EXPERIMENT 3

MOSFET Characterization

3.1 Application

In experiment 2: "Power MOSFET Motor Driver," a family of curves was plotted on the oscilloscope by adjusting the gate voltage in steps while sweeping the drain voltage. Generally, it is more convenient to be able to look at the entire family of curves for a transistor at the same time. This can be accomplished by using a device called a curve tracer. A curve tracer simultaneously sweeps the gate to source voltage (v_{GS}) and drain to source voltage (v_{DS}) in such a way that it automatically plots transistor characteristics. The curve tracer can be used to quickly find transistors with the same device transconductance parameter (k_{n}), MOSFET threshold voltage (V_{th}), or small signal transconductance (g_{m}).

The square law model for transistors is a woeful oversimplification of actual transistor performance. It provides a reasonable model for large transistors, but it does not scale to modern transistor sizes. In order to design analog circuits using transistors, we need to be able to measure the g_m of the transistor when it is operating near the desired bias conditions because the k_n value in the square law model actually varies over the operating range of the device.

3.2 Curve Tracer Overview

The general concept of a curve tracer can be seen in figure 3.1. The tracer starts by setting $v_{\mathrm{GS}} = 0\,\mathrm{V}$ and then v_{DS} is swept from 0 V to V_{DD}, producing one trace. Then, v_{GS} is stepped by a constant amount, and the process repeats until it eventually reaches the maximum v_{GS}. The curve tracer would then start over again at $v_{\mathrm{GS}} = 0\,\mathrm{V}$ and endlessly repeat the process. In the example, the current waveform v_{GS} has eight steps. i_{D} can be measured by measuring the voltage across v_{RD}. When i_{D} and v_{DS} are measured and plotted against each other on an oscilloscope with XY mode, the curves will display and update together in real time.

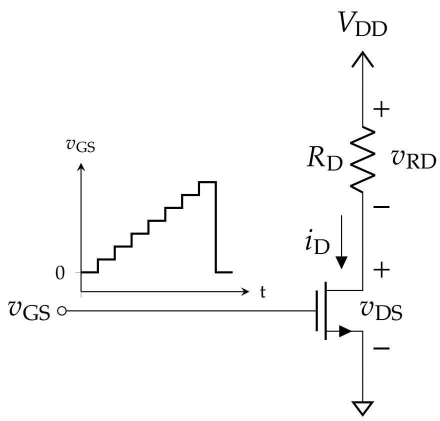

Figure 3.1: Curve tracer concept.

3.3 Metal-oxide-semiconductor field-effect transistor (MOSFET) parameters k_{n},V_{tn}, and g_{m}

The term $(v_{\mathrm{GS}} - V_{\mathrm{th}})$ is sometimes referred to as the "overdrive" voltage and is labeled v_{OV}. Here, we prefer the slightly longer but often clearer full expression.

We can use the piecewise n channel MOSFET characteristic equations in equations (3.1) to (3.3) to understand the meaning of k_{n} and g_{m}.

$$i_{\mathrm{D}} = 0 \qquad v_{\mathrm{GS}} < V_{\mathrm{tn}} \quad \text{(off)} \tag{3.1}$$

$$i_{\mathrm{D}} = k_n\left((v_{\mathrm{GS}} - V_{\mathrm{tn}})v_{\mathrm{DS}} - \frac{1}{2}v_{\mathrm{DS}}^2\right) \qquad v_{\mathrm{DS}} < v_{\mathrm{GS}} - V_{\mathrm{tn}} \quad \text{(linear/triode)} \tag{3.2}$$

$$i_{\mathrm{D}} = \frac{k_n}{2}(v_{\mathrm{GS}} - V_{\mathrm{tn}})^2 \qquad v_{\mathrm{DS}} > v_{\mathrm{GS}} - V_{\mathrm{tn}} \quad \text{(saturation)} \tag{3.3}$$

MOSFET threshold voltage

The threshold voltage of a MOSFET is defined as the point where the device turns "on." From a device physics point of

Purdue University use only – Do not duplicate – ©2022 (Spring Version)

view, this is the voltage where a conducting channel forms between the drain and source of a MOSFET. In practice, methods for determining the threshold voltage vary. The simplest definition that is frequently used in discrete transistor datasheets is the constant current definition where an effectively arbitrary current is picked to define the turn on voltage.

For example, the NMOS small signal transistor (2N7000) [1] datasheet specifies the turn on voltage to be the point where $v_{\mathrm{DS}} = v_{\mathrm{GS}}$ and $i_{\mathrm{D}} = 1\,\mathrm{mA}$ while the datasheet for the HEXFET® power MOSFET (IRL530N) [2] specifies this threshold at 0.25 mA. The N-channel MOSFET array (ALD1106) [3] datasheet specifies the threshold current at $i_{\mathrm{D}} = 1\,\mu\mathrm{A}$. We are using the ALD1106 for this experiment, so that is the threshold voltage definition that we will use for our measurements.

Device transconductance parameter

The device transconductance parameter sets the DC characteristics of a MOSFET. It is derived from the parameters of the silicon and the size of the device. In integrated circuit (IC) design, it is an adjustable design parameter; however, it can be treated as a constant for any discrete packaged transistors. The units for k_{n} are $\mathrm{A/V^2}$.

When examining the drain current versus voltage (I–V) characteristic of a MOSFET, the value of k can be estimated by solving equation (3.3) for k_n and picking a point on the horizontal part of the I–V characteristic when the transistor is in saturation.

Small signal transconductance

Transconductance is a small signal parameter used to describe the behavior of a device near a certain bias point. small signal transconductance (g_{m}) is defined in equation (3.4). In amplifier applications, we typically use a MOSFET biased in the saturation region, so we can calculate g_m directly from equation (3.3) by calculating the derivative.

We will use g_{m} extensively in the design of amplifiers in the next few labs, as it helps abstract away the complicated piecewise nonlinear MOSFET equations are replace them with fully linear equations.

$$g_m = \frac{\partial i_{\mathrm{D}}}{\partial v_{\mathrm{GS}}} \tag{3.4}$$

To estimate g_{m} from the output of a curve tracer, we can use equation (3.5) on two adjacent traces. This will give us an approximate g_m over the region between the two traces. An alternate approach is to plot the i_{D} vs. v_{GS} characteristic while holding the drain voltage approximately constant then take the discrete derivated of the measured data.

$$g_{\mathrm{m}} \approx \frac{\Delta i_{\mathrm{D}}}{\Delta v_{\mathrm{GS}}} \tag{3.5}$$

Purdue University use only – Do not duplicate – ©2022 (Spring Version)

3.4 Threshold voltage tester

As discussed earlier, the threshold voltage of discrete transistors is often defined as the voltage required to get a certain amount of current to flow through the device while $v_{DS} = v_{GS}$. We can build a simple op-amp circuit to automatically bias the transistor to this point and make measuring the threshold voltage very simple.

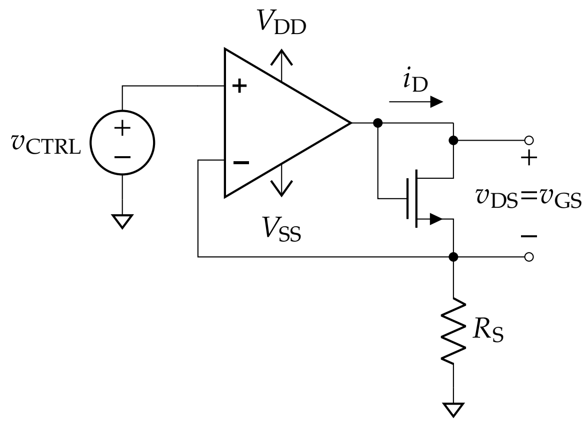

Figure 3.2: Automatic threshold voltage tester

The circuit in figure 3.2 forces $v_{DS} = v_{GS}$ by connecting the gate and drain together. The opamp will automatically set the voltage at the drain and gate node to get the desired current i_D. i_D is programmed by choosing v_{CTRL} and R_S. You will derive the relationship in the prelab. Once the circuit is built, one simply needs to insert the MOSFET into the circuit and measure v_{GS}. The measured value of v_{GS} will be the threshold voltage of the device, as the opamp ensures that the correct amount of current is flowing.

3.5 Curve Tracer Calculations

Example 3.5.1: Calculations from the output of a curve tracer

A typical output is shown in figure 3.3. In this example, each subsequent curve represents a change of v_{GS} by $V_{step} = 250\,\text{mV}$. To determine the gate voltage that corresponds to a certain curve, count the number of traces until the desired trace. For example, the sixth curve is at approximately $v_{DS} = 5.5\,\text{V}$ and $i_D = 30\,\text{mA}$. The gate voltage v_{GS} is equal to $6 \times V_{step} = 1.5\,\text{V}$. The operating point on the load line of this curve is at $i_D \approx 30\,\text{mA}$[a]. The curve tracer can be used to estimate k_n and g_m at the operating point. g_m is calculated using equation (3.5) with the fifth and sixth curve:

$$g_m \approx \frac{\Delta i_D}{\Delta v_{GS}} \approx \frac{30\,\text{mA} - 20\,\text{mA}}{250\,\text{mV}} \approx 40\,\text{mS}$$

k_n is estimated using equation (3.3), assuming $V_{th} = 0.5\,\text{V}$:

$$k_n = \frac{2 i_D}{(v_{GS} - V_{th})^2} = \frac{2 \cdot 30\,\text{mA}}{(1.5\,\text{V} - 0.5\,\text{V})^2} = 60\,\frac{\text{mA}}{\text{V}^2}$$

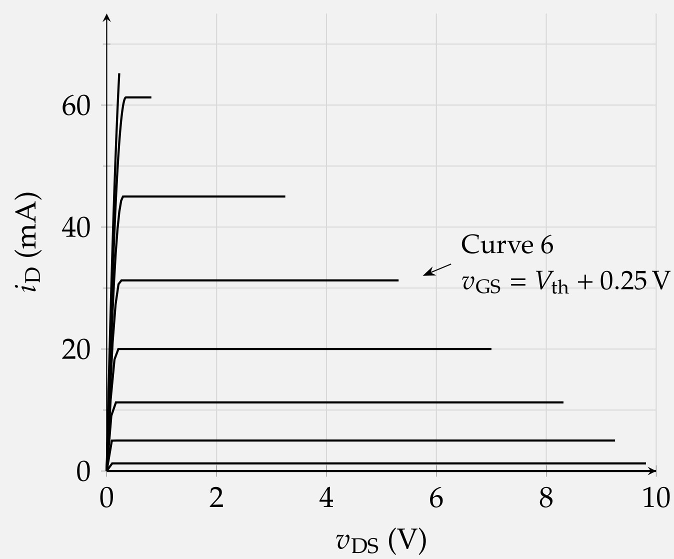

Figure 3.3: Typical curve tracer output

[a] The exact value is measured using cursors on an oscilloscope

3.6 Prelab

Task 3.6.1: Prelab

1. An N-Channel MOSFET with a threshold voltage of 1 V has a curve on a curve tracer corresponding to $v_{GS} = 1.5\,\text{V}$ where $i_D = 10\,\text{mA}$. What is the k_n value of the MOSFET?
2. Use equations (3.3) and (3.4) to calculate the ideal value of g_m in terms of v_{GS}, k_n, and V_{tn}
3. Use virtual short circuit analysis on the circuit in figure 3.2 to determine the value of i_D in terms of R_S and v_{CTRL}.
4. Using the same circuit, if $R_S = 100\,\text{k}\Omega$, what should v_{CTRL} be to set $i_D = 1\,\mu\text{A}$?

3.7 Tasks

Task 3.7.1: Determine V_{tn}

1. *Connect* your ESD wristband to ground and put on the wristband.
2. *Place* the ALD1106 into your breadboard and connect $V-$ to ground and $V+$ to V_{DD}.
3. *Build* the circuit in figure 3.2 using $R_S = 100\,\text{k}\Omega$, $V_{DD} = 5\,\text{V}$, and $V_{SS} = -5\,\text{V}$. Use any of the four transistors on the ALD1106.
4. *Set* v_{CTRL} to the value calculated in prelab step 4.
5. *Measure* the voltage across R_S to ensure that i_D is set to $1\,\mu\text{A}$.
6. *Measure* v_{GS}. This is the threshold voltage of the transistor.
7. *Repeat* the threshold voltage measurement for all four transistors on the ALD1106.
8. *Compare* the threshold voltages of the four measured transistors. Do the transistors have similar threshold voltages?
9. *Compare* the threshold voltages to the range listed on the ALD1106 datasheet. Does your measurement fall within the range listed on the datasheet?

Task 3.7.2: Estimate k_n

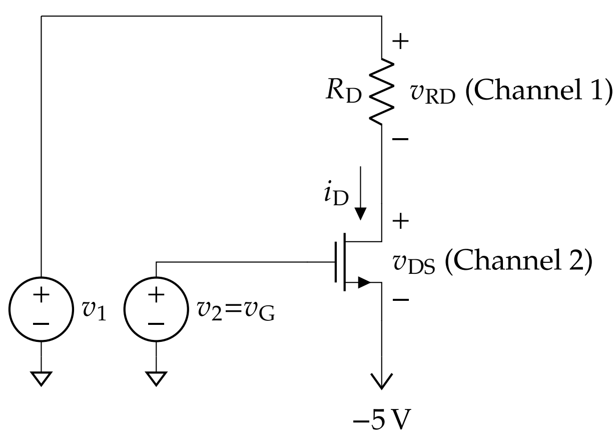

Figure 3.4: Test set for measuring the drain characteristics.

1. *Place* the ALD1106 in your breadboard and connect $V-$ to $\mathbf{V}_{SS}$ and $V+$ to V_{DD}.
2. *Set up* the to measure the drain I–V characteristics of the transistor by building the circuit in figure 3.4 with $R_D = 470\,\Omega$. Use W1 to generate v_1 and W2 to generate v_2. Use the oscilliscope channel 1 to measure v_{DS} and channel 2 to measured v_{RD}. Make sure to connect the source of the NMOS in the ALD1106 to V_{SS}.

3. *Set* the power supplies to $V_{DD} = 5\,V$ and $V_{SS} = -5\,V$ then turn them on.
4. *Open* the "Tracer" tool in Waveforms[a].
5. *Set* the device to "N-FET" and change the adapter dropdown to "No Adapter."
6. *Open* the options dropdown and change "Emitter" to $-5\,V$.
7. *Ensure* that "Measure" is set to "Id/Vds"
8. *Configure* the curve tracer to measure from $v_{GS} = 0\,V$ to $v_{GS} = 5\,V$ in even 500 mV steps over the range $0\,V \le v_{RD} < 10$.
9. *Set* $R_D = 470\,\Omega$ in the tracer tool.
10. *Run* the curve tracer and save a screenshot of the output.
11. *Calculate* the k_n value for each curve that the transistor enters saturation. Use the V_{tn} measured in task 3.7.1.

[a] If you can't find this tool, you need to update to the newest version of waveforms.

Task 3.7.3: Estimate g_m

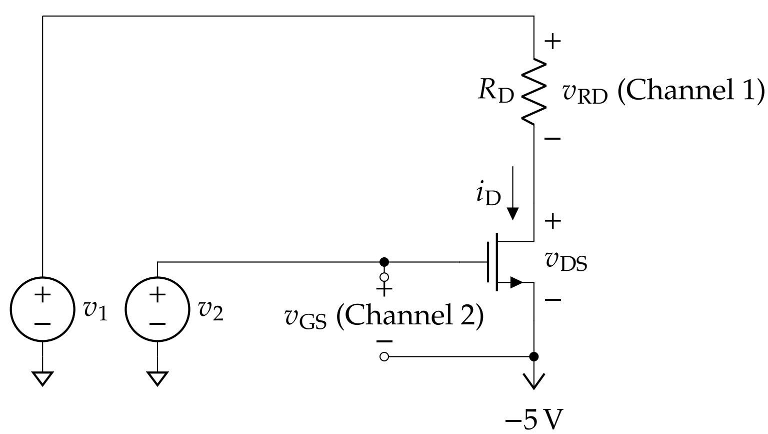

Figure 3.5: Test set for measuring the i_D vs. v_{GS} characteristics.

1. *Construct* the circuit in figure 3.5. This is almost the same circuit as task 3.7.2, except channel 2 is now measuring v_{GS}.
2. *Configure* the tracer tool in Waveforms to measure "iD/vGS."
3. *Set* the drain voltage to a constant 5 V
4. *Configure* the gate voltage to sweep from 0 V to 5 V in 100 mV steps.
5. *Run* the curve tracer.

Purdue University use only – Do not duplicate – ©2022 (Spring Version)

6. *Capture* a screenshot of the curve tracer output.
7. *Export* the data from the curve tracer and load it into MATLAB, Excel, or a similar tool.
8. *Calculate* g_m for each point using equation (3.5).
9. *Plot* g_m vs. i_D. What is the correlation between i_D and g_m?
10. *Plot* g_m vs. v_GS and your answer to prelab question 2. Use the V_tn you measured in task 3.7.1 and the k_n you calculated for the curve corresponding to $v_\mathrm{GS} = 2.5\,\mathrm{V}$ in task 3.7.2. Over what range of voltages does the model agree with the measurement?

3.8 References

[1] *Small signal MOSFET*, 2N7000G, Rev. 8, On Semiconductor, Apr. 2011. [Online]. Available: `http://www.onsemi.com/pub/Collateral/2N7000-D.PDF`.

[2] *IRL530N HEXFET® power MOSFET*, IRL530N, PD-91348C, International Rectifier, Jan. 2004. [Online]. Available: `http://www.irf.com/product-info/datasheets/data/irl530n.pdf`.

[3] *Quad/dual N-channel matched pair MOSFET array*, ALD1106/ALD1116, Vers. 2.2, Advanced Linear Devices, Inc., 2021. [Online]. Available: `http://http://www.aldinc.com/pdf/ALD1116.pdf`.

Purdue University use only – Do not duplicate – ©2022 (Spring Version)