ECE 340
Lecture 40 : MOSFET I

Class Outline:

• MOS Capacitance-Voltage Analysis
• MOSFET - Output Characteristics
• MOSFET - Transfer Characteristics
Key Questions

• How do I analyze the conductance of the channel?

• How do I find the $I_d-V_d$ characteristics in the linear regime?

• How do I find the $I_d-V_d$ characteristics in the saturation regime?
Do you remember the **MOSFET**...

Why is it called a **field effect transistor**??

- It is due to the fact that its operation depends on using a field to control the current running from the source to the drain.

- We use the field to form the thin channel at the surface of the MOSFET.

- The MOSFET is sometimes referred to as a surface field effect device.

- **No current flows between the source and the drain in equilibrium.**

  - The p-type region separating creates built-in electric fields which creates a large potential barrier.

  - Using the field to invert the surface of the semiconductor allows current to flow from the source to the drain.
MOSFET – Output Characteristics

Our knowledge of the MOS capacitor will come in handy...

Remember **threshold voltage**?

The **threshold voltage** is: \[ V_T = \Phi_{ms} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} + 2\phi_F \]

Thus, the threshold voltage must be strong enough to **achieve flatband**, **accommodate the charge in the depletion region**, and **induce the inverted region**.

Here we show the signs corresponding to each of the different effects on the threshold voltage. The total result is shown to the right for n-channel and p-channel.

\[
V_T = \begin{array}{c|c|c|c}
\Phi_{ms} & -\frac{Q_i}{C_i} & -\frac{Q_d}{C_i} & +2\phi_F \\
n\text{channel} & + & + & +\\
p\text{channel} & - & - & -
\end{array}
\]

\[Q_i=5 \times 10^{10} \text{qC/cm}^2\]
\[d=100\text{Å}\]

\[N_a, N_d(\text{cm}^{-3})\]
Let’s examine the applied gate voltage to begin to solidify our understanding...

- The negative workfunction difference causes the bands to be pulled down farther in equilibrium.
- To achieve flatband conditions, we must apply a positive voltage to overcome the inherent bending in the bands,

\[ V_G = V_{FB} - \frac{Q_s}{C_i} + \phi_s \]

The induced charge is composed of mobile charge, \( Q_n \), and fixed charge contributions, \( Q_d \).

We can substitute this relation into our equation and solve for the mobile charge...

\[ Q_n = -C_i \left[ V_G - \left( V_{FB} + \phi_s - \frac{Q_d}{C_i} \right) \right] \]
MOSFET Output Characteristics

Let’s now apply a **drain bias** across our MOSFET...

The application of the drain bias causes a **rise** in the potential.

How do the carriers move?

This will change the potential required to achieve strong inversion...

\[
Q_n = -C_i \left[ V_G - V_{FB} - 2\phi_F - V_x - \frac{1}{C_i} \sqrt{2q\varepsilon_sN_a(2\phi_F + V_x)} \right]
\]

For the time being, let’s ignore the variation of the depletion region fixed charge with increasing drain bias...

\[
Q_n(x) = -C_i(V_G - V_T - V_x)
\]

Mobile charge in the channel at point x.
MOSFET Output Characteristics

But we still don’t know how to find the conductance...

We can start by finding the conductance over a differential element of the channel...

\[
\frac{\mu_n Q(x)Z}{dx}
\]

Channel width

Surface electron mobility

Then we can find the current at any point \( x \) along the channel as...

\[
I_D dx = \mu_n Z |Q_n(x)| dV_x
\]

Why isn’t the surface mobility the same as the bulk mobility?
MOSFET Output Characteristics

But we still don’t know the currents or conductances…

So, let’s integrate our differential element from the source to the drain…

\[ \int_0^L I_D dx = \mu_n Z C_i \int_0^{V_D} (V_G - V_T - V_x) dV_x \]

We end up with an expression for the drain current…

\[ I_D = \frac{\mu_n Z C_i}{L} \left[ (V_G - V_T) V_D - \frac{1}{2} V_D^2 \right] \]

Valid only in the linear regime!!!

• Here we have assumed that the depletion charge \( Q_D \) in the threshold voltage expression is equivalent to the value with no drain current present.

\[ I_D = \frac{\mu_n Z C_i}{L} \times \left\{ (V_G - V_{FB} - 2\phi_F - \frac{1}{2} V_D) V_D - \frac{2}{3} \frac{\sqrt{2\epsilon q N_a}}{C_i} [(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}] \right\} \]

We can obtain a more accurate version by including this contribution and integrating.
MOSFET Output Characteristics

This makes sense based on what we already know about MOSFETs...

\[ I_D = \frac{\mu_n Z C_i}{L} \left[ (V_G - V_T)V_D - \frac{1}{2}V_D^2 \right] \]

For low drain voltages, the MOSFET looks like a resistor if the MOSFET is above threshold and depending on the value of \( V_G \).

Now we can obtain the conductance of the channel...

\[ g = \frac{\partial I_D}{\partial V_D} \approx \frac{Z}{L} \mu_n C_i(V_G - V_T) \]

• But again, this is only valid in the linear regime.
• We are assuming that \( V_D \ll V_G - V_T \).
MOSFET Output Characteristics

So we can describe the **linear regime**, but how do we describe the **saturation regime**...

- As the drain voltage is increased, the voltage across the oxide decreases near the drain end.
- The resulting mobile charge also decreases in the channel near the drain end.
- To obtain an expression for the drain current in saturation, substitute in the **saturation condition**.

\[
I_D(\text{sat.}) \approx \frac{1}{2} \mu_n C_i \frac{Z}{L} (V_G - V_T)^2 = \frac{Z}{2L} \mu_n C_i V_D^2(\text{sat.})
\]

\[
g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} \approx \frac{Z}{L} \mu_n C_i (V_G - V_T)
\]

\[
V_D(\text{sat.}) \approx V_G - V_T
\]
MOSFET Output Characteristics

Let’s summarize the **output characteristics** for NMOS and PMOS...

**NMOS**

- P-type Si
- N-type Si

**PMOS**

- N-type Si
- P-type Si
MOSFET Transfer Characteristics

Here we plot the drain voltage versus the gate voltage transfer characteristic...

- The linear region $I_D$ versus $V_G$ should be straight.
- Intercept on the $V_G$ axis gives the threshold voltage.
- The slope of this plot divided by $V_D$ gives the conductance of the channel.

$$I_D = \frac{Z}{L} \mu_n C_i [V_G - V_T] V_D$$

Deviation from linearity due to field-dependent mobility and source-drain series resistance.
MOSFET Transfer Characteristics

Let’s examine the **transconductance**...

- We differentiate with respect to the gate bias.
- Transconductance is zero below VT due to small current flowing through device.
- Goes through maximum and then decreases due to channel degradation of mobility and additional source/drain series resistances.
MOSFET Transfer Characteristics

What are the **transfer characteristics** in the **saturation regime**?

- There is a quadratic dependence of $I_D$ on $V_G$.
- Intercept again gives $V_{T\_SAT}$.
- $V_{T\_SAT}$ can be lower than $V_T$ for short channel devices.
- This is caused by drain induced barrier lowering.
- The transconductance is also different for short channel devices.

\[
\sqrt{I_D^{\text{(sat)}}} = \sqrt{\frac{k_N^{\text{(sat)}}}{2}} (V_G - V_T)
\]

Slope gives $k_N^{\text{(sat)}}$.