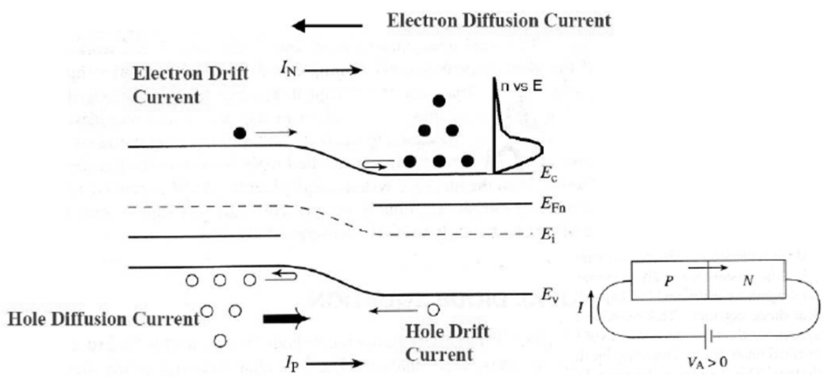
University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Non-ideal Effect, AC Response

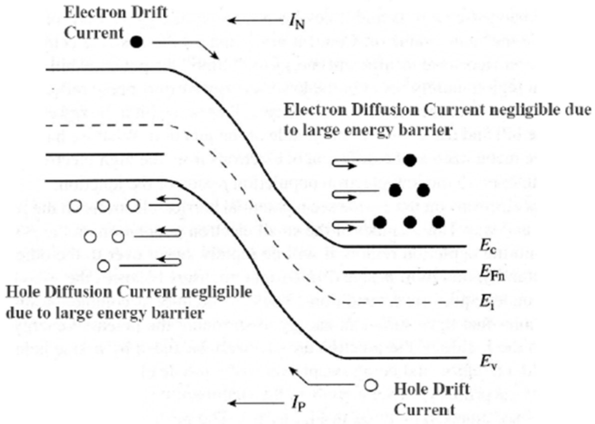
Instructor: Professor Hua Bao

Forward Bias



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

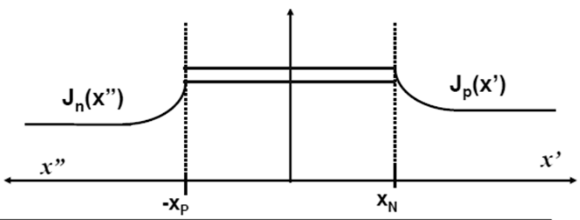
Reverse Bias



(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

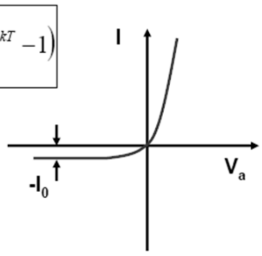
Ideal Diode, I-V



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

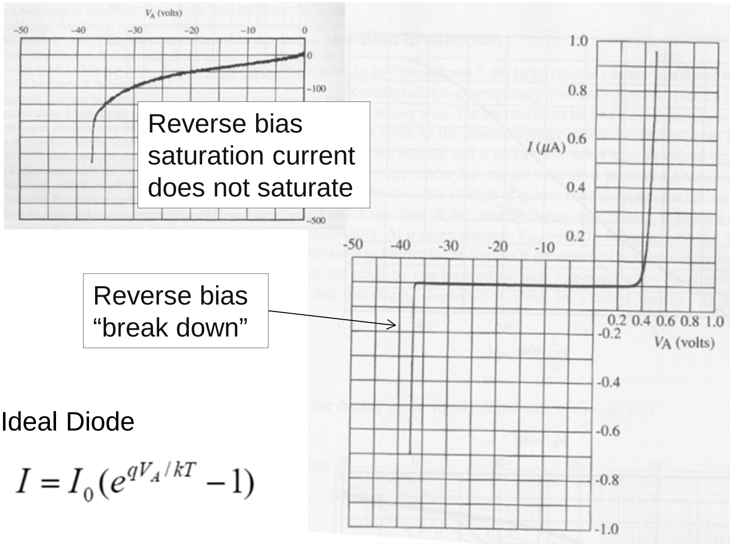
$$\boxed{I = qA\left(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right)\left(e^{qV_A/kT} - 1\right)}$$

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



I_0 = Reverse saturation current

Actual Diode, I-V

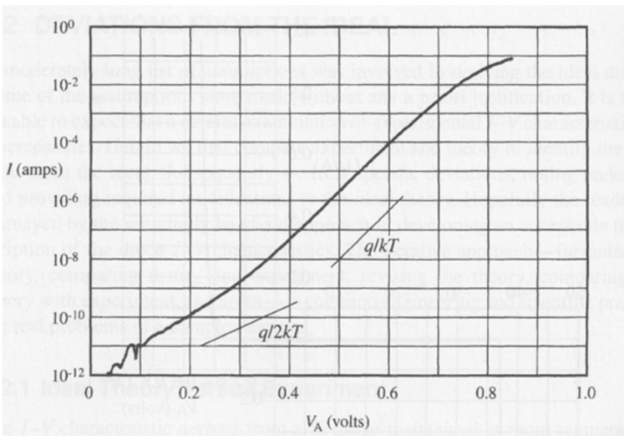


Ideal Diode

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

Forward and Reverse Bias

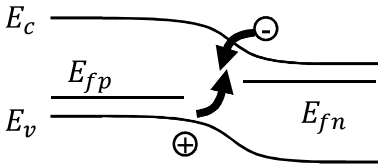
$$I = I_0(e^{qV_A/kT} - 1) \Rightarrow \ln I = \ln I_0 + q/kT \times V_A$$

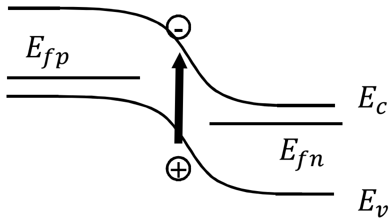


R-G In Depletion Region

Forward bias, injected carriers recombine in depletion region

Reverse bias, carriers generated in depletion region





How does the I-V relation of the diode change if R-G in depletion region is considered?

R-G Current

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

General thermal R-G

$$\left.\frac{\partial n}{\partial t}\right|_{R-G} = -\frac{np - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)} \qquad \begin{aligned} n_1 &\equiv n_i e^{(E_T - E_i)/kT} \\ p_1 &\equiv n_i e^{(E_i - E_T)/kT} \end{aligned}$$

For reverse bias > a few kT/q

$$I_{R-G} \approx -\frac{qAn_i}{2\tau_0} W$$

For small (?) forward bias > a few kT/q

$$I_{R-G} \approx \frac{qAn_i}{2\tau_0} W e^{qV_A/2kT}$$

Full expression see RFP, Eq. (6.45)

R-G In Depletion Region, Reverse Bias

Assume $E_T = E_i \quad \tau_n = \tau_p$

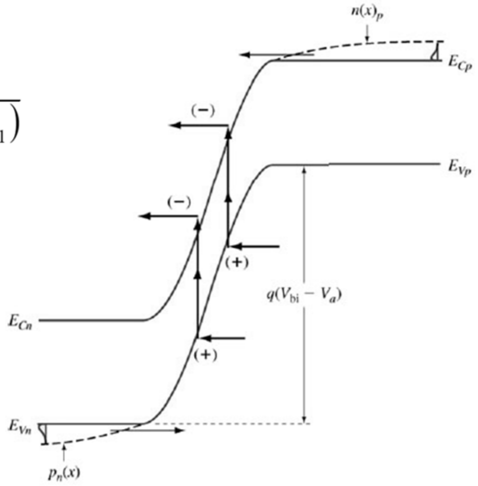
$$\left.\frac{\partial n}{\partial t}\right|_{R-G} = -\frac{np - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

$$R - G = \frac{np - n_i^2}{\tau_0(n + n_i + p + n_i)}$$

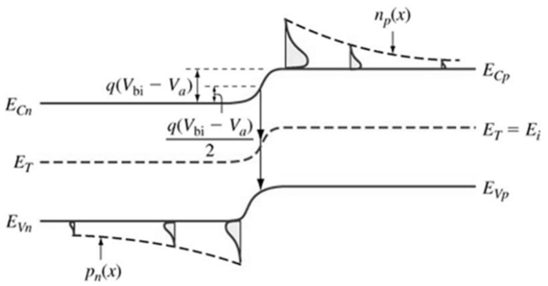
At reverse bias (n, p negligible)

$$R - G = -\frac{n_i}{2\tau_0}$$

$$J_{GR} = q(R - G)w = -q\frac{n_i}{2\tau_0}w$$



R-G In Depletion Region, Forward Bias



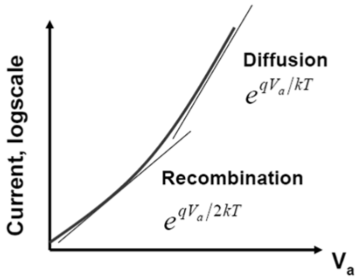
$$R - G = \frac{np}{\tau_0(n + p)} = \frac{n_i^2 e^{qV_A/kT}}{\tau_0(n + p)}$$

$$(R - G)_{\max} = \frac{n_i e^{qV_A/2kT}}{2\tau_0}$$

$$J_{GR} = J_{GR0}\left(e^{qV_A/2kT} - 1\right)$$

$$J = J_{GR0}\left(e^{qV_A/2kT} - 1\right) + J_0\left(e^{qV_A/kT} - 1\right)$$

Diffusion and R-G Current



- Recombination dominant at low bias
- Diffusion dominates at larger bias
- Recombination often represented by non-ideality factor (η) at given bias

$\boxed{J_{total} = J_{diff} + J_{GR}}$ For both forward and reverse bias cases

$$J_{total} = J_0^{diff}\left(e^{qV_A/kT} - 1\right) + J_0^{GR}\left(e^{qV_A/2kT} - 1\right)$$

$$J_{total} = J_0\left(e^{qV_A/\eta kT} - 1\right)$$

High Current Levels

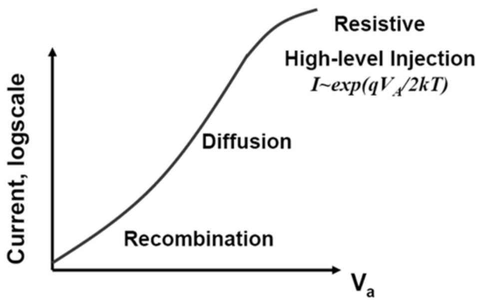
At high forward bias, I-V becomes resistive

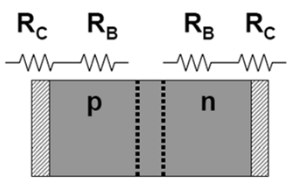
$$V_J = V_A - IR_S$$

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

$$\approx I_0 e^{q(V_A - IR_S)/kT}$$

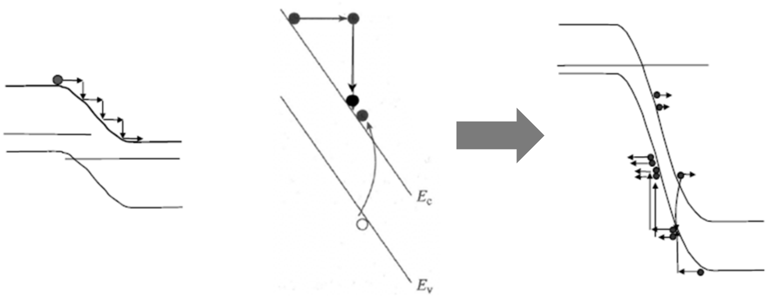
- Resistive drop across bulk semiconductor regions
- Contact resistance
- High-level injection: minority carrier density approaches majority carrier density



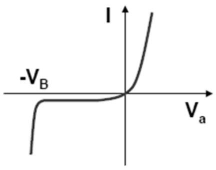


Avalanche Breakdown

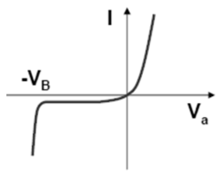
Impact Ionization



- Impact Ionization
- Created carriers can further contribute to process
- Avalanche process
- Reversible
- Application: e.g. avalanche photo-diodes

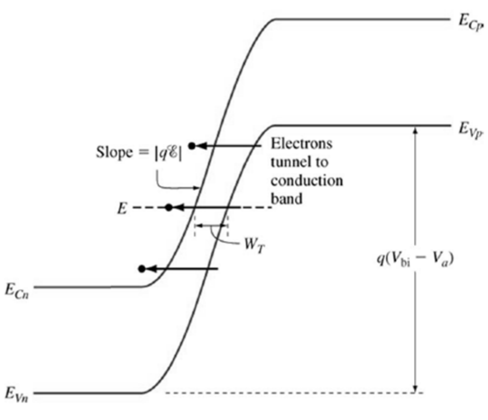


Reverse Bias Tunneling



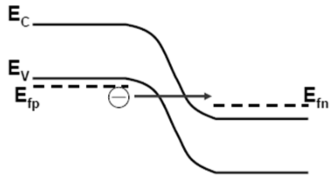
Tunneling probability

$$T = e^{-\pi W_T \frac{\sqrt{m^* E_g}}{2^{3/2}\hbar}}$$



Tunneling –Zener Breakdown

Narrow depletion region widths in reverse bias
can enable quantum mechanical tunneling



Tunneling Probability

$$T \approx \exp\left(-\frac{4\sqrt{2m^*}}{3q\hbar\mathcal{E}} E_G^{\,3/2}\right)$$

- "Barrier Thickness" is approximately equal to the depletion depth
- Important for samples with heavy doping (on both sides of the junction)

Breakdown Voltage

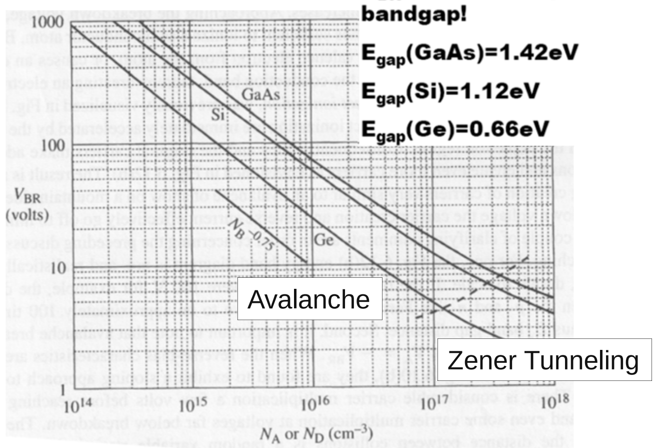
V_{BR} ↑es with larger bandgap!

E_{gap}(GaAs)=1.42eV

E_{gap}(Si)=1.12eV

E_{gap}(Ge)=0.66eV

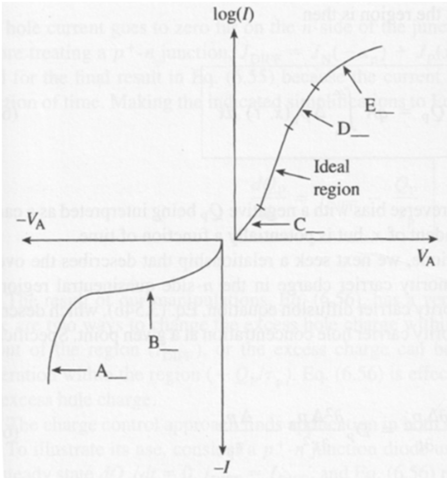
Changing doping of lighter doped side can change breakdown voltage significantly!



Breakdown Voltage

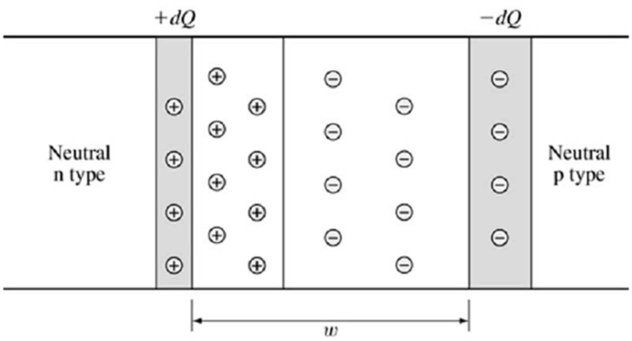
$$V_{BR} \approx 60\left(E_G/1.1\right)^{3/2}\left(10^{16}/N_B\right)^{3/4}\ [V]$$

Summary



1. Photogeneration
2. Thermal recombination in the depletion region
3. Avalanching and/or Zener process
4. Low-level injection
5. Depletion approximation
6. Thermal generation in the depletion region
7. Band bending
8. Series resistance
9. $V_A > V_{bi}$
10. High-level injection

Junction (Depletion Region) Capacitance



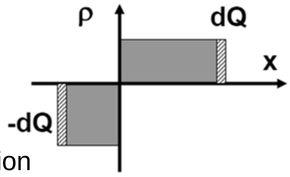
$$C = \left|\frac{dQ}{dV}\right|$$

Change in depletion region fixed charge

Junction Capacitance

Differential Capacitance

$$C = \left|\frac{dQ}{dV}\right|$$

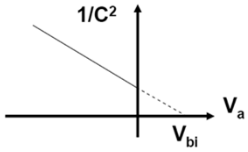


Capacitance associated with depletion region

$$|Q| = qN_aW_pA = qN_dW_nA$$

$$\boxed{C_j = A\sqrt{\frac{q\varepsilon N_a N_d}{2(V_{bi}-V_a)(N_d+N_a)}} = \frac{\varepsilon A}{W}}$$

$$C_j = C_{j0} / \sqrt{1-\frac{V_a}{V_{bi}}}$$



Depletion capacitance is proportional to applied voltage, Used as a voltage-dependent capacitor (varactor)

Diffusion Capacitance

Excess minority carrier density near depletion region edge is stored charge ->capacitance

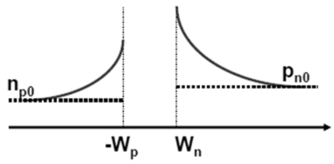
$$C = \left|\frac{dQ}{dV}\right|$$

$$Q_p = qA\int_{x_n}^{\infty}\left[p_n(x) - p_{n0}\right]dx$$

$$Q_p = qAp_{n0}L_p\left(e^{qV_a/kT} - 1\right)$$

$$Q_p = J_{p_n}(x_n)A\tau_p = I_p\tau_p$$

$$\boxed{C_D = \frac{q}{kT}\tau_p I_S e^{qV_a/kT}}$$



Junction and Diffusion Capacitance

How are junction and diffusion capacitance related?

$$C_j = A\sqrt{\frac{q\varepsilon N_a N_d}{2(V_{bi} - V_a)(N_d + N_a)}} = \frac{\varepsilon A}{W}$$

$$C_D = \frac{q}{kT}\tau_p I_S e^{qV_a/kT}$$

Under what conditions are each dominant? Why?

Detailed discussion, including cases in which the (minority) carriers cannot follow up with the applied signal (non quasistatic cases), can be found in Pierret, Ch. 7.