Lecture #13

OUTLINE

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

Reading: Chapters 6.2 & 7

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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

\[
\frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} = \frac{n_i^2}{N_d} \frac{1}{\tau_n} -L_N \leq x \leq -x_p
\]

\[
\frac{\partial p}{\partial t} = -\frac{\Delta p}{\tau_p} = \frac{n_i^2}{N_d} \frac{1}{\tau_p} \quad x_n \leq x \leq x_n + L_p
\]

\[
I_0 = qAL_N \left( \frac{n_i^2}{N_d} \frac{1}{\tau_n} \right) + qAL_P \left( \frac{n_i^2}{N_d} \frac{1}{\tau_p} \right)
\]
Deviations from the Ideal $I$-$V$ Behavior

Effect of R-G in Depletion Region

- The net generation rate is given by
  \[
  \frac{\partial p}{\partial t} = \frac{\partial n}{\partial t} = \frac{n_i^2 - np}{\tau_p (n + n_i) + \tau_n (p + p_i)}
  \]
  where $n_i \equiv n_i e^{(E_T - E_i)/kT}$ and $p_i \equiv p_i e^{(E_i - E_T)/kT}$
  $E_T = \text{trap - state energy level}$

- R-G in the depletion region contributes an additional component of diode current $I_{R-G}$
  \[
  I_{R-G} = -qA \int_{-x_p}^{x_n} \left. \frac{\partial p}{\partial t} \right|_{R-G} \, dx
  \]
• For reverse bias greater than several $kT/q$,\
\[ \frac{qA}{n_i W} \frac{I_{GR}}{2\tau_0} \] \hspace{1cm} \text{where } \tau_0 \equiv \frac{1}{2} \left( \frac{\tau_p}{n_i} + \frac{\tau_n}{n_i} \right) \\

• For forward biases,\
\[ I_{R-G} \propto qA n_i W e^{qV_A/2kT} \]
High-Level Injection Effect

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

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

or

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

⇒ 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:

\[ i = G_v + C \frac{dv}{dt} \]

Small-signal conductance:

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

\[ G = \frac{q}{kT} I_0 e^{qV_A/kT} \equiv I_{DC} / \frac{kT}{q} \]
2 types of capacitance associated with a pn junction:

1. $C_{\text{dep}}$ **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 $Q = Q_P + Q_N \approx Q_P$:

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

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### Depletion Capacitance

![Depletion Capacitance Diagram]

What are three ways to reduce $C_{\text{dep}}$?
Total pn-Junction Capacitance

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\[ \frac{1}{C_{\text{dep}}} = \frac{W^2}{A^2 \varepsilon_s^2} \approx \frac{2(V_{\text{bi}} - V_A)}{A^2 q \varepsilon_s N} \]

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Example

If the slope of the $\left(1/C_{\text{dep}}\right)^2$ vs. $V_A$ characteristic is $2 \times 10^{23}$ $\text{F}^{-2} \text{V}^{-1}$, the intercept is $0.84 \text{V}$, and $A$ is $1 \mu\text{m}^2$, find the lighter and heavier doping concentrations $N_l$ and $N_h$.

Solution:

$$N_l = 2 / (\text{slope} \times q \varepsilon_s A^2)$$

$$= 2 / \left(2 \times 10^{23} \times 1.6 \times 10^{-19} \times 12 \times 8.85 \times 10^{-14} \times 10^{-8} \text{cm}^2\right)$$

$$= 6 \times 10^{15} \text{ cm}^{-3}$$

$$V_{bh} = \frac{kT}{q} \ln \frac{N_h N_l}{n_i^2} \Rightarrow N_h = \frac{n_i^2 e^{\frac{qV_{bh}}{kT}}}{N_l} = \frac{10^{20}}{6 \times 10^{15}} e^{0.84 / 23} = 1.8 \times 10^{18} \text{ cm}^{-3}$$