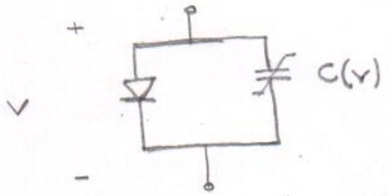
Switching behavior of pn diodes - $\boxed{\text{Course 11}}$

Equivalent model



$$I = I_s\left(\exp\frac{qV}{kT} - 1\right) + \frac{dQ}{dt}$$

ideal diode with stored charges

$$\frac{dQ}{dt} = \underbrace{\frac{dQ}{dV}}_{C}\cdot\frac{dV}{dt} = C\cdot\frac{dV}{dt}$$

$\therefore$ change in charges in a diode is equal to the change in Voltage times $\underline{\underline{C}}$.

$$C = \underset{\text{diffusion}}{C_d} + \underset{\text{junction or depletion}}{C_j}$$

C_j : related to the change of depletion width

C_d : related to the amount of charges (minority carriers) injected in the depletion region

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1. Junction capacitance C_j

- Depletion Charges : (on either side of the depletion region)

for example, on p-side: $Q_j(V) = -\underset{C}{q}\cdot\underset{cm^{-3}}{N_A}\cdot\underset{cm}{x_p}\cdot\underset{cm^2}{A} = -A\cdot\sqrt{\dfrac{2q\cdot\varepsilon\cdot N_D\cdot N_A\cdot(\phi_{bi}-V)}{N_D+N_A}}$

thus, $Q_j(V) = Q_j(V=0)\cdot\sqrt{1-\dfrac{V}{\phi_{bi}}}$ //

$$C_j(V) = \frac{dQ_j(V)}{dV} = +A\cdot\sqrt{\frac{q\cdot\varepsilon\cdot N_D\cdot N_A}{2(N_D+N_A)\cdot(\phi_{bi}-V)}} =$$

thus,

$$C_j(V) = \frac{C_j(V=0)}{\sqrt{1-\dfrac{V}{\phi_{bi}}}}$$ //

For p^+-n junction :

$N_A \gg N_D \Rightarrow C_j(V) = A\sqrt{\dfrac{q\cdot\varepsilon\cdot N_D}{2(\phi_{bi}-V)}} \Rightarrow \boxed{\dfrac{1}{C_j^2} = \dfrac{2(\phi_{bi}-V)}{\varepsilon\cdot q\cdot N_D\cdot A^2}}$

· Another way of thinking:

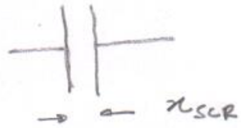
Starting from $V = 0$:

if $V \uparrow \Rightarrow SCR \downarrow \Rightarrow C \uparrow$

if reverse V is applied $\Rightarrow SCR \uparrow \Rightarrow C \downarrow$

thinking of a parallel plate capacitor:

$$C = \varepsilon \cdot \frac{A}{t}$$



$$\therefore \; C = \frac{\varepsilon . A}{x_{SCR}} = \frac{\varepsilon . A}{\sqrt{\dfrac{2 \varepsilon (N_D + N_A) . (\phi_{bi} - V)}{q N_A N_D}}}$$

$$C = \sqrt{\frac{\varepsilon q N_A N_D}{2 (N_D + N_A)(\phi_{bi} - V)}} \; . \; A$$

for the class exercise:

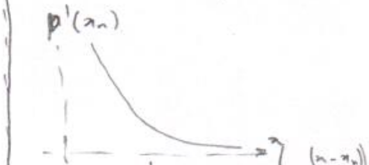
$$x_{SCR} = 0.11 \mu m$$

$$\therefore \; C_j(V=0) = A . \frac{\varepsilon}{x_{SCR}(V=0)} = 10 \times 10^{-8} \, cm^2 \times \frac{11.7 \, . \, 8.85 \times 10^{-14} \, F/cm}{0.11 \times 10^{-4} \, cm} = 1.0 fF$$

$$\therefore \; C_j(V) = \frac{C_j(V=0)}{\sqrt{1 - \dfrac{V}{\phi_{bi}}}} = \frac{C_j(V=0)}{\sqrt{1 - \dfrac{0.6}{0.94}}} = 1.66 fF$$

Diffusion Capacitance :

Integral of p' (1) #4



$$p'(x) = p'(x_n) \cdot \exp\left(-\frac{(x-x_n)}{L_h}\right)$$

$$Q_n = \int_{x_n}^{\infty} q \cdot A \cdot p'(x)\, dx$$

$$= q \cdot A\; p'(x_n) \cdot L_h$$

Diffusion (2)

$$J_e = -q \cdot n' \cdot v_e^{diff}$$

$$v_e^{diff} = -\frac{D_e}{L_e} \; \frac{[cm^2/s]}{[cm]}$$

⇒ due to minority carrier charges :

⇒ QNRs are flooded with minority carriers in exass.

$$\Delta Q_{hn} \simeq |\Delta Q_{en}| \equiv \Delta Q_n$$

using (1) and (2) :

$$\begin{cases} Q_p = q \cdot A \cdot L_e \; n'(-x_p) = A \cdot \dfrac{L_e^2}{D_e} \cdot J_e(-x_p) \\ Q_n = q \cdot A \cdot L_h \; p'(x_n) = A \, \dfrac{L_h^2}{D_h} \cdot J_h(x_n) \end{cases}$$

also

$$\begin{cases} Q_p = \underbrace{\tau_e}_{\text{lifetime minority carrier}} \times I_e(-x_p) \\ Q_n = \tau_h \times I_h(x_n) \end{cases}$$

$$\underbrace{\tau}_{\text{recombination lifetime}} = \frac{L_e^2}{D}$$

L_e — diffusion lenght

D — diffusion coefficient

$$\therefore Q_d = Q_p + Q_n = \tau_e I_e + \tau_h I_h = Q_s \left(\exp\frac{qV}{KT} - 1\right)$$

forward bias : • Q_d : charge recombining at a time τ

gives rise of $I = Q_d/\tau$

• charge increases exponentially

Reverse bias : • charge saturates to a small value

$$\therefore C_d = \frac{dQ_d}{dV} = \frac{q}{KT} \cdot Q_s \cdot \exp\frac{qV}{KT}$$

$$\simeq \frac{q}{KT} \, Q_d \quad (\text{for } V \gg KT)$$

$$\boxed{C = C_j + C_d}$$

thus :

$$\begin{cases} C_j \text{ dominates in reverse bias} \\ C_d \quad " \quad \text{in forward bias} \end{cases}$$