Jacobs University Bremen

CO-526-B: Electronics Lab

Fall 2021

Lab Experiment 5: Metal Oxide Field Effect Transistor

Priontu Chowdhury

Introduction

In this lab, we familiarize ourselves with the characteristics and application of MOSFETs, which are one of the most common transistors used in industry today. The experiments include the investigation of I-V characteristics and implementation of MOSFETs as amplifiers and switches.

Theory

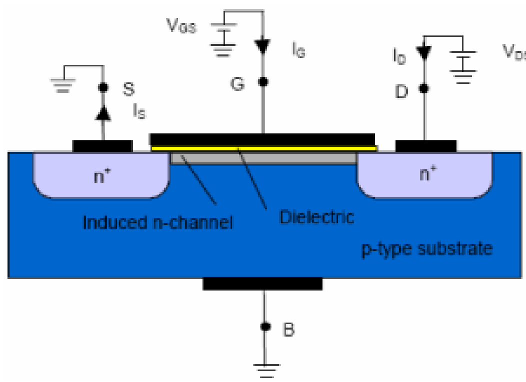


Figure: Schematic cross section of an enhancement-type NMOS transistor

The MOSFET has three regions of operation:

1. Cut-off Region

   This region occurs when gate-to-source voltage is less than the threshold voltage ($V_{GS} < V_{th}$). In this region, there is no current flow between the source and drain terminals.

2. Linear (Triode) Region
   This occurs when $V_{GS} > V_{TH}$ but $V_{DS} < V_{GS} - V_{TH}$. For this region, the current flow is a function of both gate-to-source voltage and the drain-to-source voltage. The relation is described below:

$$I_D = \mu_n C_G \frac{W}{L}\left(V_{GS} - V_{th} - \frac{1}{2}V_{DS}\right) V_{DS}$$

3. Saturation Region
   This occurs when $V_{GS} > V_{TH}$ but $V_{DS} > V_{GS} - V_{TH}$. If V_{DS} is sufficiently small, we can describe the I/V relation as follows:

$$I_D = \mu_n C_G \frac{W}{L}(V_{GS} - V_{th}) V_{DS}$$

   For a V_{DS} that is sufficiently larger than $V_{GS} - V_{TH}$, the channel is pinched off, which leads to the following I/V relation:

$$I_D = \mu_n C_G \frac{W}{2L}(V_{GS} - V_{th})^2$$

Prelab: Field Effect Transistor

Problem 1: Metal Oxide Semiconductor Field Effect Transistors (MOSFET)

Question 1

An enhanced MOSFET does not initially contain a conduction channel. The channel is generated by applying a voltage across the gate-source terminals that is larger than the threshold voltage. Therefore, in this case the channel is an induced channel.

For a depletion MOSFET, the channel is permanently fabricated during the construction of the MOSFET using doping methods.

Question 2

In PMOS, the source and the drain are made of P-type semiconductor, and in NMOS, the source and the drain terminals are made of N-type semiconductors. Consequently, the current flowing through the PMOS channel is hole current (holes are the majority carriers), while the current flowing through the NMOS channel is electron current (electrons are the majority carriers).

Problem 2: MOSFET as Amplifier

Question 1

For this task, we use the following circuit:

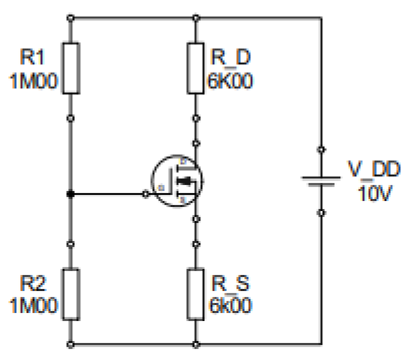


Figure: MOSFET circuit

First, we apply voltage division across the outer circuit:

$$V_{R2} = \frac{R2}{R1 + R2} V_{DD} = 5V$$

Now, we apply KVL across the V_{GS} region:

$$-V_{R2} + V_{GS} + V_{RS} = 0$$

$$V_{RS} = V_{R2} - V_{GS}$$

We know:

$$I_{DS} = \mu_n C_G \frac{W}{2L}(V_{GS} - V_{th})^2 = k * (V_{GS} - V_{th})^2$$

Where k = 0.5 mA/V^2, and V_{TH} = 1V.

$$I_{DS} = 0.5(V_{GS} - 1)^2$$

All the current in the drain passed into the source.

$$I_{DS} = \frac{V_{RS}}{RS} = \frac{V_{R2} - V_{GS}}{RS} = \frac{5 - V_{GS}}{6000}$$

Therefore, we can use these equations to obtain the following:

$$\frac{5 - V_{GS}}{6000} = 0.5(V_{GS} - 1)^2$$

$$5 - V_{GS} = 3(V_{GS} - 1)^2$$

$$3V_{GS}^2 - 5V_{GS} - 2 = 0$$

$$V_{GS} = 2V \ or \ V_{GS} = -\frac{1}{3}(< V_{TH}, so \ rejected)$$

$$\therefore V_{GS} = 2V$$

$$I_D = \frac{5 - V_{GS}}{6000} = 5 \times 10^{-4}A = 0.5mA$$

Using KVL to the left of the transistor:

$$-V_{DD} + V_{RD} + V_{DS} + V_{RS} = 0$$

$$V_{DS} = V_{DD} - I_{DS}R_D - I_{DS}R_S = 10 - 3 - 3 = 4V$$

$$V_{DS} = 4V$$

<u>Question 2</u>

Firstly, we notice that the following holds true:

$$V_{GS} > V_{TH}$$

Now, we verify the following:

$$V_{GS} - V_{TH} = 2 - 1 = 1$$

$$V_{DS} = 4$$

$$\therefore V_{DS} > V_{GS} - V_{TH}$$

Hence, the MOSFET operates in saturation region.

Problem 3: MOSFET as Switch

We are required to find the operating point of the following circuit:

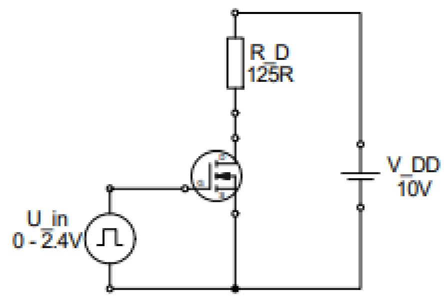


Figure: MOSFET circuit

We are using the following information to obtain our data:

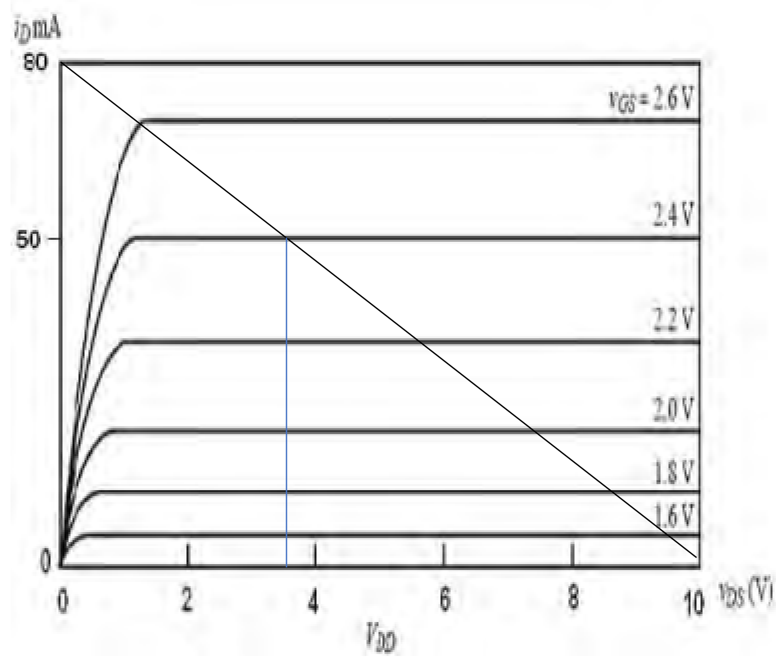


Figure: Characteristic I_D/V_{DS} curve

Using KVL across the transistor, we obtain the following relation:

$$V_{DS} = V_{DD} - V_{RD} = V_{DD} - I_D R_D$$

$$I_D = \frac{V_{DD}}{R_D} - \frac{V_{DS}}{R_D} = -0.008V_{DS} + \ 0.08$$

$$I_D = -0.008V_{DS} + \ 0.08$$

Drawing this linear relation on the curve, we see that the relation holds true. At $V_{DS} = 0V, I_D = 80mA$ and at $V_{DS} = 10V, I_D = 0mA$.

Using the intersection points, we see that at $V_{GS} = 2.4V, I_D = 50mA$, which means $V_{DS} = 3.75V$

Therefore, for $V_{GS} = 2.4V$: $I_D = 50mA, V_{DS} = 3.75V$, and the MOSFET operates in saturation mode.

Again, for $V_{GS} = 0V$: $I_D = 0mA, V_{DS} = 0V$, where the MOSFET operates in cut-off region.

Experimental Set-up and Results

Problem 1: I/V Characteristics of a MOSFET

In this section, we explore the current/voltage characteristics of an NMOS Field Effect Transistor.

<u>Task 1</u>

For this task, we were required to use the following circuit to determine U_{th}:

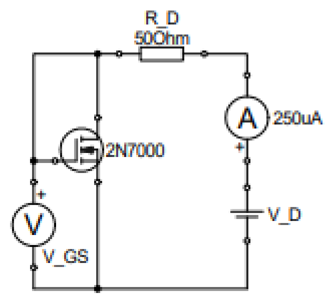


Figure: NMOS circuit

We set up the circuit as provided in lab, and we appropriated circuit conditions so as to set $I_D \approx 250\mu A$. Then, we recorded U_{th} and I_D as follows:

$$I_D = 249.18\ \mu A$$

$$U_{th} = 2.049\ V$$

<u>Task 2</u>

Then, we used the following circuit to obtain the transfer characteristic of the MOSFET:

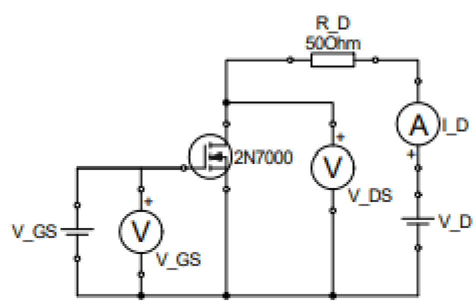


Figure: Determining transfer characteristics

To accomplish this, we keep V_{DS} at 5V and vary the gate-source voltage from 0V to 3V.

We obtain the following results:

I_D /mA	V_D/ V	V_{GS}/V	V_{DS}/V
0	5	0	5.088
0	5	1.0634	5.088
0.287	5	2.0534	5.072
0.981	5	2.1678	5.033
2.53	5.1	2.2701	5.037
40.55	7.4	2.3523	5.016
44.23	7.6	2.4499	5.033
47.28	7.8	2.5401	5.022
51.2	8	2.6555	5.019
54.94	8.1	2.7632	5.013
58.53	8.3	2.8627	5.019
63.16	8.5	2.9624	5.023

Task 3

For this task, we use the same circuit to measure the output characteristic for the gate source voltages of 2.2V, 2.4V and 2.6V. The drain-source voltages are scanned from 0V to 4V. For our case, $V_{th} = 2.049V$, which is greater than 2V. Therefore, using $V_{GS} = 2V$ is not useful in our case, as the transistor will be in cut-off region.

For the next step, we use $V_{GS} = 2.201V(V_{GS} - V_{TH} = 0.152V)$, which means the transistor is active. For this V_{GS}, we obtain the following results:

V_D/V	V_{DS}/V	I_D/mA
0.1	0.127	0.923
0.2	0.235	1.036
0.3	0.32	1.055
0.5	0.469	1.112
1	1.037	1.16
2	2.025	1.208
3	2.954	1.242
4	4.042	1.282

Next, we use $V_{GS} = 2.4V (V_{GS} - V_{TH} = 0.351V)$, which means the transistor is active. For this V_{GS}, we obtain the following results:

V_D/V	V_{DS}/V	I_D/mA
0.1	0.032	1.172
0.2	0.084	3.46
0.3	0.134	4.368
0.4	0.189	4.945
0.5	0.29	5.451
1	0.679	6.621
2	1.412	10.983
3	2.096	16.237
4	2.813	22.226

Next, we use $V_{GS} = 2.6V (V_{GS} - V_{TH} = 0.551V)$, which means the transistor is active. For this V_{GS}, we obtain the following results:

V_D/V	V_{DS}/V	I_D/mA
0.1	0.016	2.3
0.2	0.032	4.318
0.3	0.047	5.549
0.4	0.055	6.973
0.5	0.072	8.611
0.6	0.087	9.964
0.7	0.103	11.336
1	0.171	15.601
2	1.184	16.555
3	1.84	21.126
4	2.509	26.656

Problem 2: MOSFET as an Amplifier

In this section, we design and realize an amplifier circuit using a MOSFET.

For the following tasks, we use the following circuit:

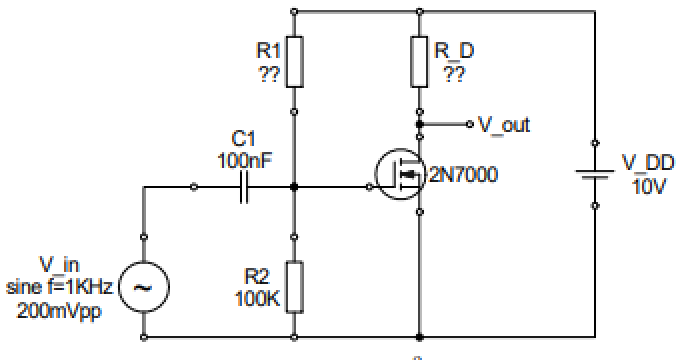


Figure: Amplifier circuit

$$V_{GS} = 2.7V, V_{DS} = 5V, k = 72.2mA/V^2, V_{th} = 2.049V$$

<u>Task 1</u>

Firstly, we are required to find R1 and RD.

Next, running a KVL around RD, we find:

$$-V_{DD} + V_{RD} + V_{DS} = 0$$

$$V_{RD} = V_{DD} - V_{DS} = 5V$$

$$I_D = k(V_{GS} - V_{TH})^2 = 0.0306A$$

$$R_D = \frac{V_{RD}}{I_D} = 163.407\Omega$$

We can find R1 by using voltage division on the outer loop:

$$V_{R2} = V_{GS} = 2.7V$$

$$V_{R2} = \frac{R2}{R1 + R2} V_{DD}$$

$$R1 + R2 = \frac{R2}{V_{R2}} V_{DD}$$

$$R1 = \frac{R2}{V_{R2}} V_{DD} - R1 = 270.37K\Omega$$

Task 2

After obtaining the resistor values, we assembled the above circuit on the breadboard. We used a 150Ω resistor for R_D, because that was the closest resistor we could find to the required value.

Task 3

We applied a sinusoidal input signal with an amplitude of 100mV and frequency of 1KHz to the input of the circuit.

Task 4

The input and output signals were displayed on the oscilloscope, and the phase relation between them is measured, as shown below:

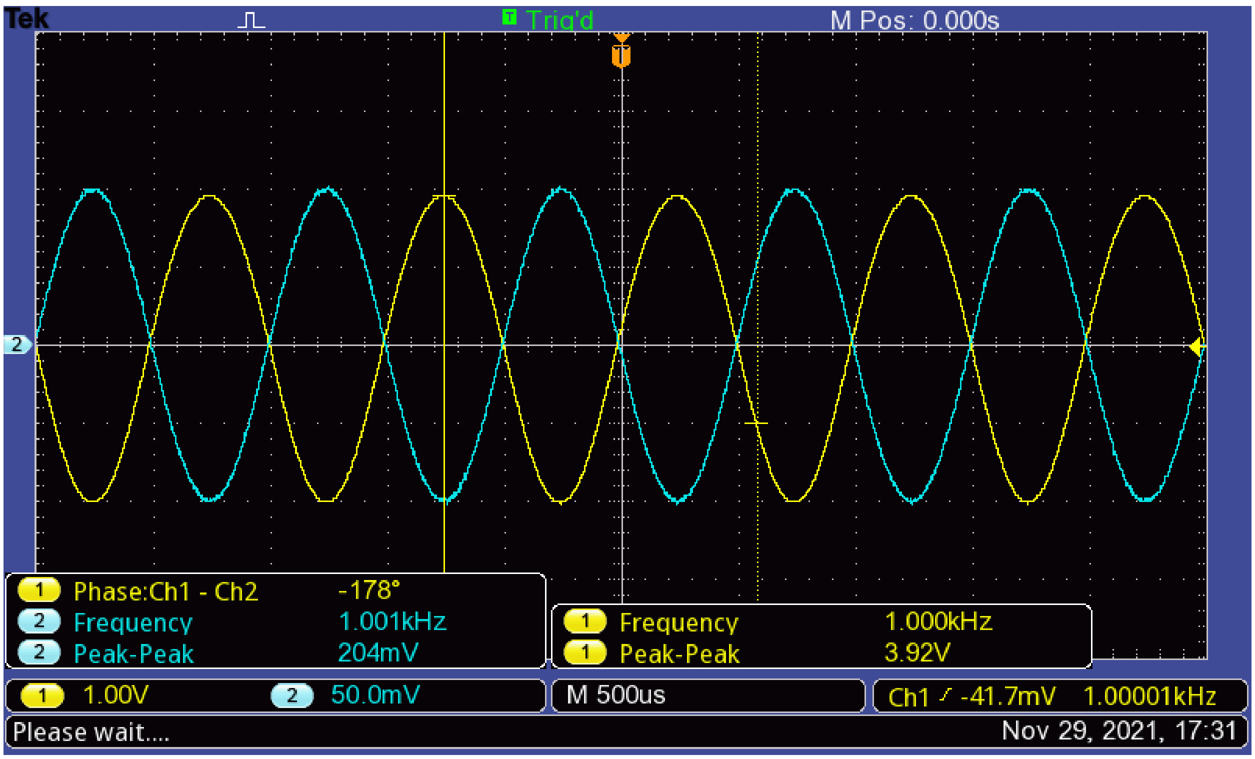
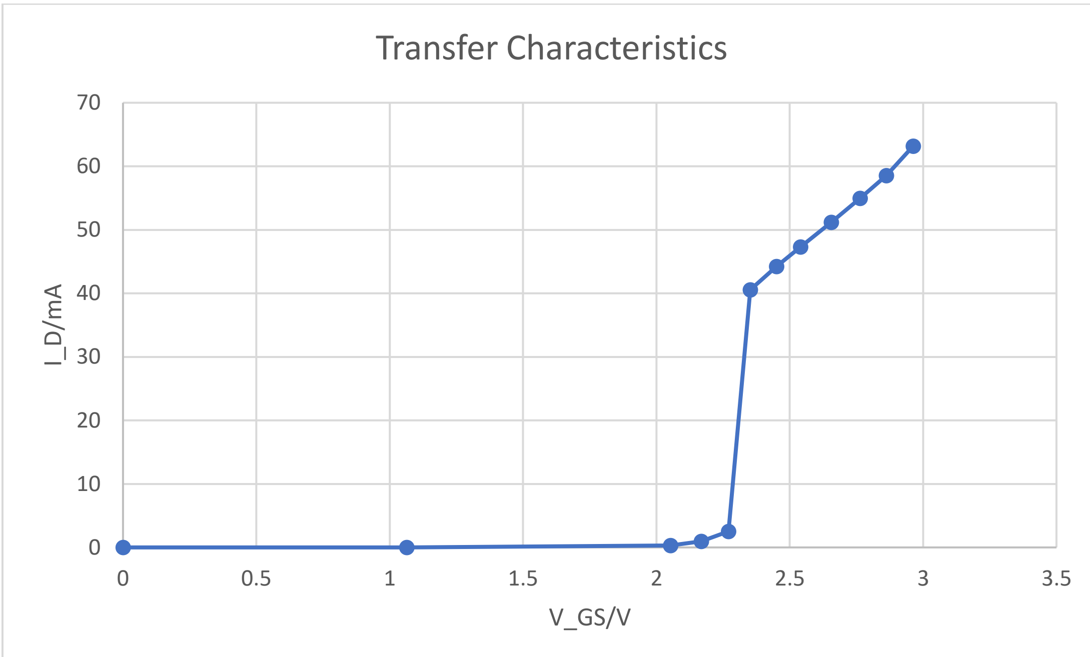


Figure: Oscilloscope display of input, output and measurements

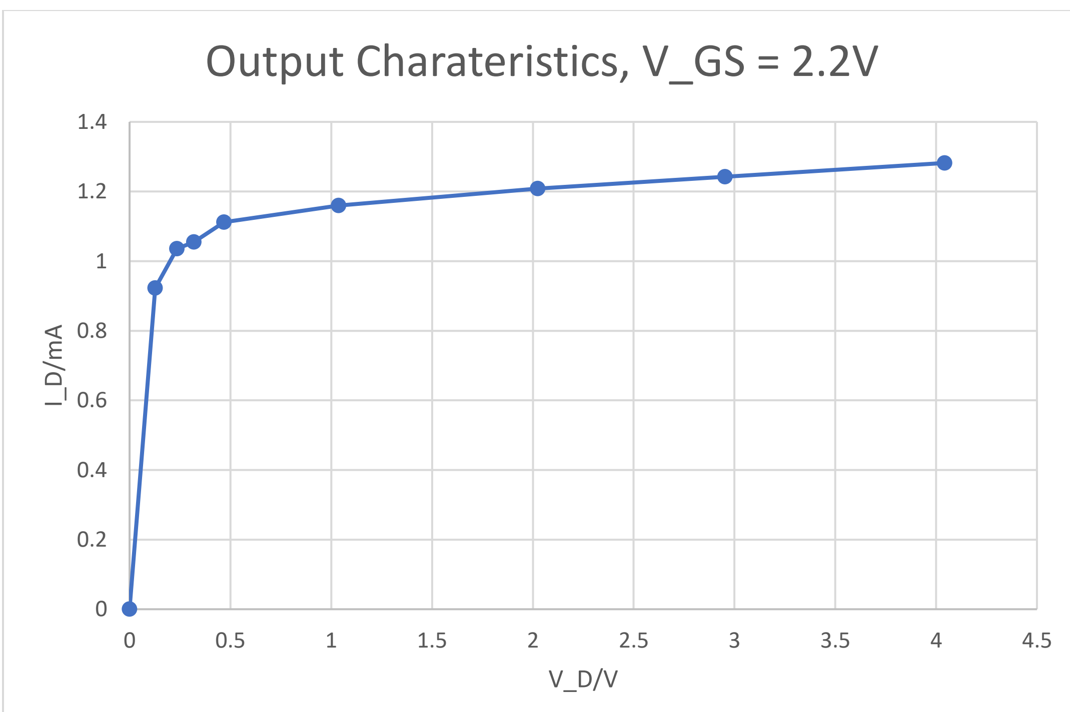
Evaluation

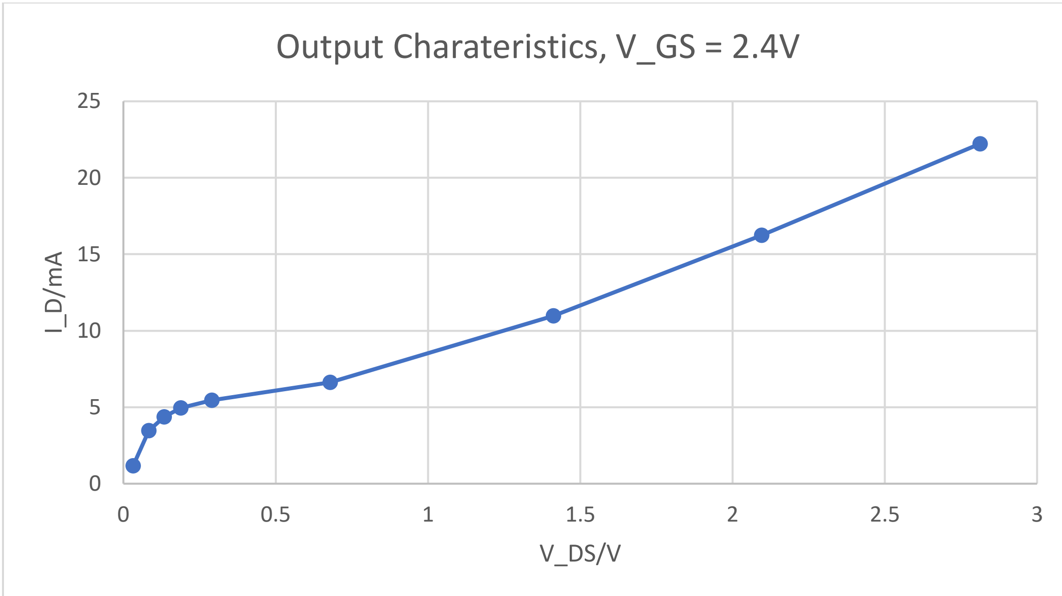
Problem 1: I/V Characteristic of a MOSFET

<u>Question 1</u>

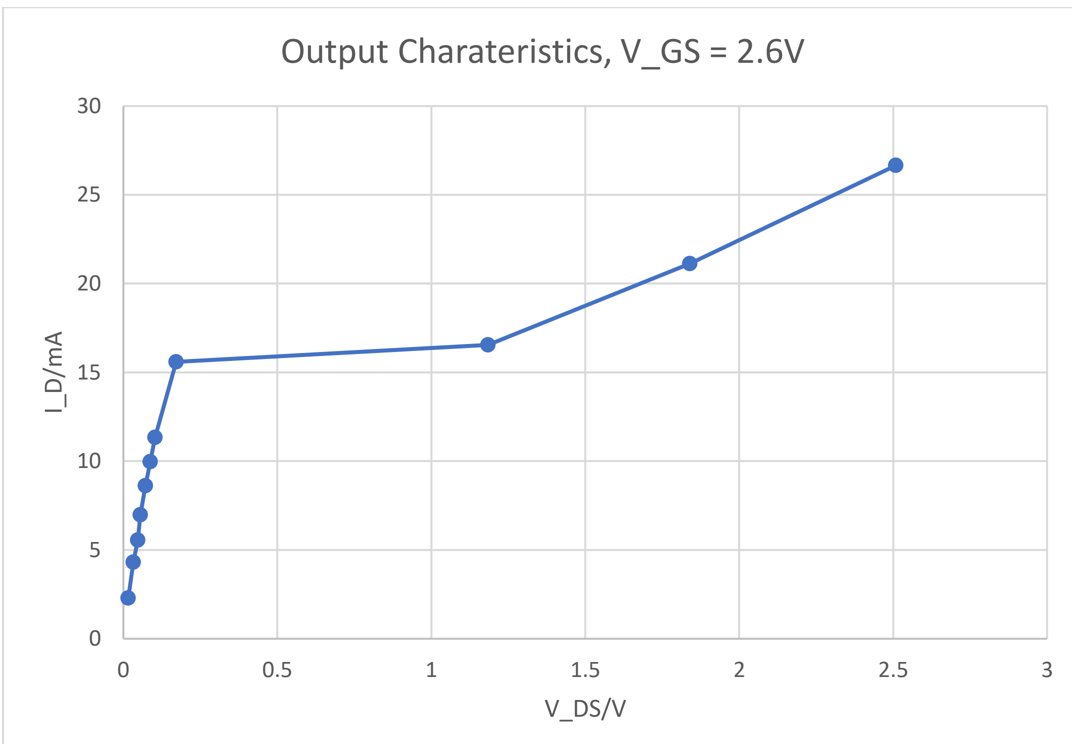


<u>Question 2</u>



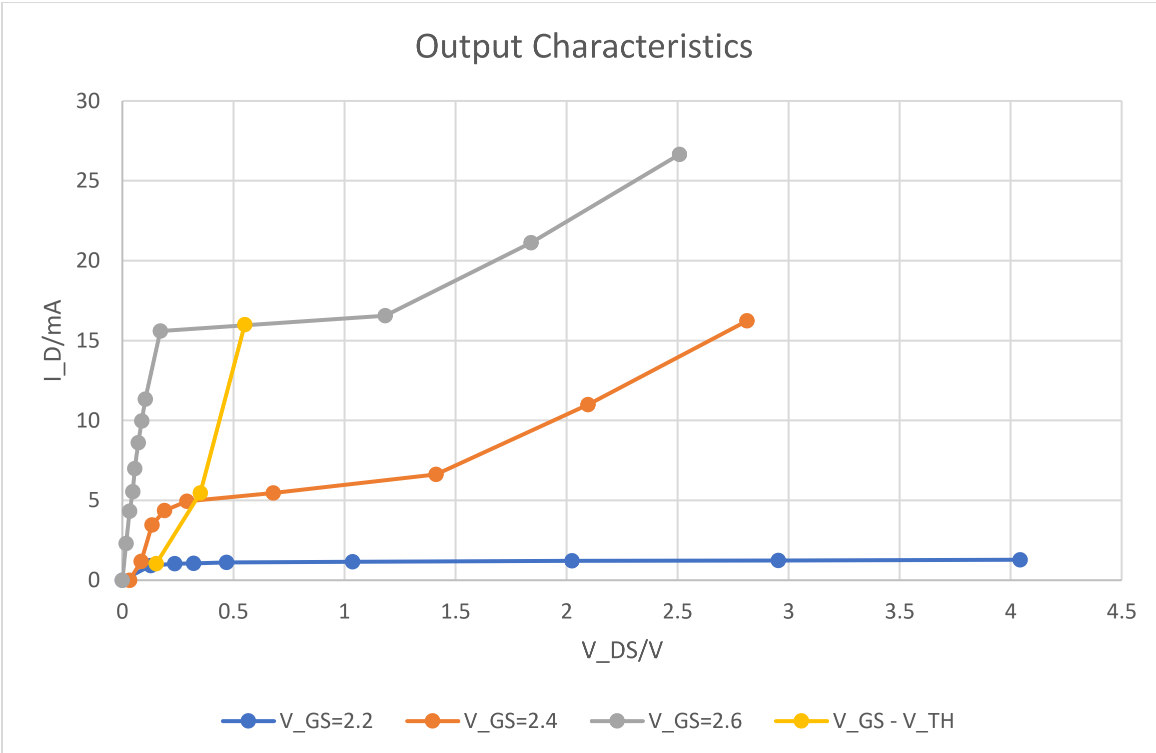


Output Charateristics, V_GS = 2.4V
I_D/mA
V_DS/V
0
5
10
15
20
25
0
0.5
1
1.5
2
2.5
3



Output Charateristics, V_GS = 2.6V
I_D/mA
V_DS/V
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3

Question 3



Problem 2: MOSFET as Amplifier

Question 1

In saturation mode, I_D only depends on V_{GS}, and we can see that the output of the circuit (V_{out}) is only dependent on the current flowing through R_D. Therefore, it can be concluded that the MOSFET is in saturation mode.

Question 2

$$A_V = \frac{3.92V}{204mV} = 19.216$$

$$V_{out(max)} = 5 + 0.5(3.92) = 6.96V$$

$$V_{in(max)} = \frac{6.96V}{19.216} = 0.362V$$

This is the maximum input voltage for which clipping doesn't occur.

Question 3

$$V_{out} = V_{DS} = V_{DD} - I_D R_D$$

$$I_D = K.(V_{GS} - V_{TH})^2$$

$$V_{out} = V_{DD} - K(V_{GS} - V_{TH})^2 . R_D$$

$$A_V = \frac{V_{out}}{V_{in}} = \frac{V_{DD} - K(V_{GS} - V_{TH})^2 . R_D}{V_{in}}$$

Theoretical value:

$$A_V = \frac{10 - 0.0722(2.7 - 2.049)^2 \times 163.407}{0.2} = 25$$

Question 4

Theoretical value:

$$A_V = \frac{10 - 0.0722(2.7 - 2.049)^2 \times 163.407}{0.2} = 25$$

Experimental value:

$$A_V = \frac{3.92V}{204mV} = 19.216$$

As we can see, the gain obtained through experimental findings is smaller, and has a significant difference from the theoretical value. It's possible that this is due to the usage of a 150Ω resistor rather than a 163Ω one for R_D. This was the only resistor we could find with the closest value to our calculated value in component box. Moreover, the transistor might have a different value from "k" than that we used in our calculations. The measure function of the oscilloscope has an error of about 5%, which might also play a role. All of this error also propagated to provide us a final output value that is lower.

Question 5

According to our findings, the input and output have a phase difference of $178° \approx 180°$. This occurs because, when the amplitude of the input signal increases in the positive direction, the drain current also increases positively, which results in a increase in the voltage across R_D, and as $V_{out} = V_{DS} = V_{DD} - I_D R_D$, this results in a decrease in output voltage. Therefore, V_{out} and V_{in} always propagate in opposite directions, which gives then a 180° phase difference.

Conclusion

In this lab, we studied the characteristics and application of MOSFETs. In the lab, we used a circuit structure using a MOSFET to determine the threshold voltage of the MOSFET. Then, we used the same MOSFET in a different circuit to determine the transfer characteristics of the MOSFET. When we evaluated the data obtained, we saw that it was a bit irregular, which could be the result of self-heating of the transistor. However, overall, the data correlated with our understanding of theoretical constructs. We were able to obtain an understanding of the relation of the drain current with the gate-source voltage. We also observed how drain current varies with drain-source voltage for different gate-source voltages that are greater than the threshold voltages. From the curves we developed based on our data, we were able to distinguish the saturation mode of operation from the triode mode of operation.

For the next experiment, we used a MOSFET as an amplifier. We determined the appropriate resistors required, and built an amplifier circuit using the MOSFET. Then, we supplied an input signal to the circuit, and observed the output. On the oscilloscope, we saw that the output is an amplified version of the input with a phase difference of 180°. When evaluating the data, we noticed that our experimental gain was smaller than the theoretical gain, which we were able to attribute to the R_D resistor we used for our experimentation, which was different from the calculated value by about 13 units.

Furthermore, the resolution of the oscilloscope also contributes to the error in experimental values. Measurements taken using the measure function have about 5% error, while those taken using cursors have about 10% error. Moreover, we do not account for the tolerances of the circuit components in our calculations. The resistors we use have about 1-2% tolerance, and the same goes for signal generator. Therefore, these errors propagate to provide us measured values that deviate largely from the simulated and theoretical values, which we consider as values obtained under ideal conditions.

References

- Electronics Lab Manual (Uwe Pagel)
- http://www.faculty.jacobs-university.de/upagel/