EECS130
Integrated Circuit Devices

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10/09/2007

MOS Cap, Lecture 1

Reading: finish chapter16

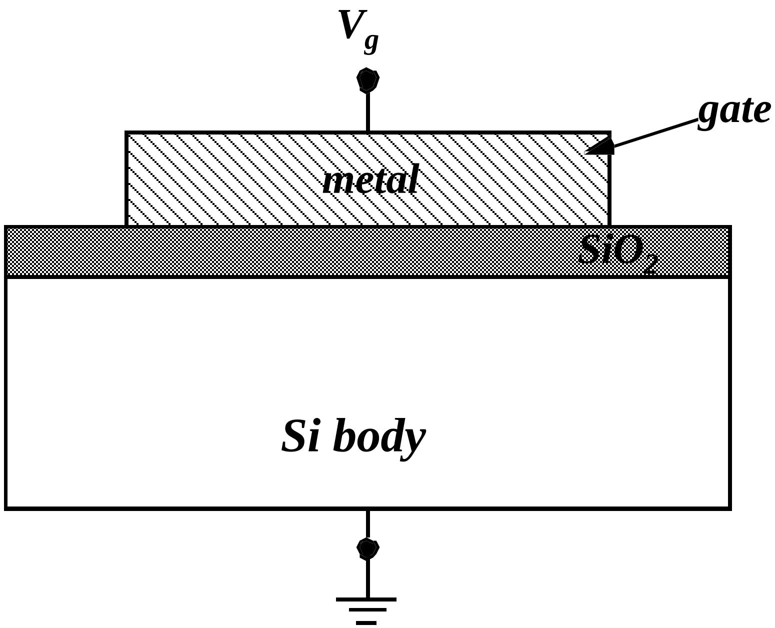
Announcements

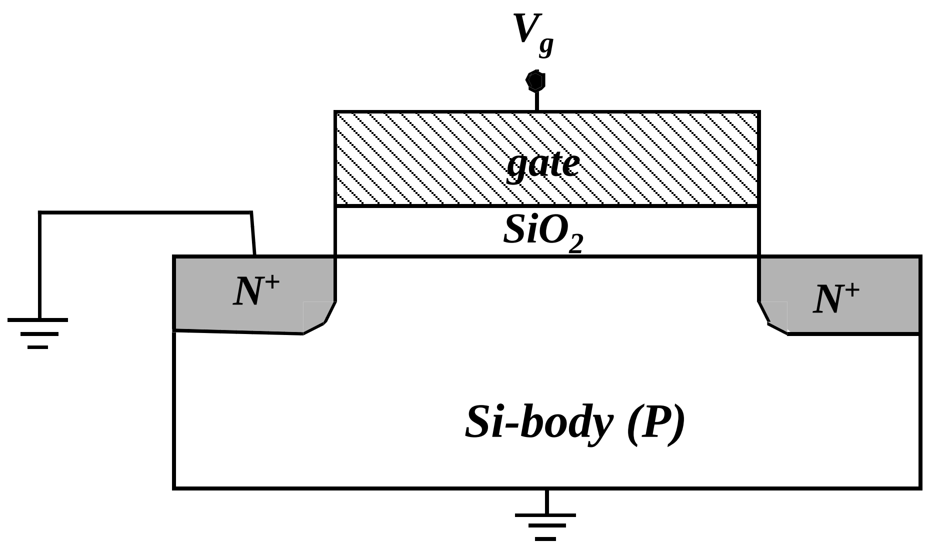
- Exam Results…

MOS Capacitors (MOSC)

Chapter 16

MOS: Metal-Oxide-Semiconductor





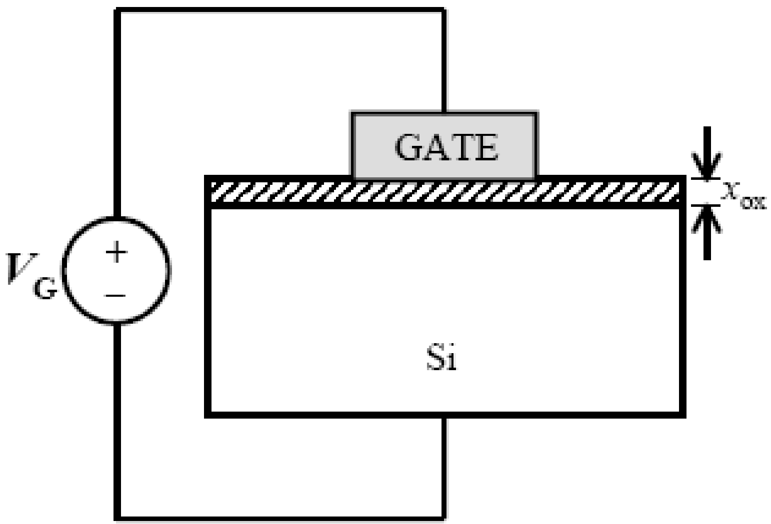
MOS capacitor

MOS transistor

MOS transistor is the most important device in modern microelectronics.

MOS Capacitor Structure

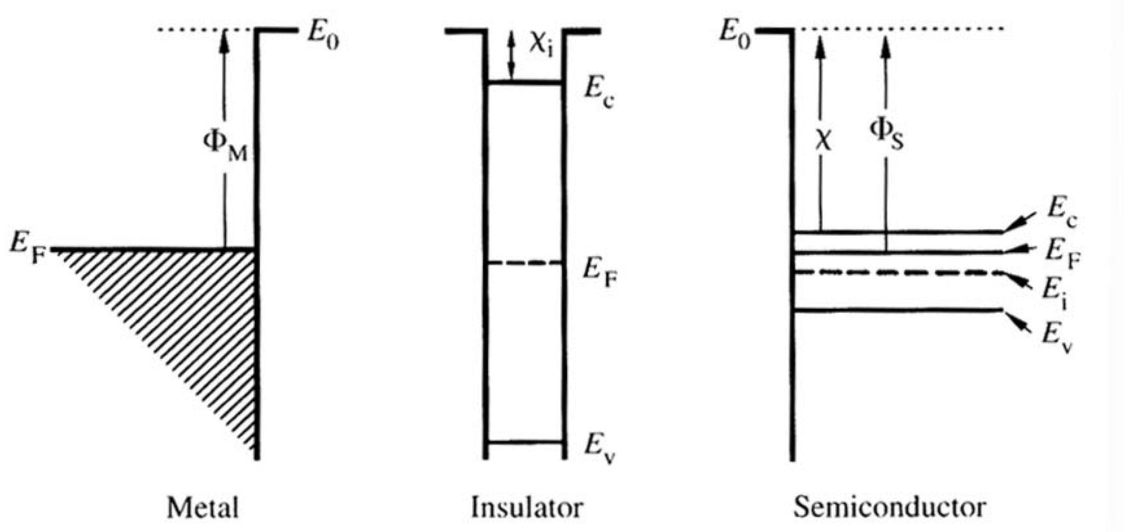
MOS capacitor (cross-sectional view)



- Typical MOS capacitors and transistors in ICs today employ
  - heavily doped polycrystalline Si ("poly-Si") film as the gate-electrode material
    - n^+-type, for "n-channel" transistors (NMOS)
    - p^+-type, for "p-channel" transistors (PMOS)
  - SiO_2 as the gate dielectric
    - band gap = 9 eV
    - $\varepsilon_{r,SiO2} = 3.9$
  - Si as the semiconductor material
    - p-type, for "n-channel" transistors (NMOS)
    - n-type, for "p-channel" transistors (PMOS)

Ideal MOS Capacitor

- Oxide has zero charge, and no current can pass through it.
- No charge centers are present in the oxide or at the oxide-semiconductor interface.
- Semiconductor is uniformly doped
- $\boldsymbol{\Phi_M = \Phi_S} = \chi + (E_C - E_F)_{FB}$



Ideal MOS Capacitor

At Equilibrium:

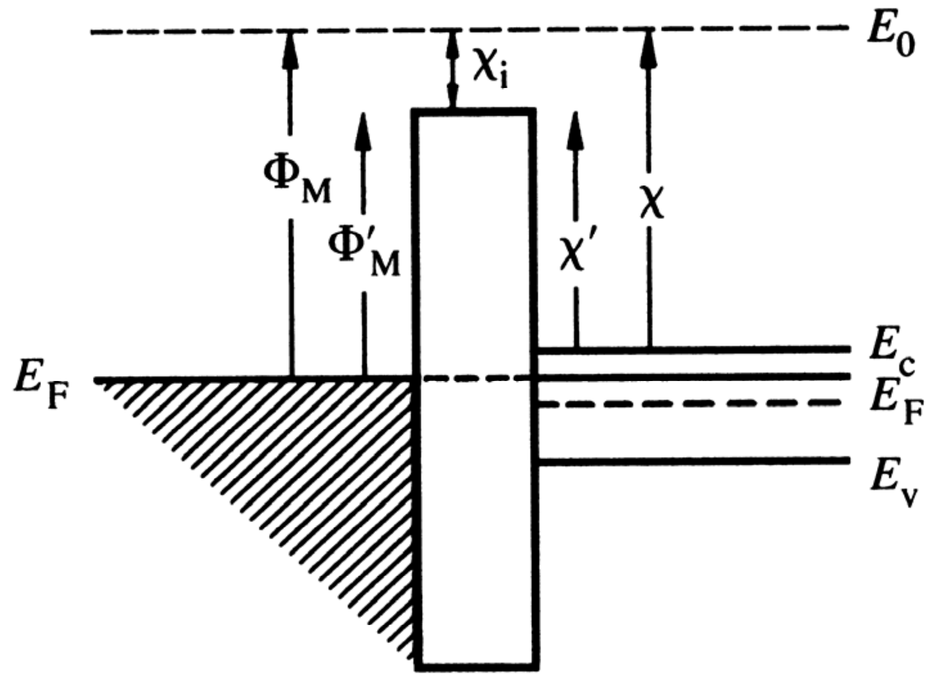


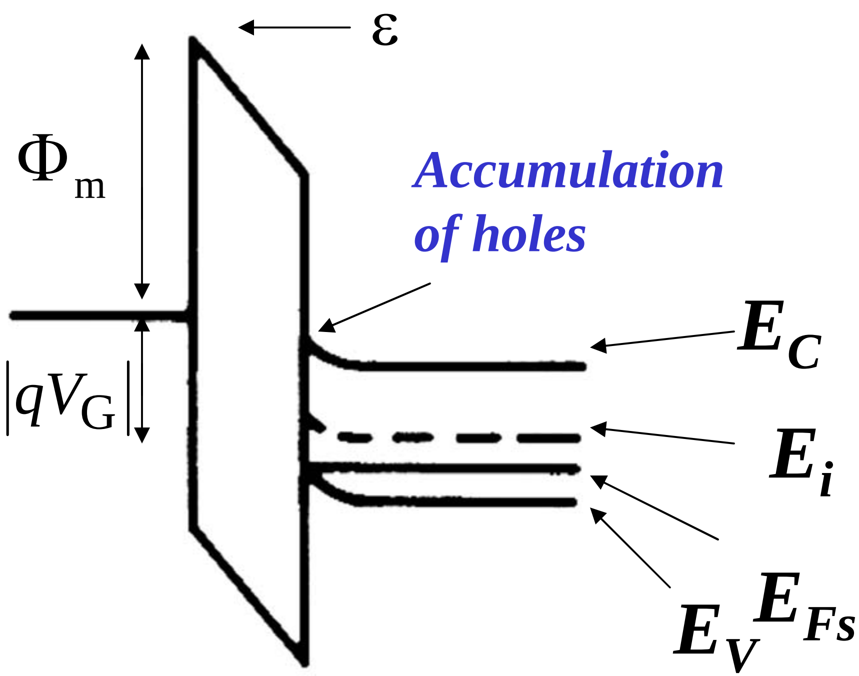
Figure 16.4

Ideal MOS Capacitor

Under Bias

- Let us ground the semiconductor and start applying different voltages, V_G, to the gate
- V_G can be positive, negative or zero with respect to the semiconductor
- $E_{F,\mathrm{metal}} - E_{F,\mathrm{semiconductor}} = -q\, V_G$
- Since oxide has no charge (it's an insulator with no available carriers or dopants), $\mathrm{d}\, E_{\mathrm{oxide}} / \mathrm{d}x = \rho/\varepsilon = 0$; meaning that the *E*-field inside the oxide is constant.

P-type Si, $V_G < 0$ (accumulation)

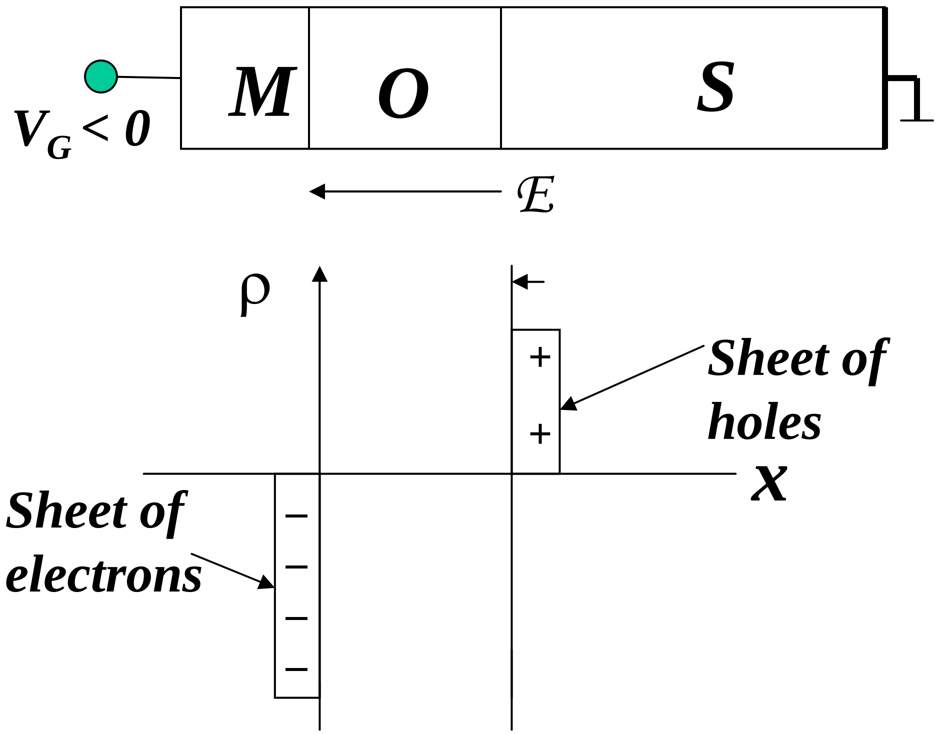


Negative voltage attracts holes to the Si-oxide interface. This is called accumulation condition. $E_i - E_F$ should increases near the surface of Si.

$$\frac{\partial \mathbf{E}_{\text{oxide}}}{\partial x} = 0 \quad \Rightarrow \quad \mathbf{E}_{\text{oxide}} = \text{const.}$$

- ***The oxide energy band has constant slope as shown.***
- ***No current flows in the SiO2 layer ➔ E_F in Si is constant.***

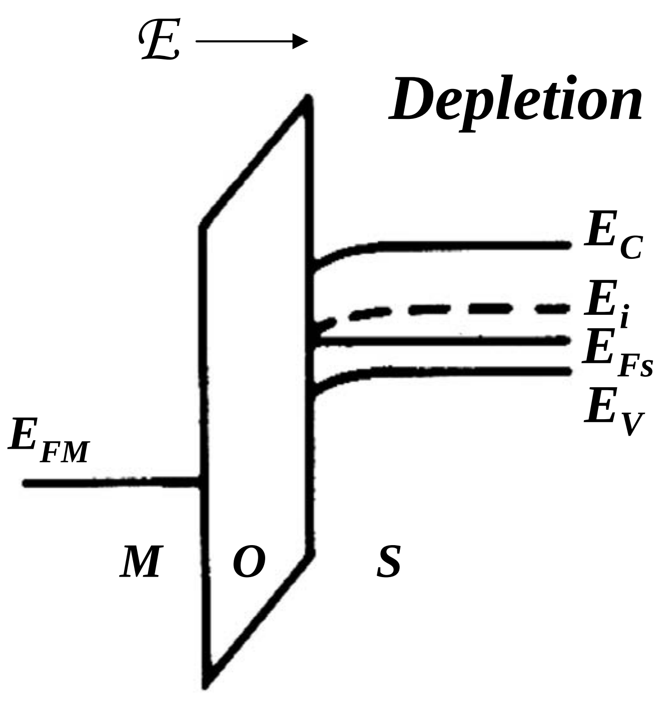
P-type Si, $V_G < 0$ (accumulation)

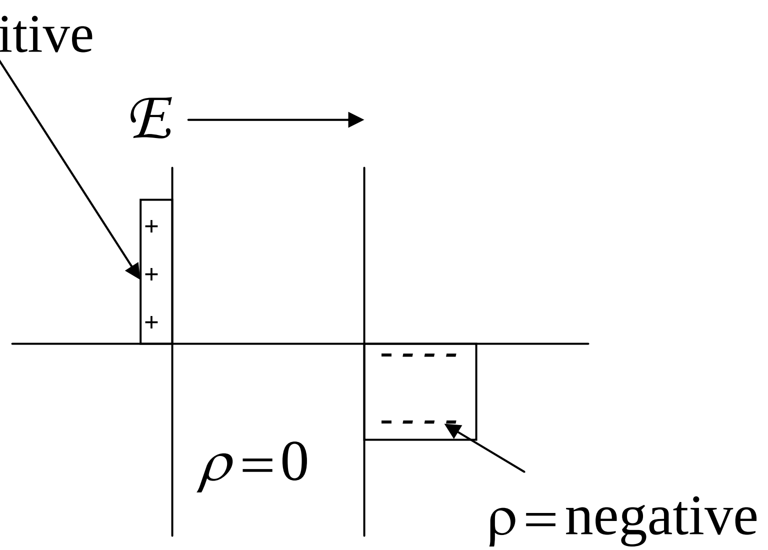


Accumulation of holes near silicon surface, and electrons near the metal surface.

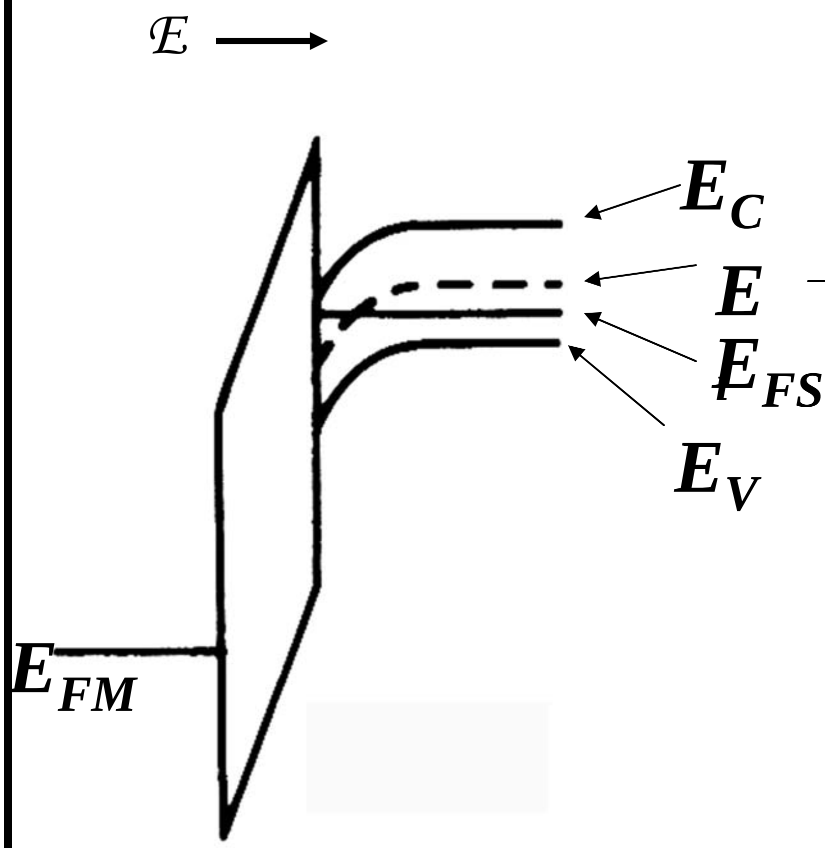
Similar to a parallel plate capacitor structure.

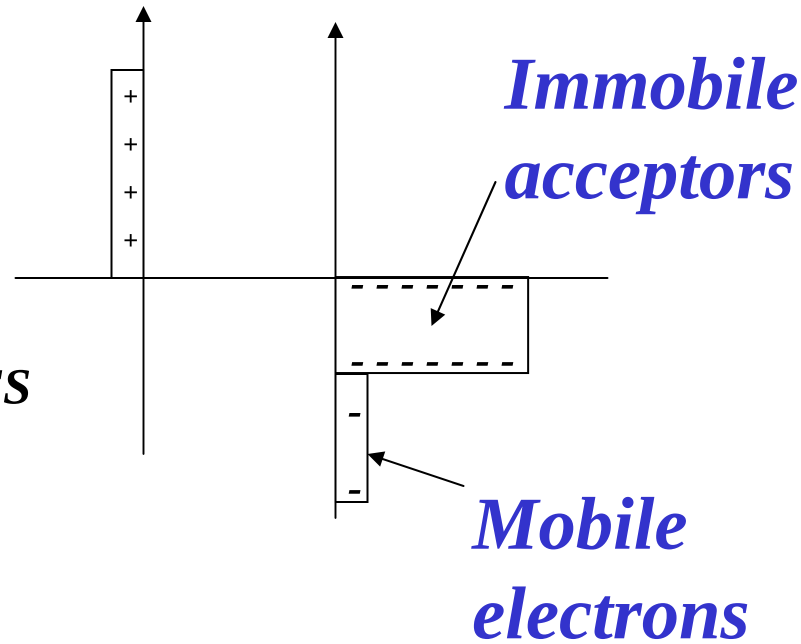
p-type Si, $V_G > 0$ (depletion)





p-type Si, $V_G >> 0$ (inversion)





Inversion condition

If we continue to increase the positive gate voltage, the bands at the semiconductor bends more strongly. At sufficiently high voltage, E_i can be below E_F indicating large concentration of electrons in the conduction band.

We say the material near the surface is "inverted". The "inverted" layer is not gotten by chemical doping, but by applying $\mathcal{E}$-field. Where did we get the electrons from?

When E_i(surface) – E_i(bulk) = 2 [E_F – E_i(bulk)], the condition is start of "inversion", and the voltage V_G applied to gate is called V_T (threshold voltage). For $V_G > V_T$, the Si surface is inverted.

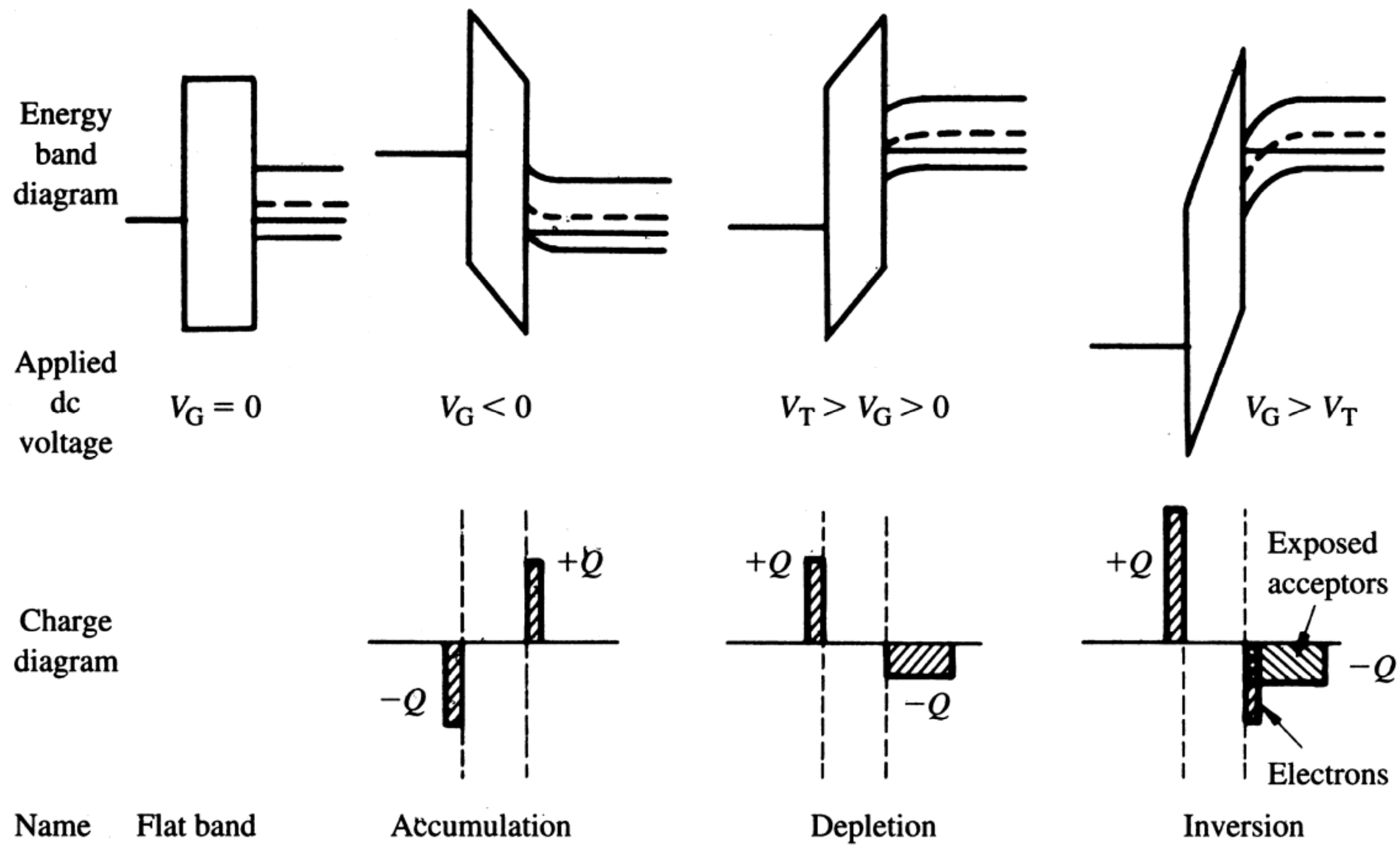
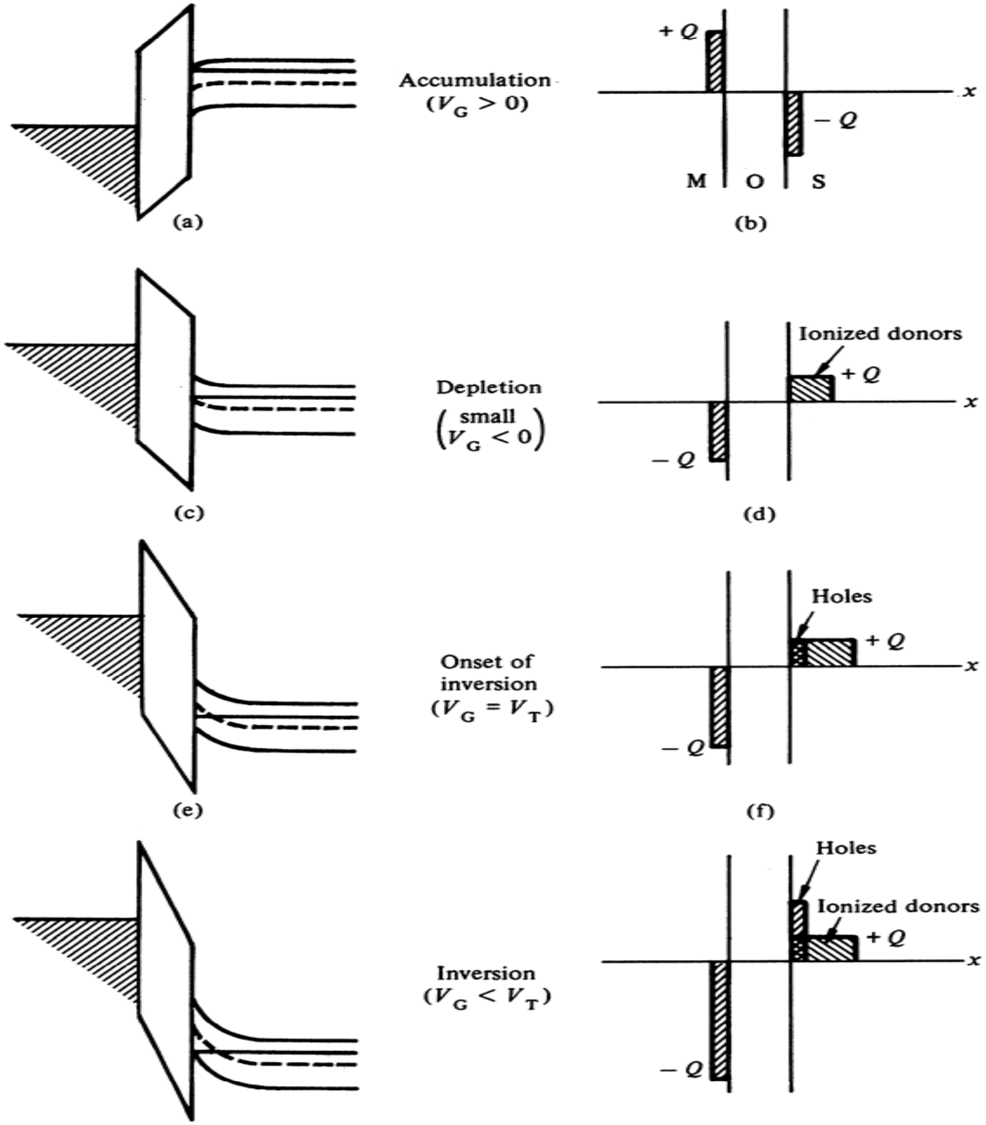
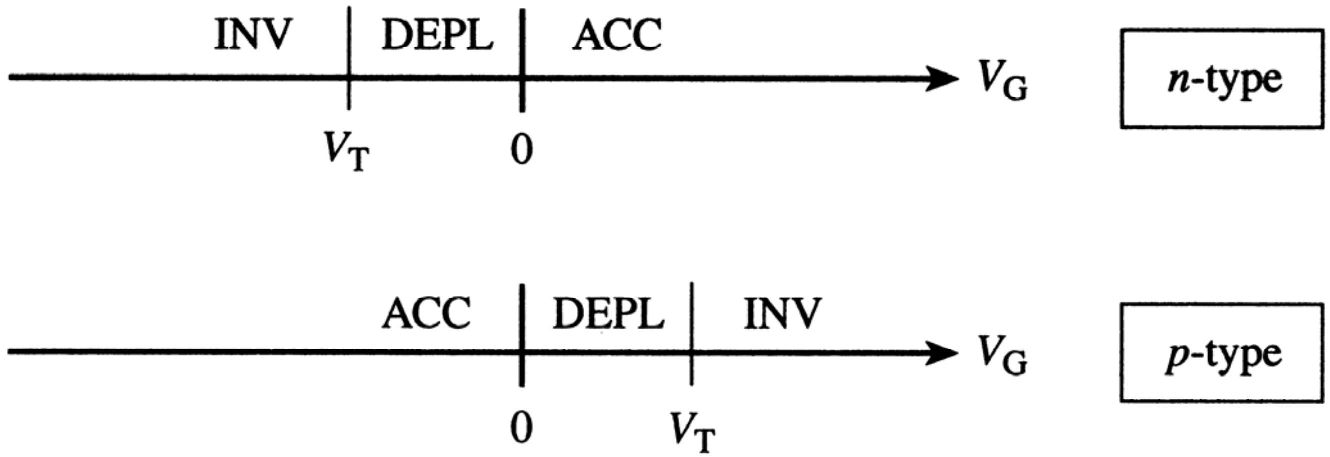

Energy band diagram
Applied dc voltage
$V_G = 0$
$V_G < 0$
$V_T > V_G > 0$
$V_G > V_T$
Charge diagram
+Q
−Q
+Q
−Q
+Q
Exposed acceptors
−Q
Electrons
Name
Flat band
Accumulation
Depletion
Inversion

Figure 16.6

Ideal MOS Capacitor – n-type Si




INV
DEPL
ACC
V_G
V_T
0
n-type
ACC
DEPL
INV
V_G
0
V_T
p-type

Electrostatic potential, $\phi(x)$

Define a new term, $\phi(x)$ taken to be the potential inside the semiconductor at a given point x. [The symbol ϕ instead of V used in MOS work to avoid confusion with externally applied voltage, V]

$$\phi(x) = \frac{1}{q}[E_\mathrm{i}(\mathrm{bulk}) - E_\mathrm{i}(x)]$$

Potential at any point x

$$\phi_\mathrm{S} = \frac{1}{q}[E_\mathrm{i}(\mathrm{bulk}) - E_\mathrm{i}(\mathrm{surface})]$$

Surface potential

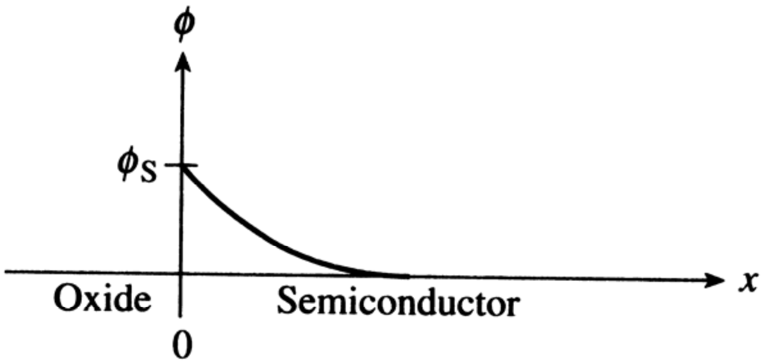
$$\phi_\mathrm{F} = \frac{1}{q}[E_\mathrm{i}(\mathrm{bulk}) - E_\mathrm{F}]$$

$|\phi_F|$ related to doping concentration

$\phi_F > 0$ means p-type

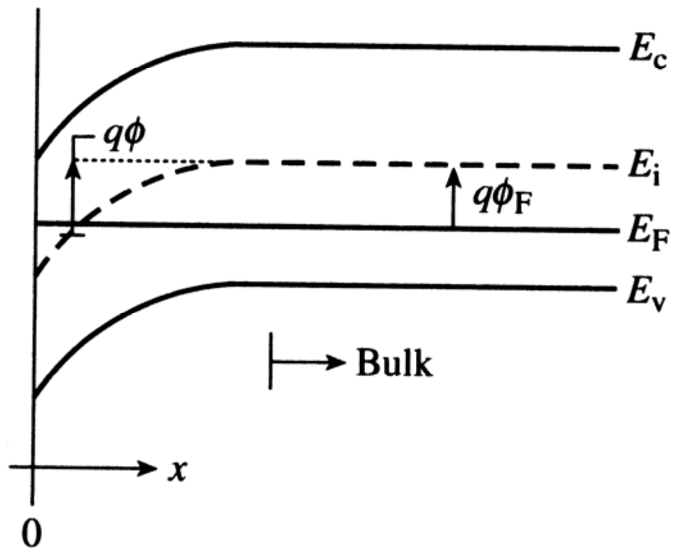
$\phi_F < 0$ means n-type

Electrostatic potential



(a)

ϕ_S is positive if the bands bend\ …….?



$\phi_S = 2\phi_F$ at the depletion-inversion transition point (threshold voltage)

Question

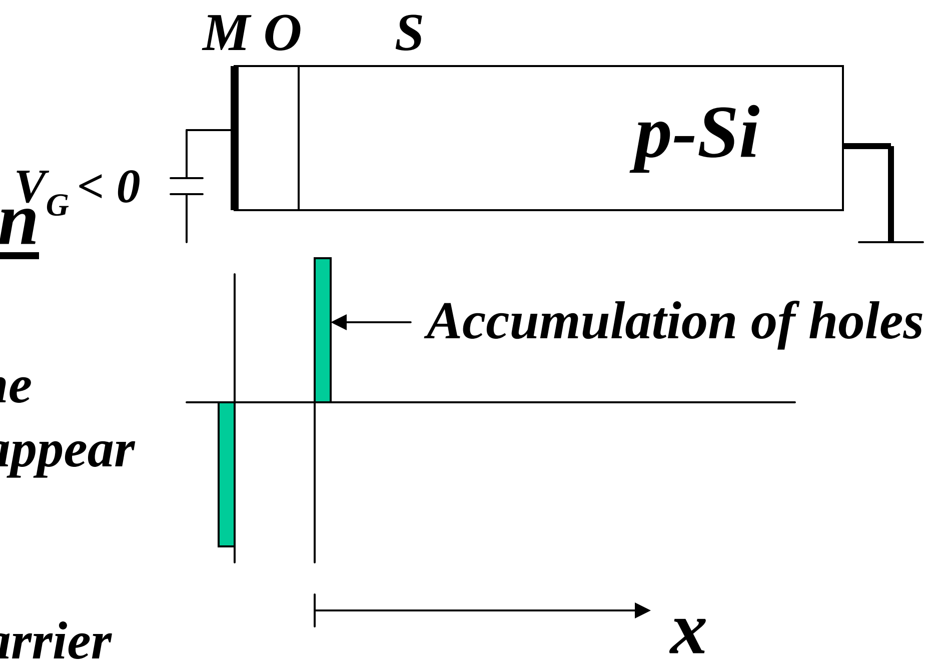
Consider the following ϕ_F and ϕ_S parameters. Indicate whether the semiconductor is p-type or n-type, specify the biasing condition, and draw the energy band diagram at the biasing condition.

(i) $\phi_F = 12\ kT/q$; $\phi_S = 12\ kT/q$

(ii) $\phi_F = -9\ kT/q$; $\phi_S = -18\ kT/q$

Charge Density - Accumulation

p-type silicon
accumulation condition



The accumulation charges in the semiconductor are ……. , and appear close to the surface and fall-off rapidly as x increases.
One can assume that the free carrier concentration at the oxide-semiconductor interface is a δ-function.

Charge on metal = $-Q_M$

Charge on semiconductor = $-$(charge on metal)

$|Q_{Accumulation}| = |Q_M|$

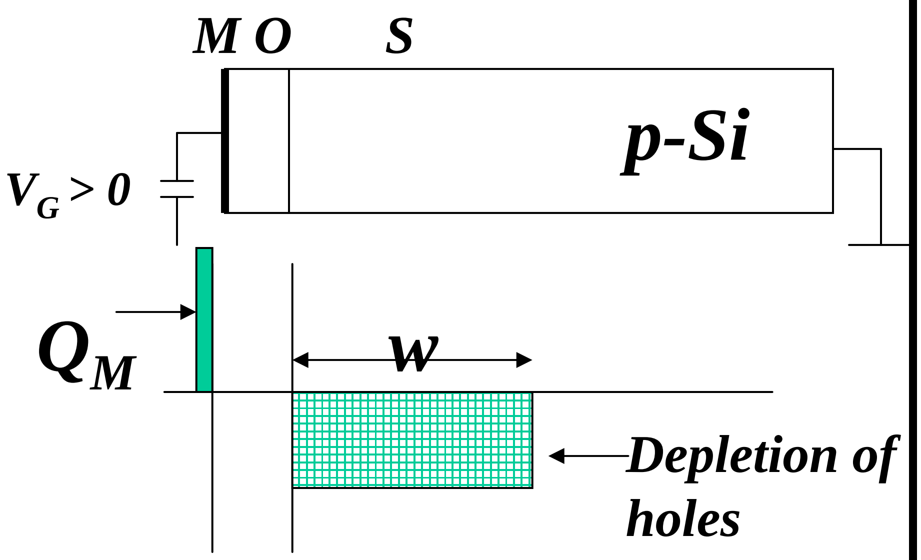
Charge Density - Depletion

p-type Si, depletion condition

The depletion charges in Si are immobile ions - results in depletion layer similar to that in pn junction or Schottky diode.

$$|q\,N_A\,A\,W| = |Q_M|$$

$$(-) \qquad\qquad (+)$$



If surface potential is ϕ_s, then the depletion layer width W will be

$$W = \sqrt{\frac{2\varepsilon_{\mathrm{Si}}}{qN_{\mathrm{A}}}\phi_{\mathrm{S}}}$$

Does this equation look familiar?

Charge Density - Depletion

For a p^+n junction, or a MS (n-Si) junction, the depletion layer width is given by:

$$W = \sqrt{\frac{2\varepsilon_{\mathrm{Si}}}{qN_{\mathrm{D}}} V_{\mathrm{bi}}}$$

Where V_{bi} is related to the amount of band bending. V_{bi} in Volts is numerically equal to the amount of band bending in eV.

$$\mathcal{E}_{\max} - \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} W = -\sqrt{\frac{2qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} V_{\mathrm{bi}}}$$

For MOS, the same equation applies, except that V_{bi} is replaced by ϕ_s.

$$\mathcal{E}_{\max}(\text{in Si}) = -\sqrt{\frac{2qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} |\phi_{\mathrm{s}}|} \quad \text{or} \quad \sqrt{\frac{2qN_{\mathrm{A}}}{\varepsilon_{\mathrm{Si}}} |\phi_{\mathrm{s}}|}$$

n-type ***p-type***

Question?

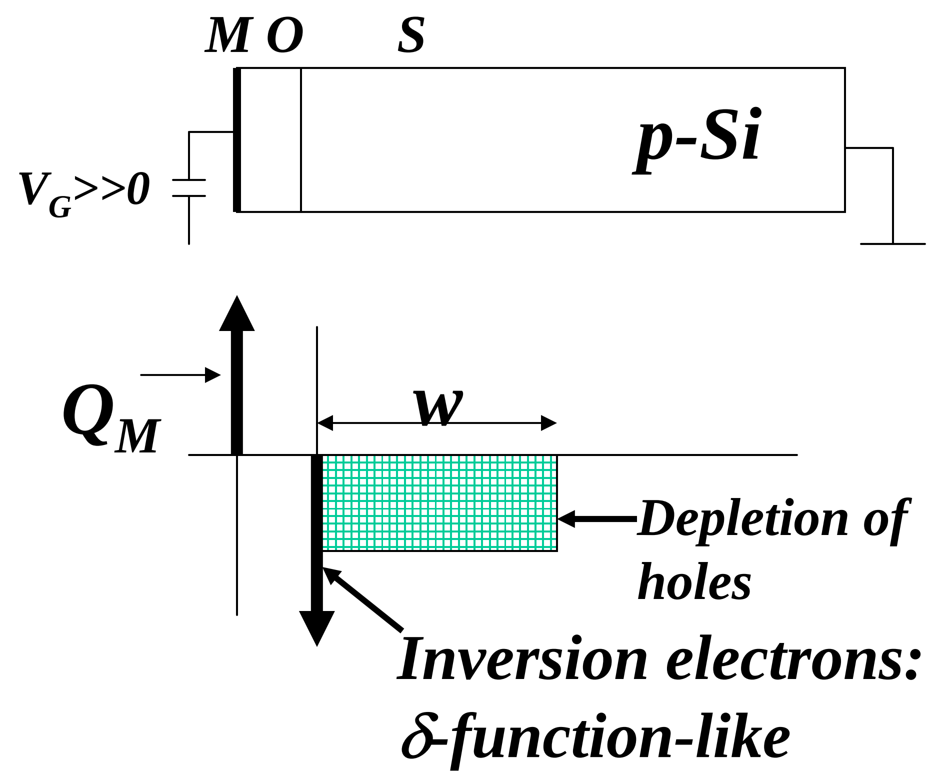
- *What V_g gives you the maximum possible depletion width in a MOSC?*

Charge Density - Inversion

p-type Si,

strong inversion

Once inversion charges appear, they remain close to the surface since they are …….. Any additional voltage to the gate results in extra Q_M in gate and get compensated by extra inversion electrons in semiconductor.



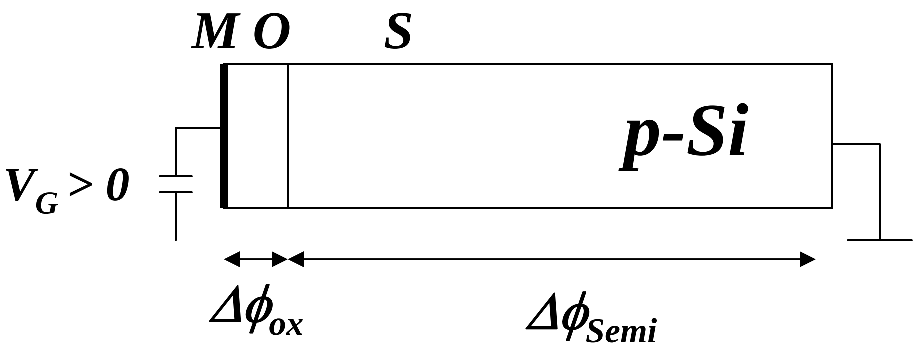
So, the depletion width does not change during inversion. Electrons appear as δ-function near the surface. Maximum depletion layer width $W = W_T$

Gate Voltage Relationship

Applied gate voltage will be equal to the voltage drop across the oxide (insulator) plus the voltage across the semiconductor.

<u>Consider p-type Si.</u>

$$V_G = \Delta\phi_{ox} + \Delta\phi_{Semi}$$



$$\Delta\phi_{Semi} = \phi(x=0) - \phi(bulk)$$
$$= \phi_S$$
$$\Delta\phi_{ox} = x_{ox}\,\mathcal{E}_{ox}$$

When is this equation valid?

Since the interface does not have any charges (idealized MOSC), we can say that:

$$\varepsilon_{ox}\,\mathcal{E}_{ox} = \varepsilon_{Si}\,\mathcal{E}_{Si}$$

$$\mathcal{E}_{ox} = (\varepsilon_{Si} / \varepsilon_{ox})\,\mathcal{E}_{Si}$$

Gate Voltage Relationship

$$\mathbf{E}_{\mathrm{Si}} = \left|\frac{qN_{\mathrm{A}}}{\varepsilon_{\mathrm{Si}}}\right| W = \left|\frac{qN_{\mathrm{A}}}{\varepsilon_{\mathrm{Si}}}\right| \sqrt{\frac{2\varepsilon_{\mathrm{Si}}}{qN_{\mathrm{A}}}\phi_{\mathrm{s}}} \qquad \text{for} \quad 0 < \phi_{\mathrm{s}} < 2\phi_{\mathrm{F}}$$

$$= \sqrt{\frac{2qN_{\mathrm{A}}}{\varepsilon_{\mathrm{Si}}}\phi_{\mathrm{s}}}$$

$$V_{\mathrm{G}} = \phi_{\mathrm{S}} + x_{\mathrm{ox}}\mathcal{E}_{\mathrm{ox}}$$

$$= \phi_{\mathrm{S}} + x_{\mathrm{ox}} \frac{\varepsilon_{\mathrm{Si}}}{\varepsilon_{\mathrm{ox}}} \mathcal{E}_{\mathrm{Si}}$$

$$= \phi_{\mathrm{S}} + x_{\mathrm{ox}} \frac{\varepsilon_{\mathrm{Si}}}{\varepsilon_{\mathrm{ox}}} \sqrt{\frac{2qN_{\mathrm{A}}}{\varepsilon_{\mathrm{Si}}}\phi_{\mathrm{S}}} \qquad \text{for} \quad 0 \le \phi_{\mathrm{S}} \le 2\phi_{\mathrm{F}}$$

Question

Draw E vs x for an ideal MOSC for the case of depletion and inversion