Lecture #13

OUTLINE

- pn Junctions
  - reverse bias current
  - deviations from ideal behavior
  - small-signal model

Reading: Chapters 6.2 & 7

Diode Current due to Generation

- If an electron-hole pair is generated (*e.g.* by light) in the depletion region of a Schottky diode or pn diode, the built-in electric field will sweep the generated carriers out, resulting in an additional component of current.

Review: Current Flow in Long-Base Diode

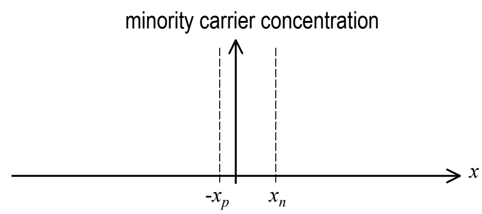
- Under forward bias ($V_A > 0$):
  - Holes are supplied (from the external circuit) through the p-side ohmic contact
    - Some of these recombine with injected electrons; the rest are injected into the n-side
  - Electrons are supplied (from the external circuit) through the n-side ohmic contact
    - Some of these recombine with injected holes; the rest are injected into the p-side

Review: Current Flow in Short-Base Diode

- Under forward bias ($V_A > 0$):
  - Holes are supplied (from the external circuit) through the p-side ohmic contact
    - If the p-side is short ($W_P' << L_n$), ~all of the holes are injected into the n-side, and recombine with electrons at the n-side ohmic contact
  - Electrons are supplied (from the external circuit) through the n-side ohmic contact
    - If the n-side is short ($W_N' << L_p$), ~all of the electrons are injected into the p-side, and recombine with holes at the p-side ohmic contact

Reverse Bias Current

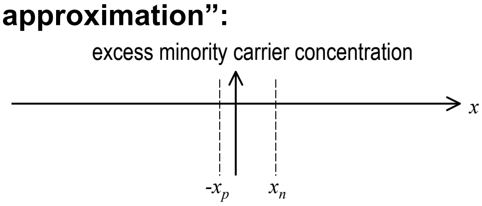
- Consider a reverse-biased (V_A<0) pn junction:



  - Depletion of minority carriers at edges of depletion region
  - The only current which flows is due to drift of minority carriers across the junction. This current is fed by diffusion of minority carriers toward junction (supplied by thermal generation).

Alternative Derivation of Formula for I_0

"Depletion approximation":



- **I_0 represents the rate at which carriers are generated within a diffusion length of the depletion region**

$$\frac{\partial n}{\partial t} = -\frac{\Delta n_p}{\tau_n} = \frac{n_i^2 / N_A}{\tau_n} \qquad -L_N - x_p \le x \le -x_p$$

$$\frac{\partial p}{\partial t} = -\frac{\Delta p_n}{\tau_p} = \frac{n_i^2 / N_D}{\tau_p} \qquad x_n \le x \le x_n + L_P$$

$$I_0 = qAL_N\left(\frac{n_i^2 / N_A}{\tau_n}\right) + qAL_P\left(\frac{n_i^2 / N_D}{\tau_p}\right)$$

Deviations from the Ideal *I-V* Behavior

Effect of R-G in Depletion Region

- The net generation rate is given by

$$\frac{\partial p}{\partial t} = \frac{\partial n}{\partial t} = \frac{n_i^2 - np}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

where $n_1 \equiv n_i e^{(E_T - E_i)/kT}$ and $p_1 \equiv n_i e^{(E_i - E_T)/kT}$

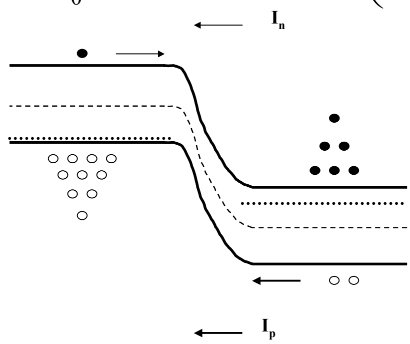
$E_T = \text{trap-state energy level}$

- R-G in the depletion region contributes an additional component of diode current $I_{R\text{-}G}$

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

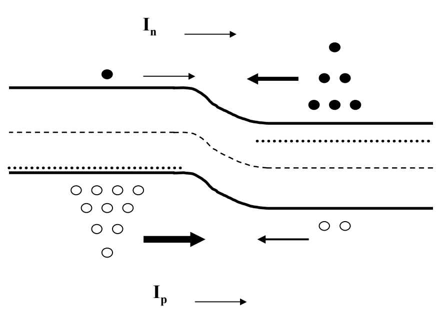
- For **reverse bias** greater than several *kT/q*,

$$I_{R-G} = -\frac{qAn_iW}{2\tau_0} \quad \text{where} \quad \tau_0 \equiv \frac{1}{2}\left(\tau_p \frac{n_1}{n_i} + \tau_n \frac{p_1}{n_i}\right)$$



- For **forward biases**,

$$I_{R-G} \propto qAn_iWe^{qV_A/2kT}$$



Effect of Series Resistance

High-Level Injection Effect

- As V_A increases, the side of the junction which is more lightly doped will eventually reach HLI:

$$n_n > n_{no} \quad \text{(p}^+\text{n junction)}$$

or

$$p_p > p_{po} \quad \text{(n}^+\text{p junction)}$$

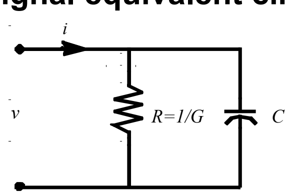
⇒ significant gradient in majority-carrier profile

Majority-carrier diffusion current reduces the diode current from the ideal

Review: Charge Storage in pn-Diode

Small-Signal Model of the Diode

Small signal equivalent circuit:



$$i = Gv + C\frac{dv}{dt}$$

Small-signal ***conductance*** :

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

$$G = \frac{q}{kT} I_0 e^{qV_A/kT} \cong I_{DC} / \frac{kT}{q}$$

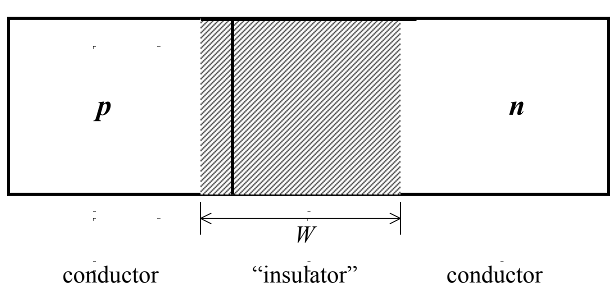
2 types of capacitance associated with a pn junction:

1. C_{dep} ***depletion capacitance***
2. C_D ***diffusion capacitance*** (due to variation of stored minority charge in the quasi-neutral regions)

For a one-sided p$^+$n junction, $Q_P >> Q_N$
so $Q = Q_P + Q_N \cong Q_P$:

$$C_D = \left|\frac{dQ}{dV_A}\right| = \tau_p \frac{dI}{dV_A} = \tau_p G = \frac{\tau_p I_{DC}}{kT/q}$$

Depletion Capacitance



$$C_{dep} \equiv \left|\frac{dQ_{dep}}{dV_A}\right| = A\frac{\varepsilon_s}{W}$$

What are three ways to reduce C_{dep}?

Total pn-Junction Capacitance

C_{dep}-vs.-V_A (Reverse Bias)

$$\frac{1}{C_{\text{dep}}^{\;2}} = \frac{W^2}{A^2 \varepsilon_s^{\;2}} \cong \frac{2(V_{\text{bi}} - V_{\text{A}})}{A^2 q \varepsilon_S N}$$

Example

If the slope of the $(1/C_{dep})^2$ *vs.* V_A characteristic is 2x10[23] $F^{-2}V^{-1}$, the intercept is 0.84V, and A is 1 μm^2, find the lighter and heavier doping concentrations N_l and N_h.

Solution:

$$N_l = 2/(slope \times q\varepsilon_s A^2)$$
$$= 2/(2\times10^{23}\times1.6\times10^{-19}\times12\times8.85\times10^{-14}\times10^{-8}\,\text{cm}^2)$$
$$= 6\times10^{15}\ \text{cm}^{-3}$$

$$V_{bi} = \frac{kT}{q}\ln\frac{N_h N_l}{n_i^2} \Rightarrow N_h = \frac{n_i^2}{N_l}e^{\frac{qV_{bi}}{kT}} = \frac{10^{20}}{6\times10^{15}}e^{\frac{0.84}{0.026}} = 1.8\times10^{18}\ \text{cm}^{-3}$$