Fabrication of MEMS Piezoresistive Accelerometer For Human Gait Analysis Using Laser Micromachining

by

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LIST OF ABBREVIATIONS

MEMS	Micro-Electro-Mechanical System
KOH	Potassium hydroxide
PCB	Printed circuit board
AC	Alternate Current
DC	Direct Current
TMAH	Tetra-methyl-ammonium-hyroxide
EDP	Ethylenediamine Pyrocatechol
HF	Hydroflouric acid
DI	Dionize water
SiO_2	Silicon dioxide
SPM	Spectrophotometer
LPCVD	Low-pressure-chemical-vapor-deposition
SOD	Spin-on-dopant
BSG	Borosilicate glass
CMOS	Complementary metal oxide semiconductor
VLSI	Very large scale integration
PR	Photoresist
UV	Ultra violet
BOE	Buffered oxixe ecth
PMMA	Poly-Methyl-Meth-Acrylate
MSDS	Material safety datasheet
SDS	Safety datasheet
MSE	Mean square error
I-V	Current-Voltage

AFM	Atomic force microscopy
Ra	Roughness
RVA	Reactangular variable aperture
KrF	Krypton fluoride
PVD	Physical vapour deposition
UniMAP	Universiti Malaysia Perlis
HPM	High power microscope
DIP	Dual inline package

LIST OF SYMBOLS

Hz	Hertz (frequency)
Pa	Pascal
m	Mass
k	Spring constant
ε	Strain
σ	Stress
I	Inertia
f_n	Resonant frequency
°	Degree (angle)
°C	Degree Celcius
Ra	Roughness
%	Percentage
Å	Angstrom
Ω	Ohm
J	Joule
E	Young modulus
V	Volt
G	Gravity force

Fabrikasi Penderia Pecutan Jenis "Piezoresistive" Untuk Menganalisa Corak Pergerakan Kaki Manusia Dengan Menggunakan Teknologi Laser

ABSTRAK

Analisis pengukuran gaya berjalan adalah satu kaedah mengenalpasti corak dan jenis gerakan yang melibatkan bahagian di bawah badan terutamanya di bahagian kaki. Kaedah ini digunakan secara meluas khususnya di dalam sukan, pemulihan kecederaaan dan untuk menganalisa kesihatan. Walau bagaimanapun, teknik semasa yang digunakan adalah terhad kerana melibatkan kos yang tinggi untuk menghasilkan system pengesanan yang efektif. Sebagai altenatif kepada masalah ini, penderia inersia seperti penderia pecutan jenis julur ('microcantilever') boleh digunakan dalam pembangunan sistem analisis gaya berjalan yang lebih mudah dan berkesan. Segmentasi corak setiap langkah dapat dikaji dan dikenal pasti berdasarkan penderia julur yang digunakan termasuklah corak berjalan, melompat dan berlari. Satu sistem yang lengkap yang terdiri daripada penderia jenis julur, litar 'Wheatstone bridge' dan penguat isyarat adalah dicadang untuk menganalisa isyarat pergerakan secara langsung. Kaedah semasa untuk pembentukan penderia ini adalah dengan menggunakan banyak gabungan bahan kimia jenis cecair dan gas. Hal ini akan meningkatkan proses dan masa keseluruhan yang diperlukan. Kaedah fabrikasi baru yang menggunakan pancaran laser adalah satu usaha yang baru dibangunkan untuk merealisasikan pembentukan penderia pecutan jenis julur dengan sangat mudah. Kajian ini juga membolehkan kita untuk mengoptimumkan keperluan 'mask' dan proses-proses fabrikasi dengan mengurangkan sebanyak 30% dan 25% secara keseluruhan. Aktiviti penyelidikan ini secara umum akan memberi tumpuan ke arah pembangunan penderia julur jenis 'piezoresistive' yang dibangunkan menggunakan pancaran laser. Teknik yang dikaji akan mengoptimumkan tempoh dan proses fabrikasi; serta berupaya untuk mengesan perbezaan gaya dan corak pergerakan.

Fabrication of MEMS Piezoresisitve Accelerometer for Human Gait Analysis Using Laser Micromachining

ABSTRACT

Gait analysis measurement is a method to access and identify gait events and the measurements of motion parameters involving the lower part of body. This significant method is widely used in rehabilitation, sports, as well as health diagnostic towards improving the quality of life. However, it is not a routine practice due to the costs involved in producing the mechanism and using gait labs. Alternatively, inertial sensors such as microcantilever accelerometer can be used in the development of cheap and wearable gait analysis systems. Human stride segmentation measurement based on micro-accelerometer cantilever is used in the study of the lower limb movement patterns that include walk, jump and run; and the measurements of the motion parameters. A complete system consists of a fabricated sensor, a Wheatstone bridge circuit and a signal amplifier tailored for real-time stride analysis measurement is proposed. As such, this thesis reporting the requirement of research studies, design, fabrication development and analysis of a MEMS acceleration sensor for gait movement measurement. Current conventional method requires high combination of dry and wet process in structuring sensor formations. A novel method for accelerometer sensor fabrication is by using laser micromachining in order to develop a simple way in realizing the sensor formation. Polysilicon doped boron material is uses as sensing material for sensor. Experimental work clearly reveals that a linearity measurement of acceleration is achievable using the fabricated sensors. The sensors also demonstrated good signal magnitudes for efficient diagnosing of movement given. This study allows us to optimize the requirements of hard-mask and fabrication process steps by reduction of 30% and 25% steps respectively. In the general framework, the research activities is focused towards development of piezoresistive cantilever formation by using laser micromachining for fast fabrication development for real life gait and stride segmentation measurement applications.

CHAPTER 1

RESEARCH OVERVIEW

1.1 Introduction

Gait analysis is a very important procedure in assessing and improving qualities of life indicators. This type of analysis consists in using different sciences such as anatomy, physiology, biomechanics, mathematics and physics. It is widely used in rehabilitation, sports and health diagnostics. Gait analysis is the study of lower limb movement patterns and involves the identification of gait events and the measurements of kinetics and kinematics parameters. There are several significant events that evaluated in this analysis. For instance, toe-off, landing, stance, swing, displacement, speed, acceleration, force and pressure (Bakar, 2012).

In order to understand further on the situation and condition that leads to the health hazard, many research parties around the world are seriously looking into the matter. Recently, it is reported that foot clearance above ground/floor during gait is also determined as a major factor for the occurrence of the fall among the elderly. This is certainly true during the phase when the foot is swaying on the air, or also called as swing phase. In particular, pressure is measured when the foot is already touching the ground, which is known as stance phase, while clearance is measured during mid-swing to terminal stance. The terms of gait movements are visually described in Figure 1.1. The acceleration sensor will be attached to the gait area to determine the specific parameter for the movement. If the clearance and acceleration parameters of this analysis are identified, a better method of injuries prevention and performance enhancement can be developed for athletes and patients.

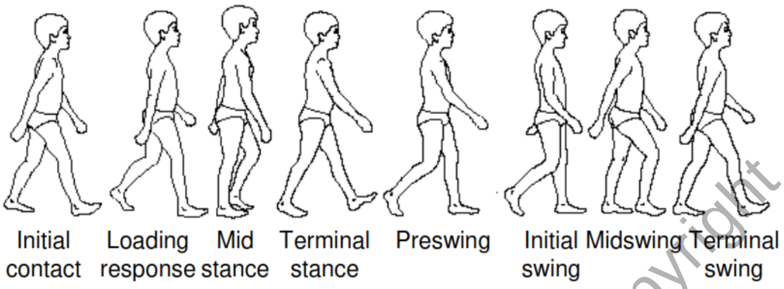

Figure 1.1: The normal gait cycle of human (Perttunen, 2002)

In addition, gait analysis also can be used to identify gait events such as heel strike, toe off, the timing of swing, stance, stride and also cadence. If stride length is known, the horizontal speed and acceleration also can be determined. On the other hand, the foot clearance measurement can also be useful in determining the vertical component of gait kinematics such as acceleration, vertical velocity and its maximum vertical displacement.

Microfabrication technology is the key for functional integration and miniaturization of electronics system. Micro-Electro-Mechanical System (MEMS) technology has grown rapidly during the previous two decades especially in commercial applications of sensors and actuators (Slaughter & Hilbert, 2009). MEMS technology is capable of producing a small integration device which involves the combination of sensors, actuators, electronic and mechanical elements on a common silicon substrate through the microfabrication technology. In terms of mechanics and biomechanics, micro-mechanical sensor such as microcantilever is well-suited to study the analysis of human movement activities and environmental sensing.

MEMS based mass-beam structure has been proven as an outstanding micro-fabrication platform for its extremely sensitive nature as environmental and bio/chemical sensors. The realisation of inertia sensor in this research is used to evaluate the biometric characteristics of human gait in acceleration or voltage magnitude. Gait cycle can be determined as a length of time within walking which bcomposed of single step of right and left foot. Every gait cycle consists of the unique characteristics of a person's movement which contributed to gait signature. The length of gait cycle for every person is different. In general, the average walking speed of a person is roughly at one gait cycle per second. Figure 1.2 illustrates the example of stride signal pattern in the suspensory ligament of a walking human measured using an industrial accelerometer.

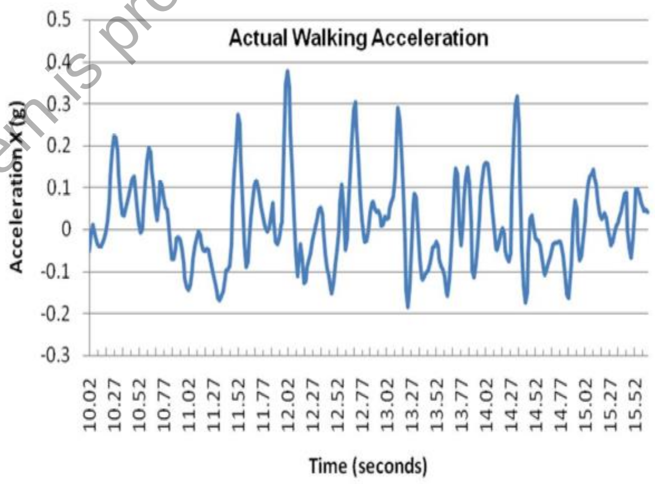

Figure 1.2: Stride pattern in the suspensory ligament of walking human measured by an accelerometer (Slaughter & Hilbert, 2009)

The need for the measurement of human motion parameters is getting higher lately, due to the increase in the number of fields requiring it, especially medical specialisations (Simon, 2004), activity of daily living assessment and sports (Billing, Nagarajah, Hayes, & Baker, 2006). At present, the measurement is mostly performed in specialised facilities such as hospital or laboratories (Best & Begg, 2006). These facilities require very high set up cost, less accuracy and limited space usable for the measurement (Aminian, 2006). The expanding use of gait analysis is catalysed by the fact that it is able to evaluate walking where most of the daily living activities are performed (Simon, 2004). Obviously, these systems can only be developed by the integration of microelectronics and micro-electro-mechanical system technologies. This type of integration is expected to bring over a number of significant improvements into biomedical instrumentation realisation which includes miniaturization, low power consumption, full integration of system and also low cost of production (Noble, Jones, Robertson, Hutchins, & Billson, 2001).

Due to the obvious limitations, latest systems based on mobile technology are highly required. As discussed earlier, this project is intended to realise and characterise the fabricated sensors which is easy to develop for gait analysis. MEMS technology is use in sensor development to increase the fabrication process efficiency. For this specific reason, the sensing techniques need to be analysed and the fabricated sensor performance needs to be identified. This requires a better understanding of the sensor structure requirements for particular measurement of gait pattern. Figure 1.3 shows a proposed gait analysis system that includes in human movement monitoring. However, this research's sole focus is on developing the sensor which focuses on human gait pattern measurement.

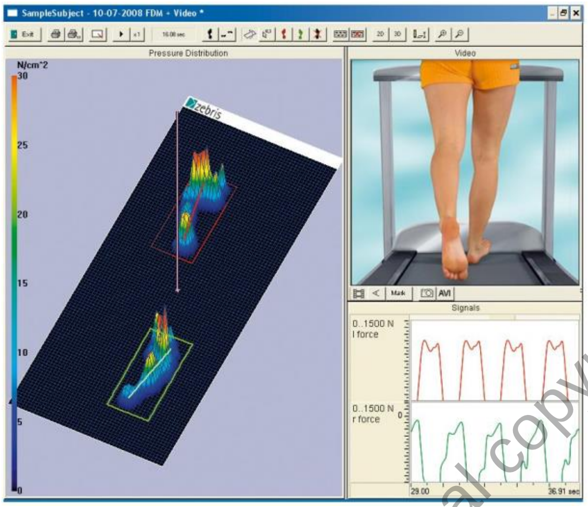

Figure 1.3: A proposed patient monitoring system that includes human movement monitoring (Dr. Jay Segel, 2010).

1.2 Problem Statement

Presently, the health system is still in need of significant improvement. While the ratio of rehabilitation, sports and medical professional is insufficient, such measurements are still mostly conducted in exclusive sports research facilities, rehabilitation centres or hospitals in major towns or cities. For example, the use of gait mats, force sensing platforms, motion analysis systems with efficient computer processing and ultrasonic ranging system are used for indoor analysis. Despite their efficiency and reliability, these state-of-the-art measurement systems are still using the bulky old fashioned technology. Considering the global trend of enhancing sports and medical measurement and monitoring system, a major paradigm shift for an exclusive and miniaturization device is therefore immensely needed. As a solution, the advances in the instrumentation technology should be explored and used to its fullest capability. The aim is to enable the measurement to be performed by the patient's or athlete's in their natural environment to support the pervasive healthcare concept.

The sensors in the monitoring system should not interfere with the actual movement itself so that the readings are the sole representation of the actual task performed. Therefore, it is required for the devices to be small, portable and can be easily attached to the shoes or feet. One possible way of satisfying such exclusive demands is, of course through the sensor fabrication in MEMS technology. In this research, laser micromachining will be introduced as a novel method in defining the formation of the sensor structures. Although it is relatively new, this kind of technology offers a promising instrumentation that will provide a great opportunity for the further advancement of intended gait measurement in a compact system.

This novel process will be proven to be capable of reducing the number of processes required, less chemical involved and high processing speed for sensor fabrication. The greatest achievement will be due to cheap and easy integration of microelectronic process by using the laser micromachining technology. Thus, the potential of these technologies should be explored in the latest generation of sensing instruments development to ensure greater progress of the gait analysis application with significant impact to the society. Therefore, in this research, the exploration and realisation of micro-sensors for the measurement of gait parameters using MEMS technology is explained.

1.3 Research Objectives

The purpose of this research is to design, fabricate, integrate and analyse the piezoresistive MEMS acceleration sensor based on environmentally responses. This study includes exploring and developing the piezoresistive microcantilever for measuring the movement parameter based on force or vibration principle in human gait motion. With the aim of developing the sensor, few objectives have been determined for this study as stated below:

1. To purpose a new way in fabricating a piezoresistive microcantilever accelerometer sensor and optimizing the fabrication process flow by incorporating laser micromachining technique.
2. To optimize the electrical output signal performance of the piezoresisitive accelerometer using an appropriate building blocks (i.e. Wheatstone bridge) within the scope of gait analysis applications.

1.4 Research Approach, Scope and Limitations

This research is focusing on the study for MEMS accelerometer development based on piezoresistive microcantilever structure, which aims to accomplish the fabrication by laser micromachining technique. Initially, the research begins with the studies, understanding and exploring the principle operation of the piezoresistive microcantilever device in terms of physical and electrical properties. Studes also covered on the optimization of the sensor formation effectiveness by laser beam method. In general, crystalline silicon substrate is chosen as cantilever beam material due to its elasticity modulus of silicon which often suitable for

MEMS engineering designs. In order to realising the piezoresistive effect, polycrystalline silicon is used as piezoresistive layer for sensing material. The primary advantages of polysilicon materials is it can withstand subsequent high temperature procedure such as spin-on dopant diffusion process. A native oxide which requires high temperature to develop can be developed on top of polysilicon layer. In order to create a thin cantilever beam, the research applies anisotropic wet etch process. Potassium hydroxide (KOH) is used as an etchant which can independently etch the cantilever beam based on recipe optimisation process. Fundamental of anisotropic wet etch is explored in experiments tailored to understand the principal, limitation and advantages of the etchant. After that, research proposes to use laser micromachining for realising the cantilever beam and piezoresistor structures in a relatively faster way. The basic principles of laser micromachining is studied in details which includes the parameter involves. Fabrication formation processes including silicon thinning process, polysilicon deposition, anneal and doping process, piezoresistor and cantilever formation are assisted by laser micromachining. Wheatstone bridge circuit is used in the characterization of the electrical properties of the sensor. Initially the measurement are performed by electro-dynamic-vibration system to emulate the real movement of gait. At last, measurements are performed in real application by attaching the sensor to the real foot which to evaluate the characteristic of the movements.

1.5 Thesis Organizations

The documentation of this thesis is organized in six chapters. Chapter 1 explained the introduction, which covering the introduction of research area, problem statements, research objectives, research scopes and overall of thesis chapter outline. The literature review for the sensing techniques, sensor architecture, conventional fabrication method and laser micromachining technology are thoroughly explained in Chapter 2. Next, in Chapter 3, research methodologies for sensor fabrication process are specifically discussed. The following chapter is devoted to the structuring process of the sensor formation by using laser micromachining technique and the complete techniques and parameters which involves in sensor physical realisation is discussed in Chapter 4. Subsequently, Chapter 5 elaborates on the efforts to develop the fabricated accelerometer sensor, wire-bonding, packaging, set-up development testing and laboratory testing implementation. Gait pattern and its analysis results are further discuss at end of chapter details. Research conclusion and further research recommendations are provided in Chapter 6 as the final chapter of this thesis.