Lecture 5: Introduction to MOS Capacitors

Announcements

Homework 1/2:
- Will be online after the Lectures Today.
- Total of 25 marks.
- Each homework contributes an equal weight.
  - All homework contributes to 20% of overall grade.
  - Each homework contributes 10% of overall grade.
- Due Wednesday 17th April at the start of the lecture (4:00pm).
- I will return it one week later (24th April).
- I will post the solutions when I return the homeworks.
- Homework 1 will consist of content covered in Lectures 1 - 6.
Last Time

- We have covered the basics of how we can grow single crystal wafers of silicon from SiO$_2$ precursor materials.

Lecture 5

- Review of Capacitors.
- Introduction to MOS Capacitors.
- Accumulation Mode.
Review of Capacitors

MOS Capacitors

- In your first few lab sessions, you will be fabricating Metal-Oxide-Semiconductor (MOS) Capacitors – MOS Caps.
- In the next two lectures we will cover the physics of MOS capacitors
Capacitors

- Before we talk about MOS capacitors, let remind ourselves what we mean by capacitors generally.
- You are probably familiar with capacitors that look like this:

  ![Capacitors Image]

- As circuits they are labeled as follows:

  ![Capacitor Labels]

  - Normal
  - Normal
  - Electrolytic
  - Variable

Capacitors

- For our purposes, a capacitor can be considered two sheets of metal separated by some insulating (dielectric) medium.

  ![Capacitor Diagram]

  - If you apply a voltage (V) across a capacitor, current will not flow between the plates (we say the resistance of the medium is $\infty$).
  - But charge ($Q$) will accumulate.

  We define capacitance ($C$) as this ratio:

  $$C = \frac{Q}{V}$$
Capacitance

\[ C = \frac{Q}{V} \]

- The amount of charge stored on the plates for a certain voltage depends on geometry (plate size & separation) and dielectric medium between the plates.
- Normally capacitors are used for their dynamic (time-dependent) properties.
- Re-arrange and differentiate with respect to time:
  \[ Q = CV \quad \frac{dQ}{dt} = C \frac{dV}{dt} \quad I = C \frac{dV}{dt} \]
  - Where \( I \) is the rate of change of charge: i.e. current flow.

Capacitance

\[ I = C \frac{dV}{dt} \]

- So what does this form tell us?
- If during a time \( t \), we change the voltage across the capacitor, a certain current will flow during this time.
- In reality the capacitor will charge or discharge through a load resistor \( (R) \).
Capacitance

\[ I = C \frac{dV}{dt} \]

- Use Ohm’s Law:
  \[ I = \frac{V}{R} \]
  \[ \frac{V}{R} = C \frac{dV}{dt} \]
  \[ \frac{dV}{dt} = \frac{1}{RC} V \]

- This ordinary differential equation states that when charging or discharging a capacitor, the rate of change of voltage is equal to voltage divided by some constant \((RC)\).

Voltage is a function of time, so for clarity we should write this as:

\[ \frac{dV}{dt} = \frac{1}{RC} \]

- This is a simple ordinary differential equation (ODE).
- How do engineers solve ODE’s? We look up the solution.
- For Charging:
  \[ V(t) = V_0 \left(1 - e^{-t/\tau}\right) \]
- For Discharging:
  \[ V(t) = V_0 e^{-t/\tau} \]

- \(V_0\) is the steady-state voltage.
- \(\tau = RC\) is the time constant.
Time Constant

- Charging:
  \[ V(t) = V_0 \left( 1 - e^{-t/\tau} \right) \]

- Discharging:
  \[ V(t) = V_0 e^{-t/\tau} \]

- Since \( e^{-x} \) only becomes zero as \( x \to \infty \), \( \tau \) defines the time it takes to reach 63.2% of the applied DC voltage.

Potential Dividers

- Consider a RC-circuit such as this:

- We apply \( V_{in} \) across a capacitor and resistor in series, and measure the \( V_{out} \) dropped just across the resistor.
- We identify this as a potential divider.
**Potential Dividers**

- The voltage output from a potential divider is given by:
  \[ V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \]

  - E.g. if \( R_1 = R_2 \) then the output is just half the input.
  - We assume resistors are independent of the frequency of the input voltage (\( f \)). I.e.:
    \[ R \neq R(f) \]

- What if we replace \( R_1 \) with a capacitor?
- The behaviour of the capacitor now strongly depends on the frequency of the input voltage.

**RC Circuit**

- First lets consider what happens if we apply a voltage across this RC circuit.
- For a resistor and capacitor in series we need to specify the frequency as well as the voltage.
- We apply a signal with an amplitude and some frequency.
Low Frequencies

- First let’s consider what happens if we apply a very low frequency (i.e. at DC).
- Here we can approximate that an infinite amount of time has passed since we started charging or discharging.
- Under these conditions, the plates are saturated or empty.
- No current will flow into the plates, the resistance is high.

RC Circuit

- If the capacitor is like an open circuit at high frequency, we can view the divider as follows.
- I.e. we can say that the resistance of the capacitor is very high.
  \[ V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \quad V_{out} \approx 0 \]
- Technically, frequency-dependent resistance is called impedance.
- Impedance values are typically labeled by \( Z \) rather than \( R \).
High Frequencies

- What happens to our circuit if \( V_{in} \) has a very high frequency?

- Here the plates are not going to have time to saturate (or empty) before the current changes direction.

- It is easy for charges to flow onto and off of the plates and a high current can flow.

- At high frequencies we say the impedance (resistance) is low.

RC Circuit

- So at high frequencies it is more appropriate to view the capacitor as a closed switch.

- I.e. we can now say that all of the voltage is dropped across the resistor:

\[
V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \quad V_{out} \approx V_{in}
\]

- The circuit we have just described is called a high-pass filter.

- It is a circuit that allows signals with a high frequency to pass, and those with a low signal are attenuated.

- They are used throughout analog electronics.
Signal Filters

- The order of the components defines the type of filter.

- **Low-Pass Filter:**

```
V_{in} \quad R \quad C \quad V_{out}
```

- **High-Pass Filter:**

```
V_{in} \quad C \quad V_{out} \quad R
```

Measuring Capacitance

- So this is reality how one would measure the capacitance of an unknown device.
- You would apply an AC signal across an RC circuit, and measure the cut-off frequency.
- The cut-off frequency \( f_c \) is defined as the frequency at which the output voltage is \( \sqrt{1/2} \approx 0.7 \) of the input voltage.
- We can then evaluate \( C \) via:

\[
\tau = \frac{1}{2\pi f_c}
\]
Introduction to MOS Capacitors

MOS Capacitors

- We are interested in a particular type of capacitor: MOS Capacitors.
- Sometimes we want a capacitor in our circuit, sometimes we don’t.
- Many devices have overlapping plates (and hence capacitance).
- Capacitance is particularly important as integrated circuit technology improves.
- Each generation has involved a reduction in device dimensions.
- As oxide thickness changes, so too does capacitance.
Oxide vs Insulator

- When we use the word oxide here we are using it as a synonym for insulator.
- You often see the term metal-insulator-semiconductor (MIS).
- The reason the acronym MOS is used is because the oxide SiO$_2$ is often used as the insulator in industry.
- The insulator you use in the laboratory will be SiO$_2$ also.
- SiO$_2$ is an insulator, but there are plenty of oxide conductors and semiconductors, so MOS is not the greatest choice of terminology.

MOSFETs

- MOS / MIS capacitors are important devices in their own right.
- But understanding their operation is crucial to understanding the operation of field-effect transistors.
- Commonly called metal oxide semiconductor field effect transistors (MOSFETs)
- You will be making MOSFETs in the lab in the second half of the course.
- We will study them in Lectures 13 and 14.
Ideal MOS Capacitors

- We begin our treatment by considering the ideal situation.
- The development of an ideal model will allow us to establish the essential MOS interface device physics.
- This will be sufficient for you to measure and understand MOS capacitors in the lab.
- Non-idealities in MOS capacitors are dealt with in ECE615.
- The ideal MOS capacitor assumptions are as follows:
  - The insulator has infinite resistance.
  - The interface has no interface states.
  - There is no charge present within the oxide.
  - The metal and semiconductor work functions are equal.

Measuring MOS Capacitors

- Semiconductors can behave as insulators or conductors depending on electrical conditions.
- So the measurements on MOS capacitors is a little more complex than the simple parallel plate devices we have been talking about so far.

Sine wave, typically $f = 1$ MHz, $V_{AC} = 25$ mV (rms)

$V_{DC} = 0$-$10$ V
Measuring MOS Capacitors

- To observe all the relevant physics, we also must scan the DC voltage to produce our \( CV \) curve.
- So in reality our voltage-time graph will look something like the following:

\[
\begin{align*}
V & \quad t \\
\end{align*}
\]

CV-Plots

- Generally when we measure MOS Capacitors we evaluate the measured capacitance as a function of applied DC voltage.

\[
\begin{align*}
C_i & \quad V \\
\end{align*}
\]

- The behavior we observe depends on the frequency of our AC probe.
- More on this after the break...
Accumulation Mode

Band Diagrams

- To describe our MOS capacitors under applied voltage we are going to use very simple band diagrams (energy vs position).
- For example, we can picture a p-type semiconductor as:

```
E

E_{VAC}

E_C

E_i

E_{FS}

E_V
```

- From this picture we implicitly assume the semiconductor is homogenous.
Band Diagram

- The complete band diagram can then be drawn as follows:

![Band Diagram Image]

- We have here assumed the work functions of the metal and the semiconductor are equal.
- This leads to so-called flat-band conditions.

Where:

- $E_{VAC}$: Vacuum level.
- $e\phi_M$: Metal work function.
- $E_{Fm}$: Fermi Energy of metal.
- $e\phi_B$: Barrier height.
- $d$: Insulator (oxide) thickness.
- $\chi_I$: Electron affinity of insulator (oxide).
- $\chi_S$: Electron affinity of semiconductor
- $e\phi_S$: Semiconductor work function.

We will come back to this later.
Band Diagram

- Where:
  - $E_C$: Semiconductor conduction band.
  - $E_V$: Semiconductor valence band.
  - $E_{FS}$: Fermi Energy of semiconductor.
  - $E_i$: Fermi Energy of intrinsic semiconductor (i.e. the Fermi level if we had not doped the semiconductor).
  - $e$: fundamental unit of charge.
- Note that some parameters are labeled as energies (e.g. $E_C$, $E_V$ etc.) and some are labeled in volts (e.g. $\phi_M$, $\phi_S$).
- Energy and voltage are related by

$$E = eV$$

Applied Bias

- Our goal is to consider what happens when we apply a DC voltage across our MOS capacitor.
- We are going to run through a set of thought experiments to rationalize the unusual CV behavior observed experimentally.
- In particular we want to know what happens to the band diagram when we apply a voltage?
- By definition, positive and negative bias refer to the polarity of the metal gate electrode.
- First, consider a negative applied bias.
- We can draw the energy band diagram using a three-step procedure, as follows.
Step 1

- Offset the semiconductor Fermi level, $E_{FS}$, with respect to the metal Fermi level, $E_{FM}$, by an energy corresponding to the applied bias $eV$:

![Diagram of Fermi levels offset](image)

If $E_{FM} > E_{FS}$, this is a negative bias.

Step 2

- Draw the bulk semiconductor bands away from the interface and the insulator band on the metal side.

![Diagram of band alignment](image)

- This latter step is possible since the metal work function and the insulator electron affinity do not depend on the applied voltage.
Step 3

- Step 3 is a little bit more complicated.
- We need to determine how do the bands bend.
- This is not trivial, as we have bending across both the insulator and the semiconductor.
  - We know that the metal work-function is independent of voltage.
- To account for the two voltage drops we will say:
  \[ V = V_i + V_s \]

- Where:
  - \( V_i \) is the voltage dropped across the insulator.
  - \( V_s \) is the voltage dropped across the semiconductor.

- Assuming the insulator has zero free carriers allows us to draw drop as straight line.
Step 3

- So, without evaluating quantitatively, we can assume the semiconductor band bends up close to the interface:

\[ eV = eV_i + eV_s \]

- Removing all the extra guide-lines, the band diagram should look something like this:

\[ eV_i + eV_s \]

- At this point, we don't know how much of \( V \) is dropped across the oxide and how much is dropped across the semiconductor.
Accumulation

- The band diagram just considered is termed **accumulation** since delocalized majority carriers (holes in this case) are accumulated at the interface.

![Diagram of band diagram with labels and symbols]

- This is seen by comparing the position of $E_F$ and $E_V$ at the interface and recalling that:

  $$p = N_V \exp \left(- \frac{[E_F - E_V]}{k_B T} \right)$$

- $p$ is delocalized hole density.
- $N_V$ is the density of valence band states.

Accumulation Conditions

- The convention is to measure the potential (i.e. band bending) with respect to the intrinsic level in the bulk:

  $$\phi_{BP} = \frac{E_i - E_F}{e} \bigg|_{\text{bulk}}$$

  $$\phi_s = - \frac{E_i(0) - E_i|_{\text{bulk}}}{e}$$

- We say:
  - $\phi_{BP}$ is the bulk potential ($p$ for p-type).
  - $\phi_s(x = 0)$ is the surface potential.
Carrier Concentration

- These definitions lead to new ways of expressing carrier concentrations in terms of the bulk or surface potentials.
- For example:

\[
p(x) = p_0 \exp\left(-\frac{e\phi_s(x)}{k_B T}\right)
\]

- Where:
  - \( p \) majority (hole) carrier concentration at \( x \).
  - \( p_0 \) majority (hole) carrier concentration in equilibrium (with no applied bias).

- If \( \phi_s = 0 \), \( p = p_0 \). This is flatband.
- If \( \phi_s < 0 \), \( p > p_0 \). This is accumulation.
- If \( \phi_s > 0 \), \( p < p_0 \). This is depletion or inversion.
  - We will talk about this after the break.
Summary

• We looked at the basic operation of conventional capacitors and metal-oxide-semiconductor (MOS) capacitors.

Next Time...

• After the break we will look at depletion, inversion, and CV curves of MOS capacitors.