EXPERIMENT 9:
MOS TRANSISTOR

EECE 310L

Group1 – Section5

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TABLE OF CONTENTS

LIST OF TABLES:

LIST OF FIGURES:

LIST OF PLOTS:

OBJECTIVES

- Investigate the characteristics of the Metal-Oxide-Semiconductor Field-Effect Transistor and study its following applications:
    - Voltage-controlled resistor
    - Logic gate
    - Amplifier
    - Current source

LAB EQUIPMENT USED

- Breadboard.
- Function generator.
- Oscilloscope.
- Digital Multimeter (DMM).

- Power Supply.

LAB TOOLS USED

- Wire stripper.
- Wire Cutter.

COMPONENTS USED

Table 1: Components Used

Resistor	Theoretical Value	Measured Value	% error
	10 Ω	16.9 Ω	69%
	100 Ω	105.43 Ω	5.43%
	220 Ω	N/A	N/A
	330 Ω	N/A	N/A
	470 Ω	461.6 Ω	1.787%
	560 Ω	N/A	N/A
	680 Ω	N/A	N/A
	820 Ω	N/A	N/A
	1000 Ω	987.9 Ω	1.21%
	3.3kΩ	N/A	N/A
	4.7kΩ	N/A	N/A
	10kΩ	N/A	N/A
	15kΩ	N/A	N/A
Capacitor	10 µF	N/A	N/A

- Connection Wires.
- BS170 MOSFET.

- Capacitors.
- Resistors.

EXPERIMENTAL PROCEDURE AND DISCUSSION

A. MOSFET Characteristics

1. CIRCUIT DIAGRAMS

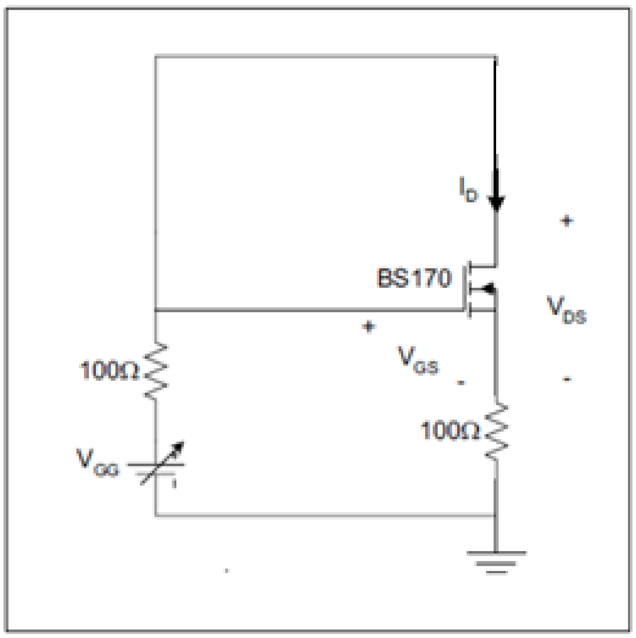


Figure 1: MOSFET Characteristics

2. DETAILED EXPERIMENTAL PROCEDURE

- To find the important parameters of the MOSFET (k: trans conductance; VT :threshold voltage):
- Steps:
  - Place an NMOS transistor on the breadboard.
  - Connect a 100Ω sensing resistor to the source terminal of the transistor. Connect it to ground.
  - Connect between the gate terminal and ground another 100Ω resistor in series with a variable DC source (V_{GG}).

- Use one of the variable outputs of the DC power supply. Connect the gate terminal directly to the drain terminal.
  - Region of Operation: $V_{DS} = V_{GS}$ and NMOS: V_t is positive so $V_{GS}>V_t$ => $V_{DS} > V_{GS} - V_T$: saturation region.

- To set the drain current ID (15,30 and 40mA):
  - Increase the variable VGG from the power supply to reach a Drain Current I_D given above.
- To measure the drain current using a sensing resistor (small resistor placed to measure the drain current):
  - $I_D=I_S$: measure the voltage across the sensing resistor, then divide by its resistance to get the current.
  - Use a Multi-meter to measure the voltage across the sensing resistor. Do not place an ammeter between the drain and gate.
- Parameters of the MOSFET: k (trans-conductance parameter) and V_t (threshold voltage)

$$I_D = (K/2)(V_{GS} - V_T)^2 \Rightarrow V_T + \text{sqrt}(2I_D).\ \text{sqrt}\ (1\backslash K) = V_{GS}$$

$V_{GS}>V_t$ and $V_{DS} > V_{GS} - V_t$ (Saturation Region)
- Steps:
  - Set V_{GG}=0.5V, then increase it slowly to get to a current of 15mA in the sensing resistor.
  - Record the value of V_{GS} using the multi-meter.
  - Change V_{GG} to get a current of 30mA and 40mA and record V_{GS}.
  - Check Values using the third equation:

$$V_T + \text{sqrt}(2I_D).\ \text{sqrt}\ (1\backslash K) = V_{GS}$$

- Assumptions:
  - Assume that the error on the resistance 100Ω (Experimental: 105.43) is negligible.

Measure

100Ω Resistor	105.43 Ω
Error: 5.43%	

Table 2: Error 100 ohms

- Wires have no internal resistance.
- MOSFET initially in saturation region.

3. MEASUREMENTS AND RESULTS

- Voltage across resistor:

Measure	
I_D	V_{GS} (V)
15 mA	2.62
30 mA	2.758
40 mA	2.824

Table 3: VGS Values - A

Using a system of two equations, two unknowns:

$$I_D = (K/2)(V_{GS} - V_T)^2$$

1 : $2.62 = V_t + \sqrt{(2*15mA/k)}$

2: $2.758 = V_t + \sqrt{(2*30mA/k)}$

Solving for k: k=0.27166 A/V^2; V_T = 2.289 V.

Calculate		Units
K	0.27166	A/V^2
VT	2.289	V

Table 4: K and VT values

Verify using the 40mA by substituting the found values:

$V_T + \text{sqrt}(2I_D).\ \text{sqrt}\ (1\backslash K) = V_{GS}$

2.289 +sqrt (2*0.04/0.27166)= 2.83166 V

Calculated vs Measured	
VGS calculated (V)	2.83166
Error	0.27%

Table 5: VGS calculated

B. MOSFET as a Voltage-Controlled Resistor

1. CIRCUIT DIAGRAMS

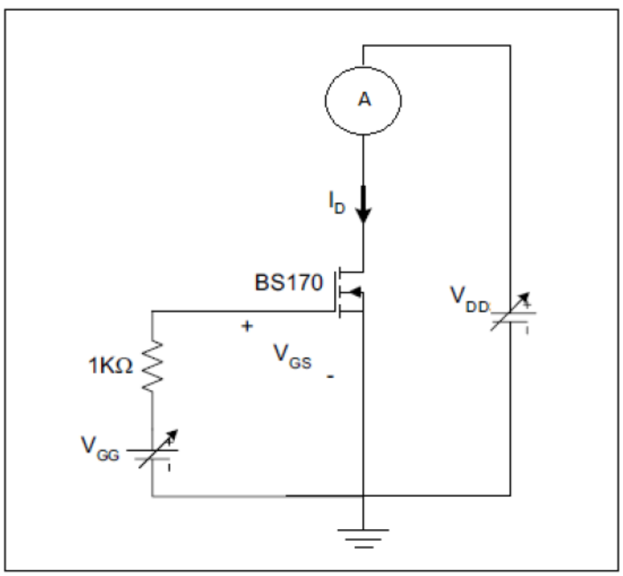


Figure 2: MOSFET as a voltage controlled resistor

2. DETAILED EXPERIMENTAL PROCEDURE

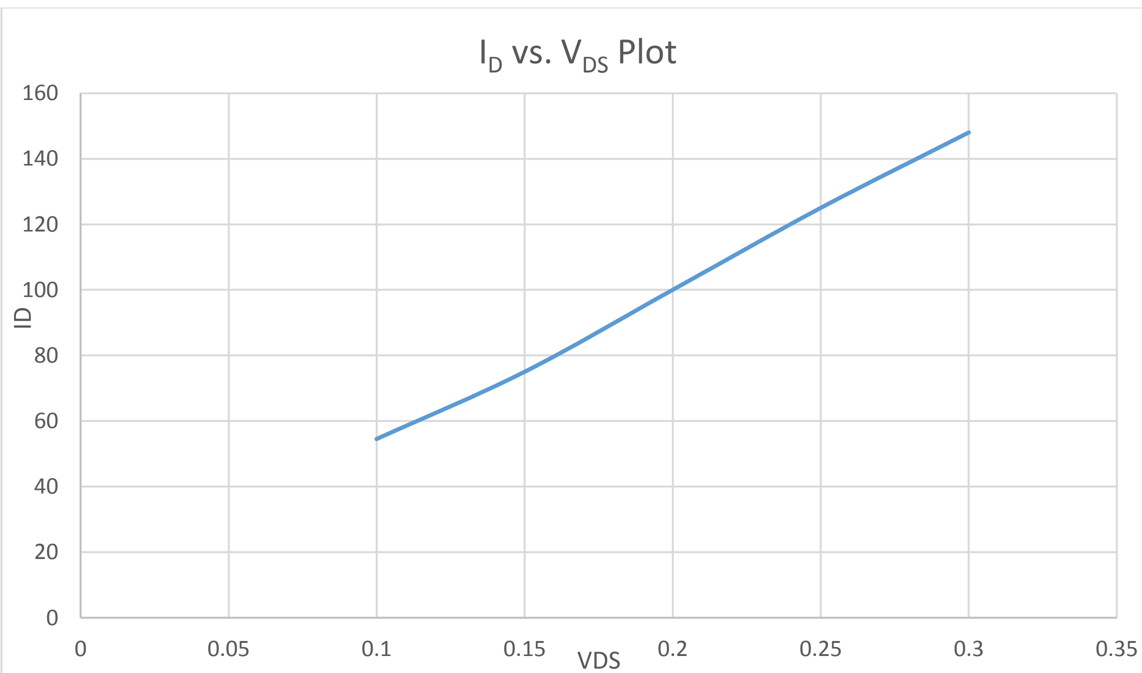
- Connect the circuit previewed above.
- Using the two variable sources from the power supply:
  - Regulate V_{GG} to set $V_{GS} = V_T + 2$, using the value of V_T (threshold voltage) calculated in part A (V_T = 2.289V).

- Regulate V_{DD} to get V_{DS} = 0.1V. (Limitation: Never exceed V_{DD}=2V, to avoid damaging the MOSFET).
- Measure the voltage across the sensing resistor used (10 Ω) using a voltmeter, in order to calculate the value of I_D (Drain Current).
- Repeat the same procedure for V_{GS} = V_T+ 3, V_{GS} = V_T+ 4.
- Assumptions: The error of the resistor and wires are ignored.

3. MEASUREMENTS AND RESULTS

V_{GS}-V_T (V)	V_{DS}(V)	V(sensing resistor)(V)	I_D(mA)
2	0.1	0.545	54.5
2	0.15	0.75	75
2	0.2	1	100
2	0.25	1.25	125
2	0.3	1.48	148

Table 6: VGS-VT = 2

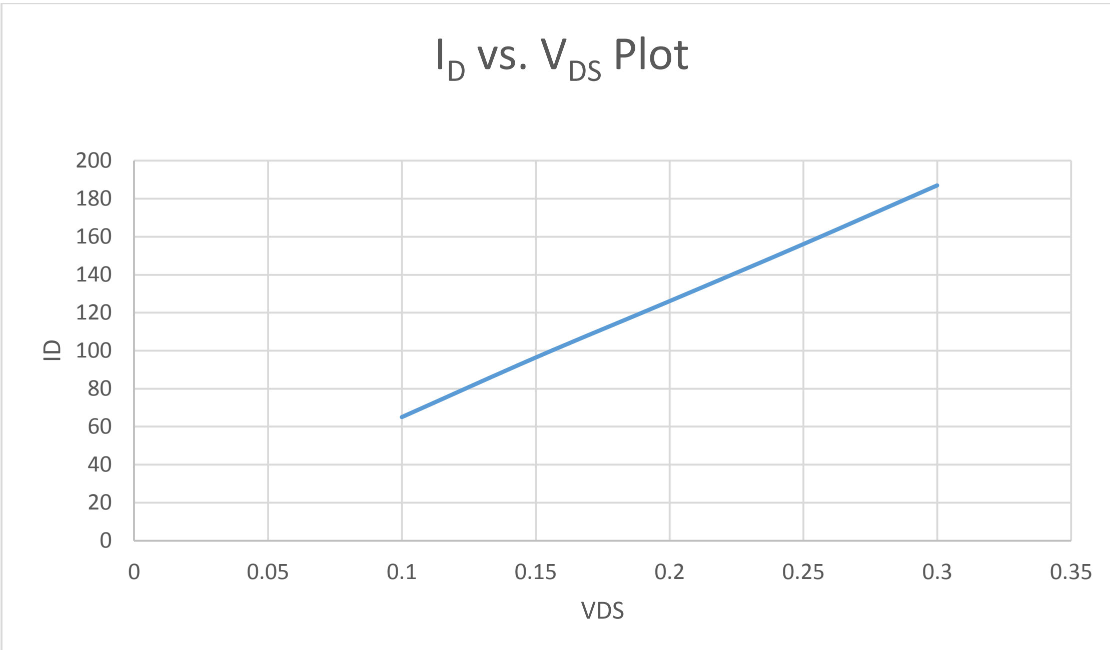


Plot 1: VGS-VT=2

V_{GS}-V_T (V)	V_{DS}(V)	V(sensing resistor)(V)	I_D(mA)

3	0.1	0.65	65
3	0.15	0.96	96.34
3	0.2	1.26	126
3	0.25	1.56	156
3	0.3	1.87	186.92

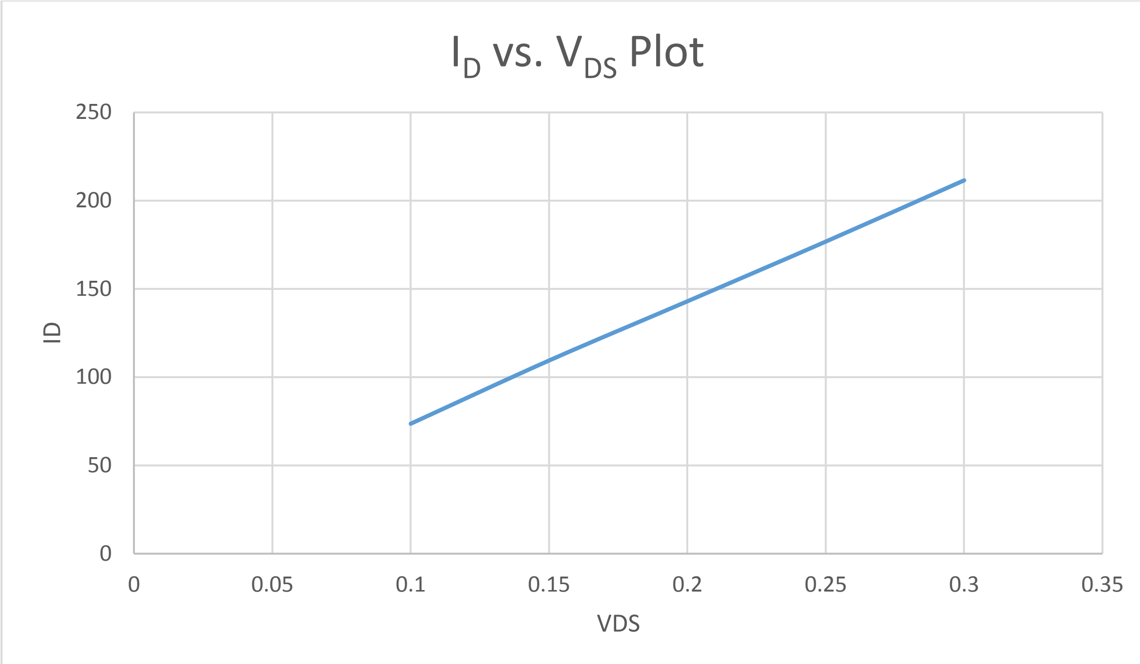
Table 7: VGS-VT = 3



Plot 2: VGS-VT=3

V_{GS}-V_T (V)	V_{DS}(V)	V(sensing resistor)(V)	I_D(mA)
4	0.1	0.736	73.59
4	0.15	1.09	109.41
4	0.2	1.42	142.98
4	0.25	1.76	176.82
4	0.3	2.11	211.53

Table 8: VGS-VT = 4



Plot 3: VGS-VT=4

4. DISCUSSIONS

- Plots included above.
- The curve resulting is almost linear in all cases given (V_{GS}-V_T=2, 3&4).
- Slope Calculation:
  - V_{GS}-V_T=2:

$$\frac{0.148 - 0.0545}{0.3 - 0.1} = 0.467$$

  - V_{GS}-V_T=3:

$$\frac{0.187 - 0.065}{0.3 - 0.1} = 0.61$$

  - V_{GS}-V_T=4:

$$\frac{0.211 - 0.0736}{0.3 - 0.1} = 0.687$$

- The resistance between drain and source of the MOSFET:

V_{GS}-V_T(V)	R_{DS}(ohm)
2	1/0.467 = 2.141 Ω
3	1/0.61 = 1.64 Ω
4	1/0.687 = 1.455 Ω

Table 9: RDS Table

- For the given circuit, the region of operation of the MOSFET depends on VDD and VGG (the variable voltages from the Power Supply). Since $V_{GG} = V_{GS} = V_T + 2$ and VDS is very small (VDS = 0.1V) we note that the region of operation of the MOSFET is Triode Region.
  This region is called Ohmic or linear since the MOSFET acts like a resistor RDS between drain and source. The plots of I_D vs V_{DS} are linear ($R_{DS} = V_{DS}/I_{DS}$). The linear plots confirms the inverse of the slope, which is the resistance, is constant for each value of VDS.
- In the triode region, the current specified by:

$$I_D = \frac{k}{2}\left(2(V_{GS} - V_T)\,V_{DS} - V_{DS}^2\right)$$

Neglect VDS (too small):

$$I_D = \frac{k}{2}\left(2(V_{GS} - V_T)\,V_{DS}\right)$$

VDS/ID = 1/k(VGS-VT) = RDS : the MOSFET acts as a linear resistor between the Drain and the source. VGS changes the value of the resistor: when VGS increases, RDS decrease: The MOSFET as a voltage-controlled Resistor.

- This approximation is only valid for small values of VDS.
- The value of RDS from the current's equation :

VDS/ID = 1/k (VGS-VT) = RDS

RDS = 1/slope.

Using K = 0.27166 A/V^2 (Part A):

$V_{GS} - V_T$ (Volts)	R_{DS} Calculated (Ohms)	R_{DS} Experimental from plots (Ohms)	% Error
2	1.84	2.141	16.36
3	1.227	1.64	33.65
4	0.92	1.455	58.152

Table 10: RDS comparison table

The calculated and experimental values of R_{DS} are close for $V_{GS} – V_T$ = 2V. This is expected because the plot is almost linear; hence, the slope and the corresponding value of R_{DS} are more accurate. The experimental values are higher than the calculated values.

- Range for V_{DS}:

  $I_D = \frac{k}{2}[2(V_{GS} – V_T) V_{DS} – V_{DS}^2]$

  Neglecting V_{DS}^2: (for small value of V_{DS})

  $I_{D\ approximated} = k (V_{GS} – V_T) V_{DS}$

  Error = $\frac{|ID - ID\ approximated|}{ID} < 0.05$ =>

  $$\frac{\frac{k}{2}[2(VGS - VT)VDS - VDS2] - k\,(VGS - VT)\,VDS}{\frac{k}{2}[2(VGS - VT)\,VDS - VDS2]} < 0.05$$

  - Eliminate k; Simplify:

    $$\frac{|-VDS/2|}{|\,[(VGS - VT) - VDS/2]\,|} < 0.05$$

    ⇨ $V_{DS} < \frac{2}{21(VGS - VT)}$, for errors in current less than 5%.

- Error Percentage on I_D must be <0.05 (Checking for V_{GS}-V_T = 2V)

I_D theoretical (calculated)	I_D experimental	% Error
52.9 mA	54.5 mA	3.02
78.4 mA	75 mA	4.33
103.23 mA	100 mA	3.12
127.34 mA	125 mA	1.8
150.77 mA	148 mA	1.83

Table 11: Error ID

- Applications of a voltage-controlled resistor:

- Voltage controlled Attenuators: used in cellphones to avoid saturation.
- Buffer Amplifiers.
- Modulation circuits
- Filters
- Oscillators
- Automatic gain controls

C. MOSFET as Logic Gate

1. CIRCUIT DIAGRAMS

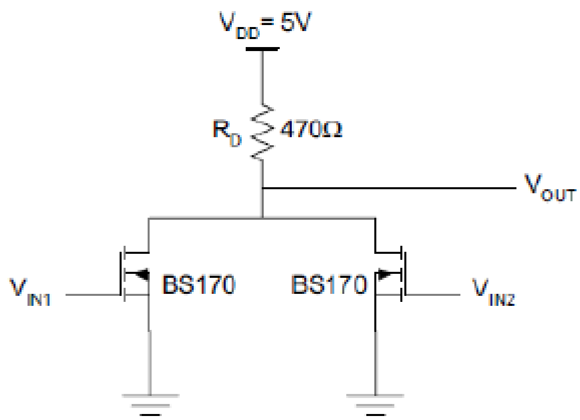


Figure 3: MOSFET as a logic Gate

2. DETAILED EXPERIMENTAL PROCEDURE

- Connect the circuit previewed above with two inputs IN1 and IN2 at the gate of the MOSFETs and one output OUT connected at the common drain.
- When the input voltage is grounded (logic zero), V_{GS}=zero<V_T: Cut-off region. The MOSFET is equivalent to an open circuit: V_{output} = 5V (logic 1).
- When the input voltage is logic one (5v), the MOSFET acts like a short circuit.
- To implement the circuit as a logic gate, Determine the truth table needed:

Vin1	Vin2	Vo
0	0	1
1	0	0
0	1	0
1	1	0

Table 12: Truth table

In order to get a logic zero as an output, we only need one on the input voltages to be logic 1. In the case of Vin1 and Vin2 are zeros, the output will be logic one.

Assumptions:

In order for the MOSFETs to act as a logic NOR gate, each will be at the triode or cut-off region.

3. MEASUREMENTS AND RESULTS

IN1 (logic)	IN2 (logic)	OUT (logic)	V_{IN1} (V)	V_{IN2} (V)	V_{OUT} (V)
0	0	1	0	0	4.996
0	1	0	0	5	0.01
1	0	0	5	0	0.04
1	1	0	5	5	0.02

Table 13: Measurements and Results C1

We notice that the output is true only when both inputs are false, so the circuit is a NOR gate.

V_{IN1} (V)	V_{OUT} (V)	MOSFET Region	Logic value at OUT
0	5	CUTOFF	1
0.4	5	CUTOFF	1
0.8	5	CUTOFF	1
1.2	5	CUTOFF	1
1.6	4.8	CUTOFF	1
2	4.1	CUTOFF	1
2.4	2	SATURATION	NO
2.8	0.79	SATURATION	NO
3.2	0.57	TRIODE	0
3.6	0.5	TRIODE	0
4.4	0.4	TRIODE	0
4.8	0.38	TRIODE	0

Table 14: Measurements and Results C2

4. DISCUSSIONS

- The value of high voltage is 5v, corresponding to logic 1.
- The values of low voltage are 0.02v and 0.04 corresponding to logic 0.
- When the MOSFET is in the linear region, the output is low, since it acts as a voltage-controlled resistor. The low voltage value is inversely

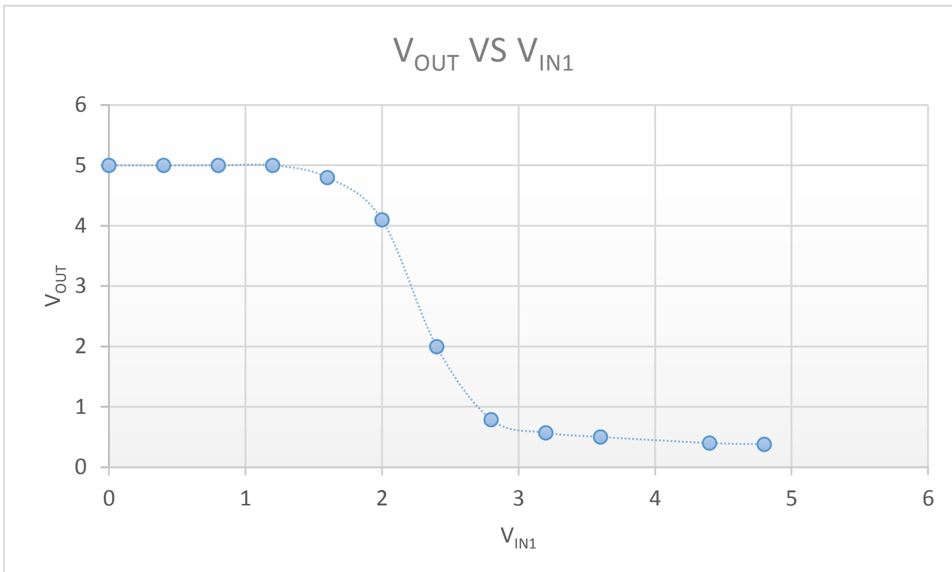
proportional to the resistor. Increasing the resistance will decrease low voltage. Apply voltage divider:

$$V_{out} / V_{DD} = R_{DS} / R_{DS} + R_D$$

$$V_{out} = V_{DD}. R_{DS} / R_{DS} + R_D$$

When R_D increases, V_{out} will decrease.

- Plot VOUT versus VIN1.



Plot 4: Vout VS Vin1

The output switch states:

- Cut-off Region: for Vin1 = 0V to Vin1 = 2V. The logic value is logic 1.
- Saturation Region: for Vin1 = 2.4V to Vin1 = 2.8V. There is no value for the logic output.
- Triode Region: for Vin1 = 3.2V to Vin1 = 4.8V. The logic value is logic 0.

D. MOSFET as an amplifier

1. CIRCUIT DIAGRAMS

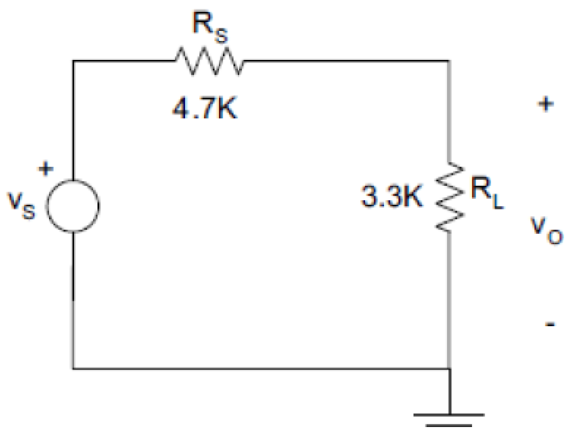


Figure 4: Circuit D1

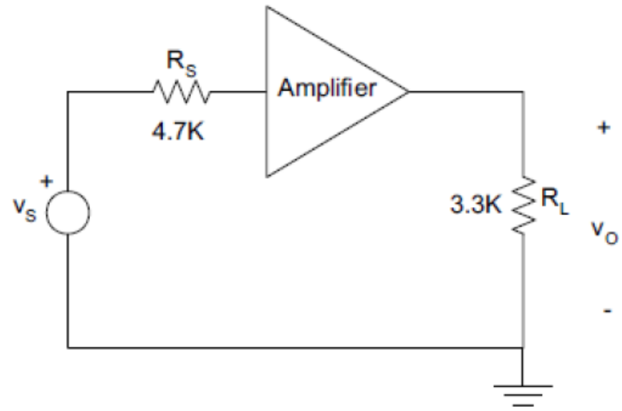


Figure 5: Circuit D2

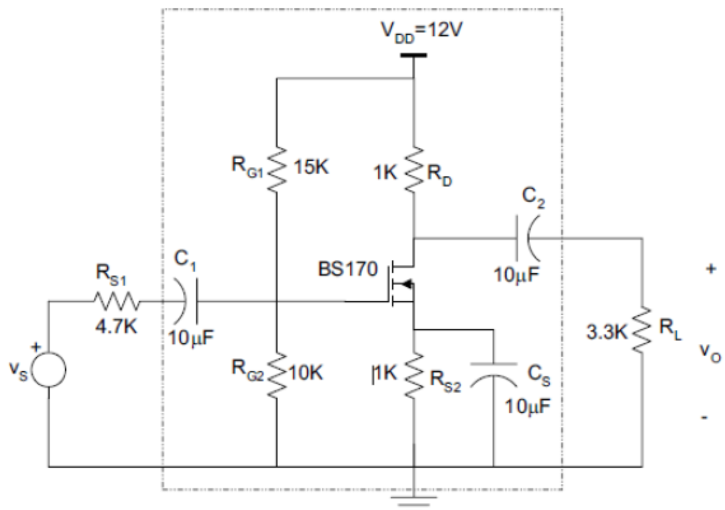


Figure 6: Circuit D3

2. DETAILED EXPERIMENTAL PROCEDURE

- Connect the circuit previewed above: the voltage source is a 100mV peak-peak – 10 KHz sine signal.
- Region of Operation: Saturation, in order to use the MOSFET as an amplifier.
- The voltage gain does not exceed 1, even if the amplitude of the input or the frequency is varied, the gain will not change.
- Add 2 capacitors C_1 and C_2 as coupling capacitors in order to eliminate DC offset.
- Add a capacitor C_s as a bypass capacitor (at high frequencies, short circuit R_{s2}.)

- To calculate the bandwidth (f_2-f_1): decrease the frequency of the input signal below 100Hz and increase it above 1MHz to find f1 and f2 at which the voltage gain of the amplifier is 0.7071 times its value at mid frequencies, with f1 being the low frequency value, and f2 the high frequency value.
- Increase the amplitude of the input signal from 400mV to 800 mV, in order to observe the phase shift.

- **Assumptions:**

- Assume that the MOSFET is in saturation region in order to operate as an amplifier.
- Resistors have each a percentage of error and wires have internal resistances.

3. MEASUREMENTS AND RESULTS

Part 1: DC Measurements

	Value
I_D (mA)	2.655
V_{GS} (V)	2.11
V_{DS}	6.774

Table 15: Measurements and Results D1

Part 2: AC Measurements

	Value
V_s pk-pk(mV)	106
V_i pk-pk(mV)	64.8
V_o pk-pk (mV)	820
Phase shift	180°

Table 16: Measurements and Results D2

Part 3: Bandwidth Measurements

Bandwidth Measurements	
F_{LOW} (Hz)	270
F_{HIGH} (KHz)	300

Table 17: Measurements and Results D3

- Theoretical Values:
  - DC analysis:

The capacitors are open circuits.

$$V_G = \frac{R_{G2}}{R_{G2}+R_{G1}} V_{DD} = \frac{10k}{10k+15k} \times 12 = 4.8\ V$$

1. MOSFET is in the saturation region: $I_D = \frac{k}{2}(V_{GS} - V_T)^2$
2. KVL: $V_{GS} = V_G - R_{S2} I_D$

Equating 1 & 2:

I_D = ½ x 0.27166 (4.8 – 1K*I_D – 2.289)^2

I_D = 2.67*10^{-3} mA OR I_D = 2.36*10^{-3} mA (Correct)

Conditions to check in the saturation region:

- V_{GS} = 4.8 – 2.36 = 2.44 >V_T = 2.289V

  => MOSFET operating.

- V_{DS} = V_{DD} – (R_D + R_{S2})I_D = 12 – (2*10^3)*2.36*10^{-3} = 7.28 V

  V_{DS} > V_{GS} – V_T > 0.151 V

- $g_m = \frac{2 \times I_D}{V_{ov}} = \frac{2 \times 2.36 \times 10^{\wedge}-3}{0.151}$ = 0.029
- $A_V = -g_m \times (R_L || R_D)$ = -0.029 * $\frac{3.3k*1k}{4.3k}$ = -22.258 V/V

- Bandwidth:

Bandwidth = $f_2 - f_1$ = 300*10^3-270 = 299.730 KHz

3. DISCUSSIONS

- The presence of capacitors limits the MOSFET:
  4. At low frequencies: the capacitor acts as an open circuit (X=1/WC; Low W) the output voltage will drop and the gain Vo/Vi drops.
  5. At high frequencies: the capacitor acts as a short circuit. The MOSFET will no longer be in Saturation region: It will not operate as an amplifier at high frequencies. The gain Vo/Vi drops.

- When the MOSFET amplifier block was not connected, the output voltage did not show any distortion even when the input amplitude became large. On the other hand, when the block is connected, the MOSFET biasing is affected by the amplitude increase changing the operation region from saturation to triode region. Hence, at high frequencies, the MOSFET will not work as an amplifier and the output signal is distorted.

E. MOSFET as a Current Source

1. CIRCUIT DIAGRAMS

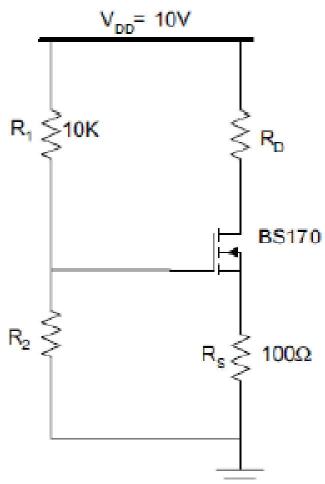


Figure 7: Circuit E1

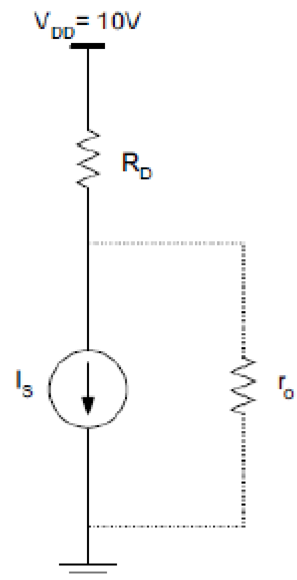


Figure 8: Circuit E2

2. DETAILED EXPERIMENTAL PROCEDURE

- Design the circuit above in order to get I_D = 10mA. Find R2:
  6. Case 1: R_D is Short Circuited:
     - Short-Circuit R_D.
     - Calculate the value of R2 (equations included below), then find the closest resistor to the calculated value from the available resistors at the lab.
  7. Case 2: R_D not Short Circuited:
     - Increase the value of R_D from 0 to 1kΩ, using 100Ω, 220Ω, 330Ω, 470Ω, 560Ω, 680Ω, 820Ω and 1kΩ resistors.
     - Measure the Drain current I_D of the transistor.
     - Measure V_{DS}: drain to source voltage.
       (RD should be measure off-circuit)

- Resistor and Internal Resistances are not taken into consideration.

3. MEASUREMENTS AND RESULTS

- Equations:
  1. Saturation Region: I_D = 10 mA – K = 0.27166

     $I_D = k/2\ (V_{GS}-V_T)^2 \Rightarrow V_{GS} = 2.56V$
  2. $V_{GS} = V_{R2} - Rs*Is \Rightarrow V_{R2} = 3.56V$
  3. $V_{R2} = \frac{R2*VDD}{R2+R1} \Rightarrow R2 = 5.527\ k\Omega$

Calculate	
R_2 (kΩ)	5.527

Figure 9: Measurements and Results E1

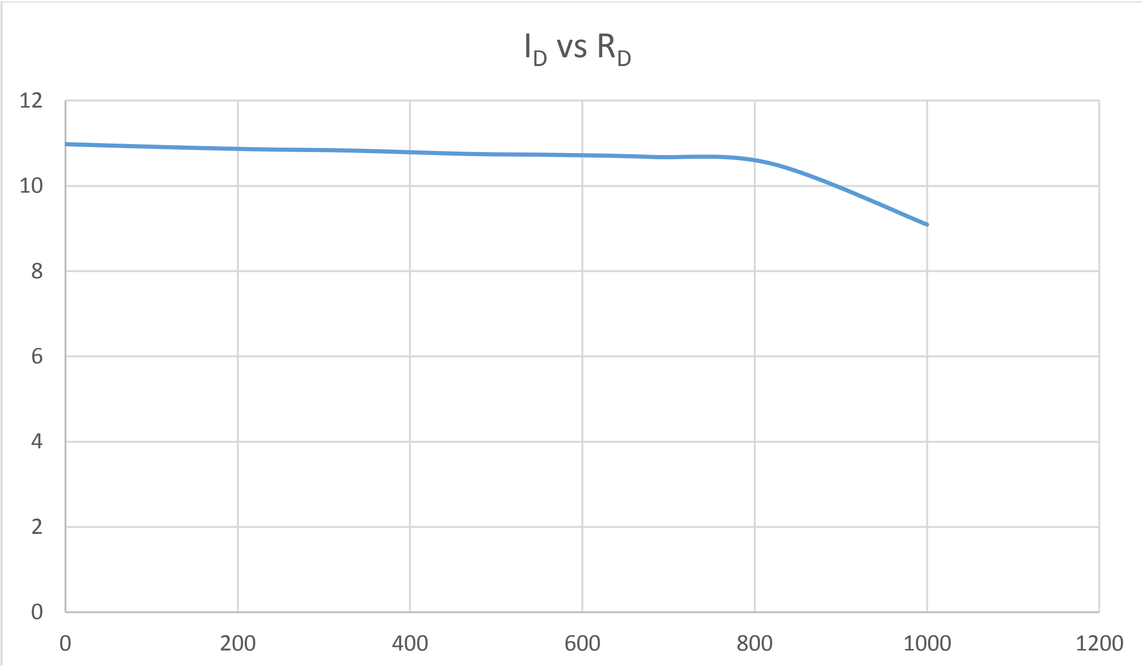
R_D (Ω)	V_S (V)	I_D (mA)	V_{DS} (V)
0	1.1	11	8.83
470	1.09	10.9	3.76
1000	0.9	9	0.062

Figure 10: Measurements and Results E2

R_D (ohms)	V_S (volts)	I_D (mA)= Vs/ Rs	V_{DS} (volts)
0	1.098	10.98	8.89
100	1.092	10.92	7.79
220	1.086	10.86	6.496
330	1.083	10.83	5.236
470	1.075	10.75	3.924
560	1.073	10.73	2.945
680	1.068	10.68	1.728
820	1.052	10.52	0.331
1000	0.909	9.09	0.067

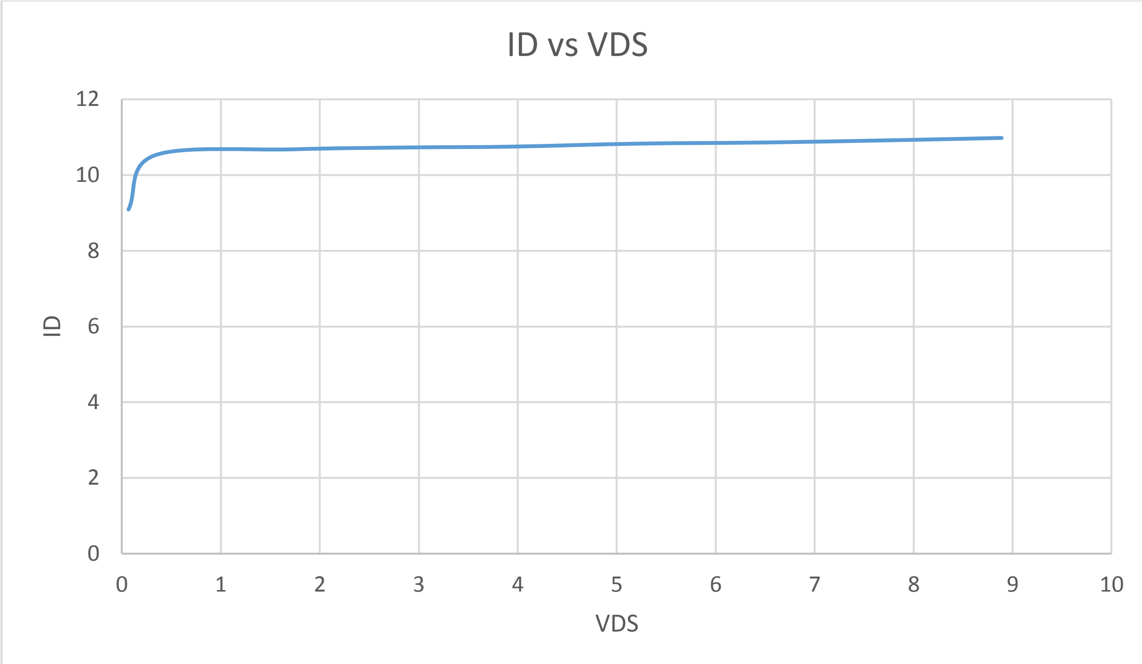
Table 18: Values Provided for analysis

4. DISCUSSIONS



Plot 5: E1 - Id VS Rd

- The current is constant for R_D = 0 - 820 Ω. We note that I_D is constant when R_D is low, the transistor behaves as a current source.
- The transistor behaves as a current source Is = 10 mA.



Plot 6: E2 - I_D VS V_{DS}

- The current is constant for V_{DS} = 7.79V – 0.067V. We note that the drain current is constant for high values of V_{DS} in saturation region. On the other hand, if V_{DS} is too small, the MOSFET will no longer be in Saturation region, it will be in triode region: no longer a current source.
- This range corresponds to the saturation region of the MOSFET.
- Resistor r_0: (Plot E2-above)

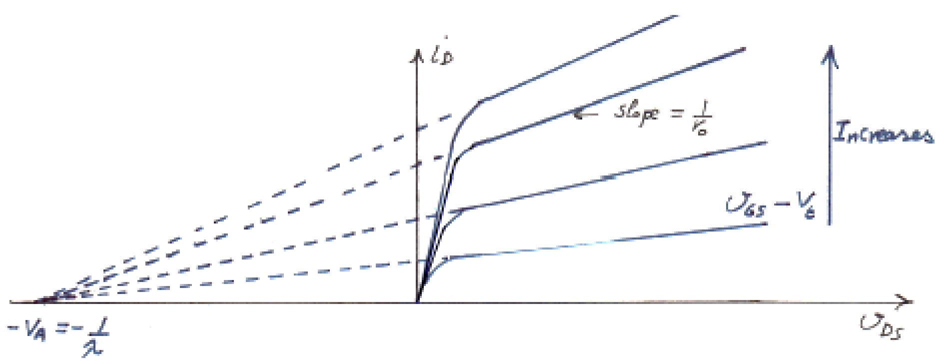


Figure 11: Slope r0

I_D (mA)	V_{DS} (V)
9	0.062
10.9	3.76
11	8.83

Table 19: Slope r0

- r_o=1/(slope of the saturation region) = 1/ (11 -10.9)*10^{-3}/(8.83-3.76) = 50.7 kΩ

REFERENCES

- EECE 310L Experiment 4
  http://moodle.aub.edu.lb/pluginfile.php/227622/mod_resource/content/2/LAB_04_RC%20and%20RLC%20Circuits.pdf
- EECE 310L Lab Report Format
  http://moodle.aub.edu.lb/pluginfile.php/227540/mod_resource/content/4/lab%20report%20format.pdf
- Moodle in lab page (Experiment 9)
  http://moodle.aub.edu.lb

MISTAKES AND PROBLEMS FACED

- The main problem faced in the lab was the malfunctioning or burned MOSFETS from previous teams.

"I HAVE NEITHER GIVEN NOR RECEIVED AID ON THIS REPORT NOR HAVE I CONCEALED ANY VIOLATION OF THE AUB STUDENT CODE OF CONDUCT."

Signature: