Development of Portable and Cost-effective Digital Microfluidics Platform for Diagnostics Applications

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CERTIFICATION:

This is to certify that **Hamad Khan**, **2020142** and **Fardad Ali Shah**, **2020122** have successfully completed the final project **Development of Portable and Cost-effective Digital Microfluidics Platform for Diagnostics Applications,** at the **GIK Institute**, to fulfill the partial requirement of the degree **Mechanical Engineering.**

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ABSTRACT

In this report, we present an innovative digital microfluidics system leveraging electrowetting on a dielectric for meticulous manipulation of microliter liquid droplets through applied DC voltage. Our focus is on the creation of an eco-friendly and cost-effective lab-on-a-chip platform aligned with the United Nations Sustainable Development Goals. The platform utilizes DC voltage to actuate liquid droplets, subjecting them to analysis at voltage levels ranging from 200V to 400V. To enable droplet actuation, we employed a patterned PCB designed on EasyEDA, incorporating readily available materials like cooking oil and grafting tape to ensure affordability in fabrication. By constructing an electrical circuit utilizing a unique combination of shift registers and MOSFETs, we achieved precise control over each electrode in the digital platform's array. Results revealed a direct correlation between droplet speed and applied voltage, while an inverse relationship was observed between droplet speed and volume. Our findings, supported by literature references and detailed experimental outcomes, underscore the platform's pioneering role in digital microfluidics research, positioning it as an effective and economically feasible solution for health diagnostics applications.

Keywords: Digital Microfluidics, Electrowetting, Contact Angle, Lab-on-a-chip, Microliters, Miniaturize, Economic, Sustainability, Hydrophobic

UNDERTAKING:

I certify that the project **Development of Portable and Cost-effective Digital Microfluidics Platform for Diagnostics Applications** is our own work. The work has not, in whole or in part, been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/ referred.

Hamad Khan

2020142

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We are also thankful to our friends and families whose silent support led us to complete our project.

Nomenclature

θ_V	Angle at voltage, V=0
θ_0	Angle at voltage, V=V
γ	Surface tension of solid-liquid interface (N/m)
E_r	Permittivity of dielectric ($\frac{C^2}{N^2 m}$)
E_0	Permittivity of vacuum ($\frac{C^2}{N^2 m}$)
d	Thickness of dielectric (mm)
V	Voltage
A	Amperes

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Chapter 1
Introduction

1.1 Background and Motivation:

The field of microfluidics has revolutionized the manipulation of small volumes of fluids at the microscale, offering transformative applications in various disciplines, including diagnostics, biotechnology, and pharmaceuticals. Conventional microfluidic platforms rely on continuous flow channels for fluid manipulation; however, these systems often face challenges in terms of precision, control, and reagent consumption.

Digital microfluidics (DMF) has emerged as a revolutionary alternative, utilizing discrete droplets of fluids instead of continuous flow. DMF employs an array of electrodes embedded on a substrate to manipulate droplets using electrowetting-on-dielectric (EWOD) forces. EWOD forces selectively modify the surface tension of the substrate, causing droplets to move, merge, or split according to the applied electrical signals.

The adoption of DMF platforms for droplet manipulation and diagnostic applications is driven by several compelling motivations. DMF offers precise control over droplet movement and manipulation, enabling accurate and reproducible fluid handling. This precision is crucial for delicate tasks such as mixing, dispensing, and analyzing minute amounts of samples. Additionally, DMF platforms utilize picolitre to microliter volumes of reagents, significantly reducing reagent consumption compared to conventional microfluidic systems. This minimization of reagent usage not only lowers costs but also minimizes environmental impact.

Furthermore, the confined nature of droplets within DMF platforms enhances, leading to improved detection limits for diagnostic assays. DMF platforms can also simultaneously manipulate multiple droplets, enabling parallel analysis of multiple samples or performing multiple diagnostic tests on a single chip. Additionally, DMF devices are typically compact and lightweight, facilitating portability and ease of use in resource-limited settings.

So, with the help of these miniaturized platforms, diagnosis of infectious diseases will become easier while also costing less. Moreover, the advantage of reduced chemical and reagent wastage will also be beneficial, environmentally. DMF platforms hold immense potential for a wide range of diagnostic applications, including rapid and sensitive detection of infectious diseases, genetic analysis, protein assays, drug discovery and development, and environmental monitoring. The ongoing development and refinement of DMF platforms are paving the way for a new era of precision diagnostics, with the potential to revolutionize healthcare and environmental monitoring.

1.1.1 Electrowetting:

Electrocapillarity, the basis of modern electrowetting, was first described in detail in 1875 by Gabriel Lippmann [1]. In his work, Lippmann reports on how to control the variation of the contact angle of a mercury drop in contact with an electrolyte by applying an electric field across such system, as shown in Figure 1. Lippmann observed what he called electrocapillarity effect, which is the basis of the modern electrowetting concept. The change in contact angle, and therefore wetting, is regulated by the Young-Lippmann equation.

$$\cos(\theta) = cos\,(\theta_0) + \frac{\varepsilon_0 \varepsilon_r V^2}{2\gamma d}$$

In 1981, Beni and his colleagues [2] introduced the term "electrowetting" to describe the phenomenon of how an electric current can change the angle at which a liquid droplet spreads on a surface. Their study focused specifically on how this effect changes the behavior of the triple contact line (TPL), which is the line where the liquid, solid, and gas phases meet.

The Electrowetting on dielectric (EWOD) concept was introduced only few years later, in the 90's, by Berge [3]. His idea was to avoid the contact between the liquid and the conductive surface by introducing a thin insulator layer in between. This feature introduces great reliability as the electrolysis problems are solved; furthermore, it unlocks the use of this technology in a wide range of applications, such as micro-lenses, electrowetting pixels and microfluidics advanced applications.

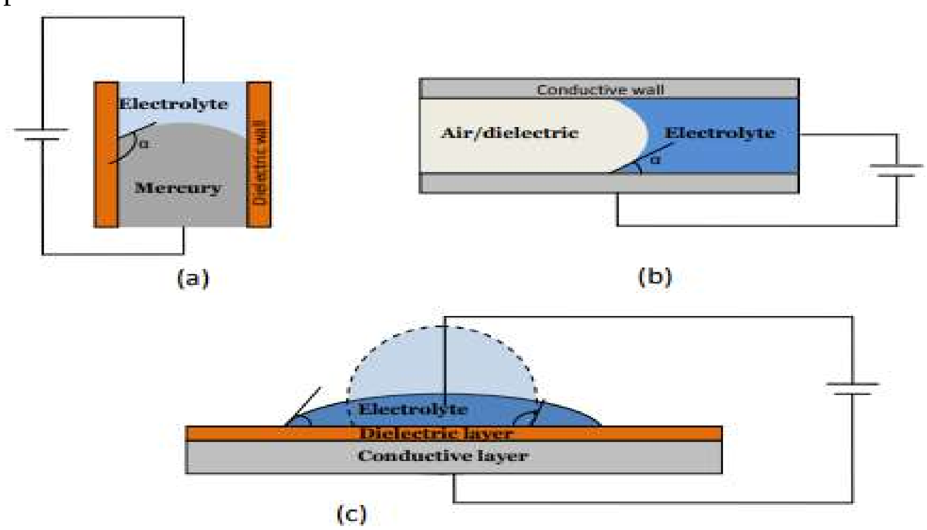


Figure 1: Schematic representation of a) an electrocapillarity device, b) an electrowetting device and c) electrowetting on dielectric device

A liquid droplet is placed on a dielectric surface that is covering a conductive layer. The conductive layer is connected to the ground. The liquid droplet is then polarized with a certain voltage. This causes the contact angle of the droplet to decrease, which means that the droplet spreads out more on the surface. The process is completely reversible and controllable. When the voltage biasing the liquid decreases, the contact angle increases; when the voltage is removed, the system goes back to its original state.

1.1.2 Digital Microfluidics and Lab-on-a-chip:

Digital microfluidics can be termed as a platform provided for lab-on-a-chip devices that use the concept of electrowetting to displace droplets. Droplets can be made to perform various tasks like linear movement, splitting into two, and merging two different or even droplets with the same content.

The platform usually consists of a few individual layers with an insulating or dielectric layer coming on top of electrodes followed by a hydrophobic layer. These layers serve different purposes which are vital to the overall movement of droplets. Other than that, the number of layers can also be changed depending on the open or closed configuration of the platform. Configurations and layers are described in chapter 3.

Traditionally, microfluidic devices were not commercially available and were only used for research purposes. However, over the years many researchers have asked the question whether a true lab-on-a-chip device is possible or not. At present time, we have seen these devices be available commercially, and being used for several applications, most of them being in the field of diagnostics and cell culture [4]

1.2 Problem Statement:

While the rapid manufacturing of microfluidic platforms is a promising advancement, the overall cost of these finished products remains prohibitive for developing countries facing resource limitations and financial constraints. This barrier impedes access to essential diagnostic services, hindering timely interventions and disease management. Even if these devices were available, the logistical challenges and financial burdens associated with their use make them impractical for many individuals in these regions.

Our goal is to address this critical need by developing and deploying affordable and accessible microfluidic diagnostic platforms specifically tailored for resource-limited settings. Traditional microfluidic devices, often large and complex, are not financially viable for these communities, particularly in remote villages with limited infrastructure. By miniaturizing these devices, we can significantly reduce their cost and enhance their user-friendliness, making them more accessible and practical for real-world applications.

Our approach emphasizes the development of low-cost, easy-to-use microfluidic devices that maintain high throughput while minimizing sample consumption. This combination of affordability, accessibility, and performance will enable us to provide essential diagnostic services to underserved populations, empowering them to take control of their health and well-being.

1.3 Scope of work and expected outcomes:

The scope of digital microfluidics encompasses a multidisciplinary approach to the design and implementation of a cutting-edge platform for the manipulation of droplets using DC voltages. This innovative technology offers a versatile and precise means of handling microscale liquid volumes, finding applications across various scientific and industrial domains. The primary objectives within the scope of this project involve defining and refining the system architecture, optimizing electrical components, designing microfluidic chips, developing a sophisticated control system, and creating user-friendly software interfaces.

In the initial phase of the project, a comprehensive system architecture will be formulated to articulate the interactions between different components. This involves specifying the types of droplets to be manipulated, their volume ranges, and the intended applications of the digital microfluidic platform. The electrical design will focus on creating circuitry that can apply DC voltages in a controlled manner, adhering to safety standards and regulatory requirements. This component is crucial for the successful manipulation of droplets within the microfluidic system.

A significant aspect of the project involves the design and optimization of the microfluidic chip. This includes considerations for channel geometry, surface coatings, and material compatibility to ensure efficient droplet movement. The chip design must facilitate functions such as droplet dispensing, merging, splitting, and mixing, aligning with the intended applications of the platform. The development of a robust control system is equally vital, as algorithms need to be implemented for precise droplet positioning, routing, and sequencing. The integration of feedback mechanisms will enable real-time adjustments, contributing to optimal performance.

Microfluidics is used in many industries where chemical and biological processes and operations are apparent. This is because they offer better efficiency as the concentration regarding cellular processes increases as the reactions and results are taking place in a confined space around a chip. They are well-suited for point-of-care diagnostics due to their portability, low cost, and ease of use. Several studies have demonstrated the use of DMF platforms for the diagnosis of infectious diseases, such as tuberculosis [5] and malaria [6]. DMF platforms have also been used for the diagnosis of non-infectious diseases, such as cancer [7] and diabetes [8]. DMF platforms can be used for drug discovery by screening for potential drug candidates and optimizing drug formulations. DMF platforms are particularly well-suited for high-throughput screening, as they can quickly and efficiently test a large number of compounds. DMF platforms can be used for food safety by detecting contaminants and pathogens in food. DMF platforms are particularly well-suited for this application because they can be used to test small sample volumes and they are very sensitive.

The expected outcomes of our device since, it is the first stage of the platforms closed configuration design process, is to achieve droplet movement, Linear actuation, merging and splitting of droplets all of which are to be controlled using digital means such as through a microcontroller, a personal computer, etc.

1.4 Report Outline:

This report comprises of 3 chapters which provide not the overall but a partial structure of our report. Starting from the introduction of the project topic up to design Methodology.

Chapter 1 includes the theory, concept, and background behind the project we are undertaking. Starting from the concept of electrowetting, we dive into the technology of lab-on-a-chip devices and digital microfluidics, which is a platform built for these device systems.

These systems allow droplet manipulation by using the concept of electrowetting. As a result, a single droplet or droplets are allowed to displace, merge, and can even be made to split into two. This allows scientists to study cell manipulation, separation, and dive deep into DNA analysis.

Chapter 2 is filled with a literature review regarding all the work that has been done on these systems and making such devices. Every effort has been made to improve the ease of manufacturing of said devices. Researchers have contributed to this field from across the world which enabled it to revolutionize diagnostic testing and improved clinical care provided to newborn children.

The reason for manufacturing these devices is to provide cheap testing and analysis while having the same efficiency as standard laboratories. As a result, people have tried different methods which introduce a new platform, each being better than the previous.

Currently, printed circuit boards or PCBs are in favor due to their ability to be rapidly manufactured and economically viable. Although this paper discusses voltage as the necessary input to droplet movement, some researchers have also introduced magnetic and optical-based microfluidics to be the next advancement going forward.

Chapter 3 encapsulates the steps of making a printed circuit board which serves as the base of lab-on-a-chip devices. The methodology part of the report starts with governing equations that set the basis for electrowetting theory. Moving forward, we arrive at the designing part of the section which is done on EasyEDA software.

1.5 Project Schedule:

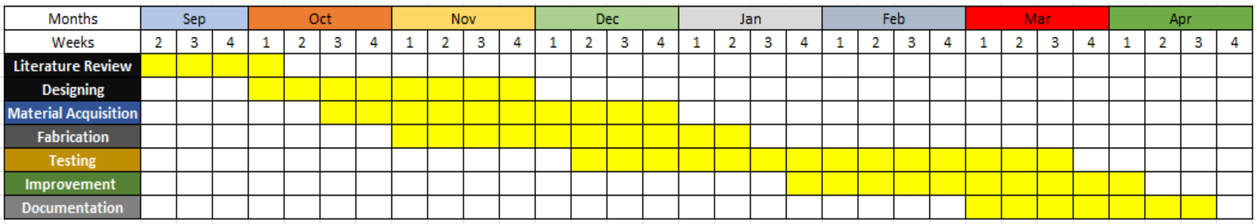


Figure 2: Timeline of Project

1.6: Individual and Team Contribution:

Table 1: Contribution to the Project and Report

Individual	Contribution
Hamad Khan	Designing of PCBs
Fardad Ali Shah	Electrical Circuitry Design

Note: Above all individuals have also been a part of **Testing and Experimentation**.

Chapter 2
Literature Review

2.1 Literature Review:

The field of digital microfluidics (DMF) has witnessed remarkable advancements, emerging as a transformative technology for precise fluid manipulation at the microscale. DMF operates on an open array of hydrophobic-insulated electrodes, offering unparalleled control over picolitre- to microliter-sized droplets. Unlike traditional channel-based microfluidics, DMF doesn't rely on complex channel networks, pumps, valves, or mechanical mixers. This simplicity allows for simultaneous execution of various processes with a compact design, providing benefits such as low reagent consumption, fast heat transfer, and easy integration with other analytical techniques [9].

One of the standout features of DMF is its reconfigurability, enabling individual control of droplets without the need for intricate channel systems. This reconfigurability is a key advantage, allowing for the execution of diverse droplet operations, including merging, mixing, splitting, and dispensing from reservoirs. The open nature of DMF devices simplifies sample collection for preparative applications, and they can handle solid samples without the risk of clogging, making them highly versatile tools in various scientific domains.

Within the realm of Computer-Aided Biology (CAB), DMF plays a pivotal role as a "digital bio converter." CAB seeks to bridge the gap between the digital aspects of the design–build–learn cycle and the physical execution of experiments. DMF, operating as a liquid-handling technology, facilitates this connection by providing a platform for the precise manipulation of biological samples. Its utility extends to genetic engineering, sample preparation for sequencing and mass spectrometry, and screening assays. The review emphasizes DMF's potential as a centralized automation platform within a fully integrated pipeline for the production of novel organisms and biomolecules [10].

However, despite its promising features, DMF faces challenges and limited adoption in biochemical experiments compared to traditional microplates and micropipettes. Microfluidics, including DMF, offers advantages such as reduced sample consumption and accelerated reactions. Still, issues related to biological and chemical compatibility, dedicated device use, and complex fabrication processes hinder its widespread acceptance. Biochemists' reluctance to embrace microfluidic systems is often attributed to unfamiliarity with on-chip sample delivery methods [11].

Efforts are underway to address these challenges and make microfluidics, particularly DMF, more user-friendly. Interdisciplinary approaches involve surface coating and the use of thermal plastic to enhance inertness and simplify mass production. A novel approach called "pico-dosing" in DMF aims to overcome subjective objections to on-chip sample delivery. Leveraging the satellite droplet ejection phenomenon, pico-dosing mimics the familiar process of micro pipetting, providing adjustable delivery volumes and greater control in on-chip sample preparation. This innovative method offers a potential solution to accelerate the integration of microfluidics into daily biochemical lab workflows.

DropBot represents a significant advancement in DMF technology, addressing challenges related to device surface variability and reproducibility. It introduces two key functionalities: real-time monitoring of instantaneous drop velocity and the application of a precise electrostatic driving force, independent of device-specific properties. The measurement of instantaneous drop velocity serves as a proxy for resistive forces, providing insights into local surface heterogeneities critical for reliable DMF operation. DropBot's automated, real-time tuning of applied potentials overcomes challenges associated with amplifier-loading sensitivity and variations in device capacitance, contributing to improved device robustness and experimental reproducibility [12].

In the realm of standard DMF platforms, droplets are manipulated through the application of electrical potentials between pairs of electrodes, typically in either air or oil-immersed systems. While oil-immersed configurations offer advantages such as lower voltage requirements and elimination of droplet evaporation, challenges include analyte partitioning into the oil phase, oil leakage, and limitations in applications relying on droplet drying. A hybrid approach involves core-shell systems, where aqueous droplets are encapsulated in oil droplets and actuated within an air-filled device.

Beyond the traditional electrical field application, alternative schemes for droplet manipulation in DMF have been explored, including optical forces, magnetic forces, thermocapillary forces, and surface acoustic waves (SAWs). Optical methods utilize photoconductive layers, magnetic forces rely on droplets containing magnetic particles, thermocapillary forces employ temperature gradients generated with thin-film resistive heaters, and SAWs utilize high-frequency power sources. Each approach introduces versatility to DMF applications, expanding its potential uses [13].

Surface flaws such as scratches, dust, or reagents adsorbed onto the surface can hinder droplet movement in DMF systems. To address this, droplet-sensing and feedback control systems have been implemented, measuring capacitance changes associated with droplet movement. These systems enable real-time adjustments to driving pulses until the desired application is completed. Different feedback control systems have been proposed, varying in complexity and precision, including those relying on impedance measurements, proportional integral derivative control algorithms, and simple feedback control systems compatible with ac driving voltages.

In conclusion, digital microfluidics (DMF) has evolved into a powerful technology with diverse applications in biology, chemistry, and medicine. Its reconfigurability, simplicity, and precise control over droplets make it a valuable tool in various scientific domains. Challenges related to user adoption and device robustness are being actively addressed through innovations such as pico-dosing and DropBot. As DMF continues to advance, it holds the potential to revolutionize laboratory automation and programmable biology, contributing to the integration of digital and physical tools in data-driven experimentation.

2.2 Inferences drawn from literature:

Inferences drawn from the literature illuminate the multifaceted landscape of digital microfluidics (DMF) and its transformative impact on fluid manipulation at the microscale. The literature underscores DMF's unique attributes, emphasizing its reconfigurability, simplicity, and precise control over droplets as key differentiators from traditional channel-based microfluidic systems. The versatility of DMF is evident in its diverse applications across biology, chemistry, and medicine, offering benefits such as reduced reagent consumption, fast heat transfer, and easy integration with other analytical techniques. Challenges identified in the literature, including limited adoption in biochemical experiments, device surface variability, and issues related to user familiarity, prompt ongoing research efforts to enhance user-friendly features and improve device robustness.

The integration of DMF into the Computer-Aided Biology (CAB) framework further emphasizes its role as a "digital Bio-converter," connecting digital design with physical experimentation. Inferences from the literature collectively point towards the promising trajectory of DMF technology, with ongoing advancements poised to address current limitations and pave the way for broader acceptance and impactful contributions to scientific research and experimentation.

2.3 Summary:

In summary, the literature on digital microfluidics (DMF) highlights its pivotal role in revolutionizing microscale fluid handling. DMF's distinctive features, including reconfigurability, simplicity, and precise droplet control, set it apart in the realm of microfluidic technologies. The technology's applications span various scientific domains, offering advantages such as reduced reagent consumption and seamless integration with other analytical techniques. However, challenges such as limited adoption in biochemical experiments and device surface variability prompt ongoing research to enhance user-friendliness and device robustness. The integration of DMF into the Computer-Aided Biology (CAB) framework further accentuates its significance as a "digital bio-converter." Overall, the literature suggests a promising trajectory for DMF, with continual advancements anticipated to overcome current limitations and further contribute to scientific research and experimentation.

Chapter 3
Design and Analysis

3.1 Design Methodology:

A commonly used DMF device, schematically shown in Figure 3, consists of two parallel-adjusted glass slides with a slit for droplet transport, called closed configuration. The bottom plate comprises individually addressable, square-shaped metal path electrodes, a dielectric layer, and a thin hydrophobic layer, typically made of spin coated Teflon AF films, which cover the surface. The top glass slide is covered with a thin, transparent, non-structured indium-tin-oxide (ITO)-electrode serving as ground electrode. The layer is passivated with a thin Teflon layer, too. In addition, the ITO and Teflon layer can be patterned to form locally hydrophilic spots.

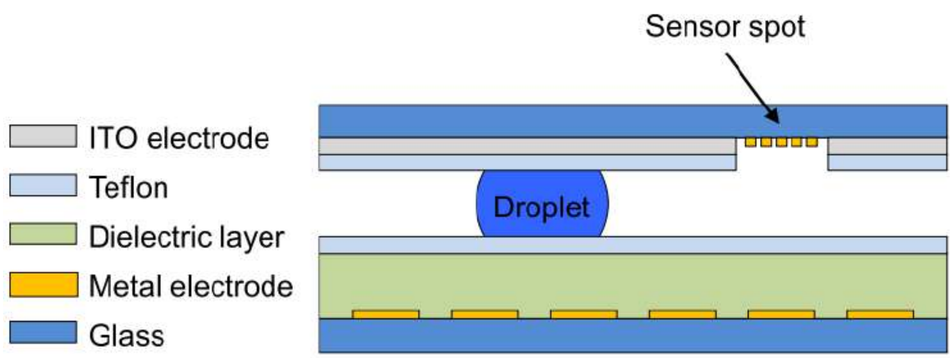


Figure 3: Key Components of an EWOD Device (Closed Configuration)

3.1.1 Components Breakdown:

3.1.1.1 Metal Electrodes:

At the core of the chip are the metal electrodes, typically made of copper. These electrodes serve as the conductive elements that interact with the droplets. By applying electrical potentials to specific electrodes, droplets can be precisely manipulated, allowing for operations such as merging, mixing, splitting, and dispensing. The choice of metal for the electrodes is critical to ensure good electrical conductivity and compatibility with the surrounding components.

3.1.1.2 Dielectric Layer:

This insulating layer prevents undesired electrical current between adjacent electrodes, ensuring that the applied potentials act specifically on the targeted droplets. It prevents direct electrical contact, ensuring controlled and precise droplet actuation. The dielectric layer's thickness and material properties are critical factors influencing the chip's performance.

3.1.1.3 Teflon Coating on Glass:

To create a hydrophobic surface, the glass substrate hosting the metal electrodes and dielectric layer is coated with a Teflon layer. Teflon, known for its non-wetting properties, minimizes droplet adhesion to the surface. This property is essential for ensuring that droplets move freely and do not adhere to the substrate during manipulation.

3.1.1.4 ITO Glass:

ITO serves as a transparent conductive layer that allows for optical monitoring and manipulation of droplets. It is particularly useful for applications where real-time visual feedback is required.

3.1.2 Design Process Flowchart:

Our design process will inherently follow the scientific method which is shown in Figure 3-2.

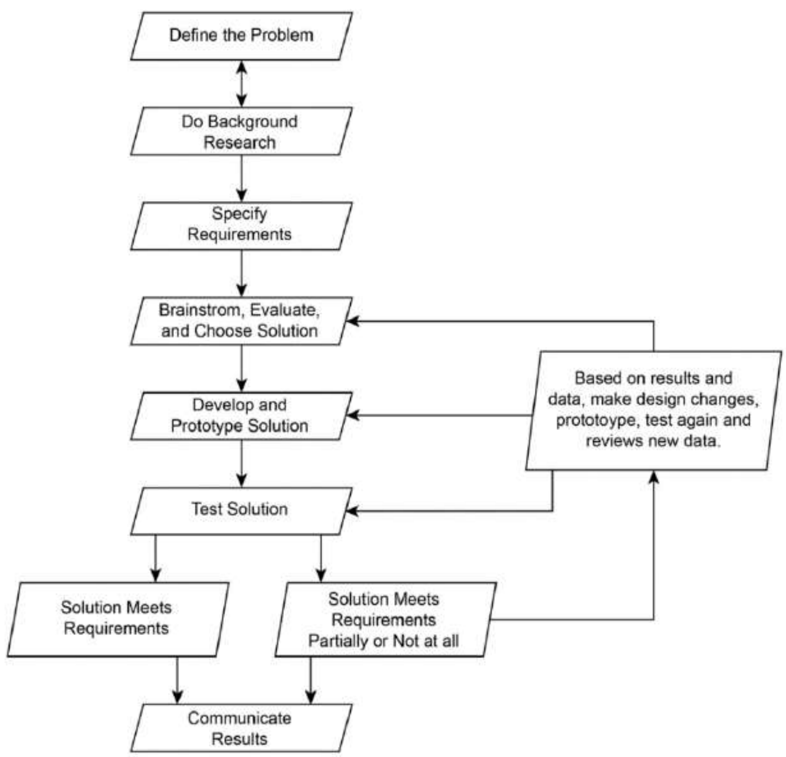


Figure 4: Design Process Flow Chart

3.2 Governing Equations / Mathematical Models:

External electric field forces counteract surface tension forces, which affect the contact angle of a liquid droplet with a solid surface. The Young-Lippmann equation explained previously provides this change in contact angle.

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_r \varepsilon_0}{2\gamma d} V^2$$

In this equation, the contact angle following the application of voltage is denoted θ, ε_0 is the permittivity of free space, and ε_r and d, respectively, are the permittivity and thickness of the dielectric layer. γ stands for the surface tension between a liquid and a gas, while V stands for the voltage supplied to an electrode.

The variable θ_o is the initial contact angle of the liquid before it is put under the influence of the electric field.

The following equation provides the initial contact angle, which depends on the surface tension coefficients at the solid-gas (SG), solid-liquid (SL), and liquid-gas (LG) interfaces.

$$cos\,\theta_o = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma}$$

The Young-Lippmann equation demonstrates unequivocally that the change in a droplet's contact angle with a solid surface is exactly proportional.

According to the Young-Lippmann equation, the change in contact angle of a droplet with a solid surface is directly proportional to the square of the applied voltage and inversely proportional to the dielectric thickness layer. It is necessary to optimize voltage levels for a specific dielectric thickness. Voltage levels below the necessary level may not cause electrowetting in the liquid droplet, while voltage levels beyond a particular threshold may cause the dielectric layer to break down.

On the electrode array, voltage is progressively switched between electrodes to produce droplet transport. A droplet is drawn toward an electrode when it is turned on by the imbalanced pressures at the contact. The droplet's estimated speed as it approaches a nearby electrode is predicted using Brochard’s model.

$$u = \frac{\varepsilon_0 \varepsilon_r (1 - \cos\theta_v)}{6\mu dl \sin\theta_v} . V^2$$

Here, ε_0 and ε_r represent the relative permittivity and the free space permittivity, respectively. After applying voltage V, the contact angle is shown by θ_v, 1 is an empirical factor, d is the thickness of the dielectric layer and μ is the viscosity. Multiple droplets are transported and afterwards carried out separately on a M x N array of electrodes with the aid of voltage applied to each electrode in the correct order.

3.3 Geometric Modeling and Design:

3.3.1 Electrode Array Design:

3.3.1.1 Easy EDA:

For the electrode arrangement, we relied on EasyEDA, a powerful Electronic Design Automation (EDA) software specifically designed for PCB modeling. This software boasts several features that make it ideal for PCB design and editing, including an intuitive interface, a vast library of readily available components, comprehensive analysis and simulation tools, multiple export formats, and a convenient collaborative design environment.

3.3.1.2 The shape of the electrodes:

While previous studies explored optimizing electrode shapes for enhanced performance, our project prioritized cost-effectiveness and ease of manufacturing. To achieve this, we opted for a specific electrode design that balanced sufficient reliability with straightforward fabrication processes. This focus on manufacturability addressed a major concern regarding the project's overall feasibility, ensuring a practical and cost-efficient approach to electrode development. The selection of square electrodes was made according to inference from previous literature considering the cost of the machines required to manufacture the electrodes.

3.3.1.3 Material for electrodes:

Material selection for our project wasn't taken lightly. Factors like cost and accessibility were paramount, leading us to ultimately choose copper. This decision stemmed from the comprehensive analysis presented in the following table, which highlights the key considerations and justifications for choosing copper.

Table 2: Properties of Most Conductive Metals

Metal	Electrical Conductivity (10e^6 siemens/m)	Electrical Resistivity (10e^8 ohms/m)	Thermal Conductivity (w/m/k)	Price/kg (USD)
Silver	62.1	1.6	420	521
Copper	58.7	1.7	386	6
Gold	44.2	2.3	317	44800
Aluminum	36.9	2.7	237	1.79

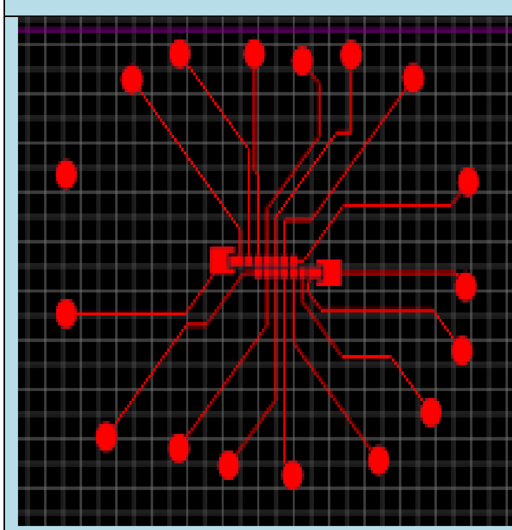
3.3.1.4 PCB Models:

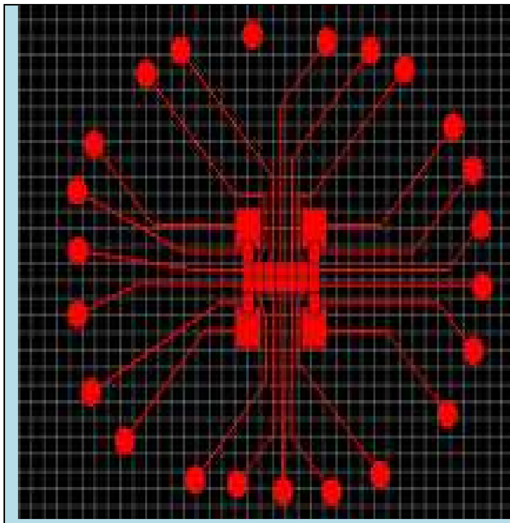
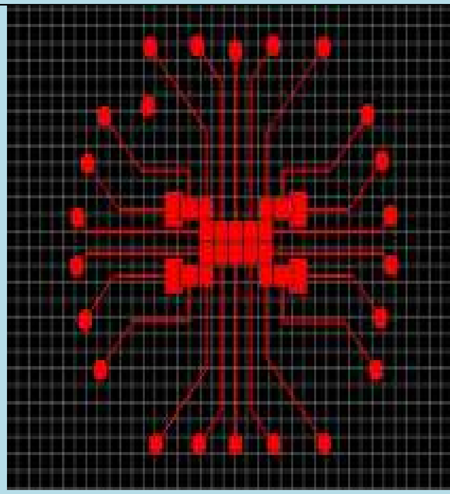
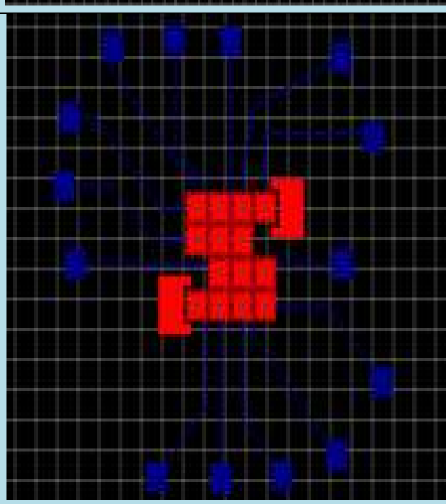
The following models were designed on the software for the electrode array. The dimensions of the electrodes were varied across the design to diversify the range of applications.

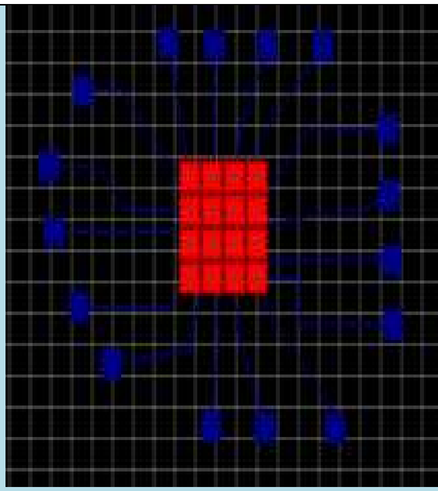
Different sizes of electrodes allow for different quantities of droplet volume to be utilized which would be invaluable for usage with different-density fluids and would not render the device inoperable if a different fluid (other than assumed test fluid of water) was to be used.

Table 3-2 shows the preliminary models fabricated which are categorized by the parameters of the type of layer in the PCB, the size of the electrode which is essentially the area of the electrode and the shape of the electrode.

Table 3: Electrode Design Pattern

DESIGN	LAYER	SIZE	SHAPE
	SINGLE LAYER	1x1 mm	Square

	Single layer	2x2 mm	Square
	Single Layer	3x3 mm	Square
	Multi-Layer	2.5x2.5 mm	Interlocking or Zigzag

	Multi-Layer	2.5x2.5 mm	Interlocking or Zigzag

The designs of the PCB were kept simple in the preliminary model to cater for future development based on experimental results. The constraints of track width (width of wire connecting square electrode and circular voltage contact pad) and electrode spacing would ideally be kept to a minimum depending on the manufacturability however for these models a track width of 0.254 mm and electrode spacing of 0.25 mm was taken.
According to different works in literature, interlocking pattern or zigzag pattern is more popular as it provides better droplet actuation. A proposed concept is that the contact length of a water droplet is directly proportional to the driving force which results in better droplet actuation and various literature is identified that the longer the contact line length is, the easier it is for the droplet to move.

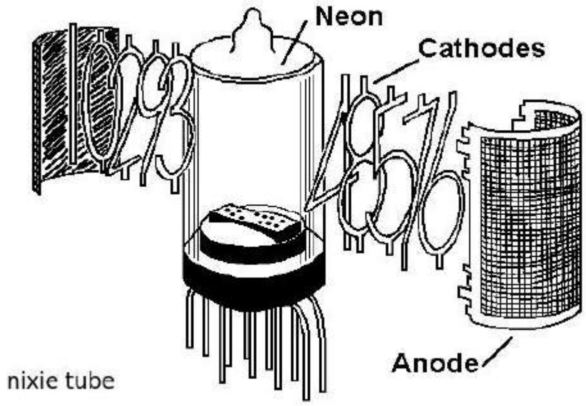
3.3.1.5 Electrical Circuit Design Considerations:

The Electrical Design of our device can be broken down into two major components one was to acquire the high voltage required for actuation (up to 400 Volts) whilst the second was a control mechanism to provide the high voltage to each electrode in the array.

For our High Voltage circuit design, the following options were thoroughly studied through a literature review for low power high voltage circuits.

3.3.1.6 Nixie Tube Circuits:

Nixie tubes are vacuum tubes that were used in electronic displays before the advent of LEDs and LCDs. They have a distinctive glow and are often used for retro or vintage projects.
Nixie tubes are made up of a series of wire mesh grids and cathodes, and each digit or character has its own set of wires. When a voltage is applied to a particular cathode, the corresponding digit or character will glow much like how we would want our electrode to receive the required high voltage and initiate the electrowetting process.



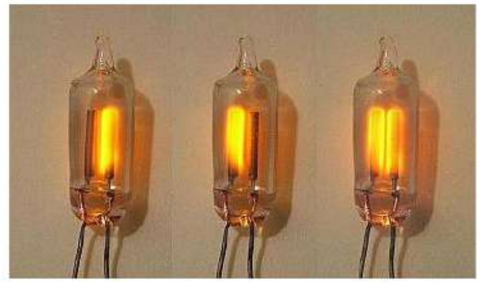


Figure 5: Nixie Tube Body and Neon Bulbs

Nixie tubes require a high voltage to operate, typically around 170-200 volts DC. They also require a current-limiting resistor to prevent damage to the cathodes. There are many Nixie tube driver circuits available, but the most common type is the "multiplexed" driver.

Multiplexed Nixie tube drivers use a series of shift registers to control the cathodes of the tubes. The shift registers are controlled by a microcontroller or other logic device, and each output corresponds to a particular cathode. The outputs are then connected to the cathodes through current-limiting resistors.

To display a particular digit or character, the corresponding cathode is selected by setting the appropriate output on the shift register too high. The anodes of the nixie tubes are connected to a high voltage power supply, typically around 170-200 volts DC.

In addition to the shift registers and high voltage power supply, nixie tube driver circuits may also include other components such as decoders, multiplexers, and transistors. These components are used to simplify the circuit and reduce the number of pins required on the microcontroller.

One important consideration when designing a nixie tube circuit is the current draw. Nixie tubes can draw a significant amount of current, especially when multiple tubes are used. This can be a problem for battery-powered projects or other low-power applications. To minimize current draw, it's important to use efficient circuit design and high-quality components.

Another consideration is the timing of the multiplexed signals. Nixie tubes require a certain amount of time to "settle" before they can display a stable digit or character. This settling time is typically in the order of a few microseconds and must be considered when designing the driver circuit.

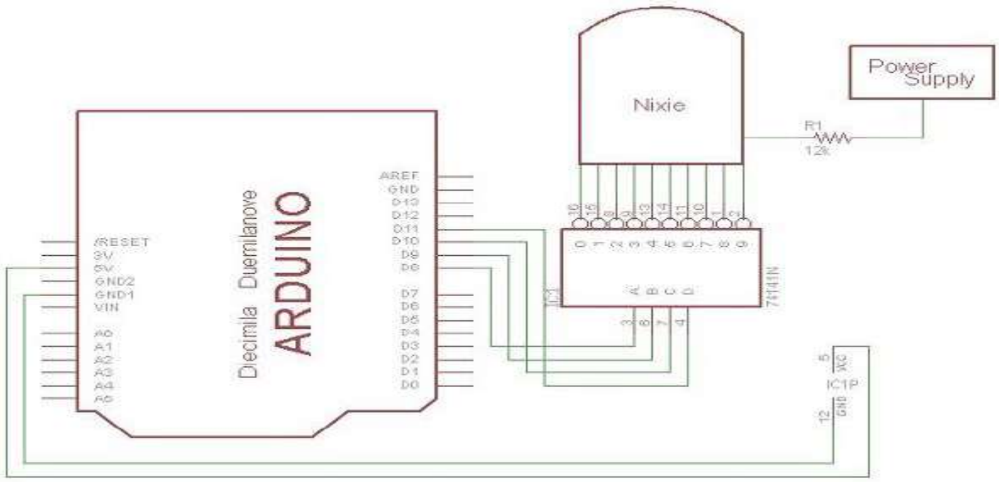


Figure 6: Conventional Circuit for Nixie Tubes

In addition to the multiplexed driver, there are also other types of nixie tube drivers available, such as the "direct drive" method. This method uses a separate driver circuit for each cathode and can be simpler in some cases. However, it requires more pins on the microcontroller and can be more difficult to implement.

3.3.1.7 Boost Converter:

A boost converter is a type of DC-DC converter that can be used to generate high voltage from a low-voltage DC input. Boost converters work by using an inductor and a switch to store and release energy from the input voltage, which is then stepped up to a higher voltage.

To implement a boost converter, you would typically use an oscillator to drive a switch, such as a MOSFET or a BJT. The switch is connected in series with an inductor and a diode, which form a voltage boost circuit. When the switch is turned on, the inductor stores energy from the input voltage. When the switch is turned off, the inductor releases the stored energy into the output circuit, which steps up the voltage.

Boost converters can be compact and efficient, making them well-suited for portable applications. However, they require careful consideration of component selection and circuit layout to avoid issues such as noise and voltage spikes. They may also require additional circuitry, such as filters and voltage regulators, to provide stable and reliable output.

3.3.1.8 Cockcroft-Walton multiplier:

A Cockcroft-Walton multiplier is a type of voltage multiplier circuit that can be used to generate high voltage from a low-voltage DC input. Voltage multipliers work by using diodes and capacitors to multiply the voltage of a DC input, producing a high DC voltage at the output.

To implement a Cockcroft-Walton multiplier, you would typically use a series of diodes and capacitors arranged in a ladder configuration. The input voltage is fed into the first stage of the ladder, which charges up the capacitors. The charged capacitors are then connected to the next stage of the ladder, which multiplies the voltage. By repeating this process for multiple stages, one can generate a high enough voltage for our project.

Cockcroft-Walton multipliers can be relatively simple and easy to implement, and they can provide high-voltage output with relatively low component count as shown in the circuit in Figure 3-5.

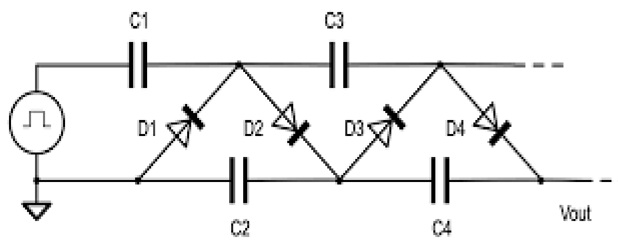


Figure 7: Electrical Circuit of Cockcroft-Walton Multiplier

However, they may be less efficient than other methods, and they may be susceptible to issues such as voltage drop and capacitor leakage.

3.3.1.9 Microcontroller:

Microcontrollers are small, single-chip computers that are used in a wide range of electronic applications. They are designed to be low-cost, low-power, and easy to program, making them ideal for embedded systems and other applications where a full-sized computer would be overkill.

A typical microcontroller consists of a CPU, RAM, ROM or flash memory, input/output (I/O) ports, and a range of peripheral devices such as timers, analogue-to-digital converters (ADCs), and serial communication interfaces. Microcontrollers are typically programmed using high-level programming languages such as C or C++, although some also support assembly language programming.

One of the main advantages of microcontrollers is their versatility. They can be used in a wide range of applications, from simple LED blinkers and temperature sensors to complex robotics and automation systems. Microcontrollers are also highly customizable, with many different types and configurations available to suit specific applications.

Another advantage of microcontrollers is their low power consumption. Because they are designed to be used in embedded systems, they are optimized for low power consumption and can operate on small batteries or even energy harvesting systems. This makes them ideal for applications where power is limited, such as remote sensors or wearable devices.

When selecting a microcontroller for a particular application, there are several factors to consider. The first is the processing power of the chip. This is typically measured in megahertz (MHz) or gigahertz (GHz) and determines how quickly the microcontroller can perform calculations and process data.

Another important consideration is the amount of memory available on the microcontroller. This includes both RAM and ROM or flash memory, which are used for storing program code and data. Some microcontrollers also support external memory expansion, which can be useful for applications that require large amounts of data storage.

Other factors to consider when selecting a microcontroller include the number and type of I/O ports available, the presence of built-in peripheral devices such as ADCs and timers, and the availability of development tools and support from the manufacturer. Programming microcontrollers typically involves writing code in a high-level programming language such as C or C++, which is then compiled and loaded onto the microcontroller using a programming tool. Many microcontrollers also support real-time operating systems (RTOS) and other software frameworks that can simplify programming and make it easier to develop complex applications.

In conclusion, microcontrollers are small, versatile, and low-power computers that are ideal for a wide range of embedded systems applications. They are highly customizable, with many different types and configurations available to suit specific applications and can be programmed using a variety of programming languages and tools. When selecting a microcontroller for a particular application, it is important to consider factors such as processing power, memory, I/O ports, and support from the manufacturer.

3.3.1.10 Shift Register:

Shift registers are electronic circuits that are commonly used in digital electronics to store and shift data. They are typically composed of a series of flip-flops, which are connected in a way that allows them to shift data from one stage to another.

Shift registers can be used in a wide range of applications, such as in serial-to-parallel and parallel-to-serial data conversion, digital signal processing, and LED and LCDs. They are also used in microcontroller-based systems, where they can be used to expand the number of input/output (I/O) pins available to the microcontroller.

There are several different types of shift registers, including serial-in, parallel-out (SIPO), parallel-in, serial-out (PISO), and serial-in, serial-out (SISO) shift registers. SIPO shift registers allow data to be input serially and output in parallel, while PISO shift registers allow data to be input in parallel and output serially. SISO shift registers allow data to be shifted in and out serially while retaining the ability to perform parallel data transfers.

One of the key advantages of shift registers is their ability to store and shift large amounts of data using relatively few input and output pins. This makes them ideal for applications where space is limited, or where many I/O pins are not available, which is of paramount importance to our circuit as there can be a huge array of electrodes.

Shift registers are typically controlled using clock signals, which synchronize the shifting of data between stages. The clock signal determines the rate at which data is shifted through the register and is typically generated by an external clock source or a microcontroller.

Shift registers can also be cascaded together to increase the number of stages and the amount of data that can be stored and shifted. This is achieved by connecting the output of one shift register to the input of another, allowing data to be shifted through multiple registers in sequence.

3.3.1.11 Demultiplexers:

Demultiplexers, also known as "DEMUX" for short, are digital electronic devices that allow a single input signal to be directed to one of several output lines based on the value of a control signal. In other words, they are used to "demultiplex" a single input signal into multiple outputs based on the value of a control signal.

Demultiplexers are the inverse of multiplexers, which take multiple input signals and combine them into a single output signal. In a typical demultiplexer, the input signal is applied to one input, and the control signal is applied to another input. The output lines of the demultiplexer are then connected to different circuits or devices, based on the value of the control signal.

The simplest type of demultiplexer is a 1-to-2 demultiplexer, which has one input, two outputs, and one control input. The control input is typically a single binary signal that determines which output line the input signal is directed to. When the control signal is low (0), the input signal is directed to the first output line, and when the control signal is high (1), the input signal is directed to the second output line.

More complex demultiplexers can be built using multiple 1-to-2 demultiplexers and logic gates. For example, a 1-to-4 demultiplexer can be built using two 1-to-2 demultiplexers and two inverters. The input signal is applied to the first 1-to-2 demultiplexer, which directs it to one of two output lines based on the value of the control signal. The output lines from the first demultiplexer are then connected to the control inputs of a second 1-to-2 demultiplexer, which further splits the signal into one of four output lines.

Demultiplexers are commonly used in digital circuit design to route signals to different devices or circuits based on the value of a control signal. They can also be used in microprocessor systems to decode instructions or to enable/disable specific parts of the system. In addition, they can be useful in data communication systems to transmit data over multiple channels simultaneously. By using a demultiplexer, it is possible to selectively apply electrical fields to different parts of a microfluidic system. For example, a demultiplexer could be used to control the movement of different droplets within a fluidic system or to activate different electrodes within a microfluidic device. This can be useful for a variety of applications, such as medical diagnostics, drug discovery, and chemical analysis.

3.3.1.12 MOSFETS:

A MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is a type of transistor that is commonly used in electronic circuits to switch or amplify signals. MOSFETs consist of a metal gate, an insulating oxide layer, and a semiconductor channel. They operate by controlling the flow of current through the channel using an electric field generated by the gate voltage.

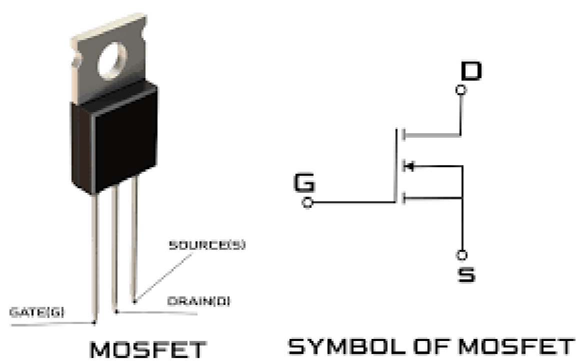


Figure 8: Visual Representation of a MOSFET

One of the key advantages of MOSFETs is their ability to handle high voltages and currents with low power loss. High-voltage MOSFETs are designed specifically for applications that require the switching or control of high voltages typically above 100 volts. High-voltage

MOSFETs have several features that make them suitable for high-voltage applications. These include:

1. **High breakdown voltage**: High voltage MOSFETs have a high breakdown voltage, which means they can withstand higher voltages without breaking down or conducting current. This makes them ideal for use in high-voltage applications where voltage spikes or surges may occur.

2. **Low on-resistance:** High voltage MOSFETs have a low on-resistance, which means they can handle high currents without generating excessive heat or power loss. This makes them ideal for use in high-power applications such as motor control or power supplies.

3. **Fast switching speed**: High voltage MOSFETs have a fast-switching speed, which means they can switch on and off quickly. This is important in high-frequency applications such as switching power supplies or inverters.

In a digital microfluidic chip, a MOSFET can be used to switch a high-voltage pulse on and off to control the movement of a droplet of liquid. The MOSFET is connected to the electrode that is in contact with the liquid, and when the MOSFET is turned on, a high-voltage pulse is applied to the electrode, causing the contact angle of a liquid to change and consequently allowing for the droplet to traverse between electrodes.

High-voltage MOSFETs are particularly well-suited for this application because they can handle the high voltages and currents required for electrowetting. They also have fast switching speeds, which are important for precise control of the electric fields.

In addition to electrowetting, MOSFETs are used in many other applications that require high-voltage switching, such as power supplies, motor control, and lighting systems. They are versatile and reliable components that can handle a wide range of voltages and currents, making them essential in many electronic systems.

For the requirements of this project, there was a need to provide high voltage in a portable form. Another design constraint was that the supply had to be economically viable and easily accessible. Even though the electric current requirements for our project were negligible, there were few avenues to explore.

3.3.2 Electrical Circuit Design:

3.3.2.1 Control Circuit Design:

The Schematic is shown in Figure 9. The Circuit is composed of most of the devices mentioned in the Electrical Design Considerations.

The Microcontroller used is ESP-32-WROOM-32-D and the pins 21,22 & 23 are connected to the three data input pins on the shift register. These three pins take serial input and output parallel outputs connected to each gate terminal of the MOSFET associated with each electrode. The eight outputs of the shift register which are pins QA-H are connected to individual MOSFETs and form an array mirroring the electrode array.

The three pins of each MOSFET are connected in the same manner i.e., the drain terminal is connected to VCC which is essentially the High Voltage needed for droplet actuation. The drain terminal also contains a 10 KΩ Resistor to limit the current in the circuit and the connection for the electrode is given in parallel from the tail of the resistor.

The control circuit is modular in the sense that adding multiple Shift Registers can allow a larger number of electrodes to be controlled alongside adding the same number of MOSFETs as there are electrodes in the array.

The code required to run this circuit is provided in Appendix B. The Code also has an allowance for additions of more 74-HC-595 Shift Registers and the logic of the circuit remains the same. The individual actuation of each electrode can also be controlled by giving the required electrodes unique identification as “ElectrodeID” to be actuated through the serial monitor. The code also contains a function such as a “fast switch” which can be directly used to actuate electrodes in a single line.

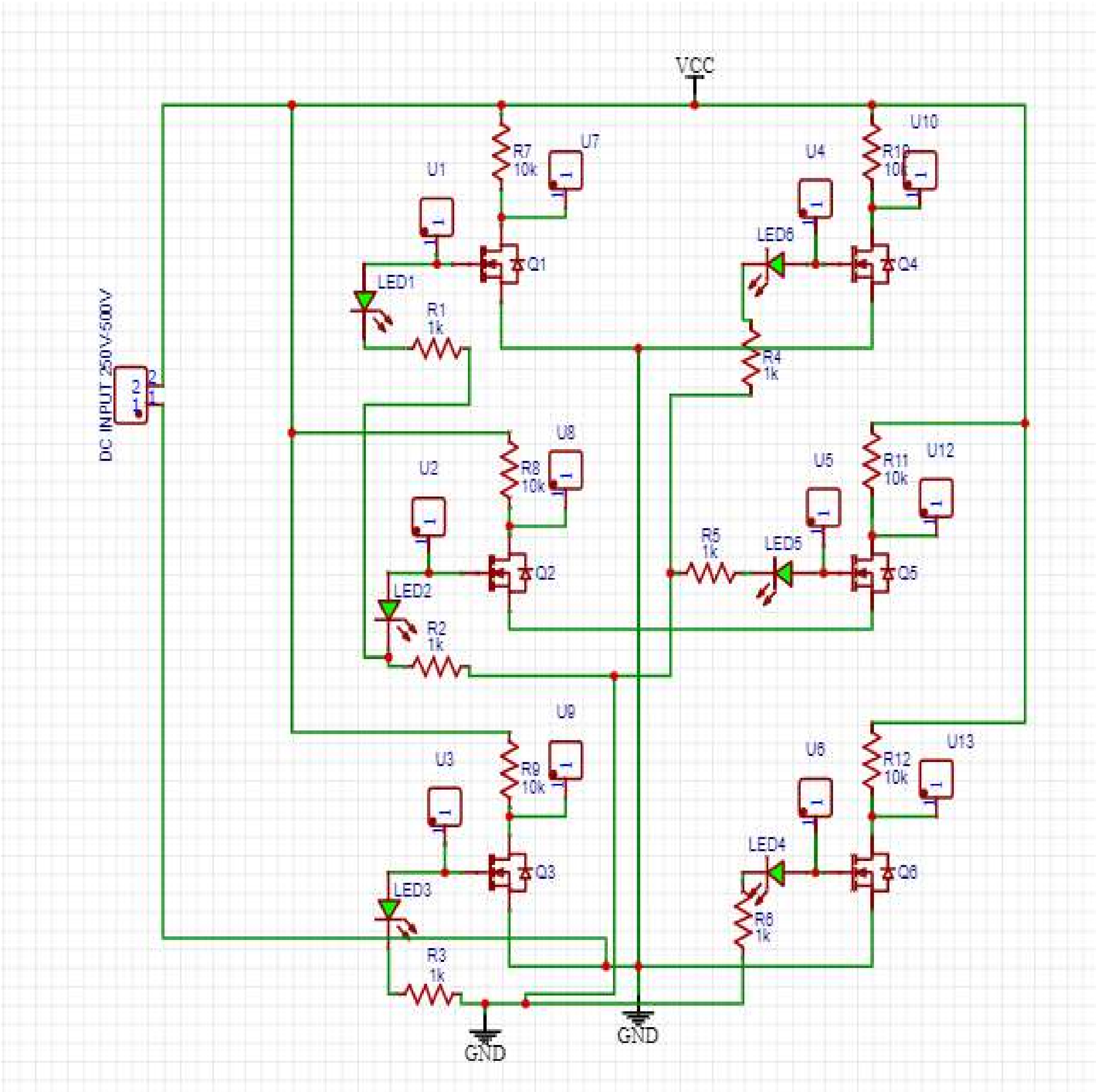


Figure 9: Schematic of Control Circuit

3.4 Analysis:

3.4.1 Prototype Fabrication:

The governing equations required gave us the basis for the physical testing conducted on One prototype was fabricated and tested. The ideology behind this testing centered around the utilization of materials and resources readily available in the labs of FME.

3.4.2 Materials Used in Prototype Testing:

The materials used for testing were PDMS and Cling Film(PVC) which possess the following dielectric Constants of 2.8-2.9 & 2, respectively [14]. The PCB substrate was chosen to be FR-4. For the hydrophobic substances PDMS, since it possesses a contact angle of 108 degrees of water with the surface, was solely utilized whilst mustard oil which has a contact angle of greater than 90 degrees was also utilized.

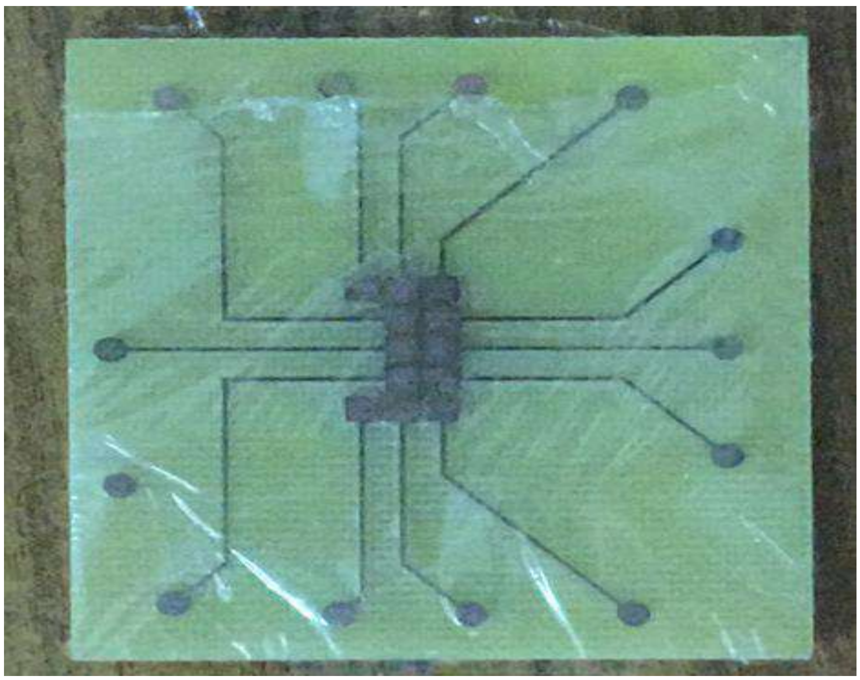


Figure 10: Fabricated PCB (Model 1) with Cling film (PVC) and Mustard Oil

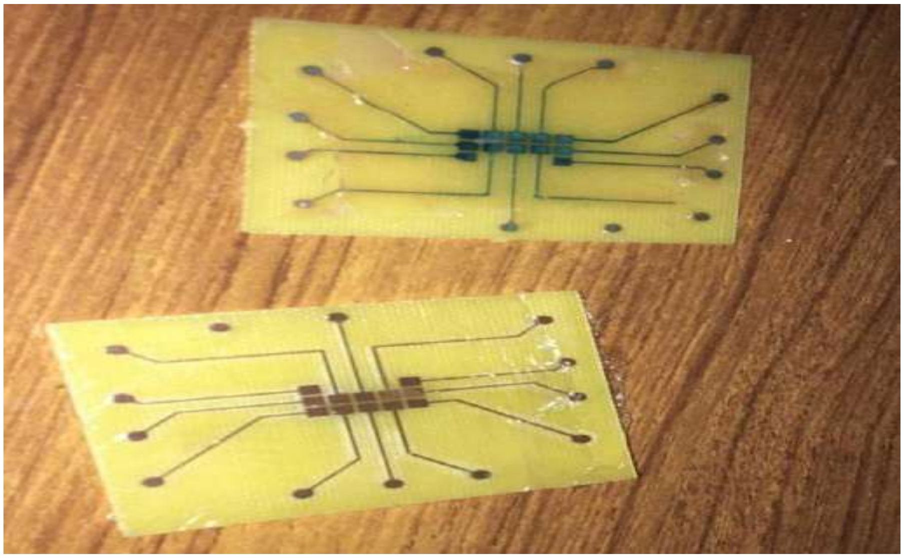


Figure 11: Fabricated PCB: Model 1(Top), Model 2 (Bottom)

3.4.3 Results and Discussion:

Table 4: Actuation Voltages Required

Model	PCB Substrate	Electrode Size	Dielectric Layer	Hydrophobic Layer	Actuation voltage
1	FR-4	2 x 2	PVC	Mustard Oil	198
2	FR-4	2 x 2	PDMS	PDMS	199

Table 3-3 shows the required actuation voltages for the transport of droplets from one electrode to the adjacent electrode however the high actuation voltage could be the result of impurities in our testing and further testing with materials outsourced shall yield better results.

3.4.4 Environmental and Social Impact:

The overall goal of this project is to produce a device that will aid in many forms of medical and/or chemical research and since our design is primarily focused on achieving a lab-on-a-chip device that will be of low cost the social impact shall be felt throughout many domains.

As for environmental impact our device does not have any direct adverse effects on the environment however the printing of PCBs and overall usage of electricity for manufacturing any segment of our physical design can be considered our only link to carbon emissions as most electricity in our country of experimentation is fossil-fuel generated.

To reduce our carbon footprint however far the link may be we shall utilize as fewer physical prototypes as possible so that the electricity consumption from our entire project is kept to a minimum.

3.5 Summary:

This chapter detailed the design process and ideology which form the basis for how we approached the platform. The Entire component-wise breakdown of each element of the entire project is given in detail and even a prototype was created to further gauge our progress. The platform was broken down into a platform design and an electrical design with multiple considerations for each element.

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