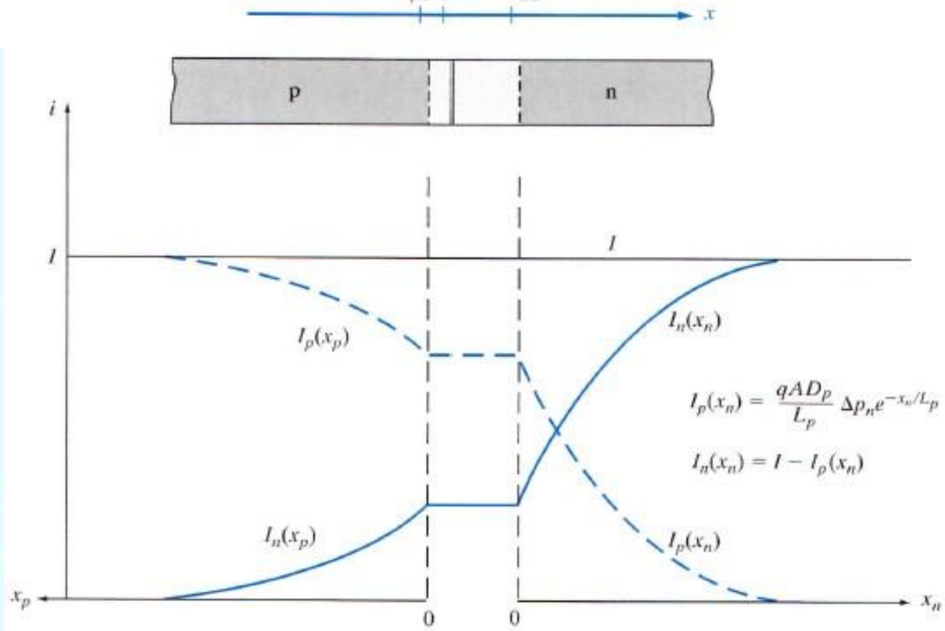
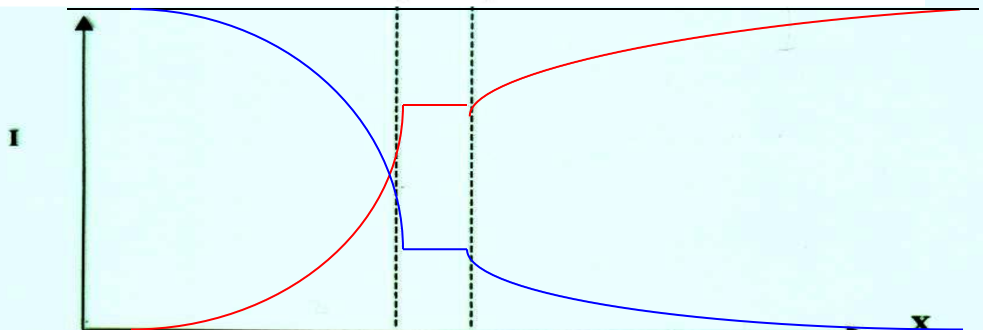


N_a N_d

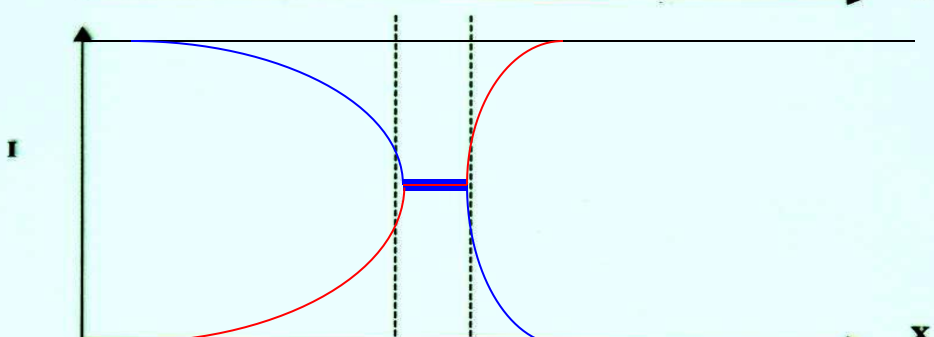
L_p L_n



N_a N_d

D_p D_n

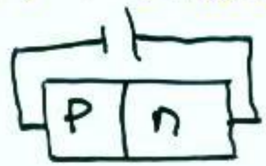
τ_p τ_n

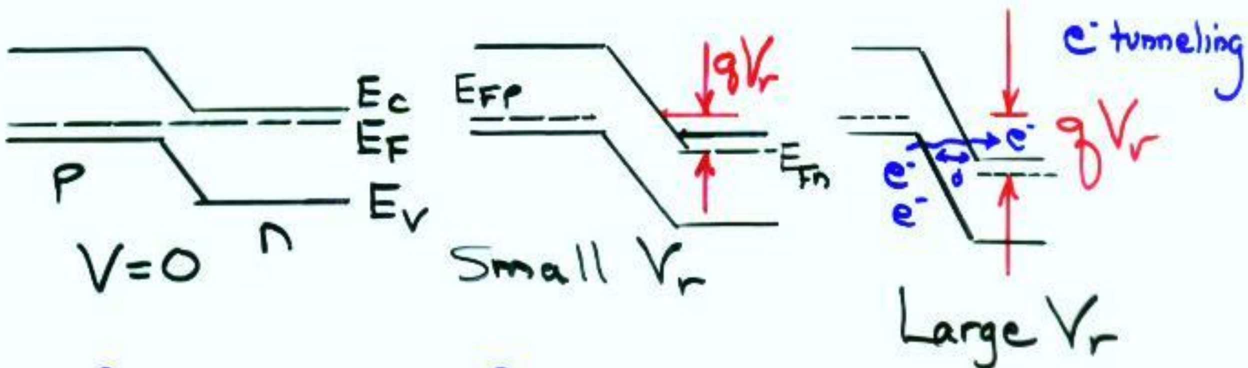


Reverse Field Breakdown

Two Breakdown Mechanisms: → Zener
→ Avalanche

① Zener





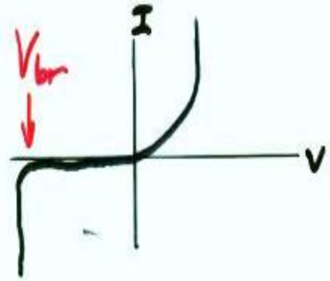
Tunnel Current of e^- from p-side valence band to n-side conduction band.

V_r usually $\lesssim$ a few volts.

$I \propto |\text{Tunnel Probability}|^2 \propto |P_T|^2$

$\propto$ # e^-'s in valence band × # empty states in conduction band.

$\propto \frac{1}{d}$



Can think of as "field ionization" of host atoms at a junction

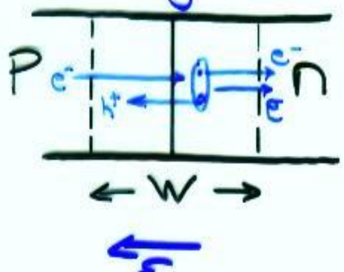
$\mathcal{E} \sim 10^6 V/cm$

V is only a few volts but d is very small.

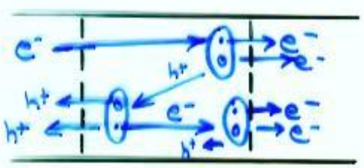
Avalanche Breakdown

For lightly-doped junctions, tunneling negligible.
Instead, impact ionization process.

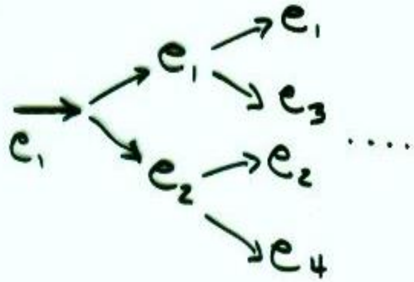
Now, higher voltages and carrier multiplication



Single ionizing collision



Multiple ionizing collisions
primary, secondary, tertiary



Avalanche Process

Probability of ionizing collision between e^- and lattice = P. $(P<1)$

n_{inc} = # of e^-'s incident from $-x_{po}$

$n_{inc} P$ = # of extra e^-'s after ionizing collision

Total # after collision = $n_{inc}(1+P)$

$n_{inc} \cdot P$ secondaries $\rightarrow n_{inc} \cdot P \cdot P$ tertiaries

$$n_{out} = n_{inc}\,(1 + P + P^2 + P^3 + \cdots)$$

Electron multiplication factor

$$M_n = \frac{n_{out}}{n_{in}} = 1 + P + P^2 + P^3 + \cdots =$$

To first order

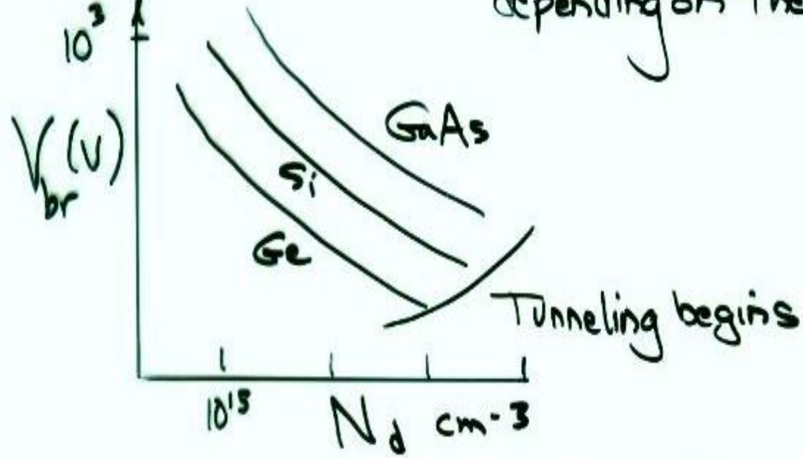
Expect multiplication to depend on V_r and doping $\rightarrow$ $\mathcal{E}_0 = -$

α

$$M = \frac{1}{1-(V/V_{br})^n}$$

Empirical

n varies from ~3 to 6, depending on the junction material



V_{br} increases with band gap E_g since more energy required to ionize electron-hole pairs.

SiC power transistors → high breakdown strength. $E_g \gtrsim 3eV$.

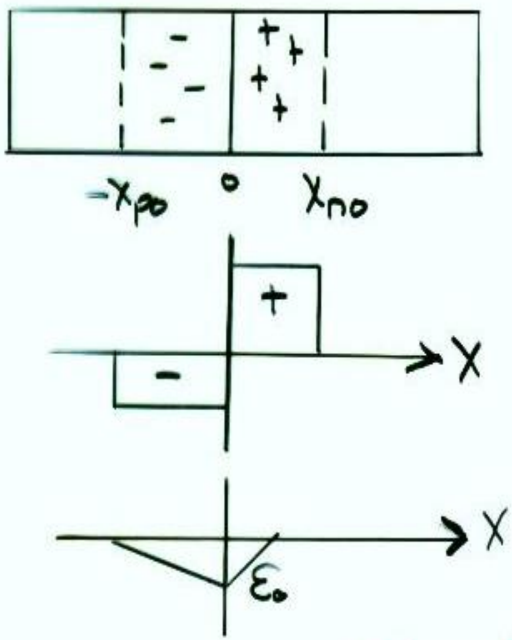
Capacitance of P-N Junctions

Two Types -

1) Junction C:
- Dipole across W
- Dominant in reverse bias

2) Storage C
- "Diffusion" capacitance: lag of V behind I (Time delay to leave W)
- Dominant in Forward Bias

Both important for time-varying devices.



Charge separation like parallel-plate capacitor

but <u>now</u>

$$C = \frac{Q}{V} \rightarrow C = \boxed{}$$

since Q varies nonlinearly with V.

This nonlinearity useful for some devices, limiting for other devices.

Nonlinearity:

$$W = \left[\frac{2\epsilon V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}$$

$V = 0$

Equilibrium (5-21)

$=$

$V \neq 0$

- W changes with bias, so uncompensated charge in W changes with V, so Q changes with bias.

$$|Q| = qAN_d\int_0^{x_{no}} dx = qAN_d x_{no} \quad \text{(n-side)}$$

$$= qAN_a\int_{-x_{po}}^{0} dx = qAN_a x_{po} \quad \text{(p-side)}$$

substitute for x_{no} and x_{po}.

$$W = x_{no} + x_{po} = x_{po}\left(1 + \frac{x_{no}}{x_{po}}\right)$$

$$= x_{po}\,(1$$

$$x_{no} = \frac{W N_a}{N_a + N_d} \qquad x_{po} = \frac{W N_d}{N_a + N_d}$$

$$\text{So } |Q| = qA\frac{N_d N_a W}{(N_d + N_a)} \qquad [\ldots]^{1/2} = W$$

$$= qA\frac{N_a N_d}{(N_d + N_a)}\left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$= A\left[2\epsilon q(V_0 - V)\frac{N_a N_d}{(N_a + N_d)}\right]^{1/2}$$

Note the $V^{1/2}$ dependence.

also $(V_0 - V)$ instead of V_0.

Now take derivative.

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\qquad\qquad\right]^{1/2}$$

j = junction

Voltage-Variable capacitance

Now take derivative.

$$C_j = \left|\frac{dQ}{d(V_0-V)}\right| = \frac{A}{2}\left[\frac{2\epsilon q}{(V_0-V)}\frac{N_a N_d}{(N_a+N_d)}\right]^{1/2}$$

j = junction

Voltage-Variable capacitance

$\frac{1}{V^{1/2}}$, not $\frac{1}{V}$

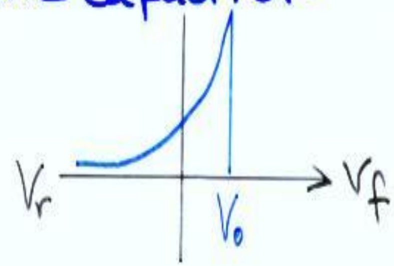
p-n junction device using voltage-variable capacitance is "varactor"

C_j has analogous form to parallel plate capacitor:

$$C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0-V)}\frac{N_a N_d}{(N_a+N_d)}\right]^{1/2} =$$

W corresponds to plate separation of parallel plate capacitor

Big difference:



Not constant

Asymmetric Junctions

W is primarily in

C is determined by only one doping concentration.

$x_{po} N_a =$

Example: p^+-n $\quad N_a \gg N_d$

so $x_{no} \gg x_{po}$

$x_{no} \simeq W, \quad x_{po} \simeq 0$

$$C_j = \frac{A}{2}\left[\frac{2\epsilon q}{(V_0 - V)} \frac{\cancel{N_a} N_d}{(\cancel{N_a + N_d})}\right]^{1/2}$$

$$= \frac{A}{2}\left[\frac{2\epsilon q}{(V_0 - V)} N_d\right]^{1/2}$$

(and vice-versa if dopings are reversed)

Can get N by measuring C_j (assuming sharp step)