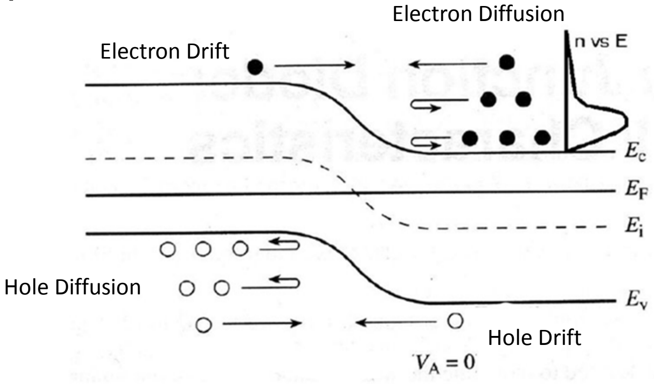
University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

PN Junction DC Response

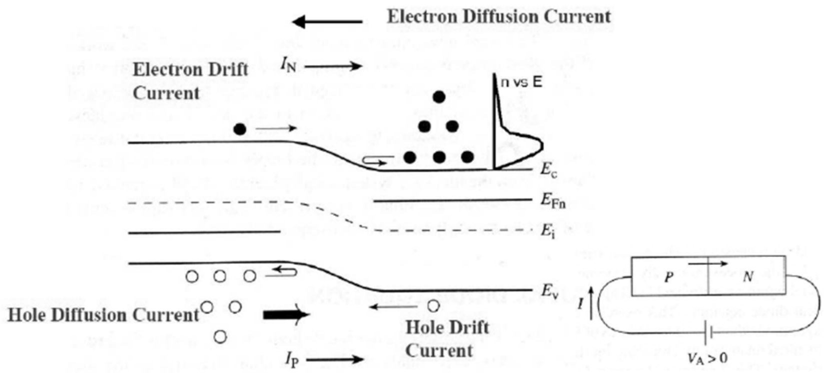
Instructor: Professor Hua Bao

Equilibrium



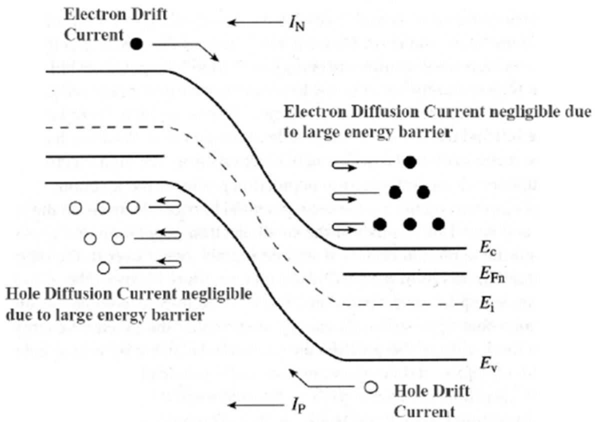
At equilibrium, the total current balances due to the sum of the individual components

Forward Bias



Current flow is proportional to $e^{(qV_A/kT)}$ due to the exponential increase of carriers in the majority carrier bands

Reverse Bias



(c) Reverse bias ($V_A < 0$)

Reverse current caused by minority carriers being swept away by electric field, and independent of the size of V_A

Qualitative Analysis

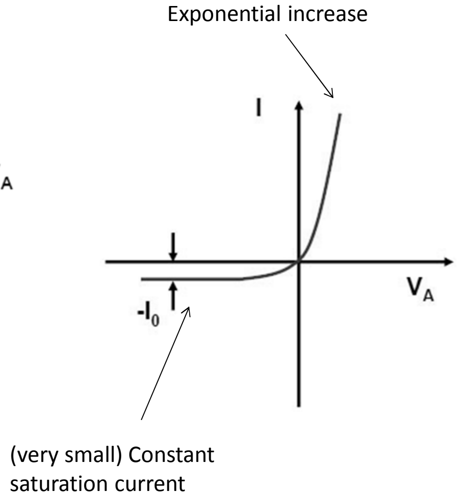
$I = I^{+} - I^{-}$

$I^{+} \propto e^{qV_A/kT}$

$I^{-} = I_0$ **Independent of V_A**

$I(V_A = 0) = 0$

$$\Rightarrow \quad I = I_0(e^{qV_A/kT} - 1)$$



I-V Relation: Quantitative

Determine current flow assuming steady state, low-level injection

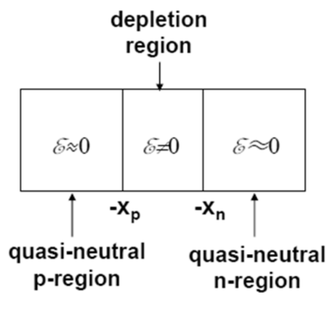
$I = AJ \qquad J = J_n + J_p$

$$J_n = nq\mu_n\mathcal{E} + qD_n\frac{dn}{dx}$$

$$J_p = pq\mu_p\mathcal{E} - qD_p\frac{dp}{dx}$$

Need to determine carrier densities and electric field….

Solve continuity equations



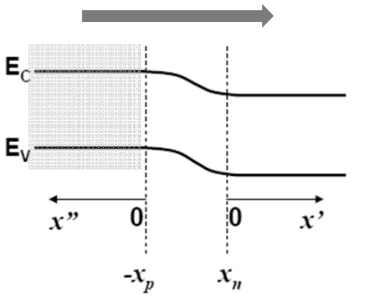
Three regions of interest

Quantitative Studies

Minority carrier diffusion eqations apply in the “quasi-neutral” regions

In the quasi-neutral p-region

$$\cancel{\frac{\partial \Delta n_p}{\partial t}} = D_n \frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_n} + \cancel{G_L}$$



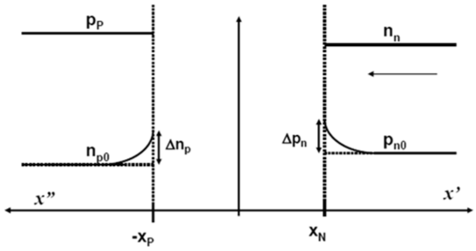
- **Steady State:**
  Currents are the same everywhere.
- **No Light**

$$J = J_N(x) + J_P(x)$$

Minority Carrier Densities

Wide base diode

$$\Delta n_p(x \to -\infty) = 0$$
$$\Delta p_n(x \to +\infty) = 0$$



Solution to Minority Carrier Diffusion Equation

$$\Delta n_p(x) = \Delta n_p(x''=0)e^{-x''/L_N} \qquad \Delta p_n(x) = \Delta p_n(x'=0)e^{-x'/L_P}$$

$$L_N = \sqrt{D_N \tau_N} \qquad L_P = \sqrt{D_P \tau_P}$$

Minority Carrier Diffusion Current

In quasi-neutral P region

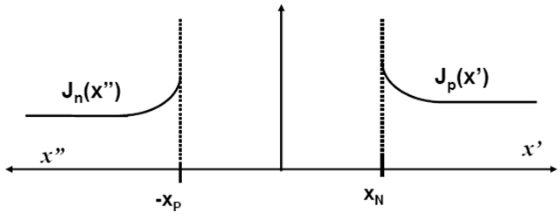
$$J_n = nq\mu_n\mathcal{E} + qD_n\frac{dn}{dx} \approx qD_n\frac{dn_p}{dx} = -qD_n\frac{d\Delta n_p}{dx''}$$

$$\Delta n_p(x) = \Delta n(x''=0)e^{-x''/L_N}$$

In quasi-neutral N region

$$J_p = pq\mu_p\mathcal{E} - qD_p\frac{dp}{dx} \approx -qD_p\frac{dp_n}{dx} = -qD_p\frac{d\Delta p_n}{dx'}$$

$$\Delta p_n(x) = \Delta p(x'=0)e^{-x'/L_P}$$



Ideal Diode

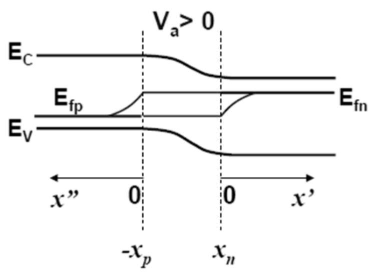
$\Delta n_p(-x_p)$, and $\Delta p_n(x_n)$ are still not known

By definition

$$np = n_i^2 e^{(F_N - F_P)/kT}$$

Assume

$$F_N - F_P = E_{F_n} - E_{F_p} = qV_A$$



Law of the junction

$$\boxed{np = n_i^2 e^{qV_A/kT}} \qquad -x_p \le x \le x_n$$

$$n(-x_p) = \frac{n_i^2}{N_A}e^{qV_A/kT} \Rightarrow \boxed{\Delta n_p(-x_p) = \frac{n_i^2}{N_A}(e^{qV_A/kT} - 1)}$$

Similarly,

$$\boxed{\Delta p_n(x_n) = \frac{n_i^2}{N_D}(e^{qV_A/kT} - 1)}$$

Minority Carrier Densities

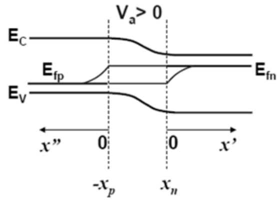
Solution of Minority Carrier Diffusion Equation

$$\Delta n_p(x) = \Delta n(x''=0)e^{-x''/L_N} \qquad \Delta p_n(x) = \Delta p(x'=0)e^{-x'/L_P}$$

$$\Delta n_p(x'') = \frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right)e^{-x''/L_N} \qquad \Delta p_n(x') = \frac{n_i^2}{N_D}\left(e^{eV_A/kT}-1\right)e^{-x'/L_P}$$

Minority electron diffusion current on P side

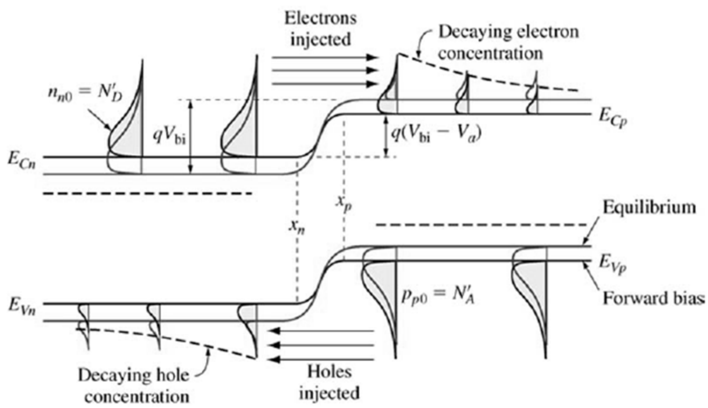
$$J_n = -qD_N\frac{d\Delta n_p}{dx''} = q\frac{D_N}{L_N}\frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right)e^{-x''/L_N}$$



Minority hole diffusion current on N side

$$J_p = -qD_P\frac{d\Delta p_n}{dx'} = q\frac{D_P}{L_P}\frac{n_i^2}{N_D}\left(e^{qV_A/kT}-1\right)e^{-x'/L_P}$$

Diffusion Current



$$J_p = \frac{qD_p}{L_p}\Delta p_n(x_n)e^{(x+x_n)/L_p} \qquad J_n = \frac{qD_n}{L_n}\Delta n_p(x_p)e^{-(x-x_p)/L_n}$$

Ideal Diode

$\mathscr{E} \neq 0$ in the depletion region, minority carrier diff. eq. not applicable

From continuity equation,

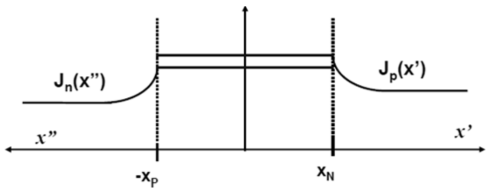
$$0 = \frac{1}{q}\frac{dJ_N}{dx} + \cancel{\frac{\partial n}{\partial t}}|_{R-G}$$

$$0 = -\frac{1}{q}\frac{dJ_P}{dx} + \cancel{\frac{\partial p}{\partial t}}|_{R-G}$$

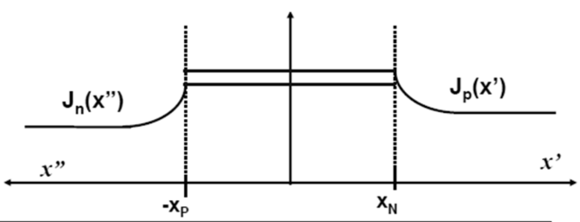
Ideal Diode: assume no R-G in the depletion region

Current is a constant inside depletion region

$$J = J_N(-x_p) + J_P(x_n)$$



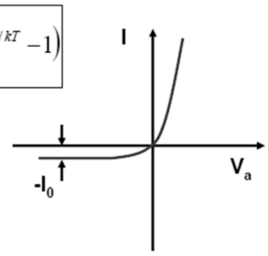
Ideal Diode, I-V



$$\boxed{J = J_n(x''=0) + J_p(x'=0) = q\left(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right)\left(e^{qV_A/kT} - 1\right)}$$

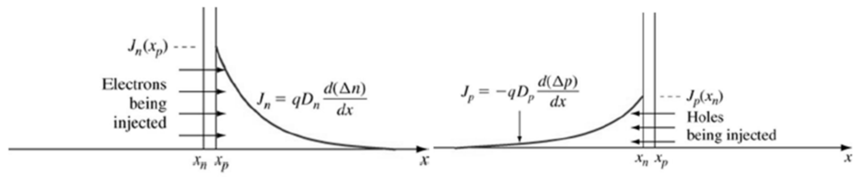
$$\boxed{I = qA\left(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right)\left(e^{qV_A/kT} - 1\right)}$$

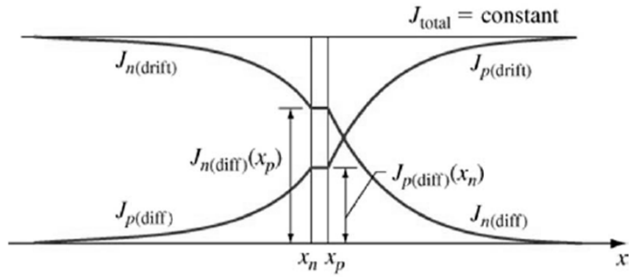
$$\boxed{I = I_0\left(e^{qV_A/kT} - 1\right)}$$



I_0 = Reverse saturation current

Total Current

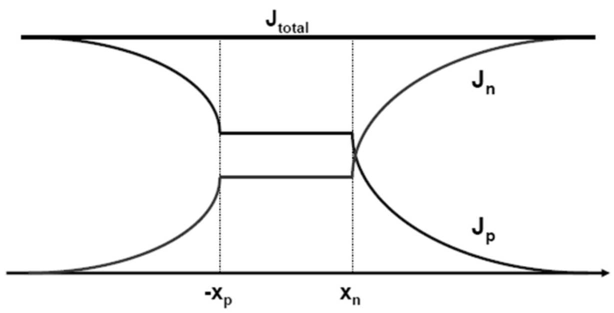




No R-G in depletion region

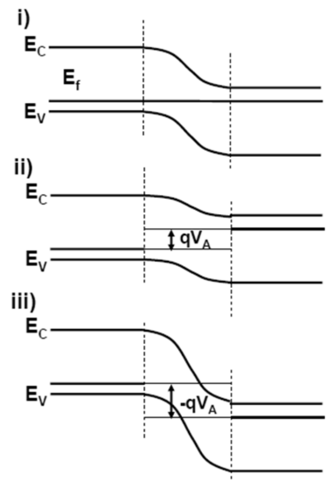
Electron and Hole Current

For all x, $J_{total} = J_n + J_p =$ constant

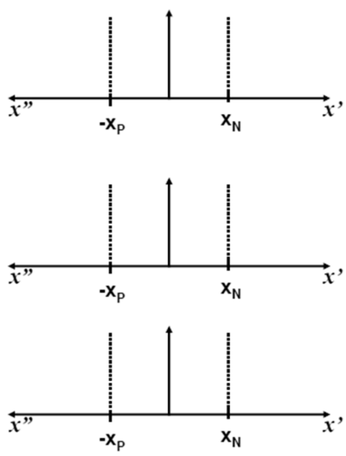


- **For every minority carrier recombination event, a majority carrier is injected from the contact**
- **$J_{total} > 0$ for $V_a > 0$**
- **$J_{total} < 0$ for $V_a < 0$**

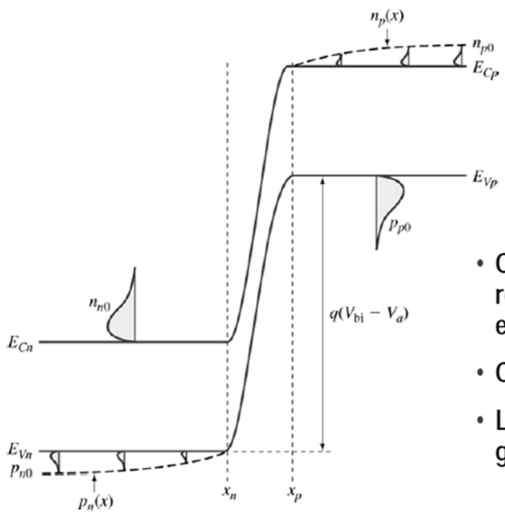
Carrier Concentration under Bias



Sketch carrier concentration within quasi-neutral regions



Diffusion Current –Reverse Bias



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

I_0 = Reverse saturation current

- Carriers at edge of depletion region swept across by electric field
- Carriers diffuse to junction
- Limited by minority carrier generation

P-N Diode With Asymmetric Doping

$$I = qA\left(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right)\left(e^{qV_A/kT} - 1\right)$$

Typically, one side of the junction is doped much more heavily

$N_A=10^{18}\ cm^{-3}$	$N_D=10^{15}\ cm^{-3}$

p^+-n junction

$N_A=10^{15}\ cm^{-3}$	$N_D=10^{18}\ cm^{-3}$

n^+-p junction

The ideal diode equation may be simplified with assymetric doping, rewrite expressions for p^+-n and n^+-p