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ECE 305 Exam 5 SOLUTIONS: Spring 2015

April 17, 2015

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This is a closed book exam. You may use a calculator and the formula sheet at the end of this exam. Following the ECE policy, the calculator **must** be a Texas Instruments TI-30X IIS scientific calculator.

There are three equally weighted questions. To receive full credit, you must **show your work**.

The exam is designed to be taken in 50 minutes.

Be sure to fill in your name and Purdue student ID at the top of the page.

DO NOT open the exam until told to do so, and stop working immediately when time is called.

The last page is an equation sheet, which you may remove, if you want.

75 points possible, 10 per question

1) 25 points (5 point per part)

2) 25 points (5 points per part)

3) 25 points (5 points per part)

------------------------ Course policy ------------------------

I understand that if I am caught cheating in this course, I will earn an F for the course and be reported to the Dean of Students.

Read and understood: ______________________________
signature

Answer the **multiple choice questions** below by **circling** the **one, best answer**.

1a) The electric field in the oxide of an MOS capacitor is typically a constant, independent of position. Why?

a) Because there is typically very little charge at the oxide-semiconductor interface.
b) Because there is typically very little charge in the oxide.
c) Because there is typically very little charge at the metal-semiconductor interface.
d) Because the dielectric constant of the oxide is typically different than the dielectric constant of the semiconductor.
e) Because the minority carrier lifetime in the oxide is typically very long.

1b) Which of the following is true for an N-type semiconductor in accumulation?

a) The surface potential is positive.
b) The surface potential is negative.
c) The surface potential is zero.
d) The surface potential is ϕ_F.
e) The surface potential is $-2\phi_F$.

1c) Which of the following is true of $C_{ox}\left(V_G - V_T\right)$ in an MOS capacitor with an N-type substrate? (Assume that $V_G < V_T < 0$.)

a) It is the magnitude of the accumulation charge.
b) It is the magnitude of the depletion charge.
c) It is the magnitude of the inversion charge.
d) It is the magnitude of the total charge in the semiconductor.
e) It is the magnitude of the fixed charge at the oxide-semiconductor interface.

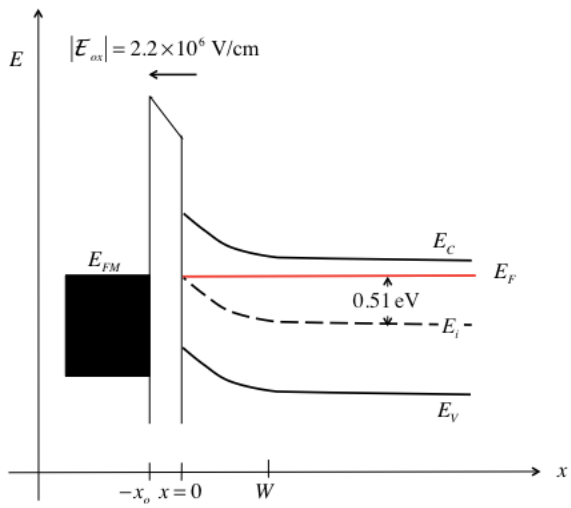
1d) How is an N-channel MOSFET biased under ON-current conditions?

a) $V_{GS} = 0, V_{DS} = 0$.
b) $V_{GS} = 0, V_{DS} = V_{DD}$.
c) $V_{GS} = V_{DD}, V_{DS} = 0$.
d) $V_{GS} = V_{DD}, V_{DS} = V_{DD}$.
e) $V_{GS} = -V_{DD}, V_{DS} = +V_{DD}$.

1e) How is an N-channel MOSFET biased under OFF-current conditions?

a) $V_{GS} = 0, V_{DS} = 0$.
b) $V_{GS} = 0, V_{DS} = V_{DD}$.
c) $V_{GS} = V_{DD}, V_{DS} = 0$.
d) $V_{GS} = V_{DD}, V_{DS} = V_{DD}$.
e) $V_{GS} = 0.05V_{DD}, V_{DS} = V_{DD}$.

2) This problem is about the MOS capacitor whose energy band diagram is show below. You may assume that the semiconductor is silicon at 300 K and that the insulator is SiO_2 with a relative dielectric constant of 3.9 and a thickness of 2 nm. You may assume that there is no charge at the oxide-semiconductor interface. Also assume that the electrostatic potential in the silicon is zero as $x \to \infty$.



Answer the following questions about this MOS capacitor.

2a) Is the semiconductor in accumulation, flat-band, depletion, or inversion? Explain your answer.

Solution:
We see that this is an N-type semiconductor. The bands bend up at the surface, which pull the conduction band way above the Fermi level and makes the electron concentration near the surface small. The semiconductor is in **depletion.**

2b) What is the numerical value of the surface potential? (Be sure to include a sign.)

Solution:
The magnitude of the surface potential is (1/q) times the difference in the intrinsic level are the surface and in the bulk, which is 0.51 V. The bands end up, so the surface potential is negative.

$$\boxed{\phi_S = -0.51\,V}$$

2c) What is the electrostatic potential voltage of the gate electrode with respect to the semiconductor? Include the proper sign. (Hint: The answer is not zero)?

Solution:

$V_M = \Delta V_{ox} + \phi_S$

$\Delta V_{ox} = -\mathcal{E}_{ox} x_0 = -\left(1.9\times10^6\right)\left(2\times10^{-7}\right) = -3.8\times10^{-1}\text{ V}$

(Note the sign: the left side of the oxide is more negative than the right side.)

$V_M = -0.38 - 0.51 = -0.89$

$\boxed{V_M = -0.89\text{ V}}$

2d) What is the numerical value of the electric field in the silicon right at the oxide-silicon interface? (Be sure to include a sign in your answer.)

Solution:

The D-field is continuous at the interface (no charge at the interface), so

$K_O\varepsilon_0\mathcal{E}_{ox} = K_S\varepsilon_0\mathcal{E}_S$

$\mathcal{E}_S = \dfrac{K_O}{K_S}\mathcal{E}_{ox} = \dfrac{3.9}{11.8}\times\mathcal{E}_{ox} = 0.33\times\left(-2.2\times10^6\right) = -7.3\times10^5$

$\boxed{\mathcal{E}_S = -7.3\times10^5\text{ V/cm}}$

2e) What is the value of the charge in the semiconductor in C/cm^2? Be sure to include the sign.

Solution:

We see that the-type semiconductor is depleted, so the charge is positive. (Another way to see this is from the direction of the electric field in the oxide.) Recall that the magnitude of the displacement field at the oxide-Si interface is the magnitude of the charge in the semiconductor, so

$K_O\varepsilon_0\mathcal{E}_{ox} = Q_D$

$Q_B = K_O\varepsilon_0\mathcal{E}_{ox} = 3.9\times\left(8.854\times10^{-14}\right)\times2.2\times10^6 = 7.6\times10^{-7}$

$\boxed{Q_B = +7.6\times10^{-7}\text{ C/cm}^2}$

Another way to solve this problem is to use:

$$Q_B = +qN_D W(\phi_S) = -\sqrt{2qK_S\varepsilon_0 N_D(-\phi_S)}\ \text{C/cm}^2$$

We know the surface potential and are given enough information to determine the electron density in the bulk from $n_0 = n_i e^{(E_F - E_i)/k_B T}$. If we assume $n_0 = N_D$ then we can solve the problem.

3) The figures below show transistor IV characteristics for Intel's 14 nm technology. Assume that the transistor has a 1 micrometer width. Also assume that $C_{ox} = 3.0\times10^{-6}$ F/cm^2 and that the source and drain series resistances are 100 Ohms each.

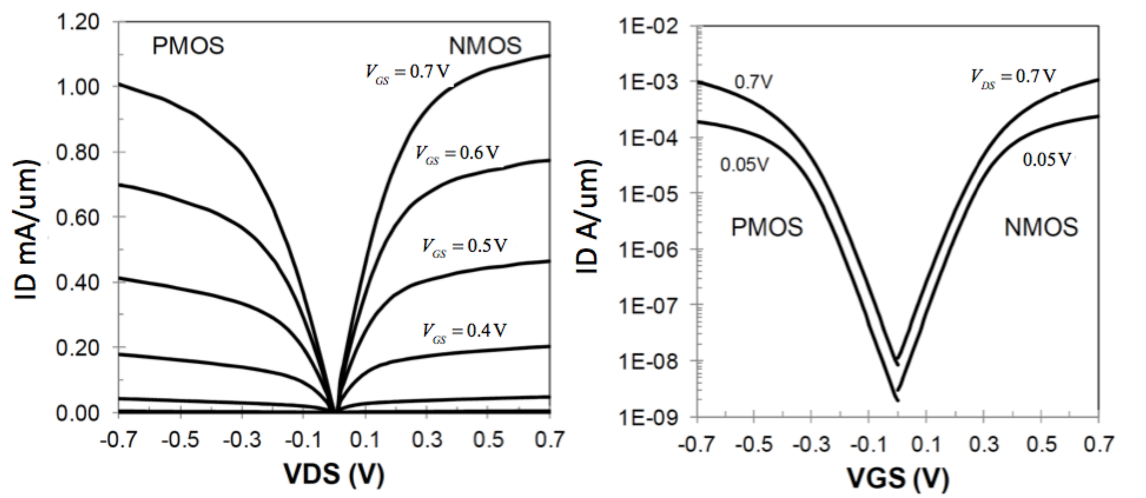


Figure 5: Transistor I-V Curves **Figure 6: Subthreshold Curves**

3a) What is the ON-current in Amperes of the NMOS device? Explain how you find it.

Solution:

The ON-current occurs when $V_{GS} = V_{DS} = V_{DD}$.

The power supply voltage is $V_{DD} = 0.7$ V.

The maximum current for the $V_{DD} = 0.7$ line is the ON-current.

$\boxed{I_{ON} = 1.1\ \text{mA}}$

3b) What is the OFF-current of the NMOS device? Explain how you find it.

Solution:
The OFF-current occurs when $V_{GS} = 0, V_{DS} = V_{DD}$.

The power supply voltage is $V_{DD} = 0.7$ V.

The current for the $V_{DD} = 0.7$ line at $V_{GS} = 0.0$ is the OFF-current on Fig. 5 above.

$$\boxed{I_{ON} = 10^{-8}\text{ A} = 10\text{ nA}}$$

3c) Approximately what is the threshold voltage of the NMOS transistor? Explain how you find it.

Solution:

The threshold voltage is the voltage at which significant current begins to flow. From Fig. 5, we see that there is little current for $V_{GS} = 0.3$ V and no observable current for $V_{GS} = 0.2$ V, so

$$\boxed{0.2 < V_T < 0.3\text{ V}}$$

3d) Approximately what is the DIBL of the NMOS device?

Solution:
From Fig. 6 in the subthreshold region, we see a parallel shift of $\Delta V_{GS} \approx 0.05$ V. The difference in drain voltage for the tow curves is; $\Delta V_{DS} = 0.7 - 0.05 = 0.65$ V

So we find:

$$DIBL = \frac{\Delta V_{GS}}{\Delta V_{DS}} \approx \frac{0.05}{0.65} = 0.077\,\frac{\text{V}}{\text{V}} = 77\,\frac{m\text{V}}{\text{V}}$$

$$\boxed{DIBL = 77\text{ mV/V}}$$

(According to Intel, the answer is 60 mV/V. The difference probably comes from how accurately we "eyeballed" the voltage shift in Fig. 5.)

3e) Approximately what is the inversion layer charge density, $n_S = |Q_n|/q$ in the ON-state?

Solution:

$|Q_n| = C_{ox}\left(V'_{GS} - V_T\right)$

The intrinsic gate to source voltage is $V'_{GS} = V_{GS} - I_D R_S$

$V'_{GS} = 0.7 - \left(1.1\times10^{-3}\right)\times100 = 0.59$

$|Q_n| = C_{ox}\left(V'_{GS} - V_T\right) = 3\times10^{-6}\left(0.59 - 0.25\right) = 1.02\times10^{-6}$

$n_S = |Q_n|/q = \left(1.02\times10^{-6}\right)/1.6\times10^{-19} = 6.2\times10^{12}\ \text{cm}^{-2}$

$\boxed{n_S = 6.2\times10^{12}\ \text{cm}^{-2}}$