Lecture 12: MOS Capacitors - Energy band diagrams
Sze And Ng: Chapter 4

Announcements

Homework 3/4:
• Online now.
• Due Tuesday 26th February at the start of the lecture (08:30am).
• I will return it one week later (5th March).
• I will post the solutions when I return your homeworks.
• Homework 3 will consist of content covered in Lectures 9 - 11.
Last Time

• We talked about charge carriers crossing the interface.

![Fig. 16](image.png)  
Sze & Ng Fig. 3.16, pg. 154  

• We quantified the ideal behavior in terms of thermionic emission.

\[ I(V) = I_s \left[ \exp \left( \frac{eV}{k_B T} \right) - 1 \right] \quad I_s = A^* T^2 \exp \left( - \frac{e\phi_B}{k_B T} \right) \]

Lecture 12

• Introduction to MOS Capacitors.
• Accumulation Mode.
• Depletion and Inversion.
Introduction to MOS Capacitors

Two Terminal Devices

- There are four important interfaces in semiconductor devices physics:
  - pn junctions.
  - Metal-semiconductor contacts.
  - Metal oxide semiconductor (MOS) capacitors.
  - Heterojunctions.
- So far, we have discussed the first two and noted the similarities.
- Heterojunctions are quite similar to pn junctions. We will start looking at heterojunctions on 5\textsuperscript{th} March.
MOS Capacitors

• Today we will begin trying to understand the physics of metal-oxide-semiconductor (MOS) interfaces.

• We consider the interface as Ohmic for simplicity.

Oxide vs Insulator

• When we use the word oxide here we are using it a synonym for insulator.

• You often see the term metal-insulator-semiconductor (MIS).

• The reason the acronym MOS is used is because the oxide $\text{SiO}_2$ is often used as the insulator in industry.

• $\text{SiO}_2$ is an insulator, but there are plenty of oxide conductors and semiconductors, so MOS in not the greatest choice of terminology but we will use it.
**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)
- These are devices studied in more detail in ECE 616 (Spring this year).

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**Ideal MOS Capacitors**

- As usual, 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.
- Later, we will consider the deviations from ideality.
- 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.
Band Diagram

- We will start by drawing the band diagram in equilibrium (flat band condition).

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 today consider p-type semiconductors, but as usual, the theory is general.
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).

Band Diagram – Sze & Ng

- The textbook uses similar labels.
  
  ![Energy-band diagrams of ideal MIS capacitors at equilibrium (V = 0). (a) n-type semiconductor. (b) p-type semiconductor.](Sze & Ng Fig. 4.2, pg. 198)

- We will come back to a few of the other labels later.
Accumulation Mode

Applied Bias

- We have three elements to our device now (c.f. pn junctions and Schottky diodes).
- 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 our 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 $eV$:

$$E_{FM} - E_{FS} = eV$$

Step 2

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

- 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:
    \[ V = V_i + V_s \] (1)
  • \( V_i \) is the voltage dropped across the insulator.
  • \( V_s \) is the voltage dropped across the semiconductor.

• We therefore say:

![Diagram showing band bending across metal, insulator, and 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:

\[
E_{Fm} \quad E_{Fp} \quad E_V \quad E_C
\]

Metal \quad Insulator \quad P-Type Semiconductor

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

\[
E_{Fm} \quad E_{Fp} \quad E_V \quad E_C
\]

Metal \quad Insulator \quad P-Type Semiconductor

- 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.

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

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

    \hspace{1cm} (2)

Accumulation Conditions

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

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

  \hspace{1cm} (3)

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

  \hspace{1cm} (4)

  - 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:
  \[ p_p(x) = p_{p0} \exp \left( -\frac{e\phi_s(x)}{k_B T} \right) \]  
  (5)
- Where:
  - \( p_p \) majority (hole) carrier concentration at \( x \).
  - \( p_{p0} \) majority (hole) carrier concentration in equilibrium (with no applied bias).

- If \( \phi_s = 0 \), \( p_p = p_{p0} \). This is flatband.
- If \( \phi_s < 0 \), \( p_p > p_{p0} \). This is accumulation.
- If \( \phi_s > 0 \), \( p_p < p_{p0} \). This is depletion or inversion.
  - We will talk about this next.
Minority Carriers

- Using the law of mass action, we can also derive equations for minority carriers.
- For our p-type semiconductor this would be electrons:
  \[ n_p(x) = n_{p0} \exp \left( -\frac{e\phi_s(x)}{k_B T} \right) \]  
  (5)
- Where:
  - \( n_p \) minority (electron) carrier concentration at \( x \).
  - \( n_{p0} \) minority (electron) carrier concentration in equilibrium (with no applied bias).

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- The textbook uses largely similar notation to us, but sometimes uses \( \psi \)'s instead of \( \phi \)'s.
  \[ n_p(x) = n_{p0} \exp\left(\frac{q \psi}{kT}\right) = n_{p0} \exp(\beta \psi) \]  
  (3a)
  \[ p_p(x) = p_{p0} \exp\left(-\frac{q \psi}{kT}\right) = p_{p0} \exp(-\beta \psi) \]  
  (3b)
  \[ n_s(0) = n_{s0} \exp(\beta \psi_i) \]  
  (4a)
  \[ p_s(0) = p_{s0} \exp(-\beta \psi_i) \]  
  (4b)
Depletion and Inversion

Applied Bias

- Now let’s consider what happens when we apply a positive bias.
- Recall, by definition, positive and negative bias refer to the polarity of the metal gate electrode.
- Go back through our three-step procedure to try and draw, qualitatively, the band diagrams.
- We will see this situation is a little more complex than negative bias.
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 $eV$:

\[
E_{FM} \quad -d\quad E_{FS}
\]

Step 2

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

\[
E_{PM} \quad -d\quad E_{VC} \quad -eV \quad E_{CI} \quad -eV \\
Metal \quad Insulator \quad P-Type\ \text{Semiconductor}
\]

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

- Drop some voltage across the insulator ($V_i$) and some across the semiconductor near the interface ($V_S$)

• How far the bands bend have a strong influence over the behavior we observe.

1. Depletion

- Depletion involves a small amount of downward band-bending.

• Specifically, we define depletion as the situation when:
  - $0 < \phi_S < \phi_{BP}$.
  - $n_S < p_S < p_B$.

• $n_S =$Surface electron density.
• $n_S =$Surface hole density.
• $p_B =$Bulk hole density.
1. Depletion

- Under these conditions we expect the majority carriers (holes) to be **depleted** near the interface.
- Contrast this with our case for accumulation, where upward band bending led to accumulation of holes:

2. Weak Inversion

- Weak inversion involves a **moderate** amount of downward band-bending.
- Specifically, we define **weak inversion** as the situation when:
  - \( \phi_{Bp} < \phi_S < 2\phi_{Bp} \).
  - \( (E_i \text{ has now dipped below } E_{FS} \text{ at the surface}). \)
  - \( p_S < n_S < p_B \).
  - More minority carriers than majority carriers at **surface**.
2. Weak Inversion

- Because the intrinsic energy is below the Fermi energy, it is now energetically favorable for electrons (minority carriers) to accumulate at the interface.

- This is where the word inversion comes from.

3. Strong Inversion

- Strong inversion involves a large amount of downward band-bending.

- Specifically, we define strong inversion as the situation when:
  - $\phi_S > 2\phi_{BP}$.
  - $E_C - E_{FS}$ at surface $<$ than $E_{FS} - E_V$ in bulk.
  - $p_S < p_B < n_S$.
  - More minority carriers the majority carriers in bulk.
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• Analogous arguments can be made for n-type semiconductors.

Regime Classification

• To summarize, we classify the operating regime of our MOS / MIS capacitor by the relative magnitude of $\phi_s$ and $\phi_{BS}$.

  • Accumulation: $\phi_s < 0$.
  • Flatband: $\phi_s = 0$.
  • Depletion: $0 < \phi_s < \phi_{BS}$.

  • Mid-gap: $\phi_s = \phi_{BS}$.
  • Weak Inversion: $\phi_{BS} < \phi_s < 2\phi_{BS}$.
  • Strong Inversion: $\phi_s > 2\phi_{BS}$.
Summary

- We spent today qualitatively looking at the band diagrams of MOS / MIS Capacitors.

Next Time...

- We are going to derive the electrostatics of MOS Capacitors.