HIGH VOLTAGE SWITCHING SYSTEM FOR ELECTROWETTING-ON-DIELECTRIC (EWOD)

by

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15306

Dissertation submitted in partial fulfillment of

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(Electrical & Electronics)

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Assoc Prof Dr Nor Hisham B Hamid)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK

September 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Amy Chua Liang Mei)

ABSTRACT

Electrowetting-On-Dielectric (EWOD) is becoming a standout amongst all the broadly used method for controlling small amount of liquid on a flat electrode surface. Scaling down the EWOD process has been a technological development recently as it appeared to have better integration and automation of numerous procedures on a single device. The applied voltage plays an important role in this study. A low voltage will diminish the ionization effect happening within the droplet. Insufficient ionization will further cause the inability of droplet movement. Therefore, a high voltage must be applied to initiate droplet movement. This study focuses on high voltage switching system for electrowetting process. Results achieved shown that MOSFET IRF 740 acted as the best switching component for the system. Besides, this study proves the feasibility of electrowetting by describing the fabrication and testing of different dielectric layers using high voltage switching system. As for the coating of dielectric layer, cooking oil showed the most noticeable results out of all the materials.

ACKNOWLEDGEMENTS

With determination and courage, I have successfully finished my final year project. It is with immense gratitude that I acknowledge the support and guidance of my final year project supervisor, Assoc Prof Dr Nor Hisham B Hamid. He continually and convincingly conveyed a spirit of patience in regards to teaching. Without his guidance and persistent advice, I would certainly not have achieved as much.

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CHAPTER 1
INTRODUCTION

1.1 Background

Beni and Hackwood were the first to introduce about the term "Electrowetting" in the year of 1981 [1]. The utilization of applied electric field for altering the wetting properties of a liquid surface is known as electrowetting (EW). It is commonly being employed as a driving mechanism to modify the surface tension of liquids for a series of fluidic applications. However lately, most of the researches are focusing heavily on the application of Electrowetting-On-Dielectric (EWOD). This is primarily because the combination of a dielectric layer with applied electric field, greatly increase the effectiveness for droplet manipulation. A digital microfluidic device serves the similar purpose as EWOD. The difference between EWOD and a digital microfluidic device is the method used to transport the droplet onto the electrode. In EWOD, the droplet is directly placed upon the surface of electrode using a syringe whereas for digital microfluidic device, the droplet is transported onto the electrode through a microchannel as a path of flow.

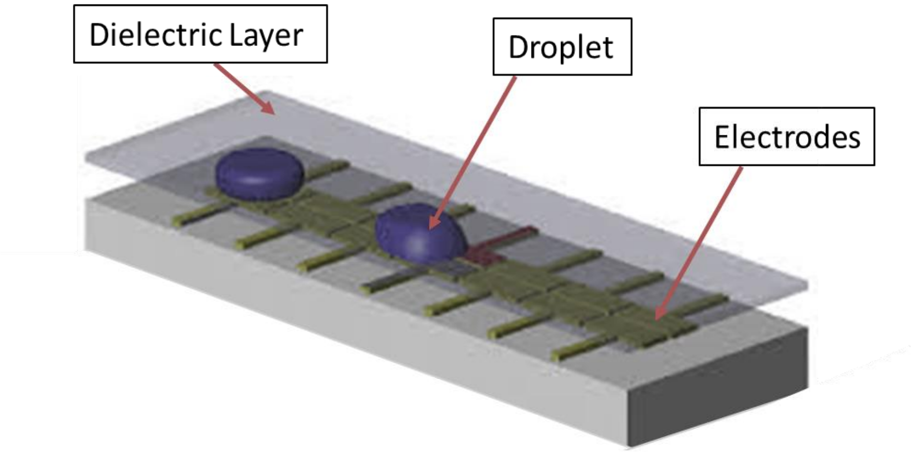


Figure 1: General Electrowetting System

Design and fabrication of EWOD involves a printed circuit board coated with a thin layer of dielectric layer as shown in Figure 1. Droplet of liquid is normally semi sphere in shape with steep sides and spread out more as there is no voltage being applied to it. There will be rows of electrodes on the printed circuit board in the form of matrix. Each and every electrode will have a control voltage being applied to it at a respective time and delay. Control voltage will not be applied on the position of the liquid droplet; however, it will be applied onto the electrode next to the droplet (vertically or horizontally). An electric potential will form along the two electrodes and further influence the direction of the droplet movement. If there are more than two droplets, the movement can be controlled so that they can either merge or split.

EWOD can be applied in various applications and fields in the whole wide world. Fields like electronic display technology, DNA extraction, mixing and centrifuging of liquids can be done through this way. Centrifuge, also known as mixing method enhances the process of for example, neutralization and precipitation which can be done through electrowetting Centrifugation is a step needed to understand better about centrifuge selection especially in the pharmaceutical industry and chemical production. The purpose of this study is to focus on transportation and switching system of liquid droplet.

1.2 Problem Statement

Fluid synthetization of mixing two different liquids is the core to most of the chemical and biological procedures. The simplest example is the neutralization process which requires the mixing of both equal volume of acidic and alkaline to yield a neutralized solution. However, during a process such as this, human error tends to exist with the incapability of naked eye to detect the miniature error for example the exact volume of the liquid for mixing. The consequence raised from this error causes the impact on the purity of fluid being synthesized. Besides, certain fluid behave differently at different scale. For example, external factors such as molecular interaction, plays a more prominent role compared to inertia force and other effects in macroscopic scale. Therefore in order to examine the critical properties of fluid more precisely, it normally requires the fluid to react at a microscopic scale. This is one of the greatest challenges for researchers to measure and mix the fluid in microscopic scale. The need to automate fluid mixing in both chemical and biological field at microscopic scale has driven the creation of electrowetting technique. There are two methods to carry out EWOD process: single plate configuration and dual plate configuration. However, due to tough configuration and inflexibility of handling process for dual plate planar, single plate is used in this study. Nevertheless, one significant concern remained in this technique is the utilization of single plate of electrode during fluid manipulation will cause evaporation to the droplet. The evaporation process is affected by multiple interrelated factors such as amount of applied voltage, properties of droplet and volume of droplet.

1.3 Objectives

1.3.1 To construct and characterize single plate based electrowetting-on-dielectric.

1.3.2 To explore a suitable dielectric layer for increasing the efficiency of droplet movement.

1.3.3 To design and construct a switching system.

1.3.4 To design various switching patterns for droplet splitting or multiple droplets mixing.

1.4 Scope of Study

The undertakings of this project will centralize on developing the high voltage switching system which is required as part of electrowetting process. Different switching components which include transistor, relay and MOSFET will be tested upon to verify the best fitting component in performing the switching operation at high voltage of 200V DC with 1 kHz. The switching system will be limited at 16 switches as a result of the matrix scale of electrode at 4 x 4. Although bigger matrix scale will provide greater flexibility in manipulating multiple droplets all at once, but matrix scale any bigger than 4 x 4 will not be covered in this project due to time constraint. With the limited moving space confined by the matrix scale, there will only be two droplets to be manipulated at a time for both splitting and mixing process. Therefore the switching system will also only accommodates the switching pattern which allows the maximum or two droplet manipulation. Applied voltage will be maintained at 200 V DC throughout the experiment although higher voltage will induce faster droplet movement. The selection of appropriate dielectric material for the coating surface of electrode will be thoroughly examined with the available materials within the country. As for those inaccessible materials such as Teflon, while it is an excellent dielectric materials, it will not be experimented in this project.

CHAPTER 2
LITERATURE REVIEW

Electrowetting-on-dielectric (EWOD) is a requisite and versatile tool for droplet manipulation [2]. It utilizes a connected electric field to control the little volumes of fluid by modifying its surface tension and subsequently the plainly visible contact angle. Electrowetting bears a proficient, fast, reversible, and exact means in controlling little volumes of fluid without the requirement for mechanical parts.

In the process of electrowetting, the surface tension that is being experienced on the liquid droplet is influenced by the electrical fields applied. As mentioned in the background of study, electrowetting is applicable in wide ranges of applications like separation of particle and quality or concentration control of the chemical droplets. These applications highly require a good control of fluid dynamic specifically in order to carry out their respective functions. Both electrowetting (EW) and EWOD vary the electric potential to control the wettability of liquid on solid surface. Even so, EWOD is perfectly suitable in this particular field as it can precisely control the volume of droplets used in small scale, low energy consumption, splitting and mixing motion of the droplets and many more [3]. Also, it enables control over the droplet shape [4]. The efficiency of chemical reaction hinges on the degree of chemical mixing. With the implementation of EWOD, greater degree of mixing could be accomplished with the lowest amount of chemical waste during testing [5].

In an ideal model of EWOD experiment, when the voltage is turned on at the left and right electrode of the droplet, it will form a low pressure region at the liquid-gas interface which is happening at the outer part of the droplet while the pressure remains high at the electrode where no voltage is being applied. With this, the droplet will experience a pulling force from the left and right side of electrode and move forward towards them where the voltage is applied. The droplet will undergo elongation horizontally and a thin line in between which looks like an inverted hourglass shape. When the applying of voltage is being stop, there will be two smaller droplets form on the left and right electrode respectively. Voltage applied is to change the wetting properties of droplet, be it AC or DC voltage [6, 7].

The device used in electrowetting is made up of several different layers and it can be in single plate or dual plate depends on the experiment as shown in Figure 2.

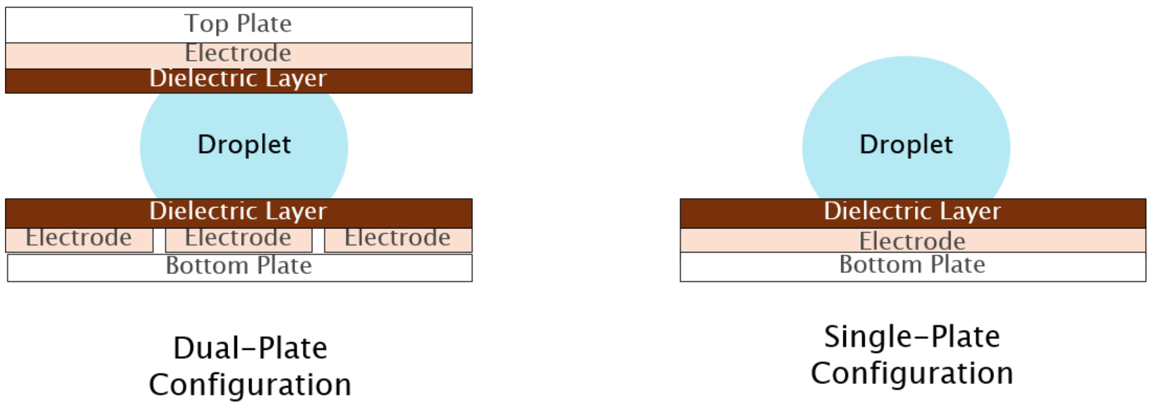


Figure 2: Configurations for Dual-Plate and Single-Plate.

Dual plates require higher input of voltage compared to single plate and the difference between them is approximately 47% [8]. It is advisable to conduct using single plate as the fabrication difficulty level is simpler and higher flexibility. Besides, for single plate configuration, it was found that there is possibility in splitting in droplet into two using single plate configuration [9]. Although single plate configuration has higher evaporation rate, it has smaller contact area which can improve the duration of droplet movement [10].

For the dual plate device, it normally consists a matrix form of electrodes, silicon dioxide, a thin layer of Teflon coating, liquid droplet, another layer of Teflon coating again and electrode. They are all tiered from bottom to top layer respectively. The difference in height between the two plates is known as the gap height [3]. The greater the height difference, the faster the droplet's motion, however it is bound to a certain gap limit as well. The gap height influences directly the speed of droplet transportation. With the range of 50μm to 600μm of gap height, the droplet transportation speed changes from 12mm/s to 112mm/s. Gap height of 120μm and 160μm show a positive result in splitting the droplet into two; droplet failed to split or move to adjacent electrode at 200μm gap height; for 300μm gap height, the whole droplet move to adjacent electrode without splitting [5].

There are a few things that must be noted during the fabrication of electrowetting device, which are dielectric constant of the material, material of dielectric layer, applied voltage, contact angle change and etcetera because of the following formula used [11, 12]:

$$\cos\theta\ (v) = \cos\theta_0 + \frac{\varepsilon\varepsilon_0}{2\gamma_{LV}d}V^2$$

where

where	$\theta\ (v)$	= Contact angle when voltage is applied
	θ_0	= Angle without applied voltage
	ε	= Dielectric constant of dielectric layer
	ε_0	= Dielectric constant of air
	d	= Thickness of dielectric layer
	V	= Applied voltage

For both single and dual plate configuration, the size of electrode and the gap between electrodes will also affect the droplet transportation. Electrode can change the surface properties of droplet.[13] Experiments were carried out by using different gap widths of 80μm, 150μm and 300μm. It was found that by using a 1.4mm x 1.4mm electrode size and 25V applied voltage, the splitting of droplet cannot be observed clearly at a 300μm gap. By decreasing the gap to around 70μm to 80μm, the splitting motion can be observed at a perfect sight.[14]

As from the aspect of applied voltage in another study, it is proven that a 150V applied voltage can increase the droplet transportation speed up to 250 mm/s [14]. However, there are several experiments that prove that it is not a need to use such high applied voltage to carry out the motion. At 15V, the droplet move to the adjacent electrode within 0.1sec with a velocity of 11mm/s; at 9V, the droplet move within 1 sec with a velocity of 1.3mm/s; at 4V, the velocity is 11mm/s to move to the next electrode and lastly at 3V, the velocity is less than 1mm/s and the droplet has a tendency to to stop moving halfway through the experiment [15].

By taking the Lippmann-Young equation into consideration, applied voltage is interrelated to the droplet curvature or contact angle [8]. The higher the voltage applied, the larger the change of contact angle [16]. Contact angle is where the droplet touches the top and bottom of the surface of the electrowetting. The decreasing of contact angle can be changed by increasing the applied voltage [17].

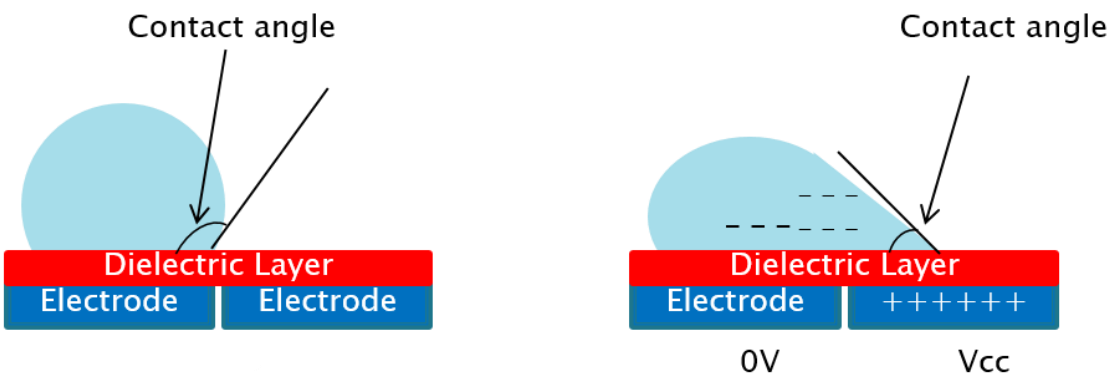


Figure 3: Contact angle for with and without applied voltage.

In single plate configuration, the contact angle change is 40 degree with 50V applied voltage while at 60V, the contact angle change is 24 degree [16, 18]. For dual plate configuration, the change in contact angle is 31 degree for 100V and 27 degree for 25V.[14] 30V is sufficient to drive the droplet [12]. Also, the contact angle depends on three kind of surface tensions: surface tension between the droplet and solid surface (γ_{SL}), between the solid surface and air (γ_{SG}), and between the droplet and air (γ_{LG}). When these three forces acting on the droplet are balanced, the droplet will not move according to Young equation below [19]:

$$\gamma_{LG} \cos\theta + \gamma_{SL} - \gamma_{SG} = 0$$

In an electrowetting device, insulator and dielectric layer are used to improve the droplet movement [20]. Applied voltage, dielectric constants and dielectric materials are interrelated with each other. During the increasing in operation of applied voltage, it will lead to the occurrence of electrochemical reactions. In addition, it will further lead to irreversible changes like oxidation which will decrease the electrowetting effect. This explains why dielectric layer is needed in electrowetting [19]. Experiments are conducted by using non-ferroelectric Bismuth Zinc Niobate (BZN), Teflon film, Silicon Nitrate and Silicon Dioxide as comparison to achieve the best dielectric layer to be used. BZN has the highest dielectric constant and it needs 14V to move the droplet in one second. Comparatively, Silicon Dioxide with the lowest dielectric constant, needs the most applied voltage (30V) to drive the droplet. Teflon film falls in the middle range of 8.5 dielectric constant and 23V driving voltage [21]. However, the combination of Telfon film and Silicon Dioxide has a low voltage operation [14].

In addition, according to experiments done previously for low voltages, different thickness of dielectric layer will have different results shown in the voltage needed to drive the droplet. A different ranges of thickness and material had been tested out. Around 60V to 80V of voltage is needed to break through the $800nm$ of Parylene C and $60nm$ of Teflon hydrophobic dielectric layer to electrically charge the droplet and move it. While approximately only 25V is needed as threshold voltage for $100nm$ of Silicon Dioxide and $20nm$ of Teflon [22].

In dual-plate operation, even though the liquid droplet is being placed in between the layers, it is still surrounded by air around it which creates a liquid-gas interface. By having energy storage between the Silicon Dioxide layer and the surface energy of the liquid-gas interface, the droplet will have the motion of driving forward because the main mechanism used is surface energy-related force [23]. At the same time, when the voltage is applied onto the electrode, the liquid droplet will eventually move from one electrode to another or making two droplets joining together through colliding or splitting them to form two droplets. Despite having pressure and external force created on the top and bottom layer of the liquid-gas interface, it has no effect on influencing the movement of the droplet [24].

Contact angle, contact angle saturation and contact angle hysteresis aspects have to be taken into consideration for the splitting of droplet in dual plate configuration. The difference in contact angles between the front and bottom ends of the droplet is known as hysteresis [25]. The contact angle hysteresis and initial contact angle are inversely proportional to each other [16]. When the initial contact angle increases, the contact angle hysteresis on the other hand decreases due to the hydrophobic property in the Teflon coating. However, when electrowetting force is equals or more than the force caused by the contact angle hysteresis, it will stop the motion of the droplet right away as the driving force is slowly receding. For the results achieved from the view of hysteresis aspect, if the contact angle saturation or hysteresis situation is not taken into consideration during the experiment, the droplet is split into three droplets instead of two and the process takes the shortest time to complete which is $10.63ms$. This is 93% faster than the theoretical results. The droplet tends to split so fast and no inverted hourglass shape is being formed which lead to the formation of three droplets. In another word, contact angle saturation definitely plays an important role in the electrowetting process as the preferable achieved result is two separated droplets.

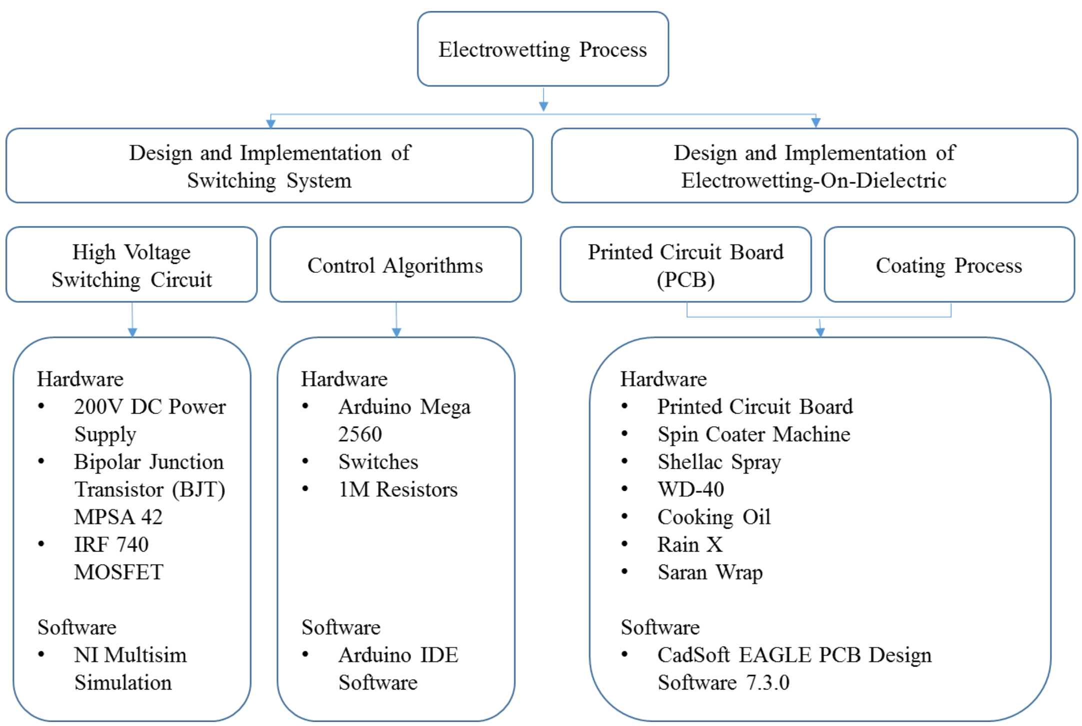
However, when the experiment is conducted with only contact angle saturation, the achieved results is similar to the theoretical results where two droplets are formed. But the time consumed is at $17.47ms$ which is quite irrelevant as well [25]. Therefore, these considerations are not to be taken lightly in the process of conducting experiment and during the analyzing of results.

CHAPTER 3

METHODOLOGY

3.1 Block Diagram

Electrowetting process is divided into few stages for this project: Design and implementation of switching system and design and implementation of EWOD. Under the designing and implementing of switching system, it is further to be divided into construction of high voltage switching circuit and control algorithms. As for the designing and implementing of Electrowetting-On-Dielectric, the process is divided into fabrication of printed circuit board and the coating process of dielectric layer on it. The steps are followed thoroughly to smoothen the process flow of the project.



3.2 Design and Implementation of Switching System

The necessity of a switching system for electrowetting process lies within the aspect that voltage is the driving factor that initiate the droplet movement. By contacting the droplet with negative terminal of voltage supply, the droplet will be ionized with positive ions attracted toward it and negative ions repel against it. While the positive terminal of the voltage supply is applied to the electrode underneath the droplet, there is no movement until it is switched to the adjacent electrode with the switching operation. Figure 4 is the illustration of the switching system required for droplet movement:

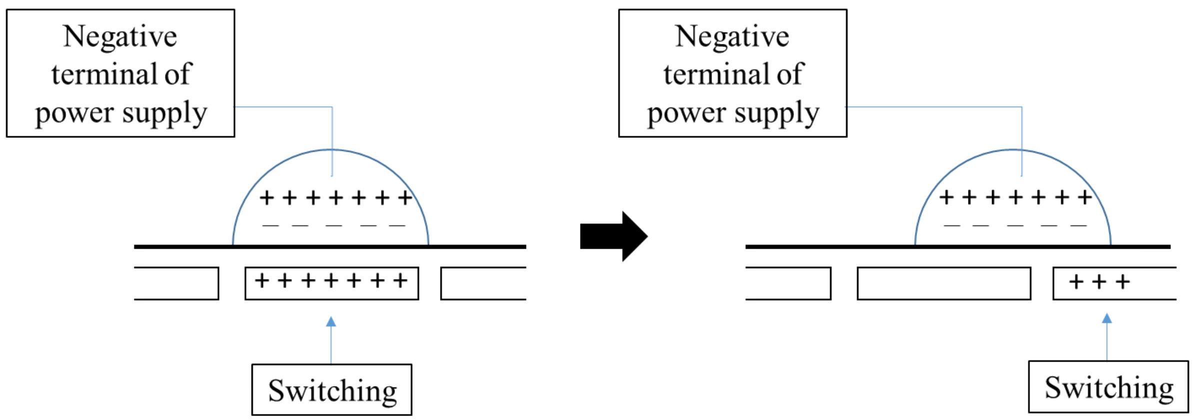


Figure 4: The movement of droplet initiated by switching system.

The applied voltage for the droplet is essential toward the ionization process of the droplet. Insufficient ionization due to low power supply is incapable to initiate the droplet movement due to incomplete separation of positive and negative ion within the droplet. Hence, the attraction between the positive ion of droplet and negative terminal of power supply is significantly reduced to move the droplet across the electrode. High voltage switching circuit is required for this project implementation.

3.2.1 High Voltage Circuit

3.2.1.1 Selection of Switching Component by Simulation

To verify the suitable switching component for this system, the Multisim Simulation from National Instrument is utilized. It is challenging to find the appropriate relay or transistor for the high voltage circuit as there are so many different specifications for both. The best condition for a suitable switching component is to be able to have a minimum triggering voltage of 5V so that it can be triggered by Arduino. A series of relays and transistor which fit the specification had been selected for the simulation. The successful components which show positive results for the simulation will be further constructed into real circuit to test its validity. Table 1 is the list of the selected components for the simulation along with its specification:

Table 1: Specification list of selected components for the simulation.

Models	Specification		
	Maximum Voltage (V)	Maximum Current (A)	Triggering Voltage (V)
IRF 540	100	28	10
IRF740	400	10	10
MPSA42	300	0.5	6
MPSA56	80	0.5	5
MPSA93	200	0.5	5
IRFM150	100	34	20
IRFZ46N	55	53	10
IRLR3303	30	35	10
SRD-06V	30	10	6
HK 19F	30	2	5

3.2.1.2 Construction of Validated Switching System

The next step is the construction of validated switching system accordingly from the simulation to manage the voltage flow into each electrode. Since all switching components are an electrically operated switch which turn on or off a circuit that carries current, it serves as an essential piece of component to manipulate the droplet movement. Figure 5 below shows the circuit connection of all switching components that are intended to be applied onto the full circuit.

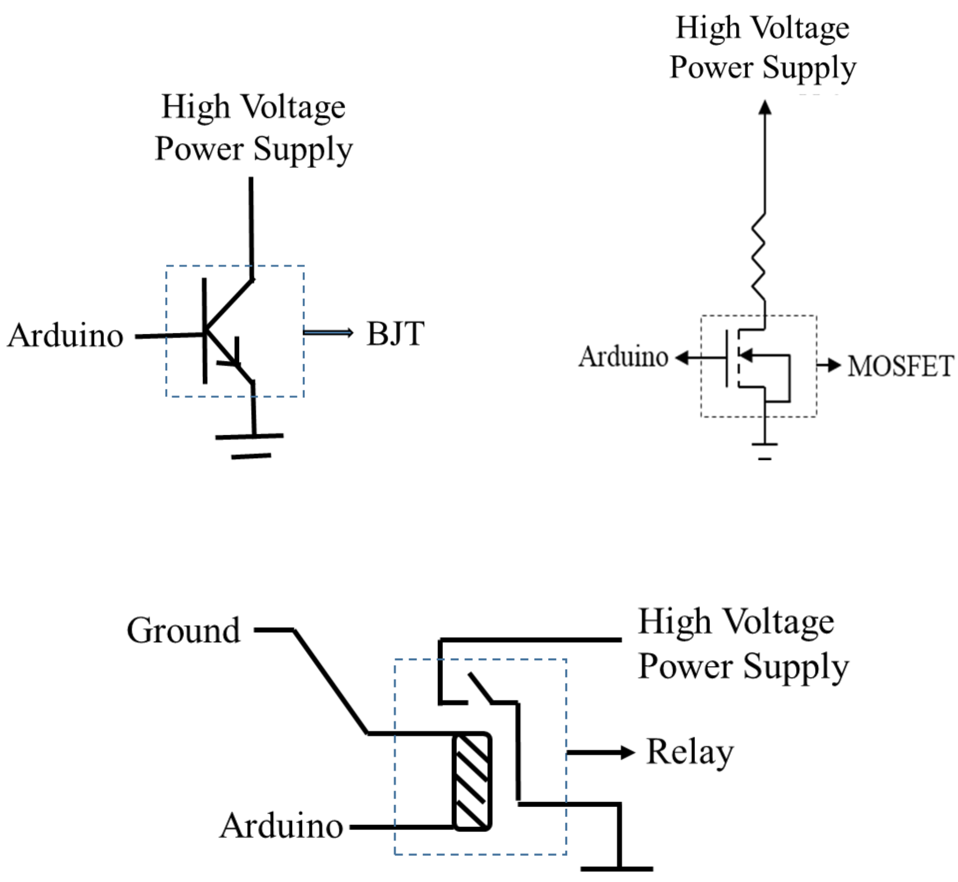


Figure 5: Connection for all switching components.

The switching terminal from all switching components will be controlled by a microcontroller (Arduino Mega 2560) via a series of high or low digital outputs. The high voltage power supply will be supplied to all switching components for driving the droplet movement. As one switching component has the capability to only switch on or off for one circuit, the presence of 16 electrodes on a printed circuit board of 4 x 4 matrix requires 16 connected switching components for turning on and off for each circuit separately. This also translates to the requirement of 16 digital output from Arduino be connected to each switching component. Each high digital output from the Arduino has a voltage value of approximate 5V.

The connection of the complete circuit is in such way that positive terminal of power supply is either connected to the source terminal of MOSFET or base terminal of BJT or one side of the relay. As for the negative terminal of power supply, it is connected to the electrode. Figure 6 shows the circuit for a single electrode with all different type of switching components.

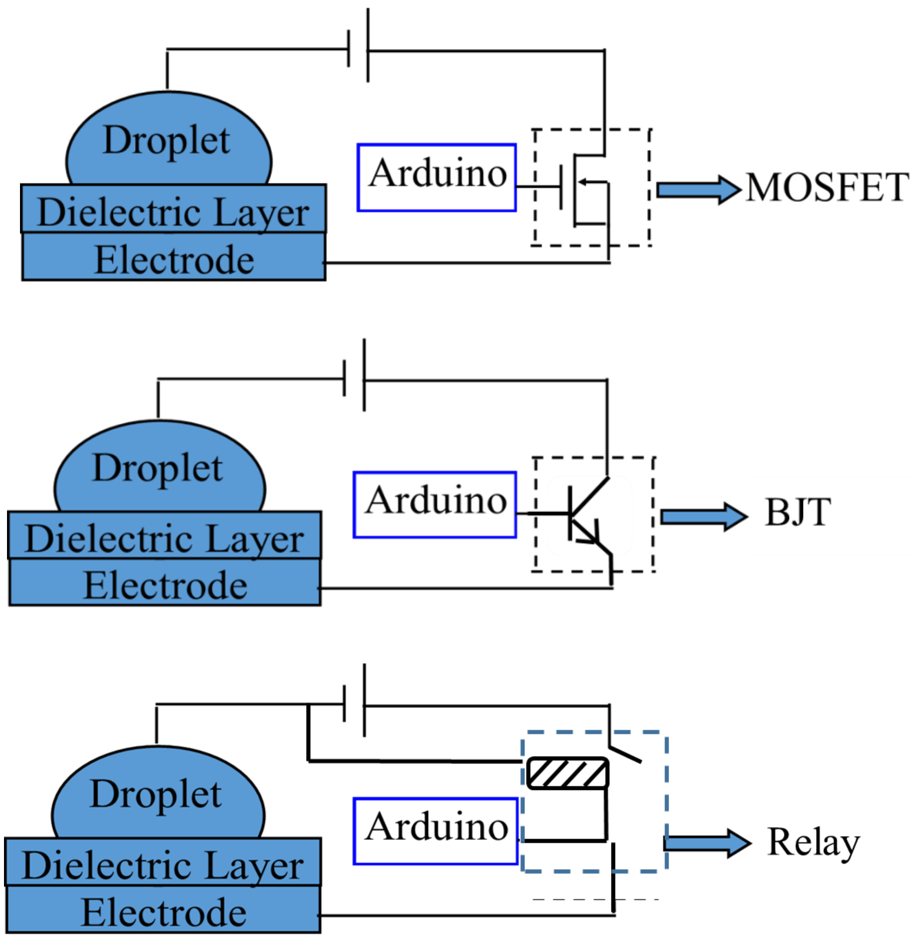


Figure 6: Circuit of a single electrode with all different type of switching components.

Besides, Figure 7 shows the general block diagram of the circuit. The complete circuit is attached in Appendices.

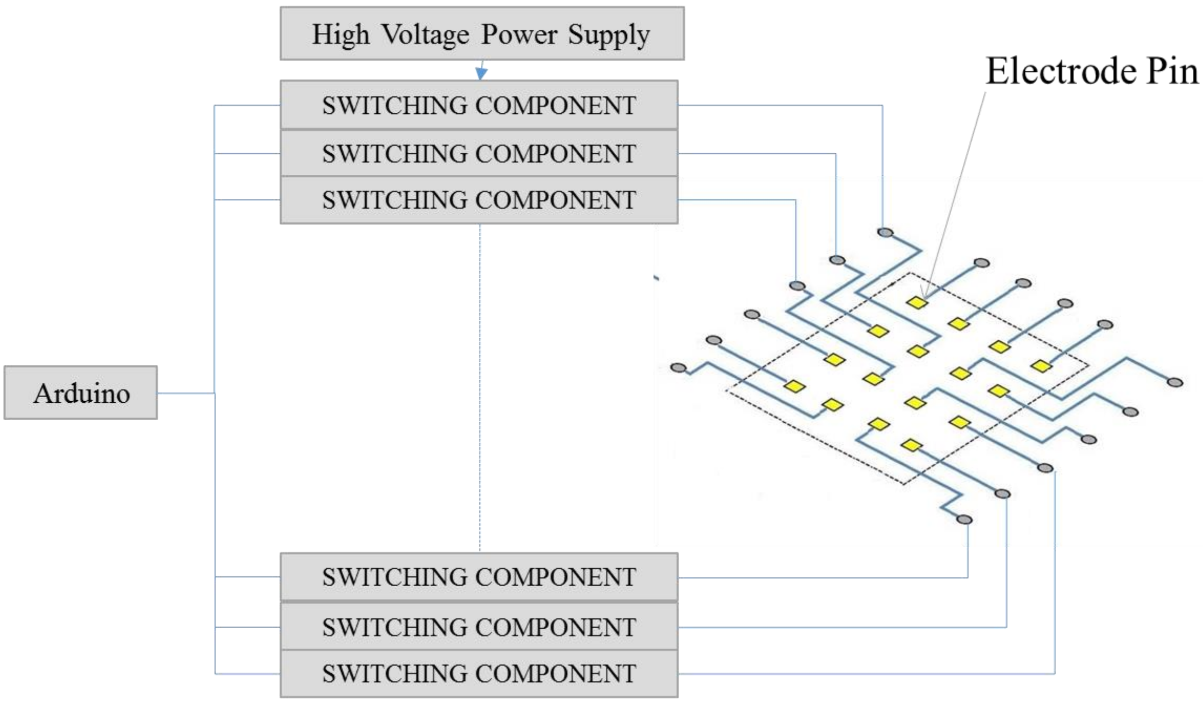


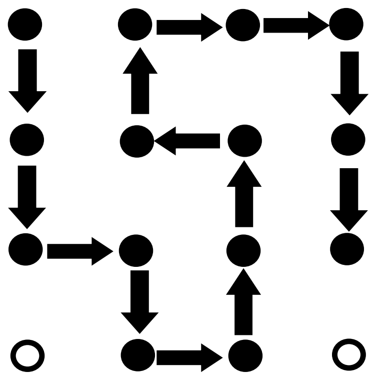
Figure 7: General block diagram for 16 electrodes.

3.2.1.3 Control Algorithms

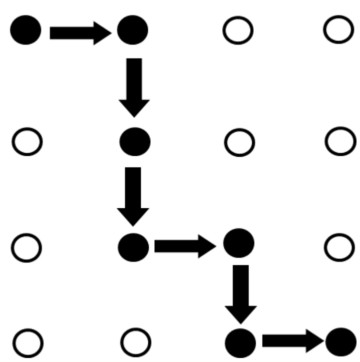
The final step is to program the sequence algorithm for droplet to move at a desired pathway by using Arduino Mega 2560. A sequence algorithm is written in programming C language then uploaded into the Arduino which runs on an infinity loop. The algorithm functions by computing a new position every time a switch is pressed on any of the six switches provided. This will be deciphered as in which digital output of high should be input to the switching component for completing that particular circuit so that the droplet will move toward that direction. The reset button on Arduino will stop the whole algorithm.

Diagram below shows the configured six switching patterns:

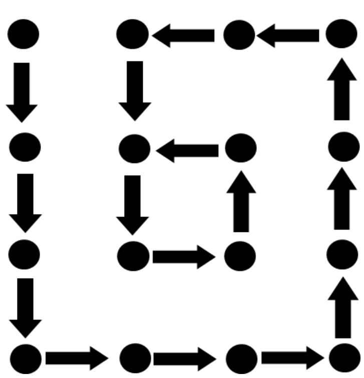
Pattern 1



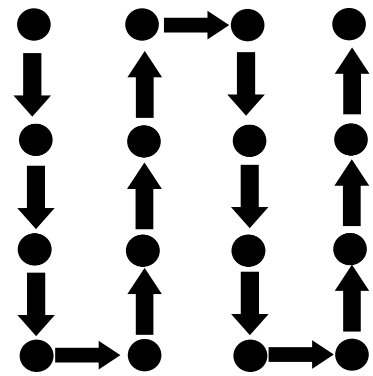
Pattern 2



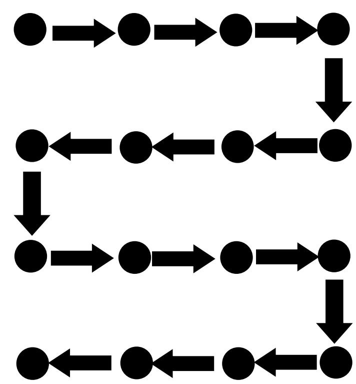
Pattern 3



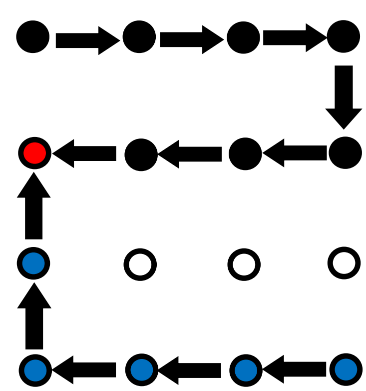
Pattern 4



Pattern 5



Pattern 6



The switching pattern from 1 to 5 are designated for the electrowetting process of single droplet movement while the last switching pattern is designated for dual droplet mixing process.

Upon the completion of all requisite for experimental setup, the initial placement of droplet onto the electrode is extremely vital. Incorrect placement of droplet will lead to the failure of droplet movement due to the absence of necessary driving factor. The ideal placement for the droplet is approximate 60% of the droplet should be within the intended location of the electrode and 40% of the remaining portion be placed around the surrounding adjacent electrode. This increases the limit for the volume of the droplet to always be greater than the size of the electrode. Absence of the droplet contact onto the adjacent electrode will deem the pointless action of voltage switching among electrodes.

3.3 Design and Implementation of Digital Fluidic Device

3.3.1 Printed Circuit Board (PCB)

The methodology starts with the first step of fabricating electrode on a Printed Circuit Board (PCB) in the form of 4 x 4 matrix. The requisite of a fitting electrode hinges on the aspect of its thickness and gap between electrodes. Since the thickness of electrode defines the transportability of droplet to ensure a moderate switching rate, hence it is crucial that the thickness must be preserve at the depth of only $18\mu m$. Thickness beyond or less than $18\mu m$ will induce a droplet movement at the rate which is unfeasible for this project. The area of each electrode used is confined at $0.09cm^2$. This is to accommodate the size of the droplet so that a portion of the droplet can always be in contact with the adjacent electrode to induce the movement. As for the gap width between electrodes, the dimension of $0.076cm$ facilitates a smoother movement of droplet from one electrode to another rendering to the effect of applied voltage. All of these design and modeling are conducted utilizing the CadSoft EAGLE PCB Design Software as shown in Figure 8.

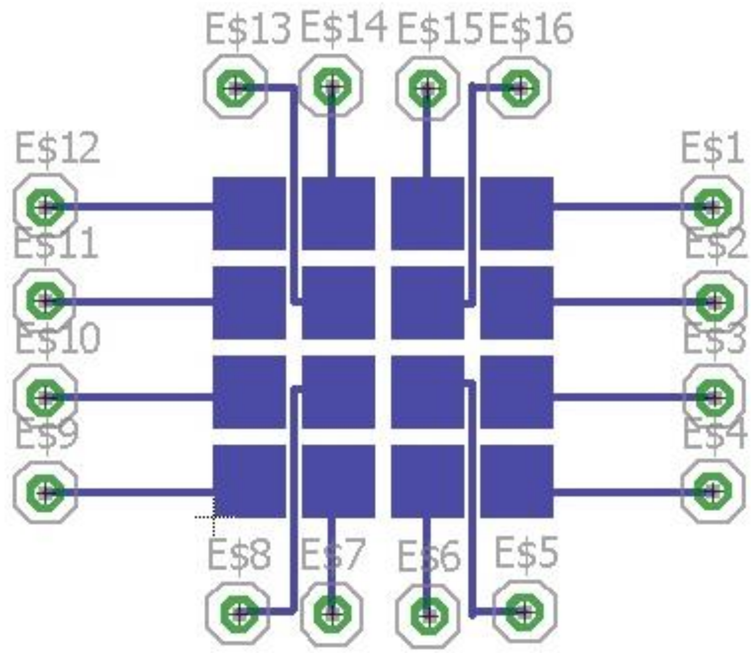


Figure 8: PCB design for 4 x 4 electrodes using CadSoft EAGLE PCB Design Software.

3.3.2 Coating Process

The following step after the construction of PCB, is the experimental on the appropriate dielectric layer. This is for the coating upon the surface of the electrode to provide a hydrophobic surface for easing the droplet movement. A variety of materials such as Shellac Spray, WD-40, RainX and cooking oil has been chosen to be tested for the best fitting material as the dielectric layer. This is primarily because of the water repellent properties they possess, to be immiscible with the water droplet. A thin layer of hydrophobic surface approaching $50nm$ will deliver a smaller contact angle hysteresis which permit the effortless movement of fluid. Besides, the dielectric constant of those materials are equally critical as they need to be sufficiently high enough to insulate the current from flowing into the droplet and causing the droplet to vaporize. Even though certain materials such as Teflon is equipped with all the necessary properties as an appropriate dielectric layer, it can't be used as a testing material due the unavailability to obtain within the country.

3.4 Project Key Milestones

Table 2: Key Milestones

Phase 1	Construction of 16 electrodes on a Printed Circuit Board (PCB) with a size of 0.3 cm x 0.3 cm and a gap distance of 0.076 cm.
Phase 2	Applying of dielectric layer coating on the constructed Printed Circuit Board (PCB).
Phase 3	Functional circuit for switching of high voltage power supply into desired electrode one at a time.
Phase 4	Compilation of working programming code for manipulating the electrical switch.

3.5 Gantt Chart

Table 3: Gantt Chart for Final Year Project I.

Task	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Select a project title from the approved list of final year projects	■													
Discussion on the selected project with respective lecturer		■												
Research on the design making of PCB		■	■											
Designing of PCB			■	■										
Consultation and fabrication of PCB				■	■									
Preparation of literature review based on existing methods used				■	■	■								
Submitting the completed version of extended proposal						■								
Purchase the required electronic components						■								
Applying of insulator layer and relay							■	■						
Programming of algorithm for Microcontroller Unit								■	■					
Preparation of proposal defence								■	■					
Assembling of the circuit									■	■	■	■		
Draft and submission of final report													■	■

Table 4: Gantt Chart for Final Year Project II.

Task	**Week**														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Synthesizing of droplet	■														
Experimenting of the movement of droplet		■	■												
Purchasing of MOSFET and BJT				■											
Building circuit for high voltage switching					■	■	■								
Testing out switching process					■	■	■	■							
Submission of progress report								■							
Configuration of switching patterns									■						
Assembling of prototype										■	■				
Presentation for Pre-SEDEX												■			
Final assembling of prototype											■	■	■		
Draft and submission of dissertation														■	
VIVA presentation															■

CHAPTER 4

RESULTS AND DISCUSSION

4.1 High Voltage Circuit

4.1.1 Initial Finding

Electrowetting was performed on electrodes of printed circuit board at applied high voltage of 30V. The applied voltage used was meant to ionize the droplet for initiating movement as discussed earlier. 16 BJT switches were used to further carry out the switching operation. The change in contact angle was observed. However, there was no visible movement in it that could be recorded. It was later found out that the applied voltage used was insufficient to ionize the droplet and a switching frequency is necessary. Therefore, an applied voltage of 30V DC was changed to 200V DC at 1 kHz and high voltage transistors had to be used. Whole experiment setting had to be changed to carry out from a different point of view as most of the selected switching component is unable to withstand that amount of voltage.

The following simulations shown are some of the switching components that had failed to meet the changed standard of the project's needed specifications from the original selected list. There are several different reasons for the failure. Most components are unable to withstand the changed high voltage of 200V requirement as the power supply. Certain components are unable to perform the switching operation such as the model of MPSA 56 and MPSA 93.

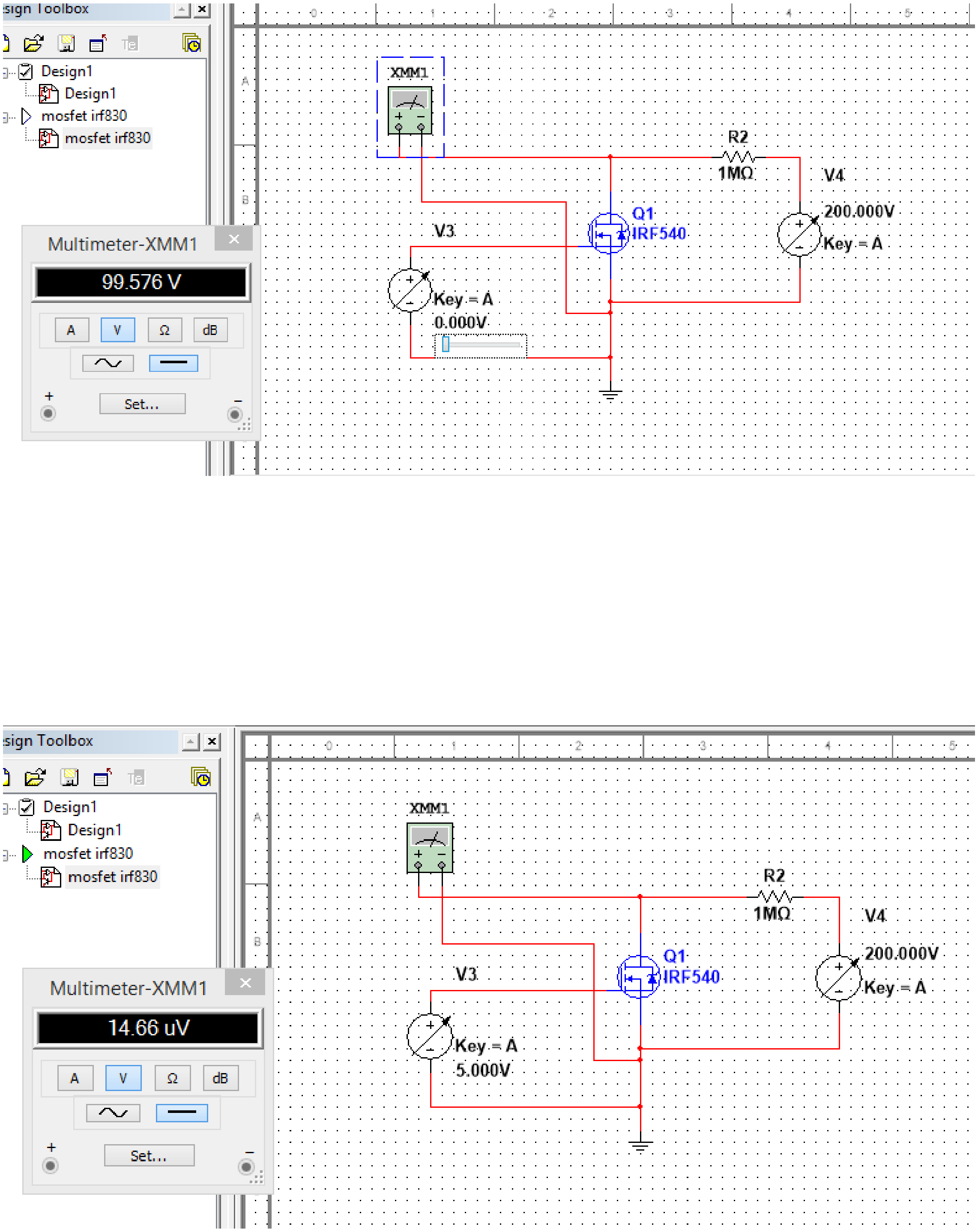


Figure 9: Simulation results of switching operation for Model IRF 540.

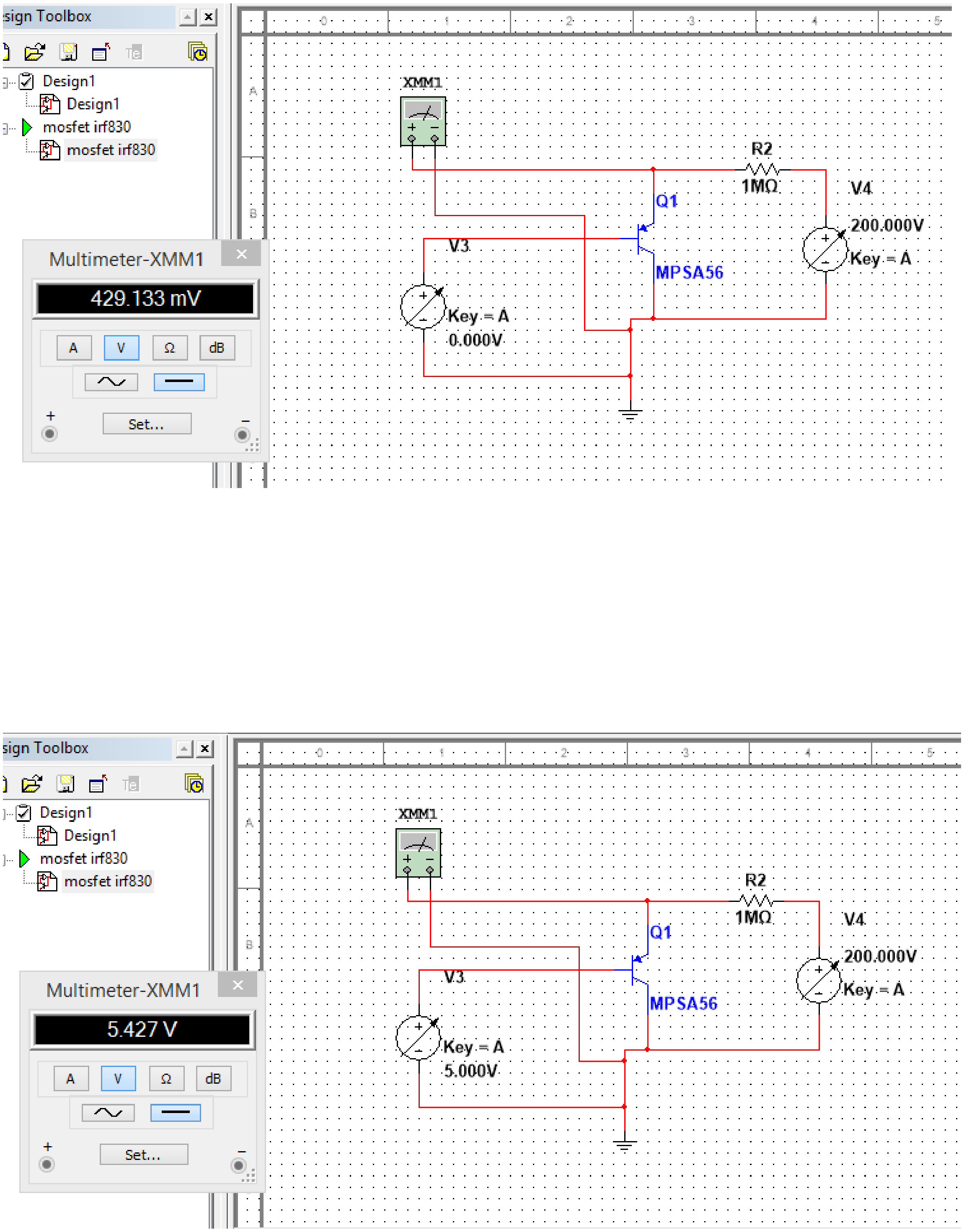


Figure 10: Simulation results of switching operation for Model MPSA 56.

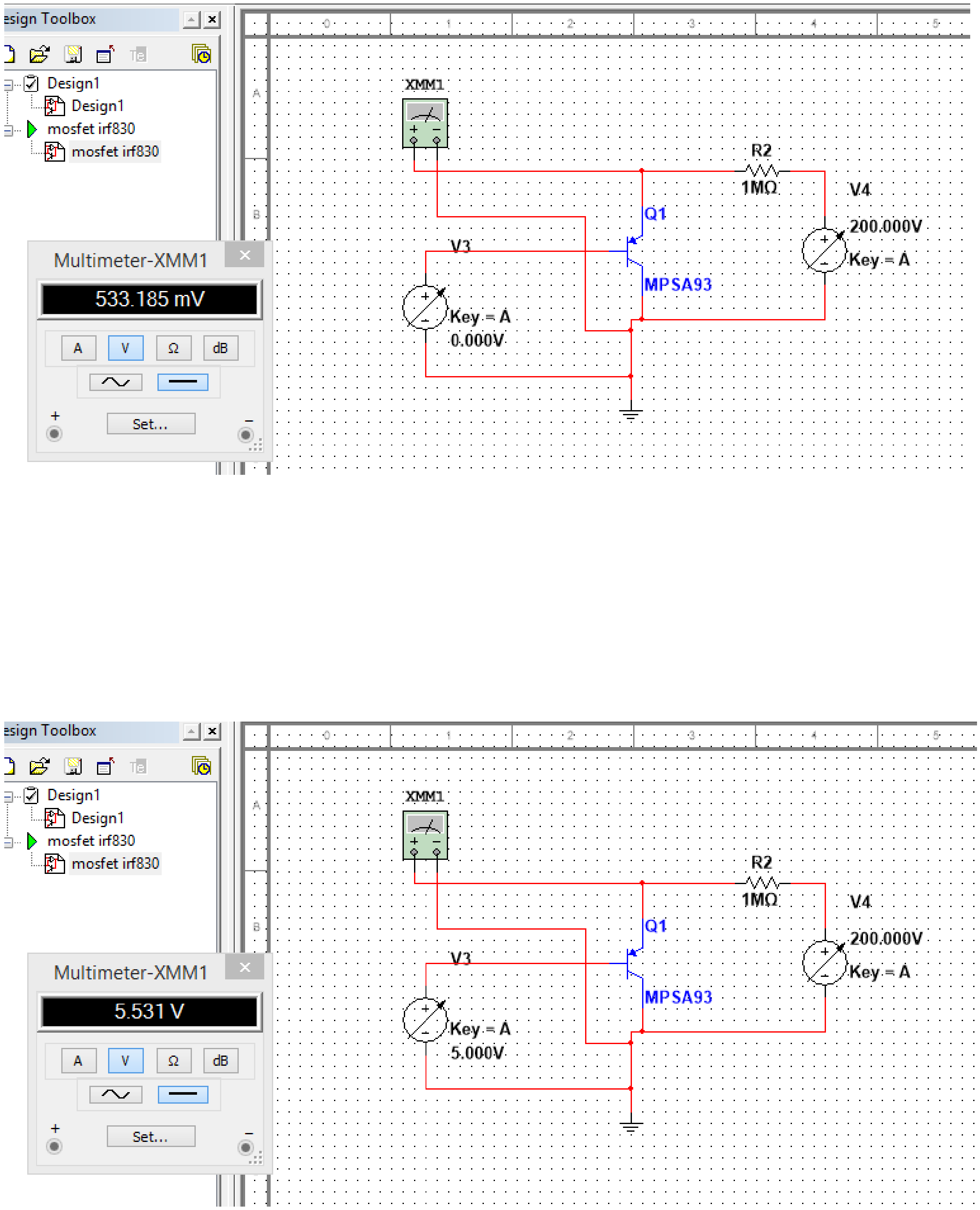


Figure 11: Simulation results of switching operation for Model MPSA 93.

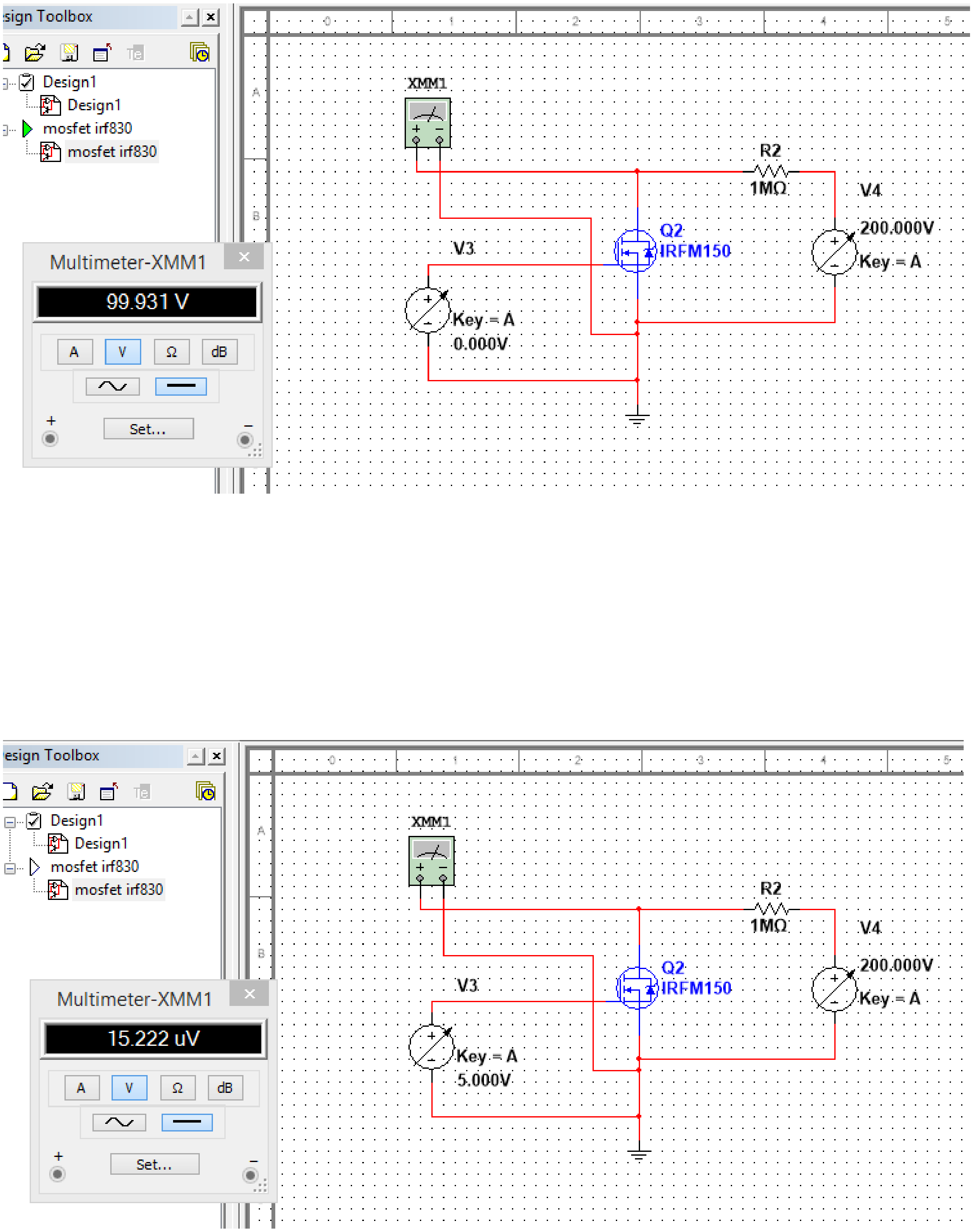
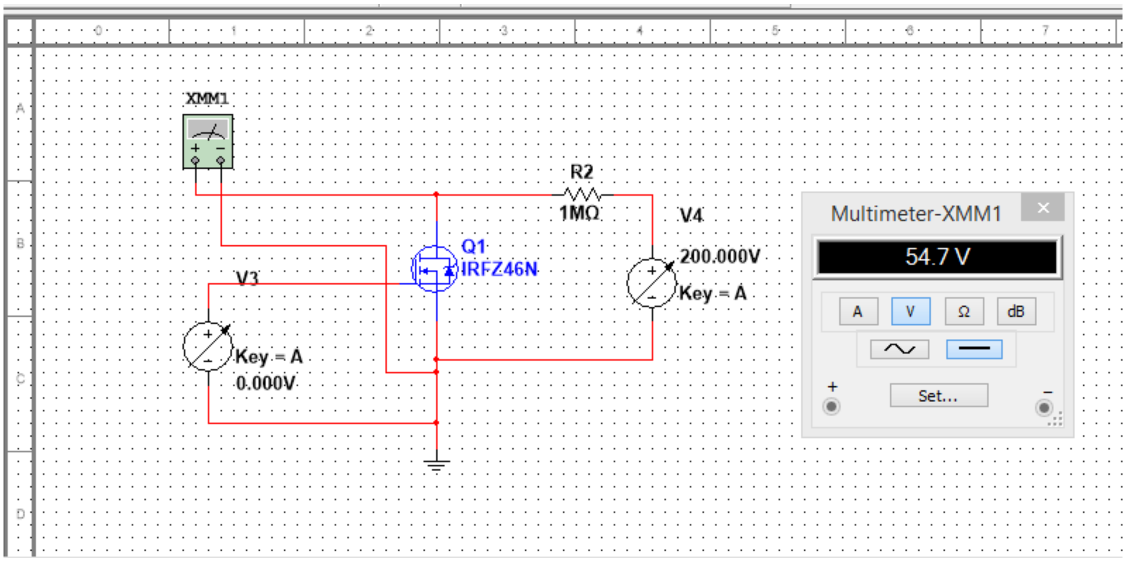


Figure 12: Simulation results of switching operation for Model IRFM 150.



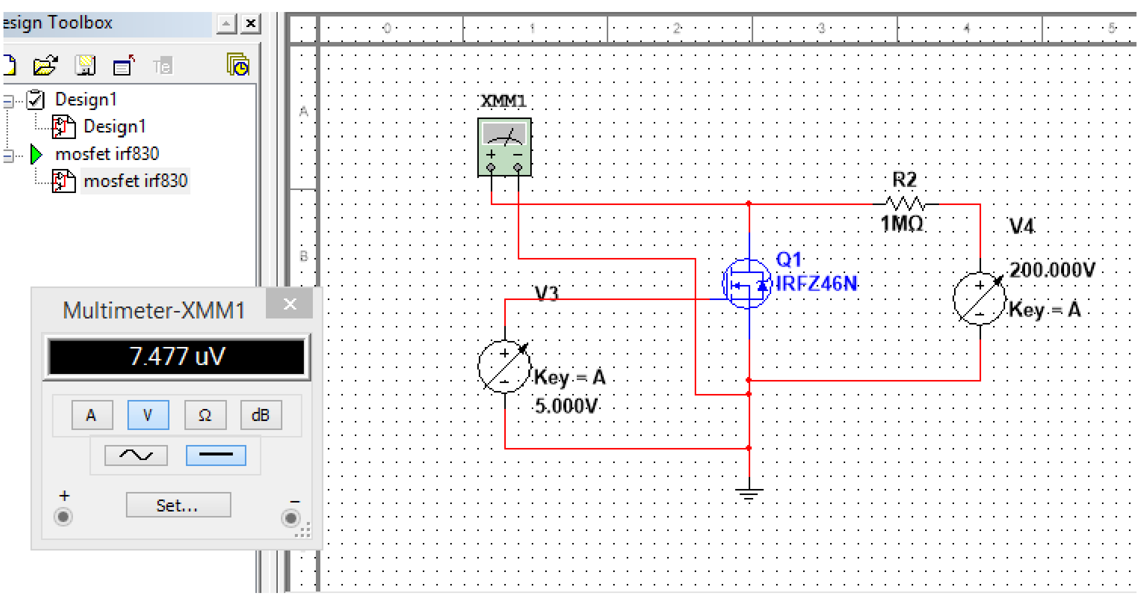
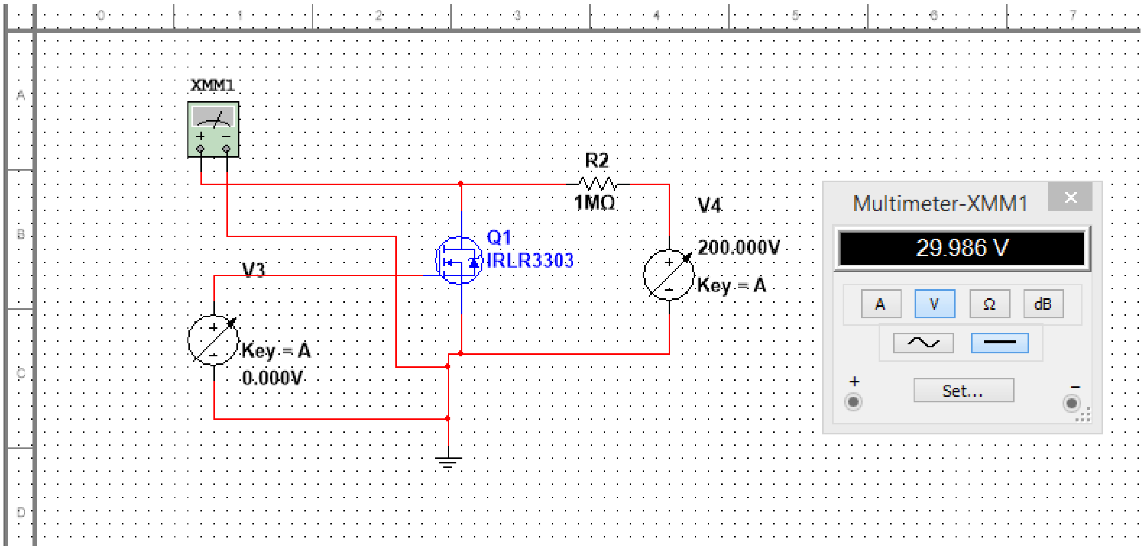


Figure 13: Simulation results of switching operation for Model IRFZ46N.



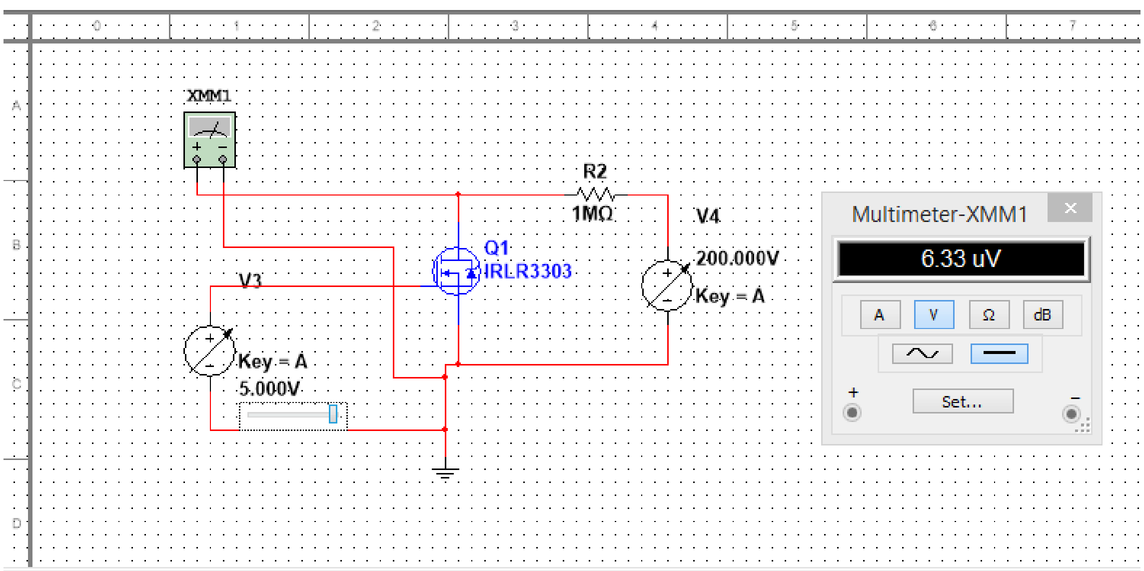


Figure 14: Simulation results of switching operation for Model IRLR3303.

4.1.2 Simulation Results for BJT MPSA 42

Switching operation plays an important role in electrowetting process. High voltage transistors that fit the changed standard of voltage to successfully carry out the switching operation are bipolar junction transistor MPSA 42. The simulation result tested out on NI Multisim is shown in Figure 15 and 16. The maximum voltage that can be withstand by Transistor MPSA 42 is 300 V.

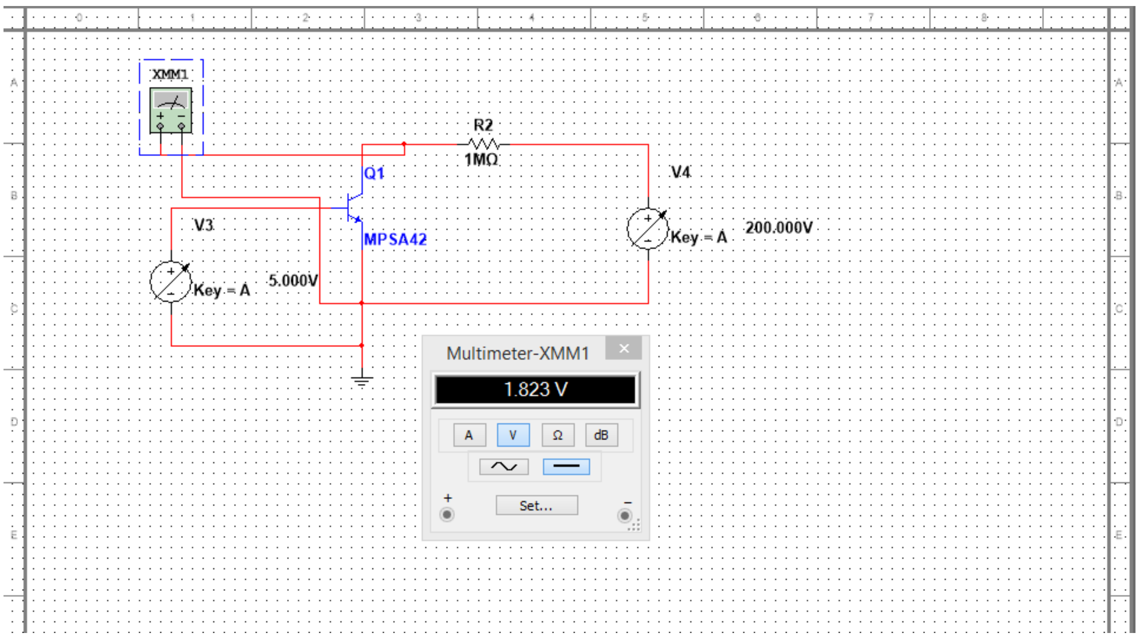


Figure 15: Simulation circuit run on NI Multisim using transistor MPSA 42 during a digital output of 5V from Arduino.

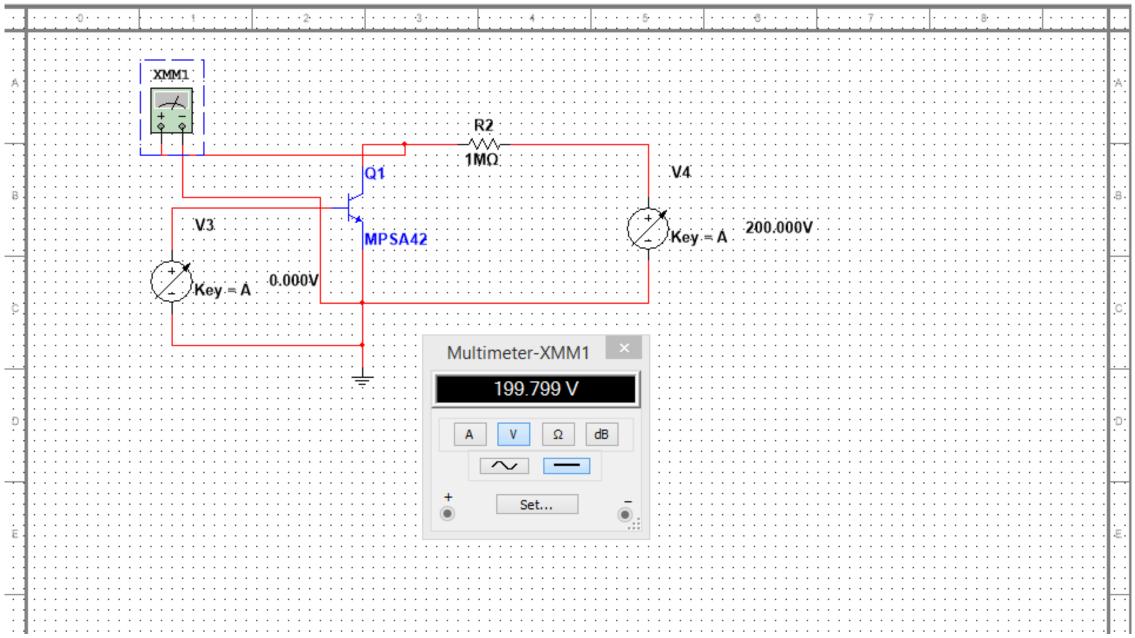


Figure 16: Simulation circuit run on NI Multisim using transistor MPSA 42 during a digital output of 0V from Arduino.

In order to determine the cutoff base voltage required to turn off the transistor completely, the potential difference of transistor between collector and emitter is monitored while varying the voltage supply to the transistor's base with 0.5V increment from 0V until 5V. Table 5 shows the theoretical results achieved.

Table 5: Theoretical results achieved for Transistor MPSA 42 collector voltage.

Base voltage (V)	Collector voltage (V)	Base voltage (V)	Collector voltage (V)
0	199.799	2.75	0.614
0.25	199.788	3	0.735
0.5	118.637	3.25	0.86
0.75	-0.021	3.5	0.989
1	-0.082	3.75	1.122
1.25	0.039	4	1.257
1.5	0.107	4.25	1.395
1.75	0.19	4.5	1.536
2	0.284	4.75	1.678
2.25	0.387	5	1.823
2.5	0.498		

From the simulation results achieved and graph shown in Figure 17, it was found that 0.75 V is needed to turn off the transistor completely. With any increase in the base voltage after 0.75 V, the transistor is being driven into saturation mode where it will be no or very little increase in the current value in collector part.

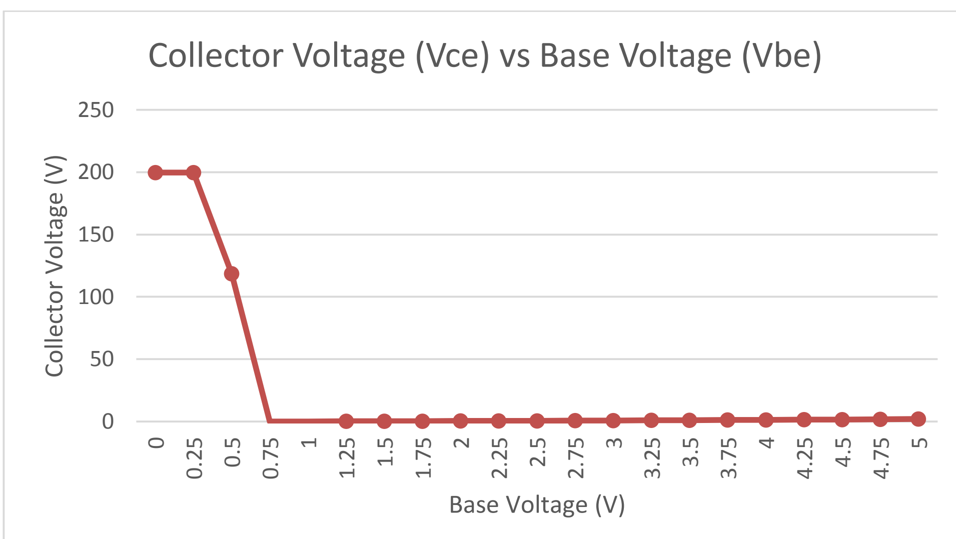


Figure 17: Graph of collector voltage versus base voltage for Transistor MPSA 42.

4.1.3 Validation Results for BJT MPSA 42

However, when the circuit is set up in the laboratory exactly like the simulation using bipolar junction transistor (MPSA 42), the multimeter is constantly measuring at the value of 101.8 V even with the change of base voltage from 0 V to 5v. This indicates that no switching operation is performed. A voltage drop across the collector and emitter should be happening when the transistor is turned on. While the datasheet shows that MPSA 42 can withstand 500 mA. After the triggering voltage of 5V is being applied in the simulation, the current shown is 3 A. This might be the reason that caused the transistor to not work.

Therefore, the alternative was to change to other fitting model of MOSFET IRF 740 from the list of selected switching components. As a voltage controlled component, the operation of MOSFET relies on its gate-source voltage (V_{GS}) when exceeding certain threshold to trigger the switching transaction between the on/off of transistor. This specification is considerably more beneficial for the application of this project as compared to BJT as a current controlled component primarily because the drive circuit of the project originates from the logic control of Arduino between digital high (5V) and low (0V). While for BJT, it is essential that a constant base current be provided to toggle from the off state of transistor to on. Therefore in a high power application such as this project, a much more complex drive circuit is required to ensure the switching operation of BJT. Aside from all of that, switching frequency is another critical element being considered during the component comparison between BJT and MOSFET. Since part of this project requirement is the 1 kHz of high voltage DC supply which necessitate the voltage alternates between 0 and 200V, the high switching frequency from MOSFET certainly poses as a better selection over BJT. Hence, MOSFET is a preferable component for high voltage switching in this project.

4.1.4 Simulation Results for MOSFET IRF 740

MOSFET IRF 740 was tested out on simulation using NI Multisim as shown in Figure 18.

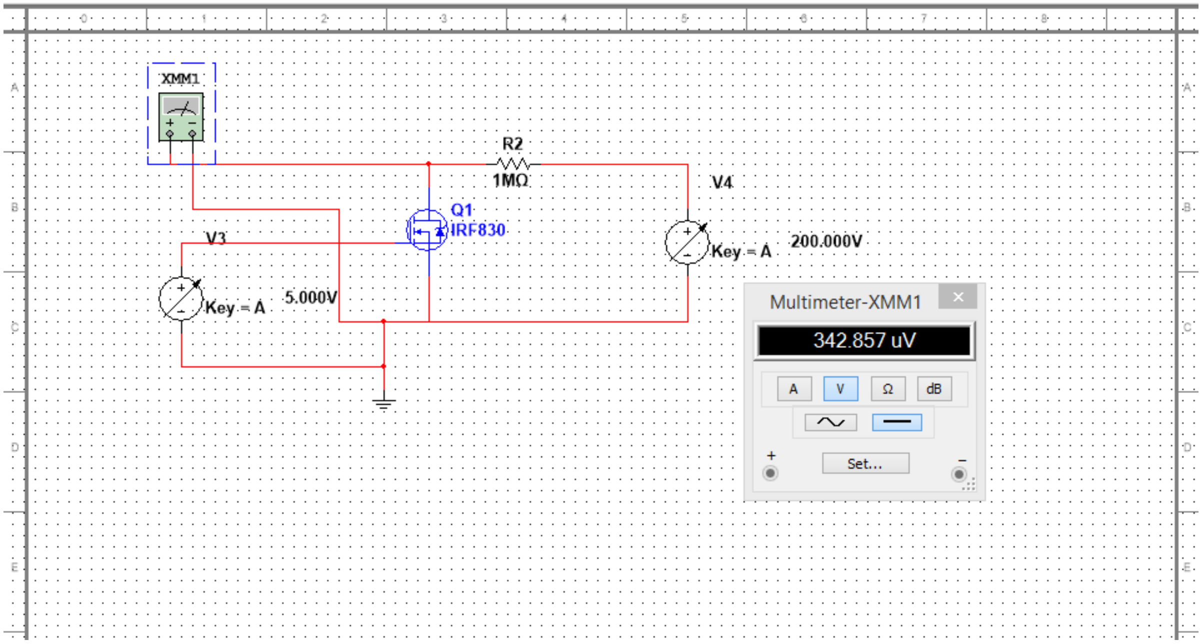


Figure 18: Simulation circuit run on NI Multisim using MOSFET IRF 740 during a digital output of 5V from Arduino.

Table 6 and Figure 19 below shows the theoretical results achieved through simulation. From the simulation achieved in Figure 19, it was found that 4 V is needed to turn off the MOSFET completely and the values are pretty much consistent compared to Transistor MPSA 42.

Table 6: Theoretical results achieved for MOSFET IRF 740 collector voltage.

Base voltage (V)	Collector voltage (V)	Base voltage (V)	Collector voltage (V)
0	190.291	2.75	190.291
0.25	190.291	3	190.291
0.5	190.291	3.25	190.291
0.75	190.291	3.5	190.291
1	190.291	3.75	190.291
1.25	190.291	4	0.000984
1.5	190.291	4.25	0.000513
1.75	190.291	4.5	0.000412
2	190.291	4.75	0.000368
2.25	190.291	5	0.000343
2.5	190.291		

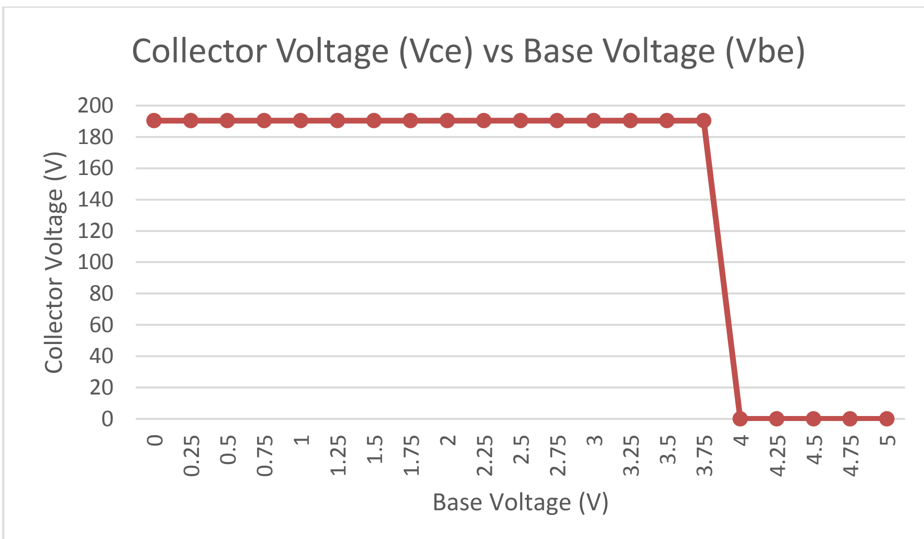


Figure 19: Graph of theoretical results of collector voltage versus base voltage for MOSFET IRF 740.

4.1.5 Validation Results for MOSFET IRF 740

While the Table 7 and Figure 20 shows the experimental results achieved. The experiment was carried out in the nanolaboratory available in campus. The experimental results are almost similar to the theoretical results.

Table 7: Experimental results achieved for MOSFET IRF 740 collector voltage.

Base voltage (V)	Collector voltage (V)	Base voltage (V)	Collector voltage (V)
0	200.5	2.75	200.1
0.25	200.3	3	198.5
0.5	200.4	3.25	189.4
0.75	200.4	3.5	141.6
1	200.4	3.75	45.86
1.25	200.4	4	8.22
1.5	200.4	4.25	0.014
1.75	200.4	4.5	0.003
2	200.4	4.75	0.001
2.25	200.4	5	0
2.5	200.4		

The collector voltage started to drop at around 3 V of base voltage and went to approximately 0 at 4 V of base voltage. Comparatively, MOSFET gives a better result.

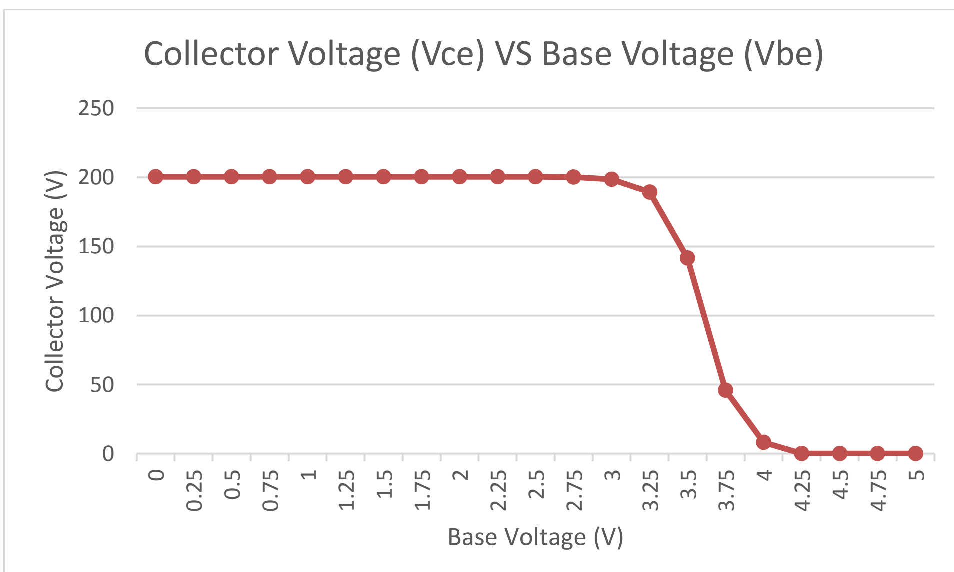


Figure 20: Graph of experimental results of collector voltage versus base voltage for MOSFET IRF 740.

4.1.6 Experimental Setup for MOSFET IRF 740

Figure 21 and 22 show the setup for the MOSFET IRF 740 with high voltage DC power supply.

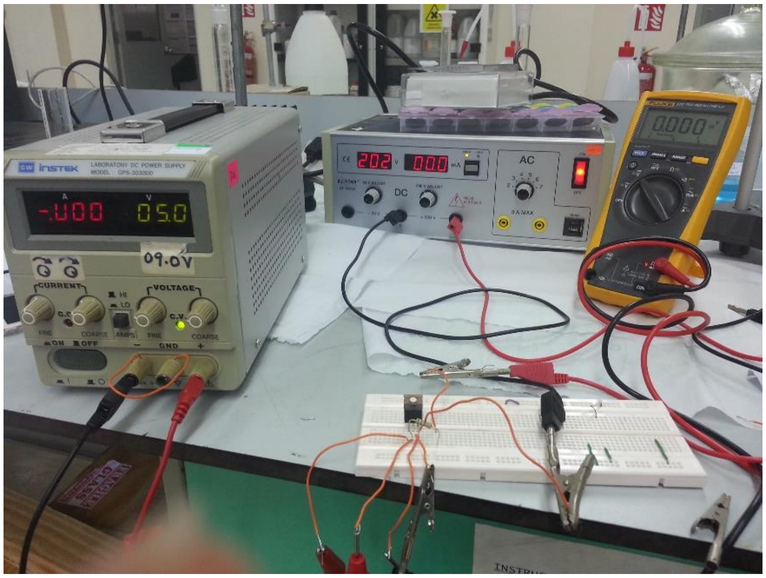


Figure 21: Experimental setup for MOSFET IRF 740 during 0V output from Arduino.

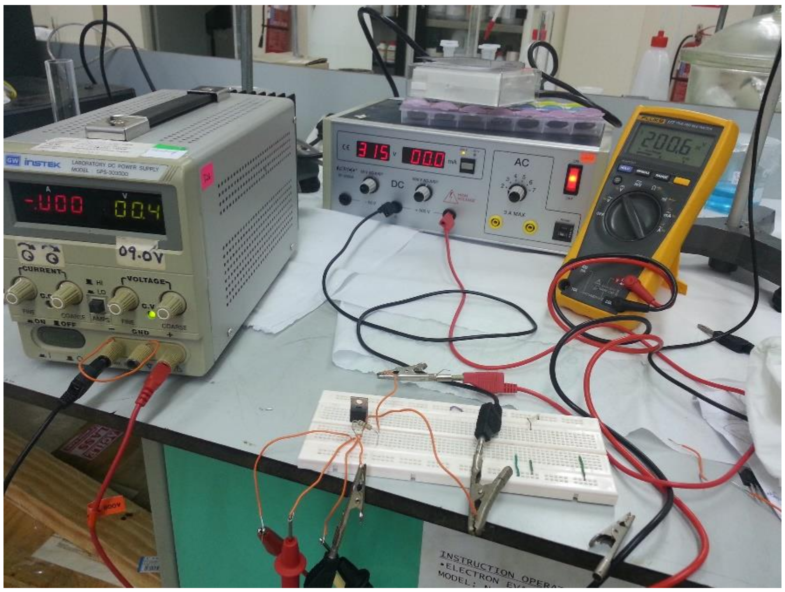


Figure 22: Experimental setup for MOSFET IRF 740 during 5V output from Arduino.

4.1.7 Experimental Setup for BJT MPSA 42

Figure 23 and 24 show the setup for the BJT MPSA 42 with high voltage DC power supply.

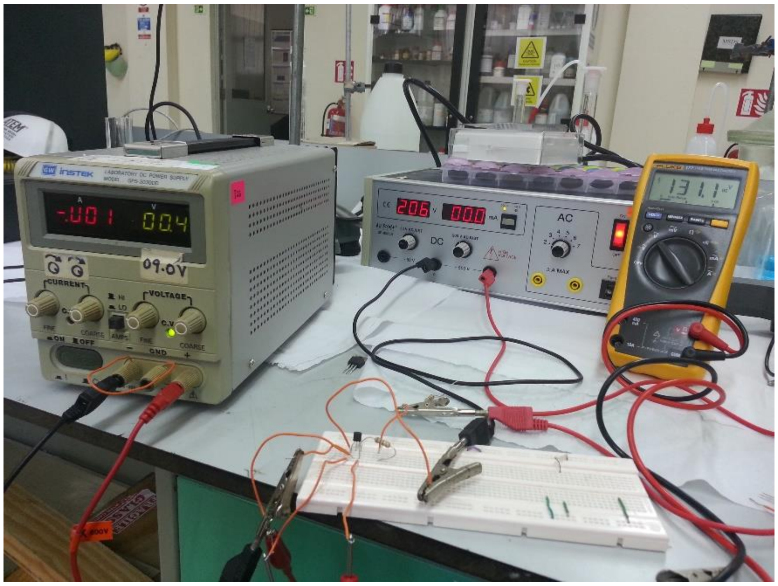


Figure 23: Experimental setup for BJT MPSA 42 during 0V output from Arduino.

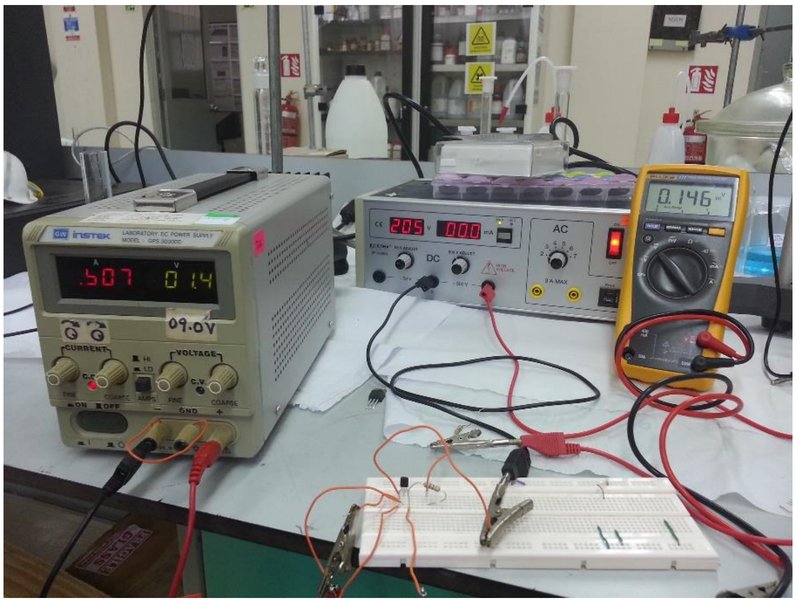


Figure 24: Experimental setup for BJT MPSA 42 during 5V output from Arduino.

4.2 Coating Process

As for the coating part, a spin coater machine is used to spread the cooking oil evenly onto the surface of Printed Circuit Board (PCB). The PCB is set to spin at the speed of $2000rpm$ for 3 minutes. Figure 25 shows the spin coater machine used while Figure 26 shows the aftermath of coating process done.

Figure 25: Spin coater machine.

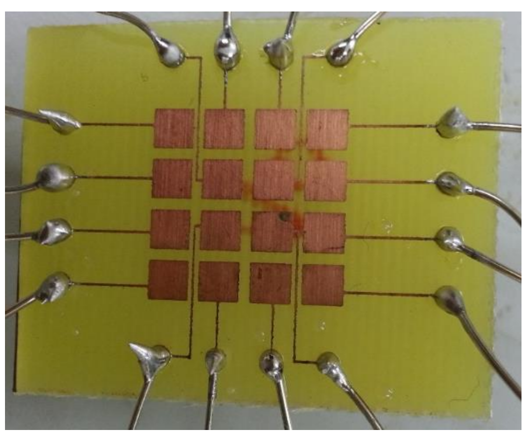


Figure 26: Aftermath of coating process.

Though there is no promising result obtained from initial experiment conducted with 30v power supply, a few finding were still discovered on the impact of coating layer during electro wetting process. The beginning of the experiment begin with the utilization of tap water for droplet manipulation. However, due to the impurities contained within which made tap water a decent conductor of electricity, the water droplet was vaporized instantly once the completion of circuit. Oxidation was formed on the surface of electrode and corroded its functionality.

To resolve the issue, deionized water was used as the replacement of tap water as it is free from impurities. The H_2O molecules from deionized water are less likely to split into $H+$ and $OH-$ which inhibit the conduction of electricity. With the low conductivity, deionized water essentially acts as an insulator and prevent the vaporization of droplet during the completion of circuit. These findings highlighted the significance of coating layer in providing a thin layer of insulation when attempting to ionize the water used.

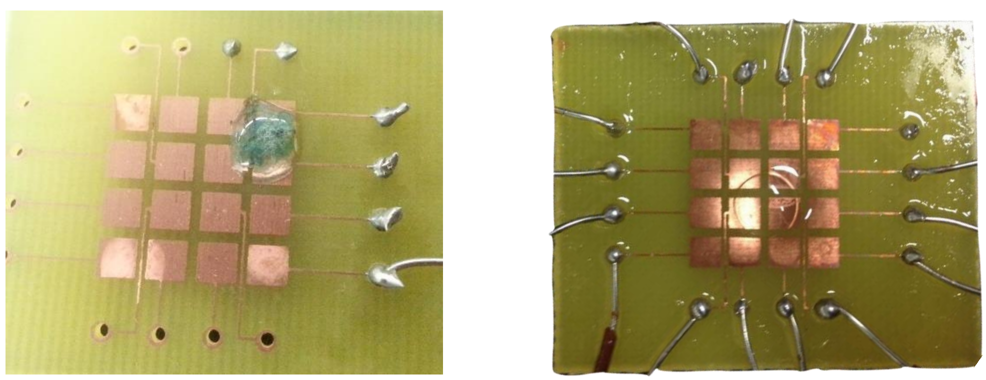


Figure 27: With and without formation of oxidation process on electrodes.

In the effort to verify the suitability of material as insulation layer between electrodes and the droplet, a few materials were tested namely RainX, Shellac Spray, WD-40 and cooking oil. Cooking oil stood out as an excellent insulation layer for this application as it is immiscible with deionized water and the droplet showed marginally movement once. No formation of oxidation is observed which indicate the sufficient thickness of insulation. As for other insulation materials, droplet showed sign of oxidation with the formation of rust upon the surface of electrode shown in Figure 27. No visible movement of the droplet was recorded. Nevertheless, the core reason for the immobility of the droplet was primarily the insufficient in power supply. Therefore, all insulation materials will be retested against 200 V power supply in the following progress of experiment to verify the validation.

4.3 Final Results

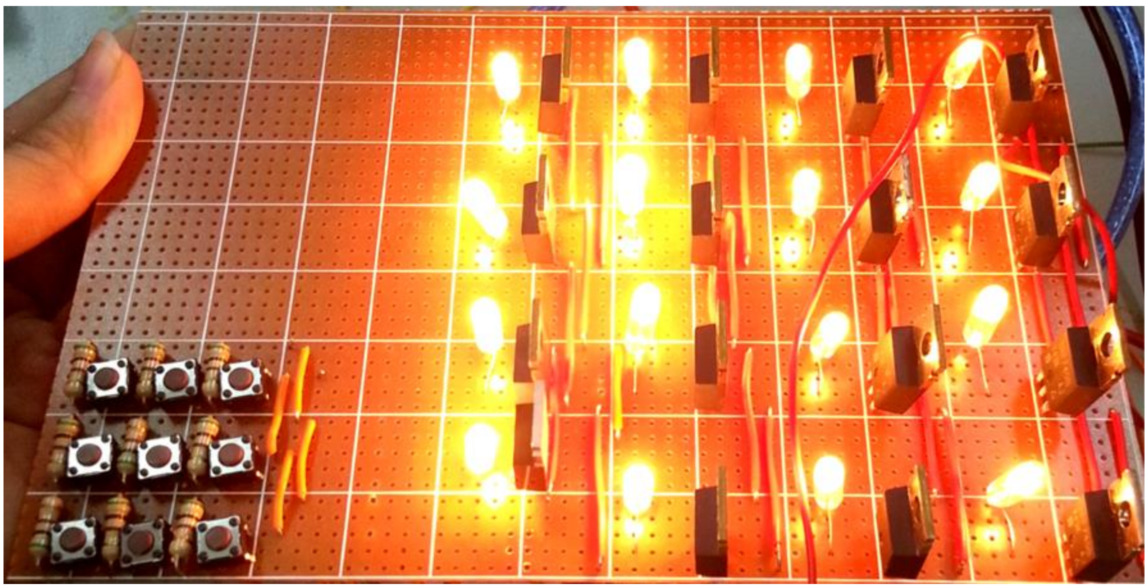


Figure 28: Substitution of LEDs to replace electrodes.

Initial experiment results of using 30V DC power supply had been proven futile due to the lack of voltage to initiate sufficient ionization within droplet. Therefore, the focus of this project has been shifted towards developing high voltage switching system. A successful switching system was developed. With the constructed switching system, Arduino managed to control the voltage into each electrode. Still, due to the inability to carry out the droplet movement for splitting and mixing process, high voltage LED was selected as a better visual representation to show the validity of the system as shown in Figure 28.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The finding from this project concludes that high voltage of at least 200V DC at 1 kHz is necessary as the minimum voltage required to initiate the droplet movement. Low voltage supply is incapable to ionize the droplet and thus unable to act as a driving factor toward the droplet movement.

Among the variety types of switching components, MOSFET is the best fitting component to perform the switching operation for electrowetting process. The model IRF 740 is the ideal model in the midst of MOSFET as the rating of current is high enough to withstand the huge amount of current passes through and the voltage required to trigger the switching operation is low enough for digital output from Arduino without the need of logic-shifter.

As for the coating layer upon electrode to ease the droplet movement and to ensure the isolation of current from passing through the droplet, cooking oil demonstrated the most promising results in achieving the objectives. Slight movement was observed once while using cooking oil as the dielectric layer.

5.2 Recommendation

For further recommendations, numerous experimental procedures and techniques can be carried out to improve the optimization of electrowetting system. The electrowetting process can be further developed to increase the robustness for working with variety of liquid substrates.

Materials used for dielectric layer as insulator is also a significant aspect for future research. An inappropriate material will limit the performance of electrowetting. More understanding and research needs to be done to minimize the reversible effect from it. Some applications in other fields of study may need different coatings. Therefore, alternative needs to be developed.

Besides, the capability of the electrowetting process can be increased to manipulate multiple liquid droplets for splitting and mixing by enlarging the matrix scale of electrode. In addition, electrowetting process can be improved by having the droplet moving in real time condition where the user can manipulate the activated electrode. Four controls namely up, down, left and right will be constructed with four push buttons to offer the flexibility of manipulating droplet into the desired direction.

Last but not least, better use of microscope or spectroscopy can be used to further investigate the electrochemical process such as corrosion or oxidation, which occur during the electrowetting process. In a usual electrowetting device, copper electrodes are used as the transporting medium. More experiments or research can be carried out for different kind of metals on electrode to reduce the sign of electrochemical process.

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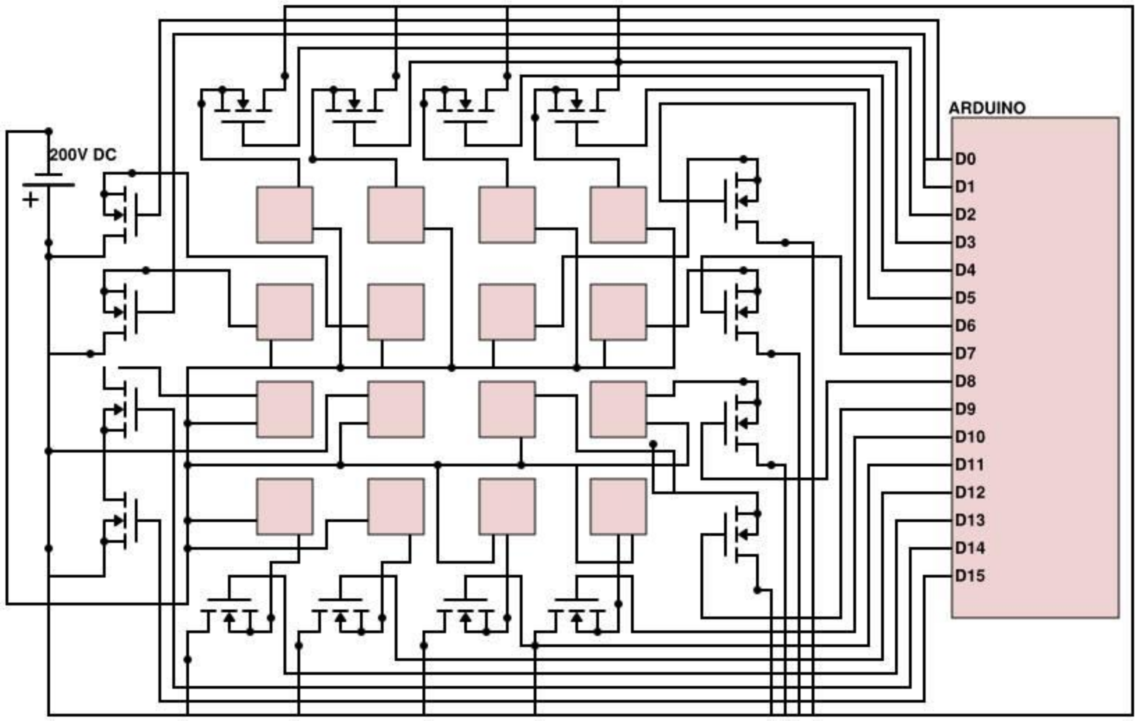
APPENDICES


ARDUINO
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