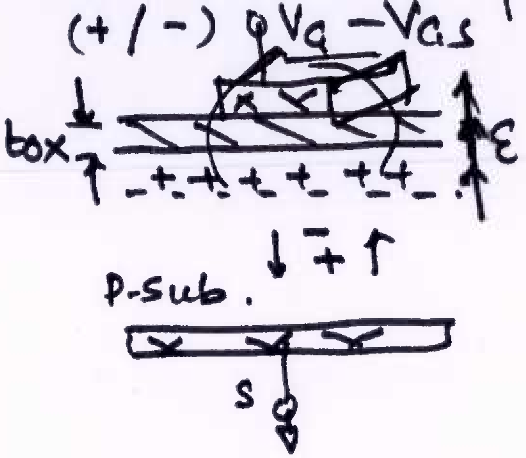
MOS Capacitor is a simple device which can be used to evaluate almost all electrical properties of SiO_2 - Si system.



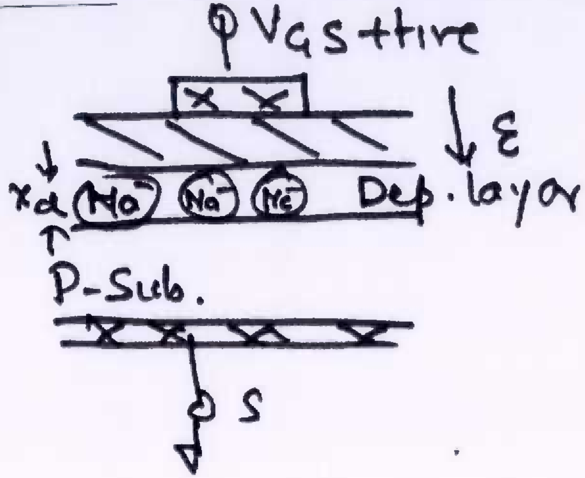
$\epsilon = K\epsilon_0$

(i) V_{GS} is −ve (Accumulation Mode)

Electrons are repelled from SiO_2-Si interface. This creates excess holes at that place. Thus interface accumulates holes (+tive charge. $-Q_m$ at the metal = Q_{Si} at Surface (Gauss's law $Q_m + Q_s = 0$)

The capacitor has now like metal-oxide-metal structure with $C = C_{ox} \cdot A$ where $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$ F/cm²

(ii) V_{GS} is +tive but Small (Depletion Mode



In getting Gauss's law statement, we assume here that there are no Charges in Oxide and hence $\epsilon_{ox}\mathcal{E}_{ox} = \mathcal{E}_s \epsilon_s$ (D is Continuous) is followed.

E

With V_{GS} small positive, we have Q_m + & small. Gauss's law not want -ve charges to reach surface of Silicon. Direction of Electrical field forces holes to move downwards leaving -ve Acceptor Ions at Si-Surface. That is surface region gets depleted of free Carriers, and one observes Depletion Region. The depletion width $\propto \sqrt{V_{GS}}$ $= -qN_a x_d$

$\propto 1/\sqrt{N_a}$ $\quad x_d = \sqrt{\frac{2K_s\epsilon_0\psi_s}{qN_a}}$

Initially due to small V_{GS}, Electric field $\mathcal{E}_s$ is also small. Hence Generation of e-h pair in D.Layer, finally recombine there it self.

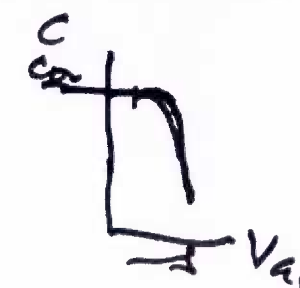
We have now two capacitors in series

$C_{ox} \cdot A = C'_{ox}$ Hence net $C = \dfrac{C'_{ox} C'_s}{C'_{ox} + C'_s}$

$C_s \cdot A = C'_s$

obviously net C now will be less than C'_{ox} as was observed in Accumulation case.

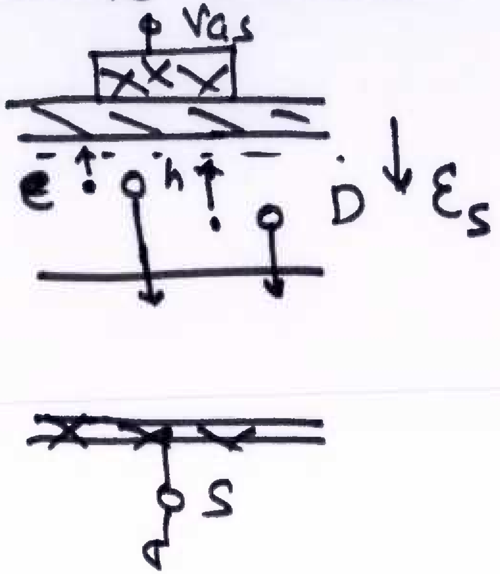
Hence increase in $+V_{GS}$ will decrease C_s as depletion width will enhance. This means C_{net} will decrease further with V_{GS} increasing.



iii) V_{GS} Positive and large (Inversion)

At some reasonably high V_{GS}, Electric Field in Semiconductor region becomes sufficiently high, that is $\mathcal{E}_s$ become large enough, then generated electron-hole pairs experience large force and they separate. Holes move along the field come out of Depletion layer and are collected at Sub-ground

While electrons more towards surface. The

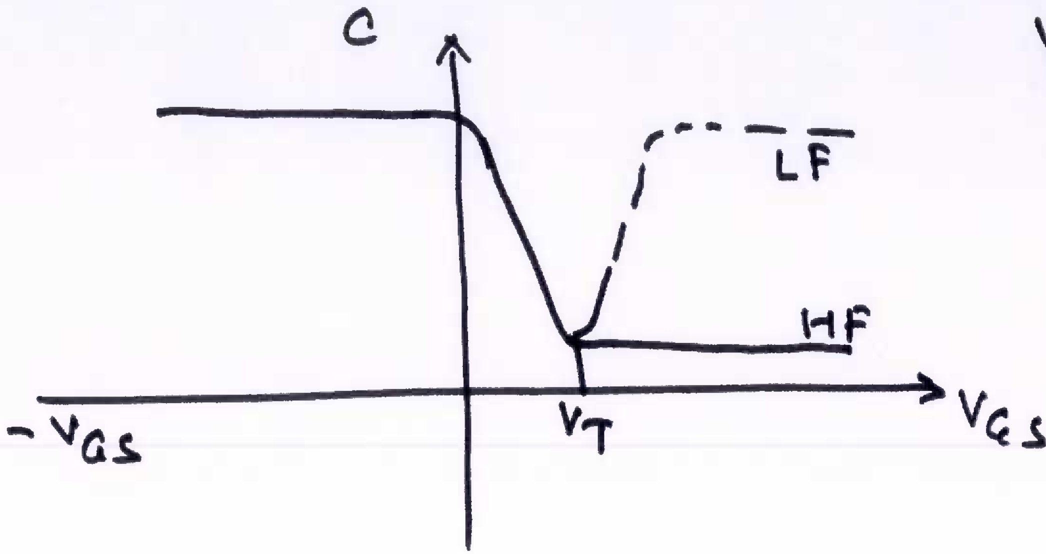


starting wafer has p-type doping, so without Bias Silicon Surface was ptype with hole conc. = N_a^-

However now electrons start Piling up at Si-Surface opposite to starting case (hole conc.). This case is called Inversion.

Since excess V_{GS} now creates free inversion electrons, Depletion layer remains constant and hence net Capacitor also becomes const independent of V_{GS}.

The value of V_{GS} (Positive for P-sub), at which inversion electron Conc. n is equal to starting p-conc, is called Threshold Voltage V_T.



$V_{GS} = V_{ox} + \psi_S$ ↑

CDEEP
IIT Bombay

Ideally $\quad V_T = \pm 2\phi_F - \dfrac{\pm Q_{Bulk}}{C_{ox}}$

where Q_{Bulk} is Depletion charge density

$= + q N_d^{+} x_{dmax}$

or $\quad = - q N_a^{-} x_{dmax}$

and $q\phi_F$ is Fermi Energy & $\phi_F = \pm \dfrac{kT}{q} \ln \dfrac{N_a \,(\text{or } N_d)}{n_i}$

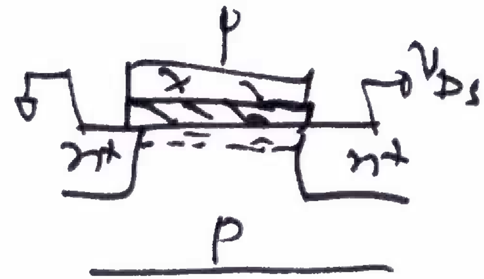
$= E_i - E_F$

In real life

$$V_T = \phi_{ms} \pm 2\phi_F - \frac{Q_{ox}}{C_{ox}} - \frac{\pm Q_B}{C_{ox}}$$

$\phi_{ms} = \phi_m - \phi_s$ Work function Difference between Metal & Semiconductor

Q_{ox} = Fixed Oxide Charge (Always Positive)

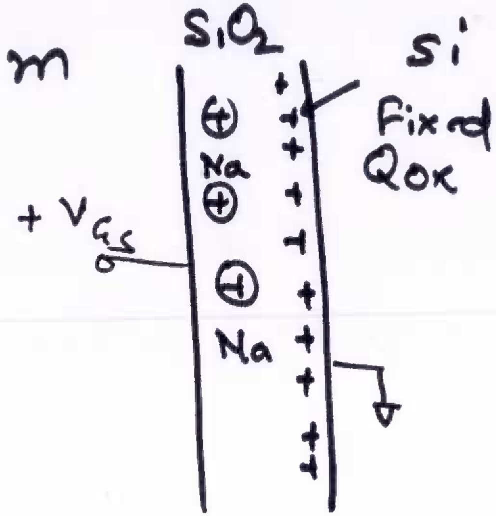


ϕ_F = Fermi Potential $= \frac{E_i - E_F}{q}$

Mos Sat current =>

$$I_{Dsat} = \frac{1}{2}\mu C_{ox}\left(\frac{W}{L}\right)\left[(V_{GS}-V_T)^2\right]\left[1+\lambda V_{DS}\right]$$

Fixed Charge Q_{ox} :—



SiO_2

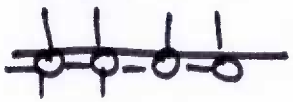
Within 25 Å of Si-SiO_2 surface, we observe that a +tive charges exist and their Density is almost constant. This Charge Density Q_{ox} (q/cm^2) is attributed to fact that at the end of oxidation time, interface proximity leaves incomplete oxidation and may end up in $Si^{3+}-O$ bonds, which results in Fixed Positive charge. $Q_{ox\,Fixed} \simeq q \cdot (10^{10} - 10^{11})$ col./cm^2

Mobile Charge :— Sodium ions (Na^+) are omnipresent in SiO_2 and they can drift in Oxide under electric field. Mobile charge density Q_{Mobile} is varying function

Interface Charge

Any Solid Surface, leaves dangling bonds which are not satisfied.

D.B.



Silicon Surface too, howsoever cleaned (Virgin surface), also have these Dangling Bonds present. These are called Schokley or Tamn States. The number of Such States could be as high $10^{20}/cm^2$

During Oxidation of Silicon, Oxygen tries to Bond with Silicon through these bonds, reducing their charge density. However not all bonds are Satisfied and leaves interface charge density of the order of $q \cdot \times (10^{10} - 10^{11})$ col/cm². Number Density is termed Dit

$\therefore$ Qit = q · Dit.

Influence of Interface charges of MOS Device characteristics.

For a MOS Capacitor (or MOS Transistor) the threshold voltage V_T is given by

$$V_T = \phi_{ms} \pm 2\phi_F - \frac{Q_{ox} + Q_{it} + Q_m}{C_{ox}} - \frac{\pm Q_{Bulk}}{C_{ox}}$$

where $\phi_{ms} = \phi_m - \phi_s$

$$Q_{Bulk} = \pm q\,(N_a \text{ or } N_d)\, x_{dmax}$$

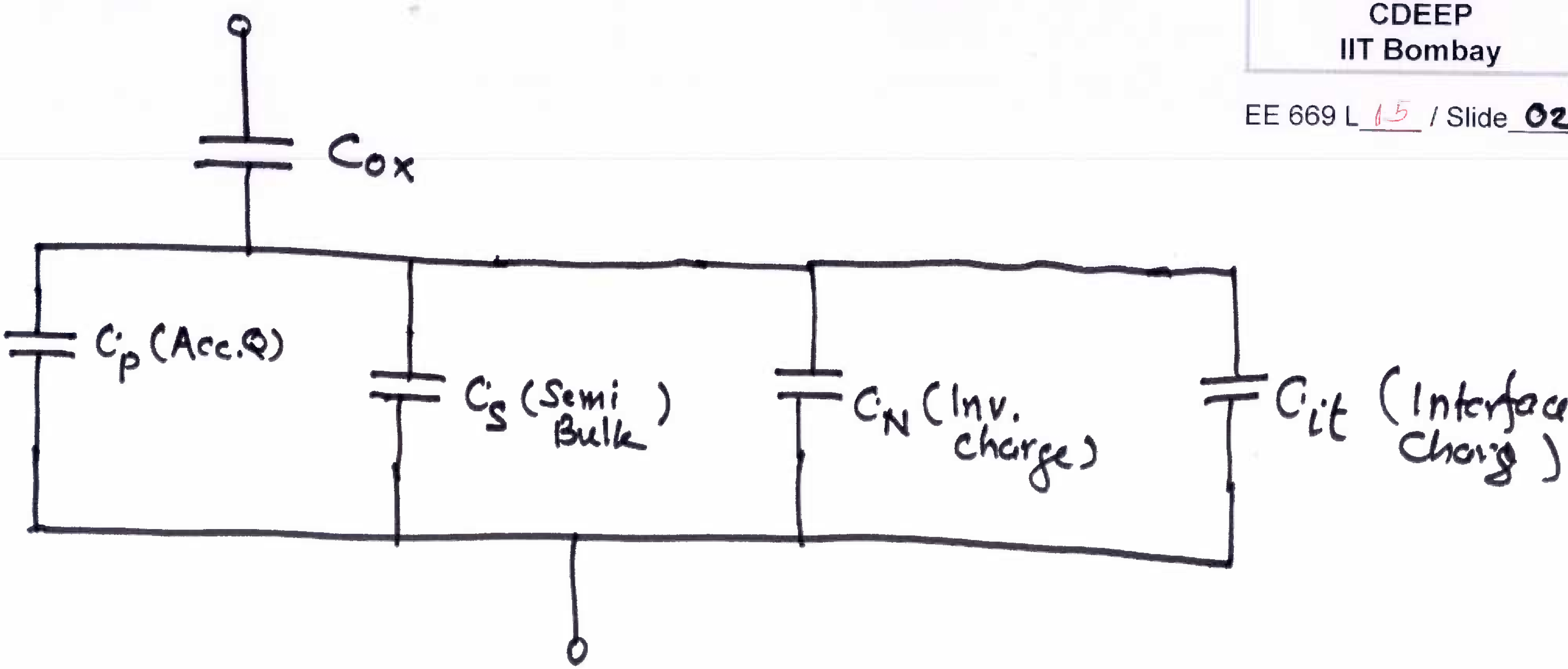
$$2\phi_F = 2 \cdot \text{Fermi Potential} = \frac{2kT}{q} \ln \frac{N_a (\text{or } N_d)}{n_i}$$

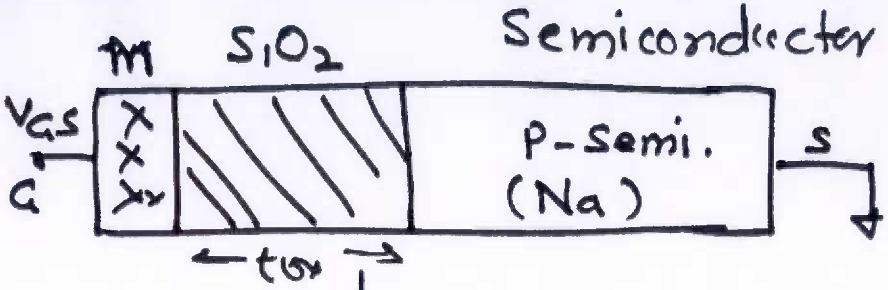
$$x_{dmax} = \sqrt{\frac{2 K_s \epsilon_0 \psi_s}{q N_a (\text{or } N_d)}}$$

ψ_s = is Surface Potential and is $= 2\phi_F$ at Inversion

Typical Equivalent Circuit of a MOS capacitor can be :

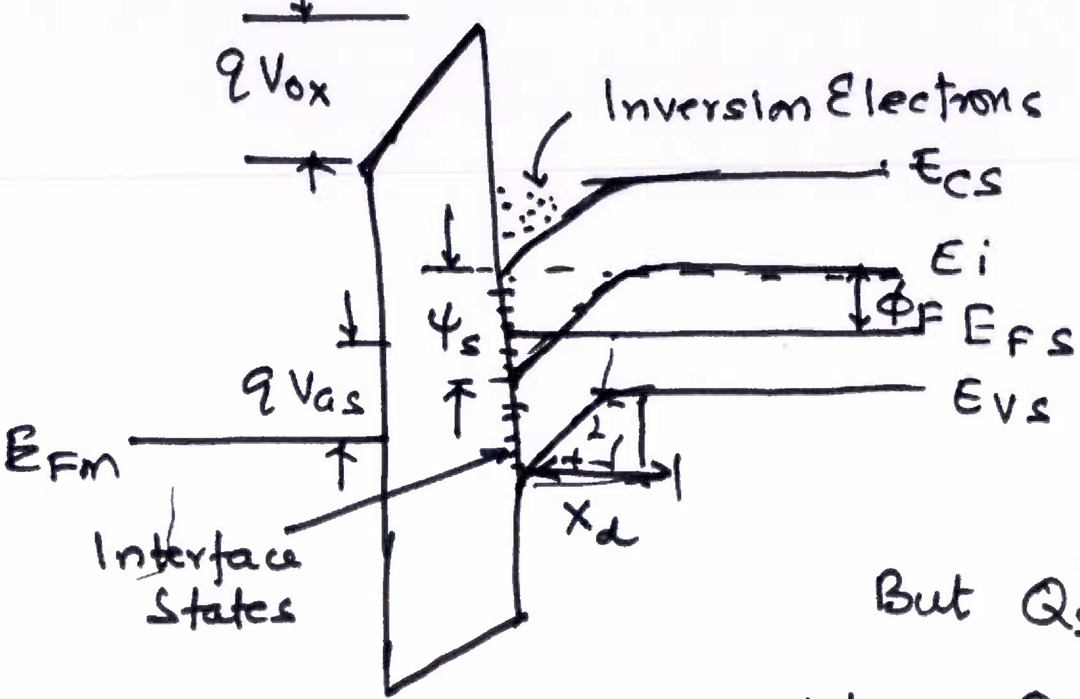
We define $C = \frac{dQ}{dV_{GS}}$, Then C is →





$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$



We know

$$C = \frac{dQ}{dV} \quad \begin{cases} Q - \text{Charge}/cm^2 \\ C = F/cm^2 \end{cases}$$

$$C_{ox} = \frac{dQ_G}{dV_{GS}}$$

But $Q_s' = -Q_G - Q_B$ = Interface charge

where Q_G is Gate Charge density

or $Q_G = -(Q_s' + Q_B) = -(Q_s' + Q_B)$

$$V_{GS} = V_{ox} + \psi_s$$

But if D is continuous

$$\epsilon_s \mathcal{E}_s = \epsilon_{ox} \mathcal{E}_{ox} \quad \text{or} \quad \epsilon_s \mathcal{E}_s = \frac{\epsilon_{ox} V_{ox}}{t_{ox}}$$

or $V_{ox} = \frac{\epsilon_s \mathcal{E}_s}{\epsilon_{ox}/t_{ox}} = \frac{\epsilon_s \mathcal{E}_s}{C_{ox}}$

But $Q_s = -\epsilon_s \mathcal{E}_s$ By Gauss's Law

$\therefore V_{ox} = -\frac{Q_s}{C_{ox}}$

$\therefore V_{GS} = \psi_s - \frac{Q_s}{C_{ox}}$

At $V_{GS} = V_T$ $\quad \psi_s = 2\phi_F$

$\therefore V_T = 2\phi_F - \frac{Q_s (\equiv Q_B)}{C_{ox}}$

Where $Q_s = Q_B$ = Depletion Charge density

$= +qN_d^+ x_{dmax} \rightarrow$ n-Sub

$= -qN_a^- x_{dmax} \rightarrow$ P-Sub

or $V_{Tn} = 2\phi_F + (qN_a x_{dmax}/C_{ox})$