Lec -25

→ Before M.S: Solid State Physics.

- Carriers, EB Diagram (Equ)
- R-G (SS) → uniform con.
- Steady state with Spatial variation
  - ↓ Diffusion
  - ↓ Drift.
- Continuity eq^n + Poisson eq^n

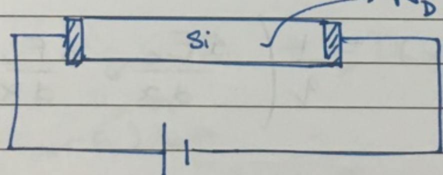
→ Now: Application to Devices.

- Resistor
- Diodes 2 weeks
- BJT 1 week
- MOSFET 2 weeks.
- New Devices 1 week

} 7 Mini Quizzes More

Resistor

$N_D = 10^{17} cm^{-3}$

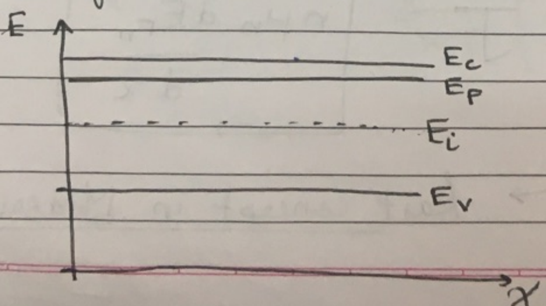


"Perfect Contact"

→ No Diffusion. → Metal contacts have no effect.

→ Constant Electric field

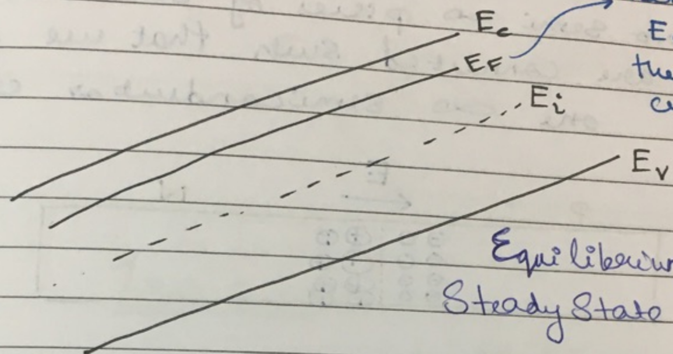
Band Diagram (At Equilibrium) (E=0)



at E = 0

Steady State, $E \neq 0$

Slope sign is Imp.



variation of E_F tells us there is a current.

Equilibrium → No current
Steady State → Current ✓

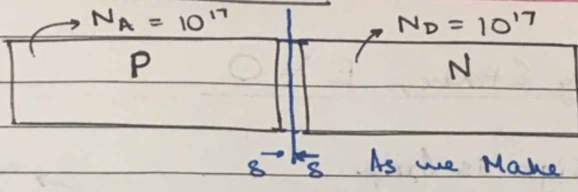
Method

Start with E_c (or E_V just E in Gen.) $= -q\,V(x)$
↳ Get $\vec{E}$

→ Are there Quasi Fermi Levels :

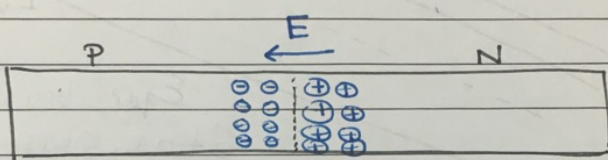
- No there is no split b/w the Quasi fermi levels.
- The n & p values are still given by the previous equations & values so we conclude no split b/w E_{Fn} & F_{Fp} Despite Steady State.

Diode



As we Make crystal contact

→ Two semi ∞ pieces of semiconductor are connected such that we get one ∞ semiconductor crystal.



→ As holes diffuse to the right and e^- diffuse to the left charge build up occurs & an electric field is set up.

→ Eventually the Generated Drift current offsets the existing diffusion current.

~~Steps~~

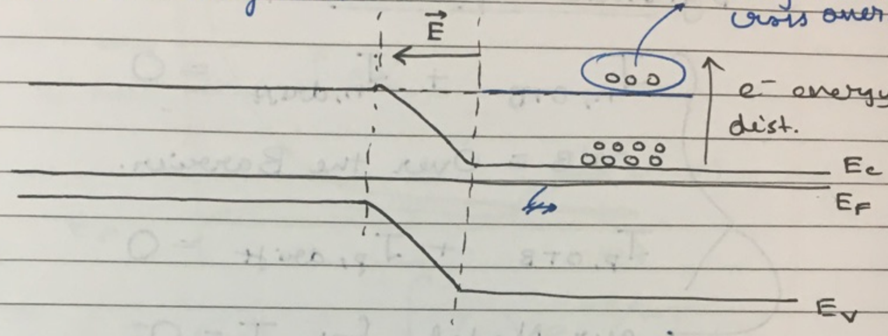
Steps

→ Diffusion
→ Generation / Uncovering of Ionic charges. **
→ Electric field.
→ Equilibrium ⇒ $J = 0$

Dynamic Eq^m

Static ✗

→ Band Diagram.



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→ Derive $I = I_0\left(e^{qV/KT} - 1\right)$

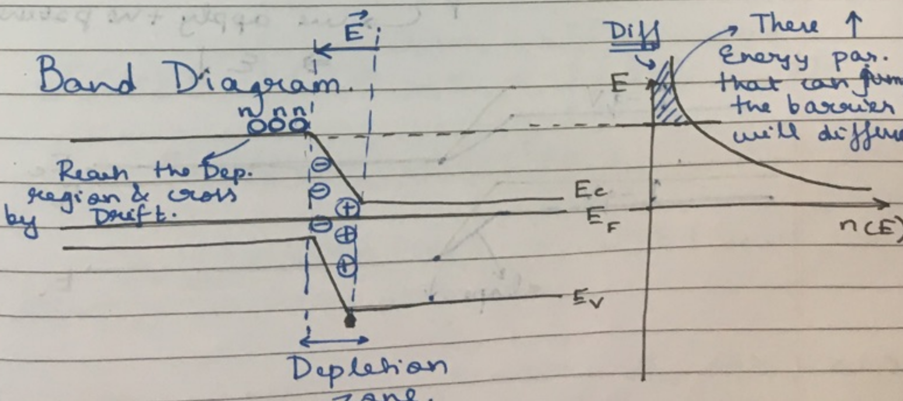
Text → SDF Chap, 5, 6 & 7

Recap

1) Even in Diode, $\frac{\delta E_F}{\delta x} = 0$ since

this comes from $J - J_N - J_P = 0$

2) Band Diagram.



Where, $n(E) = g(E)\,f(E)$

→ Dynamic Equilibrium

$$J_{n,OTB} + J_{n,drift} = 0$$

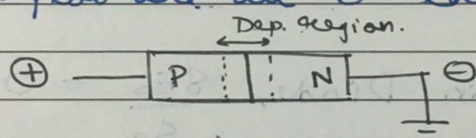
OTB ≡ Over the Barrier.

$$J_{p,OTB} + J_{p,drift} = 0$$

our Model for $J = 0$

→ Applying Bias

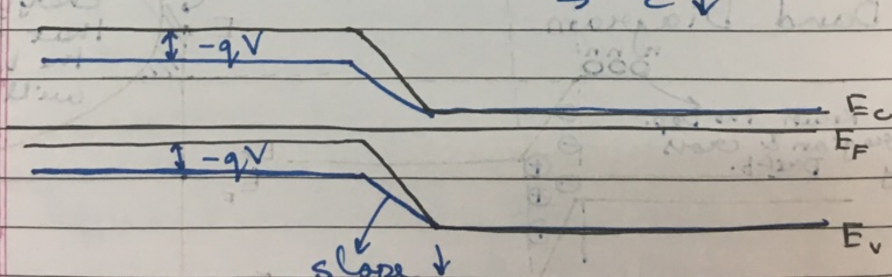
- In our band diagram the energy levels we plot are all e^- energies.

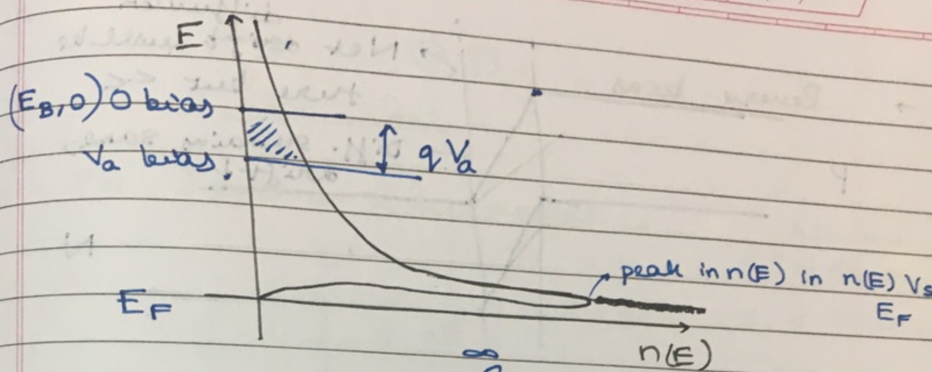


e^- energy

$\mathcal{E} = -qV$ → we apply +ve potential

⇒ $\mathcal{E} \downarrow$





$$I_{OTB}(V) = \int_{E_{B,0}-qV_a}^{\infty} (\;)\, e^{-E/KT}$$

→ Here J_n drift, Minority carrier diffusion from right to left remains unchanged since it is limited by no. available.

→ Hence J_n drift = (In mag.) to J_{OTB} at $E_{B,0}$

$$J(V) = \int_{E_{B,0}-qV_a}^{\infty} (\;)\, e^{-E/KT}\, dE - \int_{E_{B,0}}^{\infty} (\;)\, e^{-E/KT}\, dE$$

OTB (Sted. State) — OTB (Equil.)

→ Assuming constant prefactor.

$$= (\;)\left(e^{E_{B,0}/KT} - e^{(E_{B,0}-qV_a)/KT}\right)$$

new

$$= (\;)\left[e^{qV_a/KT} - 1\right]$$

- P N +

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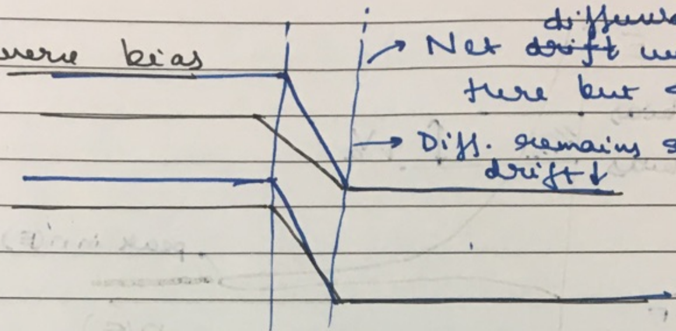
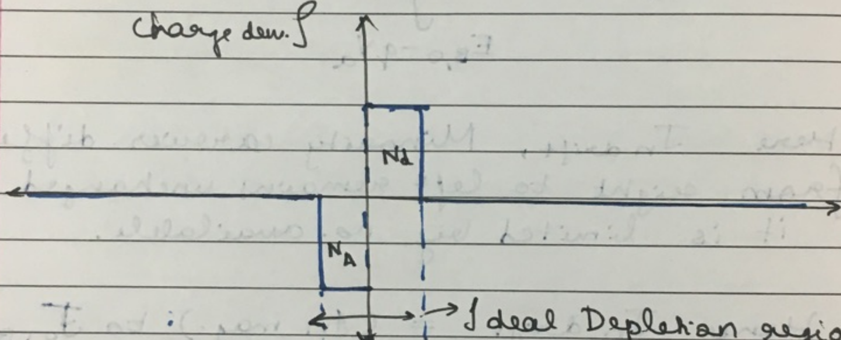
→ Reverse bias

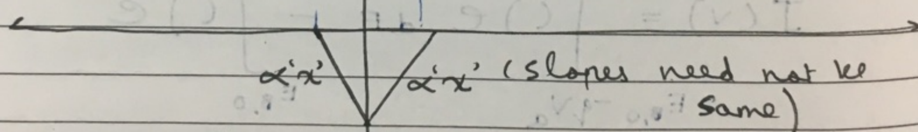


→ Charge Density Vs pos.

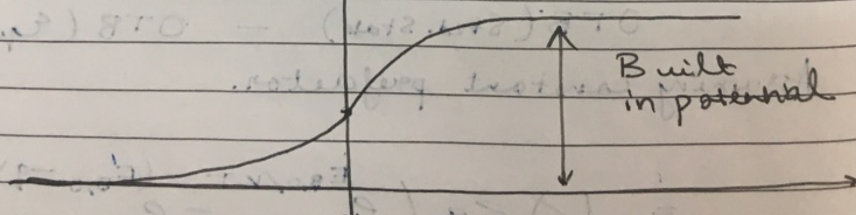


$\vec{E}$

→ Electric field



V



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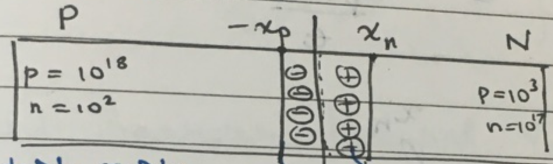
→ PN Junction Electrostatics

left end of dep. region

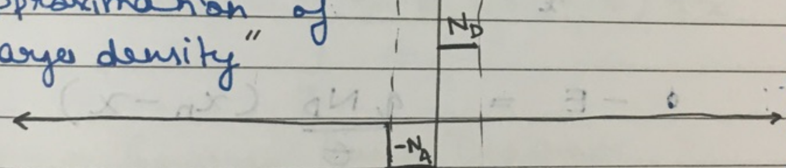
$$\rho = \begin{cases} \varepsilon \dfrac{dE}{dx} = -qN_A & -x_p < x < 0 \\ \phantom{\varepsilon \dfrac{dE}{dx}} = qN_D & 0 < x < x_n \end{cases}$$

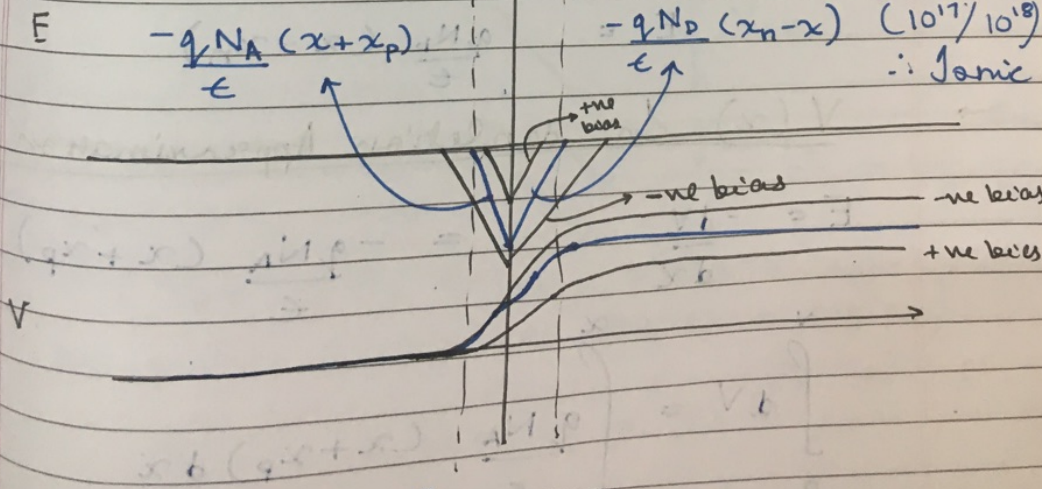


$\rho - n + N_D - N_A$

ρ "Called Depletion Approximation of Charge density"

Note Charge Density is Given by Majority carrier conc in that 1/2 $(10^{17}/10^{18})$ ∴ Ionic





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→ Calculation of Internal Electric Field

$$\int_0^E dE = \int_{-x_p}^{x} \frac{-qN_A}{\epsilon}\,dx$$

$\therefore \rho = \epsilon \frac{dE}{dx}$ & L.H.S of Dep. region

$$E = \frac{-qN_A}{\epsilon}(x + x_p) \quad -x_p \le x < 0$$

$$\int_E^0 dE = \int_x^{x_n} \frac{qN_D}{\epsilon}\,dx$$

$$0 - E = \frac{qN_D}{\epsilon}(x_n - x)$$

$$E = \frac{qN_D}{\epsilon}(x - x_n)$$

→ V (x) In depletion Approximation

$$E = \frac{-dV}{dx} = \frac{-qN_A}{\epsilon}(x + x_p)$$

$$\int_0^V dV = \int_{-x_p}^{x} \frac{qN_A}{\epsilon}(x + x_p)\,dx$$

$-x_p < x < 0$

$$V(x) = \frac{qN_A}{2\epsilon}(x+x_p)^2 \Big|_{-x_p}^{x}$$

~~Other side~~

$$V(x) = \frac{qN_A}{2\epsilon}\left[(x+x_p)^2\right]$$

$$\cancel{-\frac{qN_D}{2\epsilon}(x-x_n)^2}$$

~~Other si~~

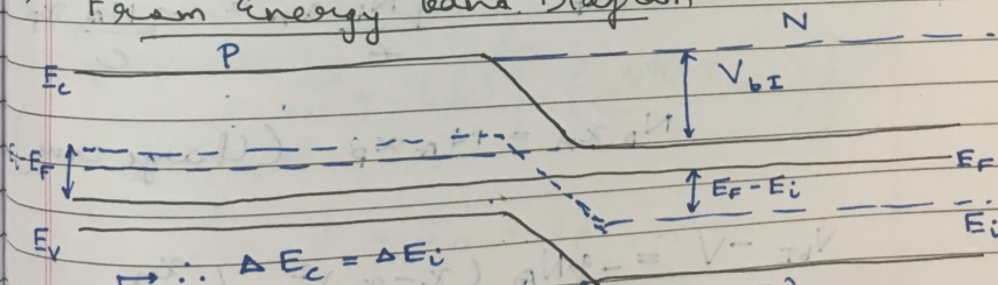
$$V(0) = \cancel{\frac{qN_A}{2\epsilon}x_p^2}$$

Voltages are relative.

→ To Get Barrier Potential V_{BI}

$$\int_{V}^{V_{bI}} dV = \int_{x}^{x_n} \frac{qN_D}{\epsilon}(x_n - x)\,dx$$

→ From Energy band Diagram



$\therefore \Delta E_c = \Delta E_i$

$= V_{bI} = (E_i - E_F)_{left} + (E_F - E_i)_{Right}$

On p side (out side depletion region)

$$p = N_A = n_i e^{(E_i - E_F)/kT}$$

L.H.S

$$\frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) = V_{left} \text{ (In terms of voltage)}$$

$$\frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right) = V_{Right}$$

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$$V_{bI} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

→ V inside in terms of x_n (R.H.S

$$\int_{V}^{V_{bI}} dV = \int_{x}^{x_n} \frac{qN_A}{\epsilon}(x_n - x)\,dx$$

~~$V_{bI} - 2V$~~ & Equating E at $x=0$

$$-\frac{qN_D}{\epsilon}(x_n - x) = -\frac{qN_A}{\epsilon}(x + x_p)$$

$$-\frac{qN_D}{\epsilon}x_n = -\frac{qN_A}{\epsilon}x_p$$

$$N_D x_n = N_A x_p \quad \text{(Charge cons.)}$$

$$V_{bI} - V = -\frac{qN_A}{2\epsilon}(x - x_n)^2 \Big|_{x}^{x_n}$$

$$V_{bI} - V = 0 + \frac{qN_A}{2\epsilon}(x - x_n)^2$$

$V - V$

$$W_{\text{Depletion region}} = x_n + x_p = \left[\frac{2\epsilon V_{bi}}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)\right]^{1/2}$$

$$V_{bI} = \frac{qN_D}{2\epsilon}(\cancel{x}-x_n)^2 + \frac{qN_A}{2\epsilon}(\cancel{x}+x_p)^2$$

$$V_{bI} = \frac{q}{2\epsilon}\left(N_D x_n^2 + N_A x_p^2\right)$$

$$= \frac{q}{2\epsilon} N_D x_n (x_n + x_p)$$

$$x_p = \frac{N_D}{N_A} x_n \quad \rightarrow \quad \frac{qN_D x_n^2}{2\epsilon}\left(1+\frac{N_D}{N_A}\right) = V_{bI}$$

if $\frac{N_A}{N_D} >> 1$ ⇒ {Entire Depletion region lies in N side}

$$x_n = \sqrt{\frac{N_A}{N_A+N_D} V_{bI} \times \frac{2\epsilon}{qN_D}}$$

$$x_p = \sqrt{\frac{N_D}{N_A+N_D} V_{bI} \times \frac{2\epsilon}{qN_A}}$$

$$x_n + x_p = \sqrt{\frac{V_{bI}\times 2\epsilon}{q}} \times \cancel{\left(\frac{1}{N_A+N_D}\right)^{1/2}} \times \left(\frac{N_A+N_D}{N_A N_D}\right)^{1/2}$$

Current Expression

→ From Last class → estimate J_0

$$J = (J_0)\left[\left(e^{qV/kT}-1\right)\right]$$

$$J = J_n + J_p$$

$$J_n = \frac{q n_i^2}{\tau_n N_A}\sqrt{D_n \tau_n}$$

$$J_p = \frac{q n_i^2}{\tau_p N_D}\sqrt{D_p \tau_p}$$

$$\cancel{I_0 = I_n + I_p}$$

$$J = q\left(\frac{n_i^2}{N_D \tau_n}\sqrt{D_n \tau_n} + \frac{n_i^2}{N_D \tau_p}\sqrt{D_p \tau_p}\right)\left(e^{qV/kT} - 1\right)$$

$$= J_0 \left(\;\cdot\; \right)$$

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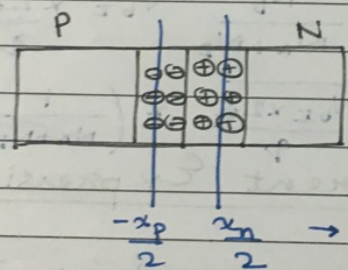
→ P-N Junction as Capacitor.

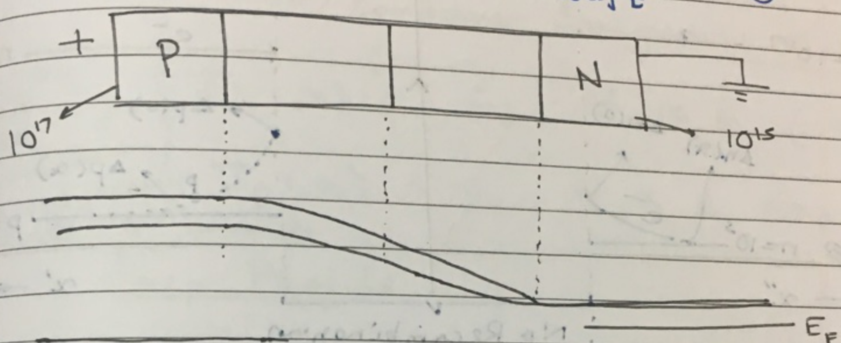


→ Assume Charge concentration at Mid-plane.

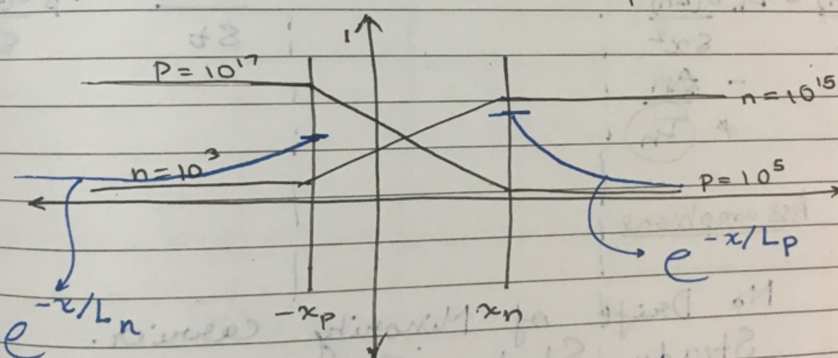
Current through Diode

At Eq.

$$J_{n\,diffusion} + J_{n\,drift} = 0$$



$J_p = p\mu \nabla E_{F_p}$ $\quad p\uparrow \Rightarrow \nabla E_{F_p} \downarrow$



→ e^- may travel all the way to the contact or recombine in b/w, in both cases it contributes to the current.

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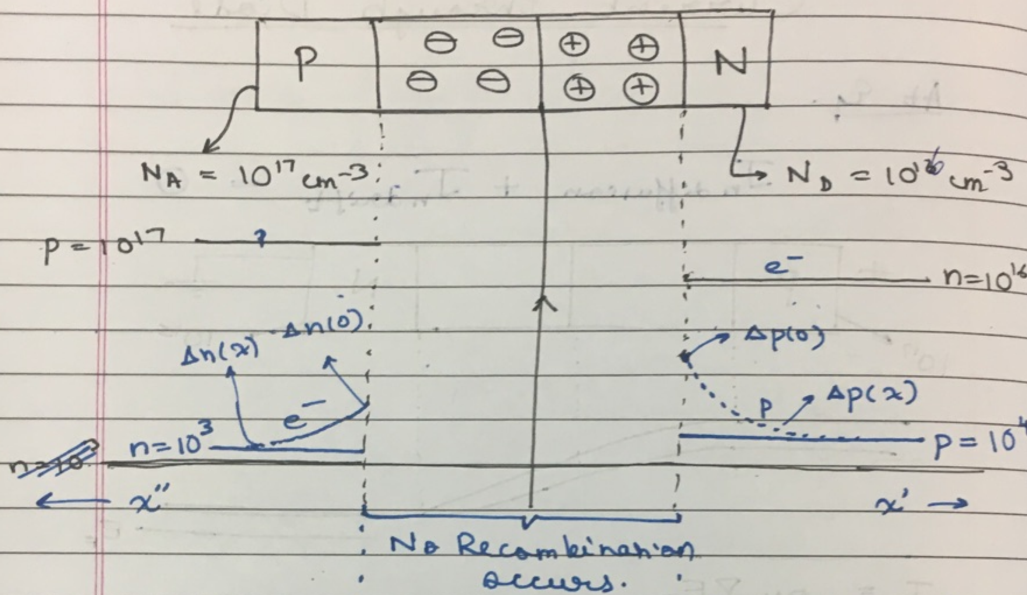


$$\frac{\delta(\Delta n)}{\delta t} = D_n \frac{\delta^2(\Delta n)}{\delta x^2} - \frac{\Delta n}{\tau_n}$$

$$\frac{\delta(\Delta p)}{\delta t} = D_p \frac{\delta^2(\Delta p)}{\delta x^2} - \frac{\Delta p}{\tau_p}$$

Assumptions

→ No Drift of Minority carrier.
→ Steady State, Semi ∞ Approx.

$\Delta n(x) = \Delta n(0)\, e^{-x''/L_n}$ $\Delta p(0)\, e^{-x'/L_p}$

L_p / L_n → Diffusion lengths.

Δn

Current Determination.

$$J = \underbrace{J_n(x) + J_p(x)}_{\text{vary}}$$

J ⟶ same / constant irrespective of x

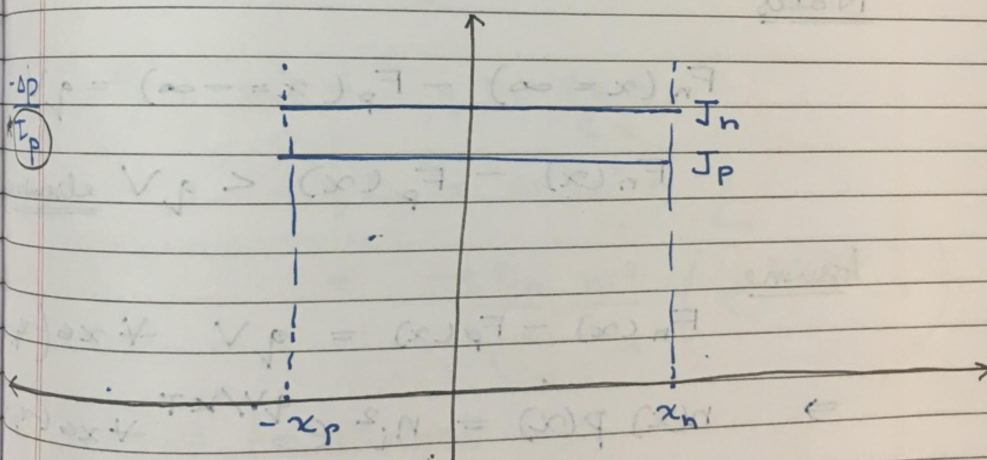
** No Accumulation, entire journey in dep. region covered

$$J_n(x) = c_1 \quad \forall\, x \in (-x_p, x_n)$$

$$J_p(x) = c_2 \quad \forall\, x \in (-x_p, x_n)$$

$J_{n/p}$ Profile

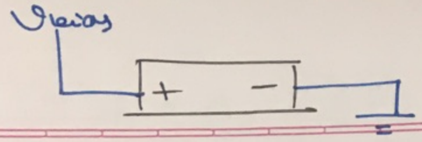
$-\Delta p$ I_p



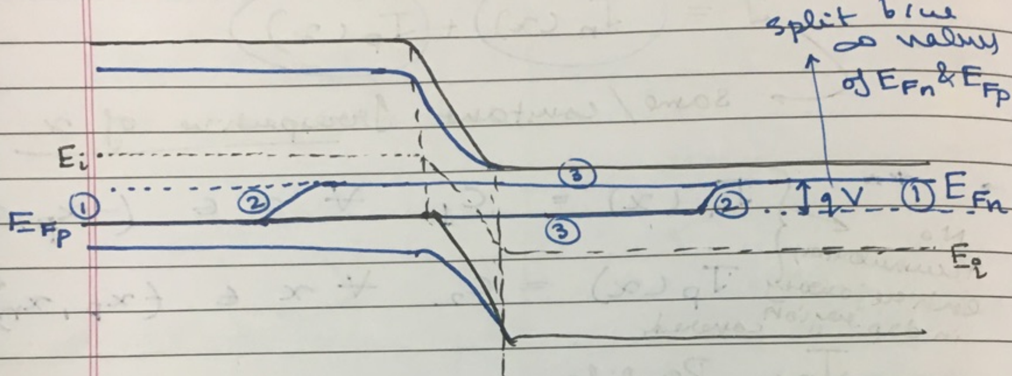
→ Using continuity of J_n / J_p

$$J = J_p(x_n) + J_n(-x_p)$$

J ⟶ using constant J



→ Band Diagram in the presence of Bias →



<u>Notes</u>

$$F_n(x=\infty) - F_p(x=-\infty) = qV$$

$$F_n(x) - F_p(x) < qV \text{ \underline{elsewhere}}$$

<u>Assume</u>

$$F_n(x) - F_p(x) = qV \quad \forall x \in (-x_p, x_n)$$

$$\Rightarrow \quad n(x)\,p(x) = n_i^2 e^{qV/kT} \quad \forall x \in (-x_p, x_n)$$

At, $x = -x_p$, $p = N_A$, $n = \frac{n_i^2}{N_A} e^{qV/kT}$ 1)

2)

At, $x = x_n$, $n = N_D$, $p = \frac{n_i^2}{N_D} e^{qV/kT}$ 3)

Current Expression

$$J_n(-x_p) = -q D_n \left.\frac{\delta(\Delta n)}{\delta x}\right|_{x=-x_p}$$

$$\Delta n(-x_p) = n(-x_p) - n_o(-x_p)$$

$$= \frac{n_i^2}{N_A} e^{qV/KT} - \frac{n_i^2}{N_A}$$

$$= \frac{n_i^2}{N_A}\left(e^{qV/KT} - 1\right) = \Delta n(0)$$

$$J_n(-x_p) = q D_n \frac{\delta(\Delta n)}{\delta x}$$

$$= q D_n * \Delta n(0) \times \frac{-1}{L_n}$$

$$= \frac{-q D_n}{L_n} \frac{n_i^2}{N_A}\left(e^{qV/KT} - 1\right)$$

Food for thought :

1) Connect Diode Across resistor, current?

2) Can we measure V_{bI} with a Voltmeter.

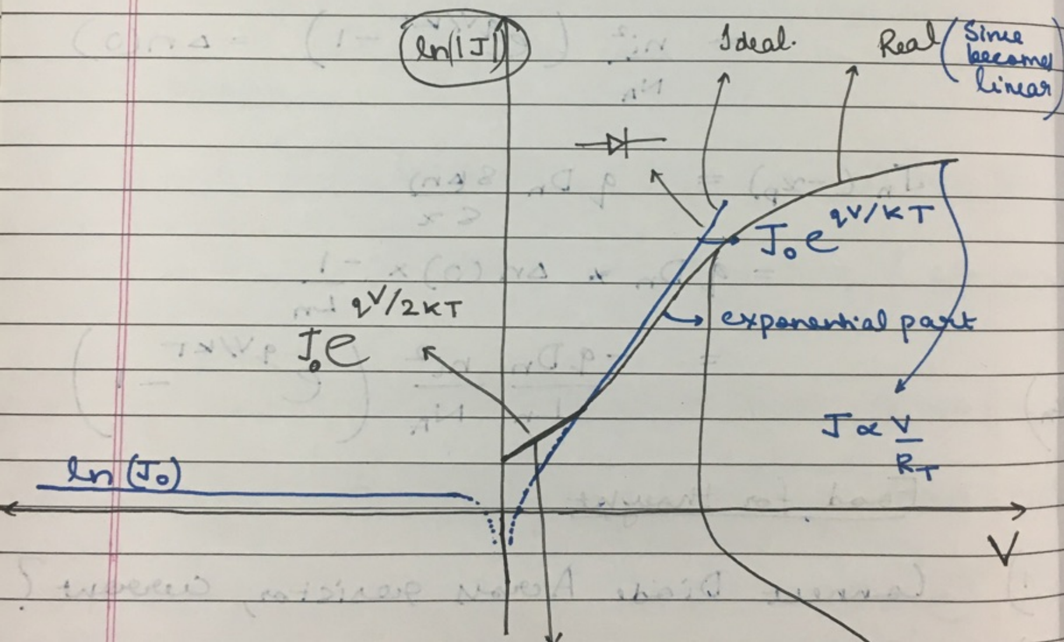
3) Reconcile the 2nd Derivation of current expression with 1st OTB derivation.

Ideal Diode Vs. Real Diode

<u>New Equations</u> (W = ( ), V_{bI} = ( ))

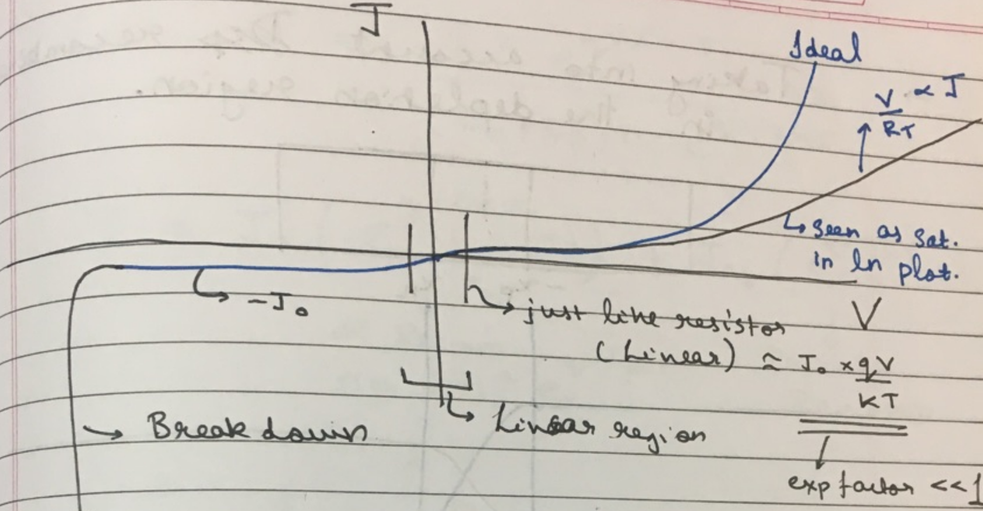
$$J = J_0 \left(e^{qV/KT} - 1 \right)$$

$$J_0 = q \left[\underbrace{\frac{n_i^2}{N_A} \frac{D_n}{L_n}}_{e^- \rightarrow P\ reg.} + \underbrace{\frac{n_i^2}{N_D} \frac{D_p}{L_p}}_{p \rightarrow N\ reg.} \right]$$

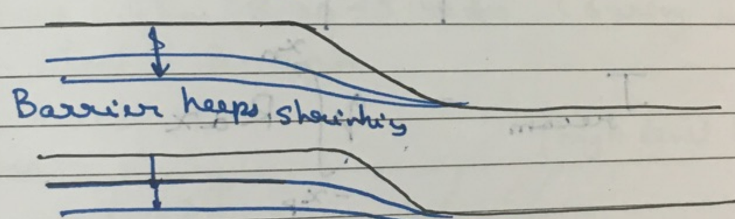


Due to the Recombination current.

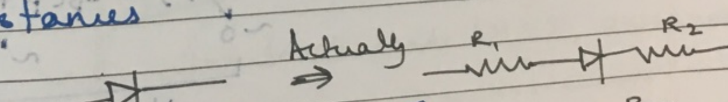
If High level Injection we get $e^{qV/2KT}$



→ from Band Diagram



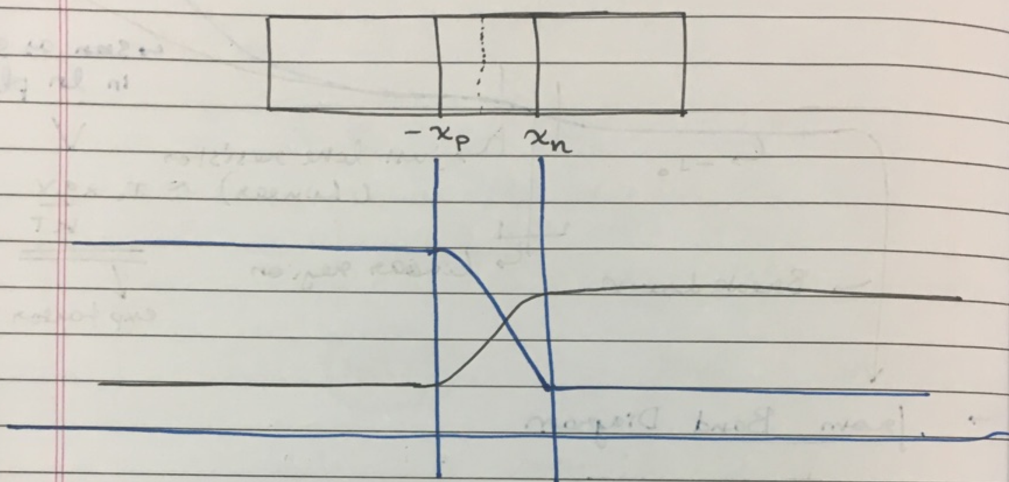
→ As barrier keeps shrinking, all e^- can overcome the barrier and current is determined by resistances



$R_1 + R_2 = R_T$

$$J \propto \frac{V}{R_T}$$

→ Taking into account ~~Dsp~~ recombination in the depletion region.



$$J_{recom} = q\int_{-x_p}^{x_n} R\,dx$$

$$= \int \frac{n_i^2\, e^{qV/kT} - n_i^2}{\tau_n (n + \cancelto{\sim 0}{n_1}) + \tau_p (p + \cancelto{\sim 0}{p_1})}$$

Mid - Band traps.

$$\int \frac{1}{\tau_n n + \tau_p p}\,dx$$

$$n = p \quad , \quad np = n_i^2\, e^{qV/kT}$$

$$n = n_i\, e^{qV/2kT}$$

$$J = \frac{n_i^2 e^{qV/kT} \quad \Delta x}{(I_n + I_p) n_i e^{qV/2kT}}$$

$$J = J_0 \left(e^{qV/kT} - 1\right) + J_{0_2}\left(e^{qV/2kT} - 1\right)$$

$\propto$ Recom.

$np = n_i^2 e^{qV/kT}$

Due to Recomb.

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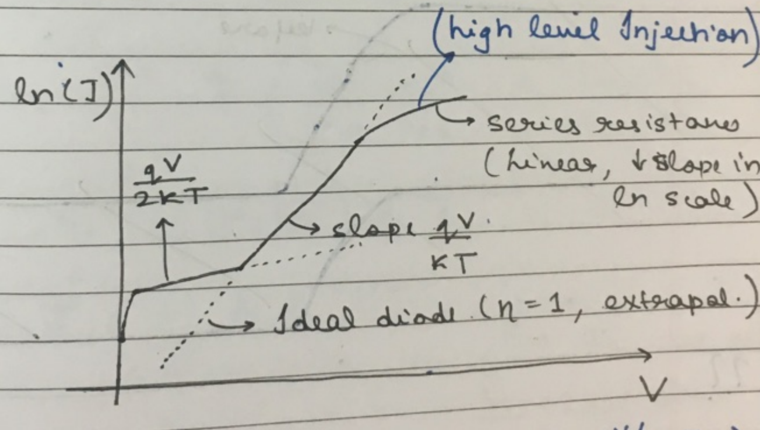
Quiz: Thu 8:30 - 8:45 am (during lecture)

Tut: 3 - 4pm

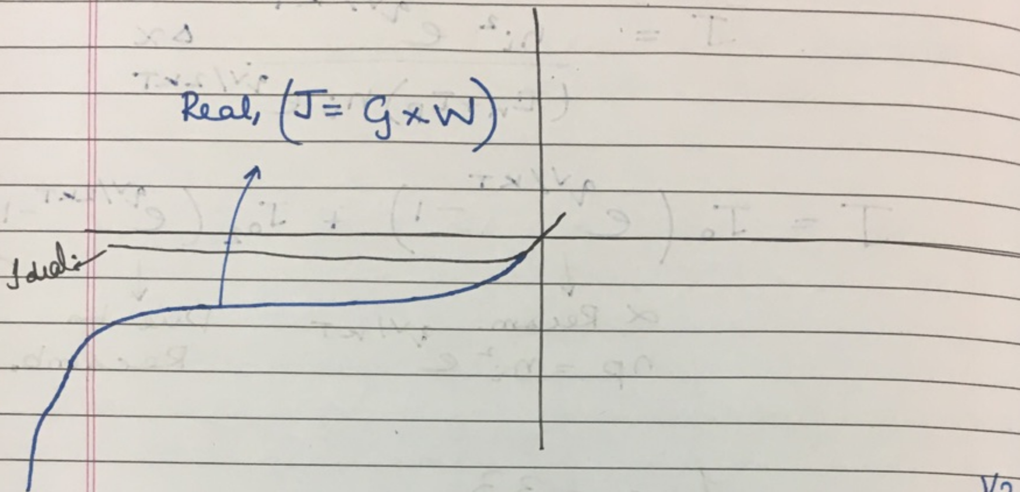
Recap



$$J = J_{0_1}\left(e^{qV/kT} - 1\right) + J_{0_2}\left(e^{qV/2kT} - 1\right)$$

V_{on} / Cut-in voltage has no connection to V_{bI}. Since we work in mA regime, we define V_{on} to voltage where current crosses 1mA. If we worked at μA scale value would be different.

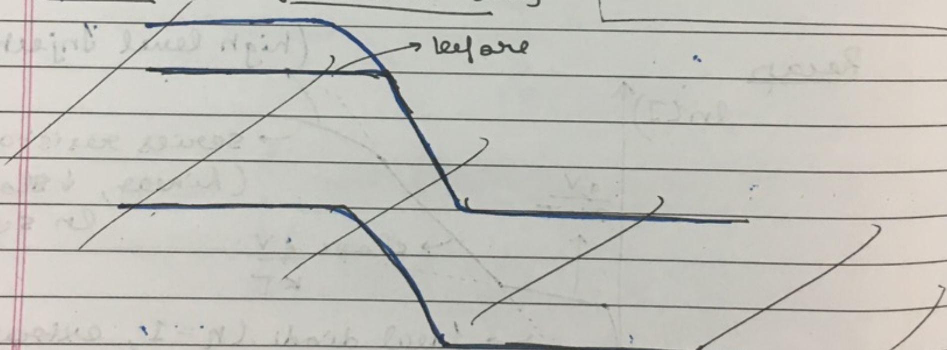
Reverse Bias



$$W = \left[\frac{2\epsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_{bi} - V_{applied})\right]^{1/2}$$

+ve / -ve

Application of Reverse bias



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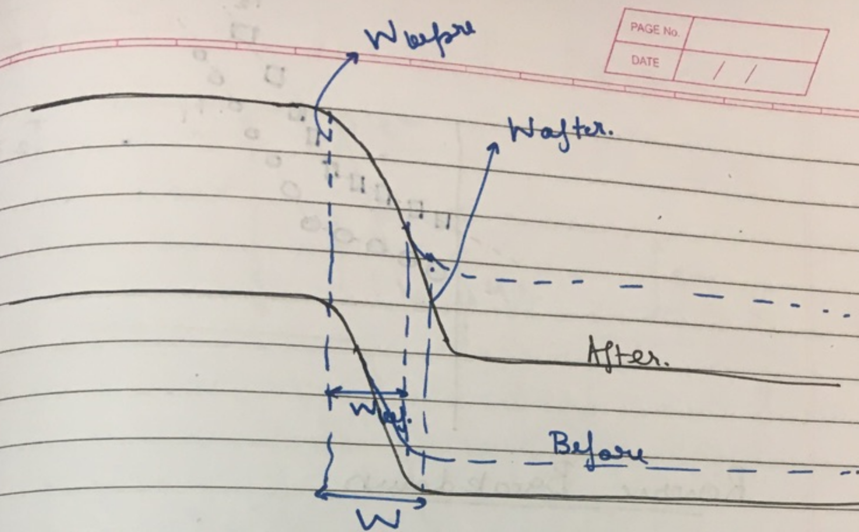


$$W \propto V_{APP}^{1/2}$$

Band Gap from temp. dependance

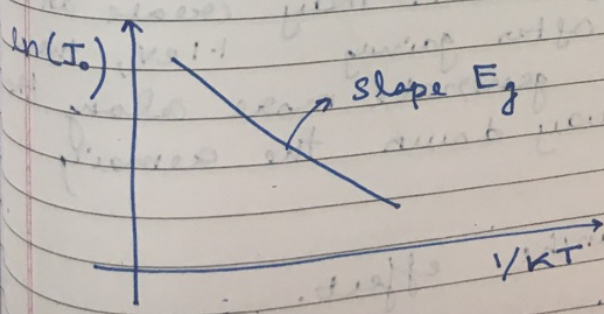
$$J_{o1}\left(e^{qV/KT}-1\right) + \underset{\propto n_i}{J_{o2}}\left(e^{qV/2KT}-1\right)$$

$\propto n_i^2$

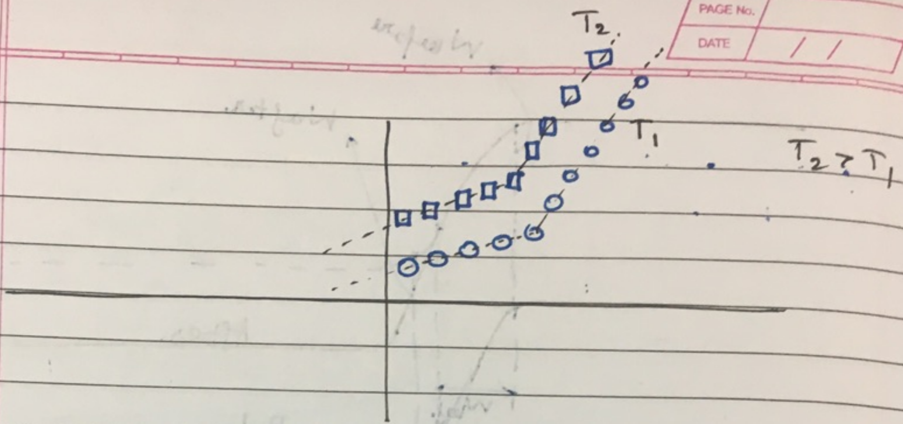
$$J_{o1} = q\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)$$

$$n_i^2 = (N_c N_v)\, e^{-E_g/KT}$$

$$J_{o1} = A\, e^{-E_g/KT}$$



For J_{o2} we get $\frac{E_g}{2}$ slope since it has n_i dependance not n_i^2 depen.



Reverse Breakdown

1) Avalanche Mechanism

→ $E_g \sim 1.1 eV$

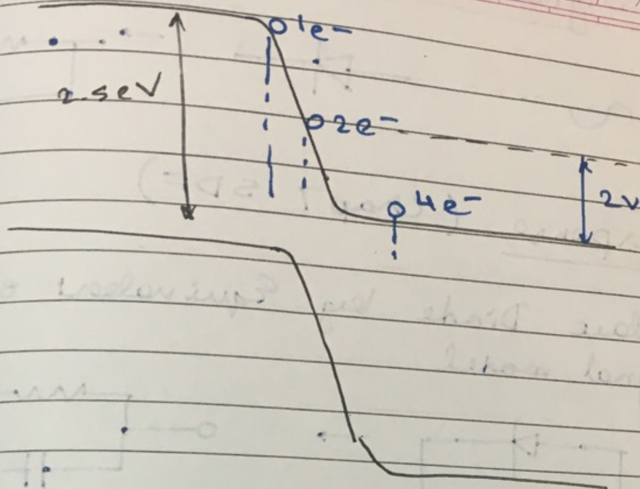
→ An e^- that goes down V_{bi} gains K.E $= eV_{bi}$

→ This energy is less than ~~F.B/~~ E_g in F.B / no bias.

→ But with sufficient R.B, K.E > E_g & it can create e^- - hole pairs

→ ~~Mid~~ While going down the V_{bi} say of 2.5V, it may create an e^- hole pair after gaining 1.1 eV, these will in turn generate more along the their way down the remaining V_{bi}

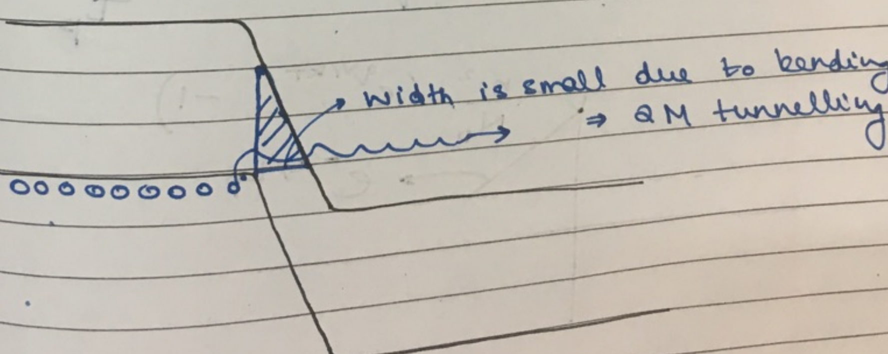
↳ Avalanche effect.



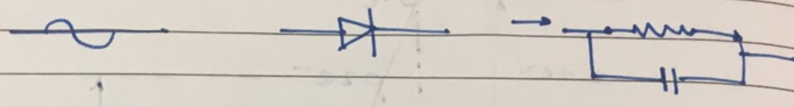
But in regular doped material this effect will be gradual & not at a fixed voltage.

<u>Sudden Drop</u> (Sharp breakdown)

Heavily doped $p^{++} \rightarrow \sim 10^{20}\,cm^{-3}$
$n^{++} \rightarrow \sim 10^{20}\,cm^{-3}$

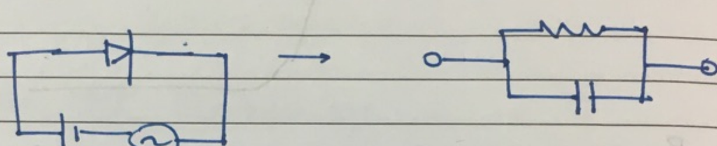


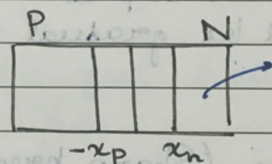
Signal Applied to Diode



AC Response ('Chap 7 SDF)

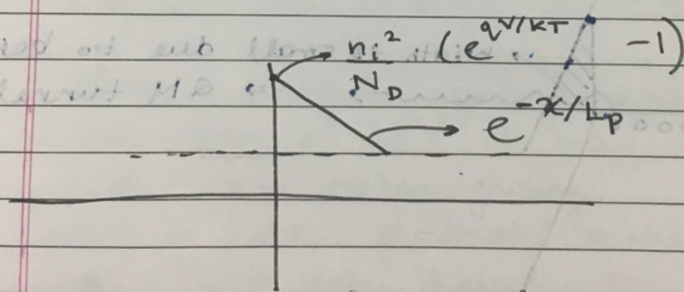
→ Replace Diode by Equivalent small signal model





→ Continuity Eqn.

$$\frac{\delta \Delta p}{\delta t} = -\frac{1}{q} \nabla \cdot J_p - \frac{\Delta p}{\tau_p}$$



$$Q_p = q\int_{x_n}^{\infty} \Delta p(x)\, dx = ?$$

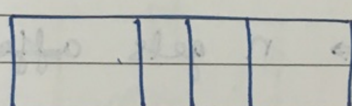
Q_p → Charge due to excess Minority carriers.

(Multiply throughout by q)

$$q\int_{x_n}^{\infty} \frac{\delta(\Delta p)}{\delta t}\, dx = \int_{x_n}^{\infty} -\nabla\cdot J_p\, dx - \int_{x_n}^{\infty} \frac{q\,\Delta p}{\tau_p}\, dx$$

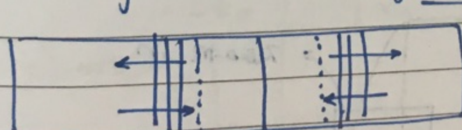
$$\Rightarrow \frac{Q_p}{\tau_p} = q\int_{x_n}^{\infty} \Delta p(x)\, dx = \frac{n_i^2}{N_D}\,\frac{L_p}{\tau_p}\left(e^{qV/kT}-1\right)$$

$$\cancel{\frac{Q_p}{\tau_p} =} \quad \frac{\delta Q_p}{\delta t} = -\frac{Q_p}{\tau_p} - \int_{x_n}^{\infty} (\nabla\cdot J_p)\, dx$$

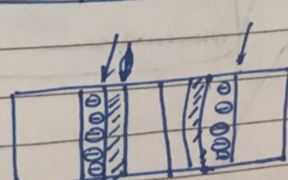


Small Signal

When we apply small signal, depletion region width gets modulated.



$$C = \frac{\epsilon}{W}$$



→ We get Voltage dependant Capacitor

→ High Level Injection.

$$np = n_i^2 e^{qV_a/KT}$$

$$p \approx \frac{n_i^2}{N_D} e^{qV_a/KT}$$

usually valid

But at high level injection

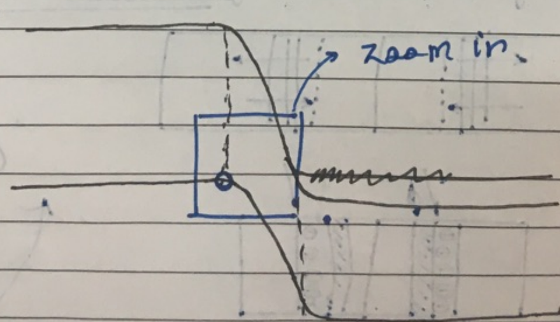
$$p - n + N_D^+ = 0$$

if $p >> N_D$

$\Rightarrow$ n gets ~~affected~~ affected

→ Zener Breakdown

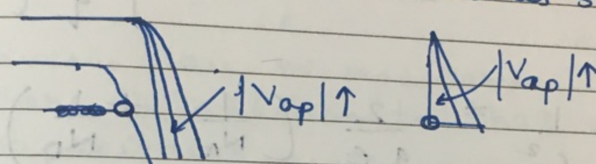
→ Quantum tunnelling breakdown.



Slope $\propto |\vec{E}|$

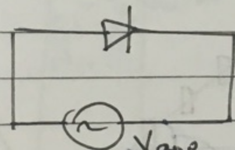
$$|\vec{E}| \propto \frac{V_{ap}}{\underbrace{W}_{\sim V_{ap}^{1/2}}}$$

$\Rightarrow |\vec{E}| \uparrow \Rightarrow$ becomes steeper



→ P(tunnelling) ↑ as $V_{ap}\uparrow$

AC Response (Rev. Bias)

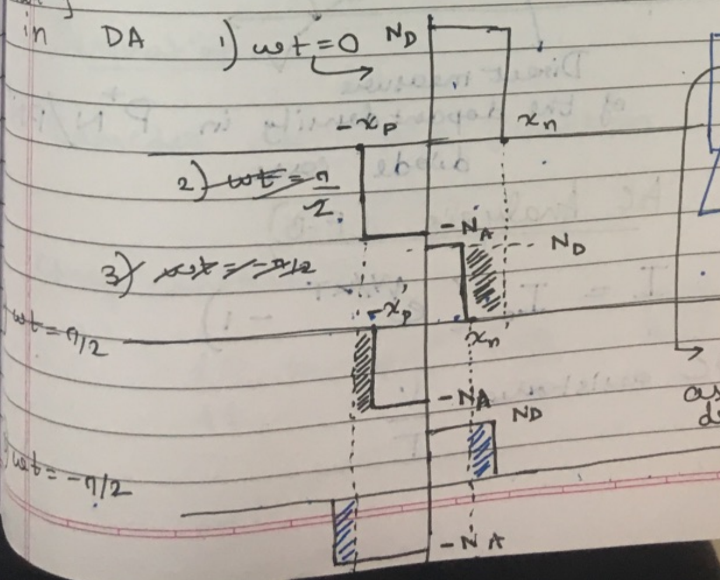


$\rho = p - n + N_D - N_A$

$V_{app} = \underbrace{V_{DC}}_{-2V} + v$

$v = 10mV \sin(\omega t)$

Plot ρ in DA



$$\boxed{C = \frac{\epsilon}{W}}$$

→ capacitance per cm^{-2}

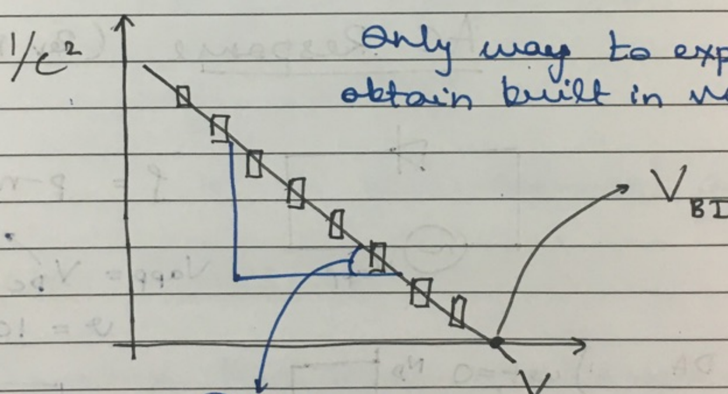
→ may be used as a voltage dependant capacitance

→ Built in voltage from C per cm^{-2}

$$C = \frac{\epsilon}{W}$$

$$C = \frac{\cancel{\epsilon}}{} \; \epsilon \times \left[\frac{2\epsilon}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bi} - V_{app}) \right.$$

$$\frac{1}{C^2} = \frac{2}{q\epsilon} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bI} - V_{app})$$



Only way to experimentally obtain built in voltage.

Direct measure of the dopant density in P^+N / PN^+ diode case.

• AC Analysis (F.B)

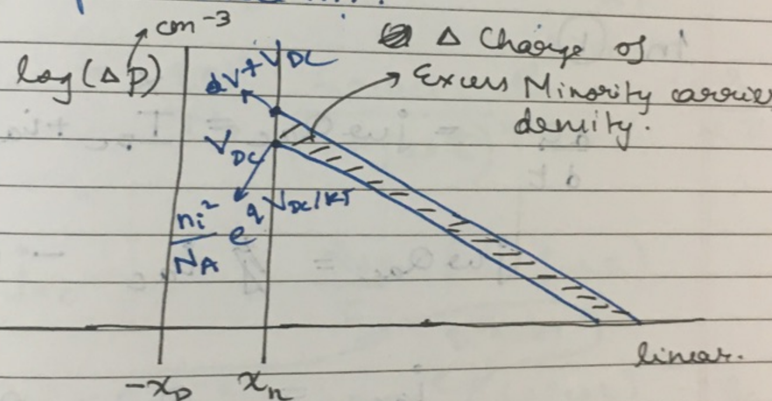
$$I = I_0 \left(e^{qV/kT} - 1 \right)$$

DC resistance: $\frac{V}{I}$

$$\text{AC Resis.} = \left(\frac{dI}{dV}\right)^{-1}$$

$$\frac{dI}{dV} = \frac{I_0 e^{qV/KT}}{\left(\frac{KT}{q}\right)} = \frac{I_{DC}}{\left(\frac{KT}{q}\right)}$$

- The previous case W modulation cap. will be there, in addition to that another capacitance .....



- <u>Derivation</u>

- Consider a p^+n junction

p^+	n

- Charge control Eqn.

$$\frac{dQ}{dt} = i_{diff} - \frac{Q}{\tau_p} \quad \text{(1)}$$

$$\boxed{Y = \frac{i_{ac}}{v_{ac}}} \rightarrow \text{our Goal!}$$

$\cancel{j\omega Q_{ac} = I_{DC} + \ldots}$

$i = I_{DC} + i_{ac}$ (Actually T values factor of e.s.A)

$Q = Q_{DC} + Q_{ac}$

$$\frac{dQ}{dt} = 0 + \frac{dQ_{ac}}{dt}$$

$$= j\omega Q_{ac}$$

In 1

$$\frac{dQ}{dt} = j\omega Q_{ac} = \cancel{I_{DC}} + i_{ac} - \frac{\cancel{Q_{DC}} + Q_{ac}}{T_p}$$

$$j\omega Q_{ac} = i_{ac} - \frac{Q_{ac}}{T_p}$$

$$i_{ac} = \cancel{\frac{Q_{ac}}{T_p}} \; Q_{ac}\left(\frac{1}{T_p} + j\omega\right)$$

$$= \frac{Q_{ac}}{\left(\frac{T_p}{1 + j\omega T_p}\right)}$$

$I_{DC} = Q_{DC} / T_p$

$i_{ac} = Q_{ac} \Big/ \left(\frac{T_p}{1 + j\omega T_p}\right)$ T_{pac}

$$J_{ac} = q\frac{n_i^2}{N_A}\, e^{qV_{DC}/KT}\left(e^{qV_{ac}/KT}-1\right)e^{-x/L_p}$$

$$Q_{ac} = q\frac{n_i^2}{N_A}\, e^{qV_{DC}/KT}\left(e^{qV_{ac}/KT}-1\right)L_p$$

↑ Area missing (~~Area~~ cm^{-2} (charge density) like σ)

$$\underset{\sigma_{ac}}{\underset{\downarrow}{Q_{ac}}} = q\frac{n_i^2}{N_D} L_p\, e^{qV_{DC}/KT}\cdot\frac{qv_{ac}}{KT}$$

$$Q_{ac} = \frac{qn_i^2}{N_D}\cdot\frac{L_{p(DC)}}{(1+j\omega\tau)^{1/2}}\, e^{qV_{DC}/KT}\cdot\frac{qv_{ac}}{KT}$$

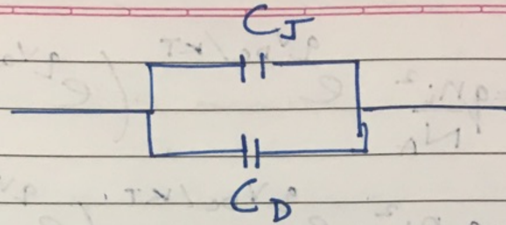
$$j_{ac} = \frac{Q_{ac}}{\tau}(1+j\omega\tau)$$

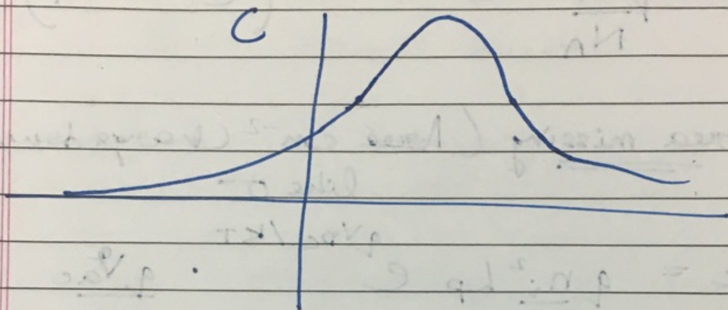
$$= \underbrace{\frac{qn_i^2}{N_D}\times\frac{L_{p(DC)}}{\tau}\, e^{qV_{DC}/KT}}_{J_{DC}}(1+j\omega\tau)^{1/2}\cdot\frac{qv_{ac}}{KT}$$

$$j_{ac} = J_{DC}(1+j\omega\tau)^{1/2}\,\frac{qv_{ac}}{KT}$$

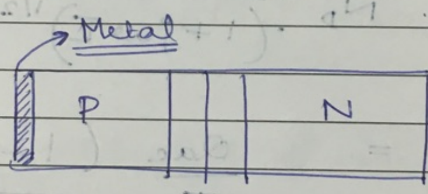
$$Y = \frac{i_{ac}}{v_{ac}} \Rightarrow \frac{j_{ac}}{v_{ac}} = \frac{J_{DC}}{\left(\frac{KT}{q}\right)}\left[1+j\omega\tau\right]^{1/2}$$

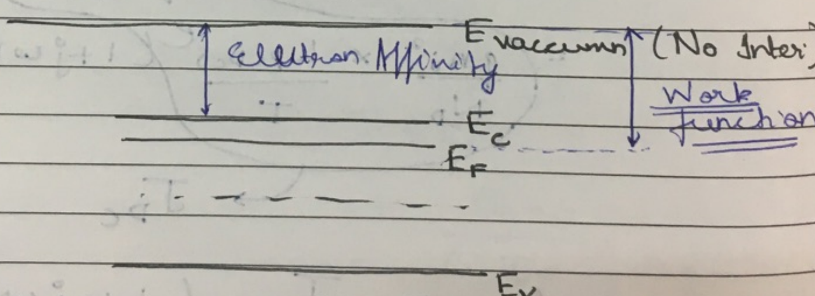
$$\boxed{Y = G_0(1+j\omega\tau)^{1/2}}$$



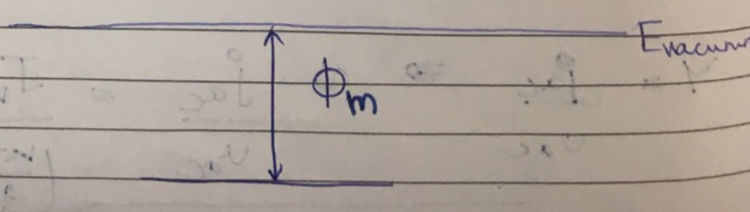


Metal - Semiconductor Contact





Metal



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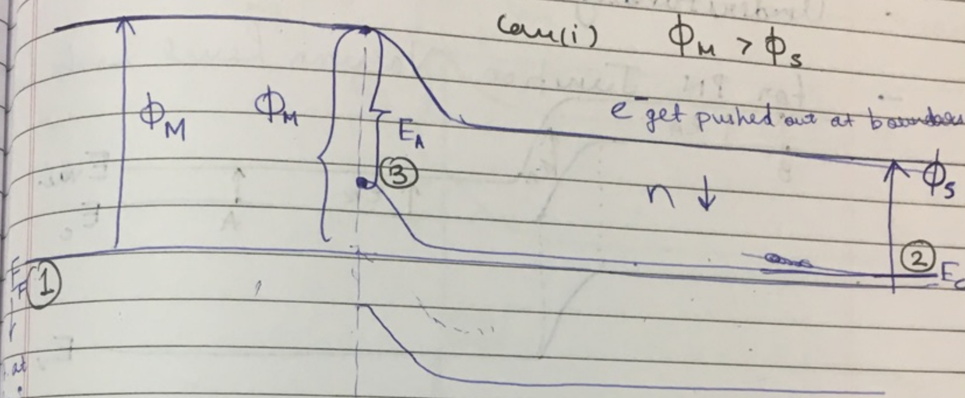
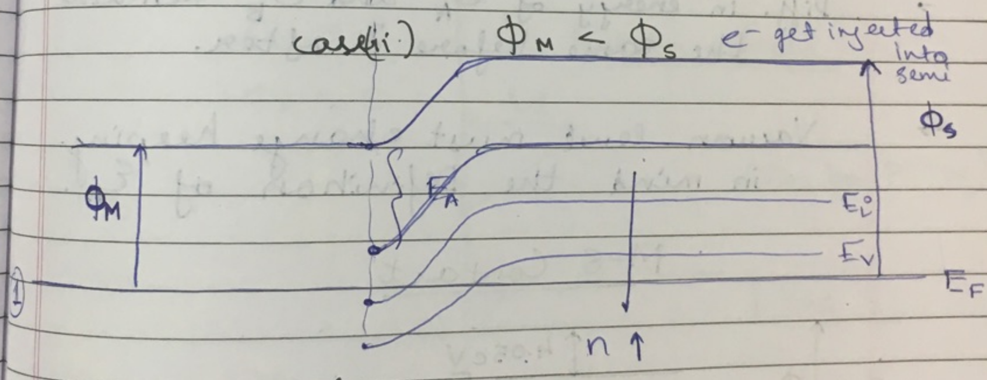
Combined band Diagram at eq. of Metal - Semi. junction.





Lec - 34

Plan, 2 extra lectures
SAT - 14/10/17
SAT - 28/10/17

→ 2 extra quizzes 8/12

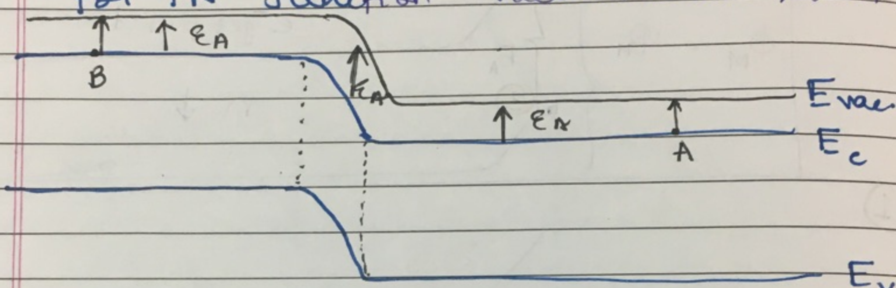
Grading

Quiz - 20%
M.S - 25%
Assign. - 5%
Endsem - 50%

→ Metal - Semiconductor Contact

- Understanding Vacumn level.

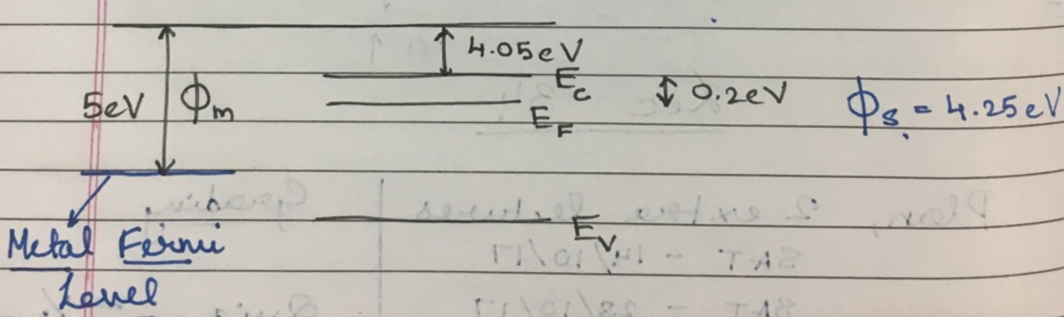
→ for PN Junction Vacumn Level Looks like.



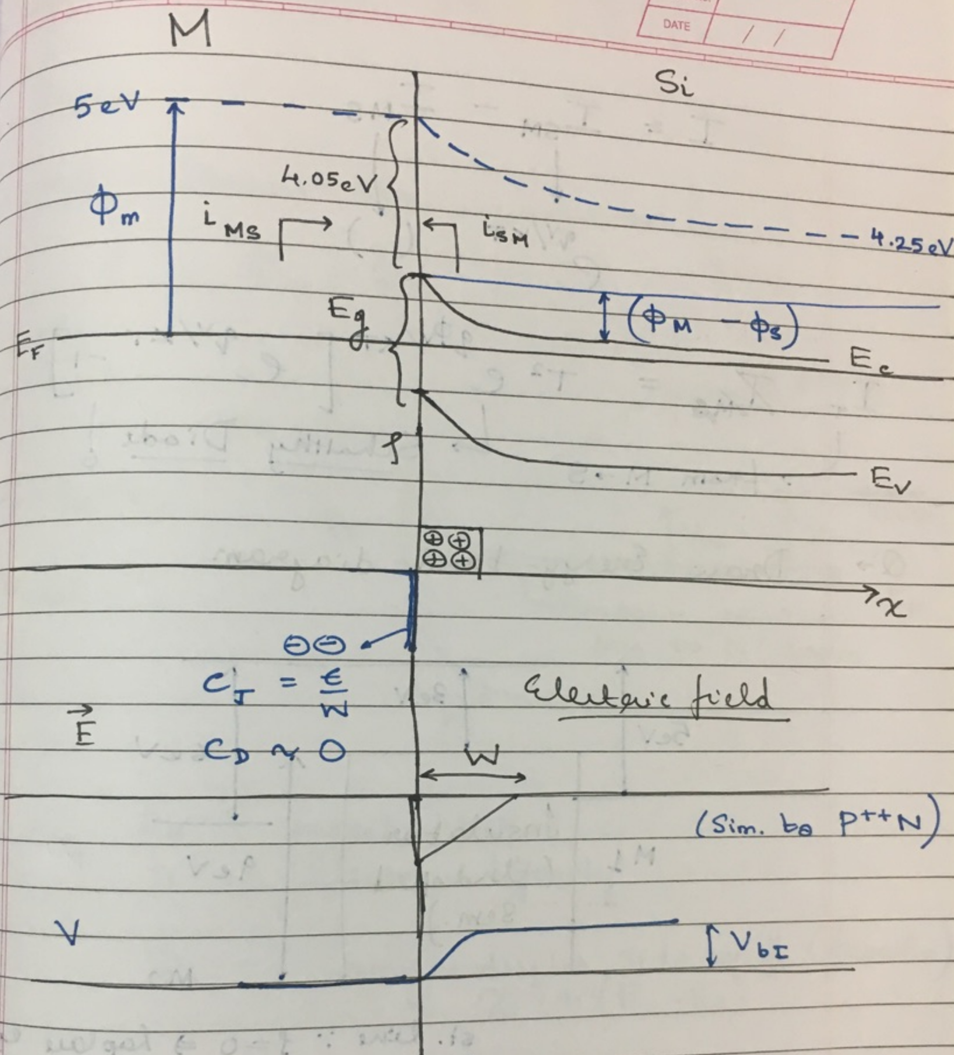
→ Diff. in energy of e^-_A and e^-_B remains the same before & after.

→ Vacumn. level must change keeping in mind the Definition of $\mathcal{E}_A$.

M-S Contact



Dep. Approx.



→ Going from Metal to Sem. barrier is const.

→ Going from sem. to Metal

-ve bias → Barrier ↓ ⇒ current ↑ dec.
w.r.t metal

+ve bias → Barrier ↑ ⇒ current ↓
w.r.t metal.

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$$I = I_{SM} - I_{MS}$$

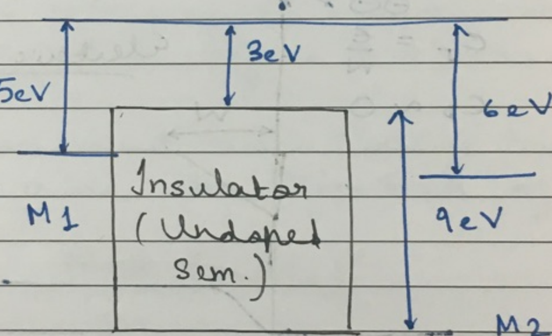
$$e^{qV/KT} \qquad (\;)$$

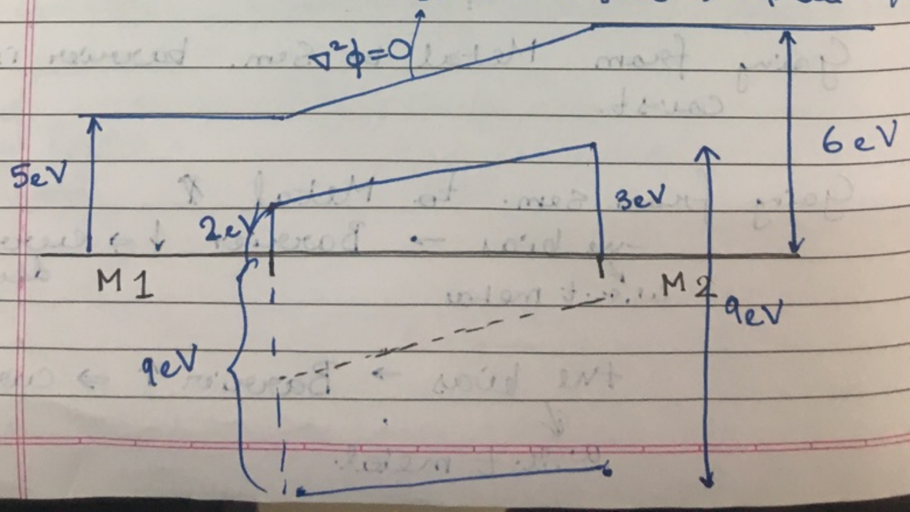
$$I_T \quad \cancel{I_{MS}} = T^2 e^{q\Phi_V/KT}\left[e^{qV/KT} - 1\right]$$

I_T → from M → S

→ Schottky Diode!

Q → Draw Energy-band diagram





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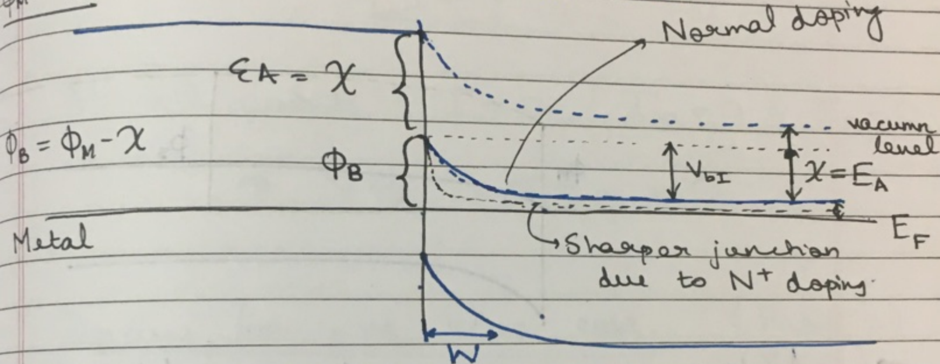
Recap.

- MS - Metal - Semi. junction

$\phi_M > \phi_S$ ⟶ n-type semi.

$\phi_M > \phi_S$



ϕ_M - metal WF
χ - Electron Affinity

ϕ_s - Semiconductor side w.f (from E_F)
$= \chi + (E_c - E_F)$

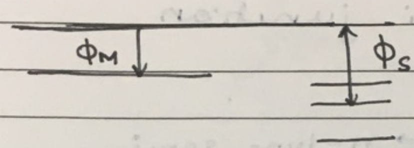
$\phi_B = \phi_M - \chi$

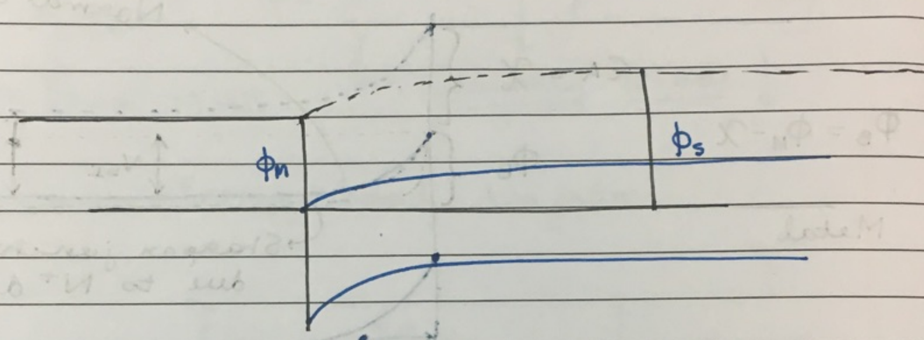
$V_{bI} = \phi_B - (E_c - E_F) = \phi_M - \phi_s$

$I = \underset{\text{Diff exp}}{(\ )} \left[e^{qV/kT} - 1 \right]$

- High Doping at junction, must start @ same pt. and go to a lower E_c ($E_c - E_F \downarrow$)

Case 2: $\phi_M < \phi_S$
↳ N-type.



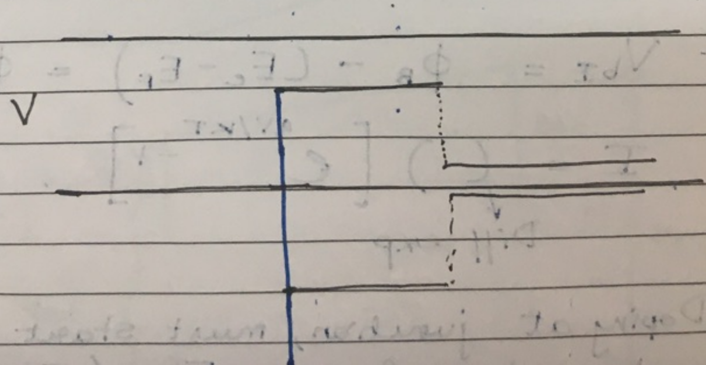


→ In this case no rectification/diode action
→ This is the desired behaviour but cannot be assured ⇒ high junction doping.

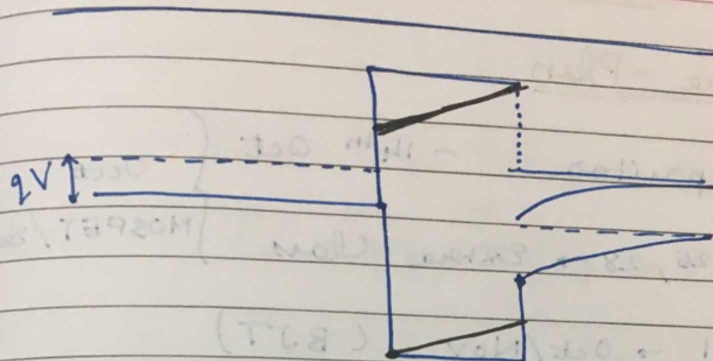
p-type

MOS Junction

→ $\phi_M = \phi_S$



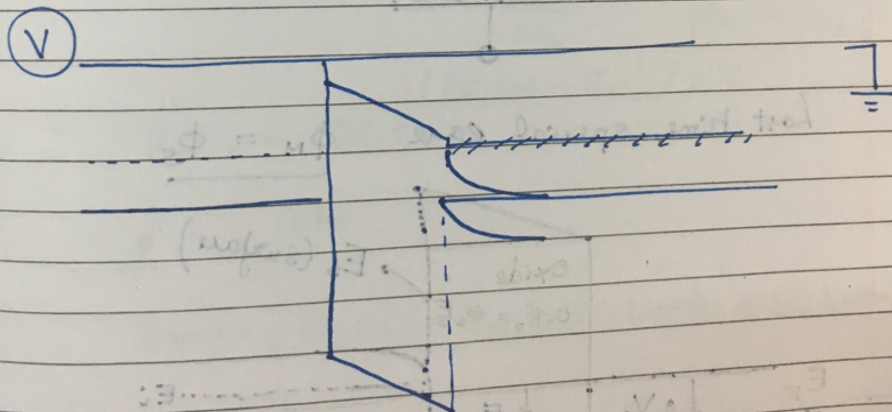
Part 1 : +ve Voltage



→ At all points $I = 0$, $I_n = 0$ & $I_p = 0$

$$\Rightarrow \nabla E_{Fn} = \nabla E_{Fp} = 0$$

→ Draw for -ve bias case. (Part 2)
($V < 0$)



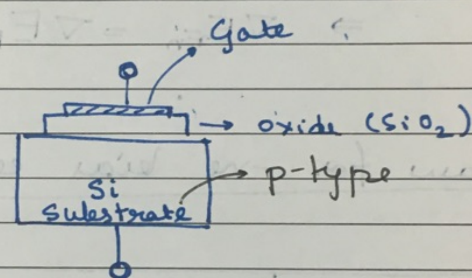
Lec - 36

Lecture - Plan

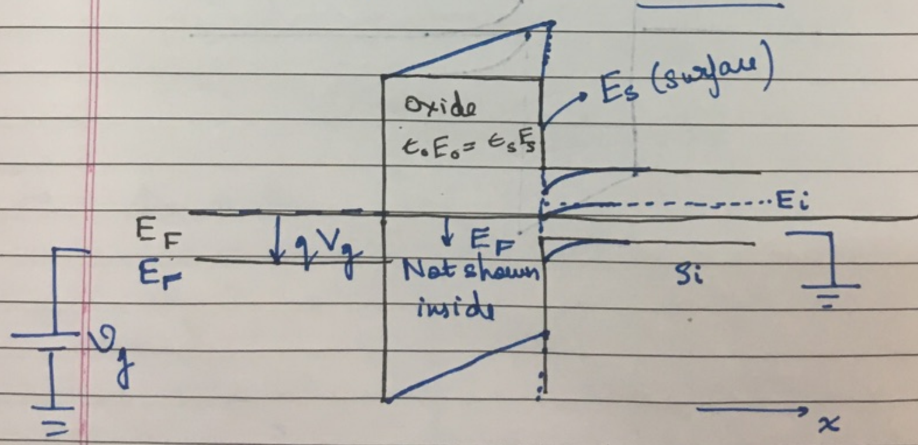
MOS Capacitor - 14th Oct
16, 17
22, 23, 25, 28 → Extra Class
29, 30, 1 → Oct/Nov (BJT)

Oct
MOSFET / Solar / LED

MOS Capacitor



→ Last time, special case $\phi_M = \phi_S$



$$\boxed{E_i(\infty) - E_i(x) = q\,\psi(x)}$$

Current = 0

$$J_n = n \mu_n \nabla E_{Fn} = 0$$

$$J_p = p \mu_p \nabla E_{Fp} = 0$$

Analysis

$$\therefore E = -\nabla \psi$$

$$\nabla \cdot (\epsilon \nabla \psi) = -(p - n - N_A)$$

$$q\psi(x) = E_i(\infty) - E_i(x)$$

fine

$$p(\infty) = N_A \qquad n(x) = \frac{n_i^2}{N_A} e^{q\psi/kT}$$

$$n(\infty) = \frac{n_i^2}{N_A} \qquad p(x) = N_A e^{-q\psi/kT}$$

$$p(x) = n_i e^{(\cancel{q}E_i(x) - E_F)/kT}$$

$$e^{(pow)}$$

$$pow = \left(E_i(x) - E_F - E_i(\infty) + E_i(\infty)\right)/kT$$

$$\underbrace{n_i e^{(E_i(\infty) - E_F)}}_{N_A} \, e^{(E_i(x) - E_i(\infty))}$$

$$\left.\begin{aligned} p(x) &= N_A e^{-q\psi/kT} \\ n(x) &= \frac{n_i^2}{N_A} e^{q\psi/kT} \end{aligned}\right\} \begin{aligned} &\text{Constant } E_F \\ &np = n_i^2 \end{aligned}$$

$$\epsilon \frac{d^2\psi}{dx^2} = -q\left(N_A e^{-q\psi/KT} - \frac{n_i^2}{N_A} e^{q\psi/KT} - N_A\right)$$

$$E = -\frac{d\psi}{dx}$$

$$\cancel{\frac{dE}{dx}} \quad \frac{dE}{d\psi} = \frac{dE}{dx} \times \frac{dx}{d\psi}$$

$$\Rightarrow -E\frac{dE}{d\psi} = \frac{dE}{dx}$$

$$\cancel{\epsilon}\left(E\frac{dE}{\cancel{d\psi}}\right) = -\frac{q}{\epsilon}\left(N_A e^{-q\psi/KT} - \frac{n_i^2}{N_A} e^{q\psi/KT} - N_A\right)$$

$$\int_0^E E\,dE = -\frac{q}{\epsilon}\int_0^\psi \left(\quad\right) d\psi$$

$$\cancel{\frac{E^2}{2} = -\frac{q}{\epsilon}\left[\left(\frac{KT}{q}\right)e^{-q\psi/KT}\right.}$$

Cases on ψ

1) Accumulation phase:
Apply large negative bias.

$$\cancel{\frac{E^2}{2} =} \; N_A\left(\overset{\text{Large}}{e^{-q\psi/KT}} - \overset{\sim 0}{\frac{n_i^2}{N_A} e^{q\psi/KT}} - \overset{\sim 0 \text{ but consider}}{N_A}\right)$$

$$\frac{E_s^2}{2} = \frac{\cancel{q}}{\epsilon}\left(\left(\frac{kT}{\cancel{q}}\right) N_A e^{-q\psi_s/kT}\right)$$

$$E_s = \sqrt{\frac{2N_A kT}{\epsilon}}\, e^{-q\psi_s/2kT}$$

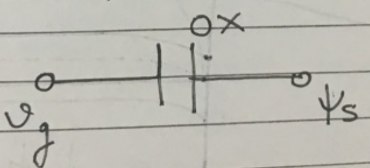
<u>Using Gauss Law</u>

$$E_s \cdot A = \cancel{A} \times \frac{q_{enclosed}}{\epsilon}$$

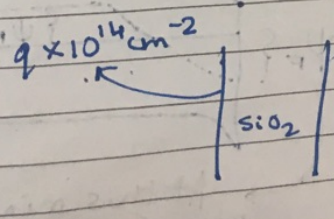
$$E_s = \frac{Q_s}{\epsilon} \quad \text{cm}^{-2} \text{ (per unit area)}$$

$$Q_s = \sqrt{2N_A\epsilon\left(\frac{kT}{q}\right) \times q}\; e^{-q\psi_s/2kT}$$

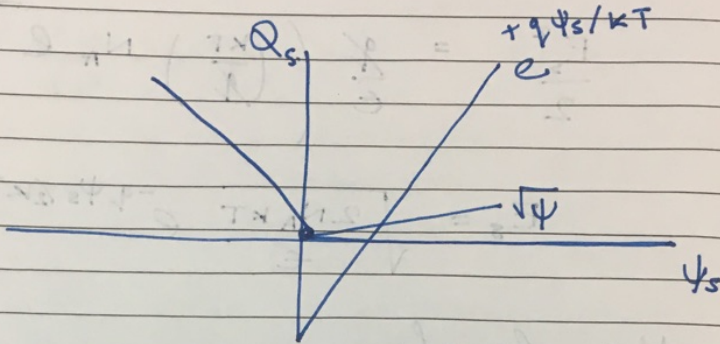
→ <u>Equivalent Capacitor</u>



→ Approx: No band bending



If we take entire drop across SiO_2 then ~ 10V at left.

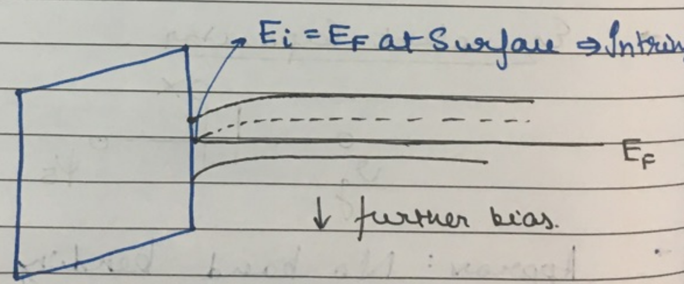


2) Depletion (Positive bias) (Low the bias)

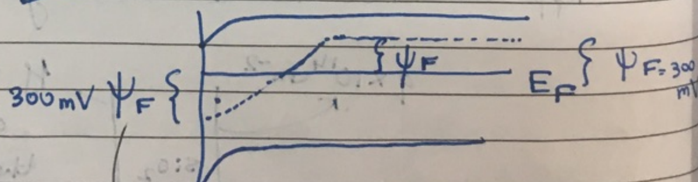
$$\frac{E^2}{2} = -\frac{q}{\epsilon}\left(\frac{kT}{q}\frac{n_i^2}{N_A}e^{q\psi/kT} + N_A\psi\right)$$

3) Inversion

Beyond a certain the voltage, band diagram becomes



→ Grade



At this minority density at Surface = Majority density in bulk.

$$\frac{n_i^2}{N_A} e^{q\psi/kT} = N_A$$

$$\frac{n_i^2}{N_A} e^{q(2\psi_F)/kT} = N_A$$

$$\ln\left(\frac{N_A^2}{n_i^2}\right) = \left(\frac{2q\psi_F}{kT}\right)$$

put $\psi_s = 2\psi_F + 8$ & check variation in R.H.S

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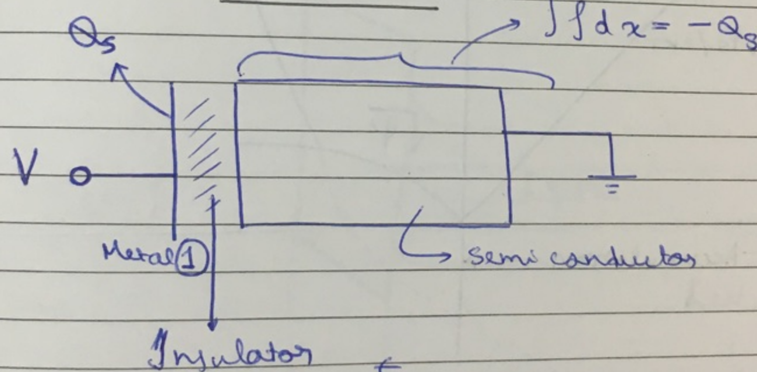
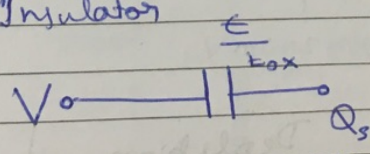




$$V = \psi_s + \frac{Q_s}{C_{ox}}$$

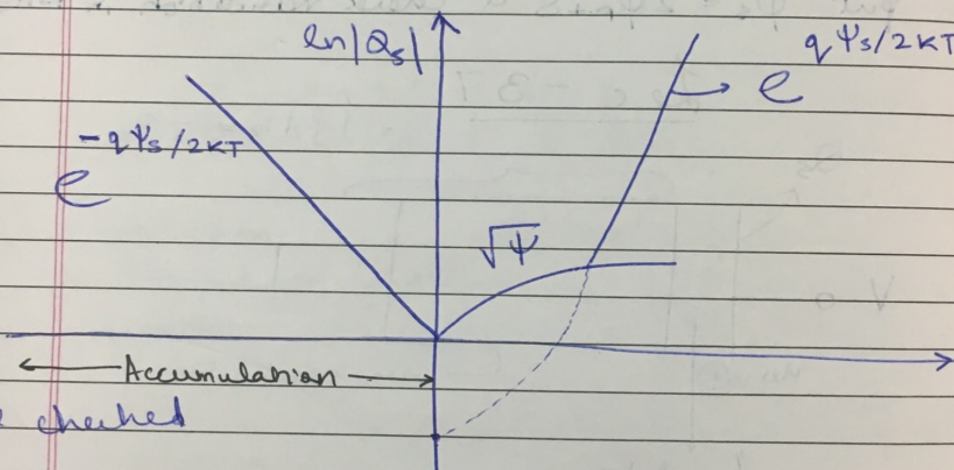
$$\epsilon \frac{d^2\psi}{dx^2} = -(p - n - N_A)$$

$$\frac{E^2}{2} = \frac{-q}{\epsilon}\int_0^{\psi_s}\left(\underbrace{N_A e^{-q\psi/kT}}_{\text{Majority}} \underbrace{- \frac{n_i^2}{N_A} e^{q\psi/kT}}_{\text{Minority}} - N_A\right) d\psi$$

$$E_s = \frac{Q_s}{\epsilon_s}$$

↓ Get the form

$$Q_s \sim \left[\frac{N_A e^{-q\psi_s/KT}}{(KT/q)} - \frac{\frac{n_i^2}{N_A} e^{q\psi_s/KT}}{(KT/q)} - N_A \psi_s \right]^{1/2}$$



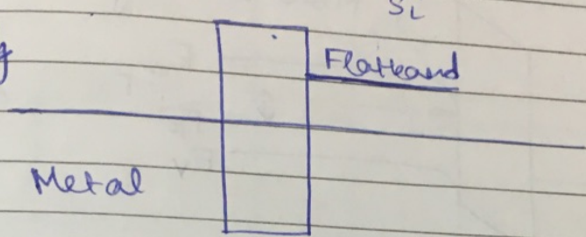
We checked

$10^{14}\, q\, cm^{-2} \Rightarrow 10V$ & $\psi \sim 250 mV$

Accumulation	Depletion	Inversion

→ When $\phi_M = \phi_S$ → Flatband ⇒ Equilibrium condition

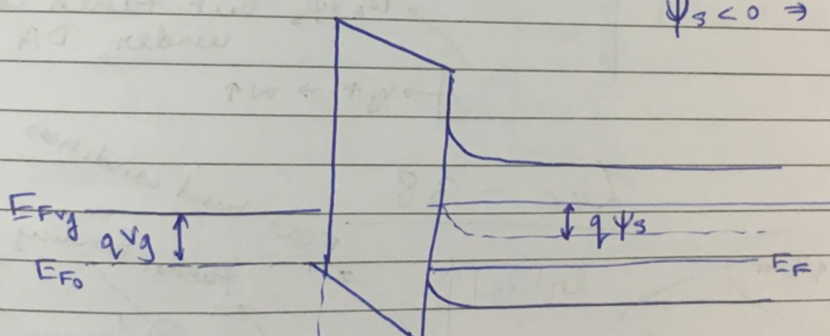
Apply $-V_g$

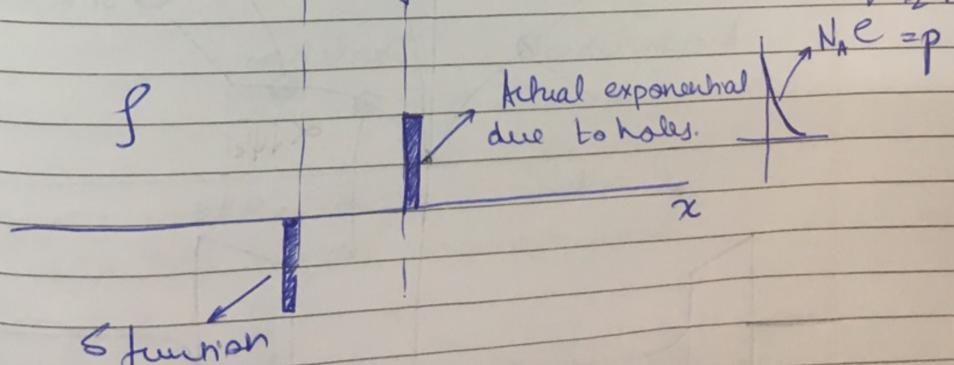


Accumulation

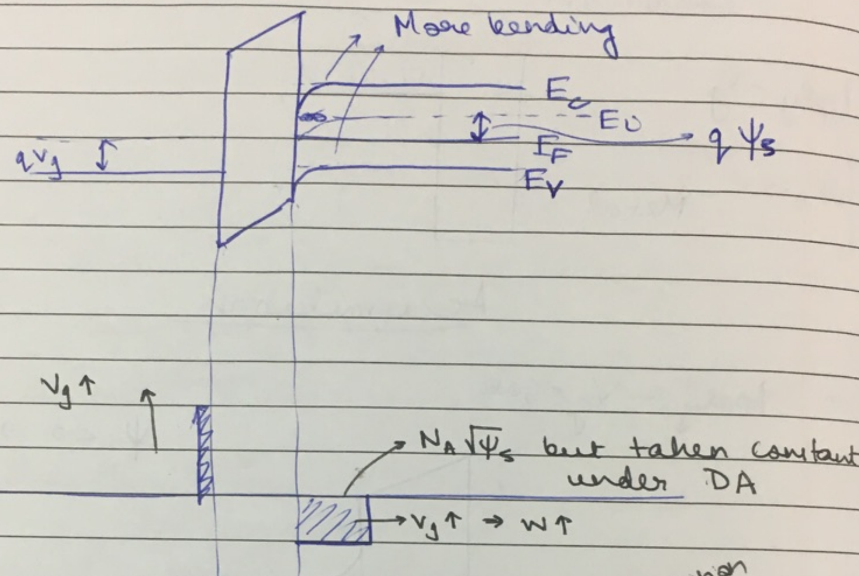
→ Apply $-V_g$ → gate.

$\psi_s < 0 \Rightarrow \uparrow$ shifting.

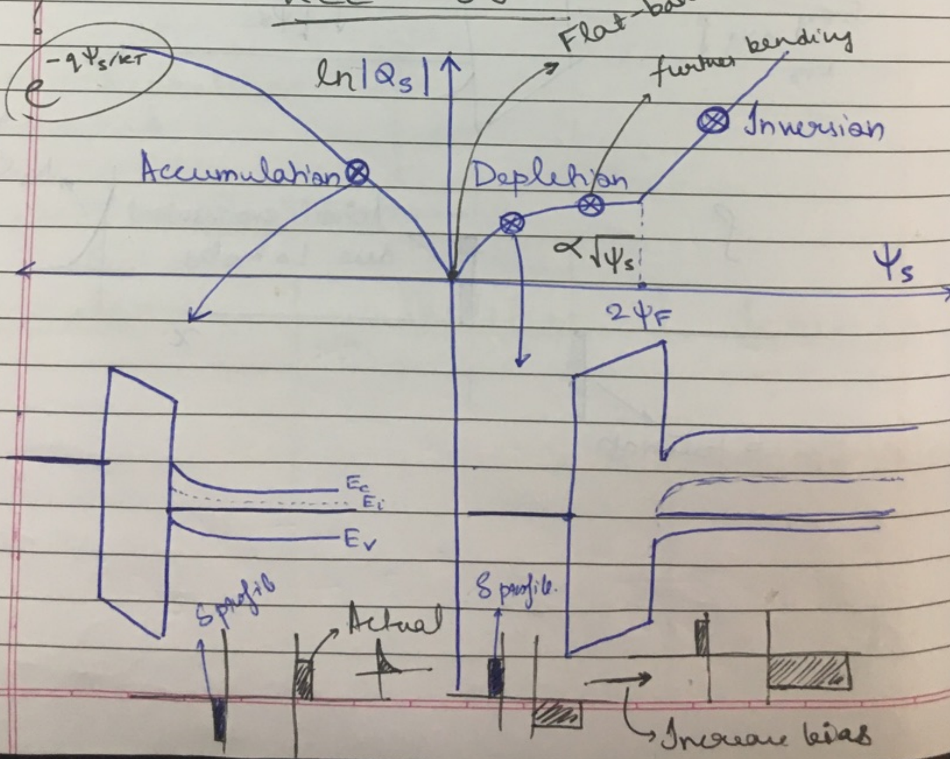




Depletion $V_g > 0$, $\psi_s > 0$ but small

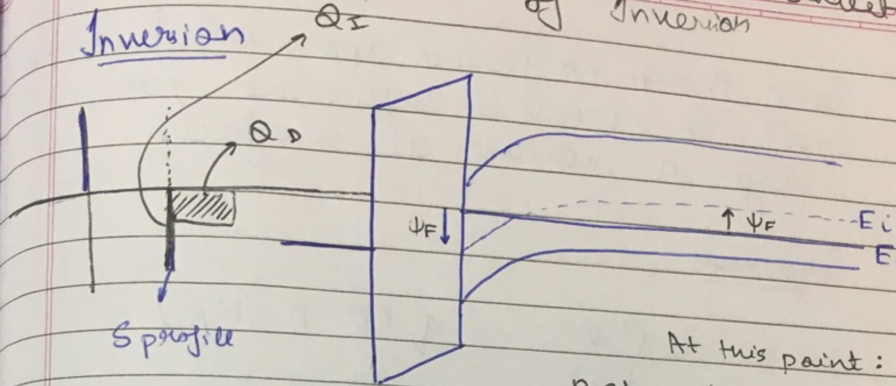


Lec - 38



→ Appears After the onset of Inversion

Inversion



At this point:
n at surface = p in bulk

→ Condition of Strong Inversion

$$n_{surface} = p_{Bulk}, \quad n_s = p_b$$

$$\psi_F = \frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

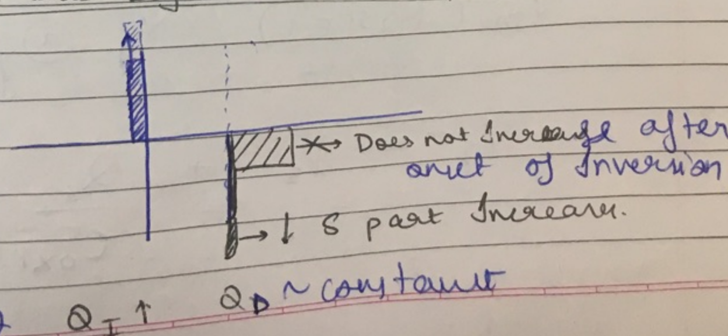
$$\Rightarrow \psi_s \text{ at Strong inversion} = \frac{2kT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

• Alternatively :

$$e^{q\psi_s/kT} = \frac{N_A^2}{n_i^2}$$

$$\psi_s = \frac{2kT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

Further bias beyond Inversion point



Beyond onset of Inversion $Q_I \uparrow$ $Q_D \sim$ constant

PAGE No.
DATE / /

→ Even though no further appreciable ↑ in ψ_s small δ increase is sufficient for large n increase at surface.

Equations

$$\epsilon \frac{d^2\psi}{dx^2} = -q(p-n-N_A)$$

$$\epsilon E \frac{dE}{d\psi} = -q(p-n-N_A)$$

$$Q_s^2 = (\epsilon E_s)^2 = 2\epsilon q \int_0^{\psi_s} (p-n-N_A)\, d\psi$$

$$p = N_A e^{-q\psi/kT} \qquad n = \frac{n_i^2}{N_A} e^{q\psi/kT}$$

$\psi + \delta\psi$

After onset of Inversion

Gate Voltage V_g

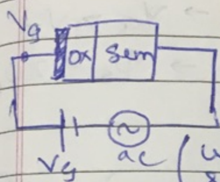
V_{TH} (MOSFET) $= V_g$ @ onset of Inversion

$$V_g = \psi_s + \frac{Q_s}{C_{ox}}$$

$$Q_s = (2\epsilon q N_A \psi_s)^{1/2}$$

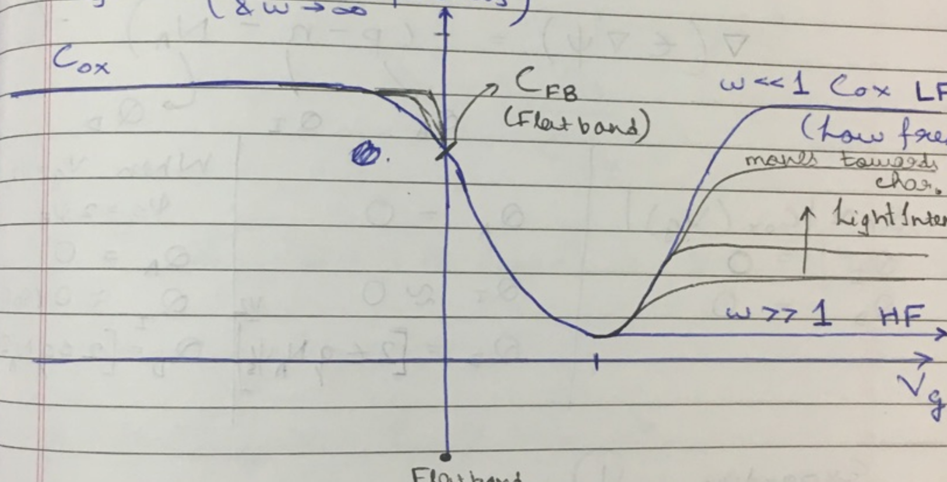
$$Q_s = q N_A W = (2\epsilon q N_A \psi_s)^{1/2}$$

$$V_{TH} = 2\psi_F + \frac{Q_s}{C_{ox}}$$

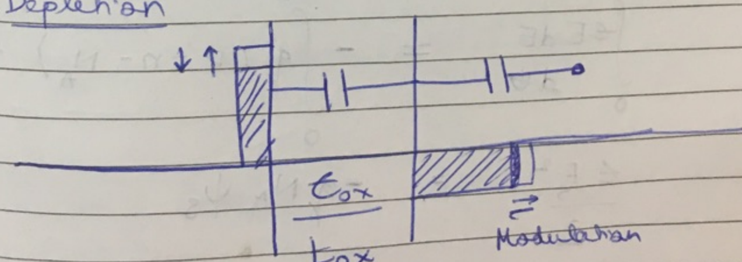


$C - V_{DC}$ Characteristics

($\omega \to 0$ & $\omega \to \infty$ separately)

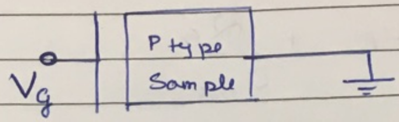


Depletion



Reference: Taur & Ning

MOS - CAP



Accumulation	Depletion	(Low) Inversion
→ $\psi < 0$, $\lvert\psi\rvert << 1$	→ $\psi << 1$	→ ~~$V_G > V_T$~~
→ Excess holes (Maj.) carrier at surface.	→ $\psi > 0$	→ $\psi_s = 2\psi_F$
	$\psi_s < 2\psi_F$	
	→ $V_g < V_T$	

$$\nabla(\epsilon \nabla \psi) = -(p - n - N_A) \quad -(1)$$

$p \rightarrow Q_A$, $n \rightarrow Q_I$, $N_A \rightarrow Q_D$

→ $Q_A \approx \lvert C_{ox}(V_g)\rvert$	$Q_A = 0$	When $V_g = V_T$, $\psi_s = 2\psi_F$
$Q_I = 0$	$Q_I \approx 0$	$Q_A = 0$
$Q_D = 0$	$Q_D = [2\epsilon q N_A \psi_s]^{1/2}$	$Q_I \approx 0$ (Still)
		$Q_D = [2\epsilon q N_A 2\psi_F]^{1/2}$

Expanding (1)

$$\int_0^{E} \epsilon E \frac{dE}{d\psi} = -\int_0^{\psi_s} q(p - n - N_A)\, d\psi$$

$$\frac{\epsilon E_s^2}{2} = -q N_A \psi_s$$

$$Q_s = \epsilon \lvert E_s \rvert = [2\epsilon q N_A \psi_s]^{1/2}$$

$V_T \approx V_t$

↳ threshold voltage

→ Strong Inversion

→ $\psi_s \approx 2\psi_F + \delta$ $(\delta \ll 1)$

$V_g > V_T$

Formulas

$$2\psi_F = (\psi_s)_I = \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

$$V_g = \psi_s + \frac{Q_s}{C_{ox}}$$

$$V_T \text{ (At Gate)} = 2\psi_F + \frac{\left[4\epsilon q N_A \psi_F\right]^{1/2}}{C_{ox}}$$

$$V_{ox} = |\vec{E}_{ox}| \times t_{ox},$$

and $\epsilon_s|\vec{E}_s| = \epsilon_{ox}|\vec{E}_{ox}|$

$$V_{ox} = \frac{\epsilon_s|E_s|}{\epsilon_{ox}} t_{ox}$$

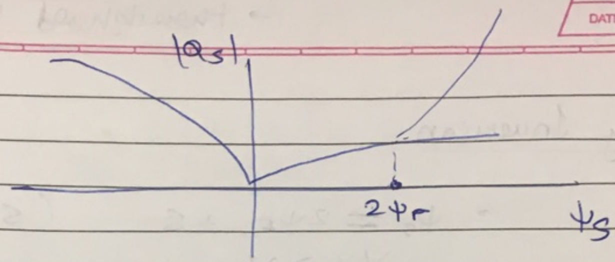
→ Strong Inversion

$$Q_A = 0$$

$$* \; Q_I = C_{ox}(V_g - V_t) \; *$$

$$Q_D = \left[4\epsilon q N_A \psi_F\right]^{1/2}$$

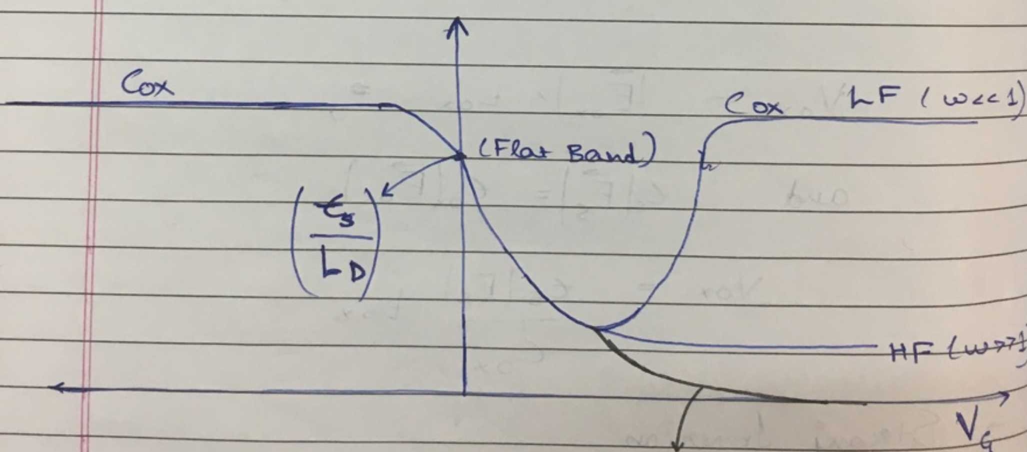
(Increases No further)



$$\epsilon E \frac{dE}{d\psi} = \frac{n_i^2}{N_A} e^{q\psi/KT}$$

$$\frac{\epsilon_s^2 E_s^2}{2} =$$

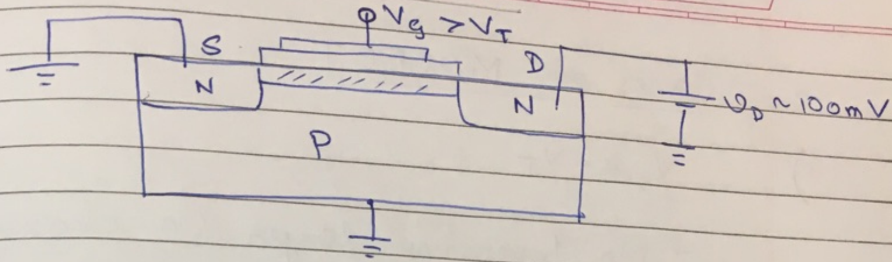
C-V Characteristics



When $\frac{dV_g}{dt} >> 1$

- Increase in Inversion Layer can't keep up.

MOSFET



$$Q_{IS} = C_{ox}(V_g - V_T)$$

$$Q_{ID} = C_{ox}(V_g - V_T - V_{DS})$$

$$I = \langle Q \rangle \langle v \rangle \qquad V = \mu \frac{V_{DS}}{L}$$

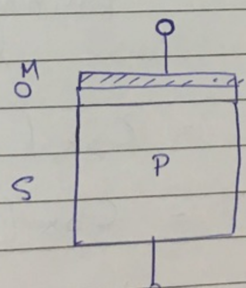
$$= \frac{(Q_{IS} + Q_{ID})}{2} \times \mu \frac{V_{DS}}{L}$$

24-10-17

Lec-39

office hours Wed 6-7pm
Sat/Sun → TBD

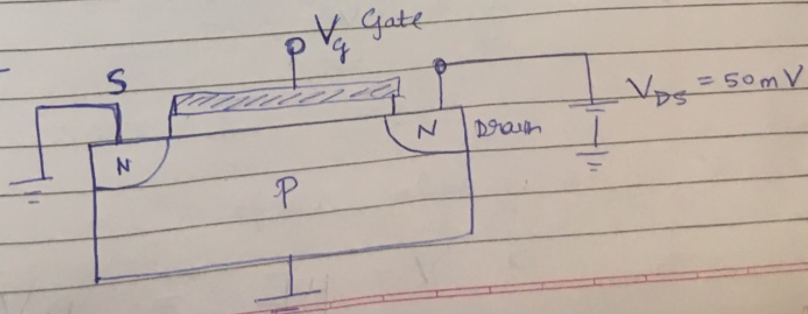
→ MOSCAP



$V_g > V_T$ (Inversion)

$$Q_I = C_{ox}(V_g - V_T)$$

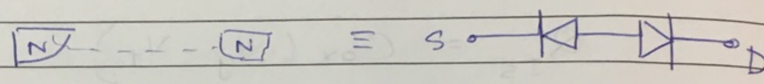
→ MOSFET



→ **Cases on MOSFET**

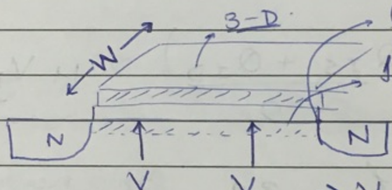
1) $V_g << V_T$

→ No Inversion layer (n-channel)



2) $V_g = V_T$ (or Greater)

→ Derive Current Expression



local potential $\sim V_{DS}$

Inversion layer (Q_I)

⇒ V varies along with position within Inversion layer

$$\Rightarrow Q_I(S) = C_{ox}(V_{GS} - V_T)$$

$$\Rightarrow Q_I(D) = C_{ox}(V_{GS} - V_T - V_{DS})$$

$$\frac{I}{W} = Q v \quad \text{speed}$$

↳ 3-D

→ Effect is only drift.

$$\Rightarrow v = \mu E = \mu \frac{V_{DS}}{L}$$

$$\frac{I}{W} = \mu^{\times} C_{ox} \left(V_{GS} - V_T - \frac{V_{DS}}{2}\right) \frac{V_{DS}}{L}$$

spatial average

$$I = \frac{\mu W}{L} C_{ox} (V_{GS} - V_T) V_{DS}$$

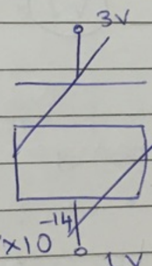
$C_{ox} \to \frac{\epsilon}{t}$

↳ Ignoring terms 2nd order in V_{DS}

$I \uparrow$ if $L \downarrow$ $t \downarrow$ $V_g \uparrow$

Q→ **MOSCAP**

Parameters



$V_T = 1V$

- $N_A = 10^{16}\ cm^{-3}$
- $t_{ox} = 3nm$
- $\epsilon_{ox} = 3.9 \times 8.8 \times 10^{-14}$

Find

→ V_T

→ $W_{depletion}$

→ CV

→ $V_g = \psi_s + \frac{Q_s}{C_{ox}}$

$$\psi_F = \frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right) \approx 360 mV$$

$\psi_s = 2\psi_F$ (for $V_g = V_T$)

$Q_s(\psi_s = 2\psi_F)$

$= [4\epsilon q N_A \psi_F]^{1/2}$

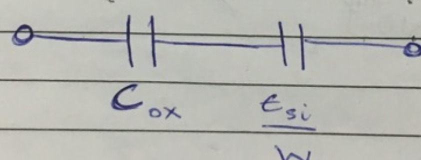
$= q$

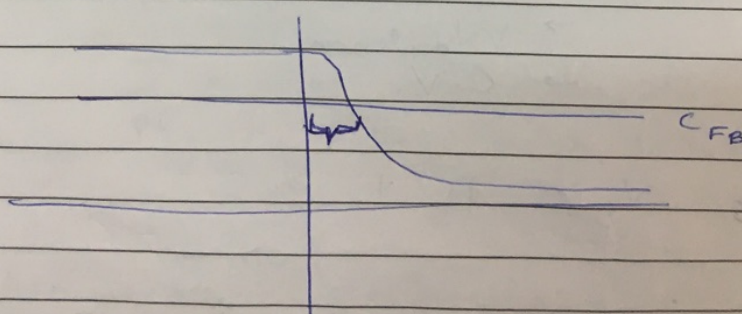
Get $V_T \approx 0.744$ V
(720 + 24) mV

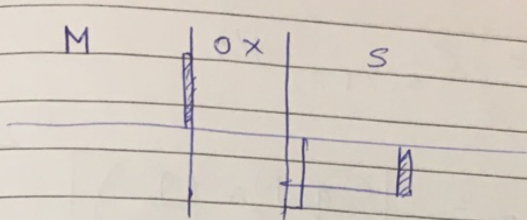
(*) Depletion width

Use $Q_s = W \times (qN_A)$

(*) CV Characteristics







Flat Band Condition ($V_g = 0$ Ideally)

$$Q_s^2 = \epsilon_s^2 E_s^2 = -2q\epsilon \int_0^{\psi_s} \left(N_A e^{-q\psi/KT} - N_A\right) d\psi$$

$$= -2q\epsilon \left[\frac{-N_A \left(e^{-q\psi_s/KT} - 1\right)}{q/KT} - N_A \psi_s \right]$$

$$= -2q\epsilon \left[\frac{-N_A}{q/KT} \left[\cancel{1} - \frac{q\psi_s}{KT} + \frac{\left(\frac{q\psi_s}{KT}\right)^2}{2} \cancel{-1} \right] - N_A \psi_s \right]$$

$$\Rightarrow \frac{\cancel{2} q \epsilon N_A}{\cancel{2}} \left(\frac{q}{KT}\right) \psi_s^2$$

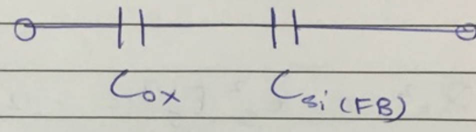
$$Q_s = \left[\epsilon q N_A \left(\frac{q}{KT}\right)\right]^{1/2} \psi_s$$

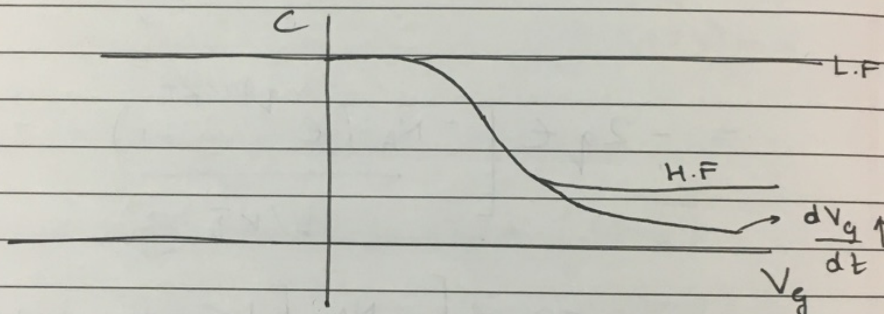
$\cancel{QQ}$ $\frac{dQ_s}{d\psi} = C$

$$Q_s = C_{si(FB)} \psi_s$$

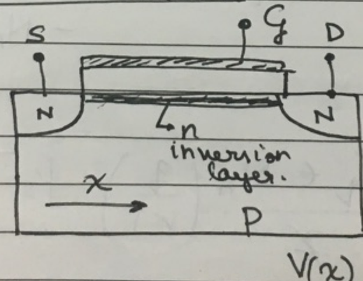
$$C_{FB} = \left[\epsilon q N_A \left(\frac{q}{kT} \right) \right]^{1/2}$$

C_{FB} =





→ <u>MOSFETS Continued</u>



$V_g >> V_T$
V_D is small

$$V_G >> V_T \;, \quad V_D \text{ is small}$$

$$Q_I = C_{ox} (V_{gs} - V_T)$$

$$Q_I(x) = C_{ox} (V_{gs} - V(x) - V_T)$$

MOSFET

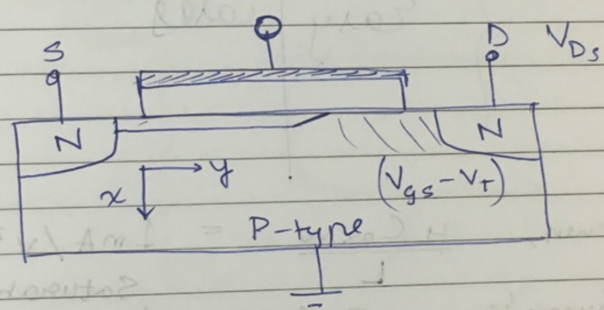
→ Sub-threshhold $V_g < V_T$

→ Linear $V_g > V_T$ $V_{DS} < V_g - V_T$

→ Saturation $V_g > V_T,$ $V_{DS} > V_g - V_T$

$$I_{(Linear)} = \mu C_{ox} \frac{W}{L} \left((V_g - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

$$I_{saturation} = \frac{\mu W C_{ox}}{2} \cdot \frac{(V_{gs} - V_T)^2}{L} (1 + \lambda V_{DS})$$



$$Q_I = C_{ox} \left(V_{gs} - V_T - V(y) \right)$$

Alternate derivation

$$\frac{I}{W} = q \mu E \int_0^\infty n\,dx$$ E → Electric field

$$\frac{I}{W} = q \mu$$

$$I = \mu C_{ox} \left(\frac{W}{L}\right) \times \left[(V_{GS} - V_t) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

Q→ Find the Regime of operation

$$V_T = 0.7V$$

V_{DS} V	V_{gs} V
Easy	cases

Q→ Given, $\frac{\mu C_{ox} W}{L} = 1 \, mA/V^2$

Supports 5mA in ~~linear~~ Saturation region with $\lambda = 0$

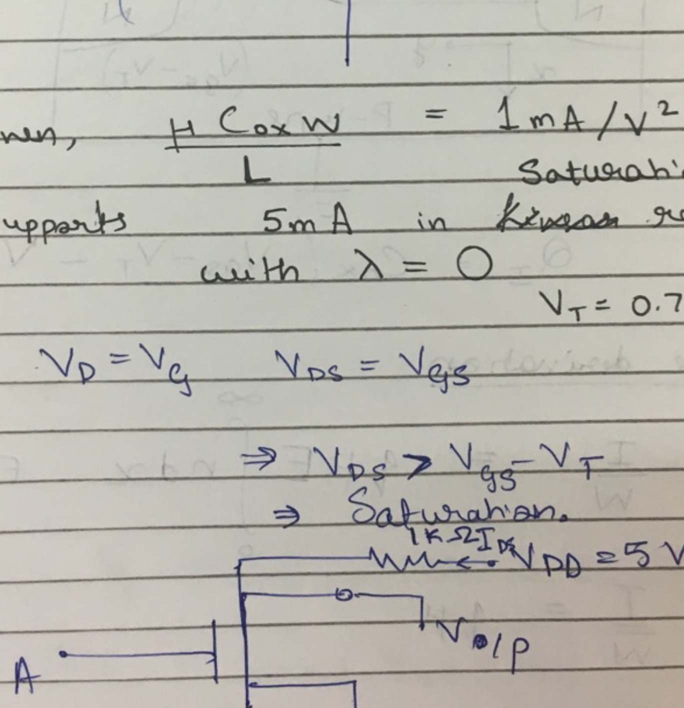
$V_T = 0.7V$

(i) $V_D = V_G \quad V_{DS} = V_{GS}$

$\Rightarrow V_{DS} > V_{GS} - V_T$

$\Rightarrow$ Saturation.

(ii)



$$5 - V_{DS} = 4.3V_{DS} - 0.5V_{DS}^2$$

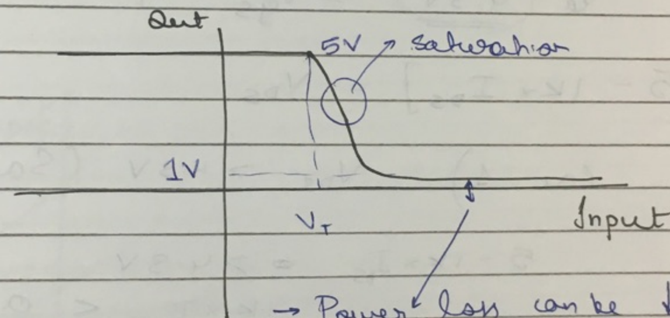
$$0.5V_{DS}^2 - 5.3V_{DS} + 5 = 0$$

$$V_{DS} = \frac{-0.5 + \sqrt{(5.3)^2 - 10}}{1}$$

$$V_{DS} = 1.04\,V$$

~~$V_{DS} = 3.75$~~ → Check again.

→ Switching Char.

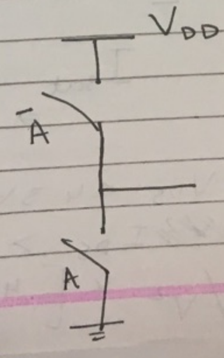


→ Power loss can be ↓

1K → 100K → V_{off} can be ↓ to 0 if we use high R

→ but $\tau = RC$ ↑ and switching time ↑

→ Ideally



Date : / /

$$\frac{\mu C_{ox} W}{L} = 1mA/V^2$$

A	O/P (Capacitive load)
0V	5V
5V	~~0.5V / 1V / 0.75V~~ 1.04V (Linear region)

$V_A = 0V$

$V_A = 5V$

$4.3V = V_{gs} - V_T$

$[5 - 1K \times I_{DS}] = V_{DS}$

Case - 1) $V_{DS} > 4.3V$ (Saturation)

$5 - 1K \times I_{DS} > 4.3V$

$1K \times I_{DS} < 0.7K$

$I_{DS} < 0.7mA$

$$I_{sat} = \frac{1mA/V^2}{2} \times (4.3)^2 (1 + \cancel{\lambda} V_{DS})$$

$I_{sat} = 9.245mA$

$\Rightarrow$ Not Sat.

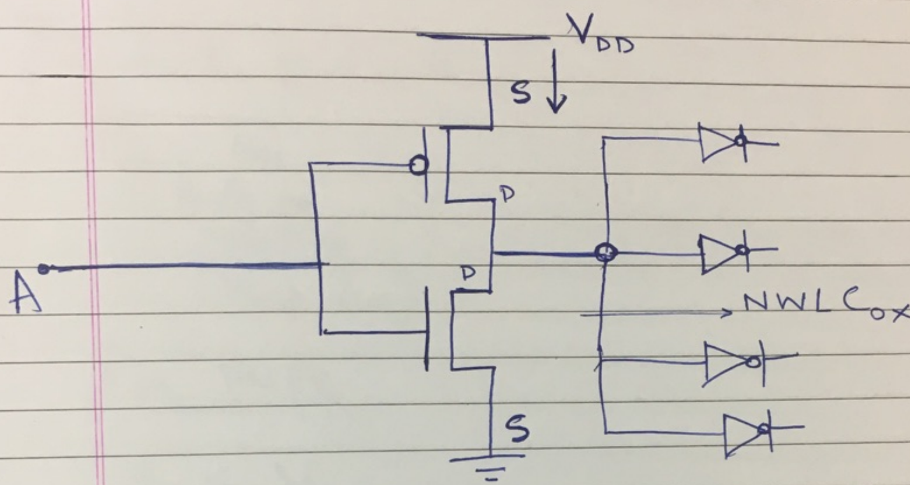
Linear

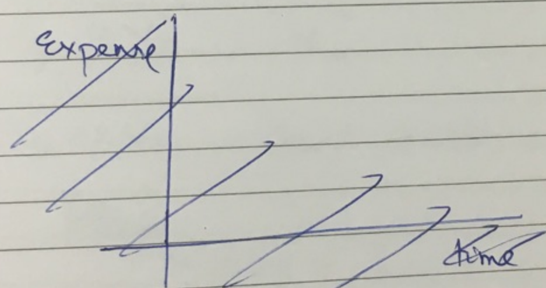
$V_{DS} < 4.3V$

$I_{DS} > 0.7mA$

$$1mA/V^2 \times \left[4.3 \times V_{DS} - \frac{V_{DS}^2}{2}\right] = \frac{5 - V_{DS}}{1K}$$

→ Solution ⇒ Use CMOS





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$$\mu E = \mu \frac{V_{ds}}{2}$$

$$Q_I(\,) = C_{ox}(V_{gs} - V_{DS} - V_T)$$

$$I = \mu C_{ox} \frac{W}{L}\left((V_{gs} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right)$$

Not bulk mobility (Much less)

$\mu \rightarrow$ Mobility near surface, smaller due to roughness

For PMOS

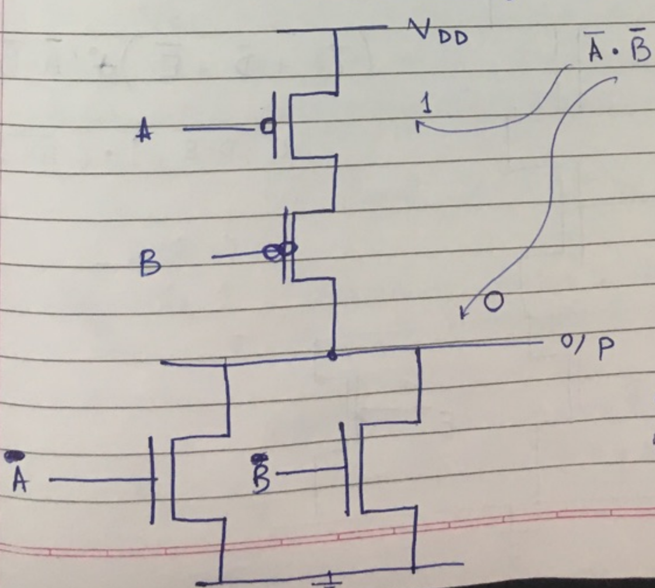
1) $V_G < V_T$

2) $V_g > V_T$, $V_{DS} \sim$

3) $V_g >> V_T$ $\quad V_D$ is Small

30-10-12 ~~Phora~~

MOSFET Logic Gates



$\bar{A} \cdot \bar{B}$

$\overline{(A+B)}$

A	B	A+B	O/P
0	0	0	5
0	5	5	0
5	0	5	0
5	5	5	0

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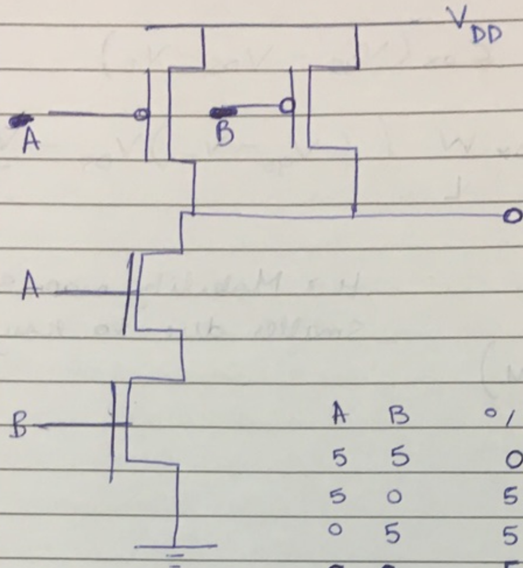


$\bar{A} + \bar{B}$

$\bar{A}\cdot\bar{B} + (\bar{A}+\bar{B})$

$= \bar{A} + \bar{B} = \overline{AB}$

$\overline{AB}$

A	B	O/P	AB
5	5	0	5
5	0	5	0
0	5	5	
0	0	5	

→ We want $\overline{AB(C+D+E)}$

$\overline{AB\,(C+D+E)}$

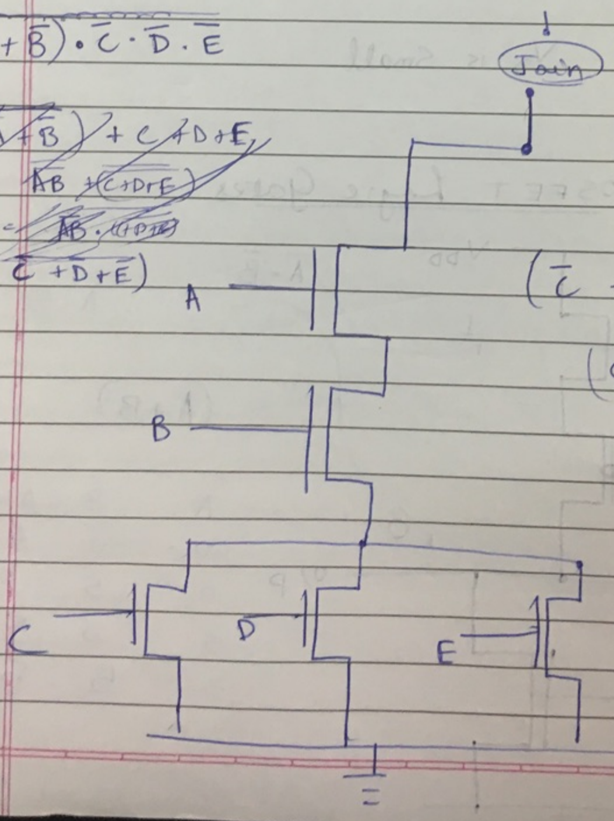
$(\bar{A}+\bar{B})\cdot\bar{C}\cdot\bar{D}\cdot\bar{E}$

$= \cancel{\overline{(\bar{A}+\bar{B})} + C + D + E}$

$\cancel{\bar{A}\bar{B} + (C+D+E)}$

$\cancel{= \bar{A}\bar{B}\cdot(C+D+E)}$

$\overline{AB} + (\bar{C}+\bar{D}+\bar{E})$

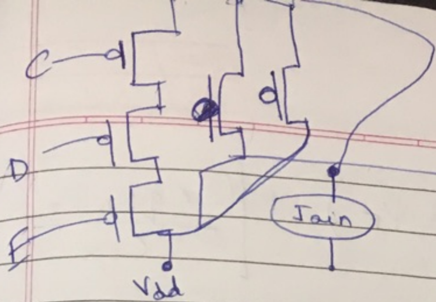


$\cancel{A}B$

$(\bar{C}+\bar{D}+\bar{E}) \cdot (\bar{A}\cdot\bar{B})$

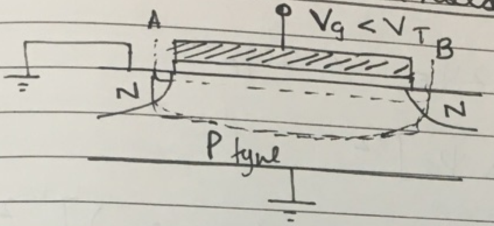
$(\overline{C\cdot D\cdot E})\cdot(\overline{A+B})$

$C\cdot D\cdot E$

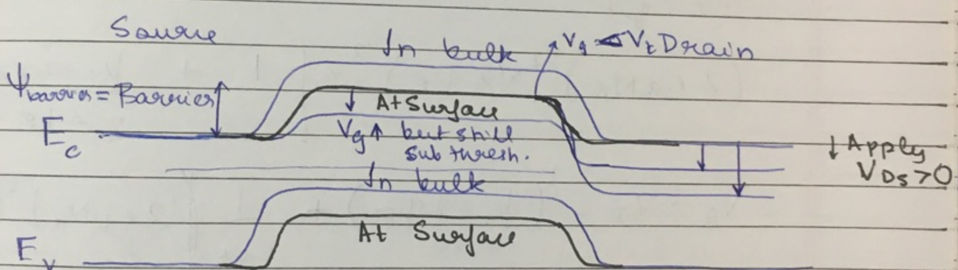


Corresponding PUN

Sub-Threshhold



(a) $V_D = 0V$ (b) $V_D = 0.3V$



→ At $V_{DS} = 0V$ → Complete symmetry ⇒ $I = 0$

→ At $V_{DS} > 0$ for sub threshhold, current is determined only by the barrier At left & hence,

for fixed V_g ($< V_t$) if $V_D \uparrow$, $I \sim k$

→ As $V_g \uparrow$, Barrier ↓ and $I \uparrow$ at sub threshhold

& $I \propto e^{-q\psi_{barrier}/KT}$

In this region

$$Q_s = (2\epsilon q N_A \psi_s)^{1/2}$$

$$V_g - V_F = \psi_s + \frac{(2\epsilon q N_A \psi_s)^{1/2}}{C_{ox}} - V_T$$

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$$V_g - V_T = (\psi_s - 2\psi_F) + \left[\frac{(2\epsilon q N_A \psi_s)^{1/2}}{C_{ox}}\right.$$

ψ_s just less than $2\psi_F$

$$\psi_s - 2\psi_F << 2\psi_F$$

$$[2\epsilon q N_A \psi_s]^{1/2}$$

$$= [2\epsilon q N_A (\psi_s - 2\psi_F + 2\psi_F)]^{1/2}$$

$$\cancel{= (2\epsilon q)^{1/2}}$$

$$(2\epsilon q N_A)^{1/2} \times (2\psi_F)^{1/2} \times \left[1 + \frac{\psi_s - 2\psi_F}{2\psi_F}\right]^{1/2}$$

$$V_g - V_T = (\psi_s - 2\psi_F) + \frac{1}{C_{ox}} \left[(2\epsilon_q N_A)^{1/2} (2\psi_F)^{1/2}\right. \left[\right.$$

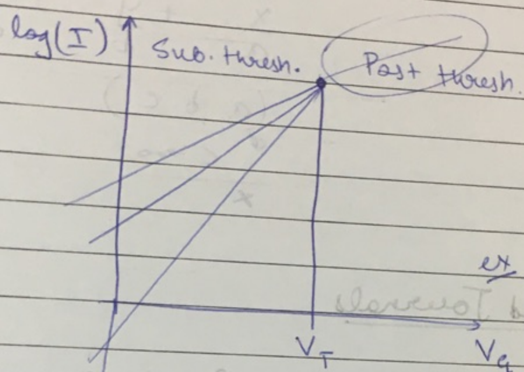
$$\cancel{(\psi_s - 2\psi_F) + \frac{1}{C_{ox}}} \left[\right.$$

Independent of ψ_s

$$V_g - V_T = (\psi_s - 2\psi_F) \times [1 + m]$$

$$m = 1 + \frac{(2\epsilon_q N_A 2\psi_F)^{1/2}}{C_{ox}}$$

$$- \left. \frac{(2\epsilon q N_A 2\psi_F)^{1/2}}{C_{ox}} \right]$$



$$SS = \left(\frac{d(\log I)}{d V_g} \right)^{-1}$$

ex 60mV/dec

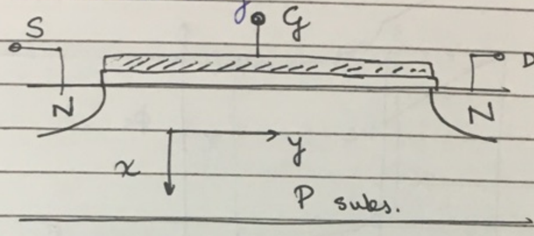
$$\Delta\psi_s = \frac{\Delta V_g}{m}$$

$$\left[\cancel{1/4} \; \frac{\psi_s - 2\psi_F}{4\psi_F} \right] - \left. \frac{(2\epsilon_q N_A 2\psi_F)^{1/2}}{\quad} \right]$$

Non-Ideal MOS

ϕ_{ms} Q_{ox} D_{it} V_T Short Channel Effects

Reliability



$\times\, \epsilon_{ox}$

$E_{ox}(y) = \frac{(V_g - V(y))}{t_{ox}}$

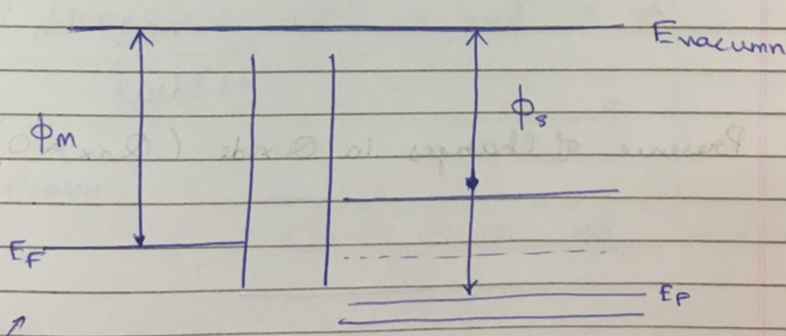
Q → ① I_D, NMOS, $V_T = 0.7V$, $V_{DS} = 0.5\,V$, $V_{gs} = 0.7V$

② $Q_I = C_{ox}(V_g - V_T - V(y))$

- For ① neither the Sub-threshhold I exp. nor the linear region exp. are valid

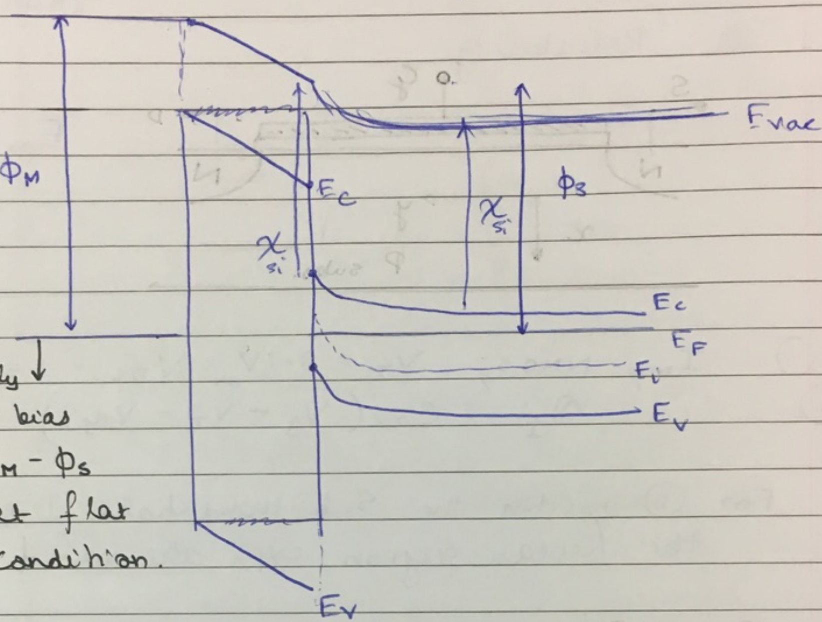
Band Diagram

$$\phi_{MS} = \phi_M - \phi_s \neq 0$$



→ Band Diagram without Metallurgical junction.

→ Equilibrium band Diagram



Apply the bias $= \phi_M - \phi_s$ and get flat band condition.

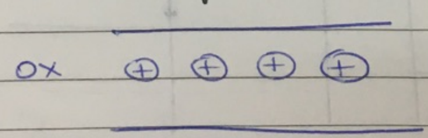
→ Hence all char. will shift by V_{fb}

$$\phi_{MS} = \phi_M - \phi_s \neq 0$$

$$V_T = \phi_{MS} + \underbrace{2\psi_F + \sqrt{2q\epsilon N_A(2\psi_F)}}_{V_{T\,ideal}}$$

→ Presence of Charges in Oxide ($Q_{ox} \neq 0$)

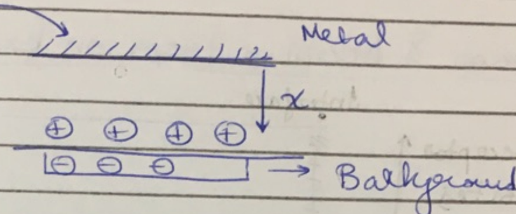
(NMOS)



→ Lowers V_T, since Inversion layer forms earlier due to background deposition of charge.

→ Find Shift in V_T? What is V_{FB}

Add equal charge here (Mirror it)



$$\Delta V_g = \frac{-\sigma}{\epsilon_{ox}} \times x$$

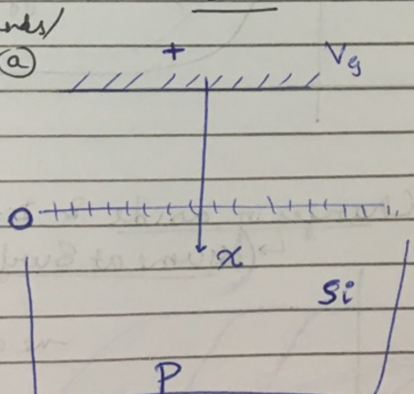
$\sigma \to \sigma(x)$

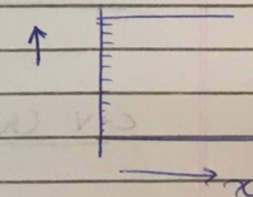
$$V_{FB} = -\int_0^{t_{ox}} \frac{\sigma x}{\epsilon_{ox}}\, dx$$

→ Immobile ions → C-V char. shifts by V_{FB}
→ Mobile ions → C-V char. further stretched out.

Dit : Interface state density

→ Dangling bonds/traps/states @ surface

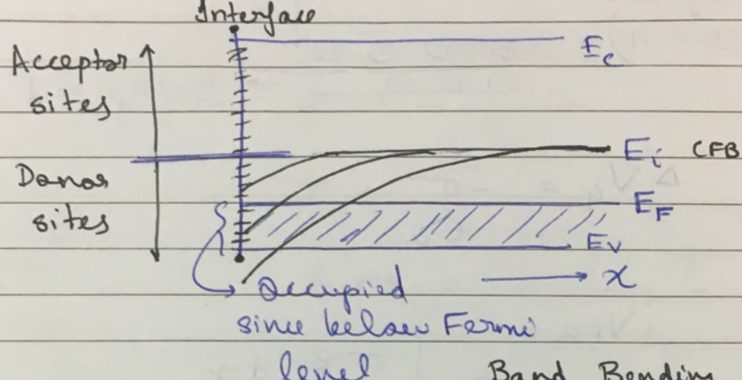




Empty states	filled states (with e⁻!)	
+ve	0	Donor
0	-ve	Acceptor

→ Effect on Band Bending

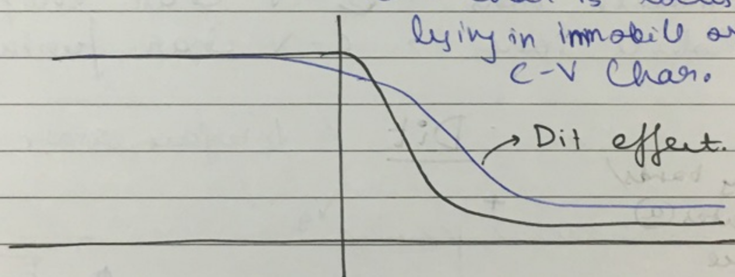
Donor & Acceptor traps on band Diagram



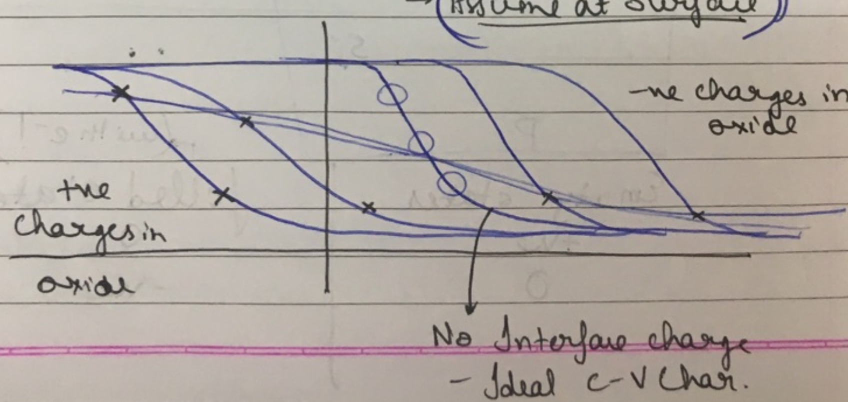
Band Bending

- As E_i bends, the nature of States changes hence final C-V Char is locus of points lying in immobile oxide charge C-V Char.

C-V Char.



C-V Char. Charges in oxide & Dit effect relation
↳ (Assume at Surface)



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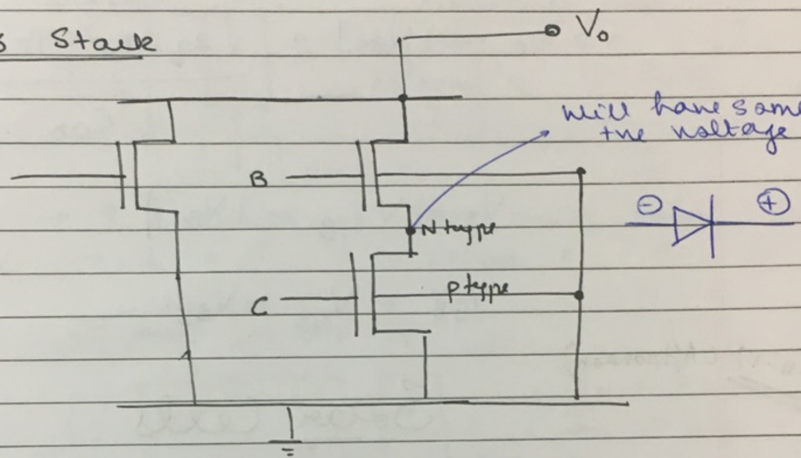
→ Back Bias

- Plays Important Role in CMOS Stacks.

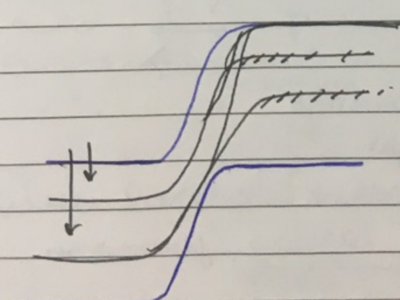
NMOS Stack



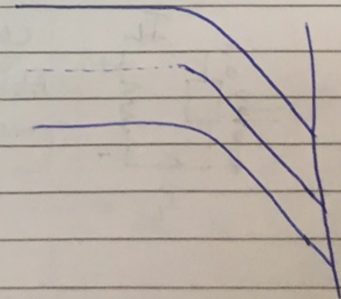
- Bodies Grounded Directly and source/drain will have some +ve potential.

→ This will change the threshhold point (Onset of Inversion)

S-B E-B Dia.



Vertical profile of Body



$$\psi_S = 2\psi_F + |V_{BS}|$$

$$V_{Th} = 2\psi_F + |V_{BS}| + \frac{Q_0}{C_{ox}}$$

$$= 2\psi_F + |V_{BS}| + \frac{\sqrt{2q\epsilon N_A(2\psi_F + (V_{BS}))}}{C_{ox}}$$

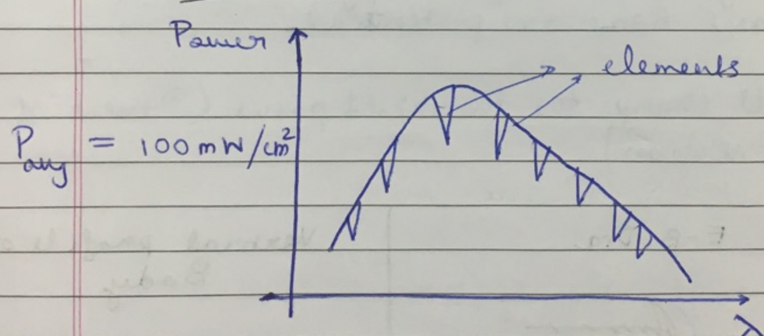
$$V_T = V_{T,B} - |V_{BS}|$$

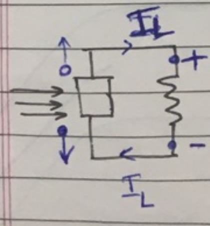
$$V_{GB} = V_{GS} - V_{BS}$$

2-11-17 (Afternoon)

Solar Cells

Solar Energy

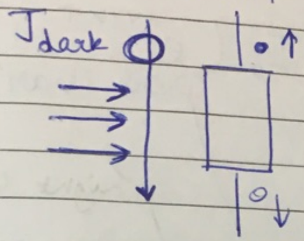




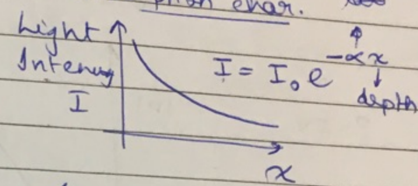
Characteristics

- Absorbs light
- We get current in external circuit
  - → through Carrier Generation
    - ↳ free carriers not bound excitons
- Carriers should be collected at different terminals.

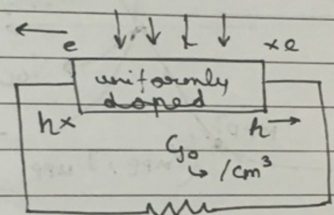
The voltage created by I_L by flowing through R, opposes the flow of I_L



Absorption char.



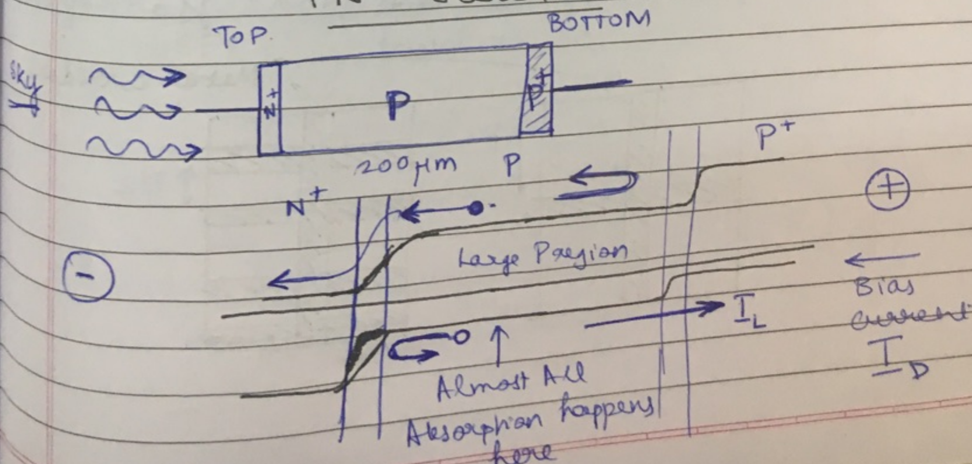
GaAs → ↑ Absorption ~ 1μm thick Solar cells
Si → ↓ " ~ 200μm " " "



$I_e = GL$
$I_h = GL$
R = 0

Note: If Electrodes were not special but Symmetric then No I due to
- Symmetry
- Recombination

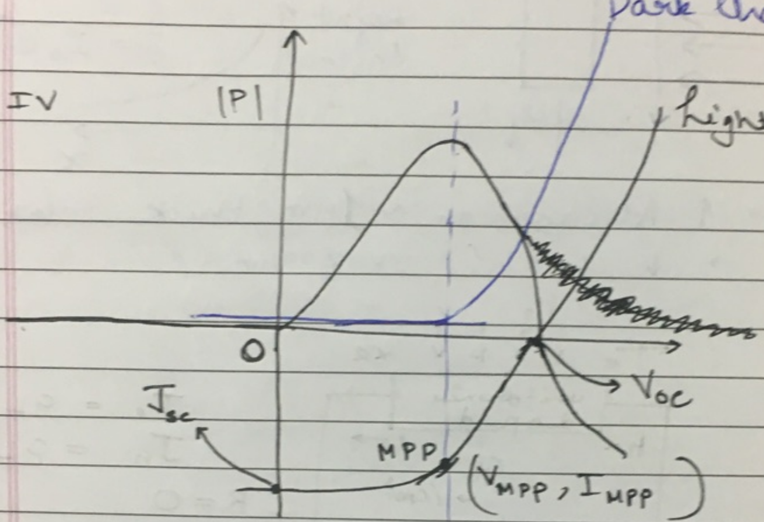
PN Junction



$$I_{Light} = -I_L + I_0\left(e^{qV/kT} - 1\right)$$

$$I_{dark} = I_0\left(e^{qV/kT} - 1\right)$$

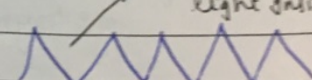
P = IV



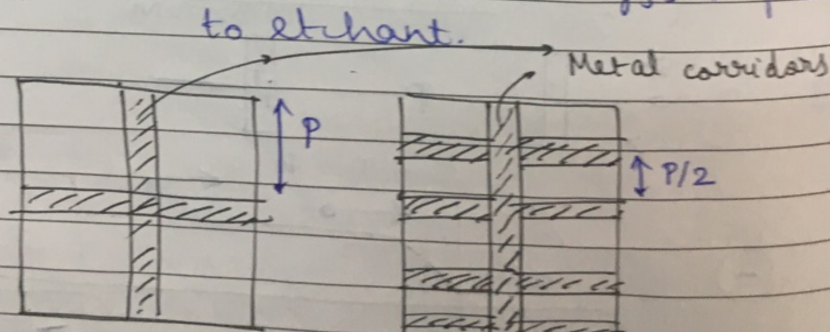
→ <u>Solar Cell Design</u>

- Eli Yablonovitch proposed

Rough Surface →



Expose Silicon ~~to~~ ~~Non~~ Non-Isotropically to etchant.



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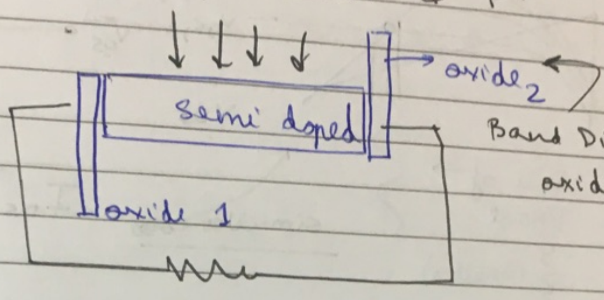
- Oxides with Easy Metallurgy junction can be used to replace N^+ & P^+



Band Diagram with oxides

→ Relation with Band Gap E_g

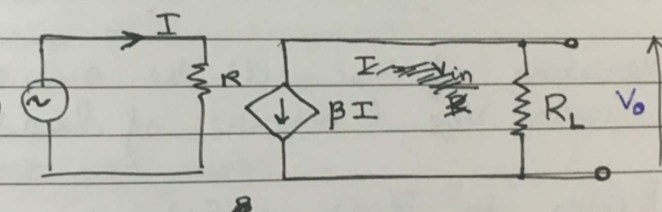
$V_{oc} \downarrow \quad E_g \downarrow$
$I \uparrow \quad E_g \downarrow$

Hence trade-off

6.11.17

→ Amplification & Ammeter.

$A_V = \frac{V_o}{V_I} = \frac{\beta R_L}{R}$

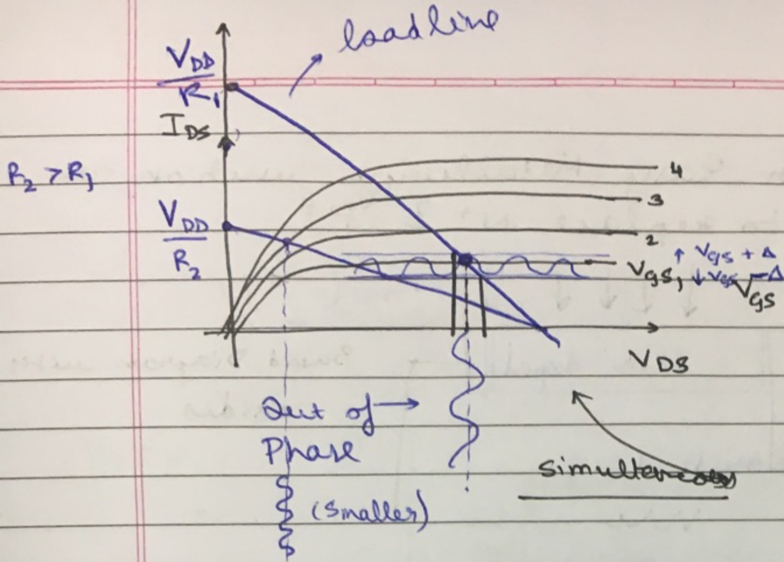


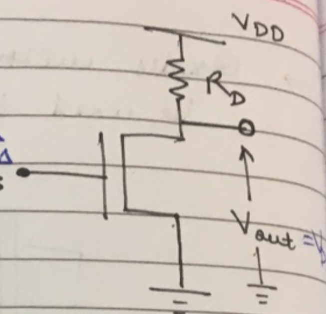
Amplified voltage.

MOSFET as Amplifier

$$I_{DS} = \frac{\mu C_{ox} W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

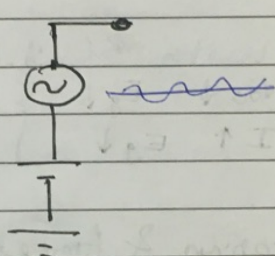
(Sat.) $$I_{DS} = \frac{\mu C_{ox} W}{2L}\left[(V_{GS} - V_T)^2\right]$$





$$I_{DS} = \frac{V_{DD} - V_{DS}}{R}$$

$V_{gs} \equiv$



→ Variation of V_{DS} will be out of phase with V_{gs} (Nature of load line)

→ Better to Bias in Saturation since we get more variation in V_{DS}
~~Mo~~ MOSFET Amps always biased in Sat.

→ Equivalent Ckt Model

$$I_{DS} + i_{DS} = I_{DS} + \frac{\delta\,(\,)}{\delta}\Big|_{V_g}$$

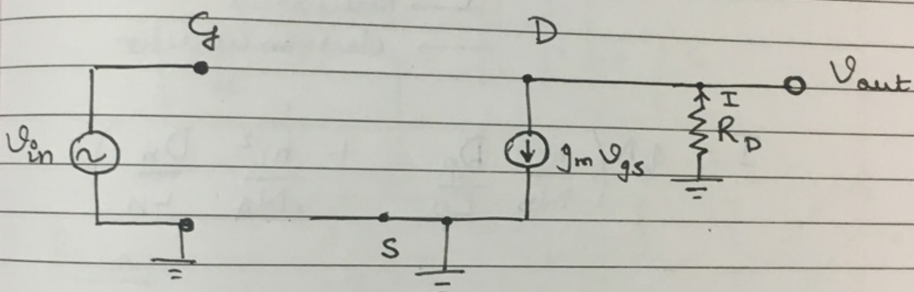
$$I_{DS} = \frac{\mu C_{ox} W}{2L}\left[(V_{gs} - V_T)^2\right]$$

$$i_{DS} = (\ )^{??} v_{gs}$$

$$i_{DS} = \left(\frac{\delta I_{DS}}{\delta V_{gs}}\right)_{V_{ds}} = g_m v_{gs}$$

$$g_m = \frac{\mu C_{ox} W}{L}(V_{gs} - V_T)$$

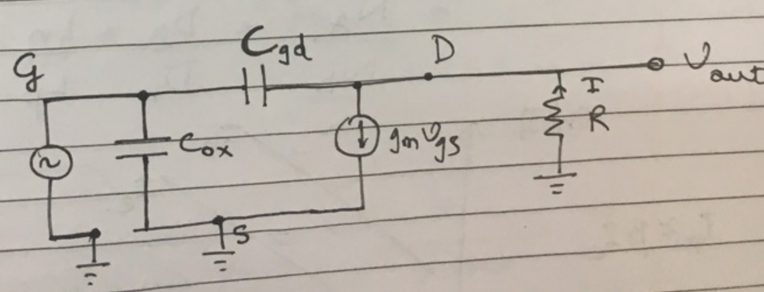
<u>Model</u> (AC. small Signal model)



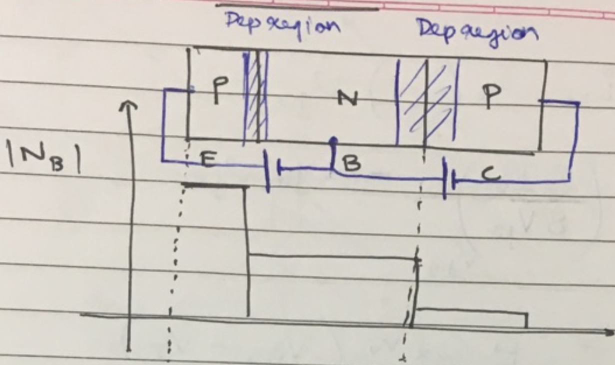
$$v_{out} = -g_m v_{gs} R_D$$

$$A_v = -g_m R_D$$

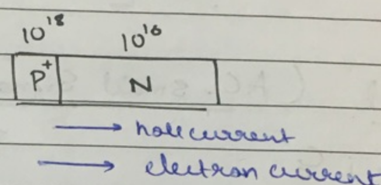
<u>At hi-f</u>



BJT



→ PN junction

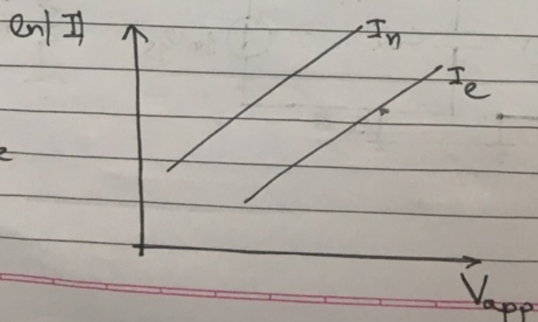


$$I = qA\left(\frac{n_i^2}{N_D}\frac{D_p}{L_p} + \frac{n_i^2}{N_A}\frac{D_n}{L_n}\right)$$

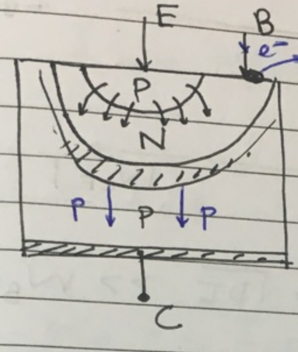
$$\beta = \left(\frac{I_h}{I_e}\right) = \frac{\frac{n_i^2}{N_D} D_p/L_p}{\frac{n_i^2}{N_A} D_n/L_n}$$

$$= \frac{N_A}{N_D} \times \frac{D_p}{D_n} \times \frac{L_n}{L_p}$$ → hidden dependent source.

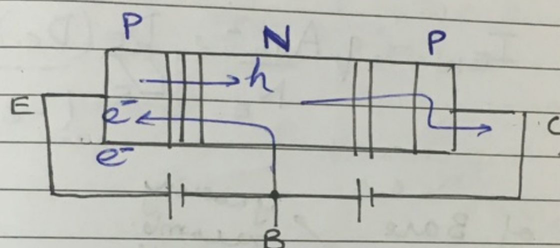
$I_p \approx \beta I_e$



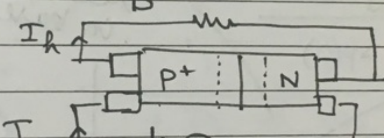
- Split e & p currents to achieve goal.

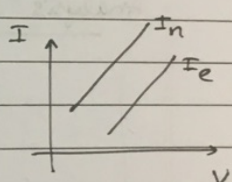


located far away
all holes use other path

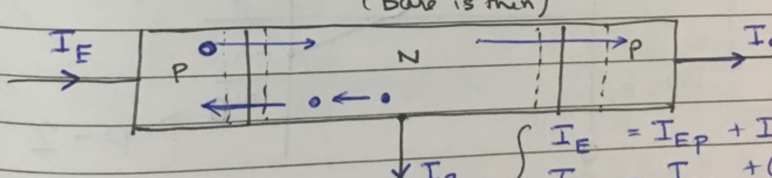


7.11.17 **Recap**



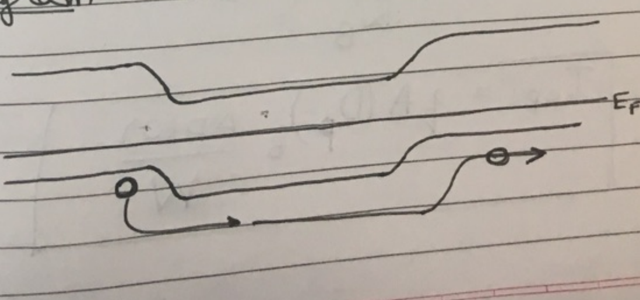


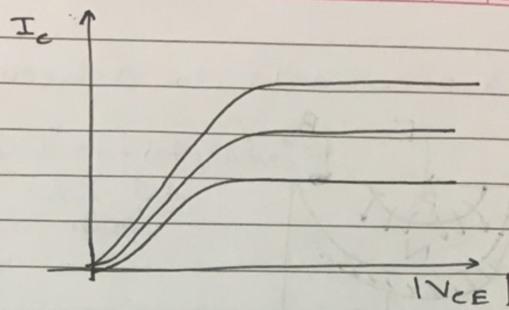
(Base is thin)



$$\begin{cases} I_E = I_{Ep} + I_{En} \\ I_B = I_{en} + (\text{Recomb.}) \\ I_{cp} = I_{ep} - (\text{Recomb.}) \end{cases}$$

E-B Diagram



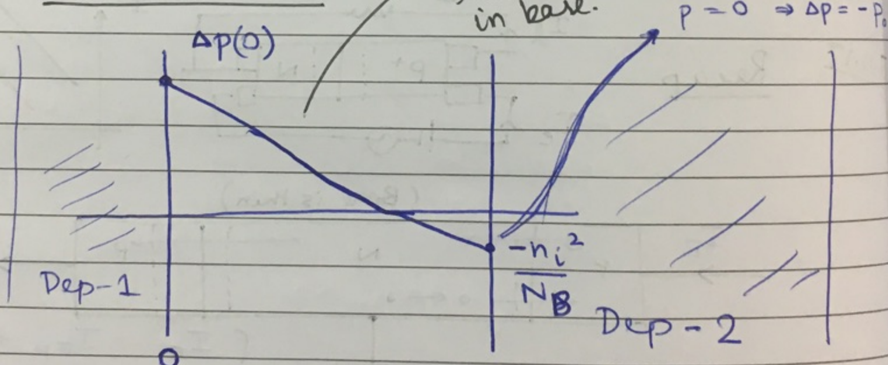


$\beta = \frac{I_c}{I_B}$ I_B controls

→ **Assumption**: $L = \sqrt{D\tau} >> W_B$

$$\cancel{I_{En}} \quad I_{En} = qA\frac{n_i^2}{N_E} \cdot \cancel{\frac{D_E}{L_E}} \frac{(D_e)_E}{(L_e)_E}\left(e^{qV_{EB}/kT} - 1\right)$$

Analysis of Base



$$\Delta p(0) = \frac{n_i^2}{N_B}\left(e^{qV_{EB}/kT} - 1\right)$$

$$\boxed{I_{cp} = qA(D_p)_B \frac{\Delta p(0)}{W}}$$

Now considering recombination

$$I(\text{recombination}) = \int_0^W \frac{\Delta n}{\tau}\, dx$$

Area under $\Delta P/P$ profile

$$I_{EP} = I_{CP} + \frac{qA\,\Delta p(0)\cdot W}{2\tau}$$

$$\alpha_T = \frac{I_{CP}}{I_{EP} + (\ )} = \frac{D_B/W}{D_B/W + W/2\tau_B}$$

$$= \frac{1}{1 + W^2/2D_B\tau_B}$$

$$\gamma = \frac{1}{1 + \frac{D_E}{D_B}\frac{W}{L_E}\frac{N_B}{N_E}}$$

$$\gamma = \frac{I_{EP}}{I_E}, \quad \gamma = \frac{qAD_B\,\Delta p(0)/W}{qAD_B\,\Delta p(0)/W + qA\frac{n_i^2}{N_E}\frac{D_E}{L_E}(\ )}$$

$$I_C = \frac{I_{CP}}{I_{EP}}\cdot\frac{I_{EP}}{I_E}\cdot I_E = (\gamma\,\alpha_T)\,I_E$$

$$I_C = \alpha_{DC}\, I_E$$

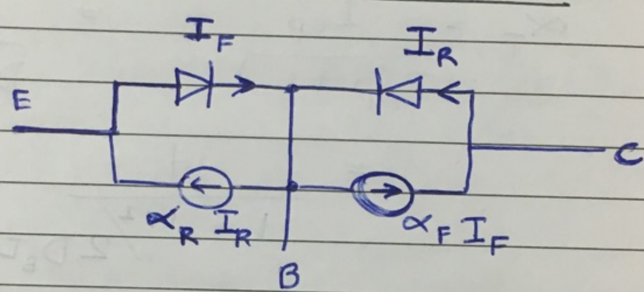
$$I_E = I_c + I_B$$

$$I_E = \alpha I_E + I_B$$

$$I_B = (1-\alpha) I_E$$

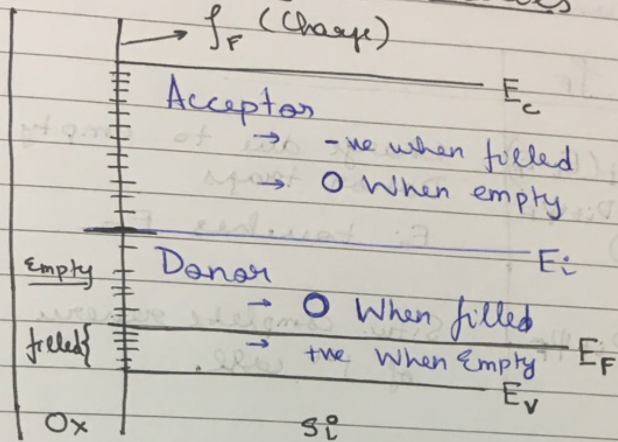
$$\beta = I_c / I_B = \left(\frac{\alpha}{1-\alpha}\right)$$

→ <u>Ebers - Bohl Model of BJT</u>

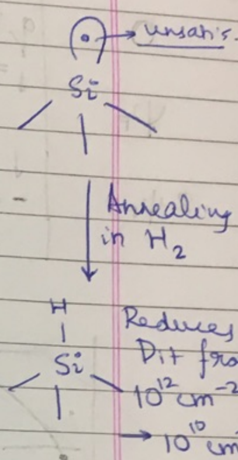


Interface States

• Nomen. based on N_A, N_D behaviour



D_{it} presence



Reduces D_{it} from $10^{12}\,cm^{-2}$ → $10^{10}\,cm^{-2}$

→ Shift in Char.

$$V_g = \psi_s + E_{ox} t_{ox} \quad \text{— Always valid}$$

using $\epsilon_{ox} E_{ox} = \epsilon_{Si} E_{Si}$, we write

$$V_g = \psi_s + \frac{Q_{Si}}{C_{ox}}$$

In absence of Interface Charges.

→ Electrostatics in presence of ρ_F

$$\epsilon_{ox} E_{ox} = \epsilon_{Si} E_{Si} + \rho_F$$
$$= Q_{Si} + \rho_F$$

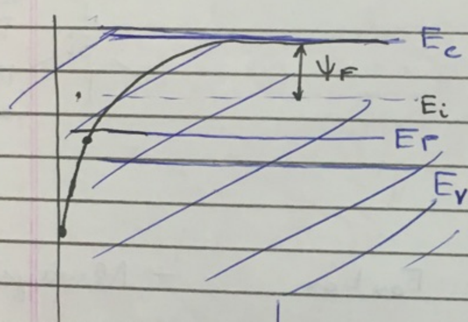
voltage modulated

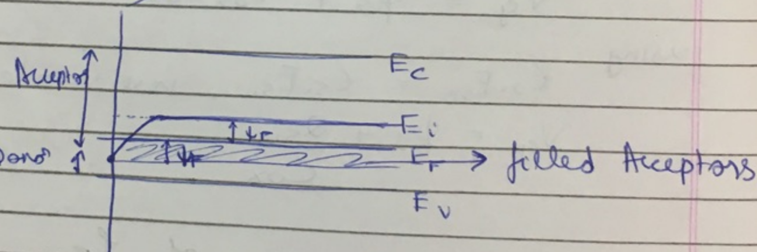
$$\Rightarrow V_g = \psi_s + \underbrace{\left[\frac{Q_{Si}}{C_{ox}} + \frac{\rho_F}{C_{ox}}\right]}_{E_{ox} t_{ox}}$$

→ D_{it} : Taken as uniform (Approx.)

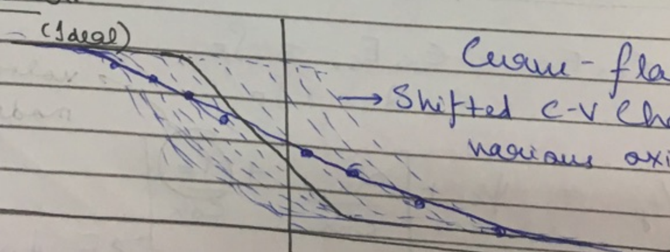
units : $cm^{-2}eV^{-1}$

ψ_s	Q_F	
0	$qD_{it}(E_i - E_F)$ $\downarrow$ $= qD_{it}\psi_F$	Charge due to empty Donor traps
ψ_F	0	E_i touches E_F
$2\psi_F$	$\downarrow$ $-qD_{it}\psi_F$	Situ. complete reverse of 1st case.





C-V Char.



Curve - flattens out.

→ Shifted C-V Char. for various oxide charges

$$\psi \to \psi + \Delta\psi$$

$$I \to I + \Delta I$$

$$\Delta V_g + \frac{q D_{it} \Delta\psi}{C_{ox}}$$