Engineering of Semiconductor

:Semiconductor Physics and Devices

Chapter 8. Properties of the metal-oxide-silicon system

In Chapter 8

The discussion of the MOS system in this chapter will greatly help us understand the physical electronics that underlie operation of the MOSFET

The ideal MOS structure
Analysis of the ideal MOS structure
Capacitance of the MOS system

The ideal MOS structure

To derive an energy-band diagram for the metal-oxide-silicon system,

we apply the basic principles that we previously used in studying systems of metals and semiconductors, and of p-type and n-type silicon

At thermal equilibrium

➡ the Fermi energy is constant throughout a system

the Fenni level is constant throughout all three materials:
the metal, the oxide, and the silicon

idealize the MOS system by considering that both the oxide and the interfaces between the materials are free of charges

⟶ But, real case interfacial state

The ideal MOS structure

Thermal-Equilibrium Energy-Band Diagram

The Fermi levels in the different materials are equalized by the transfer of negative charge from materials with higher Fermi levels (smaller work functions) across the interfaces to materials with lower Fermi levels (higher work functions).

*The vacuum level is a continuous function of position

When the materials are **separated**, the various energies are indicated on the Figure 8.1

Aluminum (work function = 4.1 V), silicon dioxide (electron affinity ~0.95 V), uniformly doped p-type silicon (electron affinity = 4.05 V) having a work function of 4.9 V are considered.
The vacuum level is designated E_o,

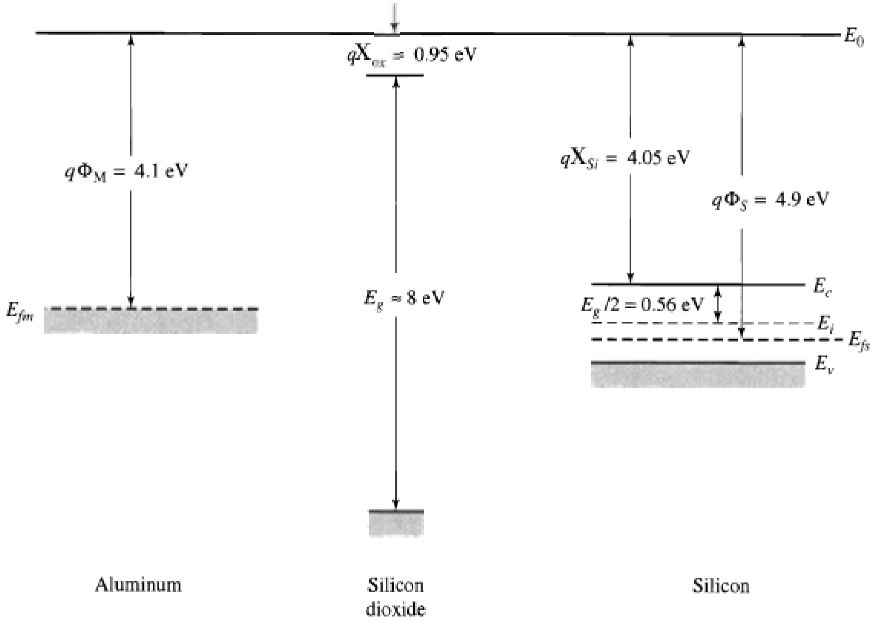


FIGURE 8.1 Energy levels in three separated materials that form an MOS system: aluminum, thermally grown silicon dioxide, and *p*-type silicon containing $N_a \approx 1.1 \times 10^{15}$ cm^{-3}. (Note that there is considerable variation in tabulated values for work functions and electron affinities. Commonly used values are indicated.)

The ideal MOS structure

Thermal-Equilibrium Energy-Band Diagram

As the materials are **brought together**,

Negative charge (electron) is transferred from the aluminum to the silicon to bring the system to equilibrium

because the work function of the metal is 0.8 eV less than the work function of the silicon

The insulator is incapable of transferring charge because it ideally possesses zero mobile charge, so a voltage drop appears across it because of the charge stored on either side.

There is a thin sheet of positive charge (a plane of charge in the ideal case of a perfect conductor) at the surface of the metal and negatively charged acceptors extending into the semiconductor from its

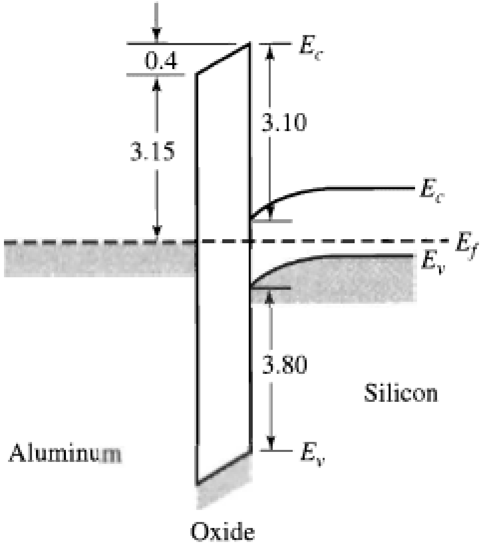


FIGURE 8.2 Energy-band diagram at thermal equilibrium for an ideal MOS system composed of the materials indicated in Figure 8.1. The oxide and Si–SiO_2 interface are assumed to be ideal and free of charges.

The ideal MOS structure

Thermal-Equilibrium Energy-Band Diagram

As the materials are **brought together**,

Negative charge (electron) is transferred from the aluminum to the silicon to bring the system to equilibrium

In fact, if the system being considered were fabricated without any path for charge flow between the metal and the silicon other than through an ideal oxide, the materials could exist in a condition of nonequilibrium (i.e., with unequal Fermi levels) for long periods

However, nearly every MOS system of interest has some alternative path for the transfer of charge that is much more transmissive to charge flow than is the oxide; e.g., the aluminum gate electrode and the silicon substrate may be connected together, or an ohmic conducting path may exist between them.

We assume that thermal equilibrium exists between the metal and the semiconductor. With these assumptions the band diagram for the MOS system formed with the materials

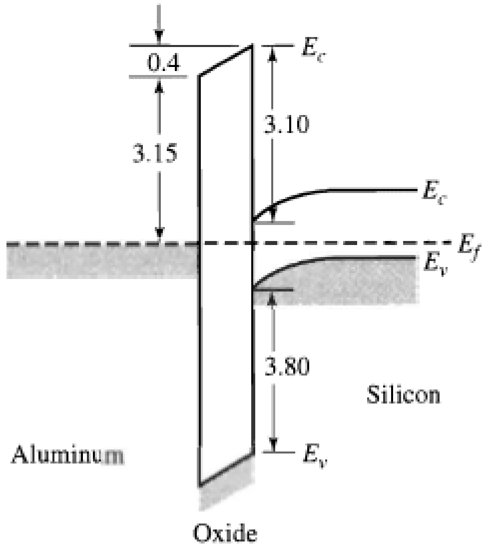


FIGURE 8.2 Energy-band diagram at thermal equilibrium for an ideal MOS system composed of the materials indicated in Figure 8.1. The oxide and Si–SiO$_2$ interface are assumed to be ideal and free of charges.

The ideal MOS structure

Polysilicon and Metals as Gate-electrode Materials

Because the surface condition of the silicon can be controlled by the metal electrode, the metal layer is usually called the *gate*, and the voltage on the metal is denoted by V_G.

Because the silicon is deposited over amorphous silicon dioxide, it is a polycrystalline film typically consisting of sub-micrometer-size crystallites.
A very high concentration of either *n-type* or *p-type* dopant is subsequently introduced into the polysilicon to make it sufficiently conducting to behave electrically like a metal

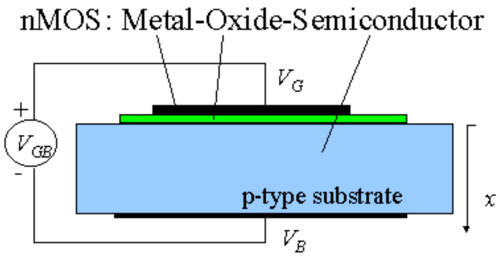
- One major advantage of polysilicon is its ability to withstand high-temperature thermal treatments

- primary drawback is the high resistance of even heavily doped polysilicon compared to that of a metal

Attempts to find attractive metals to replace polysilicon as the gate electrode are continuing

The ideal MOS structure

The Flat-Band Voltage



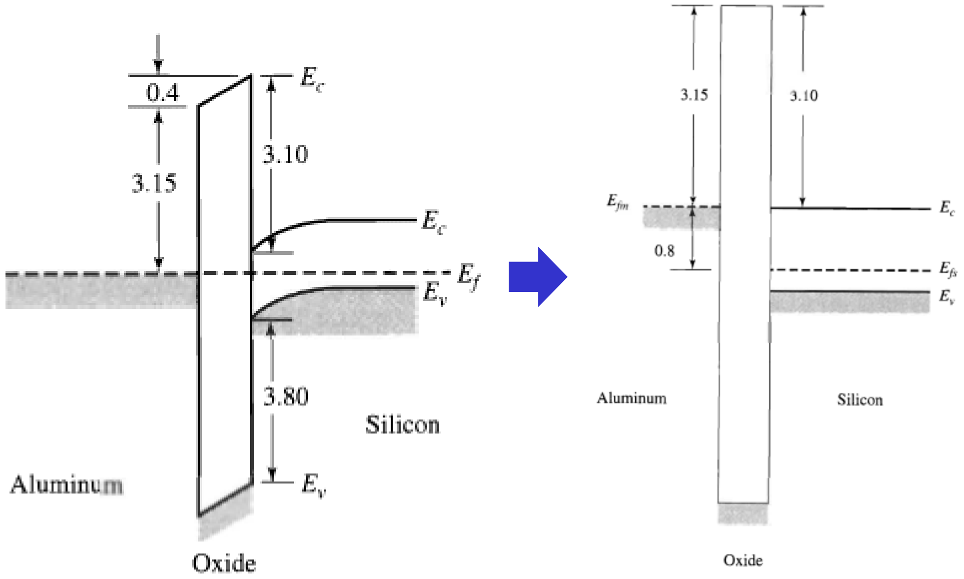
For the idealized MOS system at thermal equilibrium,
the metal and the semiconductor form two plates of a capacitor.

The capacitor is charged to a voltage corresponding to the difference between the metal and semiconductor work functions

- Applying a bias voltage between the metal and the silicon causes the system to depart from thermal equilibrium and changes the amount of charge stored on the capacitor.

Negative voltage applied to the metal with respect to the silicon opposes the built-in voltage on the capacitor and tends to reduce the charge stored on the capacitor plates below its equilibrium value.

- pulling positive holes toward the surface of the semiconductor to neutralize some of the negatively charged acceptors.



The ideal MOS structure

The Flat-Band Voltage

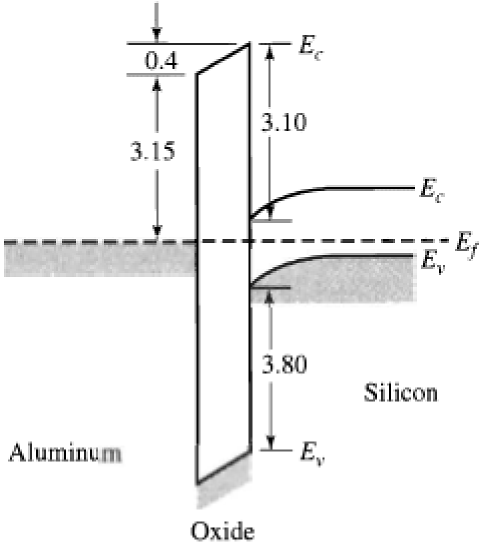
For the idealized MOS system at thermal equilibrium,
the metal and the semiconductor form two plates of a capacitor.

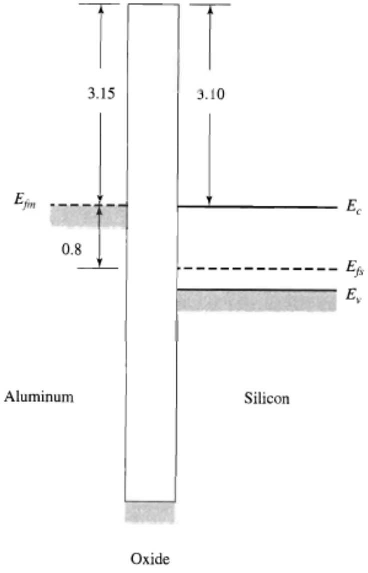
The capacitor is charged to a voltage corresponding to the difference between the metal and semiconductor work functions

- At one particular value, the applied voltage exactly compensates the difference in the work functions of the metal and the semiconductor.

The stored charge on the MOS capacitor is then reduced to zero, and the fields in the oxide and the semiconductor vanish

- The voltage that produces flat energy bands in the silicon is called the flat-band voltage and usually designated V_{FB}





The ideal MOS structure

The Flat-Band Voltage

For the idealized MOS system at thermal equilibrium,
the metal and the semiconductor form two plates of a capacitor.

The capacitor is charged to a voltage corresponding to the difference between the metal and semiconductor work functions

- The flat-band voltage varies with the dopant density in the silicon, as well as with the specific metal(work function) used for the MOS system

At the flat-band condition

→ MOS system is *not* at thermal equilibrium

The voltage applied to the ideal MOS system to bring it to the flat-band condition equals the difference in the work functions of the metal and the silicon.

$$\boxed{V_{FB} = \Phi_M - \Phi_S = \Phi_{MS}}$$

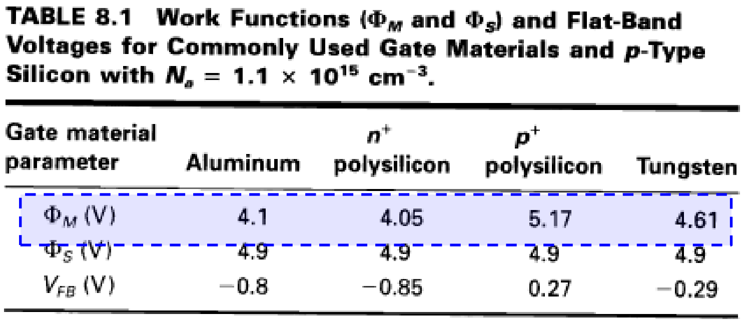


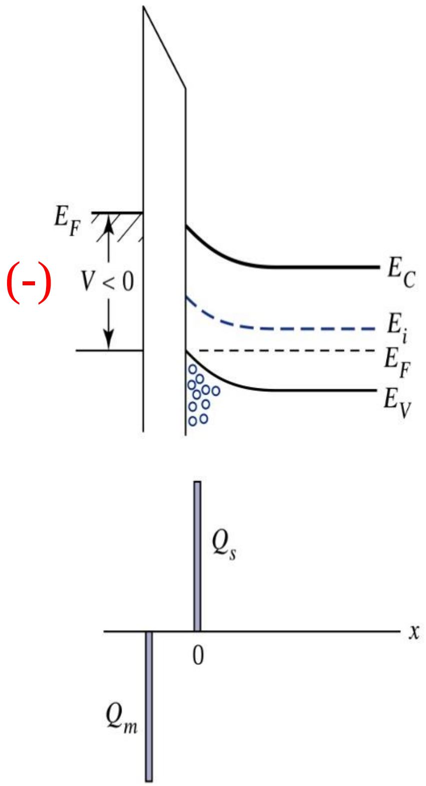
TABLE 8.1 Work Functions (Φ_M and Φ_S) and Flat-Band Voltages for Commonly Used Gate Materials and *p*-Type Silicon with $N_a = 1.1 \times 10^{15}$ cm^{-3}.

Gate material parameter	Aluminum	n^+ polysilicon	p^+ polysilicon	Tungsten
Φ_M (V)	4.1	4.05	5.17	4.61
Φ_S (V)	4.9	4.9	4.9	4.9
V_{FB} (V)	−0.8	−0.85	0.27	−0.29

Analysis of the ideal MOS structure

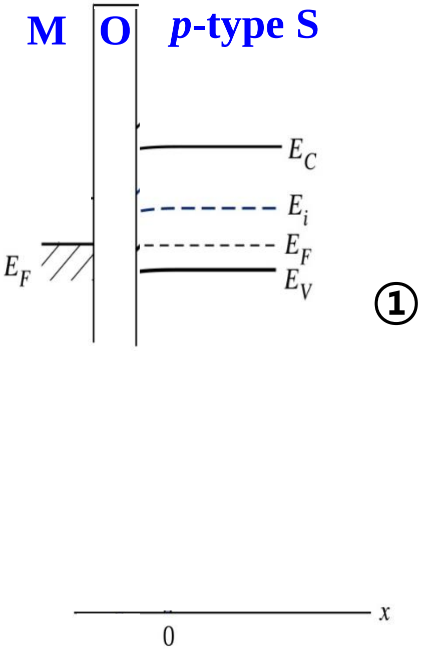
Qualitative Description (nMOS)

① Negative
(V_G - V_{FB} < 0)



“Accumulation”

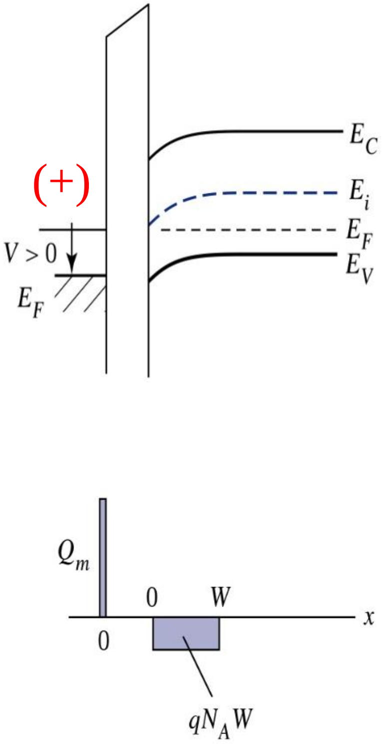
② No bias
(V_G - V_{FB} = 0)



“Flat band”

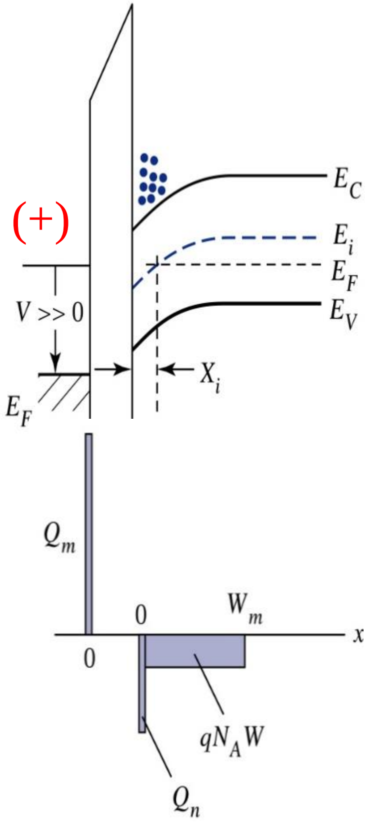
①

③ Positive
(V_G - V_{FB} > 0)



“Depletion”

④ More Positive
(V_G - V_{FB} ≫ 0)



“Inversion”

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

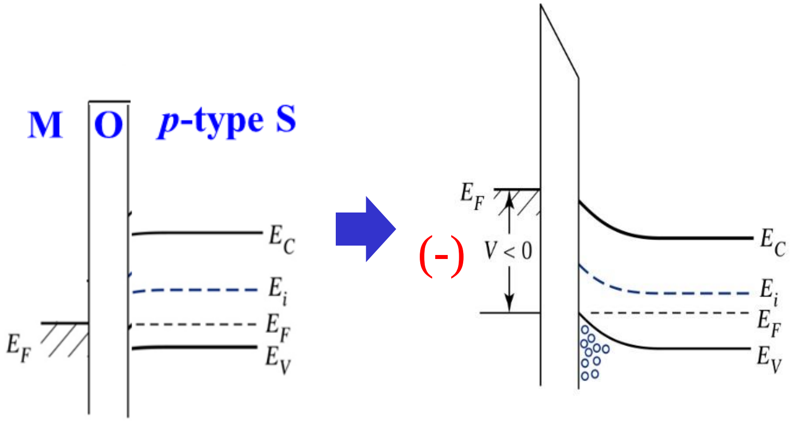
"Accumulation"

If the silicon is held at ground and the voltage applied to the metal is negative but increases in magnitude above V_{FB}

➡ Additional positively charged holes are attracted toward the silicon surface, and the MOS capacitor begins to store positive charge there.

This positive charge is made up of an increase in the hole population at the surface, so the surface has a greater density of holes than N_a, the acceptor density

Flat band **① Negative (V_G - V_{FB} < 0)**



Negative voltage applied to the metal plate

Excess positive carriers (holes) induced at the interface

Energy bands bent upward

Increase of (E_i-E_F)

Enhanced hole concentration "Accumulation"

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

The applied voltage gives rise to negative charge in the semiconductor by repelling holes from the surface to create the depletion region

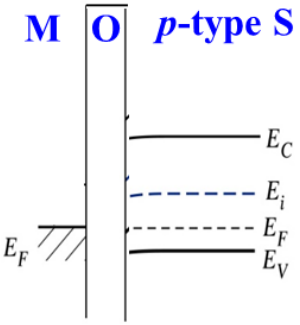
“Depletion”

If this built-in voltage is aided by applying a positive gate voltage between the metal and the silicon

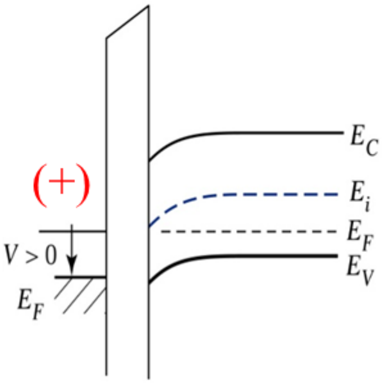
➡ The silicon becomes further depleted as more holes are repelled from its surface and more acceptors are exposed, the positive charge on the metal increases.

Because <u>mobile silicon charge is withdrawn</u> from the surface, this condition is called *surface depletion*

Flat band



③ Positive
(V_G - V_{FB} > 0)



Small positive voltage applied to the metal plate

⬇

Energy band near the interface bent downward

⬇

Decrease of (E_i-E_F)

⬇

The holes are depleted

⬇

“Depletion”

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

The applied voltage gives rise to negative charge in the semiconductor by inducing electrons to form the inversion layer

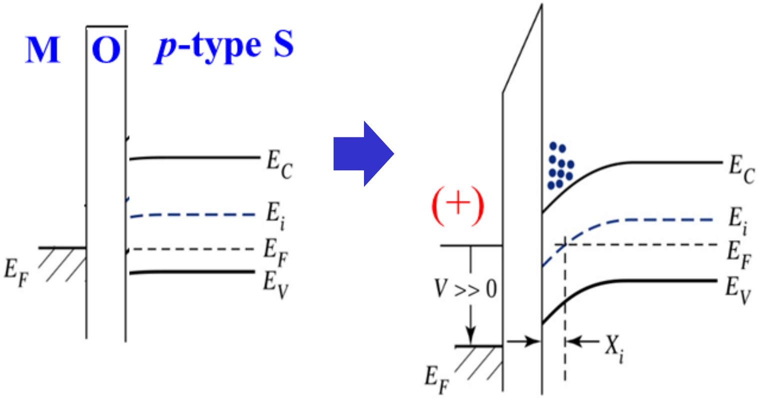
"Inversion"

If the Fermi level remains constant in the silicon while the energy bands bend as the applied voltage changes, at sufficiently high voltages the intrinsic Fermi level E_i at the silicon surface crosses the Fermi level corresponding to the silicon bulk.

➡ the Fermi level is closer to the conduction- band edge than to the valence-band edge. In terms of carrier densities, this means that the applied voltage has created an *inversion layer*, so-called because the surface contains more electrons than holes, even though the silicon was doped with acceptor impurities.

Flat band

③ More Positive (V_G - V_{FB} >> 0)



Larger positive voltage applied to the metal plate

⬇

Energy band bent downward even more

⬇

$(E_i$-$E_F)<0$

$$\left\{ \begin{array}{l} p_p = n_i e^{\frac{(E_i - E_F)}{kT}} < n_i \\ \boxed{n_p = n_i e^{\frac{(E_F - E_i)}{kT}} > n_i} \end{array} \right.$$

⬇

Minority carrier (n_p) is greater than majority carrier (p_p) at the interface (semiconductor surface)

⬇

"Inversion"

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

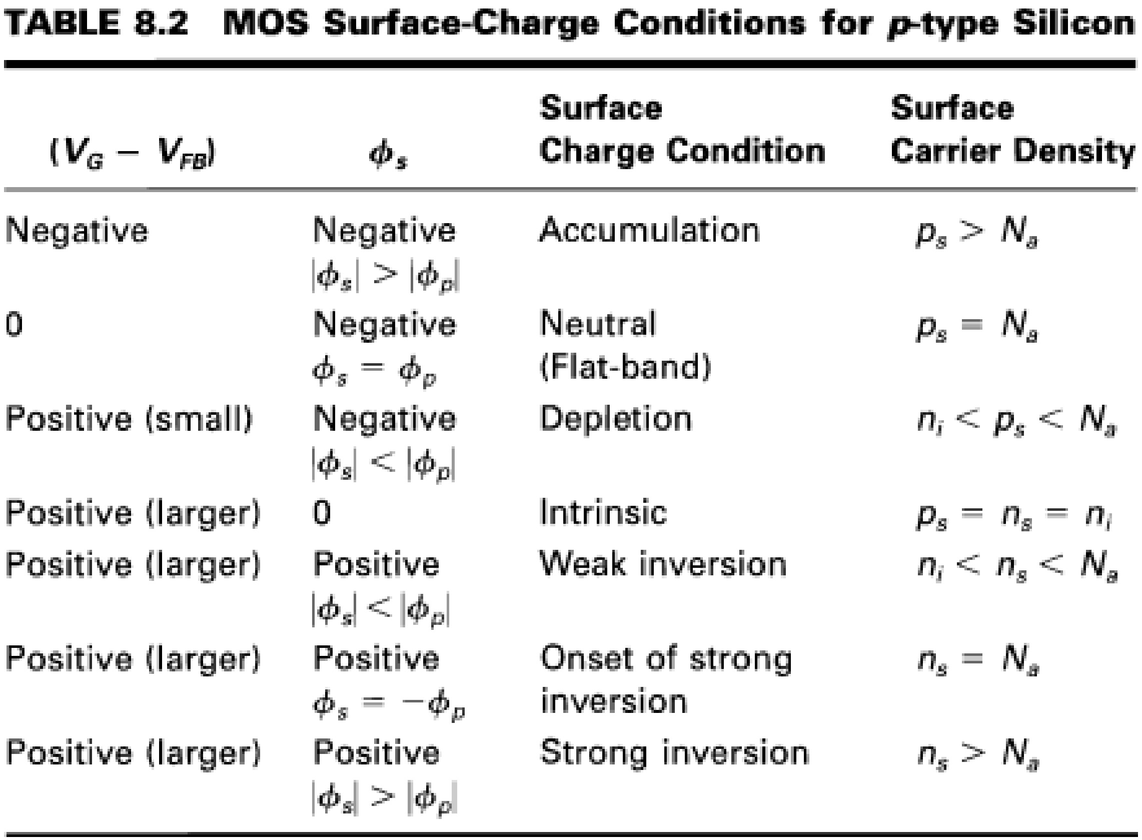


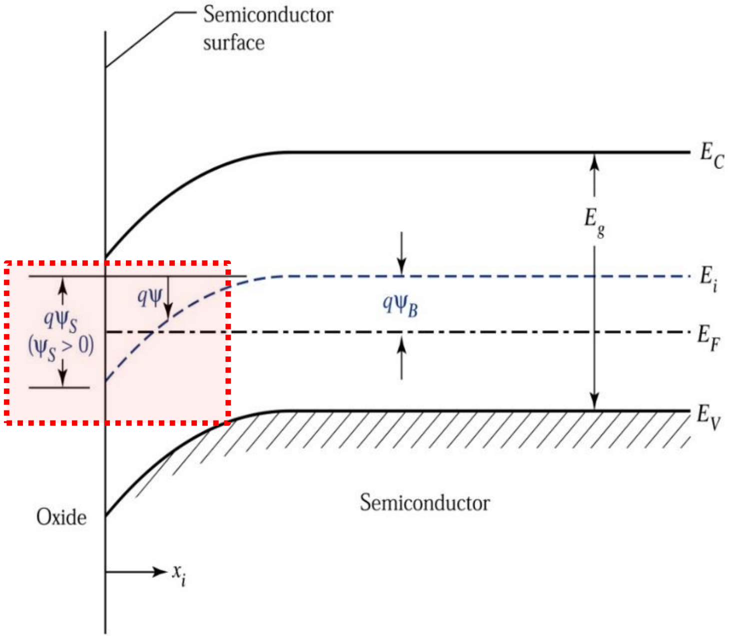
TABLE 8.2 MOS Surface-Charge Conditions for *p*-type Silicon

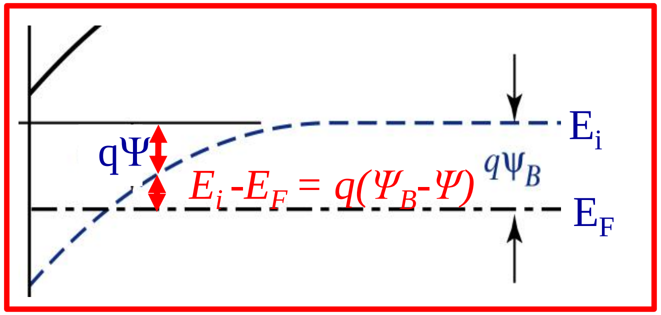
$(V_G - V_{FB})$	ϕ_s	Surface Charge Condition	Surface Carrier Density
Negative	Negative $\lvert\phi_s\rvert > \lvert\phi_p\rvert$	Accumulation	$p_s > N_a$
0	Negative $\phi_s = \phi_p$	Neutral (Flat-band)	$p_s = N_a$
Positive (small)	Negative $\lvert\phi_s\rvert < \lvert\phi_p\rvert$	Depletion	$n_i < p_s < N_a$
Positive (larger)	0	Intrinsic	$p_s = n_s = n_i$
Positive (larger)	Positive $\lvert\phi_s\rvert < \lvert\phi_p\rvert$	Weak inversion	$n_i < n_s < N_a$
Positive (larger)	Positive $\phi_s = -\phi_p$	Onset of strong inversion	$n_s = N_a$
Positive (larger)	Positive $\lvert\phi_s\rvert > \lvert\phi_p\rvert$	Strong inversion	$n_s > N_a$

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

1) Electrostatic potential in the surface *depletion region*





Electrostatic potential in semiconductor

$$\Psi = -\frac{1}{q}\left(E_i - E_F\right)$$

Ψ : Electrostatic potential in depletion region
(positive when band is bent downward)

Ψ_S : Surface potential
(Electrostatic potential in surface)

Ψ_B : Electrostatic potential in bulk

$$p_p = n_i e^{\frac{(E_i - E_F)}{kT}} = n_i e^{\frac{q(\Psi_B - \Psi)}{kT}}$$

$$n_p = n_i e^{\frac{(E_F - E_i)}{kT}} = n_i e^{\frac{q(\Psi - \Psi_B)}{kT}}$$

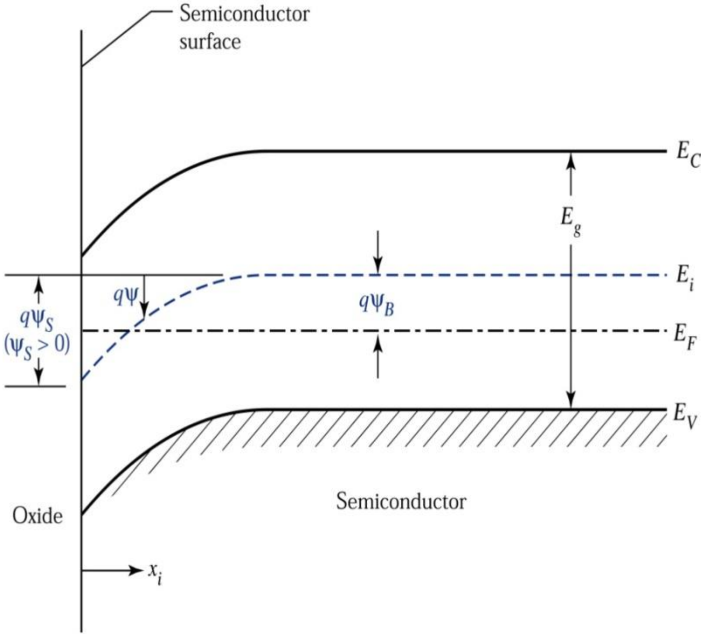
Carrier density at surface

$$p_s = n_i e^{\frac{q(\Psi_B - \Psi_S)}{kT}} \qquad n_s = n_i e^{\frac{q(\Psi_S - \Psi_B)}{kT}}$$

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

1) Electrostatic potential in the surface *depletion region*



i) $\Psi_S < 0$: Accumulation of holes
(band bent upward)

ii) $\Psi_S = 0$: Flat band condition

iii) $\Psi_B > \Psi_S > 0$: Depletion of holes
(band bent downward)

iv) $\Psi_S = \Psi_B$: midgap with $n_s = n_p = n_i$

v) $\Psi_S > \Psi_B$: Inversion (band bent downward)

$$p_s = n_i e^{\frac{q(\Psi_B - \Psi_S)}{kT}}$$

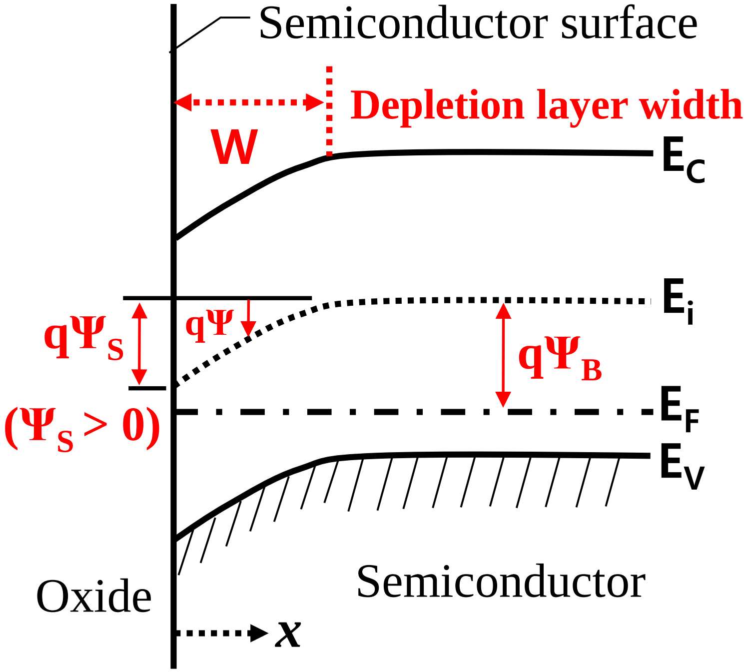
$$n_s = n_i e^{\frac{q(\Psi_S - \Psi_B)}{kT}}$$

Ψ_S : Surface potential
Ψ_B (Ψ_p): potential in bulk p-type region

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

1) Electrostatic potential in the surface *depletion region*



Potential as a function of distance

One-dimensional Poisson’s equation

$$\frac{d^2\Psi}{dx^2} \equiv -\frac{d\mathrm{E}}{dx} = -\frac{\rho_S}{\varepsilon_S}$$

$$\rho_S = -qN_A$$

$$\boxed{\Psi = \Psi_S\left(1-\frac{x}{W}\right)^2}$$

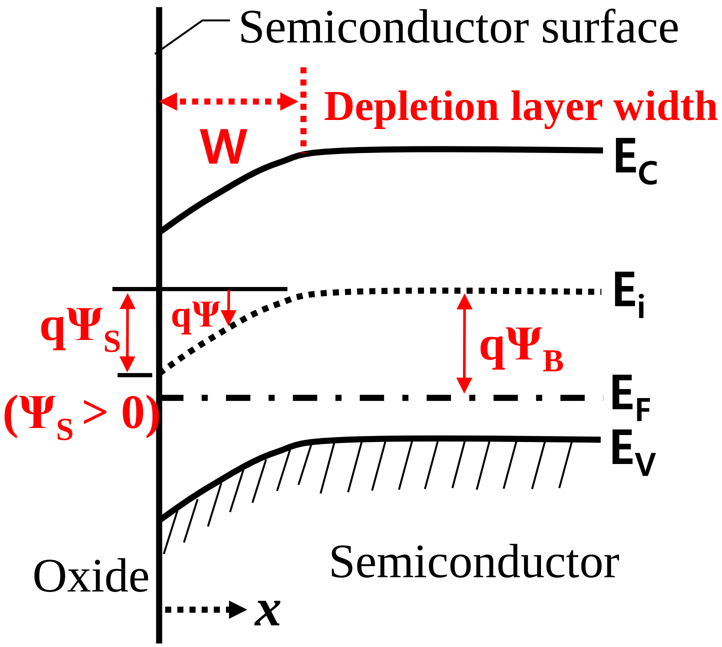
$$\boxed{\Psi_S = \frac{qN_A W^2}{2\varepsilon_S}}$$

: Surface potential

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

1) Electrostatic potential in the surface *depletion region*



One-dimensional Poisson's

$$\boxed{\frac{d^2\Psi}{dx^2} \equiv -\frac{dE}{dx} = -\frac{\rho_S}{\varepsilon_S}}$$

$$\rho_S = -qN_A$$

$$E(x) = -\frac{d\Psi}{dx} = \int -\frac{qN_A}{\varepsilon_S}dx$$

$$= -\frac{qN_A}{\varepsilon_S}x + A$$

Boundary condition

$$E(W) = 0$$

$$= -\frac{qN_A}{\varepsilon_S}x + \frac{qN_A}{\varepsilon_S}W$$

$$\Psi(x) = \int \frac{qN_A}{\varepsilon_S}x - \frac{qN_A}{\varepsilon_S}W dx$$

$$= \frac{qN_A}{2\varepsilon_S}x^2 - \frac{qN_A}{\varepsilon_S}Wx + C$$

Boundary conditions

$$\Psi(W) = 0$$

$$\Psi(0) = \Psi_S$$

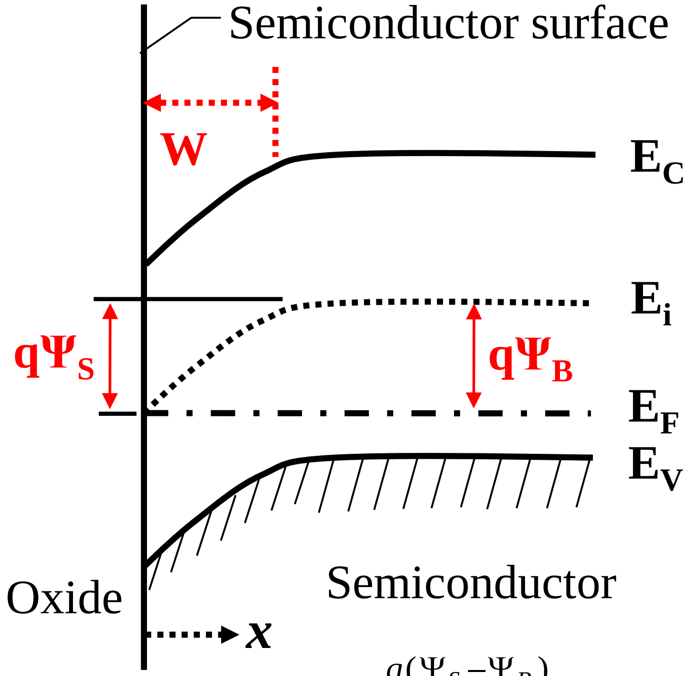
$$= \Psi_S\left(1 - \frac{x}{W}\right)^2 \qquad \Psi_S = \frac{qN_A W^2}{2\varepsilon_S}$$

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

2) Conditions for inversion

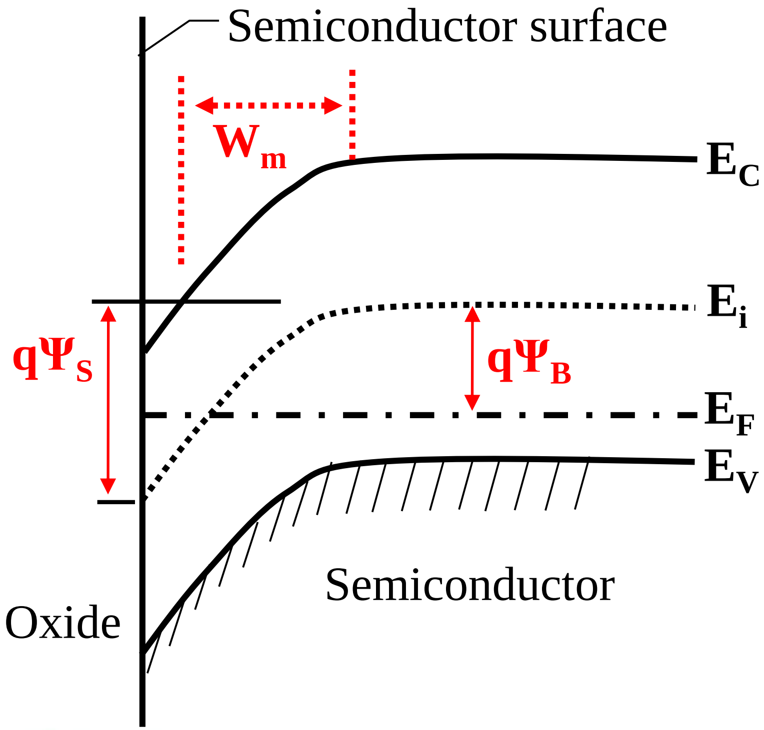
Inversion start ($\Psi_S \geq \Psi_B$)



$$n_s = n_i e^{\frac{q(\Psi_S - \Psi_B)}{kT}}$$

$$n_s \geq n_i \quad \text{for } \Psi_S \geq \Psi_B$$

Strong inversion ($\Psi_S \sim 2\Psi_B$)



Criterion

Surface electron concentration is equal to the substrate doping concentration.

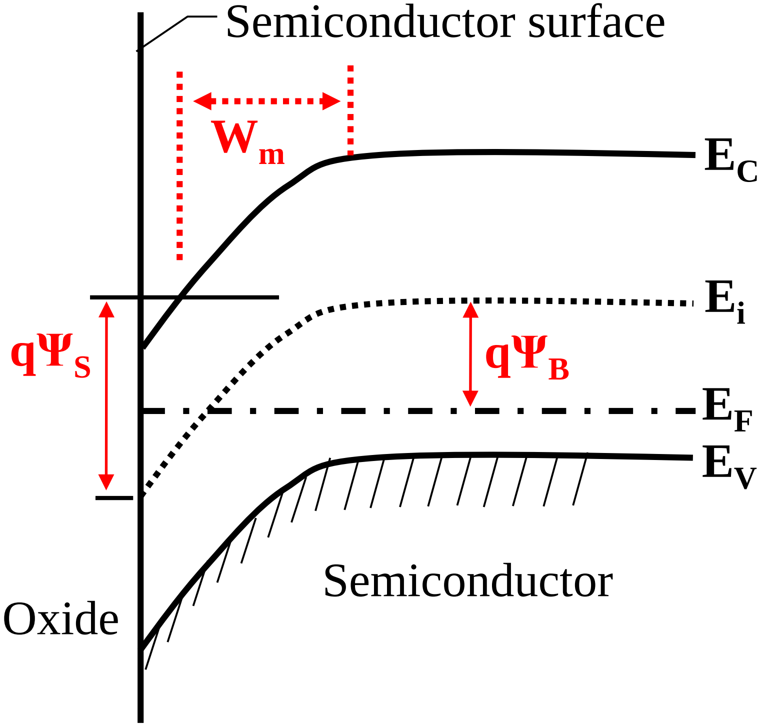
$n_s = N_A$

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

2) Conditions for inversion

Required Voltage for Strong inversion ($\Psi_S \sim 2\Psi_B$)



Criterion

$n_s = N_A$

$$n_s = n_i e^{\frac{q(\Psi_S - \Psi_B)}{kT}} = N_A = n_i e^{\frac{E_i - E_F}{kT}} = n_i e^{\frac{q\Psi_B}{kT}}$$

$$\Psi_S - \Psi_B = \Psi_B$$

$$\Psi_S = 2\Psi_B \qquad \Psi_B = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

$$\therefore \Psi_S(inv) = 2\Psi_B = \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

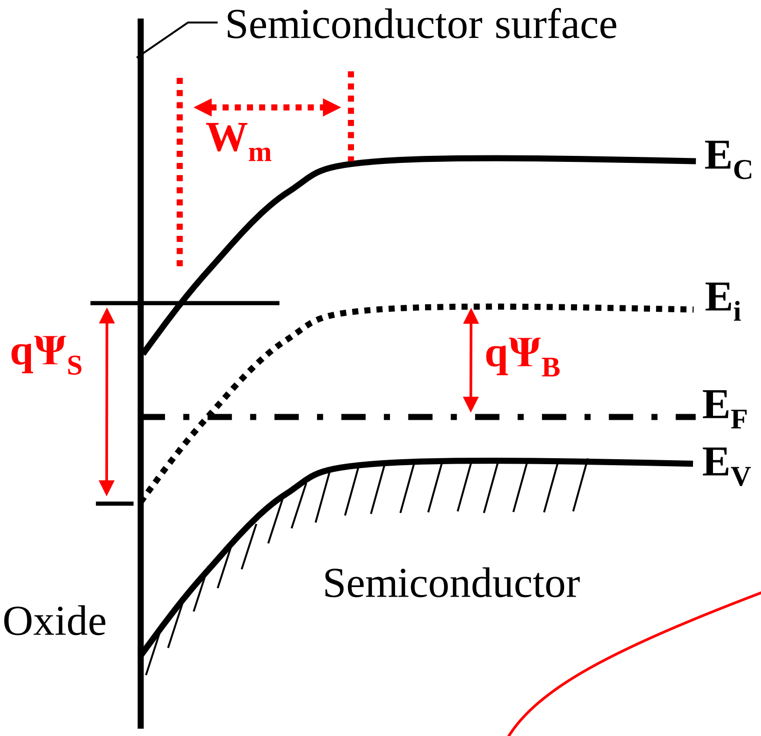
⇒ **Voltage required to be strong inversion**

Analysis of the ideal MOS structure

Qualitative Description (nMOS)

2) Conditions for inversion

Maximum depletion layer width (W_m) when strong inversion



$$\Psi_S = \frac{qN_A W^2}{2\varepsilon_S} \Rightarrow \Psi_S(inv) = \frac{qN_A W_m^{\ 2}}{2\varepsilon_S}$$

$$\Psi_S(inv) = 2\Psi_B = \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right) = \frac{qN_A W_m^{\ 2}}{2\varepsilon_S}$$

$$\boxed{W_m = \sqrt{\frac{2\varepsilon_S \Psi_S(inv)}{qN_A}} = \sqrt{\frac{2\varepsilon_S (2\Psi_B)}{qN_A}}}$$

$$\boxed{W_m = 2\sqrt{\frac{\varepsilon_S kT \ln\left(\frac{N_A}{n_i}\right)}{q^2 N_A}}}$$

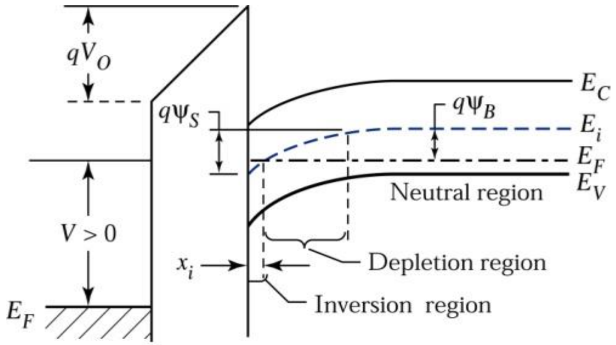
Charge density in the depletion layer

$$Q_{SC} = -qN_A W_m = -\sqrt{2qN_A \varepsilon_S (2\Psi_B)}$$

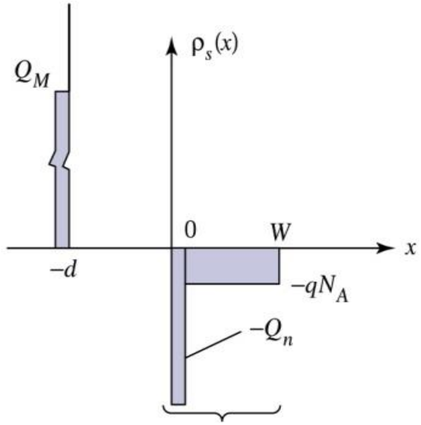
Analysis of the ideal MOS structure

Capacitance-Voltage properties of ideal MOS

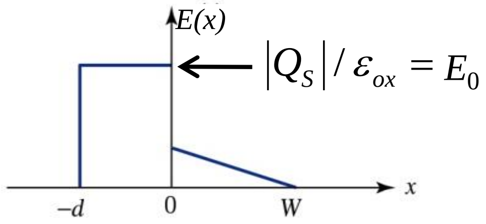
Band Diagram (inversion)



Charge distribution



Electric field



Applied voltage (V)

$$\mathbf{V = V_0 + \Psi_S}$$

V_0 : potential across the oxide ($E_0\, d$)

$$\boxed{V_0 = E_0 d = \frac{|Q_S|\, d}{\varepsilon_{ox}} = \frac{|Q_S|}{C_0}}$$

E_0 : electric field in oxide

d : oxide thickness

Q_S : charge per unit area in semiconductor

$$\left(C_0 = \varepsilon_{ox} / d\right)$$

Analysis of the ideal MOS structure

Capacitance-Voltage properties of ideal MOS

For Strong Inversion ($V \gg 0$)

Threshold voltage (the voltage at the onset of strong inversion)

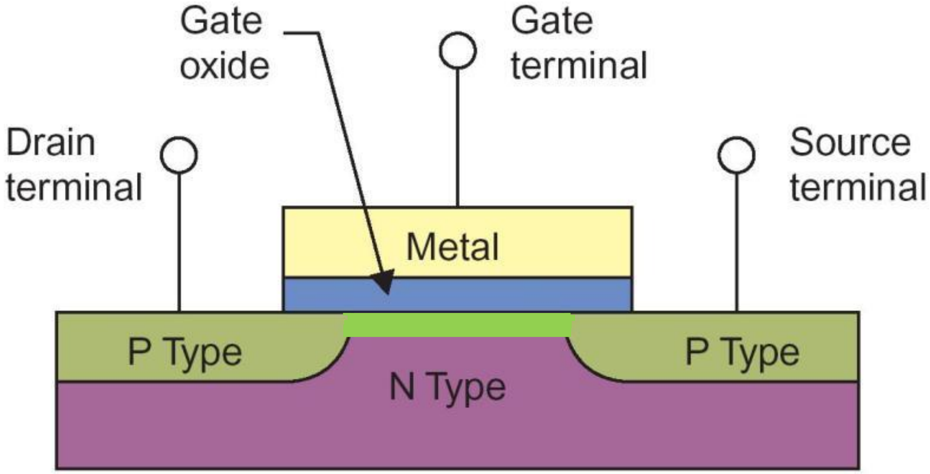
$$\boxed{V_T = \frac{qN_AW_m}{C_0} + \Psi_S(inv) = \frac{\sqrt{2\varepsilon_S qN_A(2\Psi_B)}}{C_0} + (2\Psi_B)}$$

$$V = V_0 + \Psi_S$$

$$V_0 = \frac{|Q_S|}{C_0} = \frac{qN_AW_m}{C_0}$$

→ Applied voltage to make strong inversion (to open the channel in MOSFET)

$V_G > V_T$



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