LABORATORY 3

MOSFET SWITCHING CIRCUITS

OBJECTIVES

1. To determine quiescent point of a MOSFET switch and calculate the values of the resistors.
2. To simulate the MOSFET switch using MicroCap.
3. To design, simulate on MicroCap, build, and test a light sensitive MOSFET switch.
4. To build and test Arduino-controlled DC relay.
5. To build and test Arduino-controlled light sensitive switch.

INFORMATION

1. MOSFET Transistor – Typical characteristics

The **Metal Oxide Semiconductor Field Effect Transistor** (**MOSFET)** is a voltage-controlled field effect transistor, that has a "metal oxide" electrode. This electrode (known as the gate) is a conductive layer electrically insulated from the main semiconductor n-channel or p-channel by a very thin layer of insulating material. Usually this insulator is silicon dioxide, commonly known as glass.

This ultra-thin insulated metal gate electrode can be thought of as one plate of a capacitor. The isolation of the controlling Gate makes the input resistance of the **MOSFET** extremely high; way up in the Mega-ohms (MΩ) region, thereby making it almost infinite.

As the Gate terminal is isolated from the main current carrying channel **NO current flows into the gate.** The MOSFET also acts like a voltage controlled resistor were the current flowing through the main channel between the Drain and Source is proportional to the input voltage.

Precaution: The MOSFETs very high input resistance can easily accumulate large amounts of static charge resulting in the **MOSFET** becoming easily damaged unless carefully handled or protected.

The MOSFETs are three terminal devices with a Gate, Drain and Source and both P-channel (PMOS) and N-channel (NMOS) MOSFETs are available. The main difference is that MOSFETs are available in two basic forms:

- ***Depletion Type*** – the transistor requires the Gate-Source voltage, (V_{GS}) to switch the device **"OFF"**. The depletion mode MOSFET is equivalent to a "Normally Closed" switch.
- ***Enhancement Type*** – the transistor requires a Gate-Source voltage, (V_{GS}) to switch the device **"ON"**. The enhancement mode MOSFET is equivalent to a "Normally Open" switch.

In our lab we will be using Enhancement Type n-channel MOSFET transistor IRF540, shown in Figure 3.1. The electrical symbol of the MOSFET is shown in Figure 3.2.

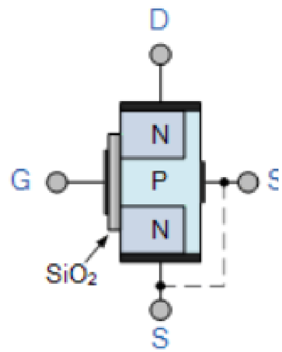


Figure 3.1. MOSFET N-P-N structure

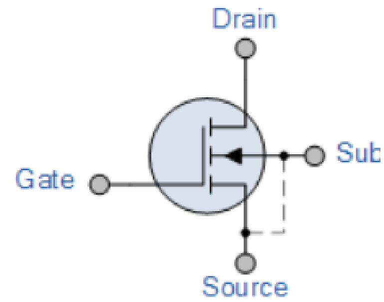
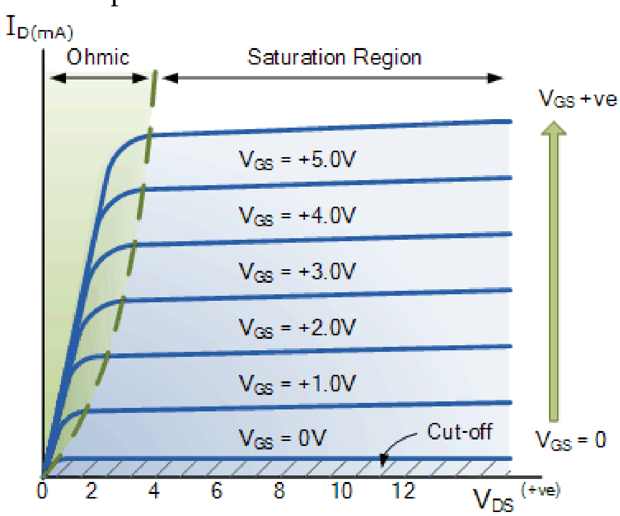


Figure 3.2. MOSFET Symbol

For the n-channel enhancement MOS transistor a drain current will only flow when a gate voltage (**V_{GS}**) is applied to the gate terminal greater than the threshold voltage (**V_{TH}**) level, after which the channel becomes conductive, making it a transconductance device. Increasing this positive gate voltage will cause the channel resistance to decrease further causing an increase in the drain current, **I_D** through the channel. In other words, for an n-channel enhancement mode MOSFET**: +V_{GS}** turns the transistor **"ON"**, while a zero or **-V_{GS}** turns the transistor **"OFF"**. Then, the enhancement-mode MOSFET is equivalent to a "normally-open" switch.

Enhancement-mode MOSFETs make excellent electronics switches due to their low "ON" resistance and extremely high "OFF" resistance as well as their infinitely high input resistance due to their isolated gate.

The Output characteristics curves of the MOSFET transistor is shown in Figure 3.3.



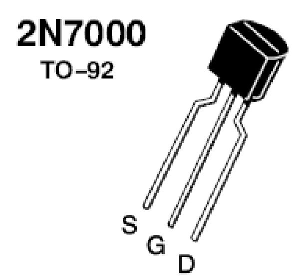


Figure 3.3. MOSFET Output characteristics

Figure 3.4. 2N7000 - package

The shaded area at the bottom of the diagram represents the "cut-off" region. Here the operating conditions of the transistor are: I_D=0mA and the gate voltage V_{GS} is less than the threshold voltage required for conduction.

In "saturation", as depicted by the area shaded in blue, the MOSFET will be biased so that the maximum amount of V_{GS} is applied, resulting in maximum drain current I_D flow. In this region the output drain-source resistance R_{DS} <1.2 Ω. In both cut-off and saturation, minimum power is dissipated in the transistor. We will be using in the lab MOSFET 2N7000, shown in Figure 3.4. Data specs for IRF540 are given in the Appendix.

2. Photo-resistive (Light) sensor

For this design you will need a light-sensitive resistor, shown in Figure 3.5 and provided in your parts kit. The photo-resistor has a low resistance when exposed to light (Rmin =1.5 kΩ) and a high resistance in darkness (Rmax = 100 kΩ).

A Photo-resistor can be used in light-sensitive detector circuits and light/dark-activated switching circuits. It is usually included as part of a voltage divider circuit, shown in Figure 2.1 where the voltage V2 changes depending on the variations of photo resistor value, caused by the external light.

Figure 3.5. Photo-resistor

3. DC relay

3.1. A Relay is actually a switch which is electrically operated by an electromagnet. The electromagnet is activated with a low voltage, for example 5V from a microcontroller and it pulls a contact to make or break a high voltage circuit, as it's shown in Figure 3.6.

3.2. Important parameters to consider when choosing appropriate relay for a Project:

- **Rated voltage**: -normal working relay coil voltage required.
- **DC resistance**: relay coil DC resistance, measured by the multimeter.
- **Pick-up current**: a minimum current required to pull the relay. In normal use, the current will be given slightly larger than the pull current, so that the relay can be operated stably.
- **The release current**: the maximum current for release action. When the relay state current is reduced to a value less than the release current, the relay will revert to the release of the unpowered state. The release current is much smaller than the pull current.
- **Contact parameters :** switching maximum power, current and voltage.

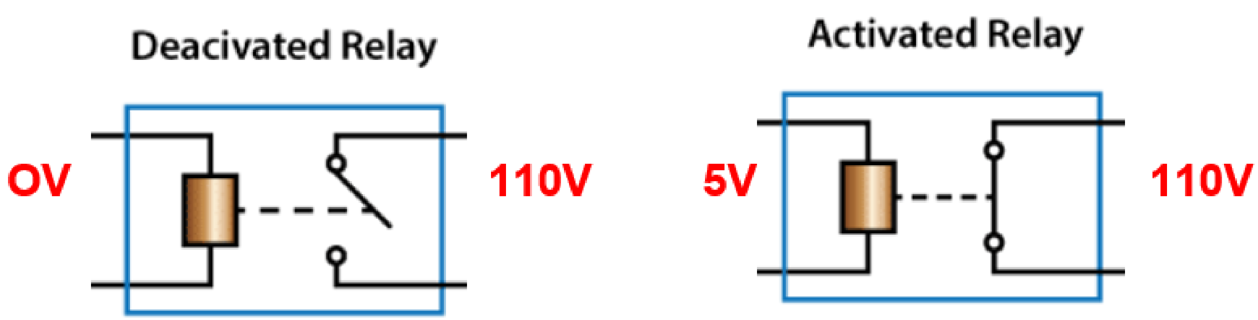


Figure 3.6. DC relay

3.3. Arduino DC relay module, shown in Figure 3.7 and consists of a DC relay and electronic circuitry for control the relay and LED indicator for the relay status, as it is shown in Figure 3.8. It has Normally Open (NO), Normally Closed (NC) and Common (COM) contact terminals and required 5V DC power supply. The relay module is controlled by the Signal input, which turns ON the relay the when +5V is applied to it and turns OFF the relay when 0V is applied to it.

3.4. The relay module parameters are as follows:
Rated Voltage: 5V
Contact parameters: 10A / 250 VAC or 10A / 30VDC

Figure 3.7. DC relay Module

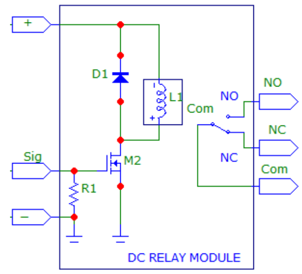


Figure 3.8. DC Relay internal connections

4. MOSFET Switch / Inverter

The circuit shown in Figure 3.9 represents the basic MOSFET switch / inverter. When applying any signal to Vin, the inverted signal can be obtained from Vout. In certain conditions this circuit operates in "switch" mode and the output voltage Vout varies from 0.2 V to V_{DD}. This could be very useful when a low-voltage signal source has to drive a higher-voltage load, such as a Light Emitting Diode (LED), relay or a DC motor.

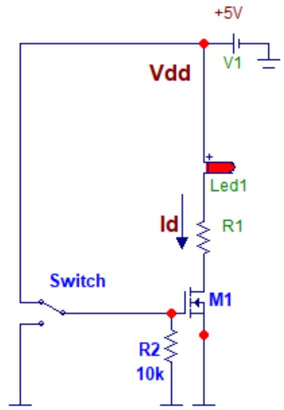


Figure 3.9. MOSFET Switch

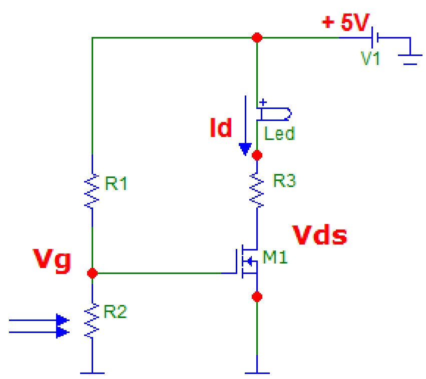


Figure 3.10. Light Sensor Switch

5. Light sensor switch

5.1. The light sensor switch can be designed using basic switch circuit and controlling it by the photo-resistor, as it is shown in Figure 3.10. The photo-resistor R2 together with the resistor R1 form a voltage divider with a variable output voltage Vg.

When the photo-resistor is illuminated, its resistance is Rmin. You should calculate the value of the resistor R1 such that the Vg will be less than 0.2V, which will cause the MOSFET to run in 'cut-off' mode.

When the light on the photo-resistor is turned off, its resistance become Rmax, which should change the Vg value to above 3V and will cause the saturation of the MOSFET.
Measure the Rmax and Rmin of the photoresistor from your lab kit using the multimeter on R mode. For Rmax cover the photoresistor with your hand. For Rmin – illuminate it with your Cellphone LED. Enter the results in Table 3.2 of the LMS and use them for the following DC biasing calculations.

5.2. The component's values of this circuit have to be calculated in order to:

- Provide I_d<1 mA (LED is OFF) when the photo-resistor is illuminated - "cut-off" mode (R_2=min).
- Provide I_d=15mA (LED is ON) when the photo-resistor is covered - "saturated" mode (R_2=max).

5.3. Using Equations (3.1) to (3.3) as described above, one can find the value of R_1 for the saturation regime of the MOSFET (when R_2=max) and check the same value against the cut-off mode conditions, when R_2=min.

Providing that Vg=4V guarantees the saturation mode for the MOSFET, find R_1 value using Equation (3.1) for $R_2=R_{2max}$ (non-illuminated):

$$R_1 = \frac{V_{dd} - V_g}{V_g} R_{2max}$$

Equation (3.1)

After that you need to check if calculated R_1 value satisfies the requirements for "cut-off" operating mode when $R_2 = R_{2min}$, $V_g < 0.5$ V using Equation (3.2).

$$V_g = \frac{R_{2min}}{R_1 + R_{2min}} V_{dd}$$

Equation (3.2)

5.4. Use Equation (3.3) to calculate R_3 value for a red LED where V_{LED}=1.7V

$$R_3 = \frac{V_{dd} - (V_{ds} + V_{LED})}{I_d}$$

Equation (3.3)

EQUIPMENT

1. Digital multimeter
2. PROTO-BOARD (breadboard)
1. MOSFET 2N7000
2. DC relay module
3. Red LED
4. Photo-resistor
5. Multiple resistors: 220, 1k, 10k

PRE-LABORATORY PREPARATION

The lab preparation must be completed before coming to the lab.

1. Hardware MOSFET Switch / Inverter

1.1. **DC biasing of Hardware MOSFET switch.**

For the circuit in Figure 3.9 calculate the value of R1 in section 1 of the LMS. The input signal is provided by the SPDT switch, connected between (+5V) and (Ground) of the circuit. DC bias this circuit for V_{dd}=5Vand I_c=15mA using Equation (3.3) and the explanations in section 5.

1.2. Tinkercad simulations of **Hardware MOSFET switch**.

- Simulate MOSFET Switch circuit in Tinkercad using standard resistors values and available MOSFET Transistor model. Please note, that the parameters of this transistor can not be modified, so the simulated values might be different from the actual circuit measurements.
- Use the Power Supply source from the Tinkercad library and set it to a 5V value.
- Read the Vds with a voltmeter and Id from the Power Supply Current gage.
- Use a push-button from the library to provide +5V to the MOSFET switch
- Run simulations and measure Id and Vds at Vg =0V and +5V. Enter the results in Table 3.1 of the LMS for both pushed-in and released positions of the button.
- Take a picture or video of both simulations and attach it to your Lab Report.

1.3.Arduino controlled MOSFET switch

- Simulate MOSFET Switch circuit in Tinkercad using standard resistors values and available MOSFET Transistor model, as it is shown in Figure 3.12.
- Connect the Arduino' +5V, GND to power the circuit and digital pin D8 to control it.
- Modify the LED sketch to turn switch ON and OFF with 3 seconds delay;
- Run simulations, make video record and upload to your Dropbox.

2. Hardware Light sensor switch

2.1. **DC biasing** [5 Marks]

- Measure the illuminated and non-illuminated resistance value of the photo-resistor, provided in your lab kit and record R_{2min} and R_{2max} measurements in Table 3.2 of the LMS.
- Calculate the DC biasing (values of R1 and R3) of the circuit in Figure 3.10 which turns a red LED ***on*** when the room lights are *off (darken condition)*. DC bias this circuit for V_{dd}=5Vand I_c=15mA using Equations (3.1) to (3.3) and the explanations at the Information part.

2.2. **Tinkercad simulations of Hardware Light Switch** [5 Marks].

- Simulate the circuit in Figure 3.10 in Tinkercad using calculated resistors values. Instead of photo resistor, install a resistor R2 on the circuit and change it's value to Rmin and Rmax values, that you have measured. Enter the results in Table 3.2 of the LMS
- Use the Power Supply source from the Tinkercad library and set it to a 5V value.
- Read the Vds with a voltmeter and Id from the Power Supply Current gage.
- Run simulations and measure Id and Vds at Rmin and Rmax. Enter the results in Table 3.1 of the LMS for both pushed-in and released positions of the button.

  Take a picture of both simulations and attach it to your Lab Report.

3. Arduino controlled DC Relay module

- Study the code provided in lecture notes for controlling a single LED by Arduino digital pin. Make a copy of the sketch ready to be uploaded in the lab.

4. Arduino controlled Light Sensor switch

4.1. Study the example tutorials and sketch for using a Photo Resistor with Arduino as a turn on-off switch to LED. Make a copy of the sketch ready to be uploaded in the lab.
http://www.instructables.com/id/How-to-use-a-photoresistor-or-photocell-Arduino-Tu/

4.2. Simulate the circuit in Figure 3.15 in Tinkercad using calculated resistors values.

- Modify the sketch to control the switching threshold of the LED under different lightning conditions, measure different ON and OFF voltages.
- Video-record the Tinkercad simulations and upload to your Dropbox.

PROCEDURE

1. Hardware MOSFET Switch / Inverter.

1.1. Build the circuit in Figure 3.11 using 2N7000 and the resistor values calculated in the pre-lab. Use standard resistor values when building the circuit. Pay attention to the MOSFET 2N7000 pin layout.
1.2. Power the circuit from the 5V built-in DC power supply of the Arduino.
1.3. Connect the digital Multimeter to measure Id current (as voltage drop across R1) and then to measure the Vds.
1.4. Attach the input of the circuit to the provided button from your Arduino kit.

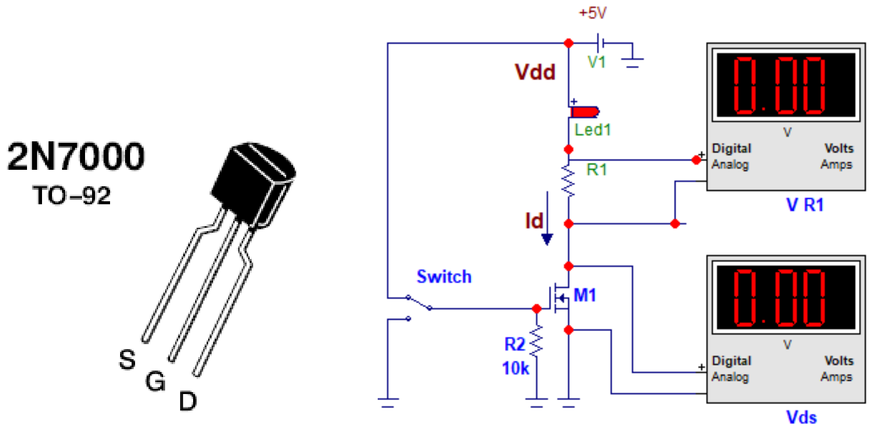


Figure 3.11. MOSFET Switch circuit -1

When the layout has been completed, demonstrate it to your TA

1.5. Initially the button is released and the MOSFET is set to "0V" input signal position. Measure the current Id and Vds of the MOSFET switch. Record your measurements in Table 3.1 of the LMS.
1.6. Press the Button and provide "+5V" input signal to the MOSFET. Measure the current Id and Vds of the switch. Record your measurements in Table 3.1 of the LMS.

2. Arduino controlled MOSFET switch

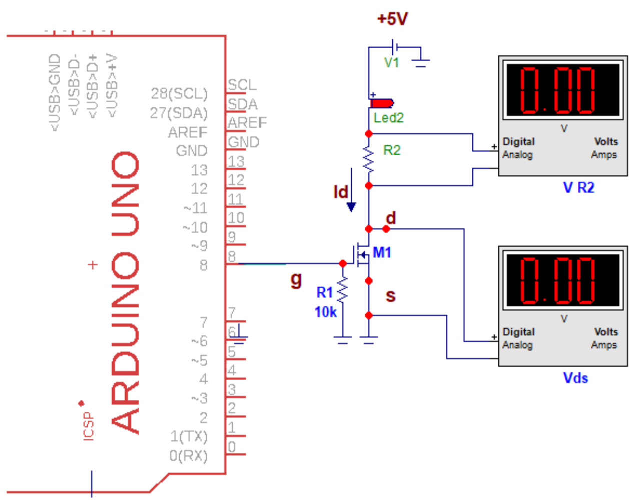


Figure 3.12. MOSFET Switch circuit-2

2.1. Using the built circuit, connect the input of the circuit to the Arduino D8, as it is shown in Figure 3.12. Load the sketch for controlling the LED on pin D8 and modify it with 3 seconds delay. This will give you enough time to complete the Voltage measurements for Vds and Id in both ON and OFF positions.

2.2. Record your measurements in Table 3.1 of the LMS.

2.3. ***When the layout has been completed, demonstrate it to your TA***

3. Hardware Light sensor switch

3.1. Build the circuit in Figure 3.13 using the component values calculated in the pre-lab.

When the layout has been completed, demonstrate it to your TA

3.2. Initially illuminate the photo-resistor by your phone LED and measure the current I_d and V_{ds} of the MOSFET switch. Record your measurements in Table 3.2 of the LMS.

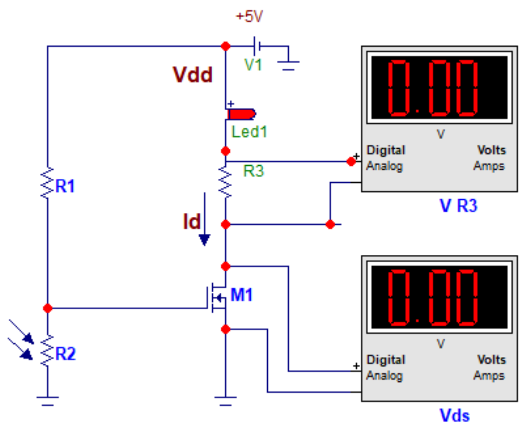


Figure 3.13. Light Sensor Switch

3.3. Cover up the photo-resistor with your hands and measure the current I_d and V_{ds} of MOSFET switch. Record your measurements in Table 3.2 of the LMS.

3.4. Compare your lab measurements with your pre-lab calculations in section 3.3 of the LMS.

4. Arduino controlled DC Relay

4.1. Build the circuit in Figure 3.14.

4.2. Connect the Signal input of the Relay module to the Arduino Digital Output #7 and upload a modified sketch for controlling LED from the lecture notes.
Connect the C (Common) contact pin to +5V and the NO (Normally Open) contact pin to external LED + R group, so the LED, or any other load, will be turned ON when the relay is ON.

4.3. ***When the layout has been completed, demonstrate it to your TA***

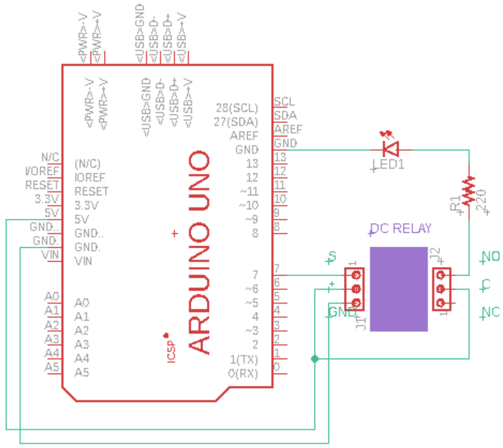


Figure 3.14. Arduino controlled DC relay

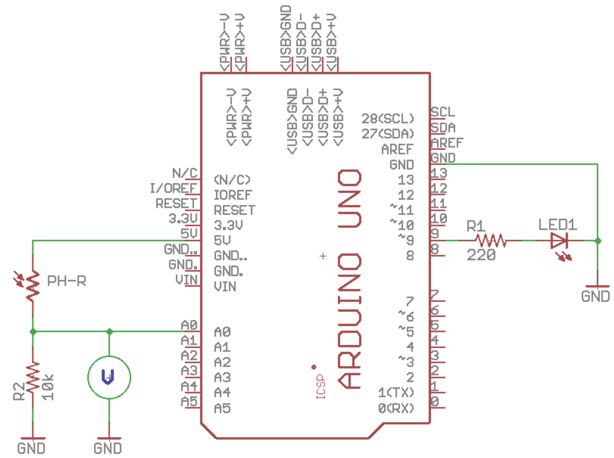


Figure 3.15. Light controlled LED

5. Arduino controlled Light Sensor Switch

5.1. Connect the Photo-resistor sensor to Arduino board and construct the circuit shown in 3.15.
5.2. Upload the Photo-resistor Reading sketch from the lecture notes.
5.3. Measure the output voltage of Voltage Divider, formed by the Photo Resistor and 10k resistor with Digital Voltmeter and record the values when the LED turns ON and OFF in Table 3.3.
5.4. ***When the layout has been completed, demonstrate it to your TA***
5.5. Upload the code to control the brightness of the LED under different lightning conditions, measure different ON and OFF voltages, enter data to Table 3.3.
5.6. ***When the layout has been completed, demonstrate it to your TA***

REPORT

Record in the LMS results for all experiments. Upload all highlighted Tinkercad simulations and video-recordings to your OWL Dropbox.

LAB MEASUREMENTS SHEET – LAB #3

Name Arnav Goyal

Student No 251244778

Workbench No _____

NOTE: Questions are related to observations, and must be answered as a part of the procedure of this experiment.
*Sections marked * are pre-lab preparation and must be completed BEFORE coming to the lab.*

1. MOSFET Switch.

1.1. * DC biasing calculations [5 Marks]

Assume Vds = 0.2 V

R = [5 - (0.2 + 1.7)] / 1.5m
R = 206 Ohm -> R = 180 Ohm (closest std value)

1.2. Measurements [20 Marks]

Table 3.1.

	TinkerCad Pre-lab*			**Button Measurements**			**ARDUINO Measurements**		
Button	**V_g [V]**	**I_d [mA]**	**V_{ds} [V]**	**V_g [V]**	**I_d [mA]**	**V_{ds} [V]**	**V_g [V]**	**I_d [mA]**	**V_{ds} [V]**
"0V"	0	0	3.66						
"+5V"	5	3.5	0.118						

2. Light sensor switch

2.1. * DC biasing calculations of **R_1 and R_3** [5 Marks]

Assume Vds = 0.2 V

Vg = 4 V

R1 = (1/4) * R2 max

R3 = [5 - (0.2 + 1.7)] / 15m = 20.6 Ohm

2.2. Measurements [15 Marks]

Table 3.2.

	Tinkercad Pre-lab*			**Measurements**		
Photoresistor Measured R	**V_g [V]**	**I_d [mA]**	**V_{ds} [V]**	**V_g [V]**	**I_d [mA]**	**V_{ds} [V]**
R_{2min} =						
R_{2max} =						

2.3. Compare your lab measurements with your pre-lab calculations [5 Marks]

____
____
____
____

3. DC relay test observations

____
____
____
____

4. Arduino Photo Resistor Sensor measurements

Table 3.3.

	Original sketch Measured Voltage (V)	Modified sketch Measured Voltage (V)
LED ON		
LED OFF		

Table 3.3. Photo Resistor Sensor measurements

____
____
____
____

SIGNATURE AND MARKING TABLE – LAB #3

TA Name:__________________

TASK	TOTAL MARKS	GRANTED MARKS
Pre-lab: 1. DC biasing of Hardware MOSFET switch - calculations 2. Tinkercad simulations of Hardware Push Button switch - video 3. Arduino controlled MOSFET switch - Tinkercad video 4. Hardware Light sensor switch – DC biasing calculations 5. Hardware Light sensor switch – Tinkercad simulations - video 6. Arduino light sensor – Tinkercad simulations	 5 5 5 5 5 5	
Procedure: 1. Hardware MOSFET switch – build, test, demonstrated to the TA. 2. Arduino controlled MOSFET switch – build, test, demonstrated to the TA 3. Hardware Light sensor switch – build, test, demonstrated to the TA 4. Arduino controlled DC relay – build, test, demonstrated to the TA 5. Arduino controlled light switch – build, test, demonstrated to the TA	 15 10 15 15 15	
TOTAL MARKS	**100**	**100**