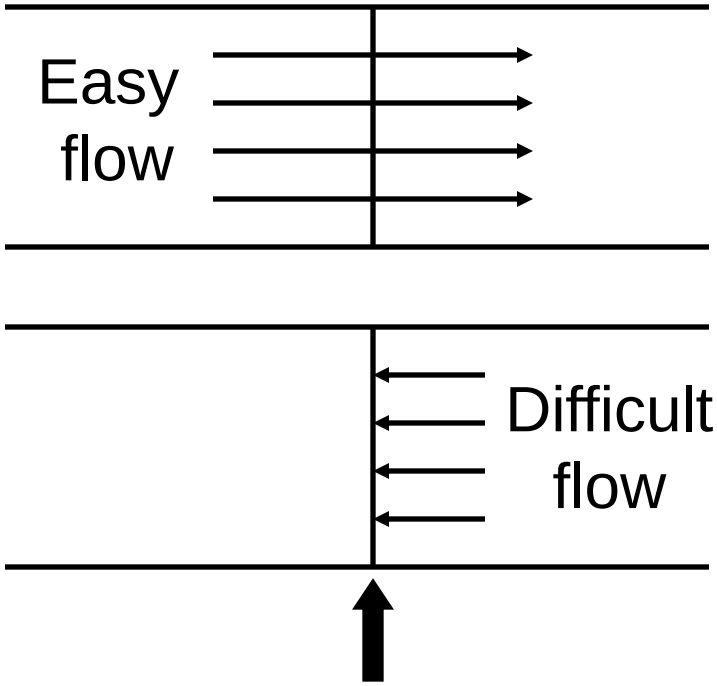
Diode Electrostatics

EECS 320

Introduction to Semiconductor Devices

Diode

- It is desirable to have a rectifying device
- i.e., A one way valve



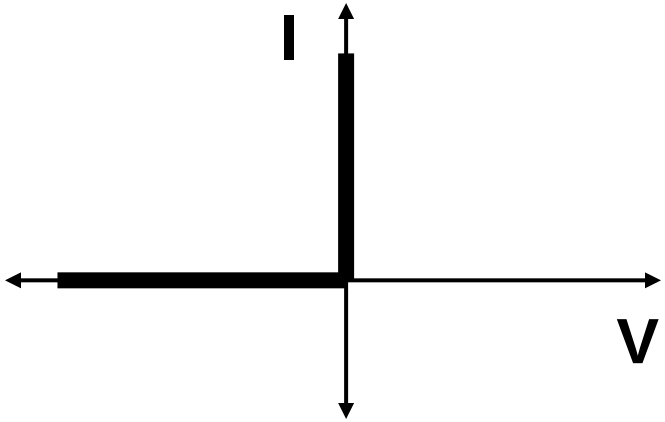
Forward direction

Reverse direction

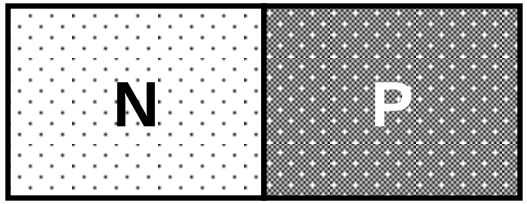
Need a physical junction for such a device

Diode

- For electronics, need a one way valve for current
- Ideal behavior:

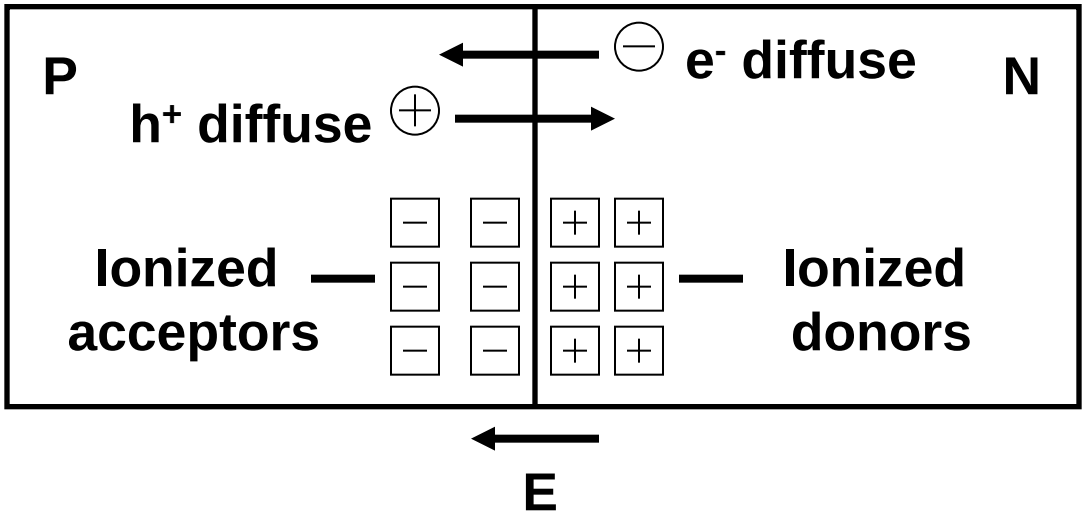


- How do we implement in a semiconductor?
- Vary spatial composition (e.g. doping)



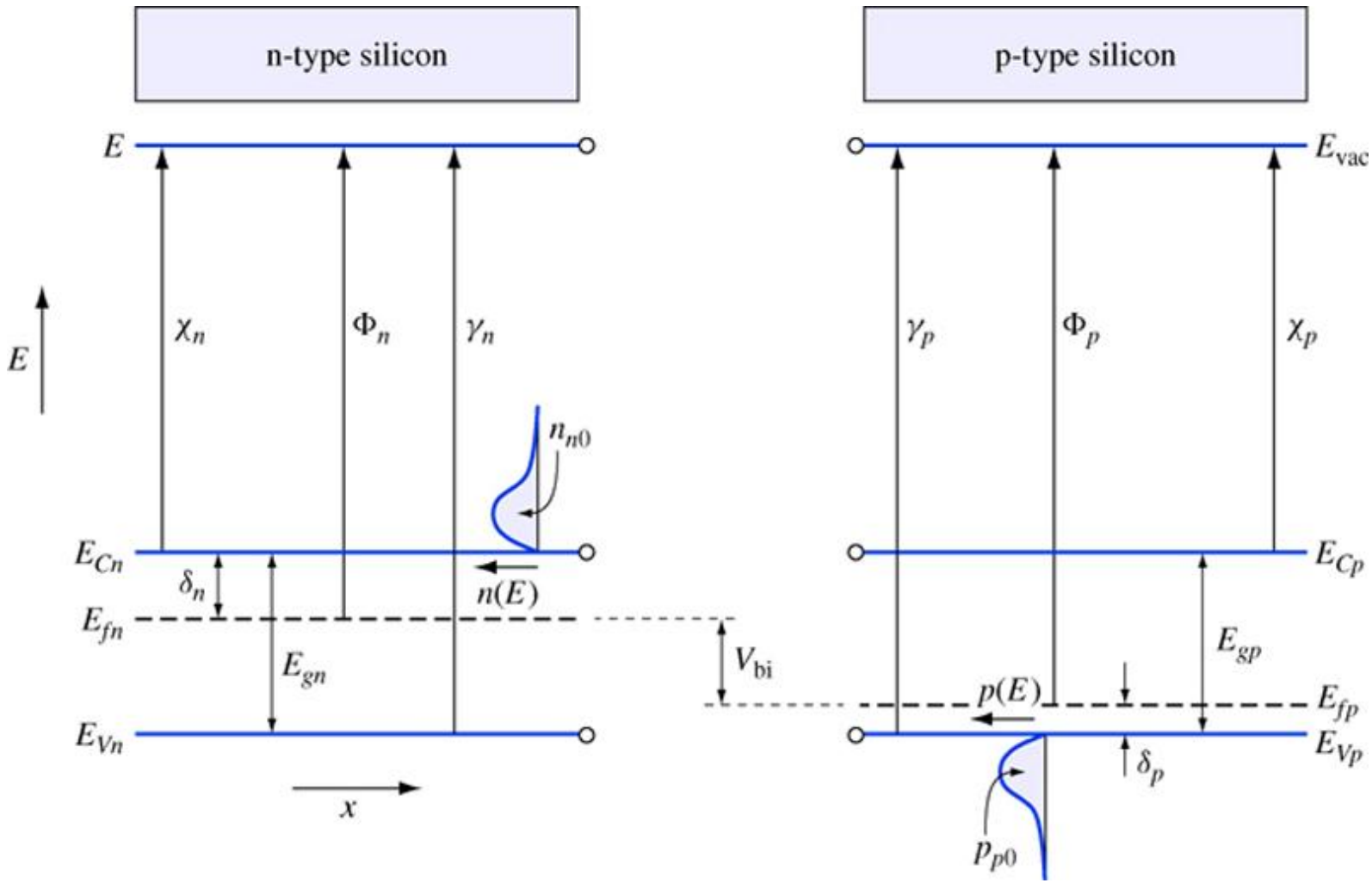
Joining P-type and N-type

What happens when you join p-type and n-type material?

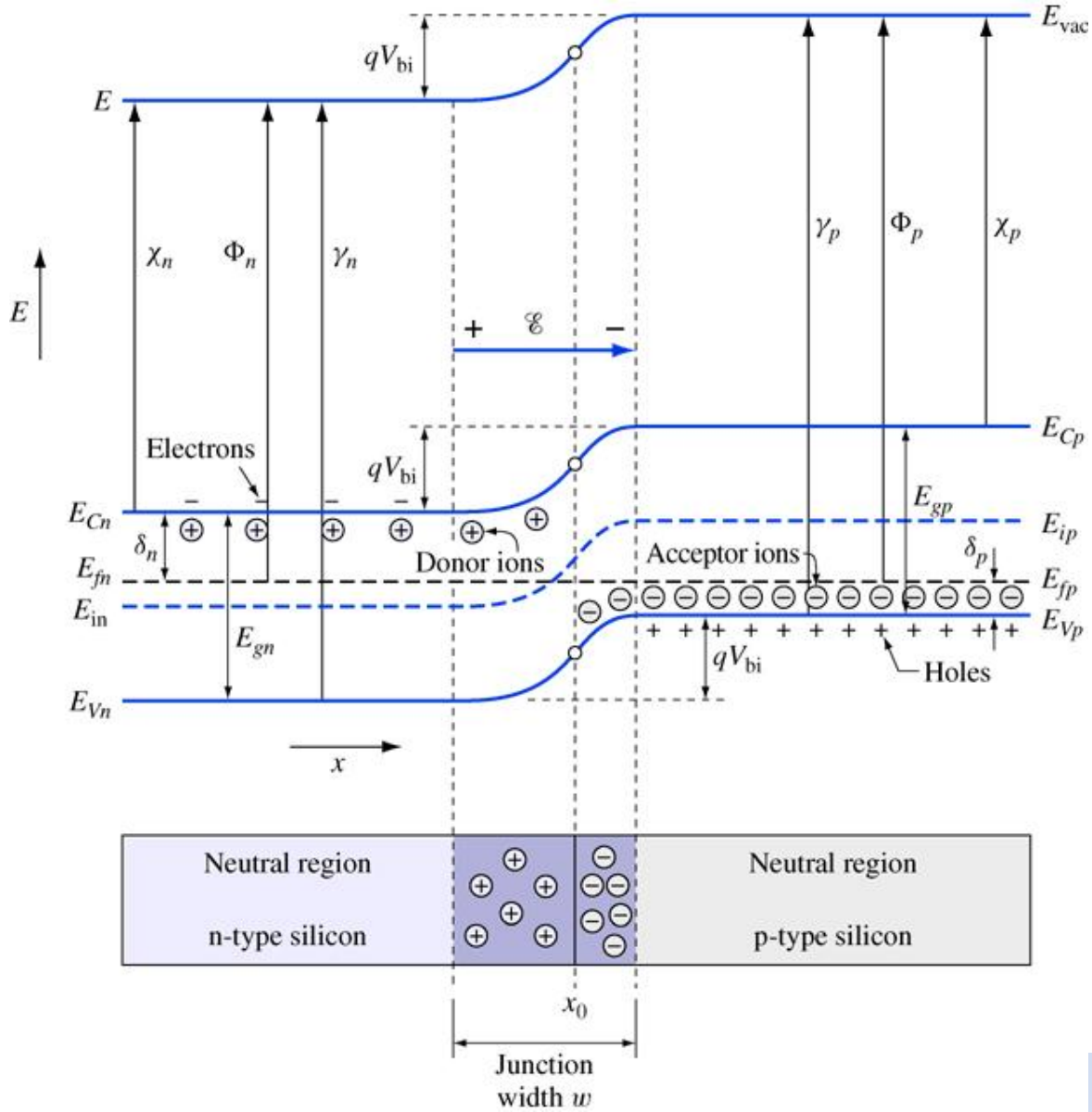


- Diffusion drives e's and h's to lower concentration regions
- Ionized dopants remain, creating an electric field
- Under equilibrium, diffusion and drift processes are balanced

Energy Band Picture

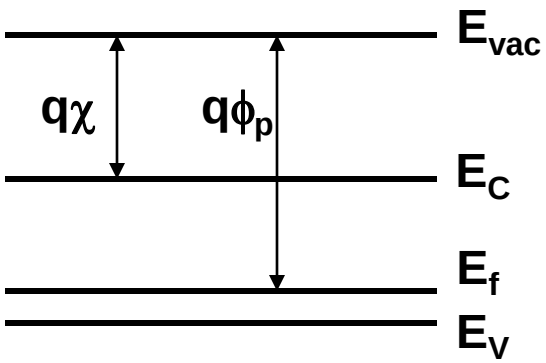


Energy Band in Equilibrium

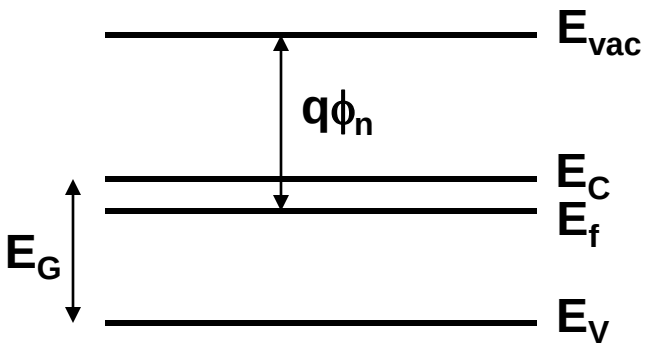


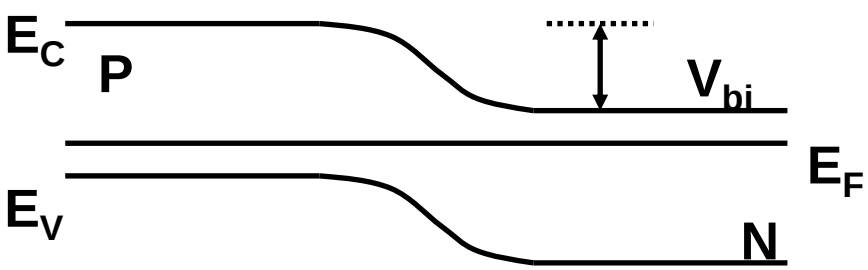
Energy Band Diagram

p-type

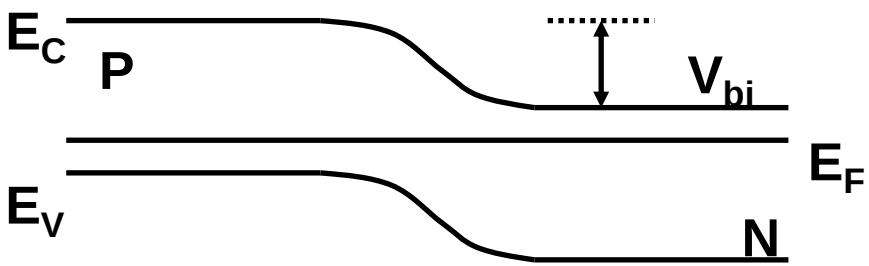


n-type





Built-In Potential



$$qV_{bi} = E_G - (E_C - E_F)_n - (E_F - E_V)_p$$

$$(E_C - E_F)_n = kT \ln\left(\frac{N_D}{N_C}\right)$$

$$(E_F - E_V)_p = -kT \ln\left(\frac{N_A}{N_V}\right)$$

$$n_i^2 = N_C N_V \exp\left(-\frac{E_G}{kT}\right)$$

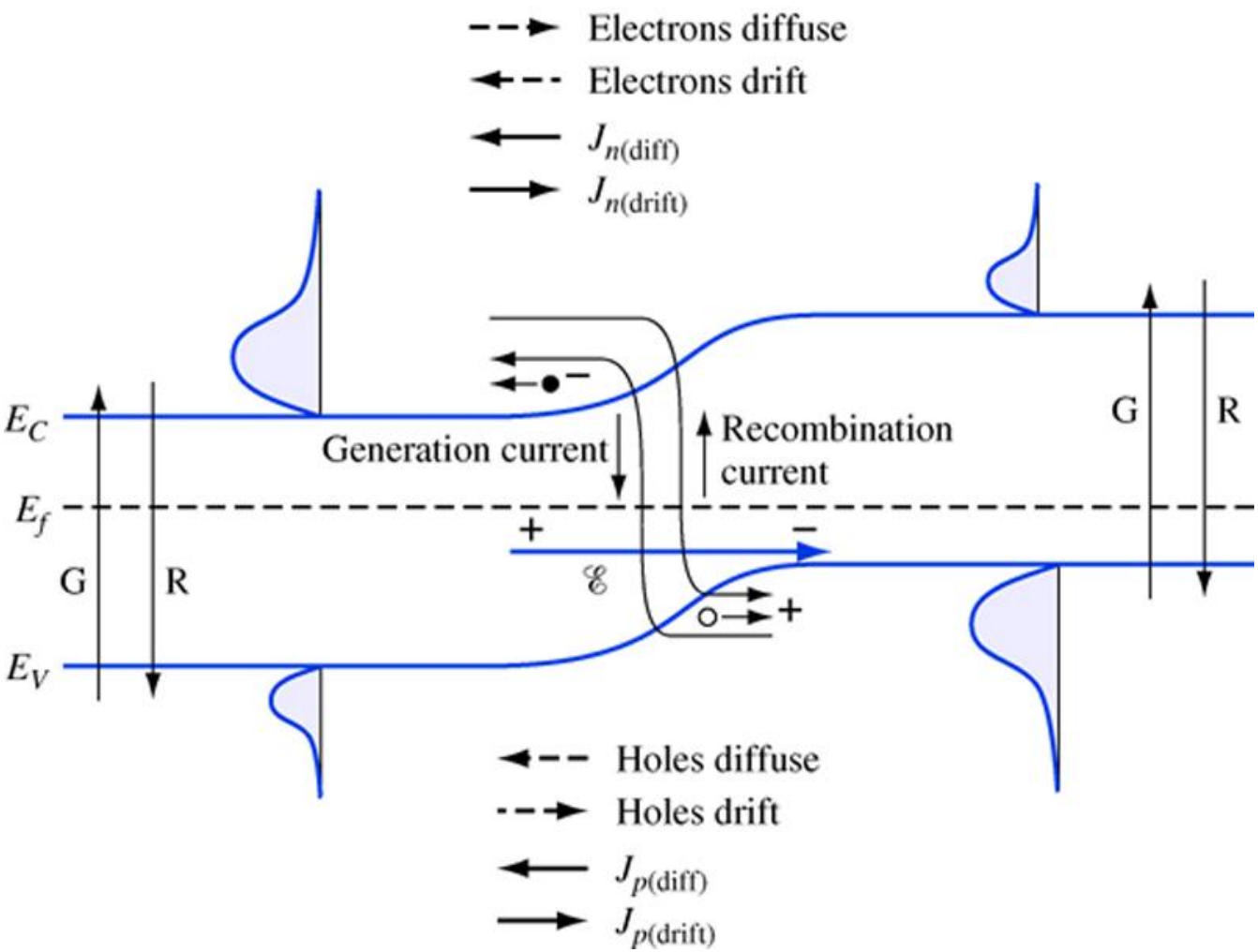
$$\boxed{V_{bi} = \frac{kT}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)}$$

Built-In Voltage

In one sentence, describe the origin of V_{bi}

In one sentence, describe the meaning of V_{bi}

Current Flow in P-N Junction (Equilibrium)

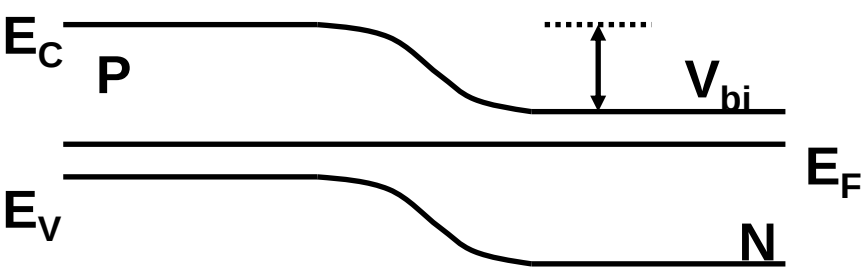


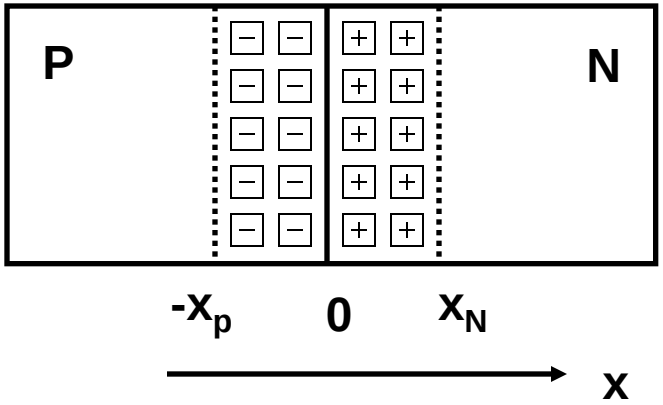
The Depletion Approximation

- Analyze p-n junction using electrostatics (Poisson's equation)
- Depletion approximation – no mobile charge in depletion region, only fixed charge from the ionized impurities

Examining the energy band diagram, is this true?

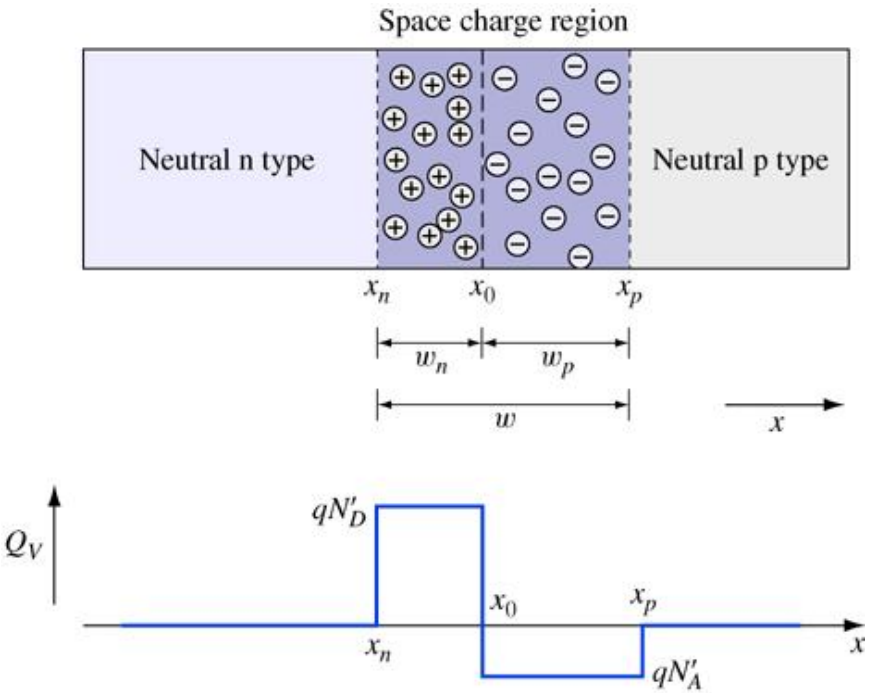
Sketch the carrier concentrations in the depletion region

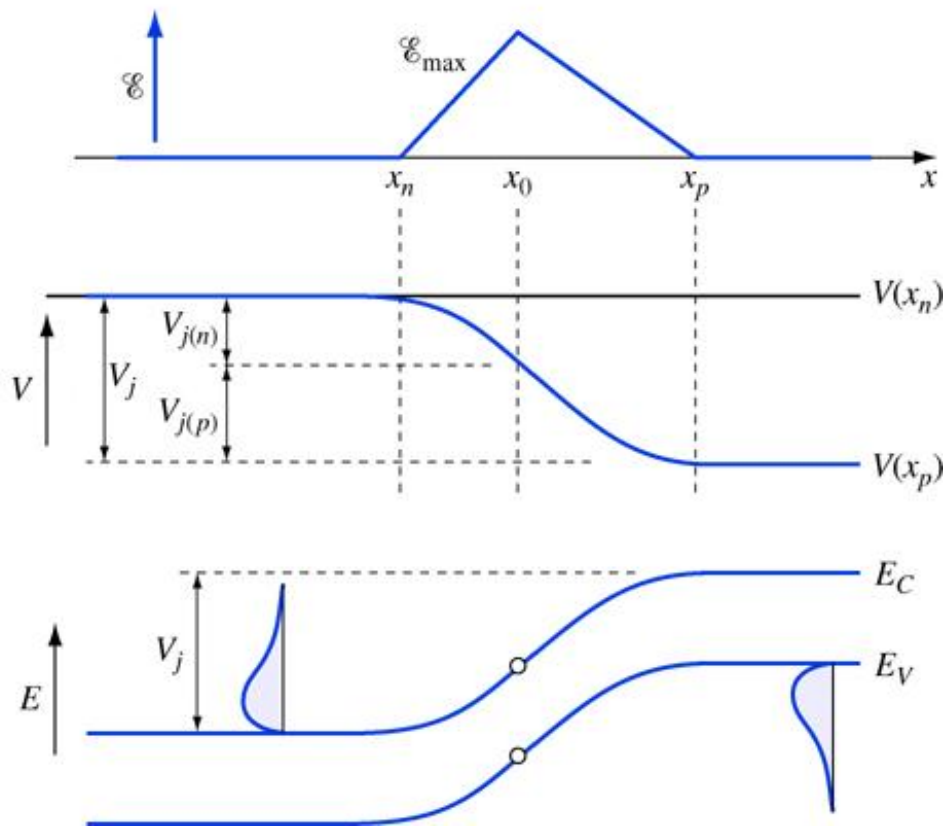




Electrostatics

Use Poisson's equation to quantify space charge region





$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$

Depletion Region

- Analyze p-n junction using electrostatics (Poisson's equation)
- Depletion approximation – no mobile charge in depletion region

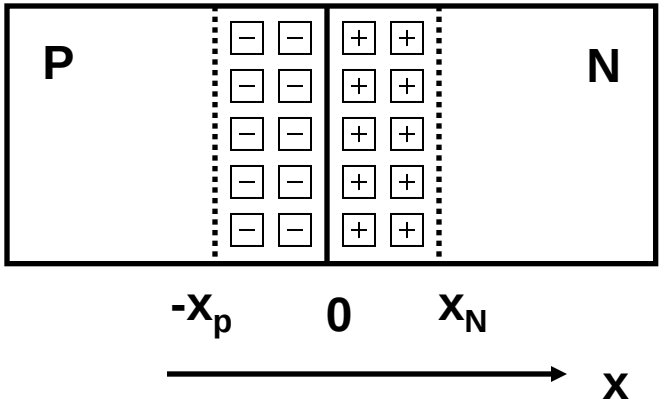
$$\frac{d^2V}{dx^2} = 0, \qquad -\infty < x < -x_P$$

$$\frac{d^2V}{dx^2} = \frac{qN_A}{\varepsilon}, \qquad -x_P < x < 0$$

$$\frac{d^2V}{dx^2} = -\frac{qN_D}{\varepsilon}, \qquad 0 < x < x_N$$

$$\frac{d^2V}{dx^2} = 0, \qquad x_N < x < \infty$$

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$



Electric Field In Depletion Region

- Electric Field

$$F(x) = -\frac{qN_A}{\varepsilon}(x + x_P) \qquad -x_P < x < 0$$

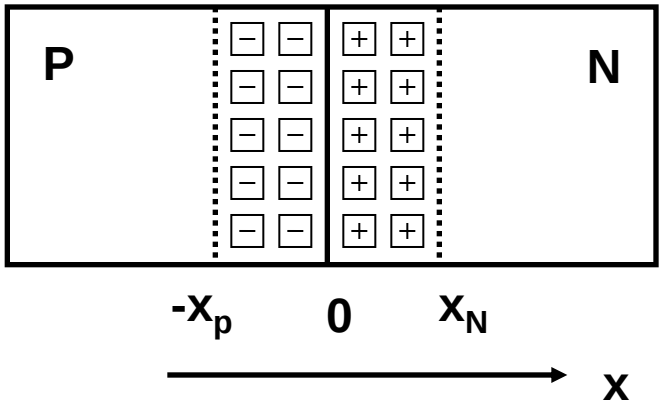
$$F(x) = -\frac{qN_D}{\varepsilon}(x_N - x) \qquad 0 < x < x_N$$

$$F(x) = 0 \quad \text{elsewhere}$$

- At x=0, field must be continuous

$$F(0) = -\frac{qN_D}{\varepsilon}(x_N) = -\frac{qN_A}{\varepsilon}(x_P)$$

$$N_D x_N = N_A x_P$$



Built-In Potential In Depletion Region

- Electrostatic potential, integrate electric field

$$V(x) = V_P \qquad -\infty < x < -x_P$$

$$V(x) = \frac{qN_A}{2\varepsilon}\left(x + x_P\right)^2 + V_P \qquad -x_P < x < 0$$

$$V(x) = -\frac{qN_D}{2\varepsilon}\left(x_N - x\right)^2 + V_N \qquad 0 < x < x_N$$

$$V(x) = V_N \qquad x_N < x < \infty$$

$$V(x_N) - V(0) = \frac{qN_D}{2\varepsilon}\left(x_N\right)^2$$

$$V(0) - V(-x_P) = \frac{qN_A}{2\varepsilon}\left(x_P\right)^2$$

$$V(x_N) - V(-x_P) = \frac{qN_D x_N^{\ 2}}{2\varepsilon} + \frac{qN_A x_P^{\ 2}}{2\varepsilon}$$

$$\boxed{V_{bi} = \text{built in potential}}$$

Built-In Potential In Depletion Region

- Electrostatic potential, integrate electric field

$$V_{bi} = V(x_N) - V(-x_P) = \frac{qN_D x_N^{\ 2}}{2\varepsilon} + \frac{qN_A x_P^{\ 2}}{2\varepsilon}$$

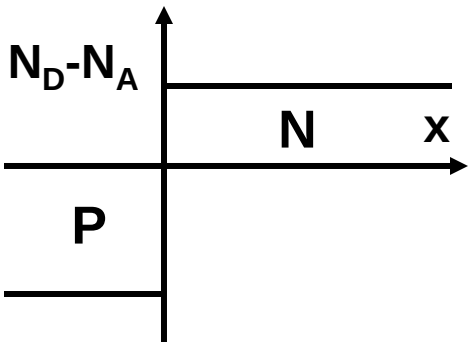
$$N_D x_N = N_A x_P \longrightarrow \text{charge neutrality}$$

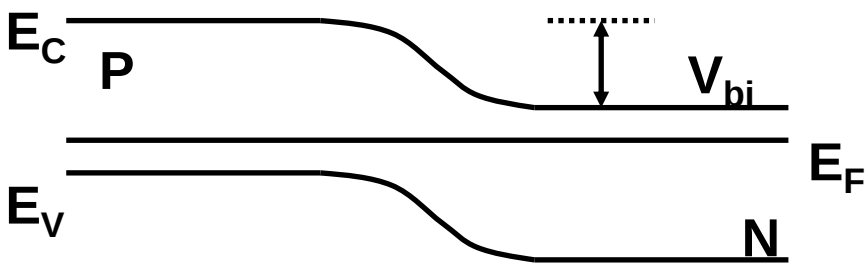
$$x_P(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left[\frac{N_D}{N_A(N_A + N_D)}\right]}$$

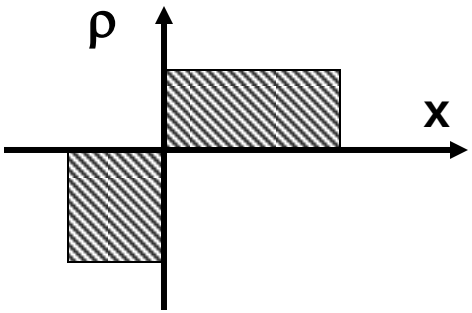
$$x_N(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left[\frac{N_A}{N_D(N_A + N_D)}\right]}$$

$$\boxed{W(V_{bi}) = x_P(V_{bi}) + x_N(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}}$$

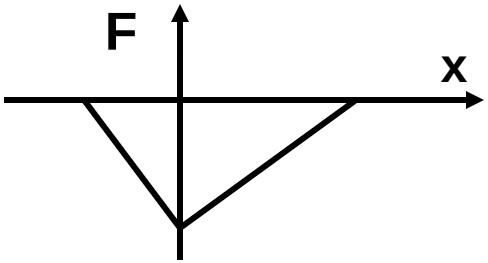
Electrostatics Summary







$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$$



$$W(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$