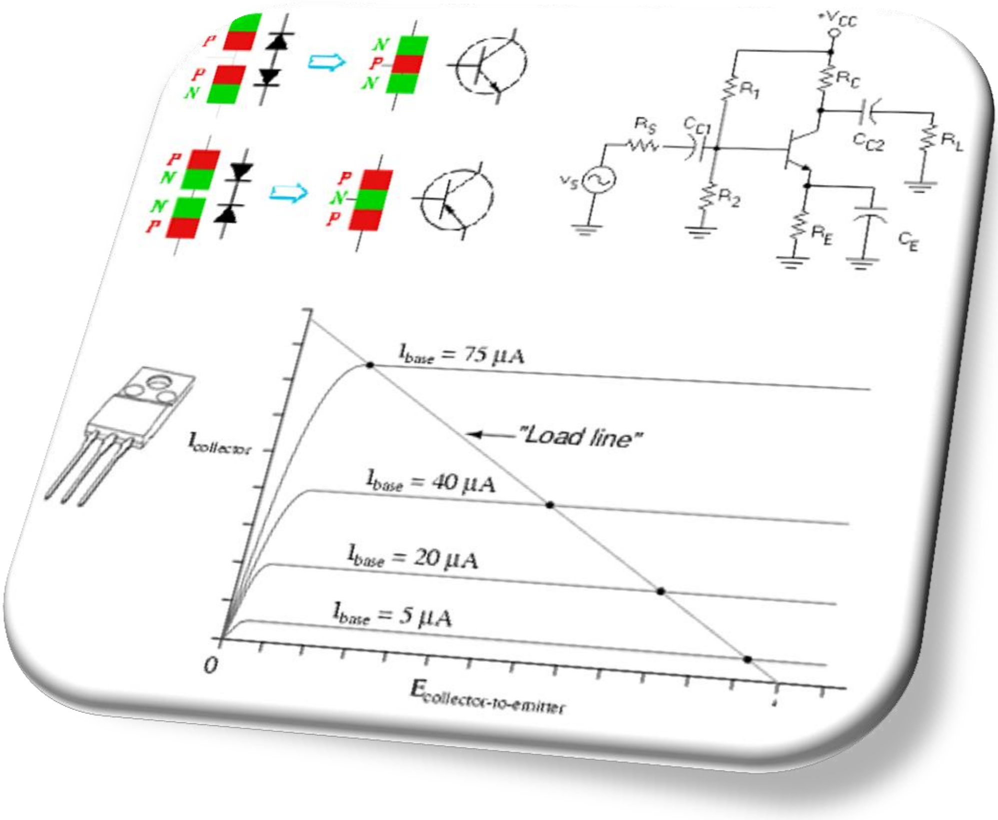
Fall | 2011

Experiment 10

MOS Transistor



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I. OBJECTIVES

In this experiment you will investigate the characteristics of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) and study its application as:

- Voltage-controlled resistor
- Logic gate
- Amplifier
- Current source

II. MATERIAL AND PROCEDURE

A. MOSFET CHARACTERISTICS

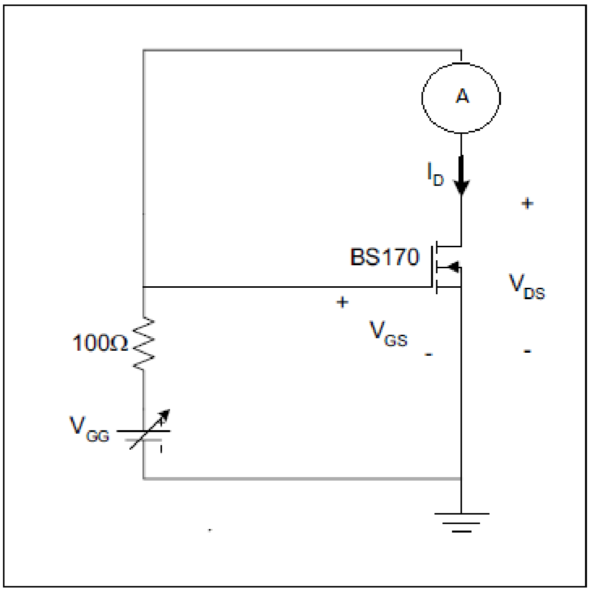

Figure A-1: MOSFET Circuit

Connect the circuit shown in Figure A-1. We will use this circuit to find the important parameters of the BS170 metal-oxide-semiconductor field-effect transistor (MOSFET), namely the transconductance parameter k and the threshold voltage V_T. These two parameters, together with the gate-to-source voltage V_{GS}, determine the drain current of the MOSFET in the saturation region:

$$I_D = \frac{k}{2}(V_{GS} - V_T)^2 \text{ when } V_{GS} > V_T \text{ and } V_{DS} > V_{GS} - V_T$$

Since V_{DS} = V_{GS} in the circuit, and since V_T is positive for the BS170, which is an enhancement type N-channel MOSFET, the transistor is in the saturation region whenever $V_{GS} > V_T$.

To find only two unknown parameters, we will take two measurements: the first measurement is the value of V_{GS} that results in a drain current I_D of 10 mA, and the other is the value of V_{GS} that results in a drain current of 25 mA.

Starting with V_{GG} = 0.5 V, slowly increase the value of V_{GG} until the drain current is exactly 10 mA. Increase V_{GG} further until the drain current is exactly 25 mA. Read the value of V_{GS}. Record your results in table A-1.

Measure	
I_D	V_{GS}
10 mA	
25 mA	

Table A-1

- From the two values of current and voltage, calculate k and V_T. Record your results in table A-2.

Calculate		**Units**
K		
V_T		

Table A-2

Increase V_{GG} to get a drain current of 40 mA. Read the value of V_{GS}. Compare the measured value of V_{GS} with that predicted from the equation:

$$V_{GS} = V_T + \sqrt{\frac{2I_D}{k}}$$

- Record your results in table A-3.

Calculated Vs. Measured	
V_{GS} Calculated	
V_{GS} Measured	

Exercise

- Refer to in-lab 10 exercise A-1

B. MOSFET AS A VOLTAGE-CONTROLLED RESISTOR

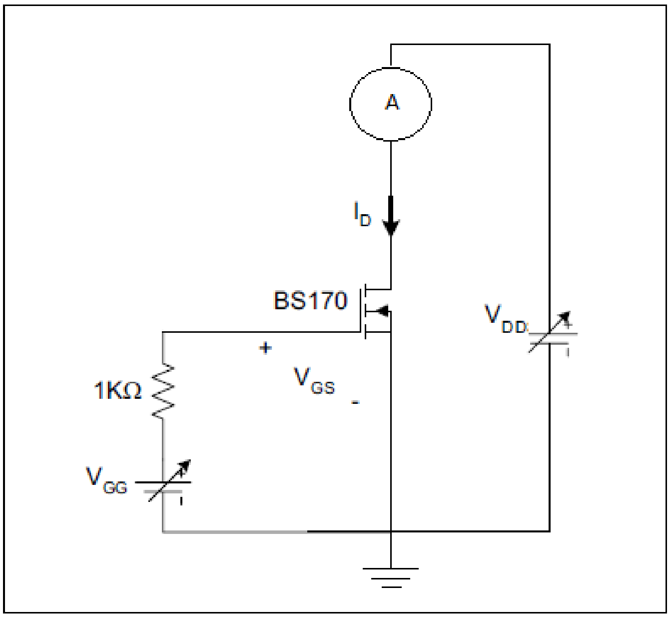

Figure B-1: Voltage controlled resistor

Connect the circuit shown in Figure B-1.

Using the value of V_T calculated in part A, set $V_{GG} = V_T + 2$ V. Since the gate current of the MOSFET is zero, $V_{GS} - V_T$ is therefore equal to 2 V.

- With the ammeter connected as shown in figure B-1, regulate V_{DD} to get V_{DS} equal to 0.1 V and measure I_D.
- Repeat for the values provided in Table B-1.
- Repeat for V_{GS} equal to V_T + 3 V and V_T + 4 V.
- Record them in tables B-1, B-2 and B-3.

$V_{GS} - V_T$ (Volt)	V_{DS} (Volt)	I_D (mA)
2	0.1	
2	0.15	
2	0.2	
2	0.25	
2	0.3	

Table B-1

V_{GS} - V_T (Volt)	V_{DS} (Volt)	I_D (mA)
3	0.1	
3	0.15	
3	0.2	
3	0.25	
3	0.3	

Table B-2

V_{GS} - V_T (Volt)	V_{DS} (Volt)	I_D (mA)
3	0.1	
3	0.15	
3	0.2	
3	0.25	
3	0.3	

Table B-3

Exercise

- Refer to in-lab 10 exercise B-1

Discussion on Part B

For each value of V_{GS} - V_T (2, 3, and 4 V), plot I_D versus V_{DS}

- What kind of curve do you get?
- What is the slope for V_{GS} - V_T = 2, 3, and 4 V?
- The inverse of the slope has units of V/A or Ohms. What is the resistance between drain and source of the MOSFET when V_{GS} - V_T = 2, 3, and 4 V? Complete TABLE B-4.

V_{GS} - V_T (Volt)	R_{DS} (Ohm)
2	
3	
4	

Table B-4

Note ***The MOSFET is effectively acting as a linear resistor connected between the drain and source terminals, since*** $I_D = \frac{V_{DS}}{R_{DS}}$. ***The value of this resistor, however, is not constant, but depends on*** V_{GS} - V_T. ***The MOSFET in this case is a voltage-controller resistor.***

- In what region of operation is the MOSFET biased for the conditions described above?
  - Can you explain why this region is called linear, or ohmic?

Discussion on Part B cont'd

- The current equation in the linear or ohmic region is given by:

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

  - How is this equation related to the voltage-controlled resistor behavior of the MOSFET that you have just seen?
  - For what range of values of V_{DS} is the linear resistor approximation valid (i.e. the error in current values is less than 5%)?
  - What is the value of R_{DS} that you get from the equation? How does it compare with the values of R_{DS} in TABLE B-4 (use the value of k calculated in part A)?

- List some applications of a voltage-controlled resistor.

C. MOSFET AS LOGIC GATE

Circuit Diagram

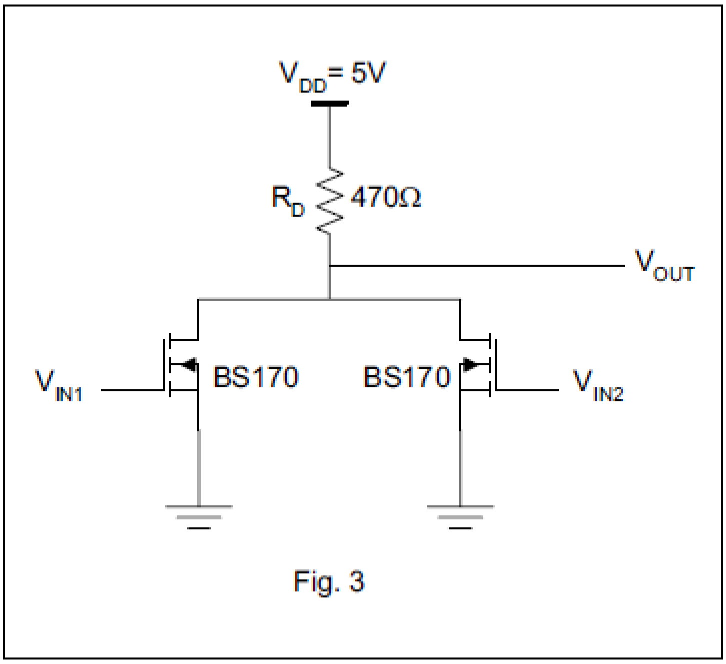

Figure C-1: MOSFET as Logic Gate

Connect the circuit shown in Figure C-1. This circuit implements a logic gate; we will determine in this part of the experiment the logic function of this gate and study its characteristics. There are two inputs IN1 and IN2, and one output OUT.

To build the truth table of this gate, we apply all possible combinations of inputs, and observe the output. Start with IN1 = logic **0** and IN2 = logic **0**. To get a logic **0**, we will connect the input nodes to ground. What is the value of the output in this case? This is the value of voltage that corresponds to logic **1**.

Apply a logic **1** at IN1, and a logic **0** at IN2, and observe the output. Repeat for IN1 = logic **0**, IN2 = logic **1**, and for IN1 = logic **1** and IN2 = logic **1**. Complete the truth table below (TABLE C-1):

IN1 (logic)	IN2 (logic)	OUT (logic)	V_{IN1} (V)	V_{IN2} (V)	V_{OUT} (V)
0	0	1	0.0	0.0	
0	1		0.0		
1	0			0.0	
1	1				

Table C-1

- ***From the truth table, what is the logic function of this gate?***

- With V_{IN2}= 0 V, vary V_{IN1} from 0 to 5 V in steps of 0.4 V and measure V_{OUT}. Complete TABLE C-2.

V_{IN1} (logic)	V_{OUT} (Volt)	MOSFET region of operation	Logic value at output
0			
0.4			
0.8			
1.2			
1.6			
2			
2.4			
2.8			
3.2			
3.6			
4			
4.4			
4.8			

Table C-2

Exercise

- Refer to in-lab 10 exercise C-1

Discussion on Part C

- For this MOSFET gate, what are the values of *high* voltage (corresponding to logic **1**) and the *low* voltage (corresponding to logic **0**)?

  Note *When the two inputs are* high, *the output voltage is lower than the* low *value when only one input is high.*

- How is the value of the *low* voltage affected by the value of the 470 Ohm resistor? Would increasing this resistance make the output *low* value higher or lower?

- Plot V_{OUT} versus V_{IN1}.
  - At what value of the input voltage does the output switch states?

D. MOSFET AS AN AMPLIFIER

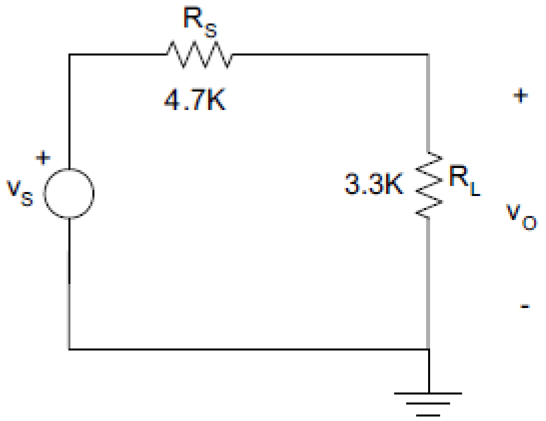

Figure D-1

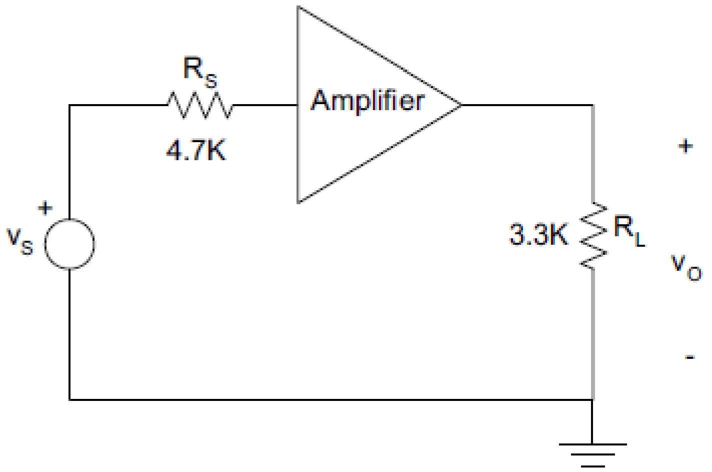

Figure D-2

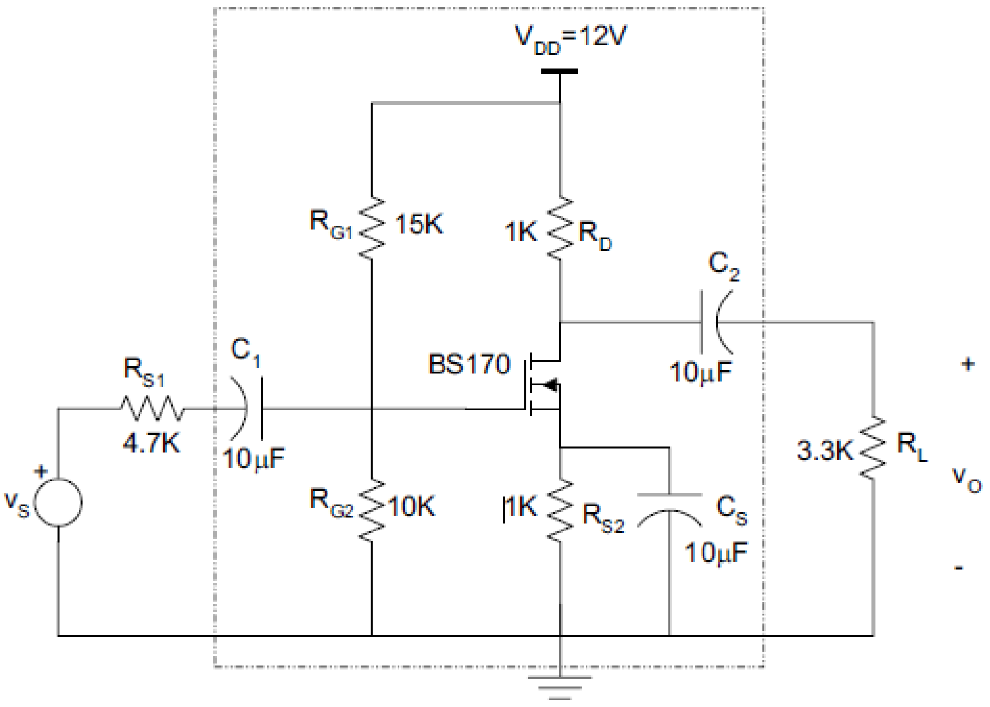

Figure D-3

In the circuit of Figure D-1 the voltage source is a 100 mV peak-to-peak, 10KHz sine signal.

The voltage gain v_O/v_S is less than 1.

If we increase the amplitude of the input signal or change the frequency (50Hz to 1MHz) and measure the ratio vO/vS we note that it is still unchanged. We will now insert an amplifier stage (Refer to figure D-2) between the source and the load, and investigate its effects and limitations.

Connect the circuit shown inside the dotted block of Fig. D-3.

- Measure the DC values of I_D, V_{GS}, and V_{DS}. Record the results in table D-1.

Measure	
I_D (DC)	
V_{GS} (DC)	
V_{DS} (DC)	

Table D-1

Note *The MOSFET* must *be in the saturation region to use it as an amplifier.*

Connect the input signal source and the load resistor to the MOSFET circuit, and observe the polarities of the coupling capacitors.

Apply a 100 mV peak-to-peak, 10 KHz sine signal as the input source.

- Measure the output voltage, and find the voltage gain, current gain, and power gain. Record the results in table D-2.

Measure	
V_S pk-pk	
V_I pk-pk	
V_O pk-pk	
Phase shift (V_I, V_O)	

Table D-2

Decrease the frequency of the input signal to less than 100 Hz and note how the output changes.

Increase the frequency of the input to more than 1 MHz and note how the output changes.

Find the bandwidth of the amplifier, defined as f_2 - f_1 where f_1 and f_2 are the frequencies at which the voltage gain of the amplifier is 0.7071 times its value at mid frequencies, with f_1 being the low frequency value, and f_2 the high frequency value. Record the results in table D-3.

Bandwidth Measurements	
V_S pk-pk	
V_I pk-pk	
V_O pk-pk	
Phase shift (V_I, V_O)	

Table D-3

Exercise

- Refer to in-lab 10 exercise D-1

Increase the amplitude of the input signal to more than 400 mV (800 mV peak-to-peak), and note how the shape of the output signal changes and becomes distorted.

Discussion on Part D

- When the MOSFET amplifier block was not connected, the bandwidth was much larger than that when we used the amplifier block. Explain what limits the bandwidth of the amplifier.
  - What causes the gain to drop at low frequencies?
  - What causes the gain to drop at high frequencies?

- When the MOSFET amplifier block was not connected, the output voltage did not show any distortion even when the input amplitude became large. This is not the case when the amplifier block is

E. MOSFET AS A CURRENT SOURCE

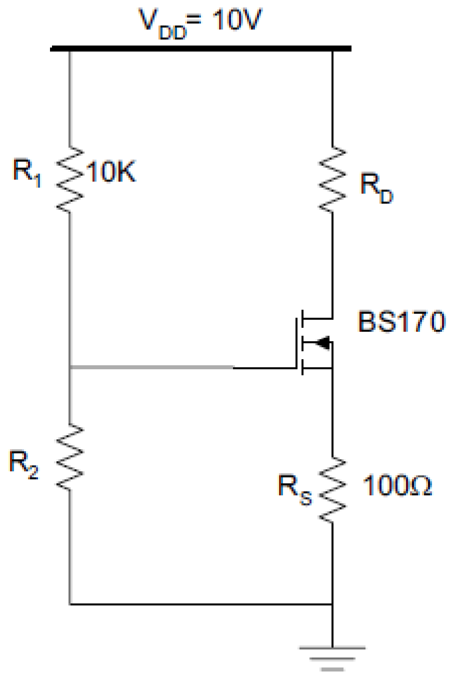

Figure E-1

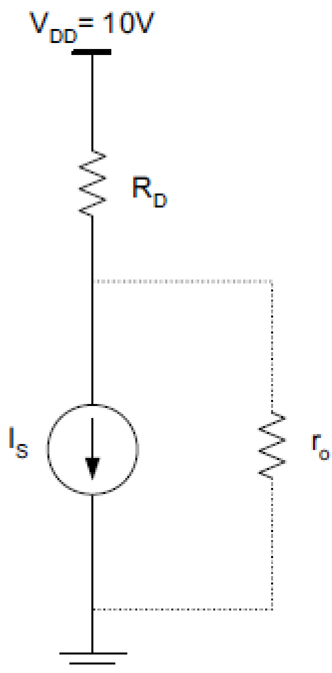

Figure E-2

Procedure

The circuit in Figure E-1 is a current source.

Using the values of k and V_T calculated in part A, find the value of R_2 needed to get a drain current of 10 mA. Record your results in table E-1.

Show your calculations to the Lab Instructor.

Calculate	
R_2	

Table E-1

Connect the circuit with R_D = 0 (short circuit).Measure I_D and V_{DS}.

Increase the value of R_D from 0 to 1 KΩ using 100 Ω, 220 Ω, 330 Ω, 470 Ω, 560 Ω, 680 Ω, 820 Ω, and 1 KΩ, resistors, and measure the drain current of the transistor and the drain-to-source voltage. Complete TABLE E-2

Note R_D should be measured *off-circuit*.

R_D (Ω)	I_D (mA)	V_{DS} (Volt)
0		
100		
220		
330		
470		
560		
680		
820		
1000		

Table E-2

Exercise

- Refer to in-lab 10 exercise E-1

Discussion on Part E

Plot I_D as a function of R_D.

- For what range of values of R_D is the current constant?

Note that for this range of R_D, the circuit in Figure E-1 is equivalent to the circuit shown in Fig. E-2. The transistor behaves as a current source.

- What is the value of the current source I_S?

Plot I_D as a function of V_{DS}.

- For what range of V_{DS} is the current in the collector constant?
- What does this range of V_{DS} correspond to?

If the current increases slightly with V_{DS}, we can model this increase by adding a resistor r_o in parallel with the ideal current source, as shown in Fig. E-2.

- Find the value of this resistor r_o.

III. OUTCOMES

By the end of Experiment 10, students:

- Are able to compute and calculate the characteristics of MOSFET
- Should understand the different application of MOSFET; voltage controlled resistor, logic gain, amplifier, and current source