Heaven's light is our guide

Design and Analysis of a Low Actuation Voltage Electrowetting-on-Dielectric Device

A Thesis submitted in Partial fulfillment for the requirements of the degree of

Bachelor of Science in

Electronics & Telecommunication Engineering

By

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to the

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December, 2020

CERTIFICATE

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ACKNOWLEDGEMENT

I wish to express special thanks to my thesis supervisor Dr. Mst. Fateha Samad, Associate Professor, Department of Electronics & Telecommunication Engineering, Rajshahi University of Engineering & Technology for her guidance, support and constructive criticism. I am grateful to her for showing me the way for designing and analyzing a low-actuation voltage Electrowetting-on-Dielectric Device and for inspiring me along the way. I am indebted to her for helping me whenever I needed and for being patient with the slow work progress due to the long computation time of the device models. This work has been possible only for her proper guidance.

Technologically, this thesis would have been very difficult without the COMSOL Multiphysics software which made the design process reliable.

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December, 2020

ABSTRACT

Electrowetting is the modification of the wetting properties of a surface (which is typically hydrophobic) with an applied electric field. Electrowetting on a dielectric (EWOD) has led to a wide range of scientific and technological investigations due to its applicability in microfluidics, especially for droplet-based optical and lab-on-a-chip systems. Studies have shown that a low-actuated EWOD structure showed better performance as it overcame issues like unexpected heat generations and thereby droplet evaporation. The work presented in this thesis was aimed at improving the performance of an EWOD device by minimizing the required actuation voltage. The simulations of were performed in COMSOL to grant insight on various parameters that play a critical role in system performance. The specific system being simulated was the Open Drop experiment and the parameters being investigated were droplet size & type, electrode size and the inter-electrode gap, filler medium and dielectric layer materials and thickness.

It was found that by using an immiscible fluid rather than air as the surrounding medium of the droplet, the actuation voltage could be reduced remarkably. Also, as the droplet overlap onto the neighboring electrode, or droplet radius to electrode size ratio, decreased, the droplet velocity increased and the actuation voltage decreased. Also, lesser inter-electrode gap showed enhanced performances. A range of different materials were used as the dielectric in the EWOD device and Titanium di-oxide (TiO_2) contributed to the lowest-actuation voltage. After the analysis of the simulated results about involved parameters using COMSOL Multiphysics software, it was possible to conclude that it is possible to get an actuation voltage as low as 0.09 volts.

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LIST OF SYMBOLS

Symbol	Meaing
TiO_2	Titanium di-oxide
CEP	Cyanoethyl pullulan
PVDF	Polyvinylidene difluoride
EWOD	Electrowetting-on-Dielectric
DMF	Digital microfluidics
NaCl	Sodium Chloride
KCL	Potassium chloride

Chapter-1 Introduction

1.1 Problem Statement

Electrowetting is a method for controlling the shape of small-volume droplets in microfluidic biochips. Its working principle is based on modification of the characteristics of droplet's surface wetting using an applied electrical field. Initially introduced in 1875 by Lippmann [1] and afterwards an addition of a dielectric-layer to the basic structure by Berge [2] in 1990 portrayed a dramatic improvement on performance and stability. This evolved structure which is commonly known as Electrowetting-on-dielectric (EWOD) has led to a wide range of scientific and technological investigations due to its applicability in microfluidics, especially for droplet-based optical and lab-on-a-chip systems. Studies have shown that a low-actuated EWOD structure showed better performance as it overcame issues like unexpected heat generations and thereby droplet evaporation. This thesis specifically focuses on investigating aspects including droplet size & type, electrode size and their inter-electrode gap, filler medium and dielectric layer materials which influences the establishment of a low-actuated EWOD device.

Before starting to discuss about the EWOD devices, first comes the Digital microfluidics (DMF). In DMF, micro-droplets are manipulated (dispensed, moved, stored, mixed, reacted, or analyzed) on a platform with a set of insulated electrodes [3]. Apart from EWOD, Electro-hydrodynamics (EHD), Opto-electrowetting, LDEP (Liquid Di-electrophoresis) are some of the DMF techniques. Among them, DMF based on EWOD is a rapidly developing technology. This is because EWOD demonstrates several unique advantages including controllability, scalability and reconfigurability, ease of fabrication and low power consumption. This is based on the EW phenomenon which means applying a voltage between a metal layer and electrolyte droplets would cause the droplet to move. Later on, thin dielectric film between the droplets and the electrodes was added to prevent electrolysis therefore it is known as Electrowetting on Dielectric (EWOD). The EWOD effect is applicable in numerous fields including Micro Total Analysis Systems (μ-TAS), Lab-on-a-chip [4], Displays technology[5,6], Adjustable lenses [7],Optic communication[8],Biomedical applications [9, 10] as a point-of-care system or Drug Delivery device, DNA repair enzyme analysis [10], Proteomics, DNA Hybridization [11], Polymer Chain Reaction (PCR) [12]. The work presented in this thesis was aimed at improving the performance of an EWOD device by minimizing the required actuation voltage. The advantages of such as low actuated EWOD device includes prevention in unexpected heat generation and eventually eliminating the chance of droplet evaporation. Therefore, In this thesis, a thorough description of the novel EWOD devices is given and the theoretical background which is needed in order to develop and design these devices is presented as well.

1.2 Background

Back In 1875, Gabriel Lippmann [16] first explained the electrowetting behavior of mercury and other liquids on variably charged surfaces. It was found by him that by applying a voltage between the mercury and electrolyte, the capillary depression of mercury in contact with electrolyte solutions could be varied. He had formulated a theory of electrocapillary effect and then developed several applications, including a very sensitive electrometer and a motor.

Later on, in 1936, surface charge was used to change the shape of water drops by A. N. Frumkin. However, in 1981, the term 'electrowetting' was first introduced by G. Beni and S. Hackwood to describe an effect proposed for designing a new type of display device. Since then, for manipulating micro-amounts of liquids on surfaces, electrowetting has become one of the most widely used tools.

The recent developments were initiated by Berge [2] in the early 1990s. He introduced the concept of separation of the conductive liquid from the metallic electrode and used a thin insulating layer. This eliminated the problem of electrolysis. At present, his concept is popularly known is as electrowetting-on-dielectric (EWOD).

In 2002, Pollack et al. [4] demonstrated that by using low-viscosity (1 cSt) silicone oil as the filter liquid, 100 mM KCl droplets can be moved with 60 Vdc at a faster speed of about 10 cm/s. Evaporation of droplets were prevented by the use of an immiscible liquid medium. It reduced the threshold voltage by reducing the contact angle hysteresis, and also by providing a thin layer of lubrication, the friction between the droplet and the solid surface was reduced.

In 2009, Hong et al. [17] emphasized on dielectric materials used in this experimental study of EWOD. The performance of EWOD devices is heavily dependent on the dielectric materials which are being used. He investigated dielectric breakdown of several typical polymeric and inorganic insulators analytically which occurs between the electrodes and conductive liquids under certain threshold potential. The electric breakdown occurring in dielectric layer and surrounding medium (air or silicon oil) were studied and a mathematical model of breakdown voltage as a function of dielectric thickness was built up by him.

In 2013, Samad et al. [13] presented an EWOD device with optimized insulating layers which operated by low actuation voltage. The device included an array of electrodes on a silicon substrate, covered by a dielectric layer of Sio2 and then a hydrophobic layer of Sio2, Su-8 and Parylene C. In the simulations, two different molar of di-ionized water droplet were considered. Results depicted that the device the 1M KCL (potassium chloride) droplet was successfully moved to the adjacent electrode at an actuation voltage of about 25 V. In the same year, Choi et al. [8] used 400nL water droplet in air atmosphere on 100nm silicon dioxide and could successfully decrease the voltage to about 18 to 25 V.

In 2014, Samad et al. [14] made variations of dielectric layers as well as hydrophobic layers in the proposed EWOD model. Dielectric layers included Su-8 2002, Polyvinylidenefluoride (PVDF) and Cyanoethyl pullulan (CEP) and hydrophobic layers included 50 nm Teflon and Cytonix. The results showed that only 7.8V of actuation voltage was required for the ferro-fluid droplet transportation.

In 2016, Semih et al. [15] proposed a micro-structured surface in order to increase the contact angle of an even hydrophobic layer. He developed two models describing the contact angle on a micro-structured surface namely, The Wenzel model and Cassie-Baxter model. The Contact area of the droplet and the surface of nanopillar were higher in the second model which resulted in a higher contact angle. Analyzed results showed that as the contact angle increased, the minimum actuation voltage decreased. For contact angle 147˚ and 20 nm Al2O3 dielectric layer, minimum actuation voltage in this case was about 16V. However, dielectric breakdown or the dielectric constant were not considered with a proper emphasis in this model.

In 2018, Torabinia et al.[18] demonstrated the significance of phase shift across multiple dielectric layers in EWOD devices. The proposed model contained two dielectric layers instead of one. This provided increased sustainability. He also depicted that frequency of Vin varies with materials for dielectric layers and also with numbers of dielectric layers in the stack.

In 2019, A numerical simulation optimizing droplet motion driven by electrowetting was performed by Jake Lesinski. He granted insight on various parameters that play a critical role in system performance. He investigated parameters such as the applied input voltage, contact angle at the advancing triple point, and droplet overlap onto neighboring actuated electrodes. It was found that the droplet velocity increased with the decreasing droplet overlap onto the neighboring electrode, or droplet radius to electrode size ratio. The droplet velocity also increased as the applied potential increased but it decreased as the induced contact angle at the advancing triple point decreased. Both the decreasing overlap and increasing voltage had a linear effect on droplet velocity. Results also showed that an increasing input voltage and increasing droplet overlap ratio, the rate of change of droplet velocity decreased.

1.3 Goals and Approach

The main subject of this thesis is developing a low-actuated Electrowetting-on-dielectric device. This chapter serves partly as an introduction to the existing EWOD models & the parameters that influence the performance of the device and partly as a presentation of the main topics dealt with in this thesis. The brief introduction and background information leads to the presentation of the thesis focus. Subsequently, an introduction to the phenomenon of electrowetting in general is given. A historical overview of the experimental research is given. Later on, acknowledgement of the existing EWOD devices is followed by the description and function of the identified individual layers. The results and the limitations of those existing models are also mentioned. The theory is explained briefly and the terms and related aspects which needs to be emphasized are also presented shortly after that. Later on, a novel model is presented in order to serve the same stated cause. Design and simulations of the proposed model was done using COMSOL Multiphysics software (version 5.5). This is followed by an analysis of the parameters which greatly affect the voltage minimization process. In order to describe the main contributions to the actuation voltage minimization aspect, the investigated parameters include filler medium, Droplet type (as in, the material used as the droplet which needs to be manipulated) , Gap between adjacent electrodes, Electrode’s length, Size of the droplet and the material of the di-electric layer used. Finally, concluding remarks are given based on the simulation results and the problems faced during the simulation and future improvement scopes are discussed.

1.4 Importance of the Thesis

The growing interest in electrowetting-on-dielectric (EWOD) which is basically a promising method of micro droplet manipulation, has led to a wide range of scientific and technological investigations due to its applicability in microfluidics, especially for droplet-based optical and lab-on-a-chip systems. In EWOD, each droplet is controlled individually by an applying external electric field to the designated electrodes. Since creating discrete droplets and pumping of liquids are done by surface tension alone, it does not require intricate systems such as channels, pumps and valves to drive and regulate. Thereby, EWOD provides direct manipulation of discrete droplets and hence enables fabrication and operation of highly automated microfluidics systems with more flexibility and higher efficiency. The work presented in this thesis was aimed at improving the performance of an EWOD device by minimizing the required actuation voltage. The advantages of such as low actuated EWOD device includes prevention in unexpected heat generation and eventually eliminating the chance of droplet evaporation. Therefore, In this thesis, a thorough description of the novel EWOD devices is given and the theoretical background which is needed in order to develop and design these devices is presented as well.

1.5 Structure of the Thesis

The thesis is organized in some parts. First the basic principle of electrowetting has been discussed elaborately. Then the layers of the device that have shown their influence in the performance of the device have been highlighted. Basically, the material properties are discussed in brief. The materials choosing plays a vital role in the design and performance of the device. For this, different electrical and mechanical properties of the materials are a great concern.

Then the design of the EWOD device is presented. The dimension of the device and the associated parts which form it as well as their sizes are presented in this work. The design of the novel model which is done using COMSOL Multiphysics software is described elaborately. However, due to the limitations of the software, some problems were faced in replicating the real-world scenario. These limitations are also mentioned in the later section of the study. In total Six parameters which were investigated for realizing the low-voltage actuated electrowetting on dielectric device. These include filler medium, Droplet type (as in, the material used as the droplet which needs to be manipulated) ,Gap between adjacent electrodes, Electrode’s length, Size of the droplet and the material of the di-electric layer used. After each parameter analysis, the best value of the previous parameter was noted and it was kept fixed for the following parameter analysis. In this way, new models were designed and simulated.

Following that, simulation results of my proposed work is presented. The simulation of some other existing works are also presented for the better comparison and analysis. The outputs of different existing works are compared with their design parameters and outputs. This comparison and analysis have come to some deductions. These deductions may play an important role in the design and simulation of the EWOD devices in the coming days.

Chapter-2 Literature Survey

2.1 Introduction

The performance evaluation parameters of EWOD are being emphasized on to improve the existing models. A brief review for each parameter and evaluation of their improvement for the enhanced performance of EWOD devices is presented in this section.

2.2 History of EWOD devices

Back in 2002, Both Fair et al. [3] and Polack et al. [4] used an approximately 800nm parylene C coating for insulation of the electrodes and showed in their experiments that an approximately 900 nL droplet of 0.1M KCL solution in air moved at an actuation voltage which is about 40 to 50 V.

However, In 2013, Choi et al. [8] used 400nL water droplet in air atmosphere on 100nm silicon dioxide and could successfully decrease the voltage to about 18 to 25 V. In the same year Samad et al. [13] presented an EWOD device with optimized insulating layers which operated by low actuation voltage. The device included an array of electrodes on a silicon substrate, covered by a dielectric layer of Sio2 and then a hydrophobic layer of Sio2, Su-8 and Parylene C. To characterize the performance of the device, simulations were performed in Coventorware software. In the simulations, two different molar of di-ionized water droplet were considered. Results depicted that the device which had Sio2 as dielectric layer and the Parylene C as hydrophobic layer moved the 1M KCL (potassium chloride) droplet at an actuation voltage of 25 V.

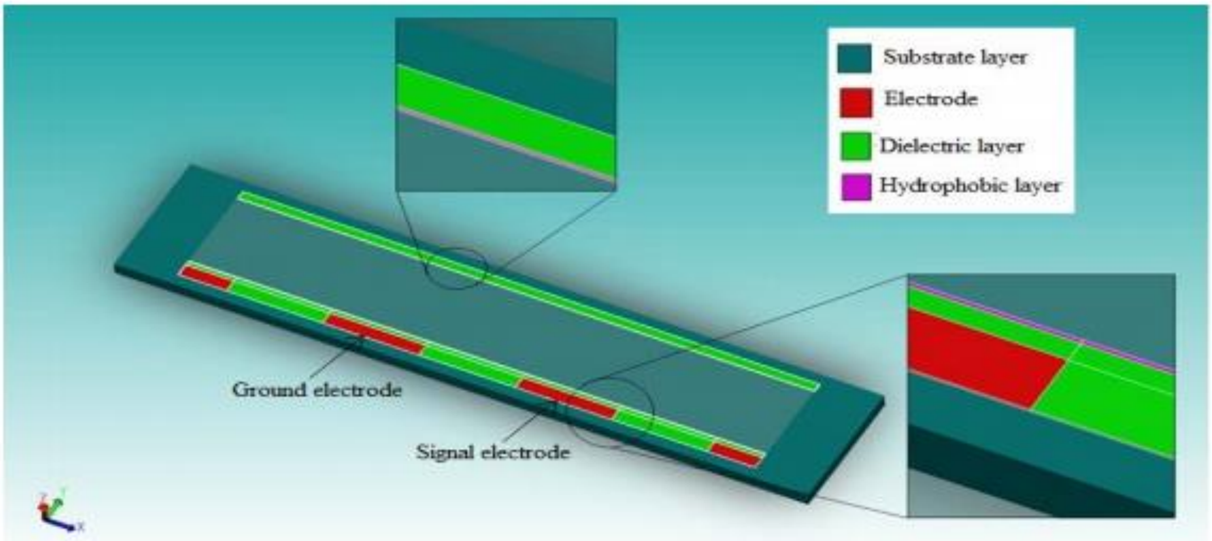


Figure 2-1Proposed 3-D model of the EWOD device [13].

In 2014, Samad et al. [14] proposed another EWOD microvalve which contained an array of chromium (Cr) electrodes on top of the soda-lime glass substrate. Over that lied both dielectric and hydrophobic layers. Variations of dielectric layers included Su-8 2002, Polyvinylidenefluoride (PVDF) and Cyanoethyl pullulan (CEP). 50 nm Teflon and Cytonix were used as hydrophobic layer. Coventorware which is a Finite Element Method (FEM) based software, was used to carry out the simulation analysis. Results depicted that the EWOD microvalve having a CEP dielectric layer with dielectric constant of about 20 and thickness of 1 µm, and a 50 nm thin Cytonix hydrophobic layer operated the conducting ferro-fluid droplet at an actuation voltage of 7.8 V.

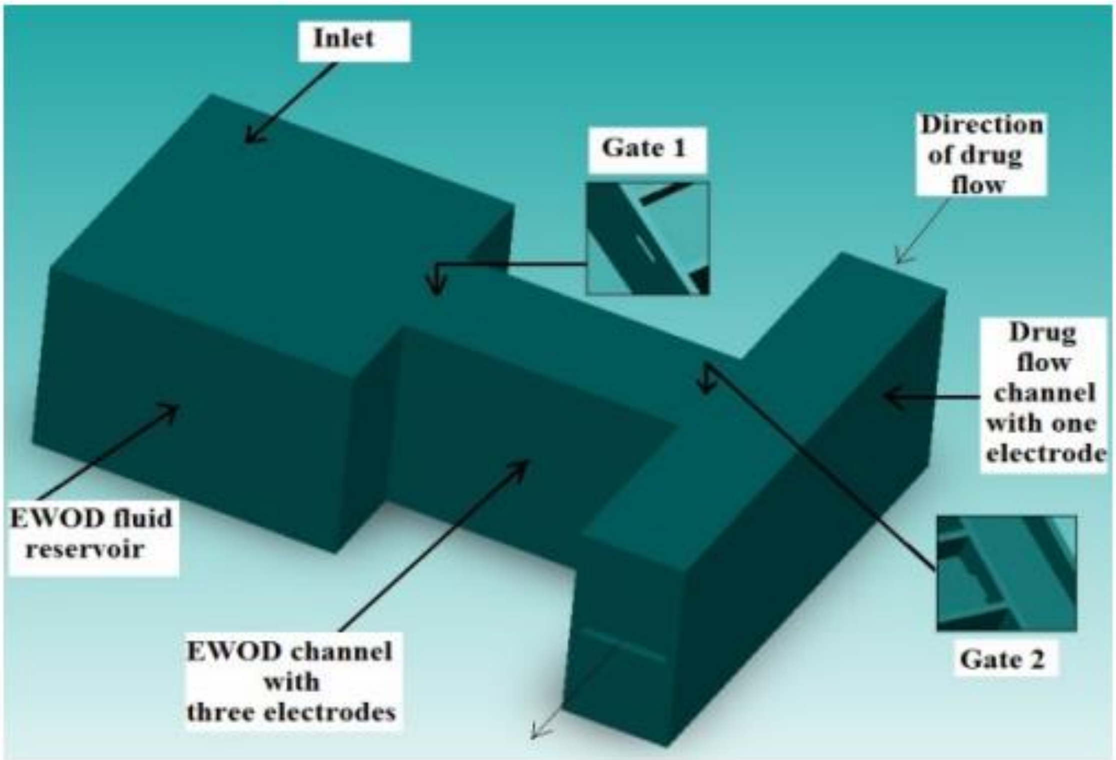


Figure 2-23-D view of the proposed EWOD microvalve [14].

Also, In 2014 - Torabinia et al. [29] theoretically and experimentally demonstrated the significance of phase shift across multiple dielectric layers in EWOD devices. The proposed model contained two dielectric layers instead of one. This provided increased sustainability. frequency of Vin varies with materials for dielectric layers and numbers of dielectric layers in the stack. Through this study, the existence of the optimum bandwidth of favorable actuation of liquid droplets in an EWOD device had been found. Also, it was shown that the frequency of input voltage where the peak actuation force was generated varied by materials used for dielectric layers, numbers of dielectric layers in the stack, and the type of liquid used to operate in the device. Analyzed Result showed that 1kHz frequency and an applied voltage of 100V could not move the droplet but 40KHz frequency with the same Vin caused droplet transportation.

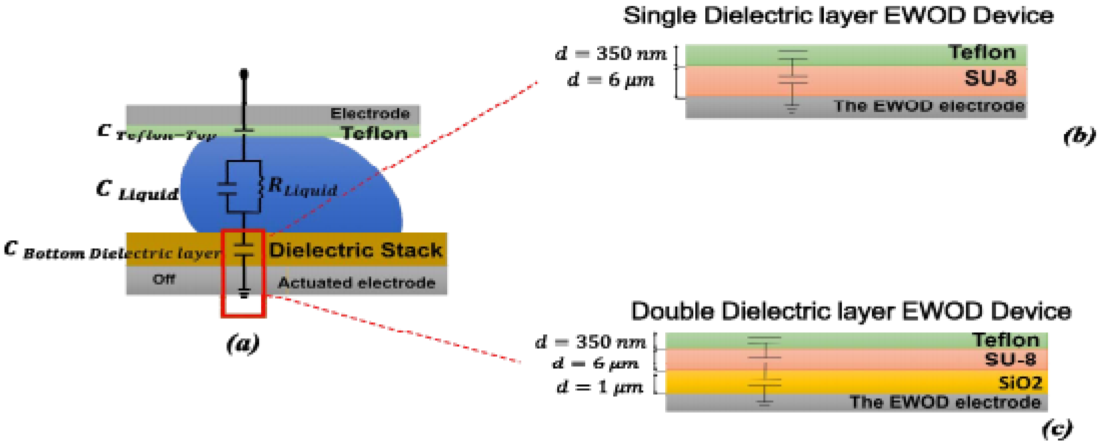


Figure 2-3(a) The equivalent circuit model of an EWOD device, (b) the single dielectric layer (c) Double dielectric layer [29].

Limitation of this model is that the presented electromechanical model has additional layers. And this makes the model somewhat complex.

In 2016, Semih et. al [15] focused on micro-structuring of the surface and the thickness of the dielectric for achieving a further reduction of the actuation voltage. Since the minimum actuation voltage is proportional to the dielectric thickness and anti-proportional to the Young contact angle, They proposed a model which had micro structured surface. This increased the contact angle of an even hydrophobic layer. There are two models describing the contact angle on a micro-structured surface. The Wenzel model in figure 2.3a.[14] and Cassie-Baxter model, as shown in figure 2.33b.[14]. Contact area of the droplet and the surface of nanopillar was higher in the second model and it resulted in a higher contact angle. Analyzed Result showed that Micro-structuring the surface increased the contact angle from 109˚ to 147˚. The analytically analyzed minimum actuation voltage was 16 volts for an EWOD model which had a combination of both micro-structured surface and 20nm thin Al2O3 dielectric layer. However, simulation results performed with COMSOL Multiphysics® showed that the droplet actuation was possible with only 3 volts. This was the lowest actuation voltage for EWOD in literature, considering that it is a simulation result.

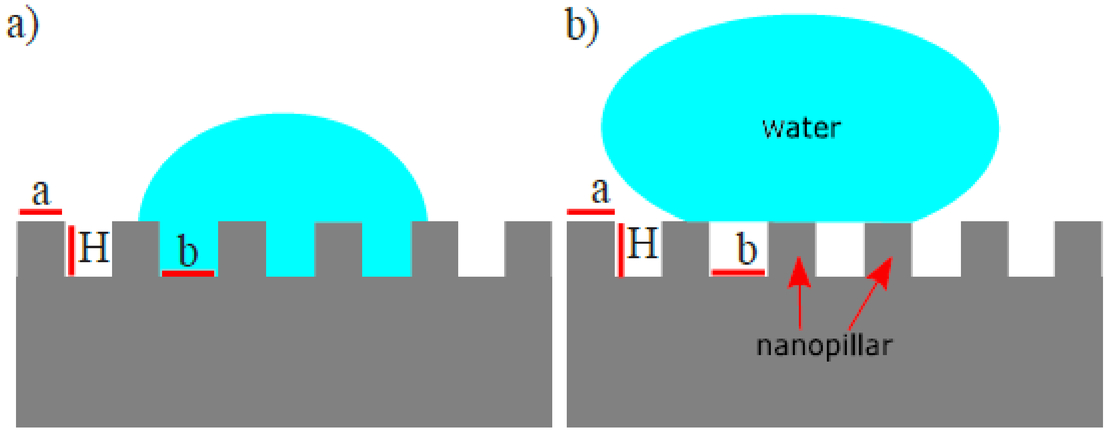


Figure 2-4In a) the droplet fills the graves and in b) the droplet sits above the nanopillars of the structure. H is the height, a is the length and b is the spacing between the nanopillars [15].

The limitations of this model was that analytically analyzed minimum actuation voltage and Simulation based Vmin differed in a huge margin. Also, Dielectric breakdown or the dielectric constant were not considered with a proper emphasis. Although higher dielectric constants could decrease the voltage even further.

Also, Nahar et al. [20] proposed a model in which the EWOD system had an array of slender electrodes instead of square electrodes. To make appropriate comparison, fabricated square electrodes and slender array of electrodes had the same dimensions. Further, In the case of slender rectangular electrodes, the number of simultaneously activated electrodes was varied to create variation in the initial actuation force and also to expose the droplet interface to different amounts of electrowetting and de-wetting forces at different locations in order to have different dynamic droplet shapes. Four different operation schemes were studied, as shown in *Figure 2.6 b–e*. The experimental results showed that droplet deformation patterns on slender electrodes were significantly different from those of the square electrodes case. The reason behind this is that Unlike the square electrodes case, a droplet does not restore its shape within one switching time, but continuously deforms while it transits over several electrodes until it reaches a certain amount of deformation. Therefore, droplet actuation force is greater in case of slender rectangular electrodes.

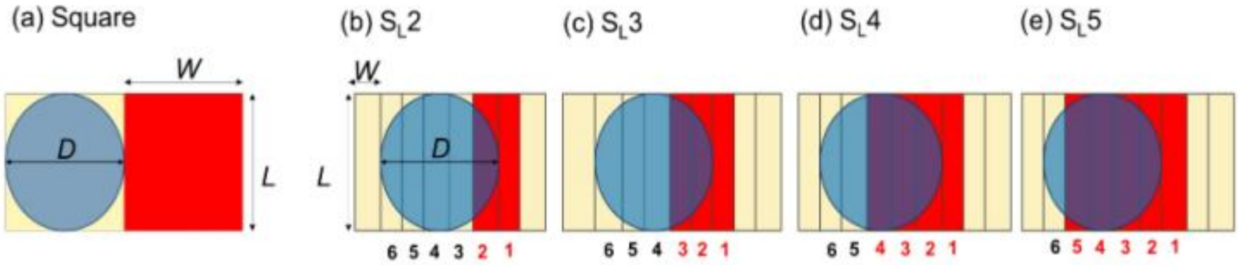


Figure 2-5 Schematic top view of: (a) Square electrode; (b)–(e) Slender electrodes with various electrode operation schemes. L, W and D denote electrode length, width and droplet diameter, respectively. Red areas represent the activated electrodes. The droplet moves

The same year, another (EWOD) device model was presented by Samad et. Al [16] in which a novel electrode shape and a multi-layer dielectric coating was presented that reduced the actuation voltage of the device to less than 12.6 V. In this model, A high-dielectric-constant multi-layer dielectric coating containing a 770 nm thick Polyvinylidene difluoride (PVDF) layer and a 1 µm thick Cyanoethyl pullulan (CEP) layer, was deposited over the electrodes for insulation. This multi-layer dielectric structure exhibited a high capacitance per unit area. Also, the actuation force at the droplet contact line was changed by the novel electrode shape which reduced the voltage required to operate the device. In addition, a hydrophobic surface was provided by an overlaying Teflon layer of 50 nm for droplet manipulation. It was observed from the experiments that the electrode shape and the dielectric structure contributed to the reduction of the actuation voltage remarkably.

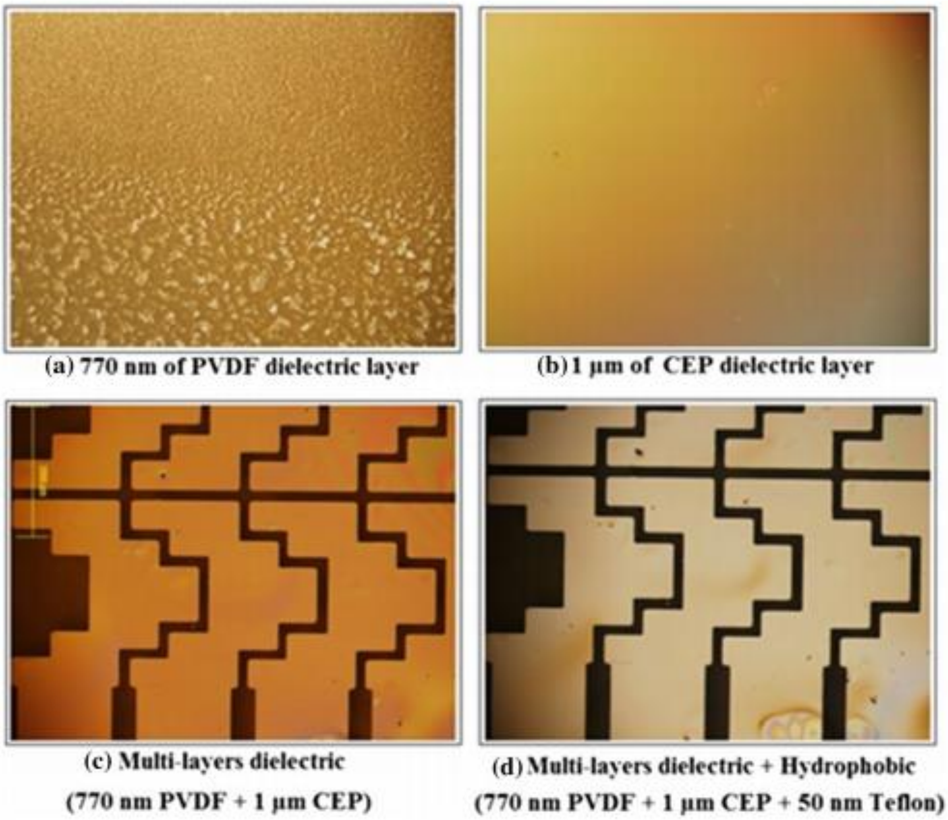


Figure 2-6 Electrode insulation using a multi-layer dielectric and hydrophobic coatings. [16]

2.3 Recent EWOD Model & Issues

Recently a numerical simulation optimizing droplet motion driven by electrowetting was done by Jake Lesinski [19] in which the proposed functional electrowetting on a dielectric numerical model was realized on COMSOL Multiphysics (version 5.3) software. The simulation considered three physics namely two-phase laminar flow, electrostatics, and the phase field method. The geometry of the simulation was simply a square with a hemispherical droplet inside, resting on the southernmost side of the square as shown in Figure 2.7. The model included a water droplet in the silicone oil domain. Two adjacent electrodes of 2 mm length of each were considered with 0.1 mm gap between them.

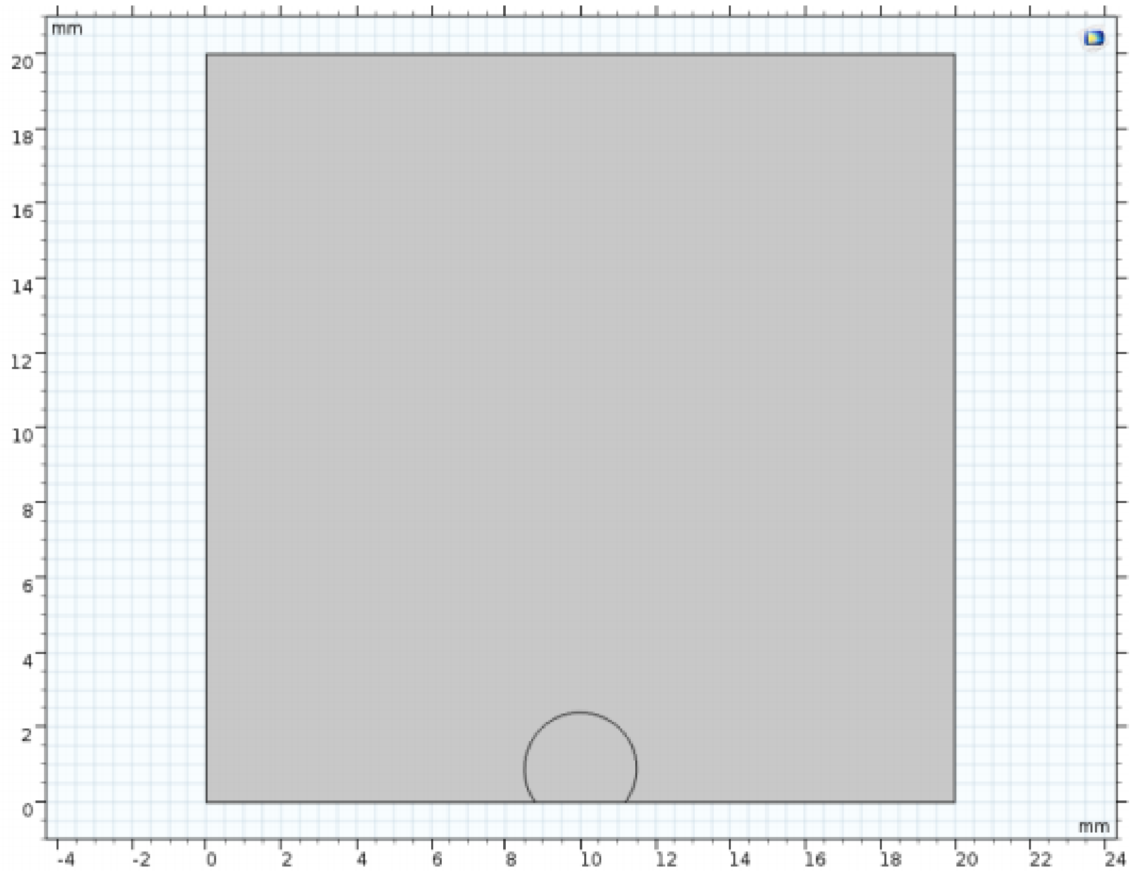


Figure 2-7 Geometry of open droplet & air domain by Jake Lesinski [19].

It was concluded that, A dielectric material could not be included in the simulation. The reason is, with the addition of a geometry below the bottom side of the square air domain, the wetted wall on which the droplet sat on became an internal wall. Internal walls were not allowed to be selected as wetted walls in COMSOL version 5.3. Also, the addition of a slip condition on the bottom wall of the square domain was the most troubling to the convergence of the simulation. navier slip, slip and slip velocity conditions were tested. The default setting for slip velocity and the viscous slip selection were attempted. Furthermore, the length specification for the viscous slip selection was attempted spanning several orders of magnitude; all failed to converge.

Amiri, et al., had performed a direct comparison of the two methods namely, Level Set method (LSM) and Phase Field Method (PFM) in COMSOL Multiphysics. Below, in Figure 2.8 (b), the instability can be seen from the LSM in contrast to Figure 2.8 (a) where a crisp interface is established by the PFM. Both the LSM and PFM are used to characterize phenomena at the interface of two phases. The LSM and PFM each have their respective advantages and considerations. The LSM has a less complex set of governing equations. On the other hand, vectoral equations are utilized by the PFM that set out to minimize the chemical potential of the system [21,22].

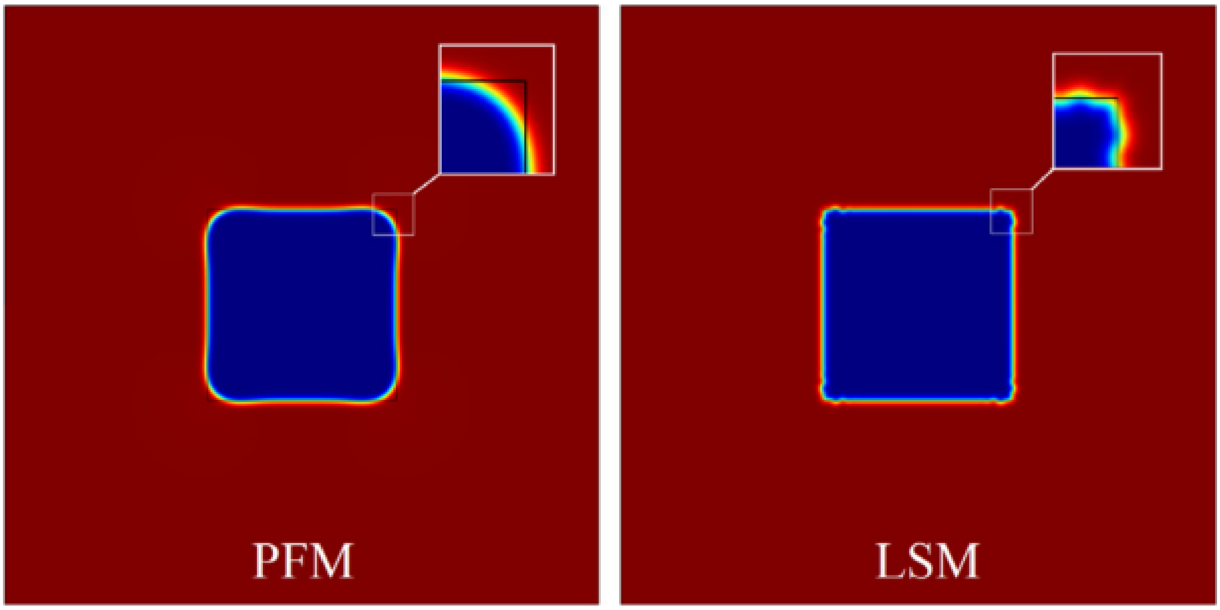


Figure 2-8 Rectangular bubble profile computed by PFM (left) and LSM (right) prior to initialization step (before time dependent solving) [23].

A comparison study was done between the two methods by Nahar, et al. [24]. Results revealed the PFM's ability to track the interface with finer detail and more accurate. The PFM is more suitable at tracking and outlining the interface.

However, there were some research gaps which were found while studying the existing EWOD models. These includes many facts. Firstly, A droplet is considered completely conductive, while in reality droplets may not be completely conductive. Secondly, Surface in reality is not so smooth. Thirdly, Dielectric constant of the hydrophobic layer and the dielectric layer are hardly equal. Fourthly, When the insulation layer is weakened by the applied high input voltage, the electric current can pass through the liquid and cause electrolysis. Lastly, Saturation of the contact angle occurs after reaching a constant value. It was also noted that unexpected heat generation and evaporation of the droplet due to high input voltage.

Chapter-3 Theory

3.1 Introduction

Electrowetting on dielectric (EWOD) is a popular technology used in digital microfluidic devices to move microscale quantity of liquid on a substrate with electrodes. A typical EWOD device. The basic structure, working principles and factors that influence the droplet manipulations are discussed in this section.

3.2 Basic structure of EWOD

A typical EWOD device consists of a substrate made of glass, silicon, paper, polyimide and more possible choices of material. The substrate is patterned with several electrodes and is coated with a thin uniform layer of a dielectric material. The entire device is then coated with a hydrophobic material to obtain a high contact angle for liquid droplets as well as to avoid adsorption of biomolecules. In can be summarized as follows: four main layers. of EWOD (depicted in Figure 3.1)

- *Main layer (substrate):* the framework of the used system.
- Insulated Electrode Layer (Arrays): used to apply the voltage.
- *Dielectric layer:* used to prevent electrolysis.
- *Hydrophobic layer:* to increase the contact angle of the surface and droplet.

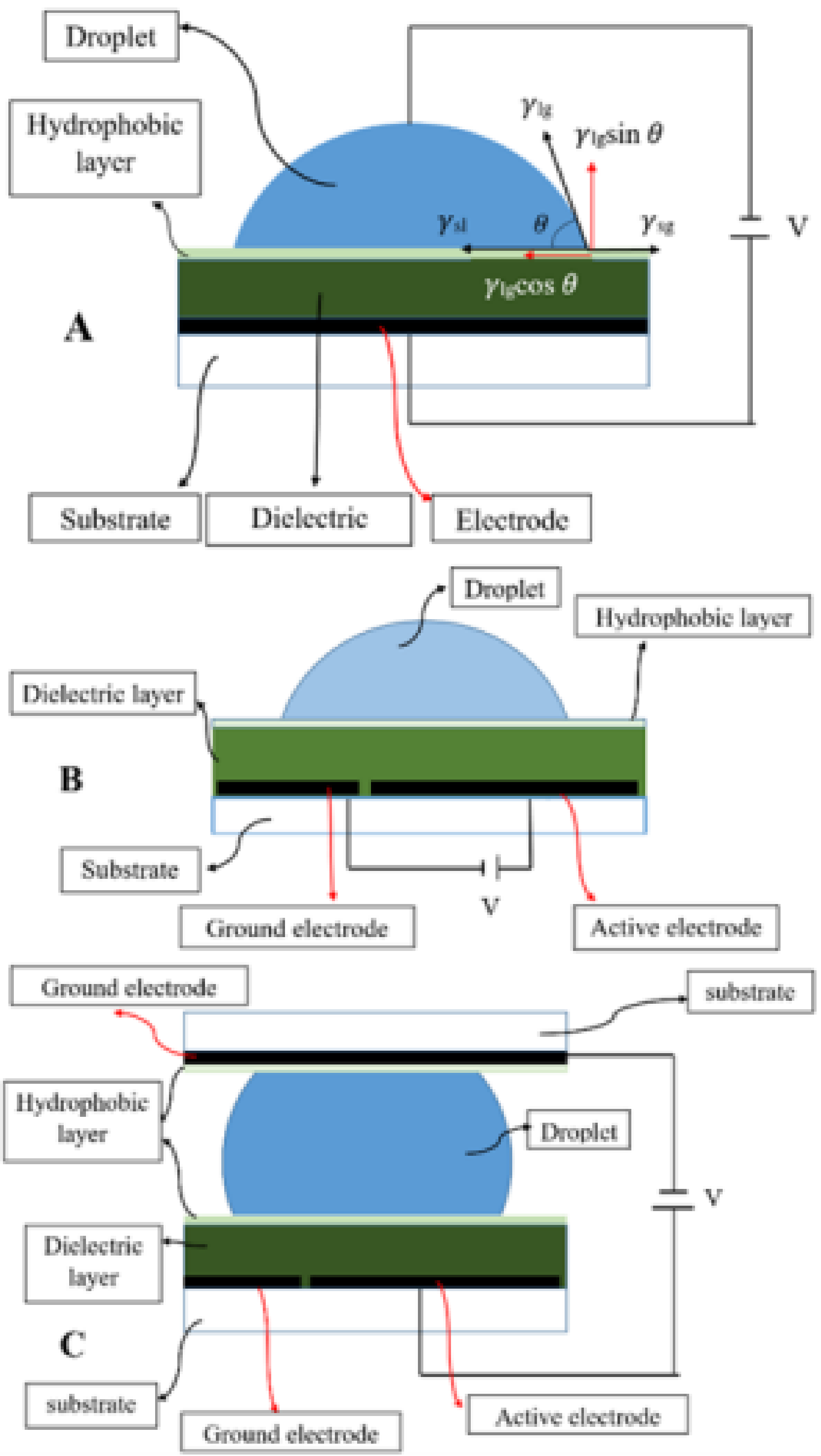


Figure 3-1 EWOD actuation configurations: (a) Two-plane (‘‘closed’’) and (b) co-planar (‘‘open’’) EWOD system; (c) Two dimensional reconfigurable digital microfluidic chip [25].

Vafaie et. al. [25] cited that EWOD mechanism can be classified into parallel-plate and single-palate structure. Firstly, the single-palate structure itself includes two different model (i.e. bi-planar and co-planar [24]). The main difference between these three structures is the applied electric potential form. The voltage is applied between the electrode and the droplet in bi-planar model. The voltage is applied between the active and inactive coplanar electrodes in coplanar case. On the other hand, the electric voltage is applied between the active electrode and the inactive non-coplanar electrodes in the parallel-plate model. In comparison to the biplanar model, the co-planar model has better results, because the disruption of the droplet does not occur. Also, single-plate structure includes many advantages such as Increased flexibility, increasing the degree of freedom of movement in two dimensions and disposal of external pressure resources in comparison to the parallel plate structure.

3.3 Basic Operating Principle of EWOD

EWOD phenomenon can be derived from classical thermodynamic approach. When sitting on a surface, each droplet creates three surface tension vectors on the surface (Figure 3.1.A). The three interfacial tensions operate together at the triple line to maintain droplet equilibrium with a certain contact angle. On application of high voltage to the electrodes an electric field is established over the corresponding electrode. This reduces the contact angle of the liquid with the hydrophobic surface. The reduction in contact angle causes the liquid to "wet" the electrode. Thereby, it sticks to the surface for the period during which electric field is prevalent. This is depicted in fig. 3.2. The change in contact angle is given by the Young-Lippman equation (Equation 1) [4].

$$\cos\theta_v = \cos\theta_0 + \frac{1}{\gamma_{LG}}\frac{\varepsilon_r\varepsilon_0}{2t}V^2 \qquad (3.1)$$

Where, $\boldsymbol{\theta_v}$ is the resulting contact angle

$\boldsymbol{\theta_0}$ is the Young contact angle defined by the Young-equation [25]

$\boldsymbol{\varepsilon_r \varepsilon_0}$ is the permittivity of the dielectric

V is the applied actuation voltage

γ_{LG} the liquid-gas interfacial tension and

$\boldsymbol{d}$ is the thickness of the dielectric.

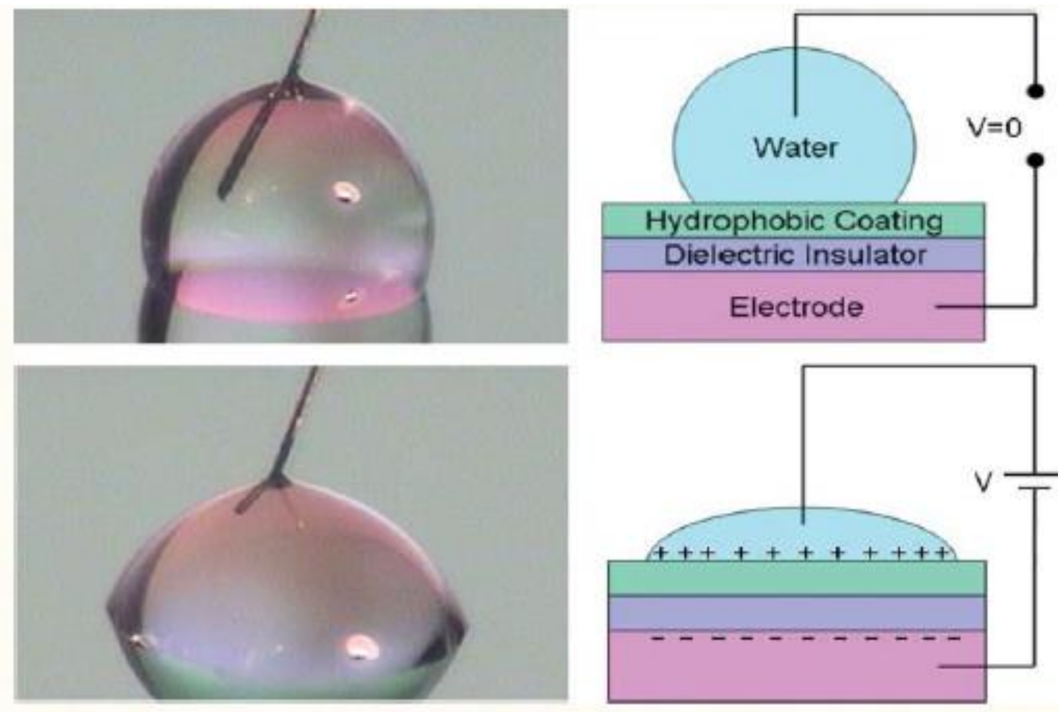


Figure 3-2 A water drop placed on a hydrophobic surface with a high contact angle. (Top) Electrowetting of the surface (Bottom) [7].

Upon removal of the high voltage and therefore electric field the droplet “de-wets” the surface. This wetting and de-wetting behavior can be used to move droplet form one electrode to the other thereby achieving transport of liquid on the microfluidic chip. Other manipulations of the droplets include droplet generation, splitting and merging. Figure 3.2 shows the working of a parallel plate EWOD device. The result of electrowetting in addition to the initial contact angle and interfacial tension can also be illustrated by the following figure 3.3

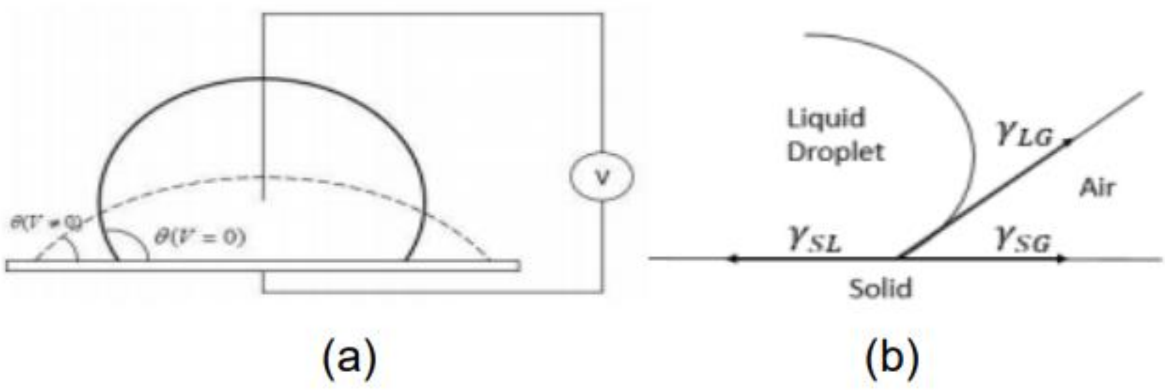


Figure 3-3 a) electrowetting result and (b) initial contact angle [26]

3.4 Parameters influencing actuation voltage

3.4.1 Flow Media

The operating voltage is greatly influenced by flow media and therefore, it is an important factor which needs to be considered. Generally, either air or any other immiscible media (e.g., oil) surrounds the conducting liquid droplet in the EWOD device. The addition of surrounded media is of a great benefit for the EWOD device as it can prevent the unacceptable electrolysis and consequently eliminate the chance of the droplet evaporation even with high applied voltage.

3.4.2 Chemical Characteristic of the Droplet

The droplet which needs to be manipulated in EWOD must be polarizable and conducting in nature. The taken amount of volume of the droplet depends on the size of the electrodes. The droplet volume is chosen such that the droplet footprint is slightly larger than the electrode size. This is done to ensure that the droplet easily overlaps onto its adjacent electrode. The range of the droplet volume is in microliter. By adding salt, the conductivity of the droplet solution can be increased. Therefore, In order to minimize the actuation voltage, different molar of di-ionized water (DI-water) is used by the EWOD device.

3.4.3 Gap Distance between Electrodes

In the bottom layer, immediately above the substrate, there is a small distance or gap between two adjacent electrodes. The array of electrodes is designed in small (micrometer range) gap distance, This is because the electrode on which the droplet sits on is on zero potential. On the other hand, the electrode on which it needs to be transported is supplied with the actuation voltage. In this way, the small inter-electrode gap makes it possible for the droplet to overlap into the adjacent electrode easily.

3.4.4 Characteristic of Electrodes

The dimension and material properties of the electrodes serve as a basic parameter for the better performance of an EWOD device. Usually, the array of electrodes is fabricated on top of the bottom base-substrate. But only in the parallel-plate configuration, a single ground electrode is placed in the cover-substrate layer.

According to the existing research, the most suitable electrode for the EWOD operation is a square shaped conductive-metal. This is true for both the parallel-plate and the single-plate configurations. Furthermore, according to the existing EWOD literature, the size of the electrode needs to be small.

3.4.5 Size of the droplet

Droplet size affects the mass of the droplet in the system which is necessary to be moved to the adjacent electrode by the electric force. It may be mentioned that, there is no fixed droplet size that is required for a digital microfluidic system to work properly. Droplet volume ranges from the order of nanoliters to microliters [27,28]. However, the size of the electrodes used clearly affects the droplet size. Generally, the radius of the droplet is taken larger than the pitch of the electrode. A droplet of radius larger than the pitch of electrode makes it possible for the droplet to reach the adjacent electrode and hence allows for electrowetting.

3.4.6 Dielectric and Hydrophobic Layers Materials

In a EWOD device, electrodes are covered with two types of insulating layer. The dielectric and the hydrophobic layers are stacked deposition between the gaps of the electrode array. The hydrophobic coating is used for getting a smooth surface that helps grasp the droplet on the EWOD device. It is demonstrated that if the dielectric constant of the insulated layer is high, then the droplet can easily move with minimum applied voltage. Also, the material properties of the different hydrophobic layers slightly lead to various contact angles of the liquid droplet.

3.4.7 Dielectric and Hydrophobic Layer Thickness

The thickness of the insulating layers of the EWOD device needs to be as thin as possible. It is shown that the dielectric layer having a thickness of 10 nm to 2 μm, and the hydrophobic layer having a thickness of 1 nm to 1 μm will enable maximum performance in the EWOD device.

Chapter-4 Design & Simulation

4.1 Methods Contributing to Final Functional Model

The functional EWOD models were realized using COMSOL Multiphysics software (version 5.5). The design employed several physical phenomena. In each model, three physics were considered. These are named as two-phase laminar flow, electrostatics, and the phase field method. Mathematical concepts and these three physics and were coupled together in order to form a complete picture for droplet motion. The geometry of the simulation for each case included a square with a hemispherical droplet inside of it. This droplet rested on the southernmost side of the square; as depicted in the Figure 4.1 below.

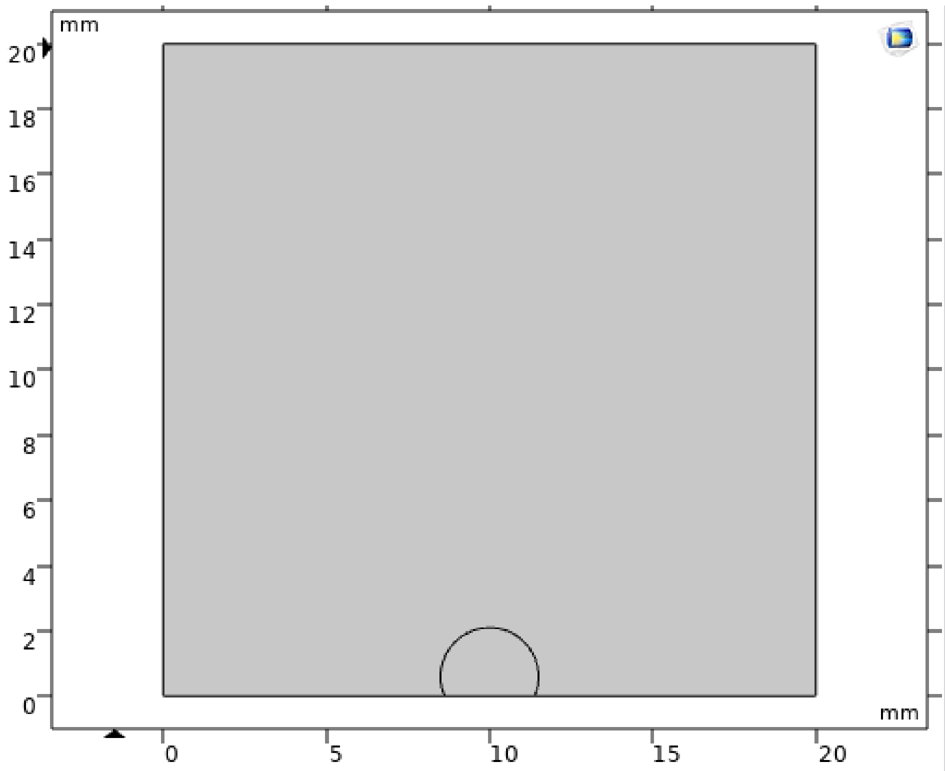


Figure 4-1Geometry of Simulated EWOD Model.

At first, a 2D space dimension was selected and the thrthree physics were added immediately after that. Time dependent with phase initialization study was chosen. Then, the geometry was designed which included a 20x20 mm Si oil medium and the droplet. The droplet was designed using a circle of radius 1.5 mm and a 4x1mm rectangle and then using a Boolean difference between them. In this way the bottom section of the droplet was truncated. In order to replicate the hemispherical-like shape of a droplet quiescent on a hydrophobic surface, the circle was partitioned at the bottom. The droplet was designed such that it maintained a contact angle of 118º with the bottom surface it sat on. A 20x20mm rectangle was taken to define the silicone oil domain. Two 2mm long line segments were taken to define two adjacent electrodes. Although the droplet rested on the easternmost electrode, it slightly overlapped onto the adjacent electrode.

In the materials section, two materials and their basic properties were defined. For the first designed model to observe low-voltage actuated EWOD device, the model included air as the filler medium and water as droplet material. Therefore, 'Silicone oil' was added to the 20x20mm rectangular domain and 'H_2O' was added to the droplet domain. In this way, each domain was linked with it's appropriate fluid.

Water and Si oil were explicitly set as the fluid properties of fluid 1 and fluid 2 respectively under the multiphysics module.

The motion of the water in the droplet and the surrounding Si oildomain was controlled by the two-phase laminar flow. Under the 'Laminar flow (spf)' section, the fluid motion was analyzed as creep flow because the inertial terms of the Navier-Stokes Equations were neglected. In order to replicate a real-world scenario, several boundary conditions were set in the design. The 'wall' was defined as the southernmost boundary of the 20x20mm rectangle. The 'open boundary' condition was placed at the top of the medium domain square. After selection, the southernmost side of the square domain was granted the boundary condition "wall". This was done to enable the selection of a the more specific boundary condition, namely 'no slip'.

Under the 'electrostatistics (es)' section, the entire domain was selected to be operated on. Two electrodes were created. These were 2mm in length and were placed at the southernmost side of the air domain.

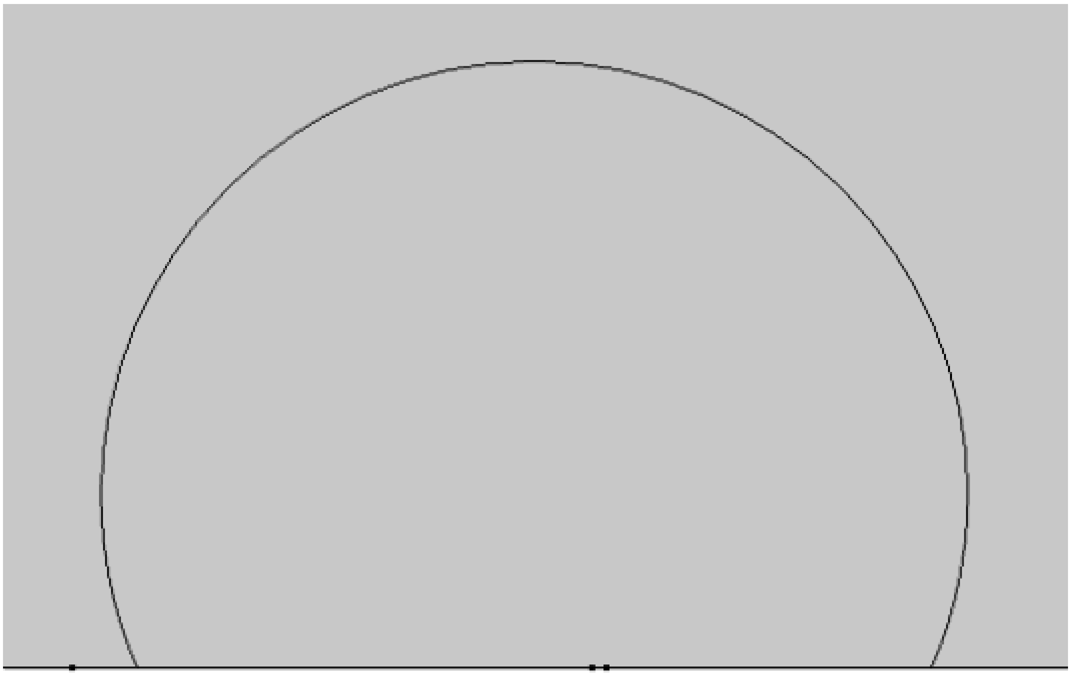


Figure 4-2 Geometry of Open Drop model – (zoomed on 2mm electrodes)

Each electrode are 2mm in length and the gap between two adjacent electrodes were taken to be 0.01mm. The whole geometry was selected for 'charge conservation'. 'zero charge' was applied on the southernmost side of the square air domain initially. After the placement of the line segments which represents electrodes, the ‘electric potential’ condition was applied to the right-side electrode. Here, the applied voltage was specified. As this thesis focuses on low actuated EWOD device, therefore, each time the actuation voltage was changed and the results were observed. The left electrode was given the boundary condition ‘ground’. Under this condition, the applied potential is zero always. On the air domains, a zero charge boundary condition was placed.

phase field module is a field-based methods in which the interface between phases is represented as an isosurface of the phase field functions. In cases where topology changes are expected and when the effects of surface tension are large, the phase field method is the preferred method for simulation. Initial values of fluid 1 (droplet) and fluid 2 (filler-medium) in the system were specified. The interface between the air and water domains was selected under the option ‘Initial interface’. On the bottom boundary of the square, a ‘wetted wall’ boundary condition was employed. Furthermore, the value of the contact angle was set as ‘118[deg]’.

Additionally, under the phase field model tab, the value of ‘parameter controlling interface thickness’ was set to be ‘hamx/2’. Prior to that, ‘hmax’ was defined in the parameter section of ‘Global definitions’. The value of ‘hmax’ was set to be equal to the maximum element size of the mesh utilized. Furthermore, under this tab, the mobility tuning parameter and phi derivative of free energy were kept in their default values.

Finally, ‘User-controlled’ mesh was built and the size taken was ‘extremely fine’.

In the similar fashion, the rest of the models for EWOD devices were designed. For analyzing the effect of different parameters on the actuation voltage several changes were made in each of the models. These are explained as follows:

4.1.1 Filler-Medium Variation:

Several other materials apart from air was considered as the filler medium of the EWOD device. These include – Castor oil, Silicone oil, Olive oil, Mineral Oil and Palm oil. All of these oils are immiscible. Immiscible liquids are those which won't mix to give a single phase. Oil and water are examples of immiscible liquids - one floats on top of the other. The Material properties of each of these oils used in COMSOL are listed below:

Table 4-1Properties of different oils used in EWOD device model in COMSOL.

Property (Unit)	Silicone oil	Castor oil	Olive oil	Mineral oil	Palm oil
Thermal conductivity (W/(m.K))	1.0e-1	0.180	0.17	0.11	0.1717
Electrical Conductivity (S/m)	1.0e-12	10e-9	322e-3	1.0e+3	
Heat Capacity at Constant Pressure (J/(kg.K))	1.37e-11	1.97e+3	1.97e+3	1.67e+3	1.861e+3
Co-efficient of Thermal Expansion (1/K)	1.07e-3	273.1507	0.00070	6.4e-4	
Dynamic Viscosity (Pa.S)	0.001	0.650	0.04	0.02	65.37e-3
Relative Permittivity (1)	2.5	4.7	3	2.22	1.80
Density (Kg/m^3)	9.6e-7	927.7	917	870	887.5

4.1.2 Droplet-Type Variation:

Droplets of different material and different volume were utilized. These includes, H_2O, 1M KCl, 1M NaCl, Methanol and Ethanol. These materials were assigned to 'Fluid-1' and then the simulation was done for each case and the results were analyzed.

4.1.3 Interelectrode Gap Variation

To analyze the effect of inter-electrode gap on the actuation voltage of EWOD devices, the inter-electrode gap which were taken into consideration were 0.10mm ,0.05mm and 0.20 mm.

4.1.4 Electrode length variation

After the study of the previously mentioned three parameters, the effect of electrode length variation was taken into account. For this, electrodes of length 2.0 mm ,2.2mm and 1.80mm were designed.

4.1.5 Droplet Size variation

Three different size droplets were modeled and the radius, 'r' ranged as 1.0 mm, 1.2 mm and 1.5 mm.

4.1.6 Dielectric Layer Material Variation

Dielectric materials used in the EWOD models were – Titanium di-oxide (TiO_2), Cyanoethyl pullulan (CEP), Polyvinylidene difluoride (PVDF), Su-8, Parylene-C, Polydimethylsiloxane (PDMS).

4.1.7 Dielectric Layer Thickness Variation

After the selection of the di-electric material, the thickness was varied to see which showed the best performance without causing dielectric layer breakdown. The thickness used in the designed models are- 250 nm, 770nm, 1.0 µm, 1.7 µm, 2.0 µm and 2.5 µm.

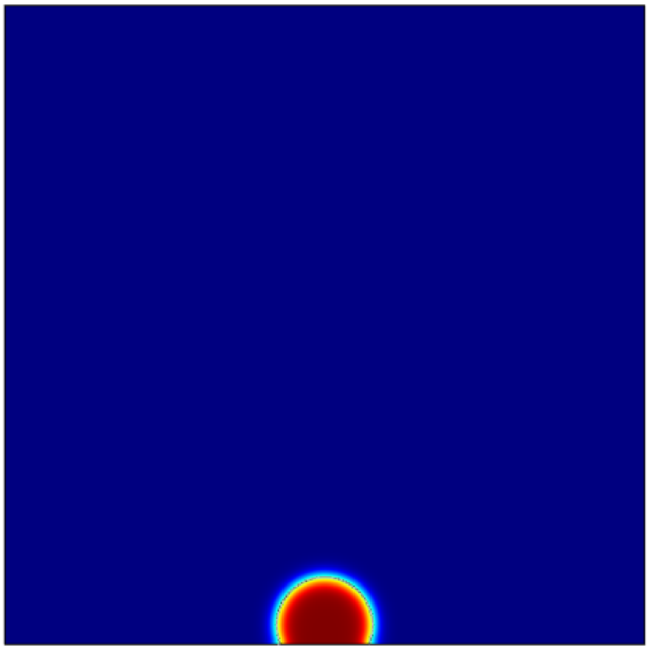
4.2 Mesh Refinement Study

In order to check which size mesh was performing the best a mesh refinement study was performed. This credibility of the performance was measured by the ability of the mesh to converge on a solution in case of a specific parameter with the mesh size variation. A parametric sweep was used. This enabled the integration of several mesh size ranges into the study. The speed at which the mesh size could produce data also determined the performance quality. By running the simulation at several decreasing mesh combination sizes, an optimal mesh element size combination relating to shorter simulation time length and greater accuracy was found. The parameter volume fraction of water was also analyzed. It was considered as a function of increasing degrees of freedom. In the same way, the interface thickness and density were also analyzed. They were analyzed as a function of increasing degrees of freedom.

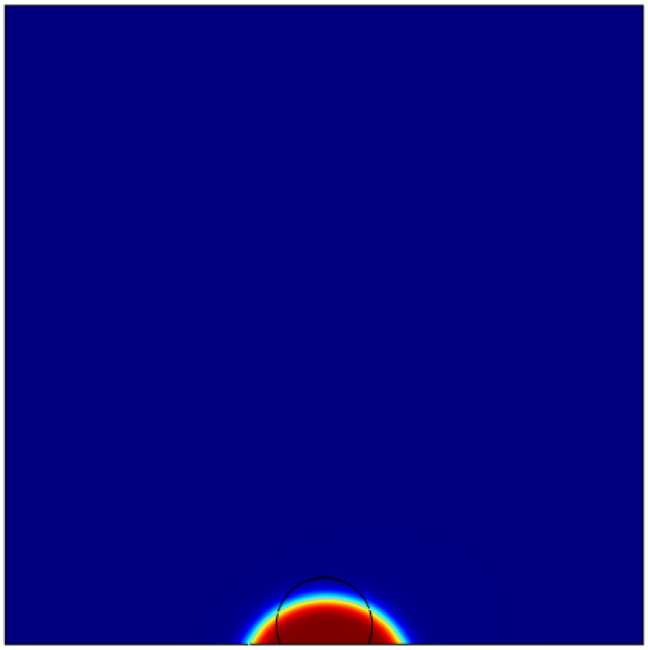
Chapter-5 Results/Discussion

5.1 Results from COMSOL Multiphysics

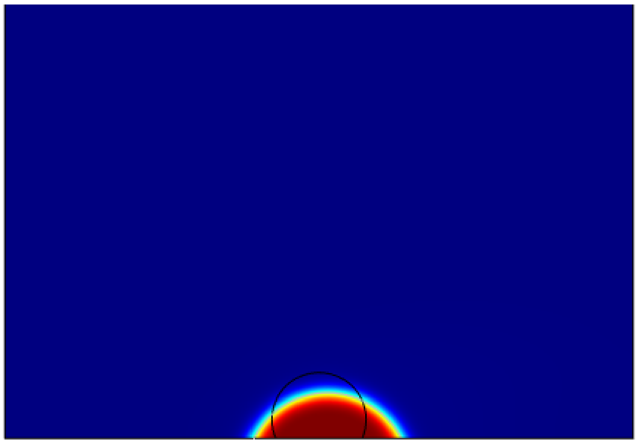
Droplet motion driven by EWOD was achieved in COMSOL Multiphysics version 5.5 and a full progression of a droplet rolling onto the actuated adjacent electrode can be seen below, in Figure 5.1 (a) – (k).



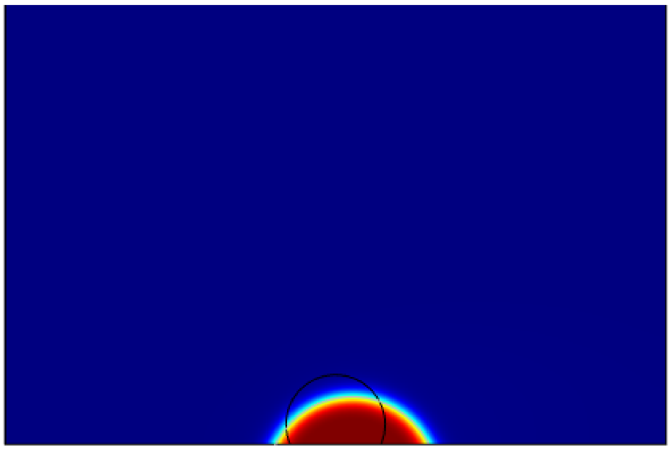
(a) t = 0 sec



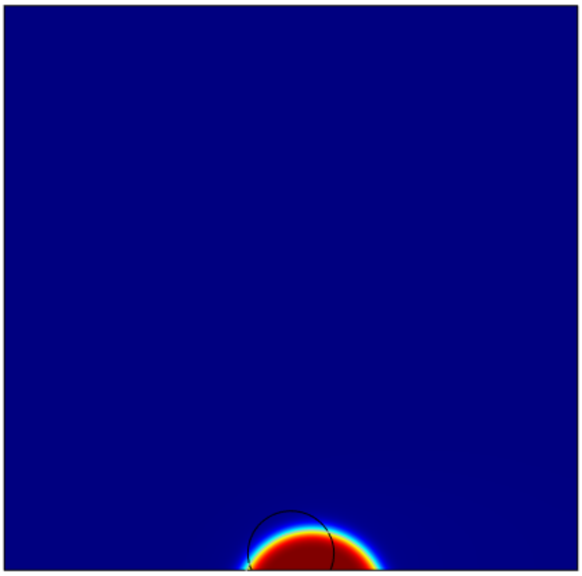
(b) t = 0.1 sec



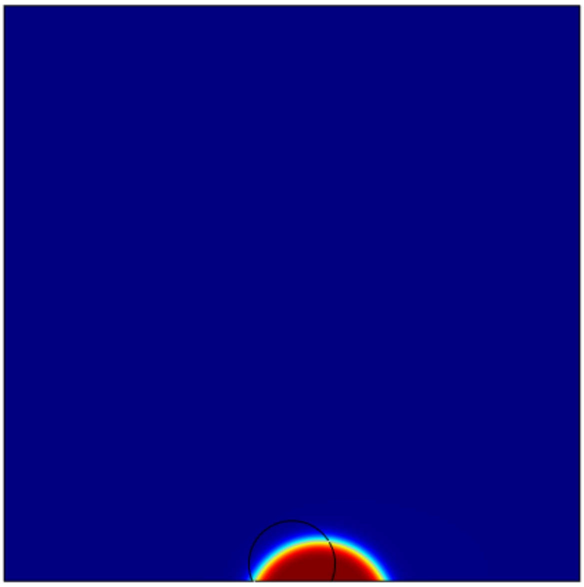
(c) t = 0.2 sec



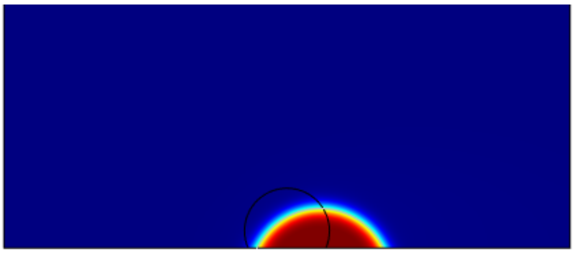
(d) t = 0.3 sec



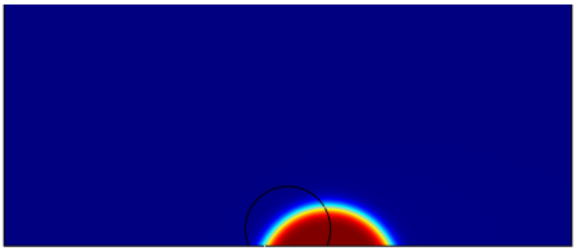
(e) t = 0.4 sec



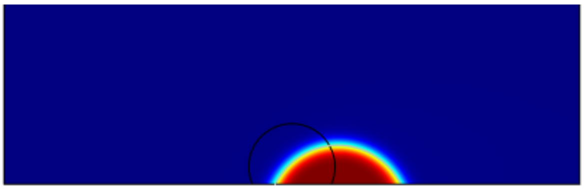
(f) t = 0.5 sec



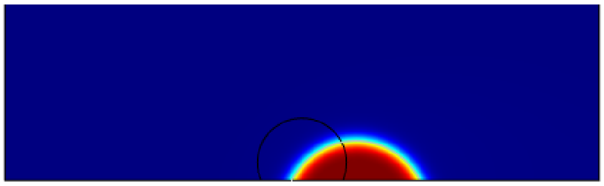
(g) t = 0.6 sec



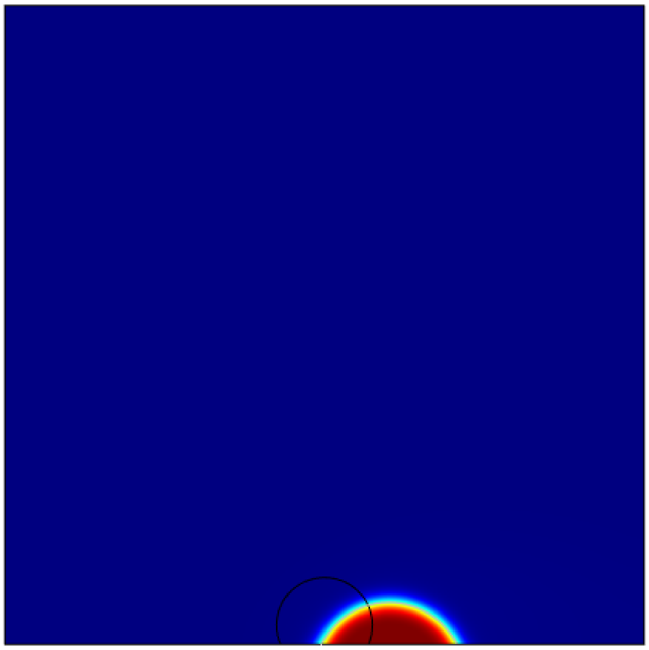
(h) t = 0.7 sec



(i)t = 0.8 sec



(j) t = 0.9 sec



(k) t = 1 sec

Figure 5-1Droplet motion progressive snapshot.

5.1.1 Result analysis of Filler-Medium Variation:

Table 5-1 Fixed parameters in case of filler-medium variation analysis in EWOD models.

Fixed Parameter	**Value**
Droplet Type (Material)	H20
Interelectrode Gap	0.1 [mm]
Electrode Length	2 [mm]
Droplet Size	R=1.5 mm

Table 5-2 Results for filler-medium variation in EWOD device models.

No.	Filler-Medium	Actuation Voltage
1	Silicone Oil	2.1 V
2	Castor Oil	9.0 V
3	Olive Oil	4.5 V
4	Mineral Oil	7.8 V
5	Palm Oil	5.2 V

Mineral oil, silicone oil, corn oil, olive oil and fluorinated oil (Fluorinert™) are generally used as oil phase for the PDMS-based microfluidic device.

The simulated results showed that Silicone-oil needs the lowest amount of voltage which is 2.1 volts for actuation. This is due to the different material properties of the oils such as viscosity which is a measure of a fluid's resistance to flow. It describes the internal friction of a moving fluid. A fluid with large viscosity resists motion because its molecular makeup gives it a lot of internal friction. Viscosity, or the thickness of the oil, is important because it determines the lubricant's film strength and efficiency in preventing friction between moving parts. Thick oil has a high viscosity, and thin oil has a low viscosity. Other properties of the oils are mentioned in table 4.1. In these models, Olive Oil with dynamic viscosity of 40 cP (0.04 Pa.S) and Olive Oil with dynamic viscosity of 40 cP (0.04 Pa.S) was used.

5.1.2 Result analysis for droplet-type variation

Table 5-3 Fixed parameters for droplet type variation analysis.

Fixed Parameter	Value
Medium	Silicone Oil
Interelectrode Gap	0.10 mm
Electrode Length	2 mm
Droplet Size	R=1.5 mm

Table 5-4 Results for droplet type variation of EWOD models.

No.	Droplet type	Actuation Voltage
1	H2O	2.10 V
2	0.1M KCl	0.92 V
3	0.1M NaCl	0.90 V
4	0.5M KCl	0.88 V
5	0.5M NaCl	0.84 V
6	Methanol	3 .0 V
7	Ethanol	1.5 V

The results showed that, 0.5M sodium chloride (NaCl) showed the best performance. The analysis also shows that as the Molarity (M) which indicates the number of moles of solute per liter of solution increases, the actuation voltage decreases.

5.1.3 Result analysis for Interelectrode Gap Variation

Table 5-5 Fixed parameters for inter-electrode gap variation analysis.

Fixed Parameter	**Value**
Medium	Silicone Oil
Droplet Type	0.5M NaCl
Electrode Length	2 mm
Droplet Size	R=1.50 mm

Table 5-6 Results for interelectrode-gap variation in EWOD models.

No.	Interelectrode Gap	Actuation Voltage
1	0.10 mm	0.9 V
2	0.05 mm	0.8 V
3	0.20 mm	1.1 V

The results depict that, as the interelectrode gap decreases, the actuation voltage also decreases. Therefore, the interelectrode gap should be kept as minimum as possible if low-actuation voltage in an EWOD device is desired.

5.1.4 Electrode Length Variation

Table 5-7 Fixed parameters for electrode length variation analysis.

Fixed Parameter	**Value**
Medium	Silicone Oil
Droplet Type	0.5M NaCl
Interelectrode Gap	0.05 mm
Droplet Size	R=1.50 mm

Table 5-8 Results for electrode-length variation in EWOD models.

No.	Electrode Length	Actuation Voltage
1	2.0 mm	0.8 V
2	2.2 mm	1.1 V
3	1.8 mm	0.7 V

The results showed that, for a fixed size droplet, as the length of the electrodes increased, the actuation voltage required also increased. However, as the length decreased, the actuation voltage required also decreased. This is due to the reason that, as the electrode length decreases, the droplet to electrode overlap ratio becomes larger, this eases the transportation of the droplet onto the adjacent electrode.

5.1.5 Droplet Size variation

Table 5-9 Fixed parameters for droplet-size variation analysis.

Fixed Parameter	**Value**
Medium	Silicone Oil
Droplet Type	0.5M NaCl
Interelectrode Gap	0.05 mm
Electrode Length	1.8 mm

Table 5-10 Results for droplet-size variation in EWOD models.

No.	Droplet Size (Radius)	Actuation Voltage
1	R = 1.5 mm	0.7 V
2	R = 1.2 mm	1.5 V
3	R = 1.0 mm	2.0 V

Analysis have shown that, he droplet radius must change with of the size of the electrode used for a particular EWOD system. This is because the droplet must be about 30% larger than the electrode.

5.1.6 Dielectric Layer Material Variation

Table 5-11Fixed parameters for Dielectric layer material variation analysis.

Fixed Parameter	**Value**
Medium	Si Oil
Droplet Type	0.5M NaCl
Interelectrode Gap	0.05 mm
Electrode Length	1.8 mm
Droplet Size	R= 1.5 mm
Dielectric layer thickness	1 µm

Table 5-12 Results for dielectric layer material variation analysis in EWOD models.

No.	Dielectric Material	Dielectric Constant	Θ_0 and Θ_v	Actuation Voltage (theory)
1	TiO_2	59	108^o-78^o	0.12 V
2	CEP	20	120^o-78^o	0.24 V
3	PVDF	8.4	118^o-79^o	0.35 V
4	Su-8	3.2	115^o-79^o	0.56 V
5	Parylene-C	3.15	115^o-79 ^{o}(let)	0.56 V
6	PDMS	2.75	120^o-95^o	0.49 V

The results have shown that for a fixed thickness of 1 micro meter, TiO_2 performs the best and the actuation voltage could be minimized as to 0.12 Volts using it because of its high di-electric constant.

5.1.6 Dielectric Layer Thickness Variation

Table 5-13 Fixed parameters for dielectric layer thickness variation analysis.

Fixed Parameter	**Value**
Medium	Silicone Oil
Droplet Type	0.5M NaCl
Interelectrode Gap	0.05 mm
Electrode Length	1.8 mm
Droplet Size	R= 1.5 mm
Dielectric layer material	TiO2

Table 5-14 Results of dielectric layer thickness variation analysis in EWOD models.

No.	Dielectric Thickness	Dielectric Constant	Θ_0 and Θ_v	Actuation Voltage
1	250 nm	59	108^o-78^o	0.09 V
2	770 nm	20	120^o-78^o	0.10 V
3	1.0 µm	8.4	118^o-79^o	0.12 V
4	1.7 µm	3.2	115^o-79^o	0.15 V
5	2.0 µm	3.15	115^o-79 ^{o}(let)	0.16 V
6	2.5 µm	2.75	120^o-95^o	0.18 V

After deriving at the conclusion that TiO_2 has the best performance for realizing a low-actuation EWOD device, various thickness of TiO_2 was analyzed. Simulated results showed that, 250 nm TiO_2 needs about 0.09V for droplet transportation to the adjacent electrode.

Finally the best value for the analyzed parameters are listed in the following table:

Table 5-15 Best Values of analyzed parameters

Parameter	**Value**
Filler-Medium	Silicone Oil
Droplet Type	0.5M NaCl
Interelectrode Gap	0.05 mm
Electrode Length	1.8 mm
Droplet Size	R= 1.5 mm
Dielectric layer material	TiO2
Dielectric Thickness	250 nm

The lowest actuation voltage obtained for an EWOD device with this configuration was 0.09 volts.

5.2 Progress Toward Future Work

Many additional features were attempted to enhance the accuracy of the simulation results but failed to converge and therefore could not be included in the results. Among them, the thickness of the electrode was very crucial. The electrodes were depicted as line segments. The thickness of the electrodes could not be added and due to that the different materials could not be assigned to the operating electrodes. Moreover, It was possible to do a lot of research with the shapes of the electrodes. This requited 3 dimensional models. Some 3-D models with different shapes of electrodes were designed in COMSOL but they failed to converge. Also, there are some theoretical EWOD models that used two layers of di-electric materials for having low-voltage actuation possible, when those models were designed to analyze in this thesis , the simulations took too long and all failed to converge. Moreover, Internal walls are not allowed to be selected as wetted walls in COMSOL version 5.3 which is the reason why a dielectric material could not be included in the simulation in previous research works.. Because, the wetted wall the droplet sits on became an internal wall with the addition of a geometry (layer)below the bottom side of the square air domain. However in version 5.5, in this thesis, the phase field model considered two domains (the droplet and the surrounding medium) since the phase-field model is a mathematical model for solving interfacial problems, the interface between droplet and surrounding medium, the droplet and the surface it sat on were given utmost priority. However, in the electro statistic model, all three domains (droplet, filler-medium, di-electric layer) were considered. Furthermore, different forms of the slip boundary condition were added to the bottom wall. These include navier slip, slip and slip velocity. For slip velocity, several variations were also attempted. But all failed to converge.

References

1. Zhao Ya-Pu and Wang Ying, “Fundamentals and applications of electrowetting,” *in Reviews of Adhesion and Adhesives*, 1(1), pp.114-174,2013.
2. B. Berge, “Electrocapillarity and wetting of insulator films by water,” *in Comptes Rendus De L Academie Des Sciences Serie Ii*, 317(2), pp.157- 163, 1993.
3. Richard B. Fair, “Duke microfluidics lab,” *microfluidics.ee.duke.edu*, para 1. Available: http://microfluidics.ee.duke.edu/ [Accessed Jul. 12, 2019].
4. M.G. Pollack, A.D. Shenderov, and R.B. Fair, “Electrowettingbased actuation of droplets for integrated microfluidics,” *in Lab on a Chip*, 2(2), pp.96-101,2002.
5. T. Roques-Carmes, R.A. Hayes, B.J. Feenstra, and L.J. Schlangen, “Liquid behavior inside a reflective display pixel based on electrowetting,” *in Journal of applied physics*, 95(8), pp.4389-4396, 2004.
6. R.A. Hayes, and B.J. Feenstra, “Video-speed electronic paper based on electrowetting,” *in Nature*, 425(6956), pp.383-385, 2003.
7. S. Kuiper, and B.H.W. Hendriks, “Variable-focus liquid lens for miniature cameras,” *in Applied physics letters*, 85(7), pp.1128-1130, 2004.
8. H. Choi, and Y. Won, “Fluidic lens of floating oil using round pot chamber based on electrowetting,” *in Optics letters*, 38(13), pp.2197-2199, 2013.
9. F. Mugele, and J.C. Baret, “Electrowetting: from basics to applications*,” in Journal of Physics: Condensed Matter*, 17(28), p.R705, 2005.
10. V. Srinivasan, V.K. Pamula, and R.B. Fair, “An integrated digital microfluidic lab-on-a-chip for clinical diagnostics on human physiological fluids,” *in Lab on a Chip*, 4(4), pp.310-315, 2004.
11. T.H. Lin and D.J. Yao, “Applications of EWOD systems for DNA reaction and analysis,” *in Journal of Adhesion Science and Technology*, 26(12-17), pp.1789-1804, 2012.
12. Y.H. Chang, G.B. Lee, F.C. Huang, Y.Y. Chen, and J.L. Lin, “Integrated polymerase chain reaction chips utilizing digital microfluidics,” in Biomedical microdevices, 8(3), pp.215-225, 2006.
13. M. F. Samad, A. Z. Kouzani and M. Samad, "Design and analysis of a low actuation voltage electrowetting-on-dielectric device," 2013 ICME International Conference on Complex Medical Engineering, Beijing, 2013, pp. 513-517, doi: 10.1109/ICCME.2013.6548303.
14. M. F. Samad and A. Z. Kouzani, "Design and analysis of a low actuation voltage electrowetting-on-dielectric microvalve for drug delivery applications," 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago, IL, 2014, pp. 4423-4426, doi: 10.1109/EMBC.2014.6944605.
15. S. H. Lee, In-Ho Lee, J. Kim, Chang-Min Keum, Eui-Sang Yu, and Sin-Doo Lee, ”Electrowetting-on-Dielectric Device Controlled by Embedded Undulating Electrode for Liquid Transport,” Journal of Nanoscience and Nanotechnology, Vol. 16, 6455–6458, 2016.

16. Lippmann G 1875 Relations entre les ph´enom`enes´electriques et capillairesAnn. Chim. Phys.5494
17. Liu, H., Dharmatilleke, S., Maurya, D.K. *et al.* Dielectric materials for electrowetting-on-dielectric actuation. *Microsyst Technol* **16,** 449 (2010). https://doi.org/10.1007/s00542-009-0933-z
18. Matin Torabinia, Arvind Venkatesan and Hyejin Moon, "Phase shift effect of double dielectric layers in electrowetting on dielectric microfluidic device," *in IEEE Micro Electro Mechanical Systems (MEMS)*, 2018.
19. A numerical simulation optimizing droplet motion driven by electrowetting by Jake M. Lesinski ,*Faculty of California Polytechnic State University, San Luis Obispo.* DOI: https://doi.org/10.15368/theses.2019.103
20. Nahar, Mun Mun & Nikapitiya, Jagath & You, Seung & Moon, Hyejin. (2016). Droplet Velocity in an Electrowetting on Dielectric Digital Microfluidic Device. Micromachines. 7. 71. 10.3390/mi7040071.
21. Ismail, Maged. "Level-Set and Phase-Field Methods: Application to Moving Interfaces and Two-Phase Fluid Flows." 2007, Claremont Graduate University & Keck Graduate Institute, Claremont Graduate University & Keck Graduate Institute.
22. Ismail, Maged. "All." Claremont Graduate University , Claremont Graduate University,2007,pp.1–14, www.math.hmc.edu/~dyong/math164/2007/ismail/finalreport.pdf.
23. Amiri, H.a. Akhlaghi, and A.a. Hamouda. "Evaluation of Level Set and Phase Field Methods in Modeling Two Phase Flow with Viscosity Contrast 101 through Dual-Permeability Porous Medium." International Journal of Multiphase Flow, vol. 52, 2013, pp. 22–34., doi:10.1016/j.ijmultiphaseflow.2012.12.006.
24. Nahar, M. M. (2015). "Numerical Modeling of 3D Electrowetting Droplet Actuation and Cooling of a Hotspot. COMSOL Conference." Retrieved from https://www.comsol.jp/paper/download/257441/nahar_paper.pdf.
25. Reza Vafaie & Shabouei, Bahman & Bahman Shabouei (2018). "Theoretical and Simulational Study of Electrowetting on Dielectric (EWOD) Effect." DOI: 10.1109/ICEE.2018.8472448
26. Azam, S. F., & Unni, H. N. (2014). Electrowetting and Droplet Transport in Digital Microfluidic Chips.
27. Mohseni, K., et al. "Behaviour of a Moving Droplet under Electrowetting Actuation: Numerical Simulation." The Canadian Journal of Chemical Engineering, vol. 84, no. 1, 2008, pp. 17–21., doi:10.1002/cjce.5450840104.
28. Paik, Phil, et al. "Rapid Droplet Mixers for Digital Microfluidic Systems." Lab Chip, vol. 3, no. 4, 2003, pp. 253–259., doi:10.1039/b307628h.
29. Guan, Yin, and Albert Y. Tong. "A Numerical Study of Microfluidic Droplet Transport in a Parallel-Plate Electrowetting-on-Dielectric (EWOD) Device." Microfluidics and Nanofluidics, vol. 19, no. 6, 2015, pp. 1477–1495., doi:10.1007/s10404-015-1662-5.
30. Yaddessalage, JB. " Study of the Capabilities of Electrowetting on Dielectric Digital Microfluidics (EWOD DMF) towards the High Efficient Thin-Film Evaporative Cooling

Platform." The University of Texas at Arlington, The University of Texas at Arlington, 2013.

31. Mohseni, K., et al. "Behaviour of a Moving Droplet under Electrowetting Actuation: Numerical Simulation." The Canadian Journal of Chemical Engineering, vol. 84, no. 1, 2008, pp. 17–21., doi:10.1002/cjce.5450840104.
32. Dolatabadi, A., and K. Mohseni. "Behavior of a Moving Droplet under Electrowetting Actuation in Microchannel." 2005 International Conference on MEMS, NANO and Smart Systems, 2005, doi:10.1109/icmens.2005.30.
33. Cho, Sung Kwon, et al. "Towards Digital Microfluidic Circuits: Creating, Transporting, Cutting and Merging Liquid Droplets by Electrowetting Based Actuation." Technical Digest. MEMS 2002 IEEE International Conference.
34. Paik, Phil, et al. "Rapid Droplet Mixers for Digital Microfluidic Systems." Lab Chip, vol. 3, no. 4, 2003, pp. 253–259., doi:10.1039/b307628h.
35. Nahar, Mun, et al. "Droplet Velocity in an Electrowetting on Dielectric Digital Microfluidic Device." Micromachines, vol. 7, no. 4, 2016, p. 71., doi:10.3390/mi7040071.
36. Moon, Hyejin, et al. "Low Voltage Electrowetting-on-Dielectric." Journal of Applied Physics, vol. 92, no. 7, 2002, pp. 4080–4087., doi:10.1063/1.1504171.

GitHub Link:

https://github.com/sharaftasnim/EWOD-COMSOL-Files