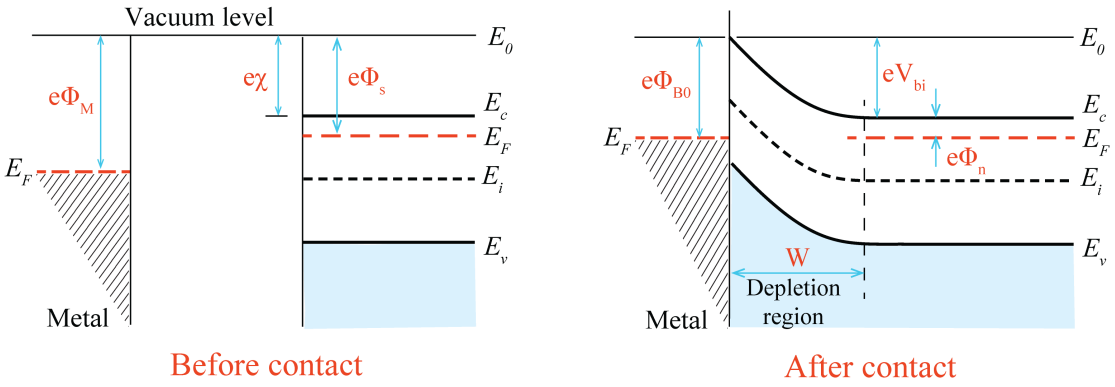
A quick recap of the material covered in lectures

Metal-Semiconductor Junctions

Like a p-n junction diode, a junction formed between a metal and semiconductor has important technological applications. Depending on the *work function* of the metal and semiconductor, the contact being formed can behave either as (i) a rectifying contact or (ii) an ohmic contact. Some key definitions to keep in mind related to metal-semiconductor junctions are:



1. **Work function** Φ_M - It is an energy required to remove an electron at the Fermi level to the vacuum E_0 outside the metal. It is an invariant fundamental property of the specified metal.

2. **Electron affinity** χ - It is the difference in energy between reference vacuum level E_0 and the conduction band energy of a semiconductor and is an invariant fundamental property of the specified semiconductor.

$$\boxed{\chi \equiv (E_0 - E_c)} \tag{1}$$

3. **Work function of a semiconductor** Φ_s - It consists of two distinct parts -

$$\boxed{\Phi_S = \chi + (E_c - E_F)} \tag{2}$$

The energy difference $\Phi_n = (E_c - E_F)$ can vary with the semiconductor doping. So,

$$\boxed{\Phi_S = \chi + \Phi_n} \tag{3}$$

4. **Schottky barrier** Φ_{B0} - The parameter Φ_{B0} is the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor. This barrier is known as the Schottky barrier and is given, ideally, by

$$\boxed{\Phi_{B0} = \Phi_M - \chi} \tag{4}$$

5. **Built-in voltage** V_{bi} - On the semiconductor side, V_{bi} is the built-in potential barrier. This barrier, similar to the case of the pn junction, is the barrier seen by electrons in the conduction band trying to move into the metal. The built-in potential barrier is given by: $V_{bi} = \Phi_{B0} - (E_c - E_F)$

$$\boxed{V_{bi} = \Phi_{B0} - \Phi_n} \tag{5}$$

6. **Space charge region width W** - Schottky diode is identical to one-sided junction and the depletion width W given by

$$\boxed{W = x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{eN_d}}} \tag{6}$$

Current-Voltage Relationship

The current transport in a metal–semiconductor junction is mainly due to majority carriers as opposed to minority carriers in a pn junction. Considering the case of rectifying contact with an n-type semiconductor the transport of electrons is over the potential barrier, described by the thermionic emission theory. The net current density in the metal-to-semiconductor junction can be written as

$$\boxed{J = J_{sT}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{7}$$

where J_{sT} is the reverse-saturation current density and is given by

$$\boxed{J_{sT} = A^* T^2 exp\left(\frac{-e\Phi_{Bn}}{kT}\right)} \tag{8}$$

The parameter A^* is called the effective Richardson constant for thermionic emission and the Schottky barrier height Φ_{Bn} is the effective barrier height changed from Φ_{B0} because of the image-force lowering.

MOS Capacitor

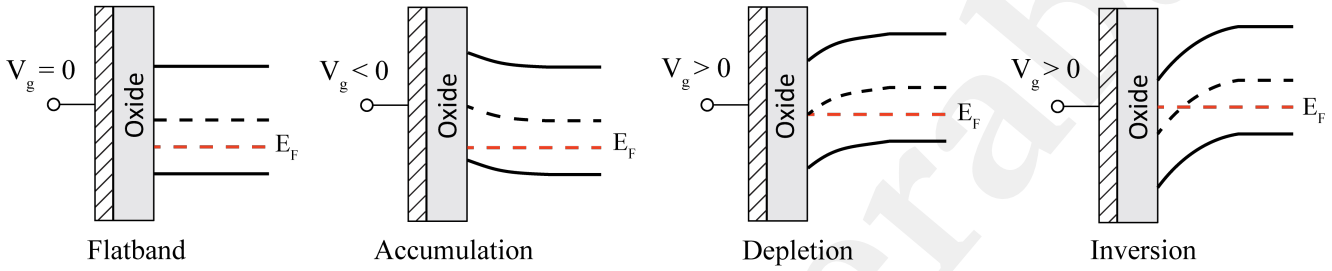
The metal–oxide–semiconductor structure is known as the MOS capacitor. The MOS capacitor is a two-terminal device and the structural heart of all MOS devices. With an analogy to parallel plate capacitor, MOSCAP can be considered a similar device with one metal plate being replaced by semiconductor. An *ideal* MOSCAP structure assumes -

- Metallic gate is thick enough to be considered as an *equipotential* region
- The oxide is a *perfect insulator* with *zero current* flowing through it

- There are no charge centers located in the oxide or at the oxide-semiconductor interface
- The semiconductor is uniformly doped
- The semiconductor is sufficiently thick so that, regardless of the applied gate potential, a field-free region is encountered before reaching the back contact

Effect of an Applied Bias

Let V_g be the d.c. bias voltage applied to the gate. Conceptually, the metal and semiconductor Fermi levels may be thought of as *handles* controlled by the applied bias. Considering the MOS structure with p-type substrate as shown in figure below, the application of gate voltage V_g leads to different biasing condition:



1. **Flat band** - In ideal MOSCAP, when $V_g = 0$, the Fermi levels of metal and semiconductor are perfectly aligned and no band bending occurs at semiconductor-oxide interface. This is called *flat band* condition.

2. **Accumulation** - The application of $V_g < 0$ lowers E_F in the metal relative to E_F in the semiconductor and causes a negative sloping of energy bands as shown in figure. This makes hole concentration near the semiconductor-oxide interface to increase or in other words, E_F moves closer to E_v at the interface. This particular condition, where the majority carrier concentration is greater near the oxide-semiconductor interface than in the bulk of semiconductor, is known as *accumulation*.

3. **Depletion** - The application of a small positive potential $V_g > 0$ places a positive charge on the gate, which in turn repels holes away from the oxide-semiconductor interface and exposes the negatively charged acceptor sites. This situation where the electron and hole concentration at oxide-semiconductor interface are less than the background doping concentration (N_d or N_a), is known as *depletion*.

4. **Inversion** - With larger and larger positive bias applied on gate, the electron concentration at the surface n_s increases and reaches a point where n_s exceeds p_{bulk} and the surface region appears to change in

character from *p-type* to *n-type*. This situation where the minority carrier concentration at the surface exceeds the bulk majority carrier concentration is referred to as *inversion*.

The biasing regions in n-type device are reversed in polarity relative to the voltage regions in p-type device; that is accumulation in n-type device occurs when $V_g > 0$, and so forth.

Solve the following questions. There are 11 questions, for a total of 25 marks.

1. (1 mark) Which of the following is the workfunction?

   A. The energy required to move an electron from E_c to the vacuum level.

   B. The energy required to move an electron from E_i to the vacuum level.

   C. The energy required to move an electron from E_v to the vacuum level.

   D. The energy required to move an electron from E_F to the vacuum level.

   E. The energy required to move an electron from E_F to E_c.

   F. The energy required to move an electron from E_F to E_v.

2. (1 mark) Which of the following is the electron affinity?

   A. The energy required to move an electron from E_c to the vacuum level.

   B. The energy required to move an electron from E_i to the vacuum level.

   C. The energy required to move an electron from E_v to the vacuum level.

   D. The energy required to move an electron from E_F to the vacuum level.

   E. The energy required to move an electron from E_F to E_c.

   F. The energy required to move an electron from E_F to E_v.

3. (1 mark) Where does the peak electric field occur in a MS junction?

   A. Deep inside the metal

   B. Deep inside the semiconductor

   C. At the edge of the semiconductor transition region.

   D. At the metal-semiconductor interface.

   E. Depends on the semiconductor type

   F. Depends on the semiconductor doping concentration

4. (4 marks) Three Schottky barrier diodes a, b and c are formed on n-type silicon with doping concentrations (a) $10^{15}\ cm^{-3}$, (b) $5\times10^{15}\ cm^{-3}$, and (c) $10^{16}\ cm^{-3}$, respectively. Assume a barrier height $\Phi_{B0} = 0.65\ V$, $E_g = 1.1\ eV$, $n_i = 1.5\times10^{10}\ cm^{-3}$, $kT = 25.9\ meV$.

(a) (*2 points*) Determine the Φ_n for all the three Schottky diodes.

A. $\Phi_n^a = 0.20\ V$, $\Phi_n^b = 0.22\ V$, $\Phi_n^c = 0.26\ V$

B. $\Phi_n^a = 0.26\ V$, $\Phi_n^b = 0.20\ V$, $\Phi_n^c = 0.22\ V$

C. $\Phi_n^a = 1.1\ V$, $\Phi_n^b = 0.65\ V$, $\Phi_n^c = 0.45\ V$

D. $\Phi_n^a = 0.45\ V$, $\Phi_n^b = 0.65\ V$, $\Phi_n^c = 1.1\ V$

E. $\Phi_n^a = 0.26\ V$, $\Phi_n^b = 0.22\ V$, $\Phi_n^c = 0.20\ V$

F. $\Phi_n^a = 0.22\ V$, $\Phi_n^b = 0.26\ V$, $\Phi_n^c = 0.20\ V$

Review definitions

$\phi_n = E_C - E_F$

$= E_C - \left(E_i + \frac{KT}{q}\ln\left(\frac{N_D}{n_i}\right)\right)$

$= 0.55 - 0.0259 \times \ln\left(\frac{10^{15}}{1.5\times10^{10}}\right)$

$= 0.26\ eV$

Repeat for $N_D = 5\times10^{15}\ cm^{-3}$

$N_D = 10^{16}\ cm^{-3}$

(b) (*2 points*) Choose the correct option for built-in potential V_{bi} in the three devices.

A. $V_{bi}^a > V_{bi}^b = V_{bi}^c$

B. $V_{bi}^a < V_{bi}^b > V_{bi}^c$

C. $V_{bi}^a > V_{bi}^b < V_{bi}^c$

D. $V_{bi}^a < V_{bi}^b < V_{bi}^c$

E. $V_{bi}^a > V_{bi}^b > V_{bi}^c$

F. $V_{bi}^a = V_{bi}^b = V_{bi}^c$

Review Eq 5. $V_{bi} = \phi_{B0} - \phi_n$

$V_{bi}^a = 0.65 - 0.26 = 0.39\ V$

Repeat for (b) and (c)

V_{bi} is the band bending in semiconductor

- At equilibrium E_F has to be uniform across the device. Hence, you can see from the band diagram in recap that $V_{bi} = \phi_{B0} - \phi_n$
- We have used eV and Volts interchangeably. We use Volts when we talk of potential and eV when talking of energy. This should not confuse you.

5. (2 marks) A pn junction diode and a Schottky diode have equal cross-sectional areas and have forward-bias currents of $0.5\ mA$. The reverse-saturation current of the Schottky diode is $5 \times 10^{-7}\ A$. The difference in forward-bias voltage between the two diodes is $0.30\ V$. Determine the reverse-saturation current of the pn junction diode. (Assume $kT = 25.9\ meV$.)

A. $46.4 \times 10^{-7}\ A$

B. $0.464 \times 10^{-7}\ A$

C. $46.4 \times 10^{-12}\ A$

D. $464 \times 10^{-12}\ A$

E. $4.64 \times 10^{-12}\ A$

F. $4.64 \times 10^{-7}\ A$

Review Eq. 7

$$I = I_{ST}\left[\exp\left(\frac{qV_A}{KT}\right) - 1\right]$$

$$\therefore 0.5\ mA = 5\times10^{-7}A \times \left[\exp\left(\frac{qV_A}{KT}\right) - 1\right]$$

$$\Rightarrow V_A = \frac{KT}{q}\ln(1000) = 0.1789\ V$$

PN junction has higher threshold and hence larger V_A needs to be applied to get the same current.

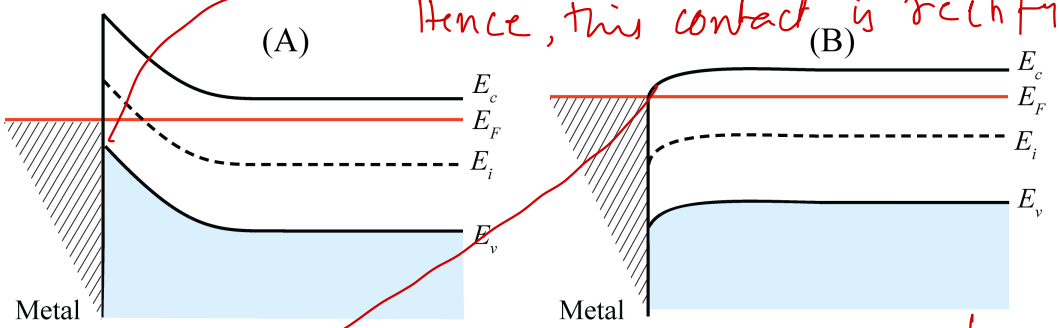
V_A for PN junction $= 0.1789 + 0.3 = 0.4789\ V$

$$I_S^{PN} = \frac{0.5\ mA}{\left[\exp\left(\frac{0.4789}{0.0259}\right) - 1\right]} = 4.66\ pA$$

Note that KT is given as 25.9 mV. $\frac{KT}{q} = 25.9\ mV$

6. (4 marks) Consider the equilibrium energy band diagram for an ideal metal-semiconductor contact as shown in the figure 1 below and answer the following questions:

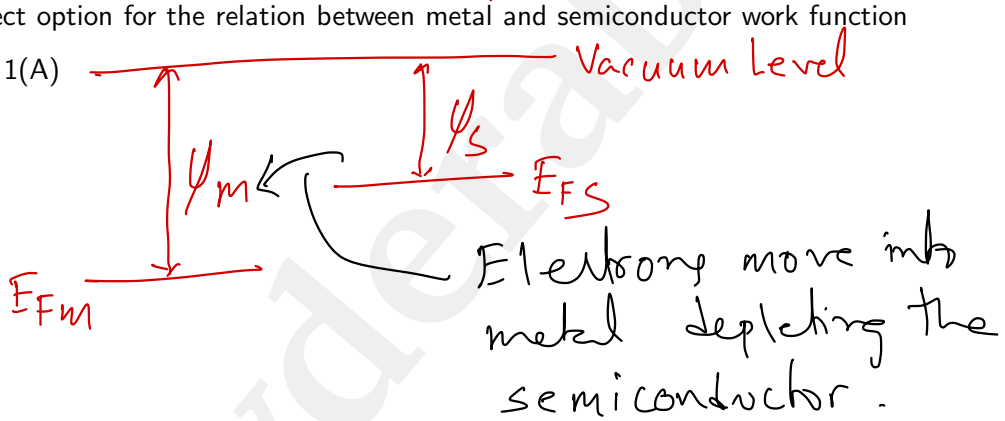
Majority carriers (electrons) are depleted. Hence, this contact is rectifying



Accumulation of majority carriers (electrons). Hence, this is ohmic contact

Figure 1: M-S contact

(a) (*1 mark*) Choose the correct option for the relation between metal and semiconductor work function for band diagram in figure 1(A)



A. $\Phi_M < \Phi_s$

B. $\Phi_M = \Phi_s$

C. $\Phi_M > \Phi_s$

D. $\Phi_M > \chi$

E. $\Phi_M < \chi$

F. $\Phi_M = \chi$

(b) (*1 mark*) The contact formed in figure 1(A) is of _____ type.

A. depletion

B. accumulation

C. ohmic

D. inversion

E. flatband

F. rectifying

(c) (*1 mark*) Choose the correct option for the relation between metal and semiconductor work function for band diagram in figure 1(B)

Electrons will flow from metal into semiconductor. Hence, this will be ohmic contact.

A. $\Phi_M < \Phi_s$

B. $\Phi_M = \Phi_s$

C. $\Phi_M > \Phi_s$

D. $\Phi_M > \chi$

E. $\Phi_M < \chi$

F. $\Phi_M = \chi$

(d) (*1 mark*) The contact formed in figure 1(B) is of _____ type.

A. rectifying

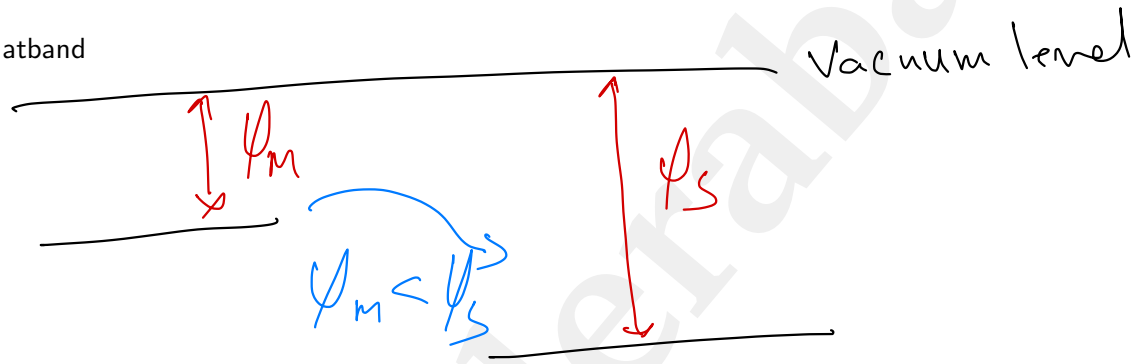
B. depletion

C. accumulation

D. inversion

E. ohmic

F. flatband



Analyze the behavior for metal - p type semiconductor contacts.

7. (2 marks) Choose the correct statement(s) from the following

   A. Schottky diodes are minority carrier devices

   B. M-S diodes have much higher saturation current densities

   C. Schottky diodes are majority carrier devices

   D. M-S diodes have much lesser saturation current densities

   E. Schottky diodes are high speed devices compared to pn diodes.

   F. M-S diodes have higher turn on voltages than pn junctions.

   G. M-S diodes have much lower turn on voltages than pn junctions.

Review lecture videos. Analyze why other options are incorrect

8. (1 mark) The I-V characteristics for three different devices (i, ii, iii) are shown in the figure 2 below:

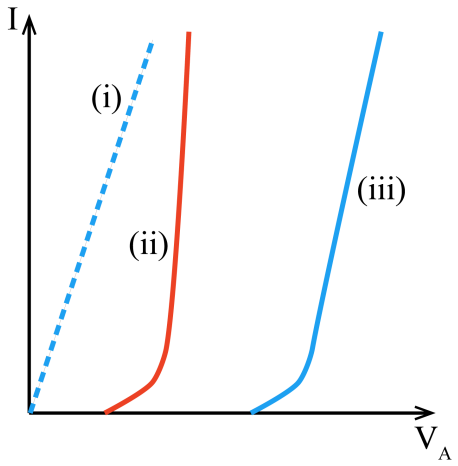


Figure 2: IV characteristics

Identify the type of device and choose the correct option.

   A. (i) - schottky, (ii) - pn, (iii) - ohmic

   B. (i) - schottky, (ii) - ohmic, (iii) - pn

   C. (i) - pn, (ii) - ohmic, (iii) - schottky

   D. (i) - ohmic, (ii) - schottky, (iii) - pn

   E. (i) - pn, (ii) - schottky, (iii) - ohmic

   F. (i) - ohmic, (ii) - pn, (iii) - schottky

9. (1 mark) The I-V characteristics for two Schottky diodes (i), (ii) are shown in the figure 3 below. Let $|\Phi_B|_i$ and $|\Phi_B|_{ii}$ be the barrier heights for Schottky diodes (i) and (ii), respectively; similarly, $|J_s|_i$ and $|J_s|_{ii}$ be the saturation current densities, respectively.

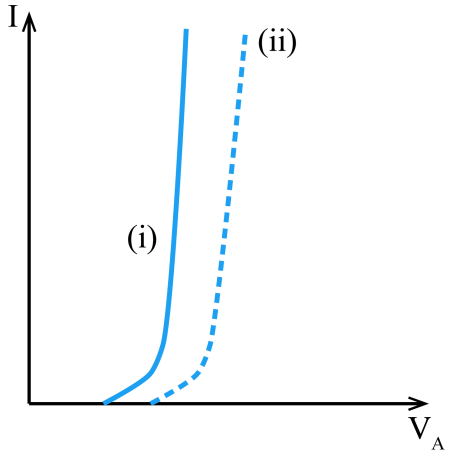


Figure 3: Two Schottky diodes

What can you interpret about the devices from their IV characteristics?

A. $|\Phi_B|_i > |\Phi_B|_{ii}$

B. $|\Phi_B|_i < |\Phi_B|_{ii}$

C. $|\Phi_B|_i = |\Phi_B|_{ii}$

D. $|J_s|_i > |J_s|_i$

E. $|J_s|_i < |J_s|_i$

F. $|J_s|_i = |J_s|_i$

Review equations 7 & 8.
Since $|\Phi_B|_i$ is smaller it turn on at lower voltage.
Eq 8 implies $|J_{s,i}| > |J_{s,ii}|$

10. (4 marks) A simplified band diagrams for MOSCAP are shown in the figure 4 below. Match the energy band diagrams labelled from $1 \rightarrow 3$, with the corresponding substrate type, applied gate voltage V_g, and the bias condition.

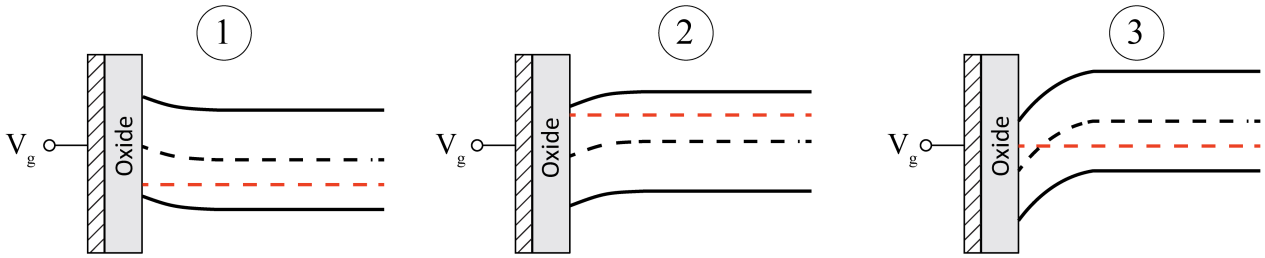


Figure 4: MOSCAP 1

(a) (*2 marks*) Identify the type of substrate and thereby MOSCAP for each of the band diagram.

A. ①→ p-type, PMOS ②→ p-type, PMOS ③→ p-type, PMOS

B. ①→ n-type, NMOS ②→ n-type, NMOS ③→ n-type, NMOS

C. ①→ p-type, NMOS ②→ n-type, PMOS ③→ p-type, PMOS

D. ①→ n-type, NMOS ③→ n-type, PMOS ③→ p-type, PMOS

E. ①→ p-type, NMOS ②→ n-type, PMOS ③→ p-type, NMOS

F. ①→ p-type, PMOS ②→ n-type, NMOS ③→ p-type, PMOS

(b) (*2 marks*) Identify the sign of applied gate voltage V_g and the bias condition for each of the band diagram.

A. ① → +ve, inversion ②→ -ve, depletion ③→ +ve, accumulation

B. ① → -ve, inversion ②→ -ve, accumulation ③→ +ve, accumulation

C. ①→ -ve, accumulation ②→ +ve, accumulation ③→ +ve, inversion

D. ①→ -ve, inversion ②→ +ve, accumulation ③→ +ve, inversion

E. ① → +ve, inversion ②→ -ve, accumulation ③→ +ve, depletion

F. ① → +ve, accumulation ②→ -ve, accumulation ③→ +ve, accumulation

Review lecture videos and review material. Analyze why each of the other choices are wrong for clearer understanding.

11. (4 marks) A simplified band diagrams for MOSCAP are shown in the figure 5 below. Match the energy band diagrams labelled from $1 \rightarrow 3$, with the corresponding substrate type, applied gate voltage V_g, and the bias condition.

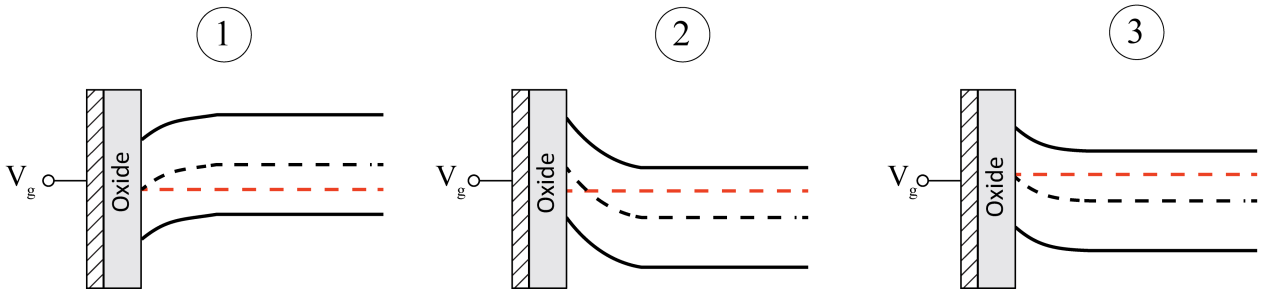


Figure 5: MOSCAP 2

(a) (*2 marks*) Identify the type of substrate and thereby MOSCAP for each of the band diagram.

A. ①→ p-type, PMOS ②→ p-type, PMOS ③→ p-type, PMOS

B. ①→ n-type, NMOS ②→ n-type, NMOS ③→ n-type, NMOS

C. ①→ n-type, NMOS ③→ n-type, PMOS ③→ p-type, PMOS

D. ①→ p-type, NMOS ②→ n-type, PMOS ③→ n-type, PMOS

E. ①→ p-type, NMOS ②→ n-type, PMOS ③→ p-type, NMOS

F. ①→ p-type, PMOS ②→ n-type, NMOS ③→ p-type, PMOS

(b) (*2 marks*) Identify the sign of applied gate voltage V_g and the bias condition for each of the band diagram.

A. ① → +ve, inversion ②→ -ve, depletion ③→ +ve, accumulation

B. ① → -ve, inversion ②→ -ve, accumulation ③→ +ve, accumulation

C. ①→ -ve, accumulation ②→ +ve, accumulation ③→ +ve, inversion

D. ①→ -ve, inversion ②→ +ve, accumulation ③→ +ve, inversion

E. ① → +ve, accumulation ②→ -ve, accumulation ③→ +ve, accumulation

F. ① → +ve, depletion ②→ -ve, inversion ③→ -ve, depletion