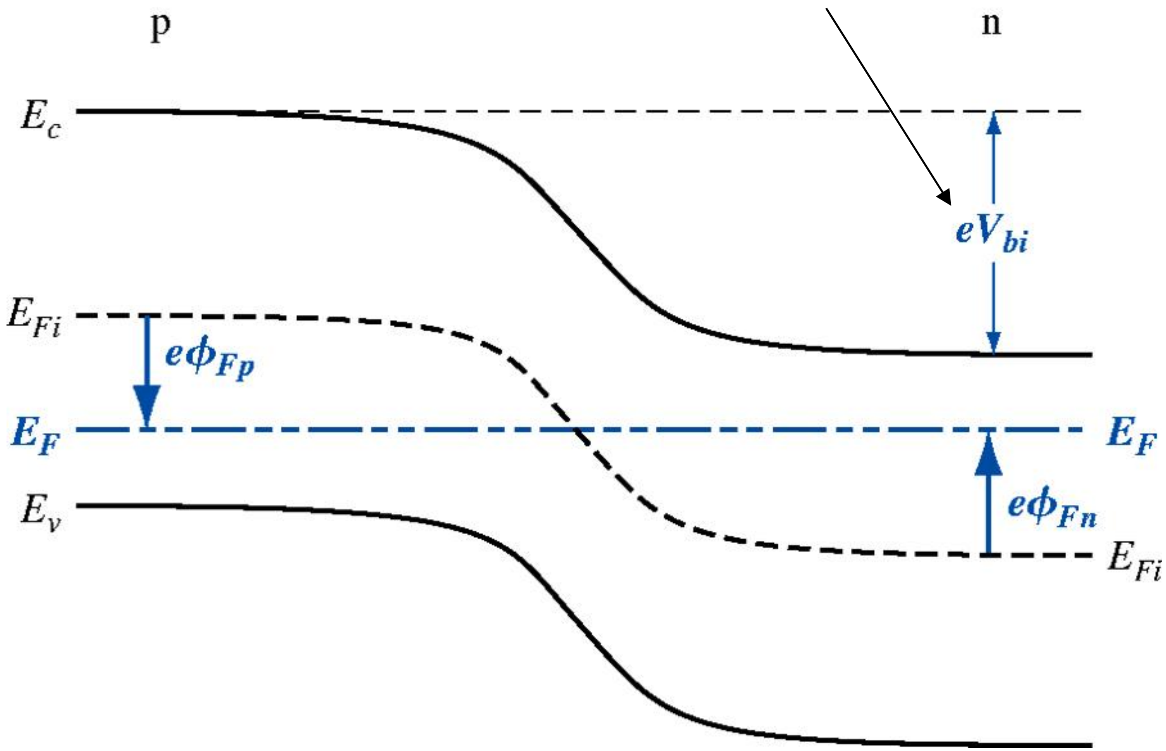
- Forward Bias



(a) Open-circuit (Equilibrium) (b) Reverse Bias (c) Forward Bias

Zero Applied Bias

$e = q = 1.6 \times 10^{-19}$ C



V_{bi}

Built-in potential barrier

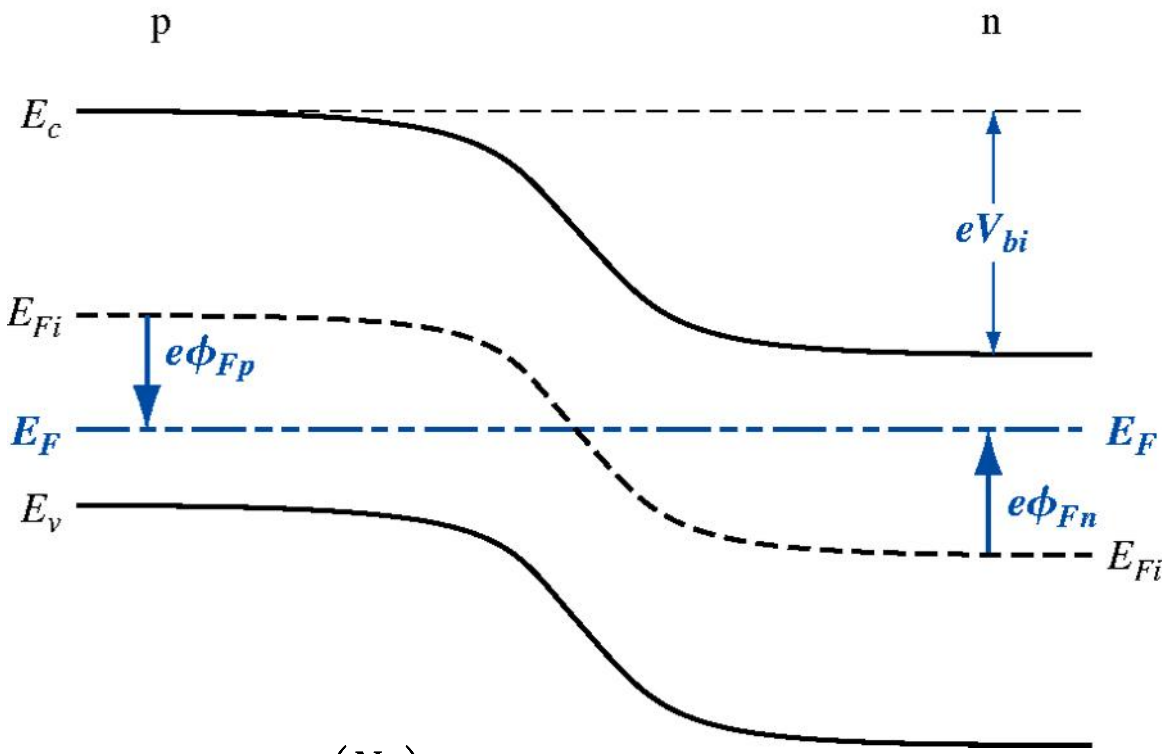
$$p_0 = N_a = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right)$$
$$= n_i \exp\left(\frac{\boldsymbol{e\phi_{Fp}}}{kT}\right)$$

$$n_0 = N_d = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right)$$
$$= n_i \exp\left(\frac{\boldsymbol{e\phi_{Fn}}}{kT}\right)$$

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

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

Zero Applied Bias



V_{bi}

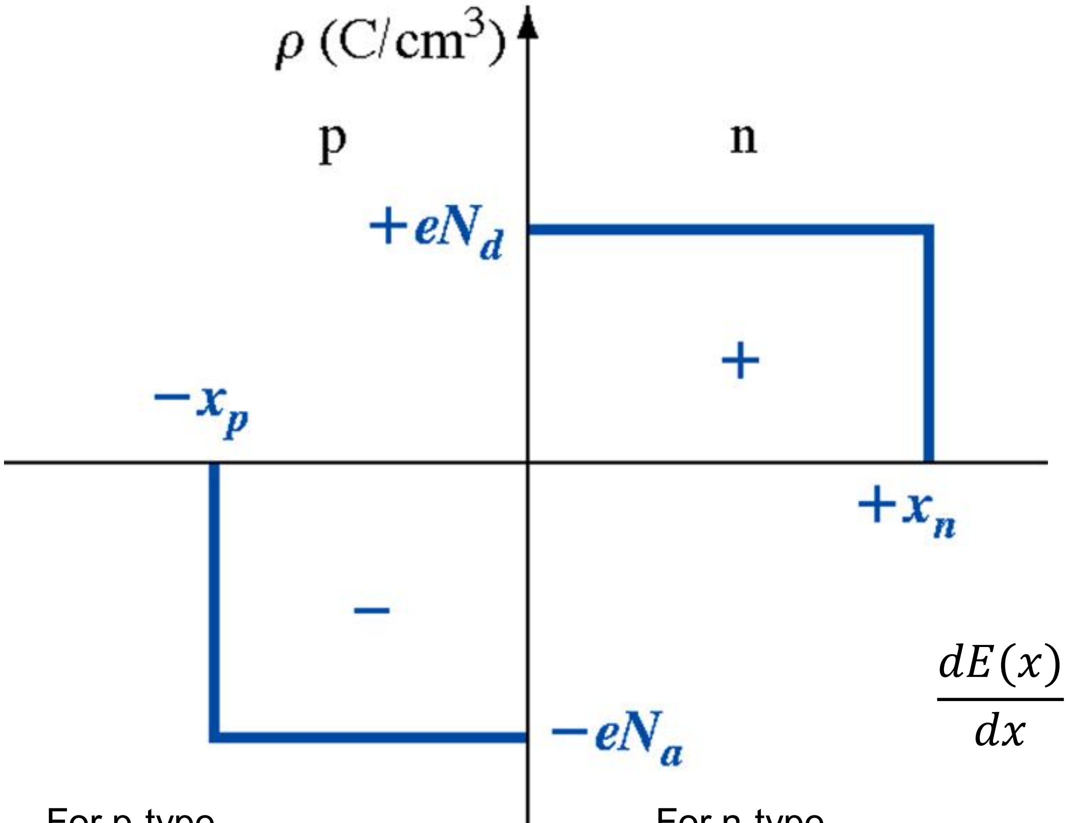
Built-in potential barrier

$$e\phi_{Fp} = kTln\left(\frac{N_a}{n_i}\right) \qquad e\phi_{Fn} = kTln\left(\frac{N_d}{n_i}\right)$$

$$eV_{bi} = e\phi_{Fp} + e\phi_{Fn} = kTln\left(\frac{N_a}{n_i}\right) + kTln\left(\frac{N_d}{n_i}\right) = kTln\left(\frac{N_d N_a}{n_i^2}\right)$$

Built-in potential barrier $$V_{bi} = \frac{kT}{e} ln\left(\frac{N_d N_a}{n_i^2}\right) = V_t ln\left(\frac{N_d N_a}{n_i^2}\right) \qquad V_t = \frac{kT}{e}$$

Charge Density, Electric Field, Potential



$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

$$\frac{dE(x)}{dx} = \frac{\rho(x)}{\varepsilon_s}$$

$$\varepsilon_s = \varepsilon_r \varepsilon_0$$

Permittivity $[F/m]$

Poisson's equation

$$\frac{d^2\phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\varepsilon_s}$$

$$\frac{dE(x)}{dx} = \frac{\rho(x)}{\varepsilon_s} \Rightarrow E(x) = \int \frac{\rho(x)}{\varepsilon_s} dx$$

For p-type

$$E(x) = -\frac{eN_a}{\varepsilon_s} x + C$$
$$= -\frac{eN_a}{\varepsilon_s}(x + x_p)$$

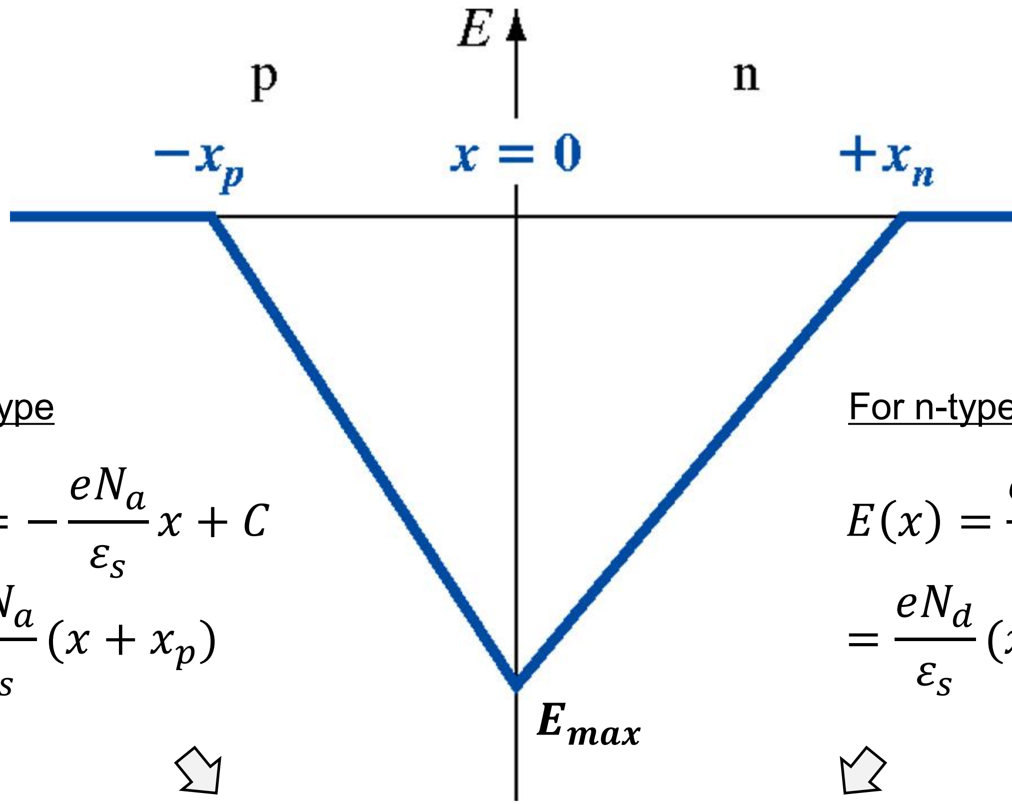
For n-type

$$E(x) = \frac{eN_d}{\varepsilon_s} x + C$$
$$= \frac{eN_d}{\varepsilon_s}(x - x_n)$$

Boundary conditions

$$E(-x_p) = 0$$
$$E(+x_n) = 0$$

Charge Density, Electric Field, Potential



For p-type

$$E(x) = -\frac{eN_a}{\varepsilon_s}x + C$$
$$= -\frac{eN_a}{\varepsilon_s}(x + x_p)$$

For n-type

$$E(x) = \frac{eN_d}{\varepsilon_s}x + C$$
$$= \frac{eN_d}{\varepsilon_s}(x - x_n)$$

$$E(0) = E_{max} = -\frac{eN_a}{\varepsilon_s}x_p = -\frac{eN_d}{\varepsilon_s}x_n$$

$$N_a x_p = N_d x_n$$

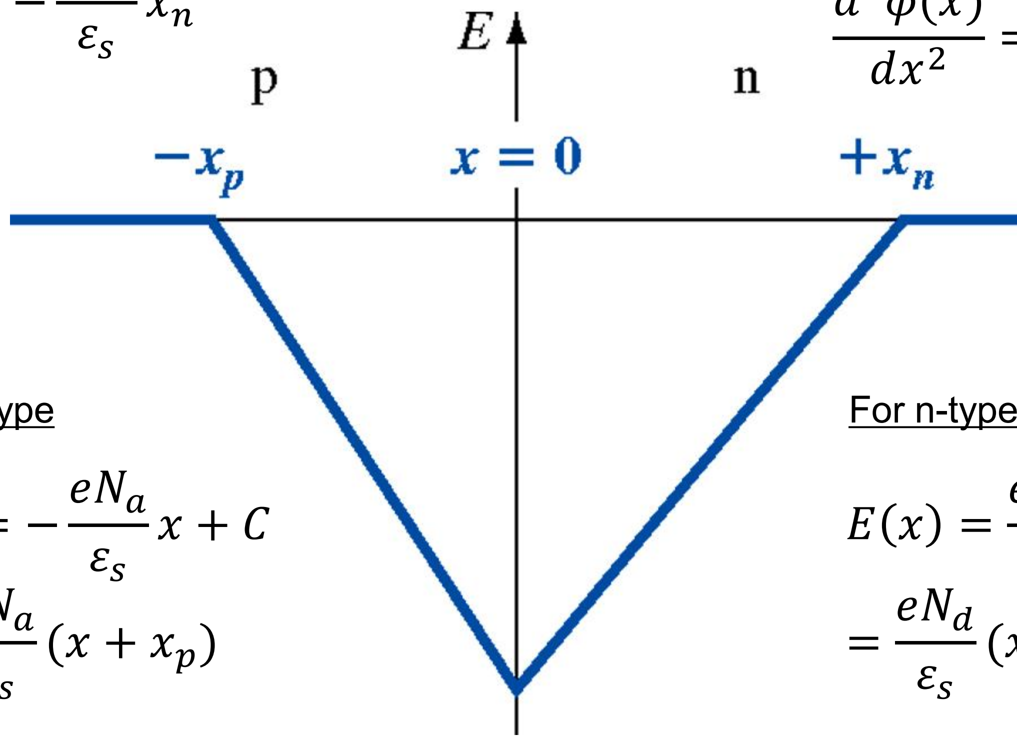
Charge Density, Electric Field, Potential

$$E(0) = -\frac{eN_a}{\varepsilon_s}x_p = -\frac{eN_d}{\varepsilon_s}x_n$$

$$N_a x_p = N_d x_n$$

Poisson's equation

$$\frac{d^2\phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\varepsilon_s}$$



For p-type

$$E(x) = -\frac{eN_a}{\varepsilon_s}x + C$$
$$= -\frac{eN_a}{\varepsilon_s}(x + x_p)$$

For n-type

$$E(x) = \frac{eN_d}{\varepsilon_s}x + C$$
$$= \frac{eN_d}{\varepsilon_s}(x - x_n)$$

$$\phi(x) = \frac{eN_a}{\varepsilon_s}\int x + x_p dx \Leftarrow \phi(x) = -\int E(x)dx \Rightarrow \phi(x) = -\frac{eN_d}{\varepsilon_s}\int x - x_n dx$$

$$= \frac{eN_a}{\varepsilon_s}\left(\frac{1}{2}x^2 + x_p x\right) + C$$
$$= \frac{eN_a}{2\varepsilon_s}(x + x_p)^2$$

Boundary conditions

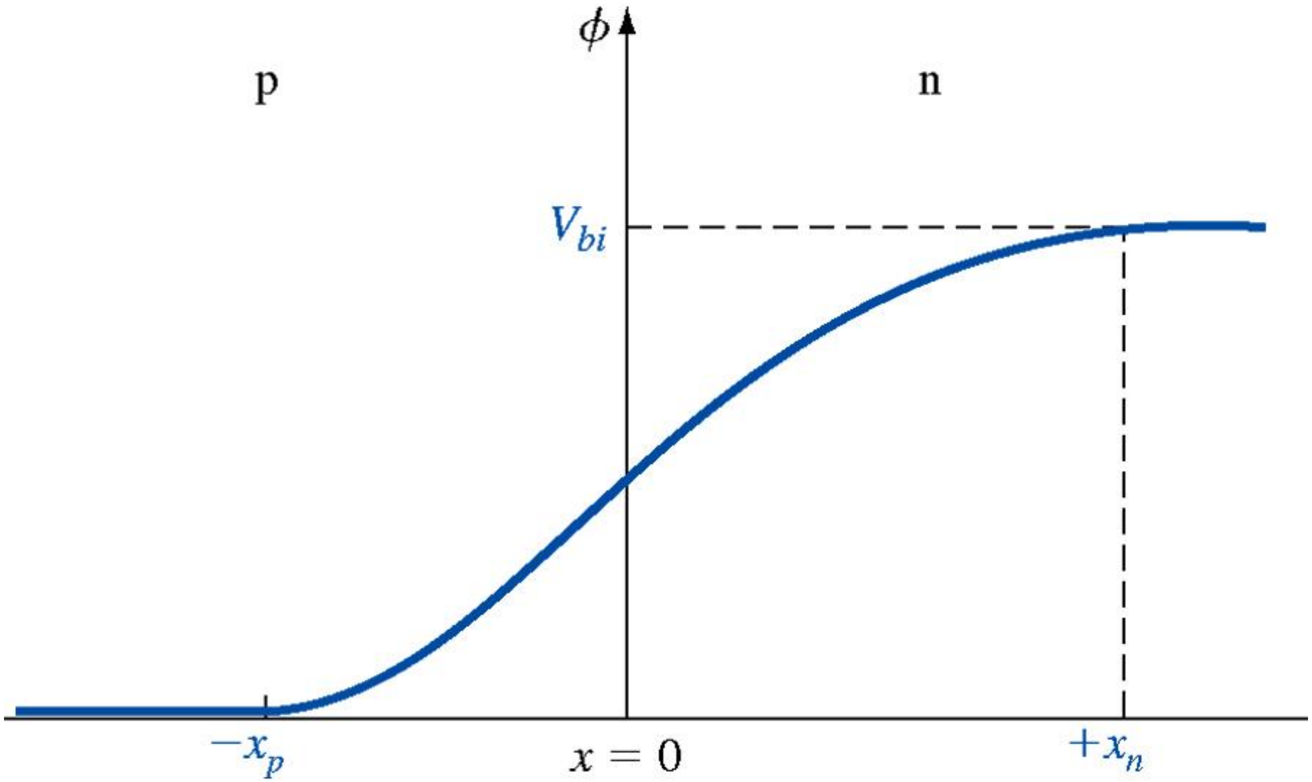
$$\phi(-x_p) = 0$$

$$\phi(0) = \phi(0)$$

For p-type For n-type

$$= -\frac{eN_d}{\varepsilon_s}\left(\frac{1}{2}x^2 - x_n x\right) + C$$
$$= -\frac{eN_d}{\varepsilon_s}\left(\frac{1}{2}x^2 - x_n x\right) + \frac{eN_a}{2\varepsilon_s}x_p^2$$

Charge Density, Electric Field, Potential



$$\phi(x) = \frac{eN_a}{\varepsilon_s}\int x + x_p dx \Leftarrow \phi(x) = -\int E(x)dx \Rightarrow \phi(x) = -\frac{eN_d}{\varepsilon_s}\int x - x_n dx$$

$$= \frac{eN_a}{\varepsilon_s}\left(\frac{1}{2}x^2 + x_p x\right) + C$$

$$= \frac{eN_a}{2\varepsilon_s}\left(x + x_p\right)^2$$

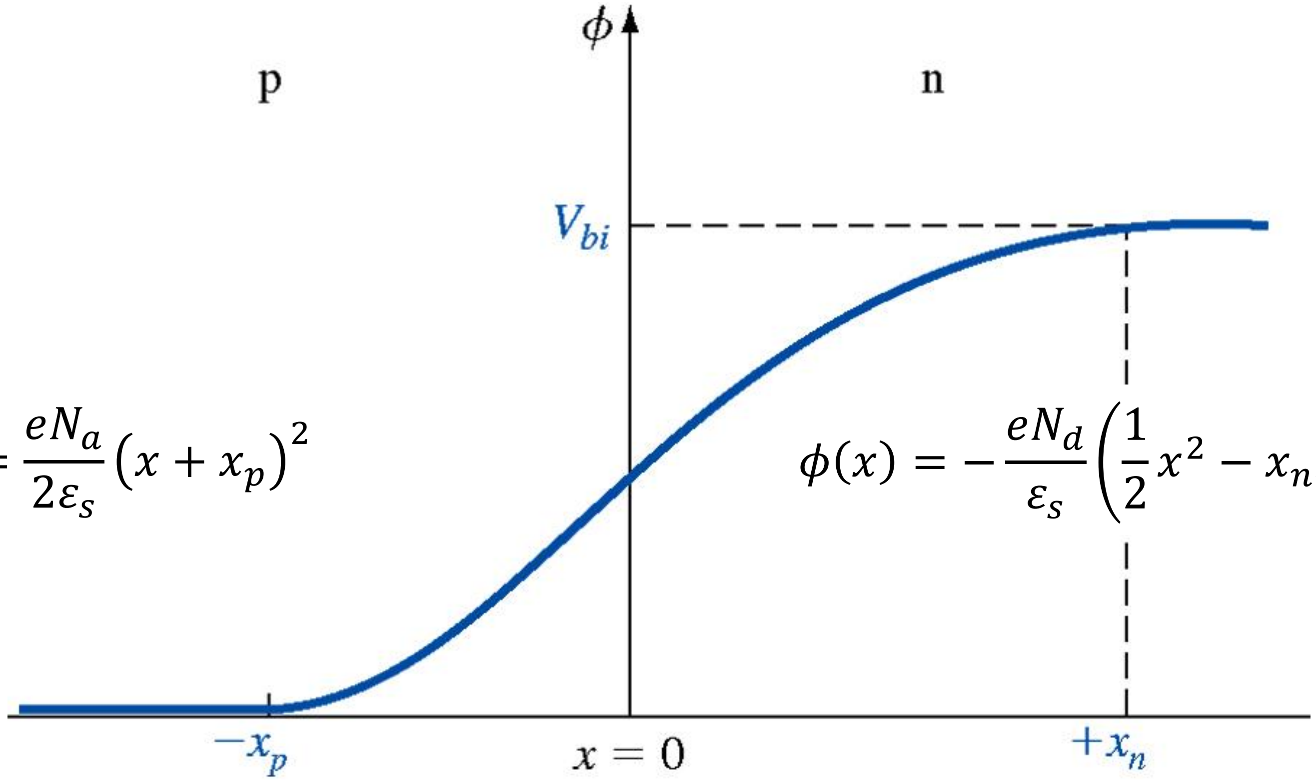
For p-type | For n-type

$$\phi(0) = \phi(0)$$

$$= -\frac{eN_a}{\varepsilon_s}\left(\frac{1}{2}x^2 - x_n x\right) + C$$

$$= -\frac{eN_a}{\varepsilon_s}\left(\frac{1}{2}x^2 - x_n x\right) + \frac{eN_a}{2\varepsilon_s}x_p^2$$

Charge Density, Electric Field, Potential



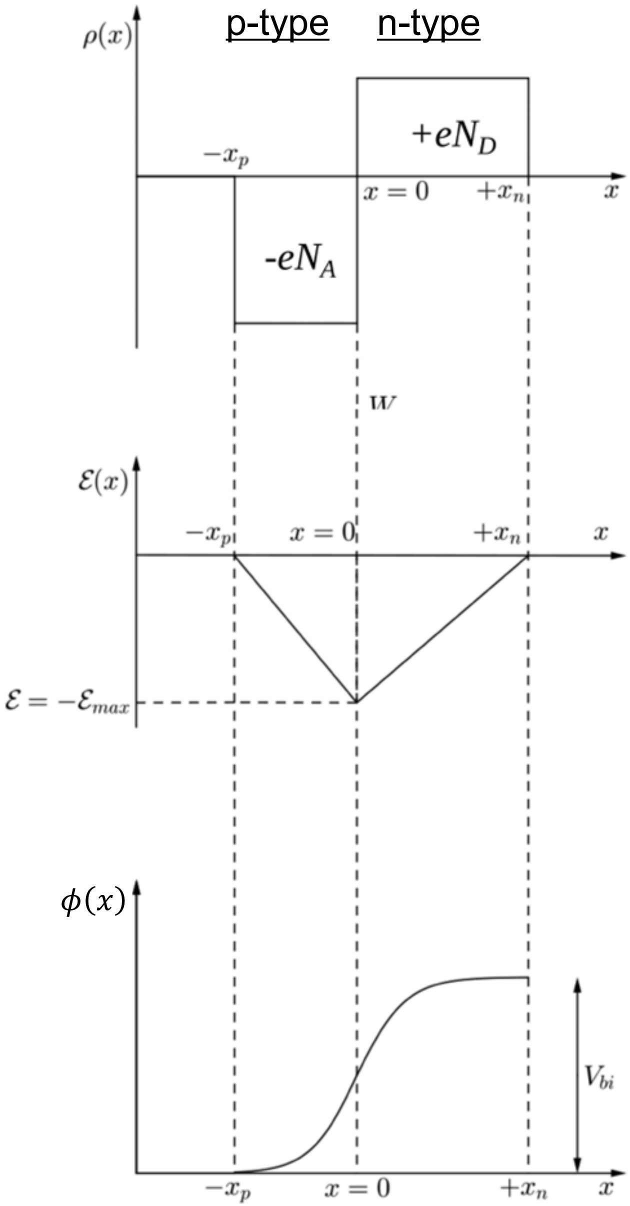
$$\phi(x) = \frac{eN_a}{2\varepsilon_s}\left(x + x_p\right)^2$$

$$\phi(x) = -\frac{eN_d}{\varepsilon_s}\left(\frac{1}{2}x^2 - x_n x\right) + \frac{eN_a}{2\varepsilon_s}x_p^2$$

$$\phi(x_n) = \frac{eN_d}{2\varepsilon_s}x_n^2 + \frac{eN_a}{2\varepsilon_s}x_p^2 = \frac{e}{2\varepsilon_s}(N_d x_n^2 + N_a x_p^2)$$

$$\Rightarrow \quad V_{bi} = \frac{e}{2\varepsilon_s}(N_d x_n^2 + N_a x_p^2)$$

Charge Density, Electric Field, Potential Summary



- **Poisson's equation**

$$\frac{d^2\phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\varepsilon_s}$$

- **Electric field**

For p-type $\quad E(x) = -\dfrac{eN_a}{\varepsilon_s}(x + x_p)$

For n-type $\quad E(x) = \dfrac{eN_d}{\varepsilon_s}(x - x_n)$

$$\Rightarrow \quad N_a x_p = N_d x_n$$

- **Potential**

For p-type $\quad \phi(x) = \dfrac{eN_a}{2\varepsilon_s}\left(x + x_p\right)^2$

For n-type $\quad \phi(x) = -\dfrac{eN_d}{\varepsilon_s}\left(\dfrac{1}{2}x^2 - x_n x\right) + \dfrac{eN_a}{2\varepsilon_s}x_p^2$

$$\Rightarrow \quad V_{bi} = \frac{e}{2\varepsilon_s}(N_d x_n^2 + N_a x_p^2)$$

Space Charge Width

$$N_a x_p = N_d x_n$$

$$V_{bi} = \frac{e}{2\varepsilon_s}(N_d x_n^2 + N_a x_p^2)$$

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

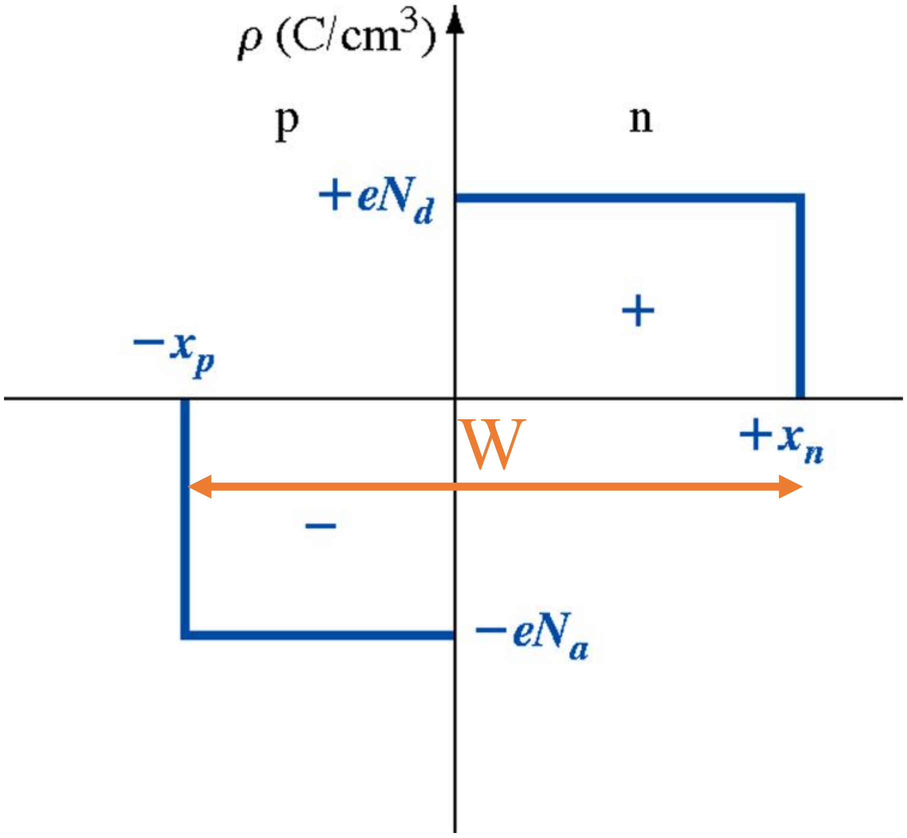
$$x_n = \left\{ \frac{2\varepsilon_s V_{bi}}{e} \left[\frac{\boldsymbol{N_a}}{\boldsymbol{N_d}}\right] \left[\frac{1}{N_a + N_d}\right] \right\}^{1/2}$$

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

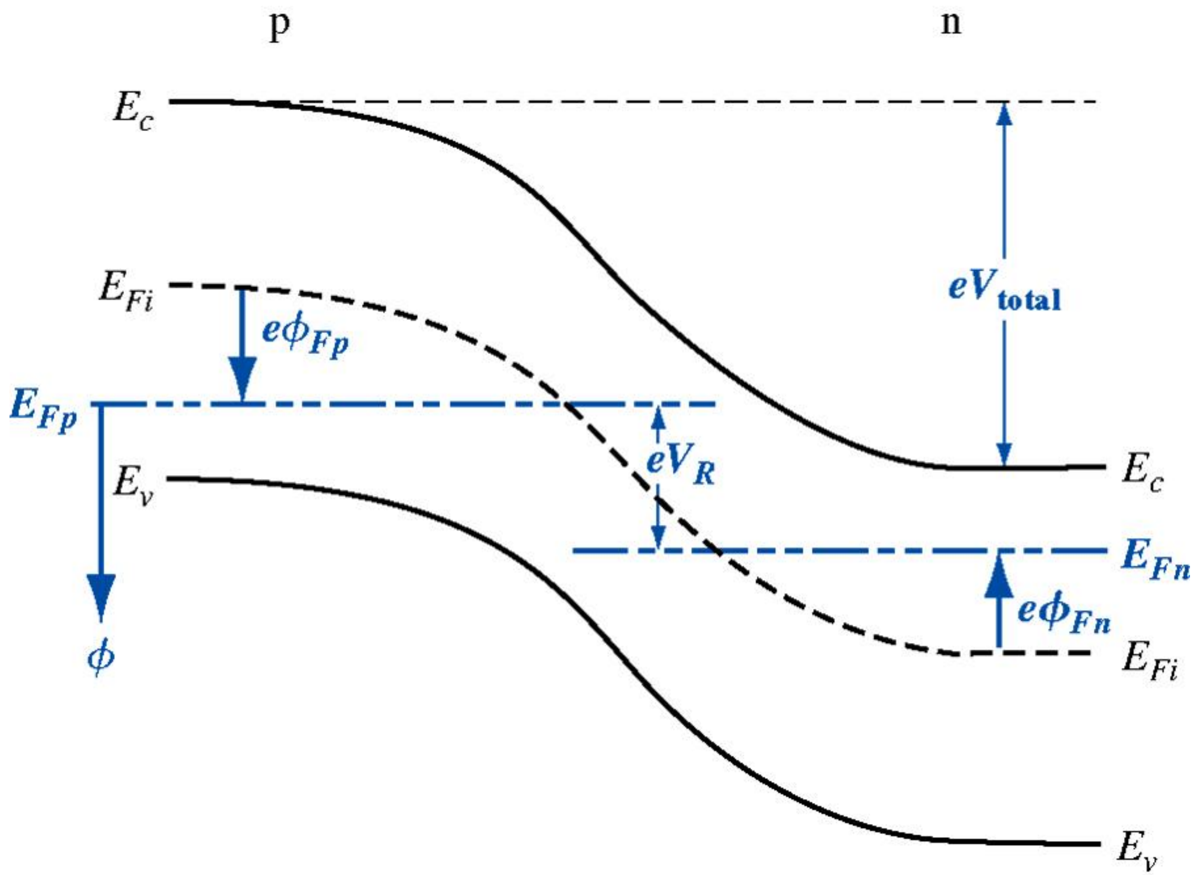
$$\Downarrow$$

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

$$x_n = W\left(\frac{\boldsymbol{N_a}}{N_a + N_d}\right) \qquad x_p = W\left(\frac{\boldsymbol{N_d}}{N_a + N_d}\right)$$



Reverse Bias

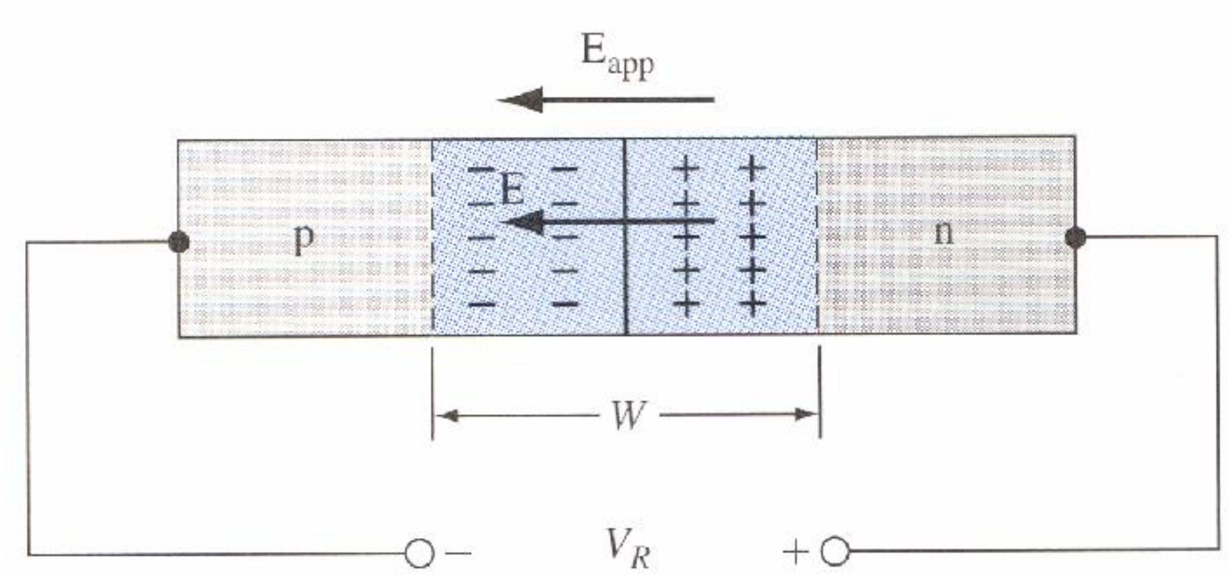


$$V_{total} = |\phi_{Fn}| + |\phi_{Fp}| = V_{bi}$$

⇩ Under application of Reverse bias

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

Reverse Bias (Space Charge Width)

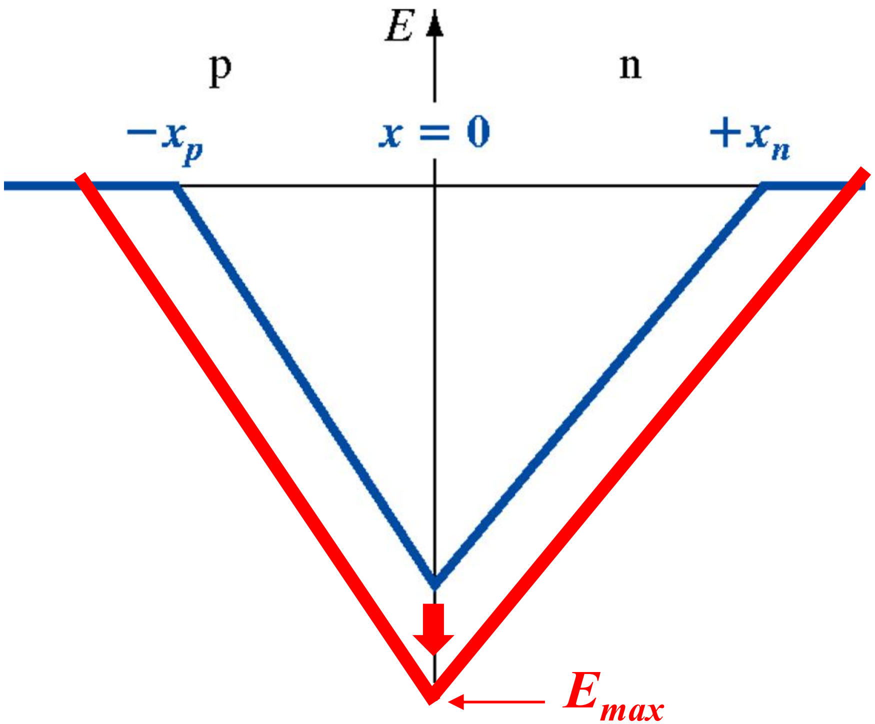


$$W = \left\{ \frac{2\varepsilon_s V_{bi}}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$

⇩ Under application of Reverse bias

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

Reverse Bias (Electric Field)



$$E(0) = E_{max} = -\frac{eN_a}{\varepsilon_s}x_p = -\frac{eN_d}{\varepsilon_s}x_n$$

⇩ Under application of Reverse bias

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

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

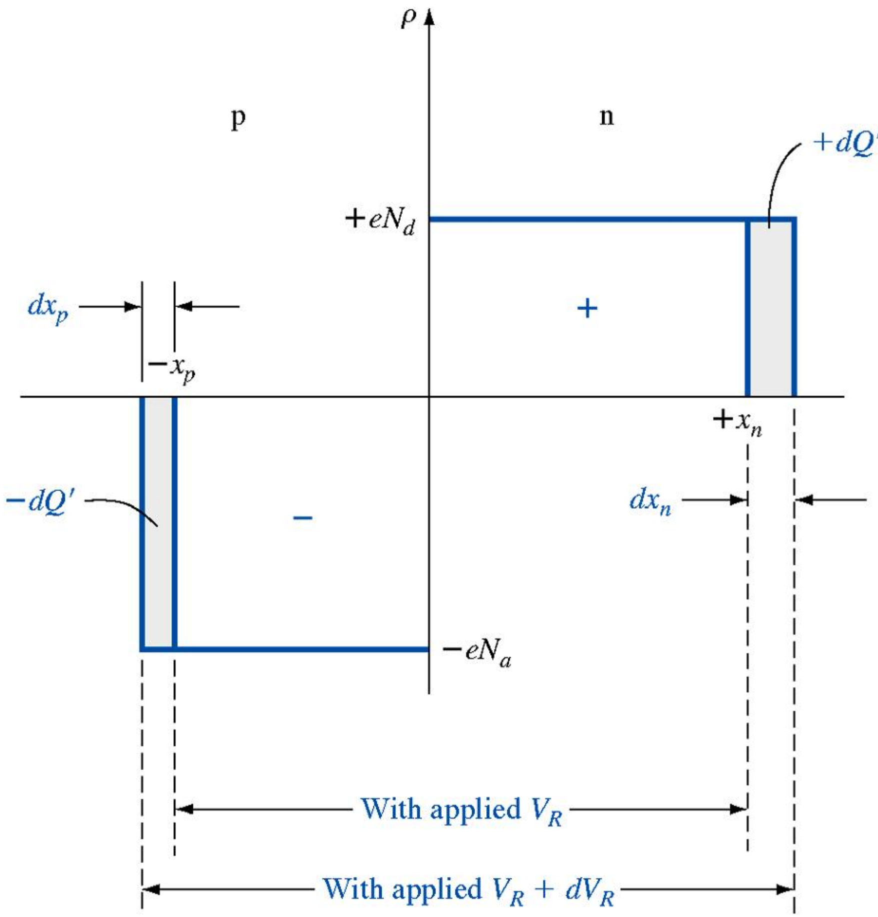
$$W = \left\{\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a+N_d}{N_aN_d}\right]\right\}^{1/2}$$

$$E_{max} = -\frac{eN_a}{\varepsilon_s}\left\{\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{\frac{1}{2}} = -\left\{\frac{2e(V_{bi}+V_R)}{\varepsilon_s}\left[\frac{N_aN_d}{N_a+N_d}\right]\right\}^{\frac{1}{2}}$$

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

$$= \frac{-2(V_{bi}+V_R)}{W}$$

Junction Capacitance



$$x_n = W\left(\frac{N_a}{N_a+N_d}\right)$$

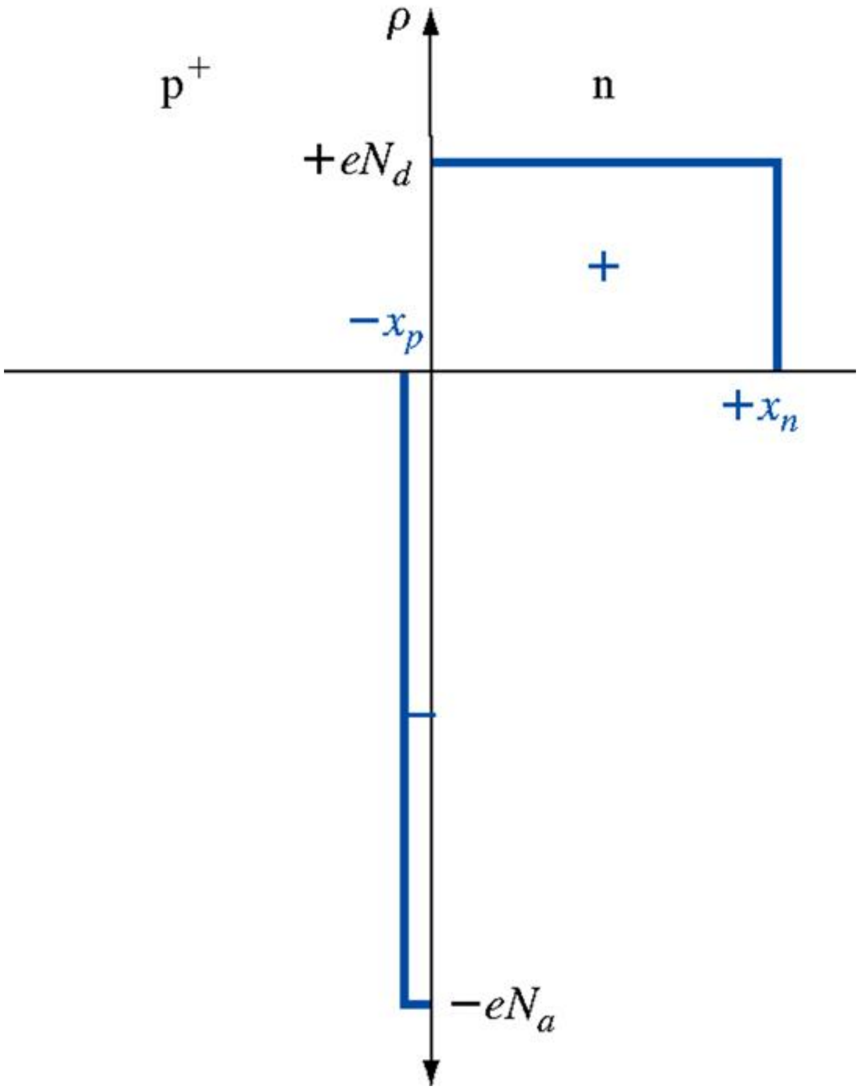
$$\frac{1}{W} = \frac{1}{x_n}\left(\frac{N_a}{N_a+N_d}\right)$$

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

$$C' = \frac{dQ'}{dV_R} = \frac{deN_d x_n}{dV_R} = eN_d\frac{dx_n}{dV_R} = \left\{\frac{e\varepsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2}$$

$$= \frac{eN_d}{2x_n}\left(\frac{2\varepsilon_s}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right) = \frac{\varepsilon_s}{x_n}\left(\frac{N_a}{N_a+N_d}\right) = \frac{\varepsilon_s}{W}\ [F/\mathrm{cm}^2]$$

One-Sided Junction



$\underline{when\ p \gg n}$ ⇨ $N_a \gg N_d$

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

⇩ Devide by N_a

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

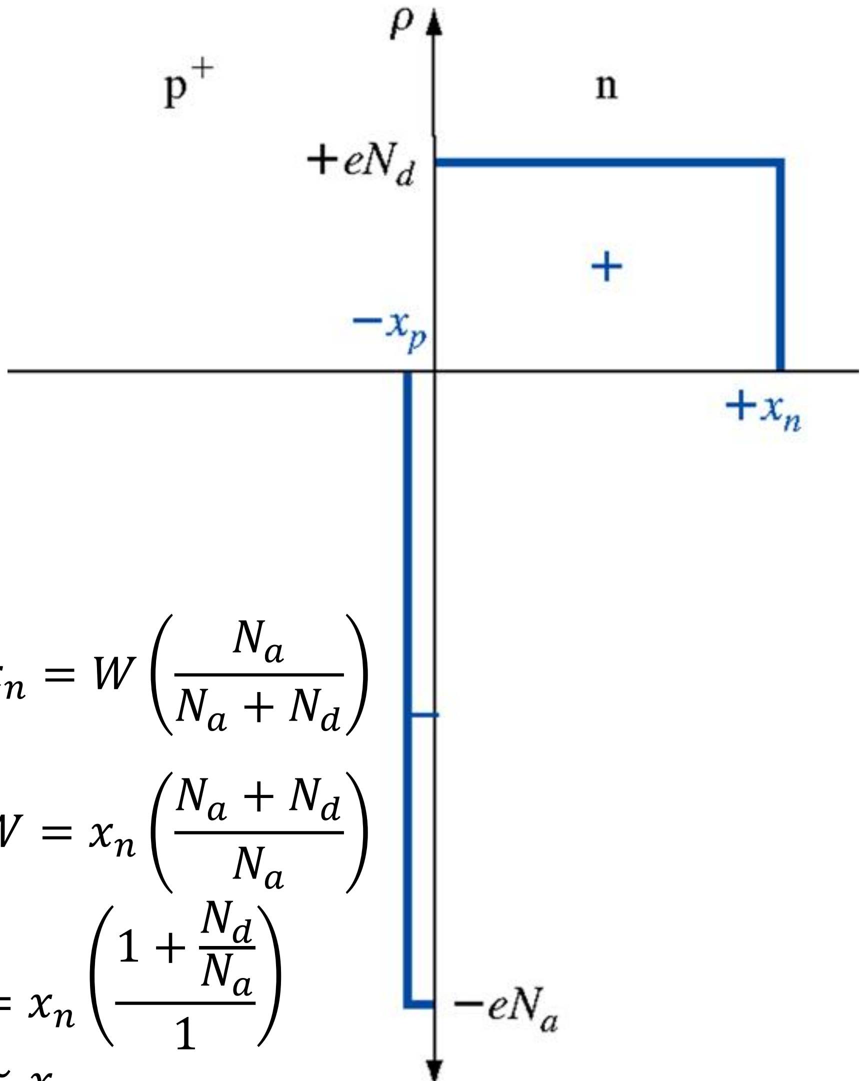
⇧

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

⇩ Devide by N_a

$$x_n \approx \left\{\frac{2\varepsilon_s(V_{bi}+V_R)}{eN_d}\right\}^{1/2}$$

One-Sided Junction



$$x_n = W\left(\frac{N_a}{N_a + N_d}\right)$$

$$W = x_n\left(\frac{N_a + N_d}{N_a}\right)$$

$$= x_n\left(\frac{1 + \frac{N_d}{N_a}}{1}\right)$$

$$\cong x_n$$

$N_a \gg N_d$

$\underline{when\ p \gg n}$ ⇨ $N_a \gg N_d$

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

⇩ Devide by N_a

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

⇧

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

⇩ Devide by N_a

$$x_n \approx \left\{\frac{2\varepsilon_s(V_{bi} + V_R)}{eN_d}\right\}^{1/2}$$

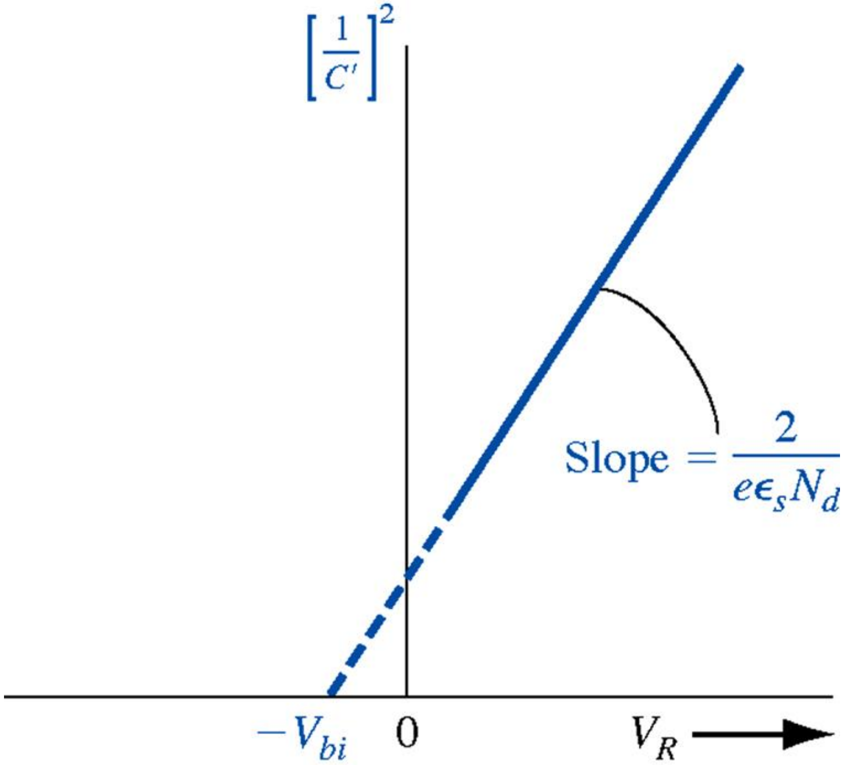
One-Sided Junction Capacitance

$$C' = eN_d \frac{dx_n}{dV_R} = \left\{ \frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2} = \frac{\varepsilon_s}{x_n} \left(\frac{N_a}{N_a + N_d} \right)$$

Devide by N_a

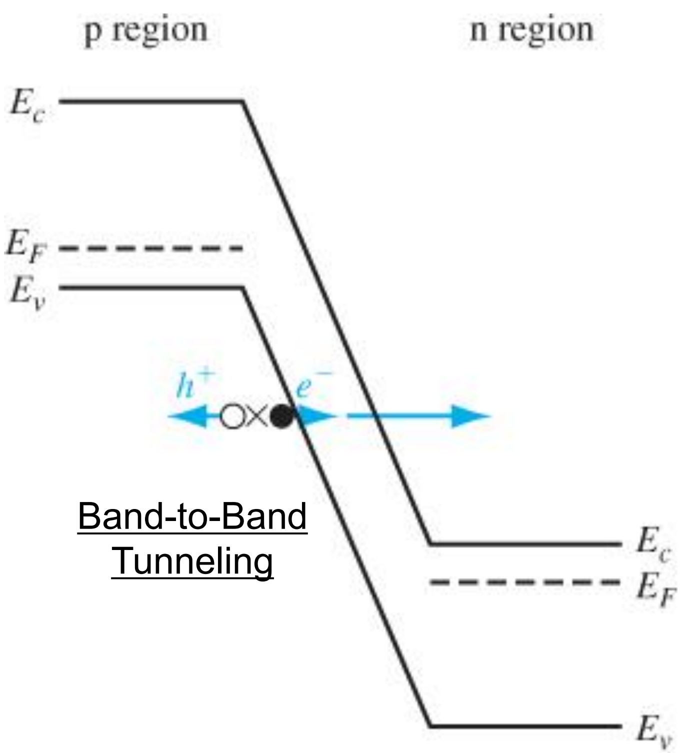
$$C' = eN_d \frac{dx_n}{dV_R} = \left\{ \frac{e\varepsilon_s N_d}{2(V_{bi} + V_R)} \right\}^{1/2} = \frac{\varepsilon_s}{x_n}$$

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



PN Junction Breakdown in Reverse Bias

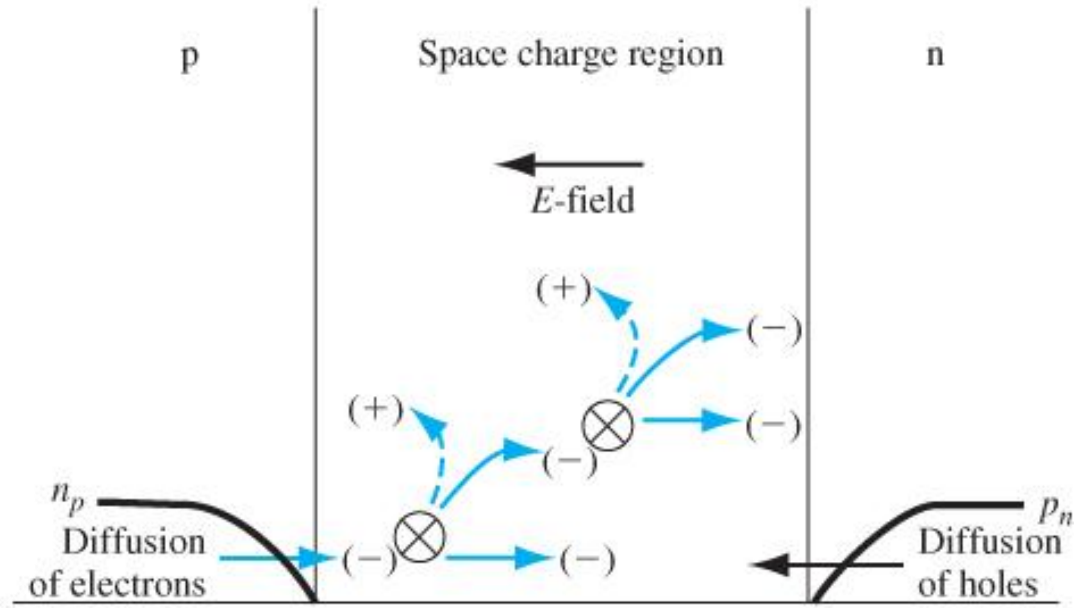
Zener breakdown



(a)

Avalanche breakdown

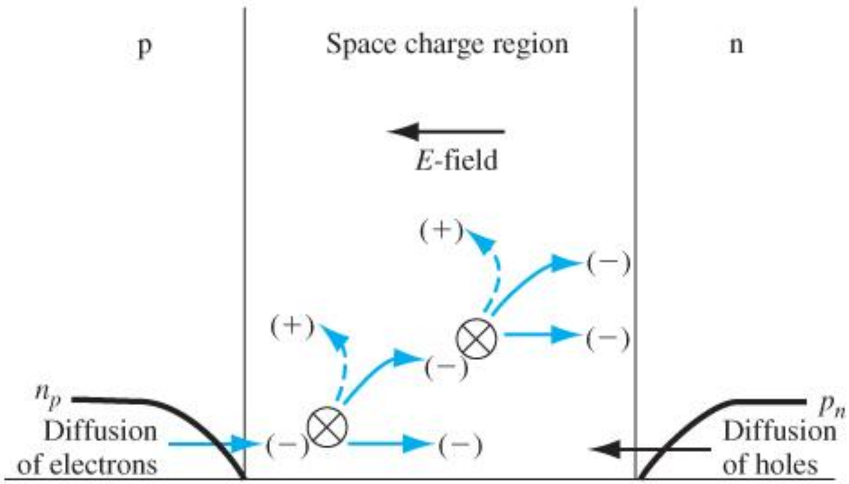
Impact ionization

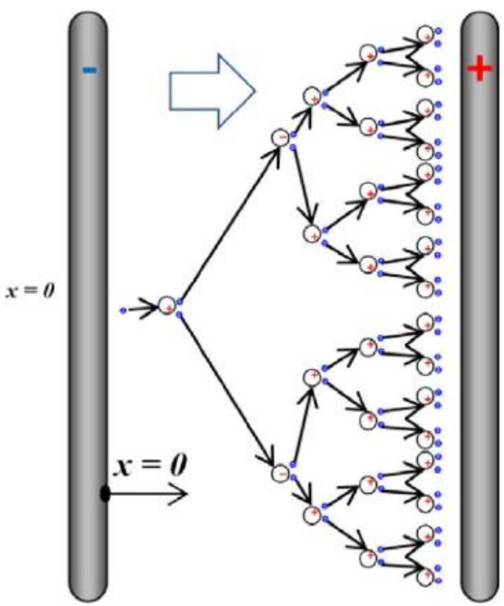


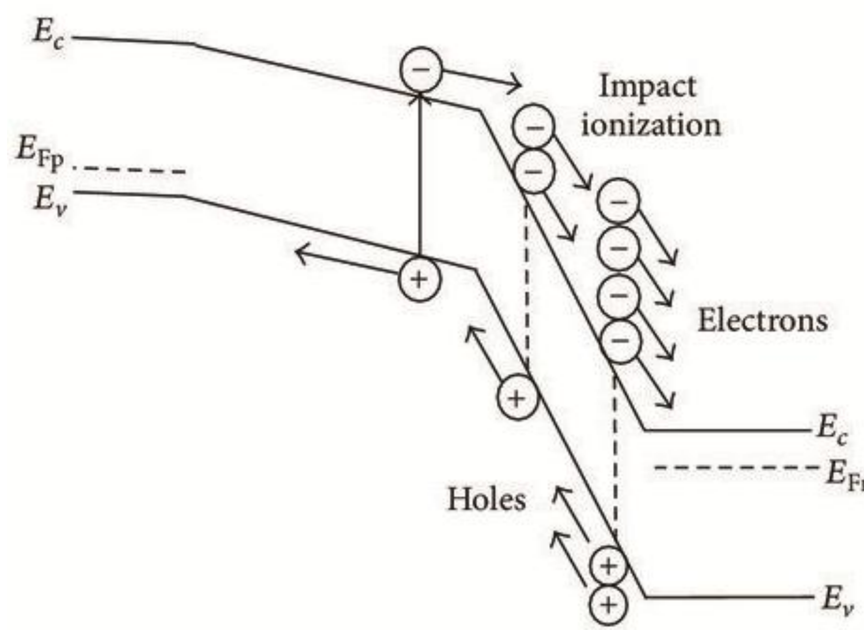
(b)

PN Junction Breakdown in Reverse Bias

Avalanche breakdown







PN Junction Breakdown in Reverse Bias

Avalanche breakdown

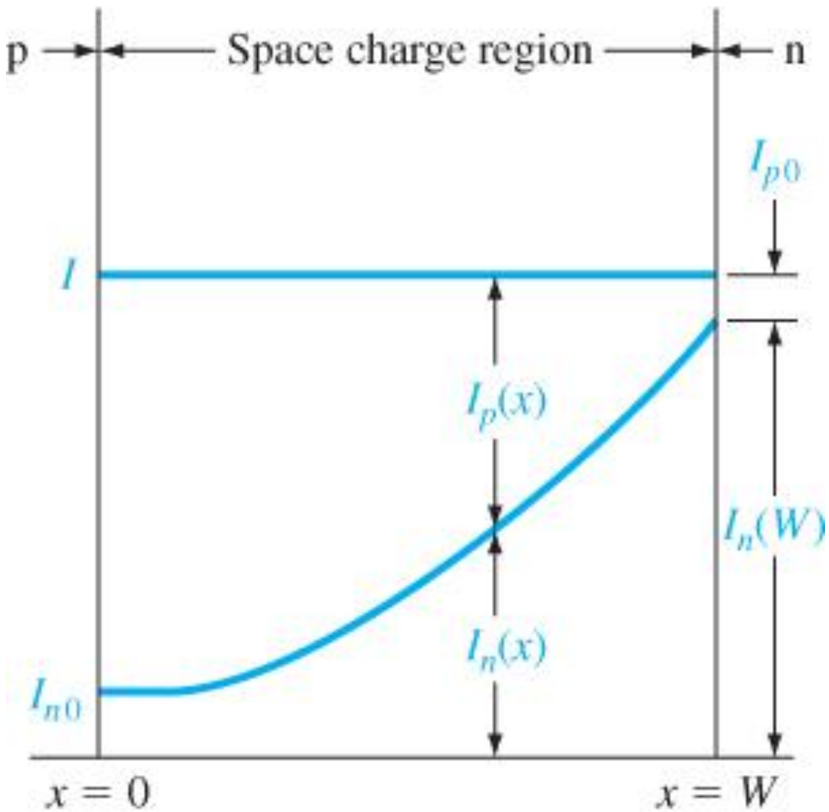
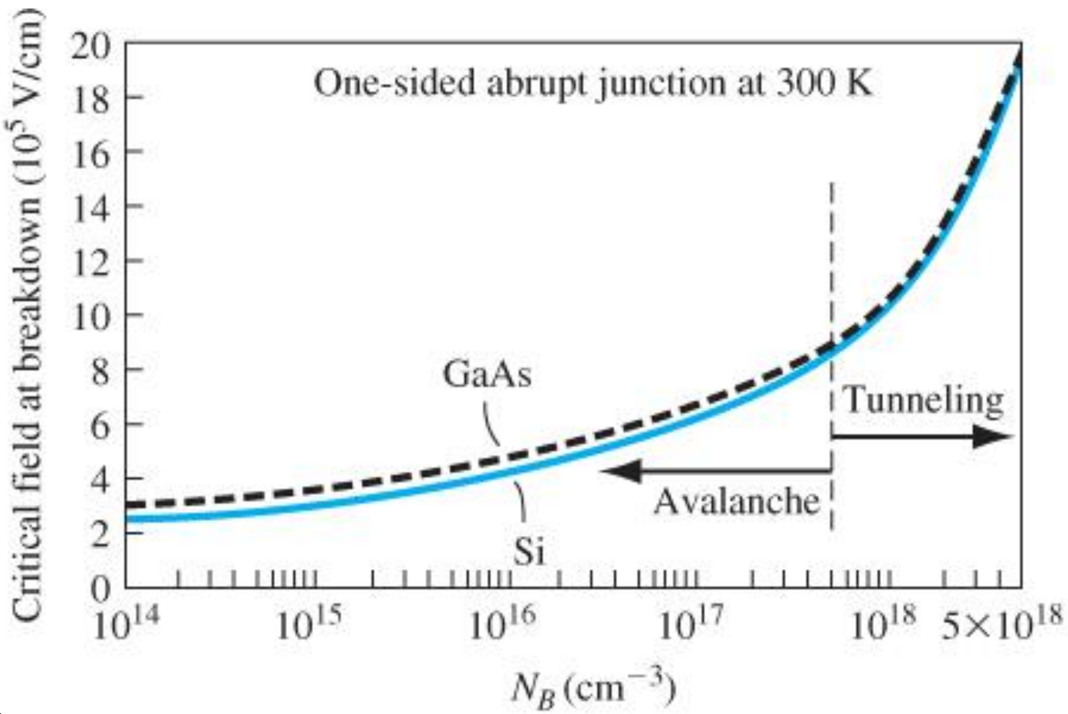


Figure 7.13 | Electron and hole current components through the space charge region during avalanche multiplication.

PN Junction Breakdown in Reverse Bias



$$E_{max} \cong -\frac{eN_d}{\varepsilon_s} x_n$$

$$x_n \approx \left\{\frac{2\varepsilon_s(V_{bi}+V_R)}{eN_d}\right\}^{1/2}$$

$$\approx \left\{\frac{2\varepsilon_s V_R}{eN_d}\right\}^{1/2} \qquad V_R \gg V_{bi}$$

Assume

$$|E_{max}| = E_{crit} \quad when \quad V_R = V_B \; in \; N_B \; doping \; concentration$$

Critical electric field **Breakdown voltage**

$$E_{crit} \cong \frac{eN_B}{\varepsilon_s}\left\{\frac{2\varepsilon_s V_B}{eN_B}\right\}^{\frac{1}{2}} = \left\{\frac{2eN_B V_B}{\varepsilon_s}\right\}^{\frac{1}{2}} \quad \Rightarrow \quad V_B = \frac{\varepsilon_s E^2{}_{crit}}{2eN_B}$$