MECHANICAL CHARACTERIZATION OF MEMS PIEZORESISTIVE MICROCANTILEVER SENSOR FOR BIOSENSING APPLICATION (DESIGN AND SIMULATION)

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

23 July 2013

HASRUL NISHAM BIN ROSLY
P65393
ACKNOWLEDGEMENT

In the name of Allah, the Most Beneficent and Most Merciful, Who has created the mankind with knowledge, wisdom and power. Alhamdulillah, praise be to ALLAH for giving me strength and guidance to finish up my master project. Without HIS blessing, it will be hard for me to complete this project successfully.

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Finally, I would like to thank to all my family, especially to my wife, Norhazwani Md Yunos and my daughter Zara Elviana for their endless love, continuous support and understanding.
Microcantilevers are now gaining popularity in biomolecular sensing. Monitoring and mass detection of biological species can be accurately determined using the micro or nano-scale cantilevers. Piezoresistive sensing method is one of the techniques used in biosensors as changes in mechanical properties can be converted to electrical output. The advantage of this method is that the readout system can be easily integrated on a chip. However, the deflection resolution for the piezoresistive readout system is only one nanometer compared with one Angstrom by optical detection method. Currently, most of the piezoresistive based microcantilevers were designed using a double layer by embedding the piezoresistive material on the top surface of the microcantilever. As the microcantilever deflects, it undergoes a stress change that will apply strain to the piezoresistor, thereby causing a change in resistance that can be measured by electronic means. However, double layer design is requires a more complicated fabrication process since the piezoresistor has to be embedded with the microcantilever. Therefore, a single layer design was introduced as an alternative to the double layer piezoresistive microcantilever where both piezoresistor and microcantilever were combined into a single layer using p-doped silicon. This, in turn, will simplify the fabrication process. In this work, a comparative study was done to evaluate the performance trade-off between the double and single layer piezoresistive microcantilever. The effect of various geometrical dimensions on the displacement and von Mises stress were studied. A series of double and single layer piezoresistive microcantilever were designed using CATIA software. Finite Element Analysis (FEA) through ANSYS 14.0 was performed on the structural model to analyze the performance of the microcantilever in terms of displacement and von Mises stress. Based on the simulation results, eventhough both double and single piezoresistive microcantilever showed similar trend of graph when applied with the same force, the single layer outstand the performance of the double layer. It was also found that the width and thickness of the single layer have greater effects on the displacement and von Mises stress than the double layer. However, for the length, double layer microcantilever have higher displacement but lower von Mises stress than the single layer microcantilever.
PENCIRIAN MEKANIKAL PADA PENGESAN PIEZORESISTIF MIKROKANTILEVER MEMS UNTUK APLIKASI BIOSENSOR (REKABENTUK DAN SIMULASI)

ABSTRAK

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<td>IC</td>
<td>Integrated Circuit</td>
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<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>AFM</td>
<td>Atomic Force Microscopy</td>
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<td>PSD</td>
<td>Position Sensitive Detection</td>
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<td>MRFM</td>
<td>Magnetic Resonance Force Microscopy</td>
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<td>STM</td>
<td>Scanning Tunneling Microscopy</td>
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CHAPTER I

INTRODUCTION

1.1 Introduction

Just as semiconductor technology enabled computers to shrink from room-sized to palm-sized, Micro-Electro-Mechanical System (MEMS) replace traditional mechanical and electronic devices such as sensors, actuators, transducers and gears with micrometer-scale equivalents that can transform the whole industries.

The micrometer-scale moving parts of MEMS devices are fabricated using techniques derived from semiconductor IC processing such as plasma etch (Bogomolov 2004), thin film deposition (Cui et al. 2006) and photolithography (Miyajima and Mehregany 1995). If integrated circuits are designed to exploit the electrical properties of silicon, MEMS takes advantage of either silicon’s mechanical properties or both its electrical and mechanical properties. MEMS devices are very small; their components are usually microscopic.

This miniaturization ability has enabled MEMS to be applied in many areas of biology, medicine, and biomedical engineering – a field generally referred to as BioMEMS (Petersen 1996). In addition, the design of the latest BioMEMS application system are baby heart rate monitoring (Trifunovic et al. 2012), monitor intracranial pressure (ICP) (Ghannad-Rezaie et al. 2012), C-reactive protein detection, detection of glucose and a blood cell counter (Khoshnoud and de Silva 2012).
The most natural and universal approach for identification of micro-sized biological objects (macromolecules, molecular complexes, viruses, glucose, bacterial spores, etc.) is to immobilize them with respective antibodies on cantilever surface and then measure the sensor mass change. Microcantilever is the simplest MEMS structure. It is essentially a beam that is clamp at only one side. This type of structure is capable to function as sensitive chemical and biological sensor (Pan and Hsu 1999). In terms of detection method, microcantilever would response to presence of analyte by changes of cantilever deflection and measurement of resonant frequency. MEMS for chemical and biological sensors applications have several advantages such as high sensitivity, small sample quantity required for analysis, portability, small dimensions even in array configuration, lower cost of fabrication, fast response time and readily to be mass produced.

1.2 Problem Statement

Optical detection method is a method of detection of the most widely applied in microcantilever because it can detect cantilever bending to nanometer range. The disadvantage of this detection method is high cost and cannot be integrated with on-chip sensors (Hansen et al. 2001). Due to these disadvantages, piezoresistive microcantilever become an alternative approach as sensing technique. It is because of their characteristic, which can convert from mechanical properties to electrical output.

Most of microcantilever sensors are embedded with piezoresistor to measure the surface stress change from biochemical reaction. As the microcantilever deflects, it undergoes a stress change that will apply strain to the piezoresistor, thereby causing a change in resistance that can be measured by electronic means. Means that, fabricated piezoresistor on microcantilever require different materials and fabrication processes are complicated. In order to counter this disadvantage, single layer piezoresistive microcantilever has been introduced where both piezoresistor and microcantilever are combined into a single layer using p-doped silicon.

Fabrication of microcantilever require repetition of various semiconductor manufacturing processing steps such as photolithography patterning; etching process
for various material removal, cleaning of etch residue and metallization. These mean that more layer on microcantilever, more complex fabrication process will be. The complexity of the process will increase the cost. Single layer piezoresistive microcantilever can simplify the fabrication process of the microcantilever. This microcantilever use p-doped silicon as main material.

1.3 Objectives

The objectives of this study are summarized as follows:
1. To understand double and single layer piezoresistive microcantilever structure and explore their potential.
2. To simulate the behaviour of the both double and single layer structures.
3. To compare the both piezoresistive microcantilever by varying the geometries of the microcantilever.

1.4 Thesis Outline

The thesis is divided into five chapters. The first chapter is the introduction. This chapter gives an introduction to the background of the problem, problem statement and objectives of the study.

Chapter two is the Literature Review. This chapter explains about MEMS, type of sensors, sensing techniques using microcantilever and piezoresistive MEMS microcantilever. The literature about recent works on microcantilever and solution method for determines double and single layer microcantilevers are also provided in this chapter.

Chapter three is the Research Methodology which discussed details on piezoersistive microcantilever design. The components used to analyze this project will be determined and the software used to implement this project will be identified.

The following chapter is chapter four. This chapter consists of the discussions and the results. The discussion starts with double layer piezoresistive microcantilever
followed by single layer piezoresistive microcantilever. Both results will be compared and the conclusion of the finding is stated in chapter five. Besides, chapter five also consists of recommendation on the future work.
CHAPTER II

LITERATURE REVIEW

2.1 Micro-Electro-Mechanical System

Micro-Electro-Mechanical System (MEMS) device has become a hallmark technology for the 21st century. Its capability to sense, analyze, compute and control all within a single chip provide many new and powerful products. MEMS device is an emerging device in several areas of science and technology such as engineering structure, electronics and life sciences field such as chemistry, physic, biology and health sciences (Chollet and Liu 2007). The two main key features for MEMS based device are mechanical structure that can be equated to motion and electrical signal. The addition of mechanical structure to an electronic chip gives a great enhancement to the functionality and performance. These devices have been dominantly used in the current market for computer storage system and automobiles. Smart vehicle are based on the extensive use of sensors and actuators. Various kind of sensors are used to detect the environment or road conditions and the actuators are used to execute any action are required to deals with conditions happen such as accelerometer for airbag system and Global Positioning System (GPS) (Hsu 2002). Most MEMS device are basically based on mechanical structure such as cantilever beam, gears, pump and motor as shown in Figure 2.1.
2.2 Finite Element Analysis in MEMS

MEMS devices deal with fabrication process which related to microelectronics fabrication technology. This fabrication involves a series of high tech and high cost process such as ultraviolet lithography and doping. Due to expensive cost of fabrication, finite element analysis (FEA) has been used to characterize the MEMS structure behavior during DNA binding, through a water flow and vibration testing (Chivukula et al. 2006). FEA software helps MEMS designers to identify potential problems at early stage in design cycle before proceed to fabrication or production line which in turn production help reducing time to market. In design cycle, MEMS devices need to be checked for design intent, working operation, collision avoidance/detection and package stack-up. FEA capability scaling down from sub-micron to angstroms level features help designers come up with lower scale device design towards nano sensor/actuator. Some MEMS based sensor devices is an assemblies of several parts and packaging. Therefore, by using FEA, collision and contact surface can be determined (Hsu 2002).

There are several FEA software available in the market that has been used for analyzing MEMS devices like ANSYS, Solidworks, and Abaqus. Besides that, there are also especially dedicated MEMS FEA software that integrates with MEMS device fabrication process such as Intellisuite, CoventorWare, and IntelliCAD. In both software the modeling and fabrication, files were combined and transferred for fabrication (Liu 2006). The fabrication will be based on the attachment or design
modeling file. This will not only help the MEMS designers to analyze and optimize the MEMS device design but also the manufacturability of the designed device. Flexibility in creating multiple design variations covering a wide range of needs such as die-mounted, package assemblies up to device efficiencies of configurations lead researchers to develop new device without any fabrication or prototype cost (Hsu 2002; Liu 2006).

2.3 Microcantilever MEMS Based Sensor

Brugger et al. (1999) and Thundat et al. (1995) have pointed out that microcantilever based sensors are the simplest devices among MEMS devices that offer a very promising future for the development of novel physical, chemical and biological sensors. They have also been proven to be very versatile devices and have been used in several fields such as accelerometer, chemical sensors, etc (Vashist 2007).

Basically, MEMS microcantilever sensor relies on the mechanical deformation of the structure, or in other words the deflection of membrane or beam structure. When the microcantilever is loaded, its stressed elements deform which cause the MEMS microcantilever to bend. As this deformation occur, the structure changes shape, and points on the structure displace. The deflection occurs when a disturbance or loading is applied to the microcantilever at the free end or along the MEMS cantilever surface. Normally the disturbance or loading is a force or mass that is attached to the MEMS microcantilever in which it will make the MEMS microcantilever to bend. Figure 2.2 illustrates MEMS microcantilever deflection working principal (Hsu 2002; Lee et al. 2007).
As the MEMS microcantilever deflects, the resulted deformation is termed bending. External applied loads which cause bending will result in reactions at the free end, consisting of displacement or deflection, $\delta_{\text{max}}$ as shown in Figure 2.3. Maximum deflection during force applied for a beam that has constant cross section can be calculated using equation (2.1) (Benham et al. 1996). Figure 2.3 shows the schematic of microcantilever deflection where it has one fixed end and one free end with force applied.

$$\delta_{\text{max}} = \frac{Fl^3}{3EI}$$  \hspace{1cm} (2.1)

where $\delta_{\text{max}}$ is the maximum deflection, $F$ is force applied, $l$ is the microcantilever length, $E$ is the Young's Modulus for the microcantilever material and $I$ is the moment inertia for the microcantilever.
The microcantilever will also sense stress that occurred during deflection. There are two types of stress occurred: tensile and compressive stress where tensile occurs at the top of microcantilever and compression acts at the bottom of microcantilever as illustrated in Figure 2.4. Since the piezoresistors are located at the top surface, research will be focuses at top surface of the microcantilever.

Maximum stress can be calculated using equation (2.2) for a constant cross section beam.

$$\sigma_{\text{max}} = \frac{Mc}{I}$$  \hspace{1cm} (2.2)

where $M$, moment = $F$, force x $l$, cantilever length, $\sigma_{\text{max}}$ is the maximum stress, $c$ is the height from the center axis to the top surface of the microcantilever and $I$, moment of inertia.
2.4 Sensing Techniques Using Microcantilevers

Extensively used as building blocks in civil and aeronautical structures, microcantilevers were first introduced in the sensors realm as strain gauges (Nokes and Carr 1997). Despite earlier applications as microphones, pressure sensors, and accelerometers, it was the invention of the atomic force microscopy (AFM) (Binnig et al. 2006) that gave a robust commercial momentum to microcantilever-based sensors. Also, it was upon the development of AFM that the potential of the microcantilever as a dynamic sensor was explored (Binnig et al. 2006).

Regardless of the sensing method (static or dynamic), microcantilever sensors can be categorized based on the employed detection scheme. The main detection schemes are listed as optical, piezoresistive, piezoelectric, electrostatic, tunneling, and thermal. The rest of this section introduces these schemes.

2.4.1 Optical

Not long after the invention of AFM, optical microcantilevers were first introduced (Martin et al. 1987). The basic operation principle of this type of microcantilever lies in optical reflection from the back surface of the beam, while the front surface interacts with the sample (Huber et al. 2006). The earlier optical detection schemes were based on laser interferometry, in which the resonance characteristic is extracted from the interference patterns between a reference light beam and the one reflected from the microcantilever’s back surface. Soon after the introduction of optical microcantilevers, the less complex scheme of position-sensitive detection (PSD) was developed. In a PSD scheme, a laser beam is emitted to the cantilever back surface at an angle; depending on the bending of the microcantilever, the reflected laser beam travels at a peculiar angle; thus the microcantilever deflection can be measured down to nano-scales. In this application, the microcantilever functions only as a light-reflecting ultra-soft spring, often called an “optical lever” (Alexander et al. 1989).
Optical microcantilevers are highly sensitive to such an extent that, for example, when implemented in the magnetic resonance force microscopy (MRFM), a single electron spin can be detected (Mamin et al. 2003). Besides the high sensitivity, another advantage of this type of microcantilever is its relative ease of fabrication, which is due to the omission of any needs for electrical connections to the microcantilever. Optical microcantilevers have been primarily made of tungsten wires, silicon, silicon nitride, and polymers (McFarland and Colton 2005).

2.4.2 Piezoresistive

Bending a microcantilever beam introduces directional stress, which will cause a resistance change if applied to a resistor. This quality, the dependence of electrical resistivity on stress, is called piezoresistance. Crystals, both metals and semiconductors, show piezoresistance, but while in metals the change of resistance is mainly a result of the geometrical variation, in semiconductors the piezoresistance originates from a change of the band-gap energy (Kanda 1991).

In a piezoresistive microcantilever the detecting resistors, called piezoresistors, are placed at potentially high-stress points of the cantilever beam; as long as the microcantilever deflection is negligible compared to its length, the resistance of piezoresistors changes linearly with the deflection. The considerable advantages of this scheme are the implementation of the detection mechanism within the microcantilever, CMOS integration capability, and the possibility of making large cantilever arrays. A limiting factor in this detection scheme is the presence of Johnson and Hooge noise with the resistors (Rangelow et al. 2007).

2.4.3 Piezoelectric

Piezoelectric cantilevers are used in a variety of applications, including accelerometers, mass sensors, mass flow sensors, chemical sensors, scanning tunneling microscopy (STM), and AFM (Indermuhle et al. 1997). The detection mechanism in this type of microcantilever is based on the generation of an electric...
field resulting from the introduction of stress (e.g., by bending) to single or multiple layers of piezoelectric materials such as ZnO.

2.4.4 Electrostatic

By forming a capacitor between the microcantilever surface and a fixed plate (i.e., counter electrode), the microcantilever deflection can be measured as a capacitance change. With this approach, not only can the static deflections be detected, but also in the dynamic mode, the resonance characteristic of the capacitive microcantilever can be used as a sensing measure. A resonating microcantilever, when used in the capacitive configuration, generates a periodic capacitance change. When implemented in an LC circuit, the cantilever resonance results in a frequency modulation. Hence, variations of the cantilever resonance frequency can be detected by demodulating the output signal (Kim et al. 2006).

2.4.5 Thermal

Unlike the mentioned microcantilever detection schemes, beam bending is not the working principle of a thermal microcantilever; rather the beam acts as a heat conduction path for a thermal probe. Thermal interaction of the scanning probe with the surface can be utilized in a voltage generation scheme as in thermocouples, or it can result in a thermal resistance variation, which in turn changes the electrical resistance of the detector (Vettiger et al. 2002). Thermal microcantilevers have been used in thermal imaging, data storage, and nano-topographical imaging (Kim et al. 2007).

The advantages and disadvantages of the different detection schemes are summarized in Table 2.1.
<table>
<thead>
<tr>
<th>Detection scheme</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Optical          | • No need for electrical connection to microcantilever.  
• Ease of fabrication with capability of making ultra thin beams.  
• Linear response.  
• Highly sensitive.  
• Reliability; highly commercialized. | • Needs external optical detection unit.  
• Needs calibration upon change of medium (e.g. liquid, gas).  
• Unsuitable for high opacity, or high turbidity media.  
• Parallel scanning of an array of microcantilever is challenging.  
• Limited to bandwidth of PSD. |
| Piezoresistive   | • Implementation of detection mechanism inside microcantilever CMOS integration.  
• Can be used in any medium.  
• Large dynamic range.  
• Reliability; well commercialized.  
• Implementation in large arrays. | • Needs a piezoresistive layer to be implemented over structural layer.  
• Thermal power dissipation in piezoresistors and thermal drift.  
• Generated heat can cause erratic beam deflection.  
• Associated noise of resistors. |
| Piezoelectric    | • Self-generating.  
• Self-sensing. | • DC leakage current makes static applications challenging.  
• Small output signal. |
| Electrostatic    | • CMOS compatible.  
• Large dynamic range. | • Needs calibration upon change of dielectric constant of medium.  
• Unsuitable in electrically conductive media.  
• Variation of dielectric constant of different parts of scanned sample should be taken into account.  
• Non-linear response. |
2.5 Piezoresistive effect in silicon and MEMS microcantilever relationship

Piezoresistive effect describes the changing electrical resistance of a material due to applied mechanical stress. The effect causes a change in resistance value. This effect has been used for semiconductor based sensor such as germanium, silicon and polycrystalline silicon. Silicon offers remarkable piezoresistive effect and it has controllability for electronic circuits (Streetman and Banerjee 2006). Semiconductor silicon is the most common material in the MEMS field. Naturally, the electrical and mechanical properties of silicon are of great interest which differs from conductor (e.g. metals) and insulator (e.g. rubbers). It has a conductivity which lies between a perfect insulator and a perfect conductor. Liu (2006) states that the resistivity of semiconductor changes as a function of deformed mechanism. Therefore, silicon is a true piezoresistor. Liu (2006) also mentioned that piezoresistive effect refers to piezoresistor or resistor which changes during applied force. The change in piezoresistance is linearly related to the applied stress and strain according to (Bhatti et al. 2007) and (Liu 2006). These related expressions are shown in equation (2.3) and (2.4) below (Chu et al. 2006):

\[
\frac{\Delta R}{R} = \pi \sigma_l + \pi \sigma_t = \pi (\sigma_l + \sigma_t) \quad (2.3)
\]

\[
\frac{\Delta R}{R} = G \frac{\Delta t}{l} \quad (2.4)
\]
where $\frac{\Delta R}{R}$ is resistance change, $\sigma_l$ and $\sigma_t$ are the longitudinal and transverse stress components, $\pi$ is the piezoresistive coefficient, $G$ is gauge factor of piezoresistor ($G = 121$, (Eklund and Shkel 2007), $\Delta l$ is strain component. From equation 2.3, the resistance change increases by maximizing the differential stress ($\sigma_l - \sigma_t$). Resistance change, $\frac{\Delta R}{R}$ is often read using the Wheatstone bridge circuit configuration (Liu 2006). Wheatstone bridge consists of four resistors connected in a loop as shown in Figure 2.5. An input voltage, $V_{in}$ is applied across two junctions that are separated by two resistors. Voltage drop across the other two junctions forms the output (Hsu 2002). By locating the piezoresistive on the surface of a microcantilever beam structure, a piezoresistive response can be correlated to the stress occurred as the MEMS cantilever deflect. Stress that occurs will be converted into voltage output, $V_{out}$.

\[ Figure 2.5 \quad \text{Wheatstone bridge circuit} \]

Figure 2.5 shows the wheatstone bridge circuit configuration; circuit consists of four piezoresistors in a loop (Chu et al. 2006).

2.6 Piezoresistive MEMS Microcantilever Design

In order to suit intended applications of MEMS microcantilever, there are many available designs for MEMS microcantilever. These designs vary in terms shape and
geometrical parameters of the MEMS microcantilever such as length, width, and thickness. In some published literatures, different designs at certain section of the MEMS microcantilever are created where the shape is different from common MEMS microcantilever design. Figure 2.6 shows the most common designs of piezoresistive MEMS microcantilever available from literature studies such as rectangular shape, paddle pad and V-shape.

Figure 2.6 Type of shape for piezoresistive MEMS microcantilever, (a) Rectangle shape, (b) Paddle shape, (c) V-shape


Table 2.2 summarizes MEMS microcantilever designs shape, additional design, type of detection and also its applications. From the Table 2.2, it shows that a rectangular MEMS microcantilever is a widely used for biosensor applications. In this research, rectangular type MEMS microcantilever is chosen.
Table 2.2 MEMS microcantilever designs shape

<table>
<thead>
<tr>
<th>References</th>
<th>Design/Shape</th>
<th>Additional design</th>
<th>Type of detection</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Gel and Shimoyama 2004)</td>
<td>Rectangular</td>
<td>Protection head</td>
<td>Piezoresistive</td>
<td>Force sensing</td>
</tr>
<tr>
<td>(Loui et al. 2008)</td>
<td>Square &amp; trapezoidal</td>
<td>-</td>
<td>Piezoresistive</td>
<td>Chemical sensor</td>
</tr>
<tr>
<td>(Park et al. 2007)</td>
<td>Paddle type</td>
<td>-</td>
<td>Piezoresistive</td>
<td>Acceleration sensor</td>
</tr>
<tr>
<td>(Peiner et al. 2008)</td>
<td>Rectangular</td>
<td>-</td>
<td>Piezoresistive</td>
<td>Force sensor</td>
</tr>
<tr>
<td>(Sone et al. 2004)</td>
<td>v-type</td>
<td>Triangle shape</td>
<td>Piezoresistive</td>
<td>Biosensor</td>
</tr>
<tr>
<td>(Yoo et al. 2007)</td>
<td>Rectangular type</td>
<td>-</td>
<td>Piezoresistive and optical</td>
<td>Biosensor</td>
</tr>
</tbody>
</table>
CHAPTER III

RESEARCH METHODOLOGY

3.1 Design and Modeling of Piezoresistive MEMS Microcantilever

Rectangular type microcantilever is chosen for this research. The selection of rectangular designs base on past literature, then simulate to determine the stress characteristics.

Two types piezoresistive MEMS microcantilevers were modeled using computer aided design CATIA. The first type is double layer piezoresistive microcantilever (Figure 3.1 (a)). The double layer piezoresistive microcantilever involves the embedding of a piezoresistive material near the top surface of the microcantilever to record the stress change occurring at the surface of the microcantilever. As the microcantilever deflects, it undergoes a stress change that will apply strain to the piezoresistor, thereby causing a change in resistance that can be measured by electronic means. Disadvantage with the method is that a piezoresistor has to be embedded in the microcantilever. It uses two type of material which is p-doped silicon and silicon dioxide. The fabrication of such a microcantilever with a composite structure is more complicated. Therefore, a single layer design was introduced as an alternative to the double layer piezoresistive microcantilever where both piezoresistor and microcantilever were combined into a single layer using p-doped silicon (Figure 3.1 (b)). This, in turn, will simplify the fabrication process. For designing and modeling both types of microcantilever, CATIA software was chosen. This is due to its properties that can be integrated with ANSYS.
3.2 Finite Element Analysis using ANSYS

The piezoresistive MEMS microcantilever model analysis is carried out by using ANSYS version 14.0. The analysis is carried out to investigate and understand the stress and deflection of the piezoresistive MEMS microcantilever when external force is applied. First, the model files were imported from CATIA into ANSYS software so that there will be no error during analysis. The model of interest must be prepared in a manner where the solver will understand.

Then pre-processing is the second step and it is an important step when using ANSYS prior to any solution execution. Some pre-processing procedures involved during analysis of piezoresistive MEMS microcantilever models will be discussed in the next section.

3.2.1 Material Properties

For this analysis, material properties used throughout both models are called linear properties. Linear properties are chosen because the analysis with these properties
requires only a single iteration and not temperature dependent. The material is also defined as isotropic which means the same mechanical properties are applied in all directions. Silicon and silicon oxide properties are applied for ANSYS models. Table 3.1 lists the material properties of silicon used for piezoresistive MEMS microcantilever models.

Table 3.1 Material properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
</tr>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>1.30191 x 10^5</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.278</td>
</tr>
<tr>
<td>Piezoresistive Coefficient (MPa^-1)</td>
<td>₁₁: 6.6 x 10^-5</td>
</tr>
<tr>
<td></td>
<td>₁₂: -1.10 x 10^-5</td>
</tr>
<tr>
<td></td>
<td>₄₄: 1.381 x 10^-3</td>
</tr>
</tbody>
</table>

Source: Chivukula et al. 2006.

3.2.2 Meshing

The piezoresistive MEMS microcantilever models are meshed by free meshing. ANSYS provide automesh feature that help to save time and to avoid crash during analysis. Both single and double piezoresistive microcantilever used this feature. Figure 3.2 illustrates free meshed for both piezoresistive MEMS microcantilever models.

Figure 3.2 Element plot after meshing for piezoresistive MEMS microcantilever: a) Double layer, b) Single layer
3.2.3 Boundary Conditions

Before solutions can be initiated, constraints or boundary conditions need to be imposed. Boundary conditions are a selected area or body that will be fixed with no displacement in any degree of freedom (DOF) or any direction. When load is applied, the selected boundary condition area will remain constant which mean no deflection or movement occurred. In ANSYS, boundary conditions or constraints are usually referred to as loads where the scope includes setting of boundary conditions (constraints, supports or boundary field specification) as well as other externally and internally applied loads. Most of these loads can be applied on the solid model (keypoints, lines, areas, and volume) or the finite element models (nodes and elements).

For this research, both models are constrained (zero DOF) in x, y, and z direction on the area as shown in Figure 3.3. Only the MEMS microcantilever structure will reflect to the applied load.

![Figure 3.3 Selected area for boundary condition or constraint](image)

3.2.4 Applied Force and Contact Area

In order to make the piezoresistive MEMS microcantilever deflect, external force should be applied at the free end area. From the literature, the external force value
depends on the limitation of the microcantilever itself which means the smaller the microcantilever geometry the lower is the force it can detect or be applied. For this research, force applied represents biological mass that is commonly applied for biosensor/ microcantilever application (Yu et al. 2007; Vashist. 2007). Force 2 µN, 4 µN, 6 µN, 8 µN and 10 µN has been chosen for this analysis. By using several value of force to test the microcantilever, the performance of the microcantilever can be determined more precise.

The force is applied on the area at the microcantilever free end. Figure 3.4 illustrates the area where the force is applied on the piezoresistive MEMS microcantilever models for ANSYS analysis.

![Figure 3.4 Pressure applied area for ANSYS analysis](image)

3.2.5 Analysis on Piezoresistive MEMS Microcantilever

Analysis the result is the most important part in simulation. ANSYS provides solution to analyze displacement and von Mises stress. There are 30 models that have been simulated and analyze. Each of the models has been given different load. The performance for all the designs and models are discussed in chapter four. Displacement and von Mises stress analysis for both double and single layer piezoresistive microcantilever are shown in Figure 3.5 and Figure 3.6, respectively.
Figure 3.5 Displacement analysis a) Double layer piezoresistive microcantilever b) Single layer piezoresistive microcantilever

Figure 3.6 Von Mises stress analysis a) Double layer piezoresistive microcantilever b) Single layer piezoresistive microcantilever
CHAPTER IV

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, simulation results are discussed. Results are divided into three parts; double layer piezoresistive microcantilever, single layer piezoresistive microcantilever and comparison between single and double layer piezoresistive microcantilevers.

4.2 Double Layer Piezoresistive Microcantilever

In order to analyze performances of double layer piezoresistive microcantilevers, the characterizations on critical geometrical features was performed. This involved effect on width, length and thickness by loading the microcantilever with different forces. To analyze those effects, forces are applied at the free end of microcantilevers. 2 µN, 4 µN, 6 µN, 8 µN and 10 µN are the forces that had been given as a load for microcantilevers.

4.2.1 Effect of Width on Microcantilever Performance

To analyze the effect of width on double layer piezoresistive microcantilevers, length and thickness were fixed to 150 µm and 2 µm, respectively. However, only the width was varied. The geometrical of widths were increased start from 50 µm, 100 µm, 150 µm, 200 µm and 150 µm. While, finite element analysis results on length are shown in Figure 4.1 and Figure 4.2.