DESIGN AND FABRICATION OF FLEXIBLE STRAIN SENSOR FOR FOOD PACKAGING

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABBREVIATIONS

PDMS	Polydimethylsiloxane
PET	Polyethylene Terephthalate
AgNP	Silver Nanoparticle
IDC	Interdigital Capacitor
LED	Light-Emitting Diode
CNT	Carbon Nanotubes
MWCNT	Multi-Walled Carbon Nanotubes
CVD	Chemical Vapour Deposition
CPDMS	Conductive Polydimethylsiloxane
PCB	Printed Circuit Board
PET	Polyethylene Terephthalate

ABSTRAK

Kerja dalam tesis ini tertumpu kepada membangunkan pengesan terikan fleksibel yang mampu mengesan terikan dalam julat kerja yang rendah untuk digunakan dalam bungkusan makanan. Atas sebab ini, pengesan terikan kapasitif telah direka bentuk, direka dan dicirikan, menggunakan unsur polimer konduktif dan bukan konduktif untuk mengesan beban. Pengesan terikan kapasitif interdigital telah dibangunkan, yang berjaya memberikan bacaan yang tinggi. Pengesan menggunakan lapisan PDMS yang bertindak sebagai substrat dan lapisan dielektrik yang mengapit lapisan elektrod. Untuk menghasilkan lapisan PDMS ini, proses tuangan titis telah dilakukan melibatkan acuan cetakan 3D untuk menghasilkan PDMS yang mempunyai bentul electrod. Selepas it, elektrod telah dituang pada topeng yang diletakkan di atas substrat dandiikuti dengan lapisan dielektrik. Pengesan terikan fleksibel yang direka menunjukkan kemuatan awal tertinggi 4.98 pF. Pengesan terikan kapasitif yang dibentangkan menawarkan kemuatan yang memuaskan. Oleh itu; ia boleh digunakan dalam pembungkusan makanan serta aplikasi lain yang juga memerlukan ukuran ketegangan. Reka bentuk pengesan terikan ini dipilih kerana kemudahan reka bentuk.

ABSTRACT

The work in this thesis was focused in developing a flexible strain sensor capable of detecting strain within the low working range for the use in food packaging. For this cause, capacitive pressure sensors was designed, fabricated and characterised, utilising conductive and non-conductive polymeric elements to sense loads. An interdigital capacitive strain sensor was developed, which successfully provided a high reading. The sensor employ polydimethylsiloxane (PDMS) layers which act as the substrate and dielectric layer that sandwich the electrode layer. To fabricate these PDMS layers, a drop casting process was done involving a 3D printed mould in order to create a rectangular shaped PDMS. The electrode was also drop casted on the pattern that was on top of the substrate and subsequently dielectric layer was added. The fabricated flexible strain sensor shows initial capacitance as high as 4.98 pF. The presented capacitive strain sensor offers a reasonable capacitance; therefore; it can be utilised in the food packaging as well as other application that also need a measurement of strain. This design of strain sensor is chosen as its ease of design.

CHAPTER 1
INTRODUCTION

This chapter provides further explanation as to the reasons why this research was carried out. An overview of the main objectives as well as the problem statement is provided, followed by the outline of the thesis.

1.1 Background Study

According to statistics provided by the Food and Agriculture Organization of the United Nations (FAO), for instance, one-third of all food produced for human use is lost or wasted on a global scale each year [1]. This amounts to around 1.3 billion metric tonnes of food waste each year. The majority of the food that is thrown away is still edible; nevertheless, it is discarded because its marked expiration date is very close to being reached or has already been reached. It's possible that smart labels could be helpful in delivering more accurate quality assessments of packaged foods in some circumstances.

During the late 1960s and early 1970s, vacuum packaging (VP) was first utilised for primal beef cuts. By the 1980s, the technology had been adapted for use with retail cuts [2]. The central slaughtering of animals and the vacuum packaging of primal beef joints are both standard procedures in Ireland's meat market. By using packaging materials that are extremely impermeable to oxygen and carbon dioxide and by strictly adhering to excellent production processes, one can easily achieve a shelf life of ten weeks or more. This can be accomplished by maintaining high levels of hygiene and refrigeration, as well as by using excellent production processes.

However, in 1989, a kind of VP spoilage called as "Blown Pack Spoilage" (BPS) was discovered in the United States [3]. Since they are created by the oxidation of the contents or the development of microbial life, the presence of undesired gases in the packaging of food may indicate that the quality of the food and the length of time it may be stored have deteriorated. In spite of the fact that deterioration can show itself in a variety of different ways, one sure symptom of microbial infection is swelling or inflation of food containers. This might be the first symptom of bacterial activity inside food packaging, leading to discoloration, nutritional loss, and eventual food spoilage [4].

The growth of sensor technology was beneficial to the food industry since it enables the food industry to detect bulges in food packages by integrating appropriate strain sensors into the packaging. A strain sensor that is incorporated into the packaging of food can be used to detect the bulging that occurs as a result of the presence of gases inside the container. In general, strain sensors are responsible for converting the mechanical deformation which is then detected into an electrical signal. The basic data from the sensor are converted to strain using a factor called the strain factor. The most common types of transduction methods are resistive sensing and capacitive sensing. Other types of transduction methods include piezoelectricity, triboelectricity, and optical methods. In order to satisfy this demand, we have developed a concept for a smart label that incorporates a flexible strain sensor and has the potential to be employed in smart food packaging.

1.2 Main Objective

The main objectives of this project could be summarised as:

- Design and fabricate flexible strain sensor that is suitable for food packaging.
- Able to demonstrate the performance of the strain sensor.

1.3 Problem Statement

Many recent occurrences involving food and public health have brought the topic of food safety to the forefront of worldwide attention. The usage of electrical device such as strain sensor in this area will greatly aid in the traceability of food spoilage. Thus, it would be great if the use of strain sensor to be integrated with food packaging labels. Most sensors these days are rigid, making it difficult to detect minor deformations in food packaging. In order to meet this need, a strain sensor for food packaging that incorporates a highly flexible material are designed and fabricated.

1.4 Thesis Outline

Chapter 1 contains the background study of this project, followed by the problem statement, the objectives, and the thesis outline. Then, the rest of this thesis is divided into four chapters.

Chapter 2 presents a brief review of the current issue on food spoilage as well as the existing work on strain sensor on food packaging. Also in this chapter, literature in the field of strain sensor and its fabrication process are discussed.

Chapter 3 contain the methodology used in the study. It consists of the design and material selection for each layer of the strain sensor. Besides, details of the fabrication steps as well as testing methods for the device are described.

Chapter 4 present and discuss the outcomes of the testing performed on the strain sensor. Then, the findings are compared with the theoretical result.

Chapter 5 analyse the findings from this project and draw conclusions about whether or not the project's primary objective has been accomplished. Following this, suggestion are made to enhance the ongoing works in order to achieve better outcomes in the future.

CHAPTER 2
LITERATURE REVIEW

2.1 Strain Sensor

A sensor is a device that turns a physical property to be measured into an electrical signal that may be processed, recorded, or transmitted [5]. Mechanical, thermal, chemical, and electromagnetic characteristics are some of the physical parameters that can be defined. For the purpose of this project, strain sensor which serves the purpose of electrical measurement methods for mechanical measurements is highlighted.

Strain sensors have unlimited use in various field. As an example in aviation industry, strain sensor are fitted to load-bearing components in aircraft to measure any strain and stress that occurs during flight. It can measure wing deflection or deformation during flight to guarantee the safety of the aircraft [6]. An object's strain is often induced by an external or internal impact. Forces, pressures, moments, heat, structural changes in the material, and other factors can all create strain. The strain are then converted into a change in electrical resistance that can be measured. With the vast array of strain sensor in the market, they are often categorized into different ways it convert the mechanical deformation that took place in the sensor that turned into an electrical output; resistive, capacitive and piezoelectric sensor. Strain sensors are a well-developed and economically viable use for mechanical sensors.

2.2 Food Packaging

Food packaging is not only the practise of enclosing or wrapping a food product but it also serves the purpose of providing the food with minimal protection against spoilage. It is essential that the product be delivered without incident and at the lowest possible price. It is important that the price of packaging be affordable. The packaging of a product might not be able to increase the quality of the product itself, but it should be able to help retain the product's quality throughout storage, transportation, and deterioration.

There are three distinct varieties of the materials used for the packing, and each variety corresponds to a different level of hardness [7]. The first category consists of materials for flexible packaging, which can include plastic films, paper, and aluminium foil among other things. The second type of packing material is known as semi-rigid materials, and it includes paperboard, cardboard, PET and PVC containers, aluminium containers, and moulded containers. Last but not least, there are rigid packaging containers, such as glass jars, cans made of metal, cans made of fibre board, and wooden crates, boxes, and barrels. However, for the purpose of this project, the first two types of packing material will receive the majority of the focus.

About two-thirds of the fresh meat that is sold is wrapped in store wrap before being packed for sale. The meat and an absorbent pad are held in place by a clear atmosphere permeable plastic film that is wrapped around a foam or PET plastic tray used for store wrapping. Because of the film's permeability, oxygen from the surrounding air can make contact with the meat; however, in order to reduce the amount of oxygen that comes into contact with the meat, both the film and the tray are put on a heated pad, which causes the film to stick to itself [8]. This method of packing is particularly cost-effective and makes use of machinery that is similarly affordable. Often, in order to detect the food spoilage inside the food packaging, the strain sensor is attached to the plastic film at the top of the packaging. This is because the material of the film is extremely flexible, making it simple to notice any minor deformation caused by the gas released by the spoiled food. This allows for a more accurate assessment of the quality of food.

2.3 Strain Sensor for Food Packaging

Pablo Escobedo et al. [9] presented a near field communication (NFC) integrated flexible strain sensor that is able to measure strain with the help of visible LED indicator that was attached to a food packaging. Given that approximately one-third of all food produced is lost or wasted around the world and the number of threats to food security is rapidly increasing, a system for food packaging that is based on NFC tags is particularly appealing.

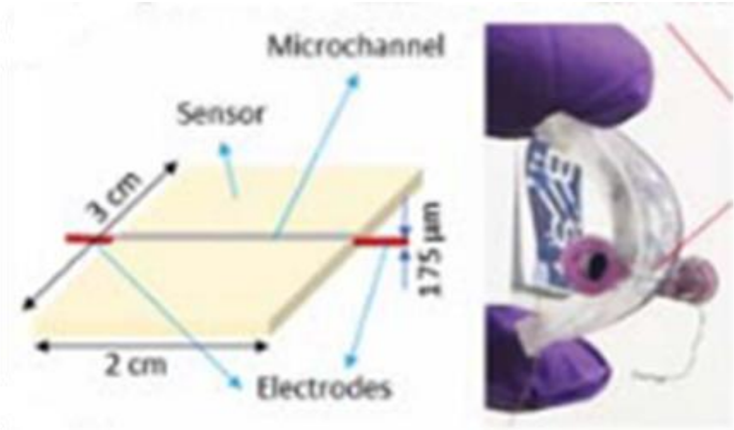


Figure 2. 1 Structure of the Strain Sensor Connected to NFC Tag

The sensor was manufactured by placing an active material made of the conductive polymer poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) inside of a microchannel made of the flexible and transparent polymer PDMS. The PDMS and PEDOT:PSS that were utilised in the production of the strain sensor were purchased from Sigma Aldrich which are both combined in a ratio of 10:1, the mixture was put into a circular mould, and a desiccator was used to remove the gas from the mixture for an hour. After that, the mould was cured in a convection oven at a temperature of 70°C for two hours. After the creation of the microchannel, it was then filled with the conductive polymer PEDOT:PSS using an injection method. After that, the electrodes were allowed to dry before being attached with metal wires.

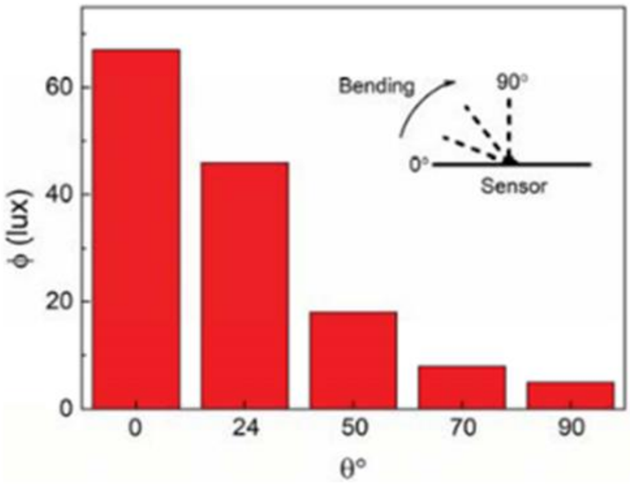


Figure 2. 2 Result of Bending Angles Against Brightness of LED

The created strain sensor is resistive, which indicates that its resistance rises as the strain value rises. This property allows it to accurately measure strain. The resistance of the strain sensor shifts in response to the varying degrees of bending applied to it which implies that the strain also changes. Therefore, the light intensity of the LED indicator is adjusted according to the strain level, displaying maximum brightness when there is no strain or when the user is comfortable, and showing almost no light at all when the user is under the highest strain possible at 90° as shown in Figure 2.2.

2.4 Capacitive Strain Sensor

2.4.1 Parallel Plate Capacitive Strain Sensor

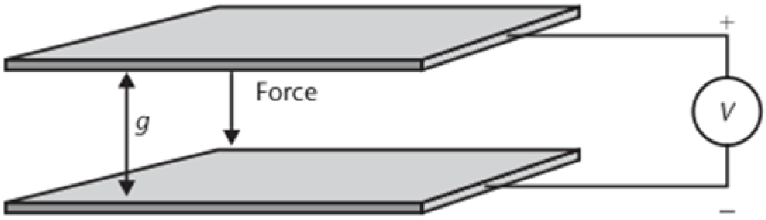


Figure 2. 3 Parallel Plate Capacitor

- **Actuation Techniques**

Electrostatic sensors function on the simple notion that two plates with opposite charges attract one other. They are fairly widespread since they are quite simple to make. However, they exhibit a nonlinear force-to-voltage connection. Figure 2.3 demonstrates a parallel plate capacitor arrangement with a spacing, g, and a region of overlapping plate, A. By neglecting the fringing field, the energy stored by the capacitor at given voltage , V is

$$W = \frac{1}{2}CV^2 = \frac{\varepsilon_0 \varepsilon_r A V^2}{2g^2} \tag{1}$$

and the force between the two plates is given by

$$F = \frac{dW}{dg} = \frac{\varepsilon_0 \varepsilon_r A V^2}{2g^2} \tag{2}$$

As a result, the force is evidently a nonlinear function of both the applied voltage and the separation between the plates. Closed loop control methods can be utilized to linearize the response [6].

This kind of sensor translates the change in separating distance between the plates as a change in capacitance of the sensor [10]. Several strain sensor research projects are conducted, with the goal of improving strain sensitivity by altering the electrode/dielectric material and sensor pattern.

- **Existing Sensor Design**

The research carried out by Shao et al. [11] exhibits how multi-walled carbon nanotubes (MWCNT) can be utilised as a conductive material for the electrodes of a capacitive strain sensor. The electrodes are made flexible by using PDMS as the substrate and then ultrasonically depositing a solution of multi-walled carbon nanotubes (MWCNTs) that have been diffused in alcohol. Over the MWCNTs, a layer of gold with a thickness of 20 nm is deposited so that the electrodes will have better conductivity. Two electrode layers that are very similar to one another are separated from one another by a dielectric layer as well as a layer of parylene coating that is 1 m thick and is created by chemical vapour deposition (CVD) on the surface of the MWCNTs. A very thin layer of parylene coatings is chemical vapour deposition (CVD) deposited over the entirety of the structure.

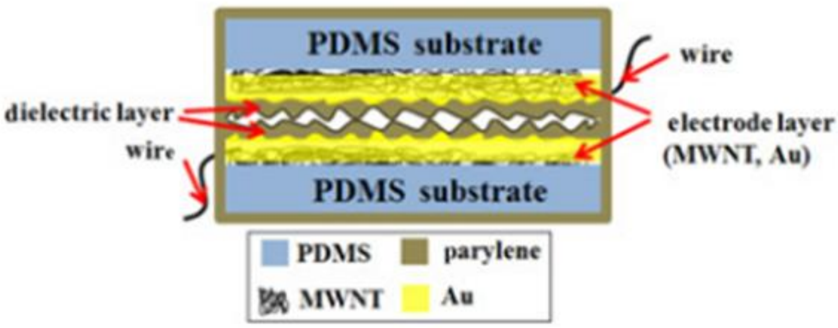
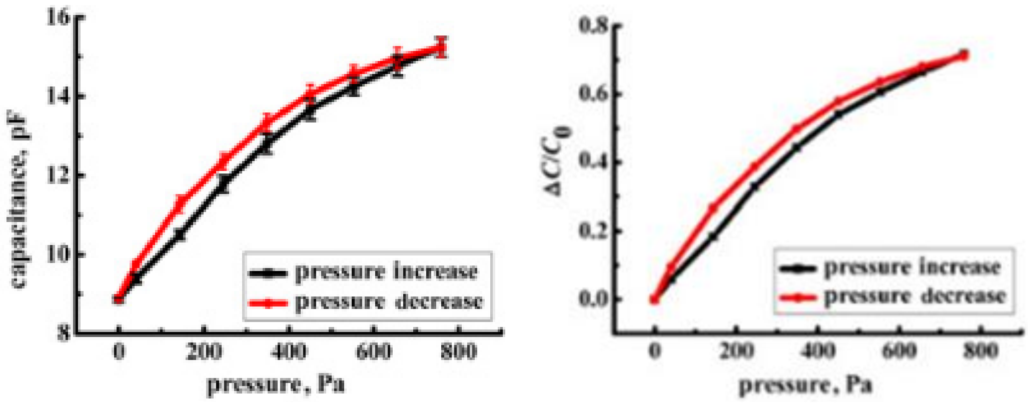


Figure 2. 4 Schematic Structure of the Flexible Capacitive Pressure Sensor [11]

The curves of capacitance relative pressure are depicted in Figure 2.5 (a). The capacitance of the pressure sensor in this study started off at 8.87 pF, but it rose to 15.23 pF when the applied pressure reached 758 Pa. Calculations were made to determine the relative change in capacitance of the sensor over the pressure range of 0–758 Pa as shown in Figure 2.5 (b), and the results showed that capacitance and pressure were positively associated. Additionally, the pressure sensor had a level of sensitivity that was relatively high, and it was capable of producing an average value that was as high as 1.33 kPa^{-1}.



(a) (b)

Figure 2. 5 Result of (a) Pressure Against Capacitance and (b) Pressure Against $\Delta C/C_0$ [11]

A low-cost method of fabricating a flexible capacitive strain sensor presented by Maddipatla et al. [12] is to screen print conductive carbon nanotubes (CNT) ink with average particle size of 105 – 113 nm on both sides of a PDMS substrate. Because PDMS has a higher adhesive property, CNT ink may be directly printed with any further adhesion enhancing agent or surface treatment, resulting in a simple manufacturing process to create a parallel plate capacitive pressure sensor.

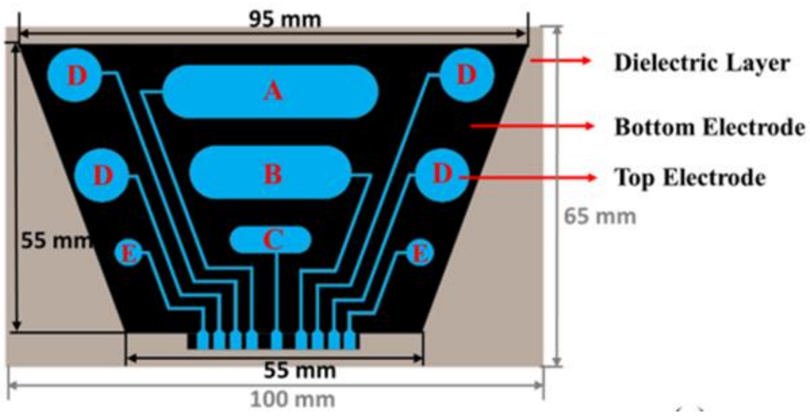


Figure 2. 6 Schematic of the CNT Pressure Sensor With Top, Bottom and Dielectric Layer [12]

Also from this study, Figure 2.7 illustrates how the capacitive response of the sensor reacts to pressures that are changed in small increments. The capacitance of the base was determined to be 6.49 pF after being tested. It was found that the capacitance increased all the way up to 7.02 pF for a pressure of 337 kPa, which is the maximum that can be detected. This led to an increase in capacitance that was 8.2% higher than the baseline value.

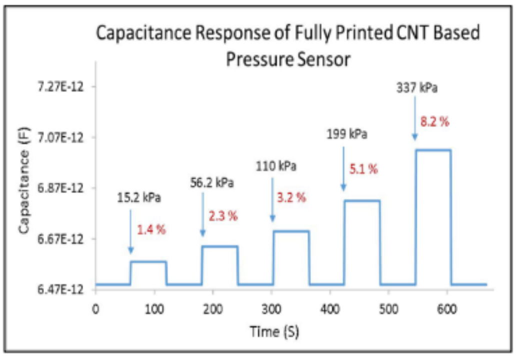


Figure 2. 7 Capacitance Response of the Printed CNT Based Pressure Sensor [12]

A layer-by-layer stacked structure of parallel plate capacitive pressure sensors was produced by using lithography and pattern transfer techniques, as can be seen in Figure 2.8. This design was presented by Woo et al. [13]. The method includes the production of a conductive material known as conductive polydimethylsiloxane (CPDMS). This material is created by combining PDMS with a 10 wt% of CNTs that have been diffused in a toluene solvent. These CNTs are used to create the conductive electrodes for the sensor. The regular PDMS material serves as the dielectric layer.

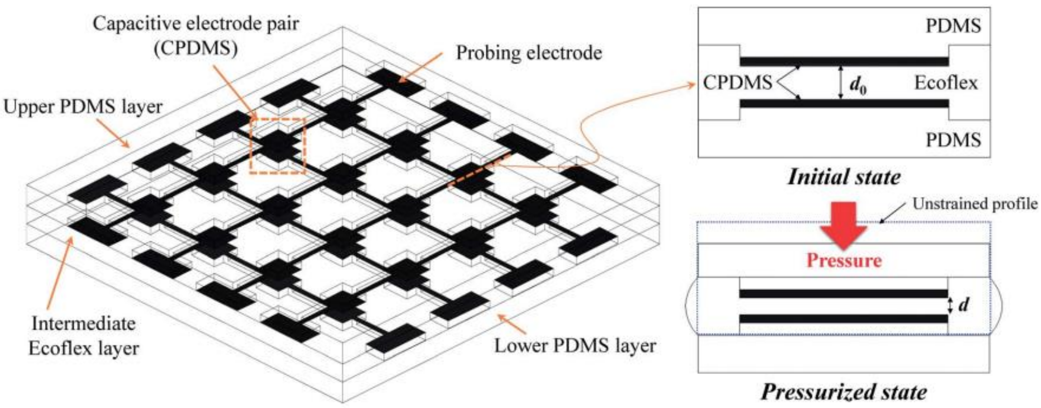
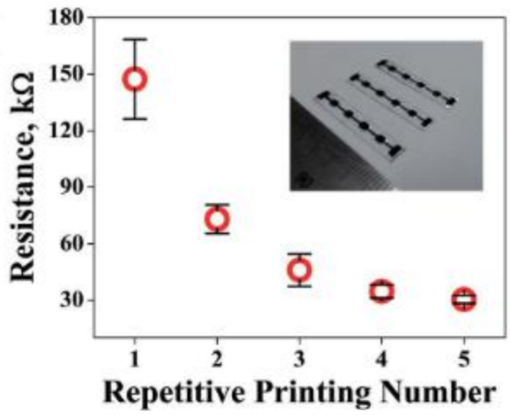
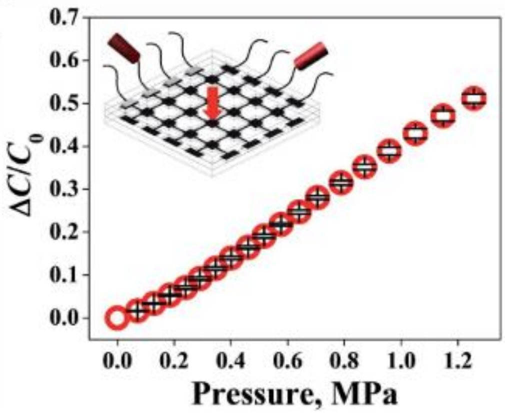


Figure 2. 8 Schematic of the All-Elastomeric Skin-Like Pressure Sensor Array [13]

As shown in Figure 2.9 (a), the electrical resistance reduced in an exponential manner as the number of printings rose, and this reduction was as much as five times more than the initial value. Because the change in resistance is mostly dependent on the change in thickness of the printed CPDMS pattern in relation to the fixed length, this would imply that the final thickness is rather consistent regardless of the printing duration it was subjected to. The relationship between the pressure that was applied and the change in capacitance ratio ($\Delta C/C_0$) is depicted in Figure 2.9 (b). The capacitance grew in a linear manner with respect to the applied pressure of up to ~1.2 MPa, which indicated a minimum detectable pressure of less than 50 kPa. In addition to this, it was discovered that the capacitive responses of the sensor are both extremely reliable and reversible.



(a)



(b)

Figure 2. 9 Result of (a) Resistance against the Number of Printing and (b) $\Delta C/C0$ against Pressure Applied to the Sensor [13]

2.4.2 Interdigitated Capacitive Strain Sensor

- **Actuation Techniques**

This layout of capacitive sensor is an alternate kind of electrostatic sensor that is known as the comb-drive. The comb-drive is made up of multiple interdigital electrodes (fingers), and it is activated by applying a voltage between those electrodes. The proportions of the lengths and widths of the fingers are such that the thickness of the fingers is relatively insignificant in contrast. As a result, the attractive forces are mostly caused by the fringing fields instead of the parallel plate fields, as can be seen in the simplified structure presented earlier in this paragraph.

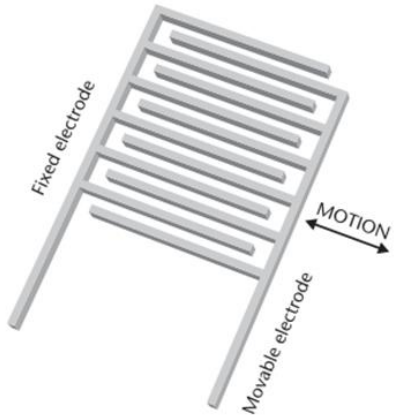


Figure 2. 10 Interdigital Capacitor [6]

As seen in Figure 2.10, the movement that is produced is in the lateral direction. Furthermore, since the capacitance can be changed by altering the area of overlap but the gap will always remain the same, the displacement will change proportionally to the square of the voltage. The permanent electrode is firmly attached to the substrate, while the moveable electrode needs to be anchored at a spot that is convenient and is located some distance from the active fingers in order to stay in place. Additional parasitic capacitances, such as those that exist between the fingers and the substrate, as well as the asymmetry of the fringing fields, can give rise to out-of-plane forces. These forces can be reduced to a tolerable level by employing designs that are more complex [6].

- **Existing Sensor Design**

Ginson and Philip [14] present an idea for creating an interdigital capacitive electrode that functions as a sensitive pressure sensor in the 0 – 120 kPa range. Fundamentally, it is a touch sensor that has been transformed into a pressure sensor, with an elastomer buffer medium functioning as the pressure transmitter. Following a photolithographic and etching procedure, the interdigital electrode patterns that are made of conductive copper are created on a printed circuit board (PCB). By laying a soft elastomer sheet over the electrode pattern and exerting pressure above it, the electrode pattern may be turned into a pressure sensor.

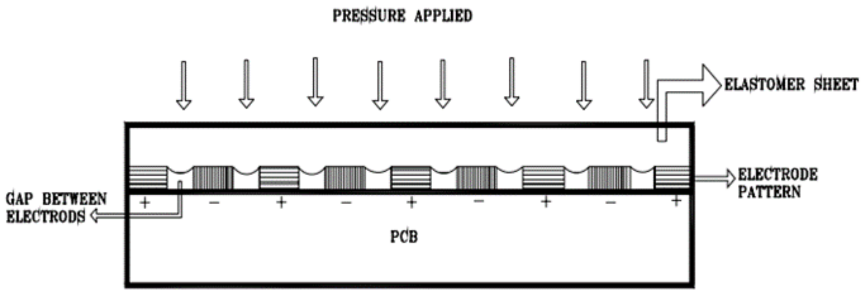
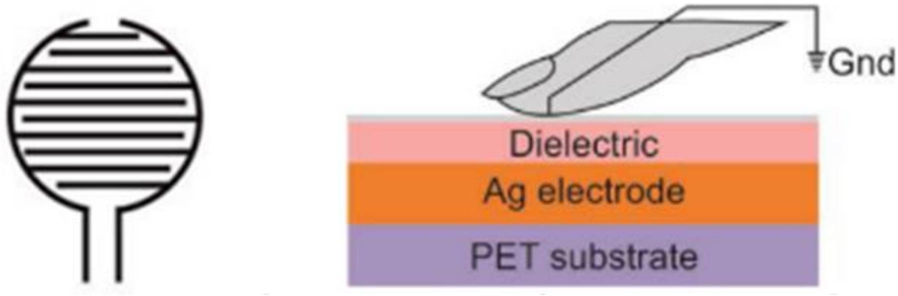


Figure 2. 11 Side View of the Interdigital Capacitive Pressure Sensor [14]

From Figure 2.12, the voltage output from the sensor increases exponentially with applied pressure up to about 110 kPa. Because of this, the sensitivity of the sensor is nonlinear; it has a high level of sensitivity up to a pressure of around 75 kPa, but after that, it begins to gradually decrease as the pressure increases. The sensitivity is roughly 1.53 mV/ kPa up to an applied pressure of around 75 kPa.

Sethumadhavan et al. [15] reported on another study in which a screen-printing method was used to produce both of the electrode structure and the sensitive composite layer for capacitive based touch sensor. One of the designs is the interdigital electrode designs that were screen printed using a mesh and were applied to 125 μm polyethylene terephthalate (PET) film. The sensitive substance is made up of two materials: a polymer paste and a conductive carbon paste that had already joined together before they were combined to form the mixture. Polymer such as PDMS, are mixed in solvents such as isopropyl alcohol and toluene to generate a less concentrated solution. This solution is then combined with silver conductive paste at loadings of 25%, 50%, and 75%, respectively. In order to produce conductive paste, silver flakes with sizes of 3–4 m are manually diffused in cyclohexane for 7 minutes. After that, a conductive silver-polymer paste is screen printed onto the interdigital electrodes, and it is cured for 10 minutes at a temperature of 120°C. Then, dielectric material is used as an active material which is deposited on to the interdigitated electrodes



(a) (b)

Figure 2. 12 (a) Electrode Pattern of the Screen Printed Interdigital Sensor and (b) Illustration of Layers of Component in the Sensor [15]

According to the findings of this research, which are illustrated in Figure 2.14, the sensor can be in one of three distinct states at any one point in time (ms) : a "ON" state, a "OFF" state, or a "Threshold" state. Changing the threshold capacitance in the software design allows for the initialization of the capacitance range of the sensor to be observed. When there is no touch, the sensor will drop to an OFF state, and as a result, it will stay in an open circuit. As a result of the presence of pinholes in the dielectric due to the fabrication process, there was noise present, which helped to dissipate the charges both while the circuit was open and when it was closed.

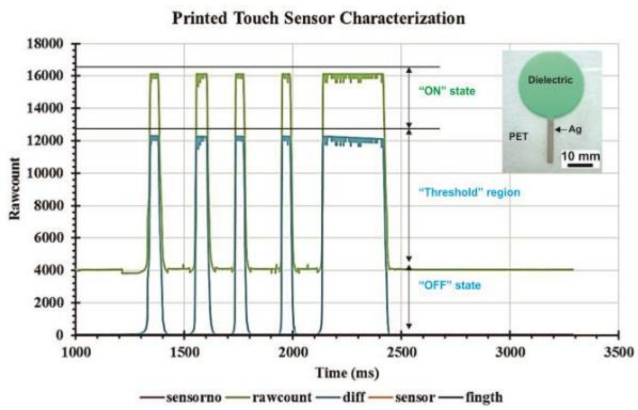


Figure 2. 13 Characterization of Screen Printed Capacitive Based Touch Sensor With Respect To Response Time And Raw Count of Sensor Signal Output [15]

2.5 Fabrication Method

2.5.1 Inkjet Printing

Inkjet printing is described as an automated deposition technique that utilizes a nozzle to eject picolitre droplets of liquid ink. Meanwhile the print-head hovering above the substrate. It enables non-contact printing on nearly any substrate. Inkjet printing is a very material-efficient technique for the additive fabrication of electronic components as it employs drop-on-demand material deposition mechanism. This additive approach varies from traditional methods of electronic manufacture because no sterile facilities, toxic chemical waste, or costly photolithography masks are required.

In today's inkjet printers, two primary technologies are utilised: continuous and drop-on-demand. A continuous inkjet printer generates a continuous stream of ink, thus it is charged by the picture and controlled electronically. A high voltage source deflects the charged droplets. The non-deflected ink, on the other hand, gets transmitted to the substrate. A considerable portion of the deflected ink is returned to the system. On the other hand, drop on demand inkjet printers generates ink droplets exclusively in the picture regions using thermal or piezoelectric techniques.

In piezoelectric print head, a microscopic piezoelectric component such as crystals and ceramics are installed beneath the print nozzles. Once an electrical charge is supplied to these components, they bend backward, pressing exact quantities of ink onto the substrate. Since electrical charges can be flicked on and off similar to a switch, there is a significant amount of control over the pace of ink discharged from the nozzle while also generating accurately spherical dots of varying droplet sizes [15].

Meanwhile, thermal print head utilize heat as compared to piezo which uses electricity to drive ink from the print head to the substrate. In, thermal inkjet device works by charging microscopic resistors beneath the print nozzle, causing an extreme heat that vaporises the ink to generate a bubble that grows so quickly that the ink essentially explodes onto the paper. After emitting ink, the chamber quickly cools to allow additional ink to refill it, and the cycle repeats.

Table 2. 1 Comparison of Piezoelectric and Thermal Inkjet Print Head [16]

Print Head Type	Pros	Cons
Piezoelectric	• Precise and variable droplet size • Can use wide range of ink due to low temperature (UV, solvent, pigment, dye) • Droplet size down to 1.5 pl • Run longer due to lower temperature	• More expensive head • Fewer print heads per printer
Thermal	• Less expensive print head • More print heads per printer • Larger droplet size	• Only two droplet sizes • Limited ink option due to extreme heat • Need to replace more often due to high heat

2.5.2 Screen Printing

The versatility of screen printing to print on nearly any surface is its fundamental strength. Because of the broad use of this technique of printing, it is impossible to address every product and substrate that may be utilised by the screen-printing technique. Screen printing is a stencilling process in which the image region is open and the non-image area is covered. A flexible squeegee is used to spread ink over the stencil. Screen printing is distinct from other kinds of printing for a variety of reasons. It is the most versatile compared to others since it can print on practically any surface, including paper, cardboard, plastic, fabrics, and other materials. Furthermore, this printing procedure is employed when a thick ink layer is required.

Furthermore, the screen-printing technique is comprised of six essential components: stencil, screen fabric, screen frame, squeegee, ink, and substrate, each of which serves a distinct purpose in the process. The image carrier for this process is formed using the frame, fabric, and stencil. The purpose of the squeegee is to push ink through picture regions and onto the substrate. By adjusting the fabric, stencil, or squeegee, the ink deposited may be modified to generate anything from a thin layer to a very thick film as desired.

CHAPTER 3
RESEARCH METHODOLOGY

The following is a chronological listing of the steps that have been completed as a part of this project. Research was conducted in the early stages of the project, and decisions on the size and shape of the sensor, in addition to its design, were made at that time. There were two different kinds of sensors that were investigated, and the decision was made to build an interdigital capacitive (IDC) strain sensor. Following this step, the materials for the interdigital electrode, the substrate, and the dielectric layer are selected on the basis of past research in addition to other factors. After that, the fabrication is done at the School of Mechanical Engineering and lastly, the sensor's characteristic is evaluated to determine whether or not it meets the requirements. This chapter will go into additional detail about each of the steps that were described.

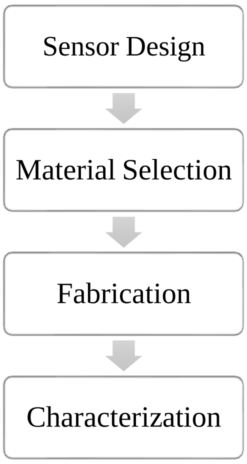


Figure 3. 1 Work Flow of the Project

3.1 Sensor Design

Schematics of the strain sensor configuration is shown in the Figure 3.2. The design was chosen after several alteration on the initial design based on its ease of fabrication and size consideration. The strain sensor consists of three layers of material with the overall thickness around 4 mm. The substrate (bottom) and dielectric (top) layers can be cut into any desired dimension. The electrode layer was sandwiched between the top and bottom layer.

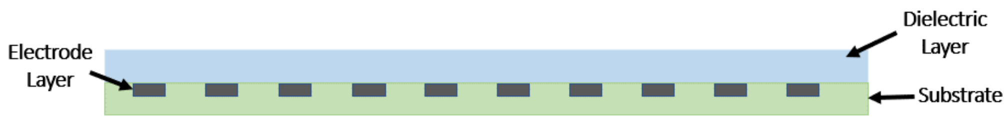


Figure 3. 2 Side View of the Strain Sensor

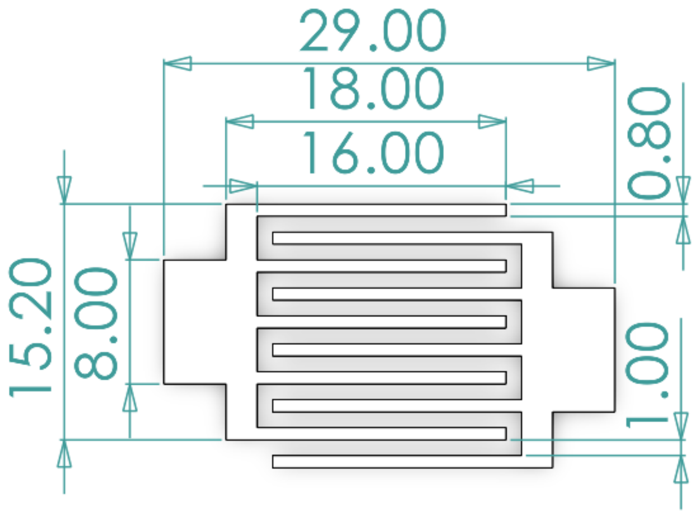


Figure 3. 3 Dimension of Electrode Pattern

The schematic design of the electrode layer is shown in Figure 3.3. It consists of 10 electrodes in total with five on each side of driving and sensing electrode. The overlapping electrode length in normal condition is 15 mm. The horizontal straight line has the width of 0.8 mm meanwhile the vertical line which connects all of the horizontal one has the width of 2 mm. The distances between each electrode are specified as 0.8 mm. Parameters of the horizontal and vertical electrode were thus chosen with the aim of having bigger width ratio of the horizontal line for the fabrication purpose.

3.2 Material Selection

It is necessary to design any interdigital strain sensor based on the geometry of the sensor pattern in addition to the dielectric characteristics of the material that will be used for the substrate, dielectric layer, and electrode layer in order to achieve an effective capacitance. The selection of the materials is going to be the topic of discussion in this chapter.

3.2.1 Flexible Substrate

Determining the suitable substrate is one of the most important factors in determining the sensor's performance and reliability. The physical properties of the substrate determined the amount of mechanical stress that must be delivered to the substrate in the form of bending, stretching, folding, or creasing can be either static or dynamic regardless of the type of electrode that is used. Polymers have excellent flexibility, are lightweight and low in cost, which makes them suitable for application in sensing device. So far, the most popular substrate used for research in this application are PET and PDMS.

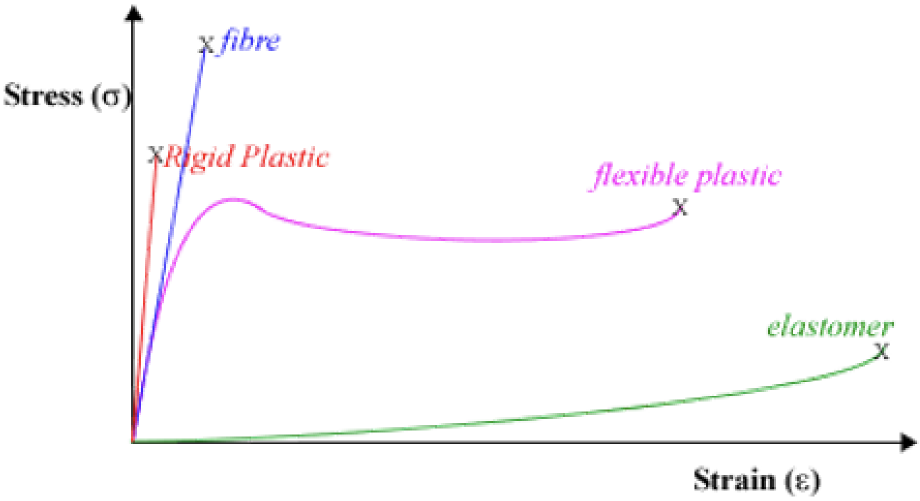


Figure 3. 4 Stress-Strain Curve of Polymers [17]

The primary distinction between flexible plastic such as PET and rigid plastic is that the former does not resist deformation as effectively as the latter, while the latter are less likely to break [18]. Its capacity to change shape is what prevents the pieces from shattering. Initial modulus is high, which indicates that it will resist deformation for a period of time; but, if a flexible plastic is subjected to sufficient stress, it will eventually deform.

Elastomers like PDMS have very low moduli as seen in the gentle slope of green plot from Figure 3.5. It is as elastic as a piece of rubber and can be bent and stretched without issue. Not only do it have a high elongation, but also have a high reversible elongation. However, to be classified as an elastomer, a polymer must have additional properties in addition to a low modulus. It is not very useful for a material to be able to stretch readily unless, after the stress is removed, it can immediately return to its former size and shape [18]. Because elastomers are able to recover their original shape after being deformed, they are an excellent choice for the role of substrate in this project.

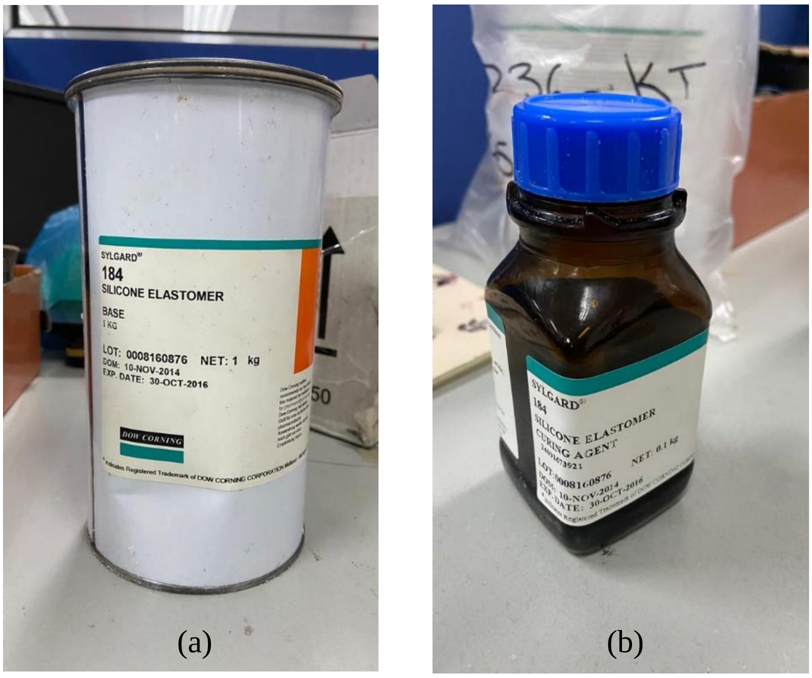


Figure 3. 5 PDMS (a) Base Polymer and (b) Curing Agent

Furthermore, the availability of the PDMS material was the primary consideration in selecting it as the substrate. This due to the fact that it is readily available at the time of fabrication, making its use significantly more convenient than the alternative of purchasing a new material.

3.2.2 Electrode

Important properties of electrode materials are conductivity, corrosion resistance and hardness. A material is said to have a high electrical conductivity when it allows an electric current to flow through it with relative ease. It is frequently expressed as a percentage of the copper standard, which is a value of 100% IACS (International Annealed Copper Standard) [19]. The ability of a material to withstand chemical deterioration is referred to as its corrosion resistance. A material that has poor resistance to corrosion can deteriorate quickly in corrosive settings, which will result in the material having a shorter lifespan. The metals in the platinum group are noted for their exceptionally strong resistance to corrosion. The level of a material's resistance to the several sorts of permanent deformations that can be caused by the application of a force is referred to as its hardness. Copper and silver are two of the most common and significant materials utilised as interdigital electrode materials, and they are mentioned in the majority of research articles.

Figure 3. 6 Silver Nanoparticles from Sigma Aldrich

Since silver's IACS is 100% [19], it possesses the highest conductivity of any metal, surpassing all metals. In addition to this, it has a high conductivity and a good oxidation resistance. In terms of its ability to conduct electricity, copper is only second to silver, which has an ICAS score of 100%. Copper is a stronger metal than silver, yet silver has a higher oxidation resistance than copper does. Because the electrodes for this project are fabricated with metal nanoparticles, the material's level of hardness is not particularly significant. In conclusion, silver is the material that is the most appropriate because of its high conductivity and its resistance to corrosion.

3.2.3 Dielectric Layer

The most common material used for the dielectric layer of a capacitive strain sensor which sits on top of the electrode is PDMS or more commonly known as a silicon. The function of this layer is to give the capacitor the medium to transfer the electromagnetic field from the driving electrode to the sensing electrode. The capacitance measured between the electrode depend on the dielectric constant of this layer. The dielectric constant for PDMS ranging from 2.32 to 2.69 [20]. Material with low dielectric constant as well as high dielectric strength signify that it is a good insulator and poor electrical conductor.

3.3 Fabrication

Although the design of this device was initially designed based on fabrication techniques that are categorised as printing techniques, such as inkjet printing and screen printing, the design of the interdigital electrode strain sensor can still be realised by the following fabrication method that will be presented in this sub-chapter. The fabrication process flow of the strain sensor is depicted in 3D view and cross section view as shown in Appendix A.

3.3.1 Preparation of Mould

In order to obtain the shape of the electrode, it was necessary to create the mould that has the interdigital electrode pattern. Due to the fact that the width of the electrode is just 0.8 mm, the pattern of the electrode is very delicate, the 3D Printing Machine offers the most favourable option to successfully complete this task. After that, Solidworks was used to build the designs of the mould, which were the exact same drawing as the electrode it was going to be fabricated.

Following the printing process, the electrode design was attached to a clean metal plate with a superglue. The glue was applied in a uniform layer across the bottom of the electrode pattern, and full contact with the plate was ensured by doing so. It was necessary to do these steps in order to guarantee that none of the PDMS solution will seep under the electrode pattern. In the event that this happened, it would be difficult to peel off the PDMS substrate once it had solidified, and the substrate may be ripped if the peeling process was not done carefully.

In order to keep the PDMS solution contained inside the mould, there must be a boundary around the electrode pattern. As a result, acrylic tape was employed in this instance rather than any other material to make the border. The tape was applied as closely to one another as possible without leaving any space in between in order to avoid the PDMS solution from seeping through it. This was done to prevent the substrate from having a thickness that is lower than intended.

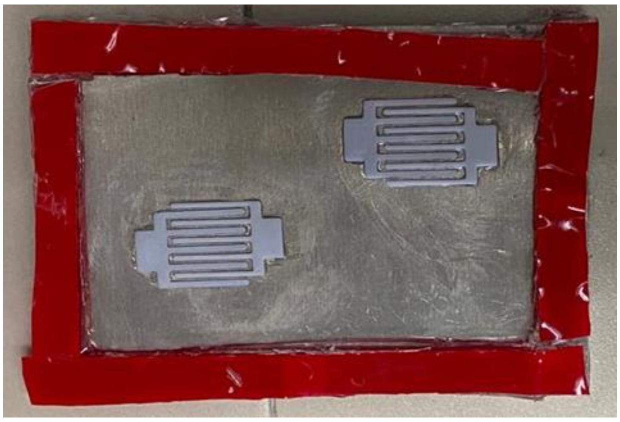


Figure 3. 7 Mould Created for the Substrate

3.3.2 Fabrication of PDMS Substrate

In order to create the PDMS substrate, the PDMS itself first needs to be prepared. It is required to prepare an elastomer base and an elastomer curing agent in a weight ratio of 1:10 respectively. A stirring tool is used to combine the two ingredients that have been placed in a dish for two minutes while the dish is being stirred. It is possible for bubbles to form when mixing; thus, it was put inside the vacuum chamber and allowed to desiccate for 10 minutes. After 10 minutes, quickly open and close the valve; this will cause the bubbles that are still present in the mixture to burst. The chamber's pressure should be released, and the dish should be removed from the device. To clean the metal plate, first spray it with rubbing alcohol and then wipe it down with a tissue.

After the elastomer base and the curing agent have been combined, the mixture is the poured into an 3D printed mould that was attached to a metal plate using a quick dry super glue. The mixture is poured little by little and then tapped until it spread a little bit. This is done to prevent high amount of waste being removed as the mixture is then scraped using a glass plate to get a flat PDMS that is the same height as the border. Any excess bubbles left in the PDMS was popped using object sharp metal tip such as needle or syringe. Following that, the PDMS substrate layer is allowed to cure at 60°C for an hour. The result is shown in Figure 3.8. After the substrate was cooled, it was pulled carefully from the mould revealing the electrode shape. After the substrate had finished curing, a ruler and a knife were used to trim it down to the size that is needed. Following that, copper tape were attached at the end of the electrode leaving the upper bit of paper that cover adhesive so that it did not stick to the substrate as illustrated in Figure 3.9.