University of Waterloo
Electrical & Computer Engineering Department

ECE 331
ELECTRONIC DEVICES

LAB 3: INTRODUCTION TO FIELD-EFFECT DEVICES

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1. Objective

Behaviour of a MOSFET (*Metal-Oxide-Semiconductor Field Effect Transistor*) as an electronic device is examined in this experiment. Gate-to-source as well as drain-to-source voltages are varied to understand their impact on the overall behaviour of the device. A semiconductor parameter analyzer is used to get accurate device characteristic graphs.

2. Background

Although the *bipolar transistor* was the first working transistor to be constructed, historically, the *field-effect transistor* was the first ever proposed. There are two major types of field-effect devices: *junction field-effect transistors (JFETs)*; and *metal-oxide-semiconductor transistors (MOSFETs)*. JFET devices are commonly used in analog circuit applications, such as in the input stages of *operational amplifiers* and in *microwave amplifiers*. MOSFET devices are used in both analog and digital applications---you may have heard about *CMOS*, a low-power digital logic family commonly used in modern digital integrated circuits. In this lab, you will be introduced only to the *enhancement* MOSFET[1].

MOSFET can be considered as a voltage-controlled-current-source (VCCS). Figure 1 shows such device.

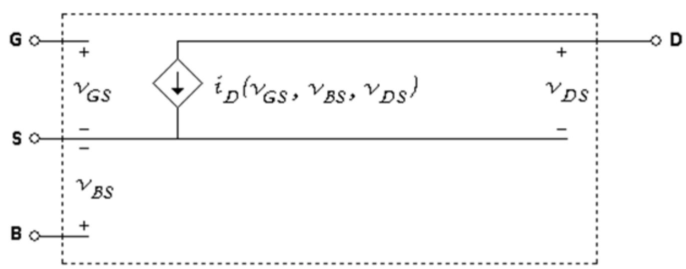


Figure 1. MOSFET as a VCCS

B (Body or Bulk) is shown as SUB (Substrate) in some texts. It is connected to substrate material. Figure 2 shows two types of MOSFETs, an n-channel and a p-channel. The distance between the drain and source diffused areas is called the ‘channel’. The material under the oxide layer (under the metal contact of the gate pin) is the same as the substrate, which is opposite to the drain and source regions. But if a gate voltage larger than a threshold value is applied to the gate contact (with respect to source contact), a tiny layer of material right under the gate oxide layer will be inverted into opposite type. This will create a channel between source and drain which is capable of carrying current.

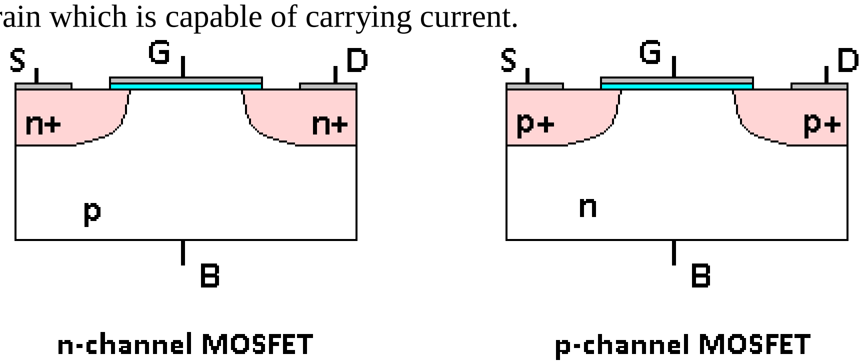


Figure 2. Two types of MOSFETs

[1] There is also a *depletion* MOSFET, but we won't analyze that device in this lab.

Depending on the voltages at gate, drain, source, and substrate, the device can be in different modes of operation. Figure 3 shows a typical characteristic graph for a N-MOSFET.

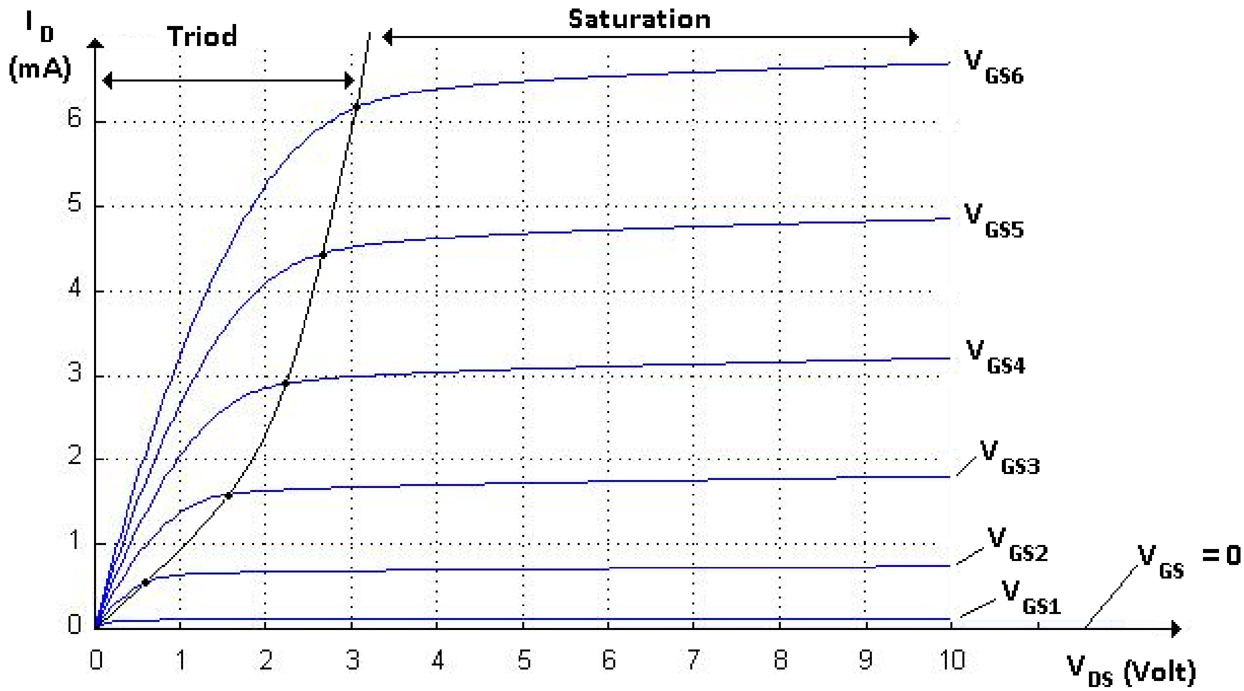


Figure 3. Typical characteristic graph of a N-MOSFET

For the given graph, $V_{GS6}>V_{GS5}>V_{GS4}>V_{GS3}>V_{GS2}>V_{GS1}>0$ (absolute values). A channel will be formed between the source and drain when V_{GS} is greater than the threshold voltage (V_T).

3. Pre Lab

1) Match the drawn MOSFETs in figure 4 with the given voltages in table 1, and then complete the last column of table 1. The MOSFET is an n-channel enhancement type with VT=+2.5 volts. Please note that the channel length and thickness (depth) are not to scale! Choose the closest graph for each given set of voltages.

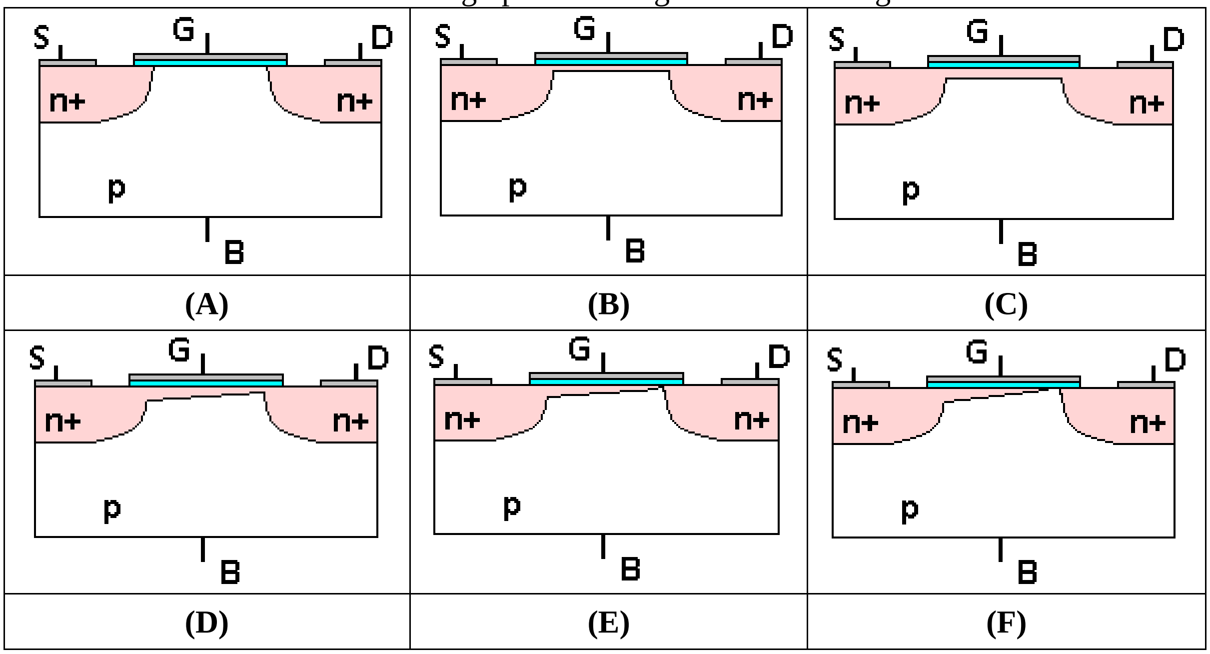


Figure 4. N-MOSFETs with different channel cases

Table 1. Different voltages applied to an n-channel MOSFET

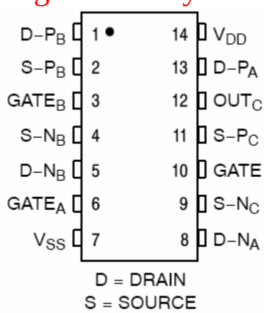
V_{GS} (V)	V_{DS} (V)	Refers to graph?
+2	0	
+5	+5	
-1	+7	
+7	+1	
+5	0	
+5	+4	
+7	+4.5	
+7	+5	
+3	0	
+5	+2.5	

2) With the aid of a cross-sectional diagram, qualitatively describe the operation of an n channel enhancement MOSFET

Please note the highlight color code throughout the rest of the lab as follows:
The grey color indicates in-lab data measurements.
The yellow color indicates report work.

4. In Lab Procedure

This section is divided into two parts. You can start your work at either part. Three n-channel MOSFETs and three p-channel MOSFETs are available on the MC14007 or CD4007 integrated circuit (IC) as shown in figure 5. The Q1, Q3, and Q5 transistors are the P-MOSFETs, and the Q2, Q4, and Q6 transistors are the N-MOSFETs. During this lab, we are going to use only one NMOS transistor which is Q4.



Pin	Function
1	Q3 drain
2	Q3 source
3	Q3 gate & Q4 gate
4	Q4 source
5	Q4 drain
6	Q1 gate & Q2 gate
7	Q2 source & N substrates (Vss)
8	Q2 drain
9	Q6 source
10	Q5 gate & Q6 gate
11	Q5 source
12	Q5 drain & Q6 drain
13	Q1 drain
14	Q1 source & P substrate (Vdd)

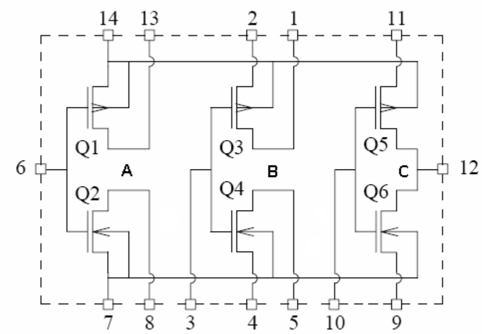


Figure 5. MC14007 or CD4007 Pin Connections

4.1. MOSFET Threshold Voltage

With the MOSFET working in saturation, a simple relationship for the current-voltage characteristics is given by:

$$I_{DS} = K\left(V_{GS} - V_T\right)^2 \qquad (1)$$

where K is a constant depending on the exact device properties.[2] This equation implies that $\sqrt{I_{DS}} \propto V_{GS}$. A plot of $\sqrt{I_{DS}}$ versus V_{GS}, with V_{DS} chosen large enough so that the device is in saturation, should hence be a straight line. This is indeed the case, so long as I_{DS} is neither too small nor too large, and if the straight line portion of the plot is extrapolated back to $I_{DS} = 0$, then the intercept yields the threshold voltage V_T.

a. Connect the circuit shown in figure 6 using the Q4 device on your IC (it is an N-MOSFET). **Please remember that V_{GS} must be positive, V_{DS} must be positive, and V_{BS} must be negative at all times! Correspondingly, note the polarity marks on the dc sources V_{GG}, V_{DD}, and V_{BB}.**
b. You will need to connect an ammeter in series with drain to measure I_{DS}.
c. Also, you will need to connect a voltmeter across drain source to measure V_{DS}.
d. For now, use $V_{BB} = 0$ so that the body-to-source voltage $V_{BS} = 0$

[2] This formula will be derived in class. You will see that K depends on such things as the MOSFET *channel mobility*, *oxide capacitance*, and *gate dimensions*.

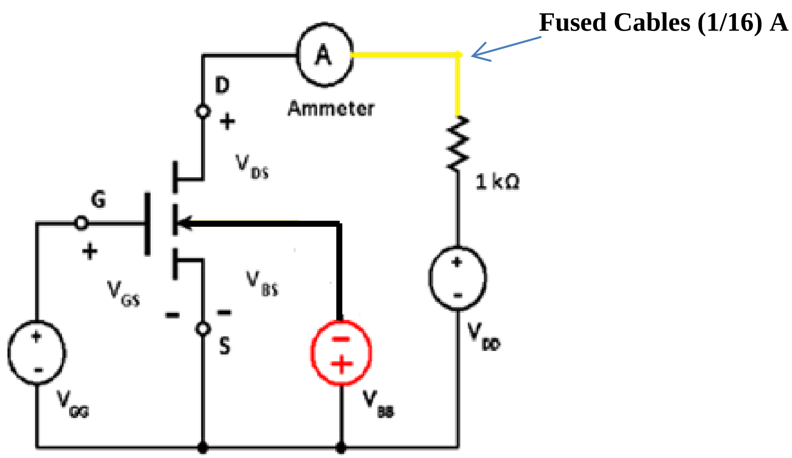


Figure 6. Circuit to study the effect of body bias on MOSFET threshold voltage.

e. Vary V_{GS} (or V_{GG}) so that I_{DS} measured by the ammeter takes on values of about 1, 2, 3, 4, and 5 mA. **For each V_{GS} value, do not forget to adjust V_{DD} so that** V_{DS} = 6 V measured by the voltmeter; record V_{DS} at each measurement, this will ensure the adjustment is done. Fill in the table in the lab template.

f. While V_{BB} kept equal zero, vary V_{GS} to estimate V_T.

g. Create a table of values of I_{DS} and $\sqrt{I_{DS}}$ versus V_{GS} for a constant V_{DS} value of 6 V.

h. Repeat part (d) for V_{BB} = -2, -6 and -10 V. **Notes**: This may take some time---please work with your partner to take readings efficiently and patiently. Once you set V_{BS} to a given value, you don't have to worry about continuously checking it to ensure it hasn't changed---it should stay constant regardless of V_{GS} and I_{DS}. On the other hand, don't forget to maintain V_{DS} at 6 V for all your readings!

i. Create a table of values of I_{DS} and $\sqrt{I_{DS}}$ versus V_{GS} for a constant V_{DS} value of 6 V.

j. Using the tables of values you got in parts (g) and (j), and on the same graph, plot $\sqrt{I_{DS}}$ versus V_{GS} for each V_{BS}. You should end up with 4 sets of plotted points, one for each V_{BS} value. Draw the best straight line through each set of points.

k. Extrapolate each line drawn in part (k) back to I_{DS} = 0 to get the corresponding threshold voltage V_T. Note that the value of V_T is not the same for the different V_{BS} values! This is called *body effect*. In lectures, we'll assume that V_{BS} = 0 in all our derivations and analyses, but now you know that a nonzero body bias can affect the device operation! Is the value of V_T for V_{BS} = 0 consistent with your observations of V_T in part (f).

l. Using the threshold voltage values from part (l), construct a plot of V_T versus V_{BS}. Draw a smooth curve through the plotted points.

m. The simple relationship

$$V_T \approx V_{To} + \gamma\left(\sqrt{\varphi - V_{BS}} - \sqrt{\varphi}\right) \qquad (2)$$

is sometimes used to model the effects of body bias on threshold voltage, where γ and ϕ are model parameters and V_{T0} is the threshold voltage at $V_{BS} = 0$. Is the shape of the curve you constructed in part (m) consistent with such a relationship?

n. Does a nonzero V_{BS} value have any significant effect on the parameter K in equation 1? Remember that $\sqrt{K}$ is just the slope of the $\sqrt{I_{DS}}$ versus V_{GS} plot, and use the lines you plotted in part (k).

4.2. Semiconductor Parameter Analyzer

With the *n*-channel enhancement MOSFET device provided, and with the assistance of a teaching assistant or lab staff, use the semiconductor parameter analyzer to obtain a plot of the three-terminal characteristics of the MOSFET, namely a plot of the *drain-to-source current* I_{DS}, as a function of the *drain-to-source voltage* V_{DS}, for different *gate-to-source voltages* V_{GS}. A typical characteristic graph is illustrated in figure 3.

4.2.1 I_{DS} Vs V_{DS} characteristics for different V_{GS} ($V_{BS} = 0$)

a. Draw the I_D versus V_{DS} for all V_{GS} values in one figure and include it in your report using Excel. Make sure to label the axes on your plot and to indicate the value of V_{GS} for each curve, as done in figure 3.

Follow the following steps:

1- Turn on Agilent B2902A device
2- Connect the "Force" of channel 1 (red cable) in Agilent B2902A unit to the Gate (pin 3) on the chassis and the "Low" (black cable) of channel 1 to the Source (pin 4) on the chassis.
3- Connect the "Force" of channel 2 (red cable) in Agilent B2902Aunit to the Drain (pin 5) on the chassis and the "Low" (black cable) of channel 2 to the Source (pin 4) on the chassis.
4- **Short circuit the bulk (pin 7) on the chassis with the Source (pin 4) on the chassis. (Remove it from + Output terminal of section 3 and connected to pin 4)**
5- Go to Start →Programs→ Keysight B2900A Quick IV Measurement Software → Quick IV Measurement Software
6- Ensure that in the top right corner Pane that "Channel Communication" is selected and do the following:
    a. Select "Search SMU" icon.
    b. In the opened window do the following:
        i. Set "Select interface type" to "USB"
        ii. Press "Search" icon.
        iii. The software should be able to locate the address of the connected Keysight B2912A/2902A unit.
        iv. Select "Close"
    c. Set "Address" to address found in the previous step.

d. Set “Channel” to Channel 2.
e. Edit “Name” to be “VDS”

7- From the top right corner Pane, select “Channel Setting” and adjust the following.
   a. Select “Source Function” to be VAR1.
   b. Set “Mode” to “V”.
   c. Set “shape” to “DC”.
   d. Set “Source Delay” to 0 sec.
   e. Set “Sweep” to “Linear Single”.
   f. Set “Start” to 0 V and “Stop” to 10 V.
   g. Set “Compliance” to 0.01 A.
   h. Set “Source Range” to Auto.
   i. Check “Voltage Measure” and “Current Measure”
   j. Set “Range” to “Limited 10mA”
   k. Set “Measure Delay” to 0.0005 S
   l. Set “Measure speed” to “Auto”

8- Select “Add Channel” icon from the top left. For the newly added Channel, ensure that in the top right corner Pane that “Channel Communication” is selected and do the following:
   a. Set “Address” to address found in the step 5-b **(It should be the only available address).**
   b. Set “Channel” to Channel 1 and Edit “Name” to be “VGS”

9- From the top right corner Pane, select “Channel Setting”. Enter other values as per part 6) except following values :
   a. Select “Source Function” to be VAR2.
   b. Set “source” to “V”.
   c. Set “shape” to “DC”.
   d. Set “Sweep” to “Linear Single”.
   e. Set “Start” to 1 V and “Stop” to 5 V.
   f. Set “Compliance” to 0.001 A.
   g. Set “Source Range” to Auto.
   h. Check “Voltage Measure” and “Current Measure”
   i. Set “Range” to “Limited 10µA”
   j. Set “Measure Delay” to 0.0005 S
   k. Set “Measure speed” to “Auto”

10- In “Common Sweep Setting” adjust the following :
   a. Set “VAR1 (Primary Sweep) Count” to 50 and “VAR2 (Primary Sweep) Count” to 5.
   b. Set “Repeat” to 1.
   c. Set “Trigger” to Auto.
   d. Uncheck “Specify Minimum Auto Trigger Period”.

11- Press the “Graph” icon.

12- In the “Quick Setting” tab, set the following:
   a. Set “X Data Type” to Voltage and “X Data” to VDS.
   b. Set “Y1 Data Type” to current
   c. In “Series 1”, set “Y axis” to “Y1” and set “Data” to “VDS Current”

13- Press the "Measure" icon. It will start plotting. Make sure you got the correct graph.
14- Right click on the resulting figure and select "Dump" to save it. Inserted into your report.
15- Select the resulting Table then right click and select "export as CSV".

b. Calculate the MOSFET output resistance r_o, in saturation, for the highest value of V_{GS} on your plot.

$$r_O = \left(\frac{\partial I_{DS}}{\partial V_{DS}}\Big|_{V_{GS}=Constant}\right)^{-1} \qquad (3)$$

Click on the marker icon at the bottom left corner and do the following:

i. Check "Marker 1", set it to "ON", and set "Series" to "Series 1 VDS current"
ii. Using the mouse click on any point in the saturation region on the curve corresponding to the highest V_{GS} to place marker1 and the corresponding X value and Y value will be displayed on the marker area.
iii. Check "Marker 2", set it to "ON", and set "Series" to "Series 1 VDS current"
iv. Place the marker 2 again in saturation region little bit farther from marker 1 on the same curve that you selected before (this is to ensure constant V_{GS}). Check the corresponding X and Y values on the marker area. Also, you will get the delta (the difference) of the X values and the Y values which you will need for calculating the output resistance:

v. Take a screen shot and include it in your Data **use snipping tool or print screen** NOT the "Dump" to have the cursor values with the plot. You will need it for your report.

c. Calculate the MOSFET transconductance g_m, in saturation, for the highest value of V_{GS} on your plot.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}}\Big|_{V_{DS}=Constant} \qquad (4)$$

i. Now to measure g_m we should move marker 2. Place marker2 on the same vertical line where marker1 is to ensure constant V_{DS} on the next curve. Check the corresponding X value and Y value for marker2 and the delta (the difference) of the X values and the Y values. Calculate g_m. Also, note that V_{GS} is changed from 1V to 5V in steps of 1 V.

ii. Take a screen shot and include it in your Data **use snipping tool or print screen**. You will need it for your report.

d. Extrapolate your curves to get the value of Early voltage for this MOSFET.

e. From your plot, what would you approximately estimate as the value of the *threshold voltage* V_T of the MOSFET?

f. For each curve on your characteristics, plot the point $V_{DS} = V_{GS} - V_T$. Join the points together to create the locus delineating the **linear** or **triode** region from the **saturation** or **active** region of the characteristics. Indicate these regions on the plot.

4.2.2 I_{DS} Vs. V_{DS} characteristics for different V_{GS}. (V_{BS} = 0) for Small V_{DS} voltage

a. **Change VDS from -0.2 V to +0.2 V by auto steps.** Keep all other previous settings the same.
b. Right click on the resulting figure and select “Dump” to save it. Inserted into your report.
c. Can we assume MOSFET is behaving like a voltage controlled resistor? Comment.

Make sure you got all measurements and screenshots. Please tidy up your station.
Submit you “data3.pdf” file to learn before leaving.

Report Submission “Report3.PDF” should include prelab, data and postlab in PDF Format.
A penalty will be applied for otherwise.