EE105
Microelectronic Devices and Circuits:
P-N Junctions and Semiconductor Fabrication

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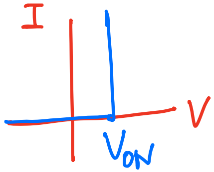
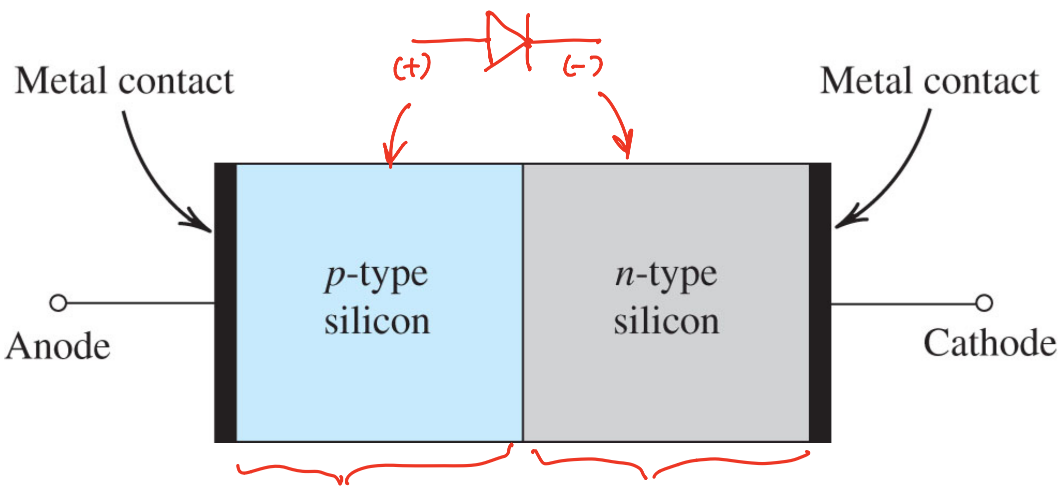
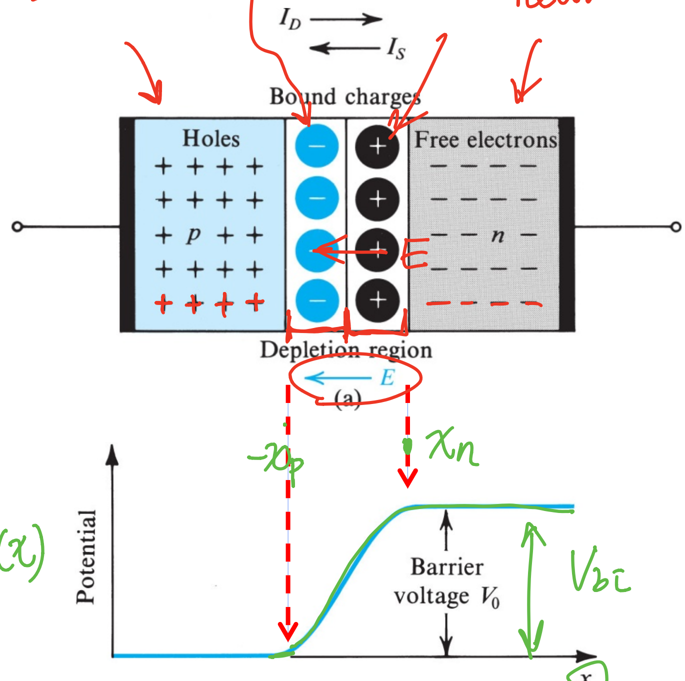


p-n Junction

- **p-type semiconductor in contact with n-type**
- **Basic building blocks of semiconductor devices**
  - **Diodes,**
  - **Bipolar junction transistors (BJT),**
  - **Metal-oxide-semiconductor field effect transistors (MOSFET)**



p-n Junction



net charge = 0

fixed charge acceptors

Donor

neutral

$-x_p$ x_n

$\phi(x)$ V_{bi}

hole + → diffusion

electron ← −

← E (<0) → $\phi = -\int_{x_p}^{x_n} E(x)\,dx = V_{bi} > 0$

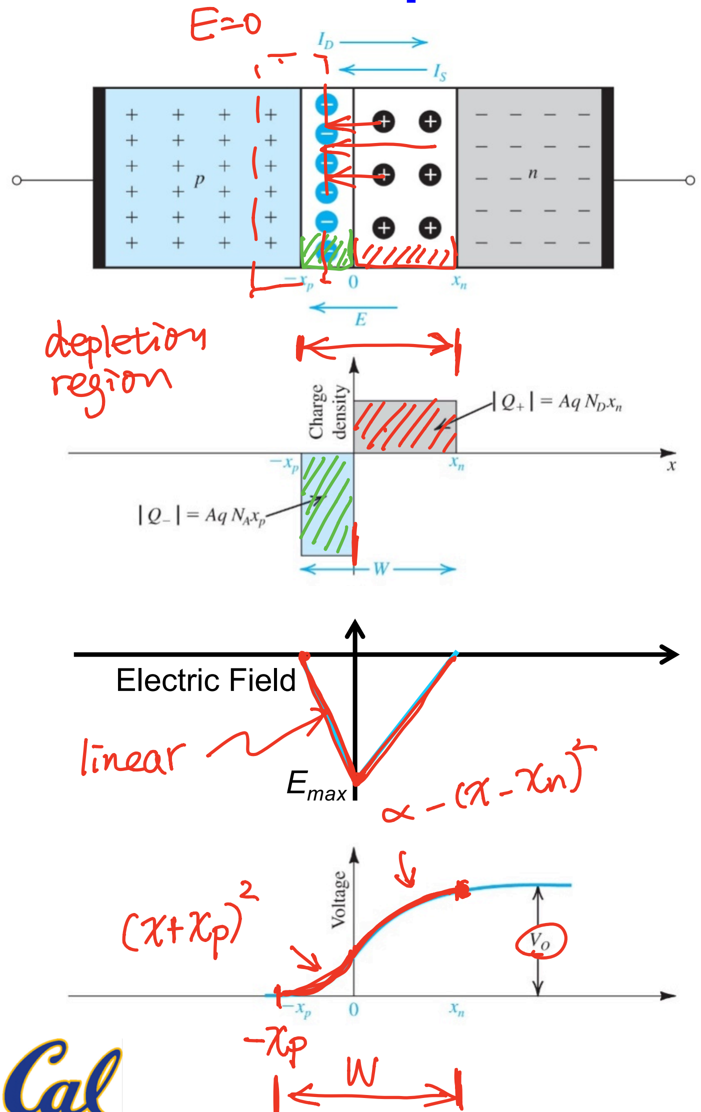
hole + ←

→ − electron

$E = -\frac{d\phi}{dx}$

- When p- and n-type semiconductors are "joined"
  - Holes near junction diffuse to n-side
  - Electrons near junction diffuse to p-side
- "Depletion region" formed near junction
  - No electrons, no holes
- A "built-in" potential is formed to oppose further movement of electrons and holes

Simplified Analysis of p-n Junction



Gauss Law:

$$\oint \vec{E} \cdot \overrightarrow{dA} = \frac{Q}{\epsilon_s}$$

Electrical potential:

$$V = -\int_{-\infty}^{x} E(x')dx'$$

$\int ax\,dx = \frac{1}{2}ax^2$

Built-in potential:

$$V_0 = V_T \cdot ln\left(\frac{N_A N_D}{n_i^2}\right)$$

controlled by doping N_A, N_D

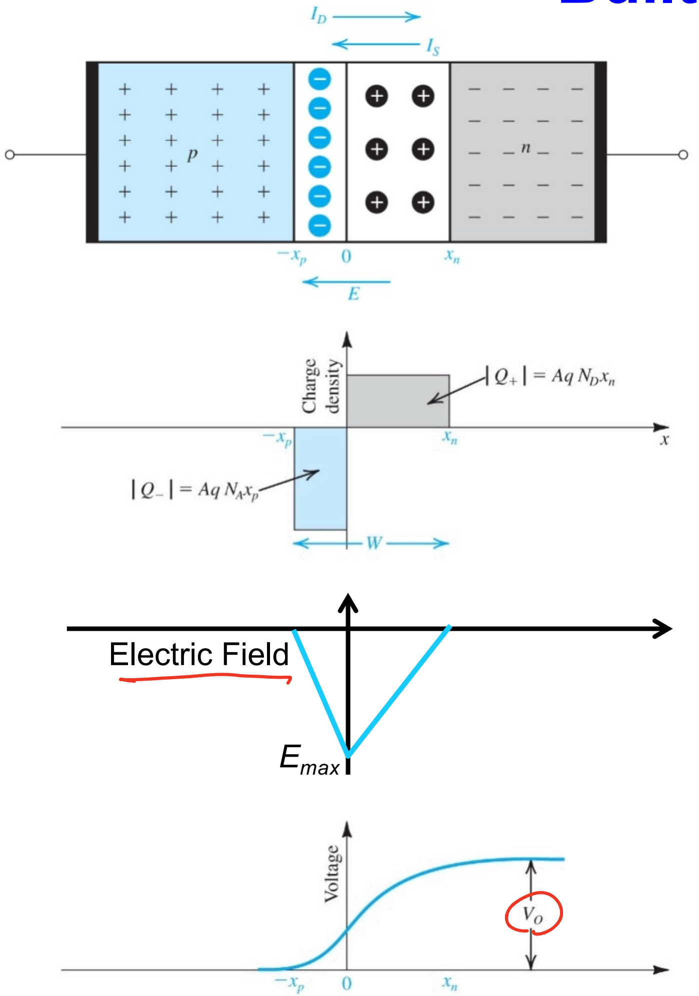
Depletion width:

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$$

$\| \; x_n + x_p$

high doping
⇒ large N_A, N_D
⇒ small W

Built-in Potential



Built-in potential:

$$V_0 = V_T \cdot ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$V_T = \frac{k_B T}{q}$: thermal voltage = 26 mV at room temperature

N_A : p-doping (Acceptor)

N_D : n-doping (Donor)

n_i : intrinsic carrier concentration

$n_i = 1.5{\times}10^{10}\ cm^{-3}$ for Si

Alternative form:

$$V_0 = 60mV \cdot log\left(\frac{N_A N_D}{n_i^2}\right)$$

$V_T \cdot ln10$

Example:

$N_A = 1.5{\times}10^{17}$, $n_D = 1.5{\times}10^{18}$ [cm^{-3}]

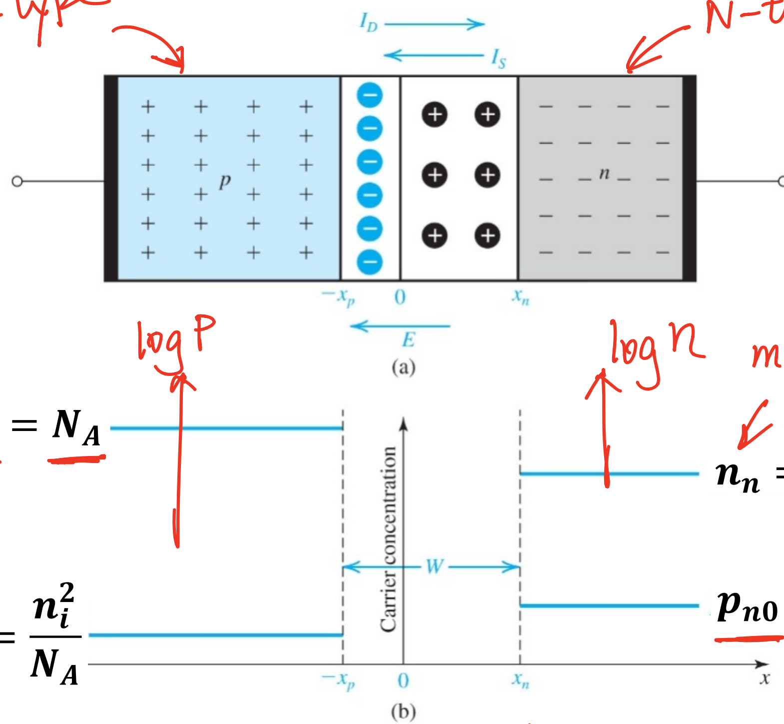
$V_0 = 60mV \cdot log(10^{15}) = 900mV$

Carrier Concentration in p-n Junction

At equilibrium:

$$n \times p = n_i^2$$

↑ Mass Action Law



majority: 10^{17} $p_p = N_A$

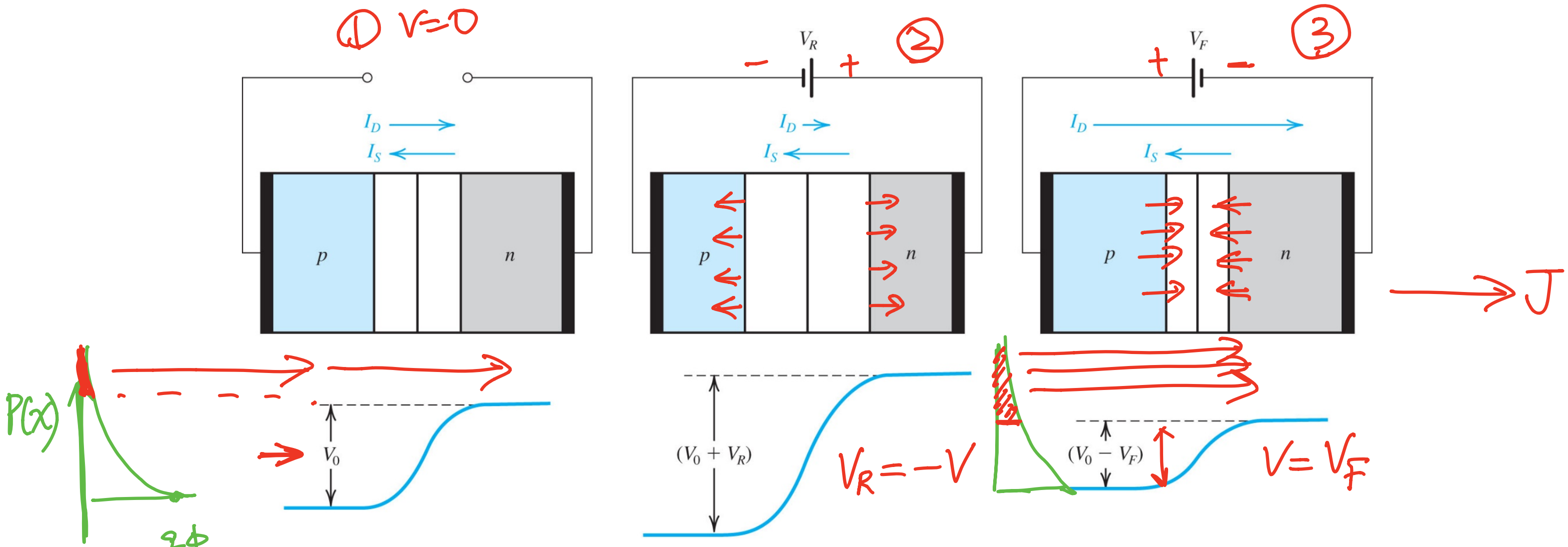
minority: 10^{3} $n_{p0} = \frac{n_i^2}{N_A}$

majority: $n_n = N_D$

$p_{n0} = \frac{n_i^2}{N_D}$

Depletion
→ No holes
→ No electrons

Depletion Width Under Bias



$P = P_0 e^{\frac{q\phi}{k_B T}}$

Open circuit
(V = 0)
Equilibrium

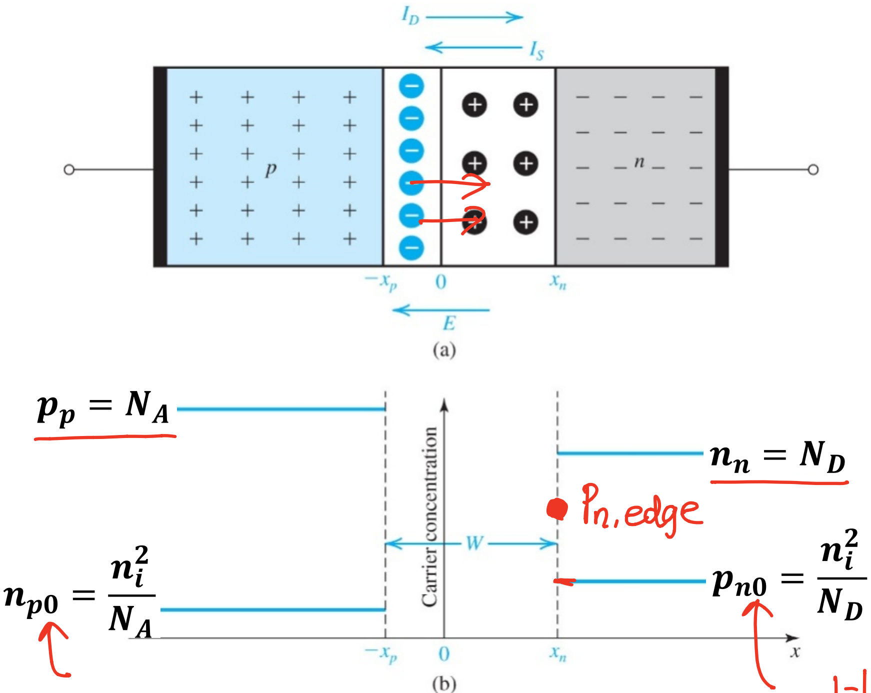
Reverse Bias
(V < 0)
- **Larger barrier**
- **Wider depletion**

Forward Bias
(V > 0)
- **Smaller barrier**
- **Narrower depletion**

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V)}$$

applied voltage
③ V > 0 : forward bias
② V < 0 : reversed bias
① V = 0

Extra Holes in N Side Under Forward Bias



Excess holes in n-doped side:

$$p_{n,edge} = p_{n0} \cdot \left(e^{V/V_T} - 1\right)$$

$$e^{\frac{qV}{k_BT}} = e^{\frac{V}{V_T}}$$

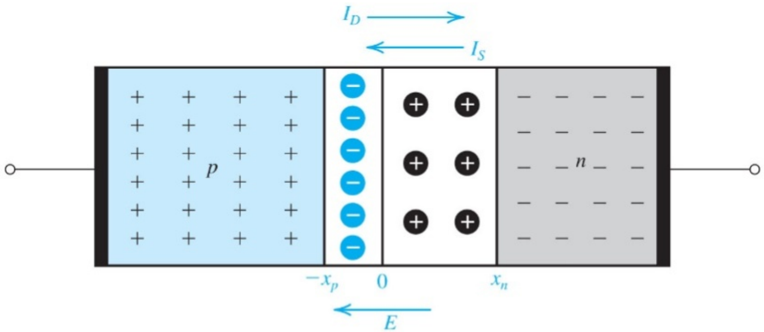
$$V_T = \frac{k_BT}{q}$$

Forward Bias
Barrier lowered
by V

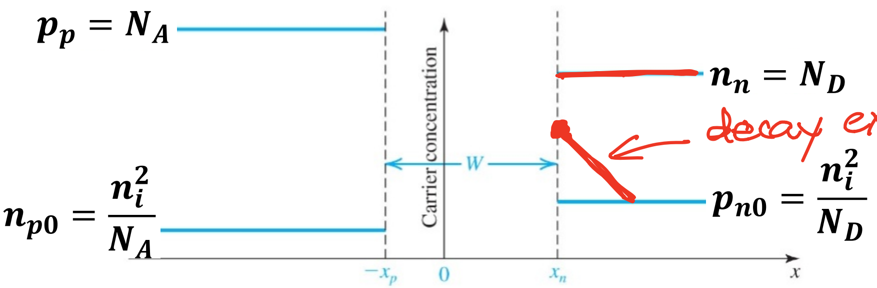
Boltzmann Dist

$$P = P_0 e^{\frac{qV}{k_BT}}$$

Holes Recombine with Electrons on N Side



(a)



(b)

Excess holes in n-doped side:

$$p_{n,edge} = p_{n0} \cdot \left(e^{V/V_T} - 1\right)$$

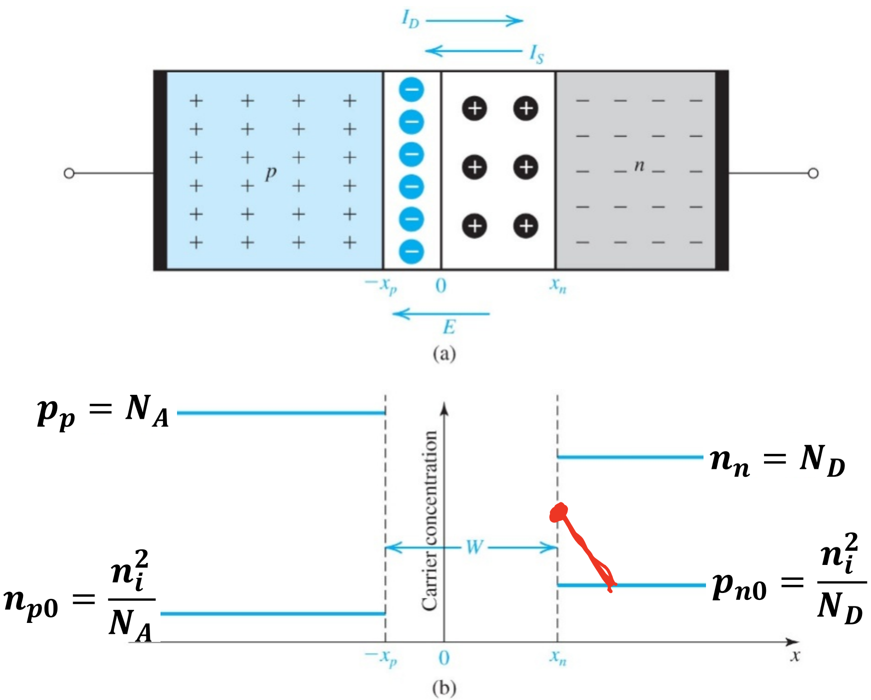
Excess holes recombines within diffusion length, L_p:

$$\frac{dp_n(x)}{dx} = -\frac{p_{n,edge}}{L_p}$$

$\Delta P \propto e^{-\frac{x}{L_p}}$: L_p = diffusion length

$$\frac{dP_n(x)}{dx} = -\frac{1}{L_p} P_n(x)$$

Diffusion Currents Under Forward Bias



Excess holes in n-doped side:

$$p_{n,edge} = p_{n0} \cdot \left(e^{V/V_T} - 1\right)$$

Excess holes recombines within diffusion length, L_p:

$$\frac{dp_n(x)}{dx} = \frac{p_{n,edge}}{L_p}$$

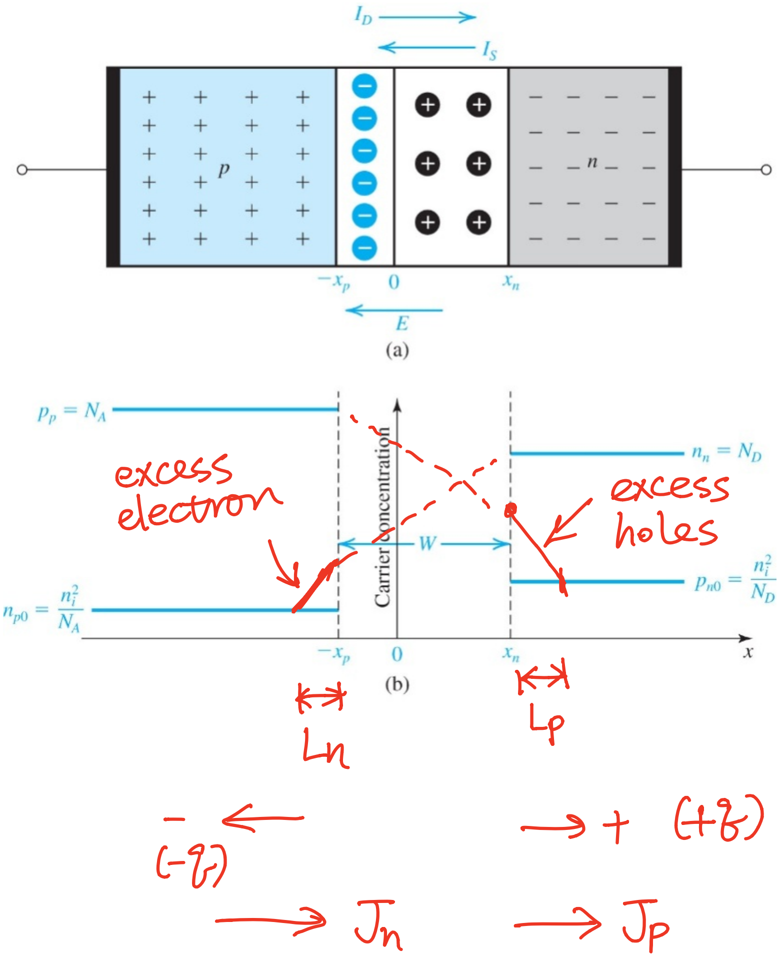
Diffusion current:

$$J_p = qD_p \frac{dp_n(x)}{dx}$$

$$= \frac{qD_p}{L_p} p_{n0} \cdot \left(e^{V/V_T} - 1\right)$$

$$\rightarrow J_p \propto \left(e^{\frac{V}{V_T}} - 1\right)$$

Total Currents Under Forward Bias



Hole Diffusion current on N-side

$$J_p = \frac{qD_p}{L_p} p_{n0} \cdot \left(e^{V/V_T} - 1\right)$$

Similarly,
Electron Diffusion current on P-side

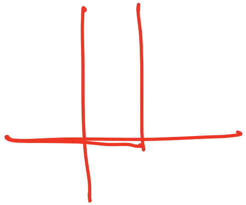
$$J_n = \frac{qD_n}{L_n} n_{p0} \cdot \left(e^{V/V_T} - 1\right)$$

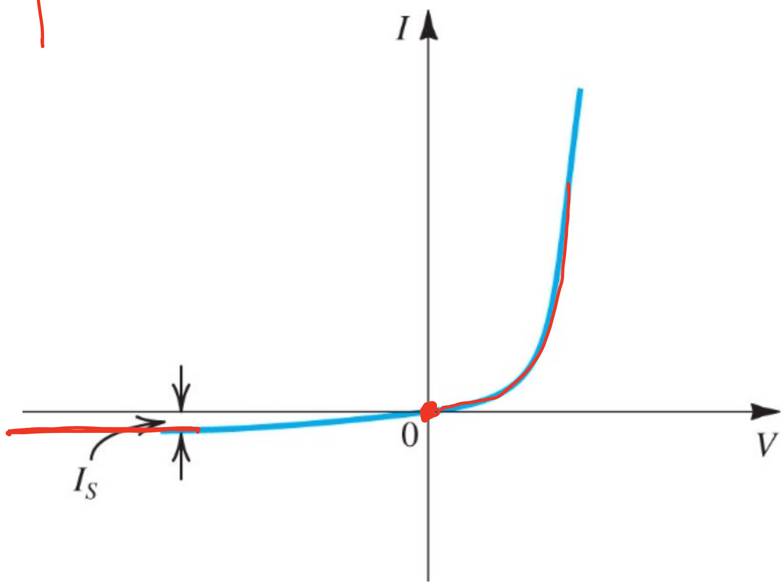
Total current

$$I = Area \cdot (J_p + J_n) \propto \left(e^{V/V_T} - 1\right)$$

[Amp]

I-V Curve





$$I = I_S\left(e^{V/V_T} - 1\right)$$

where

$$I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

Reverse saturation current

$I_S \sim 10^{-15}$ Amp

e^{V/V_T} $\quad V = .8V = 800\,mV$

$= e^{800/26} = e^{32} \approx 10^{16}$

$V < 0$

$e^{V/V_T} \ll 1$

$I = I_S(0-1)$

$= -I_S$

$V = 0$

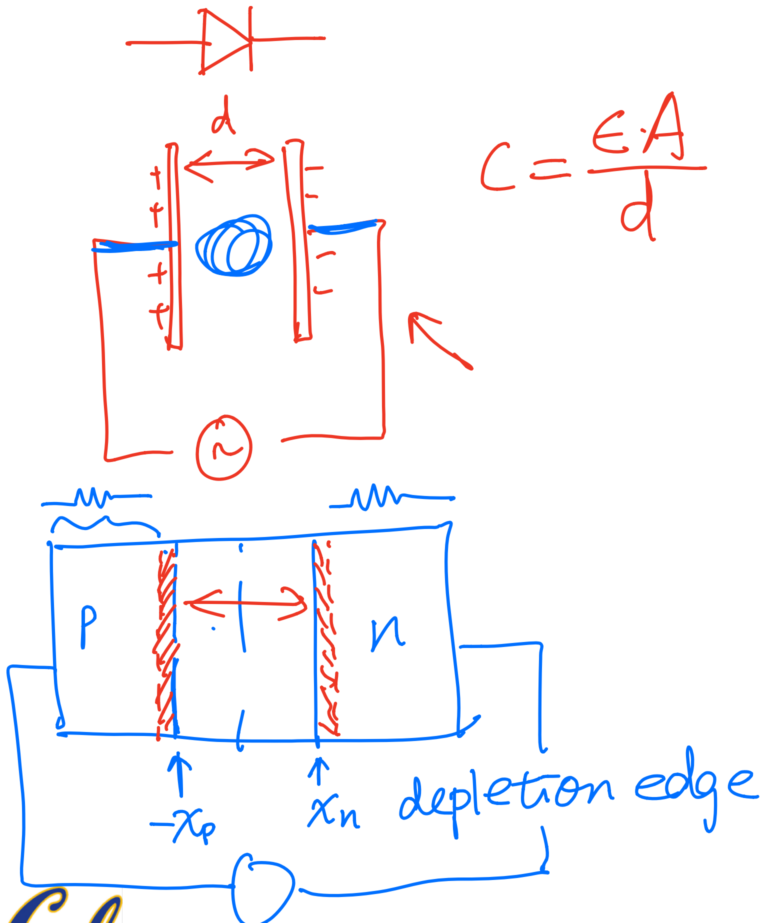
$I = 0$

$V > 0$

$e^{V/V_T} \gg 1$

$I = I_S e^{V/V_T}$

Capacitance in p-n Junction: Depletion Capacitance



Parallel plate capacitance:

$$C_j = \frac{\epsilon_s A}{W}$$

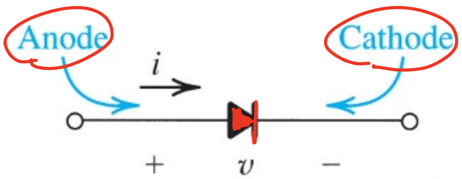
Plate separation, *W*, is voltage dependent:

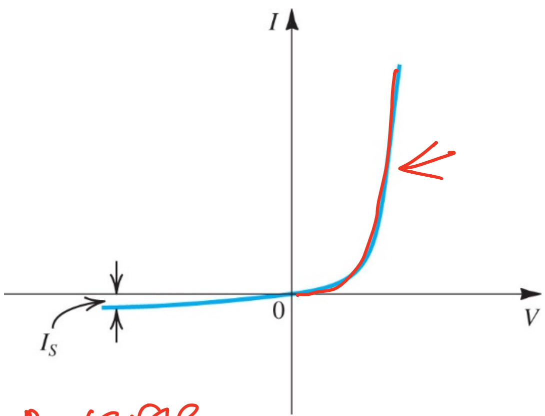
$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + |V_R|)}$$

Variable capacitance:

$$C_j(V) = \frac{C_{j0}}{\sqrt{1 + \frac{|V_R|}{V_0}}}$$

Summary of p-n Junction





Reverse

$I = -I_S$

Variable Cap

Built-in potential : $V_0 = V_T \ln\left(\dfrac{N_A N_D}{n_i^2}\right)$

I-V curve : $I = I_S\left(e^{V/V_T} - 1\right)$

Capacitance : $C_j = \dfrac{C_{j0}}{\sqrt{1 + \dfrac{|V_R|}{V_0}}}$

Depletion Width: $W = \sqrt{\dfrac{2\varepsilon_S}{q}\left(\dfrac{1}{N_A} + \dfrac{1}{N_D}\right)(V_0 - V)}$