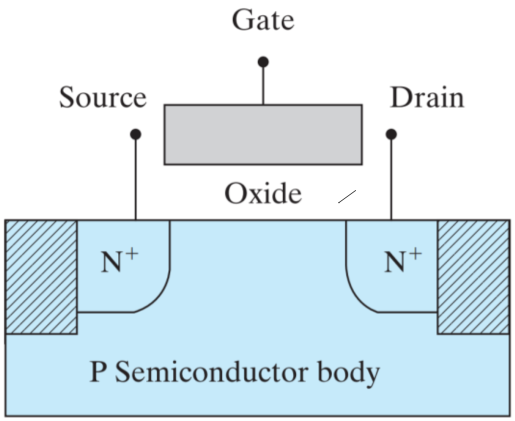
PN junction
Diode I-V Characteristics

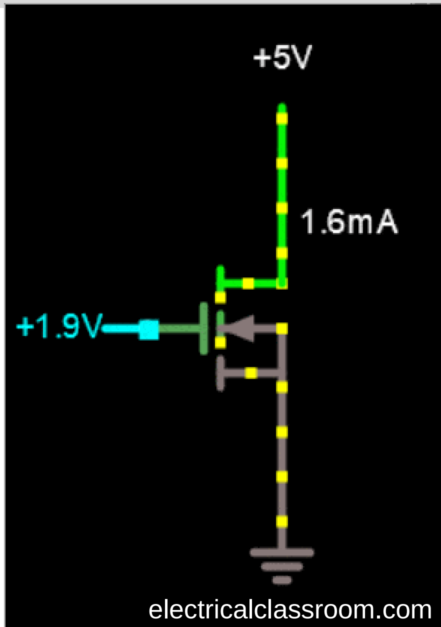


EE302

Prof. Sangyoon Han

Fall 2023

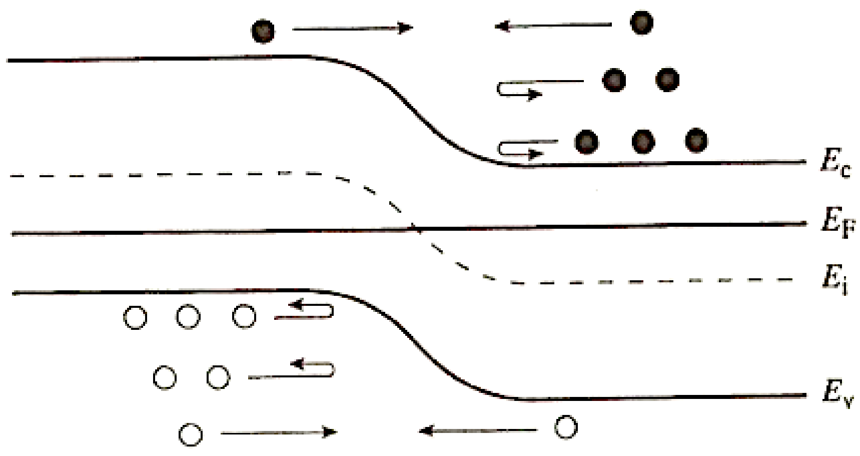
References:
- (R. Pierret) Chapter 6
- (C. Hu) Chapter 4
- Materials from SE393 (Prof. Hongki Kang)



Overview

- **<u>Steady-state response</u> modeling of the *pn* junction diode**
- **Ideal diode**
  - **Qualitative analysis**
  - **Quantitative analysis**
- **Non-ideal diode characteristics**

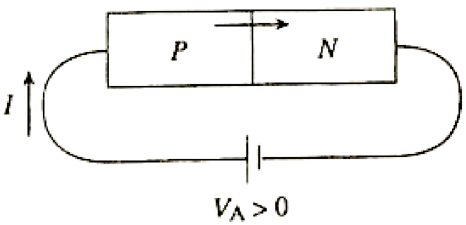
Qualitative Derivation

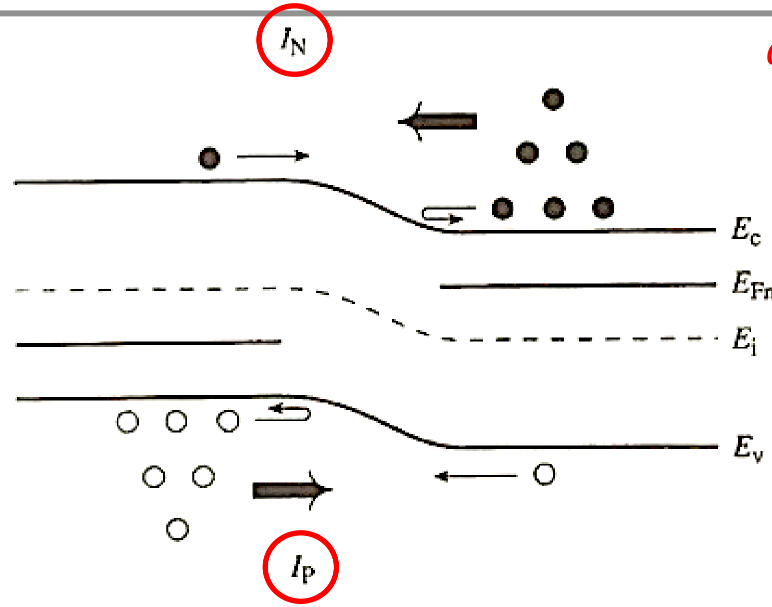


- **Under equilibrium ($V_A = 0$)**
  - **Balance of drift & diffusion for both e^- and h^+**
  - **Net current?**

Qualitative Derivation

$qV_A = E_{Fn} - E_{Fp}$

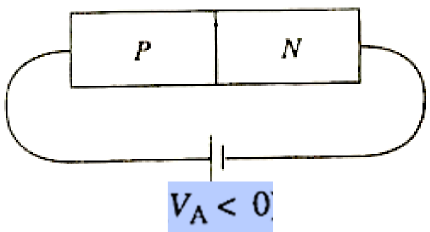


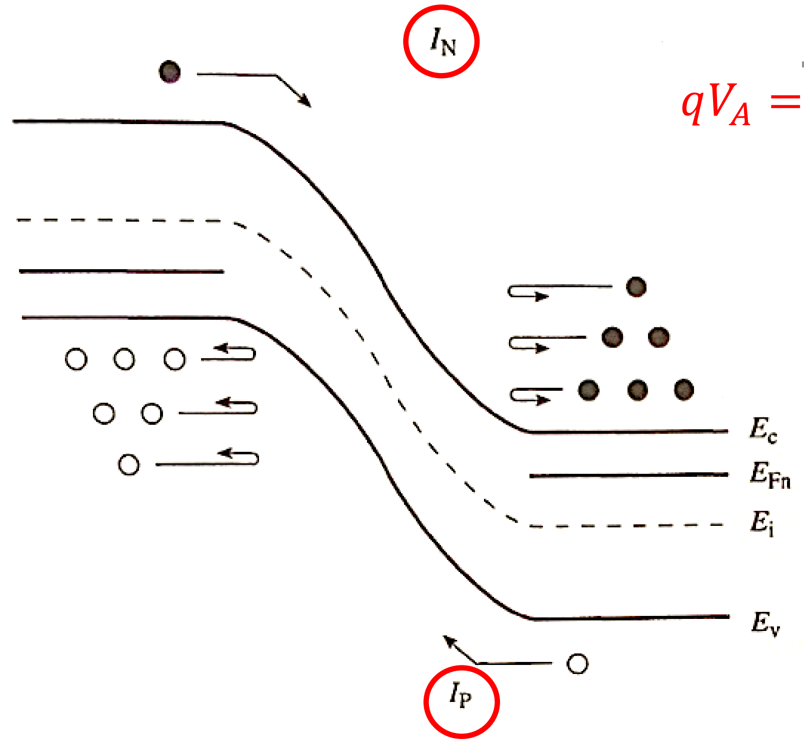


- **Forward biased ($V_A > 0$)**
  - **Quasi-Fermi level locations**
  - **Drift vs. Diffusion**
  - **Majority carriers vs. Minority carriers**
  - **Direction of net current for e^- and h^+?**
  - **Net current?**

Qualitative Derivation

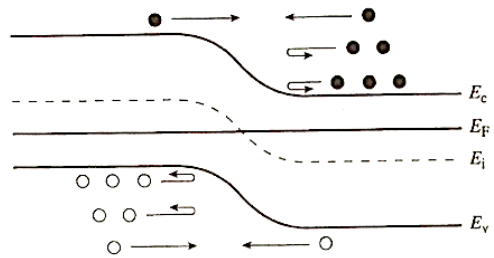
$$qV_A = E_{Fn} - E_{Fp}$$

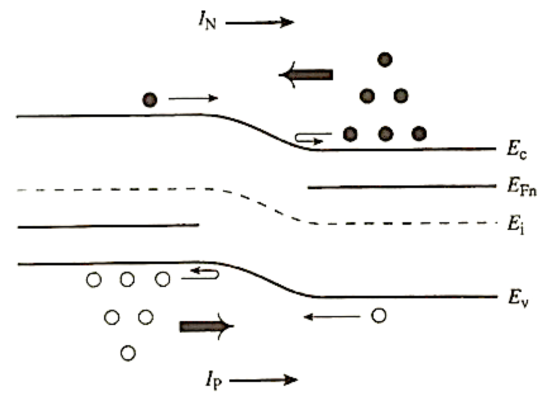


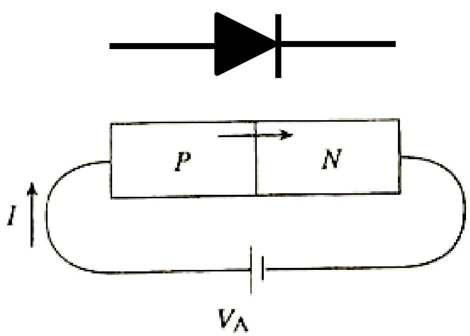


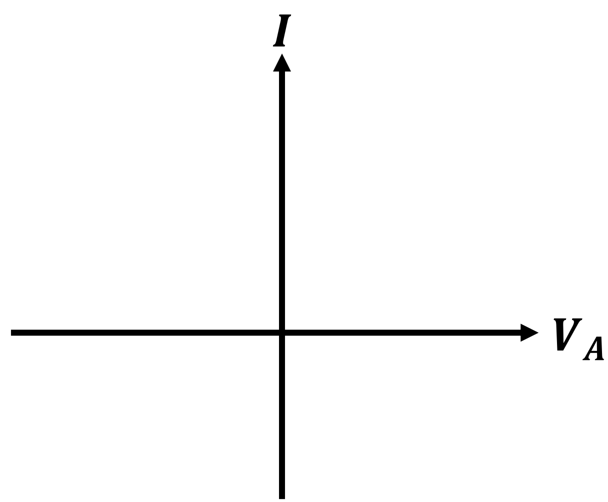
- **Reverse biased ($V_A < 0$)**
  - **Quasi-Fermi level locations**
  - **Drift vs. Diffusion**
  - **Majority carriers vs. Minority carriers**
  - **Direction of net current for e^- and h^+?**
  - **Net current?**

Qualitative Derivation









- **How would diode current (I) changes in response to applied bias (V_A)?**

Qualitative Derivation

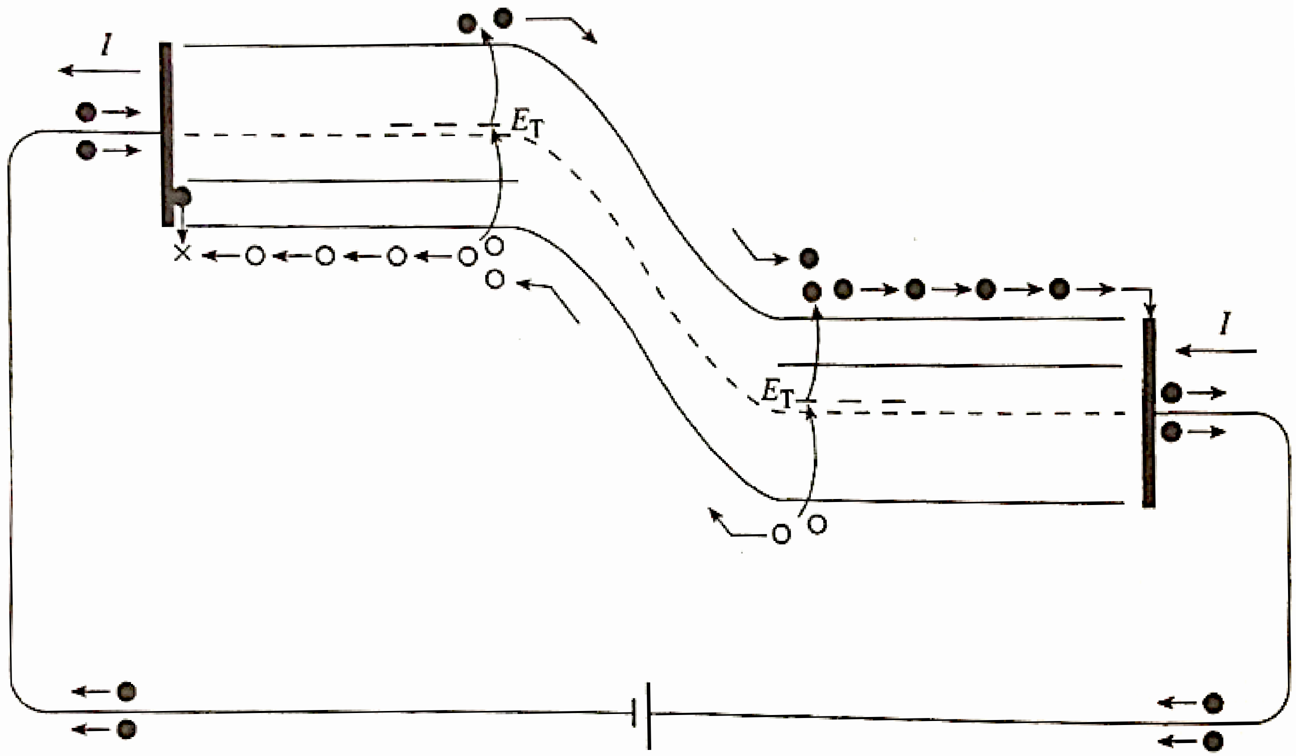
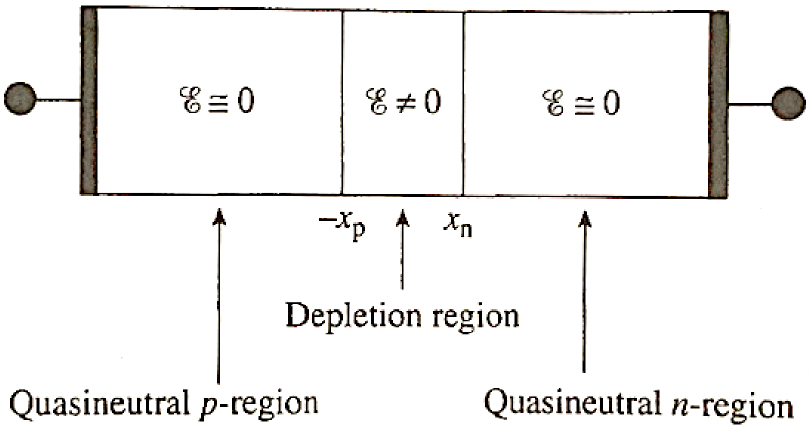


Figure 6.2 Composite energy-band/circuit diagram providing an overall view of carrier activity inside a reverse-biased *pn* junction diode. The capacitor-like plates at the outer ends of the energy band diagram schematically represent the ohmic contacts to the diode.

- **Beyond the depletion region**
- **R–G in Quasi-Neutral regions**

Quantitative Solution Strategy: *General Considerations*

- **Under steady state conditions**
- **Non-degenerately doped step junction**
- **One-dimensional**
- **Low-level injection in the quasi-neutral regions**
- **No other processes inside the diode, only;**
  1. **Drift**
  2. **Diffusion**
  3. **Thermal R-G**
  4. **$G_L = 0$ (no photogeneration)**



Diffusion length calculation & diffusion equation (begin)

Continuity Equations

$$\frac{\partial n}{\partial t} = \left.\frac{\partial n}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial n}{\partial t}\right|_{\text{diff}} + \left.\frac{\partial n}{\partial t}\right|_{\text{thermal, R–G}} + \left.\frac{\partial n}{\partial t}\right| \begin{array}{l}\text{other processes}\\ \text{(light, etc.)}\end{array}$$

$$\frac{\partial p}{\partial t} = \left.\frac{\partial p}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial p}{\partial t}\right|_{\text{diff}} + \left.\frac{\partial p}{\partial t}\right|_{\text{thermal, R–G}} + \left.\frac{\partial p}{\partial t}\right| \begin{array}{l}\text{other processes}\\ \text{(light, etc.)}\end{array}$$

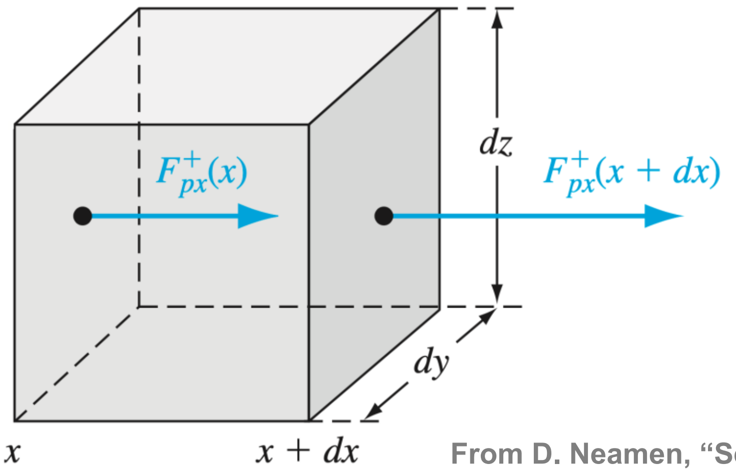
$$\left.\frac{\partial n}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial n}{\partial t}\right|_{\text{diff}} = \frac{1}{q}\left(\frac{\partial J_{\text{Nx}}}{\partial x} + \frac{\partial J_{\text{Ny}}}{\partial y} + \frac{\partial J_{\text{N}z}}{\partial z}\right) = \frac{1}{q}\nabla \cdot \mathrm{J}_{\text{N}}$$

$$\left.\frac{\partial p}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial p}{\partial t}\right|_{\text{diff}} = -\frac{1}{q}\left(\frac{\partial J_{\text{px}}}{\partial x} + \frac{\partial J_{\text{py}}}{\partial y} + \frac{\partial J_{\text{Pz}}}{\partial z}\right) = -\frac{1}{q}\nabla \cdot \mathrm{J}_{\text{p}}$$

- **Drift, Diffusion:** spatial change of *n*, *p* over time defines the *dn/dt*, *dp/dt*
  - **i.e. current flow (*J*)**

Continuity Equations

$$F_{px}^{+}(x + dx) = F_{px}^{+}(x) + \frac{\partial F_{px}^{+}}{\partial x} \cdot dx$$



$$\frac{J_p}{(+q)} = F_p^{+}$$

From D. Neamen, "Semiconductor Physics and Devices," 4th edition

Figure 6.4 | Differential volume showing x component of the hole-particle flux.

$$= -\nabla \cdot F_p^{+} dxdydz$$

$$\frac{\partial p}{\partial t} dxdydz = \left[F_{px}^{+}(x) - F_{px}^{+}(x + dx)\right] dydz = -\frac{\partial F_{px}^{+}}{\partial x} dxdydz$$

$$\left.\frac{\partial p}{\partial t}\right|_{\mathrm{drift}} + \left.\frac{\partial p}{\partial t}\right|_{\mathrm{diff}} = -\frac{1}{q}\left(\frac{\partial J_{\mathrm{px}}}{\partial x} + \frac{\partial J_{\mathrm{py}}}{\partial y} + \frac{\partial J_{\mathrm{Pz}}}{\partial z}\right) = -\frac{1}{q} \nabla \cdot \mathrm{J_p}$$

Continuity Equations

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot \mathbf{J_N} + \left.\frac{\partial n}{\partial t}\right|_{Thermal,\mathbf{R-G}} + \left.\frac{\partial n}{\partial t}\right|_{\text{other processes}}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot \mathbf{J_p} + \left.\frac{\partial p}{\partial t}\right|_{Thermal,\mathbf{R-G}} + \left.\frac{\partial p}{\partial t}\right|_{\text{other processes}}$$

- **The most general equation used for carrier action in device analysis**
  - **Computational simulation**
  - $n(x, y, z, t)$**,** $p(x, y, z, t)$

Minority Carrier Diffusion Equations

- **Simplifying assumptions**
  - **One dimensional, x-axis**
  - **Minority charrier only analysis**
  - ***E* ≃ 0**
  - **Low level injection**
  - **Indirect thermal R–G dominant**

$$\frac{1}{q}\nabla\cdot\mathbf{J}_{\mathrm{N}} \rightarrow \frac{1}{q}\frac{\partial J_{\mathrm{N}}}{\partial x}$$

$$J_{\mathrm{N}} = q\mu_{\mathrm{n}} n\mathscr{E} + qD_{\mathrm{N}}\frac{\partial n}{\partial x} \approx qD_{\mathrm{N}}\frac{\partial n}{\partial x}$$

$$\frac{1}{q}\nabla\cdot\mathbf{J}_{\mathrm{N}} \rightarrow D_{\mathrm{N}}\frac{\partial^2 \Delta n}{\partial x^2}$$

$$\left.\frac{\partial n}{\partial t}\right|_{\text{thermal, R–G}} = -\frac{\Delta n}{\tau_{\mathrm{n}}}$$

$$\left.\frac{\partial n}{\partial t}\right|_{\text{other processes}} = G_{\mathrm{L}}$$

  - **Minority Carrier Diffusion Equations**

$$\frac{\partial \Delta n_{\mathrm{p}}}{\partial t} = D_{\mathrm{N}}\frac{\partial^2 \Delta n_{\mathrm{P}}}{\partial x^2} - \frac{\Delta n_{\mathrm{P}}}{\tau_{\mathrm{n}}} + G_{\mathrm{L}}$$

$$\frac{\partial \Delta p_{\mathrm{n}}}{\partial t} = D_{\mathrm{p}}\frac{\partial^2 \Delta p_{\mathrm{n}}}{\partial x^2} - \frac{\Delta p_{\mathrm{n}}}{\tau_{\mathrm{p}}} + G_{\mathrm{L}}$$

Minority Carrier Diffusion Equations

Table 3.1 Common Diffusion Equation Simplifications.

Simplification	*Effect*
Steady state	$\frac{\partial \Delta n_p}{\partial t} \to 0 \quad \left(\frac{\partial \Delta p_n}{\partial t} \to 0\right)$
No concentration gradient or no diffusion current	$D_N \frac{\partial^2 \Delta n_p}{\partial x^2} \to 0 \quad \left(D_P \frac{\partial^2 \Delta p_n}{\partial x^2} \to 0\right)$
No drift current or $\mathscr{E} = 0$	No further simplification. ($\mathscr{E} \simeq 0$ is assumed in the derivation.)
No thermal R–G	$\frac{\Delta n_p}{\tau_n} \to 0 \quad \left(\frac{\Delta p_n}{\tau_p} \to 0\right)$
No light	$G_L \to 0$

- **Apply the assumptions above depending on the situation.**

Diffusion Lengths

$$\frac{\partial \Delta n_{\mathrm{p}}}{\partial t} = D_{\mathrm{N}} \frac{\partial^2 \Delta n_{\mathrm{P}}}{\partial x^2} - \frac{\Delta n_{\mathrm{P}}}{\tau_{\mathrm{n}}} + G_{\mathrm{L}}$$

- **For example,**
  - **Steady-state:** $\partial \Delta n_p / \partial t$ **= 0**
  - **No light:** G_L **= 0**

$$0 = D_{\mathrm{N}} \frac{d^2 \Delta n_{\mathrm{p}}}{dx^2} - \frac{\Delta n_{\mathrm{p}}}{\tau_{\mathrm{n}}}$$

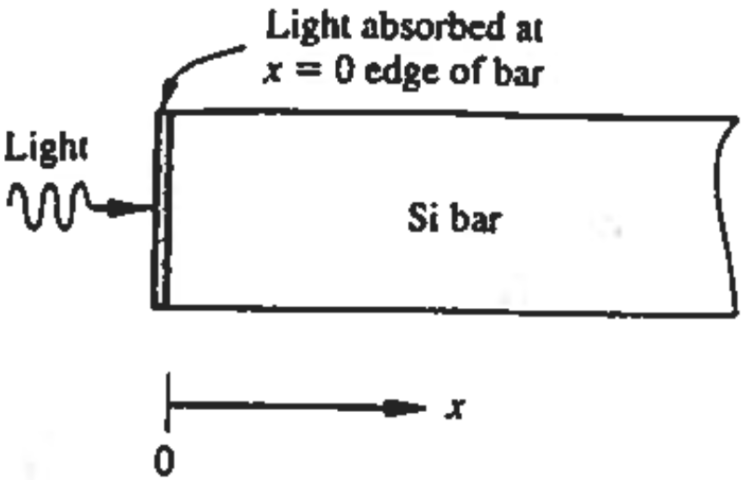
$$\Delta n_{\mathrm{p}}(x) = A e^{-x/L_{\mathrm{N}}} + B e^{x/L_{\mathrm{N}}}$$

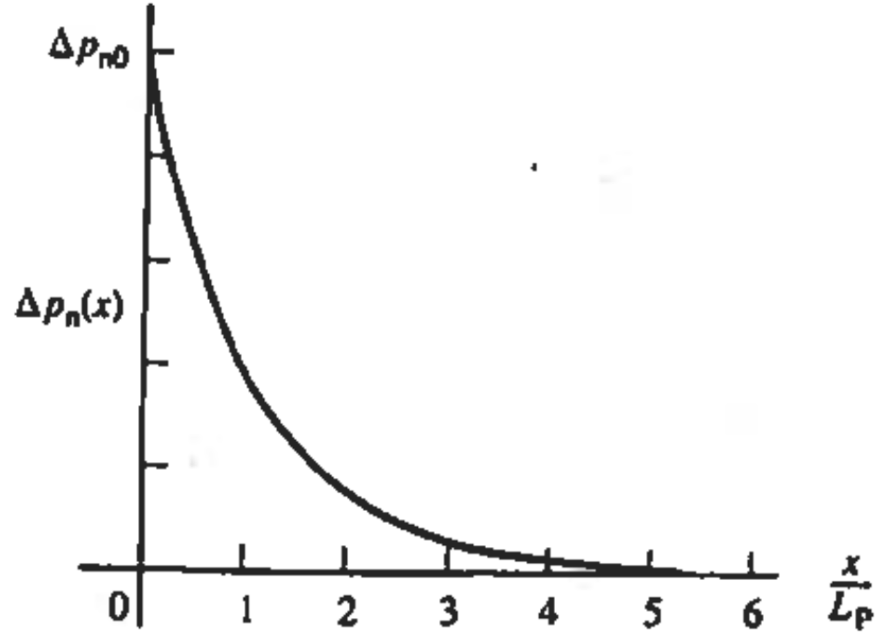
$$L_N = \sqrt{D_n \tau_n}$$

$$\Delta n_{\mathrm{p}}(x) = \Delta n_{\mathrm{p0}} e^{-x/L_{\mathrm{n}}}$$

  - L_N**: diffusion length**

Diffusion Lengths





$$\Delta p_{\mathrm{n}}(x) = \Delta p_{\mathrm{n0}} e^{-x/L_{\mathrm{p}}}$$

- **Average distance minority carriers diffuse into the semiconductor during recombination (τ_p= 1 μsec)**

- $L_p = \sqrt{D_p \tau_p} = \sqrt{\left(\frac{kT}{q}\right) \mu_p \tau_p} = \sqrt{0.026 \times 500 \times 10^{-6}} \approx 3.5 \times 10^{-3}\ cm$

Diffusion Lengths

$$\frac{\partial \Delta n_{\mathrm{p}}}{\partial t} = D_{\mathrm{N}} \frac{\partial^2 \Delta n_{\mathrm{P}}}{\partial x^2} - \frac{\Delta n_{\mathrm{P}}}{\tau_{\mathrm{n}}} + G_{\mathrm{L}}$$

- **For example,**
  - **Steady-state:** $\partial \Delta n_p / \partial t$ **= 0**
  - **No light:** G_L **= 0**

$$0 = D_{\mathrm{N}} \frac{d^2 \Delta n_{\mathrm{p}}}{dx^2} - \frac{\Delta n_{\mathrm{p}}}{\tau_{\mathrm{n}}}$$

$$\Delta n_{\mathrm{p}}(x) = A e^{-x/L_{\mathrm{N}}} + B e^{x/L_{\mathrm{N}}}$$

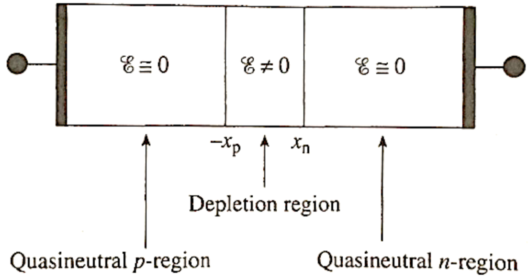
$$L_N = \sqrt{D_n \tau_n}$$

$$\Delta n_{\mathrm{p}}(x) = \Delta n_{\mathrm{p0}} e^{-x/L_{\mathrm{n}}}$$

  - L_{N}**: diffusion length**

Diffusion length calculation & diffusion equation (begin)

- **Quasineutral region (∴ net charge ≈ 0; thus, $\boldsymbol{E} \approx 0$)**
- **Minority carrier diffusion equation**



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

$$\frac{\partial \Delta p_n}{\partial t} = D_p \frac{\partial^2 \Delta p_n}{\partial x^2} - \frac{\Delta p_n}{\tau_p} + G_L$$

$$0 = D_n \frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_n}$$ ***p*-type quasi-neutral**

$$0 = D_p \frac{\partial^2 \Delta p_n}{\partial x^2} - \frac{\Delta p_n}{\tau_p}$$ ***n*-type quasi-neutral**

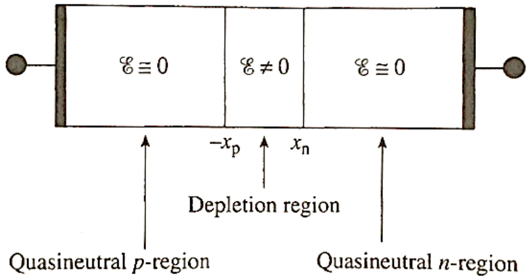
- **Current density**

$$\boldsymbol{J_n} = q\mu_n nE + qD_n \frac{dn}{dx} = qD_n \frac{dn}{dx} = \boldsymbol{qD_n \frac{d\Delta n_p}{dx}}$$

$$\boldsymbol{J_p} = q\mu_p pE - qD_p \frac{dp}{dx} = -qD_p \frac{dp}{dx} = \boldsymbol{-qD_p \frac{\Delta p_n}{dx}}$$

Quantitative Solution Strategy: *Depletion Region* Considerations

- **$E \neq 0$ (no Minority carrier diffusion equation)**



- **Continuity equations**

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot \mathbf{J_N} + \left.\frac{\partial n}{\partial t}\right|_{Thermal,\mathbf{R-G}} + \left.\frac{\partial n}{\partial t}\right|_{\text{other processes}}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot \mathbf{J_p} + \left.\frac{\partial p}{\partial t}\right|_{Thermal,\mathbf{R-G}} + \left.\frac{\partial p}{\partial t}\right|_{\text{other processes}}$$

- **Steady-state condition**

$$0 = \frac{1}{q}\frac{dJ_n}{dx} + \left(\frac{\partial n}{\partial t}\right)_{thermal,R-G} \qquad 0 = -\frac{1}{q}\frac{dJ_p}{dx} + \left(\frac{\partial p}{\partial t}\right)_{thermal,R-G}$$

- **Assumption: No *thermal R–G* in the depletion region! (Assumption from nowhere. It gives a simple solution.)**

$$\frac{dJ_n}{dx} = 0, \qquad \frac{dJ_p}{dx} = 0$$

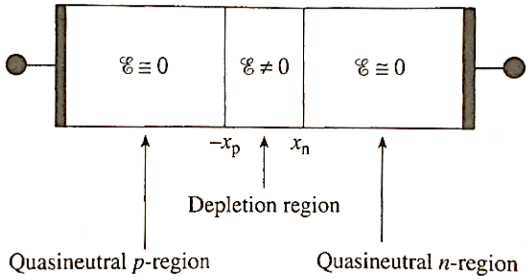
  - **Each current components inside the depletion region is constant over space (along x-axis).**

Quantitative Solution Strategy: *Depletion Region Considerations*

- **At Depletion/Quasineutral region interfaces**

$$J_N(-x_p \leq x \leq x_n) = J_N(x = -x_p)$$

$$J_P(-x_p \leq x \leq x_n) = J_P(x = x_n)$$

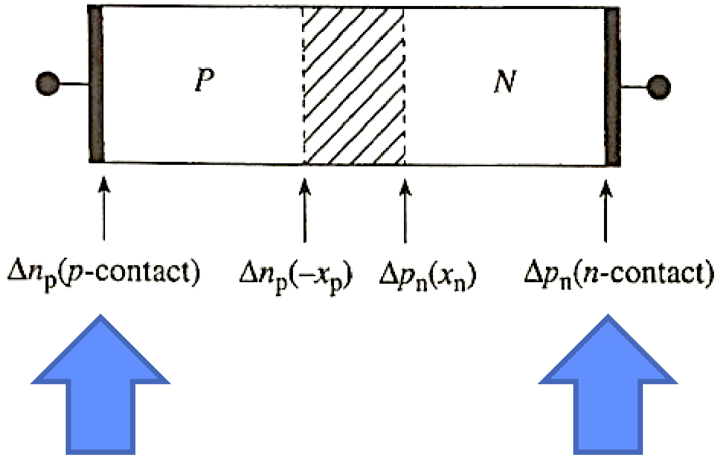


- **Total currents in the depletion region**
  - $J = J_N(-x_p \leq x \leq x_n) + J_P(-x_p \leq x \leq x_n)$
  - $\boldsymbol{J = J_N(x = -x_p) + J_P(x = x_n)}$

- **(1) Solve for the minority carrier current densities in the quasi-neutral regions and (2) calculate the edge current density**

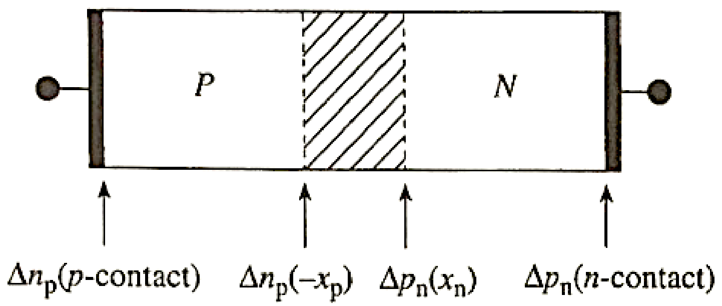
Quantitative Solution Strategy

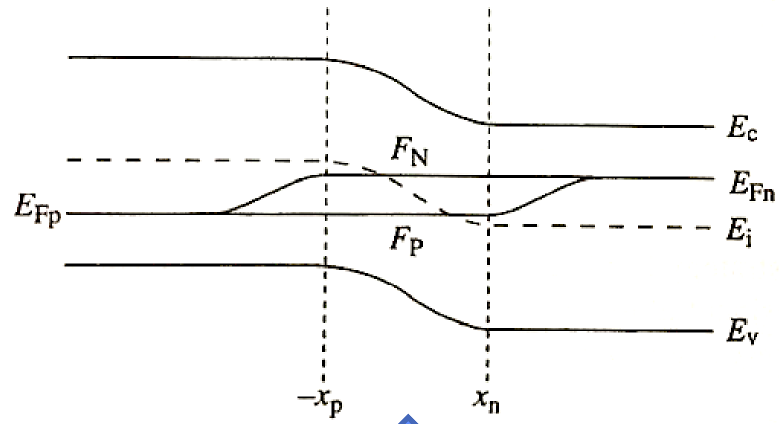
- <u>**Boundary Conditions**</u>
- **At the ohmic contacts**
  - **i.e. @ *p*-contact & *n*-contact**
  - **Quasi-neutral regions long enough to recombine all the minority carriers**
  - **Called "Wide-base" diode**
  - $\Delta n_p(x \rightarrow -\infty) = 0$
  - $\Delta p_n(x \rightarrow +\infty) = 0$



Quantitative Solution Strategy

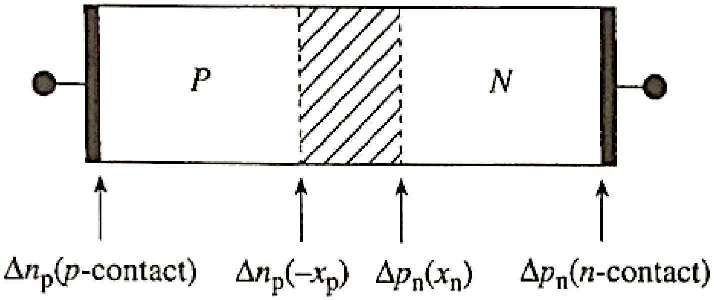
- **<u>Boundary Conditions</u>**
- **Within the depletion region**
  - **Carrier conc. relationship**
  - **Recall:** $np = n_i^2$ **(under equilibrium)**
  - **With $V_A \neq 0$,**
    - $n = n_i e^{\frac{F_N - E_i}{kT}}$
    - $p = n_i e^{\frac{E_i - F_P}{kT}}$
    - $np = n_i^2 e^{\frac{F_N - E_i + E_i - F_P}{kT}} = n_i^2 e^{\frac{qV_A}{kT}}$
    - **within depletion region**





- **Boundary Conditions**
- **At the depletion region edges**
  - $@\ \boldsymbol{x = -x_p}$
  - $n(-x_p)p(-x_p) = n(-x_p)N_A = n_i^2 e^{\frac{qV_A}{kT}}$
  - $n(-x_p) = \left(\frac{n_i^2}{N_A}\right) e^{\frac{qV_A}{kT}}$
  - $\Delta n_p(-x_p) = n(-x_p) - n_0$
  - $\boldsymbol{\Delta n_p(-x_p) = \left(\frac{n_i^2}{N_A}\right)\left(e^{\frac{qV_A}{kT}} - 1\right)}$
  - $@\ \boldsymbol{x = +x_n}$
  - $\boldsymbol{\Delta p_n(+x_n) = \left(\frac{n_i^2}{N_D}\right)\left(e^{\frac{qV_A}{kT}} - 1\right)}$

→ "***Minority carrier diffusion equation***"



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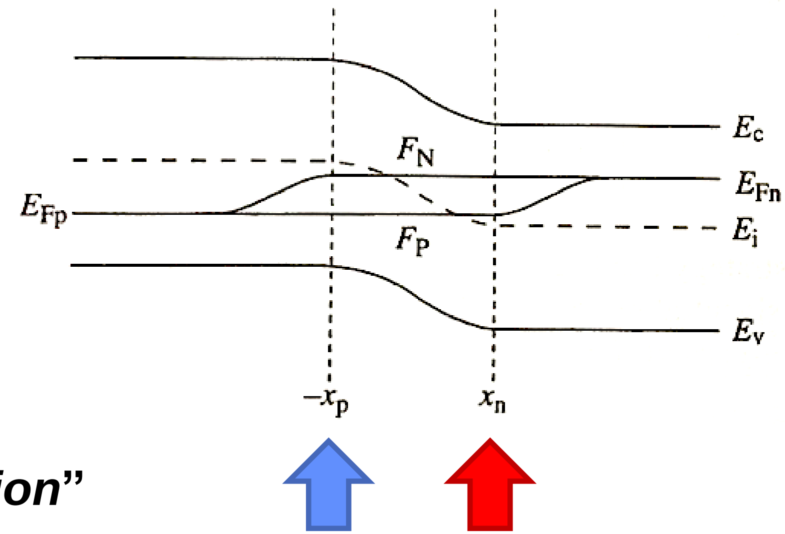
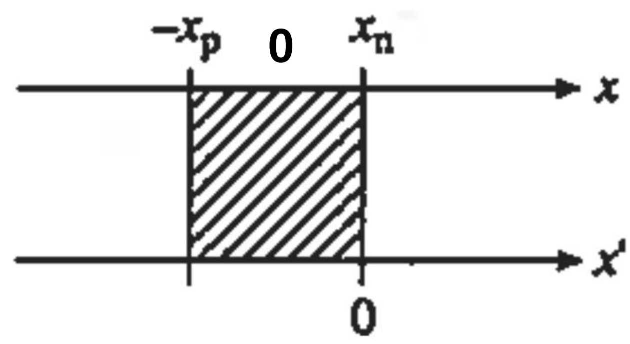


Derivation



$x' = x - x_n$

- **Minority carrier diffusion equation in *n*-semi,**

$$0 = D_p \frac{\partial^2 \Delta p_n}{\partial x'^2} - \frac{\Delta p_n}{\tau_p}$$

***n*-type quasi-neutral**

$$\Delta p_n(x') = Ae^{-x'/L_p} + Be^{x'/L_p}, \qquad x' \geq 0$$

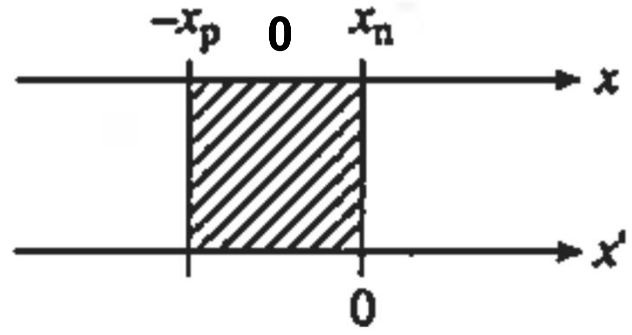
$$\begin{cases} \Delta p_n(x' \to \infty) = 0 \\ \Delta p_n(x' \to 0) = \left(\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1) \end{cases}$$

- *A*= $\Delta p_n(x' \to 0)$, *B=0*

$$\boldsymbol{\Delta p_n(x') = \left(\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1)e^{-x'/L_p}}, \qquad \boldsymbol{L_p = \sqrt{D_p \tau_p}}$$

$$\boldsymbol{J_p(x') = -qD_p \frac{\Delta p_n}{dx'} = +q\frac{D_p}{L_p}\left(\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1)e^{-x'/L_p}}$$

Derivation



- **Minority carrier diffusion current in *n*-semi,**

$$J_p(x') = q\frac{D_p}{L_p}\left(\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1)e^{-x'/L_p}$$

$$J_P(-x_p \le x \le x_n) = J_P(x = x_n) = J_P(x' = 0) = q\frac{D_p}{L_p}\left(\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1)$$

- **Hole current in the quasi-neutral n-type semi region, and depletion region**

Minority carrier diffusion current in p-semi

$$J_N(-x_p \le x \le x_n) = J_N(x = -x_p) = q\frac{D_n}{L_n}\left(\frac{n_i^2}{N_A}\right)(e^{\frac{qV_A}{kT}} - 1)$$

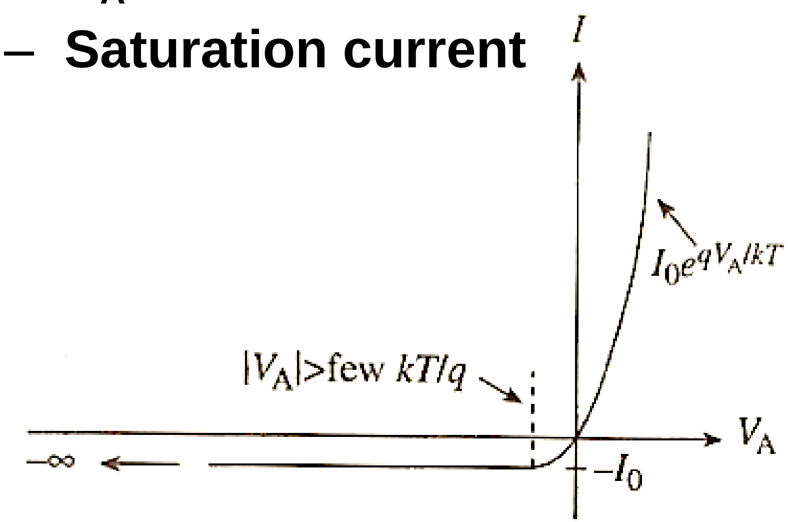
Total minority carrier current

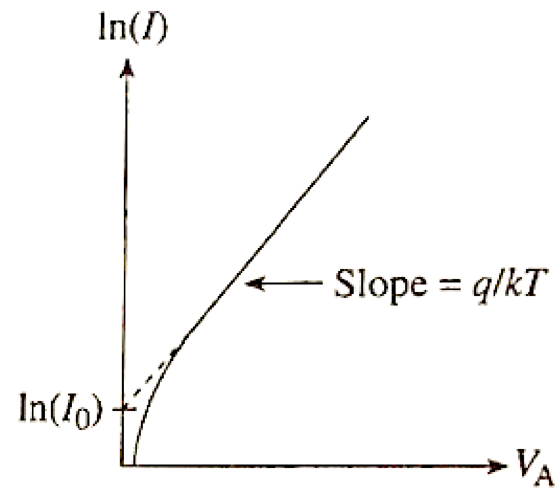
$$J_{total}(-x_p \le x \le x_n) = J_N + J_P = q\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)(e^{\frac{qV_A}{kT}} - 1)$$

- **Ideal *I–V***

$$I = J_{total} \times A = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)\left(e^{\frac{qV_A}{kT}} - 1\right) = I_0\left(e^{\frac{qV_A}{kT}} - 1\right)$$

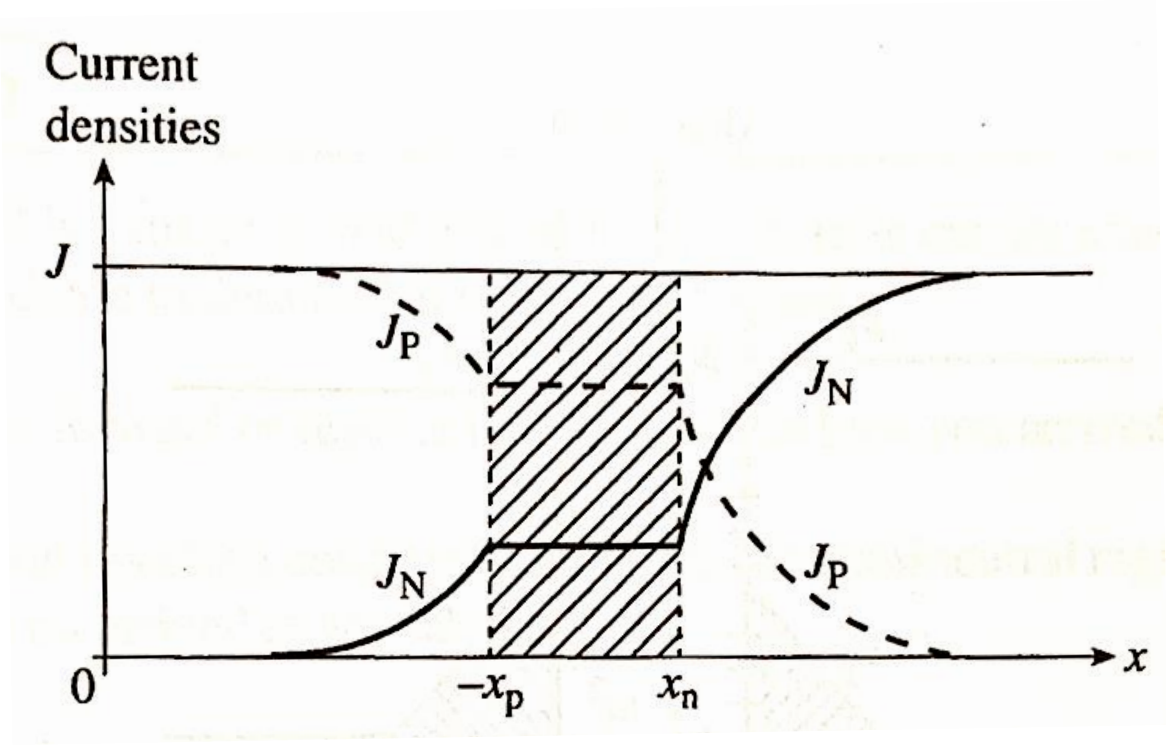
  - **V_A > kT/q**
  - **V_A < 0**
  - **Saturation current**





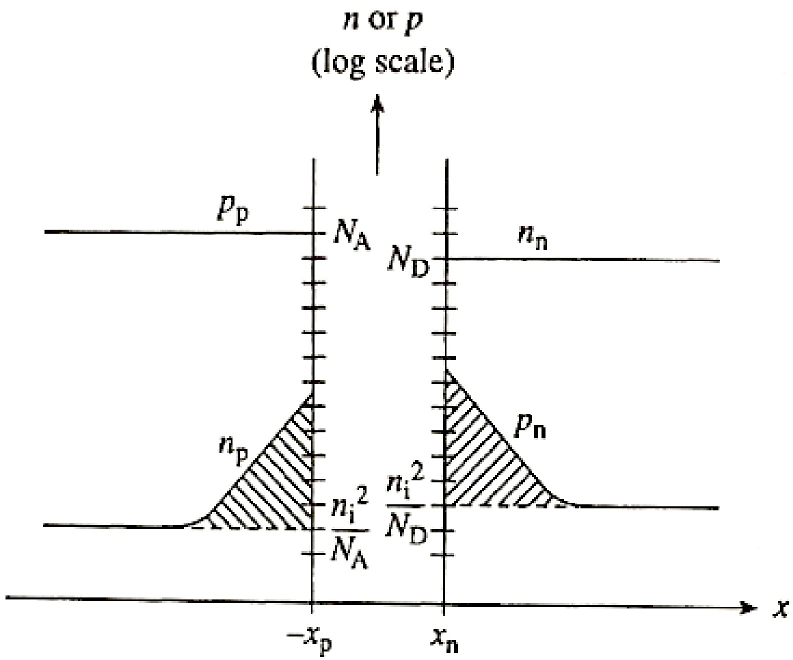
Examination of Results

- **Carrier currents under *forward bias***



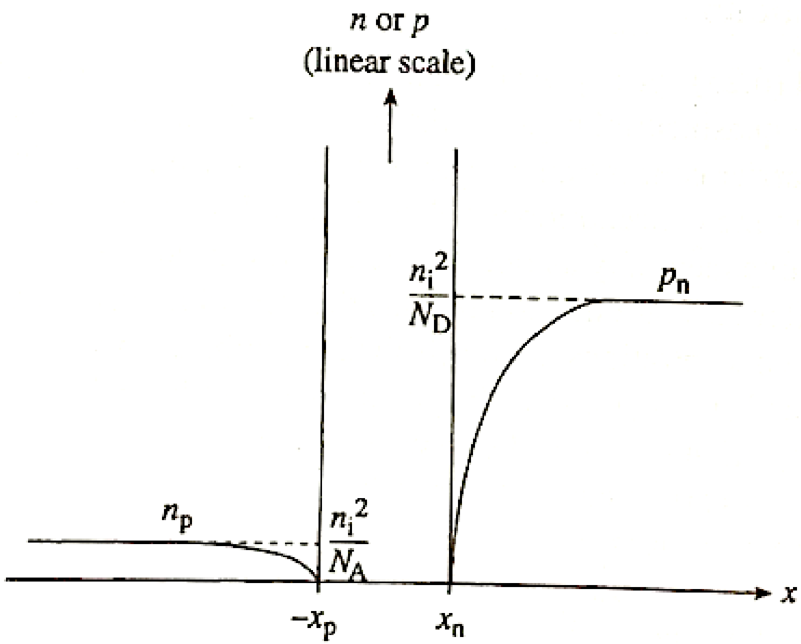
Examination of Results

- **Carrier concentrations**



Forward bias

Depletion region
: minority carrier *source*

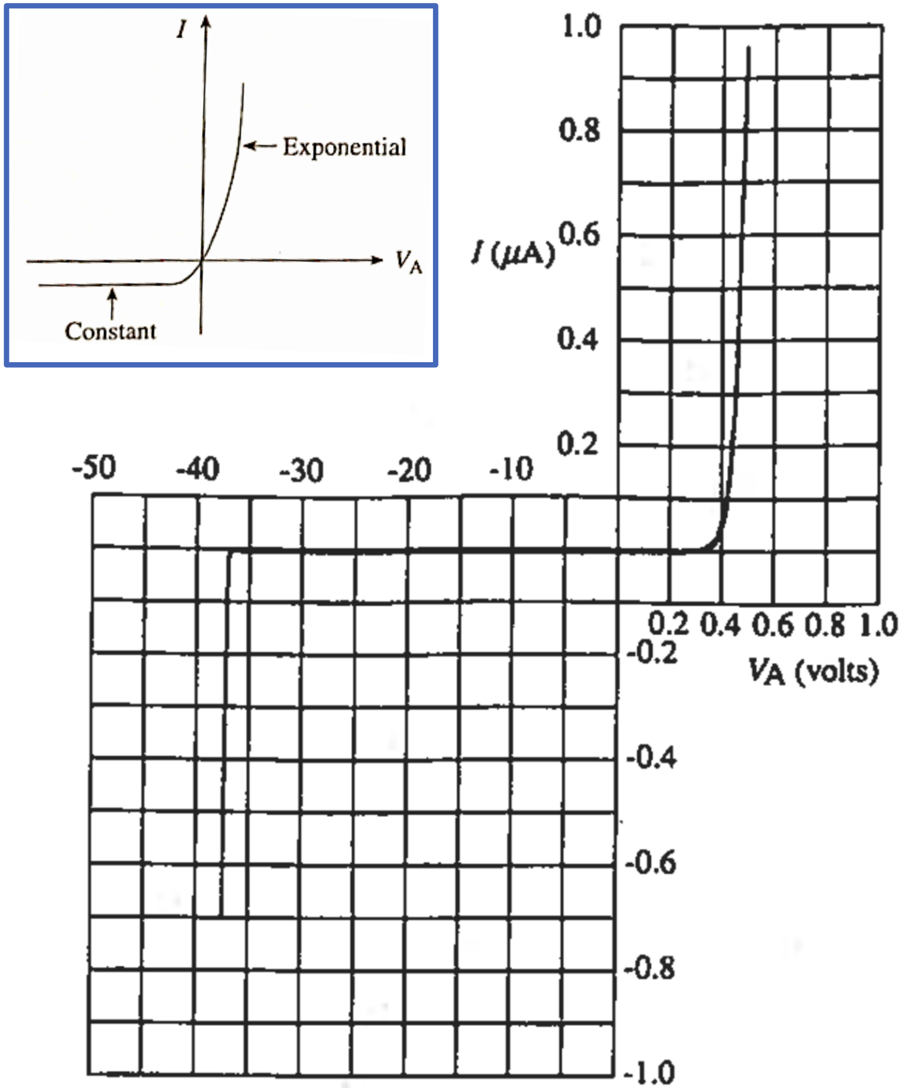


Reverse bias

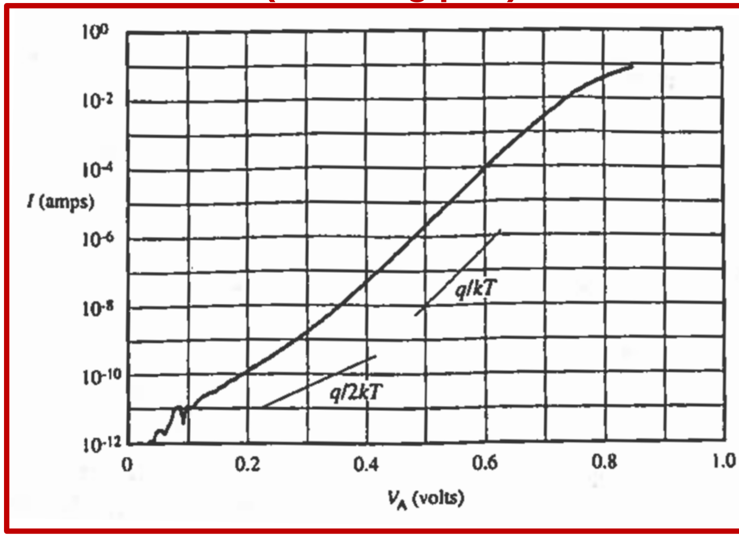
Depletion region
: minority carrier *sink*

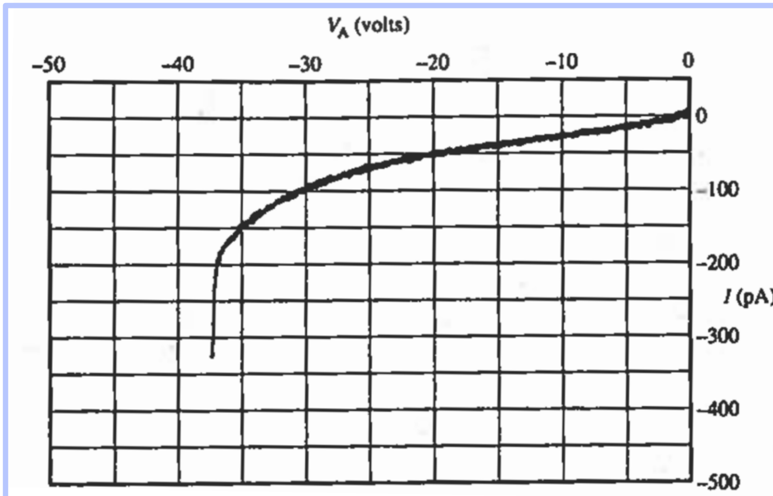
Ideal Theory vs. Experiment

Ideal



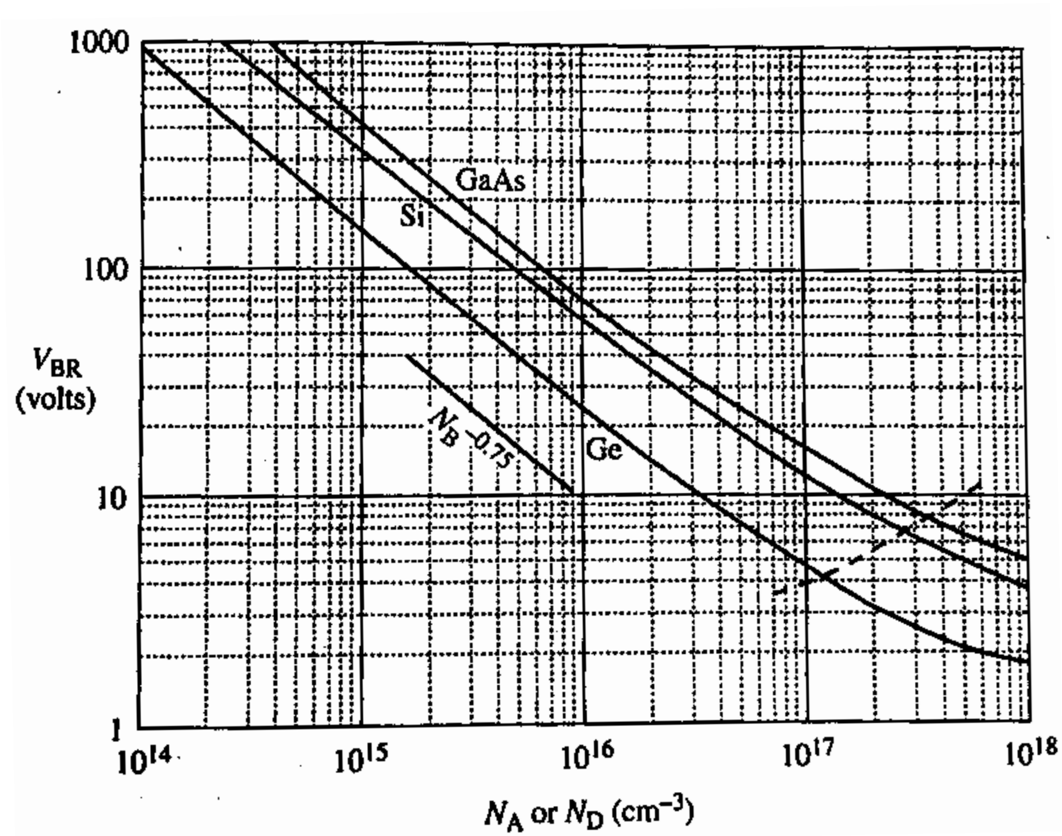
Forward bias (semi-log plot)





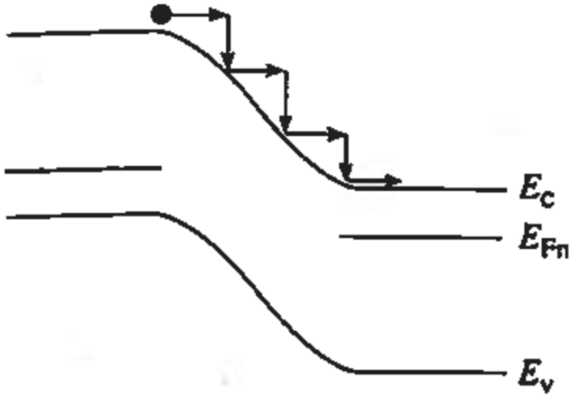
Reverse bias

Reverse-Bias Breakdown

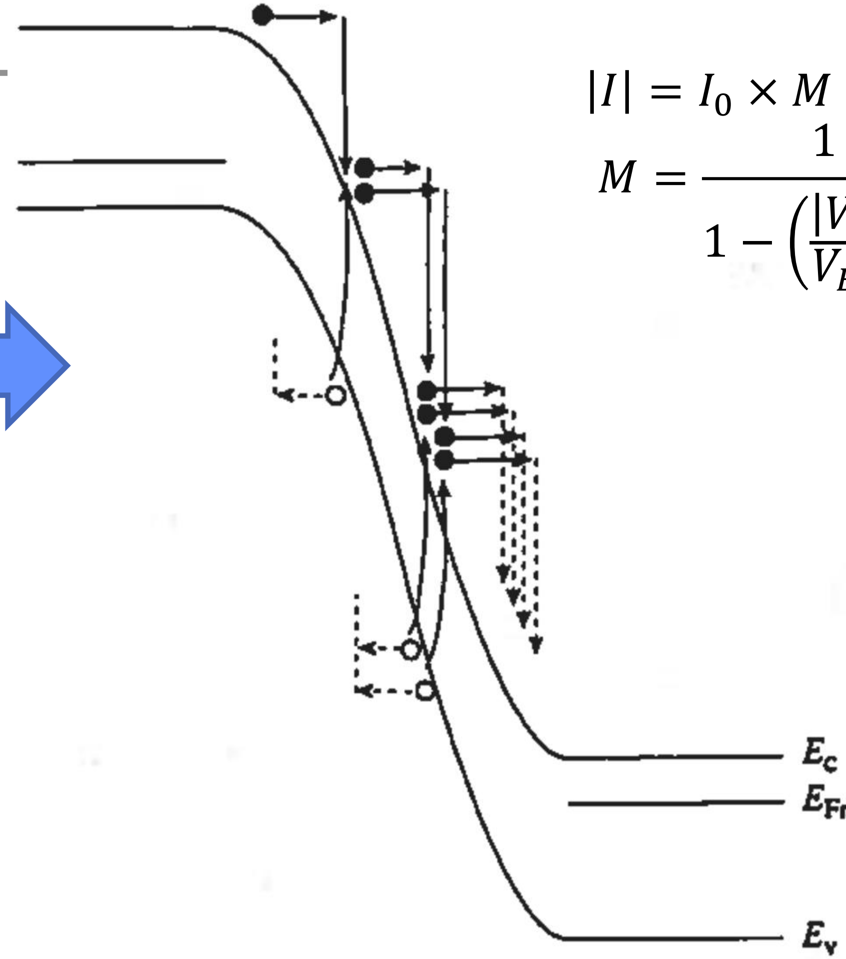


- **Breakdown**
  - **In fact, a completely reversible process (No damage in the device)**
  - **In reality, there are "other processes":** ***Avalanche*** **and** ***Zener process***
  - **<u>Doping concentration</u> and <u>Bandgap dependent</u> (why?)**

Avalanching



Small or moderate reverse bias

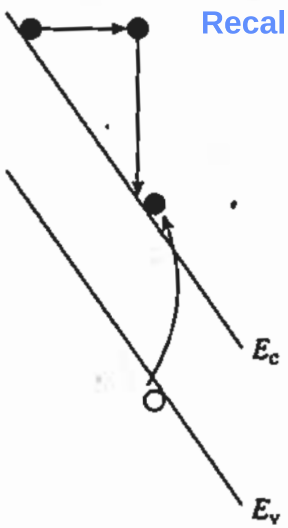


Strong reverse bias

$$|I| = I_0 \times M$$

$$M = \frac{1}{1 - \left(\frac{|V_A|}{V_{BR}}\right)^m}$$

Recall in Chap. 4

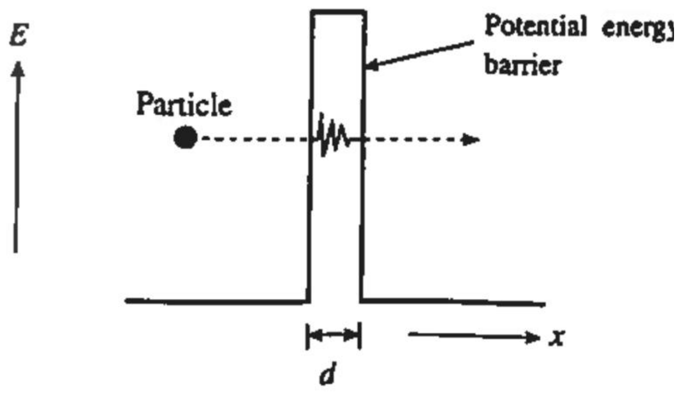


Carrier generation by *impact ionization*

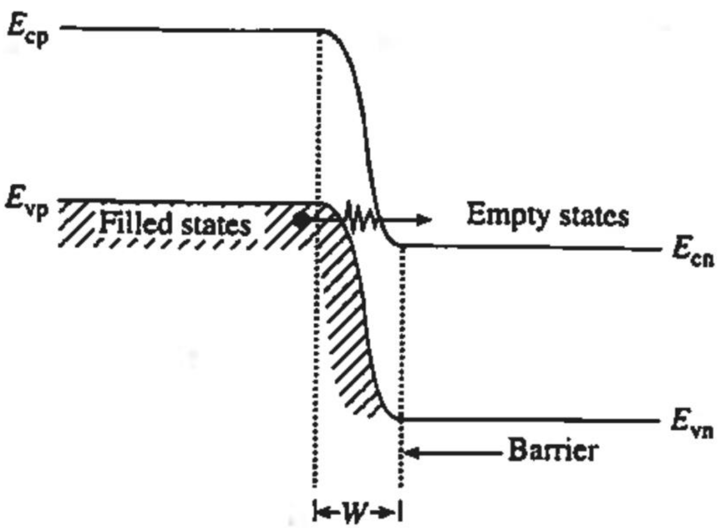
- **Mean free path between collisions: 10^{-6} cm**
- **Median depletion width: 10^{-4} cm**
- **Multiplication factor, M** (empirical fit)

Zener Process

High doping concentration



Tunneling

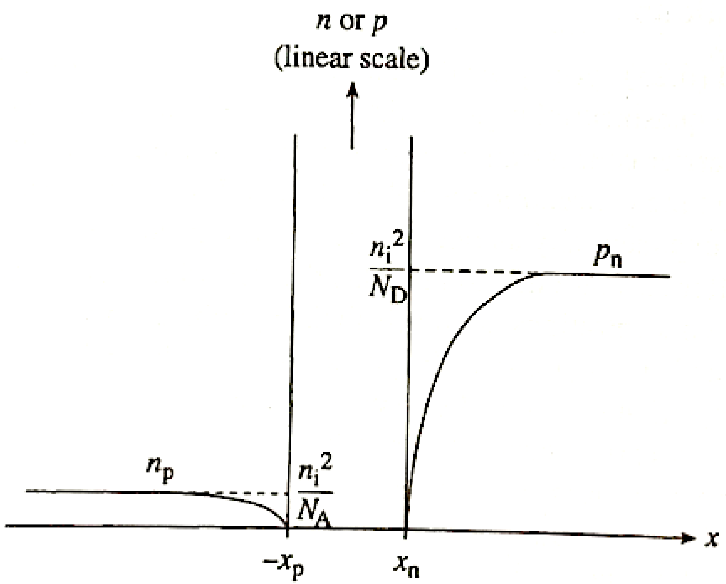


- **Zener process**
  - **Occurrence of *tunneling* in a reverse-biased pn diode**
- **Tunneling**
  - **Q-M…**
  - **Requirements: Filled state on one side ⇔ Empty state on the other side**
  - **No change in energe level**
  - **Width (thickness) of the potential energy barrier (< 10^{-6} cm)**

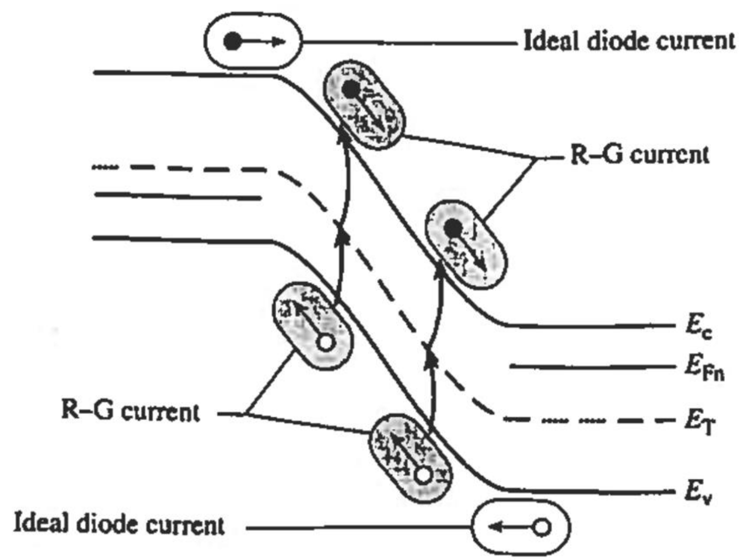
potential barrier ⬇

The R–G Current

- **Ideal diode model:** No R–G in the depletion region
- **In reality, non-zero R–G in the depletion region**
  - $\left(\frac{\partial n}{\partial t}\right)_{thermal,R-G} \neq 0$, $\left(\frac{\partial p}{\partial t}\right)_{thermal,R-G} \neq 0$
- **Under '*reverse*' bias, minority carrier concentrations in the depletion region are BELOW equilibrium conc.**
  - **Promotes thermal *generation (G)* of e⁻/h⁺ ⇒ *n, p* ↑**
  - **High E-field ⇒ sweeps the generated e⁻/h⁺ ⇒ added I_{R-G}**



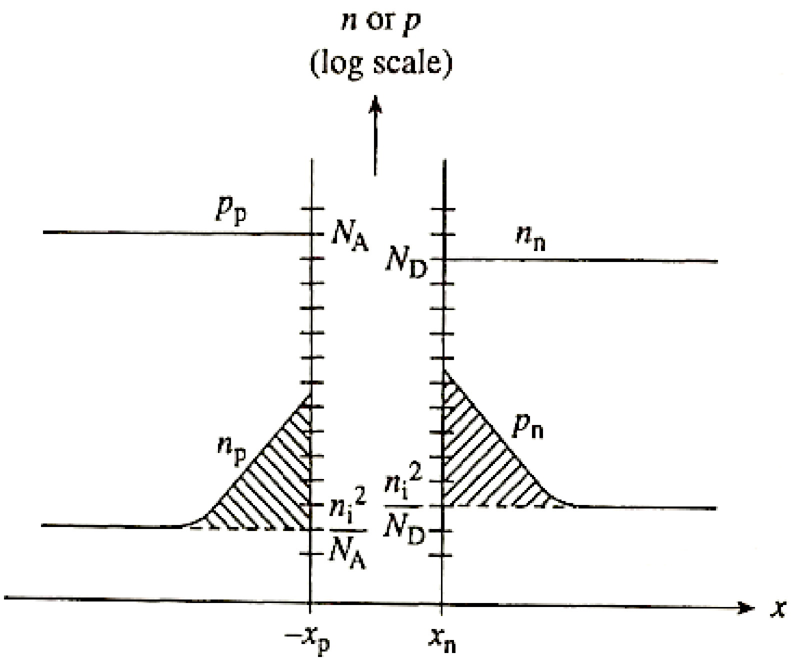
Reverse bias: minority carrier *sink*



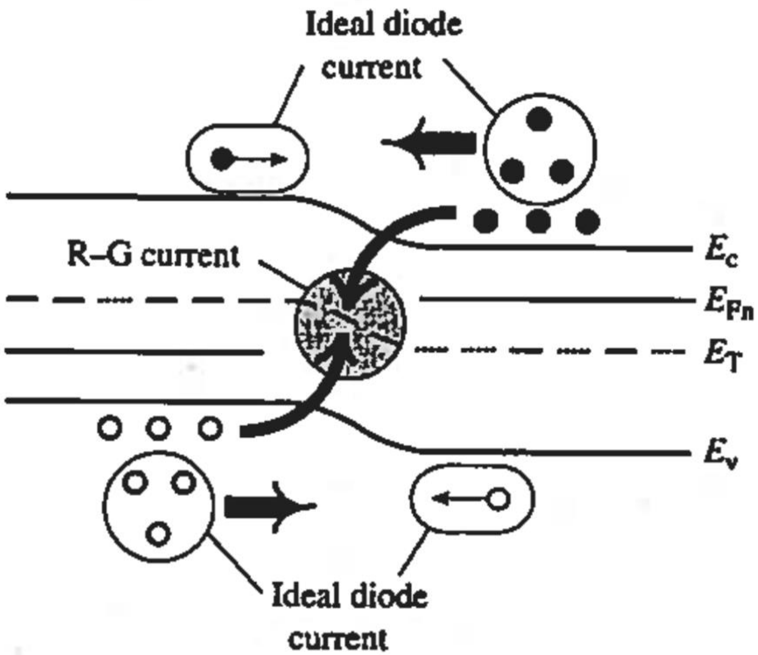
Reverse bias

The R–G Current

- **Under ‘*forward*’ bias, minority carrier concentrations in the depletion region are ABOVE equilibrium conc.**
  - **Promotes thermal *recombination (R)* of e⁻/h⁺ ⇒ *n, p* ↓**
  - **Less carriers that can overcome the potential hils**
  - **Reduced diffusion current**



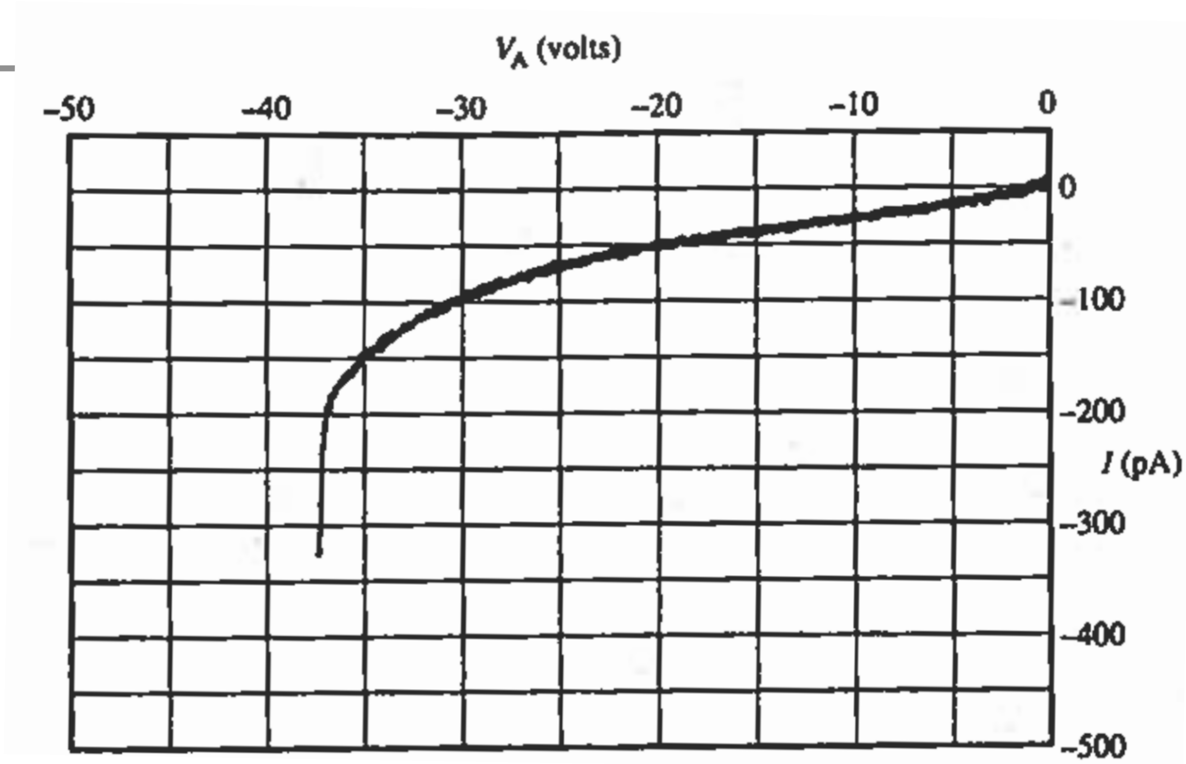
Forward bias: minority carrier *source*



Forward bias

The R–G Current

$$I_{R-G} = -qA \int_{-x_p}^{x_n} \left(\frac{\partial n}{\partial t}\right)_{R-G} dx$$



- **Reverse bias** **($-V_A >$ a few kT/q)**
- $n, p \rightarrow 0$

$$I_{R-G} = -\frac{qAn_i}{2\tau_0}W, \qquad where\ \ \tau_0 = \frac{1}{2}\left(\tau_p \frac{n_1}{n_i} + \tau_n \frac{p_1}{n_i}\right)$$

- **As you increase reverse bias, the depletion width widens.**
- $W \uparrow, \ |I_{R-G}| \uparrow$
- **In practice, reverse current does not saturate.**

The R–G Current

$$I_{R-G} = -qA \int_{-x_p}^{x_n} \left(\frac{\partial n}{\partial t}\right)_{R-G} dx$$

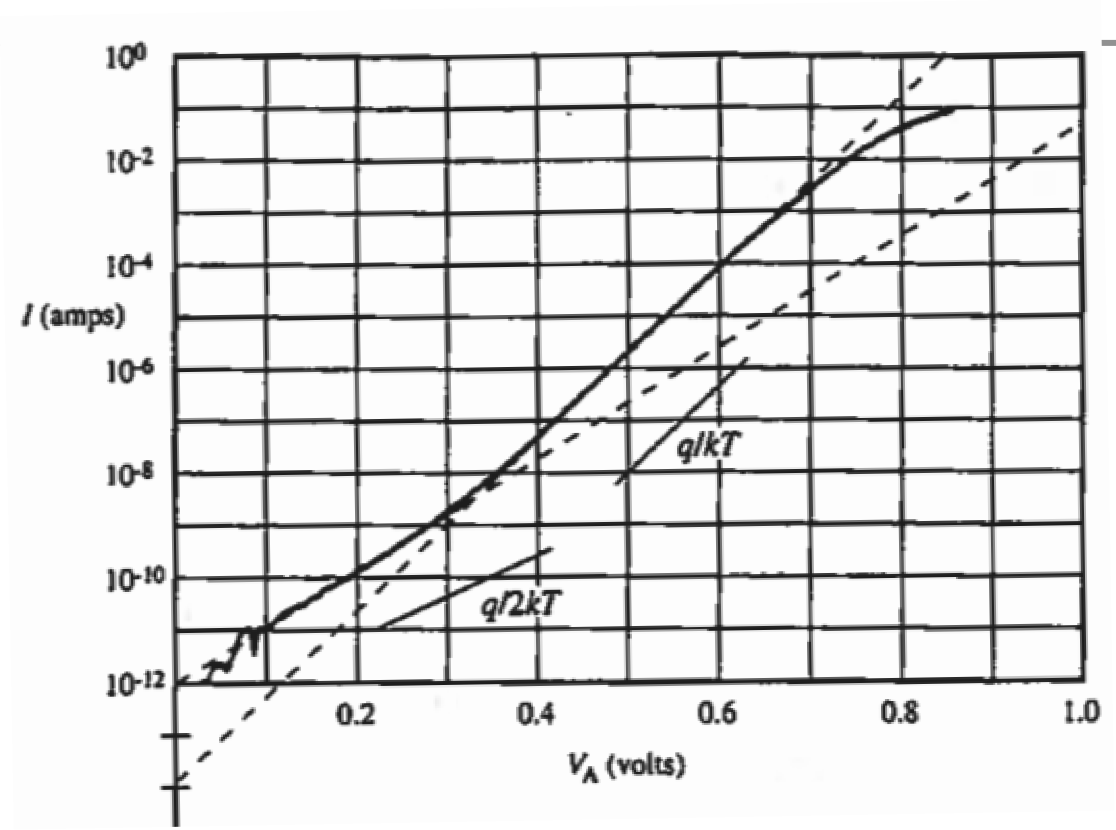
$$I_{total} = I_{DIFF} + I_{R-G}$$
$$= I_0\left(e^{\frac{qV_A}{kT}} - 1\right) + I_{R\text{-}G}$$

- **Forward bias ($V_A >$ few kT/q)**

$$I_{R-G} = +\frac{qAn_i}{2\tau_0} W \frac{e^{qV_A/kT} - 1}{1 + \left(\frac{V_{bi} - V_A}{kT/q}\right)\frac{\sqrt{\tau_n \tau_p}}{2\tau_0} e^{qV_A/2kT}} \propto e^{\frac{qV_A}{2kT}} \quad \left(\text{for } V_A > \text{few } kT/q\right)$$

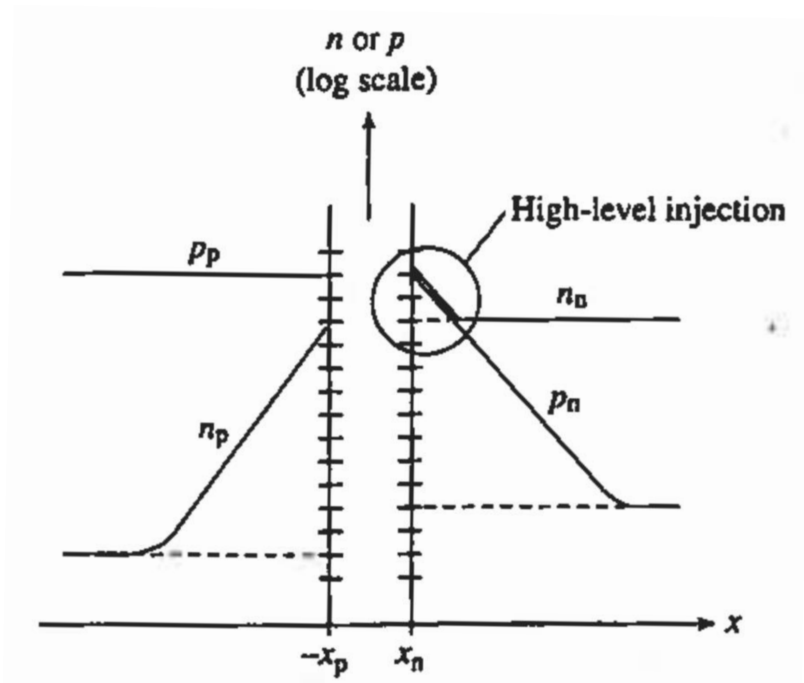
  - **At small forward bias, the recombination current dominate over the diffusion current**
  - $\propto e^{\frac{qV_A}{2kT}}$

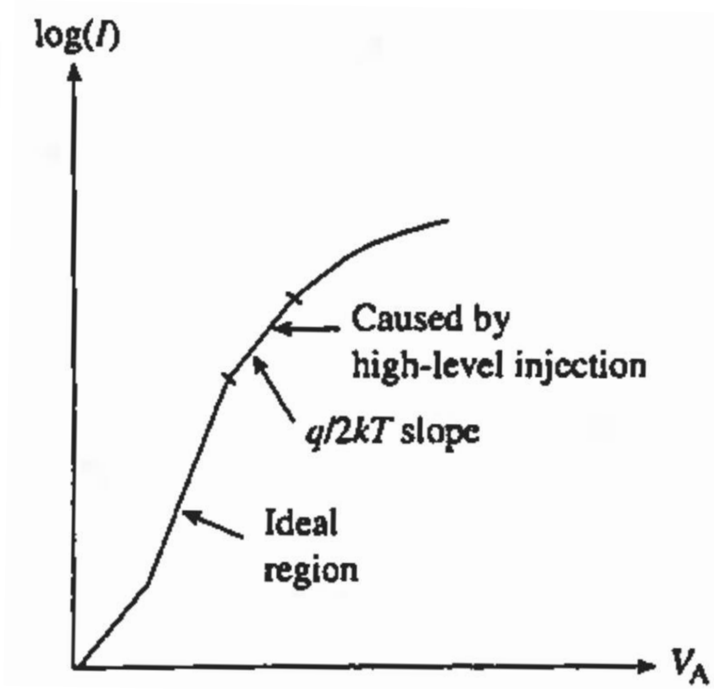
The R–G Current



- **Forward biased PN diode *I* –*V* characteristics (semi-log)**
- **At low bias** $\propto e^{\frac{qV_A}{2kT}}$
- **At moderate bias** $\propto e^{\frac{qV_A}{kT}}$

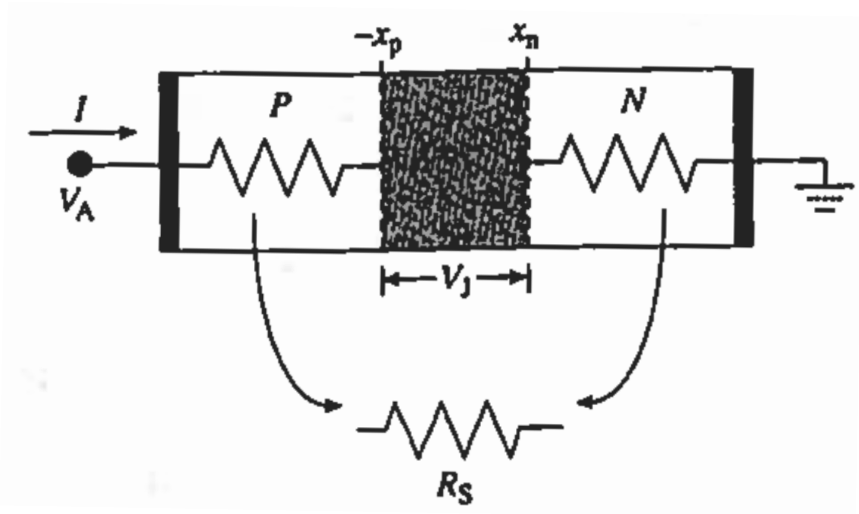
High Current Phenomena, $V_A \rightarrow V_{bi}$: *High-Level Injection*





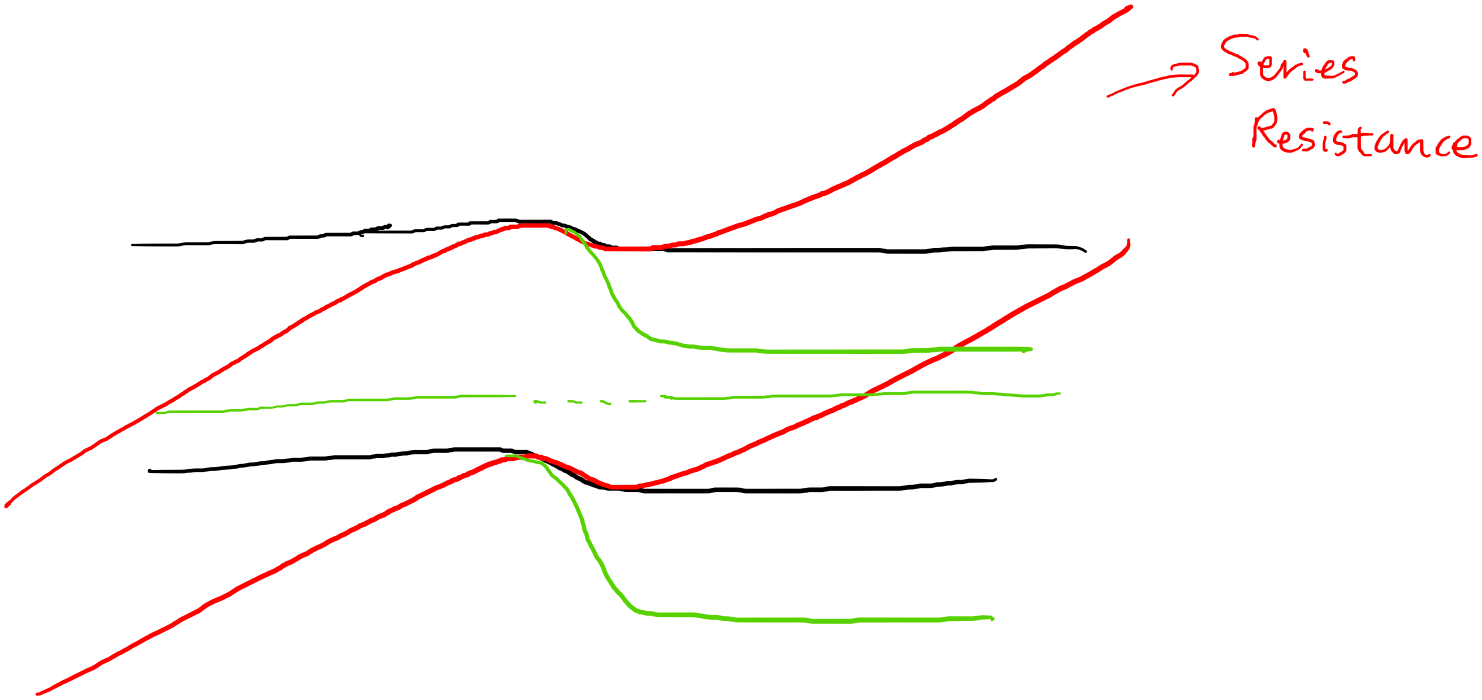
- **At high *forward* bias, diffused carrier concentration increases significantly such that no longer *low level injection assumption is valid.***
- **Majority carrier concentration increases to satisfy charge neutrality in the quasi-neutral regions.**
- **Drain current** $\propto e^{\frac{qV_A}{2kT}}$

High Current Phenomena, $V_A \rightarrow V_{bi}$: *Series Resistance*



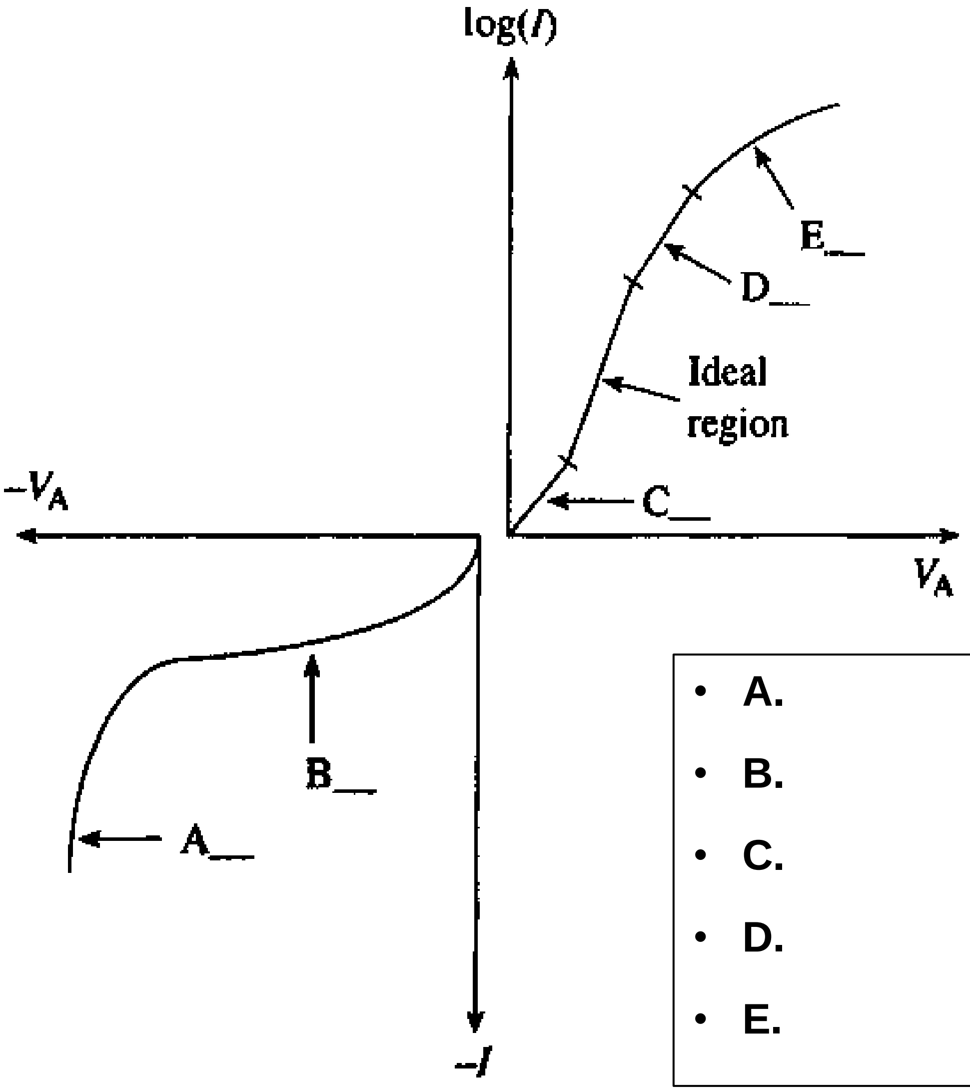
- **At *even higher forward* bias, the PN junction resistance becomes comparable to *contact resistance,***
  - **Voltage drop across the contact resistance & quasi-neutral regions cannot be ignored.**
  - **Junction voltage (V_J) < Applied voltage (V_A)**
  - $V_J = V_A - I \times R_S$

High Current Phenomena, $V_A \rightarrow V_{bi}$: *Series Resistance*



- **How would energy band diagram change in this situation?**

Summary



- Thermal Recombination (R) in the depletion region
- Thermal Generation (G) in the depletion region
- Series resistance
- Avalanching and/or Zener process
- High-level injection

- A.
- B.
- C.
- D.
- E.

Summary

- **Ideal diode behaviours**
  - **At *Forward* bias, majority carrier injection over the potential hill (diffusion)**
  - **At *Reverse* bias, minority carrier drift**
  - **Exponential increases in *forward*, saturation in *reverse* bias.**
  - **No R–G in the depletion region (W_{dep})**

- **Non-ideal behaviours**
  - **Strong reverse bias: Avalanche (impact ionization), or Zener (tunneling)**
  - **Small to Moderate reverse bias: Thermal Generation in W_{dep}.**
  - **Small forward bias: Thermal Recombination in W_{dep}.**
  - **Large forward bias: (1) high-level injection; (2) series resistance**

- **So far, these are dc characteristics (i.e. applied DC bias & steady state)**