Device Characterization Project 2: MOSFET TRANSISTOR

Summary: In this project you will be characterizing the current voltage characteristics of an n-channel MOSFET. This is a real device (2N7000). To do this, you will use the MIT Microelectronics WebLab. Refer to the User Manual for instructions on how to use the system.

Background: For background, learning goals, and help getting started please see the PN project.

Assignment[1]: This problem is about characterizing an n-channel MOSFET that is currently connected to the MIT Microelectronics WebLab. This exercise involves three separate phases: measurement, graphing, and analysis (with emphasis on the latter).

Important note: For all measurements, hold V_{GS} between 0 and 4 V, and V_{DS} between 0 and 4 V. As inputs to this exercise, you need the dimensions of the MOSFET: L =1.5 µm and W =46.5 µm. Note that the required SMU compliance is 100mA which isn't that high for this device. You may need to try a few different gate voltages to get a decent number of curves. Keep the spacing between voltages constant. Make sure you don't include any data which is "railed" (maxed out at the compliance value) when you do curve fitting.

PART I: MOSFET CHARACTERISTICS

1. Obtain the *output characteristics* of the MOSFET. This is a plot of I_D vs. V_{DS} with V_{GS} as a parameter, like Figure 10-40/42 in Neamen.
    a. (10 pts) Choose ΔV_{GS} to give you at least five decent curves. (Make sure you do not exceed 100mA and try to include one curve with very low currents.) Take a screen shot of these characteristics for later use.
    b. (5 pts) Download the data and plot it using your favorite tool (Excel, Matlab, …)
    c. (5 pts) Obtain a rough estimate of V_T from this graph using two different techniques. This means using visual observation and a ruler, rather than fitting a curve. Explain your techniques in one or two sentences.

2. Obtain the *transfer characteristics* of the MOSFET for two different drain voltages. This is a plot of I_D vs. V_{GS} with V_{DS} as a parameter, like Figure 10-48 in Neamen[2], (& Figure 6.28 in Streetman[3].)
    a. (10 pts) Using the output characteristics above choose two different values of V_{DS} so that you obtain one measurement plot in saturation and one plot in the linear region. Explain those choices. Take a screen shot of these characteristics and include them in your report.
    b. (5 pts) Download the data and plot it. Note that in saturation you will want to plot the square root of I_D. Explain why this is a good choice.
    c. (5 pts) Obtain estimates of the threshold voltage, $V_{T,}$ in the linear and the saturation regions. Do they agree? (You can do this manually using the graph using a ruler, or by using some functions in your favorite software.)

3. (10 pts) From the transfer characteristics in the linear and saturation regions, extract ($\mu_n C_{ox}$) and the threshold voltage, V_T, for this MOSFET. "Extract" means to use your knowledge of the model (Equations 10-62/67 from Neamen[2]) to fit a line to one of your

transfer curves. The modeled slope should allow you to calculate μ_n Cox. Note that we cannot separate the mobility from the oxide capacitance using this data. Are your extracted values of V_T close to your previous estimates? Summarize your results in a table.

4. First some context for this assignment: in an ideal case we would have one model and one set of parameter values that would describe our transistor across all biases and modes of operation. However, that is not the case and we often have to use models that are accurate only within some range of values or certain region so that parameters for the linear region will differ from the ones for saturation. So, which one should we use? That depends on the application – suppose you are trying to design a class A amplifier. Which region would you try to model with the greatest accuracy? Keeping this in mind, here is the actual assignment. Use the parameters that you would use for Class A amplifier design in an I-V model and compare graphically with the output and both transfer curves.
   a. (10 pts) Use equation 10-62 from Neamen[2] as your starting point for the model. Then put your calculated numbers from above into this model and plot it on the same graphs (output and both transfer) with the measured data. Use only the one set of parameter values from Part 3 you chose for the Class A amplifier.
   b. (5 pts)If the model fits the output characteristics data (Part 1) well with parameters based on the transfer data (Part 3) we have good confirmation of the validity of the model. Discuss your results in several sentences. Does the model fit the data well? If not, why not? Do you have possible explanations?

PART II: MOSFET IN SUBTRESHOLD REGION

5. Measure and download the subthreshold characteristics, that is I_D vs V_{GS} for V_{DS}=2V. Focus in on V_{GS} values which are near the threshold voltage (above & below.)
   a. (10 pts) Plot these characteristics as $\log_{10}I_D$ vs V_{GS} (like Streetman Fig 6-38[3].)
   b. (5 pts) For the full equation and explanation see Neaman Section 11.1.1 and Eqn 11.1. A more complete version of Eqn 11.1 is given below (Streetman Section 6.5.7, Eqn 6-65.) All of the constants can be lumped into one constant I_{OFF}.

$$I_D = \mu(C_d + C_i)\frac{Z}{L}\left(\frac{kT}{q}\right)^2\left(1-\exp\left(\frac{-qV_D}{kT}\right)\right)\exp\left(\frac{q(V_G - V_T)}{c_r kT}\right) \text{ where Z is the channel width}$$

$$I_D = I_{OFF}\exp\left(\frac{qV_G}{c_r kT}\right) \text{where } c_r = \left[1+\frac{C_d + C_{it}}{C_i}\right], \text{C}_\text{i} \text{ is the gate capacitance,}$$

C_d is the (sub - threshold) depletion capacitance in the channel, and

C_{it} is the "fast interface state" capacitance[3].

Subthreshold "Slope" S is defined by $S = 2.3\frac{kT}{q}c_r$

What will happen to the exp(V_D) term for our choice of V_D =2V ? Explain.

   c. (10 pts) Calling S a "slope" is a misnomer; its proper name is "inverse slope" of $\log_{10}I_D$ vs V_G but it is commonly labeled as "subthreshold slope" in the literature.

S is measured in V/decade, and it tells us how much increase in voltage is needed to increase current by one decade. Using your data and the equation above, fit a curve which will allow you to calculate your subthreshold slope, S, and hence c_r. Explain your procedure.

d. (5 pts) Comment on the effect of oxide thickness on subthreshold slope. How would you improve S? (Hint: "improving" means decreasing S in value.)

6. (5 pts) Feedback: Please give feedback on the project. Was this project instructive? Did you experience major problems or frustrations with WebLab, understanding the instructions, or completing the assignment? Any suggestions for improving WebLab, the interface, the instructions, or the project itself?

Additional information and assorted advice

- Take care with these devices. They are real. Do not exceed the recommended voltages and compliance limits. If the characteristics look wrong it could be due to a damaged device. In that case report it to MIT and choose another device.
- The required graphs need not be too fancy but they must follow the guidelines discussed in class. For example, they must have proper axis labeling and correct units. All figures must have figure captions and be explained in the text. When there are several lines on a plot, each one should be properly identified (handwriting is NOT OK). Please spend some time making your plots look "nice". Once you have a setup that looks good then it will be easy to do it for the rest.

Note on collaboration: You are encouraged to work in groups to aid in your understanding. It is appropriate to ask questions of another student and check your work against each other as you proceed. This is NOT a group project, though. Each person must obtain his/her own data, create his/her own graphs, and write up his/her interpretations individually. Any sharing of data and/or plots will result in a zero points for the entire assignment for all involved. Bottom line – don't share your data and plots with anyone.

1 This material was created by or adapted from material created by MIT faculty members, Jesús del Alamo, Dimitri Antoniadis, Judy Hoyt, Charles Sodini, Pablo Acosta, Susan Luschas, Jorg Scholvin, Niamh Waldron, 6.012 Microelectronic Devices and Circuits, (2003). Copyright © 2003, Massachusetts Institute of Technology.
This particular project was written by Professor Jesus del Alamo for his class at MIT and modified by B. Natter, B. Pejcinovic, & J. Morris for ECE 415/515.

2 Neamen, D.A., *Semiconductor Physics & Devices*, McGraw-Hill, Fourth Edition, 2012.

3 Streetman, B.G., & Banerjee, S.K., *Solid State Electronic Devices*, Prentice Hall, Sixth Edition, 2006.