MEMS Piezoresistive Accelerometer Sensor For Gait Analysis

by

Siti Nurdiyana Binti Abd. Rashid

(1632521951)

A dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science (Microelectronic Systems Design Engineering)

School of Microelectronic Engineering

UNIVERSITI MALAYSIA PERLIS

2016

DISSERTATION DECLARATION FORM

UNIVERSITI MALAYSIA PERLIS

DECLARATION OF DISSERTATION

Author's full name	:	SITI NURDIYANA BINTI ABD.RASHID
Date of birth	:	07 DECEMBER 1992
Title	:	MEMS PIEZORESISTIVE ACCELEROMETER SENSOR FOR GAIT ANALYSIS
Academic Session	:	2016/2017

I hereby declare that this dissertation becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This dissertation is classified as:

☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*

☐ **RESTRICTED** (Contains restricted information as specified by the organization where research was done)*

☐ **OPEN ACCESS** I agree that my dissertation is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this dissertation in whole or in part for the purpose of research or academic exchange only (except during a period of _____ years, if so requested above).

Certified by:

______________________	______________________
SIGNATURE	**SIGNATURE OF SUPERVISOR**
______________________	PM DR YUFRIDIN WAHAB
(NEW IC NO. / PASSPORT NO.)	**NAME OF SUPERVISOR**
Date :_________________	Date : _________________

***NOTES**: If the report is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentially or restriction.

ACKNOWLEDGEMENT

In the name of ALLAH with the most gracious and most merciful, I would like to give my greatest attitude to Him for my successfulness in completing my Project Dissertation within the time provided. I would also want to express my outmost gratitude and appreciation to my understanding and kind-hearted supervisor, Associate Professor Dr. Yufridin Bin Wahab for his supervision, guidance, moral support, encouragement and assistance throughout my Project Dissertation at School of Microelectronic Engineering.

A warmest thankful also goes to Chairman of Mixed Mode Program, Dr Norhawati Bt Ahmad and all lecturers for giving me opportunity to carry out this project. Not forgotten to all my friends that have been helping me throughout my years in Universiti Malaysia Perlis (UniMAP). Last but not least, for the persons that I love the most, Mr Abd. Rashid Bin Abu Bakar and Mrs Noor'Aine Bt Md.Yusoff, thank you so much for being the most understanding and motivating parents for me in completing the project.

Hope ALLAH blesses all of you for your direct and indirect contributions towards my project. Thank you so much.

TABLE OF CONTENTS

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULTS AND DISCUSSION

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ANSYS	Analysis System
BWM	Body Worn Sensor Algorithms
CAD	Computer Aided Design
CMOS	Complementary Metal Oxide Semiconductor
FEA	Finite Elemet Analysis
FS	Full Scale
IMU	Inertia Measurement Unit
MATLAB	Matrix Laboratory
MEMS	Microelectromechanical Systems
POM	Thermoplastic Material
SSO	Self-Sustained Oscillations
VLSI	Very Large Scale Integration

LIST OF SYMBOLS

g	Acceleration due to gravity (9.81 m/s^2)
E	Young's Modulus
ρ_s	Polysilicon sheet resistance
α_{poly}	Polysilicon Temperature Coefficient of Resistance
K	Thermal conductivity
k	Spring Constant
σ_y	Yield Strength
C	Specific Heat
μ	Poisson's ratio
ε	Relative Permittivity
T_m	Melting point
ρ	Density
F	Force
a	Acceleration (m/s^2)
f_n	Natural frequency
R	Resistance

A	Cross-sectional Area
σ_L	Longitudinal Stress
σ_T	Transverse Stress
Π_L	Longitudinal Piezoresistive Coefficient
Π_T	Transverse Piezoresistive Coefficient
V_s	Supply Voltage

Penderia Meter Pecut Perintangpiezo MEMS untuk Analisis Gaya Berjalan

ABSTRAK

Sistem Mikroelektromekanikal (MEMS) berdasarkan meter pecut telah dilaporkan sebagai salah satu aplikasi yang paling popular dalam kaedah penderia. Bagi mewujudkan teknologi mikrosistem tersebut, *Finite Elemet Analysis* (FEA) telah dilaporkan sebagai kaedah yang menjimatkan masa dan kos yang efektif untuk membina sebuah model untuk penyelakuan. Kajian ini memfokuskan kepada reka bentuk, analisis dan penyelakuan penderia meter pecut perintangpiezo MEMS untuk analisis gaya berjalan bagi saiz penderia meter pecut yang berbeza. Struktur penderia meter pecut telah dipilih untuk mengurangkan sensitiviti paksi-silang dengan memilih bahan yang sesuai dan parameter reka bentuk yang sesuai. Penderia meter pecut telah didopkan dengan silikon jenis-p (resapan boron) sebagai perintangpiezo. Model pepejal telah diselakukan dengan menggunakan perisian *COMSOL Multiphysics* untuk mencari tegasan *Von Mises*, anjakan dan sensitiviti reka bentuk yang telah dicadangkan. Penderia meter pecut direka berdasarkan kesan perintangpiezo di mana nilai perintang berubah apabila mengalami tekanan mekanikal. Perubahan dalam nilai perintang kemudiannya ditukar kepada nilai voltan yang terhasil menggunakan titi *Wheatstone*. Penyelakuan menunjukkan reka bentuk 1 menghasilkan nilai maksima bagi pemalar pegas dan anjakan iaitu 91800N/m dan 9.21×10^{-8} µm. Reka bentuk 2 mempunyai nilai maksima bagi tegasan *Von mises* iaitu 0.001684MPa sementara itu reka bentuk 3 menghasilkan nilai pemalar pegas yang paling minimum, 3400N/m.

MEMS Piezoresistive Accelerometer Sensor For Gait Analysis

ABSTRACT

Microelectromechanical Systems (MEMS) based accelerometers have been reported as one of the most popular applications in sensing methods. For establishing the microsystem technology, Finite Element Analysis (FEA) has been reported as the most time and cost effective way to build a model for simulation. Present work focuses on designs, analysis and simulations of MEMS piezoresistive accelerometer sensor for gait analysis of different size. The structure of the accelerometer is chosen to reduce the cross-axis sensitivity by selecting an appropriate material and suitable design parameters. The accelerometers are doped with p-type (boron diffused) silicon as their piezoresistor. A solid model has been simulated using COMSOL Multiphysics software to find von mises stress, displacement and sensitivity of the proposed designs. The designed accelerometers are based on the piezoresistive effect where the value of a resistor changes with applied mechanical stress. The changes in the resistors values are then converted to an output voltage using a Wheatstone bridge. The simulation shows that Design 1 has maximum value of spring constant and maximum displacement which is 91800N/m and 9.21×10^{-8} µm respectively. Design 2 has maximum value of Von mises stress which is 0.001684MPa while Design 3 has the lowest value of spring constant, 3400N/m.

CHAPTER 1

INTRODUCTION

1.1 Overview

Microelectromechanical systems (MEMS) is an advancement of the VLSI technology which can produce the design of actuators, sensors, motors, etc., in the micrometer scale (Muniraj, 2011). Recently, MEMS technology has been extensively developed to create electronic devices with better performance (Teranishi et al., 2016). Accelerometers are one of the most important types of MEMS device after pressure sensors (Dash, 2015). MEMS acceleration sensors are becoming an important role because the sensing, signal conditioning and data transmission can be integrated as a single chip (Kavitha, Daniel, & Sumangala, 2016). Gao, Bourke, and Nelson (2014) mentioned that inertial sensors such as MEMS accelerometers and rate gyroscopes are widely used for many applications.

According to Yang, Zheng, Wang, McClean, and Newell (2012), there have been many research attempts to implement accelerometers in healthcare. Some of the applications implements accelerometers to control daily activities and movements between patients and controls. Lately, accelerometers have been implemented in gait pattern analysis for different purposes such as controlling physical function of the elderly, indication of fall risk, and estimation of the result of the therapy.

Boutaayamou et al. (2015) have presented a method to automatically extract basic events of walking which is heel strike (HS), toe strike (TS), heel-off (HO) and toe-off (TO) from wireless accelerometer that is applied to the right and left foot. Boutaayamou et al.

(2015) also stated that accelerometers allow continuous, unobtrusive assessment of gait features outside the laboratory experiment as they can be used at home, for long-term continuous assessment because the power requirements are low. Measuring characteristics of gait is becoming tremendously important as a robust method to determine many aspects of health (Godfrey, Din, Barry, Mathers, & Rochester, 2015).

1.2 Problem Statement

Measurement and analysis of the foot movement have been done by using accelerometer sensors and pressure sensors. For pressure sensors, there are a few limitations that make this sensor not fully fulfilling the requirement of various biomechanical applications. The limitations include the specified pressure span, physical sensor dimensions and hysteresis. To the best of author's knowledge, no purely MEMS piezoresistive accelerometer sensor has been presented to analyze the gait pattern. To provide a better solution to the needs, therefore this project is conducted to develop a sensor that is uniquely designed for accelerometer measurement using a proven MEMS technology.

1.3 Research Objectives

The main purpose of this research is to design and develop a MEMS piezoresistive accelerometer sensor for gait analysis. Specific objectives of this project are listed as below:

i. To design piezoresistive accelerometer sensor using COMSOL Multiphysics software.

ii. To make a comparison between each design that has different length of beams.

iii. To determine the maximum and minimum measurement of applied acceleration that the sensor can detect or produce.

1.4 Structure of Dissertation

Chapter 1 represents the introduction of the MEMS research that is related to this dissertation work. This includes a briefly introduction and history of MEMS and MEMS accelerometer sensor. This chapter also includes the problem statement, main objectives and scopes of work for this dissertation. Chapter 2 details the literature review of the MEMS piezoresistive accelerometer sensor for gait analysis. This chapter also describes the design of the accelerometer sensor that has been presented by other researchers. Chapter 3 presents the empirical methodology and the data sources while Chapter 4 presents the results and discussions. Important conclusions drawn from this dissertation are presented in Chapter 5. Future works for improving the performance of the designs are discussed as well. To date, this is the first time that such an approach has been reported regarding the MEMS piezoresistive accelerometer sensor for gait analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Accelerometers

Accelerometers can be defined as a mass-displacer that changes the external forces such as gravity into kinetic motion. It consists of spring force to balance the external pressure and displace its mass which lead to the acceleration (Kavitha & Madhan, 2013). In recent years, accelerometers have showed an advance in sensor technology as they have decreased in size and cheaper where they are now widely implemented into portable devices such as Smartphone, game controller and many more. Besides that, this sensor provide powerful interaction with technology for people with physical disabilities (Nolan, Burke, & Duignan, 2009). There are many applications of accelerometer that have been discovered and being implemented such as in medical, navigation, transportation, consumer electronics, structural integrity and oil exploration (Xu et al., 2016). Pull-in voltage and pull-in time have been described as another methods to sense the acceleration (Rajaraman, Hau, Rocha, French, & Makinwa, 2010).

The first MEMS based accelerometer was recommended by Roy Lance and Angell (1979) which consists of a seismic mass and flexural beam. The piezoresistive material that was located on the upper surface of the beam was used to measure out-of-plane acceleration of the seismic mass. When the accelerometer experiences acceleration, it will convert the mechanical motion into the electrical signal (Kumar & Krushnasamy, 2013)(Kumar, 2013).

2.2 Accelerometer Sensor for gait analysis

The study of lower limb gesture and the recognition of gait events and the assessment of kinetics and kinematics parameters are known as gait analysis (Wahab & Bakar, 2011a). There are many researches on gait analysis have shown that gait patterns stay abnormal in long term and commensurable to pre-operative gait (Colgan, Walsh, Bennett, Rice, & O'Brien, 2016). Accelerometer based gait data provides several advantages such as they are cheaper, lightweight, and easy to handle. There are many types of accelerometers that are being implemented in measuring gait. For instance, Turcot et al. used two triaxial accelerometers (ADXL329) combined with gyroscopes and reflective marks to measure the tibial and femoral linear accelerations. Zhou et al. used five biaxial IDEEA accelerometers located on the body to analyse gait patterns of the subjects. Tura et al. have conducted a research where subjects wore a MTx accelerometer on the thorax to measure gait symmetry and regularity of transfemoral amputees (Yang et al., 2012).

Currently, accelerometer is the most popular sensor for measuring gait pattern due to its small size and consume low energy (Nguyen, Gupta, Venkatesh, & Phung, 2015). Jerome Peter et al. has conducted a research on structural health monitoring for sensing the acceleration and wireless communication equipment for transmitting the data to seek the advantages of wireless structural monitoring systems (as cited in Kavitha et al., 2016). (Wahab et al., 2014) has carried out a research on the evolvement of a portable shoe interspersed with wireless MEMS-based system. (Godfrey et al., 2015) has proposed a low cost body worn sensor with gait algorithms (BWM) to measure gait analysis. The BWM is an instrument that involves in measuring the overall step counters and mean spatio-temporal gait characteristics. However, the variability and asymmetry results were not satisfying. (Wahab & Bakar, 2011) reported that gait analysis is an important method in determining and developing quality of life indicators.

(Watanabe & Minegishi, 2009) have conducted a research to measure gait analysis using wearable sensors. The measurement of the stride distance for each step was taken by placing gyroscope and accelerometer on the foot. Then, the accelerations and angular velocity of the foot were measured and calculated using a 3-axis accelerometer and a gyroscope. When a person starts to walk, the signals produced are measured by using two neurologically intact subjects and off-line after the measurement. (Wahab et al., 2014) has introduced a new way of human gait analysis for rehabilitation control by using LabVIEW software tool.

(Lugade, Fortune, Morrow, & Kaufman, 2014) have been carried out a study about the identification of postural orientation and movement from acceleration data. By using tri-axial accelerometers that were placed on the waist and thigh, the orientations of standing, sitting, lying down, walking, jogging and transitions between postures were identified. The results obtained shows a high validity and sensitivity greater than 85% for sitting and lying, while walking and jogging greater than 90%. (Wahab et al., 2014) has presented a new system by using Inertia Measurement Unit (IMU), ultrasonic sensors, piezoceramic sensors array, XBee wireless modules and Arduino processing unit to measure gait analysis. MEMS technology can be implemented with the integration of microelectronic circuitry to enable rehabilitation of gait analysis (Wahab, Zayegh, Begg, & Veljanovski, 2007).

2.3 MEMS Piezoresistive Accelerometers

Due to its great usefulness and effectiveness in system realization, MEMS piezoresistive accelerometer has becoming more popular. Study on piezoresistive accelerometers have started by using a simple beam-mass structure with piezoresistor thermally diffused at the maximum stress in order to be able in detecting the forces experienced by the proof mass. Over the years, this sensor emerged into a more complex multiple beam-mass systems. Piezoresistive sensors have better sensitivity but they are also sensitive to ambient temperature. The basic design of MEMS accelerometer consists of a proof mass and flexure beams that are attached to a rigid frame with piezoresistive elements located at the maximum stress of the beams (Pak, Kabir, Neudeck, & Logsdon, 1996). They are connected in the Wheatstone bridge form as the backbone of the resistive sensing. This sensors can be designed for single-axis or multi-axis inertial sensing. In this study, single-axis accelerometers with low cross-axis sensitivity were designed.

MEMS piezoresistive accelerometers started to get high demand due to its small size, cheaper, low energy consumption and provide excellent performances. They are a few ways to implement accelerometers and the mostly used techniques are capacitive and piezoresistive. Recently, the researchers prefer piezoresistive approach as the material is easy to fabricate, have simple circuitries, good reliability and low noise but the sensitivity is low compared to capacitive sensors (Mukhiya, Gopal, Pant, Khanna, & Bhattacharyya, 2014). (Kavitha, Daniel, & Sumangala, 2012) have presented the design procedure of a MEMS silicon piezoresistive single axis accelerometer which consists of proof mass and four symmetrical beams.

Piezoresistive accelerometers indicate some improvements in terms of input range, sensitivity and frequency response. However, by having 2% to 9% of cross-axis sensitivity, this device can be assumed as not so satisfying. So, this study emphasizes in creating a piezoresistive accelerometer for air-craft motion sensing application that required <1% full scale of cross-axis sensitivity (Sankar & Das, 2013).

2.4 Design of MEMS Piezoresistive Accelerometer Sensor

(Kumar & Krushnasamy, 2013) have proposed two designs of accelerometers where it consists of silicon (100) substrate as the structure, beams, seismic mass and frames. The p-type single crystal silicon (110) piezoresistors are implanted on the substrate and the seismic mass is supported using these beams. Two piezoresistors are located at the maximum stress places on each beam, one near the seismic mass and the other one near the frame. This sensor was created to sense 20g of acceleration with low off axis sensitivity and produced natural frequency of 3.656 kHz. The parameters of this sensor are described in Table 2.1. Figure 2.1 shows the configurations of the sensors.

Table 2.1: Dimensions of accelerometer structure (Kumar et al., 2013).

Parameter	Length (um)	Width (um)	Thickness (um)
Proof mass	3500	3500	300
Beams	1200	250	35
Frames	6000	200	250
Piezoresistors	100	20	2

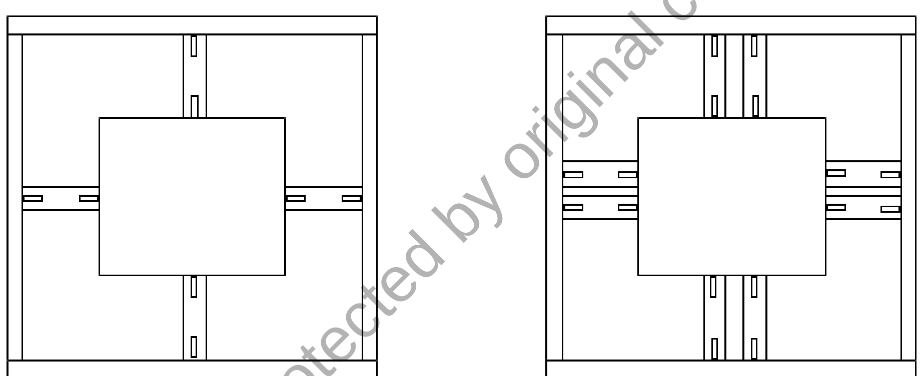

Figure 2.1: Configurations of accelerometer sensors (Kumar et al., 2013).

(Martins et al., 2014) shown that, thermoplastic material (POM) can be used in fabricating the accelerometer sensor. The sensor configuration made up of a seismic mass that are linked by four flexures. Piezoresistive material is placed at the end of each flexure as transduction. The sensitivity produced by this device was 56mV/g, with ±37g of dynamic range and 270Hz for resonance frequency. The size of the device is around $17x17x2.5mm^3$. Figure below shows the two schematic devices that have been designed by using two approaches.

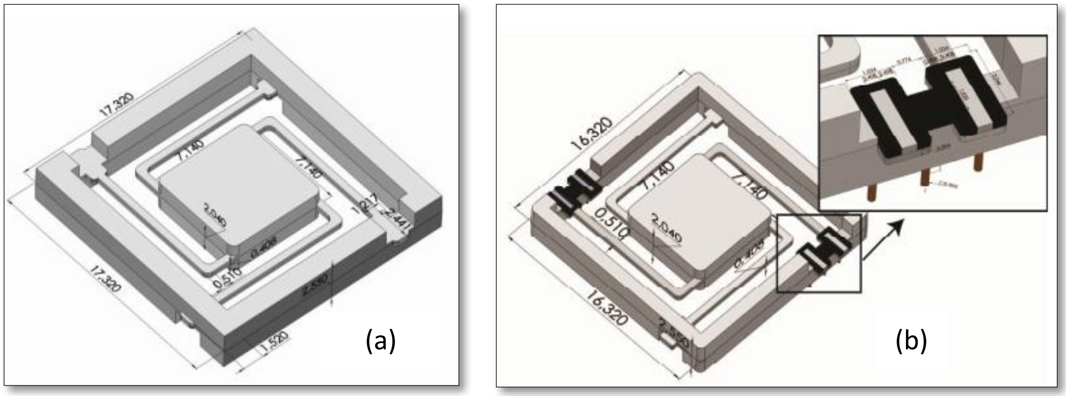

Figure 2.2 : Schematic of the two accelerometer approaches using a) commercial strain gauges and b) injection of bi-material (Martins et al., 2014).

(Khir, P. Qu, & H. Qu, 2011) have been conducted a research on cheaper, high sensitivity CMOS-MEMS piezoresistive accelerometer with a large seismic mass. The device has been fabricated by using ON Semiconductor $0.5\mu m$ CMOS technology and CMOS polysilicon thin film has been used as the piezoresistor to sense the changes of the resistance. Figure 2.3 shows the 3D model of the piezoresistive sensor and Table 2.2 summarized the sensor dimension and material properties that have been used in designing the sensor.

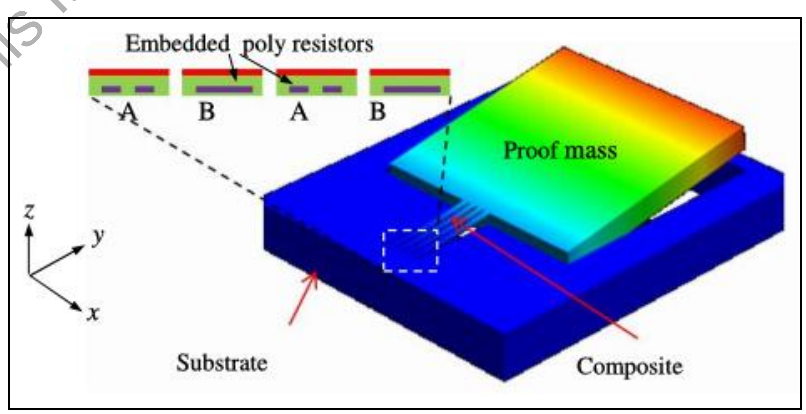

Figure 2.3: 3D model of the piezoresistive sensor (Khir et al., 2011).