3.2 d) Capacitance of pn junction diodes (pnj)

Two types of capacitance for pnj Diodes:

1. The junction cap due to the dipole in the transition region
2. The charge storage cap due charge storage effects

1. is also called as the depletion layer (or transition region) cap.
2. Is also called as the diffusion cap.

(1) : this type is dominant under reverse-bias conditions and is defined by: C-|dQ/dVa|
where Q is the charge on each side of the depletion layer (w)
which is a function of applied voltage (Va) as follows:

For an Abrupt Pn junction:

$Q = q\,A\,X_{no}\,N_d$, $X_{no} = Na\,W/(Na+Nd)$, $w = \left[\frac{2\varepsilon\,(Vo-V\alpha)}{q}\left(\frac{N_\alpha+N_d}{N_\alpha N_d}\right)\right]^{1/2}$

$$\therefore Q = A\left[2\,q\,\varepsilon\,(Vo-Va)\,\frac{N_\alpha N_d}{N_\alpha+N_d}\right]^{1/2} \qquad (3.36)$$

$$Cj = \left|\frac{dQ}{dVa}\right| = \left|\frac{dQ}{d(V0-Va)}\right| = \frac{A}{2}\left[\frac{2\,q\,\varepsilon}{(V0-Va)}\,\frac{N_\alpha N_d}{N_\alpha+N_d}\right]^{1/2} \qquad \text{Abrupt junction}$$

(3.37)

$Cj\ \alpha\ (Vo-Va)^{-1/2}$

Applications: Voltage-variable capacitive diodes (called varactors) are used in tuning circuits, etc.

eq 3.37 can be recast as:

$$Cj = \frac{Cj_o}{(1-V\alpha/Vo)^{1/2}} = \varepsilon A/W \qquad (3.38)$$

where $Cj_o = A\,[\varepsilon\,qN\alpha Nd\,/\,2Vo(N\alpha+Nd)]^{1/2}$ (3.39a)

for $p^+$-n junction: $(Cj_o)_{p+\,n} = A[\varepsilon\,q\,Nd/2Vo]^{1/2}$ (3.39b)

eq (3.38) implies that the transition region capacitance is effectively that of a parallel-plate capacitor with s/c as the dielectric and spacing between the plates equal to “w”.

Observation: This junction capacitance is somewhat different in microscopic detail from a typical parallel-plate cap as shown below:

Note: For a Reverse bias $V\alpha=-Vr$, Thus as $|V\alpha|$ increases $\Longrightarrow$ Cj decreases

OBSERVATION:

eq (3.38) indicates that theoretically Cj approaches $\infty$ (i.e., short circuit) as $V\alpha$ approaches Vo, but in practice due to current flow in forward bias, there would be losses involved in the neutral regions which prevent this theoretical result. Most of the applied voltage drop would be across these lossy regions.

However, there is an increase in the transition region capacitance under forward bias and peaks around $V\alpha=Vo$ and then decreases when $V\alpha>Vo$ as shown below:

(2) Diffusion Capacitance : This cap dominates in forward bias. Assume $p^+$ n junction: the charge stored in the injected distribution is:

$Q_p = I_p = qA\int P'(X'_n)\,dx'_n = q\,A\,Lp\,P'(X'_n=0)$

$Q_p = q\,A\,Lp\,p_n\,e^{q\,v\alpha/KT}$

$$Cs = \frac{d\,Q_p}{dV\alpha} = \frac{q^2}{KT}\,A\,Lp\,p_n\,e^{q\,v\alpha/KT} = \frac{q}{KT}\,I\,\tau_p \qquad (3.41)$$

Observation: In high freq Applications, Cs could be a serious limitation (e.g. in Switching Applications, ON/OFF)

$\tau p\downarrow \Longrightarrow Cs\downarrow$ also $I\downarrow \Longrightarrow Cs\downarrow$

Therefore operating the diode at lower currents with added recombination centers will help high frequency performance.

**3.4 – A small signal model of the diode**

for All bias : $Cj = C_{jo} / (1-\frac{V\alpha}{Vo})^{1/2}$ Abrupt junction (3.44)

For FWD bias : $G_S = \frac{q}{K_T}\,I_{Dc} = \frac{I_{DC}}{V_T}$ diff. Conductance (3.45a)

$C_S = G_S\tau_P$ diff. capacitance (3.45b)

AC Models

In Reverse bias:

In FWD bias:

Usually Cj << Cs

High frequency Effect :

Note: In the above equations we have assumed that Lp remains constant with frequency otherwise

$\tau p^* = \tau p/(1+j\omega\tau p)$ $Lp^* = (\tau p^* Dp)^{1/2} = Lp/(1+j\omega\tau p)^{1/2}$ (3.46a)

$Ys = dI/dVa = (qA\,P_n\,Lp^*/\tau p^*)\,d(e^{qv\alpha/KT})/dVa = qI_{DC}\,(1+j\omega\tau p)^{1/2}/KT$ (3.46b)

for small ω:

$$Ys \sim \frac{qI_{Dc}}{KT}(1+j\ wTp) = G_S + j\omega C_S, \qquad C_S = ½\, G_S\, \tau p,\ G_S = \text{Same} \quad (3.47)$$

**3.5) Switching Transient**

To understand and analyze switching transients, time variation of stored charge needs to be understood as follows:

- use time-dependent continuity equations. (Eqs. 2.7):

$$-\frac{\partial jp(X\acute{n},t)}{\partial X} = q\frac{\acute{P}(X\acute{n},t)}{\tau p} + q\frac{\partial \acute{P}(X\acute{n},t)}{\partial t} \qquad (3.48)$$

Integrate $\int_o^\infty$ on both sides; assuming a long "n region"

# {Equations to be given in class}

where $Qp\,(+) = \int_o^\infty p' dX_n'$ represents the excess hole charges in the n region.

at steady state: $I(t) = Qp/\tau p \Longrightarrow Qp = I\tau p$

since $dQp/dt = 0$

Note: Eq. (3.49) could have been written intuitively as well!

**3.5) Switching Transient (Cont’d)**

{Equations to be given in class}