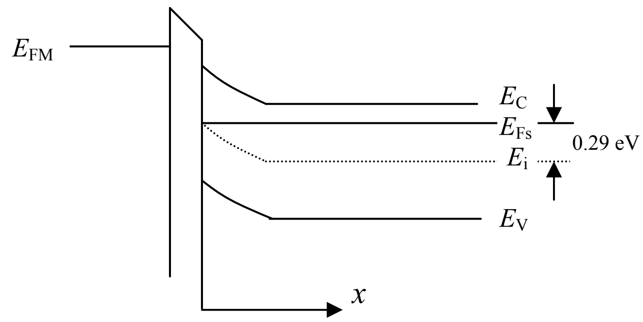
ECSE-2210 Microelectronics Technology
Class Activity 27 – Solution

1. The energy band diagram for an ideal MOS-capacitor is shown below (x_{ox} = 0.2 μm). The applied gate voltage causes band bending such that $E_F = E_i$ at the Si-SiO$_2$ interface. Answer the following.



a. Sketch electrostatic potential ϕ inside the semiconductor as a function of position.
$\phi(x)$ will be an upside-down image of the band diagram. $\phi(x)$ i.e. zero in the bulk (at large x). $\phi(x)$ near surface is called ϕ_s and will be negative, $\phi_s = -0.29$V.

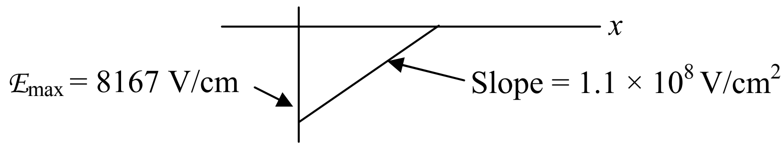
b. Is the semiconductor in ***depletion***, accumulation or in strong-inversion?
The semiconductor is in depletion because $\phi_F = \phi_s = -0.29$ V. ($2\phi_F \neq \phi_s$. Hence, it is still not inversion, but the majority carriers have reduced from the bulk material because the difference ($E_F - E_i$) is greater in the bulk than at the interface and the carrier concentration reduces exponentially)

b. N_D =? ϕ_S =?
$N_D = n_i \exp[(E_F - E_i)/kT] = 10^{10} \times \exp(0.29/0.259) = 7.3 \times 10^{14}$ cm^{-3}
$\phi_S = -0.29$ V (From the figure the difference in E_i between the bulk and the surface)

c. Calculate the depletion layer width, W.

$$W = \sqrt{\frac{2K_S \varepsilon_0}{q N_D}\phi_s} = \sqrt{\frac{2\times10^{-12}\times0.29}{1.6\times10^{-19}\times7.3\times10^{14}}} = 0.706 \ \mu\text{m}$$

d. Sketch $\mathcal{E}$-field inside the semiconductor as a function of position, and mark the numerical value of maximum $\mathcal{E}$-field inside Si.



e. What is the electron concentration at the Si-SiO_2 interface?
$n = n_i = 10^{10}$ cm^{-3} because $E_i = E_{FS}$ at the interface

f. What is the voltage drop across the oxide?
The equation 16.28 in the textbook gives the relationship between the gate voltage and the voltage drop in oxide and voltage drop in semiconductor. The first part, ϕ_s is the voltage drop or voltage difference in the semiconductor. The second part is the voltage drop in the oxide. The total should be equal to the voltage applied to the gate. You can simply plug-in the values to the second part in equation 16.28 to get the voltage drop in the oxide.

$$V_{ox} = \frac{\varepsilon_S}{\varepsilon_{ox}} x_{ox} \sqrt{\frac{2 q N_D}{\varepsilon_S} \phi_S} = 3 \times 0.2 \times 10^{-4} \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 0.29 \times 7.3 \times 10^{14}}{10^{-12}}}$$
$$= 0.493 \text{ V}$$

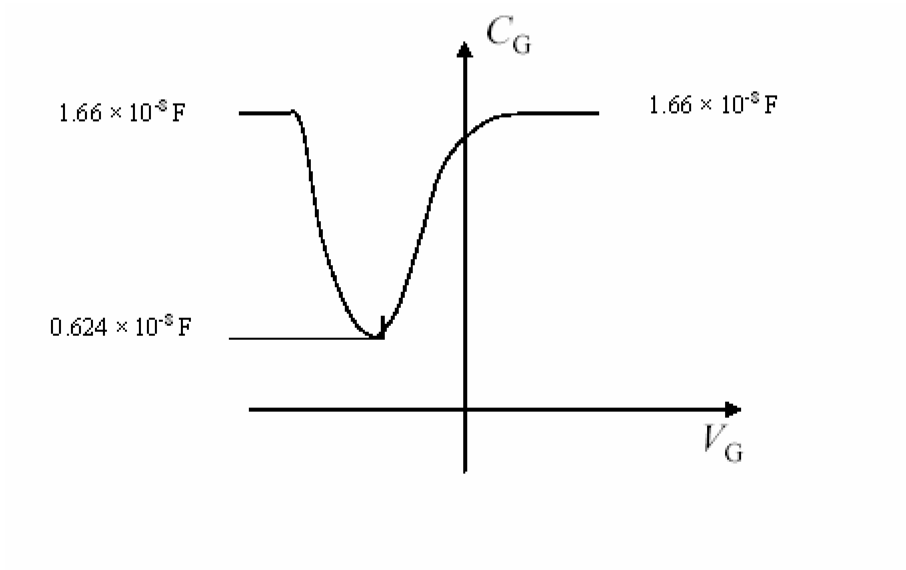
The $\mathcal{E}$-field in the oxide is 3 × 8170 V/cm; hence, V_{ox} = 0.49 V
OR
Voltage drop across oxide = Q_M / C_{ox}
$Q_M = -Q_s = -q N_D \times W = -8.167 \times 10^{-9}$ C
$C_{ox} = 1.66 \times 10^{-8}$ F
$V_{ox} = -0.49$ V

g. $V_G = V_{ox} + \phi_s = -0.29 \text{ V} - 0.49 \text{ V} = -0.78$ V

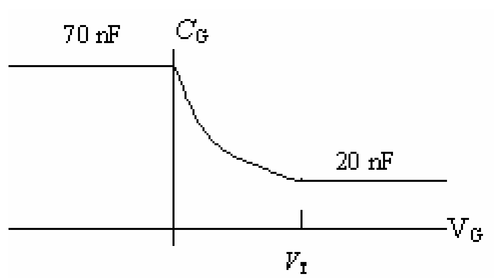
h. Plot both the high frequency and low frequency C-V_G characteristics as V_G is varied from –5 V to +5 V. Mark important points in the graph.

First find $C_{ox} = 1.66 \times 10^{-8}$ F
Find ϕ_s at start of inversion = – 2 × 0.29 V = – 0.58 V.
Find W for ϕ_s of – 0.58 V: W = 1μm
Find C_s: $C_s = 10^{-8}$ F.
Find C_{inv}: $C_{inv} = 0.624 \times 10^{-8}$ F.
Find V_G when ϕ_s is – 0.58 V: V_G = – 1.27 V (this is V_T).

Now you can plot the graph:



2.) (Do this if time permits).The figure below shows the gate capacitance (C_g) versus gate voltage (V_G) measured at high frequency (1 MHz) on a silicon MOS-capacitor with SiO_2 as the insulator. The doping in Si is 10^{16} cm^{-3}. Assume an area $A = 1$ cm^2.



a. Is the semiconductor n-type or p-type? How did you tell?
The threshold voltage V_T supplied to the gate for the start of inversion is (+) for a p-type semiconductor and (–) for an n-type semiconductor. Hence, the above semiconductor is p-type because C_G decreases as V_G increases and also the V_T is positive.

b. Which part of the curve corresponds to accumulation, depletion and inversion? Identify these regions in the figure.
The part of the curve when $V_G < 0$, corresponds to the accumulation region and the region above V_T corresponds to the inversion region. The part of the curve lying between 0 and V_T corresponds to the depletion region.

c. What is the oxide thickness?

$$C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}} = 70 \text{ nF}$$

$$x_{ox} = \frac{\varepsilon_{ox}}{C_{ox}} = \frac{3.9 \times 8.85 \times 10^{-14}}{70 \times 10^{-9}} = 0.0475 \ \mu\text{m}$$

d. What is the semiconductor capacitance, C_s, at inversion?
20 nF = $C_{ox}\, C_s / (C_{ox} + C_s)$; hence, C_s = 28 nF

e. If the gate voltage V_G equals V_T in the figure shown below this corresponds to the start of inversion. Calculate V_T.
From the graph, we have calculated C_S. When $V_G = V_T$, the depletion layer width is a maximum W_T

$$W_T = \frac{\varepsilon_{Si} A}{C_S} = \frac{10^{-12}}{28 \times 10^{-9}} = 3.57 \times 10^{-5} \text{ cm}$$

From the W_T, we can obtain the surface potential from which the threshold voltage can be calculated.

$$\phi_S = \frac{qN_D}{2\varepsilon_{Si}} W_T^2 = \frac{1.6 \times 10^{-19} \times 10^{16}}{2 \times 10^{-12}} \left(3.57 \times 10^{-5}\right)^2 = 1.01 \text{ V}$$

$$V_T = \phi_S + x_{ox} \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \sqrt{\frac{2qN_A}{\varepsilon_{Si}} \phi_S} = 1.83 \text{ V}$$

f. Suppose we apply a gate voltage of 4 V. Calculate the inversion charge Q_{inv} in Coulombs. (Hint: use the relation $C\,V = Q$; if $V_G = V_T$, the inversion layer charge is almost zero. For $V_G > V_T$ you build up inversion charges).

$Q_{inv} = C_{ox} \times (V_G - V_T)$ = 152 nC.

So, number of inversion electrons = $152 \times 10^{-9} / 1.6 \times 10^{-19} = 9.5 \times 10^{11}$ electrons