Experiment: I-V Curves

I. Objective

To become familiar with the current-vs.-voltage (*I-V*) operating curves for various circuit elements.

II. Introduction

When working with discrete circuit components (as opposed to integrated circuits), it is relatively easy to check for their correct operation and their exact operating characteristics using an oscilloscope-like instrument known as a curve-tracer. Since there are only four curve tracers (TEK 571) in the EECS40/43 lab, you will need to build your own curve-tracer circuit in this lab (same you did in the previous lab) in order to generate graphs of the current flowing through a device as a function of the voltage applied across it. For a resistor, the graph is a straight line (as you should have found during the previous lab), but for other devices, the graph is a much more interesting curve or family of curves.

III. MOSFET I-V Characteristics

A metal-oxide-semiconductor field-effect transistor (MOSFET) is a three-terminal device that can be used as a switch (*e.g.* in digital circuits) or as an amplifier (*e.g.* in analog circuits). The three terminals are referred to as the **Source**, **Gate**, and **Drain** terminals. The MOSFET also has a **Body** terminal, which is usually tied to the source terminal (so that V_{BS} = 0 Volts) in discrete transistors. **Current flow between the source and drain terminals is controlled by the voltage V_{GS} applied between the gate and source terminals:** If the gate-to-source voltage is below a threshold voltage value V_T (*e.g.* ~2 Volts, for the transistors which you will be using in this lab), no current can flow between the source and the drain – *i.e.* the transistor is OFF; if the gate-to-source voltage is higher than V_T, then current can flow between the source and the drain – *i.e.* the transistor is ON. The circuit symbol for an n-channel enhancement-mode (V_T > 0 Volts) MOSFET is shown in Figure 1, along with the terminal current reference directions.

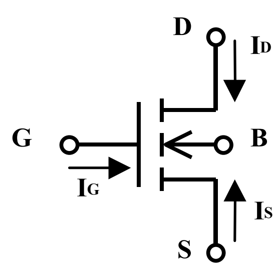

Figure 1: Circuit symbol for an n-channel enhancement-mode (V_T > 0 Volts) MOSFET.

Note that each terminal current is defined to be positive flowing into the terminal. In the physical structure of the MOSFET, the gate terminal is electrically insulated from the source, body and drain terminals, so that no DC current can flow into the gate terminal:

$$I_G = 0 \qquad \text{(Eq. 1)}$$

In addition, if the transistor is operated properly, no DC current should flow between the body terminal and the source or drain terminals:

$$I_B = 0 \qquad \text{(Eq. 2)}$$

From Kirchhoff's Current Law, we know that the sum of all the terminal currents flowing into the MOSFET must be zero:

$$I_G + I_D + I_B + I_S = 0 \qquad \text{(Eq. 3)}$$

Substituting Eq. 1 and Eq. 2 into Eq. 3, we obtain

$$I_S = -I_D \qquad \text{(Eq. 4)}$$

Thus, **all of the current which flows into the drain terminal flows out of the source terminal**.

In the ON state, the current I_{DS} flowing between the source and the drain will depend on the potential difference V_{DS} between the drain and the source: I_{DS} increases with increasing drain-to-source voltage V_{DS} as long as the drain voltage is at least V_T below the gate voltage, *i.e.* as long as V_{GS}-V_T > V_{DS}. When V_{DS} increases above V_{GS}-V_T, I_{DS} saturates at a constant value (*i.e.* it no longer increases with increasing V_{DS}.) Figure 2 shows the *I-V* operating curves for a typical n-channel enhancement-mode Field Effect Transistor (FET).

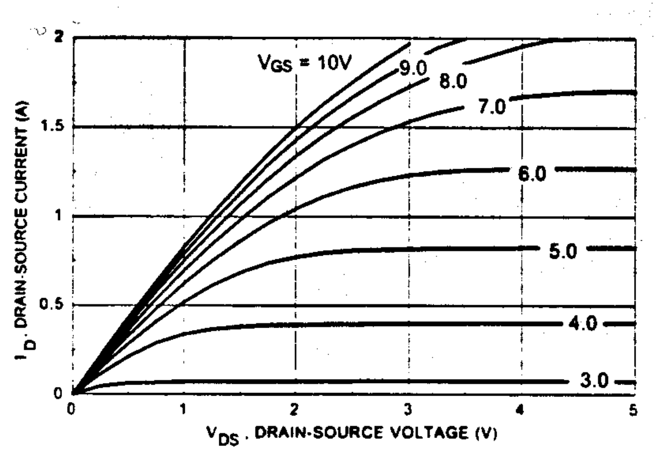

Figure 2: Current I_{DS} flowing between the source and drain terminals of an n-channel MOSFET versus the voltage V_{DS} applied between the drain and the source terminals, for various voltages V_{GS} (referenced to the voltage at the source terminal) applied to the gate terminal.

As can be seen in the figure, for each value of V_{GS} we have a unique curve of I_{DS} vs. V_{DS}.

IV. Curve-Tracer Circuit

You will build a curve-tracer circuit, which can be used to generate the *I-V* characteristic of any 2-terminal circuit element (*e.g.* a resistor, a capacitor, a diode), referred to as the "device under test" (DUT), *using the oscilloscope as a display*. The following is a description of how the circuit works:

✍ Since the oscilloscope can only measure voltage (and cannot measure current), we need to convert the current I_{DUT} flowing through the DUT into a voltage signal. This is achieved by **connecting a resistor of known value *R* in series with the DUT** (so that the current flowing through the DUT is equal to the resistor – see Figure 3 below) **and monitoring the voltage V_R across the resistor**. (From Ohm's Law, $V_R = I_R R = I_{DUT} R$.)

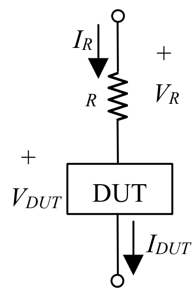

Figure 3: Series connection of resistor R with device under test (DUT), used to determine the current flowing through the DUT by measuring the voltage drop V_R across the resistor.

✍ The function generator is used to generate an AC voltage sinusoidal waveform, which is applied across the series combination of the resistor and DUT. (The DUT is connected to the ground node, as is the negative terminal of the function generator; the resistor is connected to the positive terminal of the function generator.) **The signal parameters (amplitude, DC offset) are adjusted so that the voltage across the DUT, V_{DUT}, varies between the voltages of interest.** (For example, suppose we'd like to plot the *I-V* characteristic of the DUT, for the voltage range from –5 V to +5 V; in this case, we would adjust the signal generator so that the voltage waveform across the DUT varies between –5 V and +5 V.) You can monitor V_{DUT} using the oscilloscope.

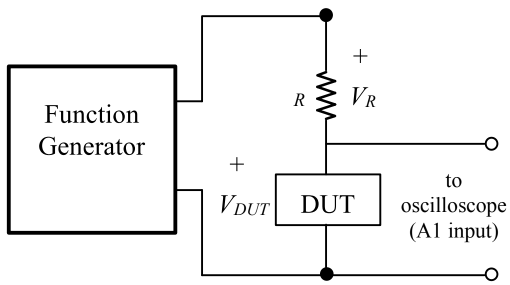

Figure 4: Applying a voltage signal to the device under test (DUT). The function generator settings should be adjusted so that V_{DUT} (which can be monitored using an oscilloscope) varies between the voltages of interest.

- I_{DUT} as a function of V_{DUT} is obtained by plotting the voltage V_{DUT} across the DUT on the *x*-axis of the oscilloscope display, and plotting the voltage V_R (proportional to I_{DUT}) across the resistor on the *y*-axis of the oscilloscope display. This is done by **using the oscilloscope in the XY mode**. (If you look carefully at the face of the oscilloscope, you will see a light-gray 'X' next to the A1 input and a light-gray 'Y' next to the A2 input.) In this mode, the voltage applied to A1 is displayed on the horizontal axis, while the voltage applied to A2 is displayed on the vertical axis. **To put the oscilloscope in the XY mode, press the Main/Delayed button, followed by the XY softkey.**

- The voltage V_R across the resistor cannot be directly monitored by the oscilloscope, because *the oscilloscope can only measure a voltage with respect to ground, i.e.* it cannot measure the voltage difference between two nodes in a circuit. (The negative terminals of the oscilloscope inputs A1 and A2 are tied to ground inside the oscilloscope!) Therefore, we need to use a circuit that will take as inputs the voltages at each end of the resistor and output a single voltage (equal to the difference between the input voltages) with respect to ground. We can then use this single voltage to drive the Y input of the oscilloscope. A **differential amplifier** circuit, connected as shown in Figure 5, fulfills this need.

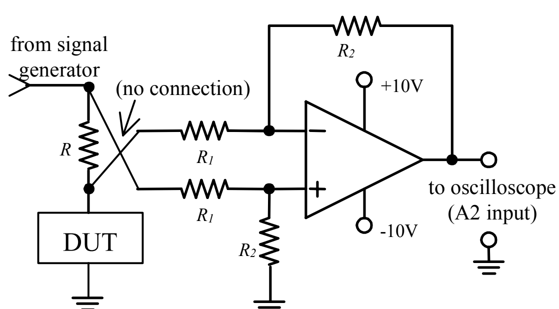

Figure 5: Application of the differential amplifier circuit to generate an output voltage signal referenced to ground, equal to the voltage difference across the R.

V. Hands-On Exercise

Part a: 2-terminal devices

1. Build the curve-tracer circuit as shown in Figure 6, with $R = 50\ \Omega$ and $R_1 = R_2 = 10\ k\Omega$.

   Note: For the most accurate operation of the differential amplifier circuit, you should use a multimeter to select closely matching R_1 resistors and closely matching R_2 resistors.

   You can use banana-plug style cables to bring the power-supply voltages and ground connection from the power supply to the binding posts on your breadboard, in case there aren't enough of the banana-to-clip cables in the lab. Be sure that all the ground connections in the circuit are connected together (*e.g.* to a single rail on the breadboard).

   Note: A 0.1μF capacitor can be connected between each op-amp power-supply pin (#4 & #8) and ground. These serve to bypass noise and current spikes from the DC power supply, and hence are referred to as "bypass capacitors."

   Set the signal generator to be 100 Hz, 2VPP sinusoidal signal with 1 V offset. Put the oscilloscope in the XY mode by pressing the Main/Delayed button, followed by the XY softkey.

2. Connect a 220 Ω resistor as the DUT. You should see a diagonal line on the oscilloscope display. The slope of the line is equal to the voltage V_R across the 50 Ω resistor, which is 50 times the current I_{DUT} flowing through the DUT, divided by the voltage V_{DUT} across the DUT, *i.e.*

$$slope = \frac{\Delta V_R}{\Delta V_{DUT}} = \frac{V_R}{V_{DUT}} = \frac{I_{DUT} R}{V_{DUT}} = \frac{R}{R_{DUT}}$$

   Thus, the slope should equal 50 times the inverse of 220 Ω.

3. Get a black box from the TA and connected it as the DUT. Sketch the I-V characteristic for the DUT and indicate the voltage scales on each axis. Can you determine what is inside the black box? Check your answer with the TA.

4. Connect a light-emitting diode (LED) as the DUT. Sketch the curve that is displayed on the oscilloscope, making sure to indicate the voltage scales on each axis. Note the approximate voltage where the diode "turns on". Reverse the diode and sketch the curve again. Pay close attention to where the zero voltages are located on these curves. Try different colors of

LEDs as the DUT. Note the turn-on voltage (voltage at which significant current flows) for each color.

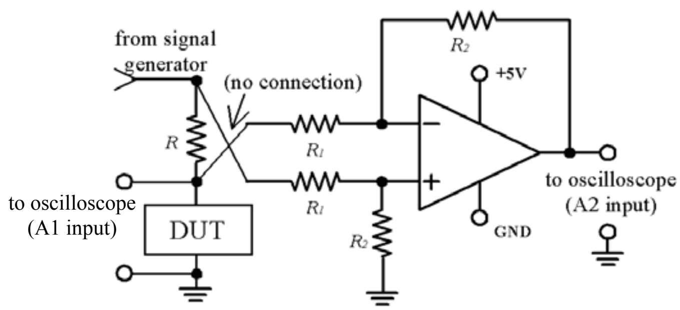

Figure 6: Schematic for the curve-tracer circuit.

Part b: N-Channel MOSFET

1. Next we'll make some changes to the circuit to allow us to measure n-channel MOSFET curves. Remember that a transistor is a three-terminal device, and that an n-channel MOSFET requires a positive voltage between the gate and the source to allow a current to flow from the drain to the source. We will provide this voltage with the 25V DC power supply.
2. Set the function generator to 4 VPP and 500 mV offset.
3. Set the 25V power supply to zero Volts initially, and connect it to the gate of the FET as your device under test as shown in the schematic and layout below. Note the pin designations for the transistor (see Figure 8).
4. You will need to slowly raise the voltage on the gate drive (the 25V power supply) to see the curve change with increasing gate voltage. Use the position knobs to move the origin to the lower left corner of the scope screen. Set A1 to 1V/div and A2 to 500mV/div. Sketch the family of curves for Vgs = 2.0, 2.6, 2.7 ... 2.7V. Be sure to clearly mark each curve with its corresponding V_{GS}.

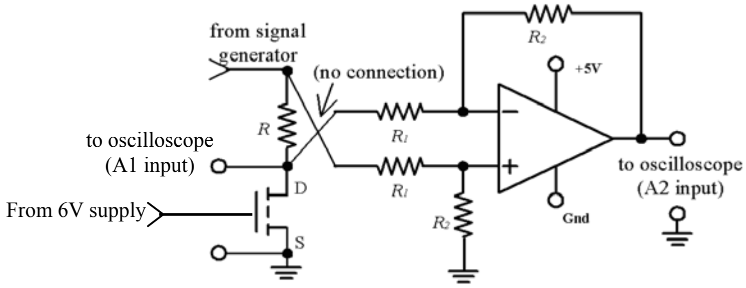

Figure 7: Curve-tracer circuit schematic for testing an n-channel MOSFET.

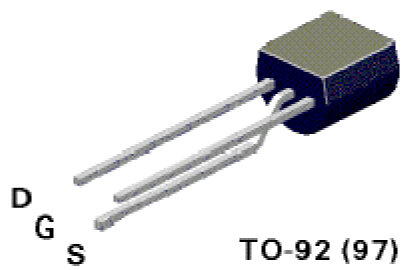

Figure 8: Pin designation for the MOSFET.