EECE 310L: Electric Circuits Laboratory

Experiment 10: MOS Transistors

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Group 2

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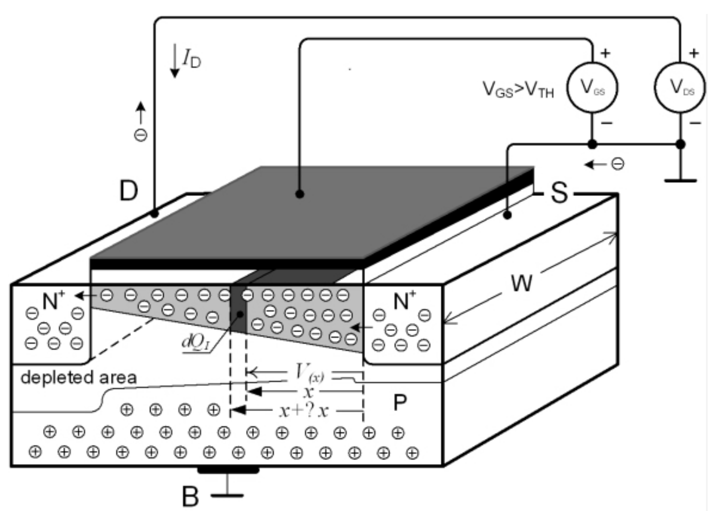

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I. Objectives:

- Investigate the characteristics of the Metal-Oxide Field Effect Transistors.
- Study MOSFET's applications as:
  - Voltage-controlled resistor
  - Logic gate
  - Amplifier
  - Current source

II. Lab Equipment Used:

- Function Generator (Agilent 33120A)
- Oscilloscope (Tektronix TDS220)
- DC Power Supply (Tektronix PS 280)
- Digital Multimeter (Fluke 45)
- Breadboard

III. **Lab Tools Used:**

No soldering or connecting tools were basically used since the circuits were built as testing circuits on the breadboard.

IV. **Components Used:**

Resistors:

Theoretical Value (Ω)	Measured Value (Ω)	% Error
100	99.6	0.4
470	466.6	0.7
1000	1038	3.8
3300	3240	1.8
4700	4667	0.7
10000	9881	1.2
15000	14939	0.4

Capacitors:

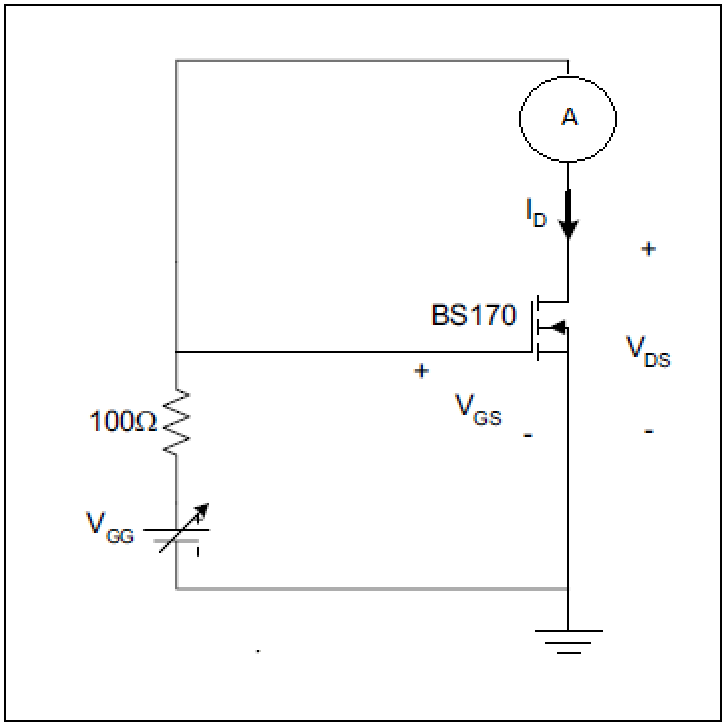
Theoretical Value (uf)	Measured Value (uF)	% Error
10 (3 units)	NA	NA

MOSFETS: BS170 N-channel enhancement type MOSFET

VI. Experimental Procedure and Discussion

A. MOSFET Characteristics

A1. Circuit Diagrams:



A2. Detailed Experimental Procedure:

We setup the circuit shown above on the breadboard in which V_{GG} represents the master or the slave of the dc power supply. Since V_{GD} = 0 V then the MOSFET is in the saturation region as long as the channel is enhanced (i.e. $V_{GS} > V_T$). In this setup we are interested in finding the threshold voltage and the transconductance parameter of the MOSFET.

We start increasing V_{GG} from 0.5V to the value that gives a 10mA current in the digital multimeter and we record the corresponding value of **V_{GS} (and not V_{GG})** using the voltmeter. Then we keep on increasing V_{GG} to read a current of 25mA and record the value as before. Now, neglecting channel length modulation the current in the drain (or the source) is given by: $i_D = \frac{1}{2}k(V_{GS} - V_T)^2$. Since the transconductance parameter k is constant and independent of the current or V_{GS} then $\frac{i_{D1}}{i_{D2}} = \frac{(V_{GS1} - V_T)^2}{(V_{GS2} - V_T)^2}$ (where i_{D1}, i_{D2}, V_{GS1}, and V_{GS2} are all known values). By solving this equation we get the value of V_T and when we substitute V_T in either of the two current equations we get k.

As to verify the values, we know that $i_D = \frac{1}{2}k(V_{GS} - V_T)^2 \Rightarrow V_{GS} = \sqrt{\frac{2i_D}{k}} + V_T$. So we keep on increasing V_{GG} further to get a current of 40mA and we measure V_{GS} using the voltmeter. The smaller the error between the measured V_{GS} and the calculated one using the formula above, then the better are the values of the parameters we got.

A3. Measurements and Results:

Measure	
I_D	V_{GS} (Volts)
10 mA	2.1122
25 mA	2.2785

Calculate		Units
K	0.244	A/V^2
V_T	1.826	V

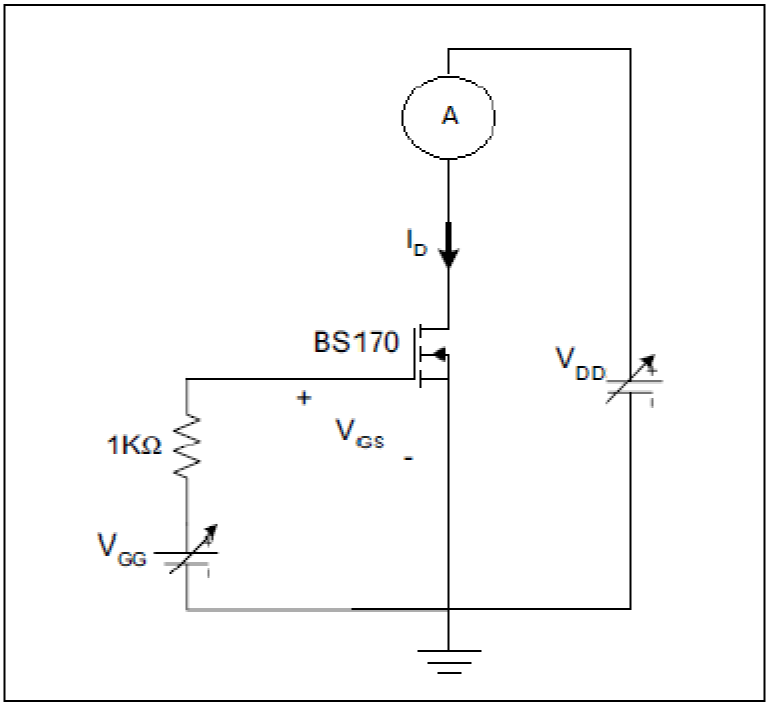
Calculated Vs Measured	
V_{GS} Calculated (volts)	2.39
V_{GS} Measured (Volts)	2.42

A4. Discussions:

The percent error between the calculated value of V_{GS} and the measured one is 1.255% which is relatively small and proves that the values of the obtained parameters V_T and k are accurate. This small error can be referred to the fact that we neglected channel length modulation and to measurement inaccuracies.

B. MOSFET as a Voltage-Controlled Resistor

B1. Circuit Diagrams:



B2. Detailed Experimental Procedure:

We build the circuit shown above in which the source is grounded and the gate and the source are connected to the master and slave of the power supply. As will be described later, the MOSFET is operating in the triode region (as long as V_{GG} > V_T and V_{GG} > V_{DD}) where it acts as a resistor. To study the resistance of the MOSFET we should get the values of V_{DS} and i_D for each setup.

So we set $V_{GG} = V_T + 2$ and we start increasing V_{DS} and recording the corresponding values of i_D. Then we repeat the same procedure for $V_{GG} = V_T + 3$ and $V_{GG} = V_T + 4$.

B3. Measurements and Results:

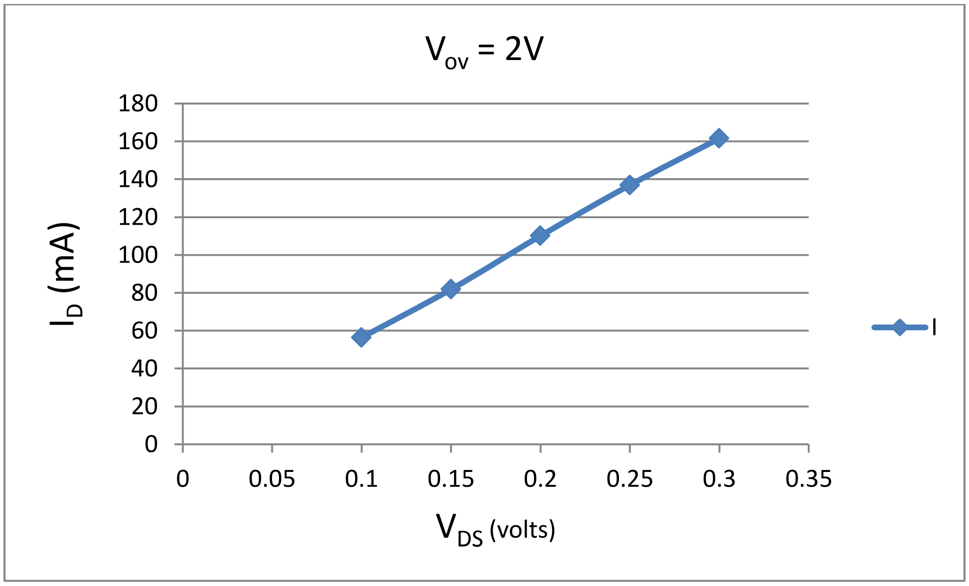
V_{GS}-V_T =2 Volts	
V_{DS} (Volts)	I_D (mA)
0.1	56.4
0.15	81.86
0.2	110.12
0.25	136.92
0.3	161.55

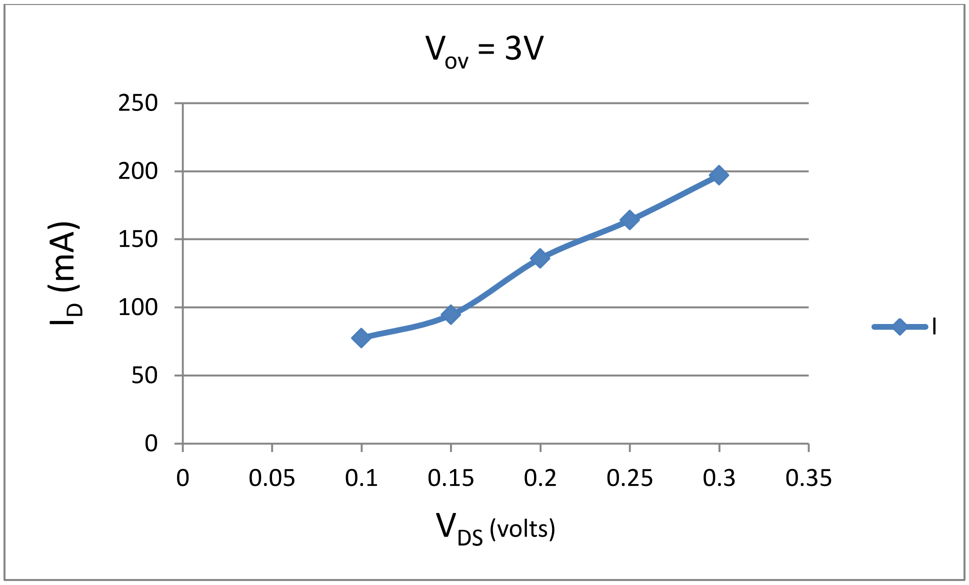
V_{GS}-V_T =3 Volts	
V_{DS} (Volts)	I_D (mA)
0.1	77.5
0.15	94.53
0.2	136
0.25	164
0.3	197

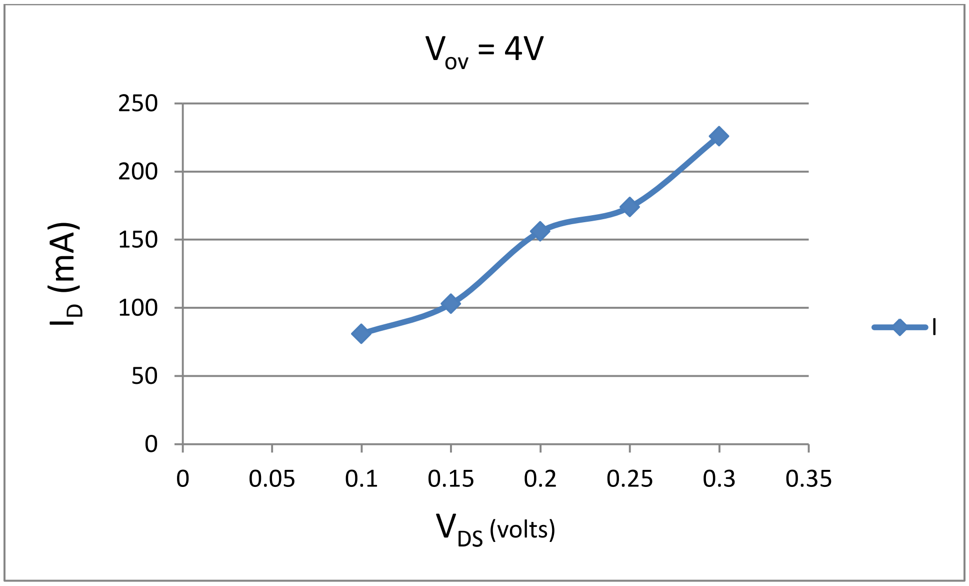
V_{GS}-V_T =4 Volts	
V_{DS} (Volts)	I_D (mA)
0.1	81
0.15	103
0.2	156
0.25	174
0.3	226

B4. Discussions:

- Below are the graphs of i_D versus V_{DS} for each V_{ov} (Plotted using Excel)







The graphs are linear. However, it seems that graphs 2 and 3 have remarkable measurement errors which lead to some fluctuations in them.

$V_{GS} - V_T$ (Volt)	Slope* (mA / V)	R_{DS} (ohm)
2	530.72	1.884
3	616.94	1.621
4	722.00	1.385

* The slopes are calculated using the least-square regression method (by Excel)

- The MOSFET is biased to operate in the triode region. This is obvious since $V_{GS} > V_T$ and $V_{GS} > V_{DS}$ for all the setups above. The triode region is also referred to as "linear" or "ohmic" since the relation between V_{DS} and i_D is linear in which the MOSFET acts as a resistor (i.e. the v-i relation satisfies ohm's law V= Ri).
- The i-v equation of the MOSFET in the triode region is given by:

  $i_D = \frac{1}{2}k(2(V_{GS} - V_T)V_{DS} - V_{DS}^2)$, but since V_{DS} is too small then the term V_{DS}^2 can be neglected yielding $i_D = k(V_{GS} - V_T)V_{DS} \Rightarrow R_{DS} = \frac{1}{k(V_{GS} - V_T)}$ which is a resistor whose resistance is controlled by the value of V_{GS}.

  The percent error in i_D after neglecting $0.5V_{DS}^2$ should be less than 5% thus:

  $$\left|\frac{i_{D1} - i_{D2}}{i_{D1}}\right| \leq 0.05 \Rightarrow \frac{k(V_{GS} - V_T)V_{DS}}{k((V_{GS} - V_T)V_{DS} - 0.5V_{DS}^2)} \leq 1.05$$

Eliminating k and V_{DS} we get $\frac{(V_{GS}-V_T)}{(V_{GS}-V_T)-0.5V_{DS}} \leq 1.05$ and thus

$V_{DS} \leq \frac{2}{21}(V_{GS}-V_T)$ for the error in the current to be less than 5%.

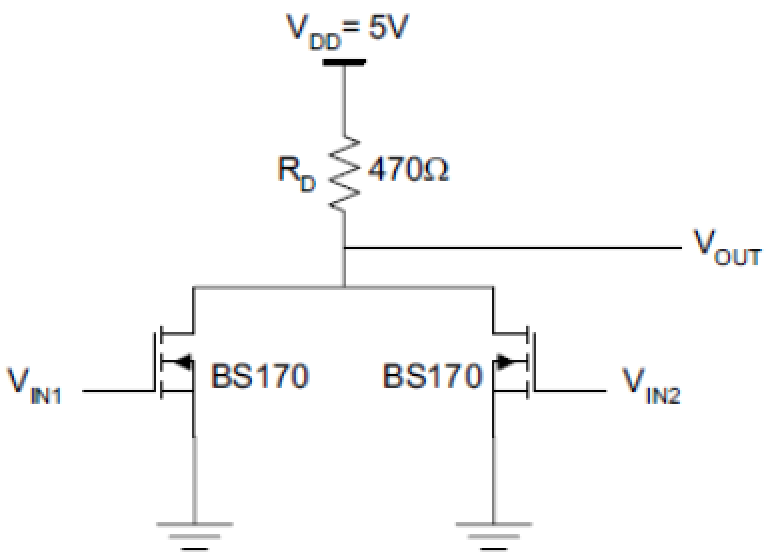
$V_{GS} - V_T$ (Volt)	R_{DS} Calculated (ohm)	% Error
2	2.049	8.75
3	1.366	15.73
4	1.024	26.06

The error is large especially in the third case and this normal if we observe the non-linearity of the curve corresponding to $V_{GS} - V_T$ = 4V. The latter maybe due to measurement errors as described before.

- Applications of MOSFETs in the linear region include:
  - Variable gain amplifiers where the gain is controlled by a variable voltage between the gate and the source.
  - Analog Filters

C. MOSFET as Logic Gate

C1. Circuit Diagrams:



C2. Detailed Experimental Procedure:

We connect the circuit shown above where the gates of both MOSFETs are connected to the inputs and the output is across the common drain. Each MOSFET in the circuit will operate either in triode or cutoff regions which allows the MOSFET to operate as 2-input NOR gate. We will apply the 4 logic input combinations to verify that. After that, we set V_{in2} to 0 and we vary V_{in1} over several values to get the output values and deduce the corresponding regions of operation.

C3. Measurements and Results:

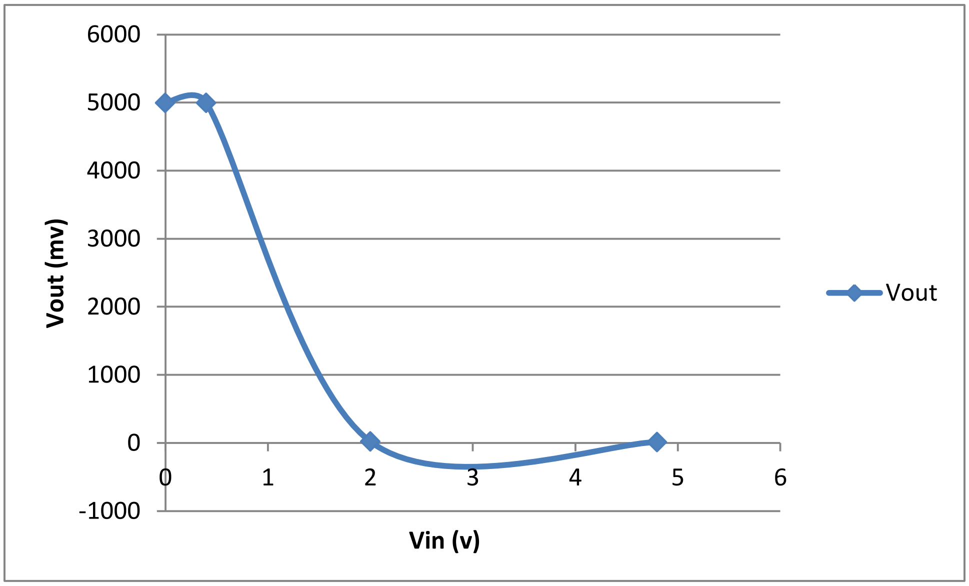
IN1 (logic)	IN2(logic)	Out(logic)	V_{IN1}(V)	V_{IN2} (V)	V_{out} (mV)
0	0	1	0.0	0.0	5200
0	1	0	0.0	5	10.2
1	0	0	5	0.0	10.2
1	1	0	5	5	1.4

V_{IN1} (V)	V_{out} (mV)	MOSFET Region (cutoff, Saturation, or Triode)	logic value at output (0,1, no)
0	4995	cutoff	1
0.4	4995	cutoff	1
2.0	2.34	saturation	no
4.8	12.53	triode	0

C4. Discussions:

- As shown in the results, this MOSFET has a V_H = 5.2 V and V_L = 10.2 mV
- When at least one of the MOSFETs is operating in triode the output of the circuit would be logic 0. The MOSFET can be modeled by a resistor in the

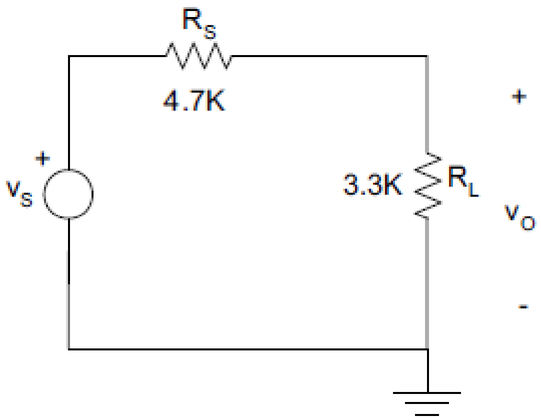
triode region with resistance $R_{DS} << R_D$, thus R_D makes the logic 0 equivalent to a very low output voltage due to the voltage divider $V_o = \frac{R_{DS}}{R_{DS} + R_D} V_{DD}$ (This divider applies if exactly one MOSFET is in triode, however, if both MOSFETs are in triode then $V_o = \frac{R_{DS1} \| R_{DS2}}{(R_{DS1} \| R_{DS2}) + R_D} V_{DD}$). Increasing R_D would make the denominator of the voltage dividers bigger and thus V_{OL} would decrease, thus R_D and V_{OL} are inversely proportional. Note: R_D has no effect on the output when the MOSFETs are both in cutoff.

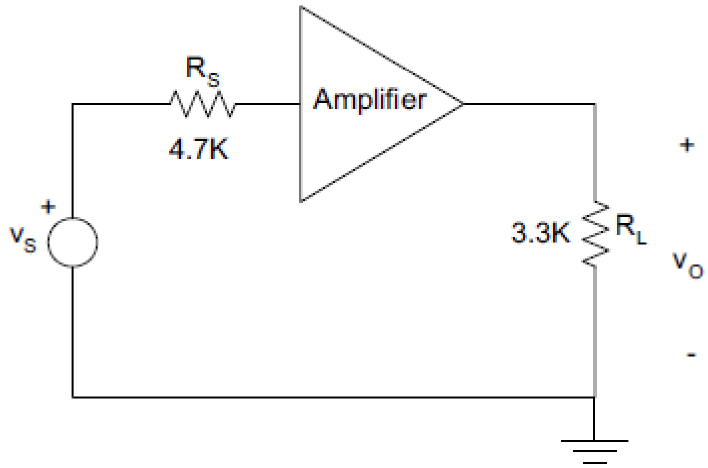


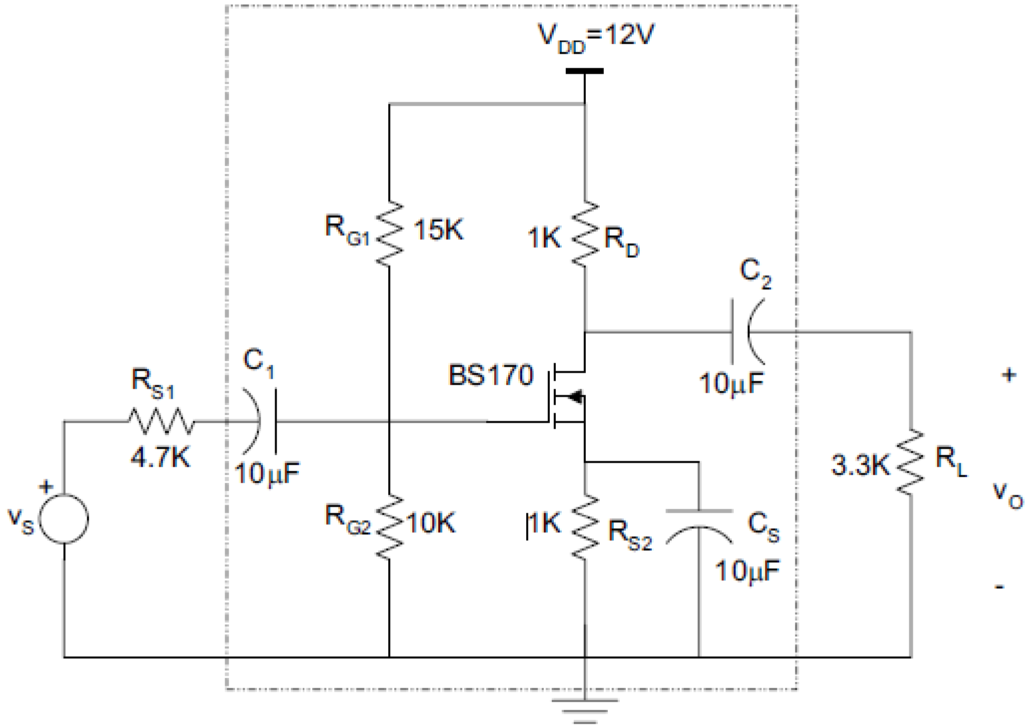
The above graph just shows the shape of the real graph due to the limited number of data points (We have 4 points only!). Graphically, the MOSFET changes from cutoff to saturation at $V_{in1} \approx 0.4V$, and it changes from saturation to triode at $V_{in1} \approx 2V$.

D. MOSFET as an amplifier

D1. Circuit Diagrams:







D2. Detailed Experimental Procedure:

We connect the first circuit where the amplifier is not inserted and we should observe two important points:

- The voltage gain can't exceed 1 and thus the circuit acts as an attenuator.
- There is input signal frequency does not affect gain.

Then we connect the circuit with the MOSFET acting as an amplifier and capacitors to isolate the DC and AC components of the input and output. Note also that the MOSFET is biased to operate in the saturation region in order to avoid output signal distortion.

After that we measure the maximum value of the output in saturation, and we vary the frequency to relatively low and high frequencies to get the high and low cutoff frequencies where the amplitude is $\frac{1}{\sqrt{2}}$ it's value at saturation.

D3. Measurements and Results:

Perform DC analysis, thus

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

$$i_D = \frac{1}{2} k (V_{GS} - V_T)^2 \Rightarrow i_D = \frac{1}{2} k (V_G - R_{s2} i_D - V_T)^2$$

$$i_D = \frac{1}{2}(0.244)(4.8 - 1000 i_D - 1.826)^2 \Rightarrow \boxed{i_{D1} = 2.8219\,mA}(accepted)\,or\, i_{D2} = 3.1342\,mA(rejected)$$

$$\boxed{V_{GS} = 4.8 - 2.8219 = 1.978V} > V_T \Rightarrow Accepted$$

$$\boxed{V_{DS} = 12 - 2x2.8219 = 6.3562V}$$

Perform AC analysis, thus

$$g_m V_{gs} + V_O\left(\frac{1}{R_D} + \frac{1}{R_L}\right) = 0$$

$$\frac{V_O}{V_{gs}} = \frac{-g_m}{\frac{1}{R_D} + \frac{1}{R_L}} = -28.5\, V/v$$

$$\Rightarrow A_v = \frac{V_O}{V_{sig}} = \frac{V_O}{V_{gs}}\frac{V_{gs}}{V_{sig}} = -28.5\,x\,\frac{60}{107} = -15.98\, V/v$$

	Value
I_D (DC) mA	3.48
V_{GS} (DC) Volts	1.22
V_{DS} (DC) Volts	5.1

For sure this measured value is wrong! Since $V_{GS} > V_T$. This was due the malfunctioning MOSFET.

	Value
V_S PK-PK (mV)	115
V_I PK-PK (mV)	64.8
V_O Pk-PK (mV)	960
Phase Shift (V_I, V_o) degrees	180

Bandwidth Measurements	
F_{low} (Hz)	430
F_{High}(KHz)	180

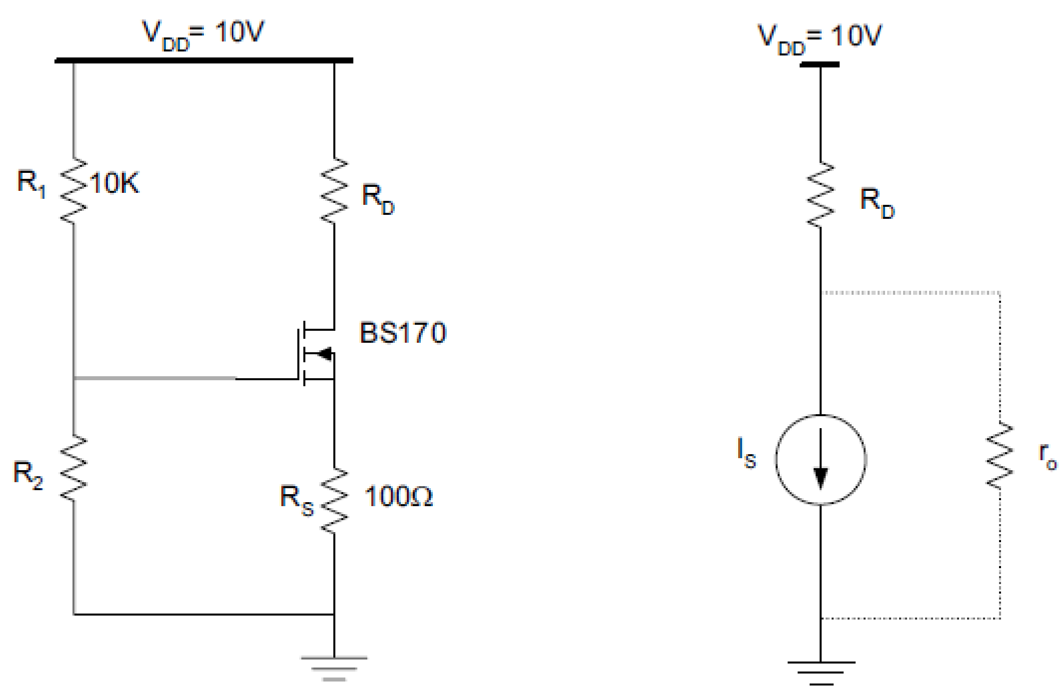
D4. Discussions

- The error between the calculated and measured values is vast (reaches 50% for the gain!) and this is due to the malfunctioning MOSFET that we got. Note: As indicated in the datasheet of the BS170 some MOSFETs may have a V_L as low as 0.8V and this may be the problem (When we measured V_T in the first part we did that on a different MOSFET).
- At low and high frequencies the capacitors in the circuit will affect the amplification bandwidth. At low frequencies, the capacitors will act as open circuits ($Z_C = \frac{1}{j\omega C}$) and thus the signal source would be disconnected from the amplifier (i.e. the MOSFET) and the output would drop to values as low as zero. However, at high frequencies the capacitors would become short circuits and thus affecting the biasing of the MOSFET and taking it from the saturation region.

- When the amplitude of the signal becomes large if the MOSFET was connected, the biasing of the MOSFET will change at the extremities (or the high values) of the signals to cutoff and triode and thus the signal would distorted. In order not to get distortion the two conditions $V_{GS(Total)} > V_T$ and $V_{DS(Total)} > V_{GS(Total)} - V_T$.

E. MOSFET as a current source

E1. Circuit Diagrams:



E2. Detailed Experimental Procedure:

Since the MOSFET is to be operated as a current source then it must be biased to the saturation region where the i-v relation is (neglecting channel length modulation):

$$i_D = \frac{1}{2} k (V_{GS} - V_T)^2$$

$$i_D = \frac{1}{2} k (V_G - R_s i_D - V_T)^2$$

$$10^{-2} = 0.122 (V_G - 1 - 1.826)^2$$ (i_D is given as 10mA)

$$\Rightarrow V_G = 3.1123 \; but \; V_G = \frac{R_2}{R_2 + 10K} 10$$

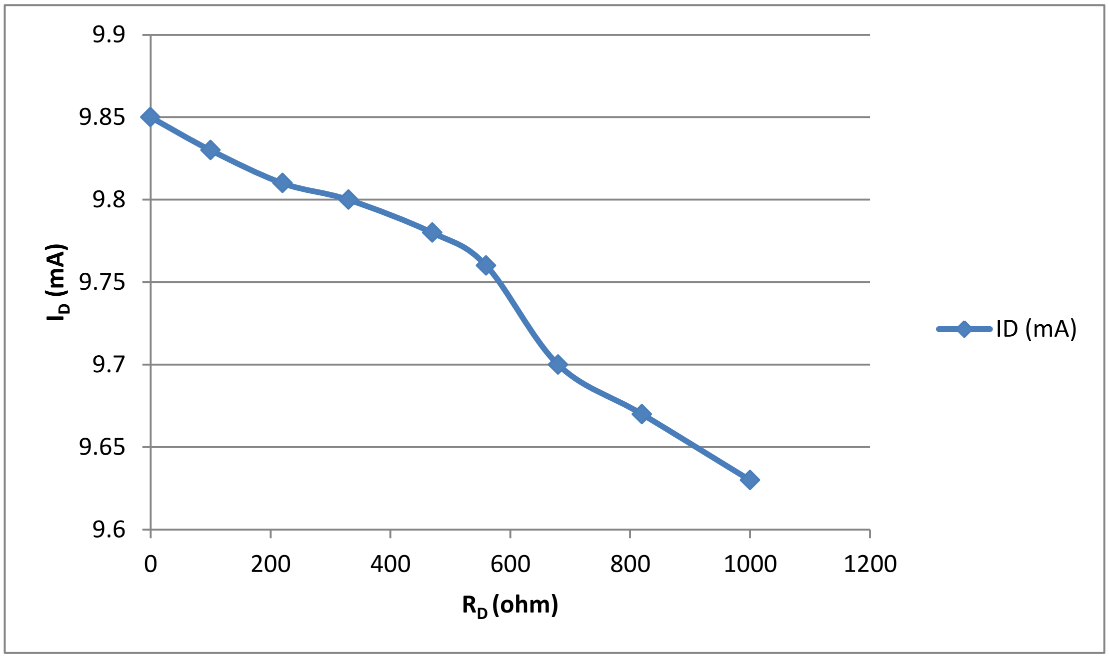
$$\therefore R_2 = 4.5186 \, K\Omega$$

So setup the above circuit with R_2 = 4.5 K Ω and vary R_D from 0 to 1000 K Ω while recording the drain current and drain to source voltage.

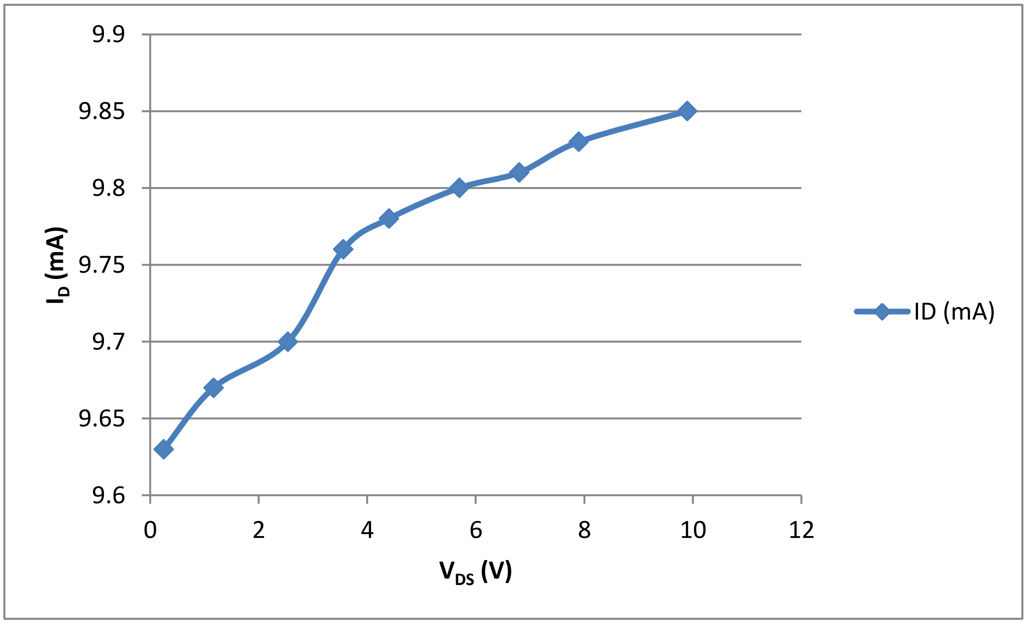
E3. Measurements and Results:

R_D (Ω)	I_D (mA)	V_{DS} (V)
0	9.85	9.9
100	9.83	7.9
220	9.81	6.8
330	9.8	5.7
470	9.78	4.4
560	9.76	3.56
680	9.7	2.54
820	9.67	1.17
1000	9.63	0.25

E4. Discussions:



- The region where I_D is constant can be approximated by the part of the curve with least value for the derivative; this i_D is constant between 220 and 560 ohms (The deviation is not given, so approximations are arbitrary).
- The value of I_D is about 9.78 mA.



- I_D is approximately constant for the range 4.4-9.9 V.
- This range corresponds to the saturation region since I_D is independent of V_{DS} (The small variation is due to channel length modulation).
- $R_O = \frac{1}{\frac{\delta i_D}{\delta V_{DS}}} = \frac{1}{slope} = 7\,k\Omega$ where R_O is the output resistance is saturation.

VI- References:

- Sedra Smith – Microelectronic Circuits 6th Edition
- Lecture Notes

VII- Mistakes and Problems faced in the lab:

We had initially a malfunctioning MOSFET, so the instructor replaced it with another malfunctioning one which wasted a lot of our time.

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