Lab 5 - DC biasing of an NMOS transistor

Ty Davis

ECE 3110

October 23, 2024

---

1 Introduction and Theory

In Fig. 1 you can see the circuit that we used in the lab. We are going to use this circuit to force the NMOS transistor into both the triode and saturation regions. To do that we will need to select certain resistors to cause the voltages at V_D, V_G, and V_S to reach specific levels that suggest triode and saturation operation of the MOSFET. In order to verify our calculations we will simulate and build/measure the circuit to compare to our analysis.

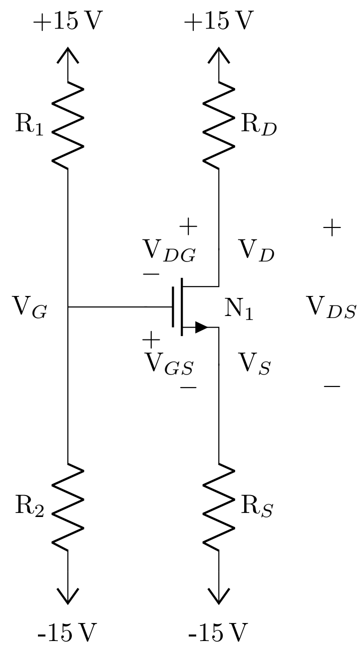

Figure 1: Circuit that we use in the lab.

2 Saturation Region

The saturation region is characterized by $V_{DS} > v_{ov}$, and we've been asked to design the circuit such that $I_D = 1$ mA, $V_G = 0$ V, and $V_D = 5$ V.

2.1 Calculations

2.1.1 Find R_D

Because I_D and V_D are provided, R_D is easy to find:

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{15 - 5}{0.001} = 10\ \text{k}\Omega$$

2.1.2 Find R_S

Calculating R_S is a little bit more involved. First we need to find V_S, but to do that we need to find V_{GS}. In the saturation region we know

$$I_D = \frac{1}{2}k_n(V_{GS} - V_{th})^2$$

This can be rearranged to solve for V_{GS}, and we get Eq. 1

$$V_{GS} = \sqrt{\frac{2 \cdot I_D}{k_n}} + V_{th} \tag{1}$$

From the datasheet we can find an operating point which we can use to calculate k_n using

$$k_n = \frac{1}{r_{DS} \cdot v_{OV}}$$

In the datasheet we read that $V_{th} = 2.15$ V, and we get the operating point $r_{DS} = 1.8\ \Omega$ @ $V_{GS} = 10$ V. Thus, we can get k_n:

$$k_n = \frac{1}{1.8 \cdot 7.9} = 0.070\ \text{A/V}^2$$

Using that k_n we can obtain V_{GS}:

$$V_{GS} = \sqrt{\frac{2 \cdot 1\ \text{mA}}{0.2462\ \text{A/V}^2}} + 2.15\ \text{V} = 2.269\ \text{V}$$

Finally, we know that $V_S = V_G - V_{GS} = -2.269$ V. And using $V_S = -2.269$ V we can calculate R_S.

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-2.269 - (-15)}{0.001} = 12.731\text{k}\Omega$$

.

2.1.3 Find R_1 and R_2

Finally, to calculate R_1 and R_2 we need to ensure that the voltage $V_G = 0$ V. With only one current path, that means that we want to select any two equal value resistors. The problem is not completely defined and we can pick any that we want, though we will likely want to pick some high-value resistors to keep the current flow low and use less power. We can use $R_1 = R_2 = 1$ MΩ.

2.2 Simulation

With the calculated values from the previous section, we were able to simulate the circuit and we got these values.

V_D	V_S	V_G	I_D
4.90 V	-2.14 V	0 V	1.01 mA

Table 1: Simulation results in saturation.

The differences between the simulation and our calculations were present but very minimal, all within 0.1 V and 10 µA.

2.3 Measurements

To build the circuit we needed to select the right resistors, but without those precise resistors in the lab we need to build equivalent resistor networks from the available resistors. All of the used resistors values are shown in Table 2.

	Calculated Resistor	**Equivalent Resistor**	**Measured Resistor**
R_S	12.731 kΩ	12.670 kΩ	12.595 kΩ
	—	2.2 kΩ	2.181 kΩ
	—	10 kΩ	9.949 kΩ
	—	470 kΩ	0.465 kΩ
R_D	10 kΩ	10 kΩ	9.875 kΩ
R_1	1 MΩ	1 MΩ	0.968 MΩ
R_2	1 MΩ	1 MΩ	0.983 MΩ

Table 2: Resistors used to operate in saturation region.

V_D	V_S	V_G	I_D **(calculated)**
4.831 V	-2.04 V	0.116 V	1.03 mA

Table 3: Measurement results in saturation region.

3 Triode Region

Now we are tasked with designing the same circuit such that the MOSFET is operating in the triode region. We need to obtain the following parameters: $I_D = 10$ mA, $V_D = 2$ V, and $V_{DS} = 0.1$ V

3.1 Calculations

3.1.1 Find R_D

Once again, finding R_D is trivial:

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{15 - 2}{0.01} = 1.3 \text{ k}\Omega$$

3.1.2 Find R_S

Finding R_S is easy this time because we know that $V_S = V_D - 0.1 = 1.9$ V.

So:

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{1.9 - (-15)}{0.01} = 1.69 \text{ k}\Omega$$

3.1.3 Find R_1 and R_2

This time finding R_1 and R_2 is a bit more difficult. We don't know V_G, but we can find it if we know V_{GS} because we already know V_S.

$$I_D = k_n\Big(v_{OV} - \frac{1}{2}V_{DS}\Big)V_{DS}$$

Substituting $v_{OV} = V_{GS} - V_{th}$, and distributing the V_{DS} in we get this polynomial equation:

$$I_D = k_n\Big((V_{GS} - V_{th})V_{DS} - \frac{1}{2}V_{DS}^2\Big)$$

Using the values that we know from the problem description, and the k_n that we calculated in the last section, we get

$$10 \text{ mA} = 0.070\Big((V_{GS} - 2.1) \cdot 0.1 - \frac{1}{2}(0.1)^2\Big)$$

Solving for V_{GS} yields $V_{GS} = 3.579$ V.

Knowing that $V_S = 2 - 0.1 = 1.9$V, we can obtain $V_G = V_{GS} + V_S = 5.679$V.

With $V_G = 5.679$ V, we can determine the voltage divider that we want for R_1 and R_2. Keeping R_2 at 1 MΩ, we can find that $R_1 = 0.4649$ MΩ.

3.2 Simulation

We designed the circuit in Multisim and the results are shown in Table 4.

V_D	V_S	V_G	I_D
1.99 V	1.91 V	5.48 V	10.0 mA

Table 4: Simulation results in triode.

Once again, the voltages are all right in line with our calculations, with only a little bit of variation.

3.3 Measurements

A similar process was done to select the resistors. They are shown in Table 5.

	Calculated Resistor	**Equivalent Resistor**	**Measured Resistor**
R_S	1690 Ω	1680 Ω	1657 Ω
	—	1000 Ω	987 Ω
	—	680 Ω	670 Ω
R_D	1300 Ω	1304 Ω	1287 kΩ
	—	68 kΩ	67.32 kΩ
	—	330 Ω	328 Ω
	—	1 kΩ	0.985 kΩ
R_1	0.465 MΩ	0.470 MΩ	0.465 MΩ
R_2	1 MΩ	1 MΩ	0.983 MΩ

Table 5: Resistors used to operate in triode region.

V_D	V_S	V_G	I_D **(calculated)**
1.889 V	1.861 V	5.193 V	10.2 mA

Table 6: Measurement results in triode region.

This time, there was a bit more discrepancy between the calculated values and our measured ones, but the difference remains small. As such, it is safe to assume that the device is operating as expected.

4 Conclusion/Post Lab Observations

When building the the circuit that was designed for saturation operation, we got the values of $V_{GS} = 2.156$ V and $V_{DS} = 6.871$ V. These values clearly suggest that the device is operating in the saturation region because $V_{DS} > v_{OV}$, and v_{OV} is incredibly close to 0.

After building the circuit to operate in the triode region, we found $V_{GS} = 3.332$ V and $V_{DS} = 0.028$ V. These show that the device is operating in the triode region because $V_{DS} < v_{OV}$. $v_{OV} \approx 1.1$ V.

The currents that we got for I_D when we built the circuits for saturation and triode operation are also right in line with the calculation. They are shown in the corresponding measurement tables.