EE 207. MOS Capacitor CV characteristics ①

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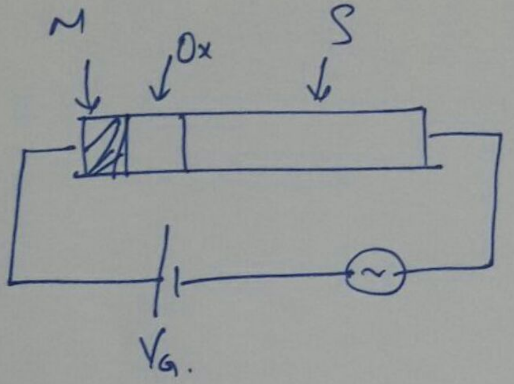
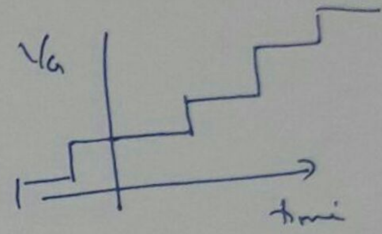
The discussion on MOS electrostatics helped us to identify different regimes of operation. Now we will see how the system responds to an applied small signal AC. The system under consideration is

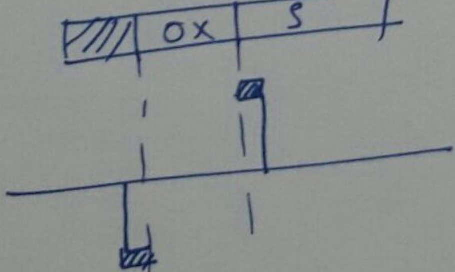




Assumptions
- V_G is increased very slowly
- The system is under steady state
- No DC current / leakage through oxide.

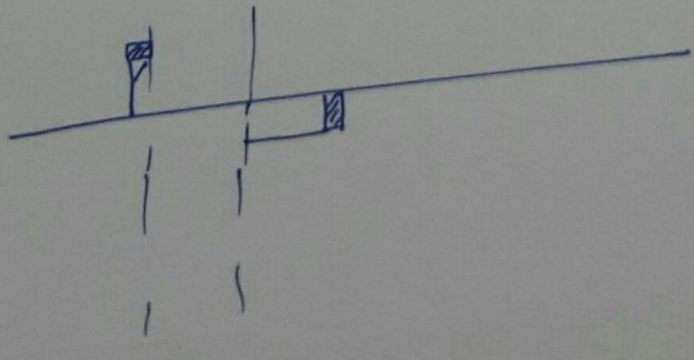
For a small signal AC, the charge ~~distributions~~ that modulate in response is as shown below

~~Accumulat~~

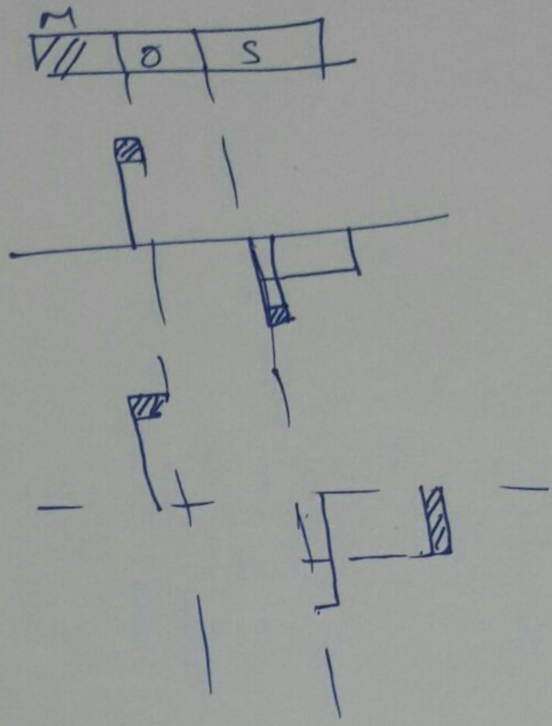


Accumulation

Depletion



For inversion, there can be two scenarios ②



Small frequency

high frequency

As evident from the charge distribution plots we get the following weights

$C = C_{ox}$ ← Accumulation

$C^{-1} = C_{ox}^{-1} + C_S^{-1}$ Depletion

where $C_S = \varepsilon_s / W_{depletion}$

$C = C_{ox}$ Inversion, ω very small

$C^{-1} = C_{ox}^{-1} + C_{s,min}^{-1}$ Inversion $\omega \to \infty$

$C_{s,min} = \dfrac{\varepsilon_s}{W_{depletion,max}}$

Hence the system is nothing but a series connection of C_{ox} & C_s.

How to estimate W?

we know that $Q_d = qN_A W$.

$= (2\varepsilon q N_A \psi_s)^{1/2}$.

$$\Rightarrow \quad W_{depletion} = \left[\frac{2\varepsilon}{q}\left(\frac{1}{N_A}\right)\psi_s\right]^{1/2}. \quad (\psi_s < 2\psi_F)$$

$$W_{depletion,max} = \left[\frac{2\varepsilon}{q}\frac{1}{N_A}\cdot 2\psi_F\right]^{1/2}. \quad \left(\text{ie, when } \psi_s = 2\psi_F\right)$$

Now the capacitance at Flat band conditions

we have from Poisson eqn

$$\varepsilon\frac{d^2\psi}{dx^2} = -q(p-n-N_A) \qquad p = N_A e^{-q\psi_s/kT}$$

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

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

$$\approx -q\left[N_A\left(1 - q\psi_s/kT \cdots\right) - \frac{n_i^2}{N_A}e^{q\psi_s/kT} - N_A\right]$$

$$\varepsilon\frac{d^2\psi}{dx^2} \approx \frac{q^2 N_A}{kT}\psi_s.$$

$$\frac{d^2\psi}{dx^2} = \frac{q^2 N_A \psi}{\varepsilon kT} \Rightarrow \text{characteristic length.}$$

$$L_D = \left[\frac{\varepsilon kT/q}{qN_A}\right]^{1/2}.$$

Hence the capacitance at flat band condition is

$$C_s = \frac{\varepsilon_s}{L_D}$$

We could arrive this by alternate argument

$$Q^2 = 2q\varepsilon \int_0^{\psi} (p-n-N_A)\, d\psi = 2q \int_0^{\psi} \left(N_A e^{-q\psi/kT} - \frac{n_i^2}{N_A} e^{q\psi/kT} - N_A\right) d\psi$$

$$Q^2 \approx 2q\varepsilon \left[-\frac{N_A (e^{-q\psi/kT} - 1)}{kT/q} - N_A \psi \right].$$

$$Q^2 \approx 2q\varepsilon \left[-N_A \left[-\psi + \left(\frac{q}{kT}\right)\frac{\psi^2}{2} \right] - N_A \psi \right].$$

$$Q^2 \approx \frac{\varepsilon q^2 N_A}{kT/q} \psi^2.$$

$$\Rightarrow \quad Q = \left[\frac{\varepsilon q N_A}{kT/q}\right]^{1/2} \psi. \quad \text{Since } Q = C_s \psi.$$

$$\Rightarrow \quad C_s = \left[\frac{\varepsilon q N_A}{kT/q}\right]^{1/2} = \varepsilon_s / L_D \Rightarrow$$

$$\Rightarrow \quad L_D = \left[\frac{\varepsilon\, kT/q}{q N_A}\right]^{1/2}$$

Typically, for $N_A = 10^{16}$, $\varepsilon = 11.8 \times 8.854 \times 10^{-14}$

$$L_D = \left[\frac{11.8 \times 8.85 \times 10^{-14} \times 25 \times 10^{-3}}{1.6 \times 10^{-19} \times 10^{16}}\right]^{1/2}$$

$\approx \underline{40 \times 10^{-7}\ \text{cm}}$ or $\underline{40\ \text{nm}}$. Hence $C_{FB}^{-1} = C_{ox}^{-1} + C_s^{-1}$

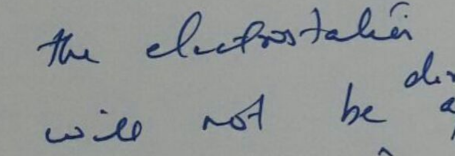
will be different from C_{ox}.

Other interesting points

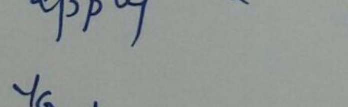
(A) The inversion layer consist of minority carriers. The source of such minority carriers is the thermal generation of carriers within the depletion region

(B) If the applied bias is changed too quickly the inversion layer might not form/respond. This explains why HF capacitance is different from LF capacitance.

(C) If the DC voltage (V_G) is changed too rapidly the electrostatics described in previous section will not be directly applicable. For example let us apply a step voltage as the gate potential.



At time $t = t_0$, $V_G > V_T$ is applied. This will ~~take at~~ instantaneously create a depletion width W, while the inversion layer might take a while to build up. So we have



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

$$Q_s = (2\epsilon_s N_a \psi_s)^{1/2}$$

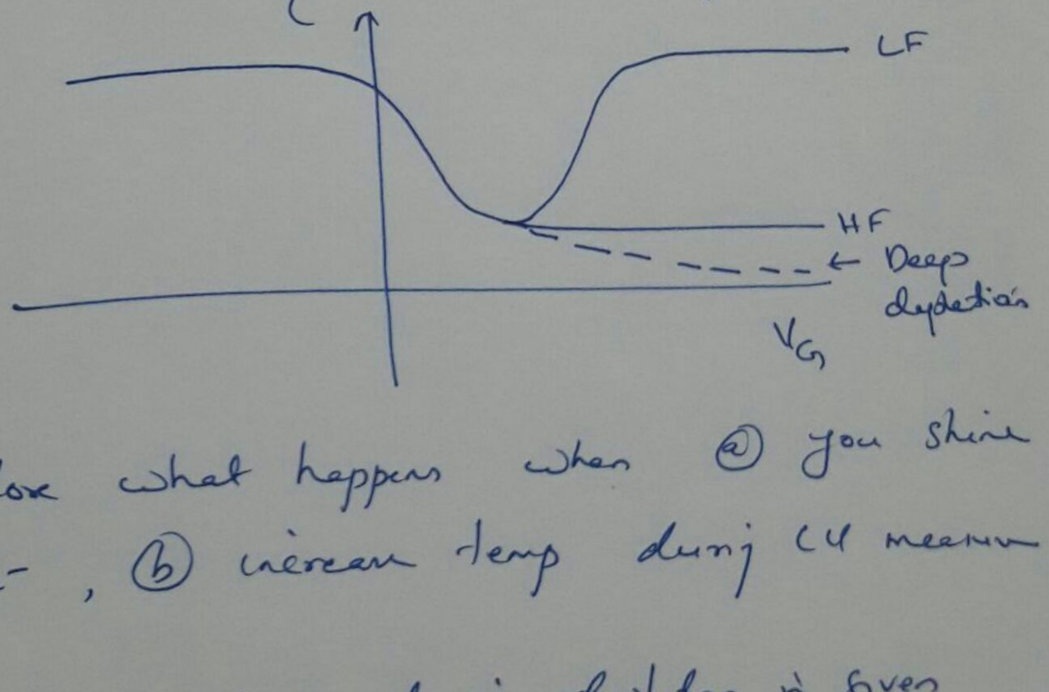
$$V_g = \psi_s + \frac{(2\epsilon_s N_a \psi_s)^{1/2}}{C_{ox}}$$

* Solve for ψ_s and then estimate W. ~~Compare with~~

Compare ψ_s and W with $2\psi_F$ and $\left(\frac{2\varepsilon}{q}\frac{1}{N_A}2\psi_F\right)^{1/2}$ (b)

(c) Estimate the time taken for the deep inversion region to build up [Hint: Use SRH R-G in the depletion region].

(D). The C-V with such a fast DC V_G bias will be different from that of HF & LF CV that we saw earlier. Based on the previous discussion, it is evident that W could be different (i.e., larger) from $W_{depletion,max}$ and hence the capacitance will be lower (known as Deep depletion CV).

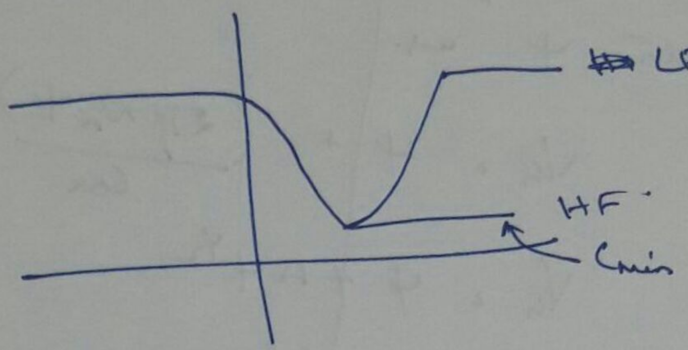


(E). Explore what happens when (a) you shine light, (b) increase temp during CV measurement

(F) The capacitance during depletion is given by
$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{W}{\varepsilon}$$
$$= \frac{1}{C_{ox}} + \frac{1}{\varepsilon}\left(\frac{2\varepsilon}{q}\frac{1}{N_A}\psi\right)^{1/2}$$

See whether a relation similar to Mott-Schottky can be obtained for MOS Capacitor.

(G). How to characterize various parameters like t_{ox}, N_A given CV characteristics?



(*) C_{ox} can be estimated from Accumulation and hence t_{ox}.

(*) C_{min} can be used to estimate N_A

$$\frac{1}{C_{min}} = \frac{1}{C_{ox}} + \frac{W_{depletion,max}}{\varepsilon_{si}}$$

$$= \frac{1}{C_{ox}} + \frac{\left(\frac{2\varepsilon}{qN_A} \cdot 2\psi_F\right)^{1/2}}{\varepsilon_{si}}$$

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

An iterative scheme will provide N_A.

(*) Now estimate Flat band capacitance and the corresponding voltage. ~~at which FB capacit~~ this will indicate the presence of any trapped charges in oxide.

(H) Non-idealities in MOS will be discussed later.