Experiment 6
Characterization of Bipolar Junction Transistors and MOSFETs

EECS 170A - Lab Bench #1
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1 Procedure

The objective of this lab is to determine the characteristics of bipolar-junction transistors (BJTs) and metal-oxide semiconductor field effect transistors (MOSFETs). The first part of the experiment involves building a circuit with a BJT. The voltage of the first source (V_1) is varied, and a plot of I_C against V_{BE} is ascertained. The second step is to vary V_2 and acquire a plot for I_C versus V_{CE}. The circuit is then changed by replacing the BJT with a MOSFET. The voltage of the first source is again varied, but this time a plot for I_D against V_{GS} is determined. A plot for I_D against V_{DS} is then acquired. More details on the implementation and measurements are included in each transistor's respective section.

2 Bipolar Junction Transistor (BJT)

The BJT is comprised of a linear array of three layers of extrinsic semiconductor materials with alternating types (NPN or PNP). The following figure aids with visualization of the physical structure of the BJT:

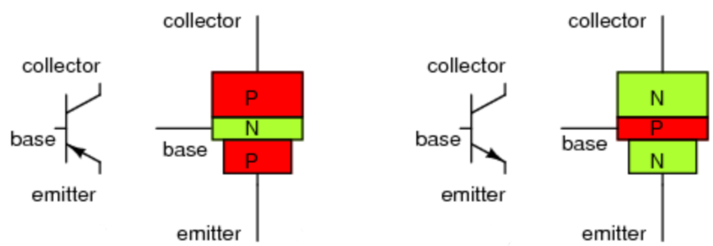


Figure 1: Schematic Symbol and Structure of PNP and NPN BJT

The three layers of semiconductor material form regions called the emitter, base, and collector. The three regions essentially form two semiconductor junctions that share a common thin base region. The emitter region has a significantly higher doping concentration than the other regions.

Charge generated in the BJT is caused by the diffusion of majority carriers from the emitter to base region. The charge carriers that passed from the emitter to the base are now the excess minority carriers of the region and they diffuse to the collector region due to the thin physical length of the base, which is assumed to be the same order of magnitude of the width of the depletion regions of the semiconductor junctions in the BJT. The thinness of the base layer is crucial so that carriers can diffuse across it much faster than the minority carrier lifetime of the base semiconductor material to prevent loss due to recombination. For a PNP BJT, holes from the p-type emitter diffuse to the n-type base and then diffuse to the p-type collector to generate the collector current across the BJT.

For an NPN BJT, electrons from the n-type emitter diffuse to the p-type base and then diffuse to the n-type collector to generate the collector current across the BJT. In this experiment, an NPN BJT, model MPSA06, is analyzed.

The charge generated by the NPN BJT is propagated by a forward bias applied across the base-emitter junction (V_{BE}) and a reverse bias applied across the base-collector junction (V_{CE}). For majority charge carriers (electrons) to overcome the depletion region at the base-emitter junction, a sufficiently large V_{BE} must be applied. At voltage values that are less than that threshold, the carriers cannot overcome the energy barrier at the depletion zone, and therefore the carrier current, I_C, is zero. This is referred to as the cut-off region. When the V_{BE} is above the threshold value, the energy barrier is lowered so that the electrons can diffuse from the emitter to base, thus turning on the junction. After the threshold value is met, increase in V_{BE} causes an exponential increase in I_C, much like the I-V behavior of a pn-junction diode.

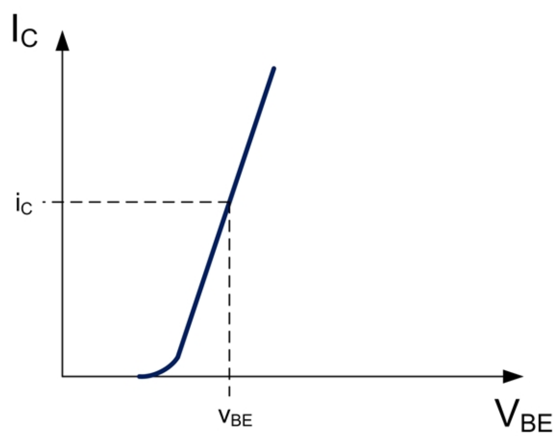


Figure 2: Expected I_C versus V_{BE} Curve for a NPN BJT

After the electrons from the emitter region diffuse to the base region, a sufficiently large voltage must be applied across the base-collector junction for the electrons to then diffuse from the base to the collector region. This voltage is referred to as V_C which is the same as V_{CE} because the emitter in our experimental schematic is grounded. A linear increase in I_C is expected for values of V_{CE} that are less than the amount of voltage in which V_{BE} has overtaken the threshold voltage. As V_{CE} continues to increase, the base region loses so many electrons that the conductivity of the base drops which effectively limits the increase in I_C and I_C is expected to reach a constant maximum beyond that threshold value. The region in which I_C increases linearly is referred to as the saturation region, as the biasing polarity of the collector-base junction is reversed when V_{CE} is lower than the threshold voltage value explained above. Increasing V_{BE} causes I_C to saturate at a larger current value.

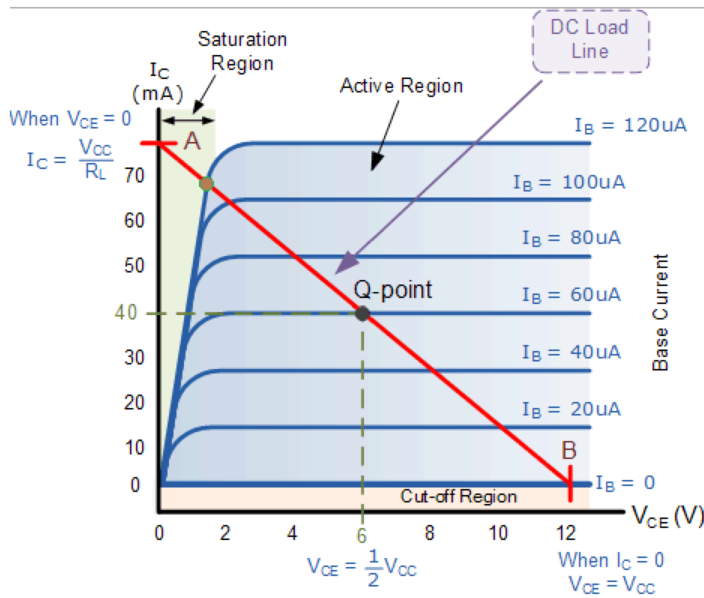
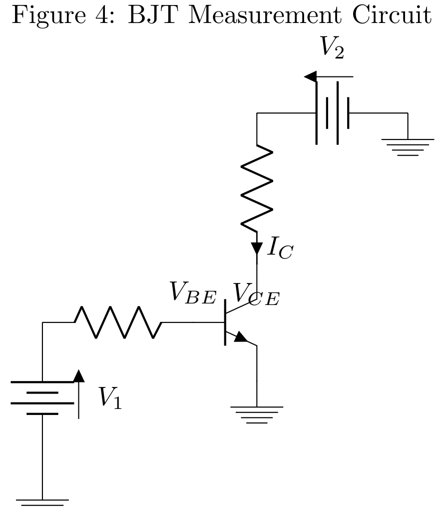


Figure 3: Expected I_C versus V_E Curve for a NPN BJT

The following circuit is used to measure and analyze the $I_C - V_{BE}$ and $I_C - V_{CE}$ curves:

Figure 4: BJT Measurement Circuit



The $I_C - V_{BE}$ plot is measured by fixing V_2 at 5V and sweeping V_1 from 0V to 5V. V_{BE} is measured by probing the base lead to the emitter lead (ground) of the BJT. The voltage across the resistor connected to the collector lead of the BJT is also probed so that I_C can be calculated from the voltages measured by the probe. I_C has a simple Ohmic relationship with the voltage across the resistor connected to the collector lead. The following values are tabulated following the configuration as described above:

Table 1: BJT I_C versus V_{BE} Data

$V_1[V]$	$V_{R2}[V]$	$I_C[mA]$	$V_{BE}[V]$
0.000	0.000	0.000	0.000
0.050	0.000	0.000	0.050
0.100	0.000	0.000	0.100
0.150	0.000	0.000	0.150
0.200	0.000	0.000	0.200
0.250	0.000	0.000	0.250
0.300	0.000	0.000	0.300
0.350	0.000	0.000	0.350
0.400	0.000	0.000	0.400
0.450	0.000	0.000	0.450
0.500	0.009	0.009	0.498
0.550	0.050	0.050	0.542
0.600	0.187	0.187	0.576
0.650	0.439	0.440	0.597
0.700	0.780	0.782	0.612
0.750	1.180	1.182	0.622
0.800	1.614	1.617	0.631
0.850	2.073	2.077	0.636
0.900	2.544	2.549	0.642
0.950	3.028	3.034	0.646
1.000	3.503	3.510	0.652
1.050	4.005	4.013	0.654
1.100	4.485	4.494	0.658
1.150	4.791	4.801	0.660
1.200	4.832	4.842	0.662
1.400	4.880	4.890	0.663
1.600	4.899	4.909	0.665
1.800	4.912	4.922	0.666
2.000	4.921	4.931	0.666
2.200	4.930	4.940	0.667
2.400	4.934	4.944	0.668
2.600	4.934	4.944	0.669
2.800	4.939	4.949	0.670
3.000	4.943	4.953	0.671
3.200	4.946	4.956	0.671
3.400	4.949	4.959	0.672
3.600	4.952	4.962	0.673
3.800	4.955	4.965	0.674
4.000	4.957	4.967	0.675
4.200	4.959	4.969	0.675
4.400	4.961	4.971	0.676
4.600	4.962	4.972	0.677
4.800	4.963	4.973	0.678
5.000	4.965	4.975	0.679

I_C has an Ohmic relationship with the voltage across the resistor connected to the collector, thus I_C is calculated using Ohm's law. The resistor connected to the collector is measured to be 0.998kΩ and the resistor connected to the base is 9.902kΩ. V_2 is fixed to 5V.

Subsequently, the following plot is generated from the values in Table 1:

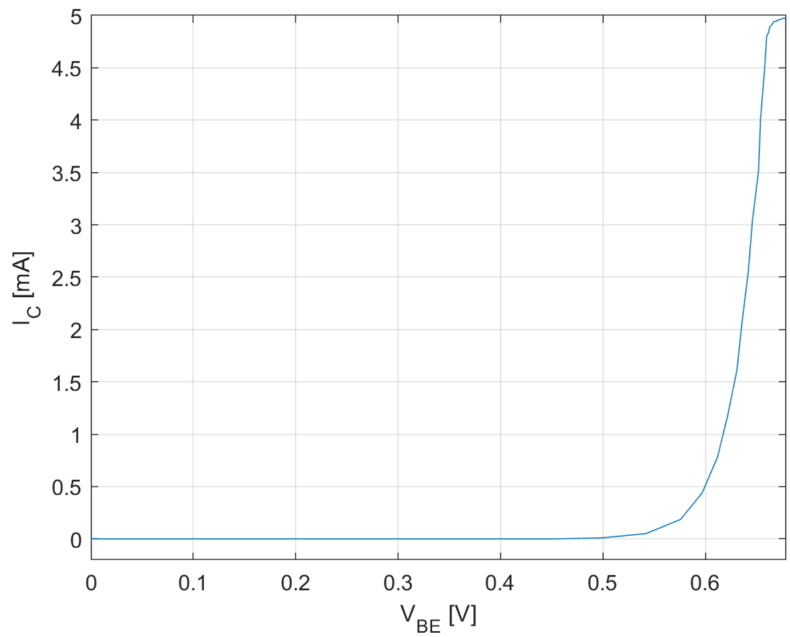


Figure 5: BJT I_C versus V_{BE} Plot

The $I_C - V_{BE}$ curve from the measured values above exhibit the expected behavior. The BJT is observed to turn on when V_{BE} reaches approximately 0.6V. This is consistent with the turn-on voltage of a typical pn-junction diode, which shares its physical composition with the base-emitter junction of the BJT. The curve is then observed to flatten when the V_{BE} becomes closer to V_{CE} as the saturation bias configuration is reached.

The $I_C - V_{CE}$ plot is measured by fixing V_1 at 1V and sweeping V_2 from 0V to 10V. V_{CE} is measured by probing the collector lead to the emitter lead (ground) of the BJT. The voltage across the resistor connected to the collector lead of the BJT is again probed so that I_C can be calculated from the voltages measured by the probe like before in the previous measuring configuration. The following values are tabulated following the configuration as described above:

Table 2: BJT I_C versus V_{CE} Data

$V_1[V]$	$V_{R2}[V]$	$I_C[mA]$	$V_{CE}[V]$
0.000	0.000	0.000	0.000
0.050	0.040	0.040	0.014
0.100	0.084	0.084	0.020
0.150	0.129	0.129	0.025
0.200	0.174	0.174	0.030
0.250	0.220	0.220	0.034
0.300	0.267	0.268	0.038
0.350	0.313	0.314	0.041
0.400	0.360	0.361	0.044
0.450	0.407	0.408	0.048
0.500	0.454	0.455	0.050
0.550	0.501	0.502	0.053
0.600	0.549	0.550	0.056
0.650	0.596	0.597	0.058
0.700	0.644	0.645	0.060
0.750	0.691	0.692	0.063
0.800	0.740	0.741	0.065
0.850	0.787	0.789	0.067
0.900	0.835	0.837	0.069
0.950	0.883	0.885	0.071
1.000	0.931	0.933	0.073
1.050	0.979	0.981	0.075
1.100	1.028	1.030	0.077
1.150	1.075	1.077	0.079
1.200	1.123	1.125	0.080
1.250	1.171	1.173	0.082
1.300	1.220	1.222	0.084
1.350	1.268	1.271	0.086
1.400	1.316	1.319	0.088
1.450	1.365	1.368	0.089
1.500	1.413	1.416	0.091
1.550	1.461	1.464	0.093
1.600	1.510	1.513	0.095
1.650	1.558	1.561	0.096
1.700	1.606	1.609	0.098
1.750	1.655	1.658	0.100
1.800	1.703	1.706	0.101
1.850	1.751	1.755	0.103
1.900	1.799	1.803	0.105
1.950	1.848	1.852	0.107
2.000	1.896	1.900	0.108
3.000	2.852	2.858	0.153
4.000	3.443	3.450	0.563
5.000	3.530	3.537	1.506
6.000	3.568	3.575	2.474
7.000	3.610	73.617	3.445
8.000	3.647	3.654	4.405
9.000	3.678	3.685	5.366
10.000	3.720	3.727	6.331

(V_1 is fixed at 1V.)

Subsequently, the following plot is generated from the values in Table 2:

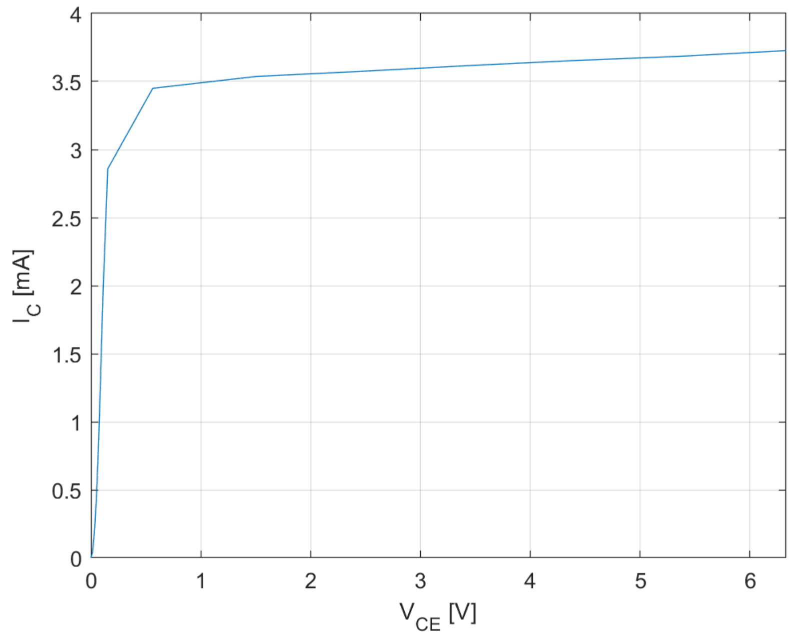


Figure 6: BJT I_C versus V_{CE} Plot

The $I_C - V_{BE}$ curve from the measured values above again exhibit the expected behavior. The BJT is observed to in the saturation region when V_{CE} is less than approximately 0.6V and I_C is observed to saturate at approximately 3.5mA and the active region is then observed.

3 Metal-Oxide Semiconductor Field Effect Transistor

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. 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 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):

$$\sigma = q(\mu_n n + \mu_p p) \tag{1}$$

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 (1).

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:

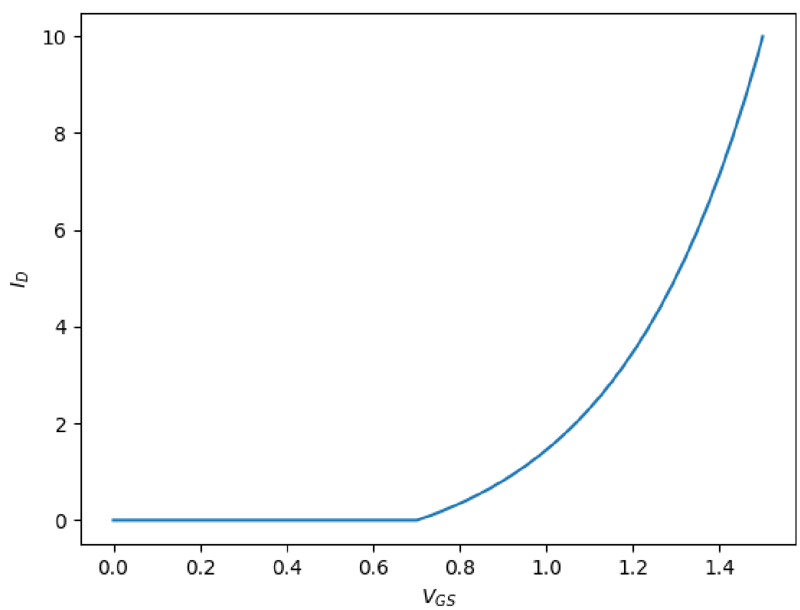


Figure 7: Expected I_D versus V_{GS} Curve for an n-Channel MOSFET

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. In integrated circuits, the channel width is small enough that the electrons are limited by velocity saturation, causing the same effect (2). This is known as the saturation region and occurs when $V_{GS} - V_{Th} < V_{DS}$ (3). 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.

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.

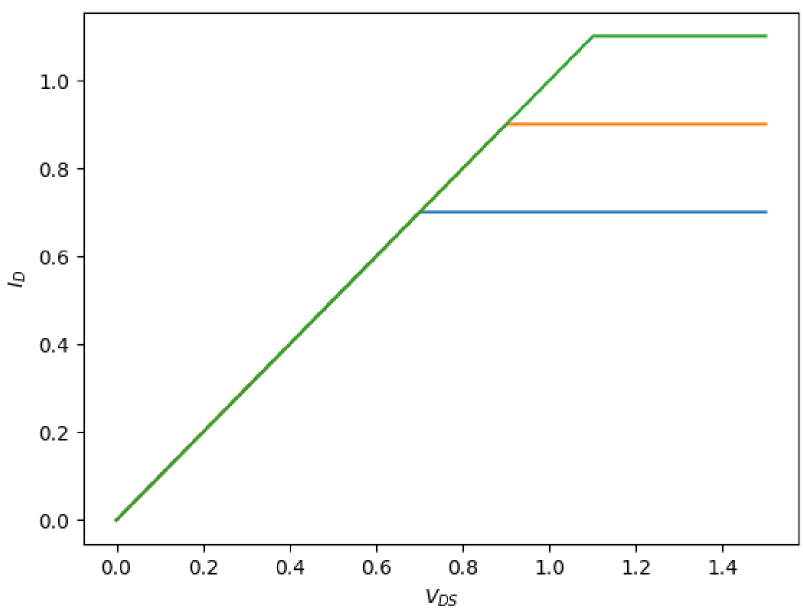


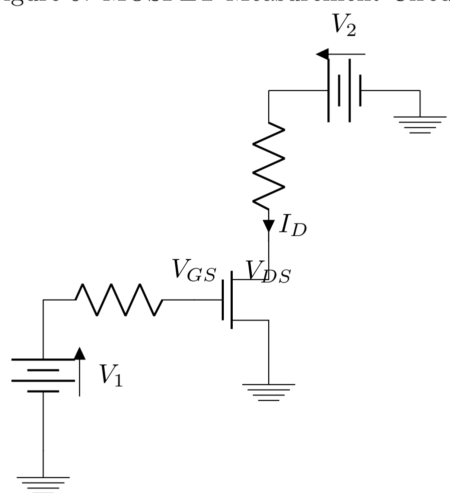
Figure 8: Expected I_D versus V_{DS} Curve for an n-Channel MOSFET

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 (9) is used to plot the MOSFET curves.

Figure 9: MOSFET Measurement Circuit



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.

Table 3: 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 0.998kΩ and the resistor connected to the gate is 9.902kΩ. V_2 is fixed to 10V.

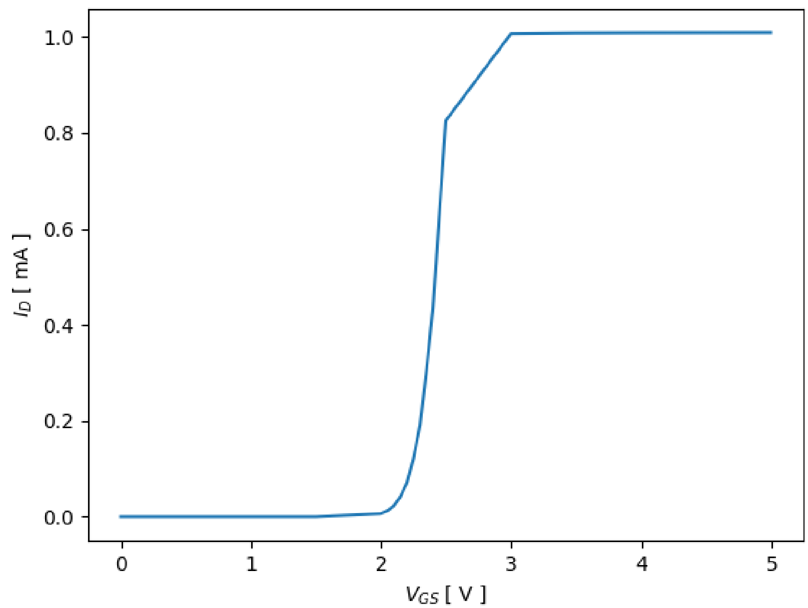


Figure 10: MOSFET I_D versus V_{GS} Plot

The plot in figure (10) 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 4: 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

V_1 is fixed at 2.3V.

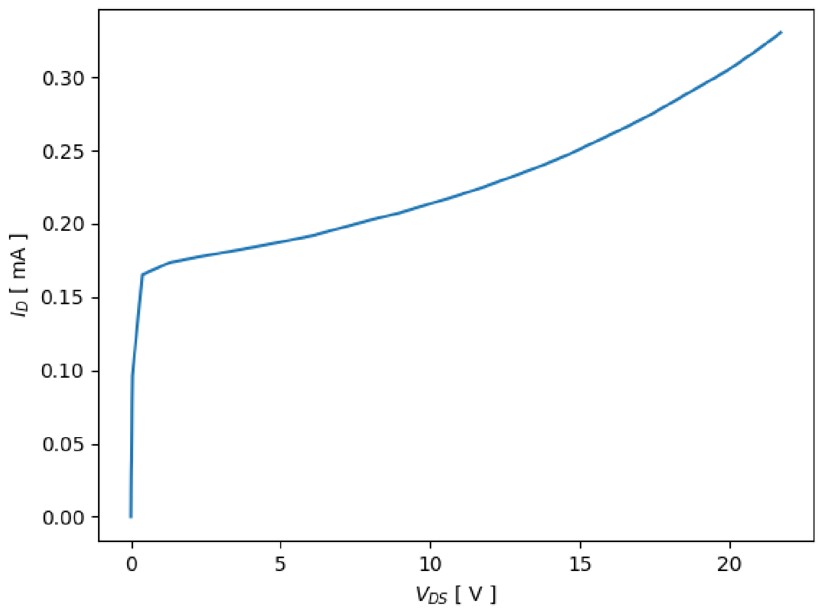


Figure 11: MOSFET I_D versus V_{DS} Plot

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.

Because V_1 is fixed at 2.3V, V_{GS} = 2.3V. The MOSFET operates in the triode region for $V_{DS} < V_{GS} - V_{Th} \approx 2.3$ V -2 V $= 0.3$ V assuming $V_{Th} \approx 2$ V. The triode region, though visible, is quite short lived due to the fact that $V_{GS} - V_{Th}$ is only greater than V_{DS} at the very beginning of the curve. As a result, it quickly enters the saturation region. Increasing V_{GS} would prolong the triode region and possibly flatten out the curve afterward.

4 Discussion

4.1 Bipolar Junction Transistor (BJT)

The $I_C - V_{BE}$ and $I_C - V_{CE}$ curves obtained from experimental measurements are very consistent with theoretically expected behavior for the NPN BJT. The cureves can potentially be smoothened by measuring more intermediate data points at the observed transitions between regions on the curve. This portion of the experiment quantifies the switching behavior of the NPN BJT and it is noted that it is very similar to that of the MOSFET despite fundamental differences in physical structure.

4.2 Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)

The I_D versus V_{GS} and I_D versus V_{DS} plots for the n-channel MOSFET are quite accurate to the ones predicted by theory. The only noticeable nonideality occurs when the MOSFET operates in the saturation region an exponential-like increasing curve. This is explained by the fact that V_{DS} becomes high enough to force electrons through the channel. Increasing V_{GS} is a potential way to get a more ideal curve because the linearity of the channel resistance can be maintained if enough electrons are in the channel. The experiment demonstrates the switching behavior of a MOSFET and its similarity to the behavior of a BJT, though the physical specification is different.

5 Appendix

The following script is used to generate the expected I_D versus V_{DS} curve for the MOSFET:

```
#!/usr/bin/python

import matplotlib.pyplot as plt
import numpy as np

first_half_1 = np.linspace( 0 , 0.7 , 100 )
second_half_1 = np.linspace( 0.701 , 1.5 , 100 )
first_half_1_id = first_half_1
second_half_1_id = [ 0.701 ] * len( second_half_1 )

first_half_2 = np.linspace( 0 , 0.9 , 100 )
second_half_2 = np.linspace( 0.901 , 1.5 , 100 )
first_half_2_id = first_half_2
second_half_2_id = [ 0.901 ] * len( second_half_2 )

first_half_3 = np.linspace( 0 , 1.1 , 100 )
```

```
second_half_3 = np.linspace( 1.101 , 1.5 , 100 )
first_half_3_id = first_half_3
second_half_3_id = [ 1.101 ] * len( second_half_3 )

v_gs_1 = np.concatenate( [ first_half_1 , second_half_1 ]
    )
id_1 = np.concatenate( [ first_half_1_id ,
    second_half_1_id ] )

v_gs_2 = np.concatenate( [ first_half_2 , second_half_2 ]
    )
id_2 = np.concatenate( [ first_half_2_id ,
    second_half_2_id ] )

v_gs_3 = np.concatenate( [ first_half_3 , second_half_3 ]
    )
id_3 = np.concatenate( [ first_half_3_id ,
    second_half_3_id ] )

plt.plot( v_gs_1 , id_1 )
plt.plot( v_gs_2 , id_2 )
plt.plot( v_gs_3 , id_3 )

plt.xlabel( "$V_{DS}$" )
plt.ylabel( "$I_{D}$" )
plt.savefig( "../images/id_vs_vds.PNG" )
```

The following script is used to generate the expected I_D versus V_{GS} curve for the MOSFET:

```
#!/usr/bin/python

import matplotlib.pyplot as plt
import numpy as np

first_half = np.linspace( 0 , 0.7 , 100 )
second_half = np.linspace( 0.701 , 1.5 , 100 )

first_half__id = [ 0 ] * len( first_half )
second_half__id = np.exp( 3*(second_half - 0.701) ) - 1

v_gs = np.concatenate( [ first_half , second_half ] )
_id = np.concatenate( [ first_half__id , second_half__id
    ] )

plt.xlabel( "$V_{GS}$" )
plt.ylabel( "$I_{D}$" )
```

```
plt.plot( v_gs , _id )
plt.savefig( "../images/id_vs_vgs.PNG" )
```

The following script is used to generate the tables and figures for the MOSFET:

```
#!/usr/bin/python

from common import *
import matplotlib.pyplot as plt

TABLES_DIR = "../tables/"
IMAGES_DIR = "../images/"
CSV_EXT = ".csv"
PNG_EXT = ".PNG"

PREC = 3
R1 = 0.998e3
R2 = 9.902e3

# MOSFET Circuit 1
mosfet_circuit_1_fname = "mosfet_id_vgs"
mosfet_circuit_1_data_fname = TABLES_DIR +
    mosfet_circuit_1_fname + CSV_EXT
mosfet_circuit_1_fig_fname = IMAGES_DIR +
    mosfet_circuit_1_fname + PNG_EXT
V2 = 10
V1 = [ 0 , 0.5 , 1 , 1.5 , 2 , 2.05 , 2.10 , 2.15 , 2.20
    , 2.25 , 2.30 , 2.35 , 2.40 , 2.45 , 2.5 , 3 , 3.5 , 4
    , 4.5 , 5 ] # 0 - 5V
Vr2 = [ 0 , 0 , 0 , 0 , 0.064 , 0.127 , 0.225 , 0.418 ,
    0.702 , 1.211 , 1.885 , 3.025, 4.314 , 6.309 , 8.172 ,
    9.965 , 9.978 , 9.983 , 9.985 , 9.987 ]
I_D = [ 1e3 * ( data_point / R2 ) for data_point in Vr2 ]
Vgs = [ 0 , 0.500 , 0.999 , 1.500 , 1.999 , 2.05 , 2.100
    , 2.150 , 2.20 , 2.25 , 2.30 , 2.35 , 2.40 , 2.45 ,
    2.498 , 2.998 , 3.497 , 3.996 , 4.497 , 4.996 ]

plt.plot( Vgs , I_D )
plt.xlabel( "$V_{GS}$ [ V ]" )
plt.ylabel( "$I_D$ [ mA ]" )
plt.savefig( mosfet_circuit_1_fig_fname )
plt.clf( )

data_matrix_mosfet_1 = []
for row_count in range( 0 , len( V1 ) ) :
        row = [ V1[ row_count ] , Vr2[ row_count ] , I_D[
            row_count ] , Vgs[ row_count ] ]
```

```
        data_matrix_mosfet_1.append( [ set_precision_str(
            data_point , PREC ) for data_point in row ] )
data_matrix_mosfet_1_headings = [ "$V_1$ [ V ]" , "$V_{R2
    }$ [ V ]" , "$I_D$ [ mA ]" , "$V_{GS}$ [ V ]" ]
data_matrix_mosfet_1 = [ data_matrix_mosfet_1_headings ]
    + data_matrix_mosfet_1
write_csv_from_matrix( mosfet_circuit_1_data_fname ,
    data_matrix_mosfet_1 )

# MOSFET Circuit 2
mosfet_circuit_2_fname = "mosfet_id_vds"
mosfet_circuit_2_data_fname = TABLES_DIR +
    mosfet_circuit_2_fname + CSV_EXT
mosfet_circuit_2_fig_fname = IMAGES_DIR +
    mosfet_circuit_2_fname + PNG_EXT
V1_2 = 2.3
V2_2 = [0, 0.1 , 0.2, 0.3, 0.4 , 0.5 , 0.6 , 0.8, 0.9, 1,
     2, 3, 4, 5, 6 ,7 ,8 ,9, 10, 11 ,12, 13, 14, 15 , 16 ,
     17 , 18 , 19 , 20 , 21 , 22 , 23 , 24 , 25 ]
Vr2_2 = [ 0 , 0.1 , 0.197 , 0.294 , 0.389 , 0.485 , 0.579
     , 0.768 , 0.860 , 0.954 , 1.636 , 1.717 , 1.755 ,
    1.789 , 1.824 , 1.861 , 1.901 , 1.953 , 2.004 , 2.051
    , 2.107 , 2.164 , 2.226 , 2.294 , 2.364 , 2.441 ,
    2.528 , 2.615 , 2.707 , 2.811 , 2.915 , 3.018 , 3.139
    , 3.270 ]
I_D_2 = [ 1e3 * ( data_point / R2 ) for data_point in
    Vr2_2 ]
Vds = [0, 0.004 , 0.007 , 0.012 , 0.021 , 0.026 , 0.031 ,
     0.038 , 0.045 ,0.052, 0.388, 1.300, 2.256, 3.217,
    4.177, 5.144, 6.108, 7.055, 8.001, 8.948, 9.884,
    10.833, 11.772, 12.704, 13.635, 14.565, 15.470,
    16.380, 17.290, 18.191, 19.083, 19.967, 20.842,
    21.724]

plt.plot( Vds , I_D_2 )
plt.xlabel( "$V_{DS}$ [ V ]" )
plt.ylabel( "$I_D$ [ mA ]" )
plt.savefig( mosfet_circuit_2_fig_fname )

data_matrix_mosfet_2 = []
for row_count in range( 0 , len( V2_2 ) ) :
        row = [ V2_2[ row_count ] , Vr2_2[ row_count ] ,
            I_D_2[ row_count ] , Vds[ row_count ] ]
        data_matrix_mosfet_2.append( [ set_precision_str(
            data_point , PREC ) for data_point in row ] )
data_matrix_mosfet_2_headings = [ "$V_2$ [ V ]" , "$V_{R2
```

```
    }$ [ V ]" , "$I_D$ [ mA ]" , "$V_{DS}$ [ V ]" ]
data_matrix_mosfet_2 = [ data_matrix_mosfet_2_headings ]
    + data_matrix_mosfet_2
write_csv_from_matrix( mosfet_circuit_2_data_fname ,
    data_matrix_mosfet_2 )
```

6 References

1. https://coefs.uncc.edu/dlsharer/files/2012/04/J3b.pdf
2. https://inst.eecs.berkeley.edu/~ee40/su05/lectures/lecture13.pdf
3. Lab manual