MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering and Computer Science

6.012 MICROELECTRONIC DEVICES AND CIRCUITS

Problem Set No. 6

Issued: October 14, 2009 **Due**: October 21, 2009

Reading Assignments:

Lecture 10	(10/15/09)	- Chap. 9 (9.3, 9.4)
Lecture 11	(10/20/09)	- Chap. 10 (10.1.1a)
Lecture 12	(10/22/09)	- Notes

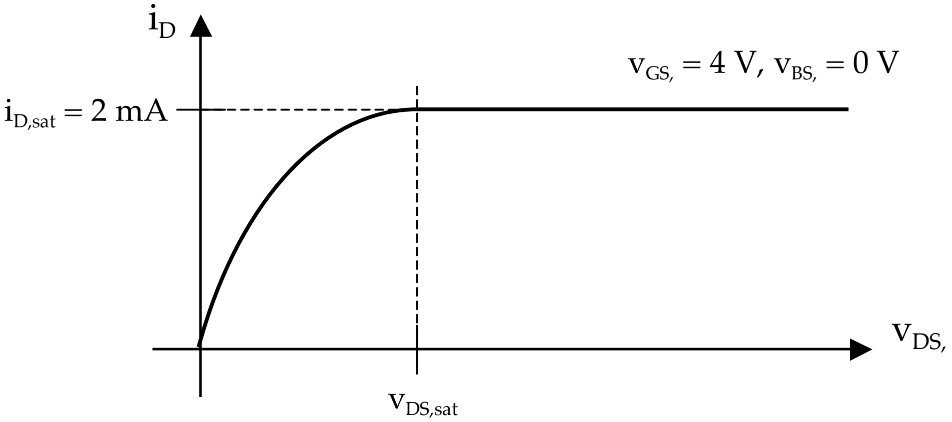
Problem 1 - Do Problem 10.2 in the course text using a substrate doping level, N_A, of 1 x 10^{16} cm^{-3} in Parts (a) thru (c) rather than 1 x 10^{17} cm^{-3}, and assuming that the value of the parameter α in the model developed in Lecture 11 is one (1). Also add the following parts to this problem:

d) Consider building the same device with t_{ox} = 100 A . What must the doping level of the substrate, N_A, be to have the same threshold voltage you found in Part (a)? For simplicity assume the flat-band voltage, V_{FB}, is still -0.2 V, but after calculating the new N_A, find the actual flat-band voltage with this new doping level.

e) Repeat Part (b) and compare the answer for this new device with that of the original.

Problem 2 - This is a former exam problem (with all the work space and blanks removed), so it won't take you long to do.

An ideal n-channel MOSFET has the i_D vs v_{DS} characteristic shown below when $v_{GS} = 4$ V and $v_{BS} = 0$ V. Note that the drain current saturates at 2 mA for $v_{DS} \geq V_{DS,sat}$.



The threshold voltage, $V_T(v_{BS})$ of this device is 1 V when $v_{BS} = 0$ V, i.e. $V_T(0) = 1$ V. It has the structural parameters listed below. Work this problem approximating α as 1.

$N_A = 10^{17}$ cm^{-3}, W = 25 μm, L = 10 μm, $t_{ox} = 10^{-6}$ cm, and $\varepsilon_{ox} = 3.5 \times 10^{-13}$ F/cm

a) What is the drain-to-source saturation voltage, $v_{DS,sat}$, when $v_{GS} = 4$ V?

b) Use the information provided to calculate the electron mobility, μ_e, in the channel.

c) Find the inversion layer sheet charge density in the channel, $q_N^*(y)$, at the source end, i.e. $q_N^*(0)$, and at the drain end, $q_N^*(L)$, for the bias condition $V_{GS} = 4$ V, $V_{DS} = 1$ V, and $V_{BS} = 0$ V.

d) Find the average net velocity, $\bar{s}_y(y)$, of the electrons in the channel at the source end, i.e. $\bar{s}_y(0)$, and at the drain end, $\bar{s}_y(L)$, for the bias condition in Part (c) above, for which the corresponding drain current, I_D, is 0.55 mA.

e) The drain-to-source voltage, v_{DS}, is <u>increased</u> to 5 V, so that the bias condition is now $V_{GS} = 4$ V, $V_{DS} = 5$ V, and $V_{BS} = 0$ V. Find the inversion layer sheet charge density in the channel, $q_N^*(y)$, at the source end, i.e. $q_N^*(0)$, and at the drain end, $q_N^*(L)$ under this new bias condition.

f) Next consider this MOSFET with a negative substrate-to-source bias, V_{BS}. What is the drain current of this device when it is biased in saturation, i.e., with $V_{DS} \geq (V_{GS} - V_T)$, with $V_{GS} = 4$ V and $V_{BS} = -5$ V? Suggestion: Calculate V_T when $V_{BS} = -5$V using the expression below, and calculate i_D in saturation with this new V_T.

<u>Threshold voltage expressions</u>:

The definition of the threshold voltage of a MOSFET is:

$$V_T(v_{BS}) \equiv V_{FB} - 2\phi_{p-Si} + \frac{1}{C_{ox}^*}\sqrt{2\varepsilon_{Si}qN_A\left[|2\phi_{p-Si}| - v_{BS}\right]}$$

It is very common to write this in terms of $V_T(0)$, the threshold when $v_{BS} = 0$, and to introduce the parameter γ as shown below:

$$V_T(v_{BS}) = V_T(0) + \gamma\left\{\sqrt{|2\phi_{p-Si}| - v_{BS}} - \sqrt{|2\phi_{p-Si}|}\right\}$$

$$\text{with} \quad \gamma \equiv \frac{\sqrt{2\varepsilon_{Si}qN_A}}{C_{ox}^*} \quad \text{and} \quad V_T(0) \equiv V_{FB} - 2\phi_{p-Si} + \gamma\sqrt{|2\phi_{p-Si}|}$$

<u>Problem 3</u> - This problem deals with the α factor in the gradual channel model for the MOSFET (see for example the Lecture 11 Foils).

a) Calculate the α factor for the two device structures in Problem 1 above. Use your results to recalculate the drain current, i_D, in Parts (c) and (e) of that problem.

b) Calculate the MOSFET α factor for a device in which N_{Ap} is 5×10^{17} cm^{-3}, and the oxide thickness is 3 nm (3×10^{-7} cm). Take ε_{ox} to be 3.5×10^{-13} F/cm and ε_{Si} to be 10^{-12} F/cm. Do this for back-to-source biases, v_{BS}, of 0, -1, and -2 V.

<u>Problem 4</u> - Diode-like connections of MOSFETs are quite useful and important to understand. Look at Figures 11.12 (a), (b), and (c) on page 351 in the course text. Calculate and plot i_D for v_{AB} between 0 and 6 Volts using the device parameters given in the figure caption. (These are curves a, b, and c in part e of this figure.)

6.012 Microelectronic Devices and Circuits
Fall 2009