Portland State
UNIVERSITY

DEPARTMENT OF ELECTRICAL
AND COMPUTER ENGINEERING

ECE 515: SPRING 2023 - SECOND PROJECT
FUNDAMENTALS OF SEMICONDUCTOR DEVICES

DEVICE CHARACTERIZATION

MOSFETS

PROF. MALGORZATA CHRZANOWSKA-JESKE

MOHAMED GHONIM

06/09/2023

Table of Contents

Introduction:

This project is a continuation of our study into the characteristics of semiconductor devices, focusing on the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). In the previous project, I delved into the characterization of the PN-Junction using Excel. While Excel provided a good starting point for data analysis, the limitations of the software became evident, especially when dealing with large data sets and complex calculations. Therefore, in this project, I decided to transition to MATLAB. MATLAB's advanced functionalities provide us with greater control over our analysis, and its efficient coding environment allows us to process our data more effectively. Furthermore, the reusable nature of MATLAB scripts allows us to extend this work to other devices and conditions, paving the way for rapid and adaptable device characterization. I have attached an appendix with all the MATLAB code used in this lab.

Part I: MOSFET CHARACTERISTICS

1- Output characteristics of the MOSFET

[20 pts] Use the data given in "Id-Vd" file to graph the output characteristics of the MOSFET. This is a plot of I_D vs. V_{DS} with V_{GS} a as parameter, like Figure 6-9/10 in Streetman.

a. [10 pts] The data include I_D vs. V_{DS} values for nine values of V_{GS} parameter. Please use at least five of them to draw nice curves. (Please notice that I_D do not exceed 100mA and try to include one curve with very low currents.) Plot the characteristics using your favorite tool (Excel, Matlab, …)

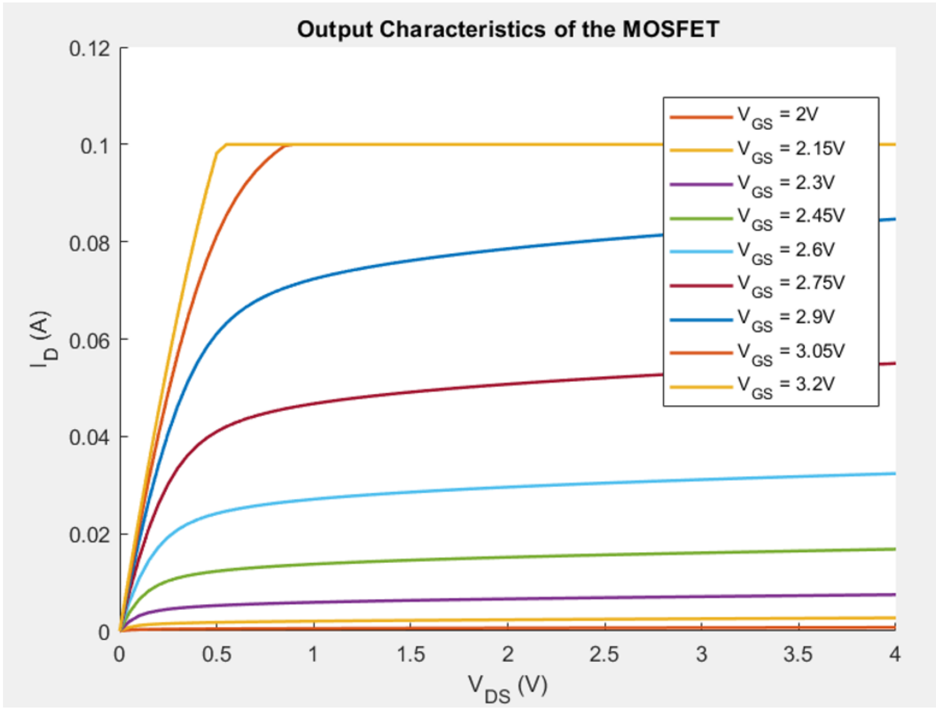


Figure 1 MOSFET I_D vs. V_DS Characteristics

b. [10 pts] Obtain a rough estimate of V_T from this graph using two different techniques. This means using visual observation and a ruler, rather than fitting a curve. Explain your techniques in one or two sentences.

Two possible techniques for obtaining a rough estimate of V_T from this graph using visual inspection:

a. Threshold Crossing Technique: Visually observe the V_{GS} value at which the I_D (Drain current) starts to increase significantly for the first time. This V_{GS} value will be a rough estimate of V_T (Threshold Voltage). This technique is based on the definition of V_T as the V_{GS} at which the MOSFET starts conducting.

The first time I_D starts increasing significantly is when we apply $V_{GS} = 2.15V$, the yellow curve on my plot above. Suggesting that the threshold voltage is in this 2.15V range.

b. Onset of Saturation Technique:

- Choose a curve in the I_D vs. V_{DS} plot for a V_{GS} above the anticipated V_T. (A plot for which we have a drain current Id (not in cut off))
- Identify the point where this curve shifts from linear to saturation (where I_D increase lessens with V_{DS}).
- Record the V_{DS} at this point, then calculate V_T by subtracting this V_{DS} from the corresponding V_{GS}.

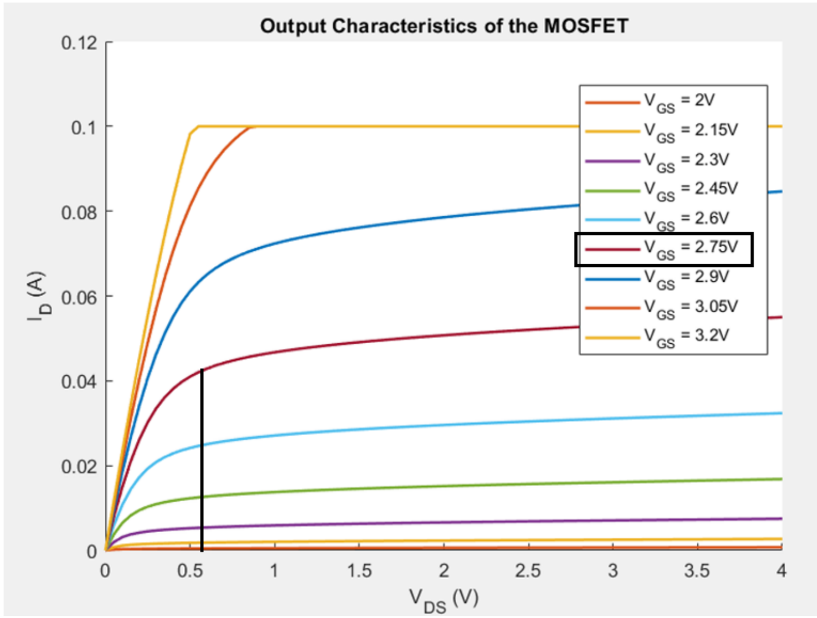


Figure 2 Looking at the onset of saturation for Vgs = 2.75V to estimate Vt

If I look at the curve where $V_{GS} = 2.75V$, I notice that the onset of saturation happens roughly at $V_{DS} = 0.6V$. I now know V_{DS} and V_{GS} for this curve and I know that $V_{DS} = V_{GS} - V_T$ at this point. Hence, we have:

$$0.6V = 2.75 - V_T, V_T = 2.75 - 0.6V = 2.15V$$

Of course, these are rough estimates and may not give a precise value for V_T as they are based on visual observation.

2- Transfer characteristics of the MOSFET

[20 pts] Obtain *the transfer characteristics* of the MOSFET for two different drain voltages. This is a plot of I_D vs. V_{GS} with V_{DS} as a parameter, like, Figure 6.28 in Streetman.

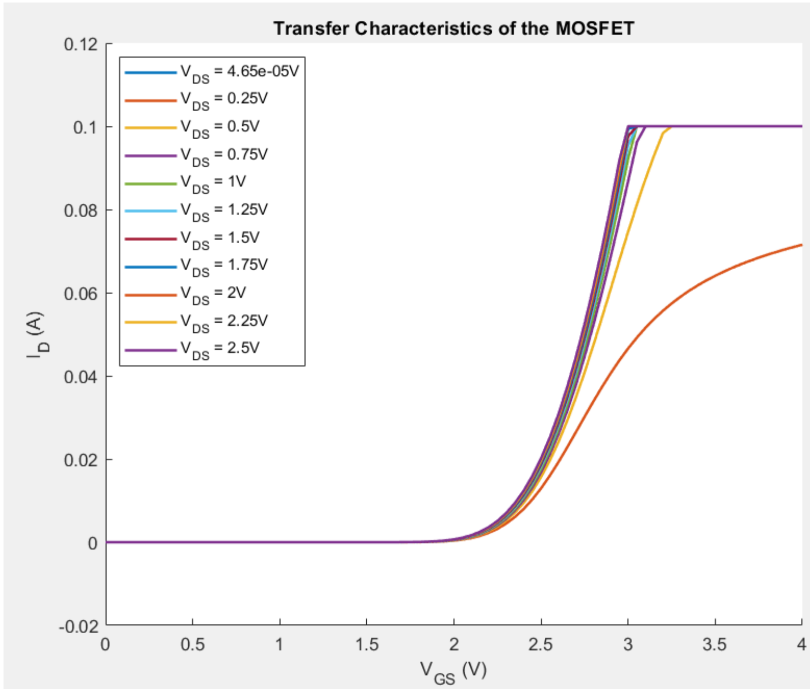


Figure 3 MOSFET I_D vs. V_GS transfer characteristics. All the drain voltages

In figure 3, I plotted all the drain voltages. The graph is very busy though, so I'll pick two drain voltages and focus on them in figure 4. I picked $V_{DS} = 0.25V$ for the linear region analysis, and $V_{DS} = 2.25V$ for the saturation region analysis.

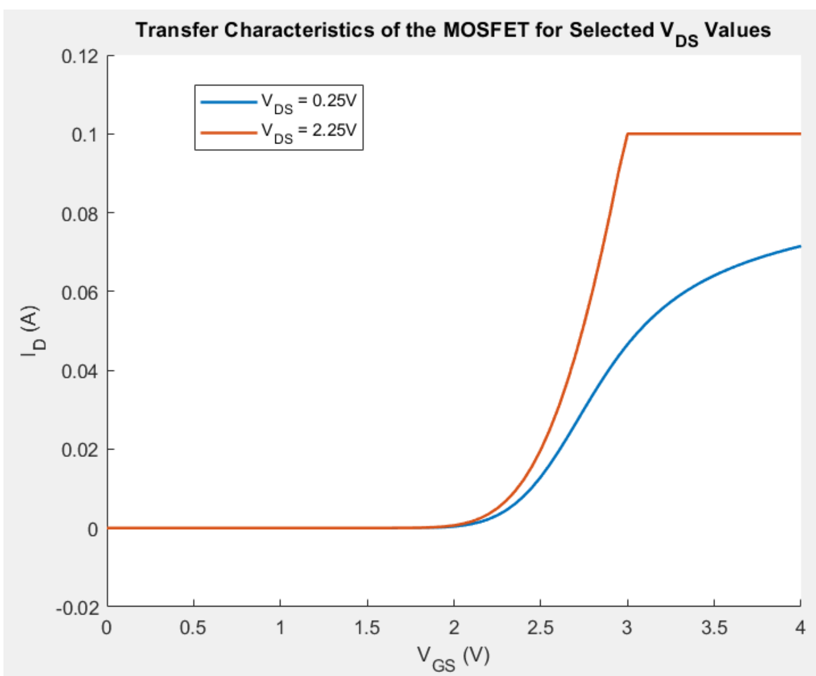


Figure 4 MOSFET I_D vs. V_GS transfer characteristics at Drain Voltages V_DS =0.25V and 2.5V

a. [10 pts] Using the output characteristics above choose two different values of V_{DS} so that you obtain one measurement plot in saturation and one plot in the linear region. Explain those choices.

I will choose $V_{DS} = 0.25V$ for the linear region, and $V_{DS} = 2.5V$ for the saturation region.

In a MOSFET, the operation mode is determined by the relative values of V_{DS} (Drain-Source voltage), V_{GS} (Gate-Source voltage), and V_T (Threshold voltage).

Saturation Region: In the saturation region (or active region), $V_{DS} \geq (V_{GS} - V_T)$. This means the Drain-Source voltage is larger than the difference between the Gate-Source voltage and the Threshold voltage. In this region, the Drain current (I_D) is largely independent of V_{DS}. Hence, to select a V_{DS} value that ensures the MOSFET operates in saturation, I selected a relatively high value of V_{DS} such that it is greater than $(V_{GS} - V_T)$ for the entire range of V_{GS} values. Looking at the I_D vs. V_{GS} plot, a V_{DS} value that is higher than the entire range of V_{GS} would be a good choice, so here I chose $V_{DS} = 2.5V$.

Linear Region (or Ohmic Region): In the linear region, $V_{DS} < (V_{GS} - V_T)$This means the Drain-Source voltage is less than the difference between the Gate-Source voltage and the Threshold voltage. In this region, the Drain current (I_D) is proportional to V_{DS}. To ensure the MOSFET operates in the linear region, I selected a relatively low value of V_{DS} such that it is less than $(V_{GS} - V_T)$ for the entire range of V_{GS} values. Looking at the I_D vs. V_{GS} plot, a V_{DS} value that is lower than all (or most of) the V_{GS} values would be a good choice. so here I chose $V_{DS} = 0.25V$.

b. [5 pts] Plot the characteristics. Note that in saturation you will want to plot the square root of I_D. Explain why this is a good choice.

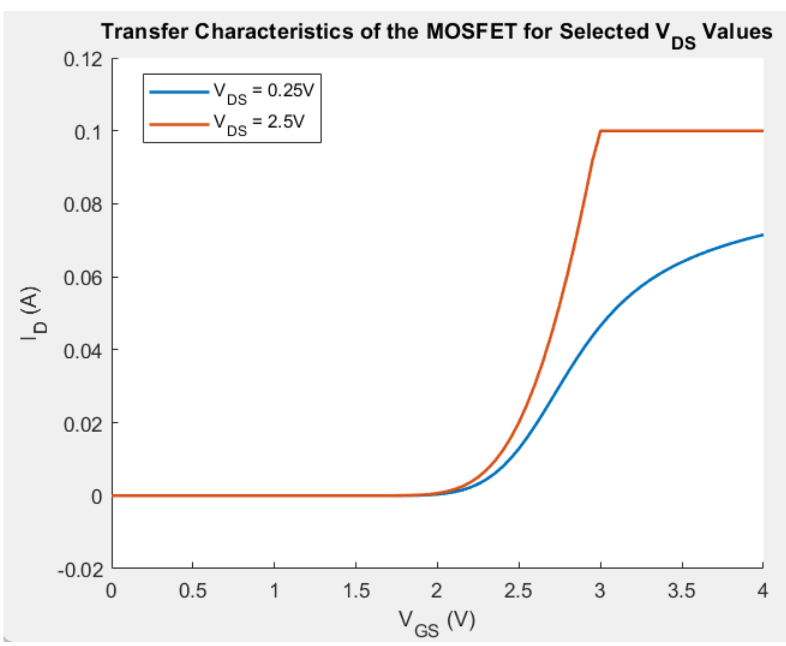


Figure 5 MOSFET I_D vs. V_GS transfer characteristics at Drain Voltages V_DS =0.25V and 2.5V

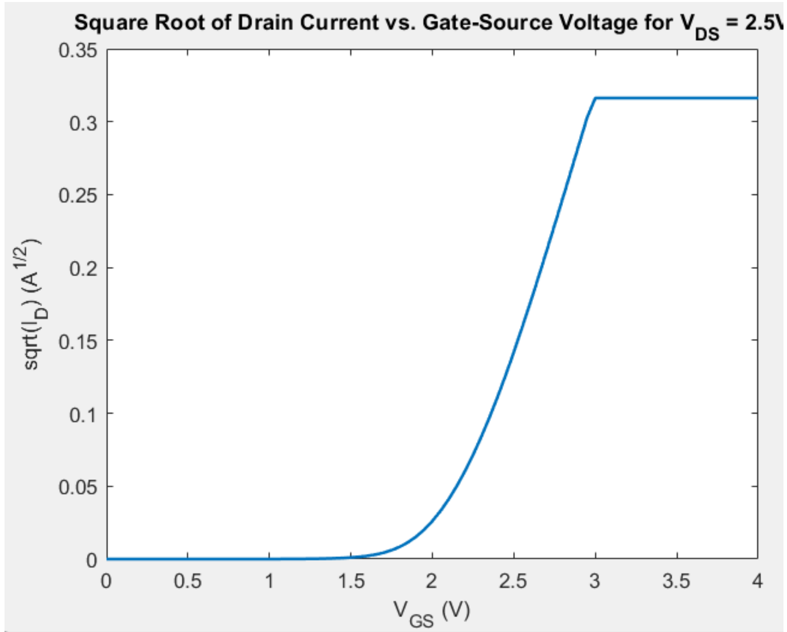


Figure 6 MOSFET $\sqrt{I_D}$ vs. V_GS transfer characteristics at Drain Voltages V_DS =0.25V and 2.5V

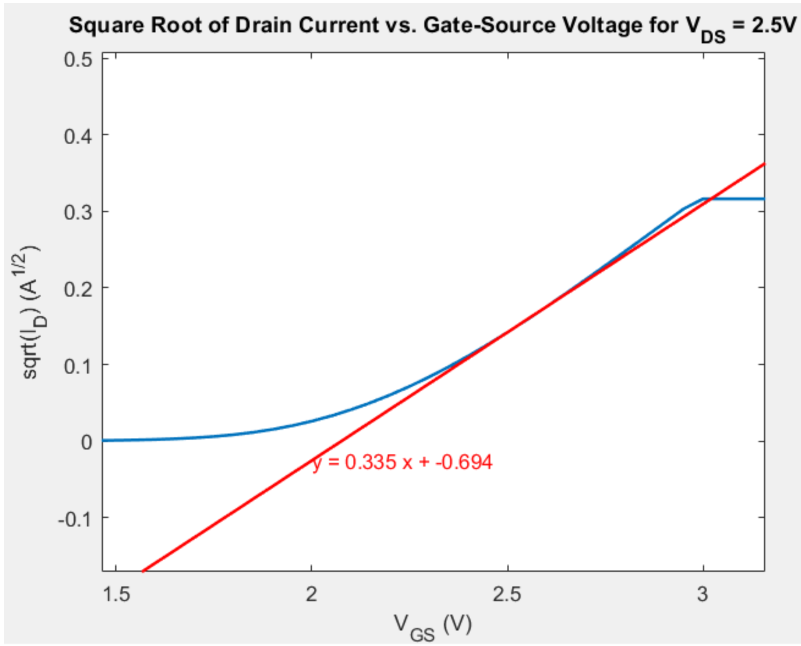
Plotting the square root of I_D in saturation is a good choice because the I-V characteristics of a MOSFET in saturation obey the square law. According to this law, the drain current (I_D) is proportional to the square of the overdrive voltage $(V_{GS} - V_T)^2$. Therefore, taking the square root of I_D linearizes this relationship, which simplifies analysis and visualization.

If we rewrite the equation for I_D in the saturation region, we have:

$$\sqrt{I_D(sat)} = \sqrt{\frac{k_N}{2}} \times (V_{GS} - V_T)$$

This equation shows that $\sqrt{I_D}$ should be a linear function of V_{GS} in the saturation region, making it easier to identify the threshold voltage (V_T) and the transconductance parameter (k) from the graph.

c. [5 pts] Obtain estimates of the threshold voltage, V_T, in the linear and the saturation regions. Do they agree? (You can do this manually using the graph and using a ruler, or by using some functions in your favorite software.)




```
The estimated threshold voltage
(x-axis intersection of the asymptote) is: 2.0754 V
```

Figure 7 Asymptotic/linear estimation of Vt in the saturation region with Vds=2.5V

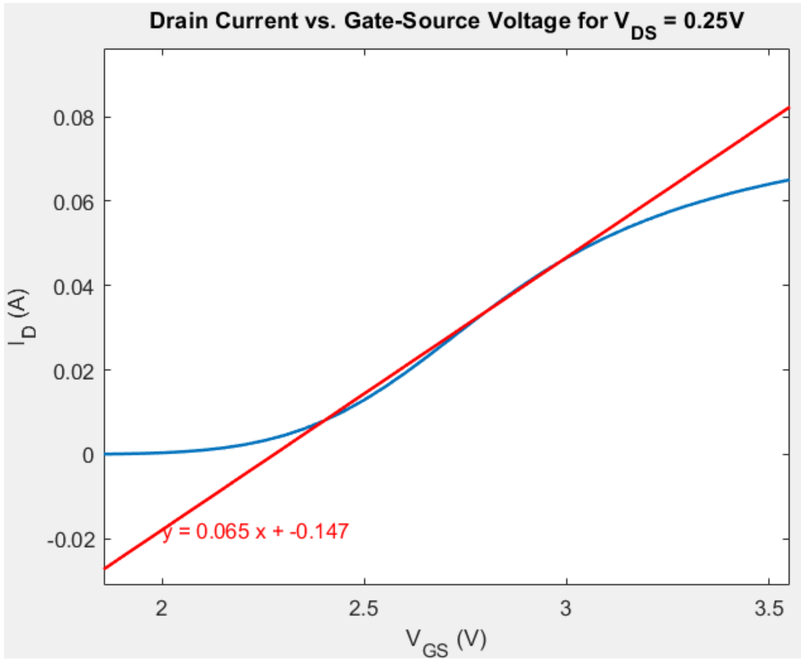
As shown in Figure 7, I used $V_{DS} = 2.5V$ for the saturation region, and drew an asymptote line in the "quasi linear" region and found the line equation to be $y = 0.335x - 0.694$, and we know that:

$$\sqrt{I_D(sat)} = \sqrt{\frac{k_N}{2}} \times (V_{GS} - V_T), \qquad \text{here } y = \sqrt{I_D(sat)}, \qquad \text{and } x = V_{GS}$$

We know that Kn is not zero, therefore when $\sqrt{I_D(sat)} = 0$, $(V_{GS} - V_T)$ *has to be* 0, which means that $V_{GS} = V_T$ at this point, by translating this to the line equation we have:

$$0 = 0.335x - 0.694, \qquad \therefore x = V_{GS} = V_T = \frac{0.694}{0.335} = 2.07V$$

Which is the same value approximate by MATLAB as shown below the plot above.




```
The estimated threshold voltage
(x-axis intersection of the line) is: 2.2763 V
```

Figure 8 Asymptotic/linear estimation of Vt in the linear region with Vds=0.25V

As shown in Figure 8, I used $V_{DS} = 0.25V$ for the linear region, and drew an asymptote line in the "quasi linear" region and found the line equation to be $y = 0.065x - 0.147$, and we know that:

$$I_D(\text{linear}) = k_N\left[(V_{GS} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2\right], \qquad \mu_n C_{ox}\frac{W}{L} = k_N$$

We know that Kn is not zero, therefore when $I_D = 0$, $(V_{GS} - V_T)$ has to be 0, which means that $V_{GS} = V_T$ at this point, by translating this to the line equation we have:

form $y = mx + b$, where m is the slope, x is the independent variable (V_{GS} in our case), b is the y-intercept, and y is the dependent variable (I_D in our case), we can calculate V_T as:

$$0 = 0.065x - 0.147, \qquad \therefore x = V_{GS} = V_T = -\frac{b}{m} = \frac{0.147}{0.065} = 2.26\,V$$

Which is a very close value to the approximate by MATLAB as shown below the plot above.

Comment:

$$\text{Saturation}, \quad V_{DS} = 2.5V, \quad V_T = 2.0754V$$

$$\text{Linear}, \quad V_{DS} = 0.25V, \quad V_T = 2.2763V$$

After conducting an analysis of the threshold voltage, V_T, in both the saturation and linear regions of the MOSFET's I-V characteristics, it is noted that the estimated values for V_T are in close agreement. Specifically, a threshold voltage of approximately 2.0754V was obtained from the saturation region plot with $V_{DS} = 2.5V$, and a slightly higher value of around 2.2763V was estimated from the linear region plot with $V_{DS} = 0.25V$.

It is important to recognize that these estimations of V_T, although slightly different, are generally consistent, demonstrating the expected behavior of the MOSFET in these two regions. However, a certain degree of sensitivity is evident in this analysis, as the estimated V_T is significantly influenced by the specific data points chosen to draw the line of fit or asymptote in the plot. This is inherent in the method of graphical estimation and serves as a reminder of the necessity for careful selection of representative points when using this approach.

Moreover, it's noteworthy to mention the phenomenon observed in short channel length MOSFETs. As per the discussion in Section 6.5.10, due to effects such as drain-induced barrier lowering (DIBL), the threshold voltage in the saturation region, VT(sat.), can be lower than that in the linear region, VT(lin.). This is in line with the obtained results, which showed a slightly lower VT(sat.) as compared to VT(lin.)

3- Extracting parameters from the transfer characteristics

[10 pts] From the transfer characteristics in the linear and saturation regions, extract ($\mu_n C_{ox}$) and the threshold voltage, V_T, for this MOSFET. "Extract" means to use your knowledge of the model Equations 6-49/54 from Streetman (Equations 10-62/67 from Neamen) to fit a line to one of your transfer curves. The modeled slope should allow you to calculate $\mu_n C_{ox}$. Note that we cannot separate the mobility from the oxide capacitance using this data. Are your extracted values of V_T close to your previous estimates? Summarize your results in a table.

To extract the parameters $\mu_n C_{ox}$ and V_T from the transfer characteristics, we will use the MOSFET's I-V equations. The drain current I_D in the linear and saturation regions can be expressed by the following equations, respectively:

Linear Region [Equation 6-49 from Streetman, 10-62 from Neamen]

$$I_D(\text{linear}) = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2\right], \qquad \mu_n C_{ox}\frac{W}{L} = k_N$$

The textbook uses Z for the width, and Ci for the oxide capacitance. I'm more used to using W for the width and Cox, and I'll keep using those notations, but they're equivalent to the book notation/equation.

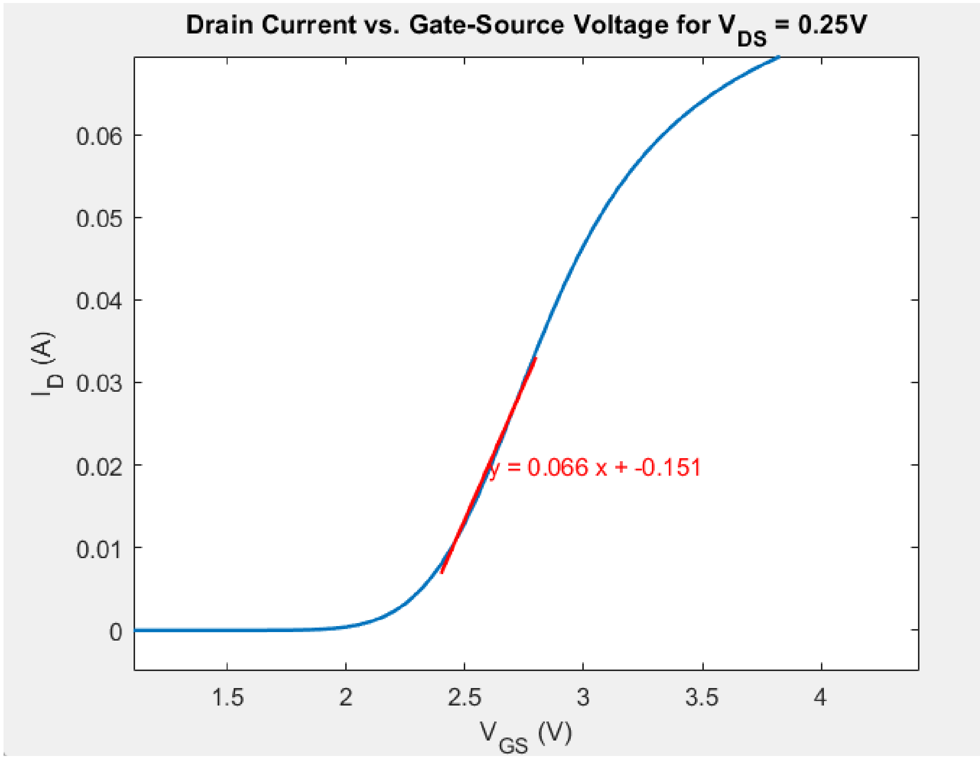
Saturation Region [Equation 6-54 from Streetman, 10-67 from Neamen]

$$I_D(\text{sat}) = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_T)^2, \qquad \frac{\mu_n C_{ox}}{2}\frac{W}{L} = \frac{k_N}{2}$$

From these equations, we see that in the linear region, the slope of the I_D vs V_{DS} curve is proportional to $\mu_n C_{ox}$, and in the saturation region, the slope of the $\sqrt{I_D}$ vs V_{GS} curve is proportional to$\sqrt{\mu_n C_{ox}}$.

We can fit a line to the data points in each region to estimate the slopes and intercepts. From the slopes, we can estimate $\mu_n C_{ox}$, and from the intercepts, we can estimate V_T.

$$\text{Given in the project,} \qquad L = 1.5\mu m, \qquad W = 46.5\mu m, \qquad \therefore \frac{W}{L} = \frac{46.5\mu m}{1.5\mu m} = 31$$




```
The estimated threshold voltage (x-axis intersection of the line) is: 2.2956 V
The estimated μnCox product (from the slope of the line) is: 0.0084662 A/V^2
```

Figure 9 Id vs Vgs Characteristics with asymptotic slope to estimate μn Cox and Vt in the linear region with Vds =0.25V

Here I called $\mu_n C_{ox}\frac{W}{L} = k_N$, I can ignore V_{DS}^2 here since V_{DS} is very small in the linear region, in this case it's 0.25V, so V_{DS}^2 will be even smaller 0.0625V, therefore.

$$I_D(\text{linear}) \approx K_N[(V_{GS} - V_T)V_{DS}] \approx K_N[(V_{GS} - V_T)V_{DS}] = K_N V_{GS} V_{DS} - K_N V_T V_{DS}$$

So here the slope the line gives $K_N V_{DS}$

From the plot generated above, I found the slope to be $0.066 = K_N V_{DS}$

$$\therefore \frac{0.066}{V_{DS}} = K_N, \qquad \frac{0.066}{0.25V} = K_N = 0.264\frac{A}{V^2} = \mu_n C_{ox}\frac{W}{L}$$

$$\mu_n C_{ox} = \frac{0.264}{31} = 0.008516\frac{A}{V^2}, \qquad \text{or } 0.0084662\frac{A}{V^2} \text{ as estimated by MATLAB}$$

$$\text{To estimate } V_T, \qquad \text{I can use the x} - \text{intersection of the linear fit by setting } I_D = 0$$

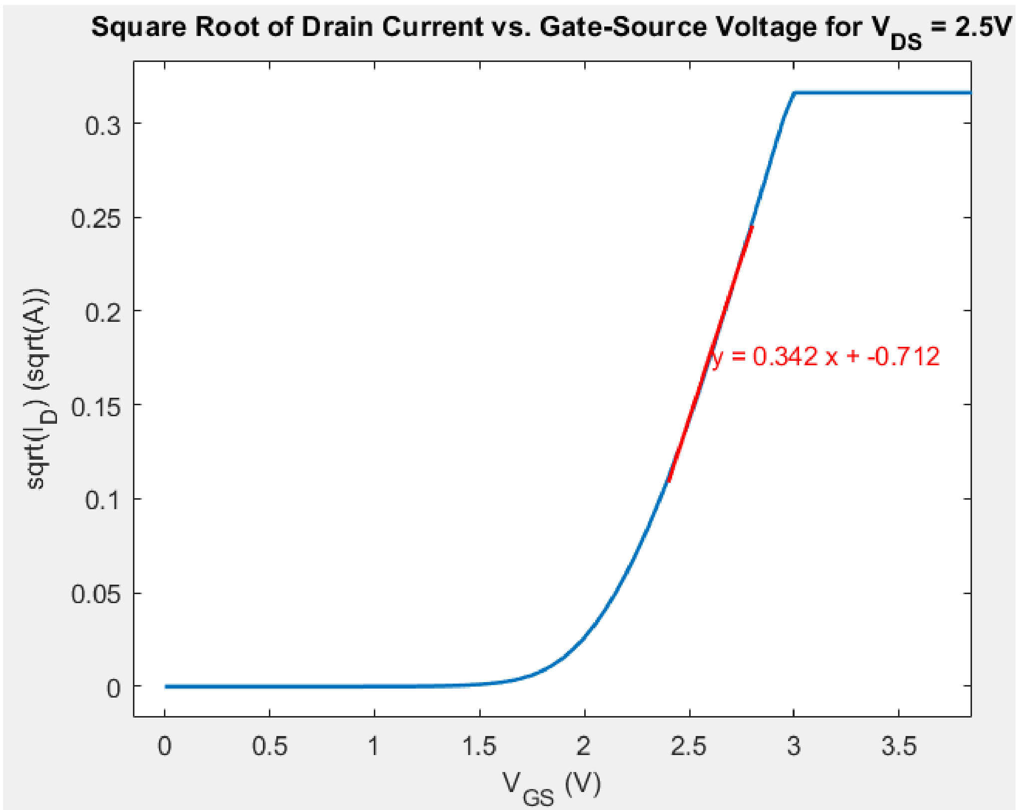
$$I_D(\text{linear}) = 0 \approx K_N V_{GS} V_{DS} - K_N V_T V_{DS}, \qquad V_{GS} = V_T, \qquad \text{when } I_D = 0$$

So, I can either extend the linear fit to interpret the x-axis and find the interception as done in part 2 above, or I'll use the linear fit's equation to find V_T as such:

In the linear region:

From the line equation of the form $y = mx + b$, where m is the slope, x is the independent variable (V_{GS} in our case), b is the y-intercept, and y is the dependent variable (I_D in our case), we can calculate V_T as:

$$V_T = -\frac{b}{m} = -\frac{(-0.151)}{0.066} = 2.2878V, \qquad \text{or 2.2956 as estimated by MATLAB}$$




```
The estimated threshold voltage (x-axis intersection of the line) is: 2.082 V
The estimated μnCox product (from the slope of the line) is: 0.0075427 A/V^2
```

Figure 10 $\sqrt{I_d}$ vs Vgs Characteristics with asymptotic slope to estimate μn Cox and Vt in the saturation region with Vds =2.5V

$$\text{here we have,} \qquad \sqrt{I_D(sat)} = \sqrt{\frac{k_N}{2}} \times (V_{GS} - V_T) = \sqrt{\frac{k_N}{2}} V_{GS} - \sqrt{\frac{k_N}{2}} V_T$$

So here the slope of the linear fit gives $\sqrt{\frac{k_N}{2}} = 0.342$

$$\frac{K_N}{2} = (0.342)^2 = 0.116964, \qquad K_N = 0.233928 = \mu_n C_{ox} \frac{W}{L}$$

$$\mu_n C_{ox} = \frac{0.233928}{31} = 0.007546 \frac{A}{V^2}, \qquad \text{or } 0.0075427 \frac{A}{V^2} \text{ as estimated by MATLAB}$$

So, I can either extend the linear fit to interpret the x-axis and find the interception as done in part 2 above, or I'll use the linear fit's equation to find V_T as such:

In the saturation region:

In the saturation region, the relationship between the square root of the drain current and the gate-source voltage is linear. The equation of this line, of the form $y = mx + b$, can be rearranged to solve for the threshold voltage, V_T, as:

$$V_T = -\frac{b}{m} = -\frac{(-0.712)}{0.342} = 2.0818V, \qquad \text{or } 2.082\text{as estimated by MATLAB}$$

	Linear region $V_{DS} = 0.25V$	Saturation $V_{DS} = 2.5V$
$\mu_n C_{ox}$ (A/V^2)	0.0084662	0.0075427
V_T (V) Rough estimate (Question1)	2.15V	2.15V
V_T (V) from the line equation	2.2956	2.082
V_T (V) from the x-intercept	2.2763V	2.0754

The table presents the results of the MOSFET characterization for the linear region ($V_{DS} = 0.25V$) and the saturation region ($V_{DS} = 2.5V$). It provides values for $\mu_n C_{ox}$, which represents the product of the electron mobility and oxide capacitance, and the threshold voltage, V_T, derived in two ways: from the line equation and as the x-intercept of the fitted line.

Observations from the table:

a) The $\mu_n C_{ox}$ value is higher in the linear region compared to the saturation region. This difference could be due to various factors, including the impact of channel length modulation in the saturation region, which effectively reduces the channel's "effective length," and hence the conductivity.
b) The V_T estimates from the line equation are in close proximity to the V_T estimates derived from the x-intercept for both the linear and saturation regions. This consistency suggests a robust analysis method.
c) The threshold voltage, V_T, appears to be higher in the linear region than in the saturation region. This discrepancy can be attributed to short-channel effects such as Drain Induced Barrier Lowering (DIBL), which can cause V_T to be lower in the saturation region.

4- Parameters in Saturation. Measurements vs Theoretical plots.

[15 pts] First some context for this assignment: in an ideal case, we would have one model and one set of parameter values that would describe our transistor across all biases and modes of operation. However, that is not the case, and we often have to use models that are accurate only within some range of values or certain region so that parameters for the linear region will differ from the ones for saturation. So, which one should we use? That depends on the application – suppose you are trying to design a class A amplifier. Which region would you try to model with the greatest accuracy? Keeping this in mind, here is the actual assignment. Use the parameters that you would use for Class A amplifier design in an I-V model and compare graphically with the output and both transfer curves.

For a class A amplifier, I would try to model the saturation (Active) region with the greatest accuracy. This is because in a class A amplifier, the input signal is amplified over the full cycle of operation. The MOSFET must remain in the saturation region for the entire signal cycle, and so the model for this region is the most relevant for class A amplifier design.

a. [10 pts] Use equation 6-49 from Streetman as your starting point for the model. Then put your calculated numbers from above into this model and plot it on the same graphs (output and both transfer) with the measured data. Use only the one set of parameter values from Part 3 you chose for the Class A amplifier.

Now, let's take the parameters extracted from the saturation region and plug them into the I-V model (Equation 6-49 from Streetman) to see how well it fits the output and transfer characteristics data.

$$I_D = \bar{\mu}_n \frac{W}{L} C_i \left[(V_G - V_T)V_D - \frac{1}{2} V_D^2 \right], \qquad \text{and,} \qquad I_D = \bar{\mu}_n \frac{W}{L} C_i \left[(V_G - V_T)V_{D\_SAT} - \frac{1}{2} V_{D\_SAT}^2 \right]$$

where, $V_{D\_SAT} = V_G - V_T$, I'll use the extracted parameters below in the saturation region to try to model the saturation region, and I'll use MATLAB to perform the analysis.

The parameters I used are:

$$\mu_n C_{ox} = 0.0075427 \left(\frac{A}{V^2}\right)$$

$$V_T = 2.082V$$

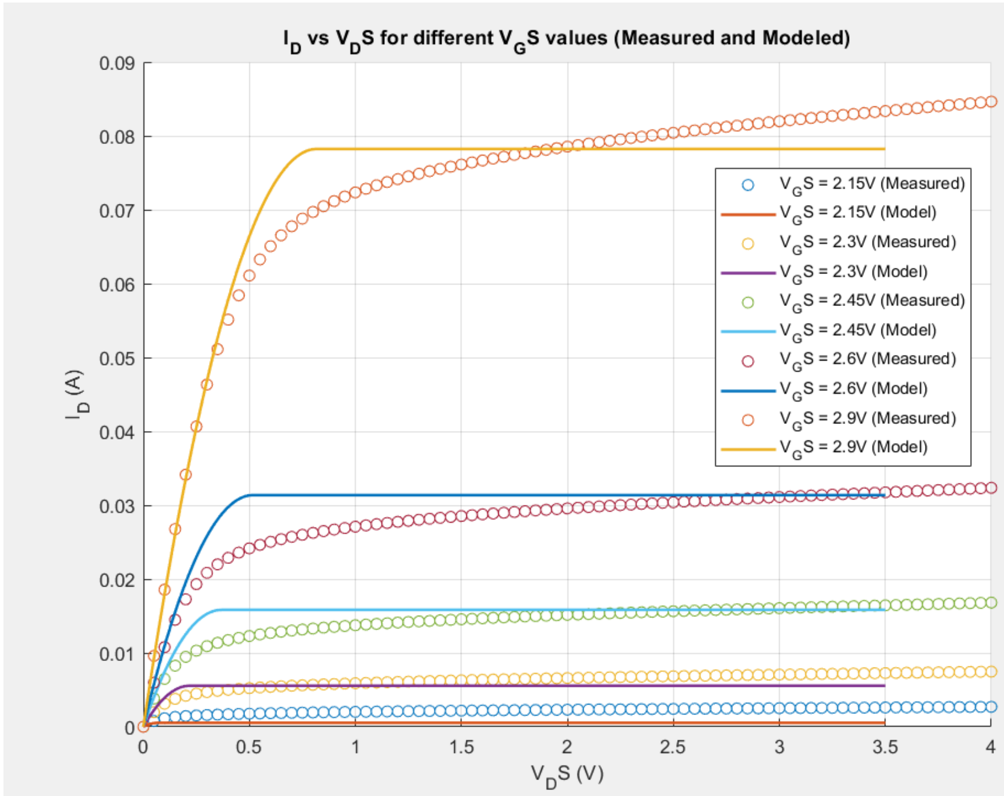


Figure 11 Output Characteristics Id Vs VdS for Vgs =2.15V, 2.13V, 2.45V, 2.6, etc Measured and modeled values

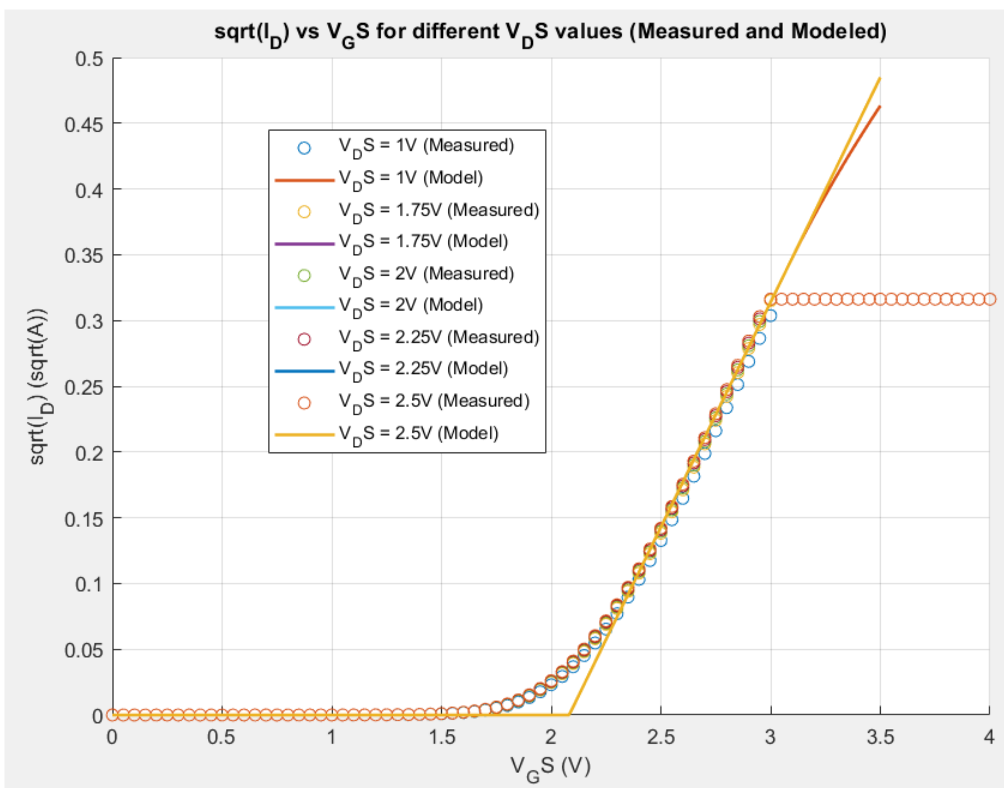


Figure 12 Transfer Characteristics Id Vs Vgs for Vds =1V, 1.75, 2V, 2.25V, 2.5V Measured and modeled Values

b. [5 pts] If the model fits the output characteristics data (Part 1) well with parameters based on the transfer data (Part 3) we have good confirmation of the validity of the model. Discuss your results in several sentences. Does the model fit the data well? If not, why not? Do you have possible explanations?

The model seems to fit the measured data quite well at lower values of gate-source voltage V_{GS}. This suggests that the assumptions underlying the model, such as the inversion layer charge distribution and gradual channel approximation, are fairly accurate for this range of operation. However, as V_{GS} increases beyond 2.9V, the discrepancy between the model and the measured data starts to become more pronounced. This may be due to factors not considered in the basic I-V model, like velocity saturation and high field effects.

An important observation is the flat saturation region in the modeled data, contrasting with the upward trend in the measured data. The discrepancy could be attributed to channel length modulation, an effect not taken into account in the simple I-V model. Channel length modulation results in an increase of the drain current with increasing drain-source voltage even in the saturation region due to the shortening of the channel length at higher drain-source voltages.

As for the $\sqrt{I_D}$ vs V_{GS} plot, the model fits the measured data well in the saturation region, with the modeled curves overlapping. This is expected, as the MOSFET is designed to operate in the saturation region for these gate-source voltage values. The highest drain-source voltage value we have is 2.5V, and the model stops working well at around V_{GS} =3V, where the device transitions from the saturation region to the linear (triode) region.

Lastly, the inclusion of a curve for $V_{DS} = 1V$, while less relevant to the saturation behavior, provides a valuable comparison point, showcasing the different behaviors in the linear and saturation regions. It gives more depth to our understanding of the model and its range of validity.

In conclusion, the simple I-V model provides a good starting point for analyzing MOSFET behavior, but it is important to remember its limitations and the range of its validity. As we've seen, effects like channel length modulation and high field effects can significantly affect the device characteristics, particularly at high gate-source and drain-source voltages.

PART II: MOSFET IN SUBTHRESHOLD REGION

5- Graphing and analyzing the subthreshold characteristics

[30 pts] Use the data given in "Id-Vg" file to graph the subthreshold characteristics, that is I_D vs V_{GS} for $V_{DS} = 2V$. Focus in on V_{GS} values that are near the threshold voltage (above & below.)

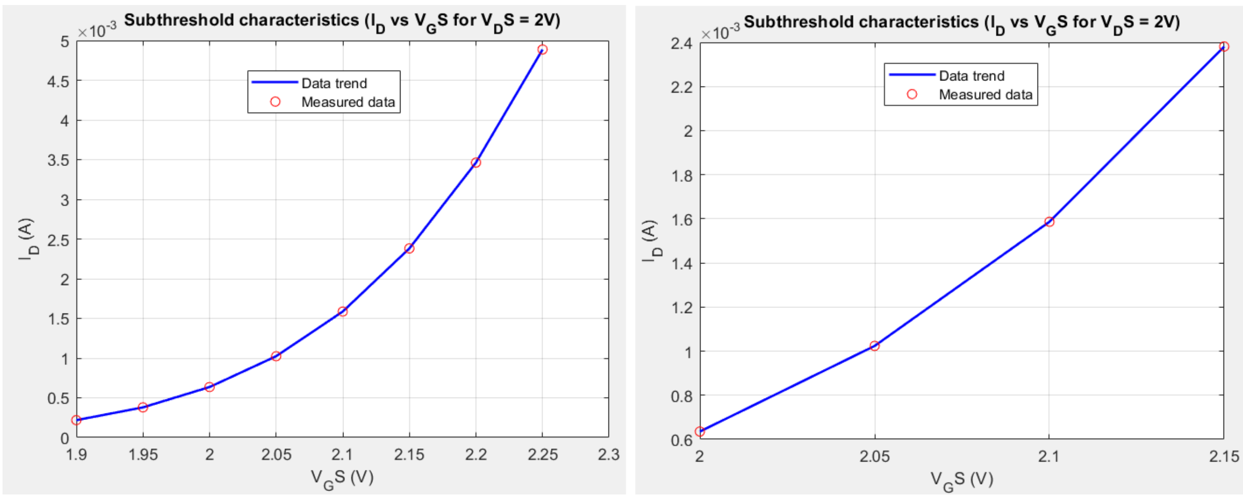


Figure 13 Plot of Id vs Vgs around the threshold voltage the plot on the right is zoomed in the region from Vgs 2 to 2.15V

a. [10 pts] Plot these characteristics as $\log_{10} I_D$ vs V_{GS} (like Streetman Fig 6-38.)

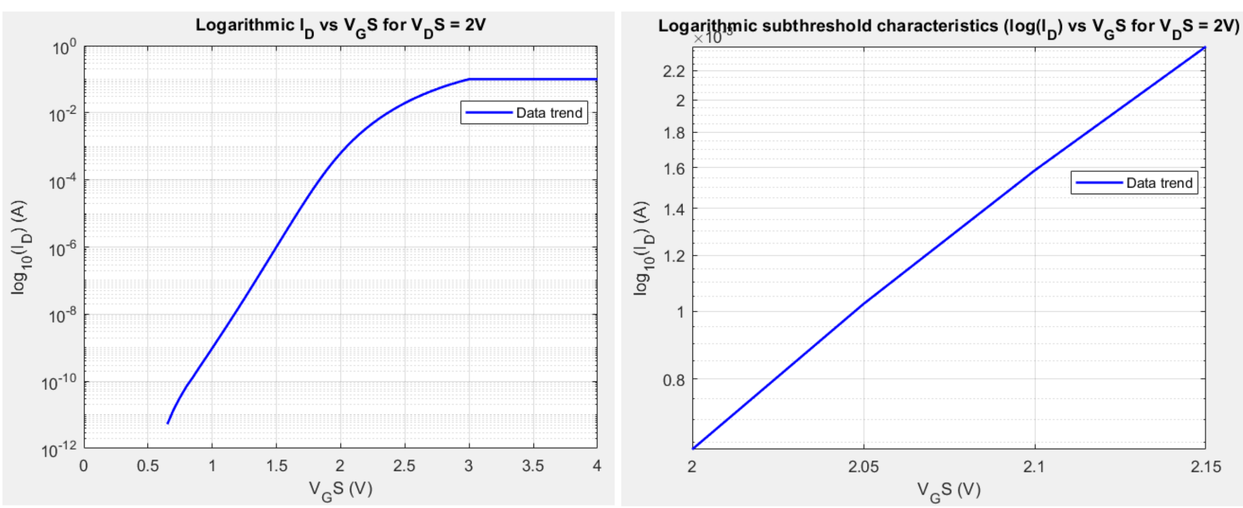


Figure 14 Plot of log10(Id), vs Vgs, the plot on the right is zoomed in the region from Vgs 2 to 2.15V

b. [5 pts] For the full equation and explanation see (Streetman2 Section 6.5.7, Eqn 6-65.). Equations are also given below. All of the constants can be lumped into one constant I_{OFF}.

$$I_D(sub) = \mu(C_d + C_i)\frac{Z}{L}\left(\frac{kT}{q}\right)^2\left(1 - \exp\left(-\frac{qV_D}{kT}\right)\right)\exp\left(\frac{q(V_G - V_T)}{c_r kT}\right)$$

Where Z is the channel width

$$I_D = I_{OFF}\exp\left(\frac{qV_G}{c_r kT}\right), \qquad \text{where } c_r = \left[1 + \frac{C_d + C_{it}}{C_i}\right], \qquad C_i \text{ is the gate capacitance}$$

C_d is the (sub-threshold) depletion capacitance in the channel, and

C_{it} is the "fast interface state" capacitance.

Subthreshold "Slope" S is defined by $S = 2.3\frac{kT}{q}c_r$

simplified version of the equation 6-65 is given in Neaman Section 11.1.1 and Eqn 11.1.

$$I_D(sub) \sim \left(1 - \exp\left(-\frac{qV_D}{k}\right)\right)\exp\left(\frac{q(V_G)}{kT}\right)$$

What will happen to the exp (V_D) term for our choice of $V_D = 2V$? Explain.

The exponential function exp(x) approaches zero as x approaches negative infinity, and approaches one as x approaches zero. Given that q, k, and T are constants, as V_D increases, the value of $-(qV_D)/kT$ will decrease and hence the expression $\exp(-(qV_D)/kT)$ will approach 1.

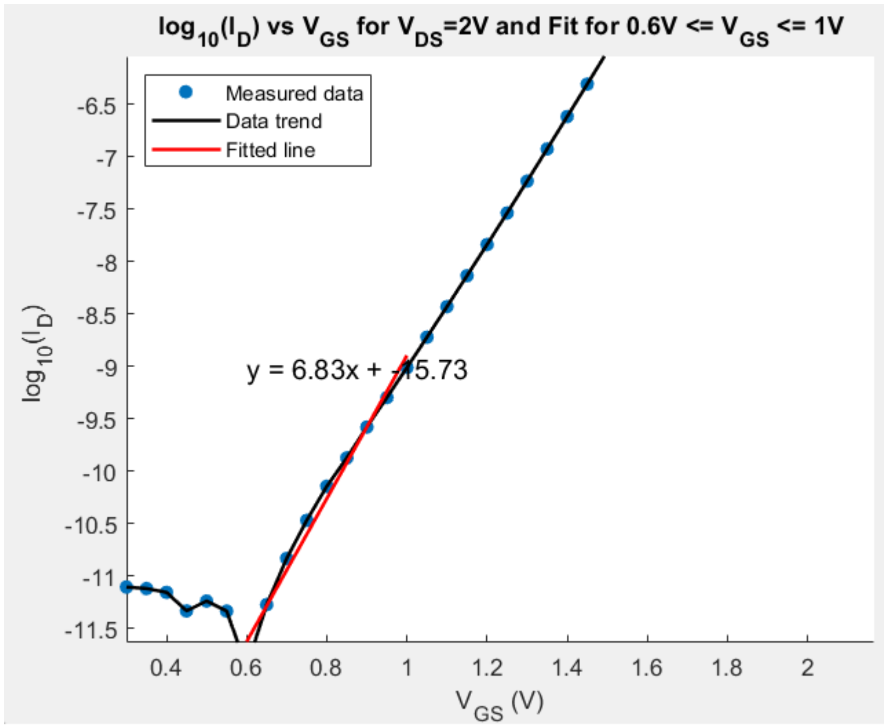
Therefore, when V_D is 2V, it's reasonable to expect this term to be close to 1.

This means that the term $(1 - \exp(-(qV_D)/kT))$ will approach 0, thereby reducing the impact of V_D on the subthreshold current. This occurs because, in the subthreshold region, the transistor is effectively 'off' and the channel is weak, meaning the impact of the drain voltage on the drain current is significantly diminished.

Thus, with $V_D = 2V$, the drain current in the subthreshold region is largely dependent on the gate voltage V_G and less dependent on the drain voltage V_D . This explains why the subthreshold current is usually expressed with an exponential dependence on the gate-source voltage $(V_G - V_T)$, as the impact of the drain voltage becomes negligible in this regime.

Of course, this analysis assumes that the thermal voltage (kT/q) is significantly less than the drain-to-source voltage V_D. If this condition is not met, then the exponential term might not be negligible, and its impact should be considered.

c. [10 pts] Calling S a “slope” is a misnomer; its proper name is “inverse slope” of $\log_{10} I_D$ vs V_G but it is commonly labeled as “subthreshold slope” in the literature. S is measured in V/decade, and it tells us how much increase in voltage is needed to increase current by one decade. Using your data and the equation above, fit a curve which will allow you to calculate your subthreshold slope, S, and hence c_r. Explain your procedure.




```
Subthreshold slope, S = 0.1367 V/decade
The parameter c_r = 2.2964e+00
```

Figure 15 Plot of log10(Id), vs Vgs, with an asymptote before the threshold voltage to estimate the “subthreshold slope”

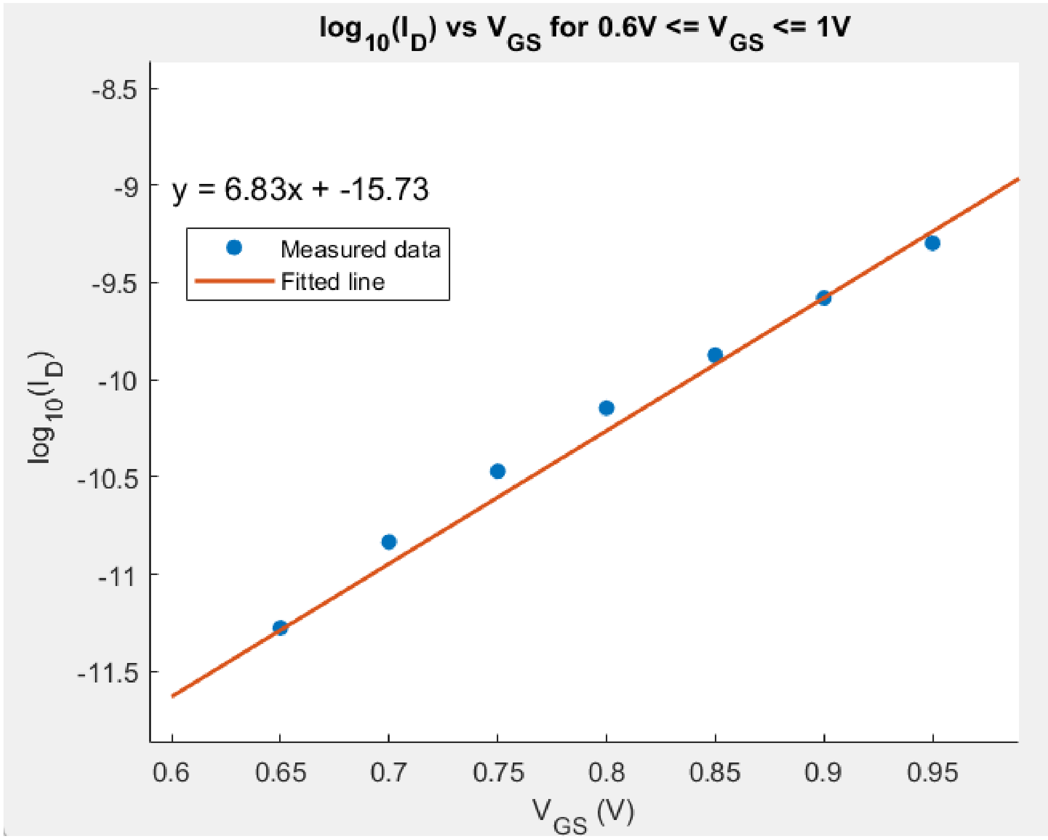
The values under the plot above are the subthreshold slope, S and cr as calculated by MALTAB.

I noticed that the linear fit/asymptote is very sensitive to the points I choose. I tried different linear fits over the range of $V_{GS} < V_T$ and got different values for S. The line drawn in figure 15 shows the region over which I drew the linear fit.

$$S = \frac{1}{\text{slope}} = \frac{1}{6.83} = 0.146 \frac{\text{V}}{\text{decade}}$$

the MATLAB code gave S=0.1367 V/decade, which is possibly more accurate because MATLAB considers more figures.

$$S = 2.3\frac{kT}{q}c_r, \qquad c_r = \frac{S}{2.3 \times 0.0259} = \frac{0.1367}{2.3 \times 0.0259} = 2.295$$




```
Subthreshold slope, S = 0.1367 V/decade
The parameter c_r = 2.2964e+00
```

Figure 16 Plot of log10(Id), vs Vgs, with an asymptote before the threshold voltage to estimate the "subthreshold slope". This plot is zoomed in between Vgs = 0.6 and 0.95V

To extract the subthreshold slope (S) and the parameter c_r, we start by analyzing the data for the drain current (I_D) versus the gate-source voltage (V_{GS}) for a specified value of the drain-source voltage (V_{DS}). This data provides us with an empirical transfer curve for the MOSFET.

In the subthreshold region (where the gate-source voltage is less than the threshold voltage), the MOSFET exhibits exponential behavior. To linearize this exponential relationship, we plot I_D on a logarithmic scale against V_{GS}, yielding a straight line in the subthreshold region.

We then perform a linear regression analysis (fit a straight line So, when we perform a linear fit to this data, the "subthreshold slope" (S) is the inverse of the slope of the fitted line. This is because S, measured in V/decade, is defined as how much increase in voltage (V_{GS}) is required to increase the current (I_D) by a factor of 10 (one decade). This inverse relationship is what provides the exponential increase in current with voltage in the subthreshold region.

Thus, after fitting the straight line to the log-transformed data in the subthreshold region, we take the inverse of the slope of this fitted line to get S. With the value of S, we then calculate the parameter c_r, which encapsulates multiple physical properties of the MOSFET. This process allows us to extract valuable parameters that describe the behavior of the MOSFET in its subthreshold operating region.

D. [5 pts] Comment on the effect of oxide thickness on subthreshold slope. How would you improve S? (Hint: “improving” means decreasing S in value.)

The subthreshold slope (S) is a key performance metric in a MOSFET, with smaller values being desirable for faster transistor operation. S is influenced by the thickness of the gate oxide layer, with thinner oxide leading to a smaller S, as it allows for better control of the gate over the channel.

However, there's a limit to how thin the oxide can be, as too thin can lead to gate tunneling, increasing leakage current. To improve (decrease) S, while avoiding excessive thinning, alternative methods can be used, like using high-k dielectric materials for the gate oxide or employing device architectures like FinFETs for better gate control over the channel.

6- Project Feedback

[5 pts] Feedback: Please give feedback on the project. Was this project instructive? Did you experience major problems or frustrations with measurements, understanding the instructions, or completing the assignment? Any suggestions for improving the instructions, or the project itself?

The project was indeed very instructive. It provided a valuable opportunity to apply the theoretical knowledge about MOSFET characteristics to real-life scenarios. Analyzing and interpreting the provided data was particularly educational, as it gave me a better understanding of the behavior of MOSFETs under different voltage conditions.

The biggest challenge was comprehending the complex relationship between the parameters and understanding the mathematics involved, especially concerning the subthreshold region. However, this also served as an excellent learning opportunity, as it pushed me to explore and research more about these aspects of MOSFET operation.

In conclusion, even though the project took a good amount of time to complete, I found it very enriching and beneficial. It helped deepen my understanding of MOSFETs, and I truly appreciate the knowledge and skills gained through this hands-on experience.

Conclusion:

In conclusion, this project has provided a detailed exploration into the behavior and properties of MOSFET devices, further deepening my understanding of semiconductor device physics. Despite the rigorous and time-consuming nature of the analysis, the richness of the insights gained from the project has been incredibly rewarding. By implementing the characterization in MATLAB, I have been able to take advantage of its high processing capabilities and versatile coding environment, thereby making the analysis more efficient and precise as well as reusable for future projects or devices characterizations.

MATLAB Code Appendix (in order of the problems).

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from CSV
filename = 'Id_Vd.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_DS = data(:,1); % Drain-Source Voltage
I_D = data(:,2); % Drain Current
V_GS = data(:,3); % Gate-Source Voltage

% Get unique V_GS values
uniqueV_GS = unique(V_GS);

% Create a figure
figure;
hold on; % This will allow multiple plots on the same figure

% Loop over unique V_GS values
for i = 1:length(uniqueV_GS)
    % Get the indices for the current V_GS
    indices = V_GS == uniqueV_GS(i);
    % Plot I_D vs V_DS for this V_GS
    plot(V_DS(indices), I_D(indices), 'LineWidth', 1.5, 'DisplayName', ['V_{GS} = ',
num2str(uniqueV_GS(i)), 'V']);
end

% Adding labels and title
xlabel('V_{DS} (V)');
ylabel('I_D (A)');
title('Output Characteristics of the MOSFET');
legend('show'); % Show legend

% Holding off the figure
hold off;
```

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Get unique V_DS values
uniqueV_DS = unique(V_DS);

% Create a figure
figure;
hold on; % This will allow multiple plots on the same figure

% Loop over unique V_DS values
for i = 1:length(uniqueV_DS)
    % Get the indices for the current V_DS
    indices = V_DS == uniqueV_DS(i);
    % Plot I_D vs V_GS for this V_DS
    plot(V_GS(indices), I_D(indices), 'LineWidth', 1.5, 'DisplayName', ['V_{DS} = ',
num2str(uniqueV_DS(i)), 'V']);
end

% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('I_D (A)');
title('Transfer Characteristics of the MOSFET');
legend('show','Location','northwest'); % Show legend

% Holding off the figure
hold off;
```

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Specify the two V_DS values of interest
V_DS1 = min(unique(0.25)); % e.g., minimum V_DS
V_DS2 = max(unique(2.5)); % e.g., maximum V_DS

% Create a figure
figure;
hold on; % This will allow multiple plots on the same figure

% Loop over the two selected V_DS values
for V_DS_val = [V_DS1, V_DS2]
    % Get the indices for the current V_DS
    indices = V_DS == V_DS_val;
    % Plot I_D vs V_GS for this V_DS
    plot(V_GS(indices), I_D(indices), 'LineWidth', 1.5, 'DisplayName', ['V_{DS} = ',
num2str(V_DS_val), 'V']);
end

% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('I_D (A)');
title('Transfer Characteristics of the MOSFET for Selected V_{DS} Values');
legend('show'); % Show legend

% Holding off the figure
hold off;
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Specify the V_DS value of interest
V_DS_val = 0.25; % e.g., V_DS = 0.25V

% Get the indices for the specified V_DS
indices = V_DS == V_DS_val;

% Create a figure
figure;

% Plot I_D vs V_GS for this V_DS
plot(V_GS(indices), I_D(indices), 'LineWidth', 1.5);
hold on; % To allow multiple plots on the same figure

% Define the points for fitting the line
V_GS_line_points = [2.4, 2.8];
ID_line_points = [I_D(V_GS == 2.4 & indices), I_D(V_GS == 2.8 & indices)];

% Fit a line through the specified points
P = polyfit(V_GS_line_points, ID_line_points, 1);

% Generate points to draw the fitted line
V_GS_line = linspace(min(V_GS(indices)), max(V_GS(indices)), 100);
ID_line = polyval(P, V_GS_line);

% Plot the line
plot(V_GS_line, ID_line, 'r', 'LineWidth', 1.5);

% Calculate the x-axis intersection
V_T_estimate = -P(2) / P(1);
disp(['The estimated threshold voltage (x-axis intersection of the line) is: ',
num2str(V_T_estimate), ' V']);

% Add the equation of the line to the plot
str = sprintf('y = %.3f x + %.3f', P(1), P(2));
text(mean(V_GS_line), mean(ID_line), str, 'Color', 'red');
```

```
% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('I_D (A)');
title(['Drain Current vs. Gate-Source Voltage for V_{DS} = ', num2str(V_DS_val),
'V']);

% Holding off the figure
hold off;
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske


clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Specify the V_DS value of interest
V_DS_val = 2.5; % e.g., V_DS = 2.5V

% Get the indices for the specified V_DS
indices = V_DS == V_DS_val;

% Create a figure
figure;
% Plot sqrt(I_D) vs V_GS for this V_DS
plot(V_GS(indices), sqrt(I_D(indices)), 'LineWidth', 1.5);
% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('sqrt(I_D) (A^{1/2})');
title(['Square Root of Drain Current vs. Gate-Source Voltage for V_{DS} = ',
num2str(V_DS_val), 'V']);
```

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Specify the V_DS value of interest
V_DS_val = 2.5; % e.g., V_DS = 2.5V

% Get the indices for the specified V_DS
indices = V_DS == V_DS_val;

% Create a figure
figure;

% Plot sqrt(I_D) vs V_GS for this V_DS
plot(V_GS(indices), sqrt(I_D(indices)), 'LineWidth', 1.5);
hold on; % To allow multiple plots on the same figure

% Define the points for fitting the line (asymptote)
V_GS_asymptote_points = [2.5, 2.6];
sqrt_ID_asymptote_points = [sqrt(I_D(V_GS == 2.5 & indices)), sqrt(I_D(V_GS == 2.6 &
indices))];

% Fit a line through the specified points
P = polyfit(V_GS_asymptote_points, sqrt_ID_asymptote_points, 1);

% Generate points to draw the fitted line (asymptote)
V_GS_line = linspace(min(V_GS(indices)), max(V_GS(indices)), 100);
sqrt_ID_line = polyval(P, V_GS_line);

% Plot the asymptote
plot(V_GS_line, sqrt_ID_line, 'r', 'LineWidth', 1.5);

% Calculate the x-axis intersection
V_T_estimate = -P(2) / P(1);
disp(['The estimated threshold voltage (x-axis intersection of the asymptote) is: ',
num2str(V_T_estimate), ' V']);

% Add the equation of the line to the plot
str = sprintf('y = %.3f x + %.3f', P(1), P(2));
text(mean(V_GS_line), mean(sqrt_ID_line), str, 'Color', 'red');
```

```
% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('sqrt(I_D) (A^{1/2})');
title(['Square Root of Drain Current vs. Gate-Source Voltage for V_{DS} = ',
num2str(V_DS_val), 'V']);

% Holding off the figure
hold off;
```

Q3 linear region

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Specify the V_DS value of interest
V_DS_val = 0.25; % e.g., V_DS = 0.25V

% Get the indices for the specified V_DS
indices = V_DS == V_DS_val;

% Define the points for fitting the line
line_indices = indices & V_GS >= 2.4 & V_GS <= 2.8;
V_GS_line_points = V_GS(line_indices);
ID_line_points = I_D(line_indices);

% Fit a line through the specified points
P = polyfit(V_GS_line_points, ID_line_points, 1);

% Generate points to draw the fitted line
V_GS_line = linspace(min(V_GS_line_points), max(V_GS_line_points), 100);
ID_line = polyval(P, V_GS_line);

% Calculate the x-axis intersection (threshold voltage, V_T)
V_T_estimate = -P(2) / P(1);

% Define the W/L ratio
WL_ratio = 31; % W/L = 31, from your provided info
```

```matlab
% Calculate the µnCox product from the slope
u_n_C_ox_estimate = P(1) / (V_DS_val * WL_ratio); % dividing by V_DS and WL_ratio
because the slope of ID vs VGS in the linear region is µnCox * V_DS * WL_ratio

% Print the estimated parameters
disp(['The estimated threshold voltage (x-axis intersection of the line) is: ',
num2str(V_T_estimate), ' V']);
disp(['The estimated µnCox product (from the slope of the line) is: ',
num2str(u_n_C_ox_estimate), ' A/V^2']);

% Create a figure
figure;

% Plot I_D vs V_GS for this V_DS
plot(V_GS(indices), I_D(indices), 'LineWidth', 1.5);
hold on; % To allow multiple plots on the same figure

% Plot the line
plot(V_GS_line, ID_line, 'r', 'LineWidth', 1.5);

% Add the equation of the line to the plot
str = sprintf('y = %.3f x + %.3f', P(1), P(2));
text(mean(V_GS_line), mean(ID_line), str, 'Color', 'red');

% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('I_D (A)');
title(['Drain Current vs. Gate-Source Voltage for V_{DS} = ', num2str(V_DS_val),
'V']);

% Holding off the figure
hold off;
```

Q3 Saturation Region

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske

clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage
```

```
% Specify the V_DS value of interest
V_DS_val = 2.5; % e.g., V_DS = 2.5V

% Get the indices for the specified V_DS
indices = V_DS == V_DS_val;

% Define the points for fitting the line
line_indices = indices & V_GS >= 2.4 & V_GS <= 2.8;
V_GS_line_points = V_GS(line_indices);
sqrt_ID_line_points = sqrt(I_D(line_indices));

% Fit a line through the specified points
P = polyfit(V_GS_line_points, sqrt_ID_line_points, 1);

% Generate points to draw the fitted line
V_GS_line = linspace(min(V_GS_line_points), max(V_GS_line_points), 100);
sqrt_ID_line = polyval(P, V_GS_line);

% Calculate the x-axis intersection (threshold voltage, V_T)
V_T_estimate = -P(2) / P(1);

% Define the W/L ratio
WL_ratio = 31; % W/L = 31, from your provided info

% Calculate the μnCox product from the slope
u_n_C_ox_estimate = (P(1) / sqrt(0.5 * WL_ratio))^2; % dividing by sqrt(0.5 *
WL_ratio) because the slope of sqrt(ID) vs VGS in the saturation region is sqrt(0.5 *
μnCox * WL_ratio)

% Print the estimated parameters
disp(['The estimated threshold voltage (x-axis intersection of the line) is: ',
num2str(V_T_estimate), ' V']);
disp(['The estimated μnCox product (from the slope of the line) is: ',
num2str(u_n_C_ox_estimate), ' A/V^2']);

% Create a figure
figure;

% Plot sqrt(I_D) vs V_GS for this V_DS
plot(V_GS(indices), sqrt(I_D(indices)), 'LineWidth', 1.5);
hold on; % To allow multiple plots on the same figure

% Plot the line
plot(V_GS_line, sqrt_ID_line, 'r', 'LineWidth', 1.5);

% Add the equation of the line to the plot
str = sprintf('y = %.3f x + %.3f', P(1), P(2));
text(mean(V_GS_line), mean(sqrt_ID_line), str, 'Color', 'red');

% Adding labels and title
xlabel('V_{GS} (V)');
ylabel('sqrt(I_D) (sqrt(A))');
title(['Square Root of Drain Current vs. Gate-Source Voltage for V_{DS} = ',
num2str(V_DS_val), 'V']);
```

```
% Holding off the figure
hold off;
```

Q4

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vd.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_DS = data(:,1); % Drain-Source Voltage
I_D = data(:,2); % Drain Current
V_GS = data(:,3); % Gate-Source Voltage

% Extracted parameters from the saturation region
mu_nCox = 0.0075427;  % (A/V^2)
VT = 2.082; % Threshold voltage (V)
W_L = 31; % Aspect ratio W/L

% V_DS values for the model
V_DS_values = 0:0.01:3.5;

% V_GS values
V_GS_values = [2.15, 2.3, 2.45, 2.6, 2.9, 3.05, 3.2];

figure;

for i = 1:length(V_GS_values)
    % Select the data for the current V_GS value
    indices = abs(V_GS - V_GS_values(i)) < 1e-3;
    V_DS_data = V_DS(indices);
    I_D_data = I_D(indices);

    % Plot the experimental data
    scatter(V_DS_data, I_D_data, 'DisplayName', ['V_GS = ', num2str(V_GS_values(i)),
'V (Measured)']);
    hold on;

    % MOSFET I-V model for both regions
    V_DSAT = max(0, V_GS_values(i) - VT); % calculate V_DSAT
    I_D_model = mu_nCox * W_L * ((V_GS_values(i) - VT).*V_DS_values -
0.5.*V_DS_values.^2);
    I_D_model_saturation = mu_nCox * W_L * ((V_GS_values(i) - VT).*V_DSAT -
0.5.*V_DSAT.^2);

    % Limiting I_D_model to saturation region when V_DS >= V_DSAT
```

```
    I_D_model(V_DS_values >= V_DSAT) = I_D_model_saturation;

    % Plot the modeled data
    plot(V_DS_values, I_D_model, 'DisplayName', ['V_GS = ', num2str(V_GS_values(i)),
'V (Model)'], 'LineWidth', 1.5);
end

title('I_D vs V_DS for different V_GS values (Measured and Modeled)');
xlabel('V_DS (V)');
ylabel('I_D (A)');
legend('Location', 'northwest');
grid on;
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vd.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_DS = data(:,1); % Drain-Source Voltage
I_D = data(:,2); % Drain Current
V_GS = data(:,3); % Gate-Source Voltage

% Extracted parameters from the saturation region
mu_nCox = 0.0075427;  % (A/V^2)
VT = 2.082; % Threshold voltage (V)
W_L = 31; % Aspect ratio W/L

% V_DS values for the model
V_DS_values = 0:0.01:3.5;

% Unique V_GS values
V_GS_values = unique(V_GS);

figure;

for i = 1:length(V_GS_values)
    % Select the data for the current V_GS value
    indices = abs(V_GS - V_GS_values(i)) < 1e-3;
    V_DS_data = V_DS(indices);
    I_D_data = I_D(indices);

    % Plot the experimental data
    scatter(V_DS_data, I_D_data, 'DisplayName', ['V_GS = ', num2str(V_GS_values(i)),
'V (Measured)']);
    hold on;
```

```
    % MOSFET I-V model for both regions
    V_DSAT = max(0, V_GS_values(i) - VT); % calculate V_DSAT
    I_D_model = mu_nCox * W_L * ((V_GS_values(i) - VT).*V_DS_values -
0.5.*V_DS_values.^2);
    I_D_model_saturation = mu_nCox * W_L * ((V_GS_values(i) - VT).*V_DSAT -
0.5.*V_DSAT.^2);

    % Limiting I_D_model to saturation region when V_DS >= V_DSAT
    I_D_model(V_DS_values >= V_DSAT) = I_D_model_saturation;

    % Plot the modeled data
    plot(V_DS_values, I_D_model, 'DisplayName', ['V_GS = ', num2str(V_GS_values(i)),
'V (Model)'], 'LineWidth', 1.5);
end

title('I_D vs V_DS for different V_GS values (Measured and Modeled)');
xlabel('V_DS (V)');
ylabel('I_D (A)');
legend('Location', 'northwest');
grid on;
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Extracted parameters from the saturation region
mu_nCox = 0.0075427;  % (A/V^2)
VT = 2.082; % Threshold voltage (V)
W_L = 31; % Aspect ratio W/L

% V_GS values for the model
V_GS_values = 0:0.01:3.5;

% Selected V_DS values
V_DS_values = [1, 1.75, 2,2.25, 2.5];

figure;

for i = 1:length(V_DS_values)
    % Select the data for the current V_DS value
    indices = abs(V_DS - V_DS_values(i)) < 1e-3;
```

```
    V_GS_data = V_GS(indices);
    I_D_data = sqrt(abs(I_D(indices)));

    % Plot the experimental data
    scatter(V_GS_data, I_D_data, 'DisplayName', ['V_DS = ', num2str(V_DS_values(i)),
'V (Measured)']);
    hold on;

    % MOSFET I-V model for both regions
    V_DSAT = max(0, V_GS_values - VT); % calculate V_DSAT
    I_D_model = mu_nCox * W_L * ((V_GS_values - VT).*V_DS_values(i) -
0.5.*V_DS_values(i).^2);
    I_D_model_saturation = mu_nCox * W_L * ((V_GS_values - VT).*V_DSAT -
0.5.*V_DSAT.^2);

    % Limiting I_D_model to saturation region when V_DS >= V_DSAT
    I_D_model(V_DS_values(i) >= V_DSAT) = I_D_model_saturation(V_DS_values(i) >=
V_DSAT);

    % Plot the modeled data
    plot(V_GS_values, sqrt(abs(I_D_model)), 'DisplayName', ['V_DS = ',
num2str(V_DS_values(i)), 'V (Model)'], 'LineWidth', 1.5);
end

title('sqrt(I_D) vs V_GS for different V_DS values (Measured and Modeled)');
xlabel('V_GS (V)');
ylabel('sqrt(I_D) (sqrt(A))');
legend('Location', 'northwest');
grid on;
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Choosing V_DS = 2V and near threshold voltage
V_DS_selected = 2;
VT = 2.082; % Threshold voltage (V)
VT_window = 0.1; % Range around VT to consider
```

```matlab
% Filtering data
mask = (V_DS == V_DS_selected) & (V_GS > VT - VT_window) & (V_GS < VT + VT_window);
V_GS_subthreshold = V_GS(mask);
I_D_subthreshold = I_D(mask);

% Plotting
figure
plot(V_GS_subthreshold, I_D_subthreshold, 'b', 'LineWidth', 1.5) % Line plot
hold on
scatter(V_GS_subthreshold, I_D_subthreshold, 'MarkerEdgeColor', 'r') % Scatter plot
hold off
title('Subthreshold characteristics (I_D vs V_GS for V_DS = 2V)')
xlabel('V_GS (V)')
ylabel('I_D (A)')
legend('Data trend', 'Measured data')
grid on
```

```matlab
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Choosing V_DS = 2V and near threshold voltage
V_DS_selected = 2;
VT = 2.082; % Threshold voltage (V)
VT_window = 0.1; % Range around VT to consider

% Filtering data
mask = (V_DS == V_DS_selected) & (V_GS > VT - VT_window) & (V_GS < VT + VT_window);
V_GS_subthreshold = V_GS(mask);
I_D_subthreshold = I_D(mask);

% Plotting
figure
semilogy(V_GS_subthreshold, I_D_subthreshold, 'b', 'LineWidth', 1.5) % Line plot
hold on
scatter(V_GS_subthreshold, log10(I_D_subthreshold), 'MarkerEdgeColor', 'r') % Scatter
plot
hold off
title('Logarithmic subthreshold characteristics (log(I_D) vs V_GS for V_DS = 2V)')
xlabel('V_GS (V)')
ylabel('log_{10}(I_D) (A)')
```

```
legend('Data trend')
grid on
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Choosing V_DS = 2V
V_DS_selected = 2;

% Filtering data
mask = (V_DS == V_DS_selected);
V_GS_all = V_GS(mask);
I_D_all = I_D(mask);

% Plotting
figure
semilogy(V_GS_all, I_D_all, 'b', 'LineWidth', 1.5) % Line plot
hold on
scatter(V_GS_all, log10(I_D_all), 'MarkerEdgeColor', 'r') % Scatter plot
hold off
title('Logarithmic I_D vs V_GS for V_DS = 2V')
xlabel('V_GS (V)')
ylabel('log_{10}(I_D) (A)')
legend('Data trend')
grid on
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
```

```
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Select data for V_DS=2V
V_DS_target = 2;
indices = find(V_DS == V_DS_target);
V_GS_target = V_GS(indices);
I_D_target = I_D(indices);

% Threshold voltage
VT = 2.082;

% Margin around V_T
margin = 0.2;

% Select data around V_T
indices_VT = find((V_GS_target >= VT - margin) & (V_GS_target <= VT + margin));
V_GS_target_VT = V_GS_target(indices_VT);
I_D_target_VT = I_D_target(indices_VT);

% Plot log10(I_D) vs V_GS
figure
scatter(V_GS_target_VT, log10(I_D_target_VT), 'filled');
hold on;

% Fitting line
P = polyfit(V_GS_target_VT, log10(I_D_target_VT), 1);
fit_line = polyval(P, V_GS_target_VT);
plot(V_GS_target_VT, fit_line, 'LineWidth', 1.5);

% Compute Subthreshold Slope
S = P(1);

% Boltzmann constant in J/K
k = 1.38e-23;

% Charge of an electron in C
q = 1.6e-19;

% Room temperature in K
T = 300;

% Calculate c_r
c_r = S * q / (2.3 * k * T);

fprintf('Subthreshold slope, S = %.4f V/decade\n', S);
fprintf('The parameter c_r = %.4e\n', c_r);

% Equation of the fitted line
m = S;
c = P(2);
str = sprintf('y = %.2fx + %.2f', m, c);

% Add equation to the plot
```

```
text(VT, min(log10(I_D_target_VT)), str, 'FontSize', 12);
hold off;

xlabel('V_G_S (V)');
ylabel('log_{10}(I_D) ');
title('log_{10}(I_D) vs V_G_S for V_D_S=2V around V_T');
legend('Measured data', 'Fitted line', 'Location', 'northwest');
```

```
% Mohamed Ghonim - ECE 515 Fundamentals of Semiconductor Devices
% Project 2 MOSFET Characterization
% Dr. Malgorzata Chrzanowska-Jeske
clc
clear % This clears all variables
close all % This closes all figures

% Reading the data from Excel
filename = 'Id_Vg.csv'; % update with your filename
data = xlsread(filename);

% Separating the data into vectors
V_GS = data(:,1); % Gate-Source Voltage
I_D = data(:,2); % Drain Current
V_DS = data(:,4); % Drain-Source Voltage

% Select data for V_DS=2V
V_DS_target = 2;
indices = find(V_DS == V_DS_target);
V_GS_target = V_GS(indices);
I_D_target = I_D(indices);

% Threshold voltage
VT = 0.8;

% Margin around V_T
margin = 0.2;

% Select data around V_T
indices_VT = find((V_GS_target >= VT - margin) & (V_GS_target <= VT + margin));
V_GS_target_VT = V_GS_target(indices_VT);
I_D_target_VT = I_D_target(indices_VT);

% Plot log10(I_D) vs V_GS
figure
scatter(V_GS_target_VT, log10(I_D_target_VT), 'filled');
hold on;

% Fitting line
P = polyfit(V_GS_target_VT, log10(I_D_target_VT), 1);
fit_line = polyval(P, V_GS_target_VT);
plot(V_GS_target_VT, fit_line, 'LineWidth', 1.5);

% Compute Subthreshold Slope
S = 1 / P(1); % Corrected computation of S
```

```matlab
% Boltzmann constant in J/K
k = 1.38e-23;

% Charge of an electron in C
q = 1.6e-19;

% Room temperature in K
T = 300;

% Calculate c_r
c_r = S * q / (2.3 * k * T);

fprintf('Subthreshold slope, S = %.4f V/decade\n', S);
fprintf('The parameter c_r = %.4e\n', c_r);

% Equation of the fitted line
m = P(1); % m here is the slope of the line, not S.
c = P(2);
str = sprintf('y = %.2fx + %.2f', m, c);

% Add equation to the plot
text(VT, min(log10(I_D_target_VT)), str, 'FontSize', 12);
hold off;

xlabel('V_G_S (V)');
ylabel('log_{10}(I_D) ');
title('log_{10}(I_D) vs V_G_S for V_D_S=2V around V_T');
legend('Measured data', 'Fitted line', 'Location', 'northwest');
```