A quick recap of the material covered in lectures

MOS Electrostatics

In a MOS capacitor, a lot could be understood from the band bending in the semiconductor, If ϕ_s is the potential at the surface, and $\phi = 0$ is the potential in the bulk, then $-q\phi_s$ is the total band bending in the semiconductor. A negative ϕ_s means the bands bend up, and a positive ϕ_s means the bands bend down. ϕ_s is given as

$$\boxed{\phi_s = E_{i,bulk} - E_{i,surface}} \tag{1}$$

An important material parameter related to the semiconductor doping; namely ϕ_F is

$$\boxed{\phi_F = E_{i,bulk} - E_F} \tag{2}$$

The sign of ϕ_F indicates the doping type, *i.e.*,$\phi_F > 0$ for p-type $\phi_F < 0$ for n-type.

$$\phi_F = \begin{cases} \frac{kT}{q}\, ln(N_A/n_i) & \text{p-type} \\ -\frac{kT}{q}\, ln(N_D/n_i) & \text{n-type} \end{cases}$$

The parameters ϕ_s and ϕ_F are extensively useful in specifying the biasing state inside the semiconductor. Clearly at flatband conditions $\phi_s = 0$. Moreover, $\boxed{\phi_s = 2\phi_F}$ at the depletion-inversion transition point. With $\phi_F > 0$ in a p-type semiconductor, it follows that

$$\text{Biasing condition} \rightarrow \begin{cases} \text{Accumulation} & \phi_s < 0 \\ \text{Depletion} & 0 < \phi_s < \phi_F \\ \text{Inversion} & \phi_s > \phi_F \end{cases}$$

For an n-type semiconductor the inequalities are merely reversed.

In the standard depletion approximation the actual depletion charge is replaced with a squared-off distribution terminated abruptly a distance $x = W$ into the semiconductor. Assuming p-type semiconductor and invoking the depletion approximation, we have the following important formulae:

1. **Electric field $\mathscr{E}$** -

$$\boxed{\mathscr{E}(x) = \frac{qN_A}{\epsilon_s}(W - x)} \qquad (0 \le x \le W) \tag{3}$$

2. **Electrostatic potential** ϕ -

$$\boxed{\phi(x) = \frac{qN_A}{\epsilon_s}\,(W-x)^2} \qquad (0 \leq x \leq W) \tag{4}$$

3. **Surface potential** ϕ_s **at** $x = 0$ -

$$\boxed{\phi_s = \frac{qN_A}{\epsilon_s\epsilon_0}\,W^2} \tag{5}$$

4. **Depletion Width** W -

$$\boxed{W = \left[\frac{2\epsilon_s\epsilon_0}{qN_A}\;\phi_s\right]^{1/2}} \tag{6}$$

5. **Maximum depletion Width** W_{max} -

$$\boxed{W_{max} = \left[\frac{2\epsilon_s\epsilon_0}{qN_A}\;(2\phi_F)\right]^{1/2}} \tag{7}$$

Gate Voltage Relationship

The external applied gate voltage V_G in the ideal structure is dropped partly across the oxide and partly across the semiconductor, or symbolically, $V_G = \Delta\phi_{ox} + \phi_s$,

$$\boxed{V_G = \frac{\epsilon_s}{\epsilon_0}\;x_0\;\mathscr{E}_s + \phi_s} \tag{8}$$

A combination of Eq. 3 and Eq. 6 gives

$$\boxed{\mathscr{E}_s = \left[\frac{2qN_A}{\epsilon_s\epsilon_0}\;\phi_s\right]^{1/2}} \tag{9}$$

Thus, the final $V_G - \phi_s$ dependence is given by the Eq. 10 -

$$\boxed{V_G = \frac{\epsilon_s}{\epsilon_0}\;x_0\,\sqrt{\frac{2qN_A}{\epsilon_s\epsilon_0}\;\phi_s} + \phi_s} \tag{10}$$

There are certain important features of the gate voltage relationship:

- ϕ_s is a rather rapidly varying function of V_G when the device is biased in depletion regime. This implies the gate voltage divides proportionally between the oxide and the semiconductor under depletion biasing.
- However, when the semiconductor is accumulated ($\phi_s < 0$) or inverted ($\phi_s > 2\phi_F$), it takes a large change in gate voltage to produce a small change in ϕ_s. Under accumulation and inversion biasing, changes in the applied potential are dropped almost totally across the oxide.

Solve the following questions. There are 12 questions, for a total of 25 marks.

1. (1 mark) At threshold, the surface potential $\phi_s =$ ______

   A. $\phi_F/2$

   B. ϕ_F

   C. $3\phi_F/2$

   D. $2\phi_F$

   E. $5\phi_F/2$

   F. 0

2. (1 mark) MOSCAP is said to be in inversion when ______ carrier concentration at the surface equals or exceeds the ______ carrier concentration in the bulk.

   A. majority, majority

   B. minority, majority

   C. majority, minority

   D. minority, minority

3. (1 mark) For a MOS capacitor, in strong inversion, the surface charge density ____________ with surface potential.

   A. decreases exponentially

   B. increases exponentially

   C. decreases linearly

   D. increases linearly

   E. remains unchanged

4. (1 mark) A MOS capacitor can be represented as ____________

   A. two constant capacitors in series.

   B. two constant capacitors in parallel.

   C. one constant and one bias dependent capacitor in series.

   D. one constant and one bias dependent capacitor in parallel.

   E. two bias dependent capacitors in series.

5. (1 mark) What is a typical thickness of SiO_2 layer in modern MOS technology?

   A. $0.1 - 0.2\ nm$

   B. $1 - 2\ nm$

   C. $5 - 6\ nm$

   D. $10 - 20\ nm$

   E. $100 - 200\ nm$

6. (9 marks) The energy band diagram of a MOSCAP device is sketched in the figure 1 below. Assume that the electrostatic potential is zero in the semiconductor bulk, (*i.e.* at large distance from Si-SiO_2 interface) and that there is no metal-semiconductor workfunction difference. Assume the relative dielectric constant of the oxide to be $\epsilon_{ox} = 3.9$. (Take $n_i = 10^{10}\ cm^{-3}$, $kT = 26\ meV$, $E_g = 1.1\ eV$, $\epsilon_s = 11.8$)

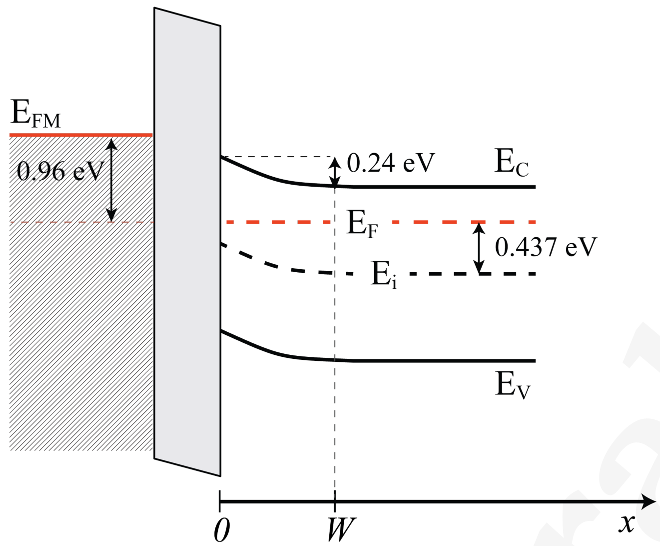


Figure 1: Energy band diagram of MOSCAP

(a) (*1 mark*) What is the value of ϕ_F?

A. $-0.24\ V$

B. $0.24\ V$

C. $0.437\ V$

D. $-0.437\ V$

E. $0.96\ V$

F. $-0.96\ V$

From Eq 2 of review material,
$\phi_F = E_{i,bulk} - E_F$
$= -0.437\ eV$ (ϕ_F is -ve for n-doping)

(b) (*1 mark*) What is the surface potential, ϕ_s ?

A. $-0.24\ V$

B. $0.24\ V$

C. $0.437\ V$

D. $-0.437\ V$

E. $0.96\ V$

F. $-0.96\ V$

From Eq 1 of review material,
$\phi_s = E_{i,bulk} - E_{i,surface}$
$= -0.24\ V$ (-ve when bands bend up)

(c) (*1 mark*) What is the applied gate voltage, V_G?

A. $-0.24\ V$

B. $0.24\ V$

C. $0.437\ V$

D. $-0.437\ V$

E. $0.96\ V$

F. $-0.96\ V$

Metal Fermi level moves up relative to semiconductor Fermi level when a negative bias is applied. Since the difference is 0.96eV the applied gate voltage must be -0.96V

(d) (*1 mark*) What is the voltage across the oxide, V_{ox}?

A. $-1.2V$

B. $1.2V$

C. $0.437V$

D. $-0.437V$

E. $-0.72V$

F. $0.72V$

$V_G = V_{ox} + \phi_s$

$\Rightarrow V_{ox} = V_G - \phi_s$

$= -0.96V - (-0.24V)$

$= -0.72V$

(e) (*1 mark*) What is the doping density, N_D in cm^{-3}?

A. 2×10^{15}

B. 2×10^{16}

C. 2×10^{17}

D. 2×10^{18}

E. 2×10^{19}

F. 1×10^{10}

$\phi_F = \frac{kT}{q} \ln\left(\frac{N_D}{n_i}\right)$

$0.437 = 0.026 \times \ln\left(\frac{N_D}{10^{10}}\right)$

$\therefore N_D = 2 \times 10^{17}\ cm^{-3}$

(f) (*1 mark*) What is the width of the depletion region, W?

A. $39.5\ \mu m$

B. $3.95\ \mu m$

C. $3.95\ nm$

D. $395\ \mu m$

E. $39.5\ nm$

F. $395\ nm$

From Eq 6 of review material

$W = \left[\frac{2\epsilon_0 \epsilon_s}{qN_D}\phi_s\right]^{1/2}$

$= \sqrt{\frac{2 \times 8.85 \times 10^{-14} \times 11.8}{1.602 \times 10^{-19} \times 2 \times 10^{17}} \times 0.24}$

$= 3.957 \times 10^{-6}\ cm$

$= 39.57\ nm$

(g) (*1 mark*) What is the maximum electric field on semiconductor side of Si-SiO_2 interface in (V/cm), $\mathscr{E}_s$?

A. -1.21×10^7

B. 1.21×10^7

C. -1.21×10^4

D. 1.21×10^4

E. -1.21×10^5

F. 1.21×10^5

Eq 9 of review material

$$\mathscr{E}_s = \left[\frac{2qN_D}{\epsilon_s \epsilon_0}\phi_s\right]^{1/2}$$

$$= \sqrt{\frac{2 \times 1.602 \times 10^{-19} \times 2 \times 10^{-7} \times 0.2\,V}{8.85 \times 10^{-14}\,F/cm \times 11.8}}$$

$$= -121278.26\,V/cm$$

$$= -1.21 \times 10^5\,V/cm$$

-ve sign of the E field indicates direction of E field w.r.t +ve x

(h) (*1 mark*) What is the maximum electric field on oxide side of Si-SiO$_2$ interface, $\mathscr{E}_{ox}$ in V/cm?

A. -4×10^4

B. 4×10^4

C. -3.66×10^5

D. 3.66×10^5

E. -1.21×10^5

F. 1.21×10^5

$$\epsilon_{ox}\mathscr{E}_{ox} = \epsilon_{si}\mathscr{E}_{si}$$

$$\mathscr{E}_{ox} = \frac{\epsilon_{si}}{\epsilon_{ox}}\mathscr{E}_{si}$$

$$= \frac{11.8}{3.9} \times -1.21 \times 10^5$$

$$\mathscr{E}_{ox} = -3.66 \times 10^5\,V/cm$$

(i) (*1 mark*) What is the thickness of the oxide t_{ox}?

A. $196\ \mu m$

B. $196\ nm$

C. $1.96\ \mu m$

D. $1.96\ nm$

E. $19.6\ \mu m$

F. $19.6\ nm$

$$V_{ox} = \mathscr{E}_{ox} t_{ox}$$

$$\therefore t_{ox} = \frac{V_{ox}}{\mathscr{E}_{ox}}$$

$$= \frac{-0.72}{-3.66 \times 10^5}$$

$$t_{ox} = 1.967 \times 10^{-6}\,cm$$

$$= 19.67\,nm$$

7. (2 marks) Match the energy band diagrams with the corresponding charge block diagrams shown in figure 2 considering ideal MOS structure. Also state the biasing condition in each of the case.

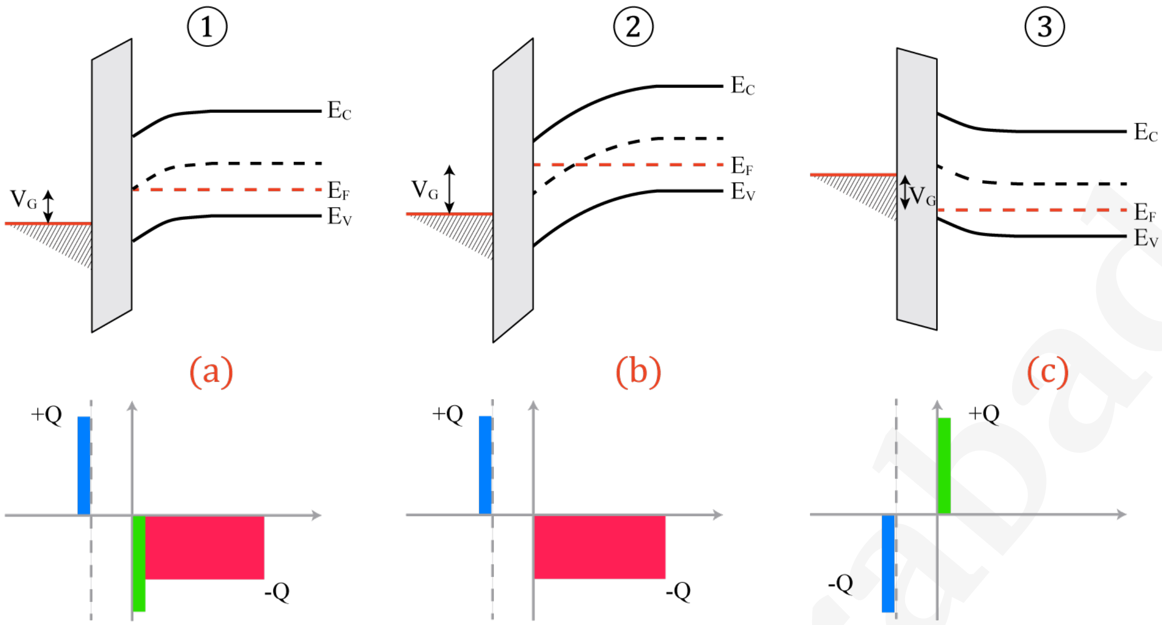


Figure 2: Energy band and charge block diagrams

A. ① → (c), depletion ②→ (a), inversion ③→ (b), accumulation

B. ① → (a), inversion ②→ (b), depletion ③→ (c), accumulation

C. ① → (b), depletion ②→ (a), inversion ③→ (c), accumulation

D. ① → (c), accumulation ②→ (a), inversion ③→ (a), depletion

E. ① → (b), depletion ②→ (c), accumulation ③→ (a), inversion

F. ① → (b), accumulation ②→ (a), inversion ③→ (c), depletion

8. (1 mark) Match the charge density profiles shown in the following figure 3 with the corresponding biasing condition. Assume substrate is p-type.

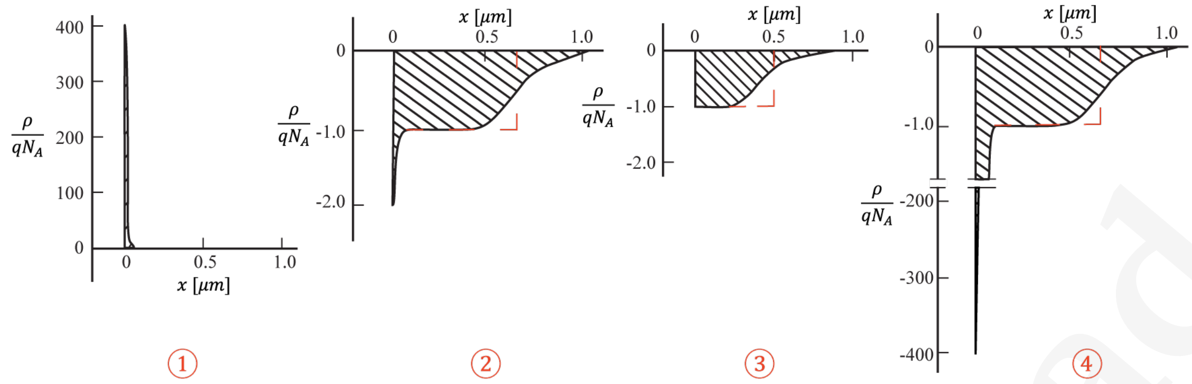


Figure 3: Charge density profile

A. ① → inversion ② → depletion ③ → flatband ④ → onset of accumulation

B. ① → accumulation ② → onset of depletion ③ → inversion ④ → deep depletion

C. ① → accumulation ② → inversion ③ → depletion ④ → onset of inversion

D. ① → depletion ② → flatband ③ → deep depletion ④ → accumulation

E. ① → accumulation ② → onset of inversion ③ → depletion ④ → inversion

F. ① → flatband ② → accumulation ③ → depletion ④ → inversion

9. (1 mark) Identify the surface potential ranges corresponding to accumulation, depletion, and inversion in ideal PMOS devices (figure 4).

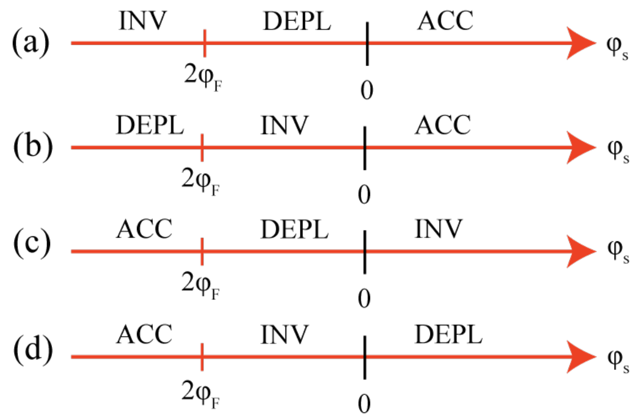


Figure 4: Surface potential

A. (a)

B. (b)

C. (c)

D. (d)

10. (1 mark) The charge block diagram of a semiconductor is shown in figure 5 below

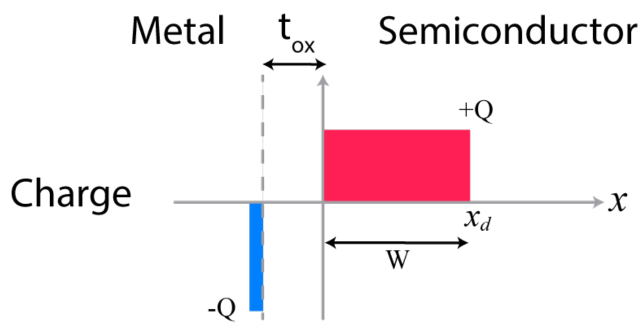
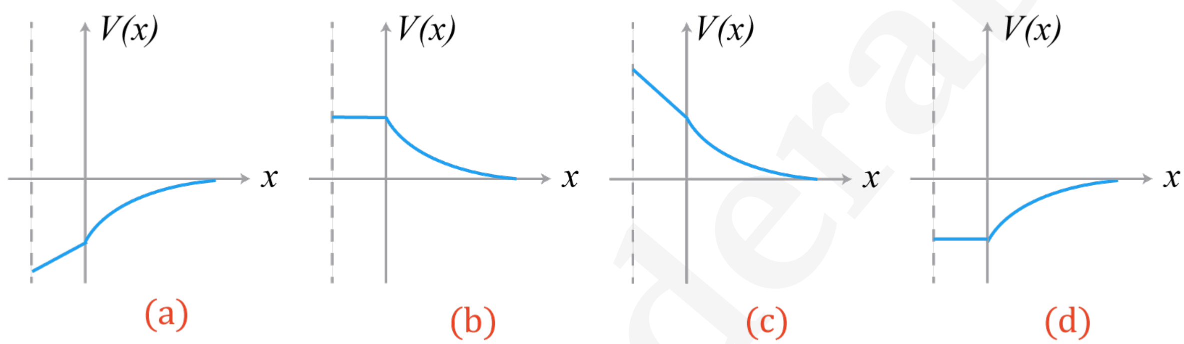


Figure 5: MOSCAP charge block diagram

Which is the correct electrostatic potential plot corresponding to given charge diagram?



A. (a)

B. (b)

C. (c)

D. (d)

11. (2 marks) The charge block diagram of a semiconductor is shown in figure 6 below

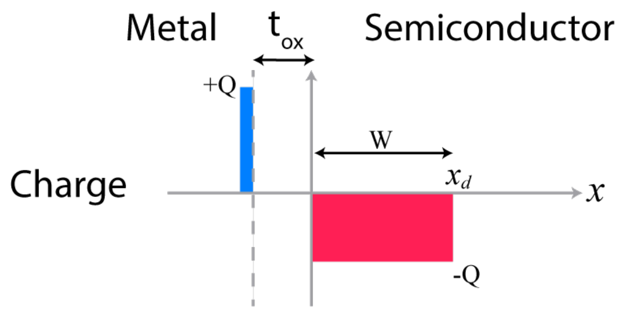
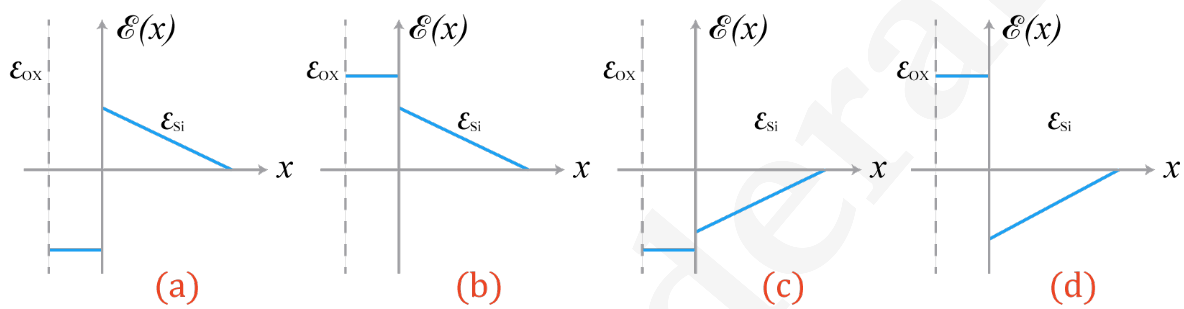


Figure 6: MOSCAP charge diagram

(a) (*1 mark*) Which is the correct E-field plot corresponding to given charge diagram?



A. (a)

B. (b)

C. (c)

D. (d)

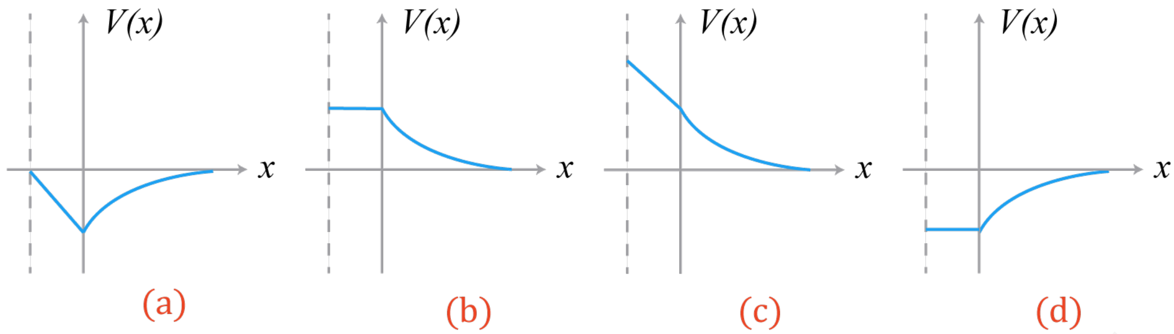
(b) (*1 mark*) Which is the correct electrostatic potential plot corresponding to given charge diagram?

A. (a)

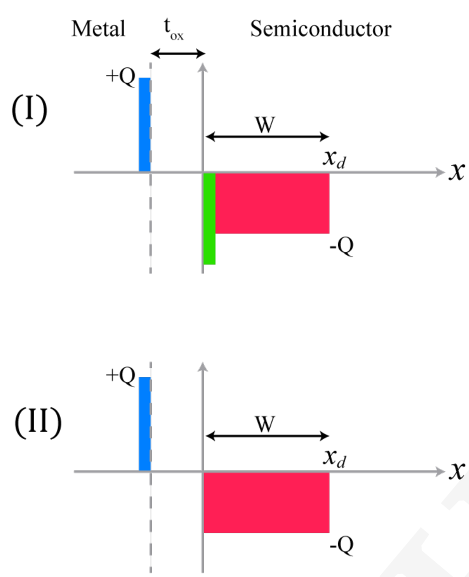
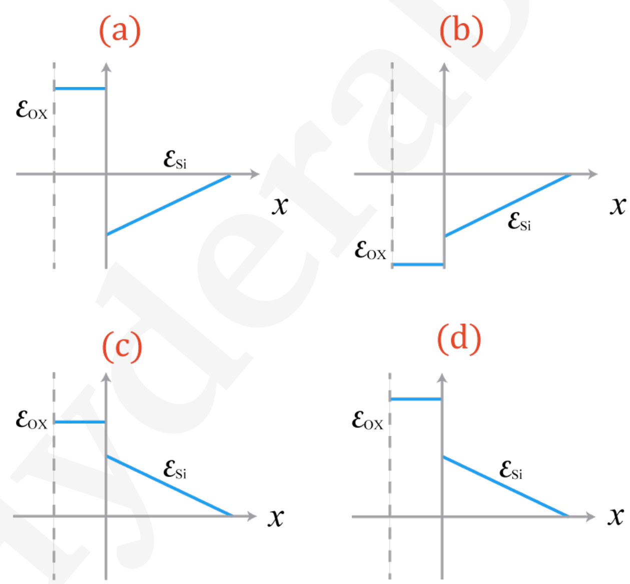
B. (b)

C. (c)

D. (d)



12. (4 marks) The table below shows the different charge profile diagrams of a MOSCAP on the left, along with the possible electric field plots on the right.

Charge block diagram	E Field
	

(a) (*2 marks*) Identify the biasing condition for charge diagrams shown in the left column

A. (I) → Inversion (II) → Depletion

B. (I) → Depletion (II) → Inversion

C. (I) → Accumulation (II) → Depletion

D. (I) → Inversion (II) → Accumulation

E. (I) → Depletion (II) → Accumulation

F. (I) → Flatband (II) → Inversion

(b) (*2 marks*) Match the correct charge diagrams (qualitatively) to the corresponding E-field plots.

A. (I) $\rightarrow$ (a) (II) $\rightarrow$ (b)

B. (I) $\rightarrow$ (c) (II) $\rightarrow$ (d)

C. (I) $\rightarrow$ (b) (II) $\rightarrow$ (c)

D. (I) $\rightarrow$ (d) (II) $\rightarrow$ (c)

E. (I) $\rightarrow$ (c) (II) $\rightarrow$ (b)

F. (I) $\rightarrow$ (a) (II) $\rightarrow$ (d)