OPTIMIZATION OF MEMS PIEZO-ELECTRIC SENSOR FOR SMART TEXTILE APPLICATION

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ABSTRACT

MEMS piezoelectric cantilever based sensor for smart textile application are useful to monitoring a various physiological parameter. Especially blood pressure necessary to measure which treat critical conditions like hypotension and hypertension and it can cause heart failures and attacks, strokes, dizziness and shock. Blood pressure is measured in millimeter of mercury(mmHg) units. During each heart beat blood pressure varies between systolic (maximum) and diastolic (minimum). Hence direct measure of heart beat can be considered as the determination of the blood pressure. Normal human systolic pressure is 120mmHg and diastolic pressure is 80mmHg. For blood pressure monitoring application, health care industry combines smart shirt with compatible sensors which are required to operate in the range of 50mmHg-180mmHg. MEMS piezoelectric cantilever based sensors are widely in blood pressure measurement because it provides higher sensitivity to pressure, tunable sensitivity, simple structure and micro in size. In this research project, a U-shaped MEMS piezoelectric cantilever based sensor is designed and demonstrated using COMSOL Multiphysics software. Result obtained from the simulation is the deflection of the U-shaped cantilever when normal diastolic pressure 80mmHg is applied. Among other piezoelectric material Lead Zirconate Titanate (PZT-5H) as a sensing layer of U-shaped cantilever gives better sensitivity at diastolic condition (80mmHg) showing displacement and electric potential of 11.456µm and 2.0523V which is 41.40 higher than rectangle shaped cantilever. For the conclusion, a piezoelectric MEMS cantilever based sensor is successfully designed, simulated and optimized. Optimization parameter had also been performed at different length of cantilever which shows that longer gives greater deflection at diastolic condition and improves the sensitivity of sensor due to the uniform distribution of stress throughout the surface of cantilever. While by using U-shaped of cantilever the size of the cantilever reduces and gives better performance as compare to rectangle shaped cantilever.

ABSTRAK

MEMS sensor cantilever piezoelektrik berasaskan aplikasi tekstil pintar berguna untuk memantau pelbagai parameter fisiologi. Terutamanya tekanan darah yang diperlukan untuk mengukur yang merawat keadaan kritikal seperti hipotensi dan hipertensi dan ia boleh menyebabkan kegagalan jantung dan serangan, strok, pening dan kejutan . Tekanan darah diukur dalam milimeter merkuri (mmHg). Semasa setiap jantung mengalahkan tekanan darah berbeza-beza antara sistolik (maksimum) dan diastolik (minimum). Oleh itu, pengukuran langsung denyutan jantung boleh dianggap sebagai penentuan darah tekanan.Tekanan sistolik manusia biasa ialah 120mmHg dan tekanan diastolik ialah 80mmHg. Untuk aplikasi pemantauan tekanan darah, industri penjagaan kesihatan menggabungkan baju pintar dengan sensor serasi yang diperlukan untuk beroperasi dalam lingkungan 50mmHg-180mmHg. MEMS piezoelektrik sensor cantilever berdasarkan secara meluas dalam pengukuran tekanan darah kerana ia memberikan sensitiviti yang lebih tinggi kepada tekanan, kepekaan tunas, struktur mudah dan saiz mikro. Dalam projek penyelidikan ini, sensor berasaskan cantilever MEMS peka berbentuk U direka bentuk dan ditunjukkan menggunakan perisian COMSOL Multiphysics. Keputusan yang diperoleh daripada simulasi adalah pesongan rasuk cantilever berbentuk U ketika tekanan diastolik 80mmHg normal digunakan. Di antara bahan piezoelektrik yang lain, Lead Zirconate Titanate sebagai lapisan penginderaan berbentuk julur U memberikan kepekaan yang lebih baik pada keadaan diastolik (80mmHg) menunjukkan anjakan dan potensi elektrik 11,456 μ m dan 2.0523V iaitu 41.40 % lebih tinggi daripada julur berbentuk segi empat. Untuk kesimpulan, sensor berasaskan cantilever MEMS Piezoelektrik berjaya direka, disimulasikan dan dioptimumkan. Parameter pengoptimuman juga telah dilakukan pada panjang cantilever yang berbeza yang menunjukkan bahawa pesongan lebih penjang memberikan pesongan pada keadaan diastolik dan meningkatkan kepekaan sensor kerana pengagihan seragam

stres di seluruh permukaan cantilever. Dengan menggunakan cantilever berbentuk julur U saiz cantilever, berkurangan dan memberikan prestasi yang lebih baik berbanding dengan cantilever berbentuk segi empat tepat.

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LIST OF SYMBOLS AND ABBREVIATIONS

MEMS	:	Micro-electromechanical systems
IC	:	Integrated Circuit
MST	:	Microsystem technology
MM	:	Micromachines
MOEMS	:	Micro-Opto-electromechanical system
HARM	:	High aspect ratio micromachining
HBP	:	High Blood pressure
PZT	:	Lead Zirconate Titanate
$BaTiO_3$	:	Barium Titanate
k	:	Spring Constant
F	:	Force
X	:	Displacement
E	:	Young's Modulus
L	:	Length of cantilever
mmHg	:	millimeter of mercury
W	:	Width of cantilever
t	:	Thickness of cantilever
SiO_2	:	Silicon dioxide
ECG	:	electrocardiogram
VCOs	:	Voltage controlled oscillators
σ	:	Applied stress
PVDF	:	Polyvinlidene Flouride
ZnO	:	Zinc Oxide
S	:	Sensitivity

FSR	:	Force Sensing Resistor
PET	:	Polyethylene terephthalate
FBGs		Fiber Bragg Grating Sensor
MR	:	Magnetic resonance
HR	:	Heart Rate
BP	:	Blood Pressure
E-textile	:	Electronic textile

CHAPTER 1: INTRODUCTION

1.1 Introduction

In Malaysia among top of 3 diseases one of this hypertension (Lauren, 2018). It is more generally referred to high blood pressure and is a major cause of other diseases like heart problem and such. It was lately reported that about 3.5 million Malaysians are not aware that they are having such problems and suffering from hypertension. Some peoples around 2.3 million turned up at the clinics for treatment while many others are not even aware that they are having problem (Abdul-Razak et al., 2016).

High blood pressure (or HBP) also known as "Silent Killer". Normally high blood flow is a caused of blood pressure, which strikes the blood vessels walls. Measurement of blood pressure is necessary to treat critical conditions like hypotension and hypertension and it can cause heart attacks, strokes, failures and dizziness shock is necessary to measure the blood pressure (DevaPrasannam & JackulineMoni, April-2014). The existing devices are costly and contains more number of components and it's difficult to handle for long time ambulatory monitoring of heart motion and its functions.

While healthcare represents one of the most attractive sectors contribute to the growth of market and new MEMS sensor technology with high potential. Wearable, disposable and portable sensors for healthcare, as well as physical activities also sense and for well-being in general are used for monitoring, e.g. breath, blood pressure, heart rate and to perform diagnoses of specific diseases (Bogue, 2014).

The smart textile idea has been introduced a few years ago and widely used in 90's. There is an amazing development of smart materials and electronics brought intrinsic potentiality in the textile technology field for advanced high-tech applications, covering market segments that are far away from the world of conventional textile. Best example is the lately growth of new intelligent and sensing cloths (Henock, 2011).

One of smart textile is smart shirt also defined as “the shirt that thinks”, is a shirt wired with conductive and optical fibers to gather biomedical information and functions like a computer. Sensors can integrate by developed interconnection technology and sensors use for monitoring the vital sings: respiration rate, heart rate, electrocardiogram (ECG), and temperature and pulse oximetry, among others. One of the most application in smart textile is telemedicine, many different types of medical sensors, right to insert in smart textile have been made and used by scientist. Sensors like blood pressure, respiration electrodes, pulse oximeter, galvanic skin response are just some examples of biomedical ones (Agarwal & Agarwal, 2011).

Smart shirt has various sensors based on piezoelectric, capacitive, piezo resistive sensing element based cantilever structure and with the help of screen printing fabrication method this free-standing structure fabricate on substrate (Wei et al., 2012a). Depends on application each element has their own advantages and disadvantages.

1.2 Problem Statements

Most of existence research and sensor used in smart textile for different applications like motion detector in safety critical conditions, body temperature, blood pressure, monitoring body movement, temperature and electrocardiogram, Control of water loss during sport or health care application like incontinence detection with different sensing elements. Such as capacitive sensor, humidity sensor, piezo resistive sensor with rectangle cantilever structure for different applications. In capacitive cantilever structure to monitor an unconscious in safety critical condition and they find out due to the parasitic capacitance is introduced into circuit caused small amount of noise in output of capacitive cantilever structure (Wei et al., 2012b). As well as piezoelectric sensor also with rectangle structure for monitoring of physiological parameters (KNJ et al., 2013). The rectangular are having higher Eigen frequency modes when compared with other cantilever structure but less displacement in load condition describing the less sensitivity (Siddaiah et al., 2017). To improve the sensitivity as well as reduce the size of sensor the sensor will be designed in U-shaped cantilever structure. U-shaped cantilever structure displacement is more in load condition describing the higher sensitivity (Siddaiah et al., 2017). U- shape cantilever allows dimensions of cantilever to be minimize, especially its width the cantilever with U-shape will act as two identical separated cantilevers corresponding to the two legs. The U-shaped cantilever will reduce the size of sensor and improve the sensitivity of sensor.

1.3 Objectives

The main objectives of this research project are:

1. To design a MEMS U-shaped piezoelectric cantilever based blood pressure sensor for smart textile and comparing different piezoelectric materials sensitivity for the sensor. To achieve, displacement 'X' more than 7.5263µm and electric potential higher than 0.7664V.
2. To obtain optimized structural parameter of MEMS U-shaped piezoelectric cantilever based sensor in blood pressure measurement.

1.4 Scope of Project

Scope of this projects will include the design of a U-shaped piezoelectric cantilever based sensor for smart textile application with different length 'L' and Piezoelectric material until specification mentioned in section 1.3(1) is achieved.

The structure of the piezoelectric cantilever is design based on the (KNJ et al., 2013). The sensor consists of sensing layer, structural layer and interface layer with various material. The sensing layer of sensor is made of piezoelectric material with U-shaped design. While structural layer is made of Polysilicon material. Finally, interface layer is made of SiO_2.

This project will be carried out using COMSOL Multiphysics software to design piezoelectric cantilever sensor for smart textile. The sensitivity and linearity of the sensor will be analyzed when pressure is applied. Normally human blood pressure varies between systolic and diastolic blood pressure. Applied pressure will be in the range of 50-180mmHg based on human blood pressure.

1.5 Thesis Organization

This report consists of 5 chapters and begin with chapter 1 with the introduction to this project and problem statement that concerns. While chapter 2 focus more on the literature review related to the MEMS technology, smart textile, piezoelectric sensor, material and structure of piezoelectric sensor. Chapter 3 will have the projects flow chart, mathematical derivations and methodology of the project. Meanwhile chapter 4 will discuss the result obtain from the simulation using COMSOL Multiphysics software. Finally, chapter 5 contains discussion on overall chapter, conclusions and recommendation for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter consist of literature review based on Mems technology, smart textile. Piezoelectric sensor, piezoelectric material, piezoelectric sensor structure. Other than that, current design of piezoelectric sensor in research work related to this project and suitable piezoelectric material for the measurements of blood Pressure will be discuss.

2.2 MEMS Technology

Micro Electro-Mechanical System (https://www.mems exchange.org/MEMS/what-is.html) is a process technology that combine electrical and mechanical components to create a tiny integrate devices or system. Integrated circuit (IC) batch processing technique is used to fabricate these devices and have feature size ranging from a few micrometers to millimeters (Allen, 2007). The ability of these systems (or devices) it can sense, control and actuate on the microscale, and generate effects on macroscale by functioning individually or in array (Karumuri et al., 2012).

The scale for various dimensions is shown in Figure 2.1.

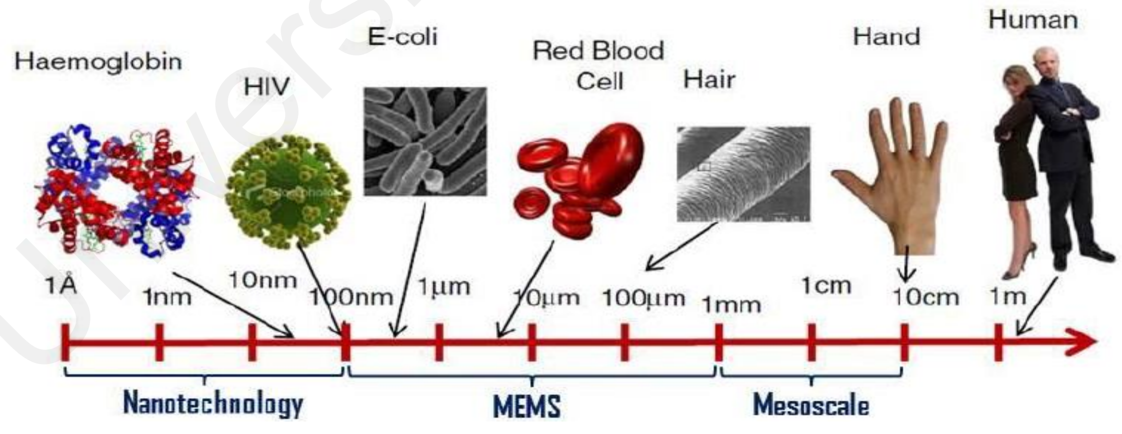


Figure 2. 1 Dimensional scale of MEMS (Nguyen et al., 2013)

MEMS term is originated in the united states, MEMS is also referred to as microsystems technology (MST) in Europe and Micromachines (MM) in japan. MEMS with optics is called Micro-Opto-Electro-Mechanical-Systems (MOEMS). Regardless of terminology, the MEMS device uniting factor is in the way it is made. While the electronics device fabricated using IC technology, manipulation of silicon and other substrates by process of micromachining to fabricate the micromechanical components. Processes such us surface and bulk micromachining, as well as high-aspect-ratio micromachining selectively remove silicon parts or additional layers to form the electromechanical and mechanical components (Bedekar & Tantawi, 2017). MEMS take benefits of either mechanical property of silicon or both its mechanical and electrical properties (van Heeren & Salomon, 2007).

Nowadays, range of devices based on MEMS are very wide starting from simple structure with no moving parts, to complex electromechanical devices (or systems) with multiple moving parts under the control of integrated microelectronics. In MEMS the main important criteria are must have some elements having mechanical functionality either it is movable or non-movable(Ciuti et al., 2015).

While the MEMS functional elements are micro sensors, microelectronics, mechanical microstructures and micro actuators, all integrated onto the same silicon chip. This is shown schematically in Figure 2.2.

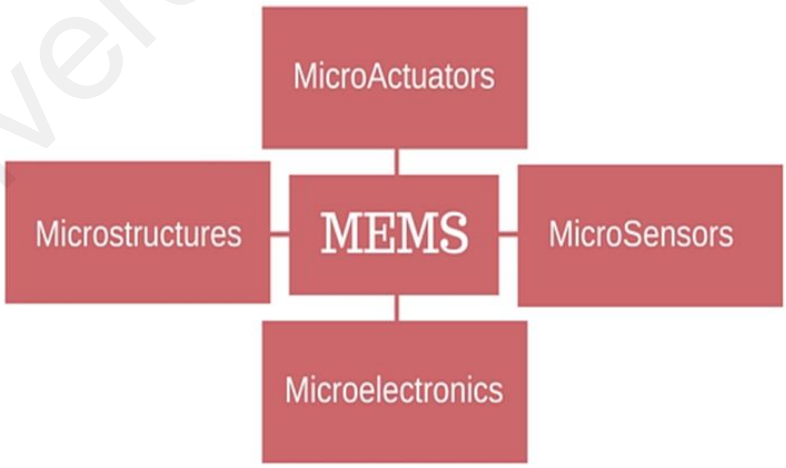


Figure 2. 2 Schematic design of MEMS components (Allen, 2007)

Most interesting or can be said most notable elements in MEMS are the micro sensors and micro actuators and classified as “transducers”, which are defined as systems (or devices) that convert one form of energy to another. Micro sensors typically defined as the device that converts measured mechanical signal into an electrical signal.

Great number of micro sensors used to measure inertial forces, chemical species, magnetic field, pressure, temperature, biosensors, radiation etc. had been produced by MEMS developers and researcher in past several decades. Remarkably, many of these miniaturized sensors have shown greatest ability exceeding those of their macroscale category (Nagod & Halse, 2017). MEMS with its batch fabrication techniques allows devices and components to be manufactured with increased reliability, performance and increased flexibility of system design combined with the clear advantages of reduced volume, cost, weight and physical size. While lately, sensors with silicon based have overcome the markets and this makes rapidly grow of MEMS sensors continuously (https://www.mems-exchange.org/MEMS/what-is.html).

Table 2. 1 Application of MEMS (Watch, 2002) .

Defense	**Medical**	**Automotive**	**Communications**	**Electronics**
Arming systems	Drug delivery systems and muscle stimulators	Airbag sensors	Filters, switches and RF Relays	Inkjet printer heads
Aircraft control	Prosthetics	Vapor pressure and fuel level pressure sensors	Voltage controlled oscillators VCOs ()	Earthquake sensors
Embedded sensors	Pacemakers	Navigations sensors	Tunable lasers	Mass storage systems
Data storage	Miniature analytical instruments	“Intelligent” tires	Couplers and splitters	Projection screen televisions
Munitions guidance	Implanted pressure sensors	Sensor for air conditioning compressor	Fiber-optic network components	Disk drive heads
Surveillance	Blood pressure sensor	Suspension control accelerometers and brake force sensors	Projection displays in instrumentation and portable communication devices	Avionics pressure sensor

Today, MEMS in high volume can be found in a diversity of applications across various markets Table 2.1.

While healthcare represents one of the most attractive sectors contribute to the growth of market and new MEMS sensor technology with high potential. Wearable, disposable and portable sensors for healthcare, as well as physical activities also sense and for well-being in general are used for monitoring, e.g. breath, blood pressure, heart rate and to perform diagnoses of specific diseases; the system also include to care for a chronically ill patient and growing aging population. The sensor is used to monitor chronic diseases, such a s obesity, diabetes, hypertension, heart failure and sleep disorders, is the main-elements to keep life quality high and health care cost reduce (Bogue, 2014).

Key factors for the proliferation of sensors in medical healthcare are the availability of low cost microsystem sensor technologies (e.g. MEMS) couples, in many cases, with low power microcontrollers, low cost and efficient telemetry modules. These features enabled the development of accurate, robust, reliable, compact and low power solutions. Medical devices based on MEMS are composed of different sensors which include temperature, pressure, optical image, accelerometer, flow, drug delivery micro dispensers, silicon microphones and microfluidic chips, strain sensors, and energy harvesting (Ciuti et al., 2015).

2.3 Smart textile

Previously textile only considered one of the necessity of human beings, has developed out as an innovative area which is only able to satisfy human desires to its supreme extent. The textile which just focused on preparatory processes considered as "first generation textiles" (Sharapov, 2011).

After the changes in industrial revolution have been moving at an extraordinary rate in various fields of technology and science. Starting from steam engine to developments of computers, electronic machines, modern machines development in industries sector, the internet, advanced engineering materials creation, communication of mobile phone etc.

The smart textile idea has been introduced a few years ago and widely used in 90's. There is an amazing development of smart materials and electronics brought intrinsic potentiality in the textile technology field for advanced high-tech applications, covering market segments that are far away from the world of conventional textile. Best example is the lately growth of new intelligent and sensing cloths (Henock, 2011).

Smart textile basic concept consists of textile material and structure that senses and react to different stimuli from its environment conditions. Automatically sense and react by textile in its simplest form without a controlling unit, and in a more complex form, through a processing unit a specific function can be sense, react and activate by smart textile. They are systems composed of various materials and apparatuses such as electronic devices, actuators and sensors together (Berglin, 2013).

There are four basic functions of smart textile (Syduzzaman et al., 2015).

1. Systems or materials which only sense the environmental conditions or stimuli also known as passive smart systems or materials. They are sensor and show up what happened on them. Such as changing shape, color, thermal and electrical resistivity. These types of textile material less or more similar with high performance and functional textile.
2. Materials and systems that perform both functions of sense and respond to stimuli or external conditions considered as active smart materials. Sensing and giving reaction to the external conditions are there prior functions. This shows they are both actuators as well as sensors to the environmental conditions.
3. Systems and materials which can perform triple functions known as very smart materials. First, they are sensors which can receive stimuli from the environment;

Secondly based on the stimuli gives the reaction; Thirdly accordingly to the environment conditions they are able to adapt and reshape themselves.

4. Materials with intelligence of high level develop computers with artificial intelligence. In current investigation of humans these type of materials or systems not fully achieved. This may be achieved from the coordination of those intelligent structures and materials with advanced computer interface.

A components of wearable smart textile system (Figure 2.3) includes:

1. sensors
2. actuators
3. data processing unit
4. communication system
5. energy supply
6. interconnections

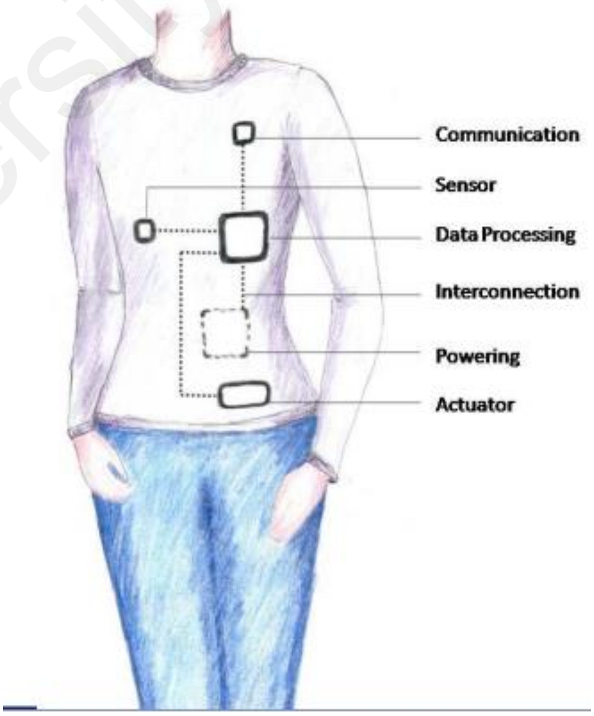


Figure 2. 3 Components of wearable smart textile system
(Drd. eng. Vlad Dragos DIACONESCU et al., 2015)

The smart or intelligent textile important external attachable module is sensor. The basic concept of sensor is that it transforms one type of signal into another form of signal. Various structures or materials of sensor that have an ability of transforming signal. For example, thermal sensor that detects thermal change. Other examples are humidity sensor that measure relative or absolute humidity. Strain sensor that convert strain to an electrical signal and pressure sensor that convert pressure into an electrical signal. Sensor series that detect concentration and presence of chemicals are called chemical sensors (Berglin, 2013).

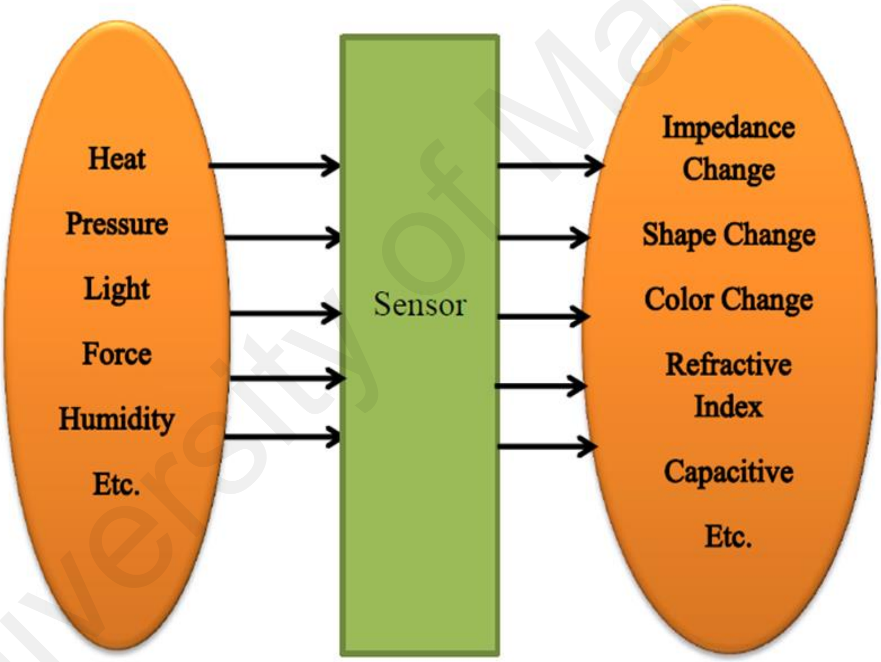


Figure 2. 4 Relationship between sensor input/output

Healthcare industry emerging new area of exploration in smart or intelligent textiles. These wearable textiles that combined sensors aim to keep well-being conditions on check. Smart textile focuses on the use of biotelemetry. This process monitor physiological parameters by means of separation. Health monitoring is a general concern for patient requiring continuous medical treatment and assistance. Patients mobility has been increased by the development of wearable systems for the monitoring of physiological parameters such as heart rate, respiration, muscle activity, blood pressure and temperature of body (KNJ et al., 2013). Especially blood pressure necessary to measure which treat critical conditions like hypotension and hypertension and it can cause heart failures and attacks, strokes, dizziness and shock. Normally high blood flow which strikes blood vessels walls causes blood pressure (DevaPrasannam & JackulineMoni, April-2014).Normally human blood varies between systolic and diastolic as shown in Table 2.2.

Table 2. 2 Stages of blood pressure (Association, 2015)

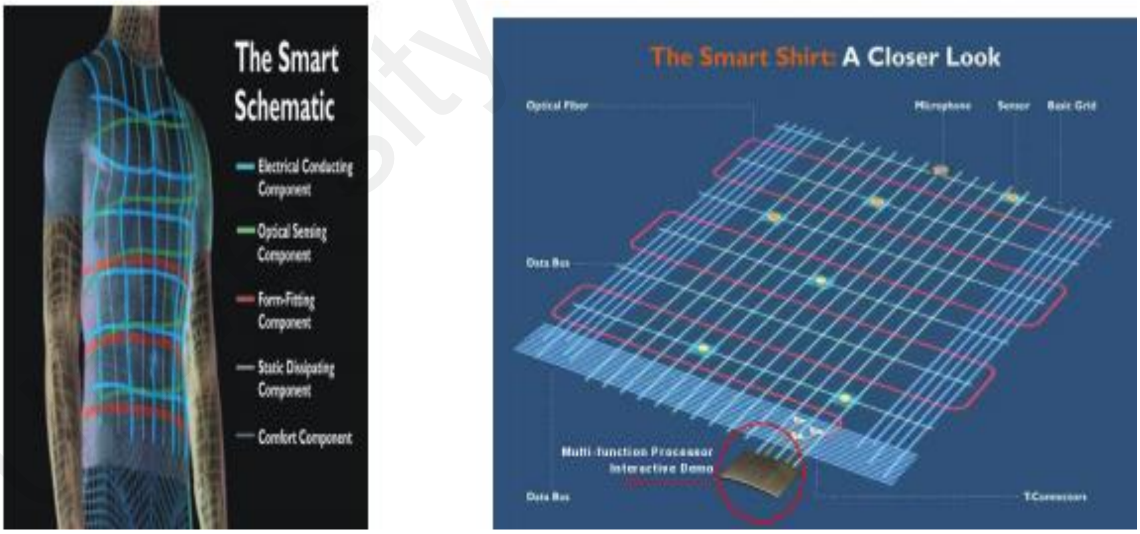
Blood pressure category	Diastolic (mmHg)	Systolic (mmHg)
Normal	Less than 80	Less than 120
Elevated	Less than 80	120 – 129
High blood pressure Hypertension (stage 1)	80 – 89	130 - 139
High blood pressure Hypertension (stage 2)	90 or higher	140 or higher
Hypertensive Crisis (seek emergency care)	Higher than 120	Higher than 180

To monitor a physiological parameter some important sensors in used in smart textile such as accelerometer, piezo-electric sensor, temperature and light sensors, flex and pressure sensors, and biosensors are placed in the clothing. The data collected by these sensors, which is then sent to, with wire or wirelessly, a computer, or a PDA where the data are stored (Paradiso et al., 2018). These sensors can be easily plugged into the smart shirt. The smart shirt has following commercial applications (Agarwal & Agarwal, 2011).

1. Maintaining lifestyle healthy
2. Continuous monitoring of home
3. Monitoring of infant vital sign

4. Monitoring of sleep studies
5. Monitoring of vital sign for mentally ill patients
6. Care solutions for battlefield combat
7. Public safety officer protection

Smart shirt also defined as “the shirt that thinks”, is a shirt wired with conductive and optical fibers to gather biomedical information and functions like a computer (Agarwal & Agarwal, 2011). A wearable system must sense, to recognize, and to classify information like physical interaction with the environment, activity, gesture and posture and to combine them with physiological parameters, like respiratory signal, galvanic skin impedance, heart rate variability, electrocardiogram etc. These platforms of sensing can give an entire report of the subject in terms of physiological state and physical activity through an analysis of multivariable (Paradiso et al., 2017). Smart shirt detailed architecture is illustrated in Figure 2.5.



(a) (b)

Figure 2. 5 (a) Woven wearable motherboard (b) Smart shirt detailed (Agarwal & Agarwal, 2011)

There are various application sensors used in medical e-textile system. Some important sensors used are magnetometer, accelerometer, temperature, flex and pressure sensor, and microphones for some applications like beam foaming, motion capturing (Agarwal & Agarwal, 2011).

One of the most application in smart textile is telemedicine, many different types of medical sensors, right to insert in smart textile have been made and used by scientist. Sensors like blood pressure, respiration electrodes, pulse oximeter, galvanic skin response are just some examples of biomedical ones (Agarwal & Agarwal, 2011).

Smart shirt has various sensors based on piezoelectric, capacitive, piezo resistive sensing element based cantilever structure and with the help of screen printing fabrication method this free-standing structure fabricate on substrate (Wei et al., 2012a). Depends on application each element has their own advantages and disadvantages. For example (Wei et al., 2012b) design a capacitive cantilever based sensor to monitor an unconscious in safety critical condition and they find out due to the parasitic capacitance is introduced into circuit caused small amount of noise in output of capacitive cantilever structure.

While (Kutzner et al., 2013) design humidity sensor in which electrodes are designed as a pair of parallel alignment or interdigital. which is suitable for applications to control of water loss during health care or sports applications like incontinence detection.

Whereas (Giovanelli & Farella, 2016) build an force sensing resistor (FSR) for wearable applications based on resistive material (Velostat) and printed conductive ink electrodes on polyethylene terephthalate (PET) substrate. Check the sensor response to pressure range of 0-2.7Kpa and structure of sensor is single point interdigital structure with dimensions of single point (15 × 30mm). one of main issue found in force sensor is repeatability and can be found ±50% error.

Among all these, based on piezoelectric sensing element an appropriate sensor is design for health care industry to monitor vital health signs by observing various physiological parameters (e.g. respiratory rate, body temperature, blood pressure and heart rate) and they find out well linear response (Wei et al., 2012a).

2.4 Piezoelectric Sensor:

The most prominent way to produce electricity from the environment is motion(vibration) based energy harvesting (Alaei, 2016). Because generating the vibration or using the natural vibration is almost easy to achieve. There are three ways to convert vibration energy into electricity are electrostatic, electromagnetic and piezoelectric transduction. Compared to other two transduction mechanism the most effective technique is piezoelectric transduction because piezoelectric material offers higher power densities and ease off application (Nia et al., 2017). Also, they are more advisable and sensible for MEMS implementation. In energy harvesting the advantages of using piezoelectric materials are ease of application, no requirement of input voltage, high power density and relatively mature fabrication techniques at micro and macro-scales (Sarma, 2018),(Tian et al., 2018). There are two piezoelectric coupling modes, meaning the way the electrical energy and mechanical energy are related. These modes are called -31 and -33 modes, as shown in fig. The force is applied perpendicular to the direction of poled molecules and resultant voltage in the -31 mode. While in -33 mode force in the same direction as the molecular poling and voltage (Anton & Sodano, 2007). Between these two-coupling mode comparison is necessary to determine which material is best for an energy harvesting application (Anton & Sodano, 2007). The -31 mode offer lower piezoelectric properties, smaller input forces in -31 loading causes larger strains, in low force situations producing more power (Rödig et al., 2010). Although -33 mode offer better piezoelectric properties, but due to high mechanical stiffness makes difficulty in straining the material in compression (Anton & Sodano, 2007).

In many applications of energy conversion piezoelectric material utilize bother of these coupling modes. They are most widely used in sensor, transducer and actuators. In case of transducer and sensors, stress or mechanical motion is converted into electrical signal (Rödig et al., 2010). Due to piezoelectricity nature is on atomic level. Devices based on energy harvesting can be made small enough to replace batteries. Even in areas which never thought possible, such as human body (Wang, 2011). Table 2.3 provide some mechanical energy sources where piezoelectric can be applied. Energy harvesting piezoelectric materials employed in these areas could robots, power sensors, laptops and personal electronics, replacing batteries need, and thereby eliminating and reducing maintenance.

Table 2. 3 Mechanical energy sources in everyday life which can be harvested for electrical energy

Human body/motion	Industry	Infrastructure	Transportation	Environment
Blood flow/pressure, Breathing, Arm motion, Finger motion, Jogging, Exhalation…	Motor, compressors, pumps, vibrations, dicing noise and cutting...	Roads, bridge, water/gas pipes, AC system…	Tires, peddles, automobile, aircraft, brakes, train…	Wing, acoustic wave, ocean current/wave…

Generally, three main steps are involved during work with piezoelectric materials are (Alaei, 2016).

1. Trapping the mechanical stress from the ambient source.
2. Converting the mechanical stress into electrical energy.
3. Storing and processing the produced power for the later uses.

Therefore, following steps must be considered in modeling of piezoelectric harvesters. To forecast their function an important approach is modeling. However, even though piezoelectric material power density is greater than the other materials, still the power is generated in microscale. Thus, using of such materials in self-powered devices their output power must be improved. The output power must enhance in different ways. Using different piezoelectric mechanical configuration, piezoelectric material and the electrical circuit will improve the power and enable for us for a better wireless and self-powered systems. Three main steps in the piezoelectric materials energy conversion as shown in the Figure 2.6.

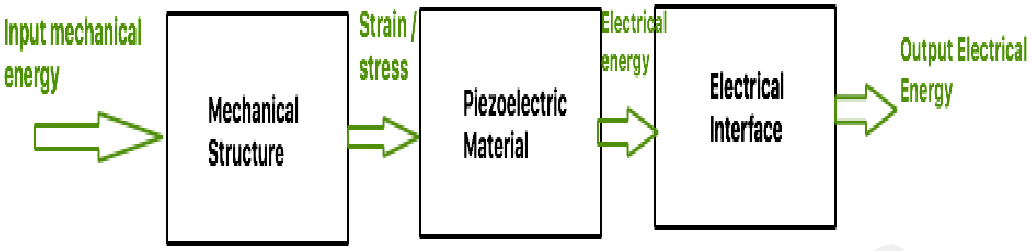


Figure 2. 6 Steps of the piezoelectric material energy conversion (Alaei, 2016)

First piezoelectric effect based practical application in 1917 when a French physicist and mathematician, Paul Langevin, suggested for detection of underwater object by using ultrasonic echo ranging device. After 1945 scope of piezoelectric transducer extended rapidly. A variety of new areas such as ultrasonic medical therapy and diagnostic, ultrasonic delay lines, level gauges, and systems for industrial control of chemical substance properties and physical and other devices with variety of applications were found for piezoelectric transducers. In technical language there is also the concept "sensor" which is equivalent to the concept "primary transducer" (Sharapov, 2011).

2.5 Piezoelectric Transduction Principle

The piezoelectricity general theory is the coupling of mechanical and electrical energy in special class of crystals and ceramics. When a mechanical strain generated from stress face by piezoelectric materials, this stress converts into voltage or electric current. The basic effect is closely related to electric dipole moments in solids where they show a local charge separation. Based on the crystal lattice fundamental structure this mechanism take place when the induced polarization and an electric field is produced across the piezoelectric crystal because of mechanically stressed. Piezoelectric material consists of charge balance where positive and negative charges are separated, but overall charge is electrically neutral because of symmetrically disturbed. When an external force, such us, physical pressure or mechanical stress is applied, this disrupts the charge balance and deformation in the internal structure (Abdal & Leong, 2017) .

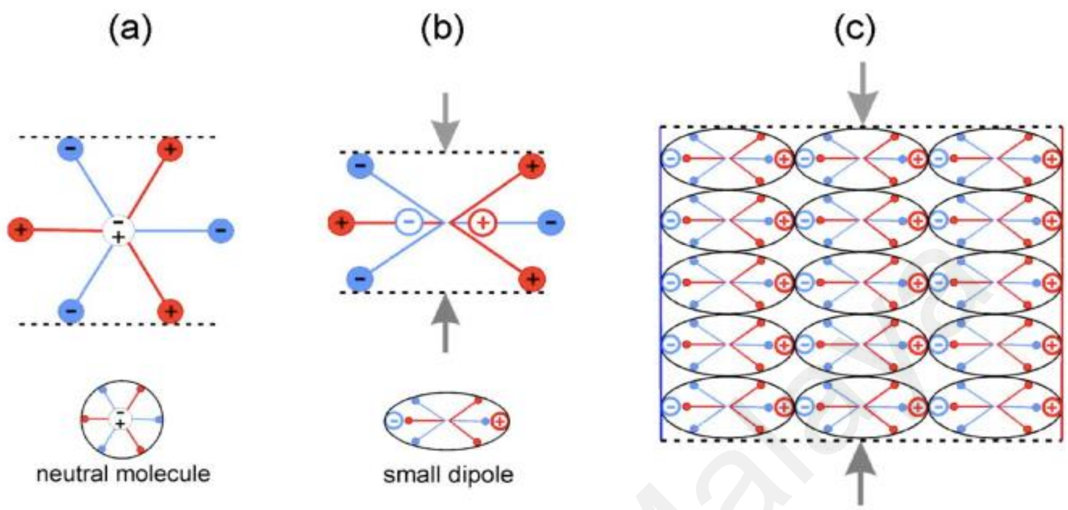


Figure 2. 7 Neutral charge disruption ("Fundamentals of Piezo Technology,")

Therefore, the charges get parted and the neutrality get disrupted, generating a surface charge density, which can be collected via electrode(Minazara et al., 2008).

Piezoelectricity depends on the crystal symmetry, orientation of dipole density, and the applied mechanical stress. In mono-crystals, all dipoles polar axes aligned in one path. Even crystal is cut into pieces they demonstrate symmetry. Though, there are different regions within material in polycrystalline that have a different polar axis and within a crystal no net polarization. This difference has been shown in figure 2.8 and 2.9

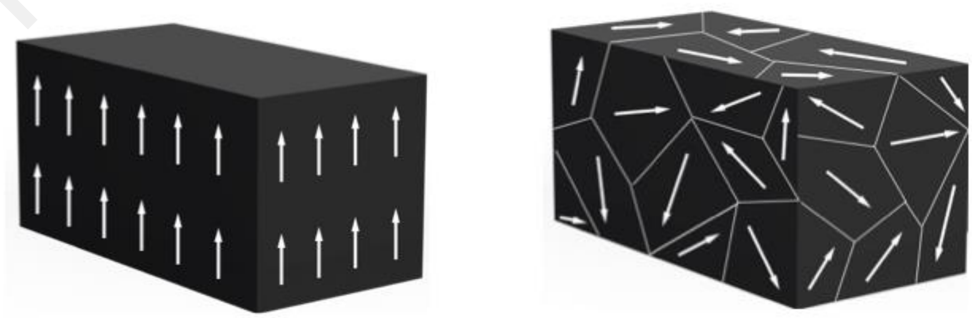


Figure 2. 8 Poles orientation in monocrystalline and polycrystalline (Caliò, 2013)

Figure 2. 9 Process of polarization and polarization surviving (Caliò, 2013)

Piezoelectric effect can be achieved in polycrystalline, the sample heated to the curie point for the particles to move freely. Strong electric field is applied along heat on the sample to push all the dipoles in the crustal to line up in one path. When removed the electric field, mostly dipoles locked into a similar configuration and achieves permanent net polarization.

2.6 Piezoelectric Material

As it was discussed before under mechanical deformation piezoelectric materials generate electricity. There are over 200 piezoelectric materials made with combination of different materials. Because of their different piezoelectric constants, the generate different voltages. Therefore, it is very important to select an appropriate material. There are three different group of piezoelectric material: piezoelectric polymers, piezoelectric single crystals and piezoelectric ceramics (Porcelli & Victo Filho, 2018) .

Most known piezoelectric materials are piezoelectric ceramics in the field of energy harvesting and piezoelectricity. The easier incorporation, low cost and shows better properties of piezoelectric related to the other piezoelectric materials has made them a good choice in the energy harvesting devices. First piezoelectric ceramic was Barium Titanate ($BaTiO3$) that was discovered in laboratory; but Lead Zirconate Titanate also known as PZT ceramic become a most common and popular materials for sensing, transduction and actuation of vibration, smart metallic, noise and health active control (Benjeddou, 2018).

Piezoelectric ceramics are selected based on the characteristics of mechanical energy applied to them. Piezo ceramics has following advantages but one main advantage is their easy integration to tinny sheets can simply be planted on a cantilever structure, because this one of the most used mechanical structure in various applications (Alaei, 2016).

2.7 Piezoelectric Sensor Structure:

A very simple structure of piezoelectric sensor is cantilever structure and cantilever main principle is that the sensor responds mechanically when there is change in external parameters like temperature, pressure and molecule adsorption. Due to its simple design and tunable sensitivity cantilever structure show superior competence compare to other sensing (KNJ et al., 2013). Over last decades, cantilever sensor have vital role due to their throughput, target elements detection and high sensitivity. Cantilever structure operate in various devices because it can work in both d_{31} and d_{33} modes. A cantilever is a rectangular bar fixed at one end and the other end free to move when it experiences any stress or some pressure. When mass absorbed or deposited on surface of cantilever shows some deflection (Serene et al., 2018).

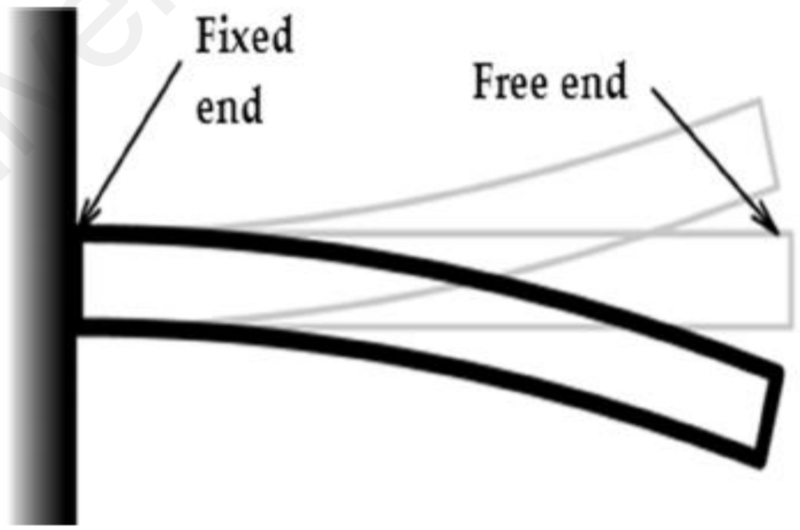


Figure 2. 10 General microcantilever structure (KNJ et al., 2013)

The structure of sensor used for monitoring of human blood pressure is cantilever structure because it has low force constant for measuring pressure or stress with enhanced sensitivity (Ghosh et al., 2013).

When free end of cantilever experienced a force (F) then deflection at free end X is:

$$X = \frac{F\,L^3}{3\,E\,I} \tag{2.1}$$

Where, L = cantilever length; µm

F = applied force: N

I = moment of Inertia = $\frac{1}{12} w\, t^3$; m^4

E = elasticity modulus of crystal's; N/m^2

Where, t = thickness of cantilever; µm

w = width of cantilever; µm

So,

$$X = \frac{F\,L^3}{3\,E}\,\frac{1}{\frac{1}{12} w\, t^3} = \frac{F\,L^3}{\frac{E}{4} w\, t^3} = \frac{4\,F\,L^3}{E\,w\,t^3} \tag{2.2}$$

Hence, cantilevers deflection at free end,

$$X \propto F \tag{2.3}$$

Since, cantilever stiffness or sprint constant K = $\frac{F}{X}$; N/m

Then cantilever sensitivity,

$$S \propto \frac{l^3}{w\,t^3} \tag{2.4}$$

Therefore, cantilever structure sensitivity is improved with decreasing the thickness and width of cantilever and length of cantilever (Panwar et al., 2017).

2.8 U-Shape Cantilever Structure

Most simplified MEMS based devices is microcantilevers. Diverse applications of cantilevers in area of sensors have been explore by many researchers. Various groups have also shown the possibility of using different shapes of microcantilever for monitoring of physiological parameters (Vashist, 2007). Thus, for improving the performances of system, it has been proposed by numerous groups (Arregui, 2009) to use a U-shape cantilever structure in which the piezoelectric uses the complete surface of cantilever. U- shape cantilever allows dimensions of cantilever to be minimize, especially its width. If L >>W, where l is the cantilever length and w is each leg width, the cantilever with U-shape will act as two identical separated cantilevers corresponding to the two legs (Arregui, 2009).

From the Stoney equation the sensitivity of a cantilever can be increased by changing the cantilever material or the cantilever geometry. Stoney equation also suggest for the displacement they deflection induced in the cantilever is directly proportional to the cantilever length and inversely proportional to its thickness. In other words, by increasing the cantilever length or reducing its thickness the deflection can be increase because high deflection shows high sensitivity (Ansari & Cho, 2008).

The rectangular are having higher Eigen frequency modes when compared with the U-shaped cantilever and U-shaped cantilever structure displacement is more in load condition describing the higher sensitivity. In overall U-shaped cantilever structure is having higher sensitivity for load condition when compared with rectangular structure (Siddaiah et al., 2017)

2.9 Previous Study on Smart textile

A lot of previous research done on smart textile for different applications like humidity sensing, motion sensing, and physiological parameters measurement by using different sensor with different sensing element such piezoelectric, piezo resistive, and capacitive. One of previous research done by Jaisree Meenaa Pria K N J, Sowmya S, and Steffie ManoChandra Devi K, Meenakshi Sundaram N on simulation of cantilever based sensor for smart textile application.to measure a physiological parameter like blood pressure. Comparison between three piezoelectric materials Lead Zirconium Titanate, Bismuth Germanate and Barium Sodium Niobate. The optimized experimental result shows that PZT is more sensitive to blood pressure variations showing an increased electric potential and displacement of 0.2753V and 3.8935um respectively (KNJ et al., 2013).

A research done by Lokesh Singh Panwar, Sachin Kala, Sushant Sharma, Varij Panwar, Shailesh Singh Panwar on design of MEMS piezoelectric blood pressure sensor. Using three piezoelectric material materials Lead Zirconium Titanate (PZT-5A), Bismuth Germanate and Barium Sodium Niobate as a sensing layer of cantilever based sensor. The optimized simulation indicates PZT-5A shows the maximum electric potential across the sensor electrodes and displacement of 2.52V and 4.95µm for normal human body diastolic blood pressure (80mmHg) among the other piezoelectric material used as a sensing layer of cantilever (Panwar et al., 2017) .

A fabrication process for structure of capacitive cantilever for smart fabric applications is done by Yang Wei, Russel Torah, Kai Yang, Steeve Beeby and John Tudor.

Screen printed capacitive free-standing cantilever use as a motion detector in clothing to monitor activity if the wearer in unconscious in safety critical applications is done by Yang Wei, Russel Torah, Kai Yang, Steeve Beeby and John Tudor. Results from the article shows that larger capacitance have lower noise shows the best response because it has the lowest resonant frequency (215Hz) (Wei et al., 2012b). It has the best motion response of the sensors tested because it is relatively close to frequency of human movement.

A research done by Yang Wei, Russel Torah, Kai Yang, Steve Beeby and John Tudora, for fabrication of humidity sensor by using screen printing technique. Results shows that fabrication of low cost humidity sensor on fabric by using screen printing technique(Kutzner et al., 2013). Thinkable applications are health care applications like incontinence detection or control of water loss during sport.

Research work done by Ali Eshkeiti to fabricate the stretchable printed wearable sensor for monitoring of temperature, electrocardiogram and body movement(Eshkeiti, 2015).

Piezoelectric cantilever structure fabrication by using the screen printing technique for smart fabric sensor applications done by Yang Wei, Russel Torah, Kai Yang, Steve Beeby and John Tudor(Wei et al., 2012a). The maximum output produced by cantilever are 38 and 27 mV at an acceleration of 11.76 m/s^2, respectively.

A research work done by D. Lo Presti, C. Massaroni, D. Formica, F. Giurazza, E. Schena, P. Saccomandi, M.A. Caponero, M. Muto on cardiac and respiratory rates monitoring during MR examination by a sensorized smart textile (Presti et al., 2017). In this work the proposed smart textile based on six FBGs is suitable to collect cardiac activities and monitoring respiratory during MR examination without artifacts on images, providing useful information about condition of patient.

A research work done by Giovanelli, Davide Farella, Elisabetta to build a force sensing resistor (FSR) based on resistive material (Velostat) and printed conductive ink electrodes on polyethylene terephthalate (PET) substrate for wearable application and check sensor response to pressure in the range 0–2.7 kPa. FSR working principle is based on the variation of sensor conductivity itself (Giovanelli & Farella, 2016).

Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, Kasper Hornbaek done research work on e-textile patch for pressure, hover and touch input, using both capacitive and resistive sensing. E-textile patch can be easily ironed onto most textiles, in any location. E-textile or z-patch can be in applications like controlling a music player, text entry and gaming input (Strohmeier et al., 2018).

2.10 Summary

Table 2.4 shows the summary of previous related work. From the table, it can be seen various sensor design having difference sensing platform and structure for various smart textile application.

Table 2. 4 Previous work on smart textile, sensors and applications

Author/Year	Application	Structure and Dimension	Output Parameter
Yang Wei, Russel Torah, Kai Yang, Steve Beeby and John Tudora, 2012	Motion detector in safety critical condition.	Structure: Rectangle shaped capacitive cantilever structure Dimensions: Sample 1 Beam (mm) 9×10 Electrode (mm) 8×8 Sample 2 Beam (mm) 12×10 Electrode (mm) 11×8 Sample 3 Beam (mm) 15×10 Electrode (mm) 14×8 Sample 4 Beam (mm) 18×10 Electrode (mm) 17×8	Sensitivity: Static Capacitances Sample 1 Measured value (pF) 3.94(pF) Experimental resonant frequency (Hz) 760(Hz) Modelling resonant frequency (Hz) 780(Hz) Sample 2 Measured value (pF) 6.02(pF) Experimental resonant frequency (Hz) 410(Hz) Modelling resonant frequency (Hz) 440(Hz) Sample 3 Measured value (pF) 6.29(pF)

			Experimental resonant frequency (Hz) 280(Hz) Modelling resonant frequency (Hz) 280(Hz) Sample 4 Measured value (pF) 7.59(pF) Experimental resonant frequency (Hz) 215(Hz) Modelling resonant frequency (Hz) 200(Hz)
C. Kutzner, R. Lucklum, R.Torah, S. Beeby, J. Tudor, 2013	Control of water loss during sport or health care application like incontinence detection.	Structure: Design: pair of interdigital or parallel alignments (Electrode) Parameter: Width: 1mm (electrode) Thickness: 125µm Interface layer thickness 120µm Electrode layer thickness 5µm	Sensitivity: Humidity range: 30% to 90% Response time: 60s to 140s

Jaisree Meenaa Pria K N J, Sowmya S, and Steffie Mano Chandra Devi K, Meenakshi Sundaram N, 2013	Blood pressure or body temperature	Structure: Rectangle shaped piezoelectric cantilever structure Dimensions: Length: 300-350µm Width: 100µm Thickness: 8µm Materials: Barium sodium niobate Bismuth germanate Lead zirconate Titanate	Sensitivity: MAXIMUM DISPLACEMENT FOR 80 mmHg (µm) Barium sodium niobate 4.8275µm Bismuth Germanate 6.5014µm Lead Zirconium Titanate 7.5263µm MAXIMUM VOLTAGE FOR 80 mmHg (V) Barium sodium niobate 0.2231V Bismuth germanate 0.3476V Lead Zirconium Titanate 0.7664V
Yang Wei, Russel Torah, Kai Yang, Steve Beeby and John Tudor, 2012	Smart fabric applications	Structure: Rectangle shaped Piezoelectric Cantilever Structure Dimensions: Sample one: Electrode (mm) 11×8 Beam (mm) 12×10 PZT (mm) 12×10 Sample two: Electrode (mm) 14×8	Sensitivity: Resonant frequencies at an acceleration of 11.76 m/s2: Sample one: 390 Hz Sample two: 260 Hz The maximum output voltages at an acceleration of 11.76m/s2:

		Beam (mm) 15×10 PZT (mm) 15×10	. Sample one: 37 mV Sample two: 27 mV
Ali Eshkeiti, 2015	Monitoring body movement, temperature and electrocardiogram	Structure: Wavy and meander structure Parameter: Width: 400µm, 800µm and 1600µm Radius: 2000µm, 4000µm, 6000µm and 8000µm Angle: 30, 45 and 60 degrees Stretching Line: 1mm, 2mm, 3mm, and 4mm	Sensitivity: Resistance: 1Ω to 1.4Ω, 1.9Ω, 2.4Ω and 3.4Ω (W=1600µm, r=4000µm) 2.5Ω, 2.9Ω, 3.6Ω, 4.2Ω and 5.2Ω, (W=1600µm, r=8000µm) 1Ω to 1.6Ω, 2.4Ω and 3.4Ω (W=800µm, r=2000µm) 2.7Ω, 4.7Ω and5.5Ω (W=800µm, r=4000µm) 3.5 Ω, 5 Ω, 5.8 Ω and 6.5 Ω (W=800µm, r=6000µm)
Yang Wei, Russel Torah, Kai Yang, Steve Beeby and John Tudor, 2012	Smart fabric applications	Structure: Rectangle shaped capacitive cantilever structure Dimensions: Sample No.1 Beam(mm) 9×10 Electrode(mm) 8×8 Sample No.2 Beam(mm) 12×10	Sensitivity: Static Capacitance Measured value (pF) Sample No.1 3.94(pF) Sample No.2 6.02(pF) Sample No.3 6.29(pF) Sample No.4 7.59(pF)

		Electrode(mm) 11×8 Sample No.3 Beam(mm) 15×10 Electrode(mm) 14×8 Sample No.4 Beam(mm) 18×10 Electrode(mm) 17×8	
Lokesh Singh Panwar, Sachin Kala, Sushant Sharma, Varij Panwar, Shailesh Singh Panwar, 2017	Blood pressure sensor	Structure: Rectangle shaped piezoelectric cantilever structure Dimensions: Length: 300-350µm Width: 100µm Thickness: 8µm Materials: Barium sodium niobate Bismuth germanate Lead zirconate Titanate (PZT-5A)	Sensitivity: MAXIMUM DISPLACEMENT FOR 80 mmHg (µm) Barium sodium niobate 1.87µm Bismuth Germanate 3.54µm Lead Zirconium Titanate 4.95µm MAXIMUM VOLTAGE FOR 80 mmHg (V) Barium sodium niobate 1.0V Bismuth germanate 1.42V Lead Zirconium Titanate 2.52V

D. Lo Presti, C. Massaroni, D. Formica, F. Giurazza, E. Schena, P. Saccomandi, M.A. Caponero, M. Muto, 2017	Respiratory and cardiac rates monitoring during MR examination by a sensorized smart textile	Using six FBGs sensor	Sensitivity: Heart rate value both during apnea and quiet breathing (~0.93 Hz in quiet breathing and ~0.96 Hz during the apnea); conversely the second volunteer showed an heart rate increase during apnea (~1.7 Hz) compared to the quiet breathing heart rate (~0.9 Hz).
Giovanelli, Davide Farella, Elisabetta, 2016	Wearable applications	Materials: Resistive material (Velostat) Conductive ink electrodes Substrate material: polyethylene terephthalate (PET) Structure: single point sensor interdigital structure Dimensions: Single point (15 × 30 mm)	Output: angular coefficient (the derivative) of the best fit line is m = 1.3×10 −4 V/Pa for 0.9 kPa offset, and m = 5.9 × 10 −4 V/Pa for 1.8 kPa offset.
N Siddaiah, B Manjusree, A L G N Aditya, D V Rama Koti Reddy, 2017	Biological and healthcare applications	Structure: U-shaped triple coupled cantilever Dimensions: 100µm*20µm*2µm Material: Silicon(c) and P-silicon	Sensitivity: Displacement: $3.4777*10^{6}$µm

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this chapter, methodology on designing and simulating the piezoelectric cantilever structure is discussed. The chapter start with explanation on the flow diagram of this research. Next, parameters for piezoelectric based cantilever structure are defined. After that, analysis the performance of sensor. Lastly, showing the simulation result using COMSOL Multiphysics.

3.2 The Flow Diagram of Study

The flow chart in Figure 3.1 describes the design procedures of research.

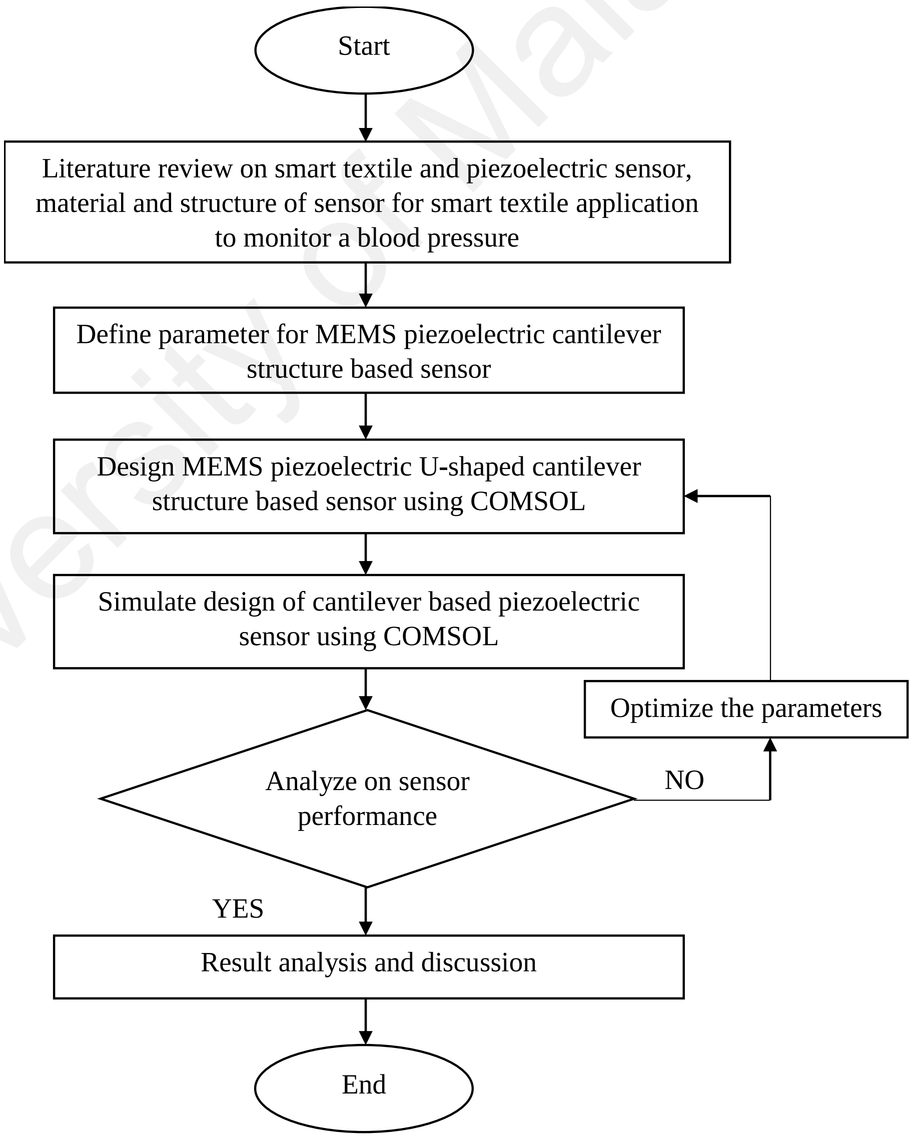


Figure 3. 1 Flow chart for piezoelectric cantilever based sensor design for smart textile

This research project begins with reading all the related literature material on smart textile, piezoelectric sensor, application of the sensors for smart textile to measure the physiological parameters like blood pressure and special type of cantilever focusing on U-shaped. Going through literature review process will give brief ideas on ‘how’ and ‘what’ this project will be doing. All the related theory and useful formula for cantilever based piezoelectric sensor such spring constant, and Stoney’s Equation is collected during the literature review.

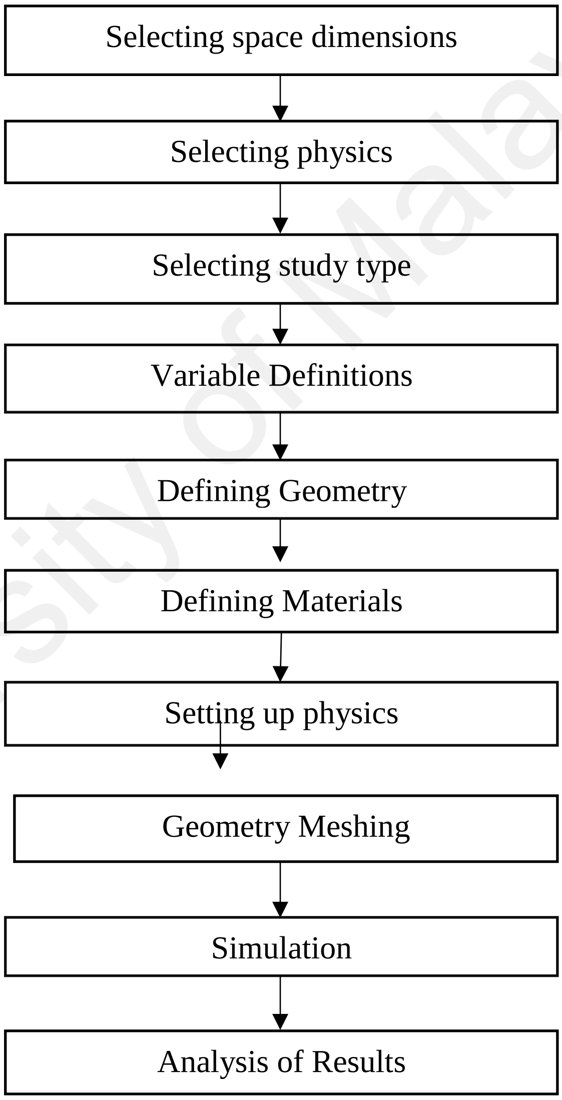


Figure 3. 2 Flow chart for developing U-shaped cantilever on COMSOL

From all the information gathered in literature review stage, sensor’s design specification is determined. From the design spec, sensor is modelled using COMSOL Multiphysics software. Based on flow chart shown in Figure3.2. Important steps to simulate the model in COMSOL Multiphysics are begin with building the geometry, define the parameters and choose related study depends on the requirement of project, selecting the materials, setting the boundary conditions, meshing the model, compute the desired parameter and finally analyze the results. The result obtained from simulations are cantilever deflection which shows a displacement and electric potential.

To compare the cantilever behavior and performance, a design with different materials and length are simulated. Results from the simulation is obtained and proceed with the analysis stage. Next. Discussion is made based on the result obtained. Finally, a conclusion is made referring to the project outcome and research project recommendation or future improvement is proposed.

3.3 Structure Parameters of Mems Piezoelectric Sensor

For this project, MEMS piezoelectric cantilever sensor is design for smart textile to monitor a blood pressure based on research paper with title Simulation of Cantilever Based Sensors for Smart Textile Applications by (KNJ et al., 2013) . The structure is a rectangle shape of cantilever.

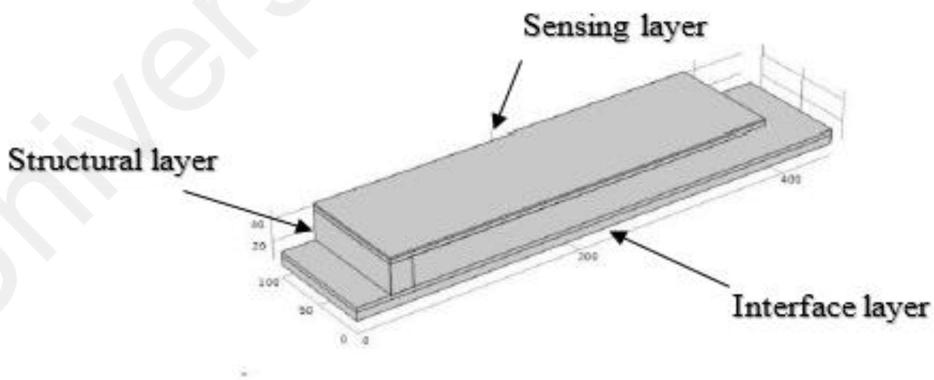


Figure 3. 3. 3D-Model of MEMS piezoelectric cantilever sensor (KNJ et al., 2013)

The cantilever integrated over a nylon cloth is composed of a sensing layer, structural layer and interface layer. Materials used in various layers of the smart textile sensor as shown in Table 3.1

Table 3. 1 Materials used in various layer of smart textile sensor

Layer	Material
Sensing layer	Barium sodium niobite/Bismuth Germanate/Lead zirconate titanate
Structural layer	Polysilicon
Interface layer	Silicon dioxide

The dimensions of cantilever are set as: length of cantilever 350um, thickness of cantilever 8um and width of cantilever is 100um. Normally human blood pressure varies between minimum (diastolic) and maximum (systolic) during each heartbeat. The normal diastolic blood pressure is less than 80 mmHg and normal systolic blood pressure is less than 120 mmHg. The systolic blood pressure can go higher than 160 mmHg and diastolic pressure can goes higher than 100 mmHg as shown in table 3.2. So applied pressure used for this research ranging from 50 mmHg (6666.1Pa) to 180 mmHg (23998Pa). Table 3.2 shows the sensor design parameter (KNJ et al., 2013) for the model in Figure 3.3

Table 3. 2 Sensor Parameter based on (KNJ et al., 2013)

Items	Specifications
Cantilever shape	Rectangle
Length	300µm-350µm
Width	100µm
Thickness	8µm

3.4 U-shaped Design Cantilever Parameters

For this project, a cantilever is designed in U-shaped by using different piezoelectric materials as a sensing layer of cantilever for the optimization purpose. In designing the U-shaped cantilever, first we check sensitivity of sensor by using PZT-5H and $BaTiO_3$ piezoelectric material as a cantilever sensing layer. Based on results of both materials then choose a suitable piezoelectric material as a sensing layer of cantilever. As mentioned in literature review U- shape cantilever allows dimensions of cantilever to be minimize. Secondly, we check the sensitivity of U-shaped piezoelectric cantilever based sensor by using PZT-5H and $BaTiO_3$ as a cantilever sensing layer at different length of cantilever range from 290µm-330µm and compare the result with the previous study done by (KNJ et al., 2013) using rectangle shaped cantilever at different length is shown in Table 3.2. Structure parameters of U-shaped cantilever is shown in Table 3.3.

Table 3. 3 Different length of cantilever

Length 'L'	Thickness 'T'	Width 'W'
290um	5.5	90
300um	5.5	90
310um	5.5	90
320um	5.5	90
330um	5.5	90

3.5 Development of U-Shaped Cantilever in COMSOL Multiphysics Software

When all the parameter for the U-shaped cantilever are defined, complete sensor has been developed using COMSOL Multiphysics software. Figure 3.4 shows the three-dimensional (3-D) axis-model symmetrical geometry of U-shaped cantilever based sensor for smart textile application build using COMSOL Multiphysics Software. Figure 3.4 – 3.9 shows the U-shaped cantilever at different length of cantilever.

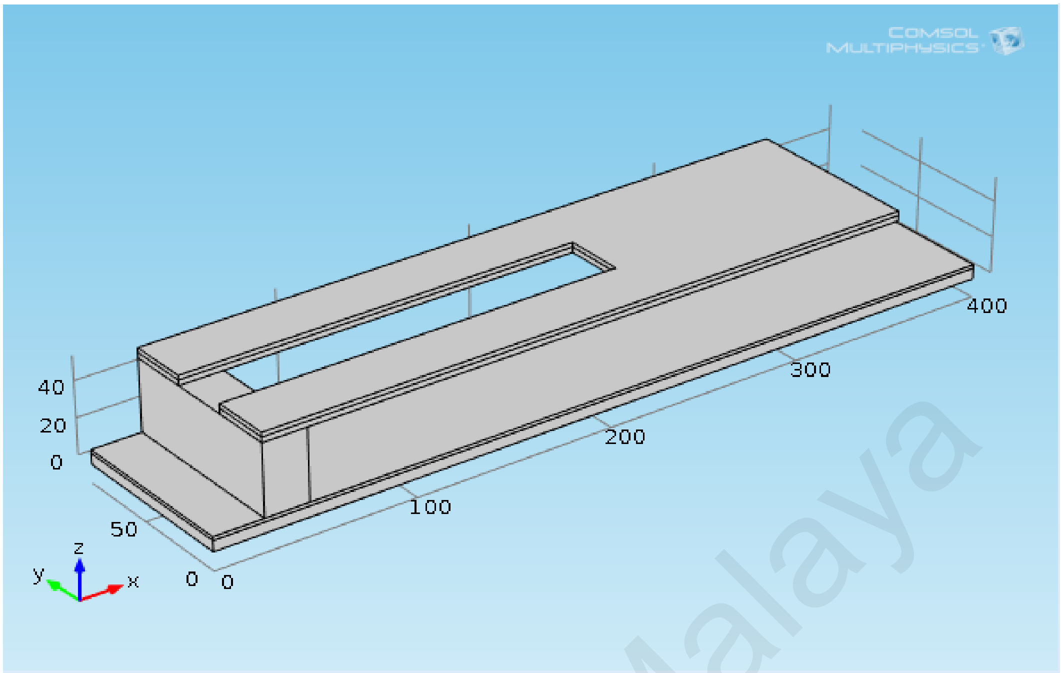


Figure 3. 4 3-D Model of U-shaped MEMS piezoelectric cantilever based sensor

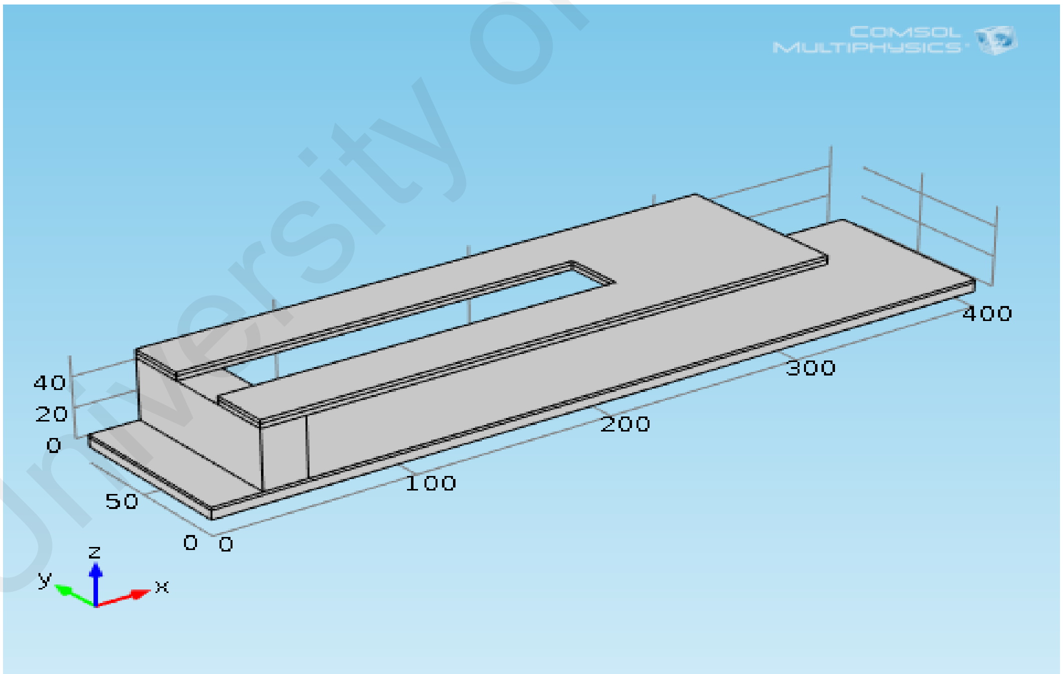


Figure 3. 5 U-Shaped cantilever with L=290µm, W = 90µm and T = 5.5µm

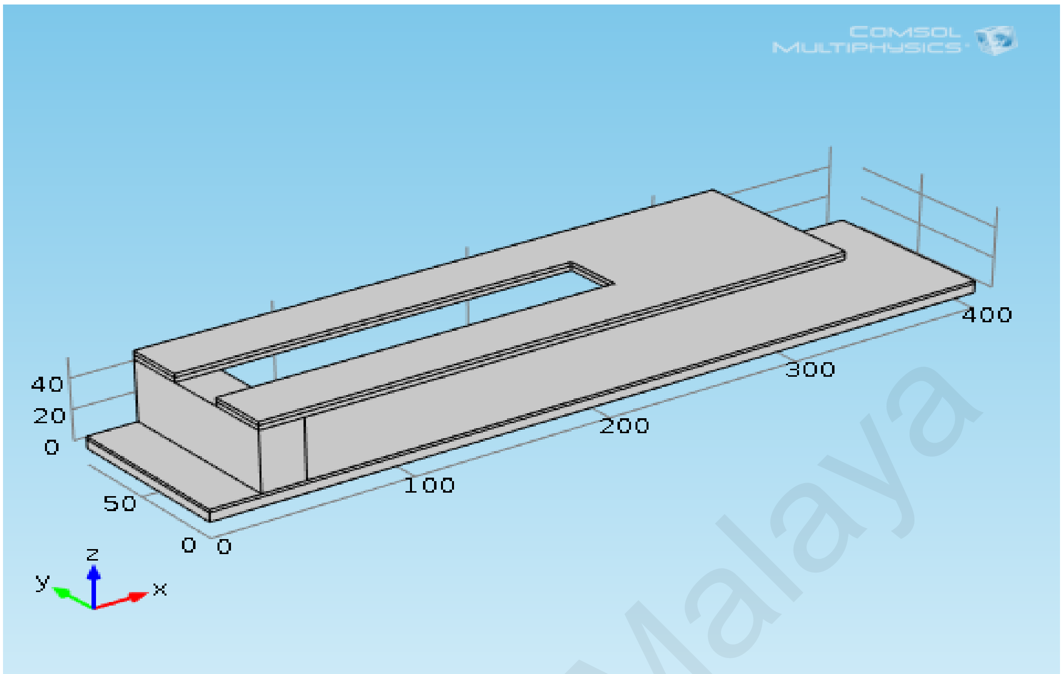


Figure 3. 6 U-Shaped cantilever with L= 300µm, W = 90µm and T = 5.5µm

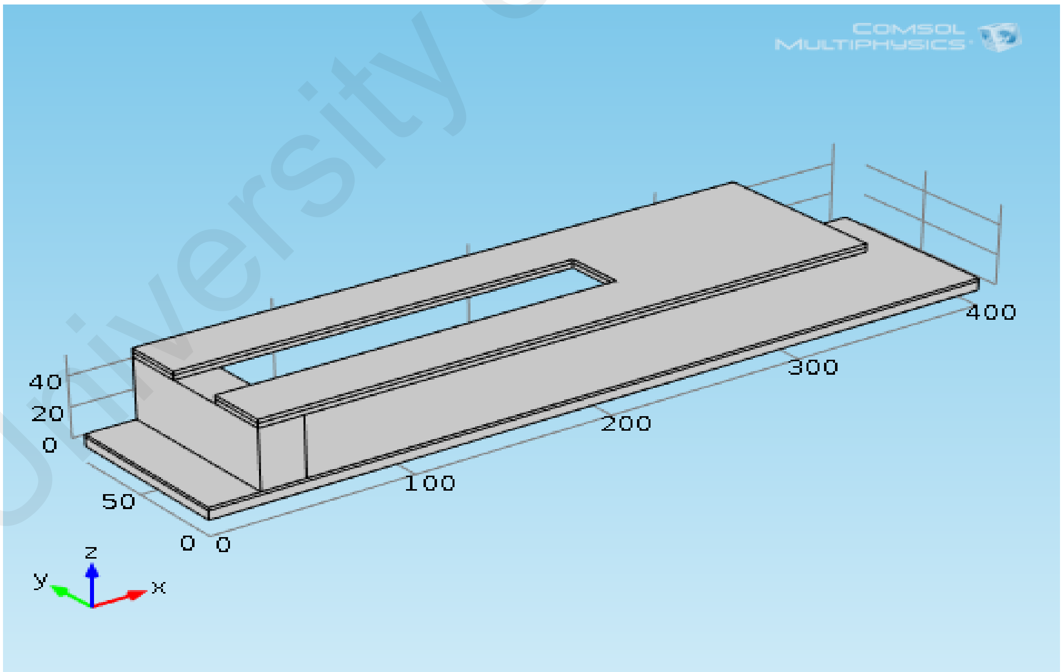


Figure 3. 7 U-Shaped cantilever with L= 310µm, W = 90µm and T = 5.5µm

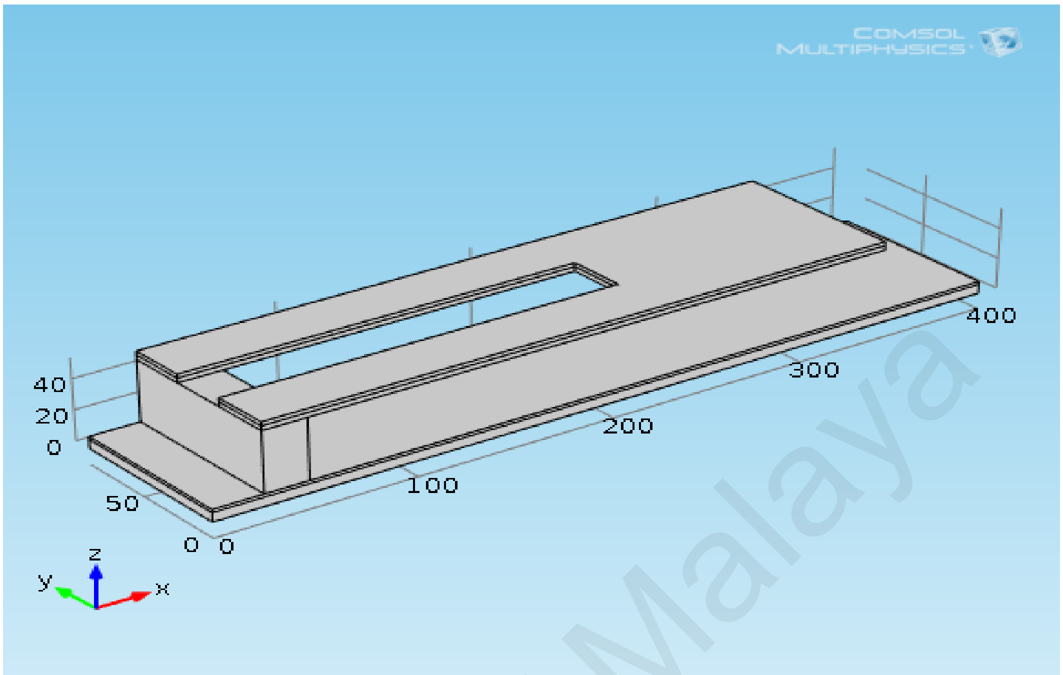


Figure 3. 8 U-Shaped cantilever with L=320µm, W = 90µm and T = 5.5µm

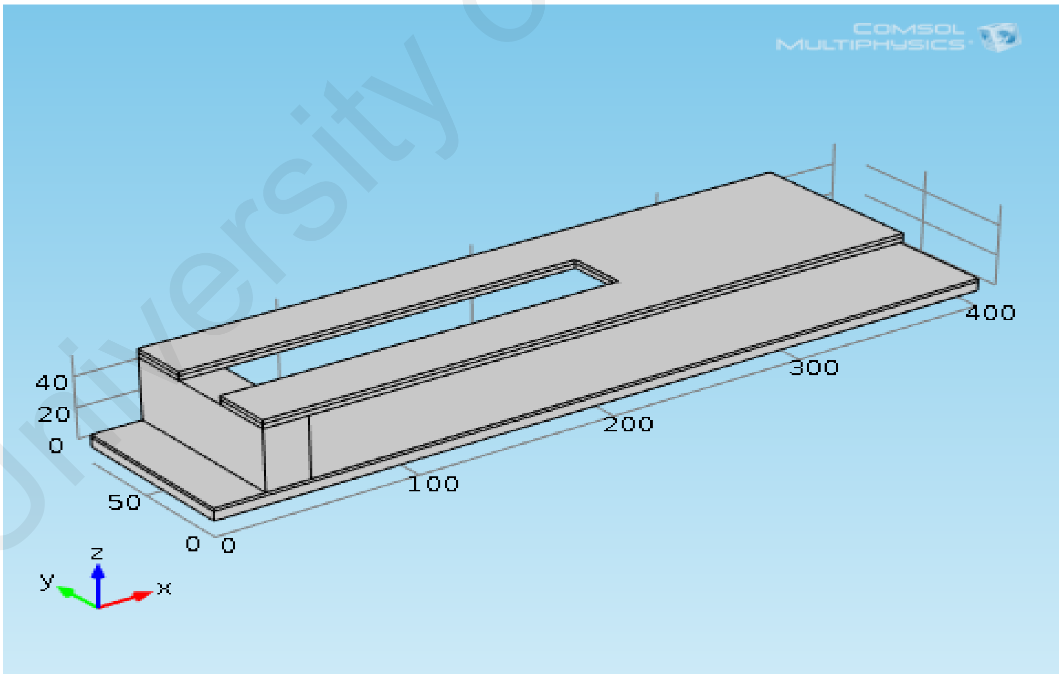


Figure 3. 9 U-Shaped cantilever with L= 330µm, W = 90µm and T = 5.5µm

In this research project materials are used in various layers of smart textile sensor as show in Table 3.4. Polysilicon material used as a structural layer for good contact of electrodes and Silicon dioxide used as an isolation purpose of U-shaped cantilever based blood pressure sensor

Table 3. 4 Materials are used in U-Shaped Cantilever

Layer	Material
Interface layer	Silicon dioxide
Sensing layer	Barium Titanate (BaTiO3)/ Lead zirconate titanate (PZT-5H)
Structural layer	Poly silicon

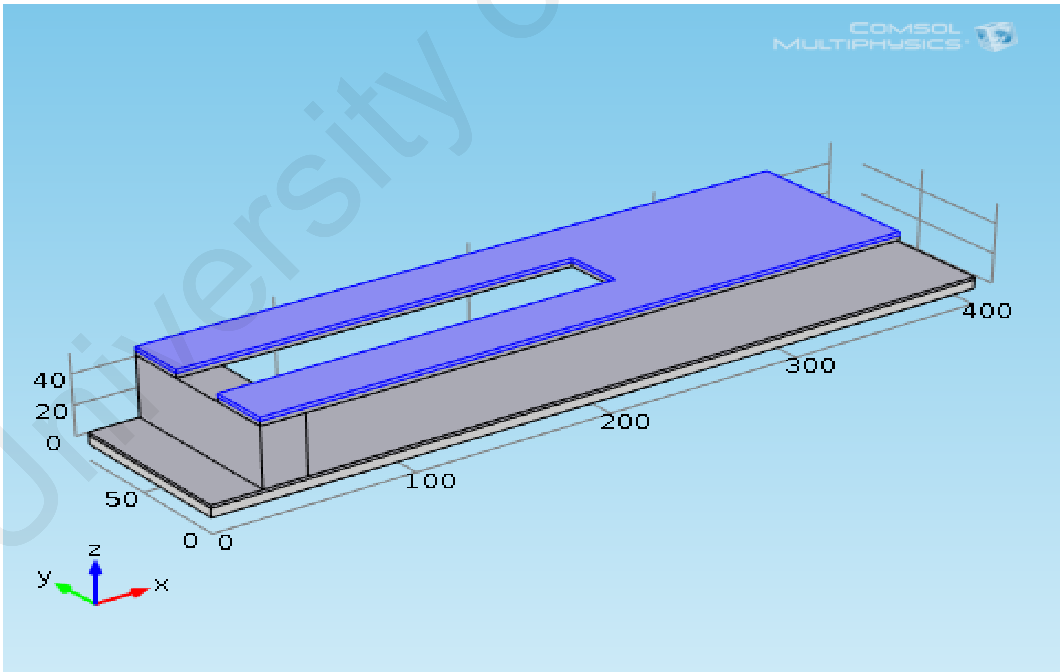


Figure 3. 10 Piezoelectric material used as a sensing layer

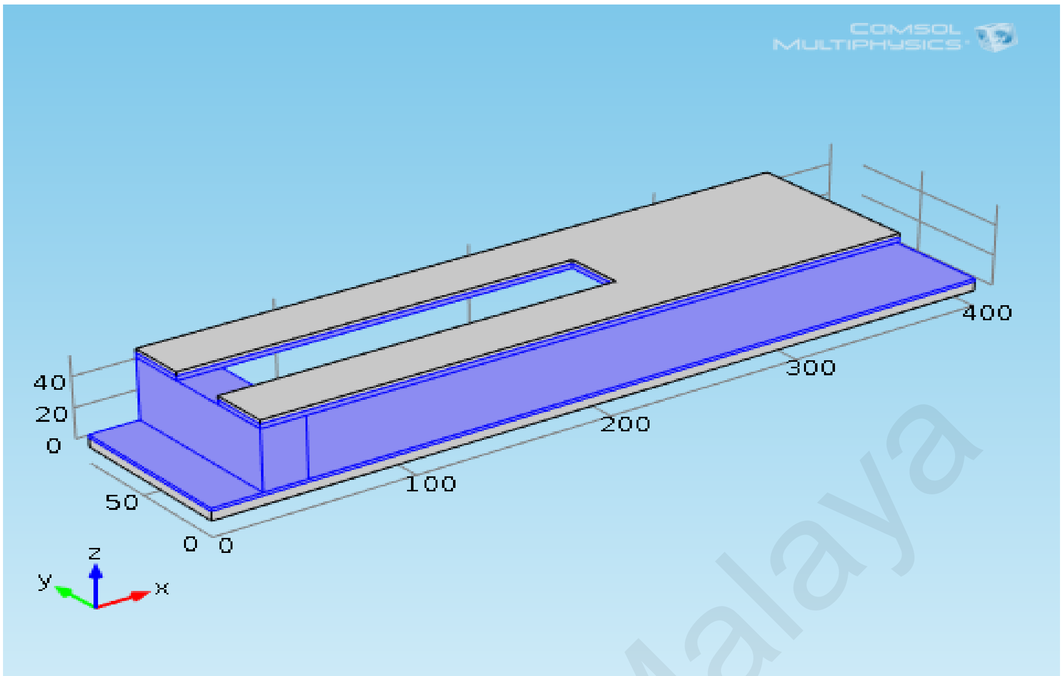


Figure 3. 11 Polysilicon used as a structural layer

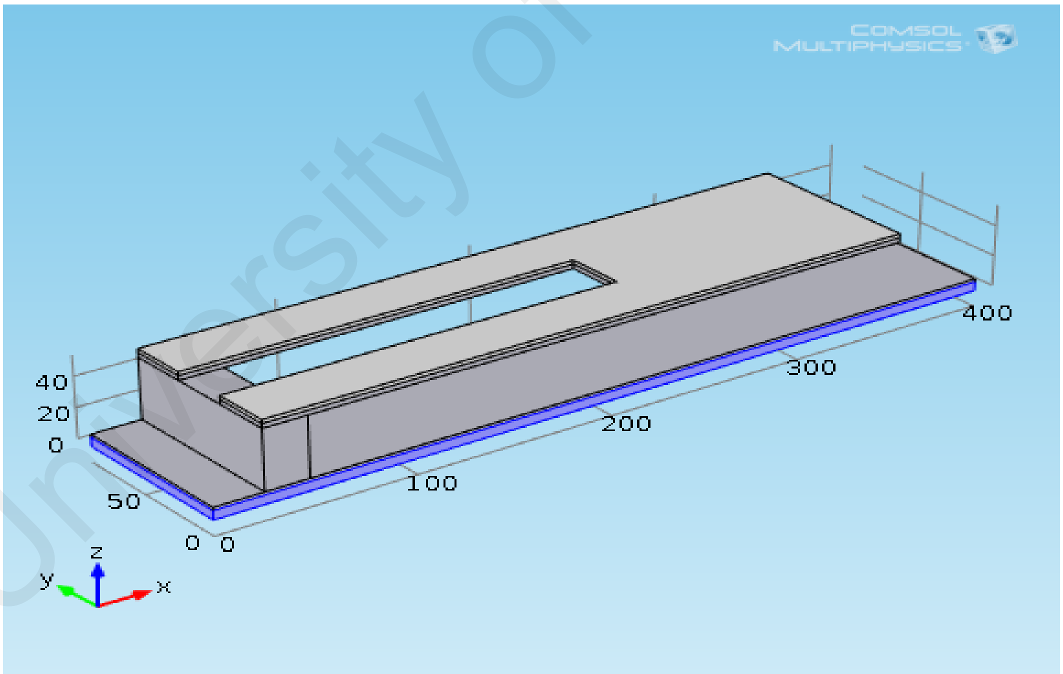


Figure 3. 12 SiO_2 used as an interface layer

Piezoelectric materials are used in cantilever based sensor for smart textile application to monitor a blood pressure. Properties of following piezoelectric materials as shown below in Table 3.5

Table 3. 5 Properties of Piezoelectric material.

Material	Lead Zirconate Titanate (PZT-5H)	Barium Titanate ($BaTiO_3$)
Piezoelectric coefficient [pC/N]	d_{31} = 274 d_{33} = 1000	d_{31} = 79 d_{33} = 580
Electromechanical Coupling Coefficient	k_{31} = 0.39 k_{33} = 0.75	k_{31} = 0.21 k_{33} = 0.49
Relative Permittivity (ε)	1705	1115
Density (g/cm^3)	7.5	5.7
Young's Modulus (GPa)	64	67
Poisson Ratio	0.31	0.22

3.6 Simulation settings

A U-Shaped piezoelectric cantilever based blood pressure sensor for smart textile applications is created in COMSOL Multiphysics software. A material is defined to each layer of cantilever. A load pressure is applied on top of sensing layer or surface of U-Shaped cantilever. The range of pressure is between 50mmHg to 180 mmHg which is converted to Pascal unit and ranging from 6666.1 – 23998Pa. Finally, boundary selections are applied to boundaries applied a boundary load on top of cantilever sensing layer and assign a fixed constraint to one side of cantilever as shown in Figure 3.14. In domain selection select sensing layer as a piezoelectric material (figure 3.15) and interface layer and structural layer as a linear elastic material (Figure 3.16). The motion of structure is constrained in X and Y directions. The piezoelectric U-shaped cantilever based sensor is mesh 'Normal' by using physics-controlled meshing as shown in 3.17.

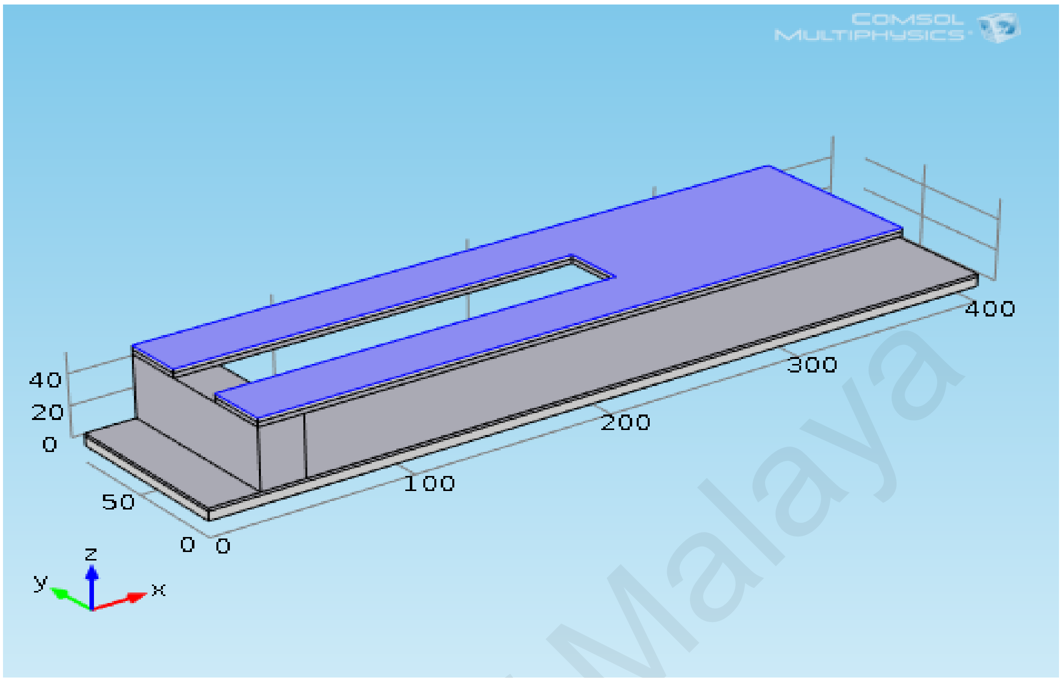


Figure 3. 13 Load pressure applied on top of sensing layer

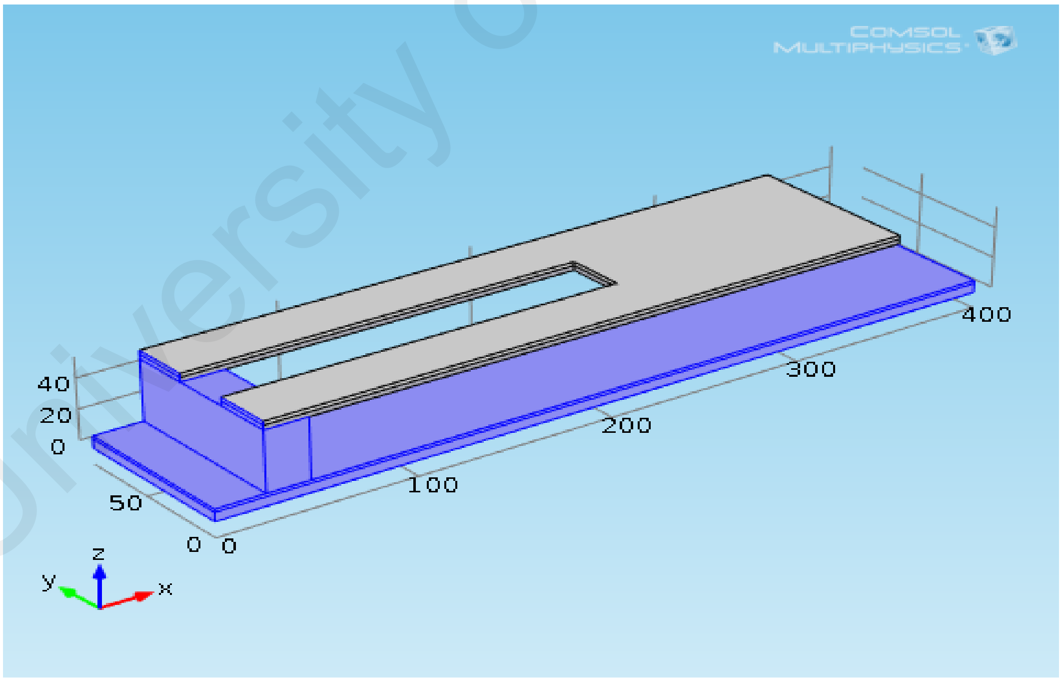


Figure 3. 14 Applied a fixed constraint

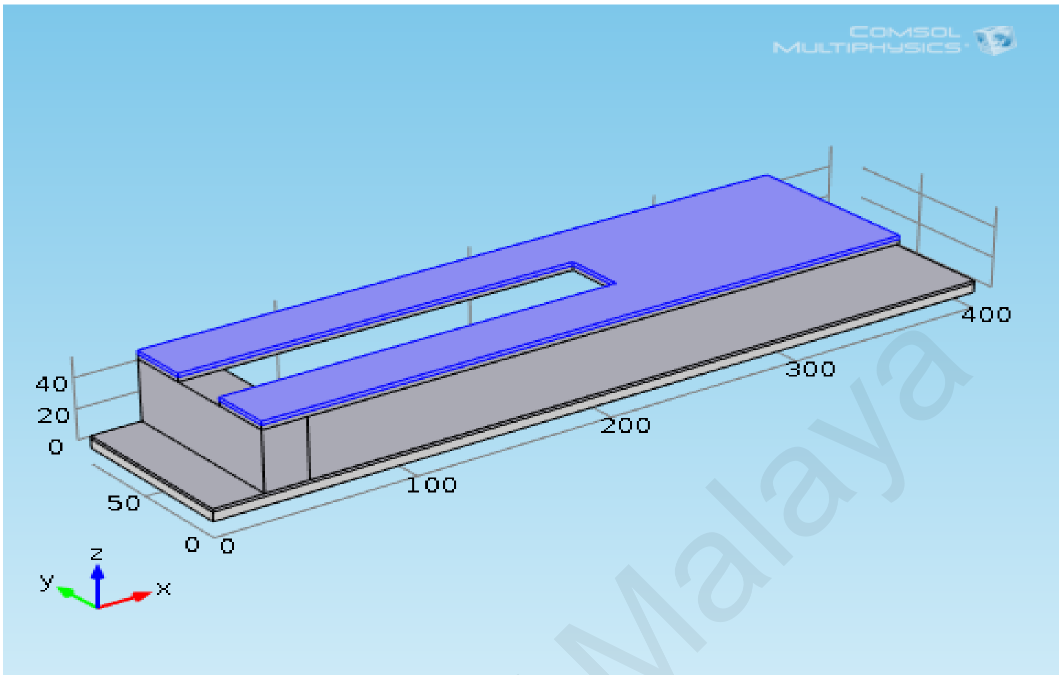


Figure 3. 15 Selection of piezoelectric material

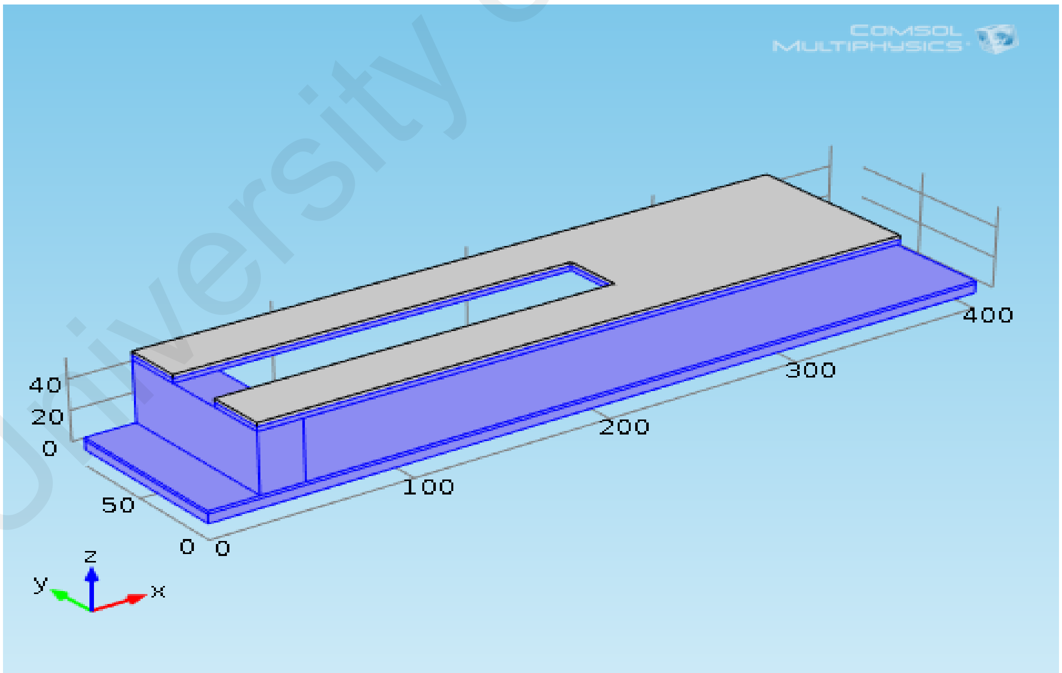


Figure 3. 16 Selection of linear elastic material

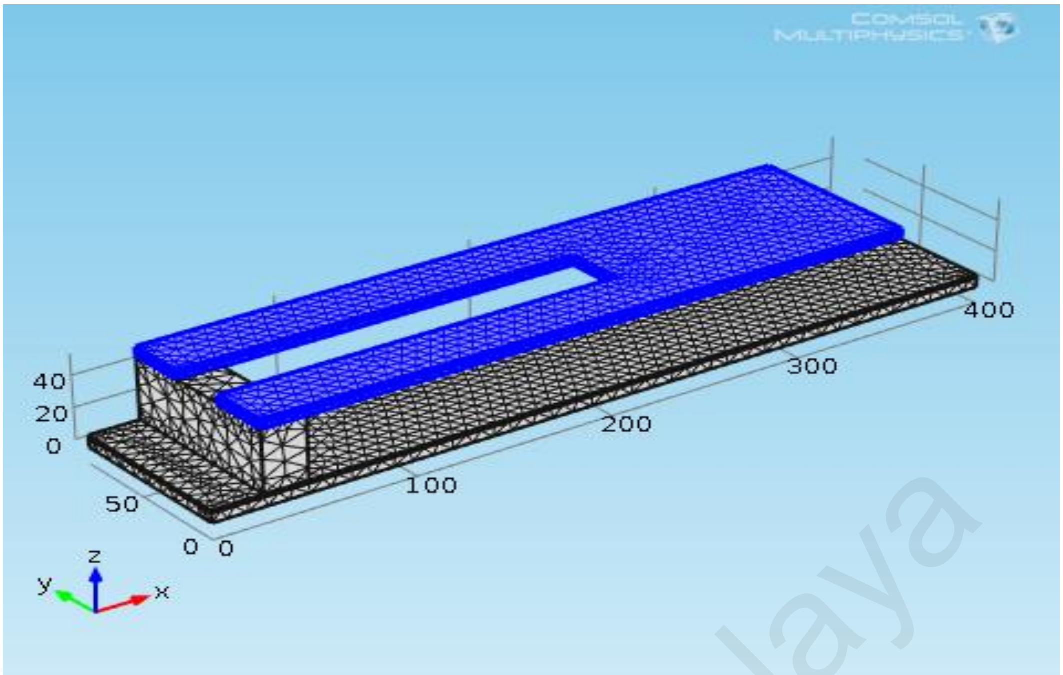


Figure 3. 17. Meshing selection for MEMS Piezoelectric cantilever based sensor

3.7 Summary

This chapter discussed on the methodology approach for this research project. Beginning of this chapter explained the flow chart of the methodology that has been used. Followed by defining the structure parameters of MEMS capacitive pressure sensor based on the research work done previously. Next, the U-shape cantilever design parameter is defined and the varied parameter is chosen for the optimization purpose. Finally, all the design is realized using COMSOL Multiphysics software. Parameter which is varied for the performance study purpose is cantilever length ‘L’ and material.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction

This chapter discussed all the simulation results of U-shaped MEMS piezoelectric cantilever based sensor which had been simulated using COMSOL Multiphysics Software. The result is the deformation of the U-shaped cantilever when a pressure is applied to top surface of piezoelectric U-shape cantilever based sensor. Displacement and electric potential value of the U-shaped MEMS piezoelectric sensor with different piezo materials and at different length 'L' of cantilever. From the result obtained, the performance of the U-shaped cantilever can be analyzed and evaluate.

4.2 Analysis and Discussion of U-Shaped Cantilever for Different Piezoelectric Material

First design of U-shaped cantilever begins with different piezoelectric material (PZT-5H and $BaTiO_3$) and dimensions of cantilever is 'L'= 330um, 'T'= 5.5um, and 'W'= 90um. Applied pressure range is 50mmHg(6666.1Pa)-180mmHg(23998Pa).

Table 4. 1 Parameters of U-shaped Cantilever

Material		Property	Value	Unit
PZT-5H	$BaTiO_3$	Length	330	µm
		Thickness	5.5	µm
		Width	90	µm

4.2.1 Case I: Lead Zirconate Titanate (PZT-5H)

Using PZT-5H piezoelectric material in Case I as a sensitive layer of cantilever. Table 4.1 shows the structure parameter of U-shaped MEMS piezoelectric cantilever based sensor. The sensor for monitoring of human blood pressure integrated over nylon fabric is composed of a structural layer, sensing layer and interface layer. As it shown in Table 3.4 In proposed design silicon dioxide used as an interface layer for isolation purpose, polysilicon used as a structural layer for electrodes good contacts and piezoelectric material is used for sensing element of human body pressure and having piezoelectric property provides output voltage across it due to sensing human blood pressure. Figure 4.2.1- 4.2.14, shows the deflection value of U-shaped cantilever at different value of pressure applied on top surface of PZT-5H cantilever and the range of applied pressure is 50mmHg to 180mmHg. Figure 4.2.1 shows the maximum value of displacement is 7.1597µm given by cantilever at applied low diastolic blood pressure of 50mmHg and whereas sensor gives the maximum value of displacement is 25.775µm when it experienced high systolic blood pressure of 180mmHg on top surface of PZT-5H cantilever. We mostly concerned what deflection value shown by sensor at normal diastolic blood pressure (80mmHg) of human being. In Figure 4.2.4, PZT-5H cantilever shows maximum value of displacement is 11.456µm when a boundary load equivalent of the normal diastolic pressure 80mmHg(10666Pa) was applied and the values increased to 25.775µm for systolic condition 120mmHg(15999Pa). Blue color indicates area of minimum deflection. While red color shows where the maximum deflection developed.

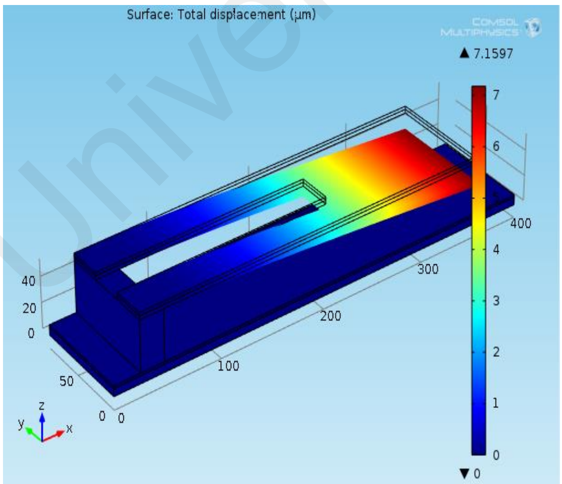


Figure 4.2. 1 Applied Pressure 50mmHg

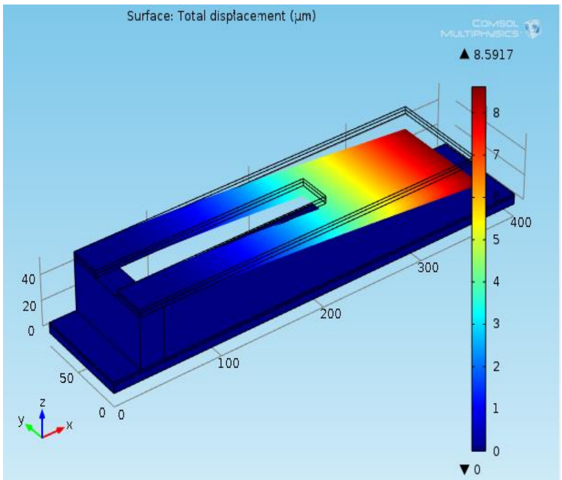


Figure 4.2. 2 Applied Pressure 60mmHg

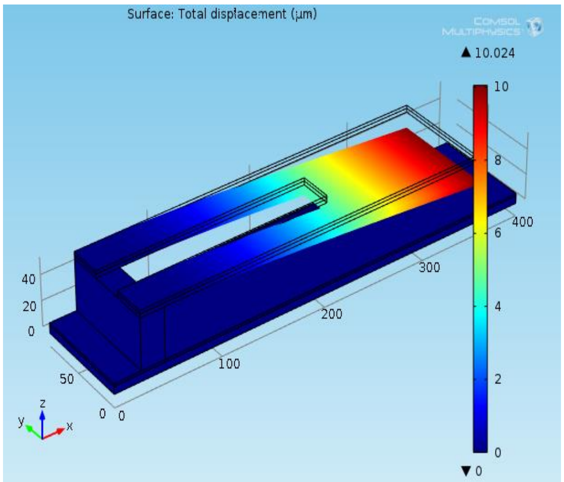


Figure 4.2. 3 Applied Pressure 70mmHg

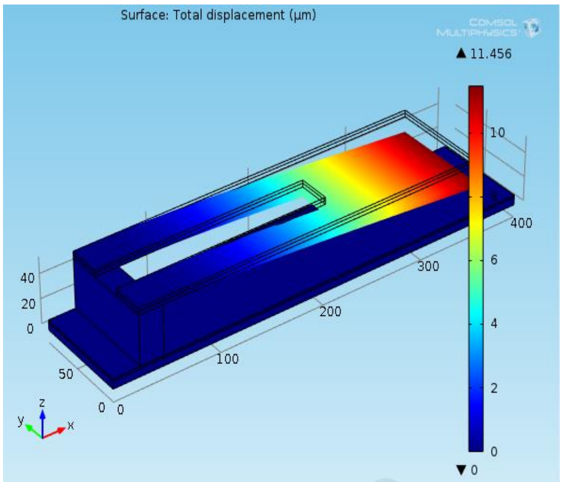


Figure 4.2. 4 Applied Pressure 80 mmHg

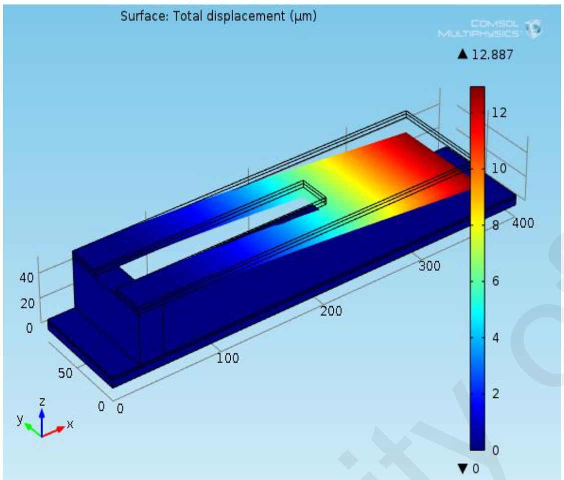


Figure 4.2. 5 Applied Pressure 90 mmHg

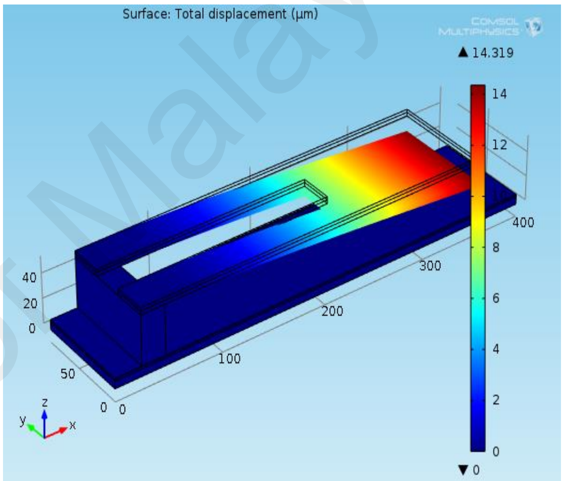


Figure 4.2. 6 Applied Pressure 100mmHg

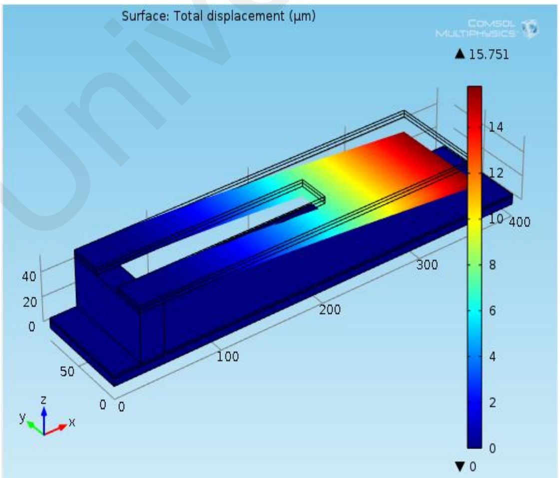


Figure 4.2. 7 Applied Pressure 110mmHg

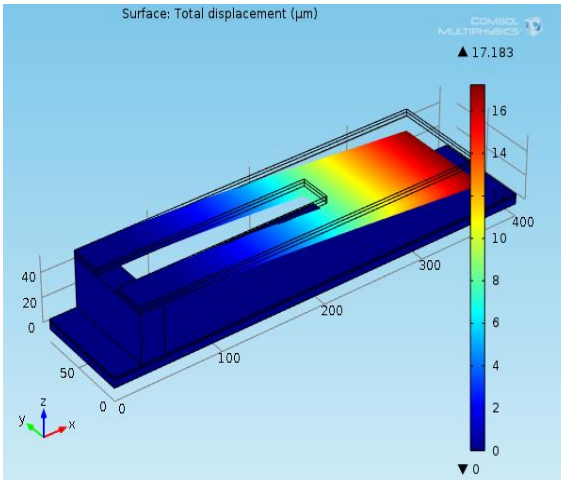


Figure 4.2. 8 Applied Pressure 120mmHg

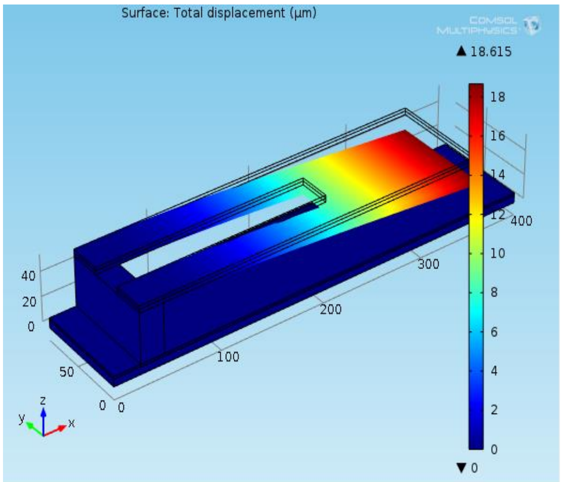


Figure 4.2. 9 Applied Pressure 130mmHg

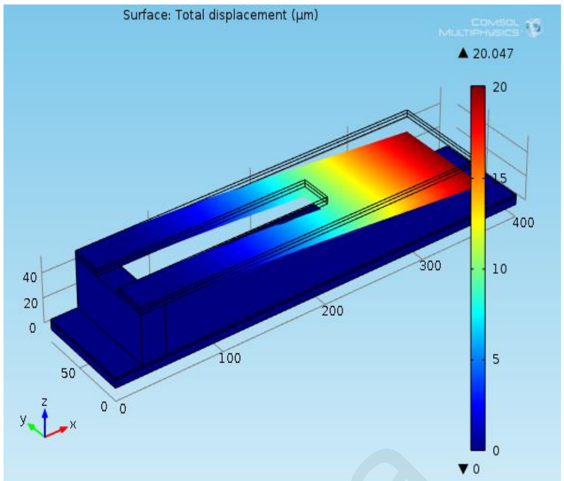


Figure 4.2. 10 Applied Pressure 140mmHg

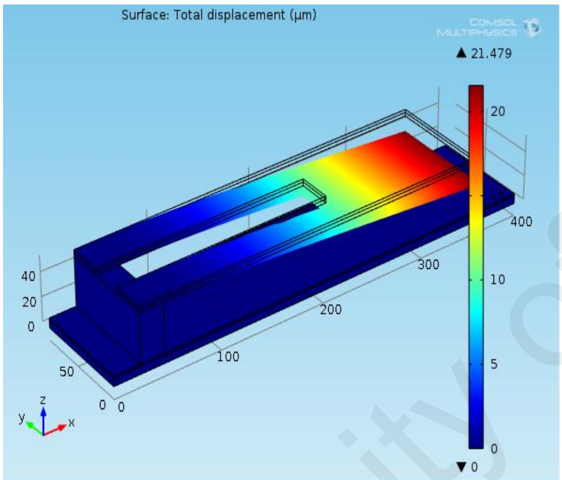


Figure 4.2. 11 Applied Pressure 150mmHg

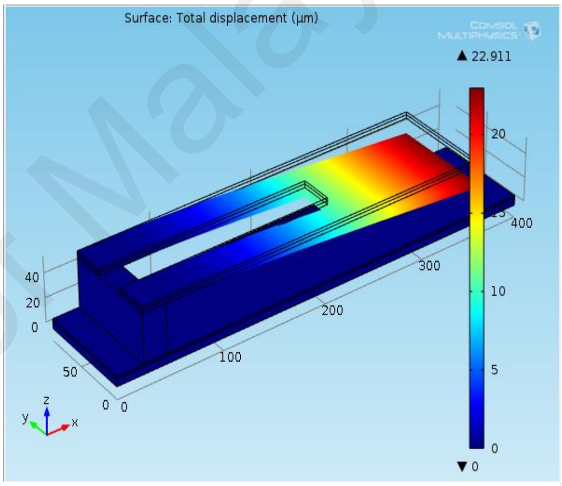


Figure 4.2. 12 Applied Pressure 160mmHg

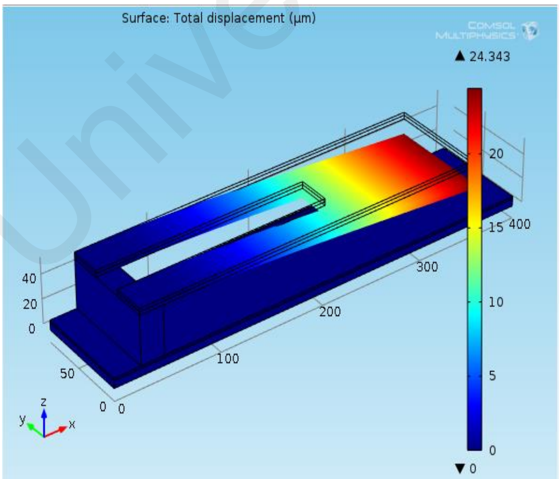


Figure 4.2. 13 Applied Pressure 170mmHg

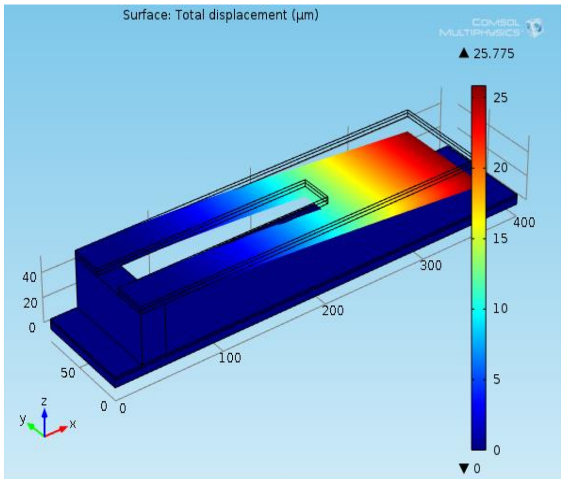


Figure 4.2. 14 Applied Pressure 180mmHg

Graph for Displacement vs Pressure is shown in Figure 4.2.15. From the plotted graph displacement change linearly with the pressure applied. As the input pressure increases the displacement value of PZT-5H material based U-shaped cantilever also increases. Maximum and average displacement at normal diastolic condition are 11.456µm and 4.93404µm. Using equation (2.2) from chapter 2, the calculated maximum displacement value of cantilever is 11.445µm.

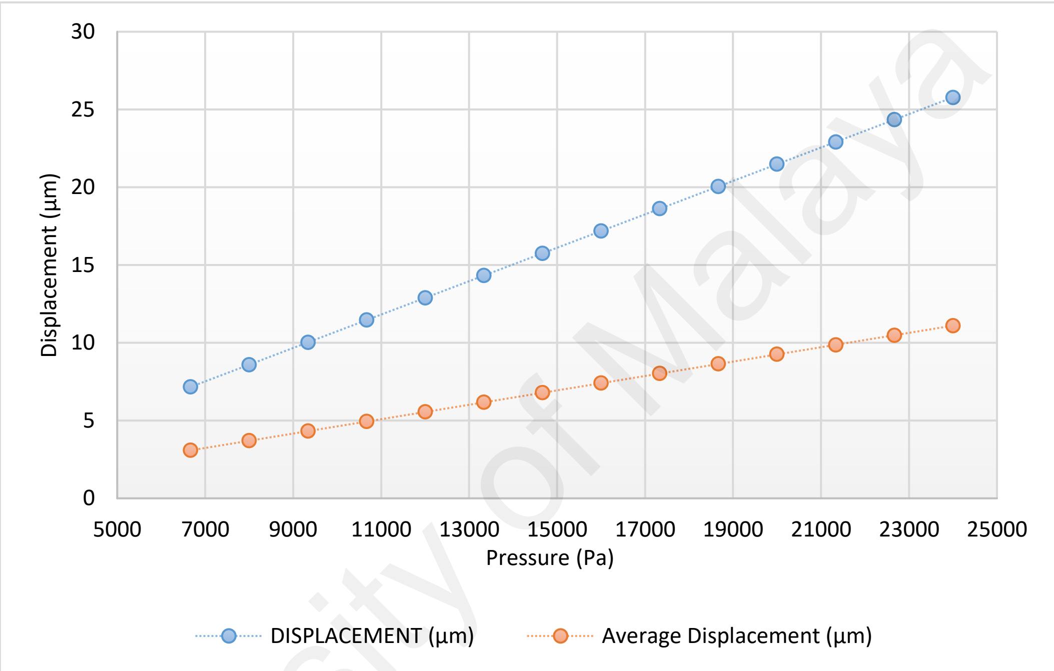


Figure 4.2. 15 Graph of Displacement vs Pressure

As we know in Case I using PZT-5H piezoelectric material as a sensitive layer of cantilever and we check the electric potential value of PZT-5H based U-shaped cantilever. Figure 4.2.16- 4.2.29, shows the values of electric potential given by U-shaped cantilever at different values of pressure applied on top surface of PZT-5H cantilever and the range of applied pressure is 50mmHg to 180mmHg. Figure 4.2.16 shows the maximum and minimum value of electric potential are1.2827V and -0.0366V given by PZT-5H based U-shaped cantilever at applied low diastolic blood pressure of 50mmHg and whereas sensor gives the maximum and minimum value of electric potential are 4.6176V and -0.1319V when it experienced high systolic blood pressure of 180mmHg on top surface of PZT-5H U-shaped cantilever. We mostly focused what value of Electric potential is shown by sensor at normal diastolic blood pressure (80mmHg) of human being. In Figure 4.2.19, PZT-5H cantilever shows maximum and minimum value of Electric potential are 2.0523V and -0.0586V when a boundary load equivalent of the normal diastolic pressure 80mmHg(10666Pa) was applied and the values increased for systolic condition 120mmHg(15999Pa). Blue color indicates area of minimum value of electric potential. While red color shows where the maximum electric potential developed.

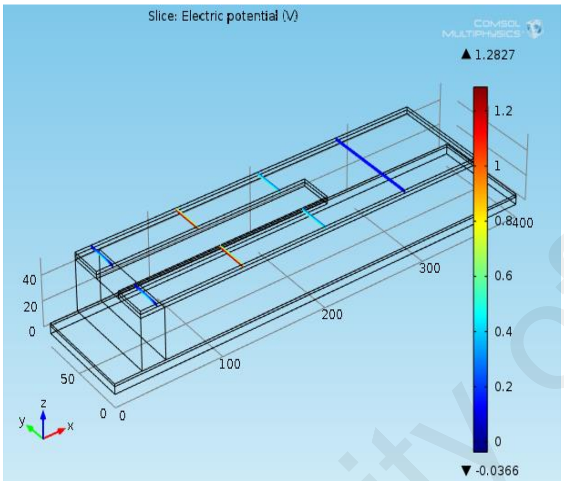


Figure 4.2. 16 Applied Pressure 50mmHg

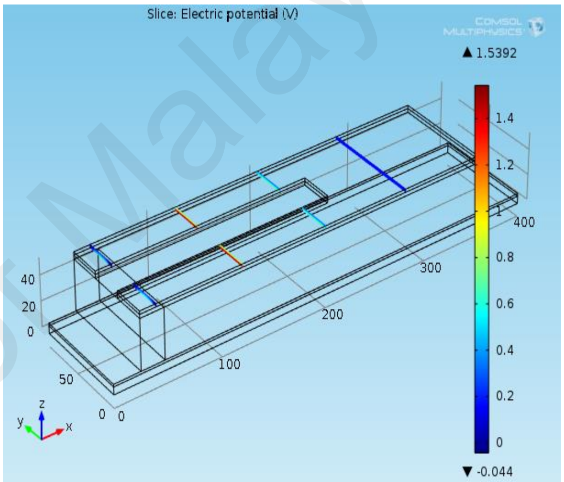


Figure 4.2. 17 Applied Pressure 60mmHg

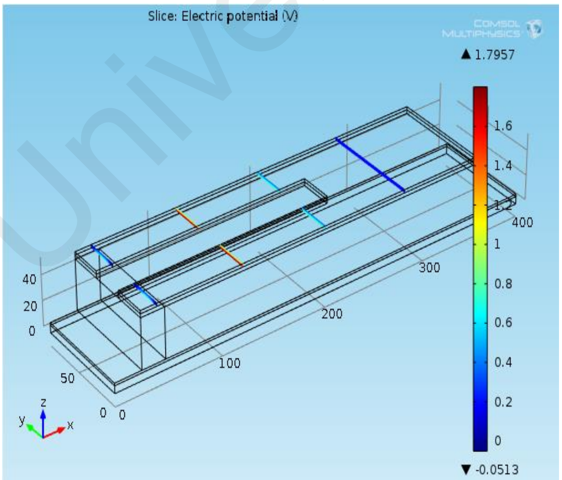


Figure 4.2. 18 Applied Pressure 70mmHg

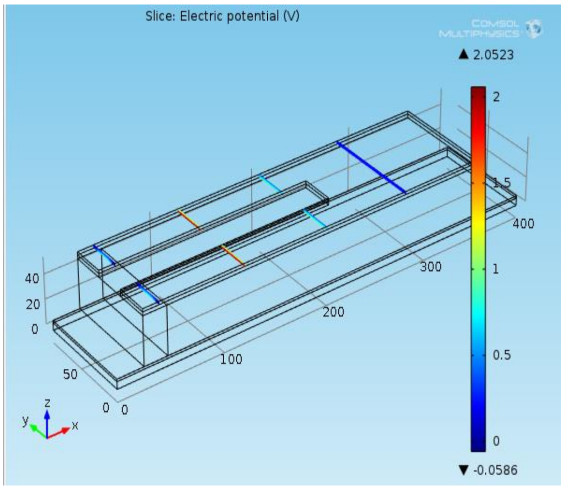


Figure 4.2. 19 Applied Pressure 80mmHg

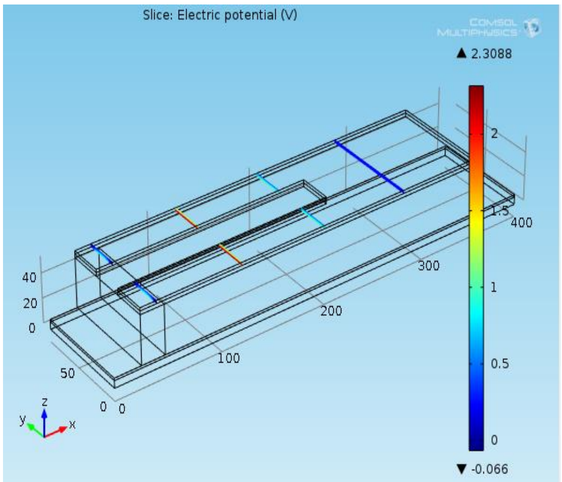


Figure 4.2. 20 Applied Pressure 90mmHg

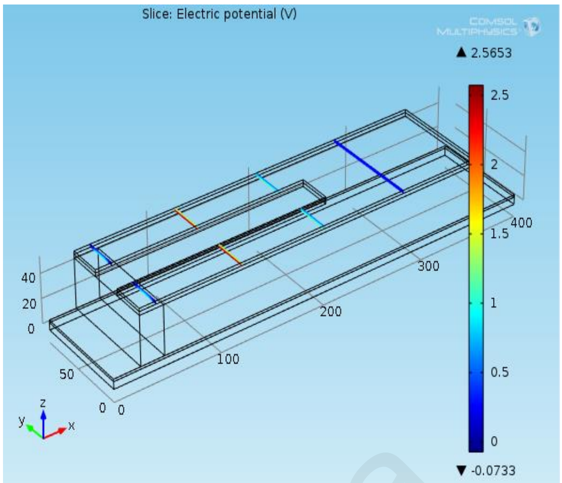


Figure 4.2. 21 Applied Pressure 100mmHg

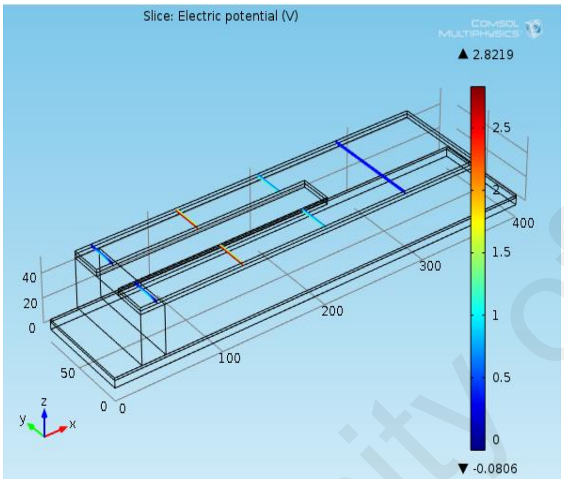


Figure 4.2. 22 Applied Pressure 110mmHg

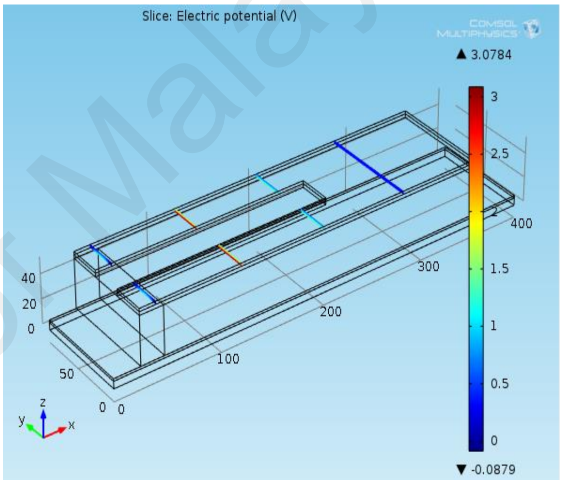


Figure 4.2. 23 Applied Pressure 120mmHg

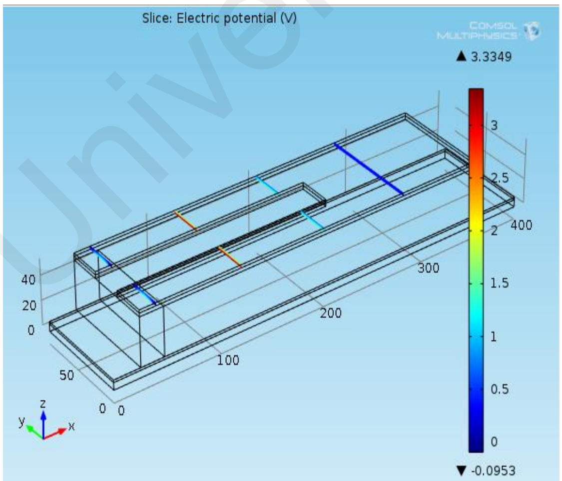


Figure 4.2. 24 Applied Pressure 130mmHg

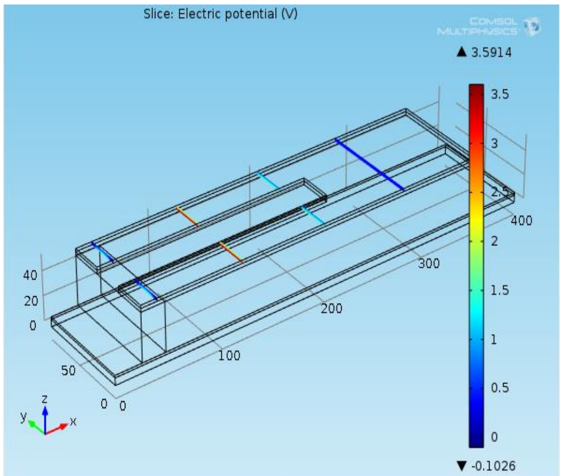


Figure 4.2. 25 Applied Pressure 140mmHg

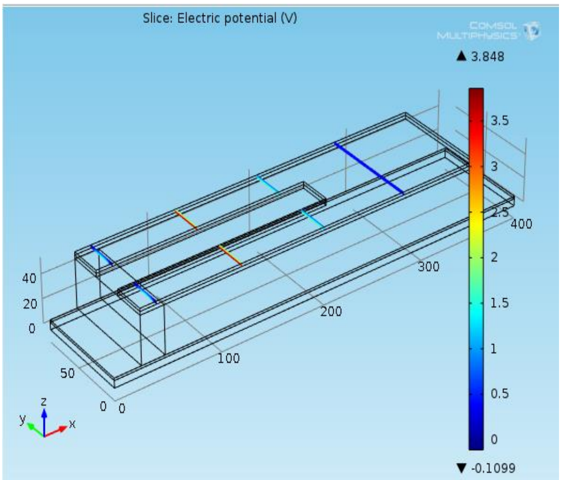


Figure 4.2. 26 Applied Pressure 150mmHg

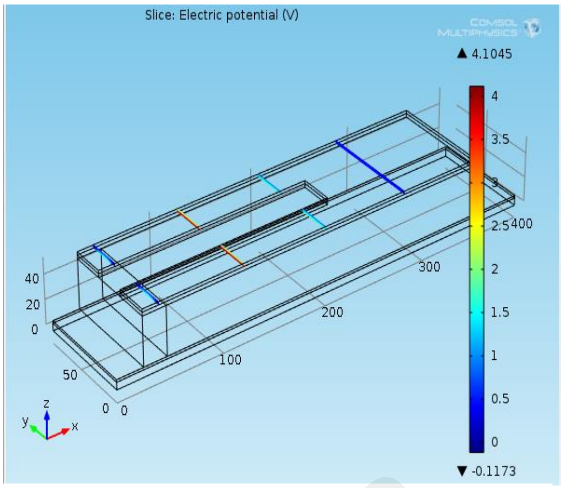


Figure 4.2. 27 Applied Pressure 160mmHg

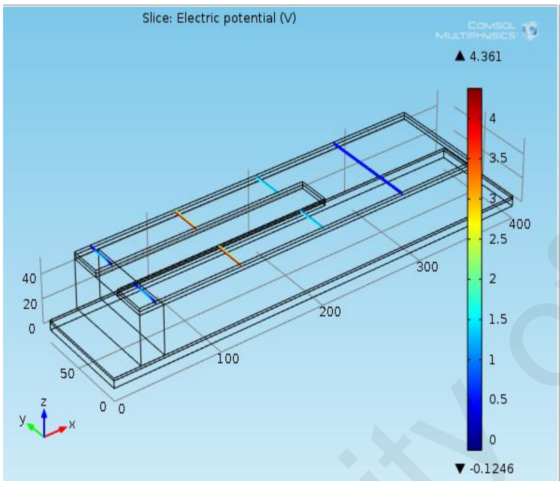


Figure 4.2. 28 Applied Pressure 170mmHg

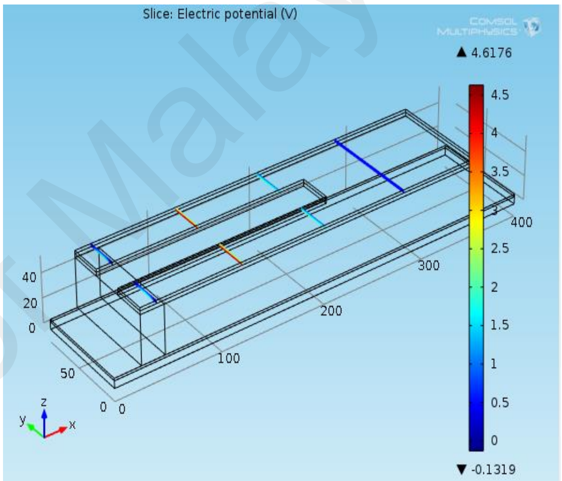


Figure 4.2. 29 Applied Pressure 180mmHg

Graph for Electric potential vs Pressure is shown in Figure 4.2.30. From the graph, the value electric potential at diastolic condition is 2.0523V. As the input pressure increases the electric potential value of PZT-5H material based cantilever also increases. Maximum and minimum electric potential at diastolic condition are 2.0523V and -0.0586V. Red color shows where the maximum electric potential developed.

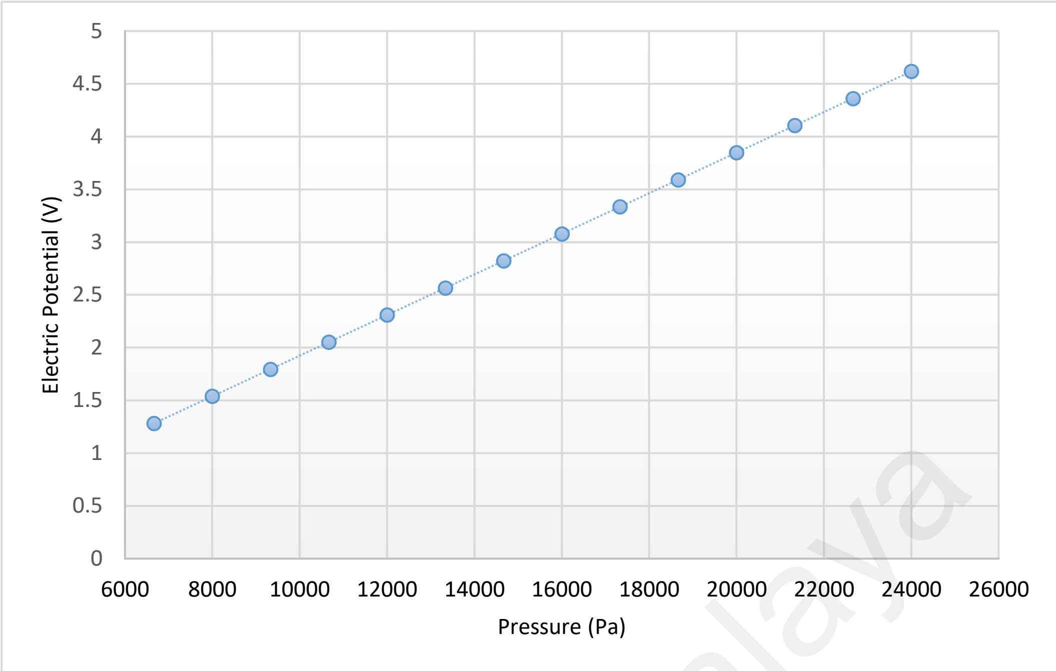


Figure 4.2. 30 Graph of Electric Potential vs Pressure

4.2.2 Case II: Barium Titanate ($BaTiO_3$)

In case II using a $BaTiO_3$ piezoelectric material as a sensitive layer of U-shape cantilever based sensor. As we already shown in Table 4.1 a structural parameter of U-shaped cantilever. The cantilever integrated over nylon fabric is composed of a structural layer, sensing layer and interface layer. As it shown in Table 3.4 Polysilicon material used as a structural layer for good contact of electrodes and Silicon dioxide used as an isolation purpose of U-shaped cantilever based blood pressure sensor. In Figure 4.2.31-4.2.44. shows the deflection value of U-shaped cantilever at different value of pressure applied on top surface of $BaTiO_3$ cantilever and the applied pressure range is 50mmHg to 180mmHg. Figure 4.2.31 shows the maximum value of displacement is 5.6105µm given by cantilever at applied low diastolic blood pressure of 50mmHg and whereas sensor gives the maximum value of displacement is 20.166µm when it experienced high systolic blood pressure of 180mmHg on top surface of $BaTiO_3$ U-shaped cantilever. We mostly concerned what deflection value shown by sensor at normal diastolic blood pressure (80mmHg) of human being. In Figure 4.2.44, $BaTiO_3$ cantilever shows maximum value of displacement is 8.9624µm when a boundary load equivalent of the normal diastolic pressure 80mmHg(10666Pa) was applied and the values reached to 13.444µm for normal systolic condition 120mmHg(15999Pa) as shown in Figure 4.2.38. Blue color indicates area of minimum deflection. While red color shows where the maximum deflection developed.

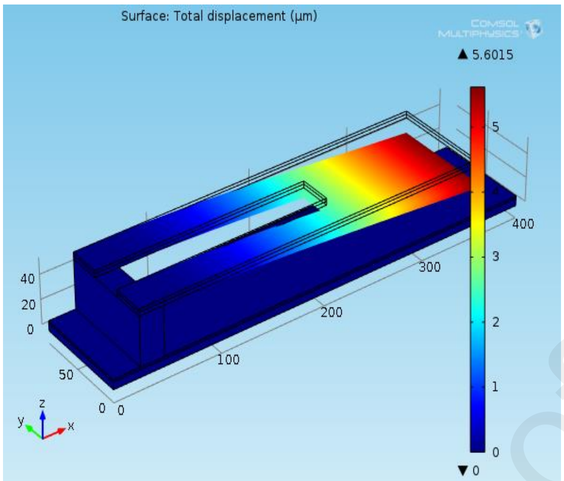


Figure 4.2. 31 Applied Pressure 50mmHg

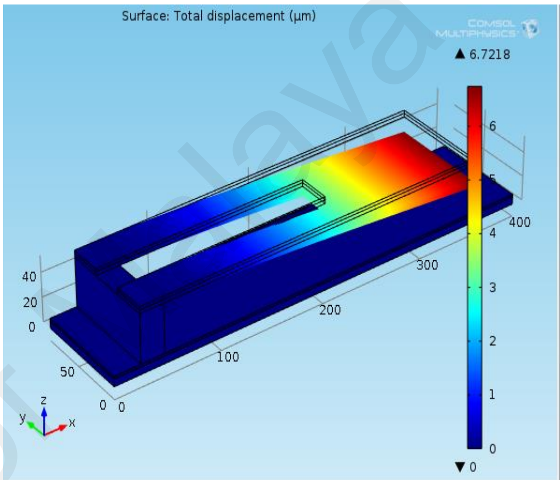


Figure 4.2. 32 Applied Pressure 60mmHg

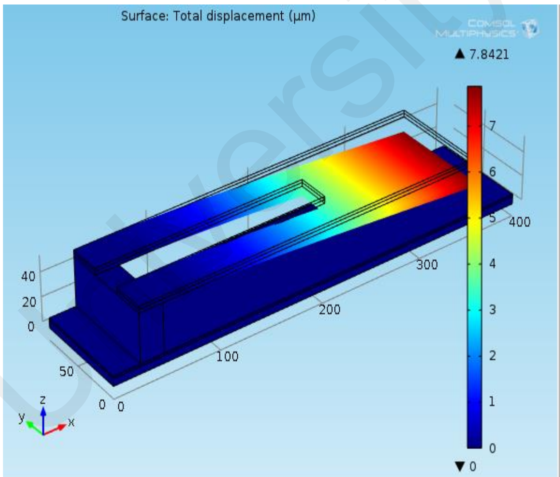


Figure 4.2. 33 Applied Pressure 70mmHg

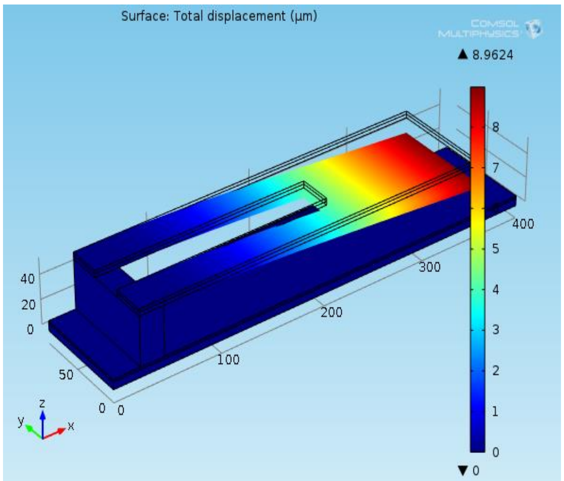


Figure 4.2. 34 Applied Pressure 80mmHg

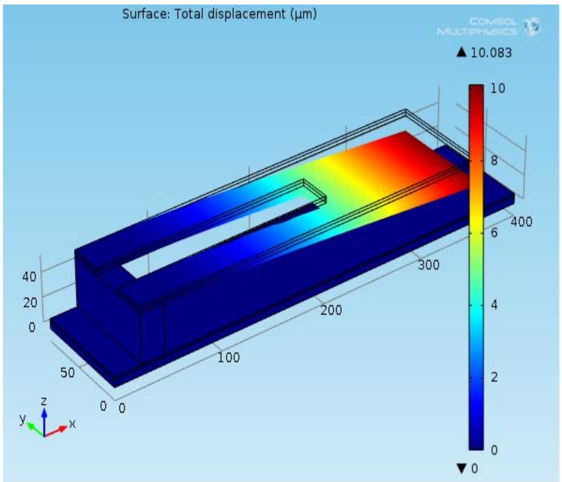


Figure 4.2. 35 Applied Pressure 90mmHg

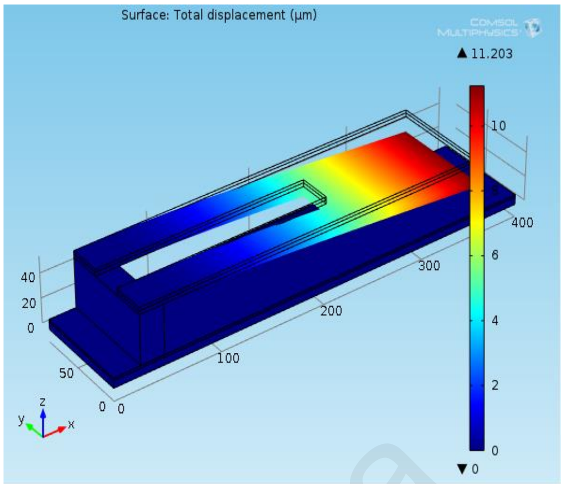


Figure 4.2. 36 Applied Pressure 100mmHg

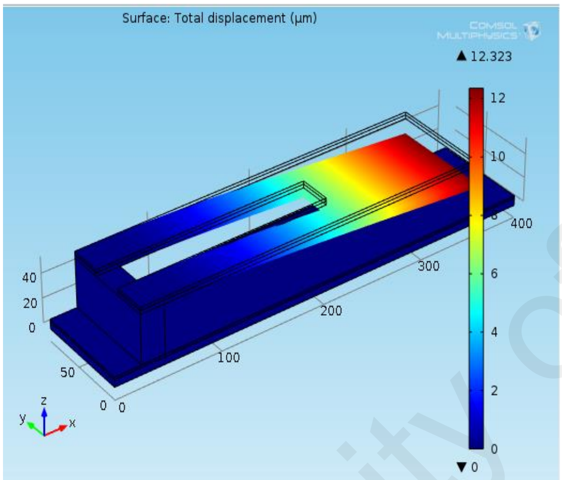


Figure 4.2. 37 Applied Pressure 110mmHg

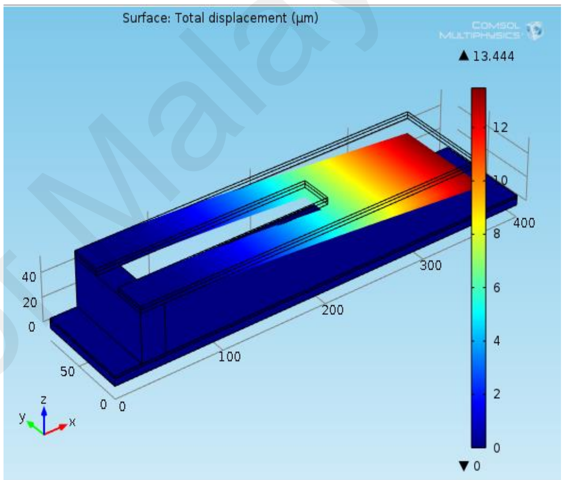


Figure 4.2. 38 Applied Pressure 120mmHg

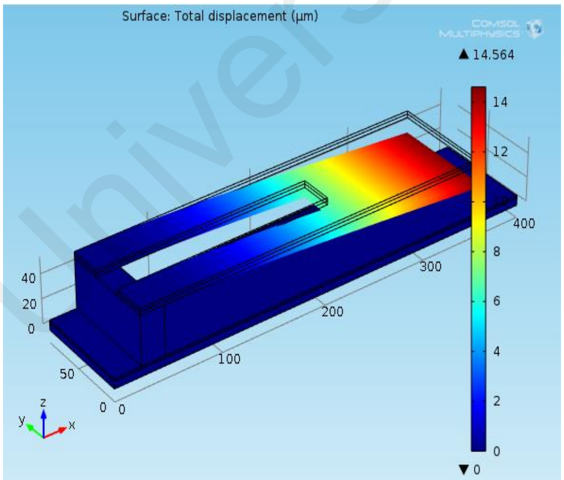


Figure 4.2. 39 Applied Pressure 130mmHg

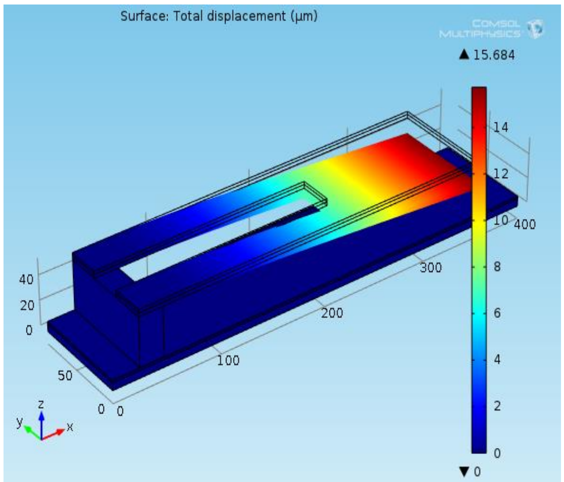


Figure 4.2. 40 Applied Pressure 140mmHg

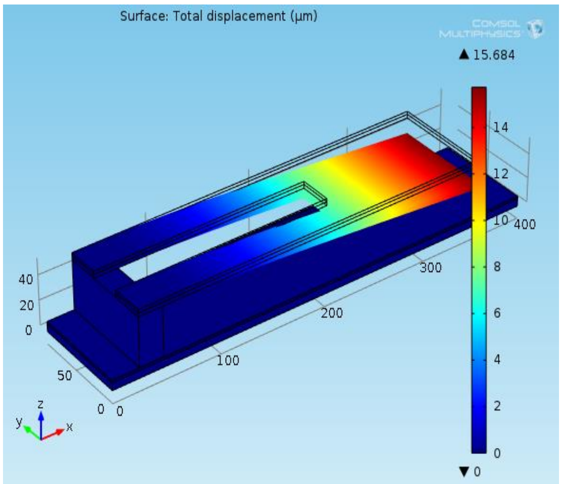


Figure 4.2. 41 Applied Pressure 150mmHg

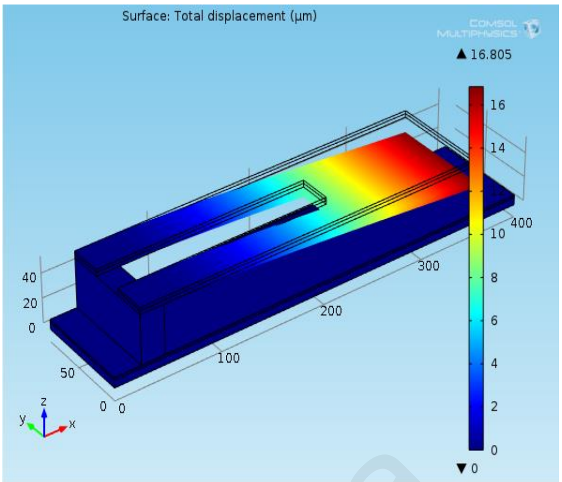


Figure 4.2. 42 Applied Pressure 160mmHg

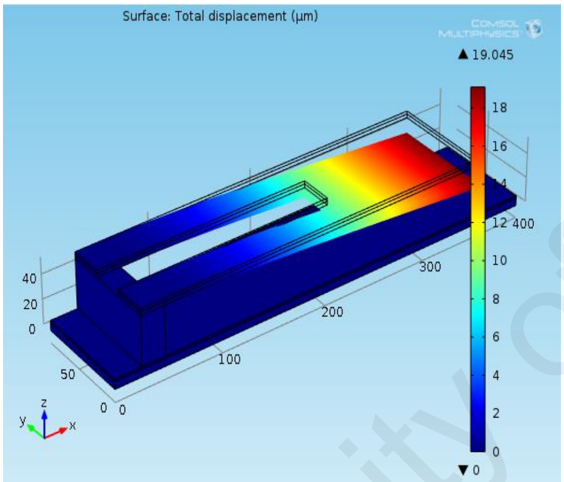


Figure 4.2. 43 Applied Pressure 170mmHg

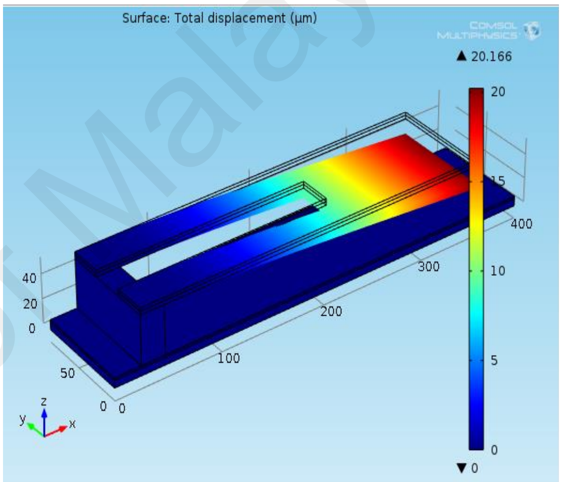


Figure 4.2. 44 Applied Pressure 180mmHg

Graph for Displacement vs Pressure is shown in Figure 4.2.45. From the plotted graph the value of displacement changes linearly with respect to applied pressure. As the input pressure increases the displacement value of cantilever with $BaTiO_3$ sensing layer also increases. At diastolic condition the average and maximum displacement value of U-shaped cantilever are 3.8670µm and 8.9624µm respectively. Using equation (2.2) from chapter 2, the calculated value of maximum displacement of U-shaped cantilever is 8.9552µm.

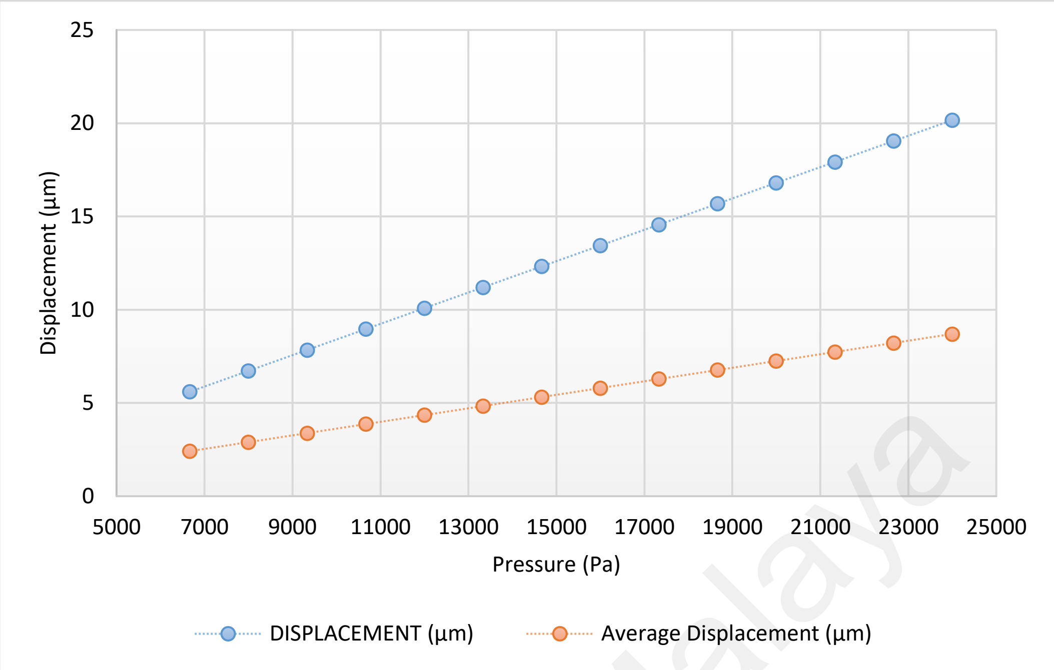


Figure 4.2. 45 Graph for Displacement vs Pressure

As we know in Case II using $BaTiO_3$ piezoelectric material as a cantilever sensing layer and we check the electric potential values of $BaTiO_3$ based U-shaped cantilever. Figure 4.2.46- 4.2.59, shows the electric potential values given by U-shaped cantilever at different values of pressure applied on top surface of U-shaped cantilever based on $BaTiO_3$ sensing layer and the range of applied pressure is 50mmHg to 180mmHg. Figure 4.2.46 shows the maximum value of electric potential is 0.9659V given by U-shaped $BaTiO_3$ cantilever at applied low diastolic blood pressure of 50mmHg and whereas sensor experienced a high systolic blood pressure of 180mmHg on top surface of U-shaped cantilever beans its shows the maximum value of electric potential is 4.6176V. We mostly focused what value of Electric potential is shown by sensor at normal diastolic blood pressure (80mmHg) of human being. In Figure 4.2.49, maximum and minimum value of electric potential are 1.5455V and 0.0394V is given by $BaTiO_3$ based U-shaped cantilever, when a boundary load equivalent of the normal diastolic pressure 80mmHg(10666Pa) was applied and the values increased to 2.3183V for normal systolic condition 120mmHg(15999Pa) as shown in Figure 4.2.53. Blue color indicates area of cantilever where the minimum value of electric potential developed. While red color indicates the area of U-shaped cantilever where the maximum electric potential value developed.

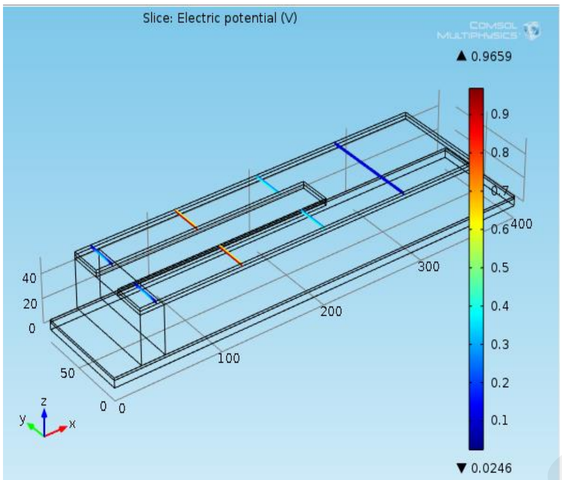


Figure 4.2. 46 Applied Pressure 50mmHg

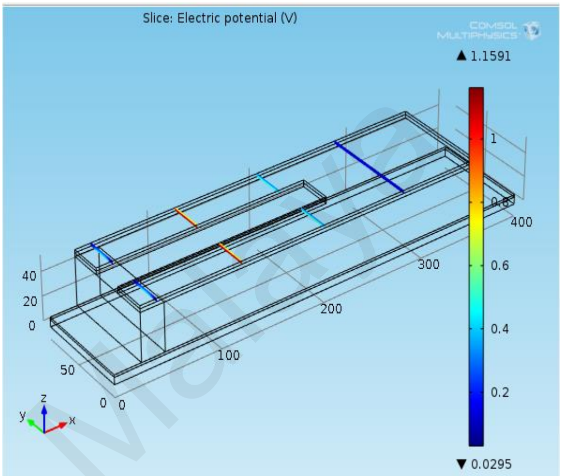


Figure 4.2. 47 Applied Pressure 60mmHg

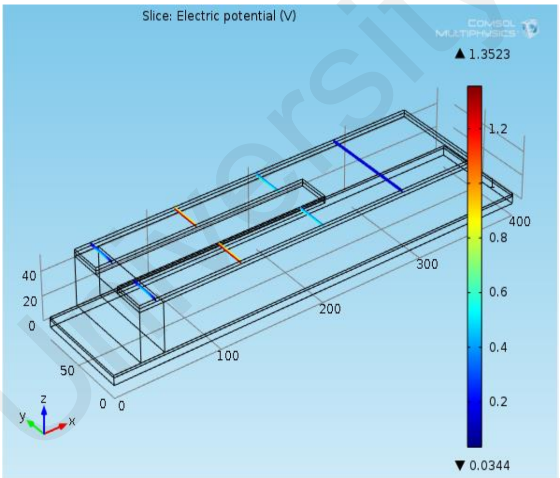


Figure 4.2. 48 Applied Pressure 70mmHg

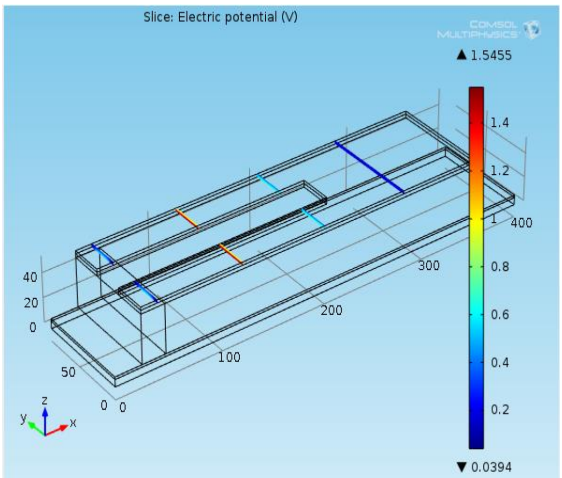


Figure 4.2. 49 Applied Pressure 80mmHg

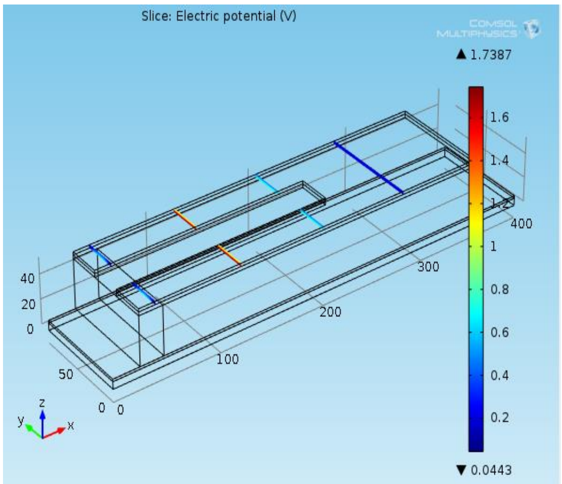


Figure 4.2. 50 Applied Pressure 90mmHg

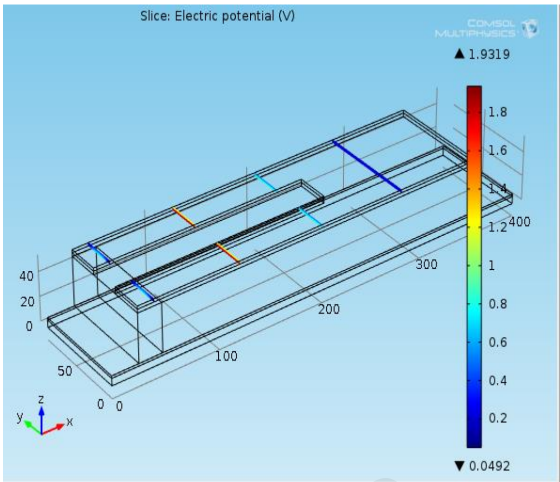


Figure 4.2. 51 Applied Pressure 100mmHg

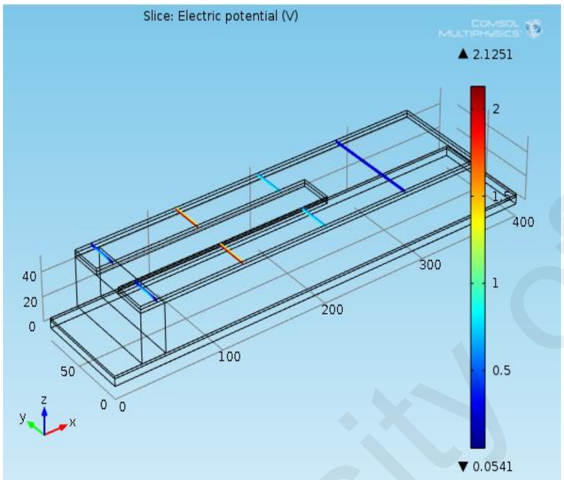


Figure 4.2. 52 Applied Pressure 110mmHg

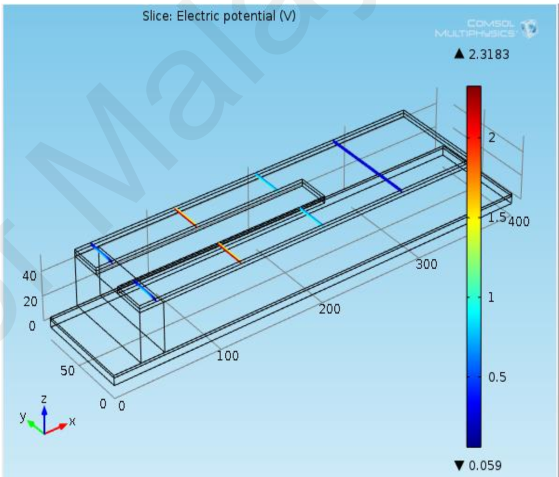


Figure 4.2. 53 Applied Pressure 120mmHg

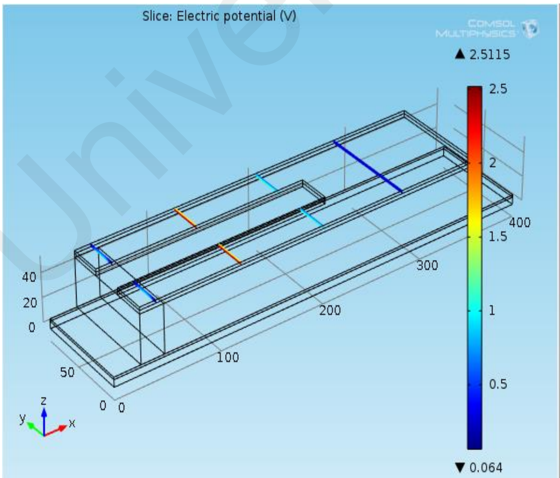


Figure 4.2. 54 Applied Pressure 130mmHg

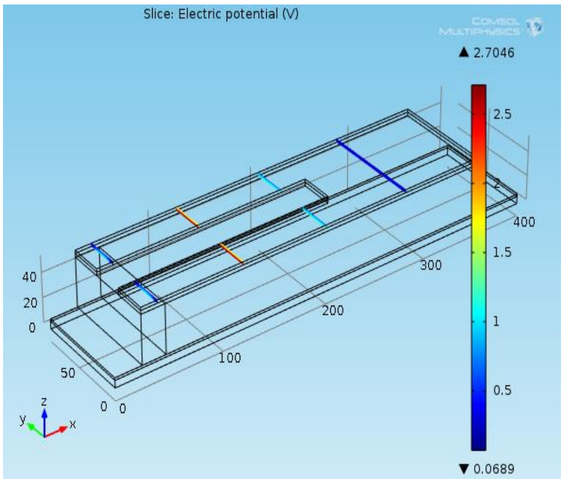


Figure 4.2. 55 Applied Pressure 140mmHg

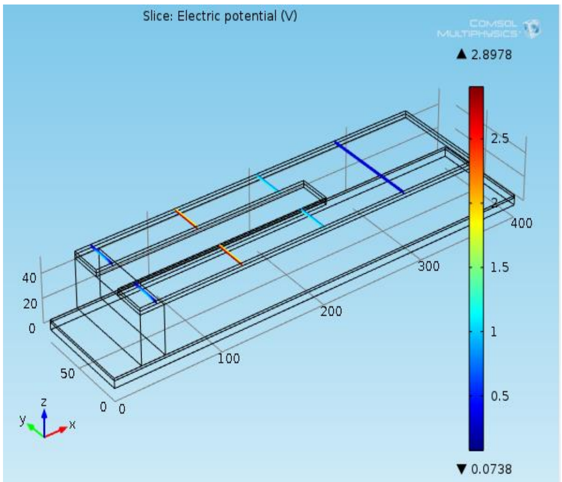


Figure 4.2. 56 Applied Pressure 150mmHg

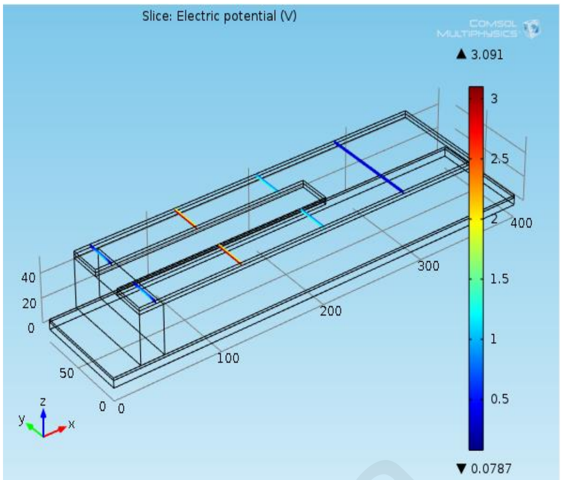


Figure 4.2. 57 Applied Pressure 160mmHg

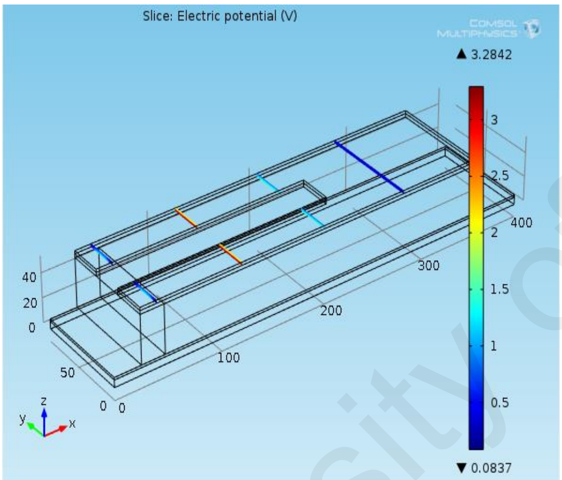


Figure 4.2. 58 Applied Pressure 170mmHg

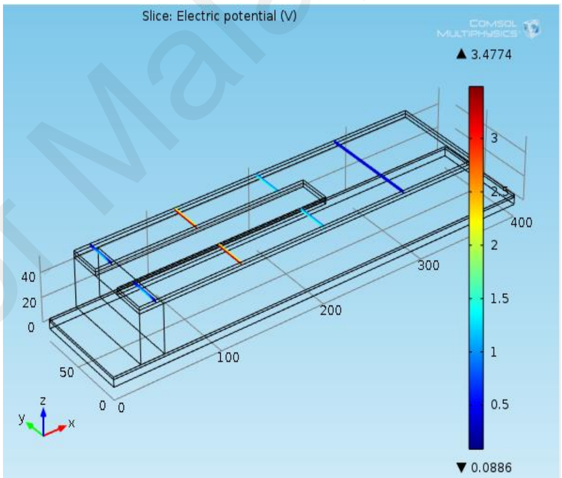


Figure 4.2. 59 Applied Pressure 180mmHg

Graph for Electric Potential vs Pressure is shown in Figure 4.2.60, shows the maximum and minimum electric potential value at diastolic condition are 1.5455V. As the input pressure increases the electric potential value of BaTiO3 based U-shaped cantilever also increases. The maximum and minimum electric potential at pressure of 80mmHg are 1.5455V and 0.0394 respectively.

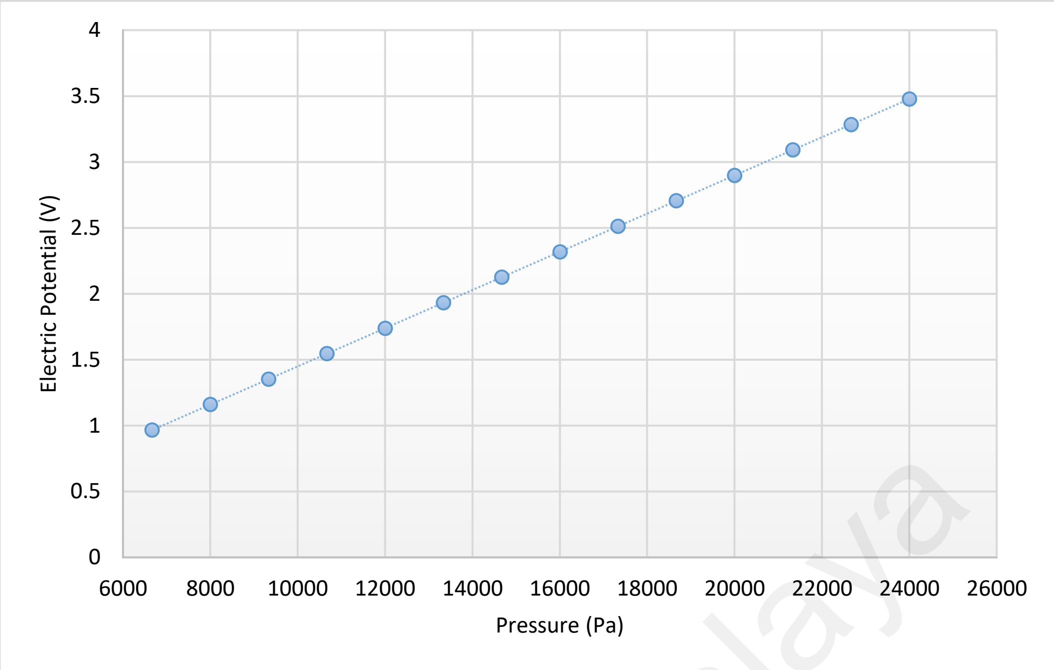


Figure 4.2. 60 Graph for Electric Potential vs Pressure

Table 4. 2 Different piezoelectric materials Displacement and Electric Potential value at Diastolic condition

Material	$BaTiO_3$	PZT-5H
Simulated Maximum Displacement for 80mmHg (µm)	8.9624	11.456
Calculated Maximum Displacement for 80mmHg (µm)	8.9552	11.445
Percentage Difference	0.080%	0.096%
Average Displacement for 80mmHg (µm)	3.86704	4.93404
Maximum Voltage for 80mmHg (V)	1.5455	2.9523

Overall U-shaped piezoelectric cantilever based sensor performances on maximum deflection of cantilever, displacement and electric potential for Lead Zirconate Titanate and Barium Titanate piezoelectric material are summarized in above Table 4.2. Based on above results as shown in the Table 4.2, it can be seen that the U-shaped cantilever with sensing layer of PZT-5H piezoelectric material shows highest value of deflection is 11.456µm at normal diastolic blood pressure (80mmHg) of human being as compare to $BaTiO_3$ piezoelectric material. It is due to the PZT-5H maintaining relatively high piezoelectric properties as compare to $BaTiO_3$ piezoelectric material(Anton & Sodano, 2007). As shown in Figure 4.2.61 and Figure 4.2.62 are representing the comparison of piezoelectric materials (PZT-5H and $BaTiO_3$). Lead Zirconate Titanate shows better sensitivity gives higher value of Displacement and electric potential and has better response with linearly increasing pressure due to its relatively large piezoelectric coefficient.

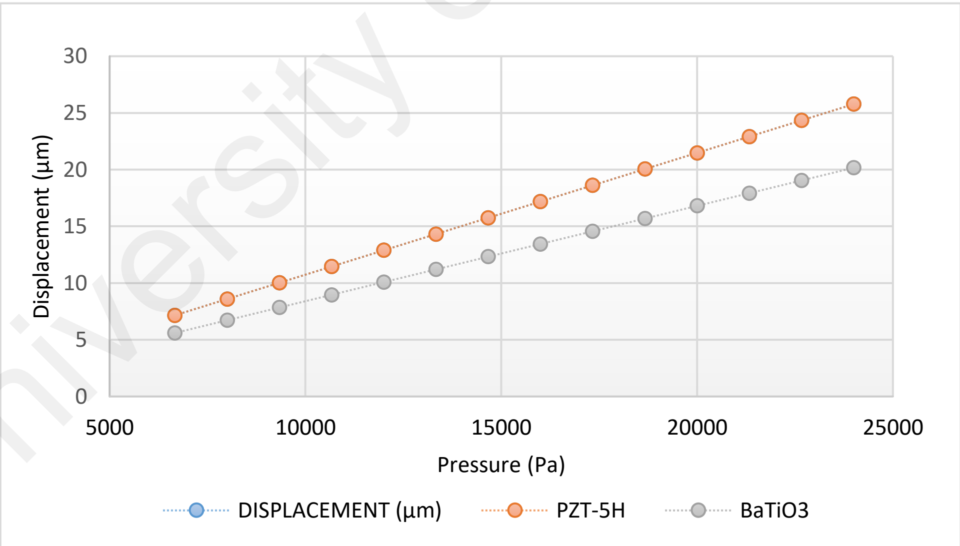


Figure 4.2. 61 Graph for Displacement of both piezo materials vs Pressure

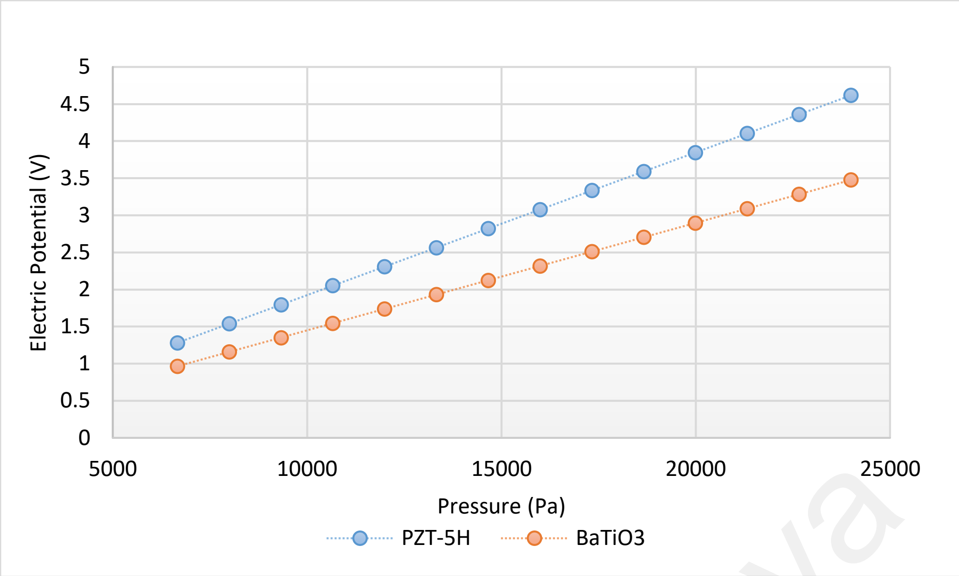


Figure 4.2. 62 Graph for Electric Potential of both piezo materials vs Pressure

4.3 Analysis and Discussion of Piezoelectric U-Shaped Cantilever at Different Length

4.3.1 Case I: PZT-5H Based Cantilever

In Case I using PZT-5H piezoelectric material as a sensing layer of cantilever and check the displacement of U-shaped cantilever at different length and range of U-shaped cantilever length from 290µm to 330µm with same width and thickness as given in Table 4.1. In Figure 4.3.1-4.5.5, shows the displacement value of the PZT-5H piezoelectric material based U-shaped cantilever at different length and amount of applied pressure on is normal diastolic blood pressure 80mmHg. Figure 4.3.1 shows at normal diastolic condition U-shaped cantilever gives the maximum deflection of 6.3581µm at cantilever length of 290µm and whereas length of U-shaped cantilever is 330µm experienced a pressure of 80mmHg on top surface of cantilever, it shows a maximum value of deflection is 11.456µm. From the Figure 4.3.6, Graph between Length of PZT-5H based Cantilever vs Displacement shows that longer length of cantilever showing greater deflection as compare to short length of cantilever. Blue color shows a minimum deflection value on cantilever. While red color indicates where the maximum deflection developed on U-shaped cantilever.

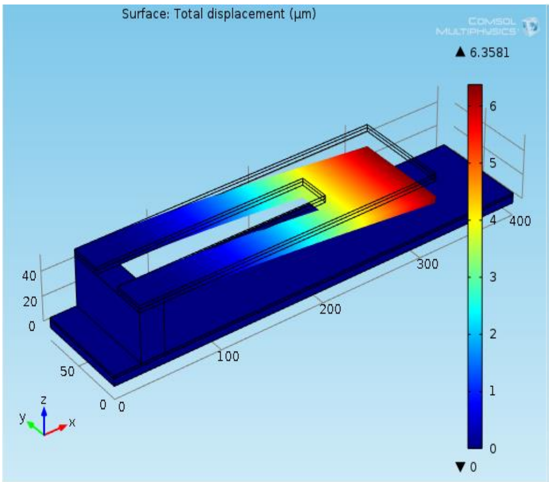


Figure 4.3. 1 Cantilever Length 290µm

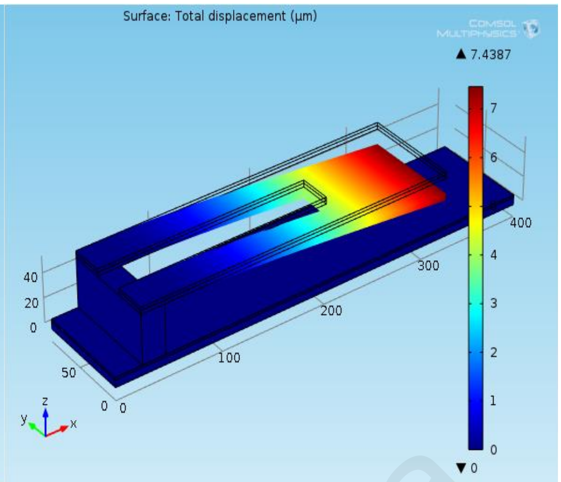


Figure 4.3. 2 Cantilever Length 300µm

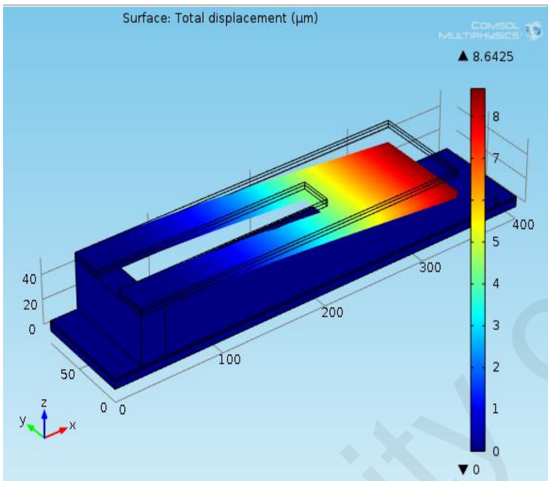


Figure 4.3. 3 Cantilever Length 310µm

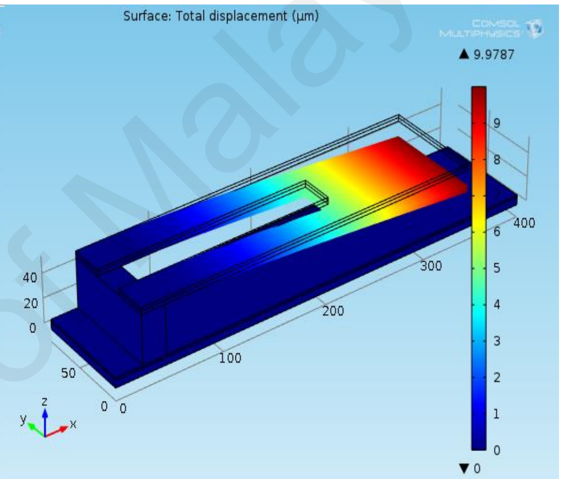


Figure 4.3. 4 Cantilever Length 320µm

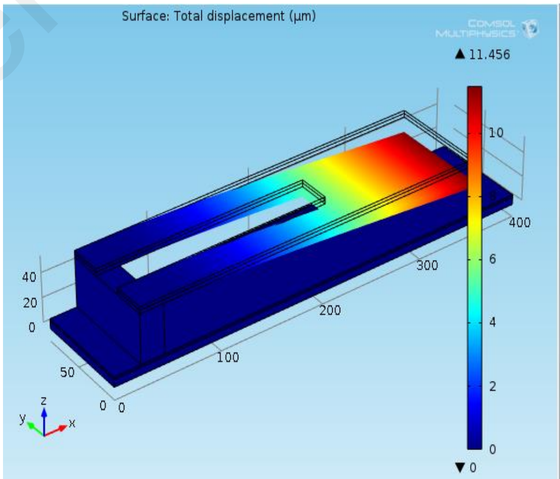


Figure 4.3. 5 Cantilever length 330µm

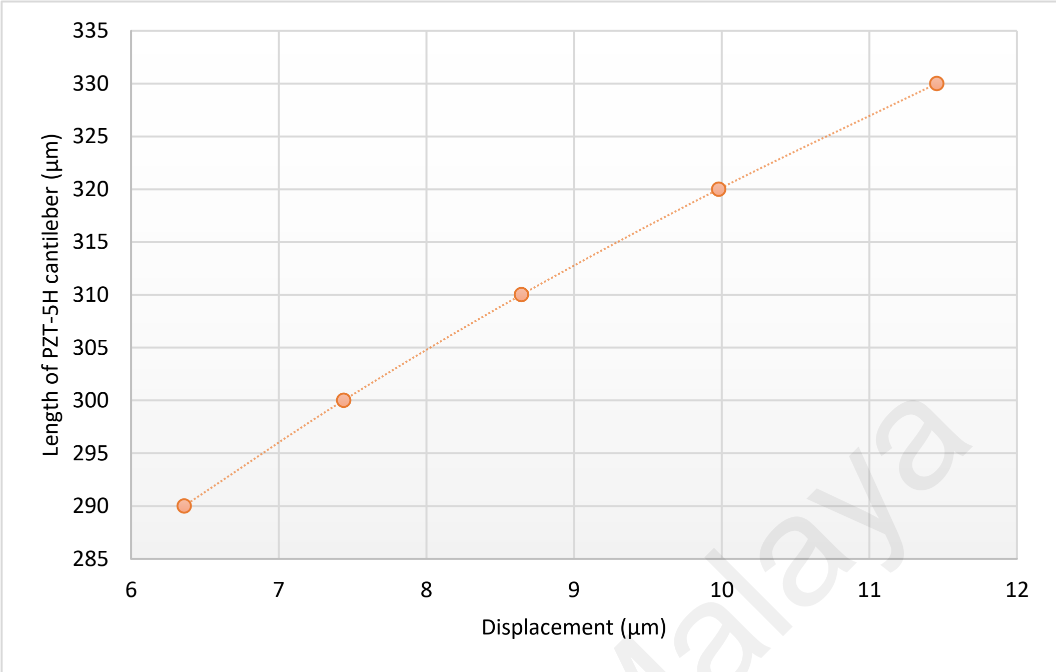


Figure 4.3. 6 Graph for Length of PZT-5H Cantilever vs Displacement

From Figure 4.3.7-4.5.11, shows the electric potential value of the PZT-5H piezoelectric material based U-shaped cantilever at different length and applied pressure on cantilever is normal diastolic blood pressure 80mmHg. Figure 4.3.7 shows at normal diastolic condition (80mmHg) U-shaped cantilever gives the maximum and minimum value of electric potential are 1.3652V and -0.0567V at cantilever length of 290µm and when length of U-shaped cantilever is 330µm experienced a pressure of 80mmHg on top of cantilever surface it shows a maximum and minimum value of electric potential are 2.0523V and -0.0586V as shown in Figure 4.3.11. From the 4.3.12, Graph between Length of PZT-5H based Cantilever vs electric potential shows that longer length of cantilever showing high value of electric potential as compare to short length of cantilever. Blue line shows minimum area of electric potential. While Red shows where the maximum electric potential developed.

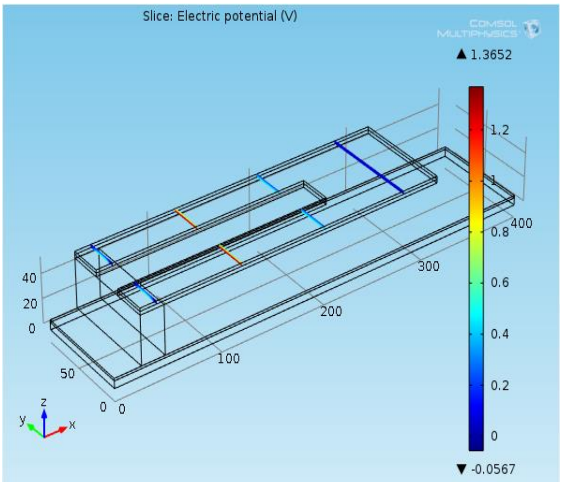


Figure 4.3. 7 Cantilever Length 290µm

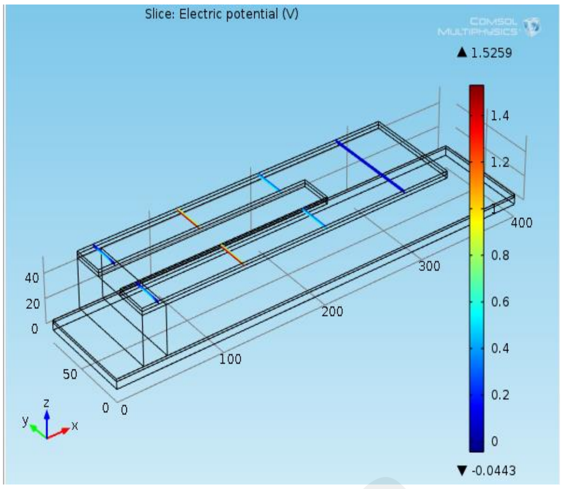


Figure 4.3. 8 Cantilever Length 300µm

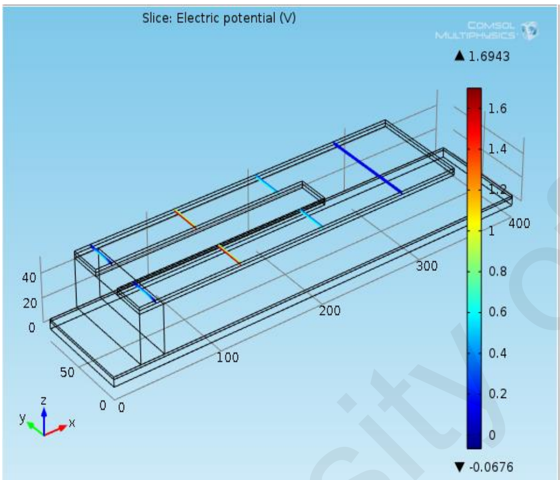


Figure 4.3. 9 Cantilever Length 310µm

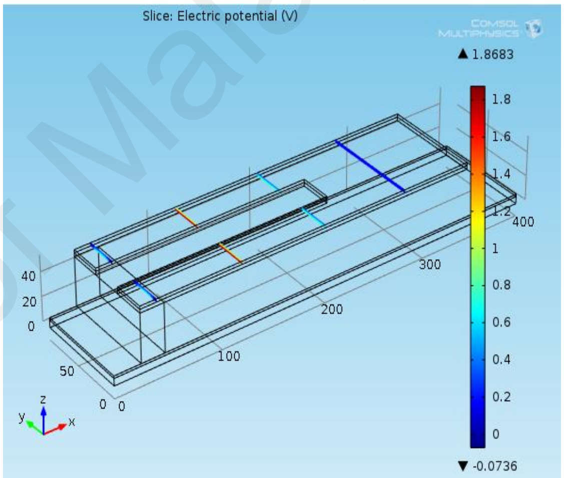


Figure 4.3. 10 Cantilever Length 320µm

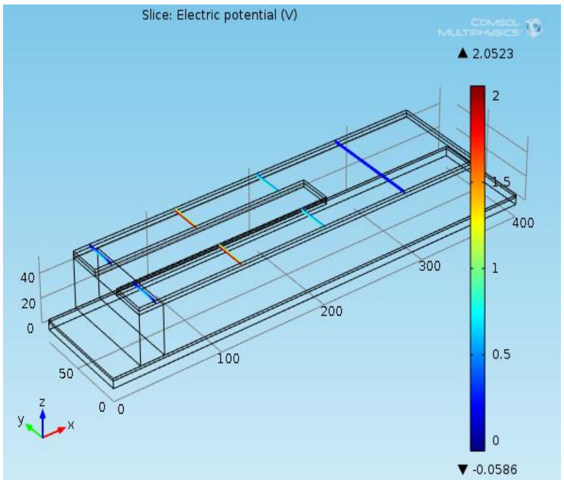


Figure 4.3. 11 Cantilever Length 330µm

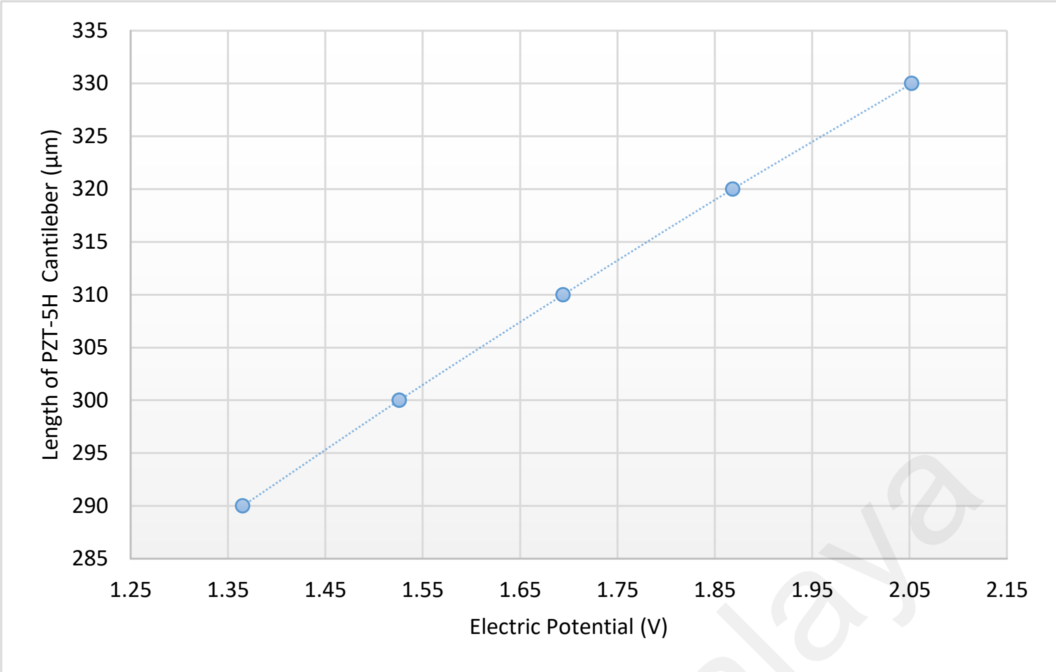


Figure 4.3. 12 Graph for Length of PZT-5H Cantilever vs Electric Potential

4.3.2 Case II: Barium Titanate ($BaTiO_3$) Based Cantilever

In Case II using Barium Titanate piezoelectric material as a sensing layer of cantilever and check the displacement of U-shaped cantilever at different length and range of U-shaped cantilever length from 290µm to 330µm with same width and thickness as given in Table 4.1. In Figure 4.3.13-4.5.17, shows the displacement value of the $BaTiO_3$ piezoelectric material based U-shaped cantilever at different length and range of applied pressure on cantilever surface is normal diastolic blood pressure 80mmHg. Figure 4.3.13 shows at normal diastolic condition U-shaped cantilever gives the maximum deflection of 4.9803µm at cantilever length of 290µm and when length of U-shaped cantilever is 330µm experienced an applied pressure of 80mmHg it shows a maximum value of deflection is 8.9624µm as shown in Figure 4.3.17. From the Figure 4.3.18, Graph between Length of PZT-5H based Cantilever vs Displacement shows that longer length of cantilever showing greater deflection as compare to cantilever with short length. Blue color shows a minimum displacement value on cantilever. While red color indicates where the maximum deflection developed on U-shaped cantilever.

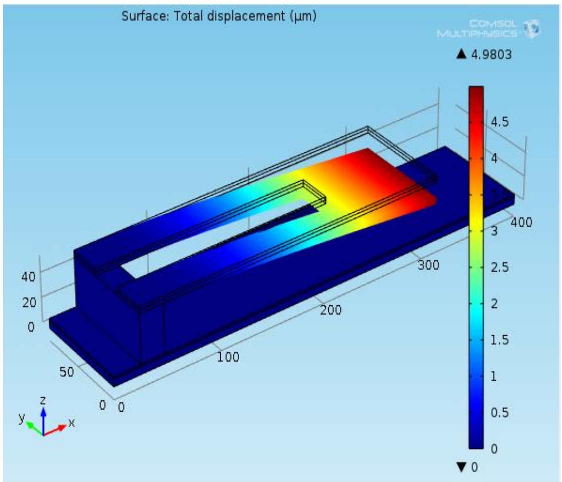


Figure 4.3. 13 Cantilever Length 290µm

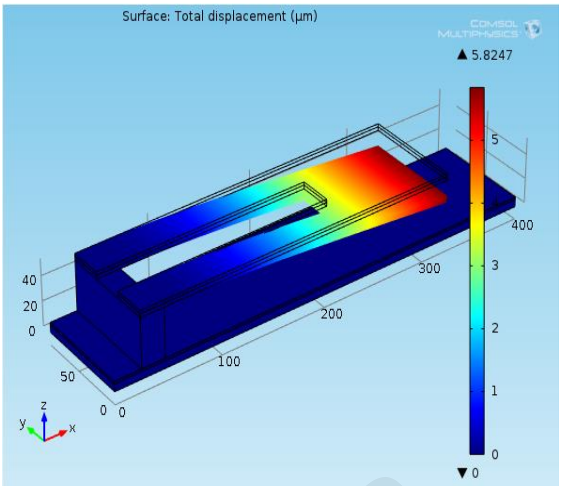


Figure 4.3. 14 Cantilever Length 300µm

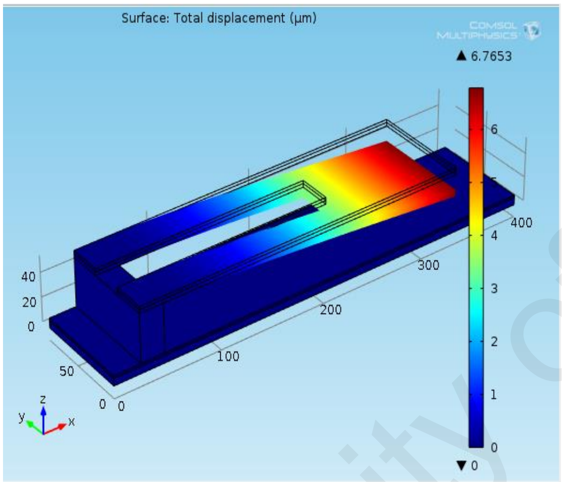


Figure 4.3. 15 Cantilever Length 310µm

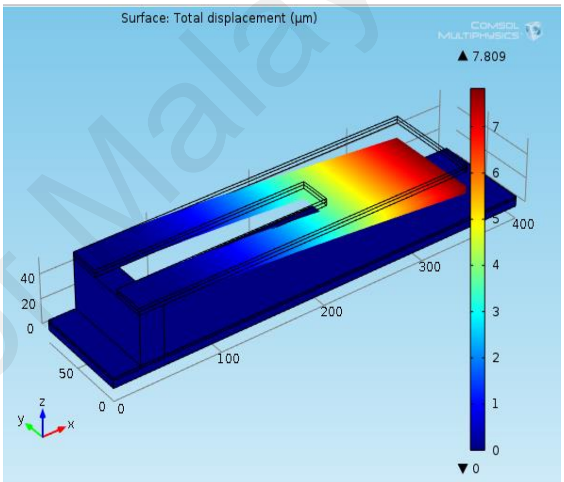


Figure 4.3. 16 Cantilever Length 320µm

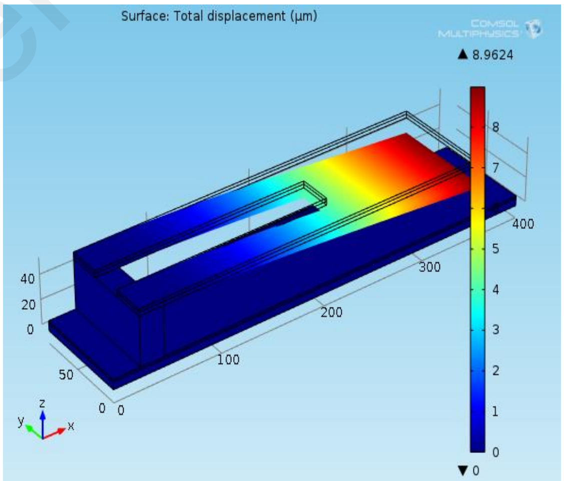


Figure 4.3. 17 Cantilever Length 320µm

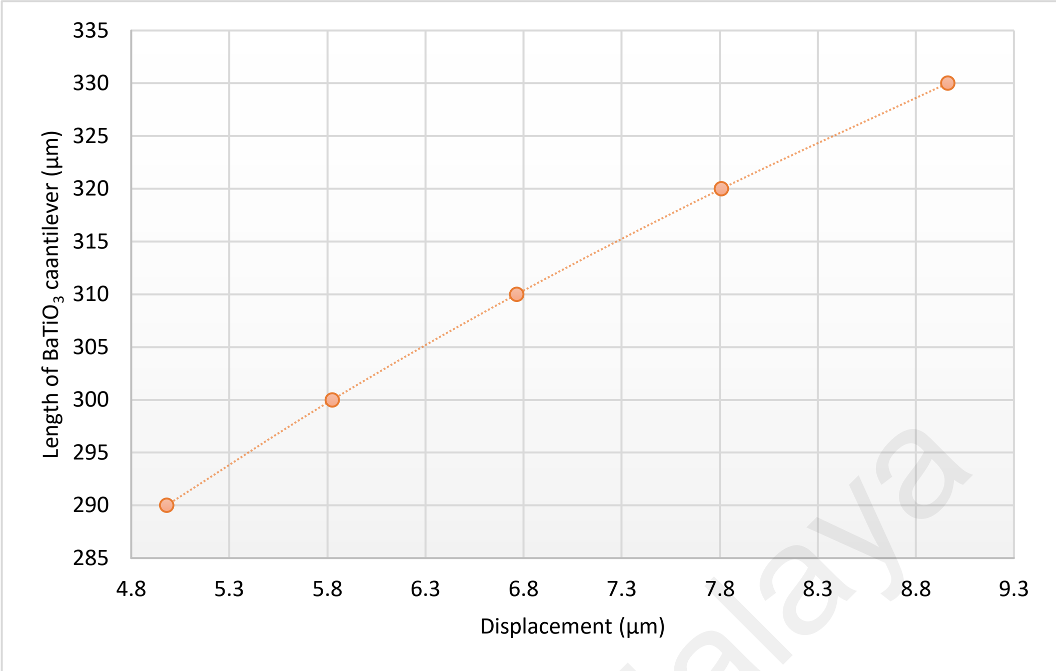


Figure 4.3. 18 Graph for Length of $BaTiO_3$ cantilever vs Displacement

From Figure 4.3.19-4.5.23, shows the electric potential value of the Barium Titanate piezoelectric material based U-shaped cantilever at different length and applied pressure on top surface of cantilever is normal diastolic blood pressure 80mmHg. Figure 4.3.19 shows at normal diastolic condition (80mmHg) U-shaped cantilever gives the maximum and minimum value of electric potential are 1.0263V and 0.0196 at cantilever length of 290µm and when length of U-shaped cantilever is 330µm experienced an applied pressure of 80mmHg it shows a maximum and minimum value of electric potential are 1.5455V and 0.0394V as shown in Figure 4.3.23. From the 4.3.24, Graph between Length of PZT-5H based Cantilever vs electric potential shows that longer length of cantilever showing high value of electric potential as compare to short length of cantilever. Blue line shows minimum area of electric potential. While Red shows where the maximum electric potential developed.

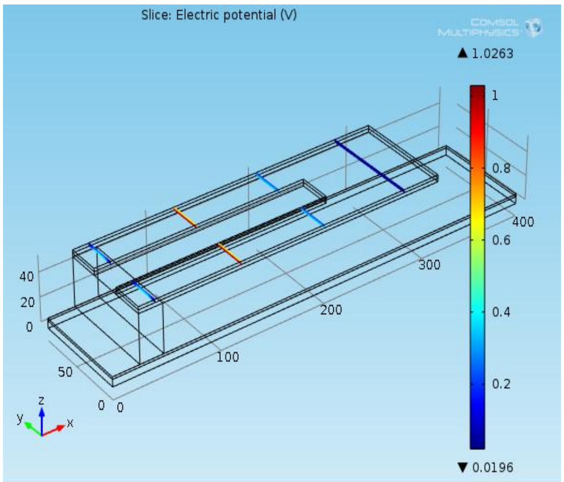


Figure 4.3. 19 Cantilever Length 290µm

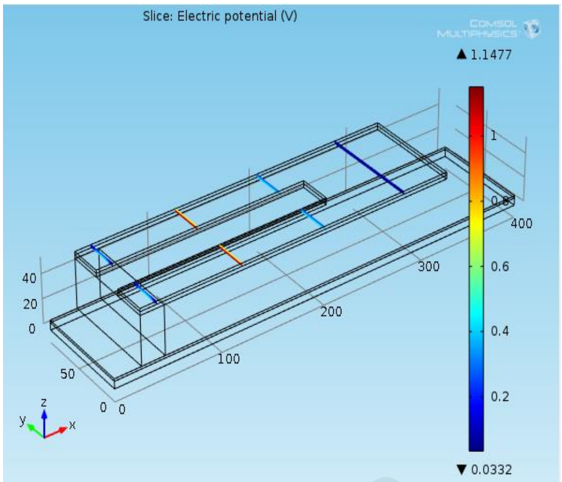


Figure 4.3. 20 Cantilever Length 300µm

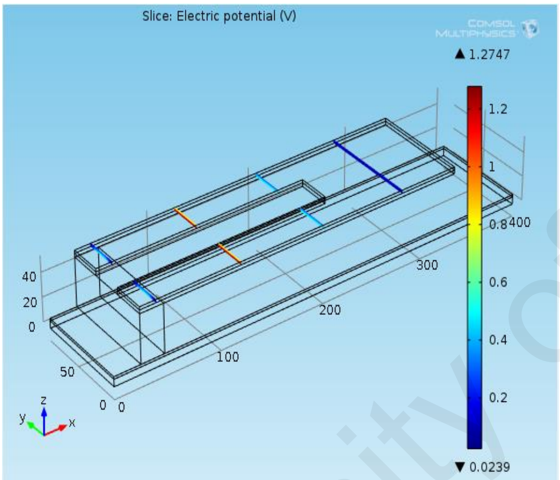


Figure 4.3. 21 Cantilever Length 310µm

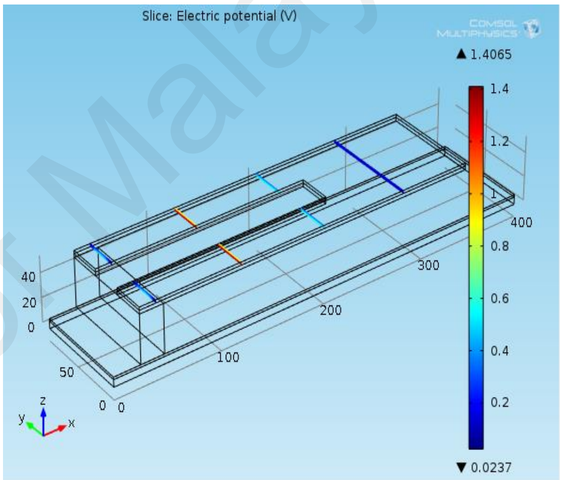


Figure 4.3. 22 Cantilever Length 320µm

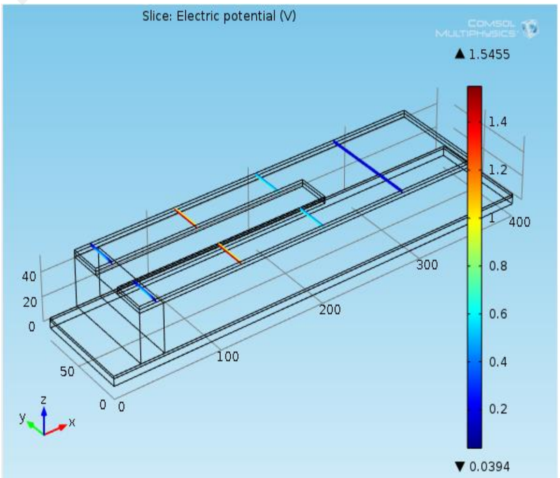


Figure 4.3. 23 Cantilever Length 330µm

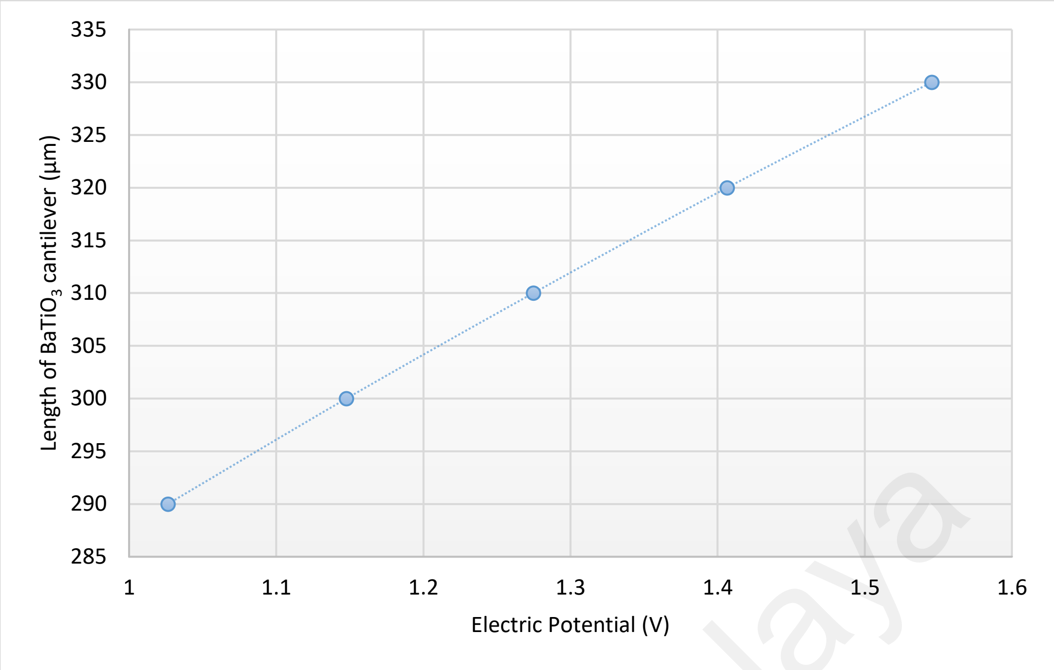


Figure 4.3. 24 Graph for Length of $BaTiO_3$ Cantilever vs Electric Potential

Table 4. 3 Displacement and Electric Potential value of PZT-5H for different length of cantilever at diastolic condition

PZT-5H				
Length (µm)	**Simulated Maximum Displacement for 80mmHg (µm)**	**Calculated Maximum Displacement for 80mmHg (µm)**	**Percentage Difference b/w Simulated and calculated Displacement value**	**Maximum Voltage for 80mmHg (V)**
290	6.3581	6.3522	0.092%	1.3652
300	7.4387	7.4380	0.009%	1.5259
310	8.6425	8.6421	0.004%	1.6943
320	9.9787	9.9707	0.080%	1.8683
330	11.456	11.445	0.096%	2.0523

Table 4. 4 Displacement and Electric Potential value of $BaTiO_3$ for different length of cantilever at diastolic condition

$BaTiO_3$				
Length (µm)	**Simulated Maximum Displacement for 80mmHg (µm)**	**Calculated Maximum Displacement for 80mmHg (µm)**	**Percentage Difference b/w Simulated and calculated Displacement value**	**Maximum Voltage for 80mmHg (V)**
290	4.9803	4.9787	0.032%	1.0263
300	5.8247	5.8239	0.013%	1.1477
310	6.7653	6.7585	0.100%	1.2747
320	7.809	7.799	0.128%	1.4065
330	8.9624	8.9552	0.080%	1.5455

Based on above results as shown in Table 4.3 and 4.4, U-shaped cantilever with sensing layer of PZT-5H gives high value of displacement and electric potential as compare to BaTiO3. The longer cantilever shows better performance and sensitivity of sensor improves for longer cantilever showing larger deflection due to the uniform distribution of stress throughout the surface of cantilever. Graphical representation of both piezo electric material results with respect to length as shown below in Figure 4.3.25 and 4.3.26.

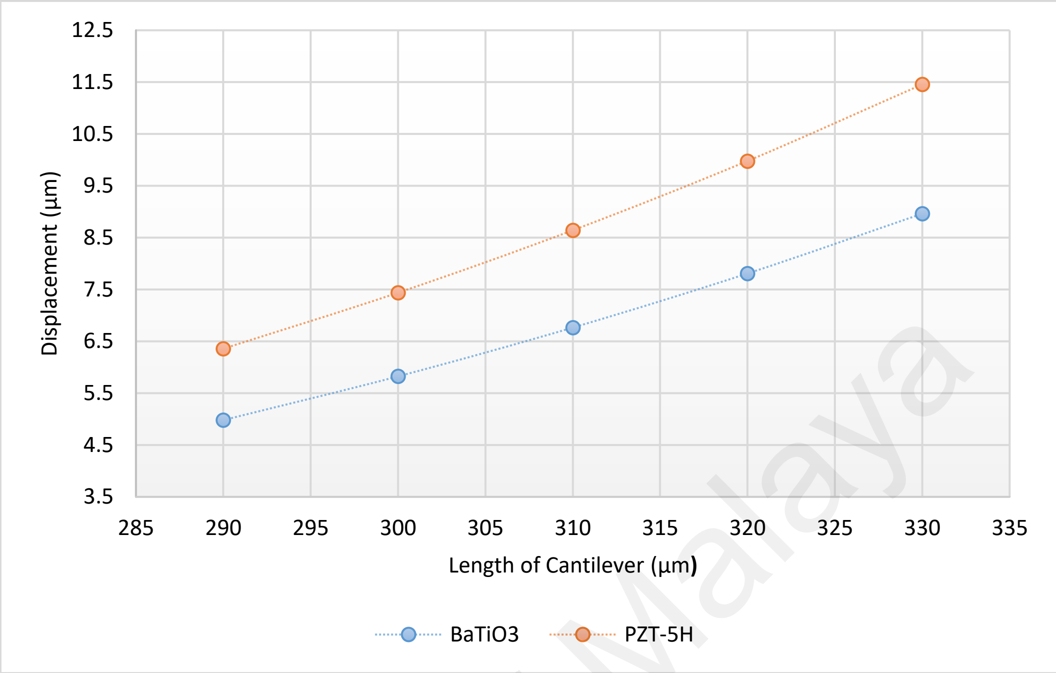


Figure 4.3. 25 Graph for Displacement of both piezo materials vs Length of Cantilever

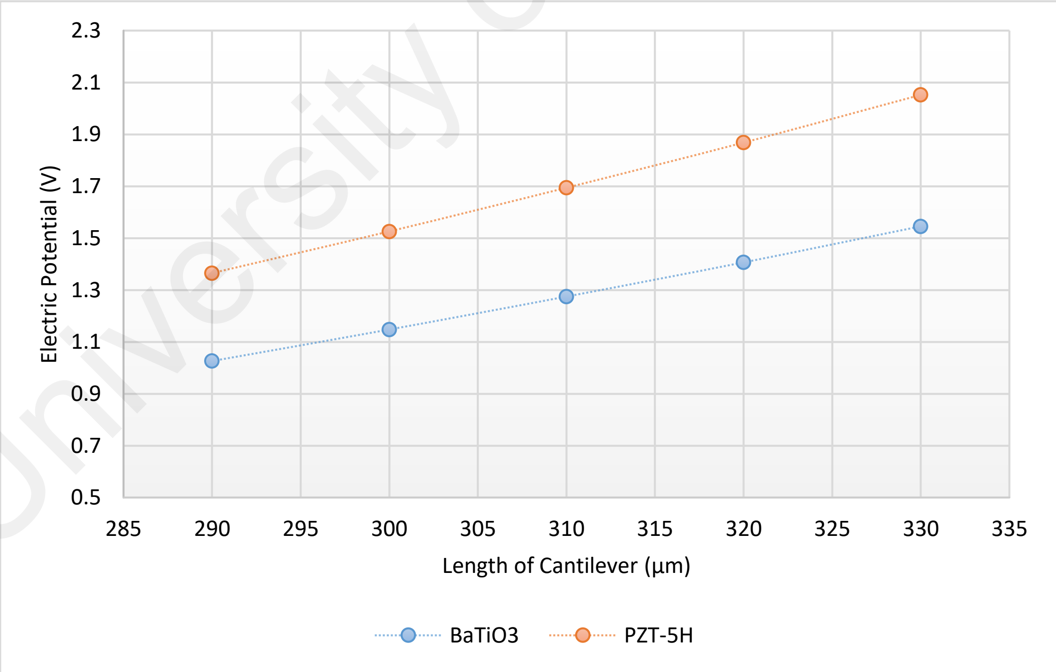


Figure 4.3. 26 Graph for Electric Potential of both piezo materials vs Length of Cantilever

4.4 Discussion

Based on the above results the optimization of sensor had been performed, U-shaped cantilever with sensing layer of PZT-5H material gives better displacement and electric potential value at diastolic condition 80mmHg as compare to previous study done by (KNJ et al., 2013) using rectangle shaped cantilever for monitoring a human blood pressure. According to results PZT-5H cantilever gives better performance at different length of cantilever ranging from 290µm-330µm as compared with previous study at different length base on Table 3.2. Results shows that, cantilever with U-shaped improves the sensitivity of sensor and reduced the size of sensor by showing displacement and electric potential value of 11.456µm and 2.0523V at cantilever length of 330µm at diastolic condition 80mmHg which is more than of target value. Which shows that cantilever with U-shape gives better performance for monitoring of human blood pressure because U-shape cantilever will act as two identical separated cantilevers corresponding to the two legs and shows that cantilever with longer length gives greater deflection and electric potential value, improve the sensor sensitivity due to the uniform distribution of Stress throughout the surface of cantilever. Graph 4.4.1 –4.4.2 compared the displacement and electric potential value of U-shaped PZT-5H cantilever at diastolic condition 80mmHg with Previous study. Graph 4.4.3 compared the displacement value at different length of U-shaped PZT-5H cantilever with different length of rectangle shaped PZT cantilever at diastolic condition 80mmHg.

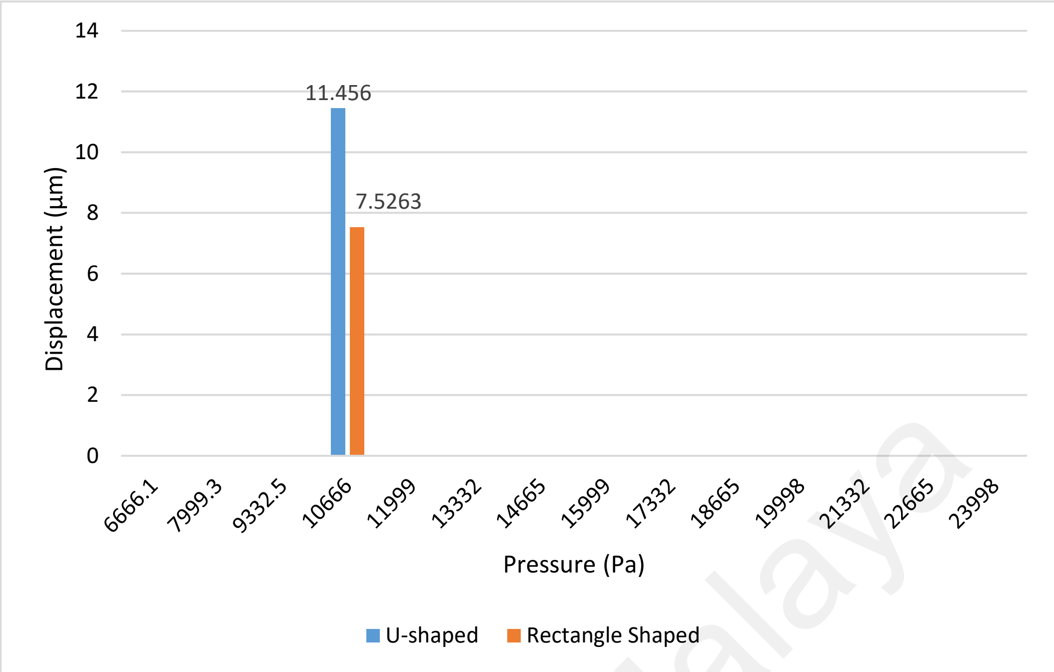


Figure 4.4. 1 Comparison of simulated Displacement value at diastolic condition between U-shaped and Rectangular shaped cantilever

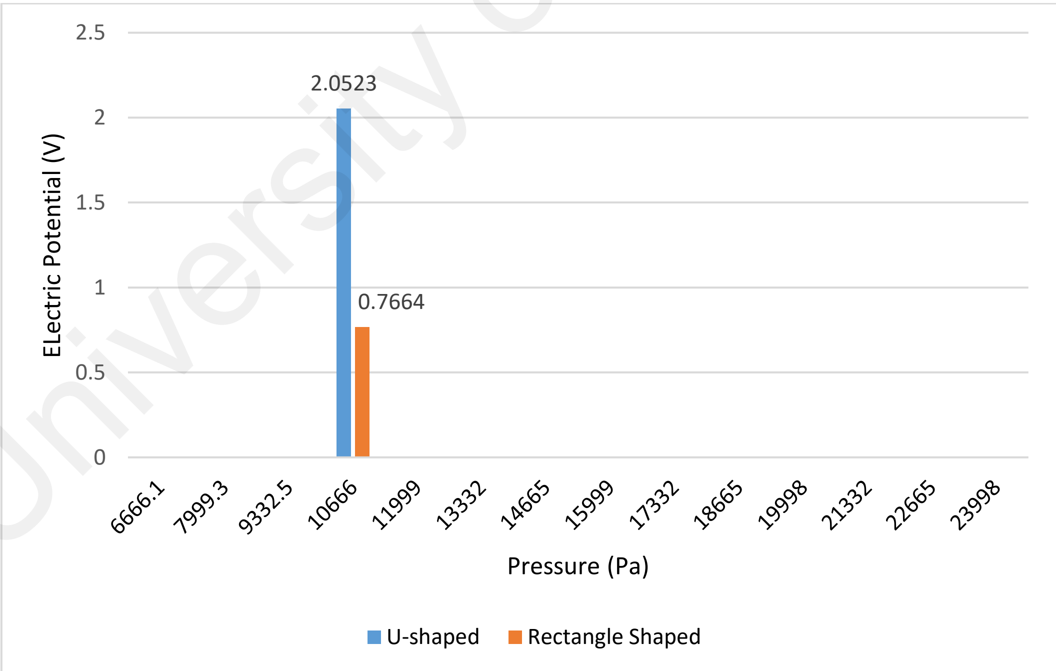


Figure 4.4. 2 Comparison of simulated Electric potential value at diastolic condition between U-shaped and Rectangular shaped cantilever

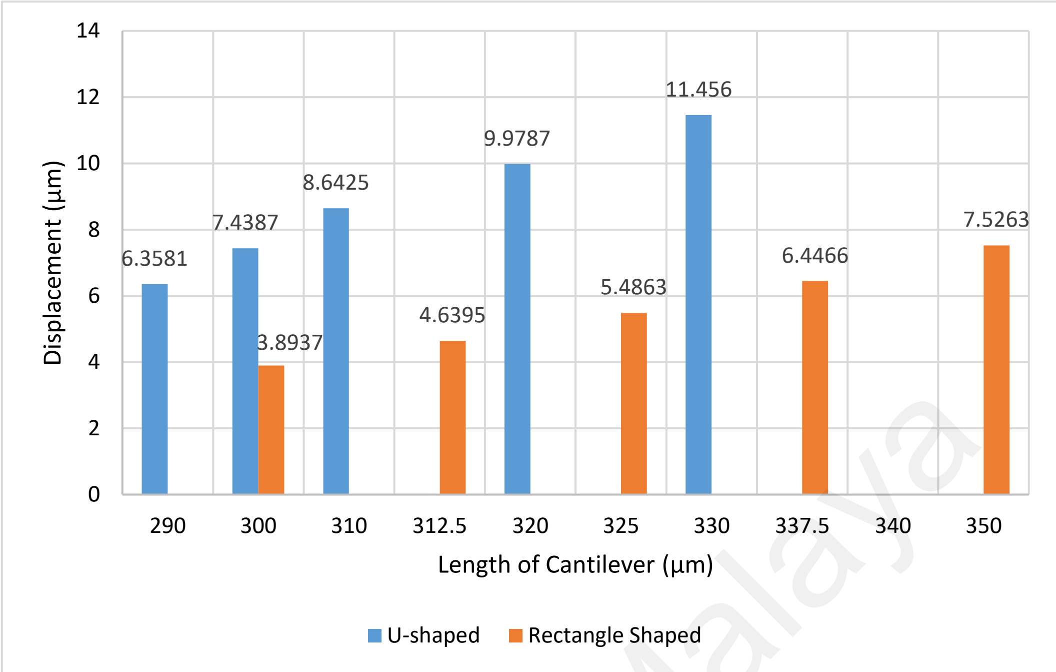


Figure 4.4. 3 Comparison of simulated Displacement value at different length of cantilever comparison between U-shaped and Rectangular shaped cantilever

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

A U-shaped MEMS piezoelectric cantilever based sensor for smart textile to monitor a human blood pressure had been successfully designed and simulated using COMSOL Multiphysics software. To analyze the sensor's performance, different piezoelectric material used as a sensing layer of cantilever. From the optimized simulated result obtained, PZT-5H shows maximum electric potential across electrodes of sensor and displacement for normal human diastolic blood pressure (80mmHg) as compare to $BaTiO_3$. Where the displacement and electric potential value are 11.456 μm and 2.0523V at diastolic condition is higher than the displacement and electric potential of previous study are 7.5263μm and 0.7664V done by (KNJ et al., 2013). As the input applied pressure increases, the electric potential across electrodes and displacement of cantilever free end also increases. Hence PZT-5H is relatively more sensitive piezoelectric material for MEMS piezoelectric blood pressure sensor. We applied different range of pressure between low blood pressure to high blood pressure. Higher electric potential might be practical in application which required piezoelectric sensing elements. While U- shape cantilever allows dimensions of cantilever to be minimize, especially its width. If L >>W, where 'L' is the cantilever length and 'W' is each leg width, the cantilever with U-shape will act as two identical separated cantilevers corresponding to the two legs due to this reason the size of sensor reduces as compare to previous study design. The optimization of sensor dimensions had been performed at different length of cantilever to improve the sensitivity of sensor. From the results obtained, it shows that longer cantilever gives better performance and improve the sensitivity of sensor for longer cantilever showing the greater displacement and electric potential value at diastolic condition. Smart piezoelectric U-shaped cantilever based blood pressure sensor have high linear behavior, high flexibility, high sensitivity, also it is a method of non-invasive sensing, so PZT-5H

U-shaped cantilever based blood pressure sensor is useful precisely monitoring of human health.

5.2 Recommendation

This research has successfully simulated, however, different shapes of cantilever such as E-shaped, T-shaped, Pi Shaped or Coupled Shaped of cantilever design and different material as a sensing layer of cantilever such as PVDF and ZnO also can be considered because these materials are lightweight and suitable for lightweight applications such as clothing to be proposed for future research. Simulated U-shaped cantilever based blood pressure sensor also can be used for other human health parameter such as monitoring of human body temperature. In addition, the designs of sensor are being simulated using COMSOL Multiphysics Software need to be proved by fabricate sensor. This is to ensure the U-shaped piezoelectric cantilever based sensor able to function as in the simulation.

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