Semiconductor Device Physics

Lecture 7

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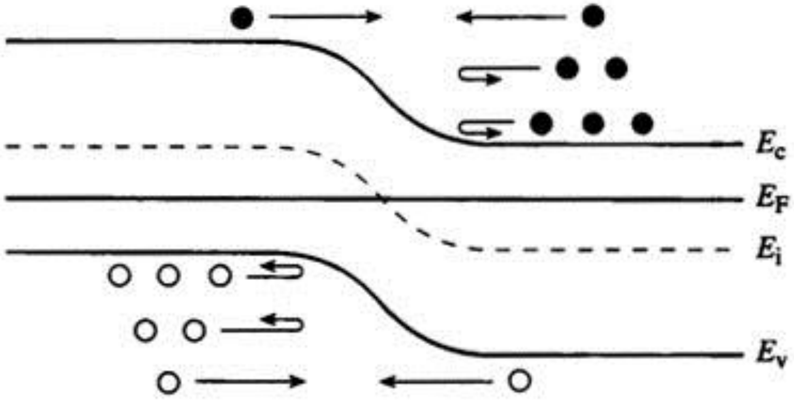
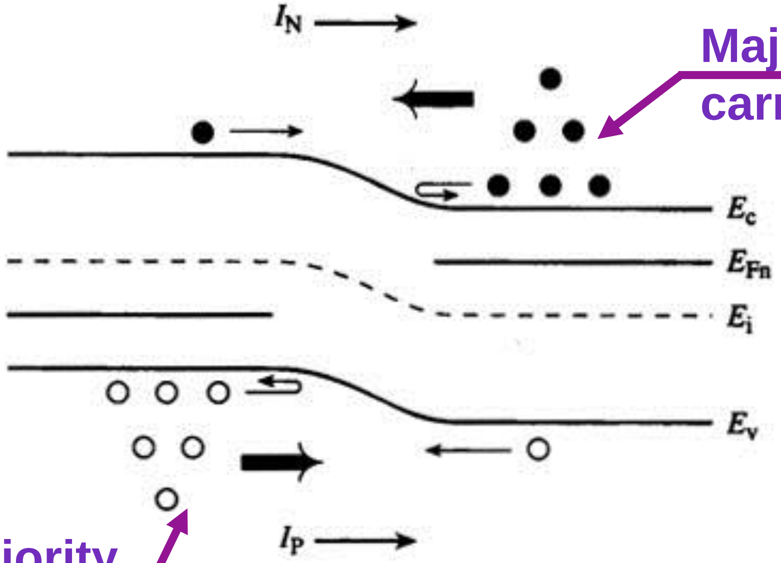
Chapter 6

pn Junction Diodes: *I-V* Characteristics

Qualitative Derivation

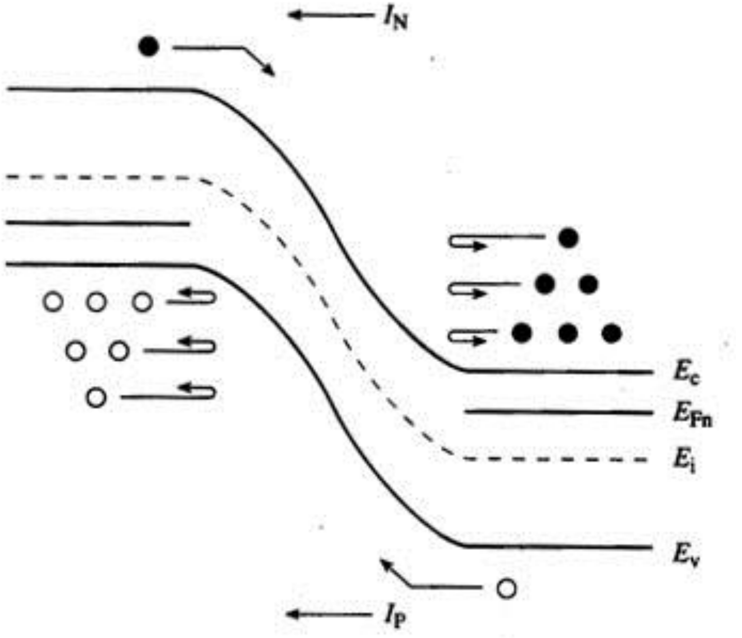


(a) Equilibrium ($V_A = 0$)

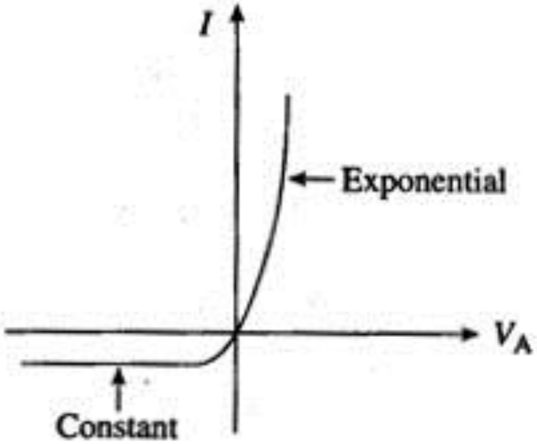


Majority carriers

Majority carriers

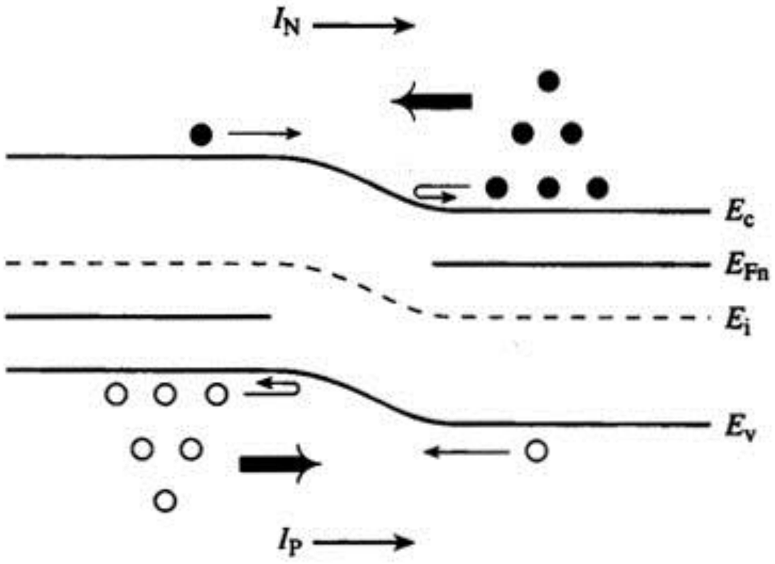


(c) Reverse bias ($V_A < 0$)



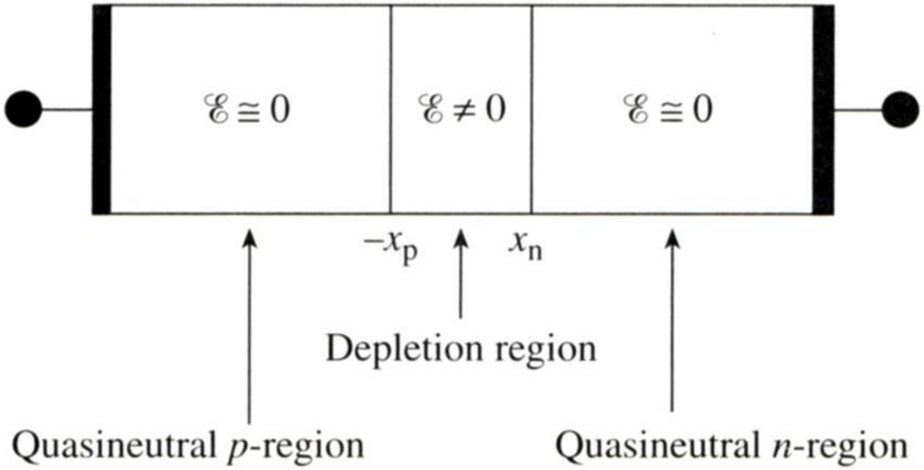
Current Flow in a *pn* Junction Diode

- When a forward bias ($V_A > 0$) is applied, the potential barrier to diffusion across the junction is reduced.
- Minority carriers are "injected" into the quasi-neutral regions ➔ $\Delta n_p > 0$, $\Delta p_n > 0$.
- Minority carriers diffuse in the quasi-neutral regions, recombining with majority carriers.



Ideal Diode: Assumptions

- Steady-state conditions.
- Non-degenerately doped step junction.
- One-dimensional diode.
- Low-level injection conditions prevail in the quasi-neutral regions.
- No processes other than drift, diffusion, and thermal R–G take place inside the diode.



Current Flow in a *pn* Junction Diode

- Current density **J** = $\mathbf{J}_\mathrm{N}(x) + \mathbf{J}_\mathrm{P}(x)$

$$\mathbf{J}_\mathrm{N}(x) = q\mu_\mathrm{n} n\mathcal{E} + qD_\mathrm{N}\frac{dn}{dx} = q\mu_\mathrm{n} n\mathcal{E} + qD_\mathrm{N}\frac{d(\Delta n)}{dx}$$

$$\mathbf{J}_\mathrm{P}(x) = q\mu_\mathrm{p} p\mathcal{E} - qD_\mathrm{P}\frac{dp}{dx} = q\mu_\mathrm{p} p\mathcal{E} - qD_\mathrm{P}\frac{d(\Delta p)}{dx}$$

- $\mathbf{J}_\mathrm{N}(x)$ and $\mathbf{J}_\mathrm{P}(x)$ may vary with position, but **J** is constant throughout the diode.
- Yet an additional assumption is now made, that thermal recombination-generation is negligible throughout the depletion region → J_N and J_P are therefore determined to be constants independent of position inside the depletion region.

Carrier Concentrations at $-x_p$, $+x_n$

- Consider the **equilibrium** carrier concentrations at $V_A = 0$:

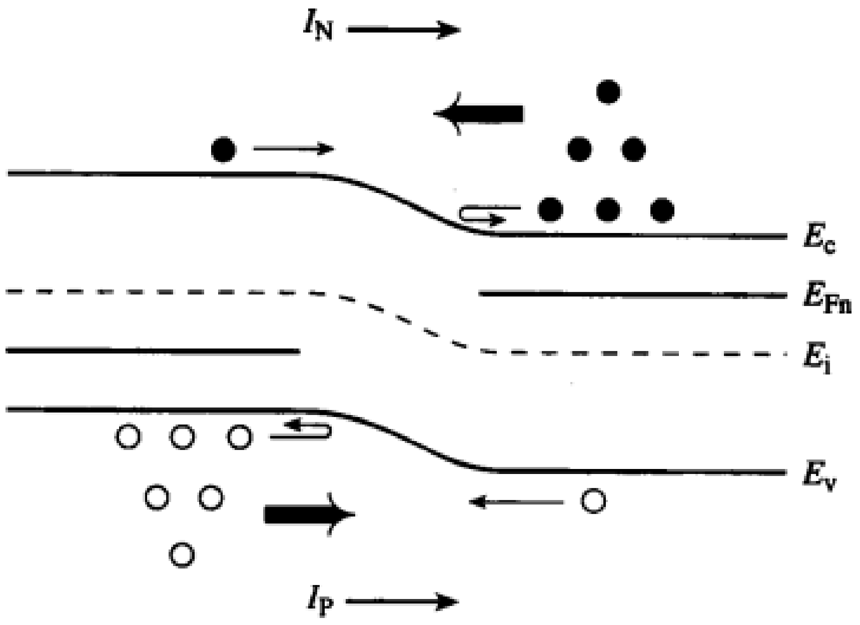
***p*-side**	***n*-side**
$p_{p0}(-x_p) = N_A$	$n_{n0}(x_n) = N_D$
$n_{p0}(-x_p) = \dfrac{n_i^2}{N_A}$	$p_{n0}(x_n) = \dfrac{n_i^2}{N_D}$

- If low-level injection conditions prevail in the quasi-neutral regions when $V_A \neq 0$, then:

$$p_p(-x_p) = N_A \qquad\qquad n_n(x_n) = N_D$$

"Law of the Junction"

- The voltage V_A applied to a *pn* junction **falls mostly across the depletion region** (assuming that low-level injection conditions prevail in the quasi-neutral regions).
- Two quasi-Fermi levels is drawn in the depletion region:



$$p = n_i e^{(E_i - F_P)/kT}$$

$$n = n_i e^{(F_N - E_i)/kT}$$

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

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

$$\boxed{np = n_i^2 e^{qV_A/kT}}$$

$$\text{for } -x_p \le x \le x_n$$

Excess Carrier Concentrations at $-x_p$, x_n

***p*-side**

$$p_p(-x_p) = N_A$$

$$n_p(-x_p) = \frac{n_i^2 e^{qV_A/kT}}{N_A}$$

$$= n_{p0} e^{qV_A/kT}$$

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

***n*-side**

$$n_n(x_n) = N_D$$

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

$$= p_{n0} e^{qV_A/kT}$$

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

Example: Carrier Injection

- A *pn* junction has $N_A = 10^{18}$ cm^{-3} and $N_D = 10^{16}$ cm^{-3}. The applied voltage is 0.6 V.

a) What are the minority carrier concentrations at the depletion-region edges?

$$n_p(-x_p) = n_{p0} e^{qV_A/kT} = 100 \times e^{0.6/0.02586} = \underline{\underline{1.192 \times 10^{12}\ \text{cm}^{-3}}}$$

$$p_n(x_n) = p_{n0} e^{qV_A/kT} = 10^4 \times e^{0.6/0.02586} = \underline{\underline{1.192 \times 10^{14}\ \text{cm}^{-3}}}$$

b) What are the excess minority carrier concentrations?

$$\Delta n_p(-x_p) = n_p(-x_p) - n_{p0} = 1.192 \times 10^{12} - 100 = \underline{\underline{1.192 \times 10^{12}\ \text{cm}^{-3}}}$$

$$\Delta p_n(x_n) = p_n(x_n) - p_{n0} = 1.192 \times 10^{14} - 10^4 = \underline{\underline{1.192 \times 10^{14}\ \text{cm}^{-3}}}$$

Excess Carrier Distribution

- From the **minority carrier** diffusion equation,

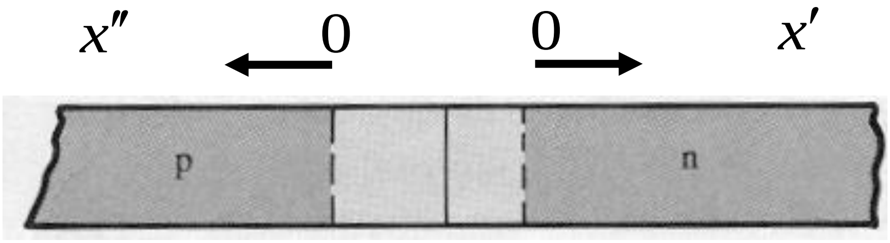
$$0 = D_{\mathrm{P}} \frac{d^2 \Delta p_{\mathrm{n}}}{dx'^2} - \frac{\Delta p_{\mathrm{n}}}{\tau_{\mathrm{p}}}, \qquad x' \geq 0$$

- We have the following boundary conditions:

$$\Delta p_{\mathrm{n}}(x_{\mathrm{n}}) = p_{\mathrm{n0}}(e^{qV_{\mathrm{A}}/kT} - 1)$$

$$\Delta p_{\mathrm{n}}(\infty) \to 0$$

- For simplicity, we develop a new coordinate system:



- Then, the solution is given by:

for $x' \geq 0$

$$\Delta p_{\mathrm{n}}(x') = A_1 e^{-x'/L_{\mathrm{P}}} + A_2 e^{x'/L_{\mathrm{P}}}$$

$$L_{\mathrm{P}} = \sqrt{D_{\mathrm{P}} \tau_{\mathrm{p}}}$$

  - **L_{P} : hole minority carrier diffusion length**

Excess Carrier Distribution

$$\Delta p_\mathrm{n}(x') = A_1 e^{-x'/L_\mathrm{P}} + A_2 e^{x'/L_\mathrm{P}}$$

- New boundary conditions

$$\Delta p_\mathrm{n}(x' \to 0) = p_\mathrm{n0}(e^{qV_\mathrm{A}/kT} - 1)$$

$$\Delta p_\mathrm{n}(x' \to \infty) = 0$$

- From the *x'* → ∞, $A_2 = 0$

  From the *x'* → 0, $A_1 = p_\mathrm{n0}(e^{qV_\mathrm{A}/kT} - 1)$

- Therefore $\boxed{\Delta p_\mathrm{n}(x') = p_\mathrm{n0}(e^{qV_\mathrm{A}/kT} - 1)e^{-x'/L_\mathrm{P}}, \quad x' \geq 0}$

- Similarly, $\boxed{\Delta n_\mathrm{p}(x'') = n_\mathrm{p0}(e^{qV_\mathrm{A}/kT} - 1)e^{-x''/L_\mathrm{N}}, \quad x'' \geq 0}$

pn Diode *I–V* Characteristic

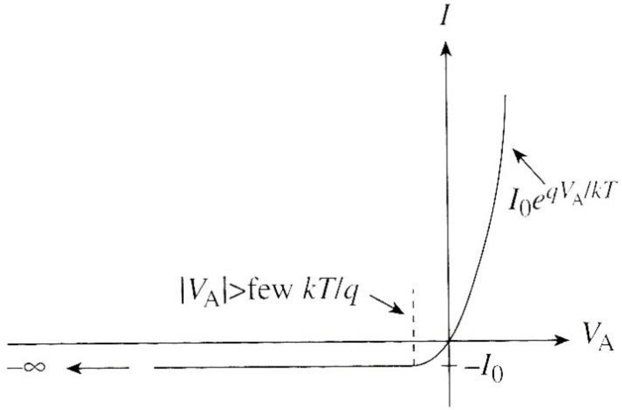
***n*-side** $$\mathbf{J}_{\mathrm{P}}(x') = -qD_{\mathrm{P}}\frac{d\Delta p_{\mathrm{n}}(x')}{dx'} = q\frac{D_{\mathrm{P}}}{L_{\mathrm{P}}}p_{\mathrm{n0}}(e^{qV_{\mathrm{A}}/kT}-1)e^{-x'/L_{\mathrm{P}}}$$

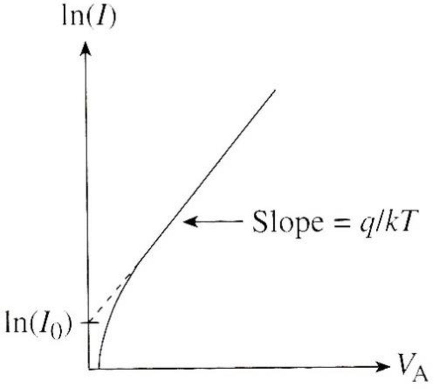
***p*-side** $$\mathbf{J}_{\mathrm{N}}(x'') = -qD_{\mathrm{N}}\frac{d\Delta n_{\mathrm{p}}(x'')}{dx''} = q\frac{D_{\mathrm{N}}}{L_{\mathrm{N}}}n_{\mathrm{p0}}(e^{qV_{\mathrm{A}}/kT}-1)e^{-x''/L_{\mathrm{N}}}$$

$$\mathbf{J} = \mathbf{J}_{\mathrm{N}}\big|_{x=-x_{\mathrm{p}}} + \mathbf{J}_{\mathrm{P}}\big|_{x=x_{\mathrm{n}}} = \mathbf{J}_{\mathrm{N}}\big|_{x''=0} + \mathbf{J}_{\mathrm{P}}\big|_{x'=0}$$

$$\boxed{\mathbf{J} = qn_{\mathrm{i}}^2\left(\frac{D_{\mathrm{N}}}{L_{\mathrm{N}}N_{\mathrm{A}}}+\frac{D_{\mathrm{P}}}{L_{\mathrm{P}}N_{\mathrm{D}}}\right)(e^{qV_{\mathrm{A}}/kT}-1)}$$

pn Diode *I–V* Characteristic





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

$$\boxed{\begin{aligned} I &= I_0(e^{qV_A/kT} - 1) \\ I_0 &= Aqn_i^2\left(\frac{D_N}{L_N N_A} + \frac{D_P}{L_P N_D}\right) \end{aligned}}$$

- **Shockley Equation, for ideal diode**
- **I_0 can be viewed as the drift current due to minority carriers generated within the diffusion lengths of the depletion region**

Diode Saturation Current I_0

$$I_0 = Aqn_i^2\left(\frac{D_P}{L_P N_D} + \frac{D_N}{L_N N_A}\right)$$

- I_0 can vary by orders of magnitude, depending on the semiconductor material, due to n_i^2 factor.
- In an asymmetrically doped *pn* junction, the term associated with the more heavily doped side is negligible.
  - If the *p* side is much more heavily doped,

$$I_0 \cong Aqn_i^2\left(\frac{D_P}{L_P N_D}\right)$$

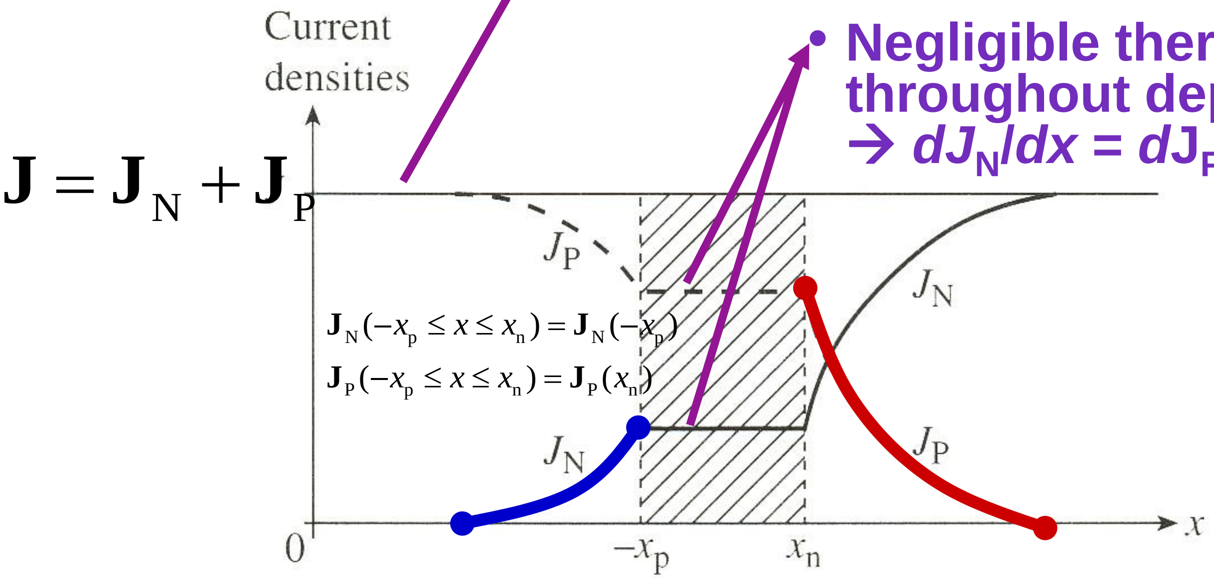
  - If the *n* side is much more heavily doped,

$$I_0 \cong Aqn_i^2\left(\frac{D_N}{L_N N_A}\right)$$

Diode Carrier Currents

- **Total current density is constant inside the diode**

- **Negligible thermal R-G throughout depletion region → $dJ_N/dx = dJ_P/dx = 0$**



$$\mathbf{J} = \mathbf{J}_N + \mathbf{J}_P$$

$$\mathbf{J}_N(-x_p \le x \le x_n) = \mathbf{J}_N(-x_p)$$

$$\mathbf{J}_P(-x_p \le x \le x_n) = \mathbf{J}_P(x_n)$$

Carrier Concentration: Forward Bias

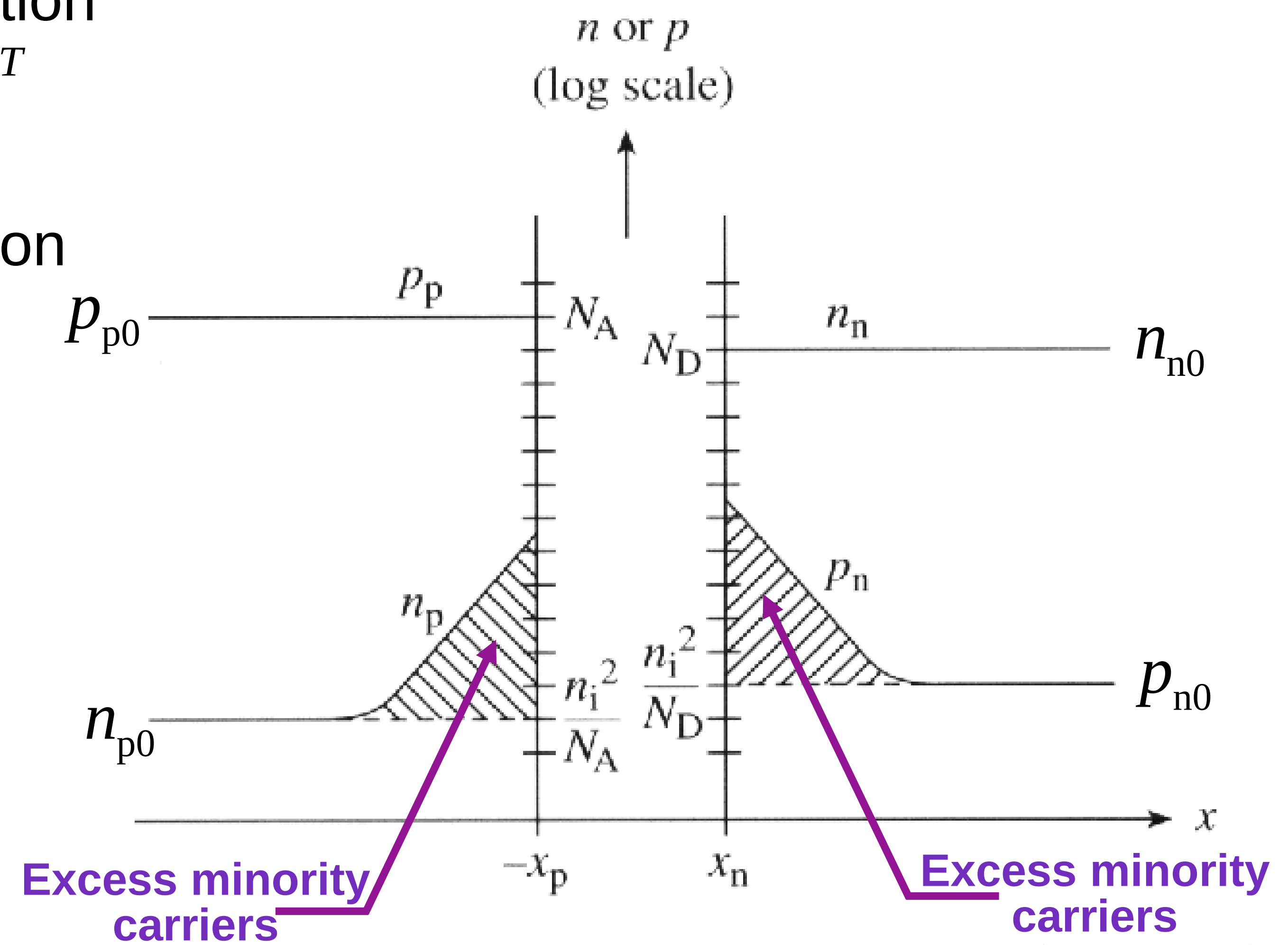
- Law of the Junction

$$np = n_{\mathrm{i}}^2 e^{qV_{\mathrm{A}}/kT}$$

- Low level injection conditions

$$p_{\mathrm{p}} = N_{\mathrm{A}}$$

$$n_{\mathrm{n}} = N_{\mathrm{D}}$$



Excess minority carriers

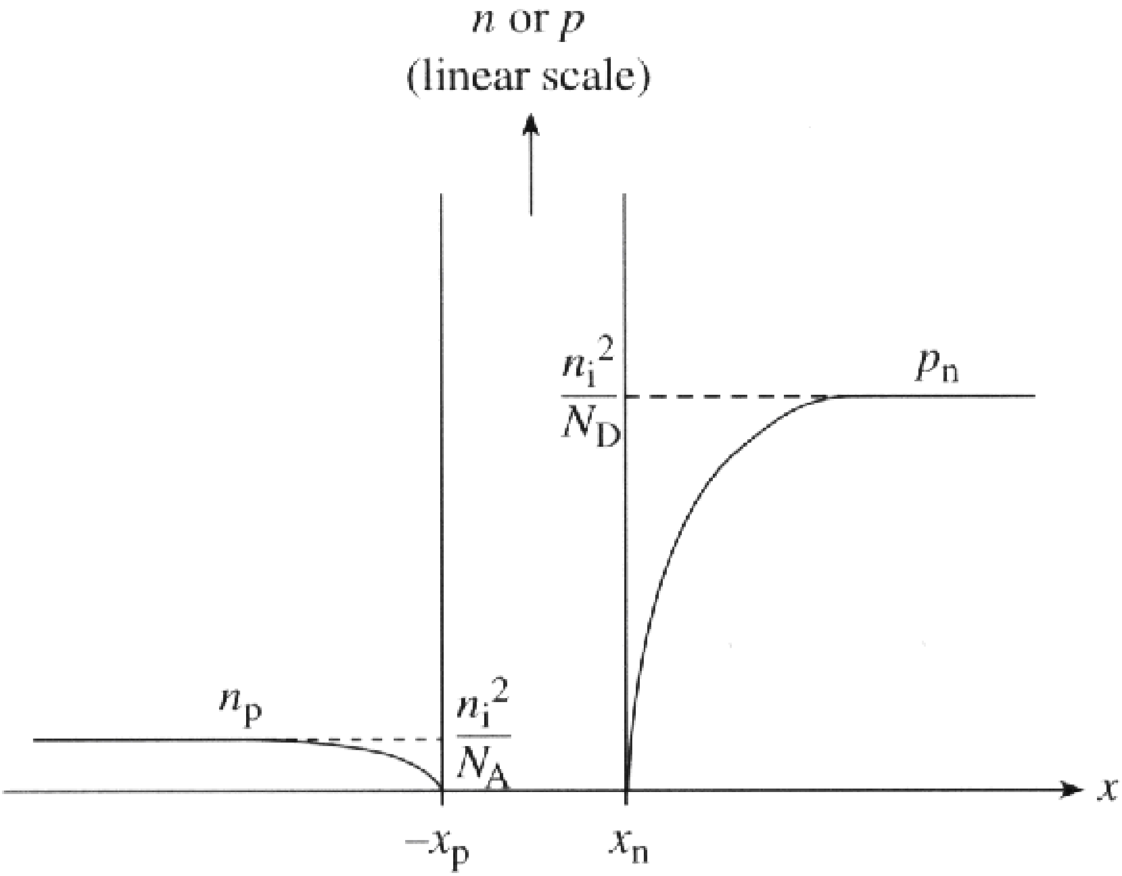
Excess minority carriers

$$\Delta n_{\mathrm{p}}(x'') = n_{\mathrm{p0}}(e^{qV_{\mathrm{A}}/kT} - 1)e^{-x''/L_{\mathrm{N}}}$$

$$\Delta p_{\mathrm{n}}(x') = p_{\mathrm{n0}}(e^{qV_{\mathrm{A}}/kT} - 1)e^{-x'/L_{\mathrm{P}}}$$

Carrier Concentration: Reverse Bias

- Deficit of minority carriers near the depletion region.
- Depletion region acts like a "sink", draining carriers from the adjacent quasineutral regions



Breakdown Voltage, V_{BR}

- If the reverse bias voltage ($-V_{\text{A}}$) is so large that the peak electric field exceeds a critical value $\mathcal{E}_{\text{CR}}$, then the junction will “break down” and large reverse current will flow.

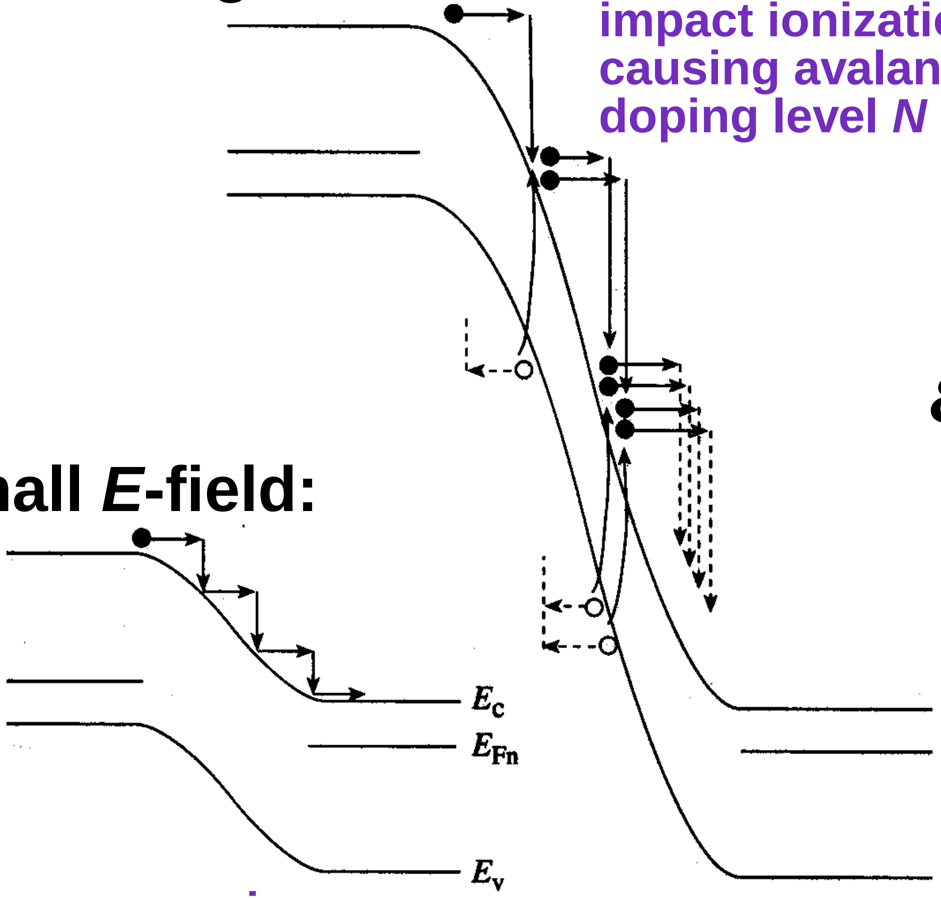
$$\mathcal{E}_{\text{CR}} = \sqrt{\frac{2q}{\varepsilon_{\text{S}}}\left(\frac{N_{\text{A}}N_{\text{D}}}{N_{\text{A}}+N_{\text{D}}}\right)\left(V_{\text{bi}}+V_{\text{BR}}\right)}$$

- **At breakdown, $V_{\text{A}}=-V_{\text{BR}}$**

- Thus, the reverse bias at which breakdown occurs is

$$V_{\text{BR}} = \frac{\varepsilon_{\text{S}}\mathcal{E}_{\text{CR}}^{\;2}}{2q}\left(\frac{N_{\text{A}}+N_{\text{D}}}{N_{\text{A}}N_{\text{D}}}\right) - V_{\text{bi}}$$

Breakdown Mechanism: Avalanching



High *E*-field:

High energy, enabling impact ionization which causing avalanche, at doping level $N < 10^{18}$ cm^{-3}

Small *E*-field:

Low energy, causing lattice vibration and localized heating only

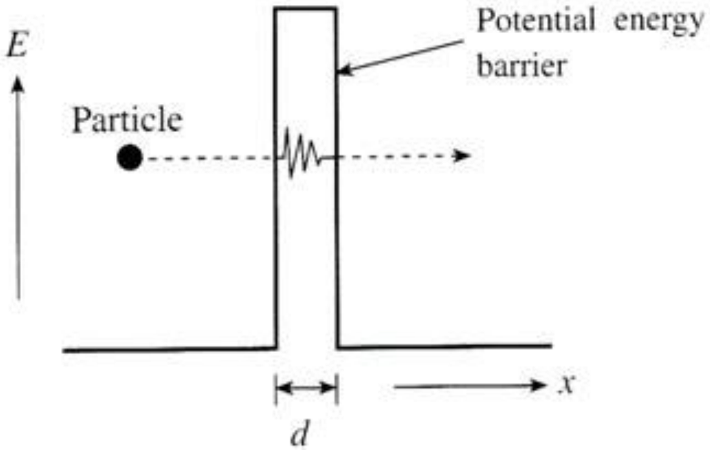
$$\mathcal{E}_{CR}^{2} \approx \frac{2q}{\varepsilon_S}\left(\frac{N_A N_D}{N_A + N_D}\right)V_{BR}$$

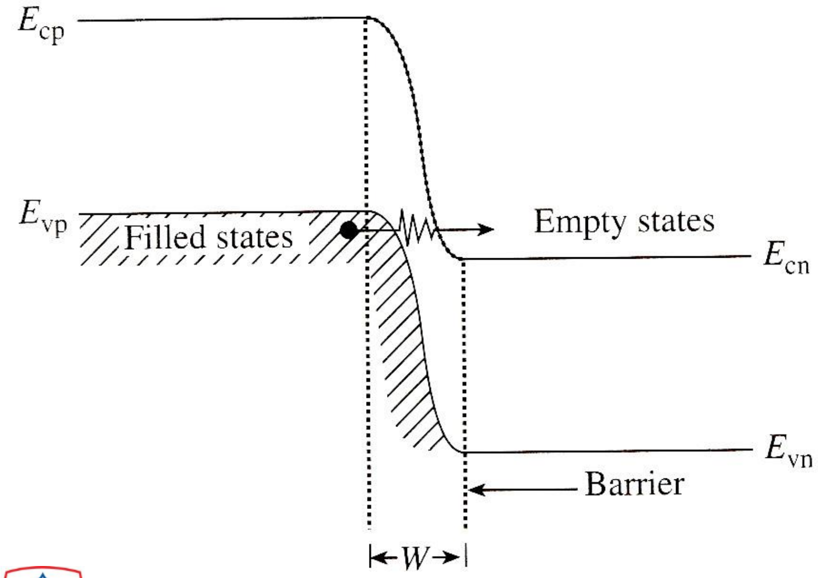
- $\mathcal{E}_{CR}$: critical electric field in the depletion region

$$V_{BR} \approx \frac{\varepsilon_s \mathcal{E}_{CR}^{2}}{2qN}$$

Breakdown Mechanism: Zener Process

- Zener process is the **tunneling** mechanism in a reverse-biased diode
  - Energy barrier is higher than the kinetic energy of the particle.
  - The particle energy remains constant during the tunneling process.





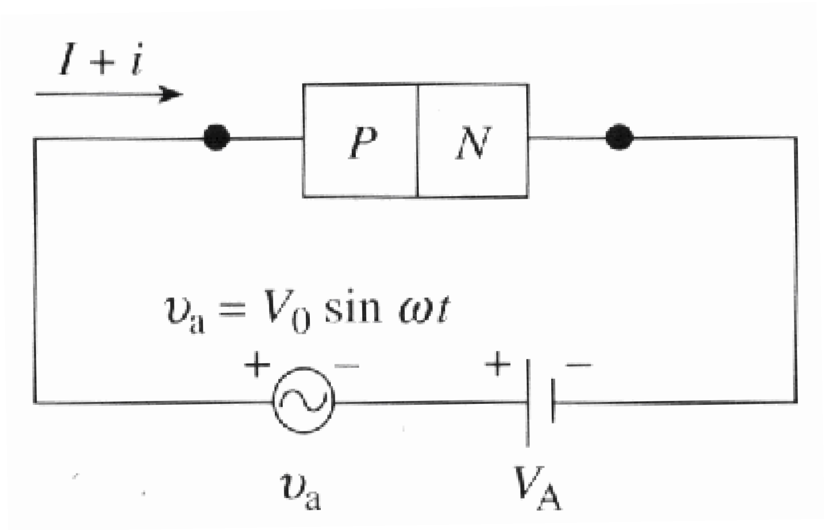
- Barrier must be thin ➔ dominant breakdown mechanism when both junction sides are heavily doped.
- Typically, Zener process dominates when $V_{BR} < 4.5$V in Si at 300 K and $N > 10^{18}$ cm^{-3}.

Chapter 7

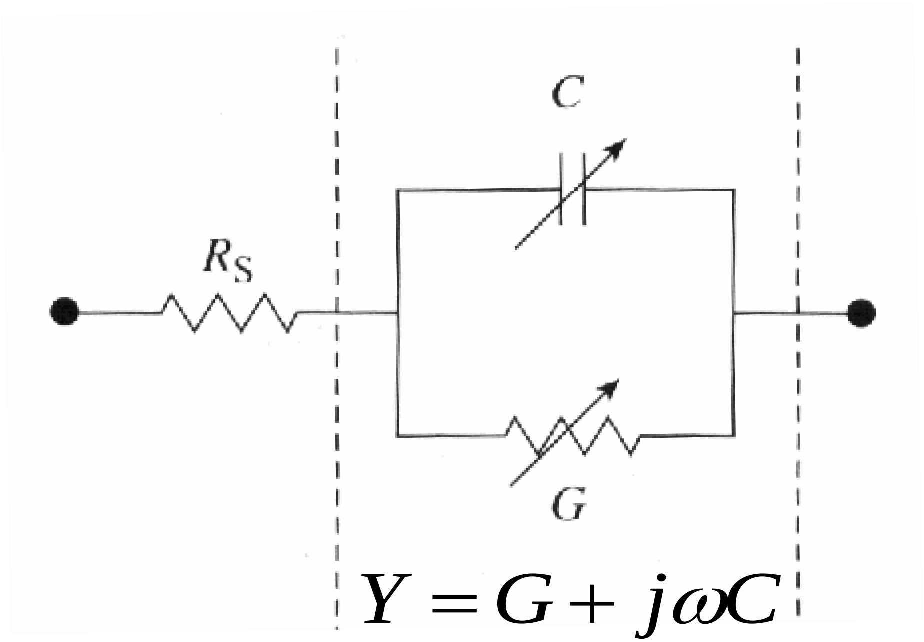
pn Junction Diodes: Small-Signal Admittance

Small-Signal Diode Biasing

- When reversed-biased, a *pn* junction diode becomes functionally equivalent to a capacitor, whose capacitance decreases as the reverse bias increases.
- Biasing additional a.c. signal v_a can be viewed as a small oscillation of the depletion width about the steady state value.



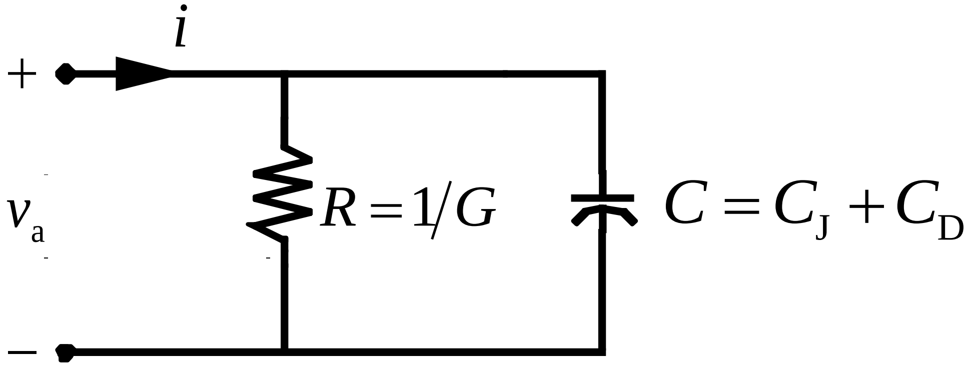
$V_0 << V_A$



$$Y = G + j\omega C$$

R_S : serial resistance
C : capacitance
G : conductance
Y : admittance

Total *pn* Junction Capacitance



$$C_J = A\frac{\varepsilon_s}{W}$$

Junction / depletion capacitance, due to variation of depletion charges

Minority carrier lifetime

$$C_D = \frac{\tau I_{DC}}{kT/q}$$

Diffusion capacitance, due to variation of stored minority charges in the quasineutral regions

- **C_J dominates at low forward biases, reverse biases.**
- **C_D dominates at moderate to high forward biases.**

Relation Between C_J and V_A

- For asymmetrical step junction,

$$W = \sqrt{\frac{2\varepsilon_S}{qN_B}\left(V_{bi} - V_A\right)}$$

N_B : bulk semiconductor doping, N_A or N_D as appropriate.

- Therefore,

$$\boxed{\frac{1}{C_J^{\,2}} = \frac{W^2}{A^2\varepsilon_S^{\,2}} \cong \frac{2}{qN_B\varepsilon_S A^2}(V_{bi} - V_A)}$$

- **A plot of $1/C_J^2$ versus V_A is linear.**
- **The slope is inversely proportional to N_B.**
- **An extrapolated $1/C_J^2 = 0$ intercept is equal to V_{bi}.**