ECE 340: Semiconductor Electronics

Review: Chapter 5 and 8

Solid State Electronic Devices (Streetman): § 5, § 8

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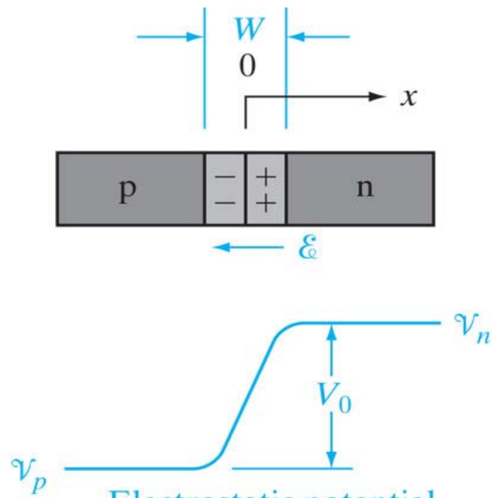
Outline

- Chapter 5: junctions
  - Equilibrium Condition
  - Forward- and reverse-biased junctions; steady state conditions
  - Reverse-bias breakdown
  - Transient and a-c conditions
- Chapter 8: optoelectronic devices
  - Solar Cell
  - Photodetector
  - Light-Emitting Diodes
  - Semiconductor Lasers

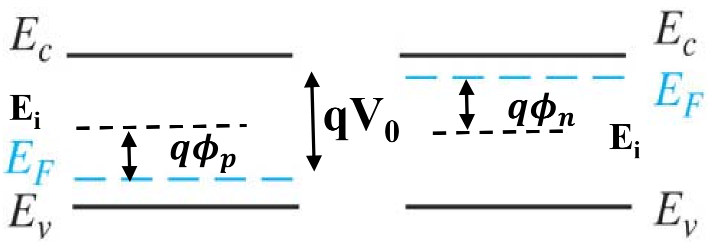
Form PN junction

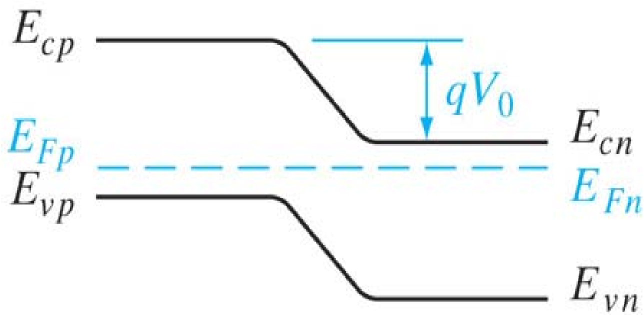
Isolated n and p region

pn junction at equilibrium



Electrostatic potential

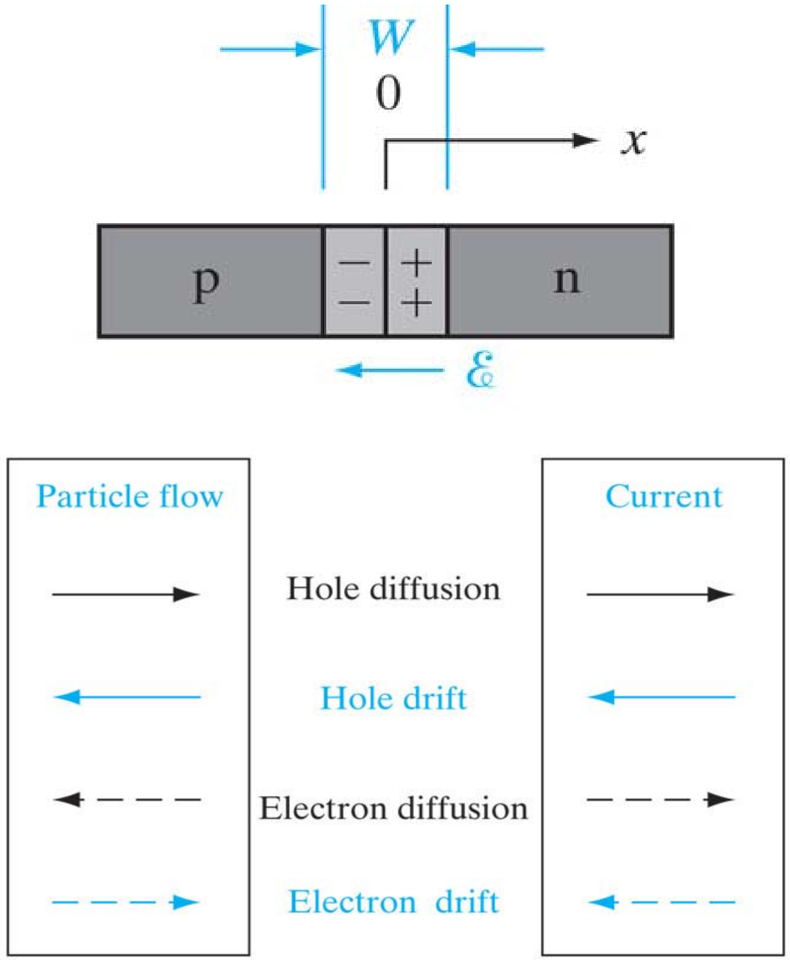




Energy bands

Built-in potential $$V_0 = \frac{kT}{q} ln\left(\frac{N_a N_d}{n_i^2}\right)$$ $$V_0 = \phi_n + \phi_p$$

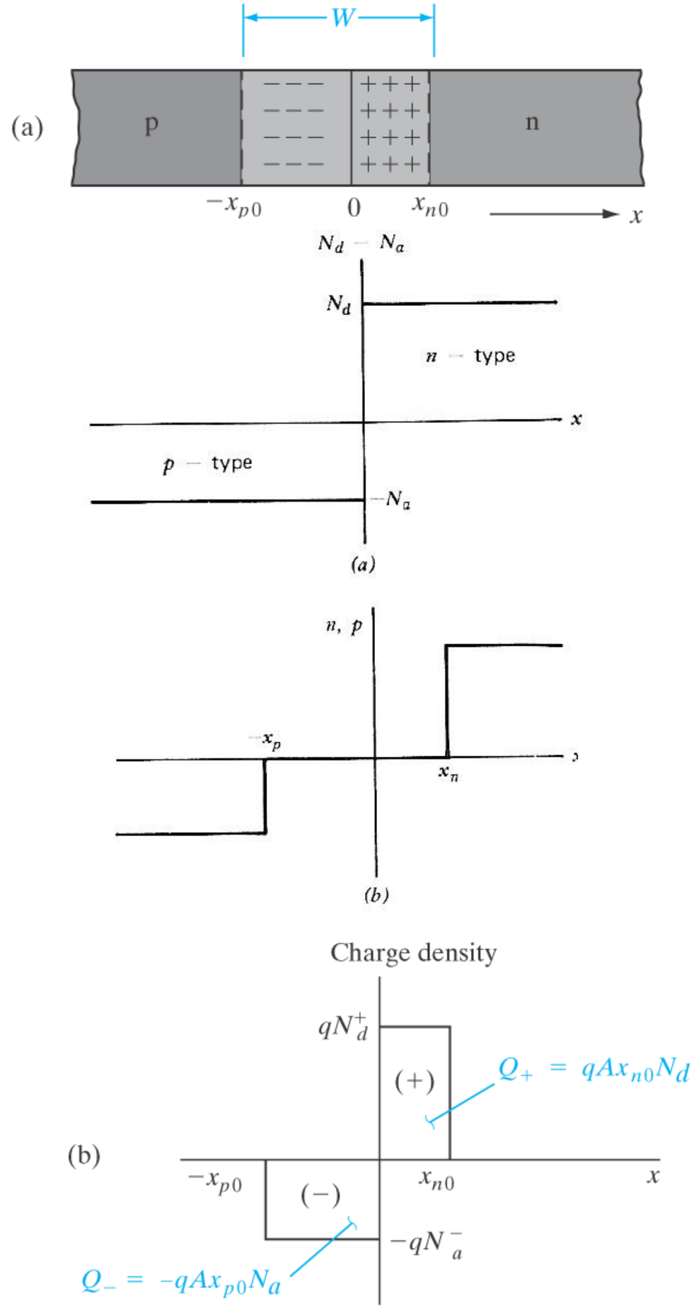
pn junction at equilibrium carrier flow



Space charge at a junction

- Depletion approximation: assumption of carrier depletion within W and neutrality outside W.

$$\boxed{x_{p0}N_a = x_{n0}N_d}$$



Electric field

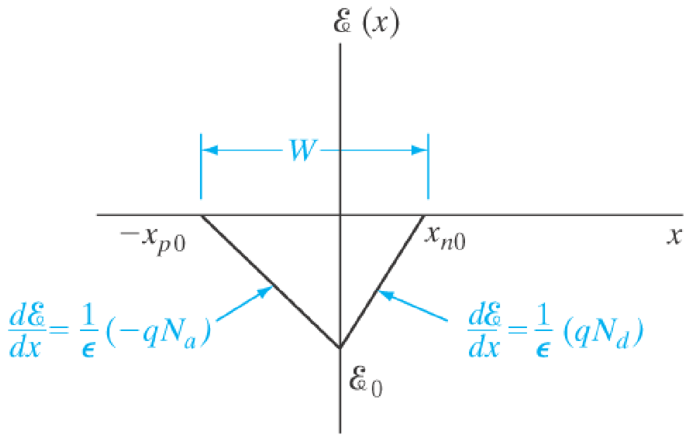
- Poisson's equation:

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$$

- If neglect the contributions of carriers in space charge, and assume complete ionization of impurities:

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}N_d \qquad 0 < x < x_{n0}$$

$$\frac{d\mathcal{E}(x)}{dx} = -\frac{q}{\epsilon}N_a \qquad -x_{p0} < x < 0$$



Built-in electric field

Built-in field:

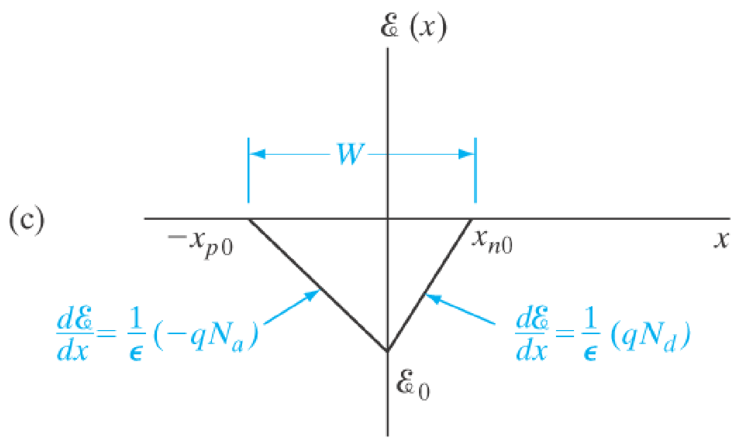
$$\mathcal{E}(x) = -\frac{qN_d}{\epsilon}(x_{n0} - x) \quad 0 < x < x_{n0}$$

$$\mathcal{E}(x) = -\frac{qN_a}{\epsilon}(x_{p0} + x) \quad -x_{p0} < x < 0$$

- The maximum electric field located at the interface of n and p junction (x=0):

$$\Rightarrow \quad \mathcal{E}_0 = -\frac{q}{\epsilon}N_d x_{n0} = -\frac{q}{\epsilon}N_a x_{p0}$$

maximum electric field



Potential

$$\frac{dV(x)}{dx} = -\mathcal{E}(x)$$

- Potential variation across the junction:

$$V(x) = \phi_n - \frac{qN_d}{2\epsilon_s}(x_n - x)^2 \qquad 0 < x < x_{n0}$$

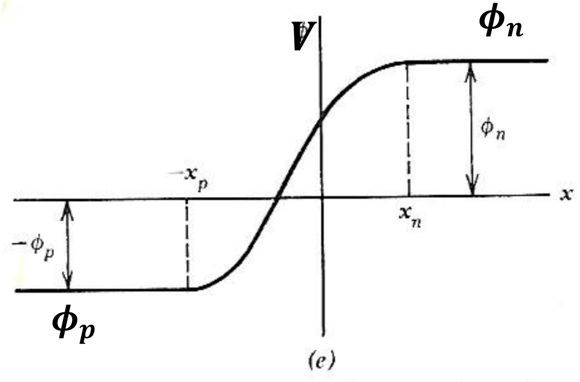
$$V(x) = \phi_p - \frac{qN_a}{2\epsilon_s}(x + x_p)^2 \qquad -x_{p0} < x < 0$$

where $\phi_n = \frac{kT}{q} ln \frac{N_d}{n_i}$

$$\phi_p = \frac{kT}{q} ln \frac{N_a}{n_i}$$

- Built-in variation:

$$V_0 = \phi_n + \phi_p = \frac{kT}{q} ln \frac{N_d N_a}{n_i}$$



Depletion width and penetration depth

$$\boldsymbol{V_0} = -\frac{\mathbf{1}}{\mathbf{2}}\mathcal{E}_0 W = \frac{\mathbf{1}}{\mathbf{2}}\frac{q}{\epsilon}N_d x_{n0} W$$

Depletion width

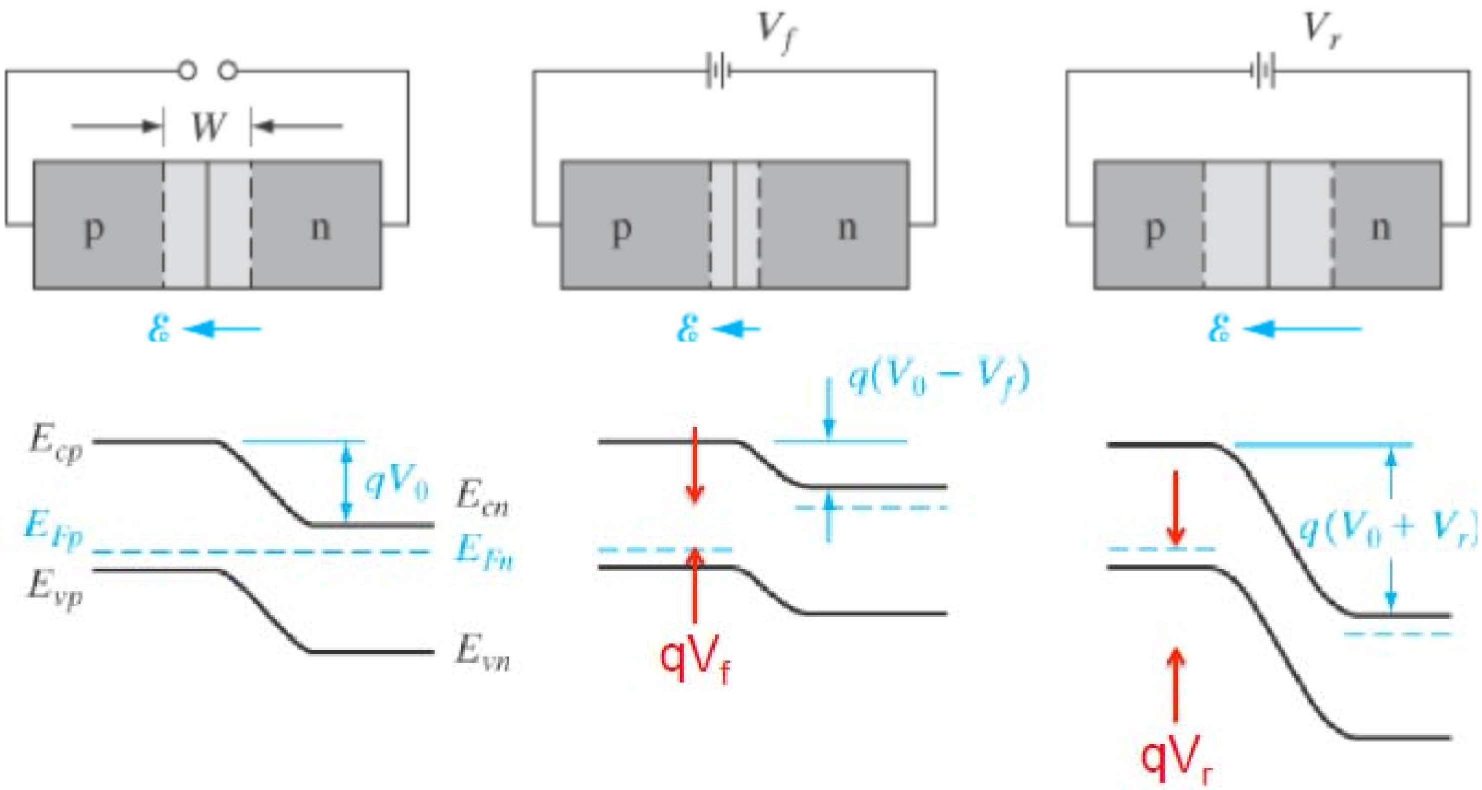
$$\boldsymbol{W} = \left[\frac{\mathbf{2}\epsilon \boldsymbol{V_0}}{q}\left(\frac{N_a+N_d}{N_a N_d}\right)\right]^{\mathbf{1/2}} = \left[\frac{\mathbf{2}\epsilon \boldsymbol{V_0}}{q}\left(\frac{\mathbf{1}}{N_d}+\frac{\mathbf{1}}{N_a}\right)\right]^{\mathbf{1/2}}$$

penetration depth

$$x_{p0} = W\frac{N_d}{N_a + N_d}$$

$$x_{n0} = W\frac{N_a}{N_a + N_d}$$

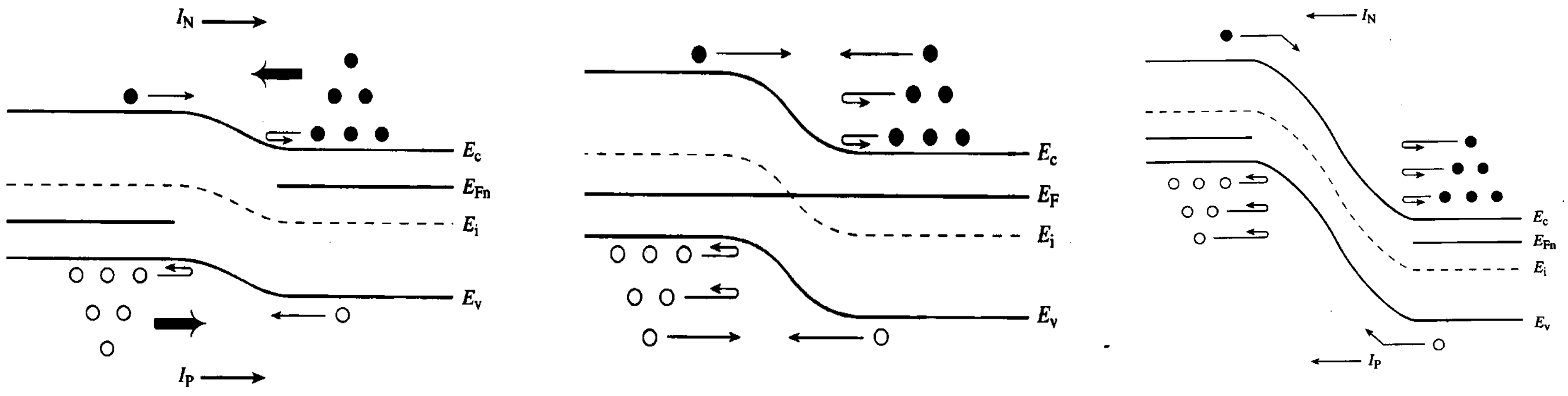
Bias, depletion width, and quasi-Fermi level

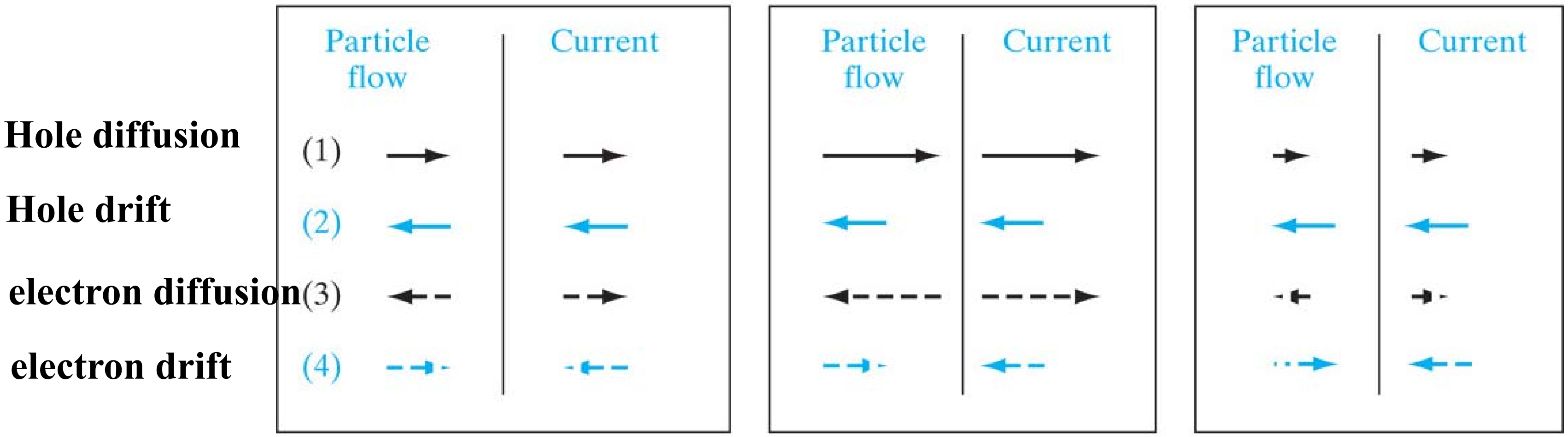


$$W = \sqrt{\frac{2\epsilon(V_0 - V_a)}{q}\left(\frac{1}{N_d} + \frac{1}{N_a}\right)}$$

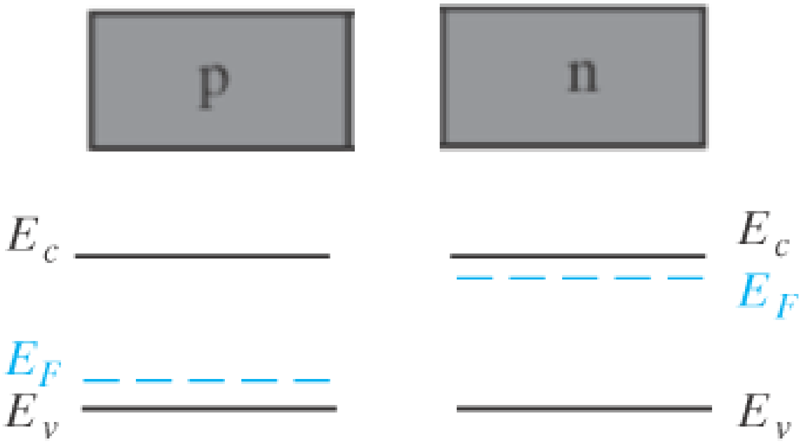
Current flow in pn junction:

Forward bias **Equilibrium** **Reverse bias**



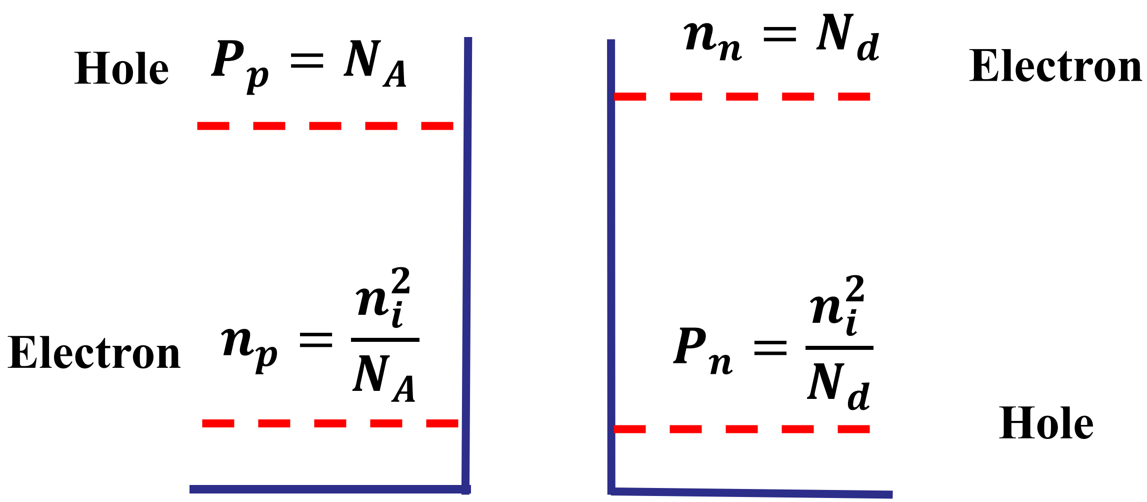


P and n region before contact

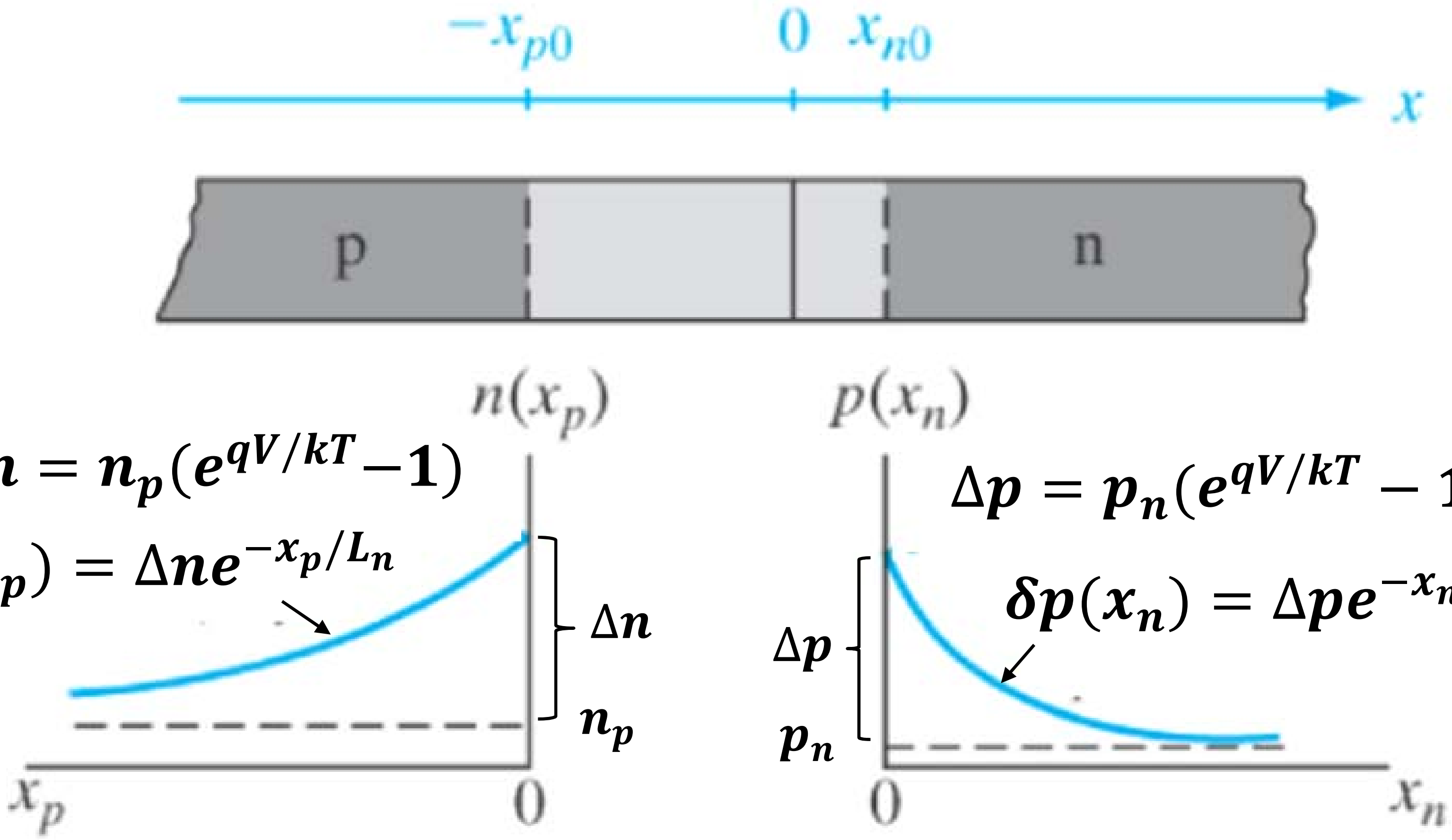


Majority carrier:

Minority carrier:



Forward bias, minority carrier diffusion



$$\Delta n = n_p(e^{qV/kT} - 1)$$

$$\delta n(x_p) = \Delta n e^{-x_p/L_n}$$

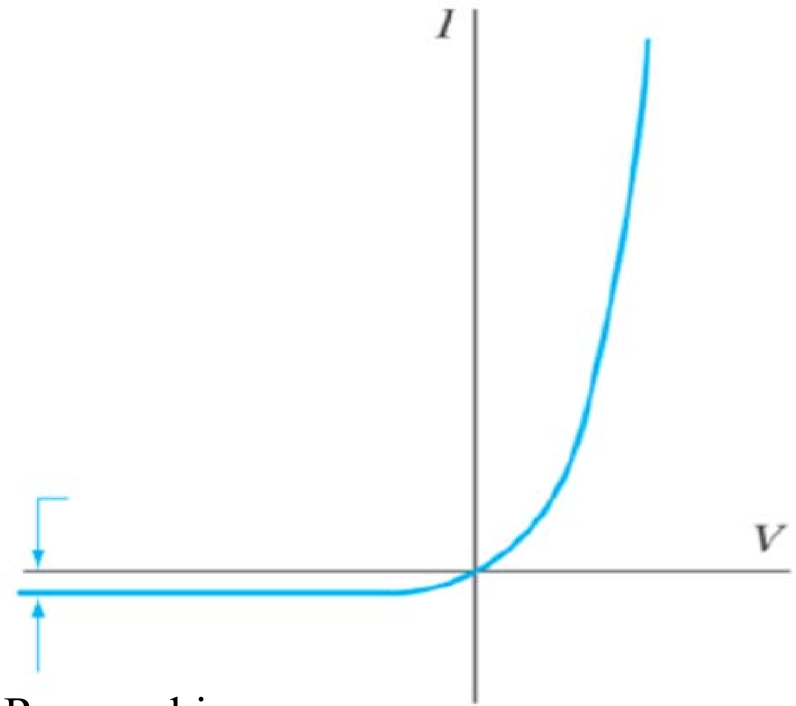
$$\Delta p = p_n(e^{qV/kT} - 1)$$

$$\delta p(x_n) = \Delta p e^{-x_n/L_p}$$

$$I_n(x_p = 0) = -qA\frac{D_n}{L_n} n_p(e^{qV/kT} - 1)$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p} p_n(e^{qV/kT} - 1)$$

Diode equation: various scenarios



Reverse bias

$$V = -V_r$$

$$I \approx -\boldsymbol{I_0}$$

$$I = \boldsymbol{I_0\left(e^{qV/kT} - 1\right)}$$

where $I_0 = qA\left(\frac{D_p}{L_p}\boldsymbol{p_n} + \frac{D_n}{L_n}\boldsymbol{n_p}\right)$

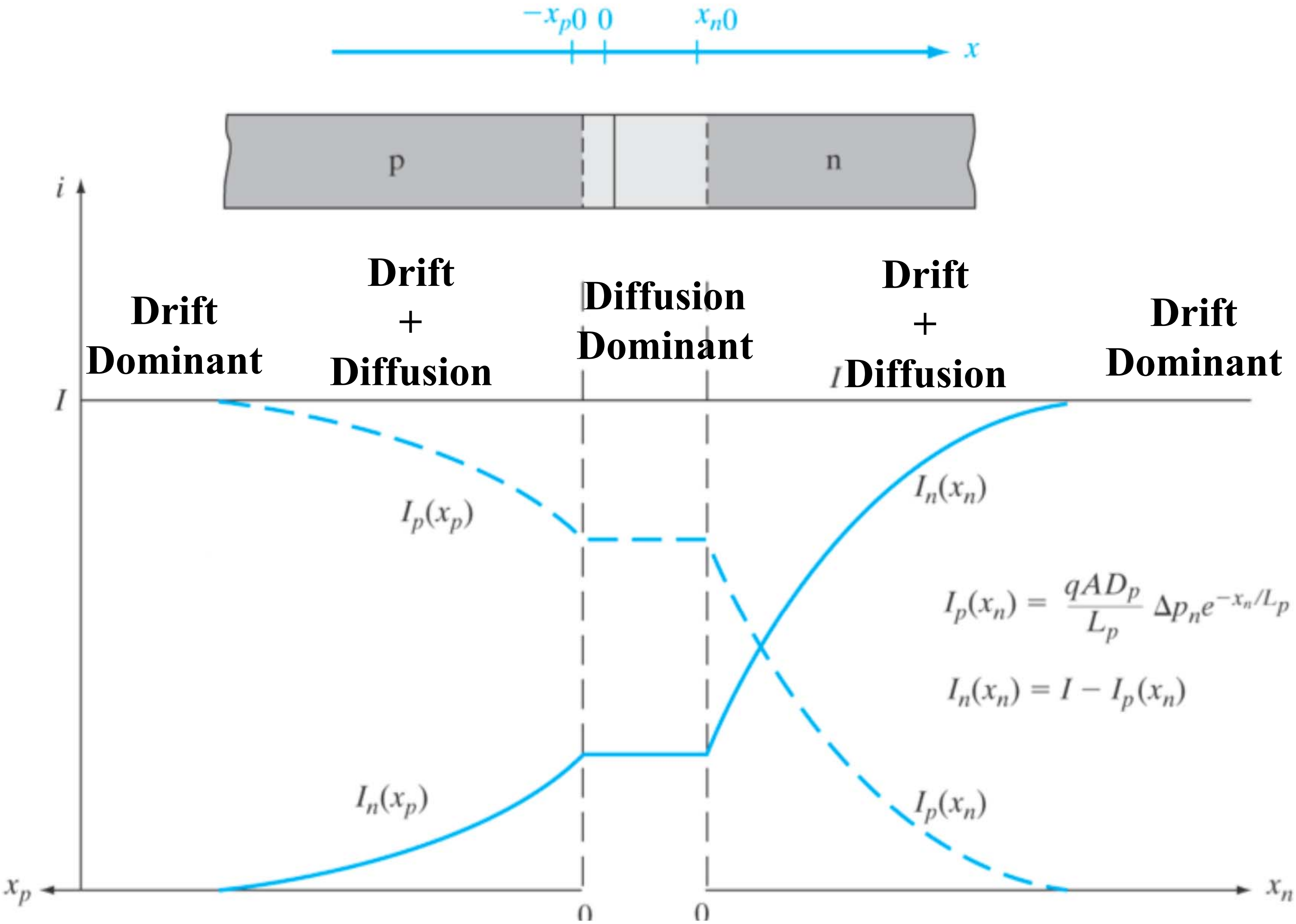
(a) p+-n junction: $\boldsymbol{p_n} \gg \boldsymbol{n_p}$

$$I_0 = qA\frac{D_p}{L_p}\boldsymbol{p_n}$$

(b) p-n+ junction: $\boldsymbol{p_n} \ll \boldsymbol{n_p}$

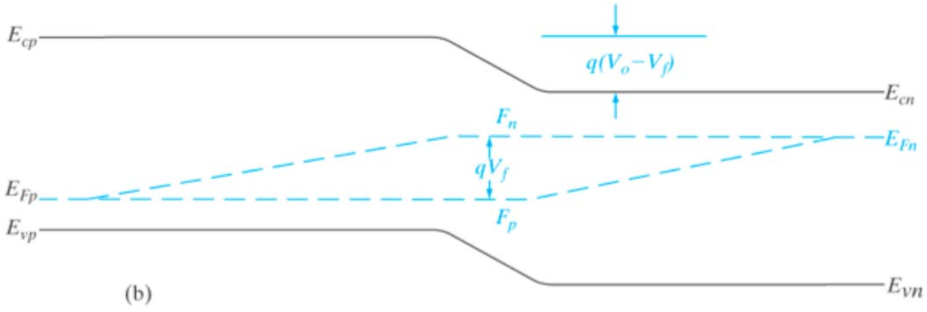
$$I_0 = qA\frac{D_n}{L_n}\boldsymbol{n_p}$$

Drift and diffusion in forward bias



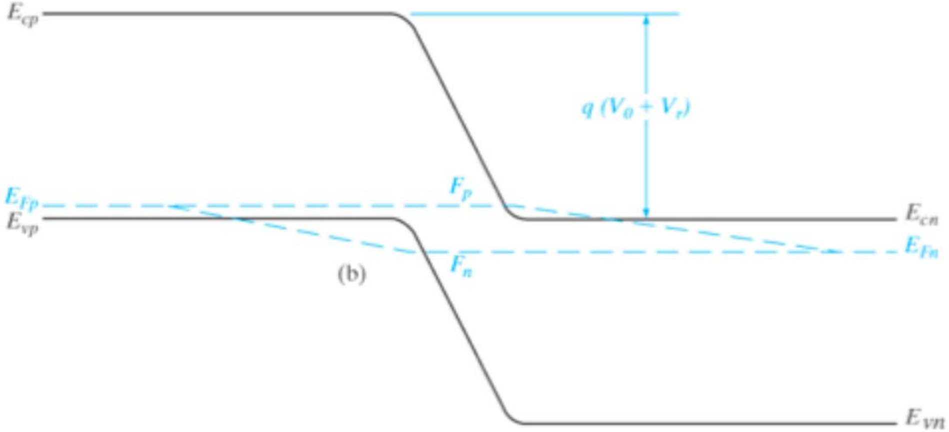
Quasi-Fermi level

Forward bias



$$pn = n_i^2 e^{(qV/kT)}$$

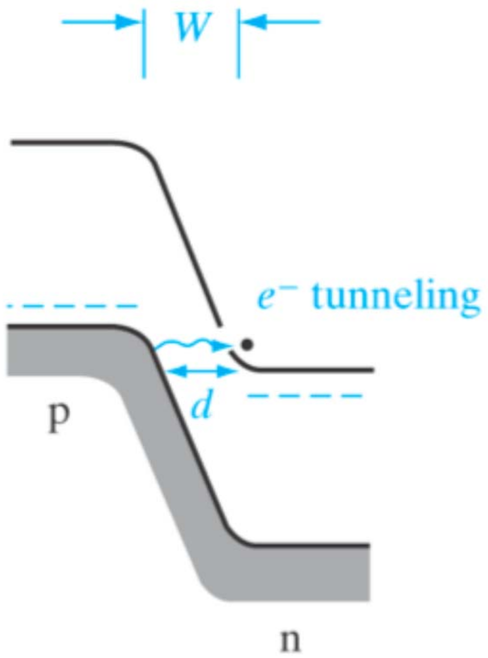
Reverse bias



$$pn = n_i^2 e^{(F_n - F_p)/kT} \approx 0$$

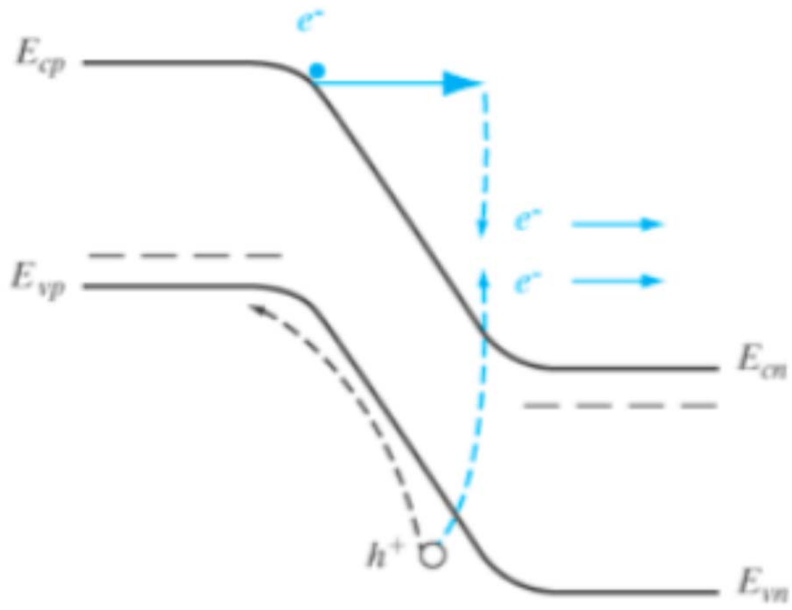
Zener breakdown

Zener breakdown



- **High doping**
- **Occurs at low voltages**

Avalanche breakdown

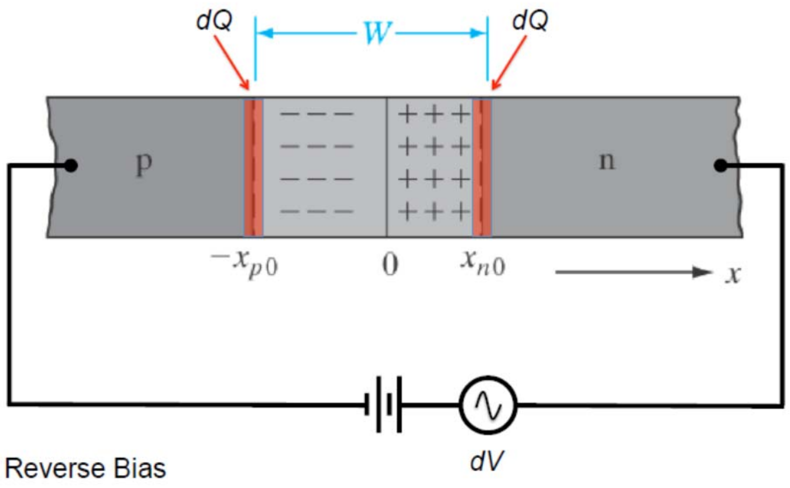


- **Low doping**
- **Occurs at high voltages**

pn junction capacitance

Junction capacitance

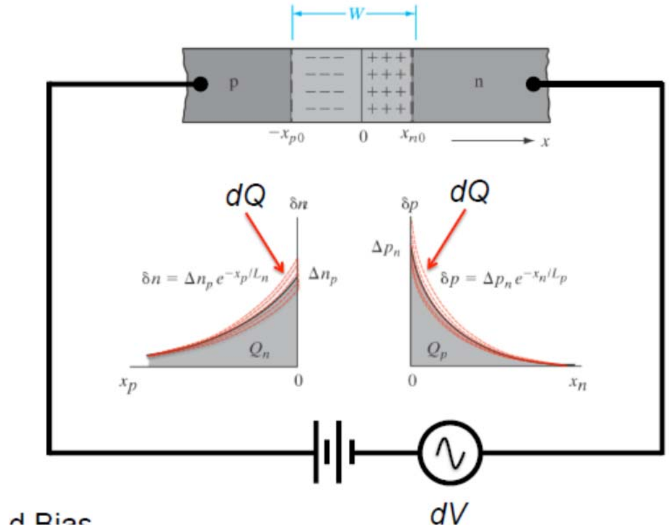
Reverse bias



$$C_j = A\sqrt{\frac{q\epsilon}{2(V_0 - V)}\frac{N_d N_a}{N_a + N_d}} = \frac{\epsilon A}{W}$$

Diffusion capacitance (Charge storage capacitance)

Forward bias

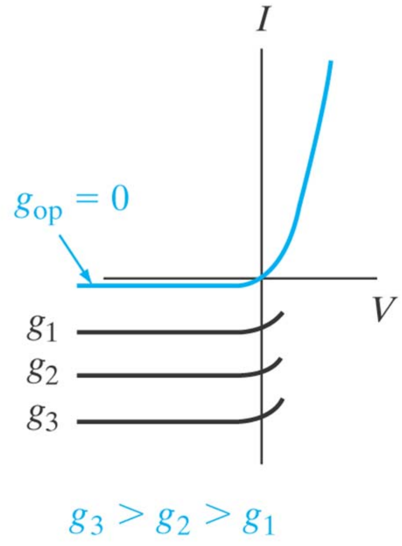


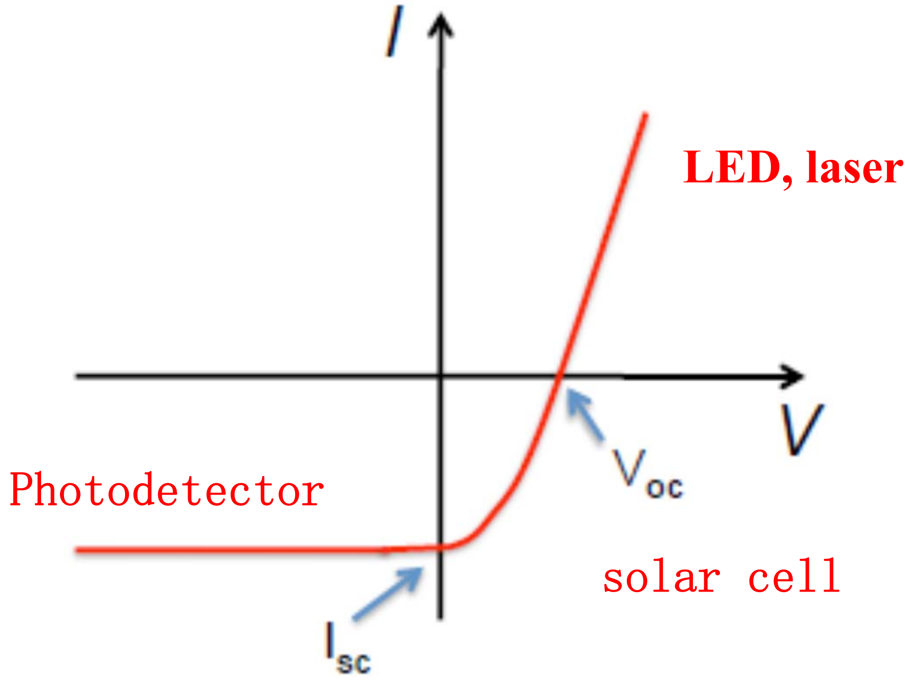
$$C_s = \frac{dQ_p}{dV} \approx \frac{q}{kT} Q_p$$

Current in an illuminated junction

- The total reverse current with illumination

$$I = I_{th}\,(e^{qV/kT} - 1) - I_{op}$$





Solar cell figure-of-merit

- Maximum power :

$$P_m = I_m V_m$$

- Fill factor:

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

- Efficiency: $$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc} V_{oc} FF}{P_{in}}$$

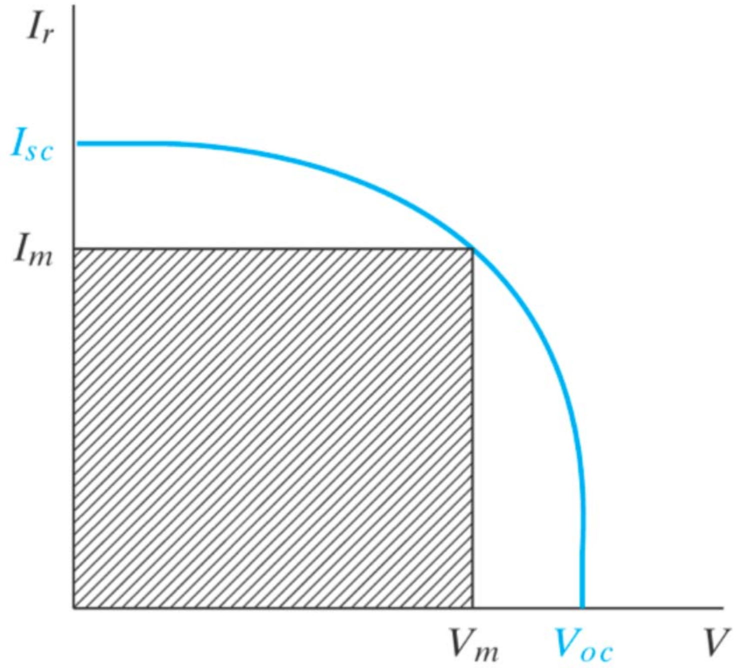


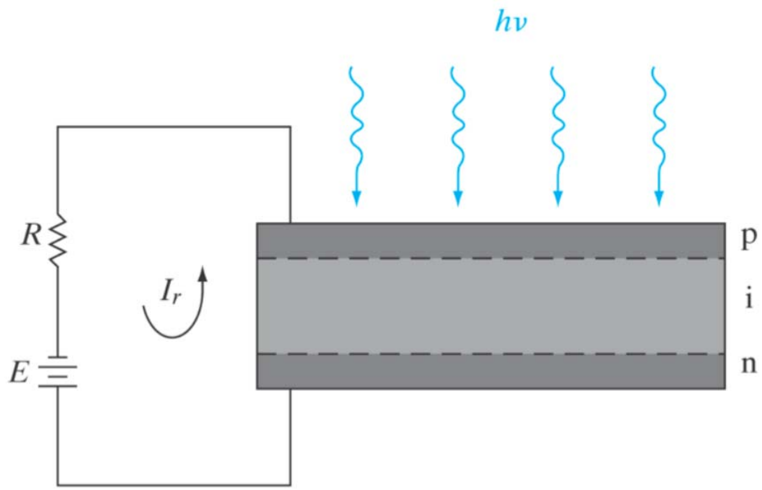
Figure of merit for photodetector

- Internal quantum efficiency:

$$\eta_{in} = \frac{EHP}{P_{op}/h\nu}$$

- External quantum efficiency:

$$\eta_{ext} = \frac{J_{op}/q}{P_{op}/h\nu}$$



- Maximum response frequency

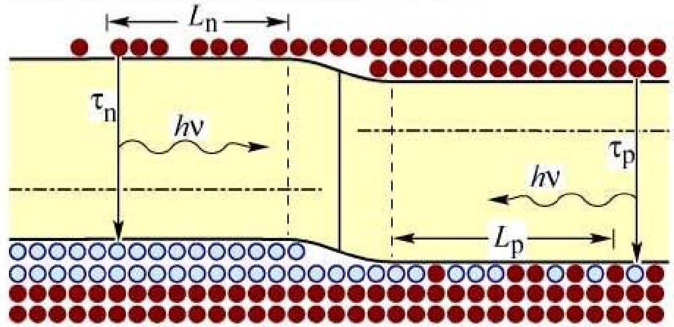
$$f_{max} \approx \frac{1}{transit\ time} \approx \frac{1}{W/V_{sat}} = \frac{V_{sat}}{W}$$

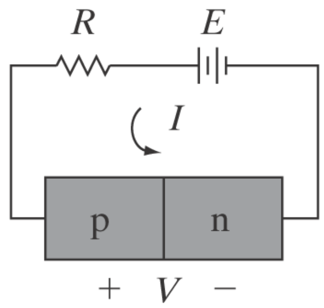
- Responsivity: $R = \frac{I_{op}}{P_{op}} = \frac{q\eta_{ext}}{h\nu}$

Light-emitting diode

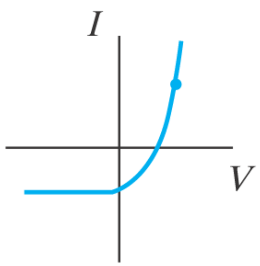
- Forward bias pn junction
- Minority & majority carriers recombine and emit light
- Operate in 1st quadrant
- Emitted light energy

$$h\nu_{out} = E_g$$

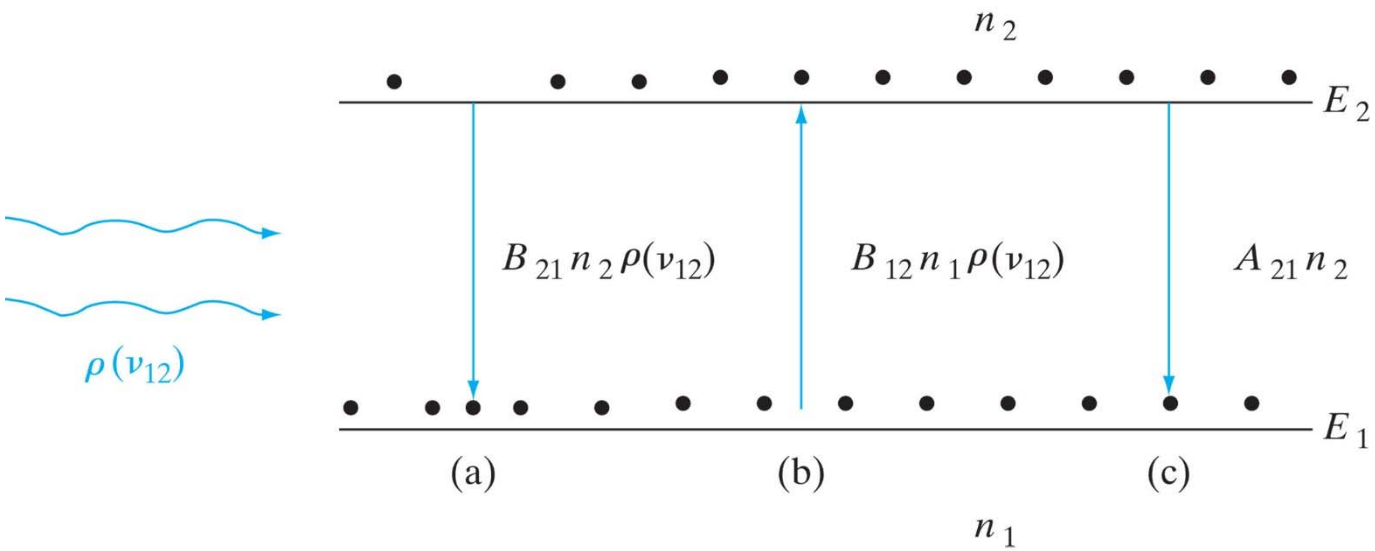




1st quadrant



Steady state condition



In steady state, the emission rates must balance the absorption rate:

$$\left.\frac{dn_2}{dt}\right|_{abs} + \left.\frac{dn_2}{dt}\right|_{spon} + \left.\frac{dn_2}{dt}\right|_{stim} = 0 \qquad \text{or}$$

$$B_{12} n_1 \rho(\nu_{12}) = A_{12} n_2 + B_{21} n_2 \rho(\nu_{12})$$

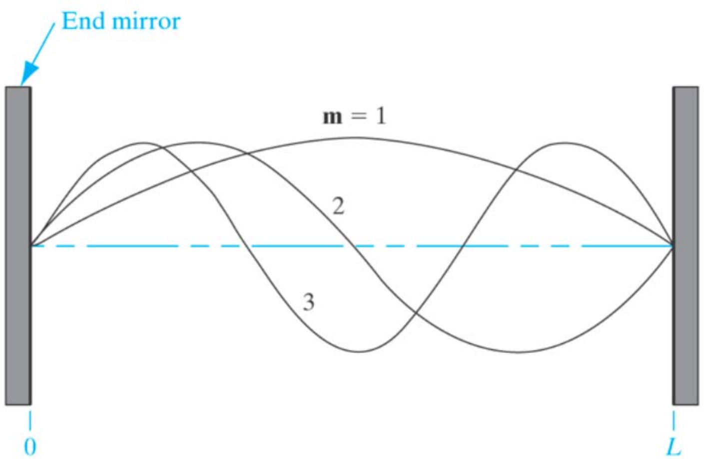
Absorption　　spontaneous emission　　stimulated emission

Laser:

Conditions for lasing:

1. $$\frac{Stimulated\ emission\ rate}{Spontanous\ emission\ rate} = \frac{B_{21}}{A_{12}}\rho(\nu_{12})$$

A large photon field energy density enhances the stimulated emission rate →use optical resonant cavity



The length of the cavity for stimulated emission must be:

$$L = \frac{m\lambda}{2} = \frac{m\lambda_0}{2n}$$

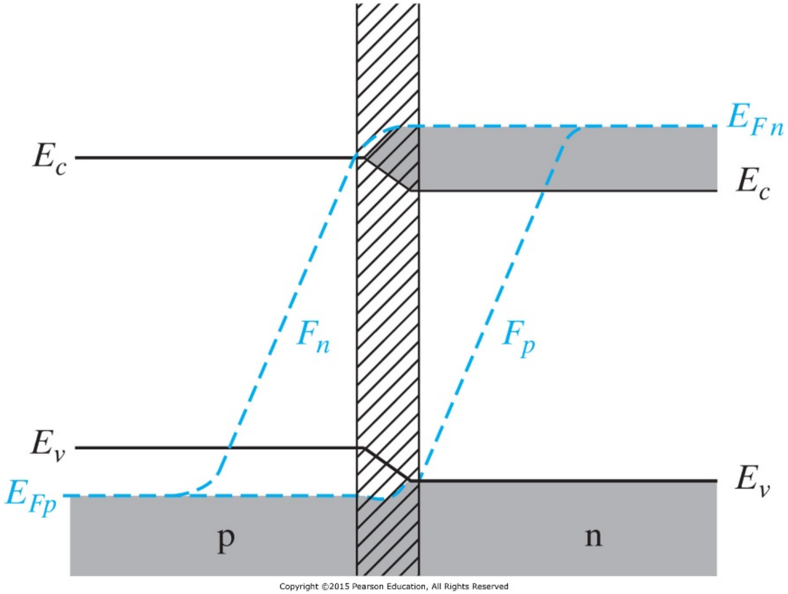
λ: Photon wavelength within the laser material
λ_0: output light wavelength in the atmosphere
n: index of refraction of the laser material

Laser

Conditions for lasing:

2. $$\frac{Stimulated\ emission\ rate}{absorption\ rate} = \frac{B_{21} n_2 \rho(\nu_{12})}{B_{12} n_1 \rho(\nu_{12})} = \frac{B_{21} n_2}{B_{12} n_1}$$

For stimulated emission to exceed absorption, n2>n1, --> need population inversion (negative temperature)



Lasing condition (population inversion):

$$F_n - F_p > h\nu$$

For band-edge transitions:

$$F_n - F_p > E_g$$