DESIGN, FABRICATION AND PERFORMANCE ANALYSIS OF SU-8 PIEZORESISTIVE MICRO PRESSURE SENSOR

by

WONG WAH SENG

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

JULY 2012

ACKNOWLEDGEMENTS

This fabrication of SU-8 piezoresistive micro pressure sensor was challenging, tiring but satisfying since the actual pressure sensor had been fabricate and shows positive result in this research. Involving in MEMS field is indeed challenging due to the totally different knowledge in equipment handling and fabrication work. This project will not success without the support from a lot of people.

First and foremost, I would like to express special thank to my supervisor, Associate Professor Dr. Ishak Bin Haji Abdul Azid for always patient with me during the research, provide guidance and assistance for my dissertation work. Moreover, I am grateful to my co supervisor, Professor Kamarulazizi Bin Ibrahim and Dr. Mutharasu Devarajan from Nano-Optoelectronic Research and Technology (N.O.R) Lab for their technique advice and guidance in the fabrication work.

On the other hand, i would like to thank my partner, Mr. Lee Kok Siong and Miss Wong Wai Chi. I am extremely fortunate to have nice partner to work together who brighten me with useful idea, suggestion and kindly assist me for my research work. Besides that, I would like to thank technical staffs from Physics and Mechanical school, especially Madam Bee Cho, Mr. Mokhtar, Mr. Jamil, Mr. Hazhar, Mr. Saiful and Mr. Ashamuddin for their constantly support during my master degree. A great appreciation go to other students and staff of Universiti Sains Malaysia (USM) for their directly and indirectly contribution for this project.

Not to forget, I would like to express my deepest gratitude to my parents and family for physically and mentally support during the period of pursuing master degree. Last but not least, I would express my gratitude to Institute of Postgraduate Studies (IPS) for financial support me with USM fellowship during my research.

Wong Wah Seng

July 2012

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

SYMBOL	DESCRIPTION	UNIT
ΔV	Voltage output of Wheatstone bridge	V
P	Pressure	Pa
S_{max}	Maximum mechanical stress	Pa
d_{max}	Maximum deflection	m
P	Applied pressure	Pa
l	Length (width) of diaphragm	M
t	Thickness of diaphragm	M
ν	Poisson's ratio	
E	Young's Modulus	Pa
ΔR	Change of strain gauge resistance	Ω
R	Resistance of unstrained strain gauge	Ω
ε	Mechanical strain	
R_1, R_2, R_3, R_4	R_1 denoted resistance of first resistor, respectively	Ω
V_i	Input voltage of Wheatstone bridge	V
ΔV	Output voltage of Wheatstone bridge	V
V_4	Voltage between second resistor (R_2) and forth resistor (R_4)	V
V_3	Voltage between first resistor (R_1) and third resistor (R_3)	V
ΔR_t	Resistance change induce by temperature	Ω
ΔV_t	Output voltage when temperature changes for ΔR_t	V
R_a, R_b, R_c and R_d	R_a denoted resistance of first resistor, respectively	Ω
R_I, R_{II}, R_{III} and R_{IV}	R_I denoted resistance of first resistor, respectively	Ω
V_0	Voltage output when non pressure loading	V
ε_{max}	Maximum strain of pressure sensor	
r_{xy}	Pearson's correlation coefficient	

LIST OF ABBREVIATIONS

MEMS	Microelectromechanical system
TPMS	Tire pressure monitor system
LPCVD	Low pressure chemical vapor deposition
PMMA	Para-Methoxy-N-methylamphetamine
Ag	Silver
UV light	Ultraviolet light
OHP	Overhead projector
FEM	Finite Element Method
IC	Integrated circuit
LIGA	Lithography, Electroplating, and Molding
SOI	Silicon on Insulator
PDMS	Polydimethylsiloxane
Si_3N_4	Silicon nitride
GF	Gauge Factor
DRIE	Deep reactive ion etching
KOH	Potassium hydroxide
TMAH	Tetramethylammonium hydroxide
HF	Acid hydrofluoric
DI	Deionised
CTE	Coefficient of thermal expansion
TEOS	Tetraethyl Orthosilicate
Ti/TiN/Al-Si-Cu/TiN	Titanium/Titanium Nitride/Aluminum-Silicon-Cooper/Titanium Nitride
FC	Fluorocarbon
SAM	Self-Assembled Monolayer
SiO_2	Silicon Dioxide
Al	Aluminum
Cr	Chromium
Au	Gold
Cu	Copper
PMGI	Polydimethylglutarimide
NOR lab	Nano-Optoelectronics Research and Technology Laboratory
Bio-MEMS	Biological microelectromechanical systems
NDIV	Number of element division
R&D	Research and development
HMDS	Hexamethyldisilazane

PEB	Post Exposure Bake
PGMEA	Propylene glycol methyl ether acetate
IPA	Isopropanol
IV	Current-Voltage
FSS	Full scale span
SEM	Scanning electron microscope

REKABENTUK, FABRIKASI DAN PENCIRIAN PRESTASI SENSOR TEKANAN MIKRO SU-8 PIEZORESISTIF

ABSTRAK

Penyelidikan melibatkan rekabentuk, pemodelan dan fabrikasi sensor tekanan mikro SU-8 piezoresistif, serta pencirian prestasi sensor akan dibincangkan dalam tesis ini. Sensor tekanan mikro piezoresistif biasanya difabrikasi dengan menggunakan silikon. Pelbagai isu dan cabaran seperti: penentuan bahan piezoresistor, kaedah pembebasan spesimen dari substrat dan peningkatan kepekaan perlu diatasi dalam usaha untuk merekabentuk piezoresistif sensor tekanan mikro yang berasaskan SU-8. Keaslian kajian ini tertumpu kepada pengintegrasikan sensor tekanan mikro dengan komposit SU-8/perak (SU-8/Ag) sebagai piezoresistor, transparensi OHP sebagai substrat dan kaedah baru membebaskan spesimen secara kering. SU-8 dipilih sebagai rangka sensor tekanan mikro disebabkan kos yang rendah dan proses fabrikasi yang senang. Selainnya, Modulus Young SU-8 yang rendah mampu menyediakan kepekaan yang lebih baik berbanding dengan silikon. Kaedah analisis menggunakan teori pesongan kecil untuk plat dan analisis unsur terhingga (FEA) dengan ANSYS ® dijalankan untuk mencari ketebalan diafragma yang sesuai. Kedua-dua kaedah menunjukkan bahawa ketebalan sebanyak 147μm dapat memberikan sensitiviti dan kelinearan yang optimum untuk SU-8 diafragma berdimensi 6000μm .FEA juga digunakan untuk mencari geometri dan lokasi yang sesuai untuk piezoresistor supaya sensitiviti ditingkatkan. Teknik memfabrikasi SU-8 sensor tekanan mikro dengan kos yang rendah telah dicadangkan dalam kajian ini. Penggantian silikon dengan Transparensi OHP sebagai bahan substrat telah mengurangkan kos fabrikasi dan memungkinkan kaedah pembebasan spesimen secara kering digunakan penyelidikan ini. Penggantian pendopan silikon dengan SU-8/Ag piezoresistor dapat mengurangkan kesan negatif terhadap kelenturan diafragma

dan menunjukan sensitiviti yang tinggi. Satu teknik baru juga diperkenalkan untuk membandingkan kepekaan sensor tekanan mikro SU-8 piezoresistif secara kualitatif. Kajian ini menunjukkan kepekaan 3.4 kali lebih tinggi daripada kajian Ko et al. (2007) berdasarkan teknik baru dan 41 kali ganda lebih tinggi berdasarkan $\Delta V/P$. Selain itu, sensor tekanan mikro ini menunjukkan kelinearan dan histerisis yang setanding dengan kajian sebelumnya. Akhirnya, sensor tekanan telah berjaya ditransformasikan kepada sensor tekanan jenis "tatasusunan" supaya dapat mengukur taburan tekanan dengan prestasi yang setanding dengan sensor tekanan yang tunggal.

DESIGN, FABRICATION AND PERFORMANCE ANALYSIS OF SU-8 PIEZORESISTIVE MICRO PRESSURE SENSOR

ABSTRACT

In this thesis, SU-8 piezoresistive micro pressure sensor is designed, modeled and fabricated, and its performance is characterized. As piezoresistive micro pressure sensor is commonly fabricated using silicon, many issues and challenges such as selection of piezoresistor material, release method and sensitivity enhancement need to be tackled in order to develop successful SU-8 piezoresistive micro pressure sensor. The novelty of this research focuses on integrating micro pressure sensor with SU-8/silver composite (SU-8/Ag) as piezoresistor, OHP transparency as substrate and novel dry release method as release protocol. SU-8 is selected as structural material for micro pressure sensor due to its low cost and easy to fabricate. Besides, the low Young's Modulus of SU-8 provides better sensitivity compared to silicon. Analytical method using small deflection theories of plate and finite element analysis (FEA) via ANSYS® are carried out to characterize the diaphragm thickness. Both methods show thickness at 147μm provides optimum sensitivity and linearity for 6000μm square SU-8 diaphragm. FEA is also applied to find the most suitable geometry and the best location of piezoresistors for improved sensitivity. A simple and low cost protocol is established to fabricate SU-8 based pressure sensor. The substitution of silicon with OHP transparency as substrate material has reduced the fabrication cost and allowed the developed novel dry release method to take place. The substitution of doped silicon with SU-8/Ag piezoresistor has reduced interfere to diaphragm stiffness and provided high sensitivity. A new benchmark is also introduced to compare the sensitivity of SU-8 piezoresistive micro pressure sensor in more qualitative manner. Present work shows sensitivity of 3.4 times higher based on new benchmark and 41 times higher based

on $\Delta V/P$ compared to Ko et al. (2007) work. Moreover, the fabricated micro pressure sensor shows that the linearity and hysteresis is comparable to previous work. Finally, the single pressure sensor has been successfully transformed to fabricate pressure sensor array for pressure distribution measurement with similar good performance as for single pressure sensor.

CHAPTER 1

INTRODUCTION

1.1. Overview

An overview of microelectromechanical systems will be presented in this chapter, followed by concepts for the understanding about pressure sensor, piezoresistive and SU-8. Besides, problem statement, thesis objectives and thesis outline will be presented as well. The main contents in this chapter are:

- Introduction to microelectromechanical systems (MEMS)
- Introduction to pressure sensor
- Introduction to Piezoresistive as sensing element
- Introduction to SU-8 as structural material
- Problem statement
- Thesis objectives
- Thesis outline

1.2. Introduction to Microelectromechanical Systems (MEMS)

MEMS are also known as Microsystems Technology in Europe or Micromachines in Japan. MEMS combine both electrical and mechanical components to form a system or device in miniature form. MEMS reduces system size to result in faster devices while reducing energy and material requirement. Francais (2003) describes the scale of MEMS dimension can be ranging from 0.1 micrometer (μm) to 1 centimeter (cm) as shown in Figure 1.1. Generally, MEMS components can be divided into four categories: microsensor, microactuators, microelectronic and microstructure. Microsensor working principle is based on transforming mechanical signal to another readable signal, for example, transforming temperature, force, pressure to voltage readout. The introduction of MEMS to sensor (microsensor) has been found to have better sensitivity, accuracy and reducing material cost compared to sensor in macro scales. Besides, microsensor has low unit cost which enables it to be disposed after usage, thus saving labour cost of treatment before reuse (Hsu, 2002). These advantages enable extensive development of MEMS device in the world market as shown in Figure 1.2.

In this work, micro pressure sensor which is one of the popular MEMS devices as shown will be designed, fabricated and analysed.

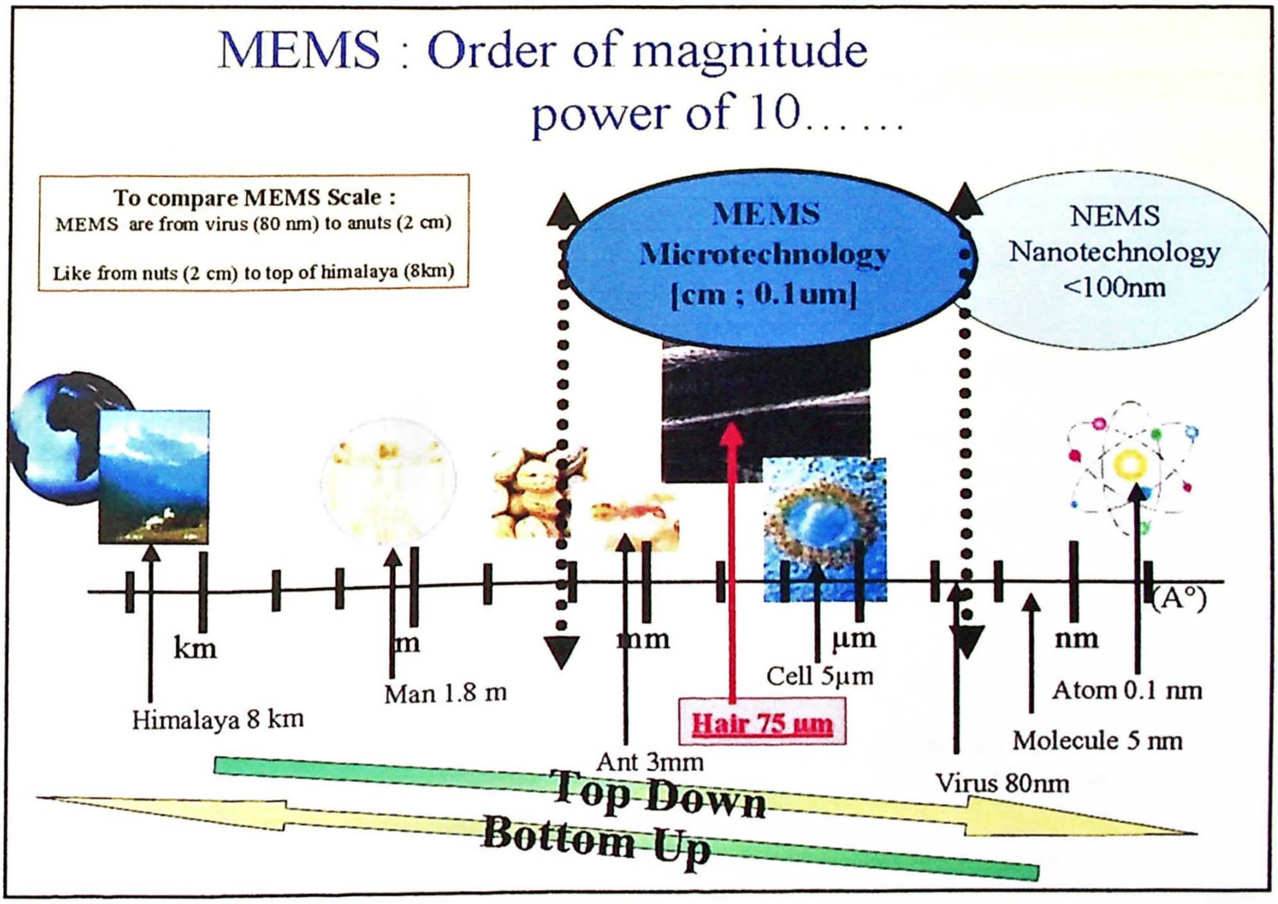


Figure 1.1: MEMS scale comparison with reference to typical object (Francais, 2003)

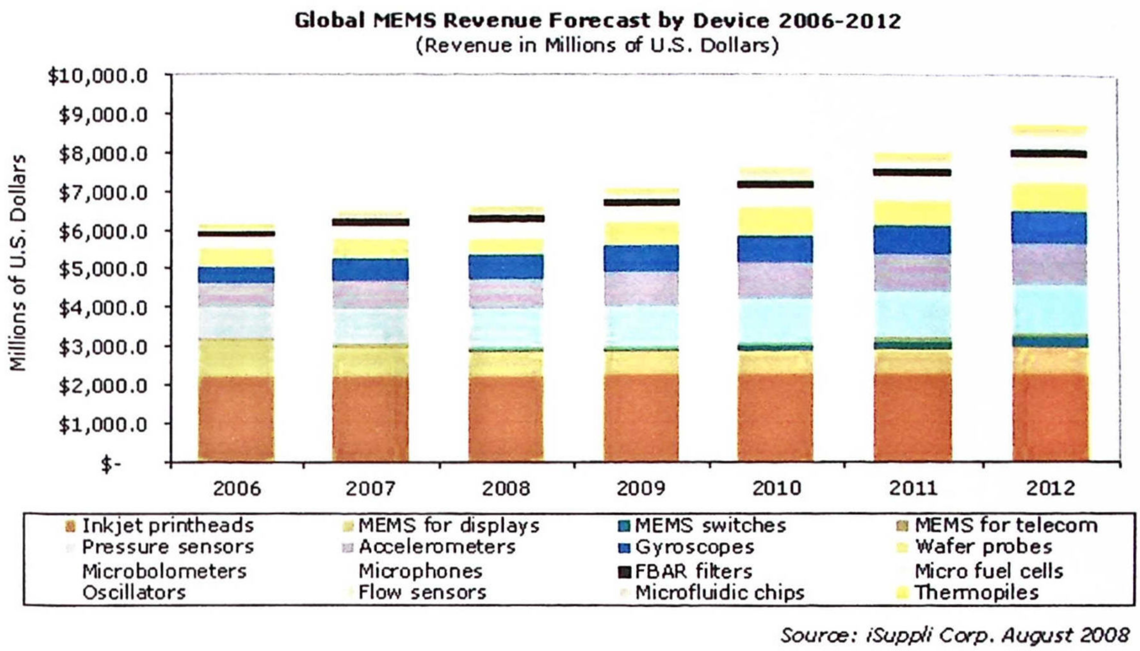


Figure 1.2: Global MEMS revenue forecast from 2006 to 1012 by device (iSuppli Corp, 2008)

1.3. Introduction to pressure sensor

Pressure sensor transforms pressure to other signal. Pressure sensor mechanism is based on the principle that diaphragm will deflect when pressure difference exists between diaphragm's surface. Then, sensing element will trace the deflection and change it to readout signal such as electrical output. Pressure sensor is utilized in many applications surrounding us, for examples altitude sensing, tire pressure monitor system (TPMS), blood pressure monitoring, printer pressure monitor system. The high demand of pressure sensor for various applications make pressure sensor market growing steadying as shown in Figure 1.2.

The first pressure sensor integrated with diffused piezoresistor was fabricated by Honeywell Research in 1962 (Barlian et al., 2009). Earlier pressure sensor commonly made use of piezoresistive or capacitive as sensing element. Both of them still popular in pressure sensor nowadays due to relatively low cost compare to other sensing element. In this research, piezoresistive type pressure sensor will be developed.

1.4. Introduction to Piezoresistive as Sensing Element

Piezoresistive is a phenomena where electrical resistance of solids changes when subjected to mechanical stress (Hsu, 2002). The property of piezoresister is first realized by Lord Kelvin in year 1856 when he found resistance of metal changed when subjected to stress. Since the discovery of this piezoresistive effect, piezoresistive sensor has been widely used for mechanical sensing because it is easy for batch processing, low cost and high linearity. Nowadays, piezoresistive has been widely applied in MEMS applications as sensing element of pressure sensor (Peng et al., 2005), flow sensor (Lou et al., 2011) and tactile sensors (Vidal-Verdu et al., 2011)

Typically, piezoresistive for MEMS device is formed by doping boron into silicon to produce p-type or doping phosphorus or arsenic into silicon as n-type (Pramanik et al., 2006). However, doped silicon is not suitable in this research since it require silicon diaphragm.

In this project, a composite form by silver nano powder with SU-8 is chosen as piezoresistive material for sensing purpose. The composite chosen exhibits good thermal matching to SU-8 substrate besides having advantages of low cost and easy to fabricate.

1.5. Introduction to SU-8 as a Structural Material

SU-8 initially is a negative photoresist developed to produce high resolution mask for fabricating semiconductor devices. Nowadays, SU-8 is found to be a good material for MEMS device, especially to produce high aspect ratio structure especially to suit the increasing demand of complex device. Lorenz et al. (1997) successfully fabricated 1200μm thick structure by SU-8 with aspect ratio greater than 18. Example of high aspect ratio structure based on SU-8 is shown in Figure 1.3.

Thickness ranging from 0.5μm to several 100μm can be readily available by spin coating. Besides, for SU-8 structure with thickness up to several mm, it can be achieved by stacking multiple layer of SU-8. The easy control of SU-8 thickness provides flexibility during fabricating MEMS structure.

Melamud et al. (2005) successfully developed a SU-8 based pressure sensor designed for measuring intravascular blood pressure. The works of Melamud et al. (2005) and Nordstrom et al. (2008) work showed that SU-8 is bio-compatible, which means it is able to integrate to tissue or body without compatibility issue. In other words, SU-8 based MEMS devices potentially to be applied in biology fields.

SU-8 can be readily fabricated by conventional lab equipment, such as spin coater and mask aligner. As a comparison, traditional MEMS device fabricated using silicon as structural material is found to be more complex and slower compared to SU-8 as structural material. Besides, conventional lab equipment also means SU-8 can be fabricated with low cost.

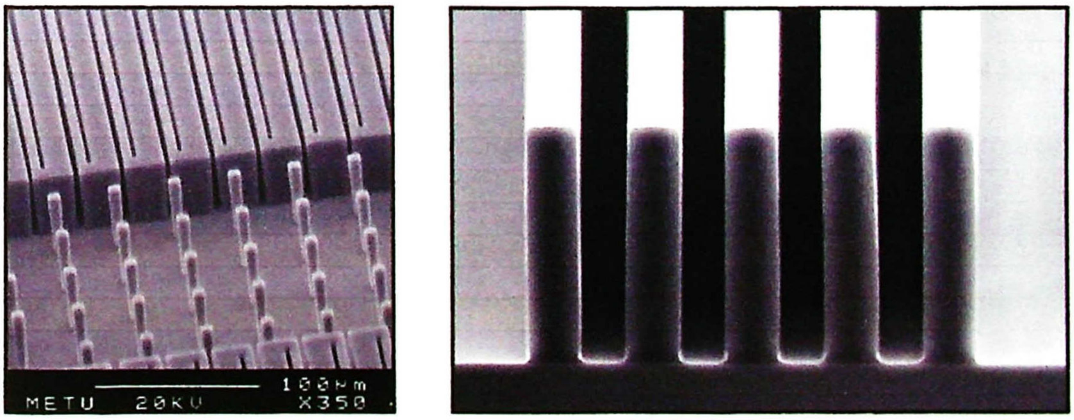


Figure 1.3: The high aspect ratio structures fabricated by SU-8 (Microchem)

1.6. Problem Statement

Previously, SU-8 pressure sensor fabrication is expensive and complex. In Ko et al. (2007), SU-8 pressure sensor requires advance equipment such as LPCVD, sputtering and involving many different materials such as Pyrex glass, PMMA and silicon, which will increase the fabrication cost. In this work, fabrication protocol involving simple equipments and steps will be suggested for SU-8 pressure sensor.

Selection of SU-8 as substrate for micro pressure sensor brings issue of piezoresistor's material. In Ko et al. (2007), SU-8 based pressure sensor used doped silicon as piezoresistor. However, doping silicon on SU-8 substrate requires silicon substrate and LPCVD to deposit Polysilicon, making the whole process complicated. Furthermore, silicon has high Young's Modulus compared to SU-8 which will reduce sensitivity of pressure sensor. Thaysen et al. (2002) and Nordstrom et al. (2005) worked using metal such as gold as piezoresistor however show low gauge factor. A novel piezoresistive material, SU-8 with silver nanopowerder composite (SU-8/Ag) will be suggested as piezoresistor for this research to overcome this issue.

The selection of substrate is essential for the fabrication process. Substrate serves as platform where fabrication takes place. Thus, substrate has to hold the device firmly and be able to withstand the environment during fabrication. Silicon is typically chosen as substrate for MEMS due to its excellent electrical and mechanical properties. However, silicon shows big mismatch of coefficient of thermal expansion with SU-8 and its opaque properties do not allow penetration of UV light during backside exposure. Therefore, alternative materials, such as glass and OHP transparency will be suggested in this work as substitution for silicon substrate.

Another issue commonly encountered in MEMS fabrication is how to release device from substrate after fabrication. Release method is generally divided to dry release and wet release. Wet release usually takes long time to accomplish while dry release usually needs special material as substrate to accomplish. In this work, low cost and fast release method suitable for release SU-8 device will be studied and applied for pressure sensor fabrication.

Sensitivity is important parameter of pressure sensor's performance. Typically sensitivity is measured based on ratio of voltage change over pressure ($\Delta V/P$). $\Delta V/P$ value is influenced by maximum design operating pressure, diaphragm geometry, piezoresistor's material and piezoresistor's design. However, $\Delta V/P$ is not suitable to be studied for the relationship between piezoresistor's material and sensitivity in this work. Thus, a new benchmark is suggested for comparing sensitivity of pressure sensor which is more accurate compared to $\Delta V/P$ value.

Incorporating SU-8/Ag composite as piezoresistor in this work will changes pressure sensor's performance. Pressure sensor's performance includes many aspects such as sensitivity, linearity and hysteresis performance. Since SU-8 based pressure sensor starts to be developed nowadays, many improvements can be made for SU-8 based device. One of the challenges in this research is to fabricate a SU-8 based pressure sensor with comparable performance compared to the previous work.

Last but not least, pressure sensor array is getting more attention nowadays for measuring pressure distribution. The ability to transform single pressure sensor to array will be studied. Pressure sensor array will be fabricated and characterized in this research to validate the transformation.

1.7. Thesis objectives

For this research of "Analysis of SU-8 Piezoresistive Micro Pressure Sensor", there are several objectives to be fulfilled as listed below:

i. To design, fabricate, and analyze the performance of SU-8 based pressure sensor integrated SU-8/Ag piezoresistor involving simple equipment and low cost material with performance comparable to previous work

ii. To study the suitable substrate and develop a release protocol for SU-8 based pressure sensor.

iii. To develop a new benchmark for comparing sensitivity of pressure sensor.

1.8. Thesis outline

This thesis is presented in five chapters which include introduction, literature reviews, methodology, results and discussion, and finally conclusion. The first chapter gives a brief introduction on the microelectromechanical systems, micro pressure sensor, piezoresistive as sensing element and SU-8. The problem statements and research objectives are also presented. The second chapter reviews the development of pressure sensor, diaphragm, piezoresistive readout method, the Wheatstone bridge, circuit material, substrate as well as pressure sensor array. This chapter also highlights issues regarding fabrication process, release method and sensitivity enhancement of previous work. The third chapter focuses on characterization of pressure sensor by analytical analysis and Finite Element Analysis (FEA). The overall explanation on sensor design, fabrication process and experimental setup is also presented here. Chapter four discusses the results collected from FEA, fabrication and experiments. Finally, the thesis ends with the conclusions as well as future work for design and fabrication of piezoresistive SU-8 pressure sensor.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a review relating to the existing work and published literature on various aspects of this research is presented. This review not only provides background knowledge on the concept that can be applied directly to the current research but also it serves as a goal for the current research work to improve the existing work. This chapter will cover the scopes as shown below:

- Development of Pressure Sensor
- Development of Diaphragm
- Development of Piezoresistive Readout Method
- Development of Wheatstone bridge and Circuit Material
- Development of Substrate
- Development of Pressure Sensor Array
- Development of Fabrication Process
- Development of Release Method
- Definition of Sensitivity and Sensitivity Enhancement
- Remarks on literature review and summary

2.2 Development of Pressure Sensor

2.2.1 Pressure Sensor in Macroscopic Scale

Many micromachined pressure sensors are the miniaturized version of their large counterparts. Examples of macroscopic sensors are shown in Figure 2.1. These macroscopic pressure sensors commonly have mechanical elements which convert pressure to motion. These mechanical elements include diaphragms (a, b, d), capsule (c), bellows (e), Bourdon tubes (f) and straight-wall tubes (g) (Eaton and Smith, 1997). Eaton and Smith (1997) review shows diaphragm is one of the popular structures of pressure sensor. It is found that diaphragm is the easiest structure to be micromachined compared to other mechanical elements. Thus, diaphragm is chosen as a mechanical element to transfer pressure to motion.

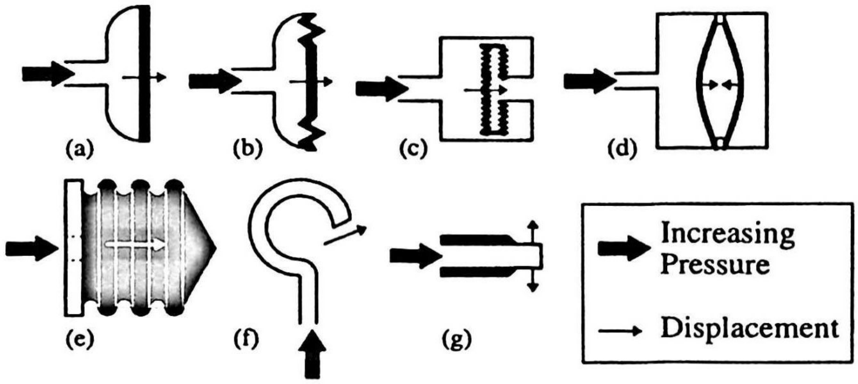


Figure 2.1 Type of Pressure Sensors in Macroscopic Scale: (a) Simple Diaphragm; (b) Corrugated Diaphragm; (c) Capsule; (d) Capacitive Sensor; (e) Bellows; (f) Bourdon Tube; (g) Straight Tube. (Eaton and Smith, 1997)

2.2.2 Diaphragm Based Pressure Sensor

Typically diaphragm based pressure sensor comprises of several parts including diaphragm, sensing element, interconnection and contact pad, and cavity. In this research, design of pressure sensor will be bases on general structure of diaphragm as shown in Figure 2.2.

a) Diaphragm- A thin membrane that will deflect when pressure exerts on it
b) Sensing element- Element to transform the deflection of diaphragm to electrical properties variation. Examples of sensing element include piezoresistive, capacitive, optical and others
c) Interconnection and contact pad- Circuit to transfer the electrical properties variation to external circuit.
d) Cavity – Free space that allows the deflection of diaphragm.

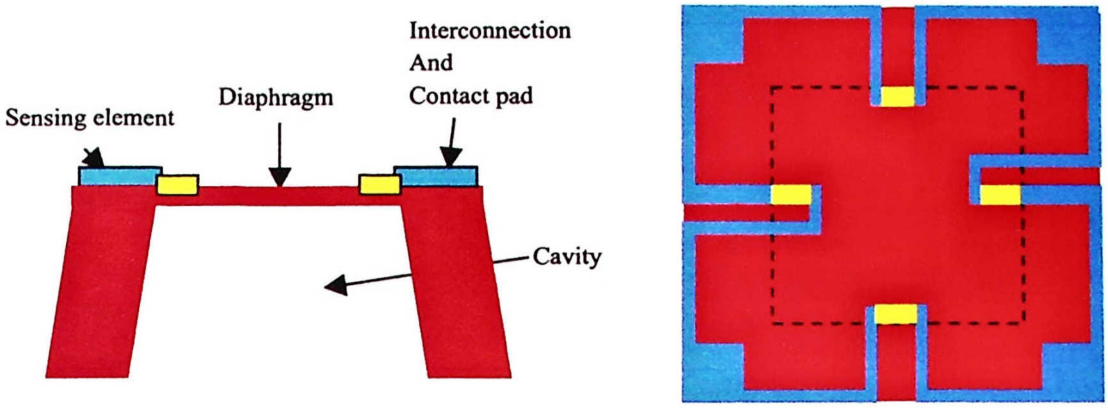


Figure 2.2 General structure of diaphragm based pressure sensor (sensing element shown here is piezoresistor)

2.2.3 Pressure Sensor Fabrication by IC Standard

Since Smith (1954) discovered the properties of piezoresistive in silicon, pressure sensor based on piezoresistive was widely developed. The early development of micro pressure sensor took advantages from the success of integrated circuit (IC) industry. With the IC technology, the first MEMS scale pressure sensor based on bulk silicon was successfully fabricated in 1971(Samaun and James, 1971).

The IC industry has provided a readily platform for MEMS (example: micro pressure sensor) to adapt and make use of the available matured technology, even though the nature of IC industry design was to deal with two dimensional structures instead of 3D structure as with MEMS device. Some novel fabrication methods have been developed purposely for MEMS fabrication, for example LIGA (German acronym for Lithography, Electroplating, and Molding) to create high aspect ratio microstructures (Hsu, 2002). However, it is undeniable IC standard helps in shorten the fabrication process and reduces the cost of MEMS. Some of the popular IC processes still useful in fabrication process of micro pressure sensor include photolithography, thermal evaporation, sputtering, wire bonding and chemical vapor deposition.

Silicon is widely applied in IC standard. However, silicon is not the only wafer used to fabricate MEMS using IC standard nowadays, instead various wafers have been applied to enhance the performance of MEMS device. One example is by Jia et al. (2010) who had successfully fabricated micro pressure sensor on SOI (Silicon on Insulator) wafer based on IC compatible process.

In this research, standard IC processes such as photolithography, thermal evaporator, and mask aligner were used to fabricate micro pressure sensor. The available IC process and equipments help simplify the fabrication process although silicon is not serving as substrate in this research.

2.2.4 Performance Improvement of Micro Pressure Sensor

Eaton and Smith (1997) showed miniaturized pressure sensor is receiving more and more demand nowadays due to its lower cost and better quality (sensitivity, linearity). Various efforts have been carried out to improve the performance and reduce the size and cost of pressure sensor (Chen et al., 2010). Nowadays, micro pressure sensor is widely applied in various applications, for example: automobile industry for intake manifold pressure monitor, inkjet pressure monitor (Jia et al., 2010), and monitoring pressure under harsh environment from 25°C to 300°C (Ayerdi et al., 2007).

In this research, SU-8 based pressure sensor is designed to have better quality besides having low cost and simple fabrication. SU-8 based pressure sensor can extend its application to bio-MEMS field and Microfuildic system.

2.2.5 The Sizes of Micro Pressure Sensor

Since the first MEMS pressure sensor made of bulk silicon circular diaphragm reported diameter of 0.5mm and thickness of 5μm as published by Samaun and James (1971), many different sizes of MEMS pressure sensor have been fabricated to suit various applications. A review as listed in Table 2.1 shows typical MEMS pressure sensor fabricated in different sizes.

Table 2.1 Dimension of piezoresistive micro pressure sensor propose by previous works.

Source	**Shape**	**Dimension(μm) (Length x Width x Depth)**
Samaun and James, 1971	Circular	Diameter=500, Depth=5
Wang et al., 1991	Square	800x800x60
Ayerdi et al., 1997	Square	3000x3000x140
Lin et al., 1999	Square	100x100x2
Merlos et al., 2000	Square	1460x1460x15
Singh et al., 2002	Square	2000x2000x60
Fung et al., 2005	Circular	Diameter =2000, Depth=300
Ko et al., 2007	Square	150x150x9
Chen et al., 2010	Square	300x300x11
Hsieh et al., 2010	Square	610x610x23

The pressure sensor size is limited to geometry of 6000μm x 6000μm x 147μm consider the limitation of equipment. However, the dimension is still under the range of MEMS as shown in Figure 1.1 where MEMS criteria for dimension range from 0.1μm to 10000μm.

2.3 Development of Diaphragm

Most commercially available micro pressure sensors detect pressure according to deflection of diaphragm. As previously discussed in section 2.1.1, diaphragm is the easiest mechanism to be applied in MEMS pressure sensor. In this section, a short review of previous work on geometry, analysis and diaphragm's material selection will be presented.

2.3.1 Geometry of Pressure Sensor

Kanda and Yasukawa (1997) show that square diaphragm is preferred more than circular diaphragm. Assuming circular diaphragm and square diaphragm fabricated in a substrate with equal thickness, and the square diaphragm's edge length is equivalent to circular diaphragm diameter, according to the theory of plates, the maximum stress of square diaphragm will be 1.64 time higher compare to circular diaphragm (Kanda and Yasukawa, 1997). In other words, square diaphragm can produce better characteristic in term of sensitivity compared to circular diaphragm within the same substrate size.

2.3.2 Material of Pressure Sensor Diaphragm

Silicon is popular as diaphragm material of pressure sensor due to its excellent electrical properties. Besides, silicon has been extensively used in the IC industry making the microfabrication process easy to be integrated with electronic circuit and microprocessor (Singh et al., 2002). Other advantages of silicon as diaphragm material include batch processing, high sensitivity, small size and mechanical stability (Merlos et al., 2000).

Silicon based diaphragm is typically fabricated using bulk micromachining or surface micromachining. Bulk micromachining is a material removal process that may cause the structure unstable and wasting many materials. Surface micromachining addresses the issue of small depth of cavity of pressure sensor which limits the deflection of diaphragm and stiction which cause low yield of surface micromachining. The detailed discussion of micromachining will be continued in Section 2.8 later. These micromachining issues force researcher to study on other materials to substitute silicon as diaphragm material.

Recently, polymer has gained more and more interest as an option to silicon as structural material of pressure sensor. Seo et al. (2004) used silicon rubber as diaphragm to solve the issue of low sensitivity of conventional pressure sensor. Lee and Chou (2008) used Polydimethylsiloxane (PDMS) as diaphragm material due to lower Young's Modulus (0.75GPa) compared to silicon (180Gpa). Therefore, PDMS can deform larger than silicon diaphragm, and able to gain higher sensitivity compared to silicon. Fung et al. (2005) fabricated pressure sensor based on PMMA which shows advantage of electrically insulating, optically transparent, biocompatible, and low-cost. Ko et al. (2007) reported that SU-8 as diaphragm and structure has advantages of flexible thickness of diaphragm and cavity's depth. Table 2.2 lists several types of diaphragm material for Piezoresistive MEMS pressure sensor as proposed by published literatures.

Table 2.2 Diaphragm material for piezoresistive MEMS pressure sensor

Material	Source (Diaphragm material)
Silicon based diaphragm	Ayerdi et al., 1997; Esashi et al., 1998(Silicon nitride (Si_3N_4)); Pancewicz et al., 1999; Merlos et al., 2000(SOI); Singh et al., 2002; Malhaire and Barbier, 2003; Yang et al., 2005; Peng et al., 2005; Lohndorf et al., 2007; Zhang et al., 2007; Chen Tao et al., 2010
Polymer based diaphragm	Seo et al., 2004 (Silicon Rubber); Fung et al., 2005(PMMA); Ko et al., 2007(SU-8); Lee and Chou, 2008(PDMS)

SU-8 is preferred to use as diaphragm material due to its low Young's Modulus (2GPa) compared to silicon, which can enhance sensitivity. Furthermore, SU-8 is low cost compared to silicon, biocompatible and has wide application in Microfuildics.

2.3.3 Analytical method: Governing Equation for Deflection and Stress of Diaphragm Due To Pressure

For diaphragm based pressure sensor, pressure data exerted on the diaphragm will be converted to deflection before processing as electrical data for readout or connecting to other digital devices. The working mechanism of diaphragm is shown in Figure 2.3. For piezoresistive pressure sensor, the piezoresistor embedded on diaphragm will change its resistance according to the change of strain. The change of resistance can be read out directly, or passed through signal processing stage such as the Wheatstone bridge. Finally, the electrical output such as voltage, capacitance, or resistance will be transferred to panel for readout or logging to data recording system.

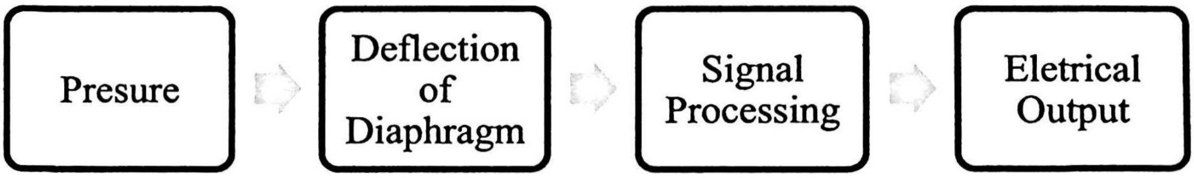


Figure 2.3 Working flow of diaphragm based pressure sensor

Figure 2.3 also implies the close connection between pressure and deflection. Therefore, the study on the relationship between pressure and deflection is important for pressure sensor optimization. Previous works carried out by Timoshenko and Woinowsky-Krieger (1970) and Wang et al. (2006) on the analytic model between pressure versus deflection and stress will be discussed here as a guideline for sensitivity optimization in this research.

Timoshenko and Woinowsky-Krieger (1970) had published small deflection theories of plate. Small deflection is defined as case where the ratio of deflection over diaphragm's thickness is less than 20%. In small deflection theories of plate, the maximum mechanical stress, S_{max} and maximum deflection, d_{max} for a square diaphragm are determined using equations 1 and 2 as shown:

$$S_{max} = 0.308(P)\,(l/t)^2\,(1 - v^2) \tag{2-1}$$

$$d_{max} = \frac{0.0151 P l^4 (1 - v^2)}{E t^3} \tag{2-2}$$

P Is applied pressure, l is length (width) of diaphragm, t is thickness of diaphragm, v is Poisson's ratio and E is Young's Modulus of the diaphragm material.

However, small deflection theories of plates are not valid when the deflection of diaphragm is larger than 20% of diaphragm thickness. Wang et al. (2006) had represented the large deflection diaphragm with equation (2-3). In equation (2-3), the deflection model is formed by two terms: small deflection term is described by linear term of the equation, while large deflection term is described by cubic term. Equation (2-3) shows deflection larger than 20% will result in non linear relationship between pressure and deflection.

$$\frac{Pl^4}{Et^4} = \frac{67.2}{(1-v^2)}\left[\frac{d_{max}}{t}\right] + \frac{25.3}{(1-v)}\left[\frac{d_{max}}{t}\right]^3 \qquad (2\text{-}3)$$

Therefore, in this research, the deflection of diaphragm is always kept below 20% of diaphragm thickness in order to gain good linearity. Thus, Equations (2-1) and (2-2) will be used to obtain diaphragm thickness for maximum sensitivity besides retaining acceptable linearity.

2.3.4 Finite Element Analysis (FEA)

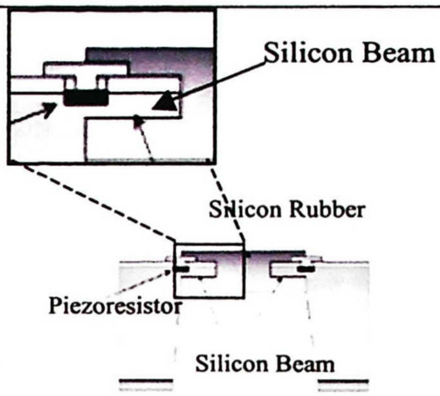
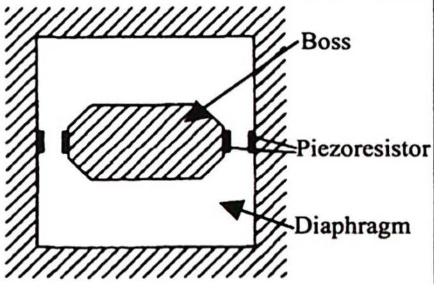
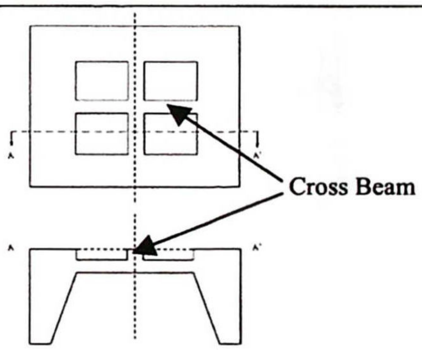
Finite Element Analysis (FEA) is commonly adopted to solve the optimization problem quickly, easily and generally more accurate than analytical. FEA has been widely applied to simulate mechanical modeling of pressure sensor; for examples, Ko et al. (2007), Lin et al. (1999), Tian et al. (2010) and Lee and Chou (2008) using ANSYS® and Pancewicz eåt al. (1999) using SAMCEF.

FEA has a lot of parameters to be defined; for examples, mesh size, mesh element and boundary condition. These parameters need to be set correctly to represent the actual device environment accurately. To verify the parameter setting in FEA, it is important to compare the simulation result with experimental data or analytical analysis to verify how far the agreement can be obtained from both methods.

2.3.5 Special design of Diaphragm

The structure of diaphragm plays an important role to the sensitivity and linearity of pressure sensor. Special design of diaphragm is usually designed to optimize the output of pressure sensor by introducing some structure to change the stress distribution on the diaphragm. For typical pressure sensor, diaphragm is formed by a flat circle or square thin plate built on cavity. To increase the sensitivity, the diaphragm has to be thinner but with the drawback of nonlinearity appearance due to the high deflection of diaphragm. So, one of the solutions to the above issue is to limit the thickness of diaphragm so that the deflection is less than 20% of diaphragm thickness when subjected to maximum desired pressure as discussed in Section 2.3.3. Therefore, special design has been proposed in order to reduce the nonlinearity of pressure sensor and at the same time, maintain or increase the sensitivity. Examples of special designs with their features and purposes are listed in Table 2.3.

Table 2.3 Special design of diaphragm

Journal	Design	Design Purpose
Seo et al., 2004		Comb-Type • Silicon beam with piezoresistor embedded in silicon rubber diaphragm • Can withstand burst pressure in harsh environment
Sandmaier and Kuhl, 1993		Rectangular Central Boss • Employing a boss structure at center of the diaphragm • Reduce nonlinearity of output signal
Tian et al., 2010		Cross-Beam Structure • Employing a boss cross structure at center of the diaphragm • Reduce nonlinearity of output signal with high sensitivity

2.4 Development of Piezoresistive Readout Method

2.4.1 Various Readout Methods

There are several readout methods for pressure sensor, for example piezoresistive, capacitive, optical, magnetic and resonant. The advantages of each readout method have been listed in Table 2.4. Piezoresistive and capacitive readout methods are among the most popular due to their low cost. Optical, magnetic and resonant read out methods have good performance but their high cost and complex process make them usually serve for specialised field which piezoresistive and capacitive sensor cannot perform well.

Table 2.4 Advantages of different readout methods for pressure sensor

Readout method	Source	Advantages
Piezoresistive	Tian et al., 2010	▪ Low cost.
Capacitive	Pang et al., 2008	▪ Low cost. ▪ Less affected by temperature.
Optical	Ge et al., 2008	▪ Immunity to electromagnetic interference.
Magnetic	Lohndorf et al., 2007	▪ High gauge factor until 600.
Resonant	Welham et al., 1996	▪ Output signal in term of frequency, can measure precisely. ▪ Can directly output digital signals, easy for circuit integration.

2.4.2 Piezoresistive as Readout Method Concept

Piezoresistive effect is defined as change in resistivity of material due to the applied mechanical stress. Piezoresistive is commonly related to semiconductor, where doped silicon is a popular piezoresistive material in MEMS. The easily adoption of piezoresistor with silicon substrate makes piezoresistive taking major share in MEMS sensor market today. However, piezoresistive effect is not limited to semiconductor material only. Beside semiconductor, many materials have been studied and found to have piezoresistive effect such as tantalum nitride thin film

(Ayerdi et al., 1997), carbon nano tube (Fung et al., 2005) and carbon black/ SU-8 composite (Nordstrom et al., 2008).

Piezoresistive sensing has the advantages in small size, less expensive, simplicity in fabrication and good performance in MEMS sensor. Its application is well known in piezoresistive strain gauges, pressure sensor, accelerometers and cantilever-based sensors. In this pressure sensor research, piezoresistive is chosen as the sensing element for the reason as discussed. Piezoresistive overtakes capacitive for pressure sensor due to issue of linearity, where piezoresistive sensor can gain linearity by a typical Wheatstone bridge circuit compared to capacitive sensor which needs a complex circuit to do so (Tian et al., 2010).

Therefore, piezoresistive is preferred as the desired readout method considering the cost and linearity factor,

2.4.3 Development of Piezoresistive Effect

Lord Kelvin, 1856 was the first to report resistivity due to the elongation of iron and copper. This resistivity change effect was purely due to the geometry change, which was given name as geometry effect in the study of piezoresistive. Smith (1954) discovers the piezoresistive effect in semiconductor including silicon and germanium. For semiconductor, piezoresistive effect is 50-100 significant compared to geometry effect (Barlian et al., 2009). The reason behind apparent piezoresistive effect on semiconductor is due to the narrow band gaps which can be influenced by mechanical strain. The developed mechanical strain will change the inter-atomic spacing and affect the band gaps energy required for electron to rise to conduction band. Thus, the conductivity (or resistivity) of semiconductor can be determined.

2.4.4 Gauge Factor (GF)

In pressure sensor, piezoresistor attached to diaphragm will detect the change in the pressure by converting the mechanical strain to change of resistance. In other words, piezoresistor functions as a strain gauge for pressure sensor.

Gauge Factor (GF) is a parameter to evaluate strain gauge. Higher GF will improve sensitivity of strain gauge by generating greater output under the same load. GF is the ratio of relative change of electrical resistance over the mechanical strain, ε, which is expressed as:

$$GF = (\Delta R/R)/\varepsilon \qquad (2\text{-}4)$$

Where ΔR=change of strain gauge resistance, R=Resistance of unstrained strain gauge, ε=Mechanical strain

For a strain gauge with resistivity ρ, change of resistivity Δp and Poisson's ratio ν, GF can be rewritten as equation below:

$$GF = (1 + 2\nu) + (\Delta p/p)/\varepsilon \qquad (2\text{-}5)$$

In the equation, GF depends on two elements that consist of geometry effect (1+2 ν) and piezoresistive effect ($(\Delta p/p)/\varepsilon$).

Doped semiconductor and metal are typical material for strain gauge, which are potentially applied in current research as sensing element for readout method. The comparison on the geometry effect and piezoresistive effect for metal and semiconductor is summarized in Table 2.5. Geometry effect depends on Poisson's ratio. Poisson's ratio value varies from -1 to 0.5 for isotropic solid. Therefore, geometry effect value is limited to 0 to 2 depending on the Poisson's ratio.

As discussed in Section 2.4.3, semiconductor such as silicon has high piezoresistive effect ($(\Delta p/p)/\varepsilon$), which value ranging from -125 until 200, depending on the direction with respect to the silicon crystal lattice. Therefore, geometry effect is negligible for semiconductor since it is too small compared to piezoresistive effect of semiconductor. As a distinct comparison, there is no piezoresistive effect for metal because metal's resistivity is constant under external stress. Thus, metal's GF solely depends on geometry effect.

Table 2.5 Geometry effect, piezoresistive effect and GF of different material (Greenwood, 1988)

Material	Geometry Effect (1+2 ν)	Piezoresistive Effect $(\Delta p/p)/\varepsilon$	GF $(1+2\nu)+(\Delta p/p)/\varepsilon$
Metal	1.4 to 2.0	0	1.4 to 2.0
Semiconductor (Silicon)	1.1-1.7	-100 to 200	≈-100 to 200

2.4.5 Concern of Doped Silicon as Piezoresistive Material to Current Work

In the design of pressure sensor, low stiffness diaphragm is preferred because it is easy to deflect and more sensitive to pressure. Typically pressure sensor uses doped silicon as strain gauge since its large value of GF can enhance pressure sensor's sensitivity to pressure changes. However, doped silicon has large Young's Modulus (180GPa) which is not suitable for low stiffness diaphragm made of polymer, such as SU-8 (Young Modulus=2GPa) as in this work. The large Young's Modulus of doped silicon piezoresistor will affect stiffness of SU-8 diaphragm. Although thickness of piezoresistor can be made thinner to reduce the effect to stiffness, but at the same time, it will increase the noise to signal ratio significantly, which will reduce the performance of pressure sensor.

2.4.6 Concern of Metal as Piezoresistive Material to Current Work

Several alternative materials have been studied to substitute doped silicon as piezoresistor. Nordstrom et al. (2005) and Thaysen et al. (2002) had introduced the piezoresistor made of thin gold film for SU-8 cantilever. It is worth to note that doped silicon always requires silicon as structural material. By using metal piezoresistor, diaphragm material can change from silicon to low Young's Modulus SU-8, thus reducing the stiffness of material and increasing the sensitivity. Thaysen et al. (2002) successfully fabricated a sensor which is claimed to have minimum detectable stress with a factor of 5 higher than optimized silicon sensor.

However, low GF of metal piezoresistor make it unfavorable as piezoresistor. An alternative material with high GF and similar stiffness with SU-8 will be discussed in next section as substitution to metal as piezoresistor.

2.4.7 Conducting Composite as Alternative Material for Piezoresistor

Recently, there is an approach to develop new piezoresistive material by mixing conducting particle with polymer such as by Nordstrom et al. (2008) who mixed SU-8 with carbon-black in form of composite. This approach resulted in a substitute piezoresistor material which has higher gauge factor than gold (GF=2) and compatible with SU-8 based fabrication process. Nordstrom et al. (2008) has successful developed SU-8/carbon-black composite with gauge factor ranging from 15 to 20.

Electrical behavior of the composite materials can be explained by using percolation theory. Under unstrained condition, the randomly dispersed conducting particles in an insulating polymer matrix form a conducting network as shown in Figure 2.4(a). Electron (e^- in the figure) can flow through conducting network (show in black line in the figure) explaining the conductivity mechanism for the composite. When external strain is applied to the composite, some of the conducting particles separate from each other, thus the conducting network breaks and causes the resistance of composite material to increase as shown in Figure 2.4 (b). Piezoresistor using composite material has higher gauge factor compared to piezoresistor using