

The source and drain of an n-channel MOSFET are both formed by a metal-semiconductor junction with an n-type region in a p-type substrate. These regions exist in a p-type substrate. The gate is formed by placing an insulating oxide between a metal contact and the aforementioned p-type substrate. When a high voltage is applied at the gate, this attracts excess electrons toward the gate. The electrons cannot leave the substrate due to the insulating oxide layer. So, they simply build up just below the oxide. The number of electrons in this region, known as the channel, increases considerably. However, by the principle of low-level injection ($\delta p \ll p$ under a perturbation, the applied voltage in this case), the number of holes in the p-type substrate does not change considerably. The conductivity of a semiconductor is given by equation (1):

$$\sigma = q(\mu_n n + \mu_p p) \quad (1)$$

Here, σ is the conductivity, q is the elementary charge, μ_n is the electron mobility, μ_p is the hole mobility, n is the electron concentration, and p is the hole concentration. Since p does not change very much, but n increases considerably, σ increases. At a certain point, the channel essentially acts like a conductor. Electrons can now move freely between the source and drain terminals (reference - mosfet_op).

The situation is actually a bit more complicated. Depletion regions exist between the source and the gate and the gate and the drain. When V_{GS} exceeds a threshold voltage, call it V_{Th} , the depletion region is overcome, much like in a pn-junction diode. Since the channel acts as a conductor, electrons, the majority carrier in the source, can now flow freely into the channel between the source and drain terminals. When $V_{GS} \leq V_{Th}$, the diode is "off" and is said to be in the cut-off region. The expected I_D versus V_{GS} plot is shown below. I_D is essentially 0 in the cut-off region and "turns on" after a certain threshold:

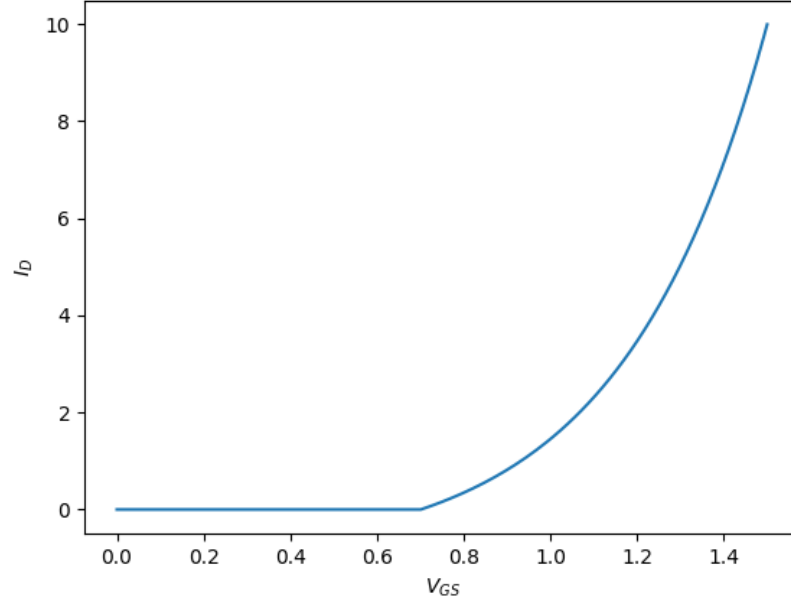


Figure 1: Expected I_D versus V_{GS} Curve for an n-Channel MOSFET

Once the electrons have migrated from the source to the channel, the drain-source voltage, or V_{DS} becomes important. Assume the MOSFET is in the "on" state in which $V_{GS} > V_{Th}$. The channel conductance is essentially constant and given by equation (1). Thus, the channel can be modeled as a simple resistor. By increasing V_D and therefore V_{DS} , the drain can attract electrons more strongly, causing a greater electron current to flow from the drain. So, for small variations in V_{DS} , I_D increases approximately linearly with V_{DS} . This is known as the triode region and occurs when $V_{DS} < V_{GS} - V_{Th}$.

However, this trend cannot continue indefinitely. At a certain point, electrons are so strongly attracted to the drain, that the channel loses many electrons, causing its conductivity to drop. This causes the drain current I_D to taper off since the effect of attracting electrons to the drain by increasing V_{DS} is counteracted by the drop in channel conductance. This is known as the saturation region and occurs when $V_{GS} < V_{Th}$. However, with a sufficiently high V_{DS} , the voltage may be high enough to produce a strong enough electric field to force electrons from the source through the channel to the drain (reference - lab_manual).

When V_{GS} is increased, a greater electron current flows from the channel to the source. Therefore, the diode can operate in the triode region for longer because it can now draw a larger electron current from the drain to the channel.

The saturation region still occurs, but at a higher drain current I_D . The expected plot is below with higher values of V_{GS} reaching higher saturation drain currents I_D .

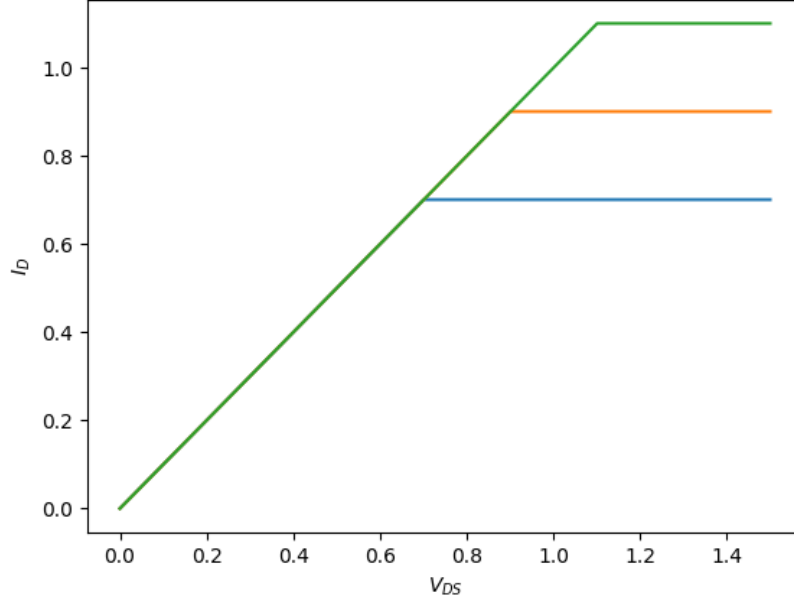


Figure 2: Expected I_D versus V_{DS} Curve for an n-Channel MOSFET

If V_{DS} is held constant and V_{GS} is increased, eventually, V_{DG} drops. If V_G becomes sufficiently large relative to V_D , then the depletion region is not going to be strong enough to actually drive carrier electrons into the drain. So, a larger electron current flows from the channel, but the gate-drain depletion region resists the flow of electrons into the drain. These two effects balance one another out and cause the drain current to level off.

The circuit in figure (3) is used to plot the MOSFET curves.

To acquire the I_D versus V_{GS} plot, V_2 is fixed at 10V. V_1 is varied to observe different measurement points. It should be noted that because the oxide layer prevents current from flowing from the gate's metal contact to the substrate, no current flows through the gate. Thus, the gate voltage V_G is simply V_1 . Since the source is grounded, $V_S = 0$, which implies that $V_{GS} = V_G - V_S = V_G = V_1$. Thus, V_1 and therefore V_{GS} is varied. As different I_D values are observed, the measurements are noted until an I_D versus V_{GS} curve is obtained. Note that gate voltages can be obtained by probing the pins in the MOSFET package. The current I_D can be measured by taking the voltage drop over the resistor connected to the drain and applying Ohm's Law.

Figure 3: MOSFET Measurement Circuit

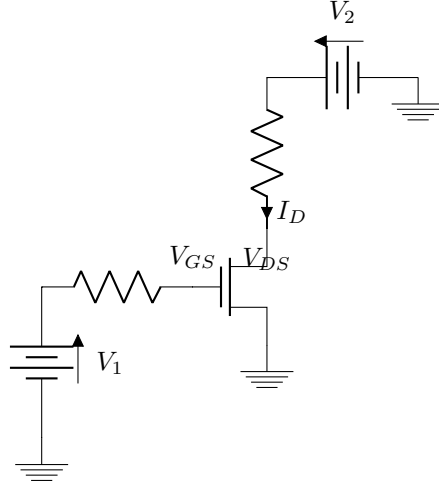


Table 1: MOSFET I_D versus V_{GS} Data

V_1 [V]	V_{R2} [V]	I_D [mA]	V_{GS} [V]
0.000	0.000	0.000	0.000
0.500	0.000	0.000	0.500
1.000	0.000	0.000	0.999
1.500	0.000	0.000	1.500
2.000	0.064	0.006	1.999
2.050	0.127	0.013	2.050
2.100	0.225	0.023	2.100
2.150	0.418	0.042	2.150
2.200	0.702	0.071	2.200
2.250	1.211	0.122	2.250
2.300	1.885	0.190	2.300
2.350	3.025	0.305	2.350
2.400	4.314	0.436	2.400
2.450	6.309	0.637	2.450
2.500	8.172	0.825	2.498
3.000	9.965	1.006	2.998
3.500	9.978	1.008	3.497
4.000	9.983	1.008	3.996
4.500	9.985	1.008	4.497
5.000	9.987	1.009	4.996

I_D is acquired by using Ohm's Law with the measured and not the reported resistance values. The resistor connected to the drain is measured to be $0.998\text{k}\Omega$ and the resistor connected to the gate is $9.902\text{k}\Omega$.

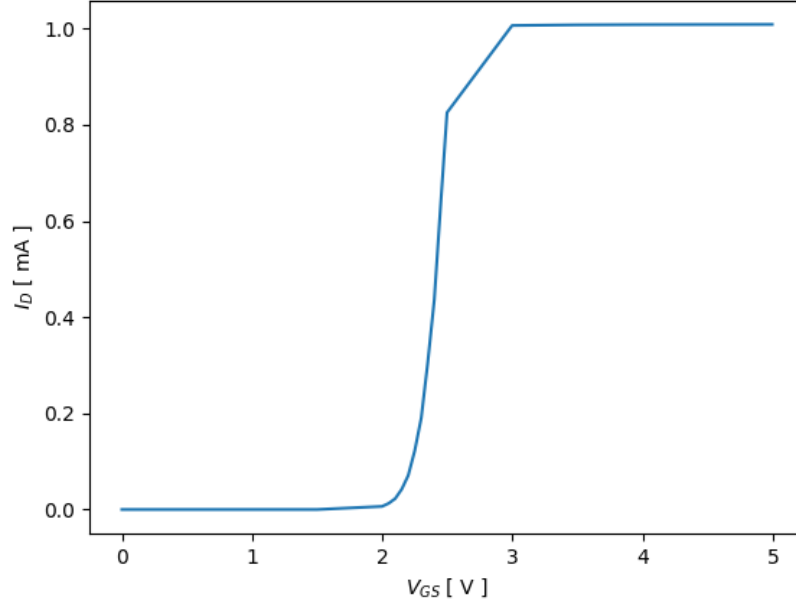


Figure 4: MOSFET I_D versus V_{GS} Plot

The plot in figure (4) is precisely as predicted. The MOSFET turns on when V_{GS} exceeds the threshold voltage V_{Th} , which is slightly above 2V. The drain current I_D rises exponentially as V_{GS} increases since a larger electron current can now be driven from the channel. Eventually, the curve levels off because the gate voltage V_G becomes sufficiently large relative to the drain voltage V_D , which begins to counteract the flow of electrons into the drain.

To acquire the I_D versus V_{DS} plot, V_1 is fixed at about 2.3V, which is around V_{Th} for the MOSFET as predicted by the previous results. Thus, V_{GS} is fixed. Increasing V_2 also increases the drain voltage V_D and thus V_{DS} since $V_{DS} = V_D - V_S = V_D$. Again, the drain current I_D can be measured from the voltage over the drain's resistor and Ohm's Law.

Table 2: MOSFET I_D versus V_{DS} Data

V_2 [V]	V_{R2} [V]	I_D [mA]	V_{DS} [V]
0.000	0.000	0.000	0.000
0.100	0.100	0.010	0.004
0.200	0.197	0.020	0.007
0.300	0.294	0.030	0.012
0.400	0.389	0.039	0.021
0.500	0.485	0.049	0.026
0.600	0.579	0.058	0.031
0.800	0.768	0.078	0.038
0.900	0.860	0.087	0.045
1.000	0.954	0.096	0.052
2.000	1.636	0.165	0.388
3.000	1.717	0.173	1.300
4.000	1.755	0.177	2.256
5.000	1.789	0.181	3.217
6.000	1.824	0.184	4.177
7.000	1.861	0.188	5.144
8.000	1.901	0.192	6.108
9.000	1.953	0.197	7.055
10.000	2.004	0.202	8.001
11.000	2.051	0.207	8.948
12.000	2.107	0.213	9.884
13.000	2.164	0.219	10.833
14.000	2.226	0.225	11.772
15.000	2.294	0.232	12.704
16.000	2.364	0.239	13.635
17.000	2.441	0.247	14.565
18.000	2.528	0.255	15.470
19.000	2.615	0.264	16.380
20.000	2.707	0.273	17.290
21.000	2.811	0.284	18.191
22.000	2.915	0.294	19.083
23.000	3.018	0.305	19.967
24.000	3.139	0.317	20.842
25.000	3.270	0.330	21.724

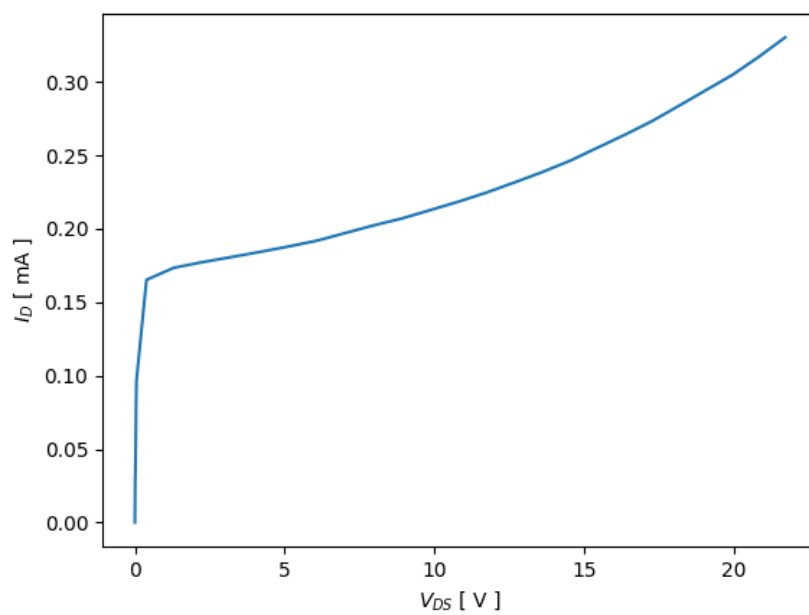


Figure 5: MOSFET I_D versus V_{DS} Plot

The I_D versus V_{DS} curve is quite close to what is expected. The curve starts off linear when it is in the saturation region. The increased drain voltage relative to the source voltage is similar to increasing the voltage drop over an Ohmic resistor with the channel acting as the resistor. The voltage and current follow a linear relationship. The steepness of the curve reflects the low channel resistance. However, at a certain point, the drain voltage V_D becomes very large relative to the gate voltage V_G . As a result, too many electrons flow to the drain, decreasing the channel's conductance and causing the curve to level off. The growth of the curve at the end is likely due to the very high voltage driving electrons to the drain as described above.