Recitation 8: MOS Electrostatics under Bias & MOS Capacitor

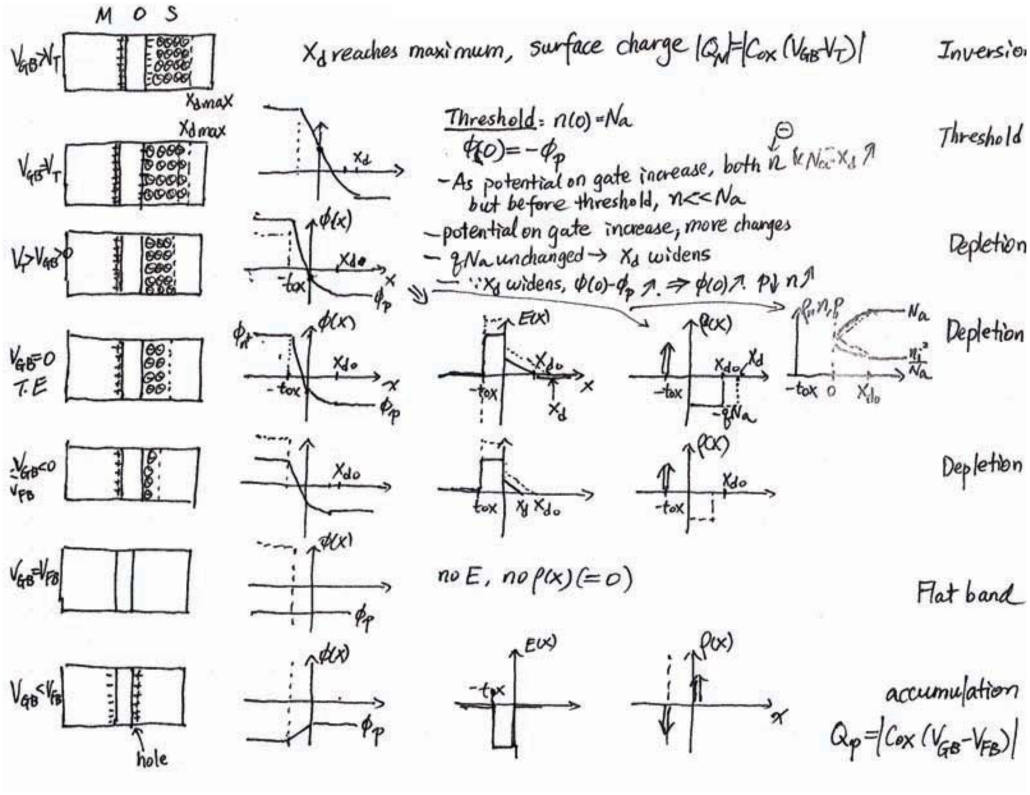
Yesterday we learned a lot of new "names": (terminologies)

- Depletion (regime)
- Flat Band
- Accumulation (regime)
- Threshold
- Inversion (regime)

These are terminologies to describe electrostatics conditions of MOS structure under bias.

MOS Electrostatics under Bias

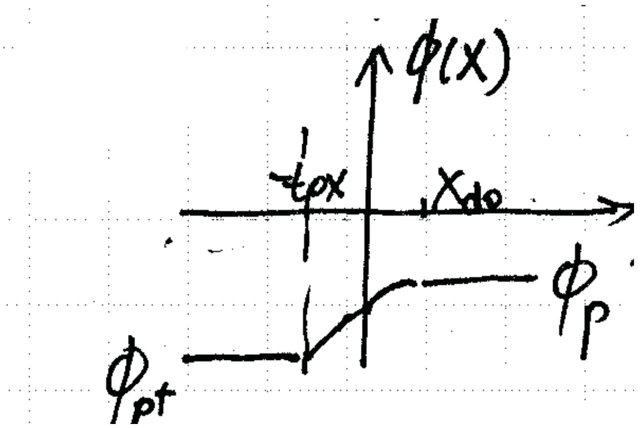
As an exercise, let us consider a situation where we have n$^+$ gate and p-type substrate.



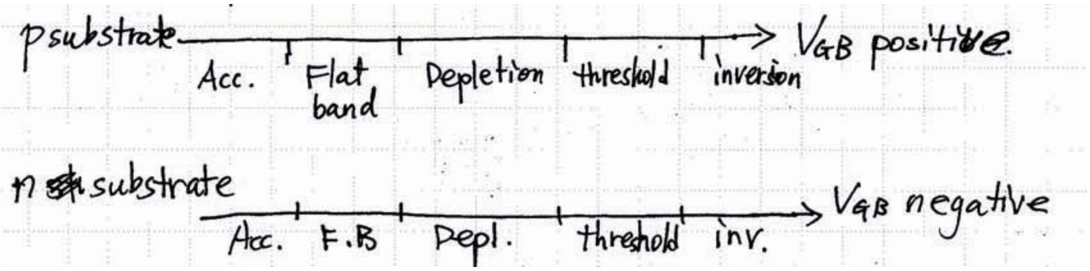
Note:

1. Surface charge
2. What about a p^+ gate, p-substrate MOS structure?

   Under T.E.,



So it does not depend on what gate



3. V_{FB} always $= -(\phi_{gate} - \phi_{body})$

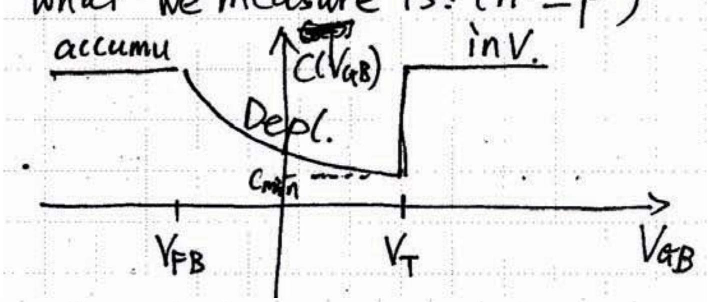
MOS Capacitor

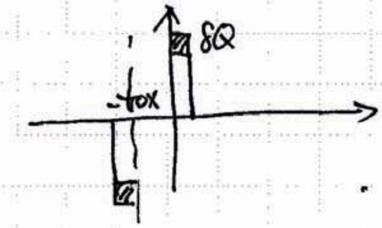
Now let us look at the capacitances of the MOS structure under these regimes:

$$C = \frac{dq_G}{dV_{GB}}\Big|_{V_{GB}}$$

1. Accumulation: → Flat band

What we measure is: (n^+-p)



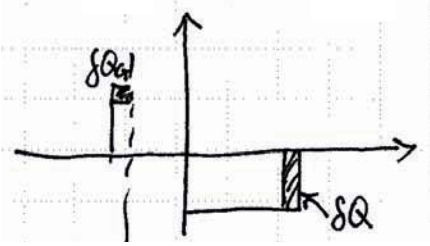


just like a parallel plate capacitor

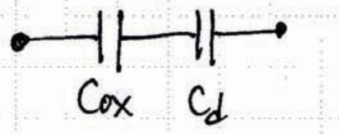
$C = C_{ox}$ (F/cm^2)

$q_G = C_{ox}(V_{GB}-V_{FB})$, $C = \frac{dq_G}{dV_{GB}}\Big|_{V_{GB}<V_{FB}} = C_{ox}$

2. Depletion Regime:



Equivalent circuit model:

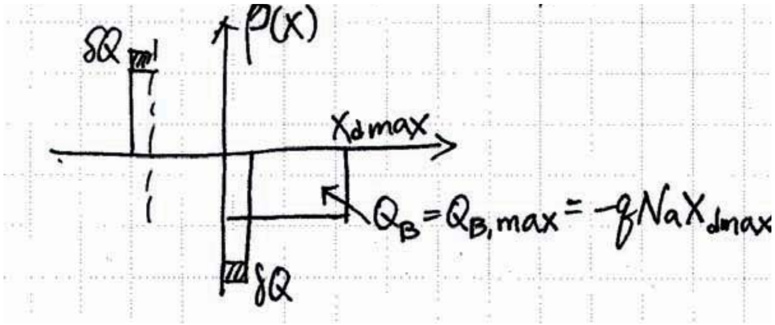


$$\begin{aligned}
q_{\mathrm{G}} &= q \cdot N_{\mathrm{a}} \cdot x_{\mathrm{d}}(V_{\mathrm{GB}}) \\
&= \frac{qN_{\mathrm{a}}\epsilon_{\mathrm{s}}}{C_{\mathrm{ox}}}\left(\sqrt{1+\frac{2C_{\mathrm{ox}}^2(V_{\mathrm{GB}}-V_{\mathrm{FB}})}{q\epsilon_{\mathrm{s}}N_{\mathrm{a}}}}-1\right) \\
\frac{1}{C_{\mathrm{tot}}} &= \frac{1}{C_{\mathrm{ox}}}+\frac{1}{C_{\mathrm{d}}} \\
C_{\mathrm{ox}} &= \frac{\epsilon_{\mathrm{ox}}}{t_{\mathrm{ox}}} \\
C_{\mathrm{d}} &= \frac{\epsilon_{\mathrm{s}}}{x_{\mathrm{d}}}
\end{aligned}$$

As V_{GB} continues increasing, $x_{\mathrm{d}} \uparrow, C_{\mathrm{d}} \downarrow, C_{\mathrm{tot}} \downarrow$ until x_{d} reaches $x_{\mathrm{d,max}}$ when $V_{\mathrm{GB}} = V_{\mathrm{T}}$:

$$x_{\mathrm{d,max}} = \sqrt{\frac{2\epsilon_{\mathrm{s}}(-2\phi_{\mathrm{p}})}{qN_{\mathrm{a}}}} \ \ \& \ \ C_{\mathrm{min}} = \frac{\epsilon_{\mathrm{s}}}{x_{\mathrm{d,max}}}$$

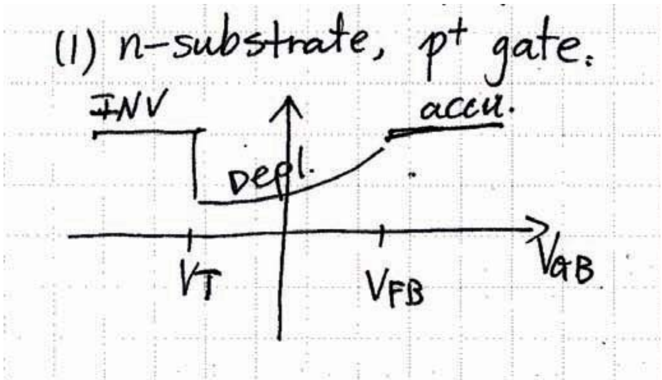
3. Inversion: $V_{\mathrm{GB}} > V_{\mathrm{T}}, x_{\mathrm{d}} = x_{\mathrm{d,max}}$

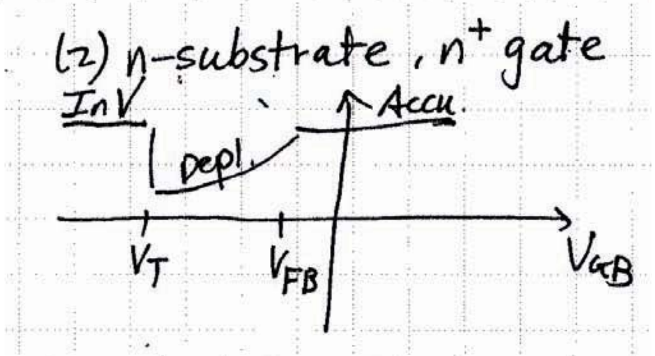


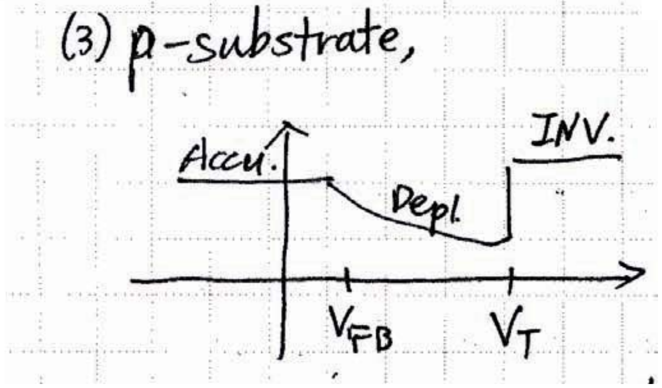
$C = C_{\mathrm{ox}}$ again:

$$\begin{aligned}
C &= \frac{d}{dV_{\mathrm{GB}}}\left[C_{\mathrm{ox}}(|V_{\mathrm{GB}}-V_{\mathrm{T}})|+|Q_{\mathrm{B,max}}|\right]\Big|_{V_{\mathrm{GB}}} \\
C &= C_{\mathrm{ox}} \quad \text{because } Q_{\mathrm{B,max}} \text{ does not change}
\end{aligned}$$

Note: This is a very powerful technique to tell a lot of information of the wafer, doping, type of devices!



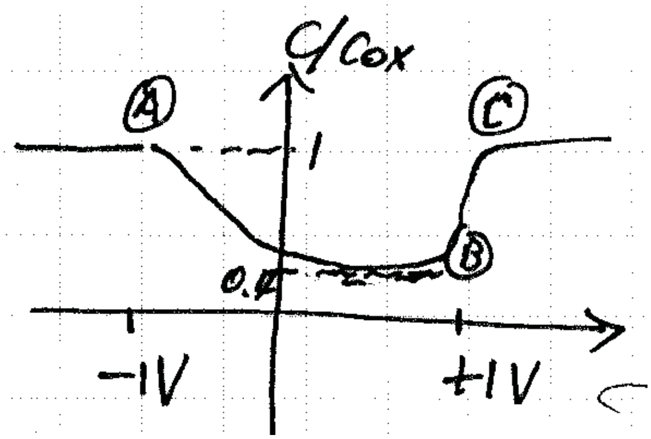




Exercise

From textbook pg. 168-170: n^+ poly gate, $\phi_{n^+} = 550\,\text{mV}$.

1. Substrate doping type? Does **A** or **C** correspond to V_{FB}?



$$\begin{aligned}
V_{FB} &= -1\,\text{V}, \text{V}_\text{T} = 1\,\text{V} \\
V_{FB} &= -1\,\text{V} = -(0.55\,\text{V} - \phi_\text{body}) \\
\Longrightarrow \phi_\text{body} &= -0.45\,\text{V} \\
\Longrightarrow \text{ p type susbstrate, } \phi_\text{p} &= -60\,\text{mV} \cdot \log \frac{\text{N}_\text{a}}{\text{n}_\text{i}} = -450\,\text{mV} \\
\text{or } N_\text{a} &= 3.2 \times 10^{17}\,\text{cm}^{-3}
\end{aligned}$$

2. Find t_{ox}:

$$\frac{C_\text{min}}{C_\text{ox}} = \frac{C(V_\text{GB} = V_\text{T})}{C_\text{ox}} = \frac{1}{\sqrt{1 + \frac{2C_\text{ox}^2(V_\text{T} - V_\text{GB})}{q\epsilon_\text{s} N_\text{a}}}} = 0.4$$

$V_\text{T} = 1\,\text{V}, \text{V}_\text{FB} = -1\,\text{V}$, solve for C_ox:

$$\begin{aligned}
C_\text{ox} &= 2.55 \times 10^{-7}\,\text{F/cm}^2 \\
C_\text{ox} &= \frac{\epsilon_\text{ox}}{t_\text{ox}} = \sqrt{\frac{q\epsilon_\text{s} N_\text{a}}{2(V_\text{T} - V_\text{FB})}\left[\left(\frac{C_\text{ox}}{C_\text{min}}\right)^2 - 1\right]} \\
t_\text{ox} &= 132\,\mathring{A}
\end{aligned}$$

or we can use $V_\text{T} = V_\text{FB} - 2\phi_\text{B} + \frac{1}{C_\text{ox}}\sqrt{\epsilon_\text{s} q N_\text{a}(-2\phi_\text{B})}$ to calculate C_ox

3. Find the gate charge Q_G for $V_\mathrm{GB} = -3\,\mathrm{V}$ and $V_\mathrm{GB} = 3\,\mathrm{V}$.

- $V_\mathrm{GB} = -3\,\mathrm{V}$ corresponds to accumulation:

$$\begin{aligned} Q_\mathrm{G} = Q_\mathrm{p} &= C_\mathrm{ox}(V_\mathrm{GB} - V_\mathrm{FB}) \\ &= C_\mathrm{ox}(-3-(-1)) = C_\mathrm{ox}\cdot(-2\,\mathrm{V}) \\ &= -5.1\times10^{-7}\,\mathrm{C/cm^2} \quad \text{charge on gate is negative} \end{aligned}$$

- $V_\mathrm{GB} = 3\,\mathrm{V}$ corresponds to inversion:

$$\begin{aligned} Q_\mathrm{G} &= |Q_\mathrm{N}| + |Q_\mathrm{B,max}| = Q_\mathrm{N} \\ &= C_\mathrm{ox}(V_\mathrm{GB} - V_\mathrm{T}) = C_\mathrm{ox}(3-1) = 5.1\times10^{-7}, \mathrm{C/cm^2} \\ |Q_\mathrm{B\cdot max}| &= qN_\mathrm{a}x_\mathrm{dmax} = \sqrt{2q\epsilon_\mathrm{s}N_\mathrm{a}(-2\phi_\mathrm{p})} \\ &= \sqrt{2\times1.6\times10^{-19}\times11.9\times8.85\times10^{-14}\times3.2\times10^{17}\times2\times0.45} \\ &= 2.8\times10^{-7}\,\mathrm{C/cm^2} \\ Q_\mathrm{G} &= 5.1\times10^{-7}\,\mathrm{C/cm^2} + 2.8\times10^{-7}\,\mathrm{C/cm^2} \\ &= 7.9\times10^{-7}\,\mathrm{C/cm^2} \end{aligned}$$

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