Fall 2008

EE 612: Nanoscale Transistors

SOLUTION TO **HW2: MOS Electrostatics (classical)**

The purpose of this exercise is to review MOS electrostatics using the numerical simulation program, MOSCap. Before you begin this assignment, familiarize yourself with using MOSCap on www.nanoHUB.org. After logging on, find and select MOSCap. After you have familiarized yourself with running MOSCap, you are ready to proceed with the homework assignment.

For these exercises, assume:

$N_A = 2.7 \times 10^{18}$ cm^{-3} for the bulk doping
$EOT = 1.1$ nm
$Q_F = 0.0$
$T = 300$K
$V_{DD} = 1.0$V
Assume an n$^+$ polysilicon gate with $(E_F - E_C) = 0.0$ and ignore poly depletion.

1) Determine the following quantities by **analytical calculations** (assume $V_g = 0.0$V). You may use the delta-depletion approximation for these calculations.

(i) The flatband voltage, V_{FB}
(ii) The surface potential, ψ_S
(iii) The electric field in the oxide, E_{OX}
(iv) The electric field in the silicon at the surface, E_S
(v) The depletion region depth, W_D
(vi) The charge in the silicon, Q_S
(vii) The charge on the gate, Q_G
(viii) The voltage drop across the oxide, V_{OX}
(ix) The threshold voltage for this MOS capacitor, V_T

Solution:

(i) The flatband voltage, V_{FB}

$V_{FB} = \phi_{ms} = -1.06V$

(ii) The surface potential, ψ_S

From $V_G = V_{FB} + \psi_s - \dfrac{Q_S}{C_{OX}} = 0$, $Q_S \approx Q_D = -\sqrt{2q\varepsilon_{Si} N_A \psi_S}$ and answer of (i),

$\psi_S = 0.80V$

(iii) The electric field in the oxide, E_{OX}

From $V_{ox} = -\frac{Q_S}{C_{OX}} = \varepsilon_{ox} E_{ox}$, $E_{ox} = 2.4 \times 10^6 V / cm$

(iv) The electric field in the silicon at the surface, E_S

From $\varepsilon_{ox} E_{ox} = \varepsilon_{si} E_{si}$, $E_{si} = 0.8 \times 10^6 V / cm$

(v) The depletion region depth, W_D

$$Q_S \approx Q_D = -\sqrt{2q\varepsilon_{Si} N_A \psi_S} = -8.34 \times 10^{-7} col / cm^2 = -qN_A W_D$$

$W_D = 19.4nm$

(vi) The charge in the silicon, Q_S

$$Q_S \approx Q_D = -\sqrt{2q\varepsilon_{Si} N_A \psi_S} = -8.34 \times 10^{-7} col / cm^2$$

(vii) The charge on the gate, Q_G

$Q_G = -Q_S$

(viii) The voltage drop across the oxide, V_{OX}

From (i) and (ii), $V_{OX} = 0.26V$

(ix) The threshold voltage for this MOS capacitor, V_T

$$V_T = V_{FB} + 2\psi_B - \frac{Q_S(2\psi_B)}{C_{OX}} = 0.23V$$

2) Simulate the above MOS capacitor using MOSCap on the nanoHUB. Use the same p-type doping and gate oxide thickness as in problem (1), and a voltage range of 2V to -4V. You can answer the following questions by reading the data from the MOSCap plots or by downloading the data as text. From the results, deduce the following quantities:

MOSCap parameters:

Model: single gate
Gate insulator thickness: 1.1nm
Gate insulator nodes: 20
Gate insulator dielectric constant: 3.9
Semiconductor thickness: 30 nm
Semiconductor layer nodes: 100
Semiconductor doping type: p-type
Gate electrode: n+ poly silicon

Gate electrode workfunction: 0 eV
Semiconductor doping: 2.7e18 cm^{-3}
Fixed charge density in gate oxide: 0 cm^{-3}
Ambient temperature: 300 K
Initial Voltage: 2 V
Final Voltage: -4 V
Number of voltage steps: 100
Frequency for AC analysis: low

MOSCap plots:

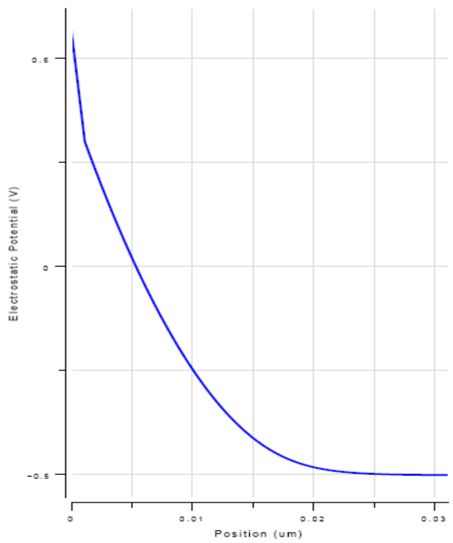

Fig. 1(a): Electrostatic potential at V_g = 0V

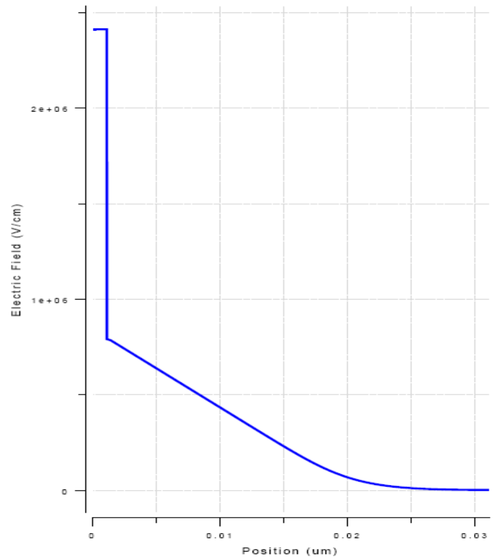

Fig 1(b): Electric field at V_g = 0V

(i) The flatband voltage, V_{FB}

Solution: Potential in the bulk: −0.502V (from Electrostatic Potential Plot)
Potential at x=0 (Gate-SiO_2 interface): 0.566V.
Flat band voltage: $V_{FB} = -(0.566 - (-0.502)) = -1.068$V.

(ii) The surface potential, ψ_S (as defined in the text by Taur and Ning)

Solution: Potential at x = 1.1nm (Si-SiO_2 interface): 0.301V (Potential Plot)
Surface potential: $\psi_S = 0.301 - (-0.502) = 0.803$V

(iii) The electric field in the oxide, E_{OX}

Solution: Electric field in the oxide: E_{OX} = 2.41e6 V/cm (Electric field plot)

(iv) The electric field in the silicon at the surface, E_S

Solution: Electric field at the silicon surface: E_S = 7.91e5 V/cm (Electric field plot)

(v) The depletion region depth, W_D

Solution: Net depletion charge in silicon: $Q_D = -\varepsilon_{si} E_S$ = –8.26e-7 C/cm^2

Depletion width: $W_D = –Q_D/qN_A$ = 19.34 nm

(vi) The charge in the silicon, Q_S

Solution: Net charge in silicon: $Q_S = Q_D = –\varepsilon_{si}E_S$ = –8.26e-7 C/cm^2

(vii) The charge on the gate, Q_M

Solution: Net charge on the gate: $Q_M = –Q_S$ = 8.26e-7 C/cm^2

(viii) The voltage drop across the oxide, V_{OX}

Solution: Voltage drop across the oxide: $V_{OX} = V$(0 nm) – V(1.1 nm) = 0.27V (Electrostatic Potential Plot)

(ix) The threshold voltage for this MOS capacitor, V_T

Solution: From the lowest value of the C-V curve, the threshold voltage for this MOS capacitor is: V_T = 0.14V.

Result comparison:	Theory	MOSCap
Flat band voltage	-1.06V	-1.07 V
Surface potential	0.80V	0.80 V
Electric field in the oxide	2.40e6 V/cm	2.41e6 V/cm
Electric field at the silicon surface	8.00e5 V/cm	7.91e5 V/cm
Depletion width	19.4 nm	19.3 nm
Net charge in silicon	-8.34e-6 C/cm^2	-8.26e-7 C/cm^2
Voltage drop across the oxide	0.26 V	0.27 V
Threshold voltage	0.23 V	0.14 V

3) From low frequency C-V characteristics of this MOS capacitor answer the following questions:

MOSCap plot:

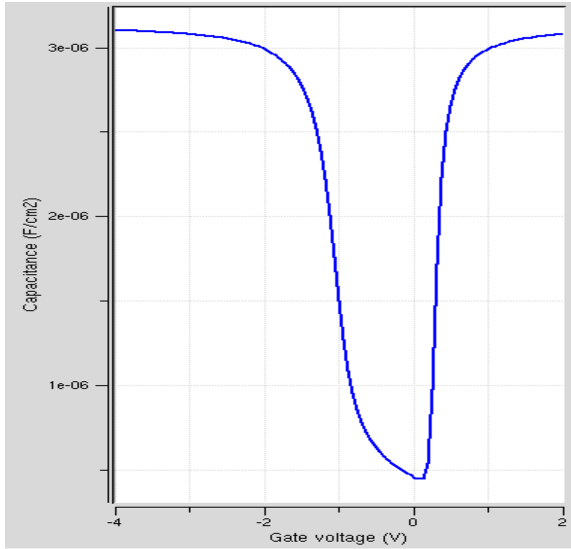

Fig. 2: C-V characteristic

(i) Deduce the equivalent oxide thickness, electrical (EOT_{elec}) at $V_G = 1.0$V.

Solution: At $V_G = 1.0$V, $C = 2.99\text{e-}6$ F/cm^2 (From the low frequency C-V plot.)

$EOT_{elec} = \varepsilon_{ox}/C = 1.15$ nm.

(ii) From the computed *C-V* plot, deduce the flatband voltage.

Solution: Theoretical prediction: $C_{ox} = \varepsilon_{ox}/t_{ox} = 3.14\text{e-}6$ F/cm^2.

$L_D = (\varepsilon_{si} k_B T/ q^2 N_A)^{1/2} = 2.52$ nm. $C_S(FB) = \varepsilon_{si}/L_D = 4.15\text{e-}6$ F/cm^2.

$C_{FB} = C_{ox}C_S(FB)/(C_{ox}+C_S(FB)) = 1.79\text{e-}6$ F/cm^2.

From the MOSCap C-V plot,

At $V_G = V_{FB} = -1.07$ V, $C_{FB} = 1.80\text{e-}6$ F/cm^2

(iii) Deduce the semiconductor capacitance in accumulation and compare it to the expected value, $Q_S/(2k_BT/q)$.

Solution: At $V_G = -4$V, $C = 3.1\text{e-}6$ F/cm^2 (From the low frequency C-V plot.)

$C_S = C_{ox}C/(C_{ox} - C) = 24.335\text{e-}5$ F/cm^2.

At $V_G = -4$V, $E_S = 2.07\text{e}6$ V/cm (From electric field at final bias.)

$Q_S = -\varepsilon_{si}E_S = -2.15\text{e-}6$ C/cm^2.

$C_S = Q_S/(2k_BT/q) = 4.17\text{e-}5$ F/cm^2 (Expected value.)

4) Estimate the effect of poly depletion on this capacitor by computing C_{MAX}/C_{OX} for N_P = 1e20, 1.5e20, and 3e20 cm^{-3}.

Solution: Using: $$\frac{C_{MAX}}{C_{OX}} = \frac{1}{1+\sqrt{8k_B T\varepsilon_{OX}^2 / \varepsilon_{Si} q^2 t_{OX}^2 N_P}},$$

For N_P = 1e20 cm^{-3}, C_{MAX}/C_{OX} = 0.74.
For N_P = 1.5e20 cm^{-3}, C_{MAX}/C_{OX} = 0.78.
For N_P = 3e20 cm^{-3}, C_{MAX}/C_{OX} = 0.83.
Poly depletion effects are reduced (C_{MAX}/C_{OX} gets closer to unity) as N_P is increased.