MEMS Pressure Sensor For Gait Analysis

by

Nurismaliza Binti Jurami
(1632521950)

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LIST OF ABBREVIATIONS

3D	Three Dimension
AlN	Aluminium Nitride
BaTiO3	Barium Titanate
CdS	Cadmium Sulfide
EMG	Electromyography
FSR	Force Sensitive Resistor
GaN	Galium Nitride
GUI	Graphical User Interface
IC	Integrated circuit
InN	Indium Nitride
MEMS	Micro Electro-Mechanical System
PbTiO3	Lead Titanate
PbZrO3	Perovskite Lead Zirconate
PDE	Partial Difference Equation
PMNPT	Lead Magnesium Niobate-Lead Titanate
PZT	Lead Zirconate Titanate
PZT-5A	Lead Zirconate Titanate
SiC-6H	Silicon Carbide- 6 Hexagonal
ZnO	Zinc Oxide
ZnS	Zinc Sulphide

LIST OF SYMBOLS

\$	Dollar
%	Percent
Å	Angstrom
°C	Celcius
cm	Centimeter
E	Young Modulus
Hz	Hertz
k	Kilo
k	Thousand
kg	Kilogram
M	Mega
mm	Milimeter
Pa	Pascal
Si	Silicon
um	Micrometer
V	Volt

Pengesan Tekanan MEMS Untuk Analisa Gaya Berjalan

ABSTRAK

Penderia tekanan memainkan peranan penting dalam pelbagai aplikasi terutamanya untuk analisa gaya berjalan. Fokus kajian ini adalah untuk mereka satu penderia tekanan untuk digunakan ke atas lapik dalam kasut. Kesan pizoelektrik digunakan bagi mengkaji prestasi sesuatu penderia tekanan. Penderia ini mempunyai unsur transduksi yang terhasil daripada bahan piezoelektrik. Pizoelektrik diterangkan sebagai sesuatu yang menghasilkan cas elektrik apabila dikenakan dengan tekanan mekanikal. Dalam kajian ini, COMSOL Multi-Fizik 5.1 digunakan untuk melakukan rekaan dan simulasi bagi penderia tekanan pizoelektrik. Dua bahan pizoelektrik utama iaitu “PZT” dan zink oksida, “ZnO” digunakan sebagai satu lapisan permukaan pada gegendang bulat penderia tekanan. Lima jenis tekanan yang berlainan iaitu 10kPa, 1MPa, 2MPa, 3MPa dan 4MPa digunakan di atas permukaan penderia tekanan dan dibandingkan dengan tiga jenis ketebalan yang berbeza. Prestasi penderia dipelajari berdasakan tekanan, sesaran dan keupayaan elektrik yang terhasil pada rekaan penderia tekanan. Satu keputusan keseluruhan fokus pada ketebalan maksimum 60um dengan dikenakan tekanan sebanyak 40MPa. Keputusan menunjukkan bahawa jumlah sesaran meningkat apabila tekanan tinggi diberikan, tetapi ketebalan bahan pizoelektrik akan menurun. Jumlah sesaran permukaan diperolehi untuk “PZT” dan “ZnO” ialah 1.79×10^{-3}μm dan 1.09×10^{-3}μm Kemudian, keputusan untuk tekanan Von Mises menunjukkan apabila tekanan yang diberikan tinggi, tekanan Von Mises akan meningkat tetapi parameter ketebalan mesti direndahkan. “ZnO” menghasilkan satu kesan yang lebih besar atau tekanan yang lebih tinggi berbanding dengan “PZT” apabila “ZnO” menghasilkan 5.24MPa berbanding “PZT” yang hanya menghasilkan 4.11MPa. Cas elektrik diantara bahan menunjukkan bahawa voltan keluaran meningkat apabila tekanan juga meningkat tetapi menurun dari segi ketebalan. Hasil keupayaan elektrik yang lebih tinggi ialah 15.9848V datang dari bahan “ZnO” manakala “PZT” hanya menghasilkan 2.7659V dengan tekanan yang sama digunakan. Sebagai kesimpulan, kedua-dua bahan boleh digunakan dalam reka bentuk ini kerana ia mengikuti penentuan-penentuan penderia tekanan.

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MEMS Pressure Sensor For Gait Analysis

ABSTRACT

Pressure sensor plays an important role in many applications, especially in gait analysis. The focus of this dissertation is to design a pressure sensor to be applied onto the shoe insole. The piezoelectric effect is used to study the performance of the pressure sensor. This sensor is characterized by having a transduction element made of a piezoelectric material. Piezoelectric can be explained as one that produces an electric charge when a mechanical stress is applied. In this study, COMSOL Multiphysics 5.1 is used to design and simulate the piezoelectric pressure sensor. Two main piezoelectric materials, Lead Zirconate Titanate, PZT and Zinc Oxide, ZnO used as a surface layer of the circular diaphragm pressure sensor. Five different pressures of 10kPa, 1MPa, 2MPa, 3Mpa and 4MPa are applied onto the surface of the pressure sensor and compared with three different thickness parameters. The performance of the sensor studied based on the Von Mises stress, surface total displacement and electric potential produce on the pressure sensor design. An overall results focus on the maximum thickness of 60um with applied pressure of 4MPa. The result shows that surface total displacement will be high when the pressure applied were increased, but decreased in thickness of piezoelectric material. The surface total displacement obtained for PZT and ZnO are 1.79×10^{-3}μm and 1.09×10^{-3}μm. Then, the Von Mises stress shows that when the applied pressure is increased, the stress produces also increased but the thickness parameter must be decreased. ZnO produces a greater effect or higher stress compared to PZT as ZnO produces 5.24MPa compared to PZT that only produce 4.11MPa. An electric potential between the materials shows that output voltage increased when the pressure increased with decreasing of the thickness. The higher electric potential produce is 15.9848V come from the material ZnO while PZT only produce 2.7659V with the same pressure applied. As conclusion, both materials can be applied in this design as it followed the pressure sensor specifications.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this revolutionary world nowadays, many technologies based on sensor application become more popular and becoming of interest by many researchers. Various types of sensor being used either in medical, electronic application, in safety area and etc. This research shows the design of a sensor for pressure measurement of gait analysis based on MEMS (Micro Electro-Mechanical System) technologies to observe the effectiveness to prevent injuries for an athlete. To prevent any injuries occur to an athlete that limited their abilities to stand, run, jump, kick or change directions, this sensor was designed in order to detect any possible movement of their feet that can lead to severe injuries due to stiff and weak muscles (Chinn & Hertel, 2010). There are many technologies nowadays and MEMS has become one of the enabling technologies as many demands have come to peak for new and revolutionary technologies (Acharya). The capability to reduce the device size, enable to integrate control circuitry and lowering the power consumption shows the important of these technologies (Wahab & Bakar). MEMS promises drive to the next technological revolution (Kutiš et al, 2012) are sort of microsystem integrating a variation of microfabrication technologies consist of a silicon micromachining, precision machining for manufacture and integration of various devices on micrometer range (Li et al., 2010). In present years, the research on micro electromechanical system (MEMS) has attracted many researchers since the past two decades (K. Ashish, Periasamy & Pant, 2014) and has demonstrated important opportunities especially in microsensors and actuators based on numerous physical mechanisms consists of piezoresistive, capacitive, piezoelectric, magnetic, and electrostatic. MEMS devices and technology consist of two main products that are microsensor and microactuator (Mohammadi & Mohammadi, 2013). Microsensor generally focuses on the pressure, temperature and flow while microactuator is a device that produce mechanical motion, force and torque (Li et al., 2010). In this research, microsensor is chosen as the focus is to design the pressure sensor. Microsensor usually transforms information of pressure from detected object into electrical signal. MEMS sensors or microsensors can detect the mechanical structure that deform or respond to some physical or chemical variable by using the integrated microfabrication technique by running a multiple physical detection methods including electronic and optical effects. These sensors are designed with amplitude proportional to the magnitude of the stimulus sense and must be sensitive to modification in resistance (piezoresistivity), changes in capacitance and also in charge (piezoelectricity). Microactuators can be classified as a positioners, valves, pumps, actuators, or microactuators that mostly based on electrostatic, piezoelectric, deformable mirrors, switches, shutters, and resonators. There are three basic MEMS structure which are diaphragm-based, a microbridge-based or a cantilever-based (Bhat & Nayak, 2013). MEMS technology provides the advantage of small size, light weight, high performance ("Simulation Of Different MEMS Pressure," 2014), easy to mass-produce, low cost (Khoshnoud & Silva, 2012), smarter function abilities and reliable (Mems, 2014).

The general definition of sensor define as the device that can detect the value or the changing in value of some physical quantity then convert them to an electrical signal used for an indicating or recording instruments (Mekid & Zhu). Sensor function as the devices that measure information from the surrounding environment and it will produce an electrical output signal due to the response of parameters measured ("Simulation Of Different MEMS Pressure," 2014). For this research, the main focus is to study the MEMS pressure sensor for gait analysis. Pressure sensor widely used in many areas either in biomedical, defense, aerospace, automobile, agriculture, industry (Yu, Qin, & Nie, 2012) or domestic applications. Due to this many applications, rapid progress has been made in micromachined pressure sensors and microsystems using these type of sensor start from metal strain gauges and move with silicon based pressure sensors with flat diaphragms (Bhat & Nayak, 2013). The basic principle of pressure sensor explained based on the bending of the membrane that caused by the pressure either in liquid or gas (Smartec, 2011). In order to measure the physical forces that exerted by our limbs, normally the pressure sensors are used in the body sensor network. Sensors such as a force sensitive resistor (FSR) and the piezoelectric sensors are the most popular sensors as both of them are made of rigid semiconductor technology. MEMS pressure sensor is usually used to measure the pressure difference that produced across a silicon diaphragm. Pressure sensors based on MEMS technique have the capacity to measure pressure with high accuracy and linearity up to high pressure levels (Morère et al., 2016). It is designed to operate in linear range and become the most widely used devices (" Simulation Of Different MEMS Pressure," 2014). There are many types of MEMS pressure sensor that can be studied such as capacitive sensor, resonance pressure sensor, optical pressure sensor, piezoresistive sensor and so on (Yu et al., 2012). Sensor with improved sensing technique in spatial resolution, accuracy and sensitivity can be implemented to the variety of research problems such as problem in footwear design or in injury prevention (Morère et al., 2016).

Piezoelectric MEMS offers many advantages compared to other MEMS technologies. A piezoelectric pressure sensor is piezoelectric elements that consist of bidirectional transducers capable of converting stress into an electric potential and vice versa. They consist of metalized quartz or ceramic materials. The dynamic effect happens when the input is changing, then output will be produced. This means that these sensors can be used only for varying pressures. Due to the effect of the pressure, piezoelectric sensor will produce an electric potential (voltage). It consists of a high impedance and therefore susceptible to extra electrical interference that leads to an undesirable signal-to-noise ratio. Among other sensors, piezoelectric sensors are preferable from the viewpoint of power consumption, simple structure, and easy integration into microsystems. The word "piezo" come from the Greek that means to press (*Fundamentals of Piezoelectricity*, 2013). The ability of certain material to generate an electric charge in response to an applied mechanical stress defined the meaning of piezoelectric effect. There are many materials that can be declared as piezoelectric materials that function as sensing element. The most popular material is quartz crystal that consists of two types that are natural such as ammonium dihydrogen phosphate, lithium sulfate and man-made crystal like aluminium nitride (AlN). Artificial ceramic such lead zirconate titanate (PZT), barium titanate or lithium niobate also have the same properties as quartz crystal (Popovici, Constantinescu, & Maricaru, 1989) which possess a strong piezoelectric properties due to its crystalline structure where an electric polarization can be observed when pressure is applied (Ledoux, 2011). Those materials are placed on silicon diaphragm, as silicon not shows any piezoelectric effect (Bhat & Nayak, 2013). For this research, two materials were used in order to analyse the pressure sensor which are PZT and zinc oxide (ZnO). These materials have their different characteristic and will be explained in more detail in the next chapter.

On the other hand, the function of this sensor is to apply for gait application. Gait can be explained as a style of walking and defined as the systematic study of human locomotion, also the study on the pattern for lower limb movement (Wahab & Bakar). Gait analyses mostly characterize the human locomotion based on the measurement, description, and assessment of quantities. This analysis has been occupied in sports, rehabilitation and health diagnostics. Example shows on the technique in the sport activities where it is able to detect the problem of an athlete performance as they can solve that problems (Weijun Tao, Tao Liu, 2012). Gait analysis shows precisely the movement of your body. The unique movement pattern of our body can be analysed including standing still that mostly trained from daily habits and lifestyle, such as body's mobility, stability, flexibility and strength.

1.2 Problem Statement

In this research, the focus is on the method that can be used to design pressure sensor for an athlete foot. The sensor is to be placed in the insole of an athlete shoes to determine their performance or can be used in order to prevent injuries during competition and daily routine training. The sensors are made from various kind of materials by using different technologies that are designed with multiples sizes and can be represent depending on many measurement techniques such as piezoresistive, capacitive or piezoelectric (Wahab & Bakar). The thickness of the overall pressure sensor diaphragm must be in between 0-3mm, therefore the analysis of acceptable thickness and the most suitable piezoelectric material of MEMS pressure sensor is done so that the maximum voltage across the sensor can be produced. There are few sensors that contain large size of sensors that may significantly affect the pressure performance. Besides that, there are few materials used in the sensor development that create many issues limit due such as hysteresis, accuracy and creep mentioned by (Wahab, 2009). As the research focusing on the maximum weight of human that effect the pressure sensor performance, the material of piezoelectric pressure sensor must be able to withstand the maximum pressure of weight. The most common reason commercial sensor being eliminated is due to the requirement that the sensors must be small and thin in order to fit in the insole. Besides that, due to permanent deformation, this sensor mostly can withstand overloads of only 100 percent before failure (Wertsch, Webster, & Willis, 1992). The current sensor shows various performance limitations as they are made of sheets of polymer or elastomer such as from Vista Medical, Tekscan and Novel. The repeatability, hysteresis, accuracy, creep and non-linearity are some of the issues that mostly related to the output sensors. Other than that, the limited pressure range and large sensor size show the weakness of this sensor. (Wahab, Zayegh, & Veljanovski, 2008) mentioned that the sensor should have better linearity, hysteresis must be low, the temperature sensitivity must operate between 20℃ to 37℃. Then, the sensor must be flexible, thin, can withstand pressure up to 200kPa, affordable price and easy to use.

1.3 Objective

The objectives of this research are:

- To design the MEMS pressure sensor by using COMSOL software.
- To study the effect of pressure sensor by using two different materials, PZT and ZnO with different thickness sizes of piezoelectric material.
- To identify the minimum and maximum pressure for gait application.

1.4 Scope of Project

Scopes of this research are:

- To design the MEMS pressure sensor by considering the effect of different piezoelectric material used.
- To compare the effect of the thickness range from 30µm to 60µm on two main piezoelectric materials.
- To compare the effect of different values of pressure of 10kPa, 1MPa, 2MPa, 3MPa and 4MPa applied to the piezoelectric materials.
- To analyse the relationship between pressure and electric potential.

1.5 Project Outline

This report is separated into several chapters covering different aspects of the research. First chapter consists of an introduction about the general knowledge of the MEMS piezoelectric pressure sensor. Chapter two focusing on the literature review that related to the research on pressure sensor consist of comparison in method, material, diaphragm design and current sensor that already in the market. In this part also explained the fundamental theory of piezoelectric. The methodologies of this research were explained in the chapter three. This chapter explained in details the steps taken to design, to simulate and analyse the MEMS pressure sensor. The result and discussion well explained in chapter four. Lastly, chapter five explained the conclusion and future work of this research report.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the basic theory of piezoelectric effect is explained in detail which includes the working principle, the general piezoelectric material review and the basic mathematical equation. Then, the next part is the review on the comparison of pressure sensor for several factors such as type, material and design structure comparison also the comparison on the current sensor available.

2.2 Fundamental of Piezoelectricity

The subsections below explain in detail the basic theory of piezoelectric consists of the history of the piezoelectricity, the types of piezoelectric effect, the example of piezoelectric material also the advantage of these materials. Then, the general equations of piezoelectric are also explained.

2.2.1 A Theory of Piezoelectricity

Piezoelectricity phenomenon first discovered by Pierre and Jacques Curie in 1880. Both of them conduct a variety of research to explore the range of the crystal. Based on their observations, it can be concluded that some of the crystals show a positive and negative charge when it is compressed in certain directions on some area of the surface

(Direct & Effect). Piezoelectricity comes due to electricity caused by the mechanical pressure and material that exists in which there is called as piezoelectric. In certain material, there are cross-coupling relationship between mechanical and electrical energy that can uses as an actuator and sensor are come from piezoelectricity (Kon, Oldham, & Horowitz, 2007). This effect then called as a piezo-effect. The original word of ‘piezo’ come from Greek which means ‘to press’. Based on this, piezoelectricity can be logically explained as electricity generated from the pressure. One of the important fundamental for the piezoelectric measurement is named as piezoelectric effects (*Piezoelectric Properties*, 2010). The piezoelectric effect exists as there is stress-induced charge polarization in a crystal due to the lacks a centre of inversion. (“Stress, Strain, Piezoresistivity and Piezoelectricity,” 2010).

Piezoelectric effect can be divided into two; direct piezo-effect and inverse piezo-effect (Al., 2014). A piezoelectric can be defined as material that develops a dielectric displacement due to an applied stress and develop a strain due to an electric field (Mohammadi & Mohammadi, 2013). This piezoelectric material when applied with electric field will cause a change in their dimensions and it develops a charge on sample surface when is exposed to an applied stress (Bassiri-gharb, 2008). From the upper and lower surface of the piezoelectric materials, the voltage is detected when an electric field is generated. The electric potential will lost when the stress is removed and this is called direct piezoelectric effect. The reverse piezoelectric effect explains as an internal generation of mechanical strain of the piezoelectric material resulting from an applied electrical field. Piezoelectric effect also can be explained as a production of electricity when certain material being applied to mechanical stress. It also shows the converse effects that exist when stress is produced in a crystal due to an applied of potential difference piezoelectricity (Madhuranath, Praharsha, & Rao, 2013).

Piezoelectric material can be divided into two; natural or man-made. The natural piezoelectric material consists of crystal material such as quartz, Rochelle salt, Topaz, Tourmaline and few organic substances like silk, wood and etc. Piezoelectric material such as quartz analog, ceramics, polymers and composite can be categorized into man-made material (Al., 2014). Piezoelectric material was found in wurtzite family such as ZnO, Galium Nitirde (GaN), Indium Nitride (InN) and Cadmium Sulfide (CdS) (Y. Zhang, Liu, & Wang, 2011). One of the advantages of piezoelectric material as it can directly use to recharge batteries; make it become a good source of energy harvesting and can produce a power to other electronic component such as sensors (Butt et al., 2016). This material manage to withstand large strain magnitude and able to provide a large quantities of mechanical energy that can be converted into electrical energy (Saadon & Wahab, 2015; Saadon, 2013).

2.2.2 Mechanical Description of Piezoelectric

Piezoelectric equation can be related to the mechanical and electric variable. Generally, piezoelectric equations consist of four forms which are electric field (E), charge density (D), mechanical stress (T) or strain (S) (Don Berlincourt, 1971). An internal electric field will produce when the piezoelectric material being strained. Reactions between electrical field and mechanical behaviour can be in either direction means that an electric field in one direction can lead to a mechanical reaction in any direction depending on the material (Ledoux et al., 2011). An expression below shows the relationship between mechanical and electrical behaviours of the piezoelectric material. Polarization of piezoelectric material can be characterized by using several coefficients and relationships. General equation can be written as below:

$$D = dT + \varepsilon^T E \tag{2.1}$$

$$S = s^E T + dE \tag{2.2}$$

where;

D: Electric charge density (Cm^{-2})

T: Mechanical stress (N/m^2)

E: Electric field (Vm^{-1})

S: Mechanical strain (m/m)

d: Piezoelectric charge coefficient (CN^{-1})

ε^T: Permittivity (Fm^{-1})

s^E: Compliance or elasticity coefficients (Pa^{-1})

The piezoelectric constant in the equation consists of piezoelectric charge coefficient, *d* define as the ratio of the mechanical energy assembled in response to an electrical output or vice versa. Then, the permittivity, ε^T is explained as the dielectric displacement per unit electric field and elasticity coefficients, s^E is the strain that produced in a piezoelectric material per unit applied stress. As can be seen, the first equation shows that when an electric field applied to the material, it will convert into mechanical stress while the second equation explained that when mechanical strain applied to the material, it will convert into electric field (Ledoux et al., 2011).

2.3 Type of MEMS Pressure Sensor

In MEMS technologies, one of the important sensors is pressure sensor. There are many various physical properties of pressure sensor such as piezoresistive, piezoelectric, capacitive sensor, magnetic and electro-static sensor (K. Ashish, Periasamy & Pant, 2014). Three groups of micro pressure sensor such as capacitive, piezoresistive and piezoelectric are commonly used. Due to the simple structure, good power consumption and easy integration into microsystems, piezoelectric sensor become most preferable methods (M. Mahboubeh & Abdolghaffar, 2016). Different types of pressure sensor are defined from different method of design that can be used to perform the same application. The main focus of this part is to compare different sensor used for foot analysis. The research studied by (Jagos & Oberzaucher, 2008) explained the development of the wearable measurement system in human gait in order to identify their characteristic. For this research, a sensor network consists of a force sensitive resistor (FSR), accelerometer and gyroscopes is designed to measure the parameter of human ambulation. Another review highlighted by (Wahab et al., 2008) studied on the sensitivity optimization of foot plantar pressure microsensor; the sensor design based on piezoresistive sensing technique and the wheatstone bridge were used in this sensing circuit. This piezoresistor dimension and placement are highly needed in order to identify and determine the best value of the sensor. This will lead to an improvement to increase the sensor sensitivity. Next study by (A.H.A. Razak, A. Zayegh, 2012) mentioned that MEMS pressure sensor was designed with a few characteristics include the smaller in size, can withstand high pressure range and excellent linearity at both low and high pressure sensing. Then a wireless integrated circuit (IC) design was implemented together with MEMS sensor in the insole of the shoes. Experiment on the