PERFORMANCE IN ENHANCEMENT OF MICROFLUIDIC-BASED CAPACITIVE PRESSURE SENSOR

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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.

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

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

LIST OF SYMBOLS

ΔC	Change of capacitance
ΔL	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
ε_{PDMS}	Dielectric constant of PDMS
l	Length
ε_o	Permittivity of vacuum
ε_r	Dielectric constant

CHAPTER 1

INTRODUCTION

1.1 Background

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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).

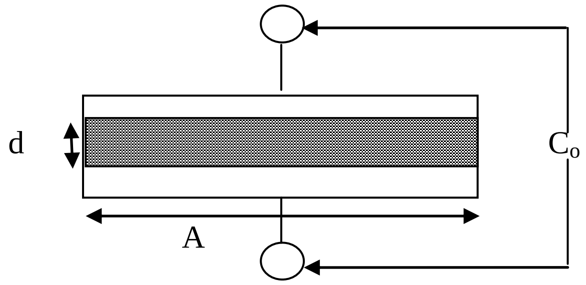

Figure 1.1. Schematic of general structure of a capacitance sensor with surface plates set, A and thickness, *d*

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 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,

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 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 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:

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.

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 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.

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.

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.

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.

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