6.012 R#9. MOS capacitors

Last time we discussed the various regimes of a MOS structure. (see below) Previously.

Today we will focus on the charge at the interface and derive the capacitance associated with the various regimes.

1. "Delta - Depletion Approximation":
   \[ \phi_s \approx \phi_s' = -\phi_p \quad \text{for} \quad V_{GB} > V_T \]

2. Some detail analysis for the Inversion regime:
   \[ V_{GB} + \phi_0 = V_{ox} + V_B \quad (\phi_0 = -V_{FB} \quad V_B = -2\phi_p) \]
   \[ V_{GB} - V_{FB} = V_{ox} - 2\phi_p \]
   \[ V_{ox} = E_{ox} \cdot t_{ox} = -\left(\frac{q_{t,B} + q_{B,\max}}{E_{ox} \cdot t_{ox}}\right) \]
   \[ E(0) = \frac{-(q_{t,B} + q_{B,\max})}{\varepsilon_S} = E_{ox} \left(\frac{E_{ox} \cdot t_{ox}}{\varepsilon_S}\right) = \frac{E_{ox}}{3} \]
In inversion, there is a 2nd discontinuity in the electric field, due to the inversion layer:

\[ E(0^+) = -\frac{Q_{B,\text{max}}}{\varepsilon_S} = E(0) \left( -\frac{Q_N}{\varepsilon_S} \right) \]

\[ V_{GB} - V_{FB} = V_{ox} - 2\phi_p = -\frac{(Q_{B,\text{max}} + Q_N)}{C_{ox}} - 2\phi_p \]

\[ Q_N = -C_{ox} \left( V_{GB} - V_{FB} + 2\phi_p - \frac{Q_{B,\text{max}}}{C_{ox}} \right) = -C_{ox} (V_{GB} - V_T) \]

3. Summary for Gate charge: (p-type substrate)

\[ Q_G = C_{ox} (V_{GB} - V_{FB}) \quad \text{for} \quad V_{GB} \leq V_{FB} \quad (Accumulation) \]

\[ Q_G = -Q_B (V_{GB}) = \frac{q N_A}{C_{ox}} x_D = \frac{C_{ox}}{C_{ox}} \left( \frac{q N_A}{C_{ox}} \right) \left( \sqrt{1 + \frac{2\varepsilon_S (V_{GB} - V_{FB})}{q N_A}} - 1 \right) \quad V_{FB} \leq V_{GB} \leq V_{T} \quad (Depletion) \]

\[ Q_G = C_{ox} (V_{GB} - V_T) + \frac{q N_A}{C_{ox}} \left( \sqrt{1 + \frac{2\varepsilon_S (V_{T} - V_{FB})}{q N_A}} - 1 \right) \quad \text{for} \quad V_{GB} \geq V_{T} \quad (Inversion) \]

If we plot,

4. Capacitance of the MOS structure: \( C_{gb}(V_{GB}) = A \cdot \frac{\partial Q_G}{\partial V_{GB}} \bigg|_{V_{GB}} \)

\( Q_G = \frac{q N_A}{C_{ox}} x_D \quad x_D = \frac{E_S}{C_{ox}} \left( \sqrt{1 + \frac{2\varepsilon_S (V_{GB} - V_{FB})}{q N_A}} - 1 \right) \)

(1) Accumulation: \( Q_G = C_{ox} (V_{GB} - V_{FB}) \)

\[ C_{gb} = A \cdot C_{ox} \]

just like a parallel plate capacitor

(2) Depletion regime: \( Q_G = \frac{q N_A}{C_{ox}} x_D \quad x_D = \frac{E_S}{C_{ox}} \left( \sqrt{1 + \frac{2\varepsilon_S (V_{GB} - V_{FB})}{q N_A}} - 1 \right) \)

we can obtain \( C_{gb} \) by doing derivative, but an easier way of understanding this picture is:
two capacitor in series: \[ \frac{1}{C_{tot}} = \frac{1}{C_{ox}} + \frac{1}{C_{dp}} \]

As \( V_{GB} \) goes more positive, \( x_D \uparrow, C_{dp} \downarrow, \Rightarrow C_{tot} \downarrow \)
when \( x_D \) reaches its maximum, \( x_{DT}, C_{tot} \) reaches its minimum

\[ x_{DT} = \sqrt{\frac{2E_{si}(-2q_p)}{q-N_A p}} \]

\[ C_{d, min} = \frac{E_{si}}{x_{DT}} \cdot A \]

\[ Q_g = |C_{ox}(V_{GB} - V_T)| + |Q_{B, max}| \]

\[ C_{gb} = \frac{\Delta Q_g}{\Delta V_{GB}} \bigg|_{V_{GB}} = C_{ox} \]

Discussions:

1. \( p^+ \) gate & \( p^- \) substrate?

2. \( p^+ \) gate & \( n^- \) substrate?

3. \( n^+ \) gate & \( n^- \) substrate?
Backgate effect: p-type substrate, n\textsuperscript{+} source & drain

\( V_{CB} \) needs to be positive, \( V_{CB} > 0 \) so p-n\textsuperscript{+} junction won't conduct.

Apply \( V_{CB} \), reverse bias the p-n\textsuperscript{+} junction, depletion layer will widen. \( \times \theta \), also \( V_B \) changes from \(-2\phi_p\) to \(-2\phi_p + V_{CB}\).

Previously, 
\[
V_T = V_{FB} - 2\phi_p + \frac{1}{\text{Cox}} \sqrt{2\varepsilon_i \text{q} N_A (2\phi_p)}
\]

New 
\[
V_T = V_{FB} - 2\phi_p + V_{CB} + \frac{1}{\text{Cox}} \sqrt{2\varepsilon_i \text{q} N_A (2\phi_p + V_{CB})}
\]
effectively, \( V_T \) \( \alpha \) when a positive \( V_{CB} \) is applied.