EE 330 Laboratory 7
MOSFET Device Experimental Characterization and Basic Applications

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**Objective:**

The objective of this laboratory experiment is to become more familiar with the operation of the MOS transistor, to develop methods for measuring key parameters of the transistor, and to investigate some basic applications of the device.

**Components Needed:**
MOSFET transistor (TI XEDU1000)
Breadboard

**Test Equipment Needed:**
B1500a Semiconductor Parameter Analyzer, DC power supply, Oscilloscope, Digital Multimeter.

**Background:**

Although MOS transistors are widely used in the design of very large and complex systems that incorporate thousands or millions of transistors or even several billion transistors today, discrete MOS transistors are seldom used and, as such, it is difficult to do experimental work with MOS transistors in the laboratory with state of the art transistors since there are few commercial components available that provide access to the terminals of individual transistors. In this experiment we will work with a set of MOS transistors available in the transistor array. Although these devices are large and fabricated in a process with a metal gate rather than a polysilicon gate, the low frequency properties are indicative of that seen in smaller feature size transistors but some of the parameter values are considerably different than what is common in smaller feature size processes.

Caution: MOS chips are very sensitive to electrostatic discharge (ESD) and can be destroyed by improper handling. Never store these parts in Styrofoam or other non-conducting containers unless the leads are covered with a conducting medium. Always use a protective grounding strap (sometimes termed “wrist bracelet”) when touching these devices or the circuit to which they are connected.
Part 1. Set up Signal Express

Signal Express is a program that automates testing by controlling the multimeters, power sources, and other equipment. However, always go through a setup procedure to make sure that all your parts are working before trying to just do the experiment. For this you will need to set up Signal Express.

There are more in depth setup instructions here
http://class.ece.iastate.edu/ee330/miscHandouts/ee_330_signal_express.pdf

First turn on the multimeters, and power supplies. Start Signal Express and click on Empty LabVIEW SignalExpress Project. In the next screen go to Add Step in the tool bar and add the IVI DMM Acquire, IVI Power Suply, and Sweep. In the project panel on the left place the Power Supply and Multimeter (DMM Acquire) in the sweep.

Connect the Power Supply to the specific devices. This is done in their configuration tab in the IVI session name drop down box. If the device is not turned on you will get a ‘configuration error’. In the power supply configuration make sure ALL channels are turned ON. Make sure unused channels are set to 0V, set the Voltage to 1V. Use the unconnected multimeter to verify the output is working.

Connect the multimeter to Signal Express. This is done in the DMM Signal Acquire configuration. Set the multimeter to measure DC Volts and edit the Sweep. In Sweep Configuration click Add and add a sweep parameter,

1: Voltage level (V) if using the 6V output
2: Voltage Level (V) if using the 25V output
3: Voltage Level (V) if using the -25V output
We advise not using the 25V or -25V source.

In the Configuration on the bottom left of the Sweep Configuration tab set a linear voltage between 0 and 3 V with 5 steps. Click the Sweep Output tab, select MyIViDmm0 as the Y-Axis and # – Voltage Level (V) as the X-axis.

Test across a resistor to make sure the sweep is working. Do this by clicking the arrow next to Run and click Run Once (or Ctrl+Shift+R). Once it has run right click on myIviDmm0 vs # - Voltage and select the output you want to see (often Excel).
Part 2. Measurement of MOSFET output characteristics

The output characteristics of a MOS transistor refers to the relationship between the drain current and the port voltage variables $V_{GS}$ and $V_{DS}$. These are often represented graphically on a plot of the $I_D$ vs $V_{DS}$ for several different values of $V_{GS}$ as shown in the following figure. From the output characteristics, several of the key model parameters of the MOS transistor can be obtained.

**Measure** the output characteristics of one of the n-channel MOS transistors in the array using Signal Express. Use 6 values of $V_{GS}$ in these measurements, specifically, $V_{GS} = 0.5V, 1.0V, 1.5V, 2.0V,$ and $2.5V$ for $0 < V_{DS} < 2.5V$. **Compare** with those predicted in the datasheet.

Part 3. Measurement of MOSFET parameters

The parameters $\mu C_{ox}$, $V_{t0}$, $\lambda$ and $\gamma$ are key parameters that characterize the MOS transistor along with the physical parameters $W$ and $L$. Most of these parameters can be measured with standard test equipment or can be obtained from a semiconductor parameter analyzer which is a piece of equipment especially designed for extracting such parameters. You will be asked to extract these parameters using both techniques in this experiment.

a) **Extraction of $\mu C_{ox}$ and $V_{t0}$**: In the saturation region, the drain current is given by the expression

$$I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

(1)

where

$$V_T = V_{t0} + \gamma \left( \sqrt{\phi} - \sqrt{V_{BS}} \right)$$

(2)
Note some authors define the product of $\mu$ and $C_{ox}$ by the parameter $k' = \mu C_{ox}$. For the purpose of model extraction in this experiment, we will not be concerned in separating these parameters and hence will only be interested in the product $\mu C_{ox}$. If the substrate (bulk) is connected to the source (to make $V_{ss} = 0$) and we estimate $\lambda = 0$, it follows that:

$$I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_{T_0})^2$$

(3)

**Measure the Current through the Op-Amp**

By measuring the voltage across the resistor we are able to determine the current $I_D$. If there is oscillation on the supply pins use a bypass capacitor to filter them out. (This uses an electrolytic capacitor of around $10 \mu F$.)

If we connect the gate of the MOSFET to the drain, forcing the device into the saturation region (provided $V_{GS} > V_T$), and plot $\sqrt{I_D}$ versus $V_{GS}$, we find that the slope of the curve becomes $\sqrt{\frac{\mu C_{ox} W}{2L}}$ and the $V_{GS}$ axis intercept is $V_{T_0}$. If $W$ and $L$ are known, the parameter product $\mu C_{ox}$ can thus be obtained from the slope.

**b) Extraction of $\gamma$:** If the bulk to source voltage is set to another value, e.g. $-1v$, the method used in (a) above can be used to measure the new value of $V_T$. As before, the value of $V_T$ will be the intercept of the $\sqrt{I_D}$ plot with the $V_{GS}$ axis. Since $\Phi$ is assumed known and is about 0.6V, and since $V_{T_0}$ was extracted above, equation (2) can be solved for $\gamma$.

**c) Extraction of $\lambda$:** From equation (1), it follows that if $I_D$ is measured at two different $V_{ss}$ values while maintaining $V_{GS}$ constant, the lambda is given by the expression

$$\lambda = \frac{I_{D_2} - I_{D_1}}{I_{D_1} V_{DS_2} - I_{D_2} V_{DS_1}}$$

(4)
Using appropriate circuits **measure** the parameters $\mu C_{ox}$, $V_{T0}$, $\lambda$ and $\gamma$ for the NMOS transistor in the array using the techniques listed above and **compare** $\mu C_{ox}$, $V_{T0}$, and $\lambda$ with the parameters in the datasheet. Make appropriate connections to the bulk for these measurements.
Part 4. Measurement of parameters using B1500a Parameter Analyzer

The parameters $\mu_{\text{Cox}}, V_{T0}, \lambda$ and $\gamma$ are key parameters that characterize the MOS transistor along with the physical parameters $W$ and $L$. Most of these parameters can be measured with standard test equipment or can be obtained from a semiconductor parameter analyzer which is a piece of equipment especially designed for extracting such parameters.

In a previous experiment you extracted these parameters from special test circuits that you built. In this experiment, these same parameters will be obtained using a semiconductor parameter analyzer. The parameters obtained with the semiconductor parameter analyzer will be compared with the results obtained in the previous experiment and with the parameters predicted by the manufacturer on the datasheet for the part. These parameters are the parameters that appear in the device model equations which, for the purpose of this experiment, is assumed to be the square law model

$$I_D = \begin{cases} 
0 & V_{GS} < V_T \\
\mu_{\text{Cox}} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & V_{GS} > V_T \text{ and } V_{DS} < V_{GS} - V_T \\
\mu_{\text{Cox}} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \left( 1 + \lambda V_{DS} \right) & V_{GS} > V_T \text{ and } V_{DS} > V_{GS} - V_T
\end{cases}$$

where

$$V_T = V_{T0} + \gamma \left( \sqrt{\phi - V_{BS}} - \sqrt{\phi} \right)$$

Measure the parameters $\mu_{\text{Cox}}, V_{T0}, \lambda$ and $\gamma$ for the NMOS transistor (the one with the gate on pin 3) in the array using the B1500A Semiconductor Parameter Analyzer. Compare the results obtained with those measured in a previous experiment and with what is given on the datasheet.

More information can be found here:
Part 4. CMOS Inverter

A CMOS inverter is shown. This circuit is widely used in digital applications but can also serve as an analog amplifier if biased properly.

Two implementations of this inverter will be considered.

In Case 1, M₁ will be an NMOS (Short Channel), and M₂ will be a PMOS (Short Channel).

In Case 2, M₁ will be an NMOS (Long Channel), and M₂ will be a PMOS (Short Channel).

For digital logic applications, the CMOS inverter is typically operated from a single power supply with $V_{DD} = 2.5\, \text{V}$ and $V_{SS} = 0\, \text{V}$. **Measure** the output voltage when $V_{in} = 0\, \text{V}$ and when $V_{in} = 2.5\, \text{V}$. Apply a 1 KHz square wave at the input that goes between 0V and 2.5V. Display both the input and output on the oscilloscope at the same time. **Comment** on the performance.