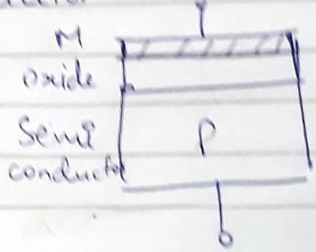
L#

wed 6-7 pm (office hours)

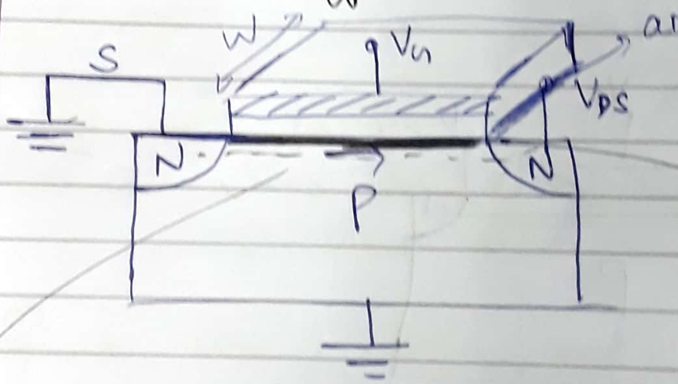
MOS Capacitor



$V_G > V_T \rightarrow$ Inversion

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

MOS Field effect transistor



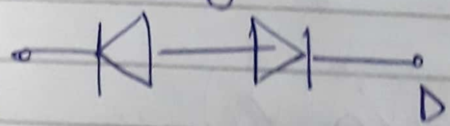
area ⊥ to dir^n of flow of current

$V_{DS} \sim$ som V

Inversion layer on (applying $V_g > V_T$)

$V_G << V_T \rightarrow$ off

device along dotted line



→ No current unless you break down the diode

$V_G > V_T \rightarrow$ Inversion layer

diffusion → negligible
charge is changing very less

charge is mainly due to drift, therefore current = QV
as e is moving to higher potential ie lower energy

When we move to drain side, there can be some potential

★ $Q_I(S) = C_{ox}(V_{GS} - V_T)$

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

$I = QV$
$= \langle Q \rangle \langle V \rangle$ q *velocity

m^2/Vs)*V/m
$V = \mu E$
velocity= mobility * electric field (definition of mobilitu

$\langle V \rangle = \mu \frac{V_{DS}}{L}$

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

in linear region
↳ doesn't take into account width

|| $Q \to \int dq$ to the depth should by x width

Text

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

★ for a switch drop → should very small

$I \approx C_{ox} \frac{\mu W}{L}(V_{GS} - V_T)(V_{DS})$ {for very small V_{DS}}

~~for~~ to have more current we ~~cant~~ can

$\boxed{W\uparrow}$, $C_{ox}\uparrow$ ↳ $\frac{\epsilon_{ox}}{t_{ox}}$, $\boxed{V_{GS}\uparrow}$, $\boxed{t_{ox}\downarrow}$, $\boxed{L\downarrow}$

but we avoid this

Current $\propto V_{DS}$

↳ kind of a resistor.

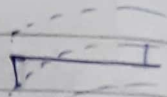
$$\left\{ I = \frac{C_{ox}\mu W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)\left(V_{DS}\right) \right\}$$

(Q) P-type doping $10^{16}\,cm^{-3}$ | $t_{ox} = 3nm$

$\epsilon_{ox} = 3.9 \times 8.854 \times 10^{-14}$

(Q) V_T | (Q) Wdep width | (Q) CV

$$V_T = 2\psi_F + \frac{\left[4\epsilon_s q N_A \psi_F\right]^{1/2}}{C_{ox}}$$



V_T occurs when ~~band~~ bending is $2\psi_F$ → surface pot

can be obtained from doping

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

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

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

$$Q_s^2 = \frac{\epsilon_s^2 E^2}{\cancel{\epsilon}} = 2(N_A) q \epsilon \psi_s$$

$$V_T = 2\psi_F + \frac{\sqrt{4 N_A q \epsilon_s \psi_F}}{C_{ox}}$$

$$Q_s = \sqrt{2 N_A q \epsilon \psi_s}$$

$$V_T = 2\left(\frac{KT}{q}\right)\ln\left(\frac{N_A}{n_i}\right) + \frac{\sqrt{4 \times N_A \times 11.8 \times \epsilon_0 \times \psi_F \times q}}{C_{ox}}$$

$$C_{ox} \rightarrow \frac{\epsilon_{ox}}{t_{ox}}$$

$\psi_F = .357$

$$V_T = 2(.357) + \sqrt{4 \times \_\_\_\_}$$

$$= 2(.357) + \frac{(4.88 \times 10^{-8})}{3.9 \times \epsilon_0}(3 \times 10^{-9})$$

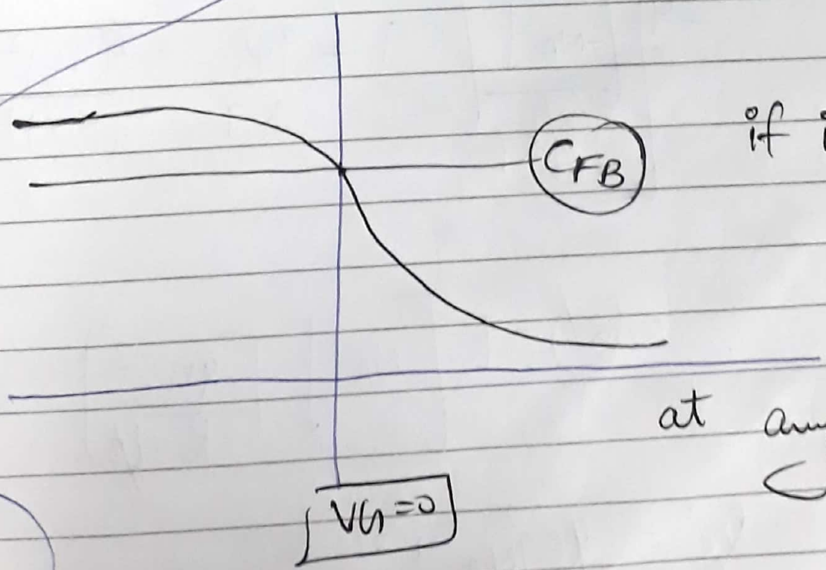
$$= 2(.357) + 4.24 \times 10^{-4}$$

$$= \checkmark \quad .7144\,V$$

(Q) W depletion region width

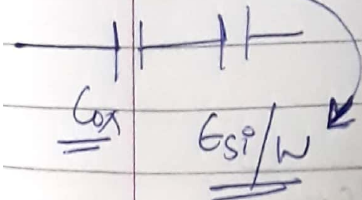
$$Q_s = qN_A W \checkmark$$

(Q) C-V



if it intersects at $x=0$ ideal

if it intersects at any other point $\Rightarrow$ non-ideal



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$$C_{ox} \rightarrow \frac{\epsilon_{ox}}{t_{ox}}$$

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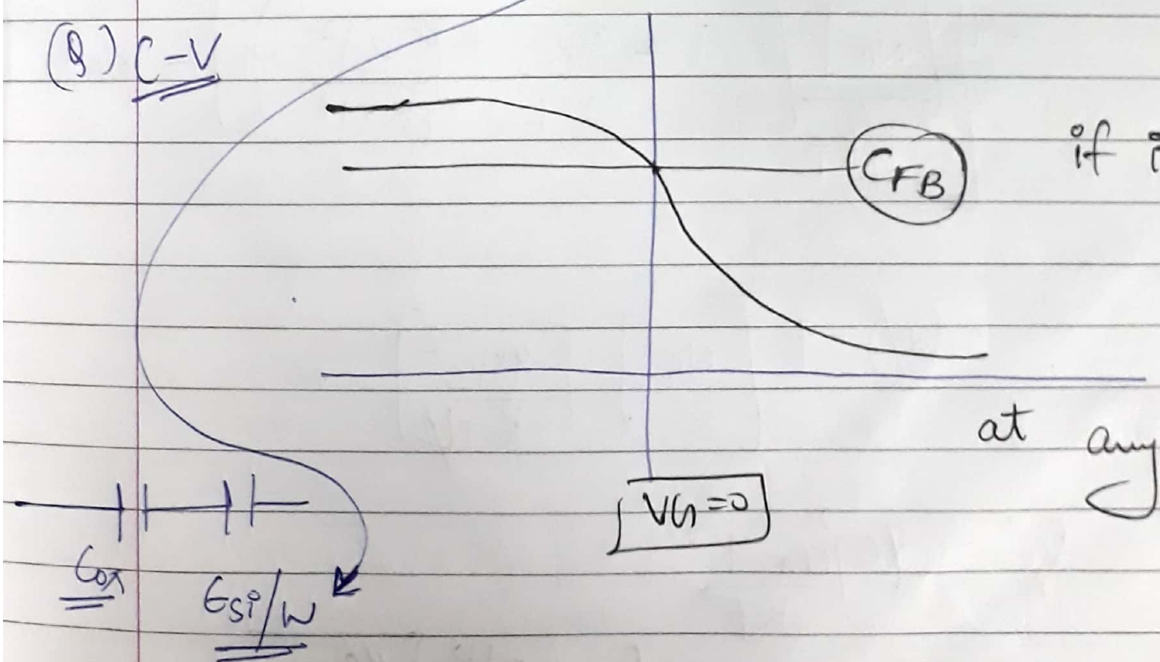
$$= \checkmark \quad .7144\,V$$

(Q) W depletion region width

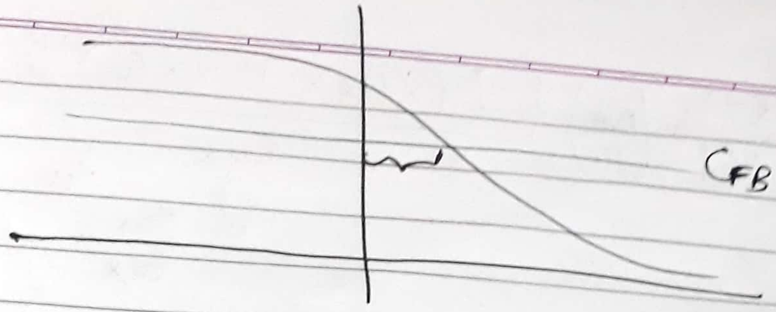
$Q_s = qN_AW$ ✓

(Q) C–V



if it intersects at $x=0$
Ideal

if it intersects at any other point
⇒ non-ideal



$C_{FB} \rightarrow$ flat band

$V_G = 0$

ac gauce

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

dominant charge

$n \rightarrow$ minority

$$P \rightarrow N_A e^{-q\psi/KT}$$

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

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

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

$$\rho_s^2 = \frac{2\epsilon q^2 N_A \psi_s^2}{KT}$$

$$\rho_s = q\psi_s \sqrt{\frac{2\epsilon N_A}{KT}}$$

L#

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

$$Q_I = C_{ox}(V_G - V_{DS} - V_T) \leftarrow$$

S → terminal through which carrier enters (supplies the carrier)

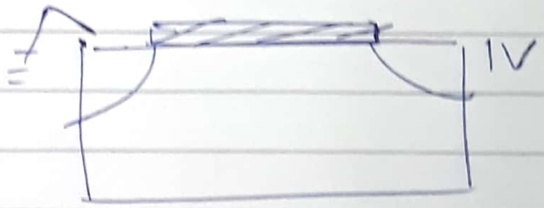
Drain → (terminal through which you take out carrier)

(1) $V_G << V_T$

(2) $V_G >> V_T$, V_{DS} -

(3) $V_G >> V_T$

V_D is small ✓



L# MOSFET

① Sub-Threshold $V_G < V_T$

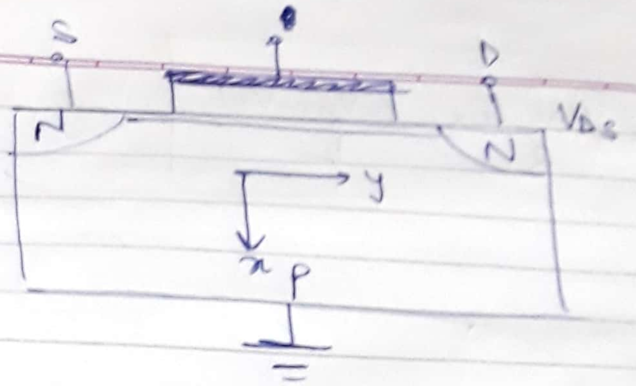
② Linear $V_G > V_T$, $V_{DS} < V_G - V_T$

③ Sat^n $V_G > V_T$ $V_{DS} > V_G - V_T$

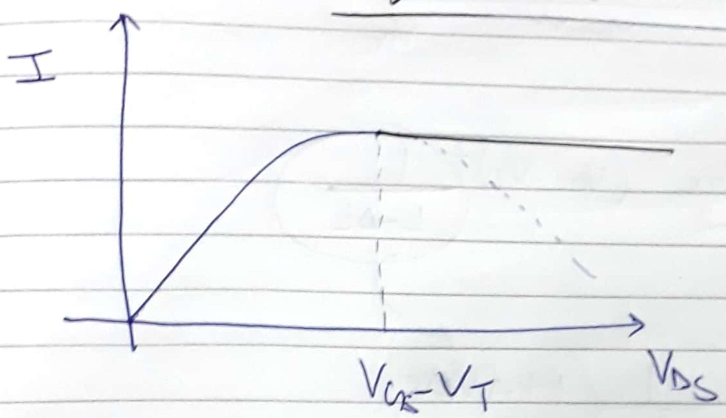
$$I = \mu C_{ox} \frac{W}{L} \left((V_G - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

Valid only when inversion ~~channel~~ layer is through the channel

Scanned by CamScanner

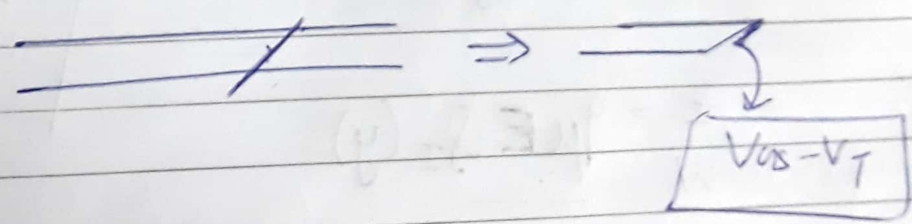


$$Q_I = C_{ox}\left(V_{DS} - V_T - V(y)\right)$$



the linear eq^n is valid only when inversion layer is throughout the channel.

- After $V_{GS} - V_T$, inversion layer gets pinched off.



Modification in I :

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

c

after pinch h off further increase in vd does not effect potential at end of channel

~~if Long channel than $L' \approx L$~~

$L' \approx L$
$\hookrightarrow L-\Delta L \to$ depletion length due to p-n

$$\boxed{I_{sat} = \frac{\mu W C_{ox}}{2} \frac{(V_{GS}-V_T)^2}{L}}$$

long channel

(Ques)

$$I_{sat} = \frac{\mu W C_{ox}}{2}(V_{GS}-V_T)^2 \frac{1}{L-\Delta L}$$

$$\frac{1}{L}(1+\lambda V_{DS})$$

$$L' = \frac{L}{1+\lambda V_{DS}}$$

$\lambda \to$ accounts for

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

No of minority carriers

Total charge $\times$ velocity
$\to$ current

$$\frac{I}{W} = q\mu E\, Q_I(y)$$

$$\frac{I}{W} = \mu \frac{dv}{dy} Q_I(y)$$

$$\int_0^L \frac{I}{W}\,dy = \int_0^{V_{DS}} \mu\, Q_I(y)\, dV$$

(Ques) $V_T = 0.7$

$V_{DS} < V_{GS} - V_T \rightarrow$ Linear

$V_{DS} > V_{GS} - V_T \rightarrow$ sat.

V_{DS} (V)	V_{GS} (V)	
2	3	→ Linear
5	2	→ Sat
0	3	→ Linear
0	0.5	→ Cutoff / sub-threshold

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

5mA can be supported in ~~linear~~ sat regime fig. out terminal bias. $V_T = 0.7$ (with $\lambda = 0$)

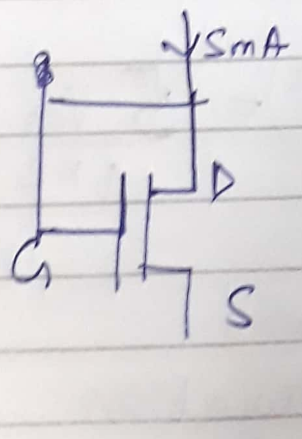
$$5 = 1\,(V_{GS} - V_T)^2\,(1 + 0)$$

$$(V_{GS} - V_T)^2 = 5$$

$V_{GS} = V_T + \sqrt{5}$

$V_{GS} = 2.236 + .7$

$V_{GS} = 2.936$



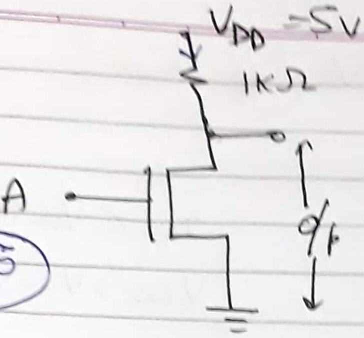
Sat

Drain & gate are shorted

$V_{DS} = V_{GS}$

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

Q)



A	o/p
0	5
5	0.75

Q5

Load → capacitive

A=0

, Sub-threshold

current = 0

Capacitive load

Assume sat. & check ur assumpt^n

$$I_{sat} = 0.5(V_{GS} - V_T)^2$$

$$I_{sat} = 0.5(4.3)^2$$

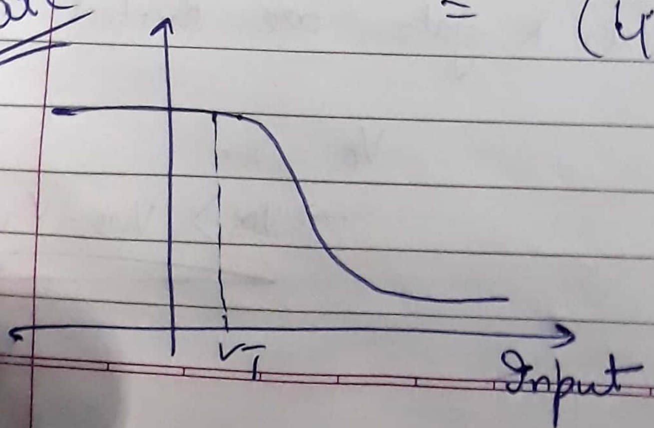
$$\frac{V_{DD} - V_{DS}}{1K} = I$$

$\not<$ sat^n

$$\rightarrow I = 1\left((V_{GS} - V_T)(V_{DS}) - \frac{(V_{DS})^2}{2}\right)$$

$$= \left(4.3V_{DS} - \frac{(V_{DS})^2}{2}\right) = \frac{5 - V_{DS}}{1K\Omega}$$

Not gate

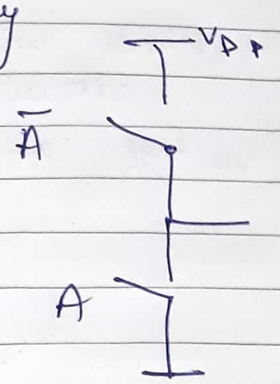


turns on in saturation region

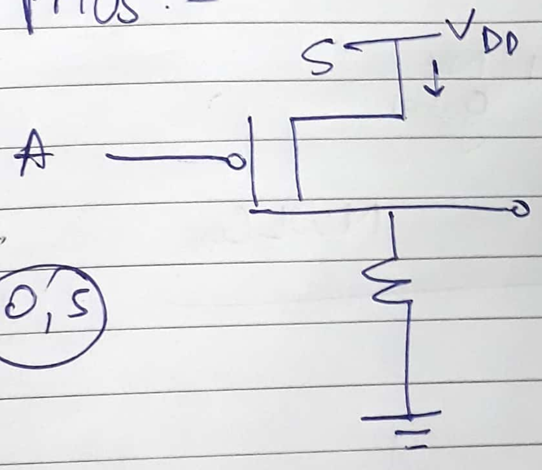
To reduce ΔV, we can increase resistance but that will increase τ of capacitor.
$\hookrightarrow \tau = RC$

So charging time will increase.

Ideally



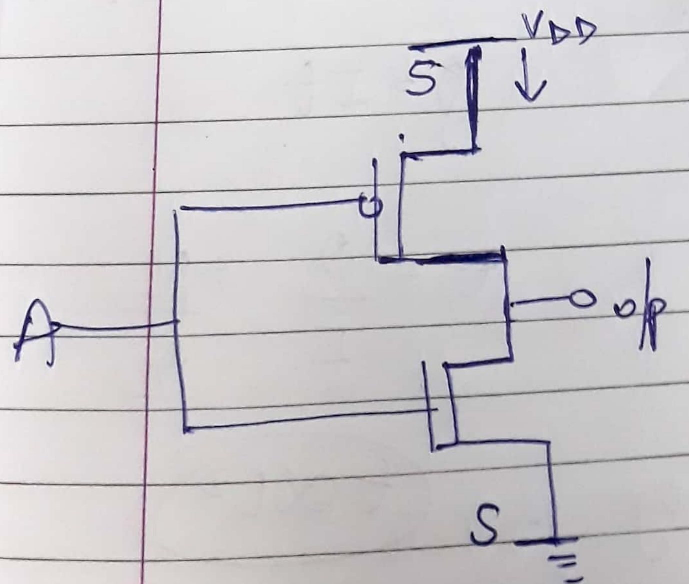
PMOS :-



(0, 5)

$V_{GS} < V_T$ for operation

when $A = 5$
$V_{GS} = 0$



PMOS coupled with N-MOS

A	O/P
5	0
0	5

At a time only one is ~~on~~

Over the steady $\rightarrow$ Only is

$A = 0$ only PMOS on

Capacitor can charge till O/P = 5V = V_{DD}

$A = 5$ NMOS on

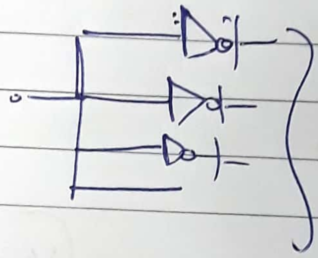
resistance in series with open circuit

$\Rightarrow$ capacitor voltage can rise to 5V. = V_{DD}

$\Rightarrow$ "No DC power loss"

Moore's law

Capacitance?



N Not gates

Capacitance = $NWLC_{ox}$

$I \propto 1/L$

Incentive to decrease Length

charging current $\uparrow$

C_{load} decrease

$Q = It$

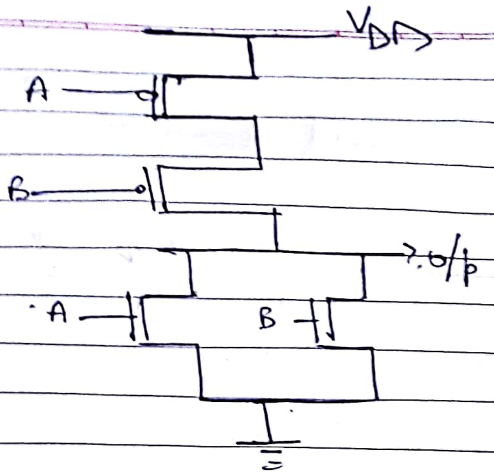
$t = \frac{Q}{I} = \frac{\beta L}{1/L}$

Charging time $\propto L^2$

as we decrease length switching time will decrease

$t \propto L^2$

Page No.



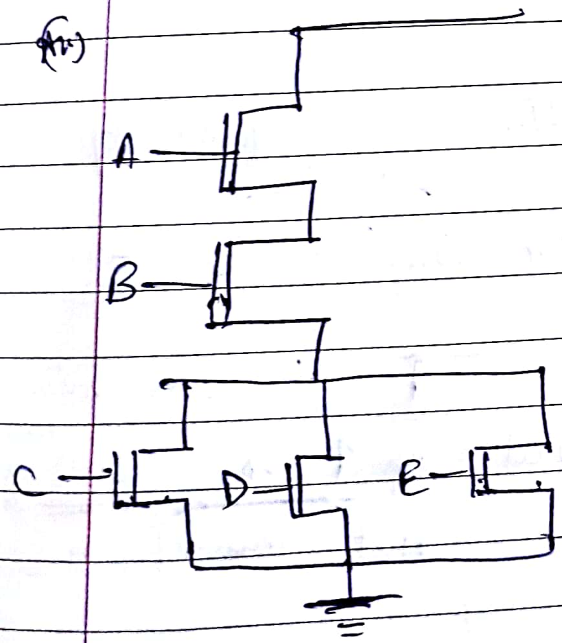
$\overline{A+B}$

A	B	o/p
0	0	5
0	5	0
5	0	0
5	5	0

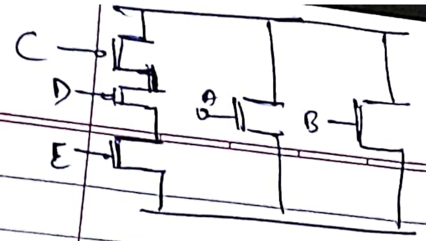
→ pmos stack is always inverted if nmos is in series

(Q) Doesn't now know pmos stack full funct^{n} & pmos stack

(Ans)



$$o/p = \overline{(C+D+E)\cdot A\cdot B}$$



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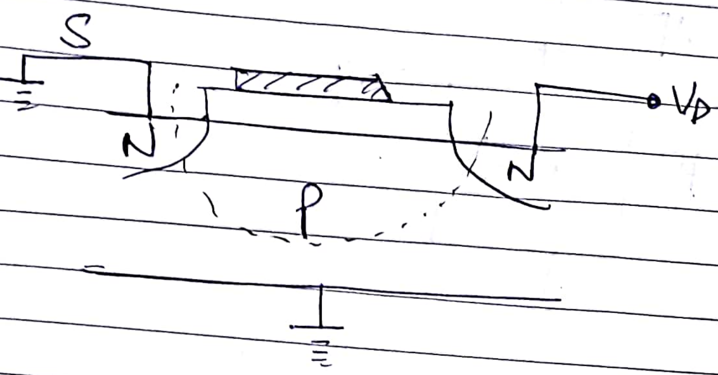
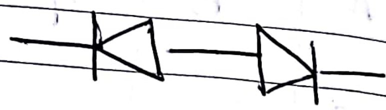
Sub-threshold



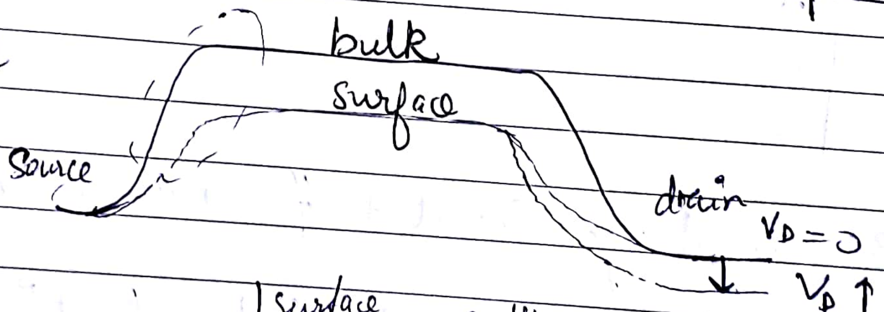
@ 0V
@ 0.3V

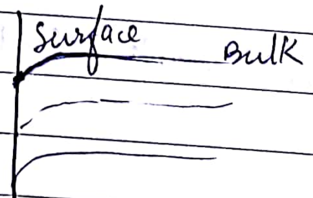
Away from SC in bulk :



~~p-n back to back~~

Case a





· As drop is in small area the drift current is very small

At $V_D = 0$, diffusion is equal & opp

$\Rightarrow \boxed{I = 0}$

diffusion cancels out

at $V_D = 0.3 \rightarrow I \uparrow$ to some value

but on $\uparrow V_D$ more (assume long channel)

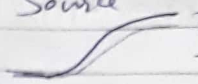
not much $\uparrow$ in I

$V_D \uparrow$

~~of diels same~~

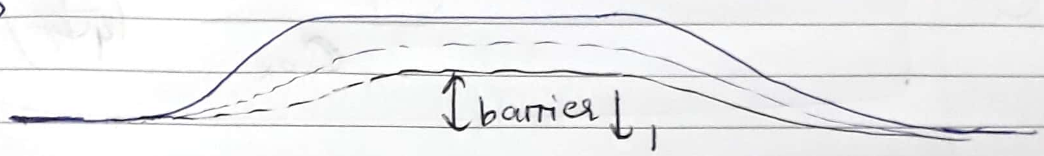
$V_D > 0$ ($V_D\uparrow$ current const^n)

diff^n from S → D, no of carriers same → I → same



V_G → const^t, $V_D\uparrow$ → I ≈ const.

$V_G\uparrow$, V_D = const^t ⇒ I↑ as barrier on right ↓



I↑ on ↑V_G

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

$$\boxed{V_G = \psi_s + \frac{(2\epsilon q N_A \psi_s)^{1/2}}{C_{ox}}}$$ (depletion region)

$$I \propto e^{\psi_{barrier}/kT}$$

$\psi_s < 2\psi_F$ (But very close to it)

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

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

Now as $\psi_s - 2\psi_F << 2\psi_F$

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

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

$$V_G - V_T = (\psi_s - 2\psi_F)(m)$$

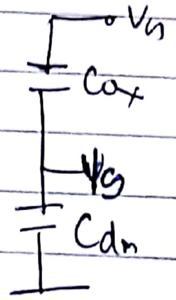
$$\star \quad \boxed{m = 1 + \frac{(2\epsilon q N_A 2\psi_F)^{1/2}}{C_{ox}} \left(\frac{1}{4\psi_F}\right)}$$

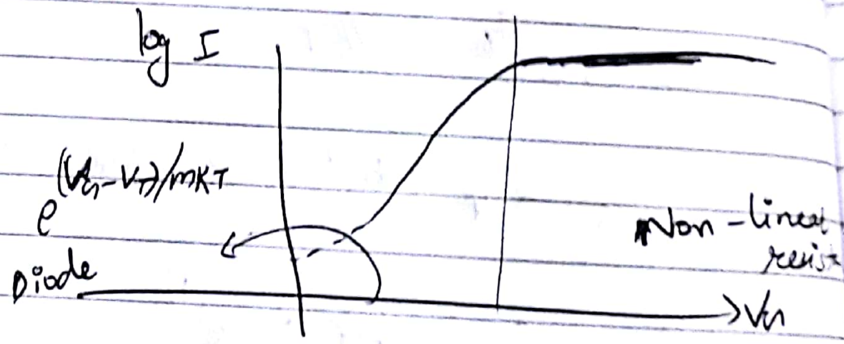
(R) $\star\star$
$$\boxed{\begin{aligned} V_G - V_T &= (\psi_s - 2\psi_F)(1+m) \\ m &= \frac{(2\epsilon q N_A 2\psi_F)^{1/2}}{C_{ox}} \left(\frac{1}{4\psi_F}\right) \end{aligned}}$$

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

$$I \propto e^{(V_G - V_T)/mKT}$$

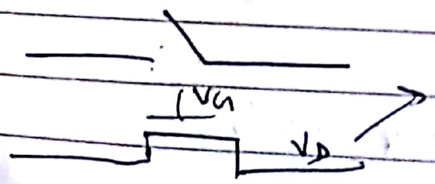
m ≃





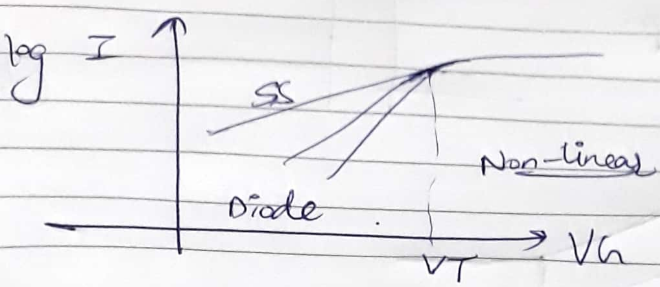
$\star$ Subthreshold slope (SS) = $\left(\dfrac{d\log(I)}{dV_G}\right)^{-1}$

~ 60mV/decade



V_D will always be there in a circuit, hence some I will be there as band is

∴ we want to lower SS

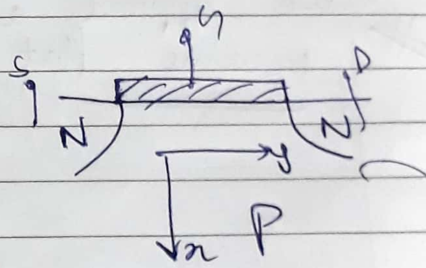


L#

NON-Ideal MOS

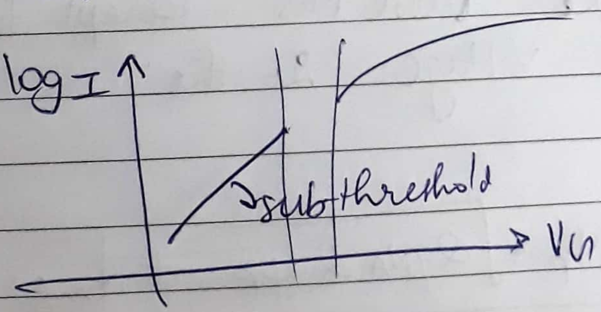
① I_D, NMOS, $V_T = 0.7V$, $V_{DS} = 0.5V$, $V_{GS} = 0.7V$

② $Q_I = C_{ox}(V_G - V_T - V(y))$



at $V_G = V_T$ we don't have any current

exp.ⁿ

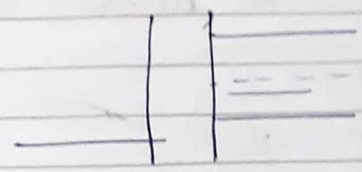


at drain the "diode" has larger depletion region

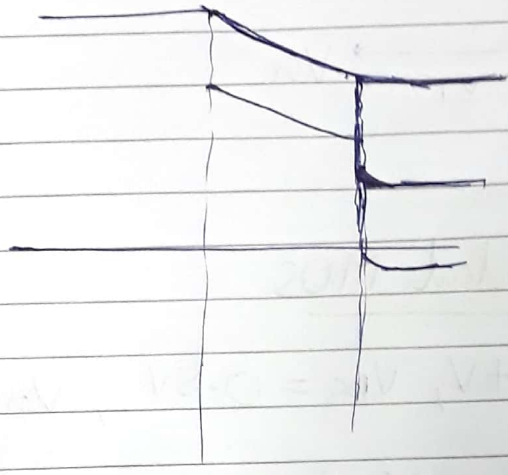
while at source the depletion region is very small ($V=0$)

eqⁿ

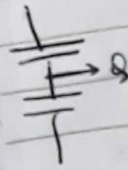
ϕ_m:- for moscap:



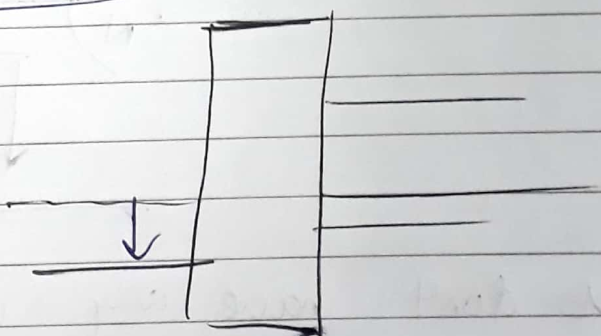
$\phi_{ms} = \phi_m - \phi_s$
$= 0$
(for ideal)



$250 USD

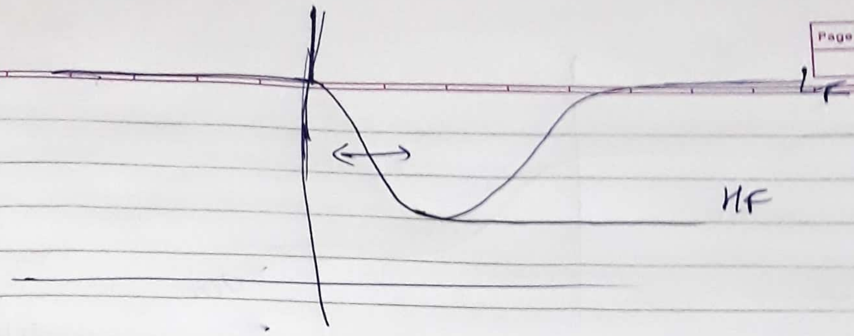


• we applied a gate biased such that the bands became flat

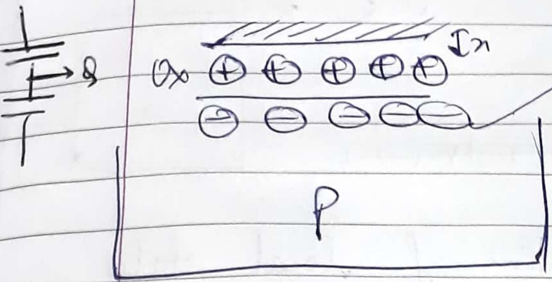


So now this is just like ideal MOS except for the add^N/extra voltage so the exp^N of V_T

for non-ideal $V_T = 2\psi_F + \sqrt{2qN_A 2\psi_F} + \phi_{ms}$



Everything will be parallely shifted (left/Right)



charge in SC | charge → depletion
↳ depletion + inversion

this could even cause inverse (depending on strength)

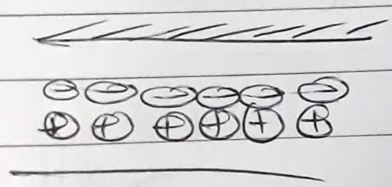
So

V_T is always going to be lower than earlier

what voltage we should apply to make it flat-band.

Electric field: $\boxed{\frac{-\sigma}{\epsilon} x = \Delta V_{T}}$

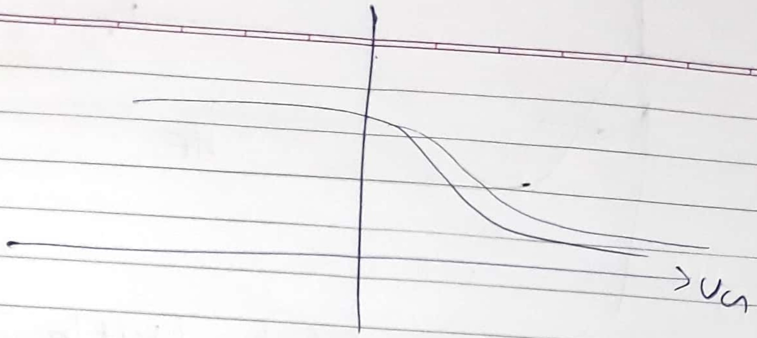
$$V_{FB} = -\int_0^{t_{ox}} \frac{\sigma \cdot x}{\epsilon_{ox}} \, dx$$ for a distⁿ



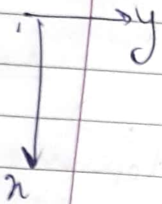
} total charge = 0

parallel shift → static charge (immobile ion)

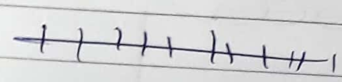
If charges are mobile → ions
as we sweep V_G → stretch out

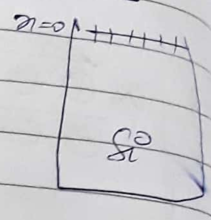


There are gonna be many dangling bonds (unsatisfied)



at $x=0$



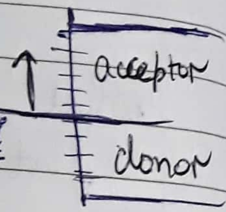


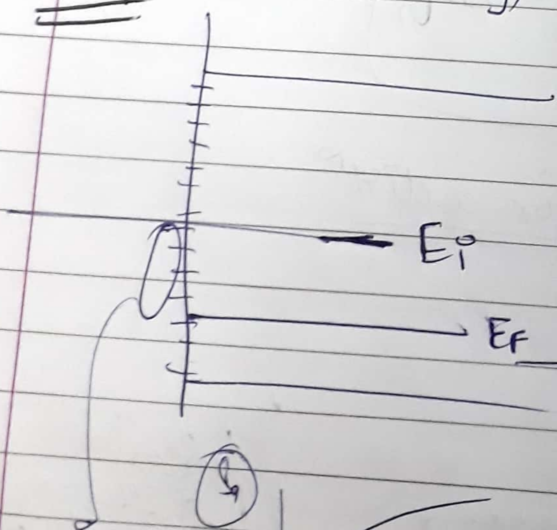
dangling bonds lead to formation of local state

Types of trap

Trap site :	Empty	Filled
donor	+ive (initially)	0
acceptor	0 (initially)	-ive

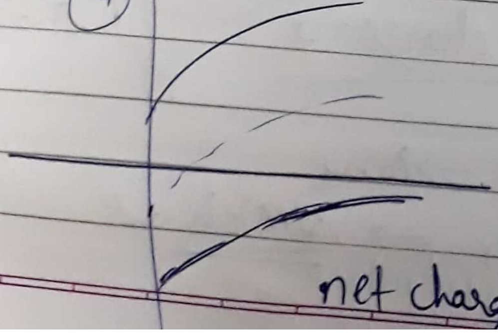
trap state





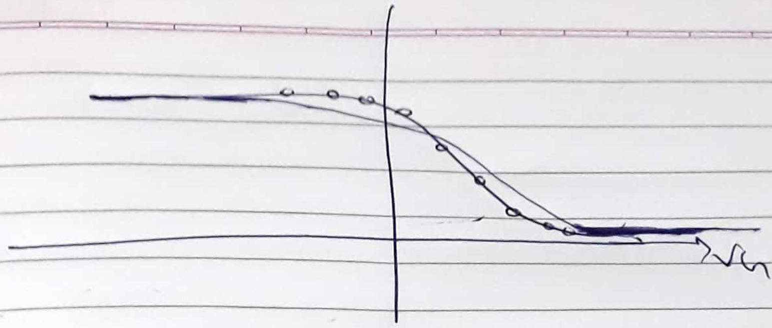
upto fermi-level the state should be filled

below E_F all be filled

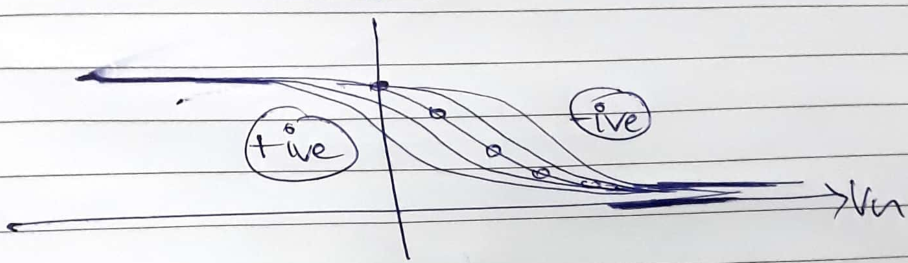


E_i crosses E_F → all donors will be occupied & even

net charge → -ive charge



for immobile charges



all we increase $V_G \rightarrow$ the charge will change & we get a curve somewhat b/w ⊕ & ⊖ive immobile charge.