ECSE-2210 Microelectronics Technology
Class Activity 26 – Solution

1. Explain what is meant by “delta-approximation”?
   The accumulation charges and the inversion charges reside in an extremely narrow portion of the semiconductor immediately adjacent to the oxide semiconductor interface. Because of their narrow extent it would be reasonable to replace these charges with a δ function of equal charge at the oxide semiconductor interface. This is the “delta-approximation”.

2. A voltage V_G is applied to the gate of an ideal MOS-capacitor made from p-type Si doped with $N_A = 10^{16}$ cm^{-3}. The gate voltage is such that the surface potential is 0.5 V. The oxide thickness is 0.1 μm and area, $A = 1$ cm^2. Calculate the following:

   a. $\phi_F = (kT / q) \ln (N_A/n_i)$
   $= 0.0259 \times \ln (10^{16} / 10^{10}) = 0.357$ V

   b. $W = [(2\ \varepsilon_{Si} / q\ N_A)\ \phi_S\ ]^{1/2}$
   $= [\ 2 \times 10^{-12} \times 0.5 / (1.6 \times 10^{-19} \times 10^{16})\ ]^{1/2} = 0.25$ μm.

   c. The total charge, Q_s, in the semiconductor.
   $Q_S = -\ Q_M$
   $= A\ q\ N_A\ W$
   $= 1 \times 1.6 \times 10^{-19} \times 10^{16} \times 0.25 \times 10^{-4} = -4 \times 10^{-8}$ C.

   d. The total charge, Q_M, in the metal.
   $Q_M = +\ 4 \times 10^{-8}$ C
   The charge on the metal is of the same magnitude as that on the semiconductor but is of the opposite sign.

   e. The voltage-drop in 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.

$$V_{ox} = \left[\frac{\varepsilon_S}{\varepsilon_{ox}}\, x_{ox} \sqrt{\frac{2qN_A}{\varepsilon_S}(\phi_S)} \right] = 3 \times 0.1 \times 10^{-4} \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 0.5 \times 10^{16}}{10^{-12}}} = 1.2\ \text{V}$$

   Or there is another way to calculate the same voltage from the capacitor analogy:
   $C_{ox} = \varepsilon_{ox} / x_{ox} = 3.33 \times 10^{-8}$ F
   $\Delta\phi_{oxide} = Q_M / C_{ox} = 4 \times 10^{-8}$ C $/ 3.3 \times 10^{-8}$ F $= 1.2$ V

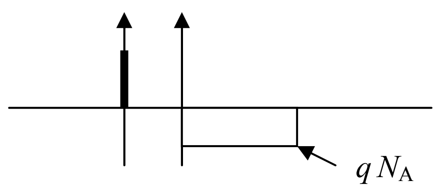
f. The electric field in the oxide.
$\mathcal{E}_{ox} = \Delta\phi_{oxide} / x_{ox} = 12 \times 10^4$ V/cm

g. The voltage-drop in the semiconductor.
$\phi_s = 0.5$ V (given above)

h. The applied gate voltage.
Applied gate voltage $V_G = \phi_s + \phi_{ox} = 0.5 \text{ V} + 1.2 \text{ V} = 1.7 \text{ V}$

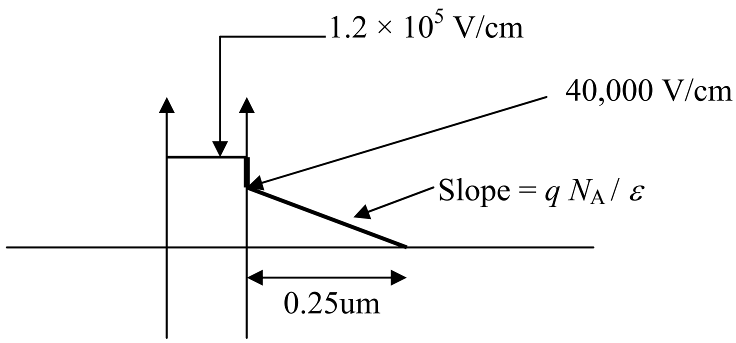
i. Draw a complete band diagram. Mark all numerical values in the diagram (such as V_G, ϕ_F, ϕ_s, etc.).
This is similar to Figure 16.7 in the text book, but the oxide and the metal need to be added. The value of $\phi_s = 0.5$ V. So, the band bends downward by 0.5 eV from the bulk value.

j. Draw the charge density as a function of position.
$\phi_F = 0.357$ V; $2\,\phi_F = 0.714$ V; $\phi_s < 2\phi_F$; therefore the MOS is still in depletion and the surface has not yet started inverting.The charge density will be similar to the depletion case.



k. Draw the electric field as a function of position.
The electric field will be constant and positive in the oxide, and the value inside silicon will be off with a triangular shape. Because,
$D_{ox} = D_{semi}$
$\varepsilon_{ox}\,\mathcal{E}_{ox} = \varepsilon_s\,\mathcal{E}_s$
$\mathcal{E}_{ox} = \varepsilon_s\,\mathcal{E}_s / \varepsilon_{ox} = 3\,\mathcal{E}_s$

That is, the $\mathcal{E}$-field in the semiconductor is about one-third of the $\mathcal{E}$-field in the oxide.



3. The energy band diagram for an ideal MOS-capacitor is shown below. It is $x_{ox} = 0.2$ μm and $E_F = E_i$ at the Si-SiO$_2$ interface. Answer the following:

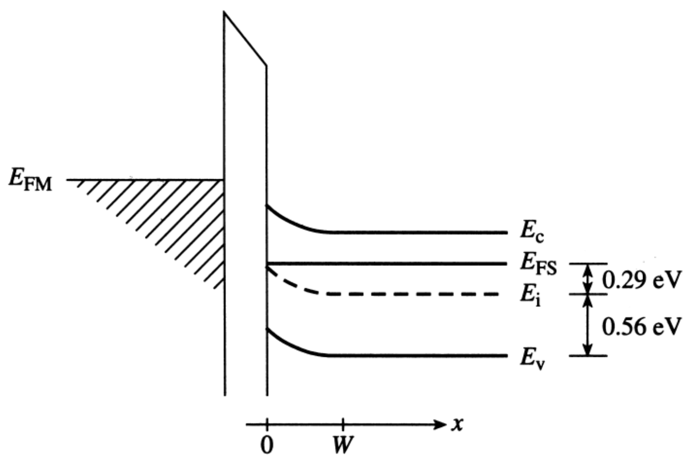
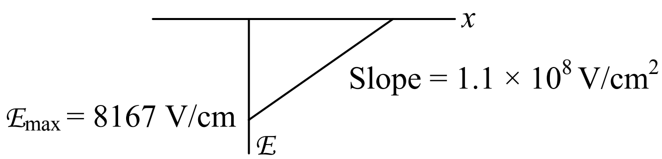


Figure P16.7

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 values of x). $\phi(x)$ near surface is called ϕ_s and will be negative, $\phi_s = -0.29$ V.

b. Roughly sketch $\mathcal{E}$-field inside the semiconductor as a function of position. $\mathcal{E}$-field will be negative at $x = 0$, and will go to zero at $x = W$.



c. Roughly sketch the electron concentration versus position inside the semiconductor.
Electron concentration will be n_i at $x = 0$ since $E_F - E_i = 0$, and will reach the bulk value at $x = W$. It will rapidly increase to the bulk value since the electron concentration varies exponentially with the value $E_F - E_i$.

d. What is the numerical value of electron concentration at the Si-SiO$_2$ interface?
$n = n_i = 10^{10}\ \text{cm}^{-3}$ since E_i is close to E_F.

e. $N_D = n_i \exp\left[(E_F - E_i) / kT \right] = 10^{10} \times \exp(0.29 / 0.259) = 7.3 \times 10^{14}\ \text{cm}^{-3}$

f. $\phi_S = -0.29$ V (From the figure the difference in Ei between the bulk and the surface)

g. $V_G = ?$
$W = 0.7\ \mu\text{m}$, $C_{ox} = 1.66 \times 10^{-8}$ F, $Q_M = -8.1\times10^{-9}$ C; $V_G = \phi_{ox} + \phi_s = -0.77$ V
OR
Use equation 16.28 for n-type, i.e.,

$$V_G = \phi_S + \left[-\frac{\varepsilon_S}{\varepsilon_{ox}} x_{ox} \sqrt{\frac{2qN_A}{\varepsilon_{ox}}(-\phi_S)} \right] \qquad 2\phi_F < \phi_s < 0$$

Note that both terms in the above equation are negative here. Remember that for ideal MOS, V_T is positive for p-type Si, and V_T is negative for n-type Si. Remember this by asking why?

h. What is the voltage drop across the oxide?
$\phi_{ox} = -0.487$ V (can be obtained from the calculation for the V_G)