Goal;

To understand the basic surface physics by way of MOS equation:

- MOS equation and Qs(phis s) relation based on classical theory
- C-V characteristics
- Nonideal surfaces
- Fixed charges
- Finite time response

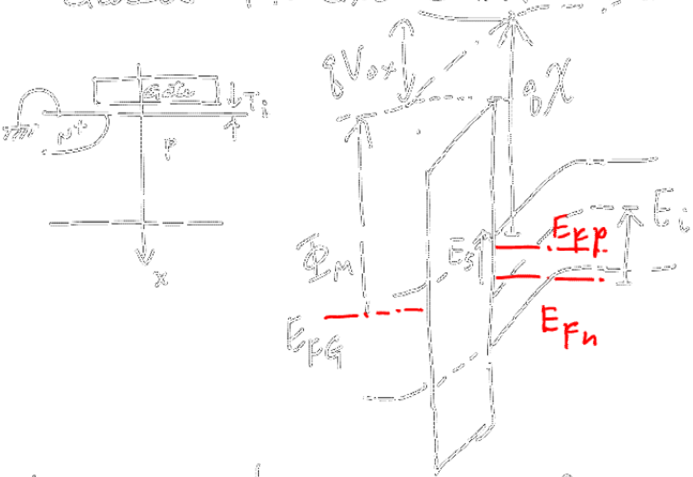
Ref : YJP et. al.,

NANOCAD, Chapter 6, Daeyoung Sa, 2005(Korean)

A. MOS Equation

- General band diagram with Source contact

Gated PN diode structure



With the $E_F|_{source}$ as the reference,

$$q\Phi_M + qV_{ox} - q\chi - E_S - \underbrace{(E_{Fn} - E_{Fp})}_{qV_{GS}} = 0$$

Surface Potential: $q\psi_S = \underbrace{(E_{Fp} - E_{Fn})}_{-qV_{SB}} + q\phi_{fp} + \frac{E_g}{2} - E_S$

Ex> If $V_{SB} = 0$

qV_{FB}

$$qV_{GS} = q\Phi_{MS} - q\chi + q\psi_S + q\phi_{fp} + \frac{E_g}{2} + qV_{ox}$$

Or $V_{GS} - V_{FB} = \psi_S + V_{ox}$

- $V_G - V_{FB} = V_{gate} + V_{ox} + \Psi_s$ (1)

(w,r,t source if MOSFET is considered)

- describes the voltage across the gate, oxide and semiconductor surface with respect some references
- $V_G = V_{FB}$ is when $\Psi_s = 0$ so that V_{FB} is called "the Flat Band Voltage"
- V_{gate} : voltage applied in the gate caused by the poly depletion effect

  V_{ox} : volage applied across the oxide

  Ψ_s : semiconductor surface potential w,r,t some reference voltage

- Flatband voltage issue:

The flatband voltage is the voltage to apply to the gate to the source to make the surface potential to be zero(no bend bending so that the no surface charge(Qs is present in the gate)
Usually, the flatband voltage is present due to the difference in the workfunction of the two materials(the gate and the substrate).
However, if the substrate is fully depleted so that no fixed voltage is applied to the substrate, the following figure for the case of the DGFET with the fully depleted substrate will be helpful.

- Find the relation V_{gate}, V_{ox} with a single variable Ψ_s, we can solve the MOS equations with respect Ψ_s
  - This can be achieved by using the "semiconductor areal charge density", Q_s.

- Material Issues

VFB can be adjusted by choosing different material for the gate materials. The following figures for the position of the Fermi level with respect to the silicon Ec and Ev is helpful to estimate the VFB for different possible gate materials.

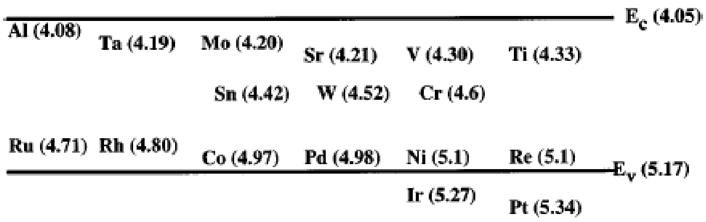


Fig. 12. Workfunctions of possible metal gates.

work function of several some important materials
http://www.physchem.co.za/Light/Particles.htm

Element	Work function (eV)
Caesium (Cs)	1.96
Sodium (Na)	2.06
Zinc (Zn)	3.08
Beryllium (Be)	3.17
Cadmium (Cd)	3.68
Antimony (Sb)	4.01
Tungsten (W)	4.25

B. $Q_s - \psi_s$ relationship

There are several approaches to find the $Q_s - \psi_s$ relationship.

Classical : MB, FD statistics
Quantum mechanical : MB, FD statistics

-Classical MB approach

Assuming that the surface is not quantized in x direction, and MB statistics is valid, the general $Q_s - \psi_s$ relation can be found as,

$$Q_s(\phi_s) = -\sqrt{2}\varepsilon_s \frac{V_t}{L_d} F(\psi_s) \tag{2}$$

where

$$F(\psi_s) = \left[(e^{-\psi_s/V_t} + \frac{\psi_s}{V_t} - 1) + \frac{n_{po}}{p_{po}} (e^{\psi_s/V_t} - \frac{\psi_s}{V_t} - 1) \right]^{1/2}$$

Then

$$V_{ox} = -\frac{Q_s}{C_{ox}} \quad \text{(from the continuity in electric flux, D)} \tag{3}$$

and

$$Q_G(V_{gate}) = -Q_s(\psi_s) \tag{4}$$

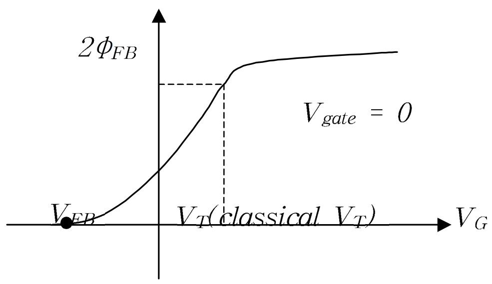
– Important physical quantities related with vertical fields : E_s and E_{ox}, and E_{eff}

E_{ox} : determines the tunneling current in thin oxide, limiting the minimum thickness of gate oxide.

E_{eff} : determines the effective vertical field which carriers see in vertical direction.

Ex) $\psi_s - V_G$ relationship

Draw $\psi_s - V_G$ relationship from Eq. (1)



– Classical V_T theory

V_T is V_G value in which Q_n is appreciable so that drain current is detectable. Eq.(2) states that Q_n is exponentially increasing function of phis whereas Q_d is increasing function in the power of 0.5. So, as we do approximate I-V of diode such that $I=0$ when V_D < V_{on} where V_{on} is around 0.7V even though I flows continuously as V_D increases from 0V, we assume that $Q_n = 0$ until ψ_s becomes a certain value ($2\Phi_{f,p}$). Also assume that phis is fixed to the value and does not increase further. With this assumptions, classical expression for MOS VT and $Q_n(V_G)$ can be found.

Assume $V_{gate} = 0$, for $V_G = V_T$, Eq. (1) becomes,

$$V_T - V_{FB} = \frac{\sqrt{2\varepsilon_s q N_a}}{C_{ox}}\sqrt{2\Phi_{f,p}} + 2\Phi_{f,p}$$

so that $V_T = V_{FB} + \gamma\sqrt{2\Phi_{f,p}} + 2\Phi_{f,p}$

where $\gamma = \dfrac{\sqrt{2\varepsilon_s q N_a}}{C_{ox}}$.

For $V_G > V_T$, since phis is fixed to $2\Phi_{f,p}$ eq.(1) becomes,

$$V_G = V_{FB} - \frac{Q_n}{C_{ox}} + \gamma\sqrt{2\Phi_{f,p}} + 2\Phi_{f,p}$$

so Q_n after inversion can be written found as,

$$Q_n = -C_{ox}(V_G - V_T).$$

B. C-V characteristics

– One of the most powerful experimental method to know the MOS surface is measurement of gate capacitance C_G vs V_G. Here, DC V_G is applied and a small signal is applied with a certain frequency so that the current through the gate is measured and transformed to Capacitance. DC V_G is scanned so that C-V_G can be plotted.

– Low frequency C-V characteristics and High frequency characteristics.

Here, the applied frequency is so low that the electron concentration can be responded so that eq. (1) with $Q_s(\psi_s)$ relation always hold. If high frequency is applied so that electron cannot be responded to the applied signal, high frequency characteristics is observed.

Differentiating eq(1) with respect to Q_G,

$$\frac{\Delta V_G}{\Delta Q_G} = \frac{\Delta V_{gate}}{\Delta Q_G} + \frac{1}{C_{ox}} + \frac{\Delta \psi_s}{\Delta Q_G}$$
$$= \frac{\Delta V_{gate}}{\Delta Q_G} + \frac{1}{C_{ox}} + \frac{\Delta \psi_s}{\Delta Q_s}$$

Notice that this eq. can be written as

$$\frac{1}{C_G} = \frac{1}{C_{gate}} + \frac{1}{C_{ox}} + \frac{1}{C_s}$$

Let us first consider C_s.
From eq. (2), C_s can be easily found as,

$$C_s = \frac{dQ_s}{d\Psi_s}$$
$$= \sqrt{2}\varepsilon_s \frac{V_t}{L_d} \frac{dF(\Psi_s)}{d\Psi_s}$$

– Fig. 2 shows that approximate C_s behavior. The following feature should be noticed.

$$V_G = V_{FB}, \quad C_G = \frac{\varepsilon_s}{L_d} \quad \text{and} \quad V_G > V_T, \quad C_G = C_{\min}.$$

(Notice that at $V_G = V_{FB}$, C_G is not Cox)

Notice also that from $C_{\min}$, N_d can be found, so be L_d.

Than V_{FB} can be obtained from ε_s / L_d.

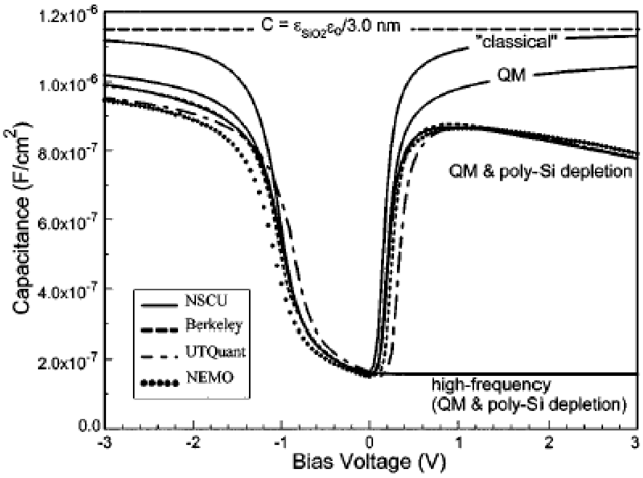


Fig. 1. Simulated C–V curves accounting for both QM confinement and poly-Si depletion. Simulated parameters are d_{ox} = 3.0 nm (2.987 nm for NEMO [10]), $N_a = 3 \times 10^{17}$ cm^{-3}, and $N_{poly} = 5 \times 10^{19}$ cm^{-3}. A classical C–V with no QM confinement or poly-Si depletion and a QM C–V which accounts for QM confinement only are also shown for illustrative purposes.

Fig 2. C-V curve from various models.
(Fig. 1. of C. Richter's, EDL p.35, Jan 2001)

C. Nonideal surfaces ; Surface States

Ref : Shur: pp. 343-352

<ref> YJP et. al.,
NANOCAD, Chapter 6, Daeyoung Sa, 2005(Korean)

– We assumed that the semiconductor is ideal. However, actual MOS has the following nonideal situations so that the ideal surface theory explained so far has to be modified. They are,
  - surface state charges,
  - infinitely quick response of surface charges as "Ψ_s" changes
  - and fixed oxide charge.

– Surface state charge(Q_{ss}):
There are surface states at Si-SiO_2 interface due to unsaturated dangling bond. According to its energy level and its time constant in capturing and emitting carriers, it is classified into "slow state" and "fast state". The "fast" state is of most importance since the state gives rise to change in surface potential thereby changing the electrical characteristics of MOS devices.

– Surface States Capacitance: C_{ss}
See Fig. 3 for $N_{ss}[/cm^2]$ distributed in the band gap. According to the type of the states, electrical charge due to N_{ss} can be written as,

$$Q_{ss} = q[N_{ss,d}(1-f) - N_{ss,a}(f)]$$

$N_{ss,d}$: density of Donor like surface states

$N_{ss,a}$: density of Acceptor like surface states

$$f = \frac{1}{1+e^{(E_t - q\Psi_s - E_f)/k_BT}}$$

Fig. 6.11 of YJP p.326

Then

$$C_{ss}(\psi_s) = -\frac{\partial Q_{ss}}{\partial \psi_s} \qquad (13)$$
$$\cong q[N_{ss,a}(E_f + q(\psi_s)) + N_{ss,d}(E_f + q(\psi_s))]$$

Notice that $C_{ss}(\psi_s)$ is simply q times the area density of Surface state charges[/cm^2].

- Surface states density can be known by this C_{ss} measurements. Comparing with the ideal C-V, N_{ss} in the energy gap can be found rather easily.
- Other method is the charge pumping method(see ref.).

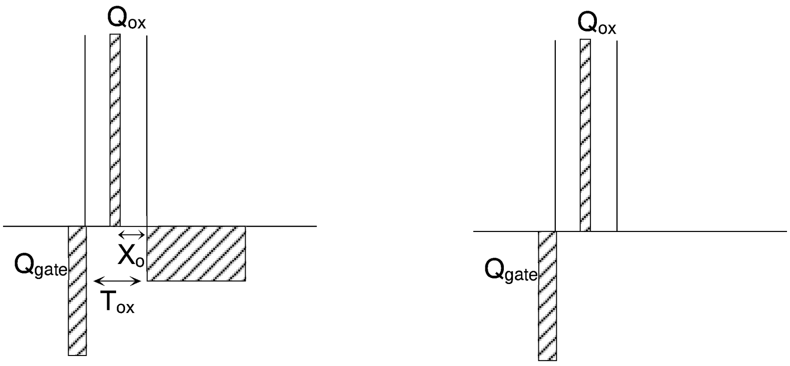
D. Effects of fixed charge in the oxide film

There are fixed charges introduced in the gate oxide. They are best described by $Q_{ox}[C/cm^2]$ located at x_0(centroid) from the surface (See Fig. 4). This charge will induce the same charge with opposite sign at the gate and substrate. Then V_{FB} necessary to nullify the charge at the surface will be,

$$\Delta V_{FB} = \frac{Q_{ox}}{C_{ox}} \frac{T_{ox} - x_0}{T_{ox}}. \qquad (14a)$$

If Q_{ox} is distributed in the oxide,

$$\Delta V_{FB} = \int \frac{\rho(x)}{C_{ox}} \frac{T_{ox} - x}{T_{ox}} dx. \qquad (14b)$$



(a) $V_G=0$ (b) $V_G=\Delta V_{FB}$

Fig. 4

E. Effects of finite time response

See eq. (1). In the equation, it was assumed that Q_s responds to ψ_s instantaneously. However, it takes a finite time for the charge to respond according to the change in ψ_s. The best way to describe the situation is drawing an equivalent circuit

— See Fig. 5 for the equivalent circuit.

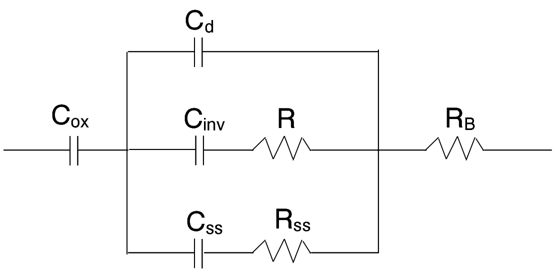


Fig. 5

Three time constants are involved in the charge redistribution according to the surface potential change.

- Surface state charge time constant
- Inversion layer charge time constant
- Depletion charge time constant

– Inversion charge time constant

In the MOS capacitor system, the inversion layer charges are supplied from the (thermally) generated carriers in the depletion region and neutral region(within the diffusion length) from the depletion edge.

Notice that the situation is similar to the reverse bias PN junction case right after the gate voltage is applied.(Draw the quasi Fermi level right after a unit step gate voltage is applied).

Now the resistance to limit the $R_{gen}C$ time constant of the situation is simply,

$$\frac{d\Psi_s}{dI_{\geq n}} = \sqrt{\frac{2N_a\Psi_s}{q\varepsilon_s}}\,\frac{\tau_i}{n_i\, s} \tag{15}$$

– Response time for hole distribution

As V_G changes, holes are pushed from the surface toward the substrate contact with the finite time determined by R_BC(R_B being the equivalent sub. resistance, and C being the total capacitance of the MOS system). This time constant is much shorter than the inversion charge time constant.

– Response time for surface states

C_{ss} in eq. (13) assumes that surface potential changes so slowly that surface states capture and/or emit carriers according to the Fermi statistics. The $R_{ss}C_{ss}$ in the equivalent circuit is determined by the emission and capture time of the surface states, which is also quite a slow process.