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)

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: Please read the maximum input ratings for the XEDU1000. Exceeding the maximum ratings may (and often will) destroy the devices.

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 I 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 5 values of $V_{GS}$ in these measurements, specifically, $V_{GS} = 1V, 2V, 3V, 4V, and 5V$ for $0 < V_{DS} < 5V$. Compare with those predicted in the datasheet (In the ON Semiconductor Datasheet the output characteristics for n-channel devices are referred to as “Output Sink Characteristics” and those for p-channel devices as “Output Source Characteristics”).

**Part 2. 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

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

(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 \( V_{BS} = 0 \)) and lambda effects are eliminated, it follows that:

\[
I_D = \mu C_{OX} \frac{W}{2L} (V_{GS} - V_{T0})^2
\]  

(3)

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 \( I_D \) 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 \( V_{T0} \). 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 \( V_{T0} \) 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 \( V_{DS} \) values while maintaining \( V_{GS} \) constant, the lambda is given by the expression

\[
\lambda = \frac{I_{D2} - I_{D1}}{I_{D1} V_{DS2} - I_{D2} V_{DS1}}
\]  

(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 3. Measurement of MOSFET parameters using B1500a Parameter Analyzer

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.

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.
\[
I_b = \begin{cases} 
0 & \text{if } V_{GS} < V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{if } V_{GS} > V_T \text{ and } V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \left( 1 + \lambda V_{DS} \right) & \text{if } V_{GS} > V_T \text{ and } V_{DS} > V_{GS} - V_T
\end{cases}
\]

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

**Measure** the parameters \( \mu C_{OX} \), \( V_{T0} \), \( \lambda \) 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.

**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.

![CMOS Inverter Diagram]

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).

**Measure** the transfer characteristics of the CMOS inverters of Case 1 and Case 2 and compare with results from the SPECTRE simulation from lab 3. Assume \( V_{DD} = 5V \) and \( V_{SS} = 0V \).

For digital logic applications, the CMOS inverter is typically operated from a single power supply with \( V_{DD} = 5V \) and \( V_{SS} = 0V \). **Measure** the output voltage when \( V_{in} = 0V \) and when \( V_{in} = 5V \). **Compare** with what is predicted from the transfer characteristics measured above. Apply a 1 KHz square wave at the input that goes...
between 0V and 5V. Display both the input and output on the oscilloscope at the same time. **Comment** on the performance.