Investigations into a silicon-based MEMS lab on a chip.

Orion. Bruckman
University of Windsor
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Investigations Into a Silicon Based MEMS Lab on a Chip

by

Orion Bruckman

A Thesis
Submitted to the Faculty of Graduate Studies and Research through the Department of Electrical and Computer Engineering in partial fulfilment of the requirements for the Degree of Master of Applied Science at the University of Windsor

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To my parents who gave me the determination to succeed and the courage to try.
List of Abbreviations

CAD  Computer Aided Design
CMC  Canadian Microelectronics Corporation
CMOS Complementary Metal-Oxide Semiconductor
FEA  Finite Element Analysis
FEM  Finite Element Methods
HF   Hydrofluoric acid
IC   Integrated Circuit
KOH  Potassium Hydroxide
LIGA Lithographie Galvanoformung Abformung
MEMS Microelectromechanical Systems
MST  Micro Systems Technology
MUMPs Multi-User MEMS Process
PCR  Polymerase Chain Reaction
RIE  Reactive Ion Etching
SEM  Scanning Electron Microscope
I would first like to thank Dr. Jullien for supporting me in my desire to do research into the lab-on-a-chip area; Dr. Miller for helping me with theoretical problems as well as the wording for some papers; Dr. Mutus for the use of his lab, lab equipment and personnel as well as his insights into the chemical world; Dr. Zamani for his unending patience with mathematical and FEM related questions; Dr. Altenhof for his ideas and knowledge of FEM; Narinder Singh Chana for assisting me with many mechanical problems; and Dr. Watt for this assistance with gel viscosities.

Thanks are directed to other faculty members, fellow graduate students, and friends for their encouragement during this project.
Abstract

The goal of this thesis is to explore the use of Micro-Electro-Mechanical Systems for biochemical analysis. The work consists of two projects; the first deals with the fabrication and testing of MEMS a die, the second an application oriented investigation providing incremental steps towards establishing an environment for a lab-on-a-chip research group. The first project relates to the fabrication of MEMS structures, and is an investigation of a low-cost post processing lab to determine if an in-house post processing environment for standard CMOS processes using KOH etching would be beneficial and feasible. This project also links available Canadian Microelectronics Corporation (CMC) supported fabrication processes (Mitel 1.5μm CMOS) to a commercial CAD package (IntelliCAD from Intellisense Inc.) The fabrication steps associated with the CMOS technology have been added to IntelliCAD to aid in visualizing structures that can be constructed using the post-processing lab. For the second project in the thesis we have taken two specific examples; a DNA replication system and a MEMS electrophoresis technique used to separate organic material using an electric field. The DNA replication technique to be used is referred to as Polymerase Chain Reaction (PCR) which involves the construction of a reservoir which is capable of receiving DNA samples in a fluid, and applying a controlled heat source. We have also introduced and examined a novel electrostatic injection technique to introduce samples into the reservoir. The ANSYS56 package (based on finite element techniques) was used to carry out a three dimensional computational dynamic analysis necessary to estimate the actual responses of the electrostatic injection system. The electrophoresis project was carried out entirely using modelling in which all of the first order effects in the process were modelled using the MATLAB environment. The simulations model both a typical macroscopic electrophoresis along with a new microelectrophoresis technique. We have also analysed the use of non-linear electric fields for the new microelectrophoresis technique.
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Chapter 1

Introduction

1.1 Introduction

The field of Microelectromechanical systems (MEMS) is known by several names: micro-machining, micro-mechanics and, commonly in Europe, Micro Systems Technology (MST). While there is no universally agreed upon definition for MEMS/MST the devices do share the following characteristics [1]:

i) small in both overall size (few millimetres) and minimum feature size (few microns)

ii) a desire for the combination and integration of both electrical and mechanical components within the same devices, and

iii) mass production potential of devices.

Many, but not all, MEMS fabrication technologies are derived from well characterized microelectronics fabrication processes. MEMS technologies borrowed from the microelectronics industry offer the potential benefits of batch fabrication at a very low unit cost. Since MEMS typically have a relatively large feature size
microelectronics fabrication processes are often sufficient for MEMS fabrication requirements. Older microelectronics equipment is also often available inexpensively [1].

This thesis is divided into two interrelated projects; the first deals with the fabrication and testing of MEMS, the second project explores applications of MEMS providing incremental steps towards establishing a lab-on-a-chip research environment.

For the first project we explored MEMS die fabrication by performing in-house post processing of a pre-processed silicon substrate using the Mitel 1.5μm CMOS fabrication technology obtained through the Canadian Microelectronic Corporation (CMC). The first test dies were bulk micromachined to test the feasibility of an in-house post processing lab for potassium hydroxide (KOH) etching. The structural layers of the Mitel 1.5μm process were simulated in a commercial Computer Aided Design (CAD) package (IntelliCAD from IntelliSense Inc.) to aid in visualizing structures that are able to be constructed using the post-processing lab.

The second section explores two bio-chemical related applications; DNA replication and electrophoresis, a technique by which organic material is separated using electric fields. A novel electrostatic injection system was also investigated associated with the DNA replication system. As a possible first application, electrophoresis was simulated both for the macro and micro implementations. Multi potential microelectrophoresis simulations were also explored.

1.2 First Project: MEMS Fabrication and Testing

1.2.1 Post Processing Laboratory

The research described in this thesis is concerned with the development and practicalities of fabricating and testing MEMS structures for lab-on-a-chip type architectures. This represents the first "hand-on" experimentation in post-fabrication of MEMS technology at the University of Windsor. The initial fabricated structures were designed with the goal of
testing a post processing lab similar to one used by Dr. Hubbard at Dalhousie University. One of the goals of this work was to determine if an in-house post processing environment would be beneficial and feasible.

The first test die developed encompassed initial designs for channels, heaters, and a reactant reservoir. A custom post processing facility was constructed to provide a small clean room type environment for the post processing of standard CMOS processes with a KOH etching solution.

1.2.2 Mitel 1.5μm Process and IntelliSense

Mitel 1.5μm process is a well characterized double polysilicon double metal process. The total height of all the layers in the Mitel 1.5μm process is approximately 6 microns [6]. As a result of the low cost, process availability, and large feature size of the Mitel 1.5μm process, it has been the standard process for MEMS design in the Canadian community for several years. Alternate MEMS fabrication methods are also discussed. The structural aspects of the Mitel 1.5μm process has been added to the IntelliSense IntelliCAD commercial MEMS design software package, allowing the user the ability to design and visualize the Mitel 1.5μm process.

1.3 Second Project: Bio-Chemical Applications

1.3.1 DNA Replication using PCR Technology

The fabrication of the University of Windsor's first MEMS die centred around the initial experiments of a MEMS based lab-on-a-chip application. The object of the design is to reduce the size and cost, and to speed up the process of certain chemical analysis techniques [2]. Specifically the DNA replication process based on the polymerase chain reactions (PCR) is presented. In this application, MEMS components, in conjunction with a glass substrate, are commonly used in the design [3]. As the PCR process requires thermal cycling, the current popular method of sample conditioning is to move the
reactants either through or into three different reaction areas where the samples are processed accordingly.

1.3.2 Electrostatic Injection System

While the handling of samples when they are on or in a MEMS device has been reported in the literature [4][5], there has not been sufficient research into the transportation of samples from the macroscopic domain, a pipettor or syringe for example, to the microscopic domain, i.e., a MEMS die, in a non laboratory setting. This thesis offers a proof of concept for a non laboratory transportation system using electrostatic fields.

This thesis also explores the development of an electrostatic injection system for transporting samples into the inlet reservoir of the MEMS based laboratory. This transport system was fabricated on the first test die using the standard Mitel 1.5μm process to create the desired geometry. A finite element analysis (FEA) package was used to carry out the three dimensional computational dynamics necessary to estimate the actual responses of the electrostatic injection system and results are discussed.

1.3.3 Electrophoresis

Electrophoresis is a widely used technique for the separation of various chemical and biochemical materials. Electrophoresis is a simple process, a medium is prepared and the sample to be separated is injected into the medium. A potential is applied across the medium and after some time the samples will separate into discrete sections based on their electric charge. This type of technique has great potential to be implemented as a MEMS device, and electrophoresis is explored as a possible project for a MEMS application. Two simulations are presented and analysed to determine their suitability for MEMS implementation.
1.4 Thesis Objectives

The work reported in this thesis is an exploration and explanation of MEMS processing with bio-chemical applications. An overview of MEMS, and the various methods by which they are fabricated is examined. Two interrelated projects are explored for this thesis dissertation: the first, a test of the physical requirements for MEMS fabrication; the second an exploration into applications of lab-on-a-chip designs, namely DNA replication, electrostatic injection, and electrophoresis.

1.5 Thesis Organization

An introduction is provided in Chapter 1, followed by an overview of MEMS background theory, applications and classifications, and fabrication processes in Chapter 2. Chapter 3 presents a post processing laboratory built at the University of Windsor which was tested using a MEMS test die pre-processed using the Mitel 1.5μm process. Chapter 4 provides a review of the initial MEMS design and a critical review of the Mitel 1.5μm process as it relates to MEMS design and fabrication. The feasibility of using the Mitel 1.5μm process along with the use of IntelliCAD as a learning tool is examined. Alternative fabrication options are also discussed. Chapter 5 examines the application of PCR technology to a lab-on-a-chip silicon based MEMS. Chapter 6 explores the concept of electrostatic injection and a review of the theory involved with an analysis of test results. Chapter 7 provides a review of the theory and physics of electrophoresis, simulations for both typical and micro implementations are presented. Chapter 8 presents conclusions and potential future work.
2.1 Introduction

Microelectronic technology has undoubtedly changed almost every aspect of daily life, both in the professional and leisure domains. Microelectronics has been advancing at a remarkable rate, the related technology of micromachining has been developing quickly but without such widespread public attention. Advancements in micromachining have changed the way engineers and scientists think about microelectromechanical structures and sensors. The development of microelectronics has driven micromachining technology due to the desire for electronic systems to interact with the environment, the desire for distributed systems, and the cost and performance advantages of silicon processing techniques for electronics and sensors [6].

2.2 What are MEMS?

MEMS are three dimensional microstructures designed to create microsensors, see Figure 2.1 [8], and microactuators, see Figure 2.2 [9], which are based on microelectronics technology or extended from microelectronics [7].
MEMS are primarily used to gather information from or effect change in the non-electronic world. MEMS can be likened to input or output modules for microelectronics [7].

Figure 2.1 An accelerometer

Figure 2.2 Tweezers

2.3 Applications and Significance of MEMS

The benefits of MEMS technology include small device size and light weight often offering an enhancement in performance and reliability with an array of devices. As with microelectronics this is available with low unit cost with batch fabrication. MEMS will soon offer wide spread levels of high integration of MEMS structures and microelectronic circuits, MEMS add functionality with the ability to sense and actuate or control [7].
2.4 Sensors and Actuators

MEMS have a very wide variety of uses or potential uses; for instance: accelerometers and yaw rate sensors in automobiles. Health care applications include sensors such as microtemperature sensors, actuators such as micro probes, pacemaker components, and lab-on-a-chip designs. Automated manufacturing which use robotics will benefit from the miniaturization of their many sensors. Environmental monitoring and control have such sensors as chemical sniffers, micro weather-stations with pressure, humidity, and temperature sensors. Consumer products include eyeglass monitors. Aerospace may benefit greatly by the reduced size and weight for such uses as miniature propulsion engines. MEMS sensors and actuators are very light and offer a great cost saving for transportation into space [7].

2.5 Fabrication process technologies

To fabricate MEMS structures (especially those on silicon substrates) the challenge is to go from the two dimensional style of integrated circuit fabrication technology to three dimensional microstructures. This is achieved through micromachining. There are many forms of micromachining, and it is possible to combine different substrates such as silicon and glass [7].

2.5.1 Bulk micromachining

Bulk micromachining is the process of removing the substrate to form a MEMS structure, and bulk micromachining is often used to remove large amounts of substrate. Bulk micromachining is used to machine cantilever beams, suspended beams, and pits. Diaphragms can be machined by using a backside etch. For anodic bonding onto a glass substrate, the silicon substrate can be completely removed. Since the substrate is etched away the substrate is considered a sacrificial layer in bulk micromachining. See Figure 2.3 [7].
2.5.2 Surface micromachining

Surface micromachining typically does not attack the substrate. When employing surface machining the structural layers and sacrificial layers are built on top of the substrate identical to that of standard microelectronic fabrication. When the layers are built the die is exposed to an etch that will attack one or more of the layers, known as the sacrificial layer. When the sacrificial layer has been etched away the desired structure remains. Hence the structure is built up upon the substrate. See the example in Figure 2.4 [7].

A mix of bulk and surface micromachining can produce superior MEMS devices. The combination of bulk and surface micromachining can produce very precise and small air gap distances [7]. With the very accurately controlled air gap distances the style and reliability of MEMS that can be manufactured is increased.
Stiction

A common problem with fabricating MEMS devices is stiction. Stiction occurs when a MEMS structure is released; i.e., the sacrificial layer is etched away. If the MEMS design requires that the resulting structure have a top layer that is suspended above the substrate, or a lower structural layer, then stiction can occur as follows. When the MEMS structure is released and the die is rinsed and taken out to dry, the top layer of a structure can be pulled down to a lower level of the structure as a result of the surface tension of the drying solvent. This process of using "pull-in forces" is referred to as stiction. Stiction is larger for structures with concave angles. Stiction is a function of air gap, area, contact angle, surface conditions and structure rigidity. To avoid stiction one can manipulate the parameters that dictate stiction such as changing the contact angles, another option that is gaining in popularity is the use of super critical point drying. When using super critical point drying, the liquid used for etching, for example CO2, is forced into its gas phase directly from the liquid. For CO2, as an example, the release pressure must be at 72.8 atmospheres while the temperature is at 31 degree Celsius.

2.5.3 Concentration Dependent Etching

High levels of boron in silicon will reduce the rate at which it is etched in KOH, and many other etchants, by several orders of magnitude, effectively stopping the etching of the boron rich silicon [10]. The boron impurities are usually introduced into the silicon by diffusion. A thick oxide mask is formed over the silicon wafer and patterned to expose the surface of the silicon wafer where the boron is to be introduced, see Figure 2.5a. The wafer is then placed in a furnace with a boron diffusion source. Over a period of time, boron atoms migrate into the silicon wafer. Once the boron diffusion is complete, the oxide mask is stripped off, as shown in Figure 2.5b.

A second mask may then be deposited and patterned, see Figure 2.5c, before the wafer is immersed in the KOH etch bath. The KOH etches the silicon that is not protected by the mask, and etches around the boron doped silicon, Figure 2.5d [11].
Boron can be driven into the silicon as far as 20 micrometers over periods of 15 to 20 hours; however, it is desirable to keep the time in the furnace as short as possible. With complex designs, etching the wafer from the front in KOH may cause problems where slow etching crystal planes prevent it from etching beneath the boron doped silicon. In such cases the wafer can be etched from the back, however this is not without the disadvantages of longer etching times and more expensive wafers. The high concentration of boron required means that microelectronic circuitry cannot be fabricated directly on the boron doped structure.

There are two major classes of etchants: isotropic and anisotropic etchants.

**Isotropic etchants**

Isotropic etchants dissolve away in all directions at the same time. Common solutions include HNA: which is a mixture of HF, HNO₃, and acetic acid (CH₃COOH). With all
sides of a sacrificial layer being attacked at the same time the sacrificial layer mask will be undercut. Undercutting occurs when the layer under the mask is dissolved away leaving part of the mask suspended above the dissolved layer. Agitation can greatly affect etching results. Without agitation there is poor reactant mass transport which leads to shallower pits with larger undercutting. With agitation there is good reactant mass transport. this results in deeper pits with less undercutting. See Figure 2.6 [7].

**Figure 2.6 Isotropic etching**

![Isotropic etching diagram](image)

- **SiO₂ Mask**
- **With agitation:**
  - Good reactant mass transport
- **Without agitation**

**Anisotropic etching**

Anisotropic etching occurs when the etchant attacks one crystal plane faster than another. Since the etchants attack different crystal planes at different rates the mask geometry becomes more important. Manhattan geometry should be used to obtain a structure with features similar to the mask. Circular or angled features not aligned with the crystal plane will be distorted during etching. Anisotropic etching is most commonly seen in silicon bulk micromachining. Most microelectronics, and a majority of MEMS, are built on a <100> orientated silicon substrate. When silicon with this crystal orientation is etched
with an anisotropic wet etchant, the sidewalls of any pits will grow out with an angle of 54.74 degrees. If the substrate was aligned to the \(<110>\) crystal plane, near vertical side walls are possible [7]; see Figure 2.7 [10].

**Figure 2.7 Anisotropic etching**

![Diagram of anisotropic etching](image)

It is important to note that corners that are etched anisotropically will not maintain their shape, if a MEMS structure requires cleanly etched corners the top mask will require corner compensation [12][13][14][15]. To understand what affects anisotropic etching and mask geometry have, an understanding of corners is necessary. There are two types of corners: convex and concave. For the purposes of this discussion concave can be defined as corners having angles less than 180 degrees, see Figure 2.8. These are usually interior angles and do not have undercutting. With silicon substrate that is anisotropically etched the side walls of a concave corner will grow out with an angle of 57.74 degrees. Convex corners have an angle greater than 180 degrees, see Figure 2.8 [7]. These are the corners that are undercut. To have sharp squared corners after post processing it is important to use corner compensation. Much research has gone into this topic, the general solution being to add onto the corner extra material to be etched away leaving only the desired corner.
There are other micromachining processes, the most common ones are briefly discussed below.

### 2.5.4 Dissolved Wafer Process

In this process a structure is created using heavily boron diffused silicon. After the silicon is doped the die is bulk micromachined until all the substrate is dissolved away leaving only the structure, see Figure 2.9 [10]. This process is often used with anodic bonding [7].
2.5.5 Deep Reactive Ion Etching

With this etching technique is it possible to create deep vertical side walls without the need for any corner compensation or wafer alignment, see Figure 2.10 [7]. The most common form of dry etching for micromachining applications is reactive ion etching (RIE). Ions are accelerated towards the material to be etched, and the etching reaction is enhanced in the direction of travel of the ions, see Figure 2.11 [10]. RIE is an anisotropic etching technique. Deep trenches and pits (up to ten or a few tens of microns) of arbitrary shape and with vertical walls can be etched in a variety of materials including silicon, oxide and nitride. Unlike anisotropic wet etching, RIE is not limited by the crystal planes in the silicon [11].
2.5.6 Glass-Silicon and Silicon-Silicon Anodic Bonding

Glass-silicon anodic bonding and silicon-silicon anodic bonding have been gaining in popularity recently. This process involves patterning structures on a silicon die. The die is post processed, often using the dissolved wafer process, then the die is inverted and placed on either a glass substrate, a popular glass to use is 7740 glass because it has a thermal expansion close to silicon, or another silicon substrate. Pressure is applied to both substrates and a voltage or temperature is applied resulting in the silicon glass interface bonding forming a seal, see Figure 2.12 [7]. This process is often used to create a sealed environment for closed cavities. For silicon-silicon bonding the temperature needed to anneal is 800-1000°C. At this temperature any metal on the dies will melt; this is a serious disadvantage. Silicon-silicon bonding has the advantage of no thermal mismatch. Both processes need to have a very flat wafer with surface roughness at approximately 5 Angstroms [7].
2.5.7 LIGA

Lithographie Galvanoformung Abformung is the German name for this process. LIGA uses a combination of lithography, electroplating, and molding processes to produce very finely defined microstructures that are up to 1000 microns high. For LIGA a special kind of photolithography that uses X-rays is used to produce patterns in very thick layers of photoresist. The X-rays from a synchrotron source are directed through a special mask, see Figure 2.13 [11], onto a thick photoresist layer that is sensitive to X-rays. This thick photoresist layer covers a conductive substrate. After the resist is developed the pattern formed is electroplated with a metal. The metal structure can be the final product, however it is common to use the metal structures as a mold. The mold can be filled with plastic or another suitable material to produce the final structure [11]. See Figure 2.14 [37].

![Figure 2.13 LIGA Process](image)

![Figure 2.14 Example of a Microstructure made from LIGA](image)
2.6 Summary

Whether microelectromechanical systems will impact the world to the same extent as microelectronics can not yet be known. Building from the knowledge gained in the microelectronic industry MEMS has many benefits and considering its early stage of development, the use of MEMS in commercial applications will undoubtedly increase. The primary function of MEMS is to interface with the “real” world, often as inputs or outputs to electronic systems.

Fabricating MEMS is one of the major challenges today. While MEMS fabrication is primarily an extension of microelectronics, the deposition and patterning of layers, along with the formation and release of the MEMS structures has been very challenging. Most of the difficulties arise as a result of micromachining. The two basic forms of micromachining are surface micromachining and bulk micromachining. There are other more specialized forms of micromachining: concentration dependent etching, dissolved wafer process, deep reactive ion etching, glass-silicon anodic bonding, silicon-silicon anodic bonding, and LIGA.
3.1 Introduction

The fabrication of MEMS poses many challenges. The University of Windsor does not have integrated circuitry (IC) fabrication equipment, as IC fabrication is supported, and funded, by the Canadian Microelectronics Corporation (CMC). As CMC did not previously support any post processing for MEMS dies, the challenge of producing MEMS devices was left to individual universities. Following the example of Dr. Ted Hubbard from Dalhousie University it has been decided to explore the feasibility of creating and maintaining, at the University of Windsor, an in house post processing lab for potassium hydrate (KOH) etching. In the current research the goal was to determine the effectiveness of the post processing lab for lab-on-a-chip type applications. An initial test chip was designed, using Cadence Virtuoso, using the Mitel 1.5\(\mu\)m process.

3.2 Initial Test Chip

For the first test chip, two input channels were constructed to experiment with the possible sizes of any channels or chambers that can be formed by post processing operations on the Mitel 1.5\(\mu\)m
process. The two test channels are approximately 700\(\mu\)m long by 300\(\mu\)m wide and 125\(\mu\)m long by 250\(\mu\)m wide respectively, and were formed using bulk micromachining etching, see Figure 3.1 and Figure 3.2. These structures were designed to explore the possibility of DNA replication and electrostatic injection. Please see Chapter 5 for more details on the PCR Replication process and Chapter 6 for electrostatic injection. The experimental efforts to carry out bulk post processing were not as effective as required since it is not possible to control the etching mechanism with the necessary precision in our simplified machining environment. Please see Section 4.2. for results of the post process of the initial test die. Alternative fabrication methods have been investigated, with the intent to use a third party supplier to do a more precise implementation of bulk or surface micromachining. The most suitable third party supplier at this time is MUMPs, the Multi-User MEMS Processes, which is a well-established, commercial program that provides cost-effective access to surface micromachining for prototyping MEMS.

Figure 3.1 Cadence pictures of first test chip
Figure 3.2 Photo micrograph of the first test chip before etching

3.3 Post Processing Environment

This project is a collaboration between the Electrical and Computer Engineering Department and the Chemistry and Biochemistry Department, both at the University of Windsor. At the time this project was initiated CMC did not support any post processing for its member universities. It was decided that the best avenue into the MEMS community in Canada was to reproduce a post processing environment that other Canadian researchers had constructed. One of the main MEMS researchers in Canada is Dr. Ted Hubbard, of Dalhousie University. Contact was made with Dr. Hubbard and after some consultation with him and James Wylde, one of Dr. Hubbard’s graduate students, a decision was made to have a “clean box” constructed.

The clean box is a post processing environment for bulk micromachining using wet chemical etchants. The clean box at the University of Windsor is an exact replication of the Dalhousie University clean box. The clean box was constructed with one quarter inch thick plexi-glass, the container is 2ft (60cm) deep by 2.5ft (75cm) wide by 2ft (60cm) tall. In the back of the clean box a Bionaire LP-1500 air filter is attached. The Bionaire
LP-1500 air filter is capable of filtering particles in the submicron range. The air filter was inserted into the clean box in such a way as to take in outside air, filter it and push it into the clean box. The continuous injection of clean air into the clean box creates a positive air pressure inside the box, with respect to the room containing the clean box, while the clean box is closed. This positive air pressure helps maintain a contaminant free environment for storing and post processing of MEMS dies. Figure 3.3 is an image of the Dalhousie clean box.

Figure 3.3 Clean Box from Dalhousie University

To perform any wet bulk micromachining post processing in the clean box a die holder had to be constructed. The design for the die holder was also obtained from Dr. Hubbard's work. The die holder was constructed of plastic and can hold two dies. The actual die holders are camera film canisters cut down to approximately one quarter of an inch (5mm) in height, see Figure 3.4, Figure 3.5, and Figure 3.6.
Figure 3.4 Custom Make Die Holder

Figure 3.5 Die Holder Close up with cut camera film case
3.4 Post Processing Etching

There are many well known wet etchants that can be used for wet bulk micromachining. For safety reasons potassium hydroxide (KOH) was used in the post processing lab. KOH is an alkali hydroxide etchant. The hydroxides of alkali metals such as KOH, NaOH, and CsOH can be used as crystal orientation dependent etchants for silicon. While the exact chemistry is under some debate it appears that the reaction sequence is as follows.

Silicon atoms at the surface react with the hydroxyl ions. The silicon is oxidized, and four electrons are injected from each atom into the conduction band

$$\text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{2+} + 4\text{e}^-$$

Simultaneously, water is reduced leading to the evolution of hydrogen

$$4\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- + 2\text{H}_2$$

The complexed silicon, $\text{Si(OH)}_2^{2+}$, further reacts with hydroxyl ions to form a soluble silicon complex and water
\[
\text{Si(OH)}_2^{2-} + 4\text{OH}^- \rightarrow \text{SiO}_2(\text{OH})_2^{2-} + 2\text{H}_2\text{O}
\]

Thus, the overall reaction is

\[
\text{Si} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2(\text{OH})_2^{2-} + 2\text{H}_2 \text{[10]}
\]

### 3.5 Summary

Results from the initial tests done for the in house post processing lab showed that maintaining a post processing lab at the University of Windsor is not an efficient means to post process MEMS, see Section 4.2. While certain devices could be successfully post processed, the mechanisms that controls the etching process could not be controlled to a suitable degree in order to produce a full range of MEMS devices. The determination of etch rates for the post processing lab would be prohibitively slow as the scanning electron microscope (SEM) is an inefficient means of determining the etch rates. The University would benefit greatly in the testing of MEMS with the addition of a camera for the department’s microscope to allow for better documentation and testing of fabricated MEMS dies. Since CMC now supports a third party machiner the effort and cost necessary to maintain the post processing facility would not be an efficient use of resources.

Therefore it is evident that the post processing of the initial test dies revealed that a simple in-house post processing lab is not the best choice for the fabrication of lab-on-a-chip MEMS designs at this time. Alternative fabrication methods have been investigated, with the intent to use a third party supplier to do a more precise implementation of bulk or surface micromachining. MUMPs, the Multi-User MEMS Processes, is a commercial surface micromachiner for prototyping MEMS. MUMPs, is designed for general purpose micromachining by various users who wish to design and fabricate MEMS devices [17]. The MUMPs process is supported through CMC, thereby allowing universities to have their designs fabricated without the significant costs normally associated with chip fabrication. See Chapter 4 for further details on the MUMPs process.
Chapter 4

Mitel 1.5 Micron 
Process and 
IntelliSuite CAD

4.1 Introduction

The Mitel 1.5μm process is a mature and well characterized double polysilicon double metal process. While the exact details of the process are confidential, the total height of all the layers in the Mitel 1.5μm process is approximately 6 microns [6]. As a result of the low cost, process availability, and large feature size, this Mitel process has represented the standard for MEMS design in the Canadian community. An attractive feature of the Mitel 1.5μm process is the double polysilicon, double metal layers both of which are standard structural layers. See Table 4.1 for the relative heights of the different structural and sacrificial layer in the Mitel 1.5μm process.

<table>
<thead>
<tr>
<th>Layer number (structural only)</th>
<th>Layer material</th>
<th>Height (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Silicon</td>
<td>5000</td>
</tr>
<tr>
<td>1</td>
<td>Silicon Dioxide</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Polycrystalline Silicon</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Silicon Dioxide</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>Polycrystalline Silicon</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>Silicon Dioxide</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>Aluminum Metal</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Table 4.1 Layers of the Mitel 1.5μm Process

<table>
<thead>
<tr>
<th>Layer number (structural only)</th>
<th>Layer material</th>
<th>Height (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Silicon Dioxides</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>Aluminum Metal</td>
<td>0.8</td>
</tr>
<tr>
<td>9</td>
<td>Silicon Dioxide</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>Silicon Nitride</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.2 An Initial Design

The initial design for the MEMS Mitel process was a multi project test die. On this first MEMS die fabricated for the University of Windsor, there are two inlet designs for an experimental electrostatic injection system as well as a large reservoir. Also on the die are two channels and a cantilever beam structure. One of the main design objectives for this test die was to test the effectiveness of the in house post processing laboratory. The laboratory was built to test bulk micromachining of pre-processed dies. The etchant used was KOH. See Chapter 3 for more details on the post processing laboratory, and KOH etching.

The test results of post processing revealed that the post processing lab is not the most effective means of machining MEMS. It was evident that the test dies were being bulk micromachined although the process was determined to be unreliable. A more reliable option is the use of the CMC supported third party machiner identified in Chapter 3. When considering the newly available post processing ready manufacture the effort and cost necessary to maintain an up-to-date post processing facility is not a cost effective option at the University of Windsor. Also the Canadian Microelectronics Corporation (CMC) has decided to discontinue scheduled fabrication runs of the Mitel 1.5μm process [35]. See “Summary” on page 35 for further details.

The entire test die can be seen in Figure 4.1. Figure 4.2 is an SEM close up of the bottom right of the test die. Figure 4.3 shows the same area after being etched in a stirred 30% KOH solution at 70°C for 10 minutes. After this die was photographed, using the SEM, it
was etched in the same solution for another 10 minutes. the same area can be viewed in Figure 4.4. The formation of the sidewall profiles can be seen in these pictures. Figure 4.5, Figure 4.6. Figure 4.7 are close ups of the top right of the previous section of the test die. The figures are SEMs of the die unetched, etched 10 minutes, and 20 minutes respectively. In these close-ups the sidewall profile can clearly be seen. As well, the surface roughness can also be seen. Surface ruffians is the measure of how smooth the surface of a die is after being etched.

Figure 4.1 Test Die
Figure 4.2 Close Up Bottom Right of Test Die

Figure 4.3 Bottom Right After Etching Once
Figure 4.4 Top Right after Two Etching Runs

Figure 4.5 Close Up of Top Right, Not Etched
4.3 Cronus CMC MEMS Supplier

One of the third party suppliers is Cronus' MUMPs which is supported by CMC. CMC also supports the surface micromachining offered by Cronus' MUMPs. All runs organized through CMC include supercritical carbon dioxide dry release. CMC plans to schedule its
service approximately every other MUMPs run [18]. What follows is a summary of the MUMPs process from the MUMPs web page, it details the process and the post-processing supported by CMC.

The Multi-User MEMS Processes, or MUMPs, is a well-established, commercial program that provides customers with cost-effective access to surface micromachining for prototyping activities and a seamless transition into manufacturing. MUMPs is designed for general purpose micromachining by various users who wish to design and fabricate MEMS devices. MUMPs is a three-layer polysilicon surface micromachining process. The design rules for the process are flexible, allowing for many types of users and design ideas. The process consists of a non-patternable nitride isolation layer, a polysilicon ground plane layer, two structural polysilicon layers, two oxide release layers, and one metal layer for electrical connection and reflectivity enhancement. Polysilicon is used as the structural material, deposited oxide (PSG) as the sacrificial material, and silicon nitride for electrical isolation from the substrate. Standard cost is $3900 ($2900 for North American universities) per 1cm x 1cm die location with 15 chips delivered, prices and process information valid as of January 2001 [17]. MUMPs offers two post processing options, the first is to release the MEMS structure with hydrofluoric acid (HF) which is a wet isotropic etchant, see Chapter 2 “Isotropic etchants” on page 11 for more details. The second post processing option is to use supercritical CO₂ drying with the HF release to reduce the occurrence of stiction. See Chapter 2 “Stiction” on page 10 for further details on stiction and supercritical CO₂ point drying.

4.4 IntelliSuite

Since the MITEL 1.5µm process is well characterized and its structural and sacrificial layers are known, it is appropriate to import the process parameters as a technology file to be used with a MEMS simulation software package. An available software package is IntelliCAD from the IntelliSense Corporation. IntelliCAD is a finite element analysis package developed for MEMS design, it also has the ability to recreate technology files for MEMS processes other than the IntelliSense proprietary process. Using this feature the
structural and sacrificial layers of the Mitel 1.5μm process have been incorporated into a technology file for the package. The complete Mitel 1.5μm technology could not be captured because of the proprietary nature of the process [19]. However, sufficient public information about the process is available to allow an IntelliCAD simulation of the structural aspects of the fabrication process. The important elements of the structural information of the Mitel 1.5μm process are available in Table 4.2, and a combdrive test structure, shown in Figure 4.8, and Figure 4.9, is used to demonstrate the ability of the CAD package to create the structural layers.

Figure 4.8 A combdrive structure created in the Mitel 1.5 μm process

![Combdrive Structure](image1)

Figure 4.9 Close-up of combdrive showing layers of process

![Combdrive Close-up](image2)

As it stands at the moment, the CAD tool can be used as an aid in visualizing structures that are possible to design using the Mitel 1.5μm technology. Because of the lack of information about the process it is not possible to provide any quantitative structural
analysis about a Mitel design such as residual stress and strain of the process layers. If a complete set of data for the process is going to be imported into IntelliCAD it should also include the effects of any post processing on the layers of the process, not only the sacrificial and structural layers but also any effect the etchant may have on any area of the design that is to remain unchanged. If this area is going to be exposed at any point during the fabrication process the designer must know what will occur and what tolerances the design has for the variances within the process. If a good set of experimental etching data

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Layer/step name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Definition Si Czochralski 100 500 μm</td>
<td>Silicon substrate</td>
</tr>
<tr>
<td>2</td>
<td>Deposition SiO₂ 1 μm</td>
<td>Thermal Silicon Dioxide layer</td>
</tr>
<tr>
<td>3</td>
<td>Definition UV Contact Suss</td>
<td>Active Mask</td>
</tr>
<tr>
<td>4</td>
<td>Etch SiO₂ Wet BOE 1 μm</td>
<td>Active Etch</td>
</tr>
<tr>
<td>5</td>
<td>Deposition PolySi LPCVD SiH₄ 0.3 μm</td>
<td>First Polysilicon layer</td>
</tr>
<tr>
<td>6</td>
<td>Definition UV Contact Suss</td>
<td>Polysilicon Mask</td>
</tr>
<tr>
<td>7</td>
<td>Etch PolySi Dry SF₆-Plasma 0.3 μm</td>
<td>Polysilicon Etch</td>
</tr>
<tr>
<td>8</td>
<td>Deposition SiO₂ SECVD Ar 0.05 μm</td>
<td>Inter Polysilicon Insulation Layer</td>
</tr>
<tr>
<td>9</td>
<td>Definition UV Contact Suss</td>
<td>Inter Polysilicon Mask</td>
</tr>
<tr>
<td>10</td>
<td>Etch SiO₂ Wet BOE 0.05 μm</td>
<td>Inter Polysilicon Etch</td>
</tr>
<tr>
<td>11</td>
<td>Deposition PolySi LPCVD SiH₄ 0.3 μm</td>
<td>Second Polysilicon Layer</td>
</tr>
<tr>
<td>12</td>
<td>Definition UV Contact Suss</td>
<td>Polysilicon Mask</td>
</tr>
<tr>
<td>13</td>
<td>Etch PolySi Dry SF₆-Plasma 0.3 μm</td>
<td>Polysilicon Etch</td>
</tr>
<tr>
<td>14</td>
<td>Deposition SiO₂ PECVD Ar 0.8 μm</td>
<td>Inter Metal-Polysilicon Glass Layer</td>
</tr>
<tr>
<td>15</td>
<td>Definition UV Contact Suss</td>
<td>Inter Metal-Polysilicon Mask</td>
</tr>
<tr>
<td>16</td>
<td>Etch SiO₂ Wet BOE 0.8 μm</td>
<td>Contact Etch (Metal-Polysilicon)</td>
</tr>
<tr>
<td>17</td>
<td>Deposition Al Sputter Ar-Ambient 0.8 μm</td>
<td>First Aluminum Layer</td>
</tr>
</tbody>
</table>
Table 4.2 Structural aspects of the Mitel 1.5μm process in IntelliCAD

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Layer/step name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Definition UV Contact Suss</td>
<td>Aluminum Mask</td>
</tr>
<tr>
<td>18</td>
<td>Etch Al Wet PAN 0.8μm</td>
<td>Aluminum Etch</td>
</tr>
<tr>
<td>19</td>
<td>Deposition SiO₂ PECVD Ar 0.8μm</td>
<td>PSG Glass Layer</td>
</tr>
<tr>
<td>20</td>
<td>Definition UV Contact Suss</td>
<td>VIA (Inter Metal) Mask</td>
</tr>
<tr>
<td>21</td>
<td>Etch SiO₂ Wet BOE 0.8μm</td>
<td>VIA Etch</td>
</tr>
<tr>
<td>22</td>
<td>Deposition Al Sputter Ar-Ambient 0.8μm</td>
<td>Second Aluminum Layer</td>
</tr>
<tr>
<td>23</td>
<td>Definition UV Contact Suss</td>
<td>Aluminum Mask</td>
</tr>
<tr>
<td>24</td>
<td>Etch Al Wet PAN 0.8μm</td>
<td>Aluminum Etch</td>
</tr>
<tr>
<td>25</td>
<td>Deposition SiO₂ PECVD Ar 0.5μm</td>
<td>Passivation (Thick Top Glass) Layer</td>
</tr>
<tr>
<td>26</td>
<td>Definition UV Contact Suss</td>
<td>Passivation Mask</td>
</tr>
<tr>
<td>27</td>
<td>Etch SiO₂ Wet BOE 0.5μm</td>
<td>Passivation Etch</td>
</tr>
<tr>
<td>28</td>
<td>Deposition Si₃N₄ Ar 0.5μm</td>
<td>Top Glass Layer</td>
</tr>
<tr>
<td>29</td>
<td>Definition UV Contact Suss</td>
<td>Top Glass Mask</td>
</tr>
<tr>
<td>30</td>
<td>Etch Si₃N₄ Wet Sacrifice 0.5μm</td>
<td>Glass Etch</td>
</tr>
<tr>
<td>31</td>
<td>Etch Si Wet KOH User defined amount</td>
<td>Post Process Etch</td>
</tr>
</tbody>
</table>

could have been obtained the etch rates of KOH for the University's post processing lab could have been calculated and incorporated into the IntelliCAD simulation. This would give designers a better understanding as to the etching time required to achieve the desired geometry with the custom post-processing lab.

4.5 Summary

Using the Mitel 1.5μm process to design MEMS for an in house post processing environment has proved to be inefficient for the types of structures required for lab-on-a-chip designs. Since this project was started, a commercial MEMS process (MUMPS by Cronus) has become available to the Canadian university community through CMC, and our recommendation is that MUMPs be explored as the fabrication process for future
MEMS structures. This recommendation also follows the recent decision by CMC to no longer offer scheduled runs of the Mitel 1.5μm process [35].

The initial IntelliCAD technology file developed for the Mitel 1.5μm process can be very beneficial as a teaching aid for students learning about the design of MEMS structures using post processing of a standard CMOS process, where the student can simulate and visualize the design process, without needing to perform a quantitative structural analysis.
5.1 Introduction

A MEMS based design to replace conventional laboratory instrumentation for DNA replication applications is considered for this work. This chapter investigates the initial designs of MEMS elements on a silicon substrate for a MEMS based realization of a micro-reaction chamber for DNA replication applications based on the polymerase chain reactions (PCR) technology, also the feasibility of the entire PCR process for a MEMS implementation is considered. PCR is a simple technique that requires thermal cycling.

5.2 PCR Process

A MEMS design of a PCR amplifier offers many potential benefits including reduced cost, size, and a reduction in replication time. Polymerase chain reaction technology is a powerful and simple technique for DNA replicating and/or amplification [16]. The PCR reaction can be performed using very small amounts of DNA. The PCR process was developed in the mid 1980’s, wherein a strand of DNA is injected into a chamber, and heated in the presence of primers (initial starting DNA sequence) to 95°C. This heating
operation will denature the target DNA, the result of which is to uncoil and separate the DNA into two complementary single-strand DNA bits. The sample is then cooled to 37°C so as to encourage the primers to anneal to their complementary sequences on the single-stranded templates. Finally the sample is heated to a temperature of 72°C, the optimum temperature for the heat-stable Taq polymerase to synthesize. Starting from the primer, the second DNA strand, which is complementary to the original template, will continue synthesizing the rest of the DNA structure [16]. Figure 5.1 shows the duplication of one strand of DNA during one cycle.

![Figure 5.1 One cycle of the PCR replication process](image)

When heated the DNA strand separates. During cooling the primers anneal to the DNA ends

Re-heating the sample will cause the Taq polymerase to synthesize a second strand, thereby replicating the DNA

### 5.3 Silicon Substrate PCR

It is proposed that the PCR replicator elements are to be placed on a silicon substrate rather than a traditional glass substrate. Using a silicon substrate leaves the possibility for
CMOS circuit integration. Any glass substrate designs that hope to use circuitry for control elements will have to bond a CMOS die to a glass die. The proposed design is to have one reaction area that is both a chamber and a passageway. With this type of reaction area the sample only needs to be moved twice, once into the area and once out of the area. Designs that need to move the samples through different reaction regions require more room than a single reaction chamber design would need. It is desired to minimize the area utilized by this single reaction chamber. With a reaction chamber that is approximately 10μm wide and 20μm long and 10μm deep in place one should be able to obtain approximately 10^8 molecules of DNA in the reaction chamber.

There is a practical desire to move chemical analysis from the laboratory to the point-of-care in order to speed up the availability of clinical test results [3]. For this reason using a silicon substrate is preferred for modular designs. Replicating small amounts of DNA is of little use if the DNA is not going to be used in another part of the same die or chip, however by making PCR modular its usability is greatly enhanced. Designs with many reaction areas require more room and this makes them less desirable than a single chamber design for modular implementations.

Heater elements are needed to perform PCR in a MEMS environment. Ideally a PCR amplifier’s reaction chamber would have on-chip heating elements. Unfortunately on-chip heating elements are not feasible with the standard Mitel 1.5μm process, which is the process used for the first test die. There is no mechanism to implant any heater elements deep into the substrate or form heater elements into the sidewalls of a reaction chamber. However for an intermediate design using only standard microelectronics fabrication techniques, it may be possible to use heating elements and control circuitry from standard CMOS processes that are fixed above the reaction chamber. Thus, the heating elements and control circuitry will be on a top chip which would have the added advantage of covering the channels and chamber of the MEMS chip.

The heating elements are typical resistive polysilicon microelectronic resistors. Adjacent to the heater resistors are temperature sensitive polysilicon resistors. The chamber can be
heated by passing current through the heating resistors. The heat sensors can be used to generate a feedback signal to the temperature control circuitry. This circuitry will control the temperature of the reaction chamber for the duration of the reaction cycling period.

5.4 Initial Test Chip

For the test chip, two input channels were constructed to experiment with the possible sizes of any channels or chambers that can be formed by post processing operations on the Mitel 1.5μm process. The two test channels are approximately 700μm long by 300μm wide and 125μm long by 250μm wide respectively, and were formed using bulk micromachining etching, see Figure 5.2 and Figure 5.3. The results from the bulk post processing experiments can be seen in Chapter 4. Please see Chapter 3 for further details on the in house post processing lab.

Figure 5.2 Cadence pictures of first test chip
5.5 Summary

PCR replication on a silicon substrate is a feasible process. Many more tests and simulations would be necessary to efficiently determine and control the heat across the entire reaction chamber. To fabricate a MEMS based DNA PCR replicator many design iterations of the MEMS structures would be needed, requiring simulation, fabrication and testing. To fabricate such a MEMS design would require a specialized MEMS post processor capable of aligning and affixing the second die, with the control circuitry and heating elements atop the MEMS die. As the runs for the Mitel 1.5μm process are no longer regularly scheduled the Mitel 1.5μm process is not recommended for this project. It is recommended that this project be continued with a more comprehensive MEMS technology, such as MUMPS.
Chapter 6
Electrostatic Injection System

6.1 Introduction

There are several reported studies of the application of MEMS structures for DNA analysis [2][3][20]. One aspect of this process that does not appear to have been addressed adequately is the means by which a sample can be moved from the external macroscopic domain (a pipette) into the microscopic domain (a MEMS die) in a non-laboratory setting. Electrostatic injection has been investigated as a sample handling technique [22]. For electrostatic injection to work a temporary charge is induced on the samples to be moved. The charged samples are then injected from a pipettor into an electrostatic field that is designed to exert a force on the samples so as to transport them between the macro-sampler (syringe or pipette) and the inlet into a MEMS reaction chamber. In this chapter we describe the analysis, simulation, and experiments used to determine the feasibility of using electrostatic injection in the macroscopic to microscopic domain transfer.

6.2 Electrostatic Injection

The concept behind electrostatic injection arises from a consideration of coulomb forces, eqn. (6.1), where $F$ represents
force, $k$ a proportionality constant, $Q_1$ and $Q_2$ are positive or negative quantities of charge, and $R$ is the distance between the two charges [34].

$$F = k\frac{Q_1Q_2}{R^2} \quad (6.1)$$

The proportionality constant $k$ is $\frac{1}{4\pi\varepsilon_0}$, where $\varepsilon_0$ is the permittivity of free space its quantity being: $\varepsilon_0 = 8.854\times10^{-12} \equiv \frac{1}{36\pi} \times 10^{-9}$. The electric field intensity is given by eqn. (6.2):

$$E = \frac{Q_1}{4\pi\varepsilon_0 R^2} \quad (6.2)$$

where $R$ is the distance between $Q_1$ and an arbitrary test charge where the field is being measured [34]. If eqn. (6.2) is substituted into eqn. (6.1) we obtain

$$F = EQ_2 \quad (6.3)$$

Where $Q_2$ is the test charge or for electrostatic injection the charge of the sample. As can be seen from eqn. (6.3) a test charge in the electrostatic field $E$ will experience a force and be displaced as a result of this electric field. Eqn. (6.1) to eqn. (6.3) use point charges; for a practical application of electrostatic injection we will need a more realistic charge model. To model the physical layout of the first test die, the electric field is created between a charged wire and a charged ring. This electrode arrangement is too complex for an analytical analysis therefore a finite element analysis package, ANSYS56, will be used to simulate the forces involved and model the displacement of a sample while it is within the electrostatic field.
The electrostatic injection system on the initial test die had two test structures, both ring structures of polysilicon. One ring consists of a single polysilicon layer that has a break in it to aid in the post processing. This break will encourage undercutting of the ring structure allowing the sample to flow from the inlet into the reservoir. The other ring structure uses two concentric layers of polysilicon. In Figure 6.1, the single ring structure is on the left while the double ring is on the right. The test die was designed using the standard Mitel 1.5μm process. Rings were used for this first design because a ring structure will help to collect the samples and guide them into the reservoir. As a drop falls it is attracted to the ring. With the Mitel 1.5μm process, the polysilicon rings are below the top silicon nitride layer on the die, therefore when a drop lands on or near the ring it will tend to fall into the centre of the reservoir.

**Figure 6.1 Close up of Electrostatic ring structures in Cadence’s Virtuoso**

Often the samples of concern will have a charge, a dipole, a temporary dipole, or will be chargeable. Furthermore, many of those samples can also be dissolved into water which is chargeable and has a temporary dipole [21]. Thus it may be possible [22] to drop small quantities of the desired sample onto a MEMS die using an electric field to guide the sample as it falls.
6.3 Theory

6.3.1 Electrostatic Injection Theory

Concepts from Millikan's oil drop experiment [23], and electrostatic precipitator design [24] have been used in the proposed electrostatic injection system. In Millikan's experiment, very small drops of oil were charged and then placed in an electric field. The field was manipulated until the oil drops were suspended in the air. Similarly, electrostatic precipitators use nonuniform electric fields to attract particles in the air from one electrode to another, thereby removing them from the air stream. In the proposed injection system arrangement the electrostatic field is intended to guide a drop of liquid, water or blood, into a small inlet on a MEMS die. In the application under consideration, the distances are in the millimetre to centimetre range. The horizontal distance over which the drops must be moved is up to one centimetre. A system using electrostatic injection would ideally have a mechanical guide to direct the macro sample handler to the approximate location over the inlet. As a result of this pre-alignment it is possible to use far less voltage than is typically found in electrostatic precipitators [25].

6.3.2 Pipettor

In the test setup a pipettor was used as the macro sample handler. The pipettor used had a range of 0.5 microlitres to 20 microlitres. The tip of the pipettor was 0.5 mm in diameter. As a result of this output orifice, when the sample was ejected from the pipettor, before it dropped from the tip, it collected as a drop on the side of the tip due to surface tension effects. The side on which the sample gathered and fell from was a random phenomenon. As a consequence of this, the results have some statistical variance.
6.3.3 Mathematical interpretation

Description

Based on the physical setup of the test to be carried out, the charging wire is placed at a general point \( P(x_1, y_1, z_1) \). The origin of the fixed frame of reference is at the centre of the charged ring and the water drop is defined by the three points (a,c,b), see Figure 6.2.

![Figure 6.2 Mathematical model of electrode placement](image)

Objective

The objective of this section is to obtain a mathematical expression for the drift velocity, which is the horizontal velocity of the water drop. Gravitational effects are not considered.

System Model

The mathematical derivation makes certain assumptions:

1. The charging wire appears as a point charge once the water drop has left the pipettor. Since the length of the wire is large when compared to the wire diameter, the wire will
appear as a line charge. As the drop will be falling below the wire, the dominant influence will be from the closest charge, which as a result of the wire’s orientation (vertical) will only be the end charge. All other charges have a negligible contribution to the system.

2. The charge on the ring is assumed to be evenly spread across the entire surface.

3. The charged ring is assumed to lay flat on the z-axis. therefore \( z = 0 \)

4. Gravitational effects are not considered.

**Charge on the water drop.** First the total charge on the water drop must be determined. With a known drop volume the number of molecules in a drop of water can be calculated as follows:

\[
\text{# molecules} = \text{volume of water drop} \times 3 \times 10^{28} \times 1000
\]

The factor of 1000 is used to convert litres to \( m^3 \). Assuming each molecule can contribute one electron [21], the total charge on the drop will equal:

\[
Q_{total} = \text{no. molecules/drop} \times 1.6 \times 10^{-19} \times 5 \times 10^{-5}.
\]

The factor \( 5 \times 10^{-5} \) is the probability of a molecule being polarized at room temperature, from Debye polarization equation [21]. When the water drop is injected into a field, the electrons in the water drop will be attracted to the more positive area of the field. This will result in a charge separation with two equal but oppositely charged ends of the water drop. Along with this charge separation, the shape of the water drop will be elongated as the charges separate. The water drop will be considered as two point charges separated by a small fixed distance \( d \), see Figure 6.2.

**Electrostatic case.** The force exerted on the water drop is given by eqn. (6.6)
where \( \vec{E}_{induced} \) is the electric field intensity due to the electrode placement. Also

\[
\vec{E} = \frac{\rho_s}{2\epsilon_0} \hat{a}_n
\]  

(6.7)

where \( \rho_s \) is the surface charge density, \( \epsilon_0 \) is the permittivity of free space, and \( \hat{a}_n \) is the unit vector of the field. In the experiment a voltage is applied and, in order to obtain the magnitude and direction of the resultant field, the given electrode placement must be considered (see Appendix C). The potential can be found by integrating from the inner ring to the outer ring:

\[
V = \frac{\rho_s}{2\epsilon_0} \int_a^b 2\pi \int_0^{\frac{\pi}{2}} \frac{rdrd\theta}{[(x-r_b\cos\theta)^2 + (y-r_b\sin\theta)^2 + z^2]^{1/2}}
\]  

(6.8)

Eqn. (6.8) can be used to obtain \( \rho_s \) which can also be used to obtain the magnitude and unit vector, \( \hat{a}_n \), for eqn. (6.7). Therefore, the force is equal to

\[
\vec{F} = Q_{total drop} \left( \frac{2\epsilon_0 V \int_a^b 2\pi \int_0^{\frac{\pi}{2}} \frac{rdrd\theta}{[(x-r_b\cos\theta)^2 + (y-r_b\sin\theta)^2 + z^2]^{1/2}}}{\frac{2\epsilon_0}{a_n}} \right)^{-1} \hat{a}_n
\]  

(6.9)

See Appendix C for the detailed mathematical derivation. Once the electric field intensity is obtained the resultant force, both magnitude and direction, can be calculated from eqn. (6.6). The force on the drop will result in an acceleration as given in eqn. (6.10):
\[ \vec{F} = m \hat{a} \]  \hspace{1cm} (6.10)

where \( m \) is the mass of the water drop, and \( \hat{a} \) is the acceleration of the water drop. Isolating for velocity and substituting in eqn. (6.9), yields

\[ Q_{\text{total drop}} \left\{ \frac{2 \varepsilon_0 V}{\int \int_{a_0} \frac{r \, dr \, d\theta}{\left[ (x - r_b \cos \theta)^2 + (y - r_b \sin \theta)^2 + z^2 \right]^{1/2}} \right\}^{-1} \]

\[ \dot{v} = \int \frac{m}{\hat{a}_n} \, dt \]  \hspace{1cm} (6.11)

We are only interested in the drift velocity and since the drift velocity is only present in the horizontal plane, the velocity due to gravity and the horizontal component of the total velocity due to the electric field is not considered. Thus:

\[ \vec{v}_{\text{drift}} = \left( \int \frac{\vec{F}}{m} \, dt \right) \hat{a}_x \hat{a}_y \]  \hspace{1cm} (6.12)

where \( \hat{a}_x \hat{a}_y \) are the unit vectors in the horizontal plane (see Appendix C for the complete analysis).

**Alternating electric field.** The remaining portion of this section is devoted to the exploration of the effects of an alternating field on a falling charged water drop. The force experienced by the water drop will have the same mathematical expression as above, except that the voltage forcing function will appear as

\[ V = V_{\text{max}} \sin \gamma \]  \hspace{1cm} (6.13)

Therefore the force on the drop will vary as the voltage applied varies:
\[ F \propto \sin \gamma \]  

(6.14)

To determine the drift velocity of a particle of water, due to an alternating electric field, two components must be found. The drift velocity of the whole drop and the drift velocity due to the movement of the charge in the water drop in the field. The drift velocity of the whole drop can be found by using eqn. (6.12) and the appropriate forcing function. In any system the sum of the forces involved is equal to the mass times the acceleration eqn. (6.10). For the system under discussion, the total force is the sum of the forces from the two oppositely charged areas, \( Q_a \) and \( Q_b \), of the water drop (see Figure 6.2 and eqn. (6.15)).

\[ \mathbf{F}_{\text{total}} = \sum \mathbf{F} = \mathbf{F}_a + \mathbf{F}_b \] 

(6.15)

Using equations for linear and angular momentums the velocity of the water drop can be found; see Appendix C. With the alternating field used to determine the force in eqn. (6.9), we obtain:

\[
\begin{align*}
\int & \left[ Q_{\text{total drop}} \left( \mathbf{a}_n \times \mathbf{a} \right) \right] dt \\
&= \left( (\hat{S}_o \hat{k} \pm d_{a/b} \hat{k}) \times m \left( \frac{\hat{v}_{o/p}}{(\hat{S}_o \pm d_{a/b} \hat{k})} \times (\hat{S}_o \pm d_{a/b} \hat{k}) \right) \right)
\end{align*}
\]  

(6.16)

where \( \hat{v}_{o/p} \) is the velocity of the particle with respect to the origin. We now isolate \( \hat{v}_{o/p} \) and substitute into eqn. (6.17).

\[
\hat{v}_{\text{total}} = \hat{v}_{\text{translation}} + \hat{v}_{o/p}
\]  

(6.17)
where \( \mathbf{v}_{\text{total}} \) is the total drift velocity of the water drop in an alternating field.

Using the following assumptions the drift velocity for the water drop was calculated. The total charge of the water drop is \( 1.6 \times 10^{-12} \) coulombs with a mass of \( 3 \times 10^{-6} \) kg. The diameter of the charged inlet is 200 microns and the disk was integrated over \( 2\pi \). To simplify the calculations, the water drop is assumed not to drift about the y-axis. For the alternating case the applied voltage magnitude was 6 volts with a 1MHz frequency; to find the solution for the velocity an algorithm that takes into account the change of velocity as the water drop position changes would be required. We use a finite element analysis to calculate an instantaneous velocity profile starting at the initial position assuming the maximum positive applied voltage. The equations for this model took into account the varying sign change associated with the applied voltage; the velocity that was found is expected to be higher than would occur in practice, but the calculated velocity should yield a favourable first approximation. Using the equations above, for the D.C. case with an applied external field of 40V, the drift velocity was found to be approximately \( 7 \times 10^{-6} \) metres per second. For the alternating field the equations predict a velocity of approximately 0.06 metres per second. These results were based on assumptions used to simplify the calculations. In order to obtain more encompassing results the electrostatic injections system was modelled using the finite element analysis package ANSYS56. These results are compared against the experimental values.

### 6.3.4 Finite Element Analysis

For this project the three-dimensional finite element analysis (FEA) software package ANSYS56 was used. ANSYS56 has electromagnetic analysis capability. The software was used to model the air surrounding the pipettor and the MEMS die inlet region. The volume was meshed and the potentials were applied to the appropriate surface elements. The ANSYS56 particle trace option was used to see what effects the electrostatic field had on a test particle with the approximate weight and charge of the drops of water what were used during the experiments. ANSYS56 was not able to simulate a time varying voltage so
only D.C. voltages and their resultant fields were simulated, see Figure 6.3 and Figure 6.4. The simulation results are compared with experimentally measured values in order to determine the validity of the modelling and computational dynamics.

**Figure 6.3 Pictures of FEA showing lines of force**

6.4 **Physical Test Apparatus**

To test the concept of electrostatic injection a set of experiments were carried out. These experiments used water as the sample carrier, a MEMS die with a circular ring of polysilicon, and a pipettor as the sample macro handler. The goal of the experiments was to have the sample fall into the centre of the ring. At some distance above the ring, less than a centimetre and a half, was the pipettor. The pipettor had a charging wire placed so as to ensure that the sample within the pipettor was at a predefined voltage. The circular ring on the MEMS die was set to a different potential. This set up a field distribution between the pipettor and the MEMS die. The water ejected from the pipettor had the same charge as the pipettor. As the drop fell it moved through a changing voltage field and a force was generated so as to move the drop towards the MEMS die.
Figure 6.4 Particle trace of water drop

For the testing portions of this investigation we fabricated the MEMS die discussed earlier in the chapter. As discussed earlier, this die contained two circular chargeable ring structures, the centre of which could be post processed to form a channel to a reservoir. The second circular ring arrangement has two chargeable rings, each capable of having a different voltage applied. This die also had the structures to evaluate post-processing operations, as well as DNA replication components.

The pipettor was set to three microlitres and aligned at a specific height and horizontal position over the test die. A potential difference was applied between the pipettor and the test die. A series of 25 water drops was ejected and the landing positions of the drops were recorded. Periodically during the tests the power was shut off and a few drops were released to ensure that the pipettor was calibrated to its original position. The vertical position and applied voltage were kept constant while the horizontal position was varied. See Figure 6.5 for a diagram of the experimental setup.
6.5 Experimental Results

For the DC test case, the drops of water did not give any indication of being influenced at all, regardless of the applied voltage of the electrostatic field. After the DC experiments an AC voltage of $6V_{\text{rms}}$ with a frequency of 1MHz was applied. Using AC voltage proved much more effective, the results can be seen in Table 6.1 and Table 6.2. In the tables a hit is defined as most or all of a drop entering the inlet. A drop is considered to be a close hit if half or less than half of the drop volume lands on or in the circular ring. If none or a negligible amount of the drop lands on the circular ring that drop is considered to be a complete miss.

<table>
<thead>
<tr>
<th>Vertical Space (mm)</th>
<th>Horizontal Space (mm)</th>
<th>Number of Hits</th>
<th>Number of Close Hits</th>
<th>Number of Misses</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.25</td>
<td>14</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>10</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>
Table 6.1 Results from Electrostatic Injection Tests 6V 1Mhz Single Ring

<table>
<thead>
<tr>
<th>Vertical Space (mm)</th>
<th>Horizontal Space (mm)</th>
<th>Number of Hits</th>
<th>Number of Close Hits</th>
<th>Number of Misses</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.5</td>
<td>0</td>
<td>12</td>
<td>13(^a)</td>
</tr>
<tr>
<td>10</td>
<td>3.25</td>
<td>0</td>
<td>0</td>
<td>25(^b)</td>
</tr>
</tbody>
</table>

\(^a\) When the pipettor was moved to 2.5mm away, there were no direct hits. Although the drops did not make contact with their desired location it was still apparent that the drops were being influenced by the electrostatic field as 12 of the 25 drops were visibly moved by the field towards the inlet.

\(^b\) In an effort to determine the range at which the six volt one megahertz field would affect the 3 microlitre drops, the pipettor was moved to 3.25mm away from the circular ring. Of the 25 drops tested 19 drops demonstrated either very little or no influence from the field.

Finally, experiments were conducted using the double ring arrangement and the results presented Table 6.2.

Table 6.2 Double Ring Experimental Results

<table>
<thead>
<tr>
<th>Experiment Ring Setup (Outer, Inner)</th>
<th>Vertical Spacing (mm)</th>
<th>Horizontal Spacing (mm)</th>
<th># Hits</th>
<th># Close Hits</th>
<th># Misses</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5V, 6V</td>
<td>10</td>
<td>1.5</td>
<td>7</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>+5V, 6V</td>
<td>10</td>
<td>1.5</td>
<td>5</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>-5V, 6V 1Mhz</td>
<td>10</td>
<td>1.5</td>
<td>12</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

6.6 Summary

The simplified calculated values agree with the experimental results. Unfortunately, the finite element analysis did not accurately represent what occurred in practice, and so the results are in question. The test particle had no volume and therefore it did not experience all of the effects that the real water drop would experience. ANSYS56 also does not have the capability to simulate time varying voltage supplies. Any further designs exploring electrostatic injection should use a simulation package capable of accounting for these effects. It is recommended that a software package such as LS-DYNA be used to continue
research on this topic. LS-DYNA is an explicitly coded FEA software package which would allow for the sample to be modelled directly.

With the single charged ring experiments the 1.25mm offset offers encouraging results. With a similar electrode placement and inlet diameter to the test die, there would be an effective circular area for electrostatic injection of approximately 3.5mm (1mm inlet diameter and 1.25 millimetres omni-directional) which would have a strong influence on a water soluble sample. From two millimetres away the potential difference has an effect on the drops, but not enough to be effective as an injection system. With the double charged ring geometry, the influence seems to be stronger, but the goal of hitting the inlet is not as successful. Although some of the improved results can be attributed to the larger ring area, the results still point to a stronger field influence. Unfortunately, the stronger field does not push the drops into the inlet, the drops are only more attracted to the general area.

The electrostatic injection method does offer the potential benefit of a simple and easy method to introduce samples from the macroscopic world to a microscopic environment in a non laboratory setting, such as a point of care application. This concept is still in its initial stages and further research needs to be done in order to obtain an efficient and reliable design.
7.1 Introduction

Electrophoresis is a fundamental tool in protein analysis. As stated by Beir, in his book: Electrophoresis Theory, Methods, and Applications. “The contribution of electrophoresis to our knowledge of proteins is second to no other method. It’s impact is felt in biochemistry, physiology, and medicine” [26]. The importance of electrophoresis has not been limited to proteins; DNA, amino acids, and enzymes, as well as other material may also be used in electrophoresis. Electrophoresis is often used to separate a mix of different particles, proteins, DNA, amino acids etc., from each other. During electrophoresis a mix containing many different types of samples, different proteins for example, are separated into discrete bands using an applied electric field. The separation mechanism is a direct result of the different charges on the proteins, with each band containing the same type of protein. Clearly, the number of bands will depend of the number of different proteins in the sample. The electrophoresis technique requires the samples to be placed in a liquid, gel, or powder medium. An electric field is applied across this medium, and the charged particles inside the sample will experience an electrostatic force. The magnitude of this force depends upon the total charge of the molecules. There are five
dominant factors that determine how the particles will behave during electrophoresis: the applied field, the total charge of the particles, the mass of the particles, the cross linking of the medium containing the sample, and the pH of the medium. With a knowledge of these five properties as well as an understanding of the mechanics involved, equations can be derived and a simulation can be created from the equations to predict the outcome of a given electrophoresis [27]. With this knowledge in hand a model can be created to simulate a MEMS implementation of electrophoresis.

A MEMS implementation of electrophoresis would be beneficial not only in reducing the size and cost (compared to batch fabrication) but also in the reduction of time for the electrophoresis process to be completed. Typical implementations of electrophoresis will require in the order of an hour just to separate. With a MEMS based electrophoresis that time can be reduced to minutes. Electrophoresis could conceivably be used at the point of care for rapid, and affordable results. Also a MEMS implementation could incorporate additional isolation and analysis with the individual groupings of specimens. With such a savings of time, space, cost, and additional analysis, a MEMS realization could greatly increase the implementation and usability of electrophoresis and associated processes.

7.2 Theory

During electrophoresis the molecules of the sample to be separated experience a force due to the applied external field. For the purpose of these initial experiments into electrophoresis the equations and relating theory will be constrained by several assumptions; see Table 7.1 for these assumptions. Electrophoretic mobility is the velocity of the samples per unit strength of the applied electrical field (DC). From the electrophoretic mobility an equation for the distance a given particle will travel in a predetermined time can be obtained, as is the case for the simulations relating to electrophoresis which are presented in this work. An important concept in electrophoresis is the electrical double layer. The electrical double layer results from the interaction of a molecule to its surrounding solution. Typically in electrophoresis the medium in which a sample is separated has many charged ions. When one of the molecules of the sample is
introduced to this environment there is a charge imbalance. As a result oppositely charged ions from the surrounding solution will be attracted to the molecule. As more ions migrate to that area they form a layer around the molecule until the apparent charge is decreased and the area is electrically neutral once more. When a charge equilibrium is attained between the molecule and the surrounding solution there will be a potential drop which is confined to the molecule and the layer of ions that surround it. When this occurs it is called an electrical double layer. When the electrical double layer is formed there is a so-called ionic atmosphere of ions surrounding the particle, they have a net charge opposite to the charge on the particle. The name can be interpreted as follows: the first word, electrical, infers the charge distribution in the area immediately around the molecule. double indicates that the molecule is of one charge and the surrounding ions of another, lastly layer is suggestive of the ions of the solution forming a layer around the molecule [28]. The electrical double layer is similar to the depletion region of a pn junction. At the interface between an n-type doped region and a p-type doped region electrons and holes

### Table 7.1 Electrophoresis Assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid colloidal particle</td>
<td></td>
</tr>
<tr>
<td>No particle interaction</td>
<td></td>
</tr>
<tr>
<td>Relaxation effect ignored $I_x$</td>
<td></td>
</tr>
<tr>
<td>Particle diameter in the order of nanometers</td>
<td></td>
</tr>
<tr>
<td>Simulated with constant current sections</td>
<td></td>
</tr>
<tr>
<td>Velocity constant with respect to time throughout simulation</td>
<td></td>
</tr>
<tr>
<td>Constant conductivity and viscosity throughout the gel medium</td>
<td></td>
</tr>
<tr>
<td>Electrophoretic mobility given by Eqn. (7.6)</td>
<td></td>
</tr>
<tr>
<td>Ideal current transport mechanisms</td>
<td></td>
</tr>
<tr>
<td>Equations are for a pH balanced aqueous solution</td>
<td></td>
</tr>
</tbody>
</table>
migrate to the oppositely charged side, these charge carriers will continue to amass on either side of the junction until an equilibrium is established, this is analogous to the ions migrating around the molecule until the net charge is zero. The depletion region is that region where the migrated n and p type carriers are positioned, there is a potential drop across the region but the entire region is charge balanced similar to the way the electrical double layer is established as the ions around the molecule cancel out the charge in that area [29].

7.2.1 Equation Derivation

A very short time after the DC field is applied the acceleration of the molecules is reduced to zero and the velocity will remain constant with respect to time. See Figure 7.1. This occurs at the velocity where the viscous resistance of the medium balances the force on the molecule due to the applied electric field. As a result of the assumptions from Table 7.1 the time and distance required to reach this state is neglected.

Figure 7.1 Electrophoretic forces acting on a charged particle

There are four different forces that act on a particle during electrophoresis under the aforementioned assumptions. Cross linking of the medium is not considered in this analysis therefore the results will not exactly match experimental data although the results given in the simulations are expected to accurately predict the magnitude of the distance the molecules travel. The first and most evident is the force exerted by the external dc field
on the charged particle. This force shall be denoted as \( \vec{F}_1 \). The force vector can be written as

\[
\vec{F}_1 = Q\vec{E}_{dc}
\]  

(7.1)

where \( \vec{E}_{dc} \) is the field strength per metre and \( Q \) is the charge of the particle. Since the particle is moving in a medium it will experience a frictional factor. In this case that frictional factor is Stokes friction which, for a rigid spherical particle that is large compared to the molecules of the surrounding liquid, can be expressed as

\[
\vec{F}_2 = -6\pi\eta r\vec{U}
\]  

(7.2)

where \( \eta \) is viscosity, \( r \) is the radius of the sphere and \( \vec{U} \) is the electrophoretic velocity measured in metres per second. The last two forces are a result of the small electrolyte ions in the colloidal solution. The electric field exerts a force on the ions in the medium as well as its influence on the particle. The ions will be attracted to the side opposite to that of the particles, the result of these interactions is an inhibitory force on the colloidal particle.

This force is called "electrophoretic retardation" \( \vec{F}_3 \). The final force is "the relaxation effect" \( \vec{F}_4 \). This force arises when the external field is applied and the ion atmosphere deforms as the particle moves away from the centre of the ion atmosphere. Coulomb forces will arise between the particle and the ions and will tend to restore the ionic atmosphere to its original place. Since it will take a finite amount of time to restore the ionic atmosphere, the centre of the ionic atmosphere will not be at the centre of the particle. \( \vec{F}_4 \) will usually inhibit the particle movement. After the particle has reached a state where the velocity is constant, the sum of all the forces acting will be zero

\[
\vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \vec{F}_4 = 0
\]  

(7.3)

Combining Eqn. (7.1), Eqn. (7.2), Eqn. (7.3) and isolating for electrophoretic velocity
\[ \hat{U} = \frac{1}{6\pi\eta r} (Q\hat{E}_{dc} + \hat{F}_3 + \hat{F}_4) \]  

(7.4)

As stated in the list of assumptions \( \hat{F}_4 \), the relaxation effect, is not considered in this analysis. If for the time being \( \hat{F}_3 \) is also neglected Eqn. (7.4) can be rewritten as

\[ \frac{\hat{U}}{\hat{E}_{dc}} = \frac{Q}{6\pi\eta r} \]  

(7.5)

In a more recent text [31], the same formula is written as

\[ \frac{\hat{U}}{\hat{E}_{dc}} = \frac{ze}{6\pi\eta r} \]  

(7.6)

where \( z \) is the number of electron units of charge and \( e \) is the charge on an electron \( (e = 1.602 \times 10^{-19}) \). Eqn. (7.5) and Eqn. (7.6) are essentially the same equation. In Eqn. (7.5) \( Q \) represents the charge of the particle where in Eqn. (7.6) \( ze \) is one unit of charge multiplied by the number of charges the molecule has. Since \( ze \) more accurately reflects the charge calculation used for molecules Eqn. (7.5) can be written as Eqn. (7.6). Eqn. (7.6) however does not take \( \hat{F}_3 \) into account. The Debye-Huckel theory is used to compensate for the electrophoretic retardation \( \hat{F}_3 \) and can be expressed as

\[ \frac{X(\kappa R)}{1 + \kappa R} \]  

(7.7)

where

\[ \kappa = \left( \frac{8\pi \kappa e^2}{1000DTkT} \right)^{1/2} \frac{1}{1^{1/2}} \]  

(7.8)
where $I$ is the ionic strength, $D$ is the dielectric constant of the medium, and $\kappa$ is the “reciprocal ion-atmosphere.” $X(\kappa R)$ is called Henry’s function, which varies between 1.0 and 1.5 as $\kappa R$ goes from zero to infinity see Figure 7.2 [31].

This factor is integrated into Eqn. (7.6) as [31]

$$\frac{\hat{U}}{\nu_{dc}} = \frac{z e}{6 \pi \eta r} \times \frac{X(\kappa R)}{1 + \kappa R}$$

(7.9)

To obtain an equation relating distance as a function of time Eqn. (7.6) must be rewritten to isolate electrophoretic velocity by multiplying both sides by $\hat{E}_{dc}$ and rewriting $\hat{U}$ as $\frac{dx}{dt}$, where $x$ is distance and $t$ is time, this results in

$$\frac{dx}{dt} = \frac{z e}{6 \pi \eta r} \hat{E}_{dc} \frac{X(\kappa R)}{1 + \kappa R}$$

(7.10)

Integrating both sides by $\partial t$ leads to
\[ x = \frac{e\varepsilon \hat{E}_d}{6\pi \eta r} \frac{X(\kappa R)}{1 + \kappa R l} \]  \hspace{1cm} (7.11)

The models that will be used for calculations will employ a constant current source, as is used in typical electrophoresis. It is therefore necessary to calculate the potential difference from the current. From Ohm's law it is known that for an element of volume of the medium with a cross section of \( A \) and a thickness \( dx \), the potential difference across this section is

\[ dV = idR \]  \hspace{1cm} (7.12)

where \( i \) is current and \( dR \) is the resistance of that portion of the medium. The resistance \( dR \) is also

\[ dR = \frac{dx}{KA} \]  \hspace{1cm} (7.13)

where \( K \) is the specific conductance of the medium. Also

\[ E = \frac{dV}{dx} \]  \hspace{1cm} (7.14)

Substituting Eqn. (7.13) and Eqn. (7.14) into Eqn. (7.12) results in

\[ E = \frac{i}{KA} \]  \hspace{1cm} (7.15)

Therefore with a knowledge of the current, the cross sectional area and the conductance of the medium, the potential difference can be calculated [32].

### 7.3 Simulation

For a typical electrophoresis application there is a constant electric field across the medium. The aim of one of the simulations is to determine how the electrophoresis
procedure would behave in a micro-environment, where the distance available for the particle to travel is less than in typical electrophoresis apparatus. Therefore a quicker separation is needed. To that end a non-uniform field electrophoresis is being proposed here. The non-uniform field will be generated using fixed potential contacts to which adaptively controlled potentials can be applied. The potentials will be adapted to provide better and quicker separation of samples. If there are two or more samples that are very close in charge or size or both, depending on the type of samples being separated, it may be difficult to separate the samples into discrete types. In a non-uniform field environment the slightly faster of the samples enters a higher field region first, causing it to travel even faster than all the other samples. The sample particles that have entered the higher field region will travel further in a given amount of time than the other particles still in a lower field region, thus a non-uniform field electrophoresis could help to separate samples that are currently difficult to isolate.

In order to test out the non-uniform field concept, two different Matlab simulations were created. The first Matlab simulation models the typical electrophoresis technique, with the dimensions obtained from the apparatus used for electrophoresis in the Biochemistry Department at the University of Windsor. The second Matlab simulation has three different uniform field regions. The first field region extends from -2mm to 2mm where zero is the starting point. From 2mm to 4mm on either side of the starting point is the second region. The third region is beyond the 4mm mark. Using Ansys56, a FEA program, a possible configuration of a microelectrophoresis is modelled to determine if the electrode configuration yields increasing potential regions. The results show that it is simple to create many different field regions, where the lowest region is in the centre of the structure. See Figure 7.3.
7.4 Simulation Results

To determine the accuracy of the equations derived in the previous section electrophoresis was carried out on a set of standard proteins. The proteins, their charge, molecular weights, and distance travelled are presented in Table 7.2. The electrophoresis ran for 80 minutes, for the full electrophoresis procedure see Appendix C. During the electrophoresis procedure either the current is kept constant while the voltage varies, for the medium, or the voltage is kept constant while current through the medium varies. For the experiment preformed the area of the electrophoresis gel where the proteins ran is $3.964 \times 10^{-6}$ m$^2$ with 125 mA of constant current. For the simulations the voltage was the constant variable, therefore the current that was used for the experiment is transferred into voltage for the simulations. The electrophoresis modelled to predict normal electrophoresis was supplied with the appropriate variable conditions, using one of the molecules, Myosin, as the mass of the test particle. The conductivity of the gel was measured by cutting a 3cm by 3cm piece of gel out to be tested, a voltage of 10 volts was applied across the 3cm by 3cm piece and a current value of 0.68 mA$^1$ was measured. Using these values a conductance of

---

$^1$ Many measurement were made, the values ranged from 0.65 mA to 0.7 mA where 0.68 was the most common value.
4.93×10⁻⁸ \frac{\Omega}{m} was calculated. The simulation modelled the 80 minute run after which

<table>
<thead>
<tr>
<th>Protein</th>
<th>Molecular Weights</th>
<th>Charge</th>
<th>Distance mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myosin</td>
<td>205,000</td>
<td>41,000</td>
<td>20</td>
</tr>
<tr>
<td>β-galactosidean</td>
<td>121,000</td>
<td>24,200</td>
<td>14.1</td>
</tr>
<tr>
<td>Bovine serum albumin</td>
<td>70,000</td>
<td>14,000</td>
<td>9.7</td>
</tr>
<tr>
<td>Ovalbumin</td>
<td>52,400</td>
<td>10,480</td>
<td>8.0</td>
</tr>
<tr>
<td>Carbonic anhydrase</td>
<td>34,900</td>
<td>6,980</td>
<td>6.1</td>
</tr>
<tr>
<td>Soybean trypsin inhibitor</td>
<td>29,100</td>
<td>5820</td>
<td>5.4</td>
</tr>
<tr>
<td>Lysozyme</td>
<td>20,700</td>
<td>4140</td>
<td>4.3</td>
</tr>
<tr>
<td>Aprotinin</td>
<td>6,900</td>
<td>1380</td>
<td>2.0</td>
</tr>
</tbody>
</table>

time the particle was predicted to travel 33.6 mm, which is within the values obtained from the protein electrophoresis. The equations and simulation for electrophoresis assumed a rigid colloidal particle and do not take into account the cross linking of the gel. Proteins tend to be long rods, therefore the simulations could not make an exact prediction on the proteins tested by the analysis. However, the analysis did accurately predict the direction and the magnitude of the actual protein as tested during normal electrophoresis.

With the success of the analysis in predicting distance travelled during normal electrophoresis, a microelectrophoresis simulation was created. This model used a channel 1 mm wide by 6 cm long, see Figure 7.4. The results from the simulation were very encouraging. Figure 7.5 shows the particles, their relative size and final position. Figure 7.6 shows the progress of each protein with time. The biggest problem with the model was that the particles were in reverse order, this is a result of the formulas not taking into account the cross-linking of the gel, further details will be given in the conclusions.
Figure 7.4 IntelliCAD visualization of Microelectrophoresis Geometry

Figure 7.5 Simulation results from Matlab
For an actual MEMS implementation of electrophoresis the potential of the medium would need to match the varying potential regions so as to ensure that the samples would experience greater potential forces as they travelled during electrophoresis. To determine if the medium would accept the potential, the medium in the form of the microchannel, was modelled in Ansys56. The analysis was performed and the result showed the medium could indeed accept the potential regions, see Figure 7.3.

7.5 Summary

The simulations successfully predict the magnitude and direction of the particles for the normal electrophoresis. The microelectrophoresis results give the expected direction and approximate distance, however the formula does not consider the crosslinking of gels. A source of error when comparing the formula to the test run is that the formula is based on rigid spherical particles, while the test run used proteins which are shaped like long rods. As a result of these two limitations the analysis predicts that the molecules will finish in the reverse order than that of experimental results. The simulation predicts the heaviest most charged particle to travel the farthest. In experiments using gel as the medium, the gel acted like a size determined filter giving the highest resistance to the biggest particles. The experimental results have the smallest least charged particle travelling the farthest. The
preliminary investigation into a MEMS implementation of electrophoresis is encouraging. Further research is necessary but the potential for a microelectrophoresis implementation is promising.
Chapter 8

Conclusions and Future Work

8.1 Conclusions

The work described in this thesis has been concerned with the fabrication, testing, and application of MEMS to lab-on-a-chip type of architectures. The research work was aimed at providing the MEMS design group at the University of Windsor a starting point for research into bio-chemical MEMS applications. The goal of this work is to help direct the MEMS design group in their future decisions for applications and fabrication options. This chapter will outline the conclusions, contributions and suggest future work for both physical fabrication and applications of the work done.

8.1.1 Section One: MEMS Mitel and Post Processing Lab

Post Processing Lab

The results from the initial test of the post processing lab revealed that an in house post processing lab is not the most efficient method for the fabrication of MEMS devices at the current time. While devices can be successfully post processed, the in house lab is not as effective as required, because it is not possible to control the etching mechanism with the necessary precision using our basic
design. If further post processing experiments are to be undertaken it would be beneficial to have a powerful microscope fitted with a camera rather than use a Scanning Electron Microscope (SEM) which requires a significant amount of time to take pictures of the MEMS die.

CMC has recently started supporting the Cronus MUMPS process for designers wishing to fabricate MEMS. MUMPS, a Multi-User MEMS Process, is a well-established commercial technology program that provides general purpose cost-effective surface micromachining for MEMS [17]. Through the CMC supported MUMPS process, the MEMS design group has access to a surface micromacher for the fabrication of MEMS designs. See Chapter 4 for further details on the MUMPs process. Since CMC now supports this third party machiner, the use of a limited in-house post processing facility for lab-on-a-chip designs is now in question.

**Mitel’s 1.5μm process and IntelliSense**

The Mitel 1.5μm process will not be supported by CMC beyond 2001. The Mitel process, however, can be beneficial as a learning tool for new students involved in microelectronic based MEMS design and manufacturing. Since the Mitel structural process has been added to IntelliSense’s IntelliCAD, students can visualize designs in this technology. The initial IntelliCAD technology files are for visualization since the structural parameters of the Mitel process were not available to be added to the IntelliCAD technology files.

**8.1.2 Section Two: Applications**

**PCR DNA Replication**

A silicon based DNA replicator based on PCR technology is a feasible process. Much design, simulation, and testing of both computer models and fabricated devices will be necessary in order to obtain a reliable silicon PCR based replicator. To fabricate such a design would require a specialized MEMS processes, and the design discussed in this thesis would need to be aligned and affixed to a second chip, with heaters and control
circuitry, on top of the MEMS die. It is recommended that this project be continued with an appropriate change in MEMS technology.

**Electrostatic Injection**

Electrostatic injection is a new concept in the transportation of samples into a microenvironment in a non laboratory setting. The simplified calculations did reflect the experimental results although ANSYS56, a FEM analysis program, could not accurately predict the behaviour of the water during testing. This discrepancy can be attributed to the test particle used in ANSYS56; test particles are assumed not to have any volume and will therefore not be correctly simulated in the water drop experiment described in the thesis. ANSYS56 also does not have the capability to simulate time varying voltage supplies. For further designs of an electrostatic injection system an explicit software package that will be able to simulate and model the sample particles should be used. We suggest the use of LS-DYNA, a dynamic program that would be able to more accurately simulate properties of a charged water drop in a time varying electric field.

Based on the test results using a single charged ring, an effective circular area for electrostatic injection of approximately 3.5\text{mm} is possible, with a one millimetre inlet diameter and 1.25 millimetres of strong omni-directional influence on a water soluble sample. If there is an offset of 2\text{mm} the electrostatic field still has an influence on the drop. At this distance and electrode placement, the influence is not sufficient to be an effective injection system but future designs may be able to increase the area of influence to this distance. Although this concept is still in it initial stages and further research needs to be done in order to obtain a efficient and reliable design, the initial results are promising.

**Electrophoresis**

The simulations successfully predicted the magnitude and direction of the particles for normal electrophoresis. For the microelectrophoresis experiment, the result did give the expected direction and approximate distance, however the analysis does not consider the
crosslinking of gels. The analysis was not able to accurately calculate the distance travelled by the proteins since it was based on an assumption of rigid spherical particles; the test run proteins have the shape of a long rod. The analysis predicted that the largest, most heavily charged, particle would travel the farthest; in the experiments, however, the gel was crosslinked thus acting as a size-determined filter which gave the highest flow resistance to the largest particles. As a result of these constraints the analysis predicted that the molecules would finish in the reverse order of the experimental results. However, this preliminary investigation into a MEMS implementation of electrophoresis is encouraging and it is recommended that this project be researched further.

8.2 Contributions

8.2.1 Section One: MEMS Mitel and Post Processing Lab

The first MEMS die designed, fabricated, and tested for the University of Windsor was completed for this thesis. Investigations into a post processing lab consisted of building and operating a clean room type environment for the post processing of MEMS dies. These investigations started prior to the current CMC support for post processing technologies. The post processing lab has now been re-evaluated and we recommend that the CMC supported Cronus MUMPs process is a more efficient choice for fabricating MEMS.

The structural layer of Mitel’s 1.5μm process were imported into the IntelliSense IntelliCAD package as a tutorial aid for designing microelectronic post-processing based MEMS. IntelliCAD also allows for the designer to visualize individual layers during the simulated fabrication process, allowing the designer a step by step view of the process of building MEMS chips.
8.2.2 Section Two: Applications

PCR DNA Replication

Although it is recommended that the PCR based replication of DNA be continued with a more suitable MEMS technology, MUMPS, this thesis has provided some important initial design considerations. The use of two dies, one which is the primary MEMS chip, would require post processing. The other, a top chip, would have the control circuitry, heating elements, feed back sensors, and would seal the PCR reaction chamber from the environment.

Electrostatic Injection

As a proof of concept of a new sample handling technique for moving samples from the macroscopic world to a microscopic MEMS chip, an initial design for an electrostatic injection system was fabricated and tested. A mathematical model was derived and simplified calculations carried out in order to determine the approximate behaviour of the system. The finite element analysis program, ANSYS56, was used to simulate the area between the pipettor and the inlet to the MEMS chip. The ANSYS56 particle trajectory option was used to trace the path of a particle with the same charge and mass as that of a drop of charged water. After analysing the experimental results an effective circular area for electrostatic injection of approximately 3.5 mm was ascertained.

Electrophoresis

Two Matlab simulations were created. The first models normal macroscopic electrophoresis, and this simulation was used to determine the accuracy of our closed form analysis. The second simulation models a microelectrophoresis application. The ANSYS56 package was used to determine the magnitude of electric fields required and to analyse the concept of non-uniform electric field electrophoresis.
The concept of a multi voltage area for generating non-uniform electric fields was explored and simulated. This multi voltage area allows for separation of samples over a short distance. The preliminary investigation into a MEMS implementation of electrophoresis is encouraging. Further research is necessary but the potential for success is high.

8.3 Suggestions for Future Work

8.3.1 Section One: MEMS Mitel and Post Processing Lab

The Cronus MUMPs technology, which is supported by CMC, is the recommended option for future MEMS fabrication. An initial step should be to add a MUMPs process technology file to the IntelliSense IntelliCAD package. This addition will allow designers to visualize and simulate their designs. If the process can be accurately synthesized in the package, a designer will be able to create more accurate models and refine designs prior to having them fabricated. For determining the structural integrity of a MEMS design, a powerful microscope, or SEM should be used. If a suitable optical microscope is to be used it would be beneficial to have a camera attachment to allow for photo micrographs of the designs to be taken.

8.3.2 Section Two: Applications

PCR DNA Replication

PCR replication on a silicon substrate is a feasible process, but many more tests are necessary to maintain and control the heat across the entire reaction chamber. Since CMC is no longer offering the Mitel 1.5μm process it is recommended that a PCR DNA replicator design be continued with the Cronus MUMPS process.
Electrostatic Injection

To further continue research into electrostatic injection a software package capable of modelling and simulating water, or another sample carrier, dropping through an electric field would be necessary. An explicit coded finite analysis program like LS-DYNA would be recommended. For further work to be done in this area a different electrode placement is recommended. A possible electrode orientation could be an inlet with the electrode suspended in the centre so when the drop lands on or near the electrode it will be able to simply roll off into the inlet.

Electrophoresis

Microelectrophoresis is the most promising application to be further explored by the MEMS research group. The major effects of electrophoresis have been successfully modelled for normal electrophoresis. For future work in the area of microelectrophoresis, the effects of small channel flow should be further addressed: specifically surface tension effects, flow type (Newtonian or non-Newtonian), as well as other open channel considerations. Also the present analysis simulates rigid spherical particles; since many of the substances that will be separated using electrophoresis will not be rigid spheres, for example the proteins which were used in the experiment were long rods, the analysis should be modified to more accurately reflect the sample shape. A potential problem that could be encountered with this issue is that long proteins or other similarly shaped material may be deformed during the electrophoresis procedure. The complexities of the deformation along with the other effects to be considered will increase the computational complexity of the analysis. It is therefore recommended that the order of magnitude of error due to these effects be determined in order to assess the need for this extra complexity in the analysis.

The medium that is used during electrophoresis should also be carefully examined and modelled. For the simulations presented here the medium was a liquid solution, the tests used a gel which can be crosslinked and affects the movement of samples to be separated. If a gel medium is to be successfully modelled, the crosslinkage should be incorporated
into the simulation in order to obtain accurate results. Once a medium is selected its properties should be examined closely and an effort made to determine how the medium will be affected in a micro open channel environment. A note to consider when selecting a fabrication technique, is how the roughness of the sides and bottom of the design will affect the flow.

The measurement of gel viscosity is also important, and there is equipment available that can be used to measure the viscosity of gels [33].

With the ability to accurately assess the forces involved in microelectrophoresis, a more space efficient design may be able to be designed (e.g., instead of a 6cm long trench, there can be bends or turns which would use more width and less length.) These types of design changes may lead to a more efficient way of creating and maintaining the necessary voltage regions.

We also recommend an investigation into the chemistry of microelectrophoresis. The type of medium plays a very important role in electrophoresis and with a design that has limited running space, as compared to normal electrophoresis, the medium properties could play a dominant role in determining the success or failure of a design. A strongly crosslinked gel may be preferred over a weaker linked one. Perhaps gels are not the best choice for microelectrophoresis, a powder or liquid may serve to improve the efficiency of the microelectrophoresis. Capillary electrophoresis [4] should be examined as the effects that control capillary electrophoresis will have a strong influence on a micro implementation.

More than three voltage regions would more than likely be beneficial to generate the non-uniform electric field. An approximate continuous gradient of electric field would allow for a continuous acceleration of the particles which would improve results.

A concern which should be addressed is the gravitational effects in microelectrophoresis. With a channel that is very shallow, compared to normal electrophoresis, the samples may
move to the bottom of the channel, especially if the medium is not a gel or other similar medium which normally helps to immobilize the samples.

For microelectrophoresis it recommended that an explicitly coded FEA program be used to accurately model moving particles, including the effect of size filtering involved with the cross linking of gels. Since the medium is affected by the external field, it is recommended that the Eulerian/Lagrangian method be investigated as a means of simulating the interactions of the medium and samples. The Eulerian/Lagrangian method involves two meshes, a Eulerian mesh of the medium and a Lagrangian mesh for the particles that will be travelling through the medium. This method may prove to be useful in creating an accurate simulation of microelectrophoresis.
REFERENCES


[18] www.cmc.ca, August 14 2000

[19] G. Hamel, Personal e-mail transaction from Mitel, June 1999


[21] G. Raju, Personal Communications, April 2000


Appendix A

Electrophoresis Procedure

There are three major steps to doing an electrophoresis run. The first step is to make the running gel, then the stacking gel, the finally inject the samples and apply the power. More details on the steps involved are given below.

For a 10% gel with a total volume of 15 ml, which is what was used for the electrophoresis experiment, see Table A.1 on page 83 for a list of the necessary chemicals and their amounts.

Table A.1 Gel Ingredients

<table>
<thead>
<tr>
<th>Chemical name and concentration</th>
<th>Amount ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>5.9</td>
</tr>
<tr>
<td>30% acrylamide</td>
<td>5.0</td>
</tr>
<tr>
<td>1.5 MTris pH 8.8</td>
<td>3.8</td>
</tr>
<tr>
<td>10% sodium dodecyl sulfite(SDS)</td>
<td>0.15</td>
</tr>
<tr>
<td>10% ammonium persulfate</td>
<td>0.15</td>
</tr>
<tr>
<td>TEMED</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Mix water, MTris and SDS. Next vacuum out all the air from the mixed solution. Add the remaining two chemicals. Using a plastic pipetter fill the gel cassette with the solution. Use butanol to level
the gel. Let sit for 20 min. If the solution has polymerised (solidified) clean off butanol and rinse with water. Place the comb in the cassette, and prepare the stacking gel.

The stacking gel is made the same way with the same chemicals except the total volume is 5 ml and the MTris has a pH of 6.8. Once the stacking gel is mixed, remove the comb and using a pipette add the stacking gel on top of the running gel. Refrigerate the gels in the cassette.

Make a buffer so that it will maintain the pH during the experiment. The buffer mixture is seen in Table A.2 on page 84. Once the gels are set and the buffer is prepared, place the

<table>
<thead>
<tr>
<th>Chemical name and concentration</th>
<th>Amount ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>60</td>
</tr>
<tr>
<td>Glycine 75 g/L</td>
<td>43.2</td>
</tr>
<tr>
<td>Tris 15 g/L</td>
<td>9</td>
</tr>
<tr>
<td>10% sodium dodecyl sulfite (SDS)</td>
<td>3</td>
</tr>
</tbody>
</table>

cassettes in the electrophoresis apparatus. Add the buffer and apply a preset amount of power. For the experiment used in this thesis a constant voltage of 130 V and an upper limit of 400 mA was used for 80 mins. Once the electrophoresis has run remove it from the cassette and submerge it in a staining buffer overnight while it is being shaken. The next day pour out the stainer and submerge in a destainer for 2 hours while shaking, finally rinse.
Appendix B

Matlab Code

B.1 NormalElectro.m

% This calculates the X distance for normal electrophoresis

i1=125e-3; %17e-3; %17mA of current
i2=24e-3; %24mA of current
i3=40e-3; %40mA of current

K=4.93e-8; %conductance mhos/m of gel (converted from micromhos/centimetre)
A=3.964e-6; % 0755mm by 5.25mm 3cm by 5mm Cross sectional area(m2) for normal electrophoresis
e=1.602e-19; %charge on an electron
z=1; % Number of electron units of charge
r=8e-9; % Radius of particle in Metres
n=1.201439736741172e+03; %Viscosity calculated from Myosin travel 2cm
%n= 0.858e-3; %Viscosity of fresh water (Pa*s) or Kg/s*m2
XXK=1.25125/(1+10e1); %Debye-Huckel factor for ion atmosphere (X(kR)/(1+kR))

Vdcl=i1./(K*A); %Calculated electric potential in V/m
Vdc2=i2./(K.*A);
Vdc3=i3./(K.*A);

T=60*80; % time in seconds

DeltaX21=[];
DeltaX22=[];
DeltaX23=[];
LongX21=[];
LongX22=[];
LongX23=[];
Totalmax1=[];
Totalmax2=[];
Totalmax3=[];
TotalX2=0;
TotalX21=0;
TotalX22=0;
TotalX23=0;

St1=0.16; %Distance at which voltage first changes
St2=0.5; %Distance when second voltage change occurs

% Velocity when acceleration is zero
% Vfin=((z.*e.)/(6*pi*n.*r))*XK*Vdc1
%v1=0:0.5:Vfin;

%DeltaX1=(X1(i)-X1(i-1));
%DeltaX2=(X2(i)-X2(i-1));

% My equation when acceleration is zero
% x=((e*1)/(6*pi*n))*Vdc*t*(X(kR)/(1+xR))
% X2 will measure the displacement when there is no acceleration
% X will measure the total displacement

format long;
flag=1;
flag2=1;
for t=0:T
t;
if TotalX2< St1
  stage=1;
  \(X_{21} = \left( \frac{e \times z}{6 \times \pi \times n \times r} \right) \times V_{dc1} \times X_K \times t\);
  LongX21=[LongX21 X21];
  if t<1
    DeltaX21=[LongX21];
  elseif t<2
    DeltaX21=[DeltaX21 (LongX21(t)+LongX21(1))];
  else
    DeltaX21=[DeltaX21 (LongX21(t+1)-LongX21(t))];
  end
  TotalX2=TotalX2+DeltaX21(t+1);
  Totalmax1=[Totalmax1 TotalX21];
elseif TotalX2< St2
  if flag=1
    flag=0;
    minus=t;
  end
  Stage=2;
  \(X_{22} = \left( \frac{e \times z}{6 \times \pi \times n \times r} \right) \times V_{dc2} \times X_K \times (t-\text{minus}) + \text{TotalX22}\);
  LongX22=[LongX22 X22];
  if (t-\text{minus})<1
    DeltaX22=[LongX22-TotalX22]; %subtract last value of first Voltage area
  elseif (t-\text{minus})<2
    DeltaX22=[DeltaX22 (LongX22(2)-LongX22(1))];
  else
    DeltaX22=[DeltaX22 (LongX22(t+1-\text{minus})-LongX22(t-\text{minus}))];
  end
  TotalX22=TotalX22+DeltaX22(t+1-\text{minus});
  Totalmax2=[Totalmax2 TotalX22];
else
  if flag2==1
    flag2=0;
minus2=t;
end
STAGE=3;
X23=((e.*z)/(6*pi*n*r))*Vdc3*XK*(t-
minus2))+(TotalX22+TotalX21);
LongX23=[LongX23 X23];
if (t-minus2)<1
DeltaX23=[LongX23-TotalX22];
elseif (t-minus2)<2
DeltaX23=[DeltaX23 (LongX23(2)-LongX23(1))];
else
DeltaX23=[DeltaX23 (LongX23(t+1-minus2)-LongX23(t-
minus2))];
end
TotalX23=TotalX23+DeltaX23(t+1-minus2);
Totalmax3=[Totalmax3 TotalX23];
end
if TotalX2< St1
TotalX2=TotalX2+DeltaX21(t+1);
elseif TotalX2< St2
TotalX2=TotalX2+DeltaX22(t+1-minus);
else
TotalX2=TotalX2+DeltaX23(t+1-minus);
end
end

LongX2=[LongX21 LongX22 LongX23];

time=0:T;
plot(time,LongX2);
TotalX2

B.2 RealAnimfunc.m

function Animfunc(r,Result);
%Electrophoresis function for animating the motion of
an electrophoresis system.
global Electrophoresis
Num=max(size(r));
for i=1:Num
    offset(i)=i*0.01;
end

for dist=1:max(size(Result))
    % Initialize the figure for use with this simulation
    animinit('Electrophoresis Animation');
    Electro= findobj('Type','figure','Name','Electrophoresis Animation');
    axis([-0.12 0.12 -0.05 0.05]);
    hold on;
    %circle
    axis('equal'); axis('on');
    grid on;
    
    % Draw the floor and side walls
    plot([-0.06 0.01],[0 0],'yellow','LineWidth',2)
    plot([-0.02 -0.02],[0 0.08],[-0.04 -0.04],[0 0.08],'green','LineWidth',1)

    xlabel('Distance travelled by particle')
    for i=1:Num
        % Draw the circle representing the particle
        m(i)=r(i)*3e2; %10^9*10^-7;
        thp = 0:0.1:2*pi;
        x = Result(i,dist)+ m(i).*cos(thp);
        y = offset(i)+ m(i).*sin(thp);
        plot(x,y);
        q=2;
    end
    drawnow;
end
B.3 ElectroTestSL.m

% This is M file that verifies the test results. X is distance for the normal electrophoresis

% ProteinDistance
% Myosin0.020m or 20.0mm
% B-galaclosidea0.0141 or 14.1mm
% Bovin serum albumin0.0097 or 09.7mm
% Ovalbumin0.0080 or 08.0mm
% Carbonic anhydrase0.0061 or 06.1mm
% soybean trypsin inhibitor0.0054 or 05.4mm
% Lysozyme0.0043 or 04.3mm
% Aprotinin0.0020 or 02.0mm

MyosinW=205000/6.02e23;
Myosinchrg=205000/5;

galaW=121000/6.025e23;
galachrg=121000/5;

BovinW=70000/6.025e23;
Bovinchrg=70000/5;

OvalW=52400/6.025e23;
Ovalchrg=52400/5;

CarbW=34900/6.025e23;
Carbchrg=34900/5;

SoybW=29100/6.025e23;
Soybchrg=29100/5;

LysoW=20700/6.025e23;
Lysochrg=20700/5;

AproW=6900/6.025e23;
Aprochrg=6900/5;
il=17e-3; %17mA of current

K=4.93e-8; %conductance mhos/m of gel (converted from: micromhos/centimetre)
A=3.8062e-6; % 0.725mm by 5.25cm Cross sectional area(m2) of gel for normal electrophoresis
e=1.602e-19; %charge on an electron
z=Aprochrg; %1; % Number of electron units of charge
Volume=AproW*1000;
r=(Volume*3/4*pi)^(1/3);

%r=1e-9; % Radius of particle in Metres
Visc = 1.201439736741172e+03; %Viscosity calculated from Myosin
%n= 100000; %Viscosity (Pa*s) or Kg/s*m2
XK=1.475/(1+10e2); %Debye-Huckel factor for ion atmosphere (X(kR)/(1+kR))

Vdc1=il./(K.*A); %Calculated electric potential in V/m

T=60*80; % time in seconds

% Velocity when acceleration is zero
%Vfin=((z.*e)./(6*pi*n.*r))*XK*Vdc1
%v1=0:0.5:Vfin;

%DeltaX1=(X1(i)-X1(i-1));
%DeltaX2=(X2(i)-X2(i-1));

% My equation when acceleration is zero
%x=((e*1)/(6*pi*n))*Vdc*t*(X(kR))/(1+xR)
%X2 will measure the displacement when there is no acceleration
%X will measure the total displacement

LongX21=[];
DeltaX21=[];
TotalX21=0;
Totalmax1=[];
format long;
flag=1;
flag2=1;
for t=0:T
  t;

stage=1;
X21=((e.*z.)/(6*pi*Visc*r))*Vdcl*XX*t;
LongX21=[LongX21 X21];
if t<1
  DeltaX21=[LongX21];
elseif t<2
  DeltaX21=[DeltaX21 (LongX21(2) LongX21(1))];
else
  DeltaX21=[DeltaX21 (LongX21(t+1)-LongX21(t))];
end

TotalX21=TotalX21+DeltaX21(t+1);
Totalmax1=[Totalmax1 TotalX21];
end
LongX2=[LongX21];

time=0:T;
plot(time,LongX2);
TotalX2

B.4 RealMicroElectro.m

function LongX2=MicroElectro(x,z)

% This function calculates the X distance for micro-electrophoresis

i1=02e-3; %2mA of current fo 6cm with 1mm by 40um area
i2=05e-3; %05mA of current
i3=10e-3; %10mA of current

K=4.93e-8; %conductance mhos/m of gel (converted from:micromhos/centimetre)
A=1000e-6*40e-6; %1000um by 40um Cross sectional area(m²)
e=1.602e-19; %charge on an electron
n= 1.201439736741172e+03; %Viscosity calculated from Myosin travelled 2cm
XX=1.45/(1+10^2); %Debye-Hückel factor for ion atmosphere (X(kR)/(1+kR)

Vdc1=i1./(K.*A); %Calculated electric potential in V/m
Vdc2=i2./(K.*A);
Vdc3=i3./(K.*A);

T=1*60; % time in seconds
% t=1:T; %Time matrix

DeltaX21=[];
DeltaX22=[];
DeltaX23=[];
LongX21=[];
LongX22=[];
LongX23=[];
Totalmax1=[];
Totalmax2=[];
Totalmax3=[];
TotalX2=0;
TotalX21=0;
TotalX22=0;
TotalX23=0;

St1=0.002; %Distance at which voltage first changes
St2=0.004; %Distance when second voltage change occurs

% Velocity when acceleration is zero
% Vfin=((z.*e)./(6*pi*n.*r))*XX*Vdc1
% v=0:0.5:Vfin;
deltaX1 = (X1(i) - X1(i-1));
deltaX2 = (X2(i) - X2(i-1));

% My equation when acceleration is zero
% x = (e+1)/(6*pi*n*r) * Vdc * t * X(kR)/(1+xR)
% X2 will measure the displacement when there is no acceleration
% X will measure the total displacement

format long;
flag=1;
flag2=1;
for t=0:T
  t;
  if abs(TotalX2) < St1
    stage=1;
    X21 = ((e.*z)/(6*pi*n*r))*Vdc1*XK*t.*0.5;
    LongX21 = [LongX21 X21];
    if t<1
      DeltaX21 = [DeltaX21];
    elseif t<2
      DeltaX21 = [DeltaX21 (LongX21(2) - LongX21(1))];
    else
      DeltaX21 = [DeltaX21 (LongX21(t+1) - LongX21(t))];
    end
    TotalX21 = TotalX21 + DeltaX21(t+1);
    Totalmax1 = [Totalmax1 TotalX21];
  elseif abs(TotalX2) < St2
    if flag=1
      flag=0;
      minus=t;
    end
    Stage=2;
    X22 = (((e.*z)/(6*pi*n*r))*Vdc2*XK*0.5*(t-minus+1)) + (TotalX21);
    LongX22 = [LongX22 X22];
    if (t-minus)<1
DeltaX22=[LongX22-TotalX21]; %subtract last value of first Voltage area
elseif (t-minus)<2
DeltaX22=[DeltaX22 (LongX22(2)-LongX22(1))];
else
DeltaX22=[DeltaX22 (LongX22(t+1-minus)-LongX22(t-minus))];
end

TotalX22=TotalX22+DeltaX22(t+1-minus);
Totalmax2=[Totalmax2 TotalX22];

else
if flag2==1
  flag2=0;
  minus2=t;
end
STAGE=3;
X23=(((e.*z)./(6*pi*n*r)) *Vdc3*XXK*0.5*(t-minus2+1))+(TotalX22+TotalX21);
LongX23=[LongX23 X23];
if (t-minus2)<1
DeltaX23=[LongX23-TotalX22];
elseif (t-minus2)<2
DeltaX23=[DeltaX23 (LongX23(2)-LongX23(1))];
else
DeltaX23=[DeltaX23 (LongX23(t+1-minus2)-LongX23(t-minus2))];
end

TotalX23=TotalX23+DeltaX23(t+1-minus2);
Totalmax3=[Totalmax3 TotalX23];
end
if abs(TotalX2)< St1
TotalX2=TotalX2+DeltaX21(t+1);
elseif abs(TotalX2)< St2
TotalX2=TotalX2+DeltaX22(t+1-minus);
else
TotalX2=TotalX2+DeltaX23(t+1-minus);
end
end
end

LongX2=[LongX21 LongX22 LongX23];
TotalX2

B.5 Visco.m

%This will calculate viscosity of the medium used in electrophoresis
%Visc = 1.201439736741172e+03

MyosinW=205000/6.02e23;
Myosinchrg=205000/5;

K=4.93e-8; %conductance mhos/m of gel (converted from: micromhos/centimetre)
A=3.8062e-6; % 0.725cm by 5.25mm Cross sectional area(m2) of gel for normal electrophoresis
E=1.602e-19; %charge on an electron
Z=Myosinchrg; %1; % Number of electron units of charge
n= 100000; %Viscosity (Pa*s) or Kg/s*m2
XX=1.475/(1+10e2); %Debye-Huckel factor for ion atmosphere (X(kR)/(1+kR))

Volume=MyosinW*1000 %Weight in grams convert to kg divide by density
r=(Volume*3/4*pi)^(1/3); % radius of a particle
i1=17e-3; %17mA of current;
Vdc1=i1./(K.*A); %Calculated electric potential in V/m;

Visc=((e.*Z)/(6*pi*r))*Vdc1*XX*(80*60)/0.02; %Calculate the viscosity of the medium
B.6 Animation.m

%This demonstration will simulate microelectrophoresis for the number of particles with radii and charge supplied by the user.

clear
Num=input('How many particles?: ');
for i=1:Num
str=sprintf('Radii of particle %d in nanometres: ',i);
Radii(i)=input(str)*10^-9;
str=sprintf('Charge of particle %d: ',i);
Charge(i)=input(str);
end

for i=1:Num
Result(i,:)=MicroElectroSI(Radii(i),Charge(i));
end

Animfunc(Radii,Result)

B.7 Demo Programs

B.7.1 Demo1.m

%This will demonstrate microelectrophoresis of particles with the radii and charge shown

clear all
close all
Num=10;
Radii=10^-9*[1 1.2 0.98 1.25 0.8 1 1.3 0.95 0.75 1.3];
Charge=[2 1 -1 -2 0 1 -2 -1 2 1];
for i=1:Num
Result(i,:)=MicroElectroSI(Radii(i),Charge(i));
end
%Result
format short
RadiiCharge=[1 2;1.2 1; 0.98 -1;1.25 -2; 0.8 0;1 1.3
-2;0.95 -1;0.75 2;1.3 1]
format long
Animfunc(Radii,Result)

B.7.2 Demo2.m

%This file demonstrates microelectrophoresis for particles with the radii and charge shown below
clear all
close all
Num=6;
Radii=10^-9*[1 1.2 0.98 1.25 0.8 1];
Charge=[2 1 -1 -2 0 1];
for i=1:Num
Result(i,:)=MicroElectroSI(Radii(i),Charge(i));
end
%Result
format short
RadiiCharge=[1 2;1.2 1;0.98 -1;1.25 -2;0.8 0;1 1]
format long
Animfunc(Radii,Result)

B.7.3 Demo3.m

%This file demonstrates microelectrophoresis with particles of the radii and charge shown
close all
clear all
Num=2;
Radii=10^-9*[0.98 1.2 ];
Charge=[2 1 ];
for i=1:Num
Result(i,:) = MicroElectroSI(Radii(i),Charge(i));
end
%Result
format short
RadiiCharge=[0.98 2;1.2 1]
format long
Animfunc(Radii,Result)
B.7.4 Demo4.m

%This file demonstrates microelectrophoresis of particles with the radii and charge shown below.
clear all
close all
Num=2;
Radii=10^-9*[1 1.2 ];
Charge= [1 1 ];
for i=1:Num
Result(i,:)=MicroElectroSI(Radii(i),Charge(i));
end
%Result
format short
RadiiCharge=[1 1;1.2 1]
format long
Animfunc(Radii,Result)

B.7.5 Demo5.m

%This file demonstrates microelectrophoresis of proteins that were tested
clear all
close all
Num=8;

MyosinW=205000/6.02e23;
Myosinchrng=205000/5;

galaW=121000/6.025e23;
galachrg=121000/5;

BovinW=70000/6.025e23;
Bovinchrg=70000/5;

OvalW=52400/6.025e23;
Ovalchrg=52400/5;

CarbW=34900/6.025e23;
Carbchrg=34900/5;
SoybW=29100/6.025e23;
Soybchrg=29100/5;

LysoW=20700/6.025e23;
Lysochrg=20700/5;

AproW=6900/6.025e23;
Aprochrg=6900/5;

Volume=[MyosinW galαW BovinW OvalW CarbW SoybW LysoW AproW]*1000;
for i=1:Num
    Radii(i)=(Volume(i)*3/4*pi)^(1/3);
end

%Radii=10^-9*[1 1.2 ];
Charge=-1*[Myosinchrg galαchrg Bovinchrg Ovalchrg Carbchrg Soybchrg Lysochrg Aprochrg];
for i=1:Num
    Result(i,:)=RealMicroElectro(Radii(i),Charge(i));
end

figure
t=0:60;
plot(t,-1*Result)
title('Distance vs. Time for Electrophoresis of Standard Proteins')
xlabel('Time in half seconds--total 30 seconds')
ylabel('Distance travelled by the proteins')
legend('Myosin','B-glαcloside','Bovin serum albumin','Ovalbumin','Carbonic anhydrase','Soybean trypsin inhibitor','Lysozym','Aprotinin')

RealAnimfunc(Radii,Result)

B.8 Animfunc.m

function Animfunc(r,Result);
%Electrophoresis function for animating the motion of an electrophoresis system.
global Electrophoresis
Num=max(size(r));
for i=1:Num
  offset(i)=i*0.01;
end

for dist=1:max(size(Result))
  % Initialize the figure for use with this simulation
  animinit('Electrophoresis Animation');
  Electrophoresis = findobj('Type','figure','Name','Electrophoresis Animation');
  % axis([-0.12 0.12 -0.05 0.05]);
  hold on;
  % circle
  axis('equal'); axis('on');
  grid on;
  % Draw the floor and side walls
  plot([-0.12 0.12],[0 0],'yellow','LineWidth',2)
  %,[-10:18;-9:19],...
  for i=1:Num
    % Draw the circle representing the particle
    m(i)=r(i)*10^9*10^-3;
    thp = 0:0.1:2*pi;
    x = Result(i,dist) + m(i).*cos(thp);
    y = offset(i) + m(i).*sin(thp);
    plot(x,y);
    q=2;
  end
  drawnow;
end

B.9 Electanim.m

function [sys,x0]=crtaniml(t,ts);
% CRTANIML S-function for animating the motion of electrophoresis.

global Electrophoresis
for dist=10:-1:0
    % Initialize the figure for use with this simulation
    animinit('Electrophoresis Animation');
    Electrophoresis = findobj('Type','figure','Name','Electrophoresis Animation');
    %axis([-10 20 -7 7]);
    hold on;
    %circle
    axis('equal'); axis('on');
    grid on;

    % Draw the floor and side walls
    plot([-10 19], [-10 -10], 'yellow', [-10:18:-9:19], [-10 -11], 'yellow', [-10 -10], [10 -11], ...
         'blue', [-10 -11], [-10:10;-11:9], 'blue', [19 19], [10 -11], 'red', [19 20], [-10:10;-11:9], ...
         'red', 'LineWidth', 2);

    % Draw the circle representing the particle

    m=2;
    thp = 0:0.1:2*pi;
    x = dist + m*cos(thp);
    y = 2 + m*sin(thp);
    plot(x,y);
    q=2;
    % dist=0:10;
    drawnow;
end
Appendix C

Mathematical Model of Electrostatic Injection

C.1 Mathematical interpretation

Description

Based on the physical setup of the test to be carried out, the charging wire is placed at a general point $P(x_1, y_1, z_1)$. The origin of the fixed frame of reference is at the centre of the charged ring, see Figure 3.1.

Objective

The objective of this section is to obtain a mathematical expression for the drift velocity, which is the horizontal velocity of the water drop. Gravitational effects are not considered.

System Model

The mathematical exploration makes certain assumptions:

1. The charging wire appears as a point charge once the drop has left the pipettor. As the length of the wire is large when compared to the wire diameter, the wire will appear as a line charge. As the drop
will be falling below the wire, the dominant influence will be from the closest charge, which as a result of the wire's orientation (vertical) will only be the end charge. All other charges have a vanishing contribution to the system.

2. The charge on the ring is assumed to be evenly spread across the entire surface.

3. The charged ring is assumed to lay flat on the z-axis, therefore \( z = 0 \)

4. Gravitational effects are not considered.

**Figure 3.1 Mathematical model of electrode placement**

\[
P(x_1, y_1, z_1)
\]

**Charge on the water drop.** First the total charge on the water drop must be determined. In one metre cube of water there are \( 3 \times 10^{28} \) molecules of water, based on water having a density of 1000 \( \text{kg/m}^3 \). With a known drop volume the number of molecules in a drop of water can be calculated as follows

\[
\text{# molecules} = \text{volume of water drop} \times 3 \times 10^{28} \times 1000
\]  

(3.1)
The factor of 1000 is used to convert litres to metres cubed. Assuming each molecule can contribute one electron, the total charge on the drop will equal

\[ Q_{total} = \# \text{ molecules/drop} \times 1.6 \times 10^{-19} \quad (3.2) \]

The factor is the probability of a molecule being polarized at room temperature, from Debye polarization equation [21]. When the water drop is injected into a field, the electrons in the water drop will be attracted to the more positive area of the field. This will result in a charge separation with two equal but oppositely charged ends of the water drop. Along with this charge separation, the shape of the water drop will be elongated as the charges separate. The water drop will be considered as two point charges separated by a small fixed distance \(d\), see Figure 3.1.

**Electrostatic case.** The force exerted on the water drop is

\[ \hat{F} = Q_{total\text{drop}} \hat{E}_{\text{induced}} \quad (3.3) \]

where \( \hat{E}_{\text{induced}} \) is the electric field intensity due to the electrode placement, but

\[ \hat{E} = \frac{\rho_s}{2\varepsilon_0} \hat{a}_n \quad (3.4) \]

where \( \rho_s \) is the surface charge density, \( \varepsilon_0 \) is the permittivity of free space, and \( \hat{a}_n \) is the unit vector of the field. In the experiment a voltage is applied, in order to obtain the magnitude and direction of the resultant field for the given electrode placement, see Figure 3.1, the following are required parameters.

The area of the ring is

\[ A_{\text{ring}} = 2\pi b^2 - 2\pi a^2 \quad (3.5) \]
where $a$ is the inner diameter of the ring and $b$ is the outer diameter of the ring. The differential ring element is

$$A_r = 2\pi r dr$$  \hspace{1cm} (3.6)

where $r$ is the radius of the elemental ring. The charge on this elemental ring is its area times the surface charge density

$$dQ = 2\pi r \rho_s dr$$  \hspace{1cm} (3.7)

The distance from the general point $P(x_1, y_1, z_1)$, where the charging wire is located, to a point on the ring $(x', y', 0)$ is

$$R = \sqrt{(x-x')^2 + (y-y')^2 + z^2}$$  \hspace{1cm} (3.8)

The ring point can be written as a circle defined by its radius and degree of rotation. Hence by substituting $x = r_b \cos \theta$, and $y = r_b \sin \theta$ the angle is defined as starting at $x = 0$ and rotating counterclockwise.

$$R = \sqrt{(x-r_b \cos \theta)^2 + (y-r_b \sin \theta)^2 + z^2}$$  \hspace{1cm} (3.9)

where the direction of $R$ is

$$\theta = \tan \frac{z}{(x-r_b \cos \theta)^2}$$  \hspace{1cm} (3.10)

and

$$\phi = \tan \frac{(y-r_b \sin \theta)^2}{(x-r_b \cos \theta)^2}$$  \hspace{1cm} (3.11)
The contribution of the elemental ring to the total ring potential is

\[ \frac{dQ}{4\pi \varepsilon_0 R} = \frac{2\pi r \rho_s dr}{4\pi \varepsilon_0 R} \]  \hspace{1cm} (3.12)

The potential can be found by integrating from the inner ring to the outer ring and round \(2\pi\).

\[ V = \frac{\rho_s}{2\varepsilon_0} \int_a^b \int_0^{2\pi} \frac{r dr d\theta}{\left[ \left( x-r_b \cos \theta \right)^2 + \left( y-r_b \sin \theta \right)^2 + z^2 \right]^{1/2}} \]  \hspace{1cm} (3.13)

Eqn. (3.13) can be used to obtain \( \rho_s \)

\[ \rho_s = 2\varepsilon_0 V \left[ \int_a^b \int_0^{2\pi} \frac{r dr d\theta}{\left[ \left( x-r_b \cos \theta \right)^2 + \left( y-r_b \sin \theta \right)^2 + z^2 \right]^{1/2}} \right]^{-1} \]  \hspace{1cm} (3.14)

which can also be used to obtain the magnitude and unit vector, \( \hat{a}_n \), for eqn. (3.4).

\[ \hat{E} = \frac{2\varepsilon_0 V \left[ \int_a^b \int_0^{2\pi} \frac{r dr d\theta}{\left[ \left( x-r_b \cos \theta \right)^2 + \left( y-r_b \sin \theta \right)^2 + z^2 \right]^{1/2}} \right]^{-1}}{2\varepsilon_0 \hat{a}_n} \]  \hspace{1cm} (3.15)

Therefore, the force is equal to

\[ \hat{F} = Q_{\text{totaldrop}} \left( \frac{2\varepsilon_0 V \left[ \int_a^b \int_0^{2\pi} \frac{r dr d\theta}{\left[ \left( x-r_b \cos \theta \right)^2 + \left( y-r_b \sin \theta \right)^2 + z^2 \right]^{1/2}} \right]^{-1}}{2\varepsilon_0 \hat{a}_n} \right) \]  \hspace{1cm} (3.16)
Once the electric field intensity is obtained the resultant force, both magnitude and direction, can be calculated from eqn. (3.3). The force on the drop will result in an acceleration as

$$\ddot{F} = m\ddot{a}$$

where $m$ is the mass of the water drop, and $\ddot{a}$ is the acceleration of the water drop.

$$\ddot{a} = \frac{d}{dt}\ddot{v}$$

Combining eqn. (3.17) and eqn. (3.18), then isolating for velocity yields

$$\ddot{v} = \int \frac{\dot{F}}{m} dt$$

Substituting eqn. (3.16) into eqn. (3.19) gives

$$\ddot{v} = \int_{Q_{totaldrop}} \left\{ \frac{2\varepsilon_0 V}{\frac{rdrd\theta}{\sqrt{(x-r_b \cos \theta)^2 + (y-r_b \sin \theta)^2 + z^2}^{1/2}}} \right\}^{-1} \ddot{a}_n dt$$

As the interest of this section is in the drift velocity the velocity due to gravity and the horizontal component of the total velocity due to the electric field is not considered, leaving

$$\ddot{v}_{drift} = \left( \int \frac{\dot{F}}{m} dt \right) \ddot{a}_x \ddot{a}_y$$

where $\ddot{a}_x, \ddot{a}_y$ are the unit vectors in the horizontal plane.
**Alternating electric field.** The experiments carried out used an alternating field on the test drop, the remaining portion of this section is devoted to the exploration of the effects of this field on a falling charged water drop. The force experienced by the water drop will have the same mathematical expression as above, except that the voltage forcing function will appear as

\[ V = V_{\text{max}} \sin \gamma \]  
(3.22)

Therefore the force on the drops will vary as the voltage applied varies

\[ F \propto \sin \gamma \]  
(3.23)

To determine the drift velocity of a particle of water due to the alternating electric field two components must be found. The drift velocity of the whole drop and the drift velocity due to the movement of the charge in the water drop in the field. The drift velocity of the whole drop can be found by using eqn. (3.21) with the appropriate forcing function substituted in. In any system the sum of the forces involved is equal to the mass times the acceleration, eqn. (3.17). For the system under discussion, finding drift velocity, the total force is the sum of the forces from the two oppositely charged areas, \( Q_a \) and \( Q_b \), of the water drop, see Figure 3.1 and eqn. (3.24).

\[ \vec{F}_{\text{total}} = \sum \vec{F} = \vec{F}_a + \vec{F}_b \]  
(3.24)

Linear momentum is the measure of the momentum of a body represented by the integration of the total force, or conversely the integration of mass times acceleration.

\[ \int \vec{F} \, dt = \vec{L} = m \vec{\dot{v}} \]  
(3.25)

From eqn. (3.25) velocity can be isolated as
\[ \dot{v} = \frac{\int \vec{F} \, dt}{m} \]  

(3.26)

The rate of change of angular momentum, a measure of rotation about a fixed point, defined as the origin in this case, is the sum of all angular moments [36]

\[ \vec{M}_o = \sum_i \vec{M}_{oi} = \dot{\vec{H}}_o \]  

(3.27)

To obtain angular momentum integrate the sum of all the angular moments

\[ \int \dot{\vec{M}}_o \, dt = \dot{\vec{H}}_o \]  

(3.28)

Moments are equal to linear momentum times the radial arm [36], eqn. (3.35). The radial arm is the distance from a fixed point, the origin in this case, to the location where the linear momentum is acting. To find the radial arm the vector from the origin to the centre of the water drop must be found

\[ S_o = \sqrt{x_c^2 + y_c^2 + z_c^2} \]  

(3.29)

The direction of \( S_o \) can be obtained in spherical co-ordinates as

\[ \theta = \tan \frac{z}{x} \]  

(3.30)

and

\[ \phi = \tan \frac{y}{x} \]  

(3.31)
Once the vector from the origin to the centre of the drop is found the radial arm can be obtained by adding, using vector addition, the displacement of the charge from the centre of the water drop.

\[ \hat{R}_{arm} = \hat{S}_o \pm d_{a/b} \hat{k} \]  

(3.32)

For angular momentum the radial arm is perpendicular to the direction of the applied force[36], therefore

\[ \hat{R}_{parm} = S_0 \hat{k} \pm d_{a/b} \hat{k} \]  

(3.33)

where \( \hat{k} \) is a unit vector in the z-axis and \( d_{a/b} \) is

\[ d_{a/b} = d_{max/\max} \sin \gamma \]  

(3.34)

\( d_{max} \) is the maximum distance the charge will travel above the centre of the water drop, and \( d_{min} \) is the maximum distance the charge will travel below the centre of the drop. This distance is assumed to only occur in the z-axis. The charges \( Q_aQ_b \) are assumed to be moving relative to the centre of the water drop as the external voltage varies, hence the distance the charges are from the centre varies as \( \sin \gamma \).

The moment can be expressed as

\[ \hat{H}_o = \hat{R}_{parm} \times \hat{L} \]  

(3.35)

Combining eqn. (3.35) and eqn. (3.25) results in

\[ \hat{H}_o = \hat{R}_{parm} \times m \hat{v} \]  

(3.36)
velocity can be given as angular velocity, \( \omega \), times its radial arm [36]. Substituting this into eqn. (3.36) and then into eqn. (3.28) gives

\[
\int \dot{M}_0 dt = \dot{R}_{arm} \times m(\ddot{\omega} \times \dot{R}_{arm})
\]

(3.37)

But [36]

\[
\dot{M}_0 = \dot{F} \times \dot{a}
\]

(3.38)

and [36]

\[
\ddot{\omega} = \frac{\dot{v}_{o/p}}{\dot{R}_{arm}}
\]

(3.39)

Where \( \dot{v}_{o/p} \) is the velocity of the particle with respect to the origin. Therefore by substituting eqn. (3.38), eqn. (3.39), and eqn. (3.32) into eqn. (3.37) one obtains

\[
\int (\dot{F} \times \dot{a}) dt = ((S_0 \dot{k} \pm d_{a/b} \dot{k})) \times m\left(\frac{\dot{v}_{o/p}}{(S_0 \pm d_{a/b} \dot{k})} \times ((S_0 \pm d_{a/b} \dot{k}))\right)
\]

(3.40)

With the alternating field used to determine the force in eqn. (3.16), eqn. (3.40) can be rewritten as

\[
\int Q_{total \_ drop} \left\{ \frac{2\epsilon_0 V \int_{a_0}^{b_0} 2\pi r dr d\theta \left[ (x - r_b \cos \theta)^2 + (y - r_b \sin \theta)^2 + z^2 \right]^{1/2}}{2\epsilon_0} \right\}^{-1} \dot{a}_n \times \dot{a} dt
\]
\[
\frac{\vec{v}_{o/p}}{m} \times \left( \frac{\vec{S}_o \pm d_{a/b}\hat{k}}{\vec{S}_o \pm d_{a/b}\hat{k}} \right) \times \left( \frac{\vec{S}_o \pm d_{a/b}\hat{k}}{\vec{S}_o \pm d_{a/b}\hat{k}} \right)
\]

(3.41)

Isolate \(\vec{v}_{o/p}\) and substitute into

\[
\vec{v}_{\text{total}} = \vec{v}_{\text{translation}} + \vec{v}_{o/p}
\]

(3.42)

Where \(\vec{v}_{\text{total}}\) is the total drift velocity of the water drop in an alternating field.

The goal of the experiments described in the thesis was to determine the validity of the electrostatic injection system, the in-depth mathematical analysis is not necessary at this time and is left for future research. This problem is addressed via finite element analysis.
Vita Auctoris

"Orion Bruckman", born June 13th, 1975 in Windsor, Ontario Canada. Orion attended the University of Windsor, where he obtained his Honours Bachelor of Applied Science in Electrical Engineering in 1998. Orion attended the University of Windsor where he completed his Masters of Applied Science in Electrical Computer Engineering in VLSI and MEMS design.