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# PERFORMANCE IN ENHANCEMENT OF MICROFLUIDIC-BASED CAPACITIVE PRESSURE SENSOR

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DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS
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(PHYSICS)

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# ABSTRAK

Kajian ini bertujuan untuk meningkatkan prestasi penderia tekanan kapasitif berasaskan mikrobendalir menggunakan membran berbentuk segi empat sama dan mikrosalur berbentuk elips dan segi empat sama. Kajian ini juga menyiasat penderia tekanan menggunakan propilena karbonat sebagai elektrolit dari segi takat didih dan pemalar dielektrik. Penderia tekanan berasaskan mikrobendalir menyiasat untuk pengukuran tekanan dengan menggunakan corak mikrosalur berbentuk segi empat sama dan elips. Apabila tekanan dikenakan pada membran, ia memberikan pesongan dan menyesarkan cecair di dalam mikrosalur. Pergerakan cecair menyebabkan perubahan dalam kapasitan. Semasa peringkat reka bentuk, analisis simulasi pada dua struktur membran yang berbeza termasuk, segi empat sama dan segi empat tepat telah dikaji. Tambahan juga, dua reka bentuk mikrosalur termasuk elips dan segi empat sama telah direka dan disimulasi. Reka bentuk penderia yang dimuktamadkan difabrikasi menggunakan proses litografi lembut, papan litar cetakan (PCB) dan proses pengedapan. Kemudian, penderia tekanan berdasarkan bendalir telah dicirikan berdasarkan mekanism bendalir, pengukuran tekanan, kesan suhu dan kesan jangka hayat. Dapatan ujikaji menunjukkan bahawa mekanism bendalir untuk mikrosalur berbentuk elips meningkat secara linear apabila tekanan meningkat berbanding bentuk segi empat sama yang tak linear. Untuk pengukuran tekanan, peratusan ralat histeresis diperolehi untuk saluran mikro bentuk elips adalah 0.6% yang mana agak rendah berbanding mikrosalur berbentuk segi empat sama yang mana ralat 23%. Untuk kesan suhu bagi mikrosalur berbentuk elips, kapasitans telah meningkat kira-kira 0.86% dari 20 hingga 50 $^{o}$C yang mana sesuai untuk penderia beroperasi pada suhu bilik. Penggunaan propilena karbonat meningkatkan jangka hayat penderia kerana ciri takat didihnya. Kesimpulannya, penderia tekanan kapasitif berasaskan bendalir berjaya dibangunkan menggunakan mikrosalur berbentuk segi empat sama dan elips. Mikrosalur berbentuk elips adalah terbaik dalam prestasi berbanding mikrosalur berbentuk segi empat sama. Untuk implikasi penyelidikan, ia dapat digunakan oleh penyelidik sebagai panduan dan rujukan terutama dalam pembangunan penderia tekanan.

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# PERFORMANCE IN ENHANCEMENT OF MICROFLUIDIC-BASED CAPACITIVE PRESSURE SENSOR

## ABSTRACT

This study aims to enhance the performance of microfluidic-based capacitive pressure sensor using square membrane shapes and ellipse and square-shaped microchannel patterns. This study also investigates the pressure sensor using propylene carbonate as electrolyte in term of boiling point and dielectric constant. The microfluidic-based capacitive pressure sensor investigates for pressure measurement by using square and ellipse-shaped microchannel patterns. When a pressure was applied on to the membrane, it provides deflection and displaces the liquid inside the microchannel. The liquid movement induces changes in capacitance. During the design stage, a simulation analysis on two different membrane structures, including square and rectangular, were studied. In addition, two different microchannel designs, including ellipse and square shape pattern, were designed and simulated. The finalized sensor design was fabricated using soft lithography, printed circuit board (PCB) and sealing process. Then, a fluidic-based pressure sensor was characterized based on fluid mechanism, pressure measurement, temperature effect and lifetime effect. The experimental result showed that the fluid mechanism for the ellipse-shaped microchannel was linearly increased as the pressure increase compared to the square shape which was non-linear. For pressure measurement, error percentage of hysteresis was obtained for the ellipse-shaped microchannel is 0.6% which was quite low compared to the square-shaped microchannel, which is 23% of error. For the temperature effect of the ellipse-shaped microchannel, its capacitance increased about 0.86% ranging from 20 to 50 $^{o}$C, which is suitable for a sensor to operate at room temperature. The use of the propylene carbonate increased the lifespan of the sensor due to its boiling point property. In conclusion, a fluidic-based capacitive pressure sensor was successfully developed using a square and an ellipse-shaped microchannel. The ellipse-shaped microchannel showed excellent performance than the square-shaped microchannel. For the research implication, it can be used by researchers as a guideline and reference especially in developing pressure sensors.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| Ag | Silver |
| Au | Aurum/gold |
| BAP | Barometric air pressure |
| CFD | Computational fluid dynamic |
| CPDMS | Polydimethylsiloxane |
| Cr | Chromium |
| DIY | Do it yourself |
| EDLC | Electric double layer capacitance |
| EGaln | Euteclic Gallium Indium |
| FEA | Finite element analysis |
| $FeCl_2$ | Ferric chloride |
| FEM | Finite element modeling |
| FPCB | Flexible printed circuit board |
| FR-4 | Flamable Retardant 4 |
| FSR | Force sensitive resistor |
| GVS | Ground view sensor |
| HF Etchant | Hydrofluoric Acid Etchant |
| LPCVD | Low pressure chemical vapor deposition |
| MAP | Manifold absolute pressure |
| MEMS | Microelectronic mechanical system |
| Np | Nanoparticle |

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| | |
|---|---|
| Nws | Nanowires |
| PCB | Printed circuit board |
| PDMS | Polydimethylsiloxane |
| PECVD | Plasma enhanced chemical vapor deposition |
| PI | Polyimide |
| PVDF | Polyvinylidene fluoride |
| R-C | Resistance-Capacitance |
| SOI | Silicon on insulator |

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# LIST OF SYMBOLS

| | |
|---|---|
| $\Delta C$ | Change of capacitance |
| $\Delta L$ | Liquid movement in microchannel |
| A | Surface area of force stick |
| a | Surface area of membrane |
| A | Surface area of electrode |
| C- | Negative charge capacitance |
| C+ | Positive charge capacitance |
| $C_D$ (E) | Capacitive down ellipse |
| $C_D$ (S) | Capacitive down square |
| $C_o$ | Initial capacitance |
| $C_U$ (E) | Capacitive up ellipse |
| $C_U$ (S) | Capacitive up square |
| D | Flexural rigidity |
| d | Thickness insulator |
| E | Elastic modulus |
| F | Force |
| h | Membrane thickness |
| L | Length of displacement of liquid in channel |
| l | Liquid movement |
| $L_o$ | Initial Liquid Movement |
| P | Pressure |

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| | |
|---|---|
| $P_D$ | Pressure down |
| $P_o$ | Initial pressure |
| $P_U$ | Pressure up |
| R | Radius of membrane |
| $R^2$ | Linear regression |
| $t_c$ | thickness channel |
| $t_{PDMS}$ | Thickness layer of PDMS |
| v | Poisson's number |
| $V_{liquid}$ | Volume of liquid |
| $V_{membrane}$ | Volume of membrane |
| W | Membrane deflection |
| w | Width microchannel |
| $w_c$ | Width channel |
| $\varepsilon_{PDMS}$ | Dielectric constant of PDMS |
| $l$ | Length |
| $\varepsilon_o$ | Permittivity of vacuum |
| $\varepsilon_r$ | Dielectric constant |

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# CHAPTER 1

# INTRODUCTION

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## 1.1 Background

The first pressure sensor built was the silicon micromachined sensor pressure which was built five decades ago by a researcher known as (Gieles, 1969). In recent years, the pressure sensor has gained popularity and have been developed into micro-electro mechanical system (MEMS) for the commercial sector. It is used in automotive, industrial, medical, military and consumer applications (DeHennis, Chae & Baroutaji, 2016). The pressure sensors have features such as low cost, low power consumption, small size and lightweight in automotive, industrial, medical, military and consumer applications (Suter et al., 2013; McDonand et al., 2000; Antony, Nandagopal, Sreekumar & Selvaraju, 2014; Singh, Joyce, Varghese & Akhtar, 2015). The uses of pressure sensor in MEMS technology provide advance optimization of the sensor such as dynamic range, calibration, frequency response, accuracy, linearity,

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sensitivity, size, data acquisition and handling as well as, temperature dependence reduction. Besides that, there are many types of pressure sensors such as piezoresistive sensors, capacitive sensors, resonant sensors, pirani sensors and optical sensors that are used in a variety of applications such as automotive, industrial, biomedical and other applications.

For capacitive-type sensors, It are able to detect and measure a variety of physical and chemical quantities such as pressure, temperature, humidity, strain, displacement and motion, acceleration, flow, concentration of gases and chemical species and many other variables (Puers, 1993; Ferrari & Prudenziati 2012). The principal of capacitive-type sensors have advantages over inductive, optical, and piezoresistive sensors which are increased pressure sensitivity, decreased sensitivity of temperature, low-power work of the system (Eaton & Smith, 1997), high resolution, low power consumption, and reduced fabrication cost, where stability and reproducibility are related to the construction and materials cost (Ferrari & Prudenziati 2012). Generally, capacitive-type sensors are based upon parallel plate capacitors (Eaton & Smith, 1997). Capacitive sensor is generating an electrical signal based on the elastic deformation of a membrane (Puers, 1993). Thus, the general structure of a capacitance sensor is illustrated in Figure 1.1 that has a surface plate set, A and is separated by a gap or distance d (Puers, 1993).

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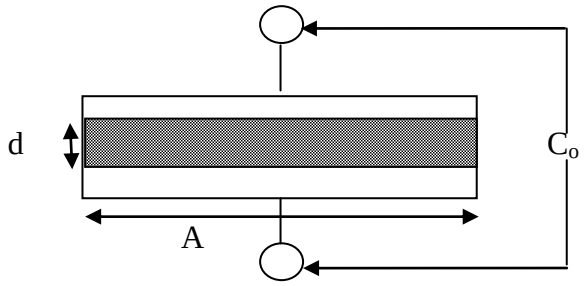




*Figure 1.1*. Schematic of general structure of a capacitance sensor with surface plates set, A and thickness, *d*

Apart from that, many types of pressure sensors such as piezoresistive, capacitive, optical, resonant, and pirani sensors use transducer technology in MEMS technology devices. However, MEMS based pressure sensors exist in a variety of forms in terms fabrication technology. Thus, pressure sensors have been focused in piezoresistive, piezoelectric, capacitive and strain gage only where the fabrication of these types of sensing elements use silicon as a main material for micromachined pressure sensors and involve a complex fabrication technique (Nawi, Manaf, Rahman, Arshad, & Sidek, 2014), such as depositions and sacrificial layer etching which require more precise control (Suter et al., 2013).

The MEMS technology has garnered a great deal of attention in recent years due to increased miniaturization and performance of devices (Eaton & Smith, 1997). However, using silicon as the material makes it difficult to miniature and increase the performance of devices. Besides that, a conventional capacitive-type of sensor which is the parallel-plate shown in Figure 1.1 is complex and difficult to miniaturize. Thus, microfluidic based capacitive-type sensors have been developed. The development of the microfluidic technique as an alternative to replace the conventional capacitive sensor is due to fabrication complexities. In a fluidic based capacitive, there are many

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types of sensors that use this system, including pressure sensors and temperature sensors (Antony et al., 2014). It offers a simple fabrication process and a simple sensing technique that require a small amount of liquid to create the value capacitance (McDonald et al., 2000). Generally, conventional capacitive-type sensors have two electrodes that are parallel. However, the fluidic based sensor uses a coplanar electrode design which is located side by side inside the microchannel. Thus, the fluid-based sensor is divided into two main parts, which are the membrane and microchannel.

For the fluid-based capacitive pressure sensor, the membrane is used as the main sensing area which indicates changes based on external pressure. Commercially, flat membranes are commonly used in pressure application while the dome membranes are only used in flow application and is used less in the pressure application. The dome membrane has been used for pressure application in a previous study (Saint, Ahmad, & Patra, 2016). There are three types of flat membrane shape designs that use pressure. There are square, rectangular and circular flat membrane designs. The most used shape of membrane is the circular shaped membrane. The other shapes of membrane including square and rectangular have been developed and tested using simulation to compare the both.

Besides that, the microchannel is the most important part of a fluidic based sensor system. The microchannel is used in a variety of mechanism to consolidate the single-phase flow of liquid. Fluid technology have been implemented using a coplanar electrode design which consists of two electrodes in one channel in the detection of microdroplets in the microchannel. (Elbuken, Glawdel, Chan, & Ren,

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2011) the acoustical processes (Rahman, Arshad, Manaf, & Yaacob, 2011) and underwater microfluidic based sensor (Rahman, Manaf, & Arshad, 2013). Apart from that, electric double layer principle capacitance (EDLC) principle was used to measure the pressure (Nawi et al., 2014) and to measure the angle changes in inclinometer sensor (Manaf, Nakamura, & Matsumoto, 2008). However, the design of the microchannel pattern in a previous study by (Nawi et al., 2014; Rahman et al., 2011) was a straight microchannel which had a large sensor.

Using the right material is important for the designing of fluidic based sensors. Commonly used materials in microfluidic system are Polyimide (PI) and Polydimethylsiloxane (PDMS). PI has high resistance against many chemicals, high glass transition temperature, high dielectric constant and biocompatibility (Zulfiqar, Pfreundt, Svendsen & Dimaki, 2015). Meanwhile, PDMS is one of the major materials used in polymer microfluidics because of material elasticity, and gas permittivity. The PDMS is used as a material for fluidic based sensors due to complex fabrication process. Fabrication process of polymer is including the fabrication of the microchannel and membrane.

## 1.2 Problem Statement

The advancement of the sensor technologies which is MEMS technology has led to the development of micro machined sensors such as pressure, flow, accelerometers, tilt devices and others. Enhancement of sensor design using silicon as material involves a complex fabrication technique, such as depositions and also sacrificial

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layer etching which requires more precise control (Suter et al., 2013). The implementations of the microfluidic system to the sensor continues to grow because it offers a simple sensing mechanism which only uses a small amount of liquid to operate the capacitive pressure sensor. In addition to that, using a Polydimethylsiloxane (PDMS) as a material, can easily create any type of geometry for various applications (Eswaran & Malarvizhi, 2012).

Generally, a microfluidic based pressure sensor consists of two electrodes which are located side by side, one is a sensing electrode and other is s common electrode. When pressure is applied to the membrane, it deforms and displaces. The liquid inside microchannel will move and the sensing electrode will sense the movement. It will give a capacitance changes which depends on the liquid distance. Based on previous research, the size of the sensor which consist of microchannel and coplanar electrode is large due to the straight design of the microchannel pattern (Yunus, Halin, Sulaiman, Ismail & Sheng, 2015; Almassri et al., 2015). It is also difficult to miniaturize the sensor. Therefore, the new microchannel sensor design pattern needs to be enhanced. From the previous research, the design is improved by increasing the length of microchannel, 44mm (nawi, one) to 60 mm for my research. The pattern of sensor in previous research, is rectangle shape for the sensor and the pattern of channel is straight shape line. From my research is, the pattern of sensor is square shape for the sensor and the pattern of channel is ellipse shape line and square shape line. So, the previous research of pattern of sensor is large than of pattern of sensor in my research due on the pattern of sensor and the pattern of channel designs. Besides that, the performance based on the hysteresis of the sensor is smallest of value in last previous. However, in my research, the hysteresis of the sensor is

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smallest than previous research (Nawi et al., 2014). For the liquid selection, liquid such as methanol has limitation in terms life span. It can sustain only for about 6 hours before it completely evaporates (Nawi et al., 2014). The propylene carbonate seems to have many advantages including high dielectric constant and high boiling point. Hence, an experiment on the sensor using propylene carbonate will be carried out to enhance the sensor performance, especially to improve longevity and also to increase sensitivity of the sensor.

## 1.3 Research Objective

The main objective of this research:

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I. To design microfluidic based capacitive pressure sensor using square membrane shapes and ellipse and square shaped microchannel patterns.

II. To investigate the microfluidic based capacitive pressure sensor for pressure measurement by using square and ellipse shaped microchannel pattern.

III. To investigate the pressure sensor using propylene carbonate as electrolyte (liquid) in term of boiling point and dielectric constant.

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## 1.4 Scope of study

In this subsection, it will discuss about the progress in my research. It have three stage, simulation, fabrication and characterization.

First, simulation. There are four parameter that measure in this simulation, type of shape of membrane, type of material to fabricate, the size of thickness membrane and the shape of channel. For the shape of membrane, selected to design, rectangular and square and the material are Polydimethylsiloxane (PDMS) and Polyimide (PI). Besides that, the size of thickness membrane is 1mm to 10mm is selected and shape of channel, ellipse and rectangular shape design is selected.

For fabrication process, there are two stage in this process. First is fabricate the sensor based and second is sealing process. For the fabrication process, the process involves two stages which are electrode printing process and mold of container of the sensor. The process of electrode printed have five stages which are design pattern (AUTODESK EAGLES), printing (LASER PRINTING), exposure (UV LIGHT BOX), developer (BEAKER DEVELOPING) and etching (MACHINE BEAKER ETHING), that process is called printed circuit board (PCB). This process is only printed in size millimeter of minimum size. For stages of exposure, developer and etching, the time taken is involved in this stage. The process made the PDMS based the sensor. The soft lithography process is used for this stage, to make the PDMS based the sensor. In the making the PDMS based the sensor, the material (PDMS) has been mixed well and to pour in the mold of container of the sensor until full. The material is poured as manually in the mold of container of the sensor to

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become material of based sensor (PDMS based sensor) which is difficult to make sure that is the material is poured whether it is full or more full that can be effect in the performance of sensor by on the surface sensor which is the size of thickness layer membrane.

The size 0.7 mm is selected for thickness membrane due to remove the material that easy broken below 0.7 mm. Before the material is poured in the mold of container of the sensor, the mold is made by using the 3D printed. Next is sealing process. For sealing process, this process is used for seal between electrode broad with the PDMS based the sensor by has a layer coated on the electrode broad using spin coater and it will harder in the oven. This process to seal the two main part by manually that need accurate and precise.

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For characterization, this process involves for test the liquid (electrolyte) in the channel. The test liquid is depending of the parameter of that liquid, boiling point, dielectric constant and viscosity. So, the selected test liquid is methanol and propanol carbonate (PC). After selected liquid to test, that liquid will used in the sensor for operating frequency, linearity and hysteretic, temperature and lifetime. The pressure value is used from 1kPa – 10kPa which is that value of pressure used based on the thickness of membrane, 0.7 mm. The sensor is depending on the lifetime of sensor which is the sensor is depend on the liquid that used in the channel based on the parameter of liquid its, boiling point.

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## 1.5 Summary of Contributions

In this research, a flat-shaped membrane was developed for pressure measurement using a fluidic system. The sensing mechanism was realized using coplanar electrode to create a form an ionic layer. Besides that, using this concept created the value of capacitance. This concept of sensing has been proved appropriate for pressure measurement (Nawi et al., 2014). The summary of the contributions of this study are:

I. Fluidic based pressure sensor consists of two-side electrode and a PDMS container was used which offers simple structure and sensing. It used a small amount of liquid to operate for pressure measurement.

II. PDMS was chosen as the material for the membrane. It was easy to fabricate using a soft lithography process and electrode printing was executed using printed circuit board (PCB).

III. Two different microchannel pattern with coplanar electrode, the ellipse shaped electrode and square shaped electrode were chosen to study the mechanism fluid and sensor performance.

## 1.6 Thesis Organization

Chapter 1 provides an overview of the pressure sensor and microfluidic based capacitive pressure sensor. The problem statements, research objectives, research scope and a summary of contribution were also presented.

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Chapter 2, presents the literature review which includes the pressure sensor in MEMS, principle of sensor, material used and fabrication process, microfluidic based sensor, coplanar electrode, characterization and simulation tool.

Chapter 3, is primarily concerned with the design and methodology employed in this research study for the fabrication process. A simple fabrication process for the sensor using PDMS material and electrode printing were explained and the characterization of the sensor was also included in this chapter.

Chapter 4 presents the results and discussions obtained from the fabrication and characterization. Apart from that, the fluid mechanism test of the pressure sensor was implemented with a fluidic system for the coplanar electrode, ellipse shape and square shape was also included.

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Chapter 5 concludes the research and provides future research recommendations for enhancement of a fluidic based pressure sensor.

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# CHAPTER 2

# LITERATURE REVIEWS

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## 2.1 Introduction

This chapter is discussed about literature reviews in overview of pressure sensor in MEMS technology, principle of detection pressure, material used and fabrication process, sensor characterization, microfluidic based sensor and coplanar electrode, simulation tool.

## 2.2 Overview of Pressure Sensor in MEMS Technology

Sensor is a technology which a very important for controlling systems The role of sensor is important of sensor technology has been increasingly explored in system for a few decades ago in order to implement in remarkable advancements for data or

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information of transmits such as manifold absolute pressure sensor (MAP sensor), barometric air pressure (BAP), and safety enhancement. There are a few of type of sensors used, as shown in Figure 2.1 as counting pressure sensor, flow sensor and optical sensor. A pressure sensor is needed for a sense of pressure of object in order to operate in rough environment (Sparks, 2013). For last decades, microelectromechanical systems (MEMS) technologies have been demonstrated with ever amazing facility with MEMS processing have also grown (Fleming, 2001). The sensor for MEMS technology has been design in last decades. MEMS technology is used in optical, flow and pressure sensor.

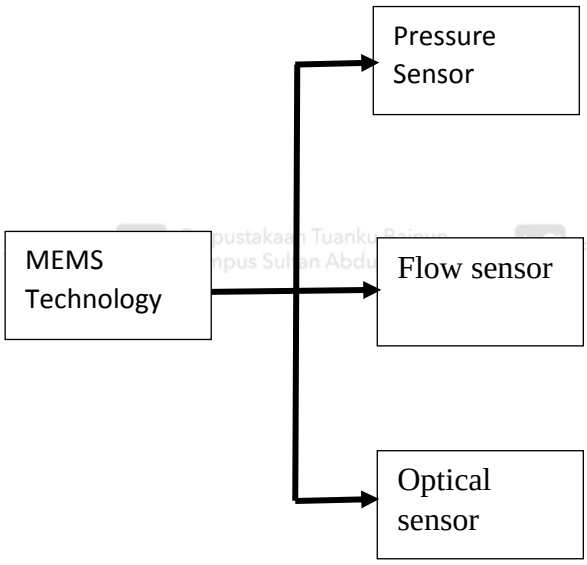



*Figure 2.1*. Several of sensor for MEMS Technology

The development of fabrication technology such as MEMS technology that gives advantages in size power consumption, size, fast response and high reliability (Eswaran & Malarvizhi, 2013; Melani et al., 2008; Chen and Liu 2003) but involves in technique of complex fabrication (Gentili, Tabaglio & Aggogeri, 2005). A pressure sensor is the sensor that measures the pressure, typically of gases or liquids which it is started by a scalar measure-type sensor to measure pressure to the vector measure-

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type sensor which that to measures velocity and pressure component value in pressure field that have been designed.

Pressure is an expression of the force required for to stop a gas or fluid from expanding, and is usually stated in terms of force per unit area. A pressure sensor is generating a signal related to the pressure imposed. By micro-electromechanical systems (MEMS), this technology uses for three other of sensing mechanisms in pressure sensor are rapidly used are piezoresistive, capacitive and piezoelectric (Eaton & Smith, 1997). The uses of this technology, the three of type of pressure sensor have been successfully design in automotive application. However, the development of the sensors in automotive application is still going on and a lot of particular designs have been proposed. A new approach has been found in order to improve the performance of sensor which investigating of mechanism in fluidic field sensing. The development of the automotive application of sensors has been increasingly in the past few years, especially for pressure sensor from fluidic sensing. In the following section, a review of the principle of pressure detection, including material used, fabrication, and characterization will be discussed.

## 2.3 Principle of Pressure Detection

Most of the pressure sensor has a pattern but have the different of principle of detection and materials. In this section, capacitive type of detection principle of pressure sensor is discussed. The capacitive is the generally have two parallel electrodes in commercially.

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The pressure is detected by make the sensor include the performance like linearity, accuracy, reliability, retrofit, versatility, recalibration cost, lifetime, robustness and simplicity. The capacitive type-based pressure sensor has been developed with two electrodes for the detection principle that is one of them is movable membrane and the other one in under by silicon substrate (Lei, Lee, & Lee, 2012; Lei, Lee, & Lee, 2014). Figure 2.2 is showing the principle of detection with one electrode at top movable membrane and other one in silicon substances.

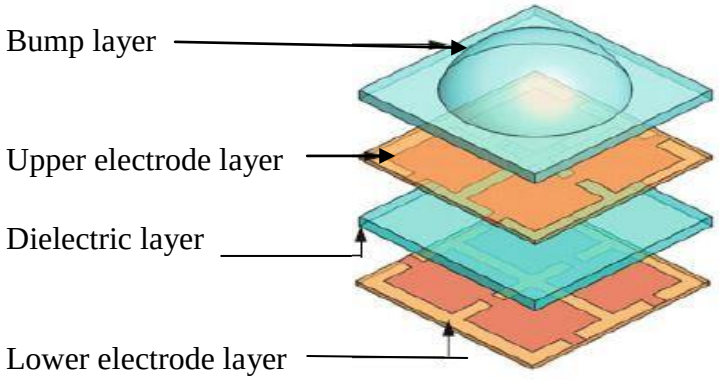



*Figure 2.2*. The design of capacitive pressure with two electrode layer, upper and lower. Source: Adapted by Lei, Lee, and Lee (2012)

Besides that, in year 2014, Lei, Lee, & Lee, *(*2014) have demonstrated and proposed again that the sensor system of shoe-integrated that can measure directly using the force-sensitive resistors (FSRs) which integrated in the shoes for plantar pressure. Figure 2.3 is show the structure of the capacitance sensor. Apart from that, polyinylidene fluoride (PVDF) film have been proposed which have high permittivity of flexible polymer materials for the dielectric layer, and high sensitivity (Shuai et al., 2017).

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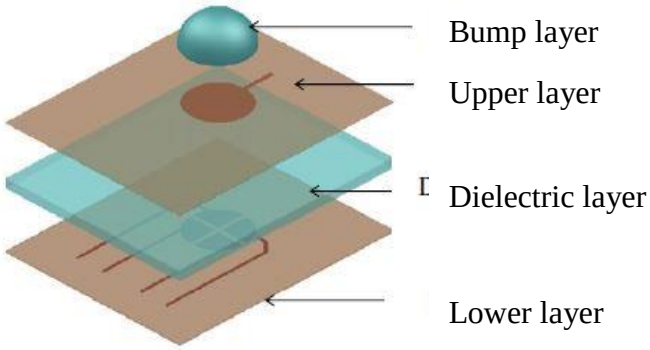




*Figure 2.3*. The design of structure of capacitance sensor. Source: Adapted by Lei, Lee, and Lee (2014)

Apart from that, PDMS membrane with the flat membrane have been proposed which have high sensitivity, that on the top membrane where it will reduces the capacitance based on the membrane deflection and fluid flow in channel using microfluidic technology (Nawi et al., 2014; Rahman, Nawi, Manaf, & Arshad, 2014) is show in Figure 2.4. Although the sensor has different structure but the materials and the principles of sensing are slightly different. Therefore, the materials used in capacitive type pressure sensor have been discuss in the next section.

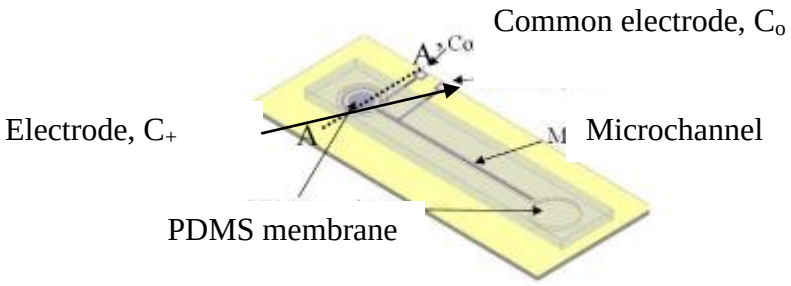



*Figure 2.4*. Illustration of the structure of the fluidic based one side electrode type pressure sensor. Source: Adapted by Nawi, Manaf, Rahman, Arshad, and Sidek, (2014)

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## 2.4 Materials Used and Fabrication Process

In this section, the different of sensing element as a material used and the fabrication complexity has been presented. A review has been made of the design of sensor from 2009 to 2017. Table 2.1 is showing the process fabrication involves for the pressure sensor. Therefore, the capacitive type only shows in Table 2.1.

For capacitive type sensors, the sensor is fabricated by carry out the membrane using the different materials such as Cr, Al and oxide sacrificial layers. The one plate is fixed and one plate is plate as electrode. Commonly using the technique include low pressure chemical vapor deposition (LPCVD) for depositing a layer of composite silicon oxide and silicon nitride that, where on the Silicon on Insulator wafers (SOI) during layers of structure polysilicon. The oxide sacrificial layer is fabricated by using LPCVD and patterned by follow the structure polysilicon form the plate moving of the capacitor. The same process is used for to define the cavity and the sensing gap and following the plasma enhanced chemical vapor deposition (PECVD) for seal the holes in the fixed plate after remove oxide layer from the cavity by using a HF etchant in the holes (Zhang, Howver, Gogoi and Yazdi, 2011).

For soft-lithography technique, this techniques has been used to obtain the shape of sensor by poured the material, PDMS in the mold that design by using rapid machine (3d printing) with the different of material sensing, copper (Nawi et al., 2014; Lei et al., 2012; Mitrakos, Macintyre, Denison, Hands, & Desmulliez, 2017), and titanium (Mitrakos et al., 2017). The screen printing and 3d printing technique was used by Narakathu et al, (2012) and Zhuo, Chen, Zhao and Guo, (2017) for

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flexible capacitance pressure sensor using Ag Np as material sensing and high sensitivity flexible capacitive pressure sensor with elastomer dielectric layer micro-structured which is with using material sensing, copper tape. Besides that, Han and Shannon (2009) using fabricated method, which epoxy bonding contact printing method that polyimide material is used for smooth contact of capacitive pressure sensors for operation in touch and peeling mode. The sensing material is Cr/Au/Cr layer for electrode is involved (Han & Shannon, 2009).

For the PDMS material, the photolithography techniques is used for carry out to obtain the membrane of shape which the spin coated, and baked are involved (Lei et al., 2012; Lei et al., 2014). Shuai et al., (2017) using the technique, 3D morphology for embedded polydimethylsiloxane (PDMS) and PVDF electrode with microarray structure and material sensing is silver nanowire (AgNw). Due to fabrication complexity, a suitable technique and material is appropriate to reduce the difficulty of fabrication process.

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Table 2.1

*Different of materials and fabrications of the capacitive type pressure sensor.*

| | References | Sensing Material | Membrane Material | Fabrication |
|---|---|---|---|---|
| 1 | Han & Shannon (2009) | Cr/AU/Cr | Polyimide | Epoxy bonding contact printing method |
| 2 | Zhang et al., 2011 | Silicon Wafer (Silicon On Insulator) | Oxide Layer | Low Pressure chemical vapor deposition |
| 3 | Narakathu et al., 2012 | Silver (Ag) nanoparticle (Np) | PDMS | Screen Printing |
| 4 | Lei et al., 2012 | Copper | PDMS | Photolithography |
| 5 | Lei et al., 2013 | FPCB | PDMS | Photolithography |
| 6 | Woo et al., 2014 | CPDMS ink | PDMS | Soft- lithograph |
| 7 | Nawi et al., 2014 | Copper | PDMS | Soft lithograph |
| 8 | Shuai et al., 2017 | Silver nanowires (AgNWs) | PVDF | 3D morphology |
| 9 | Zhuo et al., 2017 | Copper tape | PDMS | -3D printing |
| 10 | Mitrakos et al., 2017 | Copper and titanium | PDMS | -Soft lithography |

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## 2.5 Sensor Characterization

The measurement of pressure rate in establish the pressure sensor is fundamental in order to prove its capability. Table 2.2 is showing the different pressure characterized of the pressure sensor. The most of researcher is characterized to measurement of pressure rate either at low- or high-pressure measurement. Zhuo et al., (2017), characterized the measurement the presssure for sensitivity, for higher, low detection limit, good tolerance, fast response and durability of excellent. Narakathu et al., (2012), also characterized by varying compressive force that observed that the minimum and maximum detectable pressure was 800 kPa and 18 MPa, respectively.

The characterization of pressure measurement for pressure sensor, which touch and peeling mode have been developed by Han and Shannon (2009). The sensitivities of peeling-mode are higher than touch-mode sensitivities which by an order of magnitude for each cavity shape sensor. Thus, the different from touch-mode capacitive sensors, the peeling- mode capacitive sensor is needing a dc voltage to actuate, and a limited is showing in the capacitance response but in the low-pressure regime of linear response is less than 1000 Pa (Han & Shannon, 2009).

Most of the researchers focused their design for air, plantar (Lei et al., 2012; Lei et al., 2014) and human skin (Woo et al., 2014) application. For plantar application, it is used for measure the pressure which that the pressure sensor is put into the shoe. Besides that, human application for detect the pressure which is depend on the sensor where is placed and movement of sensor. Therefore, a suitable sensing mechanism need be examining in order to enhance the sensing capability.

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Table 2.2

*Different of pressure characterization of the capacitive type pressure sensor.*

| | References | Sensing environment | Characterization | Notes (Advantages or Limitation) |
|---|---|---|---|---|
| 1 | Han & Shannon (2009) | Air | Pressure measurement<br>-Touch mode<br>-Peeling mode | -Lower power comsumption |
| 2 | Zhang et al., 2011 | Air | Pressure measurement | -Large sensor size |
| 3 | Narakathu et al., 2012 | Air | Varying compressive force | -Flexibility, and low manufacturing temperature |
| 4 | Lei et al., 2012 | Human | Pressure measurement | -Measurement limit |
| 5 | Lei et al., 2014 | Human | Pressure measurement | -Durable, highly flexible (FPCB) |
| 6 | Robert et al., 2013 | Air | Measuring shaer and pressure deformation | - |
| 7 | Woo et al., 2014 | Human | Pressure measurement | -Electrical and mechanical performance |
| 8 | Nawi et al., 2014 | Air | Pressure measurement | -Methanol is easy evaporated at the 6 hours |
| 9 | Shuai et al., 2017 | Air | Pressure measurement | -Simple and low-cost strategy |

(*Continue*)

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Table 2.2 (*Continue*).

| | References | Sensing environment | Characterization | Notes (Advantages or Limitation) |
|---|---|---|---|---|
| 10 | Zhuo et al., 2017 | Air | Pressure measurement | -Higher sensitivity |
| 11 | Mitrakos et al., 2017 | Air | Pressure measurement | -Enable small, compact, and cost-effictive sensors |

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## 2.6 Microfluidic Based Sensors And Coplanar Electrode

The microfluidic based sensors offer many advantages and give a lot of attraction in many applications counting in medical, underwater, industrial, chemical and automotive. There are a lot of types of microfluidic sensors, including pressure and flow sensor.

For a microfluidic pressure sensor, the researchers have been developed based on the membrane deflection (Liechtenebrg & Hierlemann, 2005; Sekimori, Yoshida, & Kitamori, 2004; Nawi et al., 2014; Rahman et al., 2014) which to measure the pressure rate with the movement of liquid in channel. The fluid rate in pressure sensor is measured by the force on the membrane and the liquid movement in channel through the surrounding electrical result. Touch mode type sensor has been developed a last decade before microfluidic type sensor is develop. Touch mode type pressure sensor has been used for high pressure environment. Meanwhile, the microfluidic pressure sensor has been developed by used a thermal principle that to measure the flow rate inside the channel in (Dijkstra, Lammerink, Wiegerink, & Elwenspoek, 2006; Dijkstra et al., 2007; Dijkstra et al., 2008; Mizuno, Liger, & Tai, 2004; Wu, Lin, Yuen, & Tai, 2001; Patsis, Petropoulos, & Kaltsas, 2012) which is measured the heating element temperature or temperature difference for fluid flow in a symmetric temperature profile. From the profile of temperature which is the force convention by fluid flow is apply through the channel. So, a new design of micromechanical plate encapsulated in a fluidic based channel is presented due to the low pressure for sensitivity of sensor compared to the touch-based pressure sensor which is the high pressure for sensitivity of sensor.

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Lately, the microfluidic based sensors have been carrying out with other sensors by accommodate with channel for detection. Channel is used to changes of detect in the environment which that changes is converts from a physical quantity into an electrical signal with the electrode help. The material that used in microfluidic technologies is using polymer which PDMS where is more compatible and provides advantage of greater which especially in mechanical yield strain than commonly used material like silicon (Liu, 2007). Besides that, using the PDMS polymer is offer simple structure and fabrication is easy which relate a simple fabrication process like casting and molding.

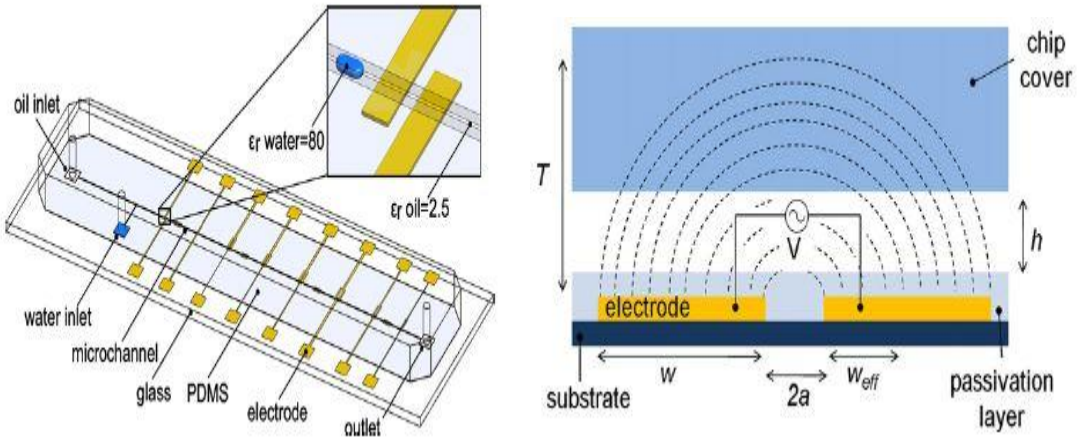
An example for fluidic based sensor is for the detection of microdroplet which using a coplanar electrodes design (Chen, Darhuber, Troian, & Wagner, 2004). Apart from that, some researchers have used a structure channel with the different design of coplanar electrode (Nawi et al., 2014; Elbunken et al., 2011). The procedures of robust of fabrication and components of existing have been used for achieved inexpensive and scalable droplet detection size and speed. The PDMS channel is used by using two electrode that is put in parallel each other inside the channel for convert the fluid component into capacitance changes (Wu, Liao, & Tung, 2011; Suter et al., 2013). It also has advantages including fabrication easy, ability to live in harsh environment and plantar measurement for a foot (Lei et al., 2012; Lei et al., 2014).

The coplanar electrode is used as a passivation layer which to prevent the electrodes and droplets from direct contact. Figure 2.5 (a) and (b) are shows the coplanar electrodes are used for form a capacitance in fluidic channel which the capacitance change is depends to a speed and size of the droplet (Elbuken et al.,

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2011). So, in our design, coplanar electrode which different shape is used inside the microchannel are proposed to enhancement for minimize the size of the sensor channel which coplanar electrode in microchannel is straight shape has been developed (Nawi et al., 2014; Rahman et al., 2011)




(a) (b)

*Figure 2.5*. (a) The schematic structure of PDMS microchannel, (b) Design of coplanar electrode in detection of droplet. Source: Adapted by Elbuken, Glawdel, Chan, & Ren, (2011).

## 2.7 Simulation Tool

The Finite Element Modeling (FEM) COMSOL Multiphysics software has been used which it is similar to mechanical analysis (Nawi et al., 2014). The performance of the sensor is depending on the membrane of deflection, when it has induced of strains within device, pressure and capacitance change within micro-channels. COMSOL Multiphysics software is used as a tool to understanding stresses in modeling. This software is allowing the researchers to conclude that the stress dissemination in

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specific of cross-sectional area. From previous studies, stress dissemination which is membrane of deflection has been design the modeling including circular, square, and rectangular. So, it is important in modeling for develop the model with the dimension for optimum. Besides that, it is needed some data which are the uses of material properties, and the type of strain element used.

For study the channel, the common software that is used in modeling which this software is related to fluid are computational fluid dynamic (CFD) COMSOL Multiphysics software. CFD COMSOL Multiphysics software is can be solved by used Euler and Navier-Stokes equation that for the problems of fluid flow (Jeong & Seong, 2014). COMSOL Multiphysics has whole complete software that includes pre-process and laminar flow method. Pre-process is the process to create the design and mesh generation. Preprocessing is the process create the parameter exact as input data with using the next step in this software for produce output. After a mesh generation is finale, the laminar flow method is used for the simulation setup, the process of clear up and post-processing of the result. The analysis of the result and visualize is processed in the post processing process.

The equation for solving the numerical simulation for CFD of momentum conversation in term variable pressure and velocity (Marjani & Shirazian, 2011),

$$\rho\frac{\partial V}{\partial t} - \nabla\cdot\eta(\nabla V + (\nabla V)^T) + \rho(V.\nabla)\mathrm{V} + \nabla\mathrm{P} = \mathrm{F} \qquad (2.1)$$

$$\nabla.V = 0$$

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Where η is the dynamic viscosity, v is the velocity vector, *p* is the pressure, ρ is the density of the fluid and *F* is a body force term. Equation (2.1) was used for model the laminar flow of fluid, incompressible and flow of stationary, where was assumed during the whole simulation process.

## 2.8 Summary

The pressure sensor design from various researchers have been discussed in this study. This design will be adopted during the process in Chapter 3. Flat membrane is used to create and to improve the robustness of sensor.

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Most the researchers in pressure sensor is not start to simulation analysis to study the effect of the structure, membrane deflection and distribution of velocity. The fabrication process and material used, is difficult to use. So a few researcher have been proposed the new sensing and a new material methods to reduce the fabrication complexity.

The pressure sensors are characterized in air, plantar and human for the pressure measurement. A researcher also tested the performance for the pressure is apply which to study the limitation and deflection. The microfluidic technology is offering the simple design, survivability of harsh environment and fabrication easily. The pressure sensing of pressure sensor can be achieved by implementation of system of fluidic to the sensor that have a flat membrane mechanism. The numerical analysis simulation were also discussed in details in this chapter.

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# CHAPTER 3

# METHODOLOGY

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## 3.1 Introduction

There are four stages in designing and developing the microfluidic pressure sensor which is mapped in Figure 3.1. This chapter describes a design process, simulation analysis, experimental studies and the characterization.

This chapter is starts by designing the structure, where a few different models are selected for simulation. A simple fabrication process for rectangular-shaped and ellipse-shaped microchannel will be described in this chapter. Then, the fluidic based pressure sensor is tested for fluid mechanism and pressure measurement for both design. Temperature analysis and lifetime effect were also discussed.

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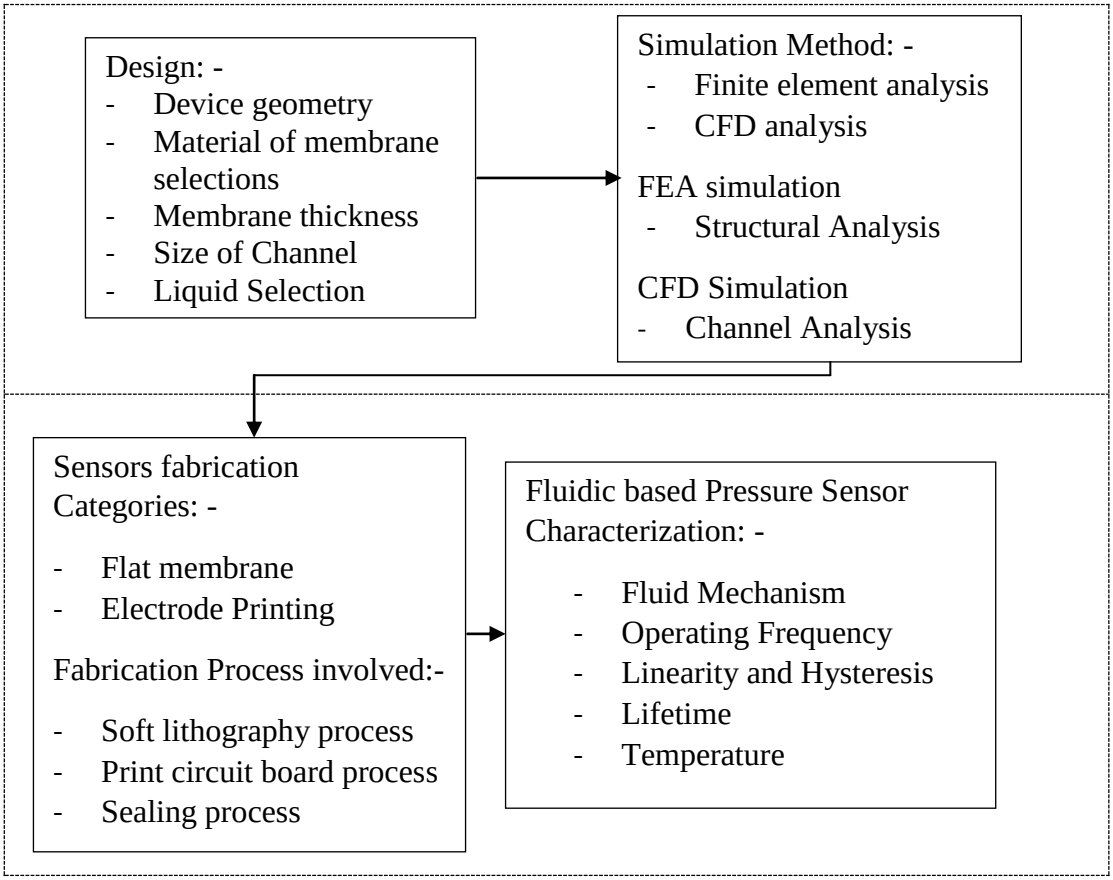




*Figure 3.1*. Research Activity

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## 3.2 Sensor Design and Principle

This subchapter is discussed about design structure, sensor principle, and liquid selection for microchannel. The design structure is about the design of microchannel pattern. For sensor principle is that used the test of pressure measurement. Last is the selection of liquid for microchannel is different also discussed in the subchapter.

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### 3.2.1 Design Structure

The process flow of sensor design is shown in Figure 3.2. The design is started by the selecting square shape membrane and rectangular shape membrane. The purpose of simulation is used to find the best structure of membrane based on the input pressure by using finite element analysis (FEA) which threshold value of pressure input is 0 to 10 kPa. The pressure is applied on the top of membrane where the displacement and mises stress are recorded. The area of these two structures is fixed to 100 $mm^2$, where the dimension of square shape membrane is 10 mm x 10 mm, and rectangular is 5 mm x 20 mm. Table 3.1 is showing the details of dimension of two different type structure of membrane. Figure 3.3 is showing the 3D model of square shape, and rectangular shape membrane.

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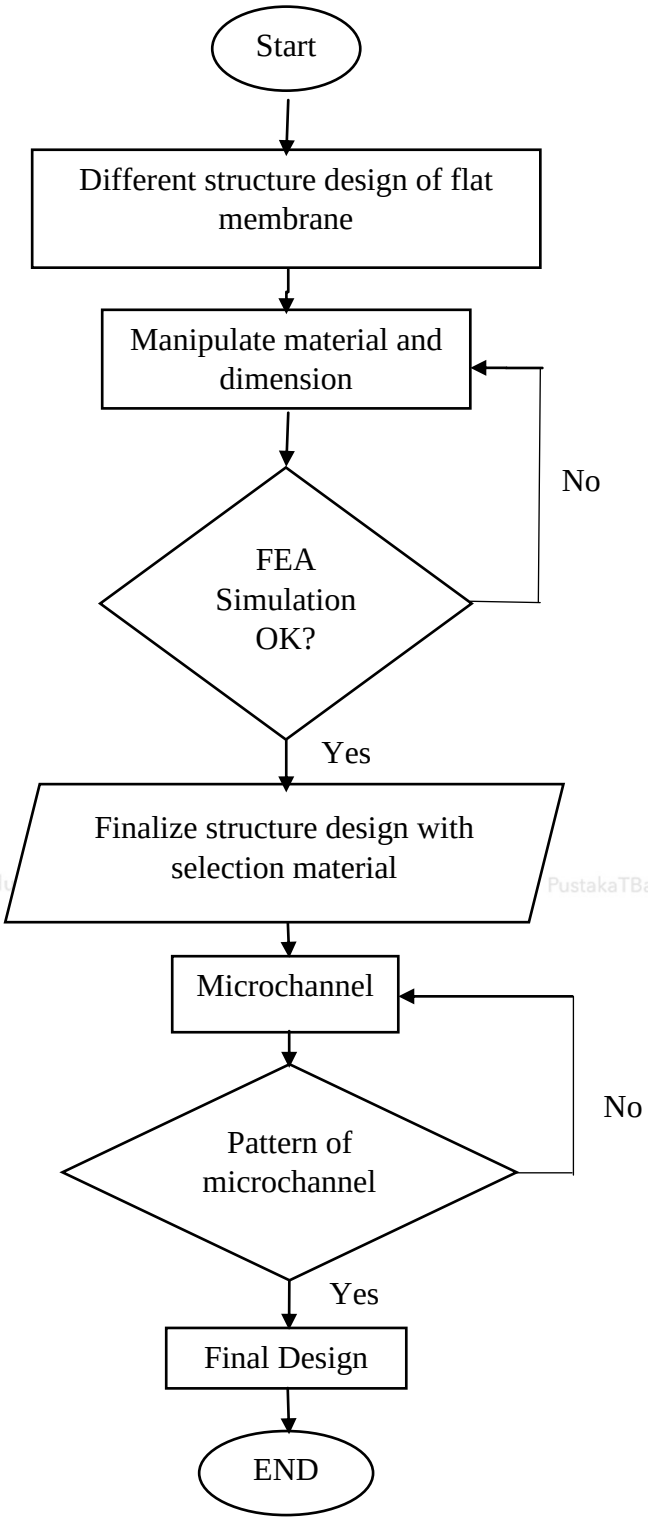
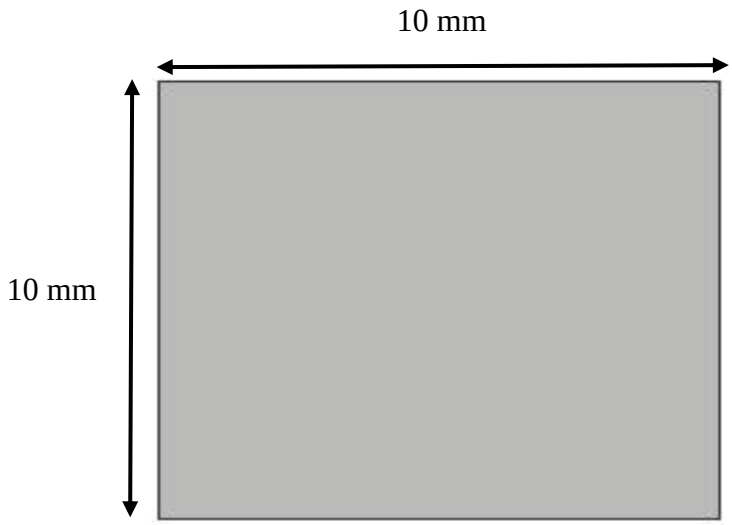



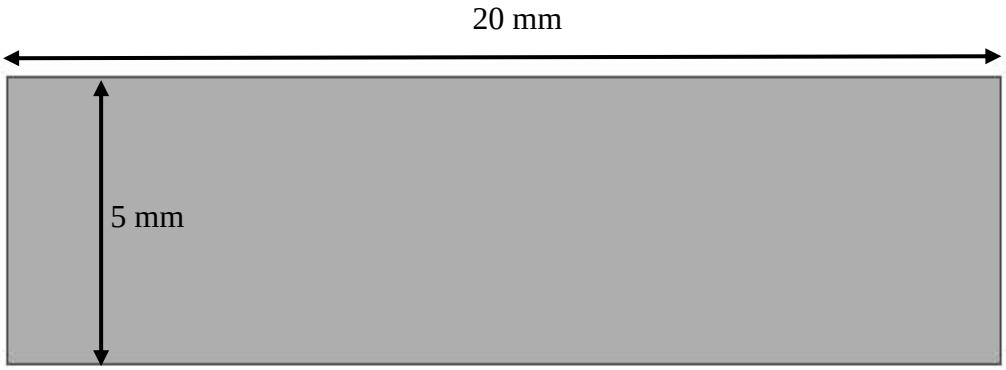

*Figure 3.2*. Flow chart for design process

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(a)




(b)

*Figure 3.3*. Different of membrane structure (a) Square shaped, and (b) Rectangular shaped

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Table 3.1

*The two different type of flat membrane with the surface area*

| **Type of structure** | **Length (mm)** | **Width (mm)** | **Surface area (mm)** |
|---|---|---|---|
| Square | 10 | 10 | 100 |
| Rectangular | 5 | 20 | 100 |

For the material selection, the polymer materials such as Polyimide (PI) and Polydimethylsiloxane (PDMS) were selected due to their capability which has greater advantages, especially in mechanical yield strain from other material, silicon and easy to deform (Liu, 2007). Both materials are commonly used material in microfluidic. PI has high resistance against many chemicals, high glass transition temperature, high dielectric constant and biocompatibility (Zulfiqar et al., 2015). Meanwhile, PDMS is one of the major materials used in polymer microfluidics because of material elasticity, and gas permittivity. Therefore, four different material properties were selected including PDMS (10:1), PDMS (5:1), PDMS (2:1) and Polyimide.

There are two mechanical properties that were considered for this analysis, which includes young's modulus and poisson's ratio. The details of the material properties are listed in Table 3.2. The dimension of the membrane was also varied in this simulation to study the effect of thickness and area based on the applied pressure.

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Table 3.2

*The material properties for PDMS and PI.*

| | | |
|---|---|---|
| PDMS (10:1) | Young's modulus (MPa) | 0.85 |
| | Poisson'ratio | 0.5 |
| PDMS (5:1) | Young's modulus (MPa) | 1.00 |
| | Poisson'ratio | 0.5 |
| PDMS (2:1) | Young's modulus (MPa) | 2.10 |
| | Poisson'ratio | 0.5 |
| PI | Young's modulus (MPa) | 2500 |
| | Poisson'ratio | 0.34 |

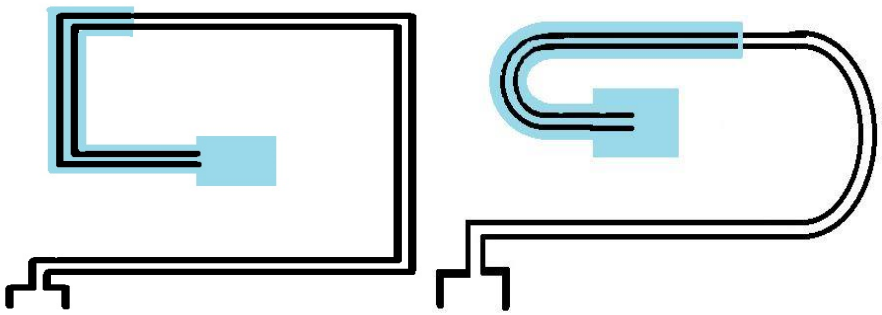
Source: Adapted by Park et al., (2010).

Lastly, microchannel is integrated with the membrane, the purposed of membrane is a as a sensing mechanism to transfer the liquid movement based on the membrane deflection. The proposed pattern of microchannel is square shaped in order to optimize the sensor dimension based on the previous design (Nawi et al,. 2014). However, due a few limitations, ellipse shape microchannel pattern is proposed. Square shaped pattern has a sharp corner meanwhile ellipse shaped pattern has a

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round corner. These two different patterns will be simulated and tested for several analyses.



(a) (b)

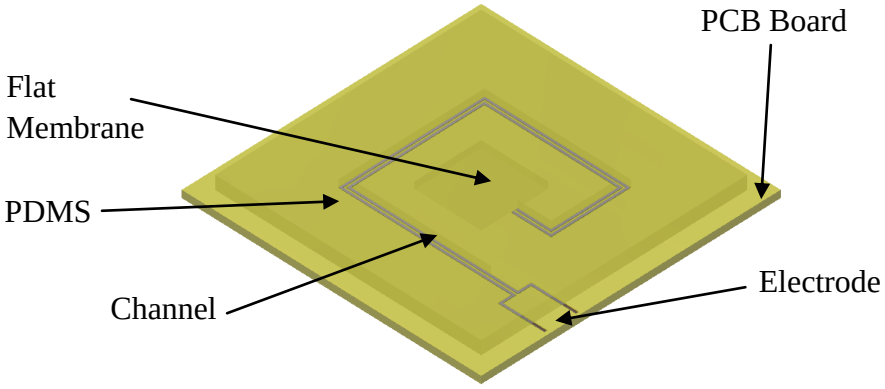
*Figure 3.4*. The pattern of microchannel (a) square shaped and (b) ellipse shaped

A finalized design is fabricated using soft lithography process, printed circuit board process and sealing process. The coplanar electrode design is used and located below the microchannel. There are two lines of electrode side by side and copper electrode is chosen as an electrode material. A schematic of the proposed fluidic based pressure sensor for square shape pattern is shown in Figure 3.5 (a) and ellipse shape pattern is shown in Figure 3.5 (b).

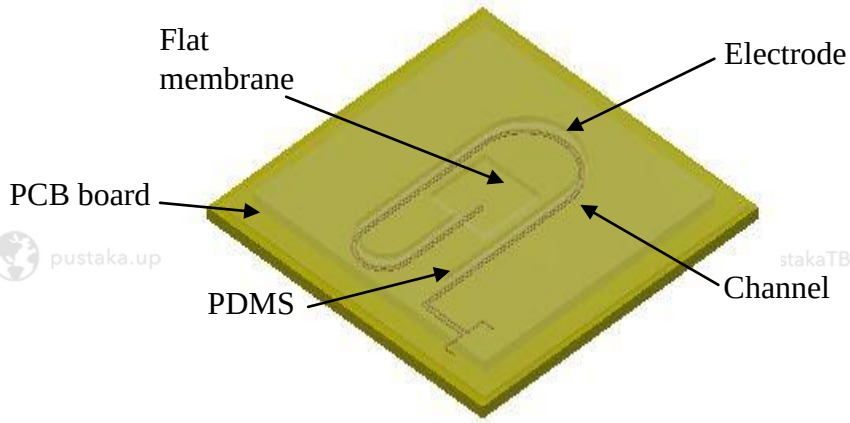
The liquid or electrolyte will be used to fill in the cavity to create the capacitor as shown in Figure 3.6 for fluidic based capacitive pressure with ellipse and square of pattern electrode. The ionic layer will behave as a conductor and create the capacitance. Sensor using coplanar electrode design is gives difficulty to miniaturize the channel. Fabricated sensor for both designs is shown in Figure 3.7.

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(a)




(b)

*Figure 3.5*. The schematic diagram of fluidic based pressure sensor (a) square shape microchannel pattern (b) ellipse shape microchannel pattern

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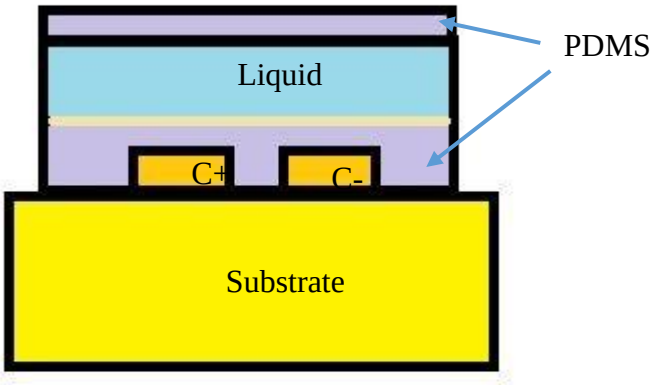
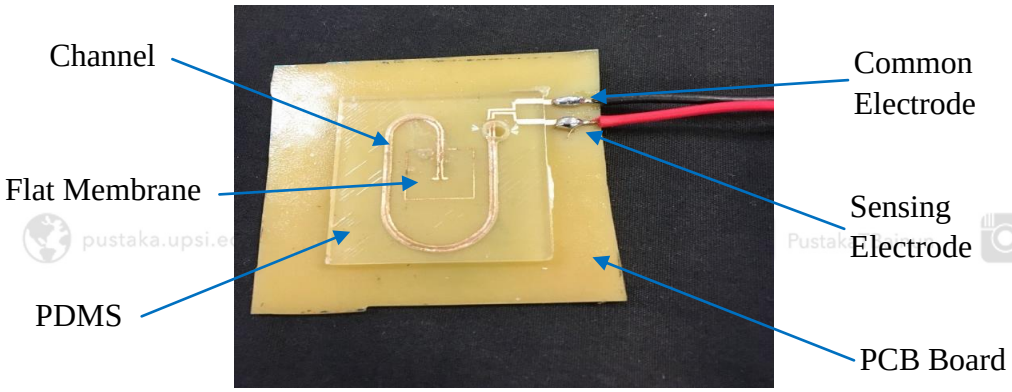
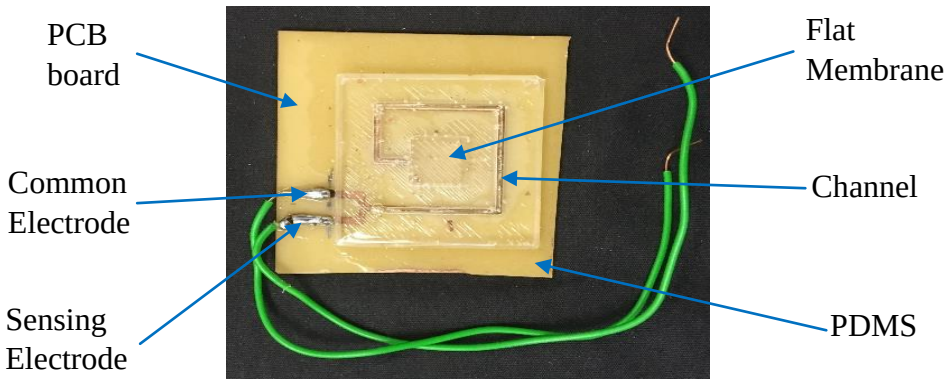




*Figure 3.6.* Cross sectional area of coplanar electrode




(a)




(b)

*Figure 3.7.* The fabricated fluidic based pressure sensor (a) ellipse shape microchannel pattern (b) square shape microchannel pattern

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### 3.2.2 Sensing Principle

The membrane is used for pressure measurement in order to prove the sensing and fluid mechanism for fluidic based pressure sensor. Figure 3.8 shows the flat membrane pressure sensor by integrating the membrane with a fluidic system. When pressure is applied to the membrane, it produces deflection which will push the liquid inside the microchannel towards the outlet. The coplanar electrode under the microchannel sense the liquid movement and produce a capacitance change. In other word, the movement of the liquid inside the channel (L) is depend on the pressure is apply. A microchannel liquid position for applied pressure and no-load condition shows in Figure 3.9 (a) and (b) for ellipse and square electrode pattern design. When the liquid movement (L) inside the microchannel is increase, the capacitance is also increase. The relationship between the Liquid movement (L) and the capacitance changes (C) is give in equation below (Elbuken et al., 2011):-

$$C = \frac{2\varepsilon_r \varepsilon_o l}{\pi} \ln\left[1 + \frac{w}{a} + \sqrt{\left(1 + \frac{w}{a}\right)^2 - 1}\right] \quad (3.1)$$

Where $C$, $l$, $\varepsilon_r$, $\varepsilon_o$, $a$ and $w$ are final capacitance, the length of the electrodes, dielectric constant, electric constant, area of half-gap between the both electrodes and width of electrodes. The size of channel is fixed 0.8 mm × 0.8 mm for height and width. A pressure for pressure measurement is using lower than 10 kPa is chosen for sensitivity sensing of sensor and a preliminary test is using a constant metal load (slotted mass).

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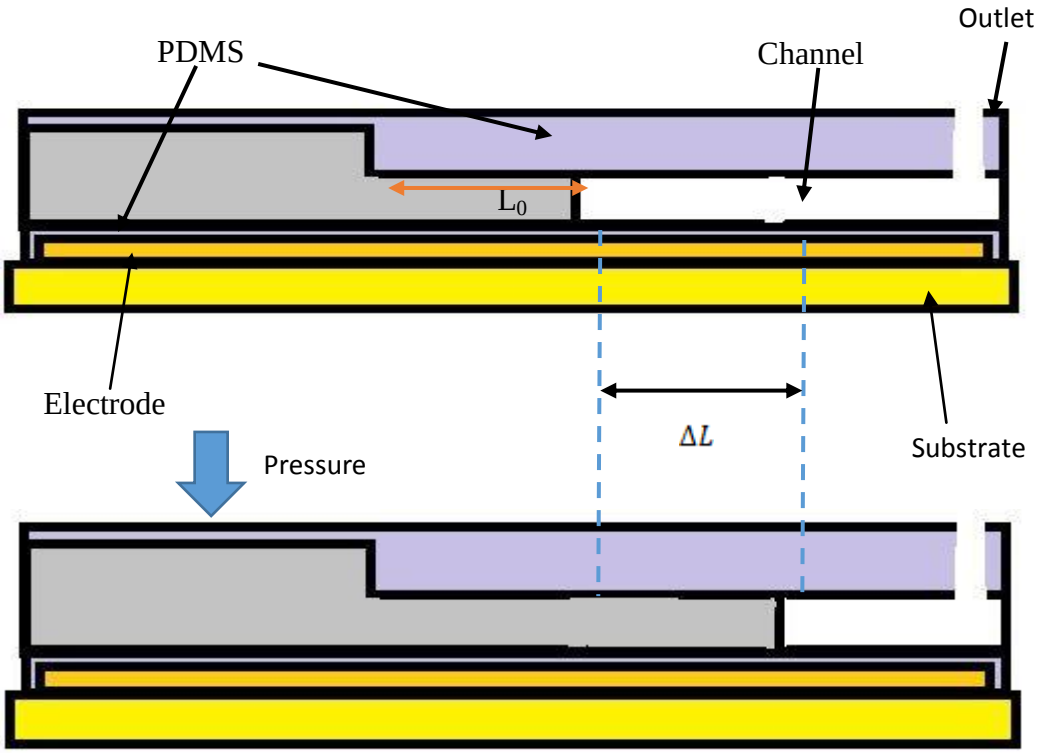
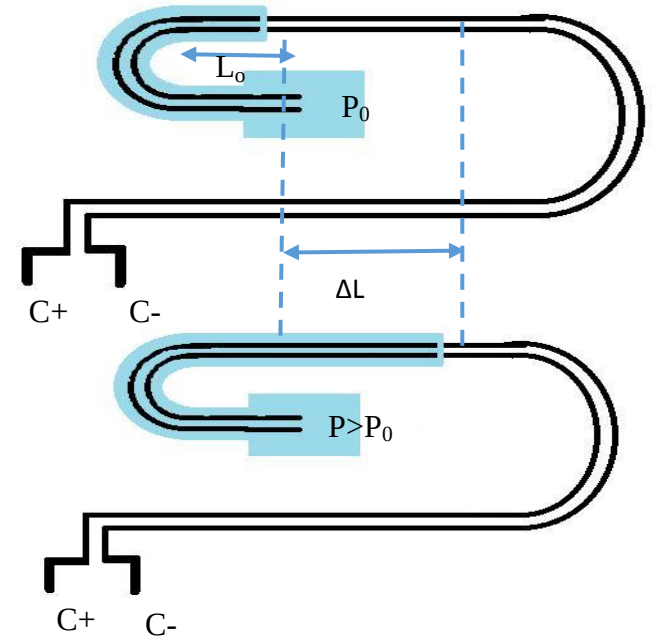



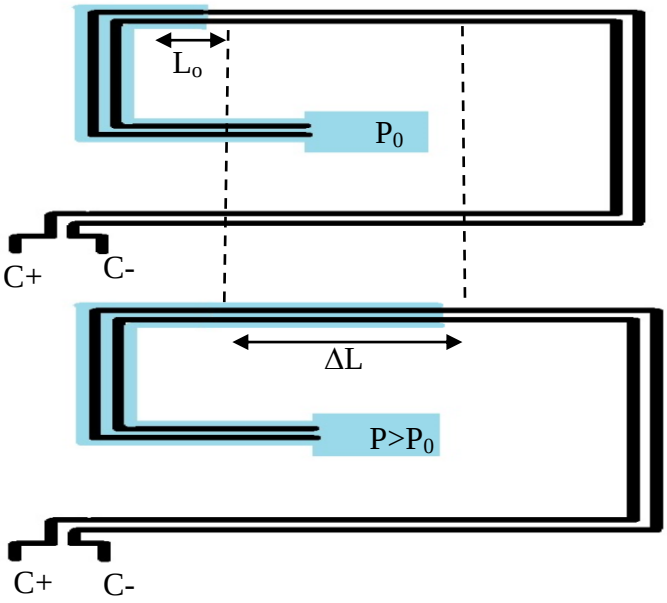

*Figure 3.8.* The illustrated of fluidic system for fluidic based pressure sensor

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(a)




(b)

*Figure 3.9.* The image of sensor that has apply pressure and no-load condition on the membrane (a) ellipse design and (b) Square design

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### 3.2.3 Liquid Selection For Microchannel

In order to study the sensing mechanism of coplanar electrode the microchannel need to be analyzed. To achieve the optimum design of microchannel, three parameters is simulated. There is liquid inside microchannel, size of the cross sectional area of microchannel and the most important is the microchannel pattern. Two size of cross sectional area of microchannel are chosen including 0.8 mm multiply 0.8 mm and 0.9 mm multiply 0.9mm, both microchannel length is fixed. The two microchannel pattern are suggested including ellipse shape and square shape. For the liquid selection, there are two liquids that are commonly used that are methanol and propylene carbonate. The important properties of liquid such as dielectric constant, boiling point, melting point, surface tension, kinematic viscosity and density were listed in Table 3.3.

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Table 3.3

*List of liquids for microchannel*

| | | |
|---|---|---|
| Propylene Carbonate | Density ($kg/m^3$) | 1205 |
| | Dielectric constant | 64.9 |
| | Surface Tension (mN/m) | 40.9 |
| | Kinematic viscosity ($mm^2/s$) | 2.50 |
| | Melting Point | -48.8 |
| | Boiling Point (°C) | 242 |

(*Continue*)

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Table 3.3 (*Continue*)

| | | |
|---|---|---|
| Methanol | Density (kg/m$^3$) | 789 |
| | Dielectric constant | 25.02 |
| | Surface Tension (mN/m) | 22 |
| | Kinematic viscosity (mm$^2$/s) | 1.07 |
| | Melting Point | -114.1 |
| | Boiling Point (°C) | 78.37 |

## 3.3 Simulation Method

The COMSOL MULTIPYHSICS SOFTWARE is used for simulation of structure analysis and channel analysis. Simulation is divided into two-part, first part is FEA simulation for structural analysis and second part is CFD simulation for microchannel analysis.

### 3.3.1 FEA Simulation Method

The FEA simulation method is a tool that gives result in deflection and stress distribution for the membrane structure. There are a few steps involved in FEA analysis, including geometry construction, mesh generation and load implementation as shown in figure 3.10. The geometry was constructed and meshed in the pre-processor and included for load implementations as well. The model was solved using

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built in solver and the result were generated. The results were plotted in post-processor for the geometry model on deflection and strain/stress distribution.

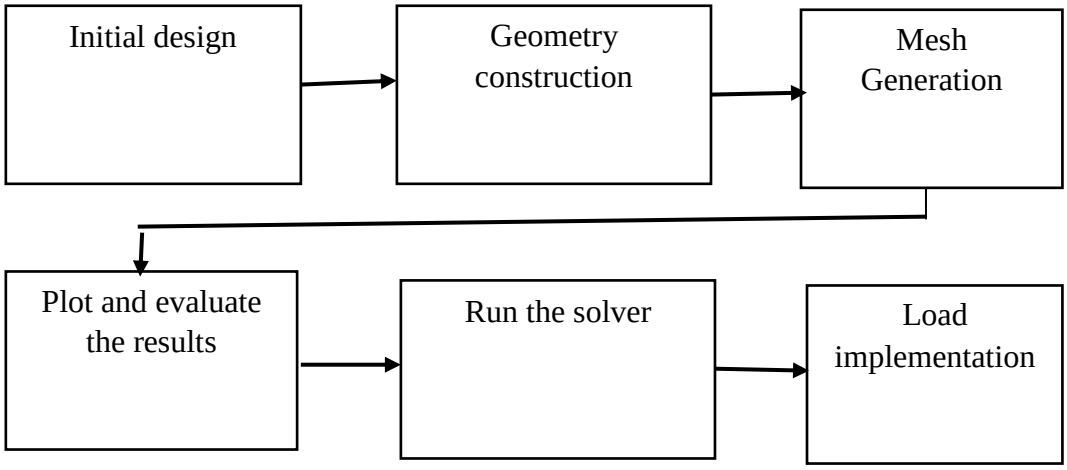



*Figure 3.10*. The Procedure of FEA simulation

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#### 3.3.1.1 Initial Design

The designing process used FEA tool to do structural analysis including deflection and the mises stress distribution on the membrane structure. There are two different type of structures is chosen and modelled. There are square shape membrane and rectangular shape membrane. The area of membrane and the thickness are fixed. Then, the membrane thickness and area is varied to study the membrane performance for different dimension. The procedures of simulation will be explained by using the square shape membrane.

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### 3.3.1.2 Geometry Construction and Mesh Generation

The 3D model of membrane was created based on the dimension given Table 3.1. The parameters of dimension were need to set-up. The parameter dimension is thickness and area of the membrane. Figure 3.11 is shows the 3D model of the membrane with area 100 $mm^2$ and thickness 0.5 mm. PDMS with different ratios and PI were used in this simulation where the properties such as density, poisson's ratio and young's modulus are considered. Then, the mesh was created on the membrane by using tool mesh where finest mesh is selected.

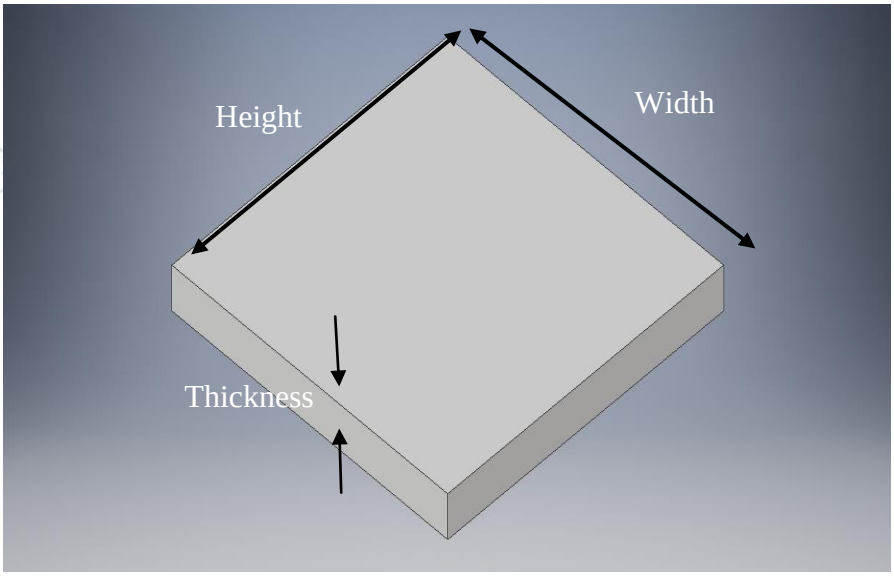



*Figure 3.11*. 3D model of membrane in FEA simulation for square shape

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### 3.3.1.3 Define Loads

In this analysis, there were two type of load is required to set which are pressure and displacement. Figure 3.12 shows the meshed of square flat shape model and also the loads that have been defined.

i. Pressure

Pressure is applied at the top of membrane.

ii. Displacement

For displacement, the edge around the membrane is set as 0 mm displacement to fix the location of membrane.

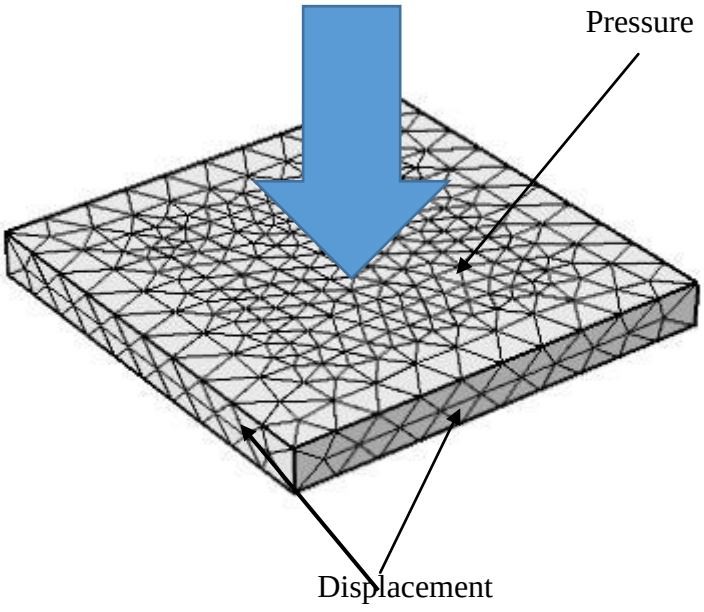



*Figure 3.12*. The 3D mesh of square flat shape after define load

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#### 3.3.1.4 The result of FEA simulation

In this subsequence section, the simulation is running to show the result which the result shows the total displacement and stress of the membrane.

### 3.3.2 CFD Simulation Method

For this simulation, Laminar flow in COMSOL MULTIPHYSICS was used to study the liquid movement inside the microchannel when the pressure applied on the membrane. The performance of microchannel using different liquids and dimension were studied. It started with the initial design. After that, the construction of geometry and mesh generation. Then, the boundary condition and computational parameter is set up. Lastly, solver is running. The procedure of CFD simulation method is shows in Figure 3.13.

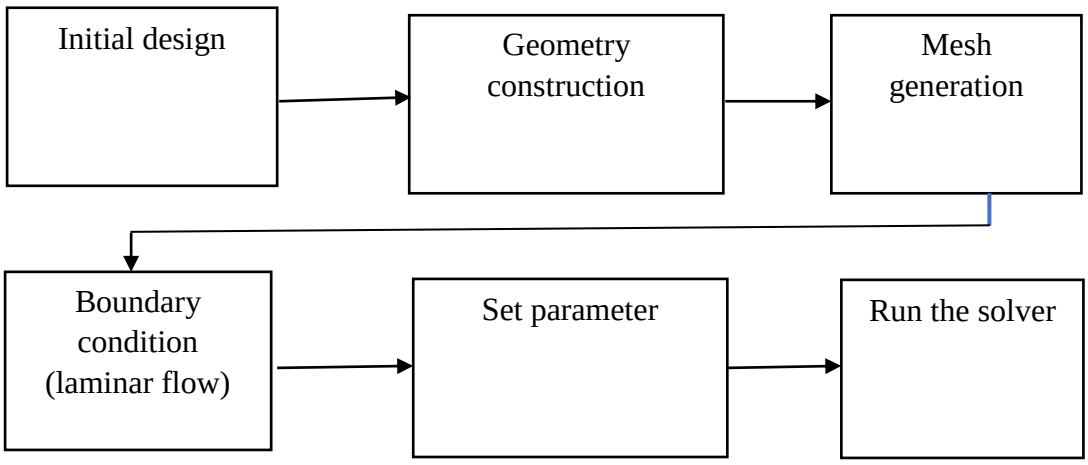



*Figure 3.13*. The procedure of CFD simulation

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### 3.3.2.1 Initial Design And Geometry Construction

The microchannel of ellipse shape is used for evaluated the channel with varying of height which are 0.8 – 0.9 mm. Geometry design and geometry is constructed in AUTODESK INVENTOR 2017. Then, it is import to COMSOL MULTIPHYSICS simulation software.

### 3.3.2.2 Mesh Generation

Mesh Generation was created on the channel with using tool of mesh with the finest mesh. Figure 3.14 is show that the ellipse shape microchannel was meshed with using tool mesh with finest mesh in COMSOL MULTIPHYSICS simulation software.



*Figure 3.14.* The mesh generation on the ellipse shape microchannel

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### 3.3.2.3 Boundary Condition

For this simulation, the condition of boundary was evaluated as below:

i. Inlet

The Inlet of velocity is applied on the front of the channel for varying of pressure.

ii. The Wall

The wall of the channel is set as fixed wall.

iii. Outlet

The outlet is set up at 0 Pa for pressure. The pressure condition at flow was set as suppress flow.

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The wall, inlet and outlet are showing in Figure 3.15

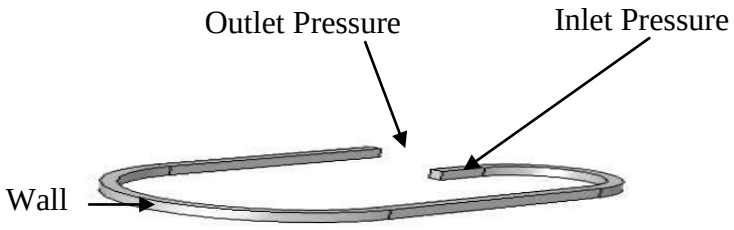



*Figure 3.15*. The Inlet pressure for liquid move inside the channel, outlet and wall on ellipse shape

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#### 3.3.2.4 The Movement Of Liquid Inside Channel

For the movement of liquid inside channel, the process is same process with before, two different microchannel patterns is designed including ellipse shape and square shape microchannel. The dimension of the microchannel is fixed at 0.8 mm and the apply pressure is varied 0-10kPa at the inlet velocity while the outlet is set value at zero. The velocity is recorder for both microchannel patterns. The liquids used for this simulation are propylene carbonate, and methanol. The properties of this liquid have been listed in Table 3.2 for the density and kinematic viscosity However, the surface friction of the wall in this simulation is not considered and the material of this wall is PDMS.

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## 3.4 Sensor Fabrication

For this section will focus on a simple fabrication for fluidic based pressure sensor for both Ellipse shape and square shape microchannel pattern. The fabrication process of fluidic based pressure sensor involved three major steps, PDMS fabrication process, electrode fabrication process and sealing process. Both microchannel patterns used the same fabrication process. Therefore, in this section, only ellipse microchannel pattern is demonstrated. The fabrication process was started by designing the mold is show in Figure 3.16 (a). After that, the PDMS solvent wish ratio 10:1 was poured on the top of mold. After PDMS is totally cure, the hardened is removed as shows in Figure 3.16 (b-c). Then, the electrode is fabricated using printed circuit board (PCB) process is shown in Figure 3.16 (d-e). In order to form an insulator, the electrode was

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coated using PDMS solvent, see in Figure 3.16 (f). Finally, the PDMS container was sealed with the electrode as shown in Figure 3.16 (g). The process is repeated for the square microchannel shape pattern design. All the processes for each step will be discussed in detail in next subsections.

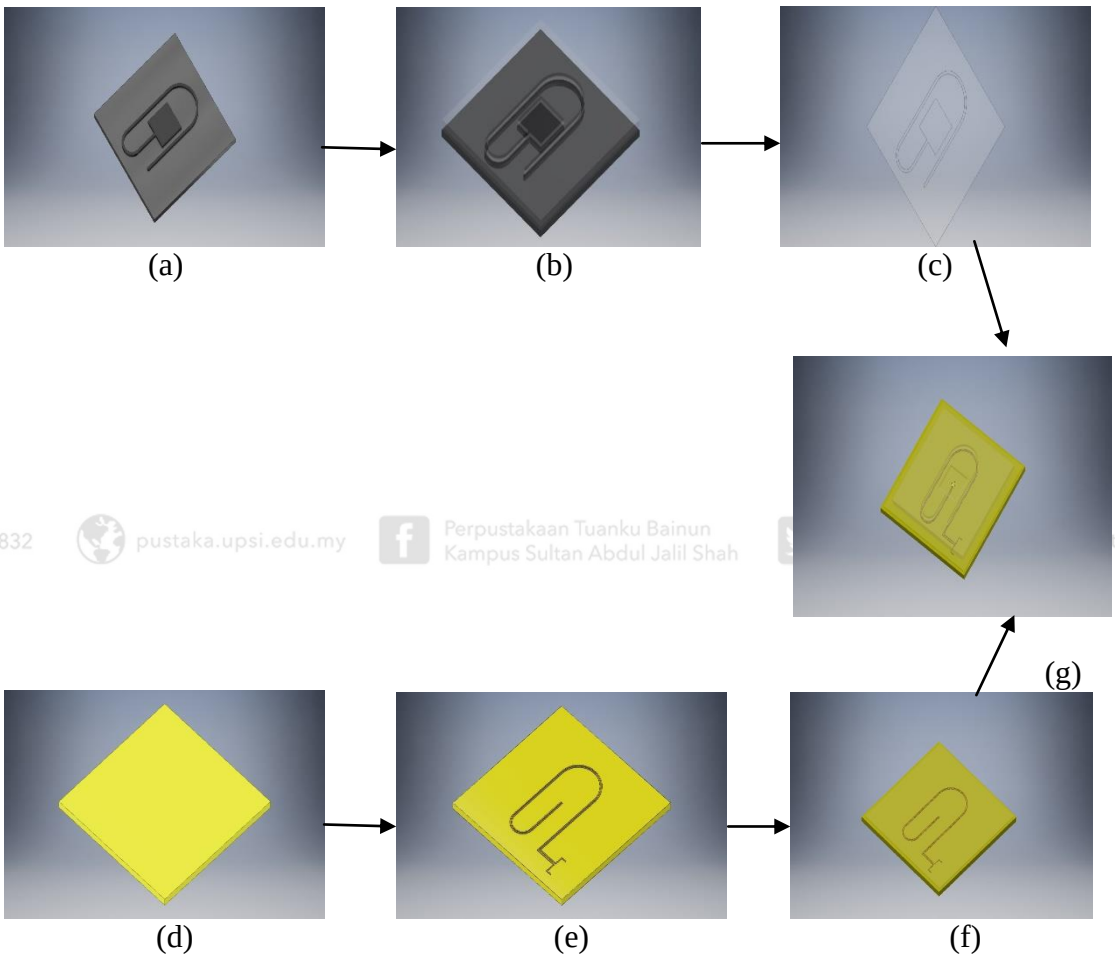



*Figure 3.16*. The schematic of Process Fabrication of flat membrane of capacitive pressure sensor for ellipse shape coplanar electrode (a) Designing of mold, (b-c) Solvent PDMS is pour and remove once hardened, (d-e) PCB process, (f) PDMS solvent is coated on top of the electrode and (g) The PDMS container sealed with electrode.

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### 3.4.1 PDMS Fabrication Process

The use of membrane container was used in the different type of application such as immersion application (Rahman et al., 2014), and tactile sensor (Kim et al., 2011). The fabrication of PDMS membrane is using the common method which is called soft lithography process. The PDMS with a ratio 10 for base :1 for curing agent is used. The mold structure is fabricated using 3D printer with dimension of membrane is 10mm x 10mm and the microchannel 0.8 mm x 0.8 mm for width x height. The fabricated mold is shows in Figure 3.17. Then, the thickness of membrane was achieved when PDMS solvent was poured fulling into the base mold in Figure 3.18. After that, the base mold was heated in an oven at a temperature 30°C for 24 hours to harden the PDMS. After PDMS was completely hardened, the container of PDMS is need to remove carefully to ensure that the hardened PDMS was not broken during peel off process. The final hardened PDMS is shown in Figure 3.19 and Figure 3.20.

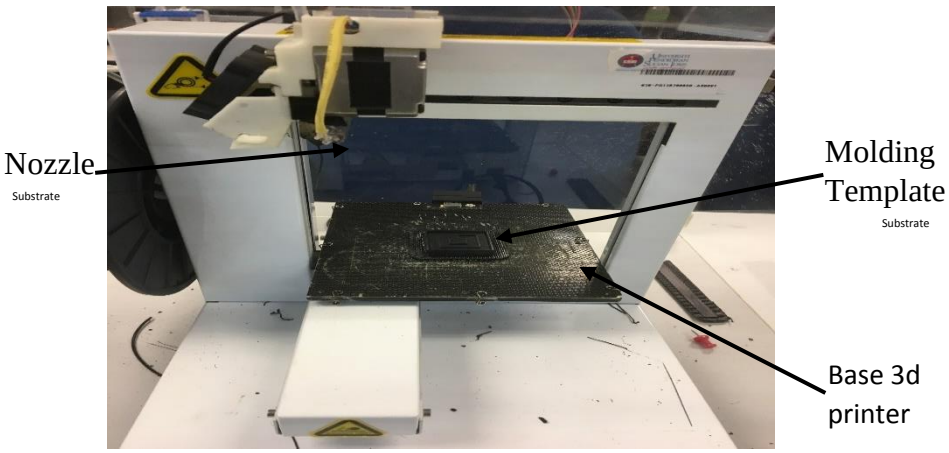



*Figure 3.17.* The image of 3D printer for fabricated the mold

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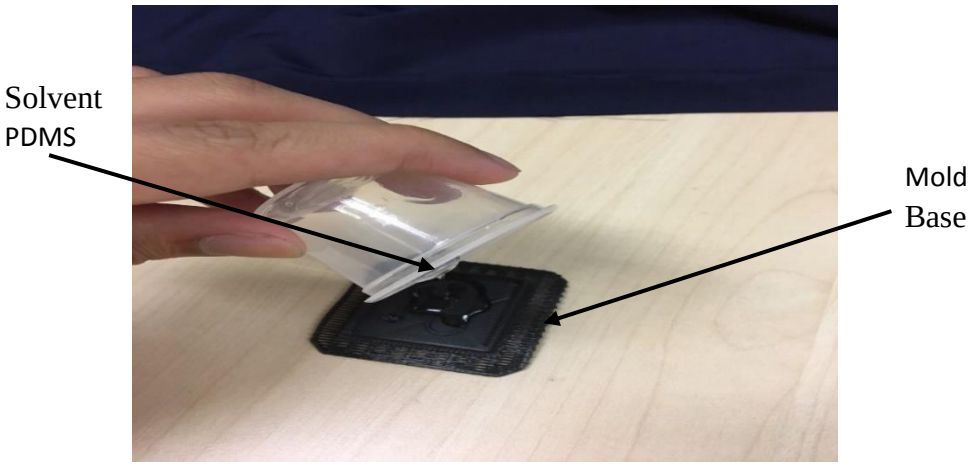




*Figure 3.18*. The image of the PDMS solvent pour in the mold base

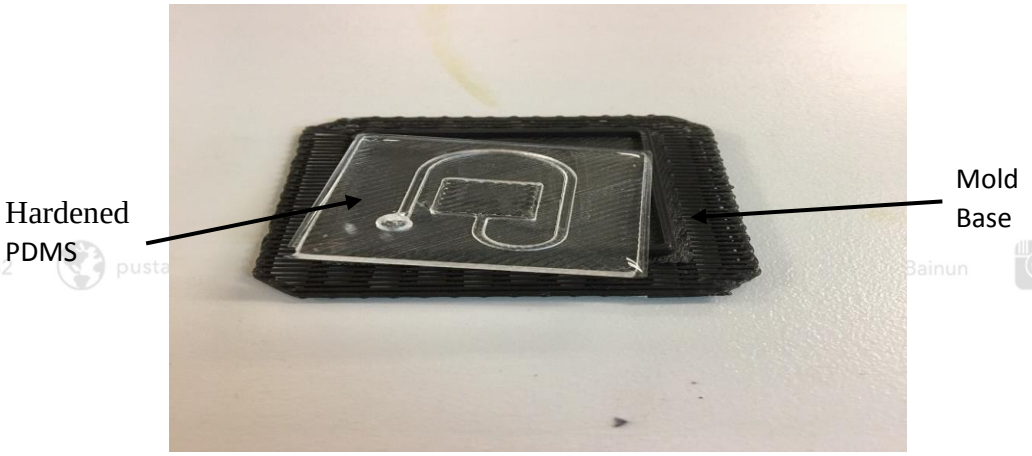



*Figure 3.19*. The image of the PDMS has remove from the mold

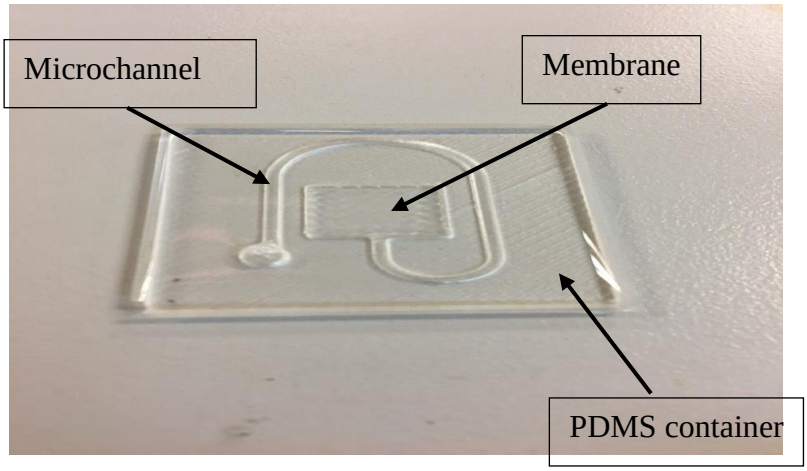


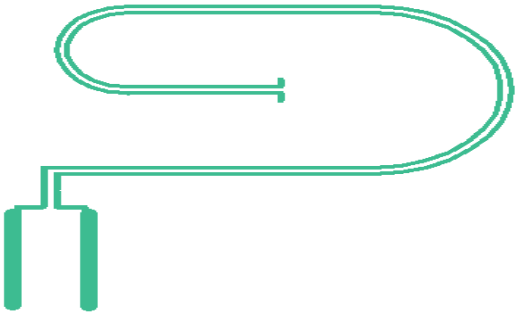

*Figure 3.20*. The image of the mold has hardened PDMS

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### 3.4.2 Electrode Fabrication Process

For electrode fabrication process, the pattern of electrode is design using EAGLE 8.4.1 software ass shown in Figure 3.21 (a) and Figure 3.21 (b) for ellipse electrode and square electrode, respectively. The printed circuit board (PCB) process is used for electrode fabrication. Printed circuit board (PCB) has a few processes which are printing process, exposure process, developer process and etching process. The whole process is illustrated in Figure 3.22. The processes are discussed detail in next subsequence section for other ellipse coplanar electrode pattern because the process of square coplanar electrode pattern is also used the same process.



(a)



(b)

*Figure 3.21*. The Pattern of copper electrode (a) Ellipse electrode and (b) Square electrode

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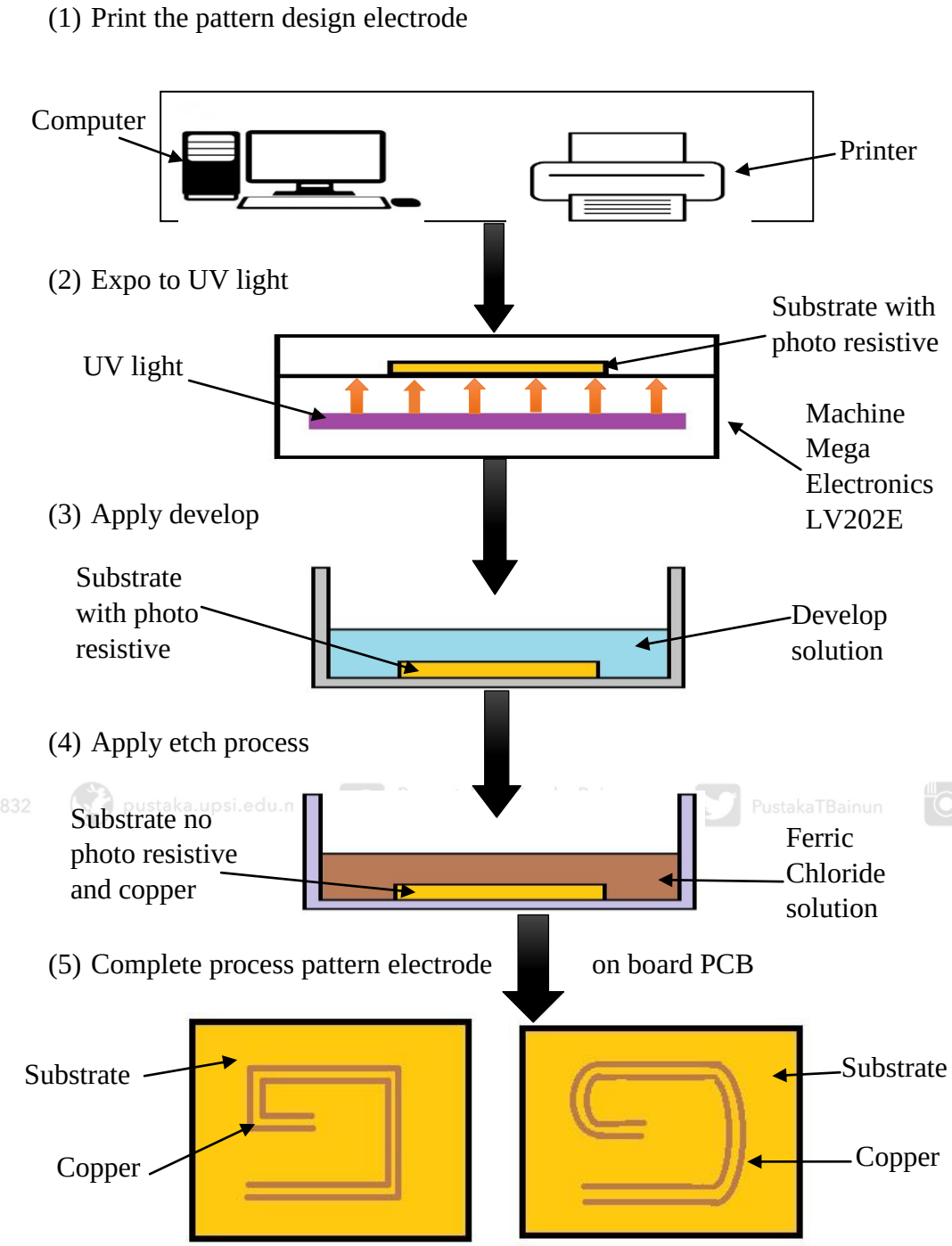




*Figure 3.22*. The complete process of PCB

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### 3.4.2.1 Printing Process

The pattern of electrode is printed using laser printer BROTHER HL6300D on a plain paper, as Figure 3.23. The material (FR4) was used as a substrate for the electrode. Figure 3.24 shows the complete design of electrode for ellipse design.




*Figure 3.23*. The image of laser printer is using for print the pattern of electrode

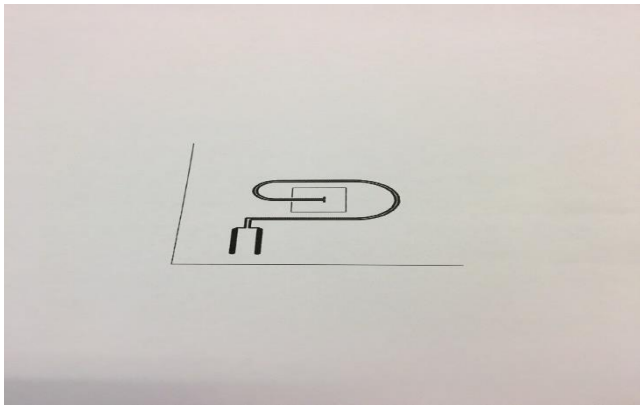


*Figure 3.24*. The image of complete design of electrode after printed

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### 3.4.2.2 Exposure Process

Exposure process is used when the printed process has been done and pattern of electrode is transferred on the FR4 board. In order to do that, the UV machine (Mega Electronics LV202E) is used to expose the pattern using UV light, the UV machine is shown in Figure 3.25. The design electrode is exposed for certain time to get good pattern on the FR4 board. The FR4 board use a material that has a photo resistive positive (green layer) is shown in Figure 3.26. The complete process expo is shown in Figure 3.27. The pattern transferred is hardly visible, to make it visible, we proceed to the next process.



*Figure 3.25*. The image of machine Mega Electronics LV202E

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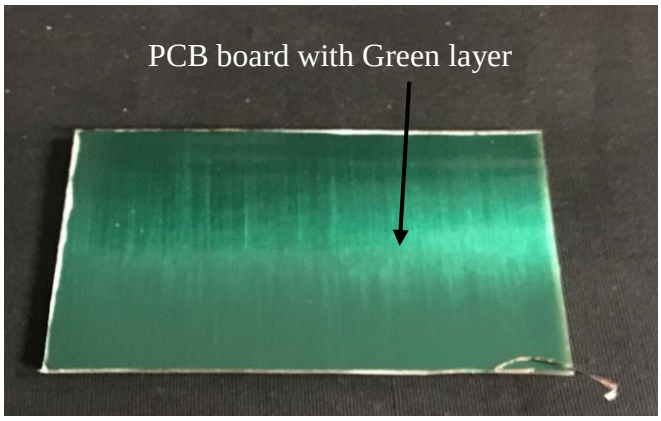




*Figure 3.26*. The image of FR4 board that has a positive photoresistive.

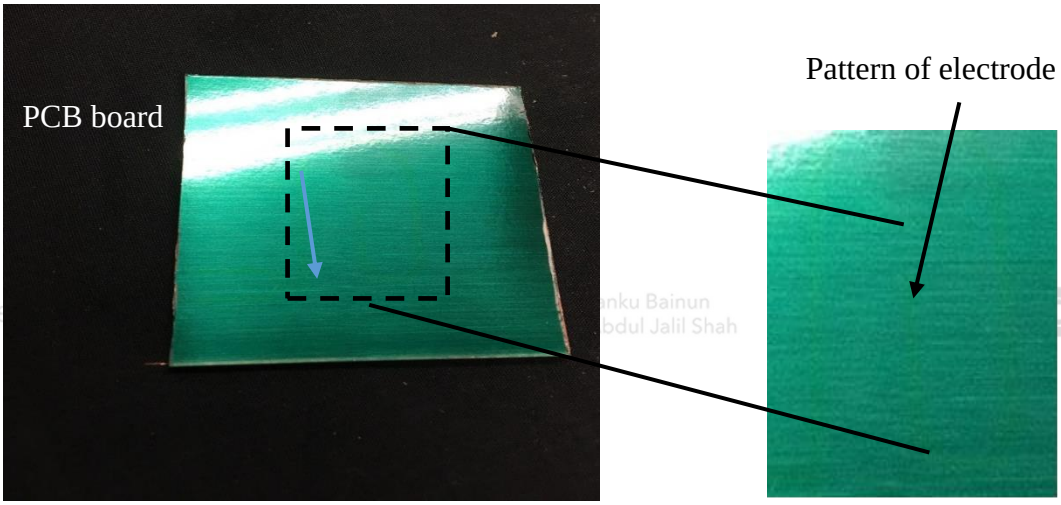



*Figure 3.27*. The complete process of exposure process with the transferred pattern

### 3.4.2.3 Developer Process

Developer process is used for remove the green layer on the top the FR4 board, the green layer will be removed for pattern that has not been exposed to UV. When green layer is removed green, the pattern will be visible and copper plate can be seen as shown in Figure 3.28. The developer material used to remove the green layer green is

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crystal material that is shown in Figure 3.29. Figure 3.30 is showing the complete process develop.

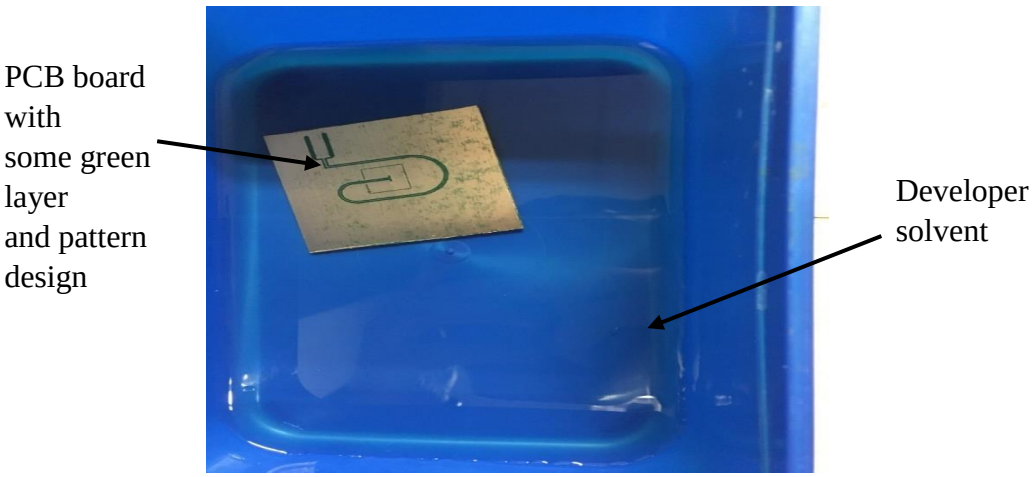



*Figure 3.28*. The image of top of material (FR4) the green layer with transferred pattern




*Figure 3.29*. The image of crystal material that used in developer process

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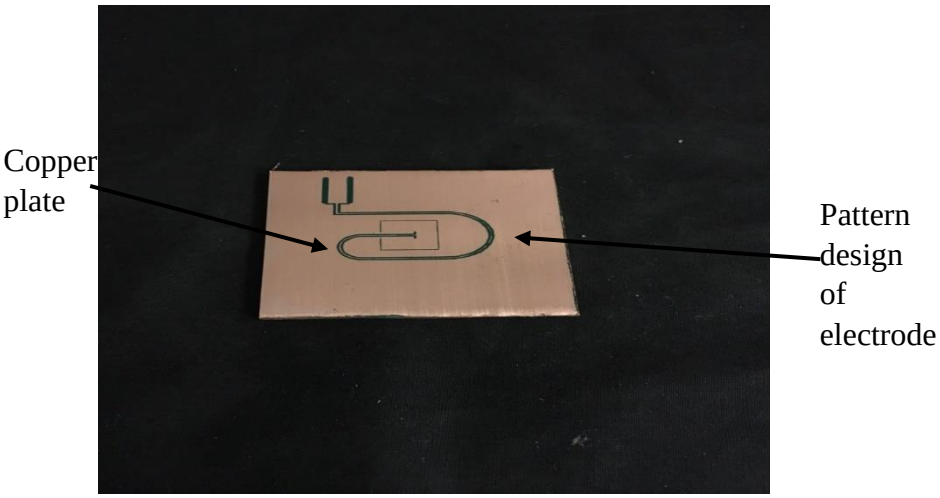




*Figure 3.30*. The developed pattern of PCB process

### 3.4.2.4 Etching Process For PCB

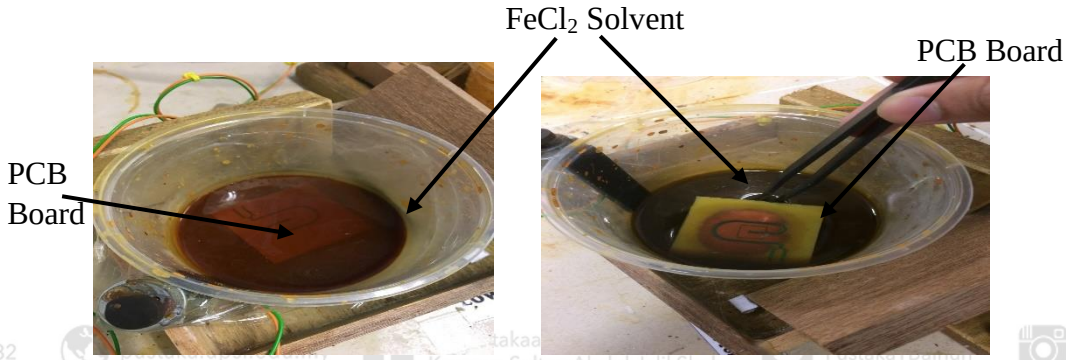
Final process for print circuit board is an etching process. Etching process is used for to remove copper layer that do not have transferred pattern electrode. The etching solution that it Ferric Chloride ($FeCI_2$) is used to remove the copper layer. Etching solvent is make by using $FeCI_2$ power as shown in Figure 3.31 and water. Then, the FR4 board is fully merged into the solution and this process certain time is taken to completely etch. Figure 3.32 shows the etching process and. Figure 3.33 shows the complete FR4 board after etching process.

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*Figure 3.31*. The Ferric chloride ($FeCl_2$) material.




(a) (b)

*Figure 3.32*. Etching process (a) FR4 board fully merged in the etching solution (b) the complete process

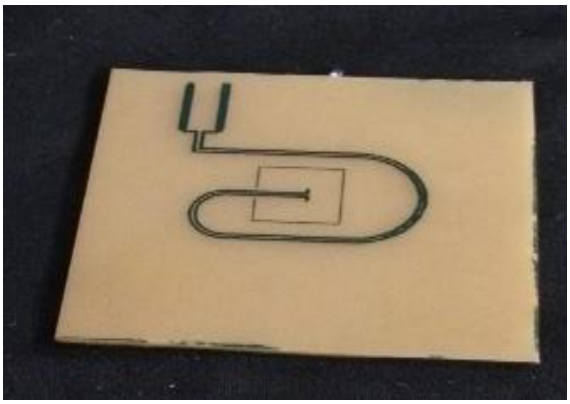


*Figure 3.33*. The complete process for etching process on the PCB board with no copper plate and only has pattern design

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### 3.4.3 Sealing Process

The sealing process is a final stage to make a bonding between hardened PDMS container and the electrode. The PDMS solvent is deposited on the top of electrode prior to sealing process. The spin coater is used for deposition process of PDMS solvent to make a thin layer. The PDMS solvent was also acted as an intermediate layer for sealing process. To partially cure the PDMS, the intermediate layer was baked at 30 ℃ at about 24 hours. The illustrations for the deposition process is shown Figure 3.34.

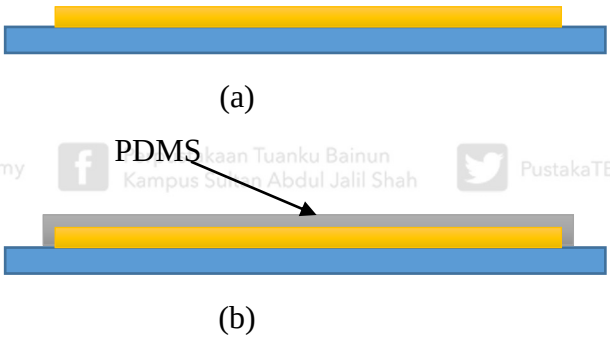



*Figure 3.34*. The illustration of PDMS deposition (a) before and (b) after

Then, the PDMS container with channel was placed on the top of electrode by manual alignment process is show in Figure 3.35. The PDMS container with membrane and channel must adjusted well to make sure the position of microchannel and the electrode was perfectly aligned with the electrode. Finally, the sample was baked in the oven to strengthen the sealing region. The sealing region of the sensor is testing using the principle of bonding test and will be discuss on next chapter.

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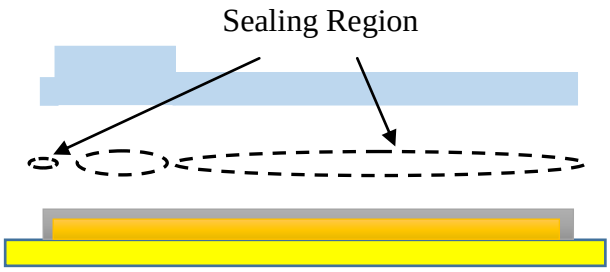




*Figure 3.35*. The schematic diagram of final sealing process

### 3.4.4 Wire Bonding And Injection Process

The wire was soldered on the sample using multicore wire which connected to sensing and common electrode. The small hole was manually punched at the end of the membrane using mini drill PCB to create an outlet. The liquid was manually injected by using a syringe at the membrane until the liquid was fully tribe inside the microchannel as shown in Figure 3.36.

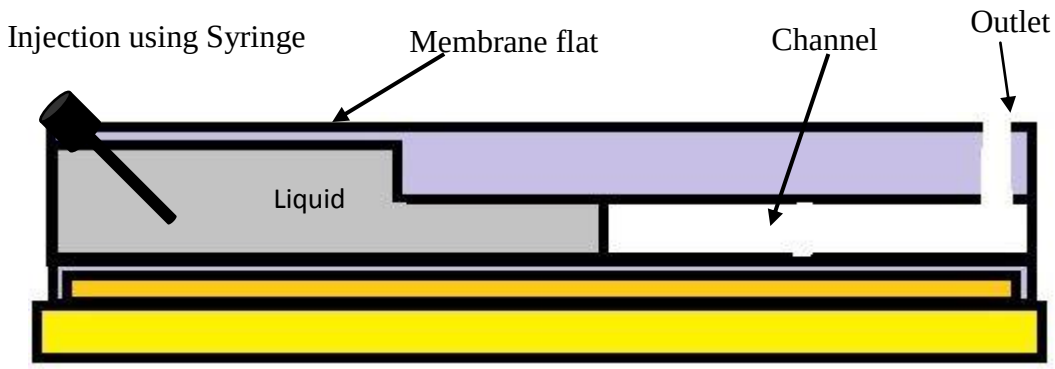



*Figure 3.36*. The schematic diagram of injection process using syringe

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## 3.5 System Integration

For system integration, the sensing and common electrodes were connected to the LCR meter (model: Wayne Kerr 4100). This LCR meter allows the capacitance reading and record the data of pressure measurement in real time. Figure 3.37 is showing the diagram of measurement setup.

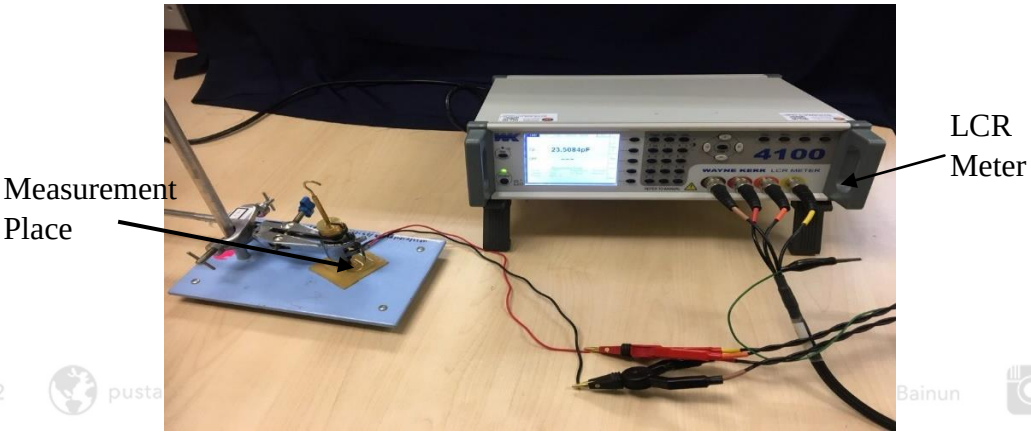



*Figure 3.37*. The diagram of the measurement setup

## 3.6 Characterization Method For Fluidic Based Pressure Sensor

The experimental studies for ellipse shape and square shape microchannel pattern is carried out in this section. The list of characterization including fluid mechanism, operating frequency, pressure measurement, temperature analysis and lifetime analysis as shown in Figure 3.38. Detailed the measurement setup and analysis will be explained in the following section. The characterization of fluidic based pressure sensor involves the fluid mechanism inside the sensor and the experimental result will be validated with the analytical result. The operating frequency based on the different

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type of liquid for the measurement in capacitance. The pressure measurement, temperature and lifetime analysis were setup for the experiment.

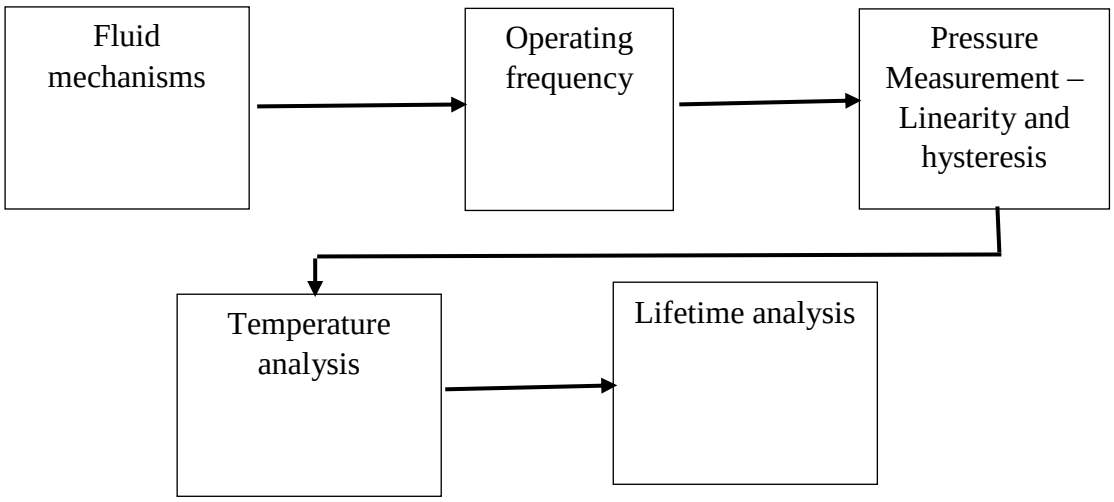



*Figure 3.38*. Characterization of fluidic based pressure sensor

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### 3.6.1 Fluid Mechanisms

The liquid is selected based on the viscosity, boiling point, surface tension, and dielectric constant. The pressure is applied on the top of membrane for ellipse shape and square shape microchannel pattern. The displacement of liquid is measured in mili scale, the comparison is made for both microchannel patterns.

### 3.6.2 Operating Frequency

Next, the dielectric constant also needs consider in order to generate the capacitance. Therefore, the capacitance value for variation of frequency is recorded. The frequency

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is applied from 120 Hz to 100 kHz. It is because the LCR meter that used has that range of frequency which from 120 Hz to 100 kHz.

### 3.6.3 Pressure Measurement Setup

For this experiment, the propylene carbonate is selected in this experiment. Figure 3.39 shows the image of pressure measurement setup. In this experiment, pressure from 0 to 10kPa by using slotted mas load was applied. Two parameters is obtained including linearity of the sensor and hysteresis effect for pressure up and pressure down. In addition, sensitivity of each sensor can be calculated from the plotted graph.

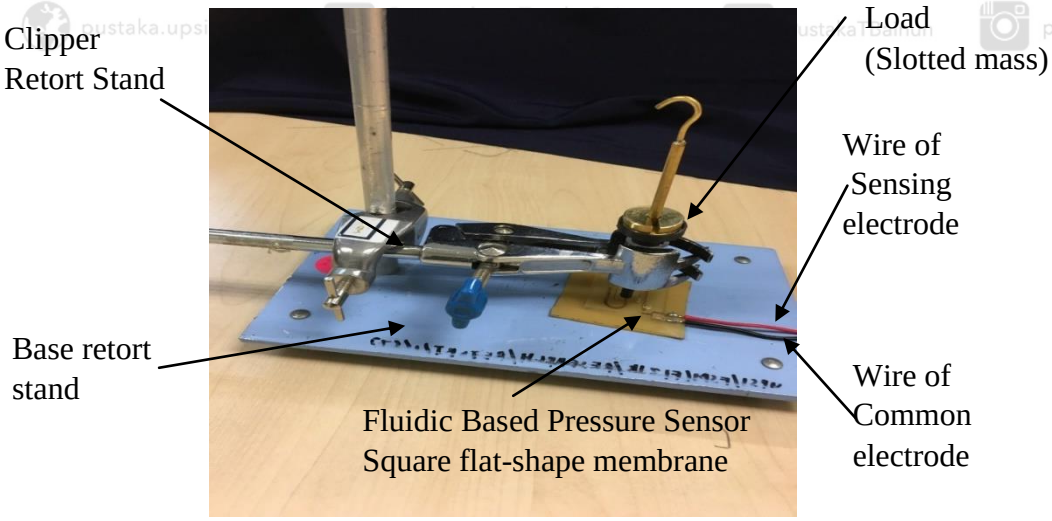



*Figure 3.39*. The image of pressure measurement setup

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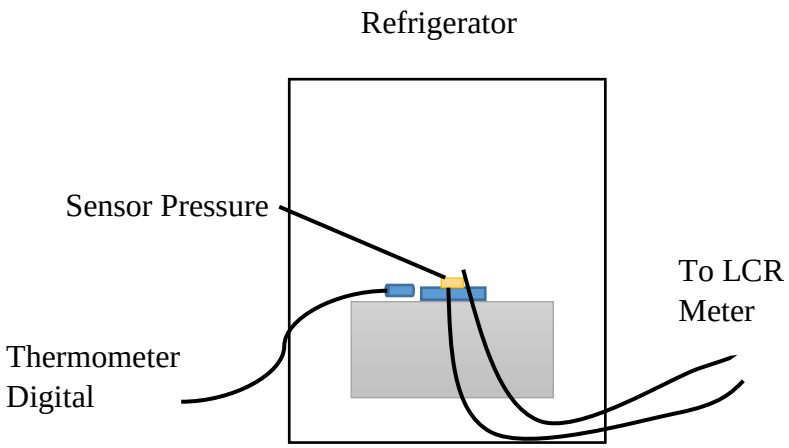
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### 3.6.4 Temperature Analysis Procedure

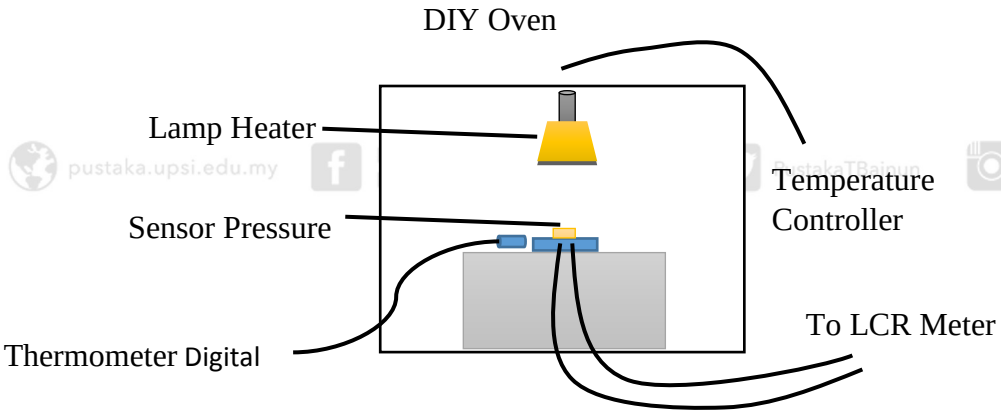
For temperature analysis, the schematic diagram for experimental setup is shown in Figure 3.40. The oven with temperature controller is used to obtained the reading the hot temperature at range 20 to 250 ℃ and the refrigerator was used for reading of cold temperature at range, -10 to 10 ℃. The additional sensor temperature is used to monitor the actual temperature reading. The range of temperature to test the fluidic based pressure sensor using the propylene carbonate was -10 to 120℃. It is because the sensor is that not used for harsh environment which is high temperature.

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(a)




(b)

*Figure 3.40*. The schematic diagram for temperature analysis (a) Refrigerator for cold temperature and (b) DIY Oven for hot temperature.

### 3.6.5 Lifetime Analysis Procedure

For lifetime analysis, the fluidic based pressure sensor that used propylene carbonate as a liquid is tested that has high boiling point. The propylene carbonate which has high boiling point compare to methanol that previously been used (Nawi et al, 2014).

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The time was recorded for ten hours. The output of the sensor in capacitance was recorded for each thirty minutes. The result finding is plotted and has been discussed in the next chapter.

## 3.7 Summary

Simulation process using FEA and CFD for structural analysis and microchannel analysis has been discussed in this chapter. The final model is fabricated using PDMS fabrication process, PCB process and sealing process. The characterization of fluidic based capacitive pressure sensor was discussed for different pattern of microchannel, which are ellipse and square shape. The operating frequency, fluid mechanism and pressure measurement were done for both pattern For ellipse shape microchannel pattern, the effect of temperature and lifetime analysis were discussed.

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# CHAPTER 4

# RESULT AND DISCUSSION

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## 4.1 Introduction

In this chapter will be discussed the simulation results for the two different type of structure of membrane. The FEA analysis will be carried out to classify the performance of the membrane. There are three analysis were carried out including different structure, different materials and for the liquid selection. The selected membrane based on the simulation will be fabricated and the a few limitations will be discussed. The fluidic based pressure sensor will be characterized for pressure measurement. The characterization for square-shaped and ellipse-shape microchannel will be carried out for liquid displacement and pressure measurement. Besides that, the temperature analysis and lifetime of the sensor also discussed.

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## 4.2 Simulation Results

In this section, all parameters are considered such as type of membrane structure, dimension, and material. The membrane performance was investigating and will be discussed in order to achieve the highest performance. The simulation using FEA was carried out for square shape and rectangular shape membrane structure. The area of surface is fixed and the pressure distribution is recorded. Then, the analysis for difference area of membrane surface will be evaluated. Next, the comparison was made for different types of polymer materials to determine the most suitable material for membrane. In addition, the membrane was simulated by varying an area and thickness. Lastly, the microchannel analysis is carried out for different dimension and liquid for the microchannel.

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### 4.2.1 Membrane Structure Analysis

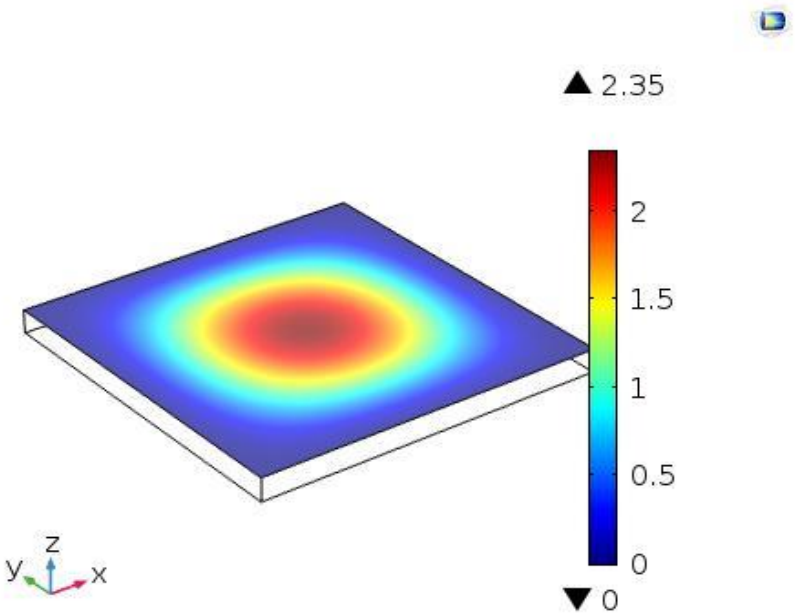
The proposed membrane structure was simulated using static model in COMSOL Multiphysics using method of Finite Element Analysis (FEA). There are two different type of membrane which are square shape, and rectangular shape. The area and thickness of membrane are fixed to 100 $mm^2$ and 0.50 mm, respectively. Data is obtained based on the results plotted after the solver finishes simulation.

The example of plotted contour for displacement and mises stress of square shaped membrane is shown in Figure 4.1. The color indicates the different values for displacement. At pressure 5kPa, the maximum displacement is 2.35 mm as shown in

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Figure 4.1(a). The color indicates the different values at different points. The blue color indicates 0 mm of deflection due to a fixed position and red color indicates maximum deflection which is located in the middle of the membrane. Mises stress is also another parameter that can be accessed using the simulation. Mises stress is used in the simulation to check whether it is sustainable for membrane to be used based on the pressure range. According to Figure 4.1(b), the maximum Mises stress value is 270 kPa.

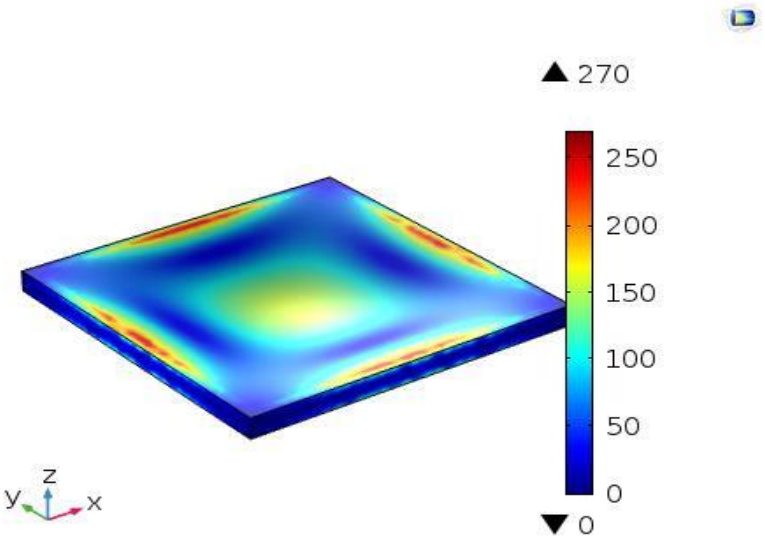



(a)

*Figure 4.1*. Plotted contour for square shaped membrane (a) Displacement vector (b) Mises stress distribution

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(b)

*Figure 4.1*. (*continue*)

Two different structures, which are square, and rectangular had been created to be tested based on applied pressure. Figure 4.2 shows the findings of the drag force acting on different types of structures. The pressure within the range 0 to 10 kPa was applied on the top surface of the membrane and the result was recorded. Figure 4.2 shows the graph for two shapes from which we can observe that the displacement had increased as the pressure increased. The square shape produced the highest deflection compared to the rectangular shapes which has high resolution. Therefore, the square shape membrane was chosen for the next analysis.

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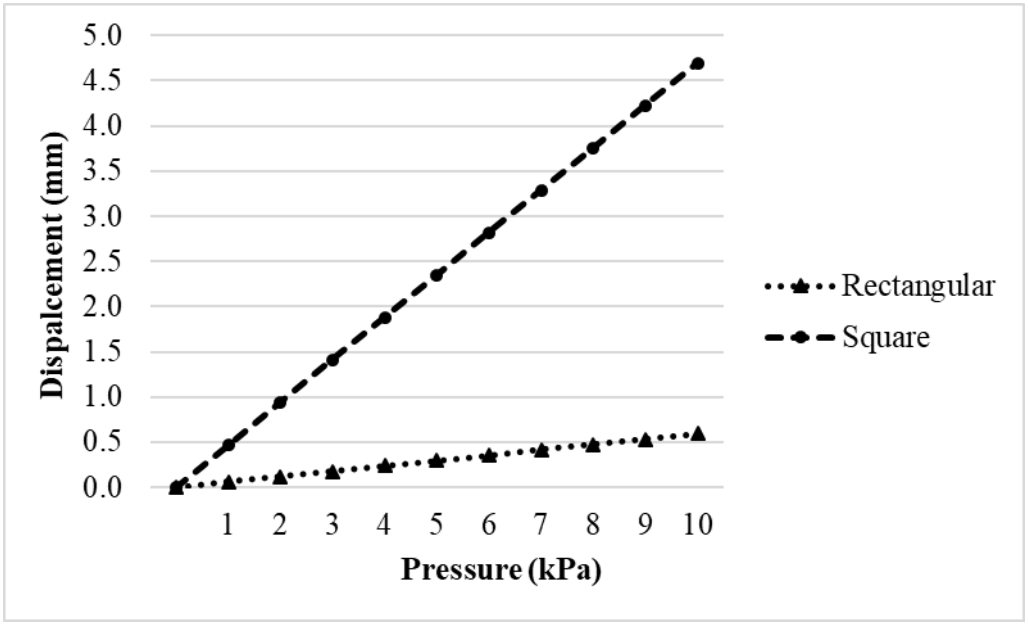




*Figure 4.2*. Displacement-pressure for different types of shape

Next, the dimensions of the square shape membrane were varied. The area of membrane within the range 60 - 100 $mm^2$ was selected for this analysis. Figure 4.3 shows the plotted graph for the membrane displacement with respect to pressure for different areas. As expected, the highest performance of the sensor with larger area, which produced maximum displacement. In addition to that, the larger area, 100$mm^2$ produced the highest displacement which was 4.6976 mm. From the figure 4.3 is show that the bigger of the area of membrane, the highest of the performance.

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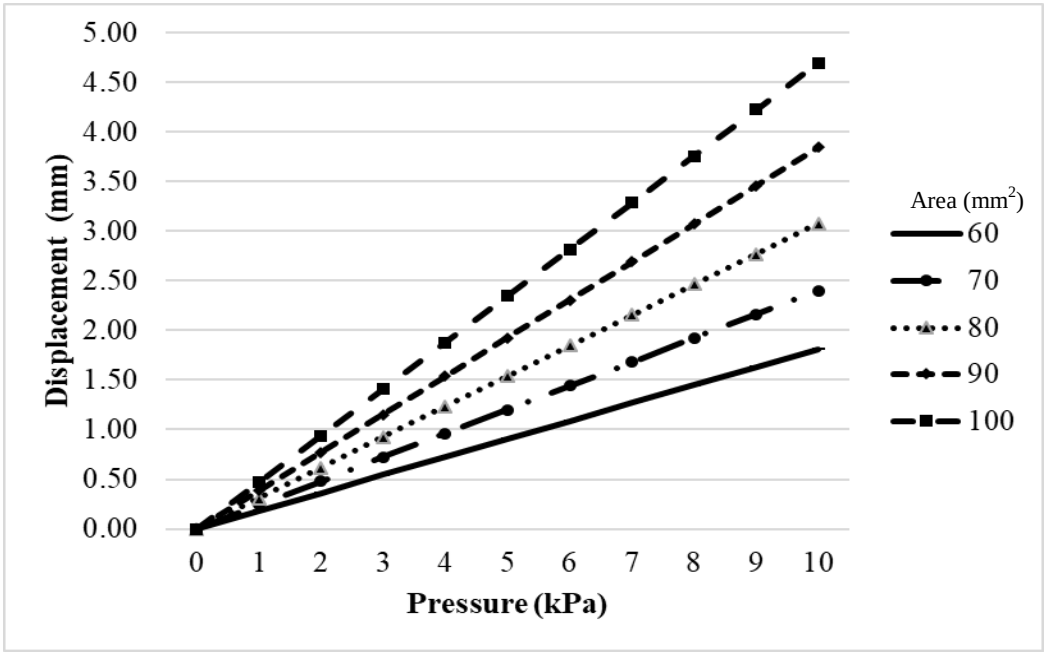




*Figure 4.3*. Displacement-pressure of square shape membrane for different areas

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### 4.2.2 Evaluation Of Membrane Performance

The material properties as listed in Table 3.2 was used for the square shape membrane. A variation of the pressure was applied for different material, including PDMS with different ratio and Polyimide (PI). Figure 4.4 shows the deflection of the membrane versus pressure. The membrane of PDMS (10:1) material produced a higher displacement compared to the others. The maximum value of deflection is 6.5 mm. Meanwhile, the PI material produced the lowest deflection which is 0.0035 mm. Which shows that PDMS (10:1) is more sensitive than PI.

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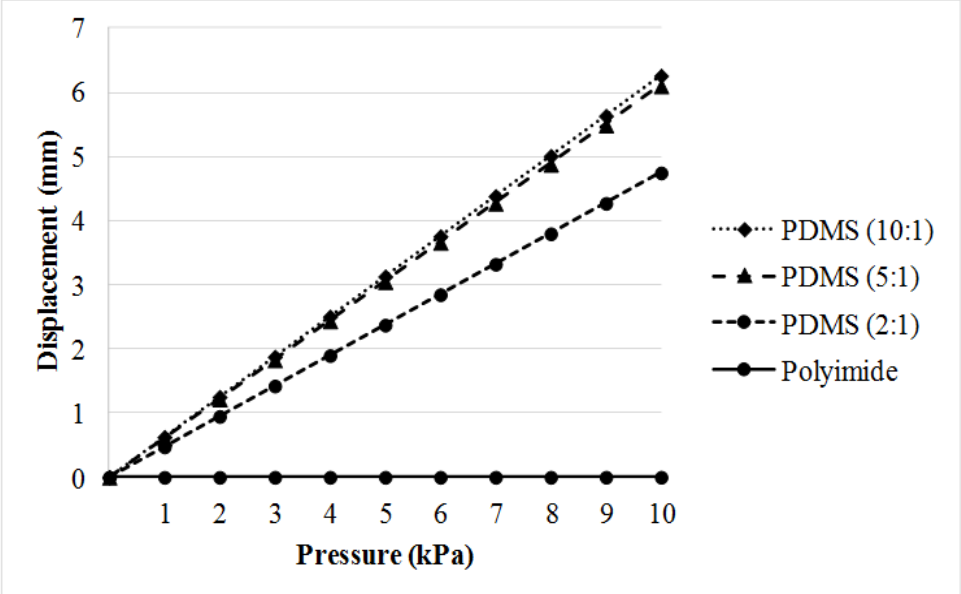
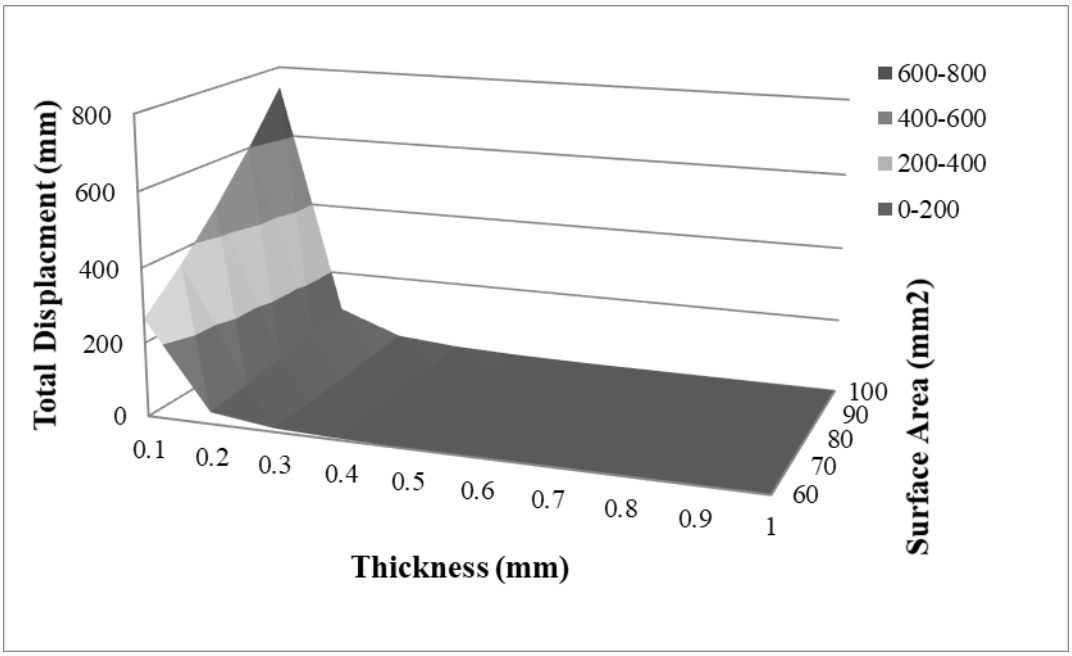




*Figure 4.4*. The different material for total displacement with different pressure (0 – 10 kPa)

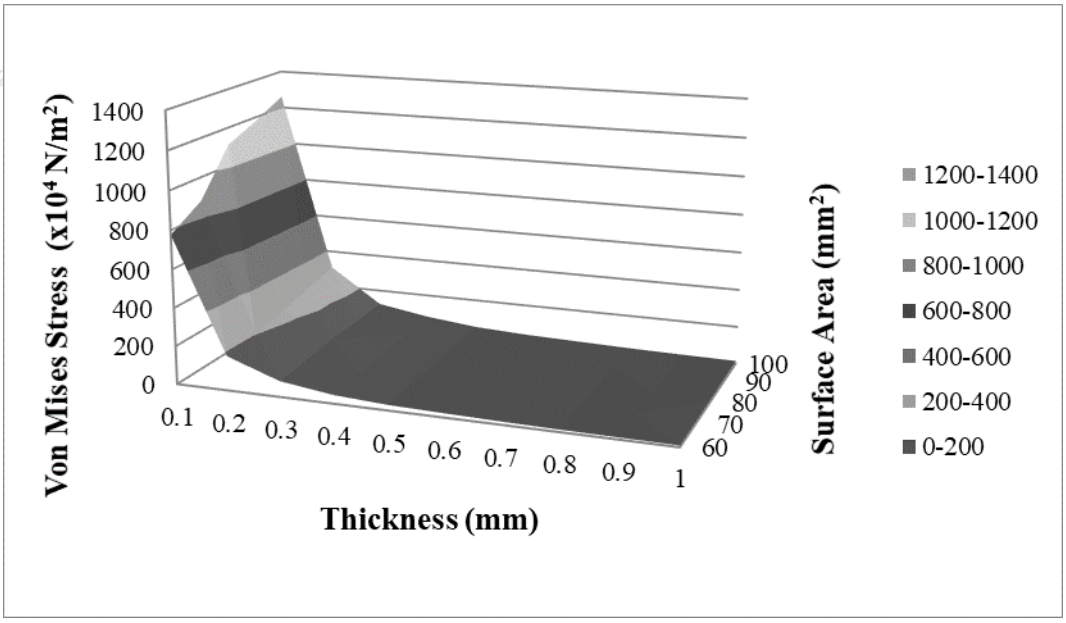
For the next analysis, the applied pressure was fixed at 5 kPa, while the dimensions, including area and thickness were changed. The PDMS material was used for this simulation. Figure 4.5(a) shows the membrane displacement. As expected, the larger area with the smallest thickness give the maximum performance of membrane displacement. However, the selection of final dimension must consider the limitation of the fabrication process. Besides that, the mises stress is recorded to study the sensor limitation. Figure 4.5(b) shows that the highest mises stress was 1.26 x 107 $N/m^2$ for the largest area and smallest thickness. However, the PDMS membrane cannot be broken or damaged during pressure measurement, because the tensile strength of PDMS is 2.24 Mpa (Mark, 2009). Although, the thinness of the membrane produces highest displacement, it can still rupture when taken out over covering during the fabrication process (Nawi et al., 2014).

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(a)




(b)

*Figure 4.5*. The performance of membrane (a) displacement and (b) Mises stress

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### 4.2.3 Microchannel Analysis

For the microchannel analysis, the 3D model of square-shaped microchannel and ellipse-shaped microchannel has been designed and simulated by using two different liquids including methanol and propylene carbonate. The size microchannel is fixed to 800 μm x 800 μm. We consider the steady laminar flow of an incompressible fluid with constant properties inside the microchannel. The moving liquid is forced to flow due to the membrane displacement. As predicted, the velocity increased as the pressure increased as shown in Figure 4.6. The comparison was made between methanol and propylene carbonate where it showed that methanol has a better performance due to viscosity. As presented in Table 3.3, the viscosity of methanol is lower than propylene carbonate. For the next stage, the propylene carbonate was selected due to the high boiling point and high dielectric constant compare the methanol which has lower viscosity. For fabrication process, both square and ellipse shaped microchannel is fabricated and the experimental studies was carried out.

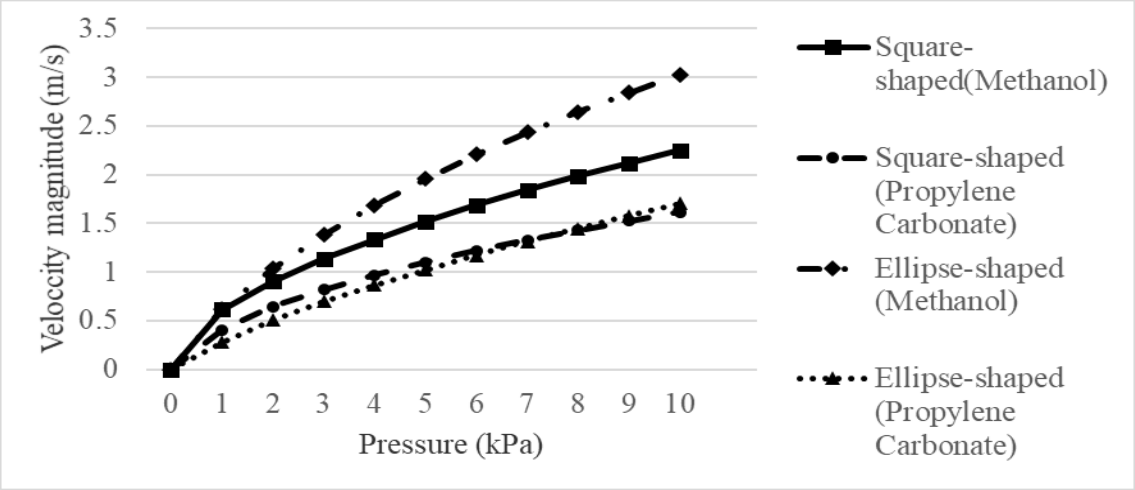



*Figure 4.6.* Velocity of liquid based on the pressure applied for methanol and propylene carbonate

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By selecting propylene carbonate as a liquid, the size of microchannel is varied for two difference dimensions including 800 μm and 900 μm. Figure 4.7 shows the velocity magnitude for different width of microchannel for ellipse-shaped microchannel. It is clearly showing that the high velocity magnitude depends on the larger microchannel. However, in order to miniatuarize the microchannel, the 800 μm is selected for the fabrication process.

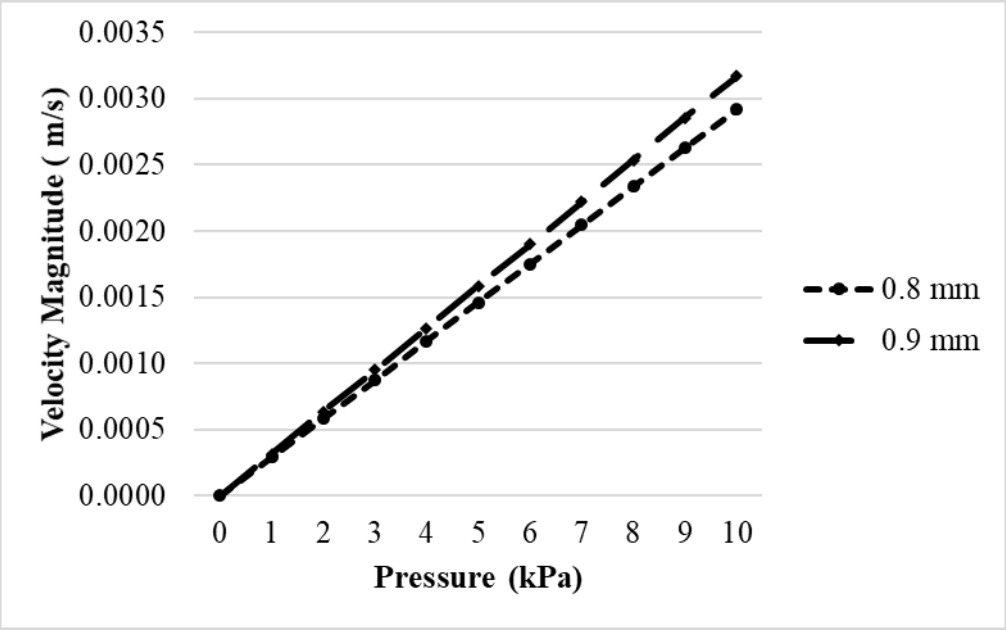
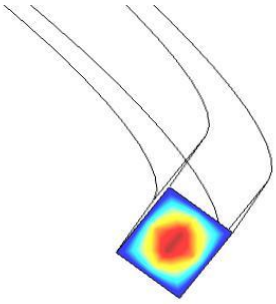



*Figure 4.7.* The velocity magnitude for varying height with varying of pressure applied for ellipse shape channel

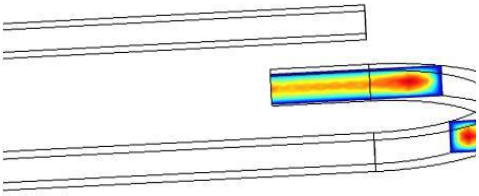
Figure 4.8 shows the cross section of microchannel for velocity magnitude. The maximum of velocity is located at center and indicated as a red color, meanwhile the blue color indicated zero magnitude which located near the wall of microchannel.

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(a)



(b)

*Figure 4.8*. The maximum and minimum of velocity in channel for ellipse design channel pattern (a) Inlet view and (b) Wall view

## 4.3 Fabrication Process

For this chapter, the Fabrication of membrane container will be explained for PDMS fabrication process, Print Circuit Board (PCB) process and sealing process. The Limitation of each method is also discussed. This fabrication of PDMS is discussed for both ellipse and square shape of microchannel pattern. For PCB process and sealing process, only ellipse shape pattern is discussed due to the same method used for square shaped microchannel pattern.

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### 4.3.1 Fabrication of Flat-Shaped Membrane Container

Soft lithography is the process to fabricate the PDMS. This process is used to determine the membrane thickness. Therefore, to study the thickness of membrane, micro size screw is used as a tool for measurement to measure the thickness. The same process is used for three sample of thickness are listed in Table 4.1 for ellipse and square shape of microchannel pattern. From the observation, this process has a limitation because the three sample has different although the same process is used, it may be due to the PDMS viscosity which is high and not spread completely. This limitation will give effect on the measurement of the characterization of pressure sensor.

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Table 4.1

*The thickness of the three sample of different of pattern of coplanar electrode design*

| **Ellipse shape** | | **Square shape** | |
|---|---|---|---|
| **Sample** | **Thickness (mm)** | **Samples** | **Thickness (mm)** |
| 1 | 0.7 | 1 | 0.74 |
| 2 | 0.65 | 2 | 0.7 |
| 3 | 0.74 | 3 | 0.69 |

Besides that, the thickness of membrane was varied for 0.1mm, 0.2mm, 0.3mm 0.4mm, 0.5 mm, 0.6mm and 0.7mm. The process of soft lithography was repeated for many times and observation was made for both pattern of microchannel. Figure 4.9 is show the image of the broken membrane during peel of process from the mold. From the observation, the thickness of membrane 0.1 mm until 0.4 mm is easy

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to broken and hard to remove from the mold compared to the thickness of membrane 0.5mm, 0.6mm and 0.7mm. However, the thickness of membrane 0.5 mm and 0.6mm is non-durable because the membrane is not lasting and not durable for repeated use in measuring the pressure measurement compared to the 0.7 mm. Therefore, 0.7 mm for the thickness of the membrane was selected as the sensing membrane and sensor is enhanced.

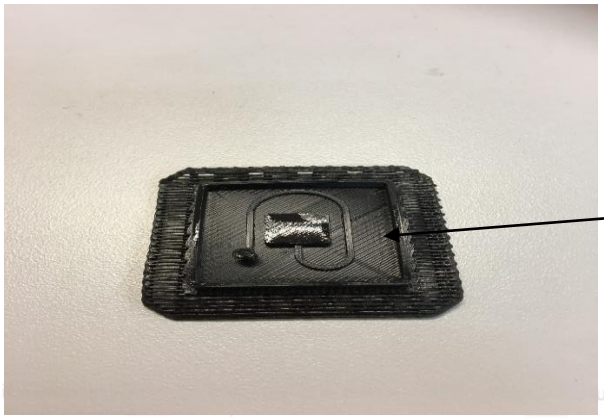



*Figure 4.9.* The image of the membrane is broken during the removed in mold ellipse shape coplanar electrode

### 4.3.2 Print Circuit Board (PCB) Process

For the PCB process, it has a limitation in terms of process time. The PCB board used FR4 material. There are several processes in this method which are printing process, exposure process, developer process and etching process as mention in chapter 3. The process that involves process time are exposure process, developer process and etching process. Table 4.2 is shows the average time needed for each process by using three different samples.

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Table 4.2

*Time taken for each process using three sample of PCB board.*

| **Time (minute) /Board** | **Board 1** | **Board 2** | **Board 3** | **Average Time** |
|---|---|---|---|---|
| Exposure Process | 3 minutes | 3 minutes | 3 minutes | 3 minutes |
| Developer process | 30 minutes | 31 minutes | 29 minutes | 30 minutes |
| Etching Process | 44 minutes | 45 minutes | 47 minutes | 46 minutes |

From the table, time taken to complete one cycle of PCB fabrication process is around 1 hour 19 minutes that is not included the design and printing process. The details on the design and printing process have been discussed on previous chapter.

For exposure process, if the process is done less than 3 minutes, the pattern is not fully exposed. In other word, the design of pattern is not fully transferred on PCB board. Besides that, for developer process, the process time must not more than 35 minutes. Figure 4.10 shows the image of transferred pattern of electrode. If the process time more than 35 minutes, the PCB board will remove the pattern during developer process as show in Figure 4.11. However, the process time also depends on the concentration of solvent develop solution.

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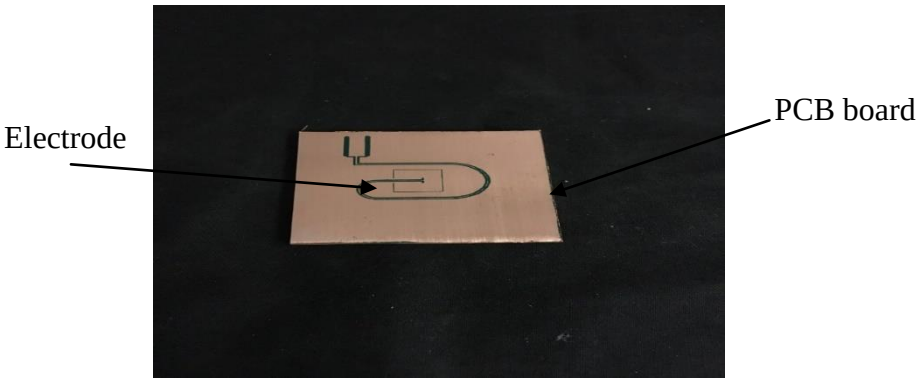




*Figure 4.10*. The image of design pattern on the PCB board before 35 minutes

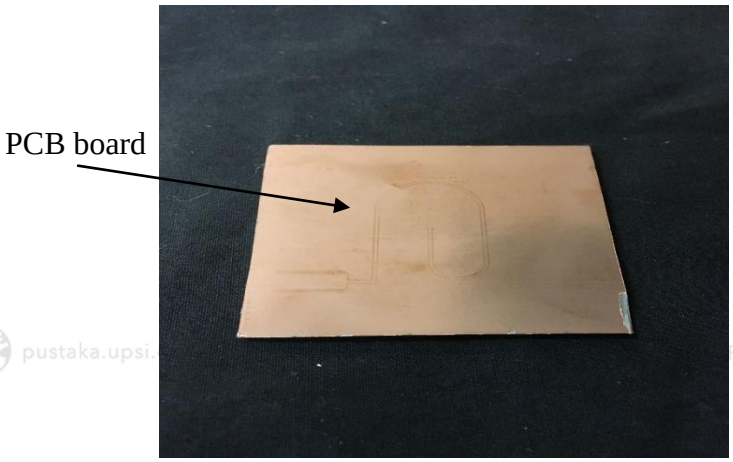



*Figure 4.11*. The image of design pattern after 35 minutes

For etching process, the time process must not exceed than 50 minutes for fully etching the copper. Figure 4.12 shows the successful process which the pattern of electrode is clearly can be seen without any damage. The solvent for etch is fixed compound with the combination of $FeCl_2$ powder and water. Then, Figure 4.13 shows that the pattern is slightly disappear on the board when the time process exceed 50 minutes. However, the process of developer and etching is a long time process due on the time taken to process as shown in Table 4.2. The etching process is depending on the developer process. If the developer process is good, then the process of etching is should be no problem.

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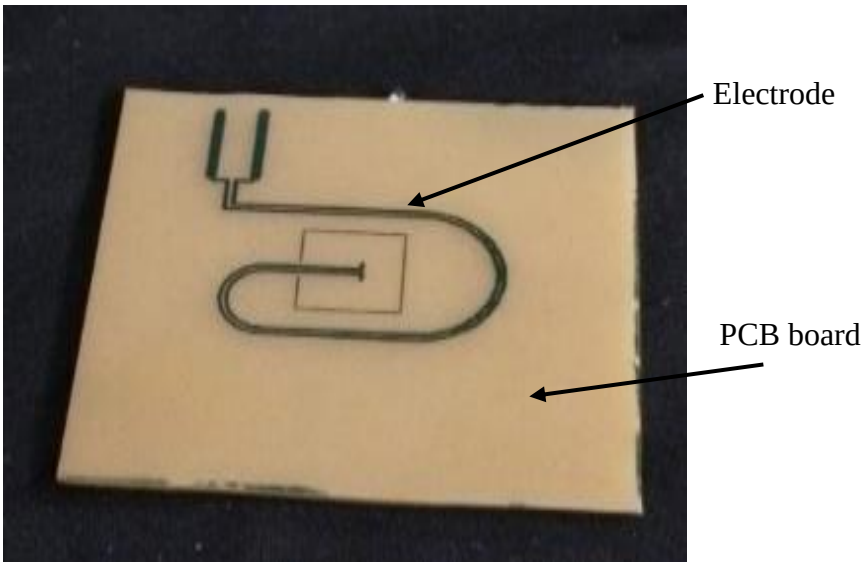




*Figure 4.12*. The clear image of the pattern design on the board

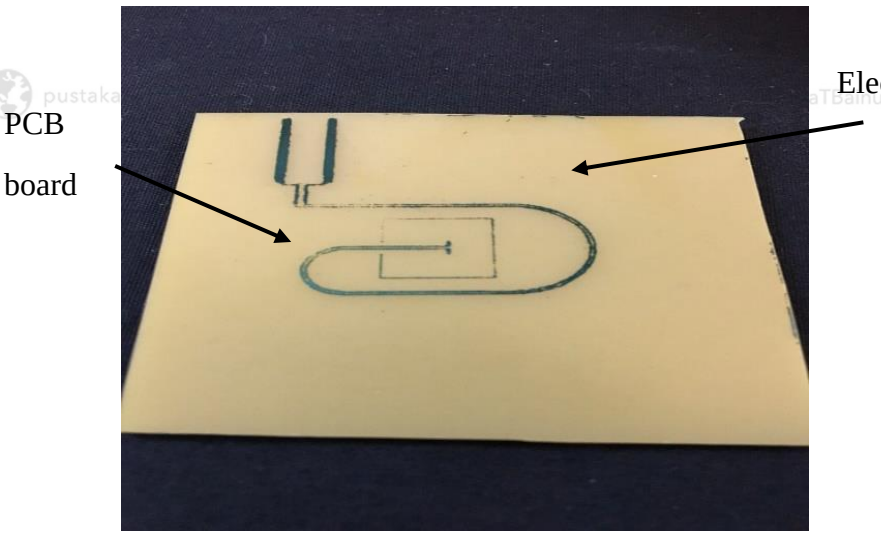



*Figure 4.13*. The pattern design on the board after more than 50 minutes

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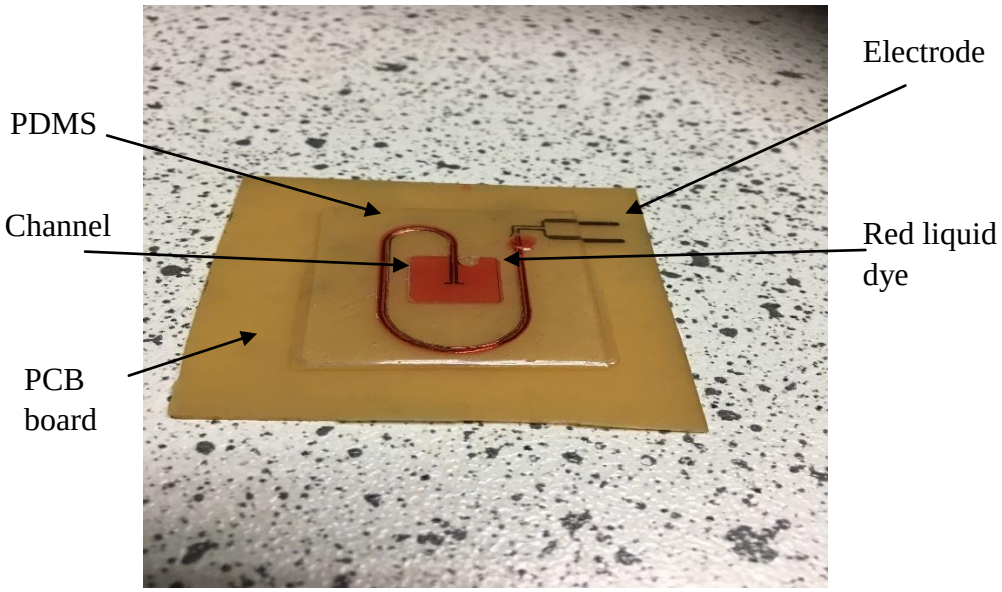

### 4.3.3 Sealing Process

Sealing process is used in this experiment to seal the PDMS container and the PCB board. For sealing process, bonding test is carried out in order to analyze the bonding strength between PCB board and PDMS container. The experiment was test by applying liquid dye which is red colour inside the membrane and the channel, the membrane is hardly push until the liquid dye is moved toward the outlet. The purpose it to examined either there has a leakage or not within the bonding area which is between PCB board and PDMS container.

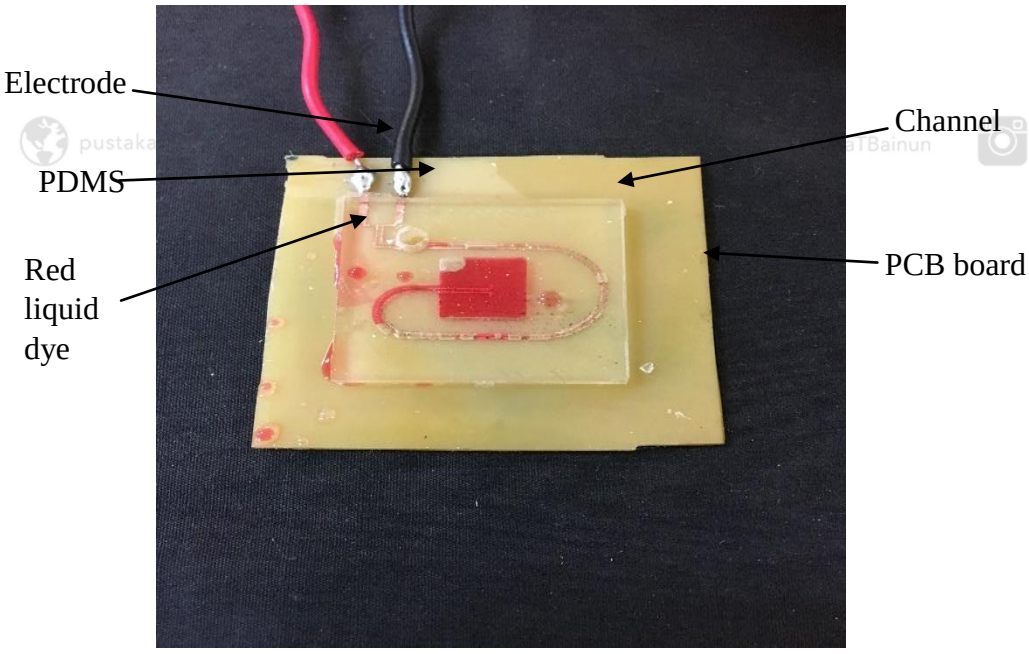
Figure 4.14 is showing the bonding test that obtained during experiment. The experiment is successfully done where there is no leakage during the applied pressure for Figure 4.14(a) and leakage for Figure 4.14(b). The sealing process is depending on the PDMS solvent and the process. It needs to carefully done to make sure the PDMS solvent is distributed properly.

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(a)




(b)

*Figure 4.14.* The Bonding test on the sensor with ellipse shape design electrode pattern; (a) No leakage and (b) Leakage

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## 4.4 Sensor Characterization

The sensor characterization including fluid mechanism, operating frequency, pressure measurement, temperature effect and lifetime analysis. In this subchapter, the pressure is applied on the top of membrane in order to study about fluid mechanism and pressure measurement. The liquid displacement inside the microchannel is depend on the applied pressure. Therefore, for the fluid mechanism, the liquid displaced is measured. Next, the operating frequency is need to be measured for both ellipse shape and square shape of microchannel pattern. Then, the linearity and hysteresis were discussed for pressure measurement. Pressure up and pressure down is applied for both pattern of microchannel. Besides that, the sensor robustness was test for temperature affect. Then, lifetime of the sensor was also discussed.

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### 4.4.1 Selection of Liquid

For selection of liquid, propylene carbonate, and methanol are selected based on its properties for ellipse shape and square shape of microchannel pattern. The important of properties liquid are dielectric constant, surface tension, kinematic viscosity and boiling point as shown in Table 3.1. The liquid that have high dielectric constant, and high boiling point are considered in this liquid selection. The sensor needs a high dielectric constant liquid to ionize and high boiling point for long lifespan and maintain the performance. Propylene carbonate has higher dielectric constant and high boiling point compare to methanol. Therefore, propylene carbonate is used as a

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main liquid in this characterization. However, methanol has advantage which is low viscosity which allow the easy movement inside microchannel (Nawi et al., 2014).

### 4.4.2 Validation For Fluid Mechanism

The membrane deflection will push the liquid inside the microchannel. Figure 4.15 shows a picture of area cross section and mechanism of the sensor. When the pressure is pressed, the liquid will move toward the outlet due to the deflection membrane. The outlet of sensor is located at the end of the sensor with a small hole. Using the formula of pressure measurement, (Almassri et al., 2015):

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$$P = \frac{F}{A} \tag{4.1}$$

That for the square shape pattern structure. The P is applying pressure and A is area of sensing force. According to the previous researcher (Timoshenko, Stephen & Woinowsky-Krieger, 1959), the membrane deflection, W is

$$W = \frac{P a^4}{4\pi^4 D} \tag{4.2}$$

Where is x, D and y are coordinates of x, flexural rigidity and coordinates of y. Formula of D, (Nallathambi & Shanmuganantham, 2015) is as below,

$$D = \frac{E h^3}{12\,(1-\nu^2)} \tag{4.3}$$

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Where, E, h and ν are elastic modulus, membrane thickness and Poisson's number. From equation 4.3, it is substituted in equation 4.2 which is;

$$W = \frac{Pa^4}{4\pi^4} \frac{12(1-v^2)}{E\,h^3} \tag{4.4}$$

According the principle of fluid mechanism, that's the volume of the membrane deflection, $V_{membrane}$ is equal to the volume of the channel where the displacement of liquid in the channel, $V_{liquid}$. ;

$$V_{liquid} = V_{membrane} \tag{4.5}$$

For the volume of membrane deflected, it is like a volume of truncated square pyramid. It is relationship with the volume and the deflection of membrane

$$V_{membrane} = \frac{\pi}{6} W(3R^2 + W^2) \tag{4.6}$$

Then, the volume of rectangular channel is used for the volume of liquid displacement inside the channel as given;

$$V_{liquid} = w_c L t_c \tag{4.7}$$

Which is ***w***, $t_c$ and *L*, the channel width, channel thickness and length of displacement of liquid in channel. After that, the equation of (4.6) and (4.7) are substituted into (4.3):

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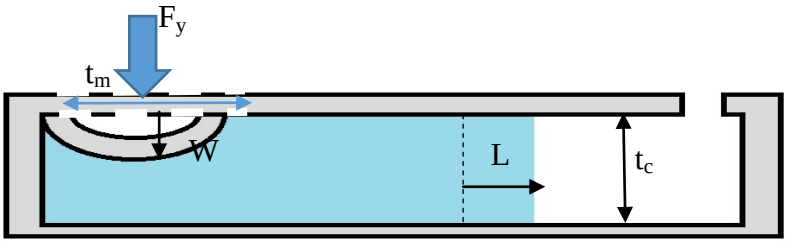
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$$wt_c L = \frac{\pi}{6} W(3R^2 + W^2) \tag{4.8}$$

Lastly, the equation (4.4) is substituted into (4.8). It is simplifying for length of displacement of liquid found inside the channel as show an equation below:

$$L = \frac{\frac{\pi}{6} W(3R^2 + W^2)}{t_c w_c} = \tag{4.9}$$

From the equation (4.9), it is shows that the movement of liquid is depends of the membrane material, membrane dimension, and the applied force on the membrane. Theoretically, the pattern of microchannel does not affect based on the equation (4.9). However, from the observation, liquid movement might affect if liquid move in ellipse shape and square shape of microchannel. Therefore, the experimental studies have been done for fluid mechanism, the measurement is in unit millimeter scale for variation of applied pressure.

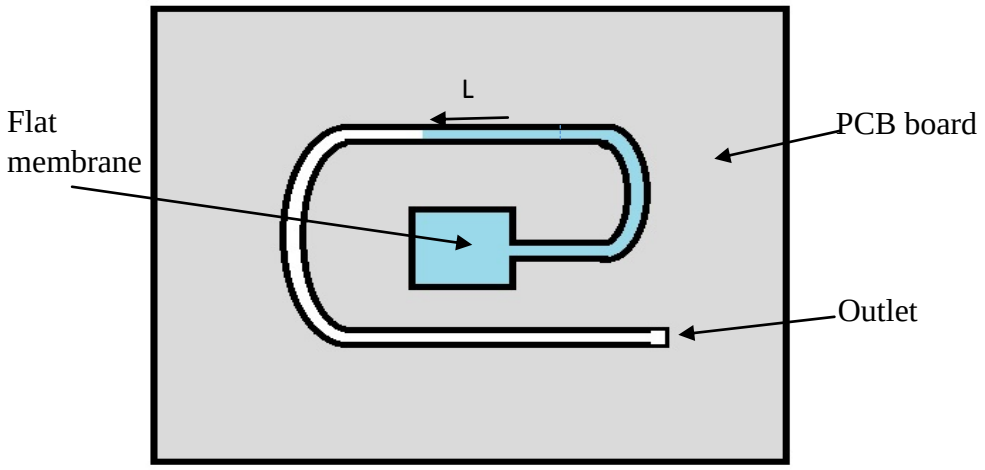



(a)

*Figure 4.15*. The image of cross section of the sensor for ellipse shape coplanar electrode (a) side view and (b) top view

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(b)

*Figure 4.15*. (Continue)

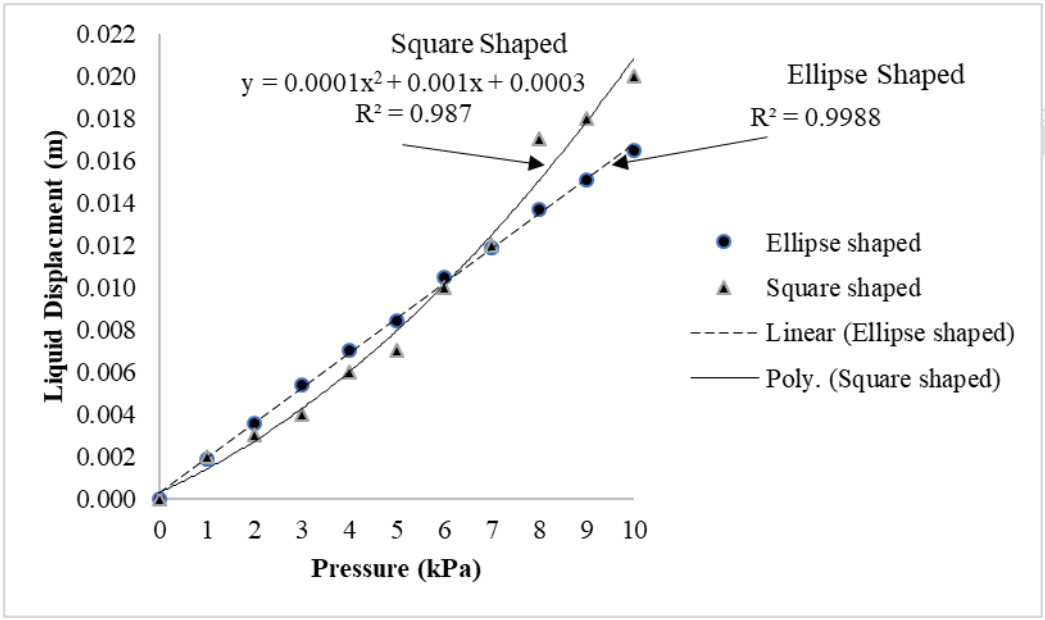



*Figure 4.16*. The liquid displacement for different shape of microchannel pattern by using propylene carbonate

The propylene carbonate has been chosen as a liquid to fill in the cavity. Pressure is applied from 0 to 10 kPa and liquid displacement is recorded for both ellipse shape and square shape microchannel pattern. Figure 4.16 shows the plotted graph of liquid displacement. From the graph, the result for liquid displacement for

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ellipse shape of microchannel pattern is linearly increase from 0 until 10 kPa with regression 0.9988. For square shape, the linear fitting shows the regression value is 0.9673, meanwhile the polynomial line fitting shows the best curve with regression 0.987.

From the observation, the ellipse shape produced the linear data with respect to the applied pressure. It may due to the structure of microchannel which square shape has a sharp corner 90 degree compared to ellipse shape that has round corner. The sharp junction may cause nonlinear movement of liquid inside the microchannel. Besides that, the meniscus angle is occurred depend on surface tension of liquid values which the angle of meniscus of propylene carbonate in the both pattern electrode is the same. Then, the pressure measurement is carried out for both pattern to study the linearity and hysteresis effect. For the temperature effect and lifetime, the ellipse shape of microchannel pattern is used.

### 4.4.3 Operating Frequency

To obtain the operating frequency, the propylene carbonate is used for both microchannel pattern and the frequency is varied from 110 Hz to 100 kHz. The capacitance is recorded. The measurement was recorded using the resistance-capacitance (R-C) series model. Propylene carbonate was selected for this experiment which are high dielectric constant than the methanol in Table 3.2 for square shape and ellipse shape of microchannel pattern.

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Figure 4.17 shows the value of capacitance is decreased when the value of frequency is increased for the both square and ellipse shape design of microchannel. The capacitance is high when the value of frequency is low because complex impedance. The complex impendence is remains because the electrons from the ions was form in an electrical change on the plates. At the same time, as the frequency is increase, the value of capacitor is charge across the plates which is resulting for current flow through the capacitor. Due to that, the value of capacitor of internal impedance has decreased (Gunawardane & Kularatna, 2015). There is no capacitance change for air (without propylene carbonate) although the frequency is varied.

In order to find the suitable frequency to operate for the sensor, the sensor performance was evaluated and the capacitance of the sensor was calculated using the equation 4.10 (Nawi et al., 2014) as show below.

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$$C = \frac{\varepsilon_o \varepsilon_{PDMS} A}{d_{PDMS}} \quad 4.10$$

Which A is $l_1 \, x \, w_1$ and $l_2 \, x \, w_2$

$$C = \frac{\varepsilon_o \varepsilon_{PDMS}((l_1 \, x \, w_1)+(l_2 \, x \, w_2))}{d_{PDMS}} \quad 4.11$$

Where, C, $\varepsilon_0$, $\varepsilon_{PDMS}$, $d_{PDMS}$ , $A$, $l$ $and$ $w$ are the capacitance value, permittivity vacuum, dielectric constant of PDMS, thickness of PDMS, surface area of electrodes, length and width the sensing area of electrode. The table 4.3 (a) is shows the result of calculation for capacitance of ellipse shape and Table 4.3 (b) for square shape of

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microchannel pattern. From the graph, the operating frequency were obtained for ellipse shape and square shape are 4.3 kHz and 0.43 kHz, respectively.

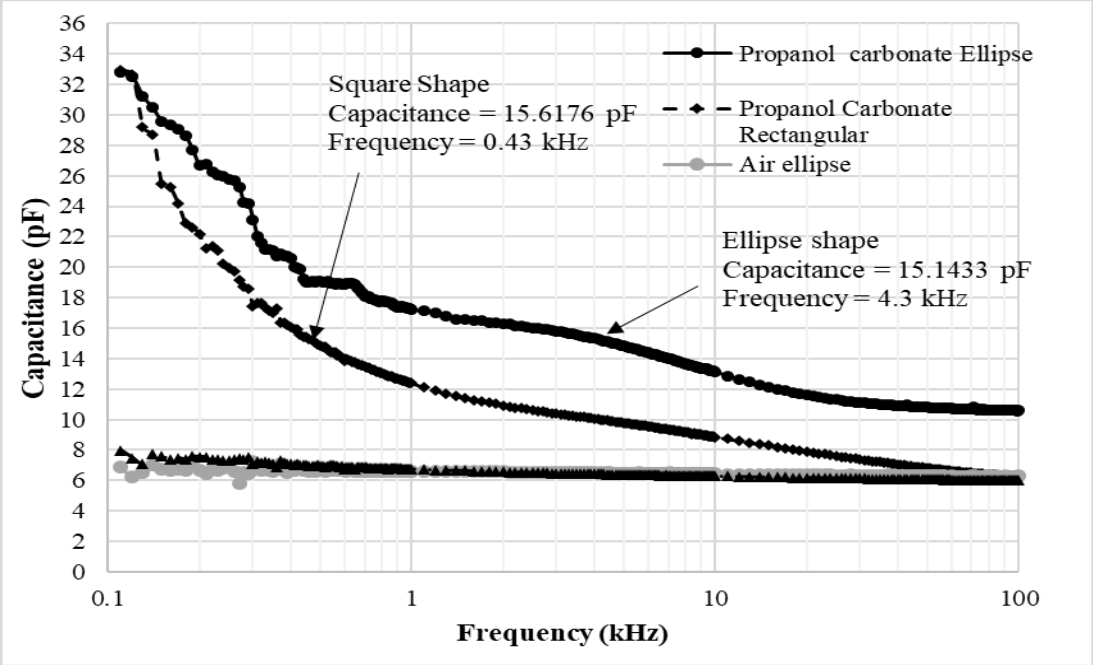



*Figure 4.17*. The capacitance response for variation of frequency different types of microchannel pattern.

Table 4.3 (a)

*The calculation of the capacitance value for ellipse shape*

| | |
|---|---|
| Permittivity of vacuum, $\varepsilon_0$ | 8.85 x $10^{-12}$ |
| Dielectric constant of PDMS, $\varepsilon_{PDMS}$ | 2.3-2.8<br>(2.5) |
| Surface Area, A / $m^2$ | 6.16 x $10^{-5}$ |
| Thickness layer of PDMS, $d_{PDMS}$ / mm | 0.09 |
| Initial Capacitance / pF | 15.143333 |

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Table 4.3 (b)

*The calculation of the capacitance value for square shape*

| | |
|---|---|
| Permittivity of vacuum, $\varepsilon_0$ | 8.85 x $10^{-12}$ |
| Dielectric constant of PDMS, $\varepsilon_{PDMS}$ | 2.3-2.8<br>(2.5) |
| Surface Area, A / $m^2$ | 6 x$10^{-5}$ |
| Thickness layer of PDMS, $d_{PDMS}$ / mm | 0.085 |
| Initial Capacitance / pF | 15.6176 |

### 4.4.4 Linearity and Hysteresis for Pressure Sensor Measurement

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For linearity and hysteresis, the measurement of pressure was obtained by carried out for pressure up and pressure down. The operating frequency of the sensor for the ellipse shape pattern and square shape pattern are 0.43 kHz and 4.3 kHz, respectively. The hysteresis is the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and decreasing a pressure. Meanwhile the linearity

For measurement of pressure of up and down, the load is increase and decrease which the process is done manually. Therefore, there is a disturbance during pressure measurement. In prevent this happen, the each of pressure was triplicate and the average value of each data is taken. The propylene carbonate is used for both type of sensors. Figure 4.18 shows the capacitance change for pressure up and pressure down for sensor with square shape of microchannel pattern. The range of capacitance

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change for pressure up is from 13.0 pF to 17.4 pF, meanwhile range of capacitance change for pressure down is 16 pF to 17.4 pF in the Figure 4.18. Given the relationship between capacitance change, pressure up, $P_U$ and pressure down, $P_D$ below:

$$C_{U\,(S)} = 0.4956P_u + 12.143 \quad (4.12)$$

$$C_{D\,(S)} = 0.1578P_D + 15.496 \quad (4.13)$$

where $C_{U(S)}$ and $C_{D(S)}$ are the value of capacitance for pressure up and pressure down of square shape pattern of microchannel.

The linear regression-squared approaching one indicated that the data has a good. From the graph, which the value of linear $R^2$ for pressure up and pressure down are 0.9664 and 0.8803, respectively. The maximum hysteresis occur at range 0-3 kPa where the pressure up from 13 pF to 13.4 pF, then pressure down from 15.9 pF to 16 pF. The error percentage is about 23%. From the graph, the sensor sensitivity can be obtained where the value of sensitivity is 0.5 pF/kPa.

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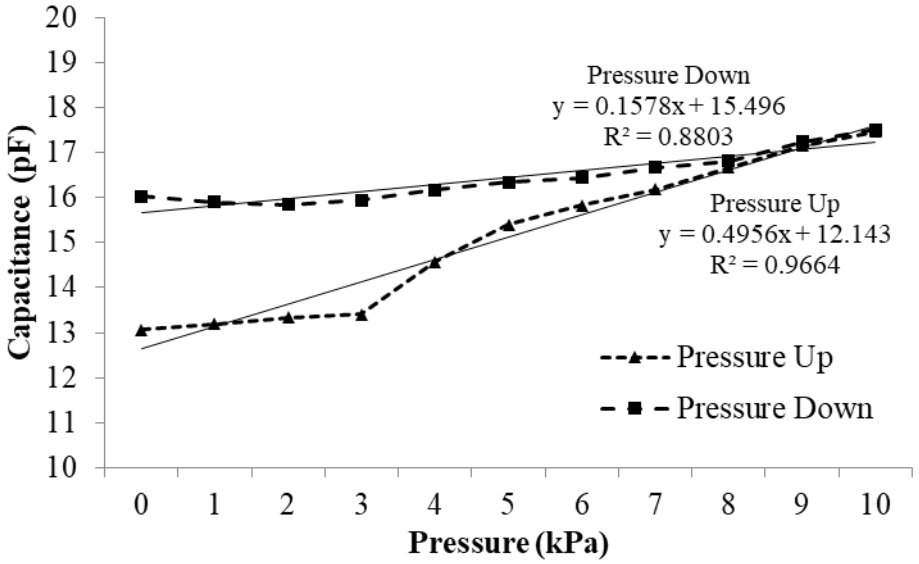




*Figure 4.18.* The capacitance changes for Pressure up and Pressure down for the sensor that has square shape of microchannel pattern

Next, the capacitance changes of pressure up and pressure down for ellipse shape of microchannel pattern is plotted as shown in Figure 4.19. The range of capacitance change for pressure up is from 13.0 pF to 16 pF, meanwhile range of capacitance change for pressure down is the same as pressure up. Given the relationship between capacitance change, pressure up, $P_U$ and pressure down, $P_D$ below:

$$C_{U\,(E)} = 0.3018P_U + 12.714 \quad (4.14)$$

$$C_{D\,(E)} = 0.3107P_D + 12.079 \quad (4.15)$$

where $C_{U(E)}$ and $C_{D(E)}$ are the value of capacitance for pressure up and pressure down of ellipse shape pattern of microchannel.

The maximum hysteresis occurs at 9 kPa where the pressure up is 15.76 pF, then pressure down is 15.86 pF. The error percentage is quite low about 0.6%. For

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linear $R^2$ values, ellipse shape shows a good data which approaching 1, where the $R^2$ for pressure up and pressure down are 0.9989 and 0.9976, respectively. From the graph, the sensor sensitivity can be obtained where the value of sensitivity is 0.3 pF/kPa.

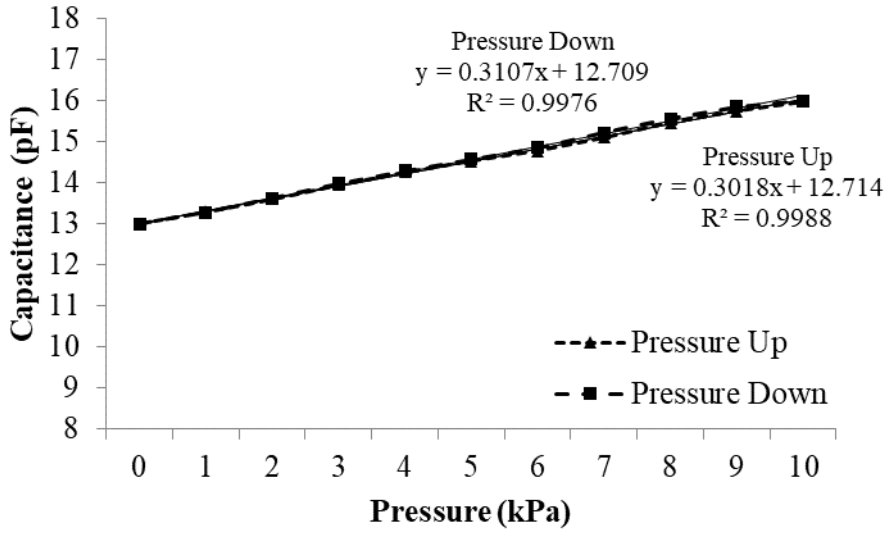



*Figure 4.19.* The capacitance changes for Pressure up and Pressure down for the sensor that has ellipse shape of microchannel pattern

Although the sensor with square shaped of microchannel pattern shows a high sensitivity compared to ellipse shape, hysteresis error is quite large. It may be due to the sharp corner which give the effect of liquid movement during the increment and decrement of pressure. Ellipse shape of microchannel patter shows a good performance in terms of linearity and hysteresis due to round corners which easier the liquid to move. Therefore, the ellipse shape was selected to test the temperature effect and lifetime effect as mention in a previous study in fluid mechanism.

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### 4.4.5 Temperature Effect

The temperature effect is done with using the refrigerator and microvan and the temperature is applied from -10 – 0 $^{o}$C for using refrigerator and 10 – 120 $^{o}$C is for microvan. The sensor with ellipse shape of microchannel pattern is selected for this experiment based on the previous experiment. The value of capacitance respond has been recorded for each temperature difference. The value of capacitance versus temperature is plotted as shown in Figure 4.20. From the graph, value of capacitance is increase when the temperature is increase. However, the percentage of temperature increase is about 16.2162 % for temperature range -10 to 120 $^{o}$C. The increasing of capacitance is depending on propylene carbonate due to effects of different reaction conditions on the synthesis of propylene carbonate (Xiaoli, 2013). However, the error of percentage of the capacitance change within range 20 - 50 $^{o}$C is small which is about 0.86 %, means the sensor can be operate at this range. Within this temperature range, it is suitable to use in monitoring of pressure in various type of application.

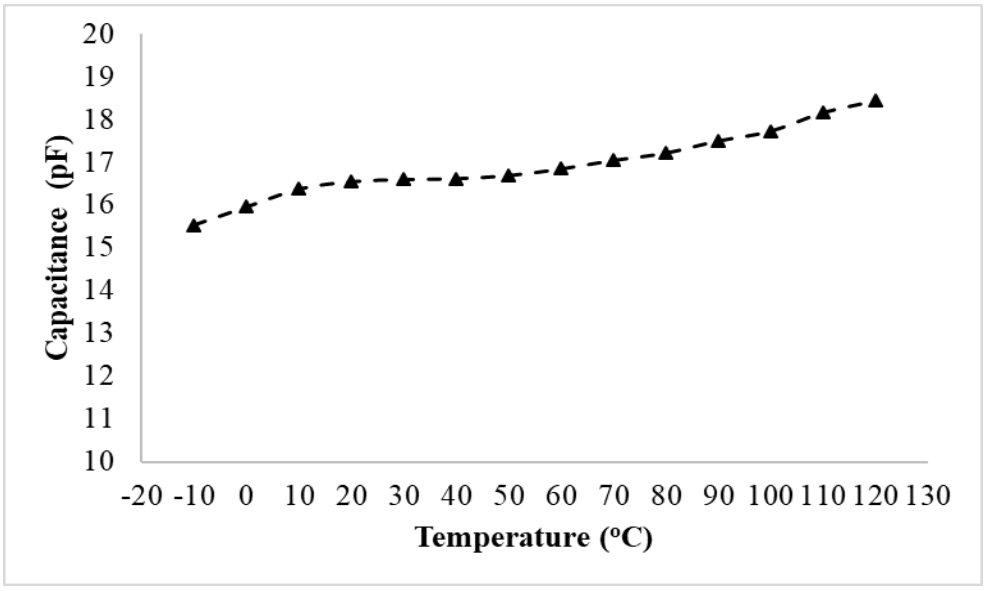



*Figure 4.20*. The performance of sensor of ellipse shape with effect of temperature

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### 4.4.6 Indictment Test

For the indictment test, the experiment is done to study limitation of sensor in terms of sensor life span. By using sensor with ellipse shape microchannel pattern and the propylene carbonate is used as a liquid. The sensor is placed at the room temperature and the capacitance value is recorded for each 30 minutes. The responses of output for the lifetime effect have been observed. Figure 4.21 is showing the experimental result for a period life of 10 hours. From the graph, the time from 0 to 240 minutes shows there is no change in terms of capacitance. When the time at 270 minutes, the capacitance change of the sensor is slightly down. The error percentage is about 2.16 %. However, this sensor can be used for long time because it can be hold off more than 10 hours due on the liquid used which are propylene carbonate which has high boiling point.

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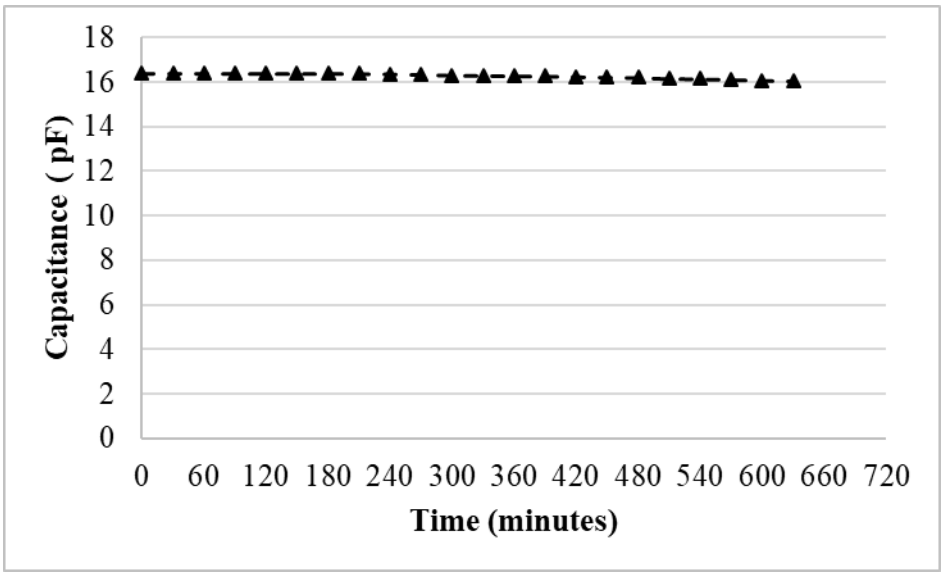



*Figure 4.21*. Lifetime effect of ellipse of structure of coplanar electrode

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## 4.5 Summary

The membrane of fluidic based pressure sensor has been analysis using COMSOL MULTYPHYSICS, Finite Element Analysis (FEM) for different membrane shapes, which are square, and rectangular was presented. Square shape is selected. Two different patterns of microchannel, which are square and ellipse shape is study in both simulation and experiment. For the membrane materials, the material of PDMS (10:1) is selected for produced the highest value of deflection of membrane.

For fabrication, the effect of the membrane container fabrication was explained due to the thicker area on the base and center of applied pressure. The soft-lithographing is selected for fabrication of membrane shape. The PCB process including printing process, exposure process, developer process and etching process is presented. The sealing process is discussed.

For the characterization sensor, Propylene carbonate was selected as electrolyte which have high boiling point and high dielectric constant. The operating frequency for square shape and ellipse shape has been obtained. Besides that, fluid mechanism and linear and hysteresis also were discussed for the ellipse and rectangular shape of structure of coplanar electrode were also the performance of the sensor which one will be selected for the temperature and lifetime condition. The temperature and lifetime is examined for the ellipse shape only to classify their effect for the performance of sensor due fluid mechanism, linear and hysteresis. As conclusion, the capacitive pressure sensor using the rllipse shape pattern

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microchannel can reduce the size of the sensor and propylene carbonate as electrolyte can improve the performance in term life span of sensor.

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# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

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## 5.1 Conclusion

An enhancement of microfluidic based capacitive pressure sensor has been successfully developed. In order to demonstrate mechanism principle, pressure measurement which is a drag force from the mechanical, pressure will generate the electric signal, capacitance value by the movement of liquid in the channel. Based on this mechanism, a pressure sensor that has flat-shaped membrane structure has been proposed with the instrumentation of the fluidic based system has been proposed. FEA analysis is shows that the square shape flat membrane is more suitable than rectangular shape flat membrane. For CFD analysis, the different of size of channel and the design of pattern coplanar electrode has been carried out. The area of the square shape flat membrane is fixed 100 $mm^2$. The flat-shape membrane of deflection can be archived high value when using a small thickness that is not torn. A PDMS is

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used with a ratio 10:1. The pattern design of microchannel are ellipse shape and square shape. The dimension of microchannel is fixed, 0.8 mm and 0.8 mm for width and height.

In the fabrication process, the PCB technique is used for electrode printing for electrode shape that are ellipse shape and rectangular shape, which are have 4 methods which are printing process, exposure process, developer process and etch process. For printing process is not related to time and vision, but exposure, developer and etch process is related to time and for each process has different time. For exposure process, 3 minutes, developer process and etch process are not more 35 minutes and also not more 50 minutes. For flat shape membrane, a smooth fabrication process of PDMS square-shaped membrane using soft lithography techniques was demonstrated. This technique is can archived the uniform membrane thickness. The thickness of membrane is obtained is 0.7 mm based on the limitation of fabrication in simulation FEA. Propylene carbonate was selected from methanol for the liquid used in the channel. It is because it has high dielectric constant and high boiling point for the performance the sensor response.

The characterization of fluidic based pressure sensor that has a flat membrane has been investigated for different design pattern microchannel, ellipse shape microchannel and rectangular shape microchannel. The result the mechanism of liquid inside the channel, the ellipse microchannel pattern is regression linear, $R^2$ = 0.9988 and for square microchannel pattern is regression linear, $R^2$ = 0.9870. The error percentage for ellipse microchannel pattern shape is about 0.6 % and for the rectangular microchannel pattern shape is about 23%. The operating frequency of the

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propylene carbonate, ellipse microchannel shape is 4.3 kHz and for rectangular microchannel shape is 0.43 kHz. From fluid mechanism and error percentage of hysteresis, the ellipse shape microchannel is selected for temperature and lifetime effect for performance of the sensor. For temperature effect, the error increasing is 0.86 % for the normal temperature, the range from 20 -50 $^{o}$C. Meanwhile, in term of lifetime, the performance of sensor is more 10 hours using propylene carbonate due to high boiling point. The error percentage for the 10 hours is 2.16%. The propylene carbonate is used for the sensor has long lifetime based on the high boiling point property and ellipse shape electrode is selected for coplanar electrode in the microchannel and flat-shape membrane. Therefore, enhance of design of fluid based capacitive pressure sensor can improve the performance in sensor due the term of lifetime and temperature.

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## 5.2 Recommendations

For recommendation, there is a lot of the recommendation that can be made the work for become good application or sensor. The process of modelling and simulation, must have been carried out for microchannel that is can be used others of different of design shape. Open-source software should can be keep in the equation of mathematic modelling for predict the value of electric in microchannel, coplanar electrode and also can be study the change of liquid with create new equation in that software. Explored the other liquid that can also create a greater that propylene carbonate in performance to improve sensor response.

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The sensor dimension that can be improved by a small size of the sensor can reduced due to optimize the microchannel and electrode design. The process of the PCB is should be carried out with has a machine that can be a warning or alarm that the process is done for three process; expo, develop and etching. This process is related to time and vision. Apart from that, the sealing process of sensor is need carried out the new method for easy of seal of the sensor which is has leakage and not fully seal is can be reduced. The process like soldering that need be consider by replace with using a wire bonding machine and using the thickness of size of connection wire that are can be reduced the effect of value of capacitance.

Besides that, study the characteristic of PDMS polymer in term of lifetime and the other ratio for deformation of membrane. The sensor can be implemented in touch mode sensor and lab-in-chip modern for integration of the converter of capacitance-voltage system. The circuit is that can be calibrate for reduced the error of performance sensor such as temperature and humidity.

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