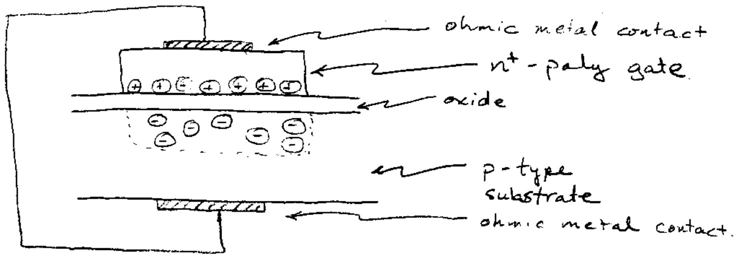
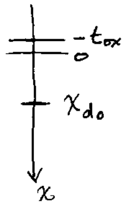
Tutorial #3 10/2/2000 & 10/3/2000

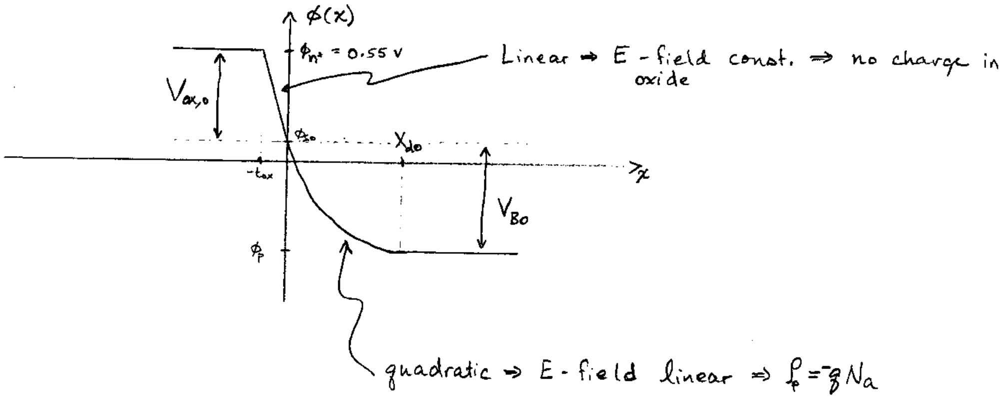
MOS Capacitor in thermal equilibrium:





What is happening in thermal equilibrium?

- ϕ_{n^+} poly is 0.55 volts.
- ϕ_p substrate has some potential that can be solved w/ 60mV rule.
- since $\phi_{n^+} \neq \phi_p$, there is a potential difference going from the poly to the substrate.
- This potential difference gives rise to E-field in the oxide and the depletion region of the p-substrate.
- Since there is an E-field, there must be non-zero charge densities.
- In the p-substrate, there is a portion depleted of mobile carriers (holes) near the Si-SiO$_2$ interface. There are N_a^- in this depletion region, giving rise to the negative charge there.
- The negative charge in the depletion region is matched by positive charged in the poly right at the poly-SiO$_2$ interface
- The size of the depletion region in TE depends on the doping (N_a) and the thickness of SiO$_2$.



$$Q_{Bo} = -Q_{Go} = -q N_a X_{do}$$

$$V_{ox,o} + V_{Bo} = \phi_{n+} - \phi_p$$

Boundary condition at oxide-Si interface: $\epsilon_{ox} E_o(x=0^-) = \epsilon_{si} E_o(x= \ )$

$$E_o(0^+) = \frac{-Q_{Bo}}{\epsilon_{si}} = \frac{q N_a X_{do}}{\epsilon_{si}} \qquad E_{ox} = E_o(0^-) = \frac{q N_a X_{do}}{\epsilon_{ox}}$$

valid for $-t_{ox} \le x \le 0$

$$E_o(x) = \frac{q N_a (x_{do} - x)}{\epsilon_{si}} \quad \text{for } 0 \le x \le X_{do}$$

$$\phi_o(x) = \phi_{n^+} - \frac{q N_a X_{do}}{\epsilon_{ox}}(x + t_{ox}) \quad \text{for } -t_{ox} \le x \le 0$$

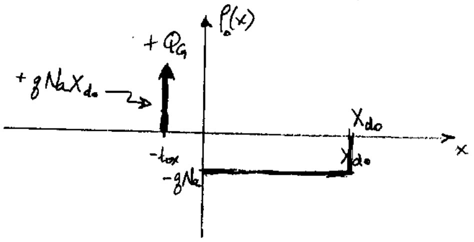
$$\phi_o(0) = \phi_{so} = \phi_{n+} - q N_a X_{do} \frac{t_{ox}}{\epsilon_{ox}} = \phi_{n^+} - \frac{q N_a X_{do}}{C_{ox}} \quad \text{where } C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

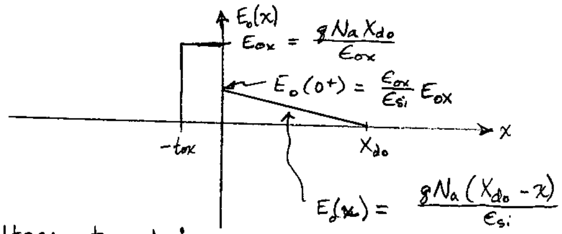
$$V_{ox,o} = \phi_{n+} - \phi_{so} = \frac{q N_a X_{do}}{C_{ox}} = \frac{Q_{Go}}{C_{ox}}$$

$$\phi_o(x) = \phi_{so} - \frac{q N_a}{\epsilon_{si}}\left(X_{do} x - \frac{x^2}{2}\right) \quad \text{for } 0 \le x \le X_{do}$$

$$\phi_o(X_{do}) = \phi_{so} - \frac{q N_a X_{do}^2}{2\epsilon_{si}} = \phi_p \Rightarrow \phi_{n+} - \phi_p = \frac{q N_a X_{do}}{C_{ox}} + \frac{q N_a X_{do}^2}{2\epsilon_{si}}$$

$$X_{do} = t_{ox}\left(\frac{\epsilon_{si}}{\epsilon_{ox}}\right)\left(\sqrt{1 + \frac{2 C_{ox}^2(\phi_{n^+} - \phi_p)}{q \epsilon_{si} N_a}} - 1\right)$$





Now apply voltage to gate:

Regions of MOS-C operation: (For p-type substrate)

- accumulation ($V_{GB} < V_{FB}$)
- depletion ($V_{FB} < V_{GB} < V_T$)
- inversion ($V_T < V_{GB}$)

Other conditions

- Flatband ($V_{GB} = V_{FB}$)
- Onset of Inversion ($V_{GB} = V_T$)

Flatband Condition when there is no E-field or charge through device.

$$V_{GB} = V_{FB} = -(\phi_{n+} - \phi_p)$$

When $V_{GB} < V_{FB}$: (Accumulation Region)

- gate is negatively charged.
- holes accumulate at $SiO_2 - Si$ boundary. $\phi_s \approx \phi_p$

When $V_{FB} < V_{GB} < V_{Tn}$: (Depletion Region).

- gate has positive charge.
- matched by immobile charge (N_a^-) in depletion region.

$$X_d(V_{GB}) = t_{ox}\left(\frac{\epsilon_{si}}{\epsilon_{ox}}\right)\left(\sqrt{1 + \frac{2C_{ox}^2(V_{GB} - V_{FB})}{q\epsilon_{si}N_a}} - 1\right)$$

$$\phi_s(V_{GB}) = (V_{GB} + \phi_{n+}) - \frac{qN_aX_d(V_{GB})}{C_{ox}}$$

Onset of inversion when X_d no longer grows with V_{GB} increase. The positive charge on gate due to V_{GB} increase no longer matched by acceptor atoms in depletion region, but by electrons at the surface. This happens when $\phi_s = -\phi_p$ ($n_s = p_0$).

$$X_{d,max} = \sqrt{2\frac{\epsilon_{si}}{qN_a}(-2\phi_p)}$$

$$V_B = \frac{qN_a}{2\epsilon_{si}}X_{d,max}^2 = -2\phi_p \qquad \varphi_{B,max} = -qN_aX_{dmax} = -\sqrt{2\epsilon_{si}qN_a(-2$$

$$V_{ox} = \frac{-\varphi_{B,max}t_{ox}}{\epsilon_{ox}} = \frac{1}{C_{ox}}\sqrt{2q\epsilon_{si}N_a(-2\phi_p)}$$

$$V_{GB} - V_{FB} = V_B + V_{ox}$$

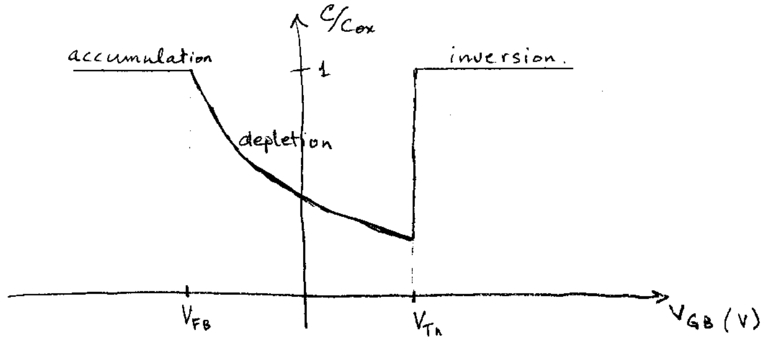
At threshold, $V_{GB} = V_{Tn}$

$$V_{Tn} - V_{FB} = V_B + V_{ox} \Rightarrow V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2q\epsilon_{si}N_a(-2\phi_p)}$$

When $V_{GB} > T_{Tn}$: (Inversion Region).

$$\underset{\uparrow \text{ inversion charge.}}{Q_n} = -C_{ox}(V_{GB} - V_{Tn})$$

Capacitance of MOS Structure:
(p-type):



- For accumulation & inversion, the incremental charge is being added on either side of oxide.
- For depletion region, the incremental charge is added by growth of depletion region far from the oxide interface.