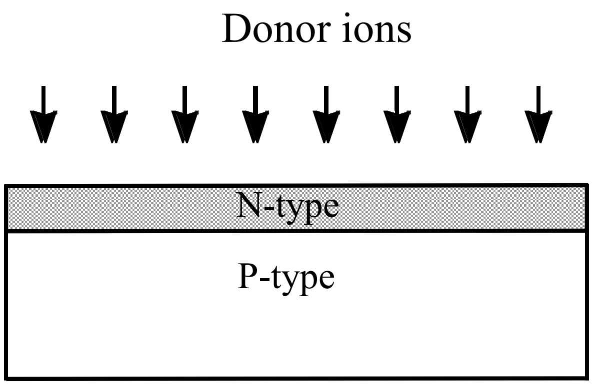
Semiconductor Devices
Spring 2019

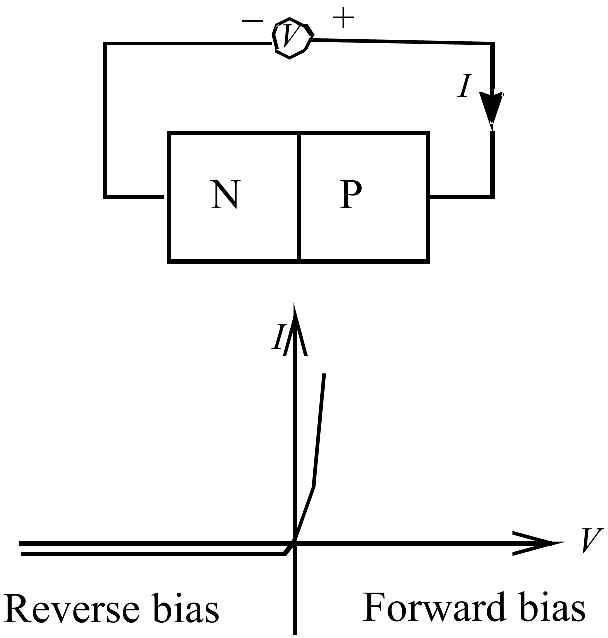
Lecture 5

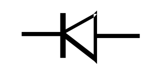
This Lecture

- Reading
  - 4.6-4.9 PN and Metal Semiconductor Junctions
- Concepts:
  - Minority carriers and diffusion current
  - Current continuity equation

4.1 Building Blocks of the PN Junction Theory





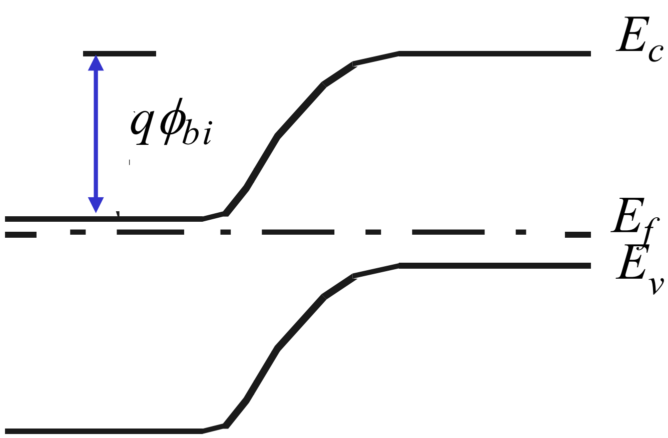


diode
symbol

4.6 Forward Bias – Carrier Injection

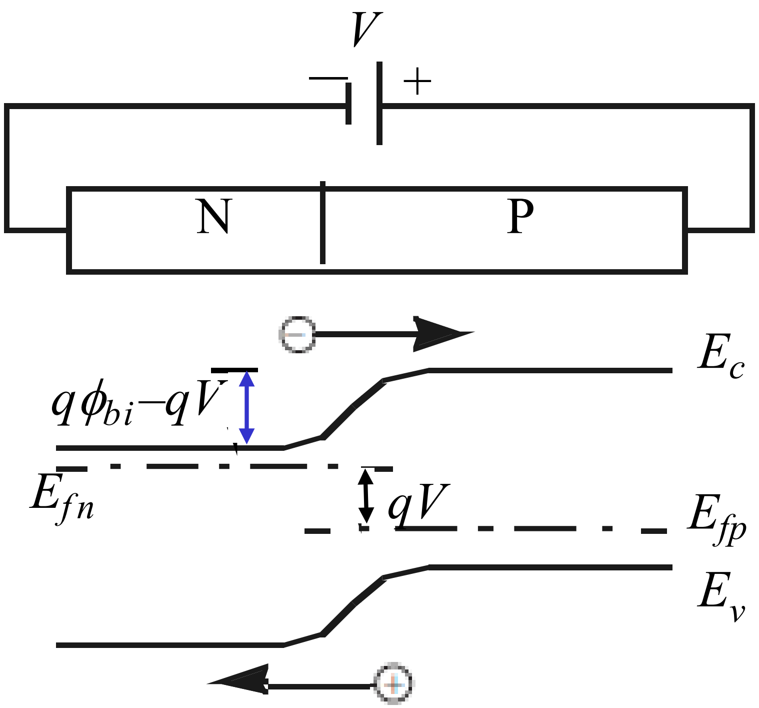
V=0

I=0



Drift and diffusion cancel out

Forward biased

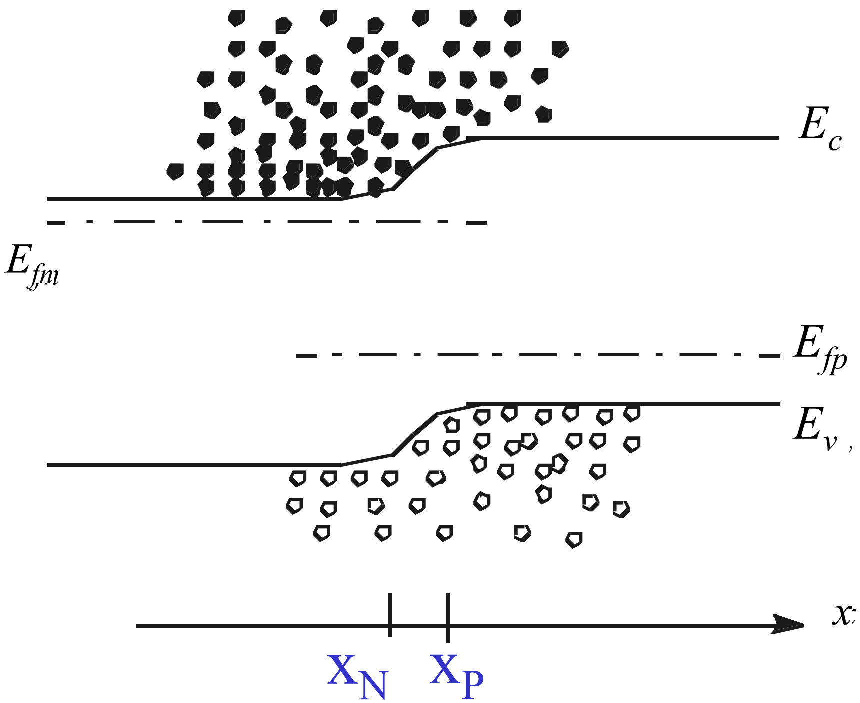


Minority carrier injection

4.6 Forward Bias – Quasi-equilibrium Boundary Condition

$$n(x_{\mathrm{P}}) = N_c e^{-(E_c - E_{fn})/kT} = N_c e^{-(E_c - E_{fp})/kT} e^{(E_{fn} - E_{fp})/kT}$$

$$= n_{P0} e^{(E_{fn} - E_{fp})/kT} = n_{P0} e^{qV/kT}$$



- The minority carrier densities are raised by $e^{qV/kT}$
- Which side gets more carrier injection?

4.6 Carrier Injection Under Forward Bias– Quasi-equilibrium Boundary Condition

$$n(x_P) = n_{P0}e^{qV/kT} = \frac{n_i^2}{N_a}e^{qV/kT}$$

$$p(x_P) = p_{N0}e^{qV/kT} = \frac{n_i^2}{N_d}e^{qV/kT}$$

$$n'(x_P) \equiv n(x_P) - n_{P0} = n_{P0}(e^{qV/kT} - 1)$$

$$p'(x_N) \equiv p(x_N) - p_{N0} = p_{N0}(e^{qV/kT} - 1)$$

EXAMPLE: Carrier Injection

A PN junction has N_a=10^{19}cm^{-3} and N_d=10^{16}cm^{-3}. The applied voltage is 0.6 V.

***Question**: What are the minority carrier concentrations at the depletion-region edges?*

***Solution**:*

$$n(x_P) = n_{P0}e^{qV/kT} = 10 \times e^{0.6/0.026} = 10^{11}\ \text{cm}^{-3}$$

$$p(x_N) = p_{N0}e^{qV/kT} = 10^4 \times e^{0.6/0.026} = 10^{14}\ \text{cm}^{-3}$$

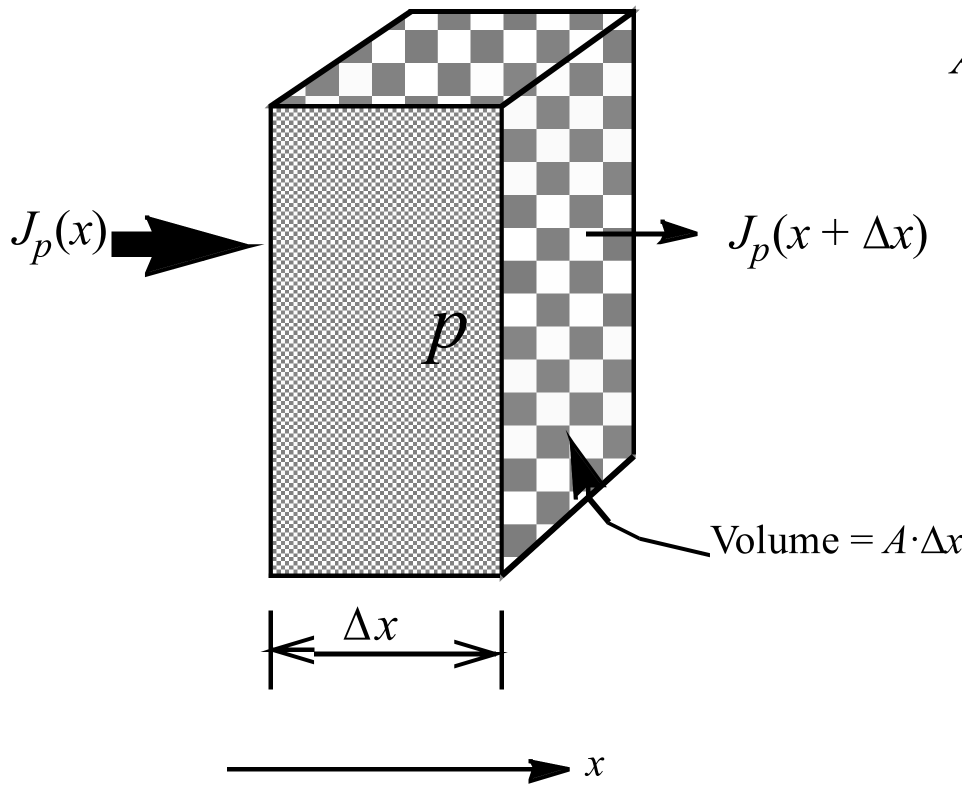
***Question**: What are the excess minority carrier concentrations?*

***Solution**:*

$$n'(x_P) = n(x_P) - n_{P0} = 10^{11} - 10 = 10^{11}\ \text{cm}^{-3}$$

$$p'(x_N) = p(x_N) - p_{N0} = 10^{14} - 10^4 = 10^{14}\ \text{cm}^{-3}$$

4.7 Current Continuity Equation



$$A \cdot \frac{J_p(x)}{q} = A \cdot \frac{J_p(x+\Delta x)}{q} + A \cdot \Delta x \cdot \frac{p'}{\tau}$$

$$-\frac{J_p(x+\Delta x) - J_p(x)}{\Delta x} = q\frac{p'}{\tau}$$

$$-\frac{dJ_p}{dx} = q\frac{p'}{\tau}$$

4.7 Current Continuity Equation

$$-\frac{dJ_p}{dx} = q\frac{p'}{\tau}$$

Minority drift current is negligible;

$\therefore \quad J_p = -qD_p dp/dx$

$$qD_p \frac{d^2 p}{dx^2} = q\frac{p'}{\tau_p}$$

$$\boxed{\frac{d^2 p'}{dx^2} = \frac{p'}{D_p \tau_p} = \frac{p'}{L_p{}^2}}$$

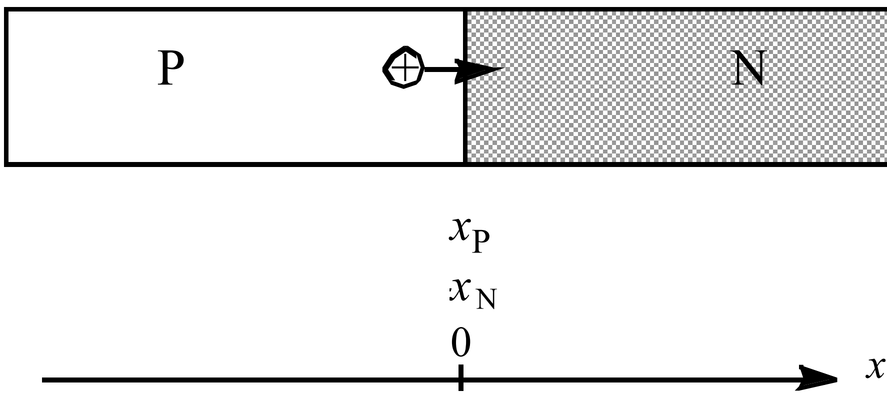
$$\boxed{\frac{d^2 n'}{dx^2} = \frac{n'}{L_n{}^2}}$$

L_p and L_n are the diffusion lengths

$$\boxed{L_p \equiv \sqrt{D_p \tau_p}}$$

$$\boxed{L_n \equiv \sqrt{D_n \tau_n}}$$

4.8 Forward Biased Junction-- Excess Carriers



$$\frac{d^2 p'}{dx^2} = \frac{p'}{L_p{}^2}$$

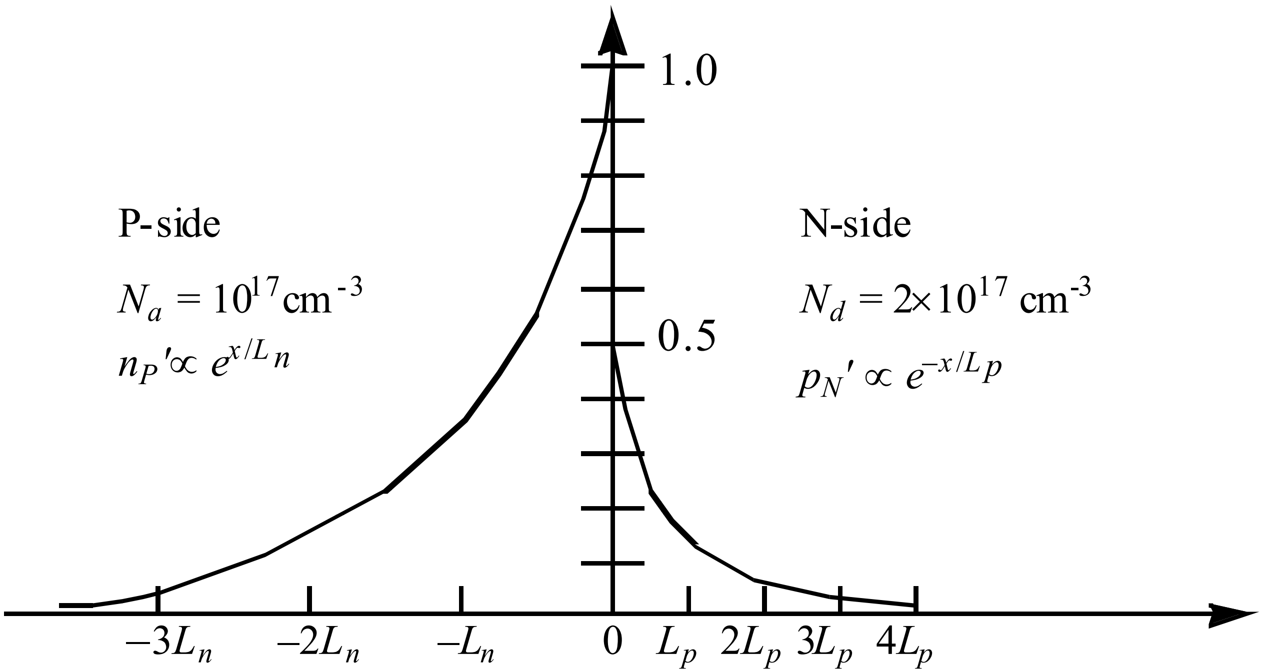
$$p'(\infty) = 0$$

$$p'(x_N) = p_{N0}(e^{qV/kT} - 1)$$

$$p'(x) = Ae^{x/L_p} + Be^{-x/L_p}$$

$$p'(x) = p_{N0}(e^{qV/kT} - 1)e^{-(x - x_N)/L_p}, \ x > x_N$$

4.8 Excess Carrier Distributions



$$p'(x) = p_{N0}(e^{qV/kT}-1)e^{-(x-x_N)/L_p},\ x > x_N$$

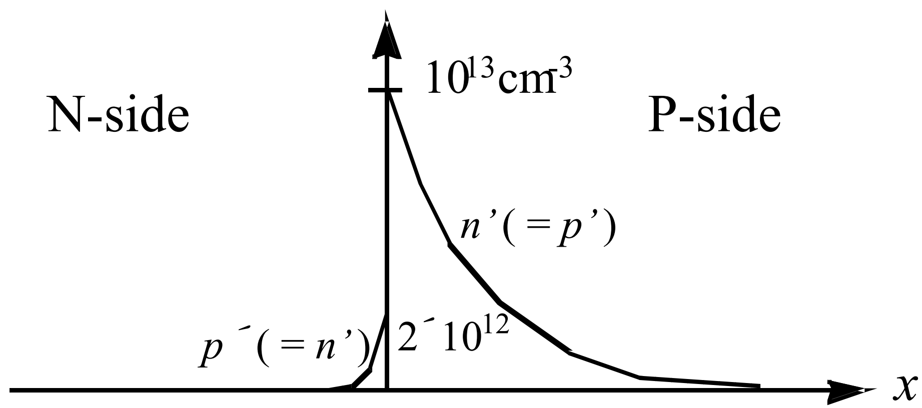
$$n'(x) = n_{P0}(e^{qV/kT}-1)e^{(x-x_P)/L_n},\ x < x_P$$

EXAMPLE: Carrier Distribution in Forward-biased PN Diode

N-type	P-type
$N_d = 5\times10^{17}$ cm^{-3}	$N_a = 10^{17}$ cm^{-3}
$D_p = 12$ cm^2/s	$D_n = 36.4$ cm^2/s
$\tau_p = 1$ μs	$\tau_n = 2$ μs

- *Sketch n'(x) on the P-side.*

$$n'(x_P) = n_{P0}(e^{qV/kT} - 1) = \frac{n_i^2}{N_a}(e^{qV/kT} - 1) = \frac{10^{20}}{10^{17}} e^{0.6/0.026} = 10^{13} \text{ cm}^{-3}$$



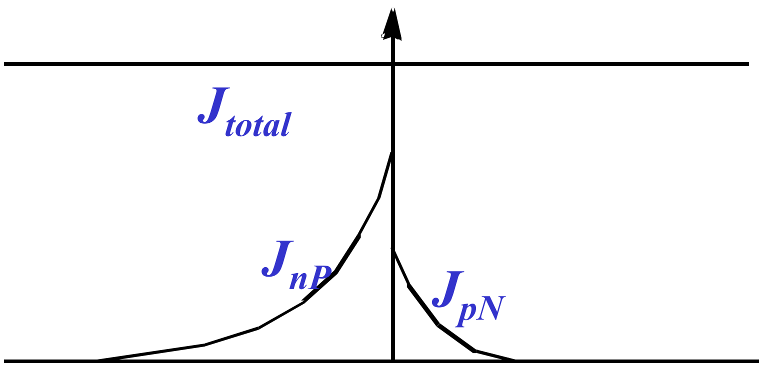
EXAMPLE: Carrier Distribution in Forward-biased PN Diode

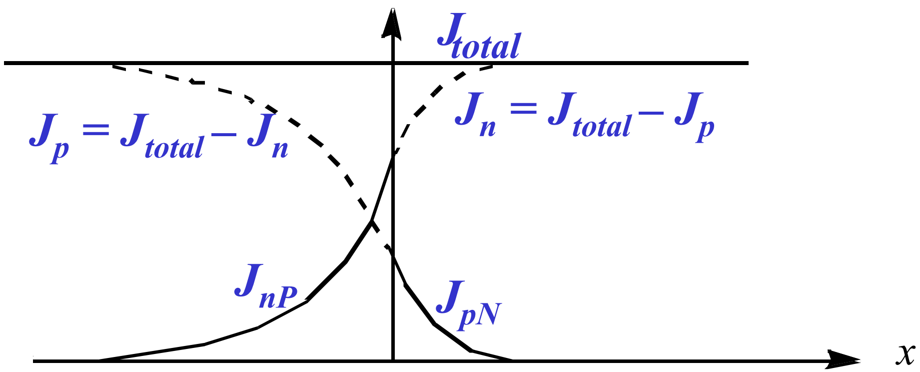
- *How does L_n compare with a typical device size?*

$$L_n = \sqrt{D_n \tau_n} = \sqrt{36 \times 2 \times 10^{-6}} = 85 \ \mu\text{m}$$

- *What is p'(x) on the P- side?*

4.9 PN Diode I-V Characteristics





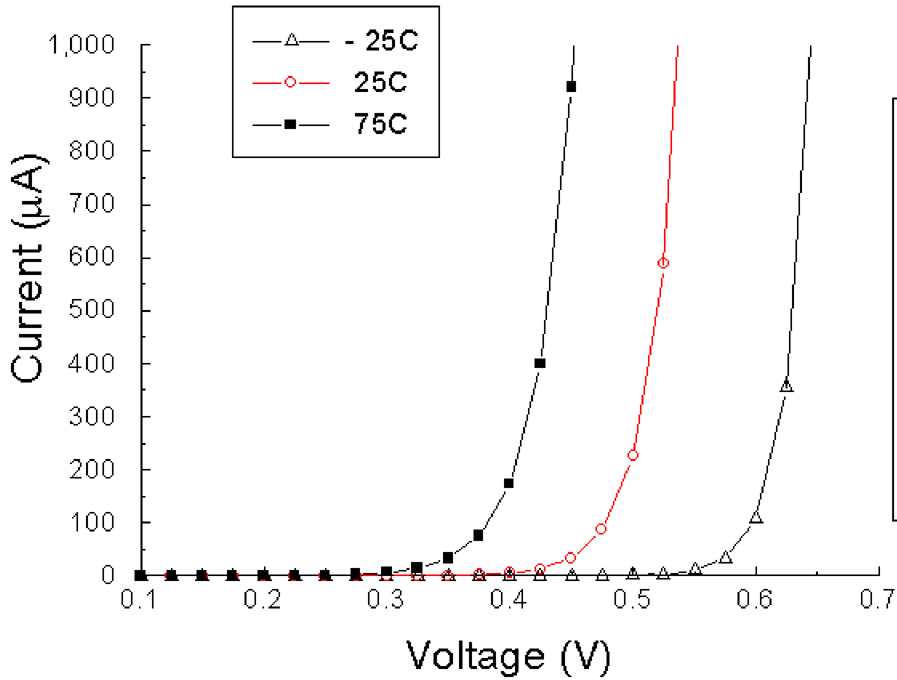
$$J_{pN} = -qD_p \frac{dp'(x)}{dx} = q\frac{D_p}{L_p} p_{N0}(e^{qV/kT} - 1)e^{-(x-x_N)/L_p}$$

$$J_{nP} = qD_n \frac{dn'(x)}{dx} = q\frac{D_n}{L_n} n_{P0}(e^{qV/kT} - 1)e^{(x-x_P)/L_n}$$

$$\text{Total current} = J_{pN}(x_N) + J_{nP}(x_P) = \left(q\frac{D_p}{L_p} p_{N0} + q\frac{D_n}{L_n} n_{P0} \right)(e^{qV/kT} - 1)$$

$$= J \text{ at all } x$$

The PN Junction as a Temperature Sensor

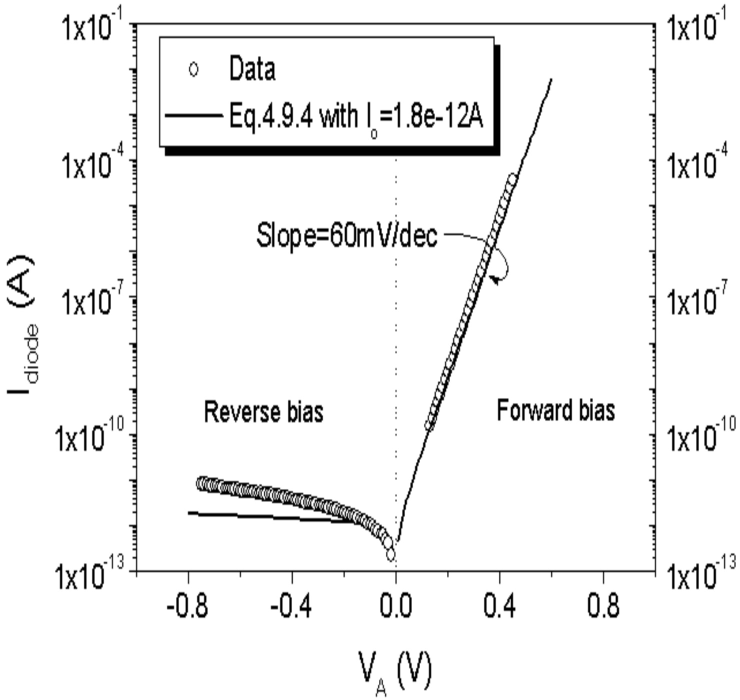


$$I = I_0 (e^{qV/kT} - 1)$$

$$I_0 = Aqn_i^{\ 2} \left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a} \right)$$

What causes the IV curves to shift to lower V at higher T ?

4.9.1 Contributions from the Depletion Region



$$n \approx p \approx n_i e^{qV/2kT}$$

Net recombination (generation) rate :

$$\frac{n_i}{\tau_{dep}}(e^{qV/2kT}-1)$$

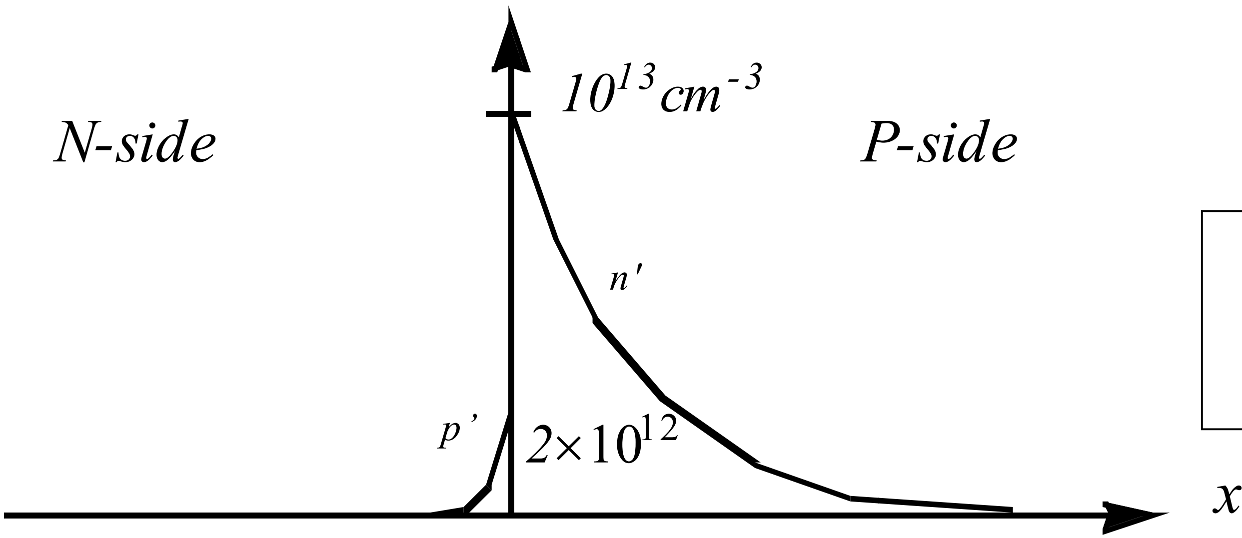
$$I = I_0(e^{qV/kT}-1) + A\frac{qn_iW_{dep}}{\tau_{dep}}(e^{qV/2kT}-1)$$

Space-Charge Region (SCR) current

$$I_{leakage} = I_0 + A\frac{qn_iW_{dep}}{\tau_{dep}}$$

Under forward bias, SCR current is an extra current with a slope 120mV/decade

4.10 Charge Storage

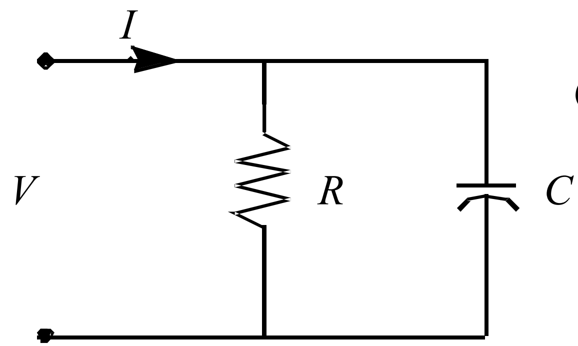


$Q \propto I$

$$\boxed{\begin{array}{l} I = Q/\tau_s \\ Q = I\tau_s \end{array}}$$

What is the relationship between τ_s (charge-storage time) and τ (carrier lifetime)?

4.11 Small-signal Model of the Diode



$$G \equiv \frac{1}{R} = \frac{dI}{dV} = \frac{d}{dV} I_0 (e^{qV/kT} - 1) \approx \frac{d}{dV} I_0 e^{qV/kT}$$

$$= \frac{q}{kT} I_0 (e^{qV/kT}) = I_{DC} / \frac{kT}{q}$$

What is G at 300K and $I_{DC} = 1$ mA?

Diffusion Capacitance:

$$C = \frac{dQ}{dV} = \tau_s \frac{dI}{dV} = \tau_s G = \tau_s I_{DC} / \frac{kT}{q}$$

Which is larger, diffusion or depletion capacitance?

Summary

- Concepts:
  - Minority carriers are injected into the lighter doping side
  - The minority carrier gradient is plugged into the diffusion equation to determine the current
  - The current depends exponentially on the applied forward voltage
- Reading for next time
  - 4.12-15 PART II Application to Optoelectronic Devices