INVESTIGATION AND CHARACTERIZATION OF ELECTROLYTE FOR FLUIDIC BASED PRESSURE SENSOR

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UNIVERSITI SAINS MALAYSIA

2015

INVESTIGATION AND CHARACTERIZATION OF ELECTROLYTE FOR FLUIDIC BASED PRESSURE SENSOR

By

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A Dissertation submitted for partial fulfillment of the requirements for the degree of Master of Science (Microelectronic Engineering)

August 2015

ACKNOWLEDGEMENTS

Alhamdulillah, Praise to Allah the Most Merciful and the Most Benevolent. Finally, I have completed my dissertation. Once this documentation is completed, 6 months seem to be very short for me. Therefore, I want to take this opportunity to express my gratitude for all the guides, constructive criticism and friendly advice from all people around me.

First of all, I want to express my gratitude and appreciation to my supervisor, Dr. Asrulnizam Abd Manaf whose encourage, guidance, and support from the early through the end of my master project. With his continuous advice and support, I have finally reached the ending point of my master project.

Then, I want to thanks my parents whose has been supportive and always encourage me to never give up and strive for my goal. Their words of encouragement and wisdom have kept me focus to whatever I want to do. I am really glad and blessed to have such wonderful parent.

Last but not least, special thank for Underwater Robotic Research Group (URRG), University Science Malaysia for their help and support on my master project. Thank you a lot for all your assistance.

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LIST OF ABBREVIATIONS

Al	-	Aluminum
Au	-	Aurum
Cr	-	Chromium
DOF	-	Degree of Freedom
EDLC	-	Electrical Double Layer Capacitor
FR-4	-	Flammable Retardant 4
PCB	-	Printed Circuit Board
PDMS	-	Polydimethylsiloxane
RP	-	Rapid Prototype
SiO_2	-	Silicon dioxide
UV	-	Ultraviolet

LIST OF SYMBOLS

A_i	-	initial surface area of liquid
d	-	thickness of PDMS membrane
l	-	length of microchannel
R	-	radius of the membrane
w	-	width of the membrane
F_y	-	vertical force
ε_o	-	vacuum permittivity
ε_r	-	dielectric constant
W	-	fluid displace inside microchannel

PENYIASATAN DAN PENCIRIAN ELEKTROLIT UNTUK PENDERIA JENIS TEKANAN BERASASKAN BENDALIR

ABSTRAK

Metanol telah digunakan sebagai elektrolit kepada penderia jenis satu-bahagian-elektrod yang dicadangkan oleh Norzaidi *et al* (2015). Metanol mudah tersejat dan menyebabkan operasi dan masa tindak balas terganggu. Objektif penyelidikan adalah untuk menyiasat, mencirikan dan memilih elektrolit yang terbaik bagi penderia jenis tekanan. Parameter yang dicerap adalah pemalar dielektrik, kelikatan kinematik dan takat didih. Berdasarkan parameter tersebut, tiga jenis elektrolit telah dipilih. Elektrolit yang dipilih ialah metanol, etanol, dan propilena karbonat. Pembikinan bagi rekabentuk penderia adalah panjang mikrosaluran 22 mm, lebar mikrosaluran 0.5 mm, tebal mikrosaluran 0.5 mm, dan jejari selaput bulat 3.2 mm. Mekanisme penderia jenis tekanan adalah berdasarkan perkemuatan daripada pelaksanaan konsep Lapisan Ganda Elektrik (LGE). Berdasarkan dimensi penderia, nilai kiraan perkemuatan ialah 14.34 pF. Antara pencirian daripada elektrolit yang dijalankan adalah dengan memberikan tekanan, memerhatikan jangka hayat dan masa tindak balas penderia jenis tekanan. Tekanan daripada 2.5 kPa kepada 25 kPa telah diaplikasikan dan tempoh analisa bagi jangka hayat elektrolit telah ditetapkan kepada 7 jam. Berdasarkan daripada keseluruhan data, elektrolit yang sesuai ialah propilena karbonat. Kekerapan bagi propilena karbonat adalah 0.25 kHz dan ditentukan oleh pengiraan nilai kemuatan. Propilena karbonat mempunyai ketidaklurusan yang rendah pada 0.794%. Propilena karbonat mempunyai jangka hayat yang panjang melebihi 7 jam dan tempoh tindak balas yang pendek pada 0.073 s. Semua elektrolit telah di analisa dan propilena karbonat telah dipilih sebagai elektrolit yang terbaik bagi penderia jenis tekanan yang berasaskan bendalir.

INVESTIGATION AND CHARACTERIZATION OF ELECTROLYTE FOR FLUIDIC BASED PRESSURE SENSOR

ABSTRACT

Methanol was used as an electrolyte for one-side-electrode-type proposed by Norzaidi *et al* (2015). Methanol was easily evaporated and affects the operation and response time of pressure sensor. The objectives of this research are to investigate, characterize and select the best electrolyte for pressure sensor. The parameters observed are dielectric constant, kinematic viscosity and boiling point. Based on the parameters, three electrolytes were selected. There are methanol, ethanol and propylene carbonate. A sensor design with microchannel length of 22 mm, microchannel width of 0.5 mm, microchannel thickness of 0.5 mm and circular membrane radius of 3.2 mm was fabricated. The characterization for the electrolytes was conducted by applying pressure, lifetime and response time measurement. The pressure of 2.5 kPa to 25 kPa was applied and duration of lifetime analysis was set to 7 hours. The sensing mechanism of pressure sensor is based on capacitive changing by implementing the concept of Electrical Double Layer (EDL). Based on the sensor dimensions, calculated capacitance value was 14.34 pF. Based on the results, the suitable electrolyte was propylene carbonate. The measured operating frequency of propylene carbonate was 0.25 kHz and it was determined based on calculated capacitance value. The propylene carbonate has a lowest non-linearity at 0.794%. Propylene carbonate has the longest lifespan more than 7 hours and faster response time at 0.073 s. All the electrolytes were analyzed and propylene carbonate was chosen as the best electrolyte for fluidic based pressure sensor.

CHAPTER 1

INTRODUCTION

1.1 Background

Currently, rapid growth in flow sensor is influences by numerous applications of underwater sensing towards industrial demand. For an example, underwater sensor was needed in autonomous underwater vehicles (AUV's), remotely operated vehicles (ROV's), and robotic (Arshad, 2009; Ovaliadis et al., 2010; K. Yeh et al., 2012). Underwater sensor can be divided into acoustic sensor, flow sensor and optical sensor (Heidemann et al., 2012; Norzaidi et al., 2013).

Basically, acoustic sensor was used to detect the mechanical or acoustic wave that propagated through a piezoelectric material (Bill, 2000). The drawback of acoustic sensor was due to its disadvantages such as bigger size and pricey compared to optical sensor (Toal et al., 2005; Norzaidi et al., 2015). Moreover, the optical sensor was dependent to the amount of light rays into the sea and cannot provide enough information to the mean stream flow velocity (Fan et al., 2002). Thus, flow sensor has been introduced in the underwater sensing. Flow sensor has several advantages such as short response time, low-detection threshold, high sensitivity to flow measurement and high durability (Tao and Yu, 2012).

Flow sensor has been used in biomedical and engineering field and can be divided into two types which are thermal and non-thermal. Since decades ago, researches focused on the non-thermal flow sensor due to the drawback of thermal flow sensor which often related to the non-linearity of the calibration curve and cause sensitivity decrease with fluid flow hence affected sensor accuracy (Silvestri and Schena, 2012).

Bio-inspired flow sensor is a part of the non-thermal flow sensor. The bio-inspired flow sensor was inspired by mimicking the nature such as cricket (Krijnen et al., 2007), bat (Sterbing et al., 2011) and fish (Nawi, 2014). A fish has a fast response towards an object due to its natured sensing mechanism from its lateral line system. Lateral line system of a fish has the ability to form hydrodynamic images that can determine the size, shape, identity of another fish (Bleckmann, 1993). In the fish lateral line, there were two types of neuromasts which are canal and cilia (Norzaidi et al., 2013).

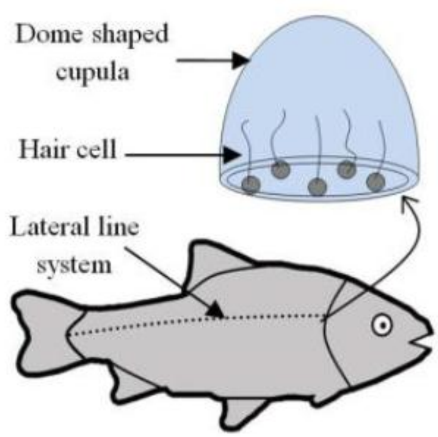

Figure 1.1: The canal neuromasts in the fish lateral line system

(Norzaidi, M., Nawi, M., Manaf, A. A., Arshad, M. R., & Sidek, O. (2013). Modeling of Novel Microfluidic based Flow Sensor Inspired from Fish Canal Neuromast for Underwater Sensing. Jurnal Teknologi, 1(2009), 33–38. *pg.34)*

Based on the canal neuromasts in the fish lateral line system, Norzaidi et al (2013) proposed a one-sided-electrode-type sensor. The one-sided-electrode-type sensor was proposed to minimize the complexity in fabrication on the dome structure. Furthermore, it also can be used to protect the sensor from the external pressure and the electrical double layer capacitance (EDLC) was used as the sensing principle (Norzaidi et al., 2015). This one-sided-electrode-type sensor also has the capability to detect in multidirectional compared to an individual micromachined artificial lateral line sensor proposed by Fan et al (2002) which can only detect in a direction.

In addition, a one-sided-electrode-type sensor provided a simple fabrication process and straightforward sensing technique. The one-sided-electrode-type sensor proposed by Norzaidi *et al* (2015) is also named as fluidic based type sensor. Methanol was used as the electrolyte in the fluidic based sensor. The lifespan of methanol was not more than 6 hours, easily evaporated and affected the operation and performance of the fluidic based sensor.

1.2 Problem Statements

Electrolytes easily evaporated and affect the longevity of the sensor performance.

Different electrolyte has different properties. Methanol used for one-sided-electrode-type sensor only stands for 6 hours and completely dried because of low boiling point which is at 64.7˚C (Norzaidi et al., 2015). Methanol has disadvantages in term of it properties which is easily evaporated and highly flammable. Thus, different electrolytes need to be investigated to extend the lifespan of a fluidic based pressure sensor. Aqueous solvent such as propylene carbonate can be used to extend the lifespan and increase the ionic conductivity of a fluidic based pressure sensor (Burt et al., 2014).

An electrolyte with low dielectric constant has low sensitivity and lead to longer response time.

Methanol has low dielectric constant and sensitivity which lead to longer response time. The dielectric constant for methanol is 32.6. From the dielectric constant, the sensitivity and response time for the fluidic based pressure sensor achieved was at 0.81 pF/ kPa and 0.35 s, respectively (Norzaidi et al., 2015). The investigation and characterization of different electrolytes was needed to shorten the response time of fluidic based pressure sensor. An electrolyte such as propylene carbonate need to be used due to its high dielectric constant and can boost the sensitivity and the response time by increasing its ionic capacitance (Burt et al., 2014).

1.3 Research Objectives

The objectives of this research are:

i. To investigate different electrolytes and select the best electrolyte for fluidic based pressure sensor.
ii. To characterize different electrolytes for fluidic based pressure sensor.

1.4 Research scope

The main feature in this research is to optimize and characterize electrolytes for fluidic based pressure sensor. Sensor design from the one-sided-electron-type proposed by Norzaidi *et al* (2015) was used. Norzaidi *et al* (2015) proposed two designs. First, the dome-membrane shaped sensor and second, the flat membrane shaped sensor. The flat membrane shaped sensor was used instead of dome-membrane shaped sensor due to the straightforward sensing, simple fabrication and it compatibility to pressure measurement.

Fluidic based pressure sensor was fabricated at room temperature and PDMS was selected as a based material. By using the Rapid Prototype (RP) machine, the mold was fabricated. The flat membrane was fabricated on the sensor by using electrode printing, stamping technique and sealing process. The flat membrane shape for fluidic based pressure sensor was fabricated by using Printed Circuit Board (PCB) process on the Flammable Retardant 4 (FR-4) material.

For electrolytes investigation, three different electrolytes were used. The electrolytes were methanol, ethanol and propylene carbonate. The characterization for pressure sensor involved was pressure measurement, lifetime and response time. The sensitivity and response time of the fluidic based sensor were conducted in order to choose the best electrolyte for the fluidic based pressure sensor.

1.5 Summary of contribution

In this research, few contributions can be claimed as follow;

First, this research offered an alternative to improve the performance of fluidic based pressure sensor by using an electrolyte with the high dielectric constant and boiling point.

Second, fluidic based pressure sensor can be operated by using a small amount of liquids. The liquid was injected into pressure sensor by using a needle and can reduce the cost in terms of liquid used. Last but not least, this fluidic based pressure sensor can be used for low pressure sensor applications.

1.6 Thesis Organization

Chapter 2 focused on the literature review included sensing and fluid mechanism, an overview of flow sensor, sensor optimization, sensor characterization, microfluidic based sensor and electrical double layer theory.

In Chapter 3, the sensor fabrication and process involved were introduced. The optimization and characterization method for fluidic based pressure sensor were studied. All the related theory was explained.

Chapter 4 presents the result and discussion on the investigation and the characterization of the fluidic based pressure sensor. All the characterization was analyzed. The best electrolyte for fluidic based pressure sensor was chosen in this chapter.

Chapter 5 concludes the discussions and provides recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses sensing mechanism, an overview of flow sensor, material used, fabrication process, optimization and characterization. The main feature in this chapter is to review the current flow sensor and propose a new optimization of electrolyte for fluidic based pressure sensor. Theoretical background of electrical double layer and microfluidic based sensor has been discussed.

2.2 Sensing and fluid mechanism

Lower power consumption, high resolution, a robust structure, high sensitivity were the advantages of the pressure-type flow sensor (Oosterbroek, 1999; Sadeghi et al., 2013; Norzaidi et al, 2015). The advantages offered by the flow sensor were the factor the researches on flow sensor are still progressing. To extend the contribution to the flow sensor, the design of one-sided-electrode type sensor was proposed by Norzaidi et al (2015). This design is unlike the conventional capacitive pressure sensor but still implementing the electrical double layer capacitance theory. The electrical double layer capacitance theory (EDLC) will be presented in the next subtopic.

The flat membrane design as shown in Figure 2.1 consists of microchannel, common electrode C_o, electrode C_+ and a PDMS membrane. An electrolyte was injected into the ionic layer to create a conductor and produce capacitance (A. Manaf et al., 2008). Based on EDLC concept, capacitance was increased after pressure was applied due to the movement of the electrolyte inside the microchannel.

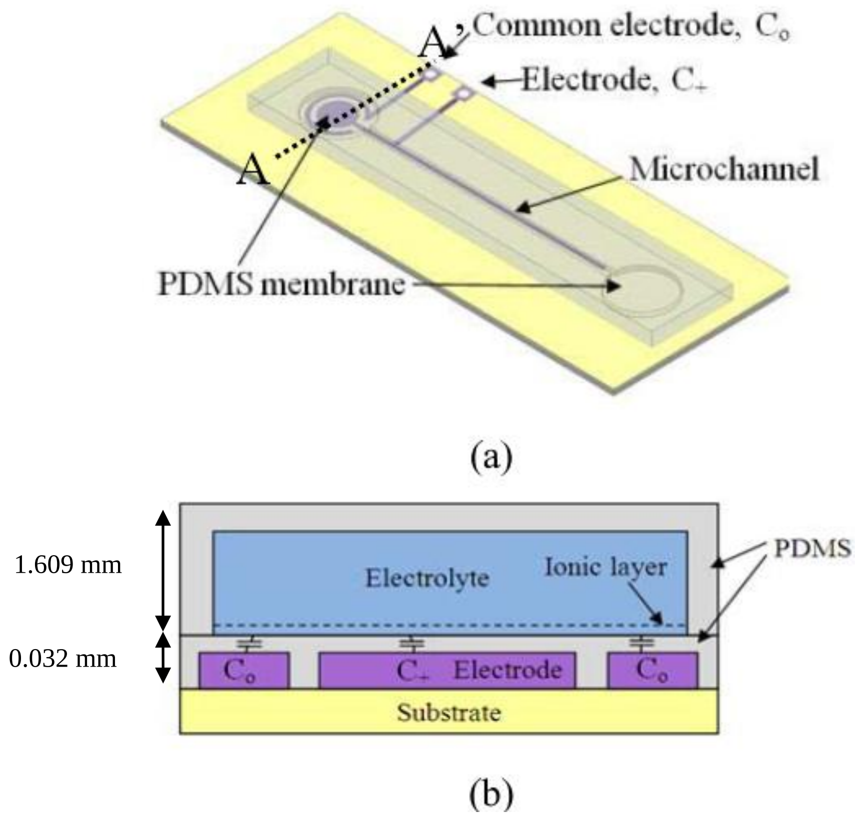

Figure 2.1: Design of the fluidic based pressure sensor a) side view
b) cross sectional area view.
(Norzaidi, M., Nawi, M., Manaf, A. A., Faizal, M., & Rahman, A. (2015). One-Side-Electrode-Type Fluidic-Based. IEEE SENSORS, 15(3), 1738–1746. pg. 1739)

The relationship between the changes in capacitance is as follow (Norzaidi et al., 2015);

$$\Delta C = C - C_o \quad (2.1)$$

The changes in capacitance, ΔC can be interpreted as the differences in between the measure capacitance, C and initial capacitance, C_o. The equation of basic capacitance between two parallel plates is as follow;

$$C = \frac{\varepsilon A}{d} \quad (2.2)$$

Equation (2.1) and (2.2) were combined as follow;

$$\Delta C = \frac{\varepsilon_o \varepsilon_r}{d} (A - A_i) \quad (2.3)$$

where $\varepsilon_o, \varepsilon_r$, d, A, A_i represent the vacuum permittivity, dielectric constant, measure surface area and initial surface area, respectively. The area which represents flat membrane shape as in Figure 2.1 (a) is equal to the area of rectangle which is $A = wl$. The final formula for the changes in capacitance is as follow;

$$\Delta C = \frac{\varepsilon_o \varepsilon_r}{d} w \Delta l \quad (2.4)$$

The symbols of C_o, A_i, ε_o, ε_r, d, w, and l represent the initial capacitance, initial surface area of liquid, vacuum permittivity, dielectric constant, the thickness of PDMS, the width and the length of microchannel, respectively.

For fluid mechanism, according to Norzaidi et al (2015) pressure applied to the sensor can be expressed as

$$P = \frac{F_y}{\pi R^2} \tag{2.5}$$

Based on the Equation (2.5), F_y is the vertical force and R is the radius of the membrane and it shows that the movement of liquid or electrolyte inside the microchannel will move towards the outlet when the pressure applied. The membrane deflection, W displaces the fluid inside the microchannel can be interpreted by using formula according to Timoshenko and Woinosky (2011) is as below;

$$W = \frac{3}{16}\frac{R^4}{t^3}\left(\frac{1-v^2}{E}\right)P \tag{2.6}$$

From Equation (2.6) t, E and v are the thickness of membrane, elastic modulus and Poisson's number, respectively. Based on the Equation (2.5), liquid distance also depends on the force applied to the membrane (Norzaidi et al., 2015).

2.3 Flow Sensor Overview

Flow sensor has been introduced as a type of underwater sensor decades ago. Underwater sensor generally been applied in underwater vehicle such as autonomous underwater vehicles (AUV's), remotely operated vehicles (ROV's), and robotic (Arshad, 2009; Ovaliadis et al., 2010; K. Yeh et al., 2012).

Recently, the underwater sensor applications are widely used due to its ability to detect and assist an object from another object in water environment (Arshad, 2009). Underwater sensor has been divided into three types which are acoustic sensor, flow sensor and optic sensor. Basically, acoustic sensor was used to detect the mechanical or acoustic wave that propagates through a piezoelectric material (Bill, 2000). The drawback of acoustic sensor is due to its disadvantages such as has a bigger size and pricey compared to optical sensor (Toal et al., 2005; Norzaidi et al., 2015).

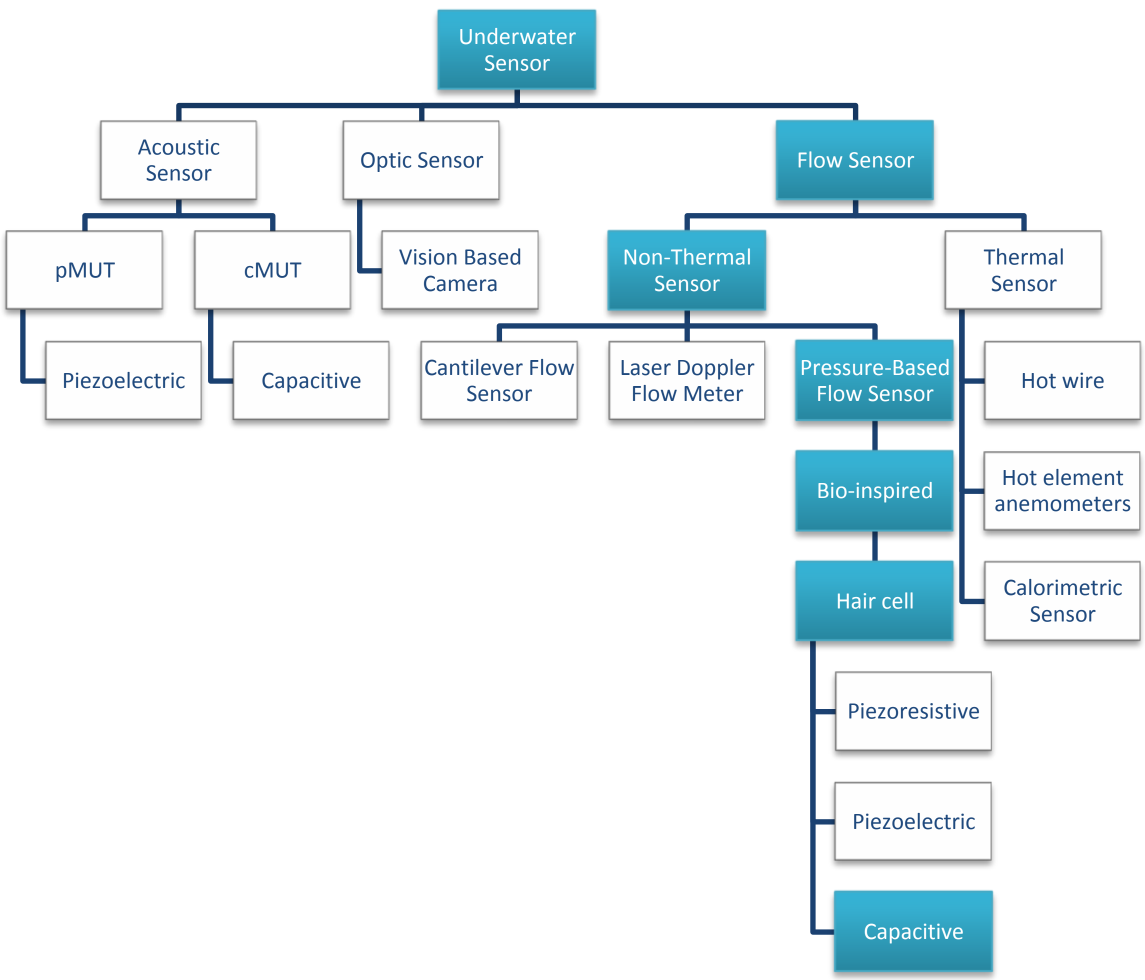

Figure 2.2: Flow chart of underwater sensor development

Moreover, the optical sensor was dependent to the amount of light rays into the sea and cannot provide enough information to the mean stream flow velocity (Fan et al., 2002). Thus, flow sensor was implemented in the underwater sensing. Flow sensor has several advantages such as short response time, low-detection threshold, high sensitivity to flow measurement and high durability (Tao and Yu, 2012).

As shown in Figure 2.2, flow sensor can be categorized into two types, thermal sensor and non-thermal sensor. Thermal sensor is a measurand (flow) undergo a thermal process, modulation and produces an output voltage signal. Moreover, non-thermal sensor is a measurand (flow) did not undergo any modulation thermal exchange and produce an output voltage signal. Researcher nowadays are more focusing on the non-thermal flow sensor due to the limitation of thermal flow sensor which often related to the non-linearity of the calibration curve and causes sensitivity decrease with fluid flow hence affected sensor accuracy (Silvestri and Schena, 2012).

The essential factor for a flow sensor is to have a miniaturization design, good accuracy and a fast response. Research were conducted to correspond the requirement good flow sensor such as the drag-force or cantilever type flow sensor, laser Doppler flow meter and pressure based flow meter. For drag-force or cantilever flow sensor the limitation was due to the low sensitivity which cause by the lift-force principle (Gass et al., 1993). Laser Doppler flow meter is widely used in biomedical field. The disadvantages of laser Doppler flow meter is due to periodic variations of the intensity of the scattered light when particles passed the fringes and affect the fluid density in a flow sensor (Silvestri and Schena, 2011).

For the pressure based sensor, the decrease in capacitance between electrodes caused by pressure gradient when there a deflection of a membrane between two plates of a capacitor (Berberig et al., 1998). The examples of different type of flow sensor as stated in Figure 2.2 also known as traditional flow sensing. Decades ago, the nature been used as inspiration and flow sensing based on the nature arise called bio-inspired flow sensor. The example of bio-inspired hair flow sensor from the nature nowadays were cricket (Krijnen et al., 2007), bat (Sterbing et al., 2011) and fish (Nawi, 2014) in order to improve the performance of the flow sensor generally.

Mimicking the biological system to the engineering application is a very good idea to enhance the sensing performance in underwater vehicles and vehicles flight control (Yang et al., 2007). The hair on the lateral line system of a fish is the key sensory unit system which defined the number of neuromasts (Tao and Yu, 2012). The bio-inspired hair flow sensor from a fish was emphasized due to the sensing mechanism, and the ability to form hydrodynamic images that can determine the size, shape, identity of another fish from its lateral line system (Bleckmann, 1993). Development based on the bio-inspired hair flow sensor is still ongoing and material used, fabrication process, the sensor optimization and characterization will be further studied in the next section.

2.4 Material Used and Fabrication Process

One of the objectives is to investigate different type of electrolyte of fluidic based pressure sensor. Then, to fulfill the requirement, a review on the material used and fabrication on the pressure flow sensor was presented in Table 2.1. Based on Figure 2.2, there are three types of sensors which are piezoresistive, piezoelectric and capacitive based pressure sensor. The review on Table 2.1 is focusing on the capacitive sensor to study the fabrication used, hence reduce the complex fabrication process involved in capacitive pressure sensor (Norzaidi et al., 2015).

The fabrication for capacitive pressure sensor proposed by Van Baar *et al* (2003) is the surface micromachining techniques. The drawback of micromachining techniques are the disability to combine into high-density arrays and it is only sensitive in a direction. Artificial hair was created by using deep reaction ion etching (DRIE) to create a hole. The material used is Si_xN_y. Then, by using the LPCVD, a 1μm of Si_xN_y layer was deposited on the surface of the silicon. Artificial hair was exposed in the end of the process by using wet etching technique on the backside of the patterned (Van Baar et al., 2003). The fabrication process used was considered as the complex and risky fabrication. The wet etching process at the end of the fabrication is to expose the artificial hair has some etching profiles problem such as tapering and notching.

Capacitive pressure sensor proposed by Chen et al (2004) was a symmetrical coplanar design and varied the field penetration depth and the effective electrode width. An electron beam evaporation technique was used to deposit the metal electrode. The sensing materials used were Ti and followed by Au on the glass substrate. After deposition process, the symmetrical coplanar sensor design undergo the plasma-enhanced chemical vapor deposition of SiO_2 to inactive the metal electrode. Photolithography process was used to pattern the electrode (Chan et al., 2004). The equipment used was categorized as the high end equipment and masking process used is a complex lithography.

Review on Table 2.1 shows different approach of photolithography process can be used for pressure based flow sensor. The photolithography process was used to obtain cylinder shape of artificial hair and few techniques involved to do a photolithography process such as masking, baking, coating and UV exposure (Chen et al., 2003; Dijikstra et al., 2004; Sadeghi et al., 2013). Microfluidic based pressure sensor are mostly used micromolding technique to fabricate a sensor using PDMS polymer. This technique has been implemented by Engel *et al* (2005) to create a polyurethane hair cell (Engel et al., 2005). From the review in Table 2.1, a new fabrication technique is needed to reduce the complexity of the fabrication process. Thus, one-side-electrode-type fluidic based is proposed by Norzaidi *et al* (2015) to simplify the fabrication process by using soft photolithography process (Norzaidi et al., 2015).

Table 2.1: Review on the materials and fabrication used for pressure based flow sensor.

	Reference	Sensing Material	Hair material	Hair fabrication
1	Van Baar et al, 2003	Metal electrode	Si_xN_y	Bulk/ surface micromachining
2	Chen et al. 2004	Ti/ Au	Glass	Photolithography
3	Dijikstra et al 2005	Cr (top electrode)	SU-8	
4	Jaganatharaja et al, 2009	Al	SU-8	
5	Izadi et al. 2010		SU-8	
6	Riedl et al. 2010	Copper	PDMS	
7	Yeh et al. 2012	Polyalcohol/ silicon oil	PDMS	Photolithography
8	Dagamash et al. 2013	Al	SU-8	
9	Sadeghi et al. 2013			Stereolithography
10	Norzaidi et al. 2015	Methanol	PDMS	Soft lithography

2.5 Sensor Optimization and Characterization

Sensitivity, measurement of flow rate and response time for fluidic based pressure sensor inspired by nature was important to measure the competency of a sensor (Jaganatharaja et al., 2009; Chen et al., 2007; Dagamash et al., 2013; Sadeghi et al. 2013; Fan et al., 2002). Table 2.2 shows variation of characterization in a bio-inspired flow sensor (Norzaidi et al., 2015). Different sensing environment for different design have been studied decades ago to improve the performance of bio-inspired pressure based flow sensor.

For underwater sensing, Fan et al (2002) proposed individual micromachined artificial lateral line sensor for flow sensing application and it is the earliest prototype. The characterization of flow measurement is range from 0.2 to 1 m/s, and the sensitivity was not been covered. Resistance versus mean flow rate showed that the increase in resistance with increasing in mean flow rate (Fan et al., 2002).

To optimize the performance of bio-inspired flow sensor, the different dimension of hair cell were developed and tested in air flow measurement where the longest hair cell was the most sensitive compared to the wider width and shorter hair cell (Chen et al., 2003). Enhancement for characterization of low sensor was proposed by Chen et al., (2007) in different sensing environment, which is in air and water and sensitivity to prove the capability of flow sensor (Chen et al., 2007).

Based on the review in Table 2.2, current bio-inspired flow sensors focused on the sensing capability on two sensing environment; air and water, and the multidirectional sensing. Furthermore, a characterization on the flow measurement and angle were proposed (A. Manaf et al., 2008). Hence, the variation on the angle increase the directional sensitivity and the problem arise due to the vibration and instability (Sadeghi et al., 2013). Characterization on the vibration and temperature on air and water were studied by Norzaidi et al (2015) to improve the sensing capability in multidirectional flow sensor (Norzaidi et al., 2015).

The electrolyte used by Norzaidi et al (2015) for fluidic based pressure sensor has a shorter lifespan which is not more than 6 hours. The electrolyte proposed was methanol. The sensitivity and response time for methanol were 0.81pF/kPa and 0.35s respectively (Norzaidi et al., 2014). Different electrolyte properties such as propylene carbonate need to be used due to its high dielectric constant and can improve the sensitivity and the response time by increasing its ionic capacitance (Burt et al., 2014).

Table 2.2: Review on optimization and characterization of bio-inspired flow sensor

(Norzaidi Mat Nawi. (2015). *One-side-electrode-type Fluidic Sensing Mechanism Inspired From Fish Cupula*. Universiti Sains Malaysia. *pg 29*)

	Design	Environment	Characterization	DOF	Notes (Advantages or limitation)
1	Fan et al. 2002	Water	Flow measurement	1DOF	Earliest prototype
2	Chen et al. 2003	Air	Flow measurement		Test for different hair cell dimension
3	Chen et al. 2007	Air and Water	Flow measurement and direction		Limited only 55° deflections
4	Paleshanko et al. 2007	Water	Cupula properties and flow measurement		Can sustain high flow
5	Wang et al. 2008	Air	Flow measurement and direction	2DOF	Four cantilever on one substrate
6	Kottapalli et al 2013	Air and Water	Flow measurement		High sensitivity and good resolution
7	Dijkstra et al. 2005; Jaganatharaja et al. 2009	Water	Flow measurement and direction	1DOF	Sensing low-frequency air flows
8	Izadi et al. 2010				
9	Dagamesh et al. 2010		Flow pattern		High resolution flow camera
10	Sadeghi et al. 2013		Flow measurement and angle	2DOF	-

2.6 Microfluidic based Sensors

Pressure based sensor proposed by Norzaidi *et al* (2015) can be classified as the microfluidic based sensors. Microfluidic based pressure sensor used in many sensor applications such as in automotive, chemical, biomedical, marine and industry due to its advantages offered on sensing future. The minimization of technology nowadays also one of the factor microfluidic based sensor was preferred.

Microfluidic based sensor consists of electrodes and a microchannel. Microchannel in microfluidic based sensor used as a detector to detect the changes in the environment and react as modulator to convert a physical interruption into the electrical signal which connects by electrodes. Microchannel technologies based on PDMS polymer was used due to the mechanical yield in polymer characterization compared to silicon (Liu, 2007). PDMS polymer was a user-friendly material because its flexibility which can be used with glass and easily fabricated by using casting and molding techniques (Norzaidi et al., 2015).

Microchannel with PDMS technologies has limitations that need to be highlighted. The limitations by using PDMS material were included the temperature stability, the tolerance of high electric field and chemical or environment stability (Liu, 2007). Then, researches on the PDMS material need to be further studied to enhance the fluidic based pressure sensor performance.

2.7 Electrical Double Layer Theory

The charge accumulation in the electrical double layer (EDL) was stored in the electric double layer capacitors (EDLCs). An EDLC also defined as the energy storage devices. EDLC structure consists of electrodes, a microchannel as connecter connected to the electrodes. EDLC theory used by a sensor was a demand application due to its advantages in sensing mechanism, power buffering, power saving, energy recovery and long cycle life compared to batteries (A Manaf et al., 2008; Burt et al., 2014).

Helmholtz was the one who explained and proposed the EDL structure and stated that a small distance was separating the opposite charge formed at the electrode and electrolyte by a small distance (Burt et al., 2014). The theory explained is the same as the capacitance between two plates theory. The structure proposed by Helmholtz did not consider the movement of the ions and remains incomplete. Then, Gouy and Chapman modifying and extending the theory on ions mobilizing in the electrolyte (Hou, 2008).

The characterization of the performance of an EDLC is depends on two parameters which are the energy density and power density (Burt et al., 2014). Due to the charge adsorption and desorption released and mechanism of energy storage, EDLC have the high power density and low energy density. Hence, to increase E in order to increase capacitance, the only option is electrolyte. The performance of the EDLC cell was defined as follow (Burt et al., 2014);

$$E = \frac{1}{2} CV^2 \tag{2.7}$$

where E, C, and V are the storage energy, capacitance and applied voltage, respectively.

Gouy and Chapman proposed diffusion electrical double layer model and the limitations of this model is the overestimating the capacitance reading when there disruption on the electrode surface. Thus, Stern model with the basic from Helmholtz theory was proposed to overcome this problem. The Stern model used to explain the two different regions of charge and called as the Stern layer. In the development of EDLCs, the Gouy-Chapman-Stern EDL theory was widely used (Burt et al., 2014).

2.8 Summary

The overview of flow sensor has been discussed in this chapter and the bio-inspired flow sensor by mimicking the nature gave the inspiration in developing the pressure sensor specifically from the lateral line system. Development based on the bio-inspired hair flow sensor has been elaborated in term of material used, fabrication process, the sensor optimization and sensor characterization.

For sensor optimization and characterization, most of the researches did not cover the directional test and electrolytes for flow sensor. Generally, the characterization on applied pressures was conducted to study deflections, advantages and limitation to improve the performance of the pressure sensor. Hence, the electrolytes need to be investigated to optimize the pressure sensor. Microchannel in the microfluidic based flow sensor was studied. Microchannel can be defined as a detector to detect the changes in the environment and react as modulator to convert a physical interruption into the electrical signal which connects by electrodes. The electrical double layer theory was discussed to give a better perspective for fluidic based pressure sensor.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this research, the methodology was divided into three phases which are fabrication, electrolytes investigation and sensor characterization. The summary of methodology was mapped as in Figure 3.1. The fabrication of fluidic based pressure sensor with flat shaped membrane consists of molding, stamping and sealing techniques. The fabrication of those techniques was discussed in the next section. Electrode printing process also discussed for the first phase.

Phase 2 or electrolytes investigation, different types of electrolytes were used. The electrolytes used were defined as methanol, ethanol and propylene carbonate. The basic properties of electrolytes are also discussed. By using different types of electrolytes, the sensor characterizations were conducted. The sensor characterization focused on a sensing environment; air. The sensor characterizations involved were operating frequency, pressure, response time and lifetime.