ELECTRICAL ENGINEERING
School of Engineering

EGRE 224 Introduction to Microelectronics

Laboratory No. 5

Characterization and Modeling of an NMOS Transistor

I. Introduction

In this laboratory you will characterize two (2) VN2222LL NMOS transistors that you will use in laboratory 6, laboratory 7, and the design project. You will use the characterization data to build a Spice model of the transistors that will also be used in these labs and the design project.

II. Theory

The Spice model for MOS transistor is based on the equations for I_d that were discussed in class for operation in the triode and saturation region, namely:

(1) Triode ($V_{DS}<V_{GS}-V_T$):

$$I_D = k_n' \left(\frac{W}{L}\right)\left((V_{GS}-V_T)V_{DS}-\frac{V_{DS}^2}{2}\right)$$

(2) Saturation ($V_{DS} \geq V_{GS}-V_T$):

$$I_D = k_n'\left(\frac{W}{L}\right)\left((V_{GS}-V_T)^2(1-\lambda V_{DS})\right)$$

In order to develop the Spice model, we must obtain values of the parameters of L, W, V_T, k'_n, and λ. We will take L and W for this transistor as givens and use values of 9μm and 13000μm respectively. Therefore, it is only left to obtain values for V_T, k'_n, and λ. If we plot I_d vs. V_{GS} for an NMOS transistor for a V_{DS} of a very small value, say 0.1V, we get a curve like the one below.
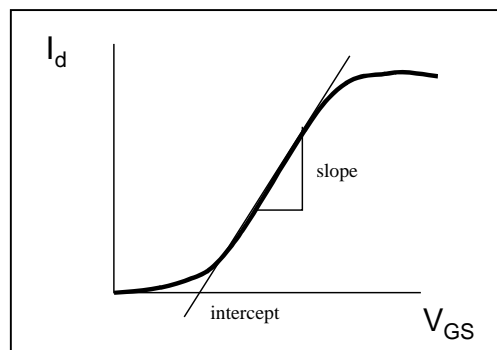
This region of operation is governed by (1) above. If we draw a linear approximation of this curve like the one in the graph above, it can be represented as the equation of a line:

Y= slope*(X + X$_{int}$) + Y$_{int}$

By comparing (1) with the equation of the line, it can be seen that for the linear segment:

k_n = slope/(V_{DS}(W/L)) V_T = X$_{int}$ - V_{DS}/2

1

This means that we can derive values for k'_n and V_T from the graph of I_d vs. V_{GS} for small values of V_{DS}. These values are called the low field values of k'_n and V_T, and they may be different then the values derived from the saturation characteristics, but the will be a sufficient starting point for our purposes.

Next we need to derive a value for the channel length modulation parameter, λ. Recall that λ can be derived from the graph of I_D vs. V_{DS} in the saturation region as shown below:
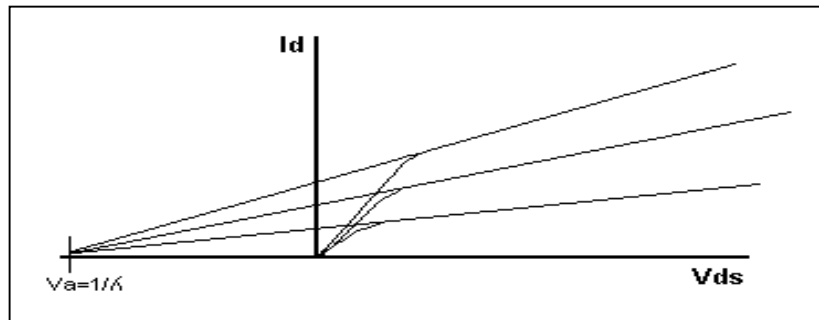
All we need to do is find the X intercept of the I_D vs. V_{DS} curve in saturation. This is easily done using the capabilities of the semiconductor parameter analyzer.

II. Parameter Extraction Procedure (week 1)

Select two VN2222LL NMOS transistors from the provided supply and mark them with your lab group name and number them 1 and 2. Take good care of these transistors from now on – they are yours until the end of class! They only cost about 35¢, but if you damage or loose them, you will have to characterize their replacements!

Let one team member lead the data collection effort for the first transistor. Place the transistor into the HP16442A (Agilent 16442A) Test Fixture. The drain terminal connects to SMU1, the gate terminal connects to SMU2, and the source terminal connects to SMU3.

On the channel page, setup the SMUs as shown in the table below:

Unit	Vname	Iname	Mode	Fctn
SMU1	V_d	I_d	V	VAR2
SMU2	V_g	I_g	V	VAR1
SMU3	V_s	I_s	COMMON	CONST

On the measurement page, set VAR1, V_g to a linear sweep from 0V to 5V in 50mV steps with the compliance set to 100μA. Set VAR2, V_d, to a start value of 0.1V and a number of steps to 1 with a compliance of 100mA.

On the display page, set the X axis to V_g and the Y axis to I_d **for both the graphics and list display mode**, and run a single sweep. Hit the "*Scaling*" horizontal soft key and the "*Auto Scaling*" vertical softkey to expand the graph. It should look like the first example above. You may want to go back to the measurement page and increase the

start value of V_g to remove the initial portion of the graph that contains no useful information (i.e., where $I_d=0$).

Now we need to add a line approximation to the graph to measure the slope and the X intercept. Make sure that the marker is turned on before going to the next step.

Begin by pressing the "*Line*" horizontal soft key button. The vertical soft key menu will change to Line menu. On the vertical soft key menu, hit *the "Line Select None*" softkey. Next find the find the button labeled "*Line ____*"; if the button says "*Line Off*" hit the button, if it says "*Line On*" then just continue on. Next, use the *Cursor Knob* to position the cursor to the first point of the line and hit the vertical soft key, "*Cursor to Marker*." Then hit the vertical soft key "*Select Cursor*" to chose the other cursor, move the marker to the second point of the best-fit line, and then hit the "*Cursor to Marker*" vertical soft key. The slope (grad) and Y intercept will be in the upper left-hand corner of the screen and the X intercept will be centered at the bottom of the screen. Record these values to use in determining your Spice model parameters.

Go back to the Graph/List page and save an ASCII version of this data on a floppy disk as you did for the diode lab. Show your graph to the instructor before you save the data.

Now we will generate a plot of I_d vs. V_{DS} for values of V_{GS} (i.e., the I-V characteristic family of curves for a MOS device). Our goal will then be to tune the Spice model of the NMOS transistor to match these curves.

Go back to the channel page and setup the SMUs as shown in the table below:

Unit	Vname	Iname	Mode	Fctn
SMU1	V_d	I_d	V	VAR1
SMU2	V_g	I_g	V	VAR2
SMU3	V_s	I_s	COMMON	CONST

On the measurement page, setup VAR1, V_d, for a sweep from 0V to 5V in 50mV steps with a compliance of 100mA. Setup VAR2, V_g for a sweep from about 0.5V under the threshold voltage measured above to 4.0V with a 500mV step and the compliance set to 100μA. On the display page, set the X axis to V_d **for both the graphics and list display mode** and run a single sweep. Autoscale the display. Adjust the step size for V_g on the measurement page so that the top curve just comes in below the 100mA compliance value – your goal is to obtain 4 or 5 good I_d vs. V_{DS} curves above the threshold and below the compliance value. It may help to change the start value of V_g too.

When you have an acceptable set of curves, let the instructor see them and save them on disk as before. Note that this time, you will need to keep the header information when you import the file into Excel as it tells you the values of V_{GS} for each curve!

Next, add a line, as you did above, that is parallel to the top curve. Note the value of the X intercept. This is the V_A voltage which is $1/\lambda$. Record this value and move the line down to the second curve. Record this value. You can use an average of these two values as your λ parameter. Note that V_A is fairly large, which indicates that the curves are fairly flat in the saturation region, as we would expect for a long channel device. This means that in the saturation region, the I_d vs. V_{GS} curves should be very similar for different values of V_{DS}.

To check that, go back to the channel page and set V_g as VAR1 and Vd as VAR2 as in the first step. On the measurement page, set VAR1, V_g to a sweep from just below threshold to 3.5V (use the range you found in the second step above) with a compliance of 100µA. Set VAR2, V_d, to a sweep from just above the threshold voltage (say 2.5V) to 5V in 200mV steps. On the display page, set the X axis back to V_g **for both the graphics and list display mode** and start the sweep. Autoscale the display and notice how all of the curves fall right on top of each other. Show the results to the instructor for verification and save them to disk as before. Note again that you must keep the header information when you import the data into Excel so that you know what value of V_{DS} each curve represents.

Now repeat the above procedure to collect data for the second transistor. Let the second lab team member lead the data collection effort for this transistor.

III. NMOS Transistor Modeling (week 2)

As a pre-lab assignment, use the data collected for each transistor and calculate the parameters necessary to fill-out the table below:

Table 1

Parameter (simulation value)	Transistor 1	Transistor 2
L (on transistor symbol)	9µm	9µm
W (on transistor symbol)	13000µm	13000µm
k'_n (KP)	µA/V^2	µA/V^2
V_T (VTO)	V	V
λ (LAMBDA)	V^{-1}	V^{-1}

Also as a pre-lab assignment, use Excel to graph your data for the three runs collected above for each transistor. In the case of the final run of I_D vs. V_{GS} for the transistor in saturation, pick a single set of data for a value of V_{DS} in the middle of the saturation region and only graph that value.

As your final pre-lab assignment fill out the table below using the data from the second run above with the values of I_D vs. V_{GS} for V_{DS} values of .5V above your saturation voltage ($V_{DS}=V_{GS}-V_T$) for the largest value of V_{GS} you measured (we'll call it $V_{GS(max)}$), and $V_{DS}=4.5V$. You will use this data to help you adjust the parameters you found above to match your simulated transistor to your measured one. Note that you may not have enough data to completely fill this table.

Table 2

V_{GS} value (e.g. 1.8V, 2.0V, etc.)	I_D value for $V_{DS}=V_{GS(max)}-V_T+0.5V$	I_D value for $V_{DS}=4.5V$

When you are ready to begin the simulation, go to the class web page:

http://www.people.vcu.edu/~rhklenke/egre224

Click on the *Basic Schematic Capture and Analog Simulation with Design Architect and Accusim* link under the Mentor Tools item. Go through *Tutorial 4 - MOS Transistor Simulation with Accusim*. When you write the Spice file for the MOS transistor, **use the values of VT0, KP, and LAMBDA from Table 1 above for the individual transistor that you are modeling. In addition, change the values of VGS that the run is swept through to match the values of VGS that you recorded in Table 2 above**.

When you have generated the I_D vs. V_{DS} family of curves and placed the cursors on the chart as instructed (using your value of V_T to place the first cursor), compare the values of the I_D currents to the values in Table 2. Adjust the values of VT0, KP, and LAMBDA to match the simulation values to the measured values in Table 2. Note that you can edit the values of the parameters in the Spice file, save the file, and re-run the simulation without exiting Accusim - the new parameter values will be automatically read from the file when the simulation is re-run. You will have to re-generate the chart and add the cursors though.

In adjusting the parameter values, it is helpful to note that increasing the value of VT0 will shift all of the I_D curves upward, including those curves that are below the threshold voltage, and will increase the spacing between the curves as V_{GS} increases. Increasing the value of KP will simply increase the spacing of the curves above the threshold voltage. Increasing LAMBDA will increase the slope of the curves in the saturation region. A useful method to adjust parameters is to change the value of VT0 first to match the curves that are just above and just below the threshold voltage. Then adjust KP so that the upper curves match at the cursor that is placed at $V_{DS}=V_{GS(max)}-V_T+0.5V$. Finally, adjust the value of LAMBDA so that the curves match at the $V_{DS}=4.5V$ cursor.

IV. Write-up

The write-up **can be done as a group with your lab partner**, and should include the following sections:
1. Abstract
2. Introduction
3. Theory - Show the calculations required to derive the values of V_T, k'_n, and λ from the data collected in using the parameter analyzer for each transistor.
4. Results and conclusions - the write-up should include plots of your measured data for each transistor in Excel, a table listing the original calculated values for of V_T, k'_n, and λ for each transistor, a table listing the adjusted values of for each transistor, and a graph of the I_D vs. V_{DS} family of curves for each transistor with both the measured and simulation data for comparison. Discuss the results in terms of the match between the measured and simulation data.