Design and Displacement Analysis of Three different Cantilever based MEMS Piezoresistive Pressure Sensor with Polymer (PDMS/PMMA) Thin Flim

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Abstract

This paper mainly focuses on to get high displacement from polymer based piezoresistive cantilever for MEMS/NEMS pressure sensor applications. The displacement has been analyzed and compared with three different cantilever using PDMS (Poly dimethyl siloxane) and PMMA (Poly methyl methacrylate) materials. The p-type silicon piezoresistors connected the form based on wheat stone bridge to get high sensible pressure sensor with respect to low response. An according to get high displacement, obviously the other performance of parameters such as stress, strain gets high range. So, this analyzed cantilever structure used to design a pressure sensor with high sensitivity. The design and simulation are done by using COMSOL Multiphysics.

Key-words: MEMS/NEMS Pressure Sensor, PDMS, PMMA, Displacement, COMSOL.

1. Introduction

Polymers have many advantages like biocompatible, non-porous, weight, cost, portability, conformability, flexibility, disposability etc. Here we use two polymer materials PDMS and PMMA. These two polymers enormously used in Bio-MEMS applications. PDMS easily detect very low pressures/forces such as Biomechanics interactions from cells and it used to fabricate multilayer

devices and also integrated devices. PDMS polymer gives support to the manufacturer [1]. Unlike silicon, PDMS/PMMA have lower friction coefficient at high velocity, highly hydrophobic and these have independent adhesive force of rest time. These two polymers are suited to operate with varying environment conditions in MEMS/NEMS devices [2]. Piezoresistive pressure sensor produce linear results over a wide range of pressure compared with capacitive pressure sensor [3]. MEMS Technology, currently using in biomedical devices. MEMS cantilever piezoresistive pressure sensor has a promising technology in biomedical with high sensitivity [4]. The MEMS technology and polymers, both are connected together used to design a single device plays vital role in biomedical applications. A design with PDMS got higher displacement [7]. This cantilever piezoresistive pressure sensor designed with all above said features.

Micro-cantilever sensors have a great attraction because of its considerable capacity of detecting molecules [8]. Piezoresistive Cantilever biosensors give greater stability and flexibility compared with normal cantilever methods [9]. Which enable more compact and non-optical detection systems have been implemented for atomic force microscope and the application of bio/chemical sensors [10]. In cantilever based biological and chemical sensors converting the mechanical deformation of cantilever into an equivalent electrical signal [11]. A highly sensitive micro pressure sensor used for bio-mechanical characterization. Displacement of the cantilever is related to applied pressure. Thus, the applied pressure could be detected by measuring the displacement of the reference cantilever sensor. These sensing methods for detection of micro pressures are: Piezoresistive, Capacitive and optical / laser detection [13].

This paper is a comparative displacement study of three different cantilevers with two different materials based piezoresistive pressure sensor to improve the sensitivity for biomedical applications. The material selection plays important role to get high displacement. The proposed structure having piezoresistors, that would be connected in a form of Wheatstone bridge. It's used to get high sensitivity for low response.

2. Design Methodology and Modeling

Figure 1 shows conventional cantilever MEMS piezoresistive pressure sensor for proposed structure.

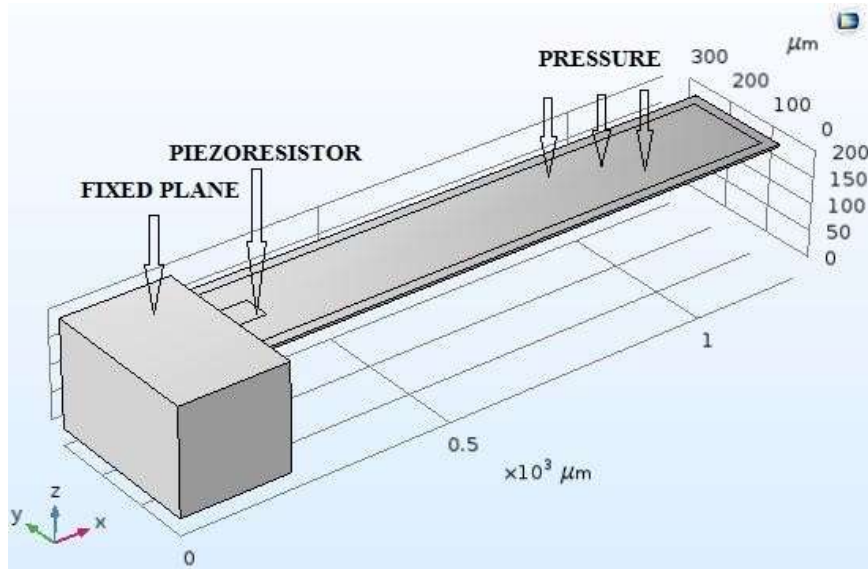Figure 1- Schematic view of Cantilever Pressure Sensor Model

Table 1- Dimensions of MEMS Piezoresistive Pressure Sensor

	Width (μm)	Depth (μm)	Height (μm)
Rectangular cantilever	1000	200	5
Piezoresistor	50	50	5

2.1. Performance Parameters

2.1.1. Wheat Stone Bridge

The most common and simplest circuit used where small changes in resistance are to be measured. The wheat stone bridge circuit is in balanced condition, until we apply some pressure on cantilever. Due to applying pressure on cantilever, it gets displacement and it will be change the resistance [6].

Figure 2- Schematic Representation of Wheat Stone Bridge Circuit
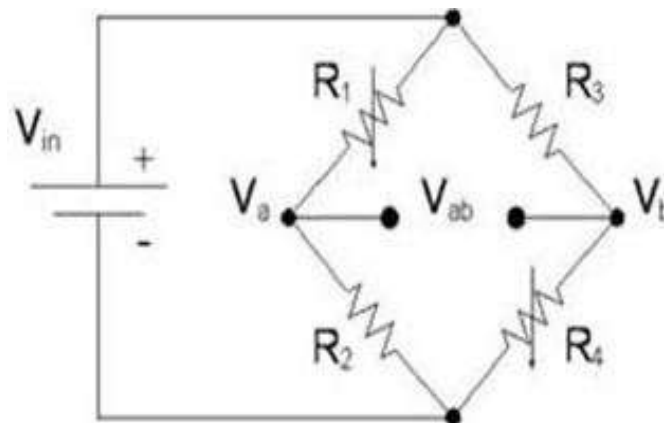
where

V_a and V_b are the voltage dividers.

$R_1, R_2 =$ we would set a value of resistance

R_3 the resistance changes till we get $V_{a-b}=0$.

$R_4 =$ It will be calculated (i.e. unknown value).

V_{ab} must be zero. Then only the bridge is balanced condition.

2.1.2. Piezoresistive Effect

Due to applied pressure the resistivity of a material has varied is called piezoresistive effect. Change of piezoresistors causes by applied pressure is transferred into voltage due to the piezoresistive effect [12]. It can be calculated by using gauge factor [5]. Strain on crystal (like single crystal silicon, doped p, n-type material) structure changes its energy band structure. Because of this energy band structure changes; we have a change in mobility of carrier (electrons or holes) and that actually changes the resistance.

2.1.3. Gauge Factor (G)

Measure of change in resistance with respect to the strain.

$$G = \frac{\Delta R}{R} \cdot \frac{1}{\epsilon} \qquad (1)$$

$$\epsilon = \frac{\Delta L}{L} \qquad (2)$$

Where

$\Delta R =$ Change in resistance

R = Resistance

ϵ = Strain

L = Length of the resistor

$\Delta L =$ Change in length of the resistor

From basic electronic physics,

$$R = \frac{\rho L}{A} \qquad (3)$$

Where

ρ = Resistivity

$$A = \left(\frac{\pi D^2}{4}\right) \qquad (4)$$

A = Area of resistor

D = Diameter of the resistor

Equ (3) written as

$\Delta R = \frac{\rho}{A}\Delta L + \frac{L}{A}\Delta\rho + \rho L(-\frac{1}{A^2})\,\Delta A$

$\frac{\Delta R}{R} = \frac{\Delta L}{L} + \frac{\Delta\rho}{\rho} - \frac{\Delta A}{A}$

From equ (4), we can get $(\frac{\Delta A}{A})$ value

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} + \frac{\Delta\rho}{\rho} - 2\frac{\Delta D}{D} \qquad (5)$$

When length of the resistor increased; the diameter of the resistor gets decreased. Its related by poisson's ratio(γ)

$\gamma = -\frac{\Delta D/D}{\Delta L/L} \;=> \frac{\Delta D}{D} = -\gamma\frac{\Delta L}{L} = -\gamma\epsilon$

$(5) => \frac{\Delta R}{R} = \epsilon + \frac{\Delta\rho}{\rho} + 2\gamma\epsilon$

Gauge factor $(G) = \frac{\Delta R}{R}\cdot\frac{1}{\epsilon} = \frac{\Delta\rho}{\rho\epsilon} + (1+2\gamma)$

The material with high gauge factor can produce much higher amount change in resistance. It's widely used for making piezoresistive pressure sensor.

2.1.4. Piezoresistive Co-efficient (π)

$G = \frac{\Delta R}{R}\cdot\frac{1}{\epsilon}$

Stress $(\sigma) = y\epsilon$

$$\boxed{\frac{\Delta R}{R} = G\epsilon = G\frac{\sigma}{y} = \pi\sigma}$$

Stress and strain related by Young's Modulus.

3. Material Properties

Figure 3 shows the three different cantilever structure with piezoresistor. The piezoresistor made by using p-type silicon material and the cantilever material is PDMS (poly dimethyl siloxane) / PMMA (poly methyl methacrylate). But, the third structure of the cantilever is silicon, only the inbuilt part is PMMA/PDMS.

Figure 3
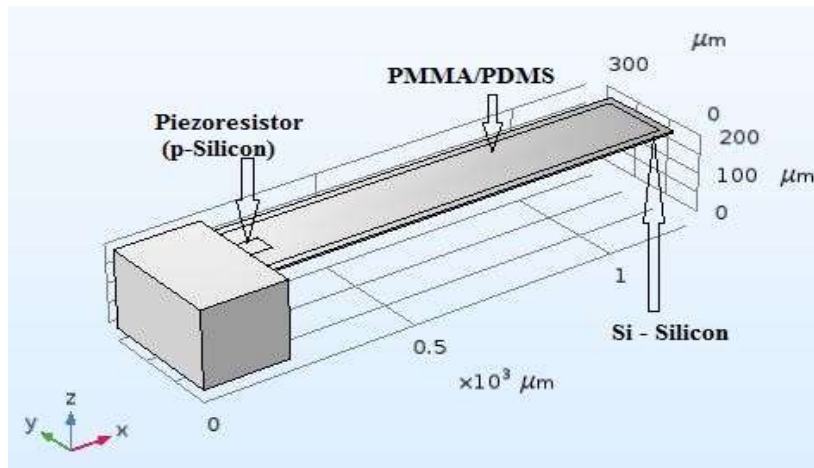Structure 1
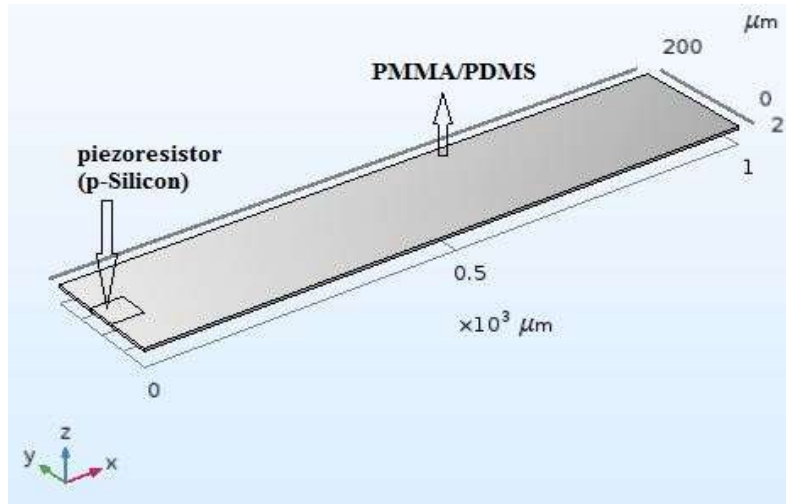
Structure 2
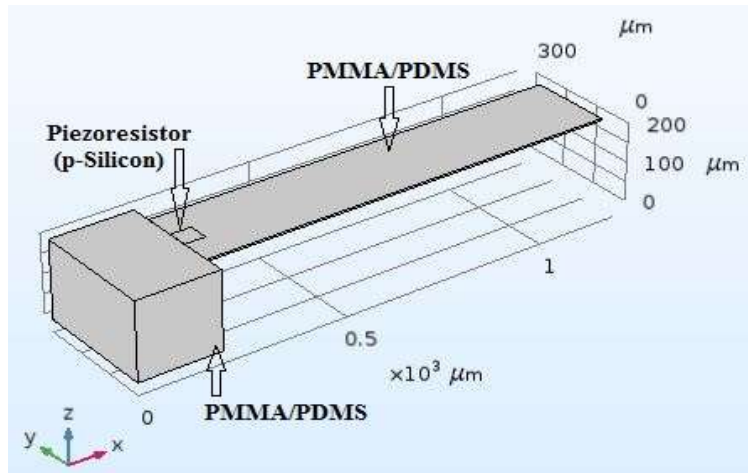
Structure 3

Table 2- Physical Properties for Cantilever based Piezoresistive Pressure Sensor

Material	Density (kg/m^3)	Young's modulus (Pa)	Poisson's ratio
Si-silicon	2329	170[GPa]	0.28
p-silicon	2330	140[GPa]	0.265
PMMA	1190	3[GPa]	0.40
PDMS	970	750[kPa]	0.49

Piezoresistive coupling matrix X 10^{-11}(m^4/(s·A²))

p-silicon

$$\begin{bmatrix} 6.6 & -1.1 & 6.6 \\ -1.1 & -1.1 & 6.6 \\ 0 & 0 & 0 \\ 138.1 & 0 & 0 \\ 0 & 0 & 138.1 \\ 0 & 0 & 0 \\ 0 & 0 & 138.1 \end{bmatrix}$$

n-silicon

$$\begin{bmatrix} -102.2 & 53.4 & -102.2 \\ 53.4 & 53.4 & -102.2 \\ 0 & 0 & 0 \\ -13.6 & 0 & 0 \\ 0 & 0 & -13.6 \\ 0 & 0 & 0 \\ 0 & 0 & -13.6 \end{bmatrix}$$

Elasticity   matrix   (GPa)

p-silicon

$$\begin{bmatrix} 166 & 64 & 166 \\ 64 & 64 & 166 \\ 0 & 0 & 0 \\ 80 & 0 & 0 \\ 0 & 0 & 80 \\ 0 & 0 & 0 \\ 0 & 0 & 80 \end{bmatrix}$$

$$\begin{bmatrix} 166 & 64 & 166 \\ 64 & 64 & 166 \\ 0 & 0 & 0 \\ 80 & 0 & 0 \\ 0 & 0 & 80 \\ 0 & 0 & 0 \\ 0 & 0 & 80 \end{bmatrix}$$

n-silicon

Elastoresistive   coupling   matrix   (Ω·m)

p-silicon

$$\begin{bmatrix} 9.6 & 1.8 & 9.6 \\ 1.8 & 1.8 & 9.6 \\ 0 & 0 & 0 \\ 110 & 0 & 0 \\ 0 & 0 & 110 \\ 0 & 0 & 0 \\ 0 & 0 & 110 \end{bmatrix}$$

$$\begin{bmatrix} -101.4 & 57.6 & -101.4 \\ 57.6 & 57.6 & -101.4 \\ 0 & 0 & 0 \\ -10.8 & 0 & 0 \\ 0 & 0 & -10.8 \\ 0 & 0 & 0 \\ 0 & 0 & -10.8 \end{bmatrix}$$

n-silicon

The material selection is very important to design a structure to get high sensitivity device.

Table 2 shows the physical material properties such as density, young's modulus, poisson's ratio,

piezoresistive coupling matrix, elastoresistive coupling matrix and elasticity matrix for silicon, p-type, n-type silicon, PDMS/PMMA.

4. Results and Discussion

Figure 4- (a) and (b) Represents Simple Piezoresistive Cantilever Structure Displacement with Two different Materials for 100kPa Applied Pressure. The Displacement almost similar for Both Materials. (c) and (d) Graph Shows the Total Displacement for Arc Length. (e) Graph Represents the Displacement for different Pressure (10 to 100kPa) Applied on Cantilever Structure 1:

PDMS	PMMA

(a)

(b)
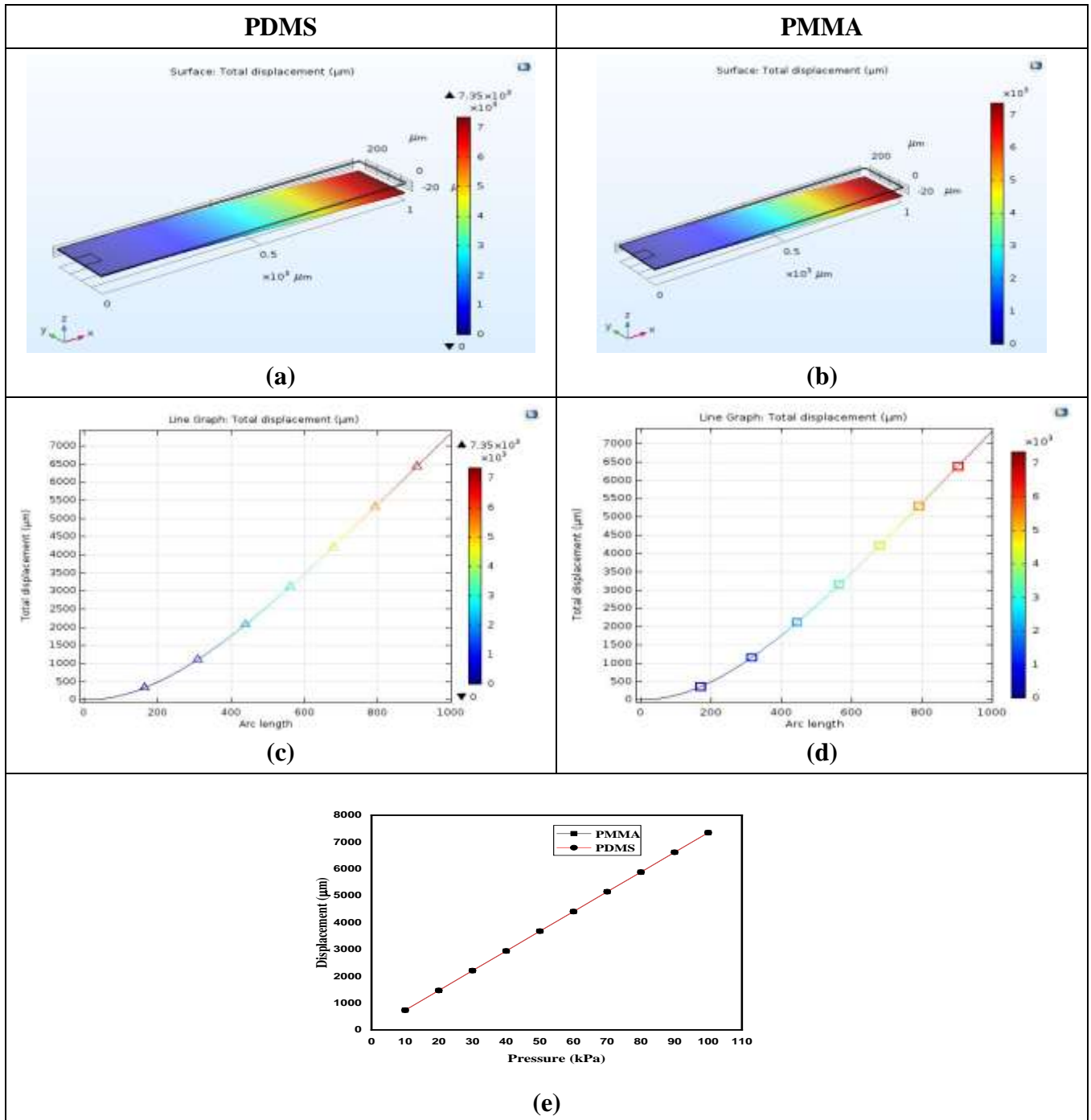

(c)

(d)

(e)

Figure 5- (a) and (b) Represents Piezoresistive Cantilever Displacement with two different Materials for 100kPa Applied Pressure. The Displacement is 7.41e^3 (μm) for PDMS Material Used Structure and almost similar for PMMA Materials. (c) and (d) Graph Represents the Total Displacement for Arc Length. (e) Graph Shows the Displacement for different Applied Pressure (10 to 100kPa)

Structure 2

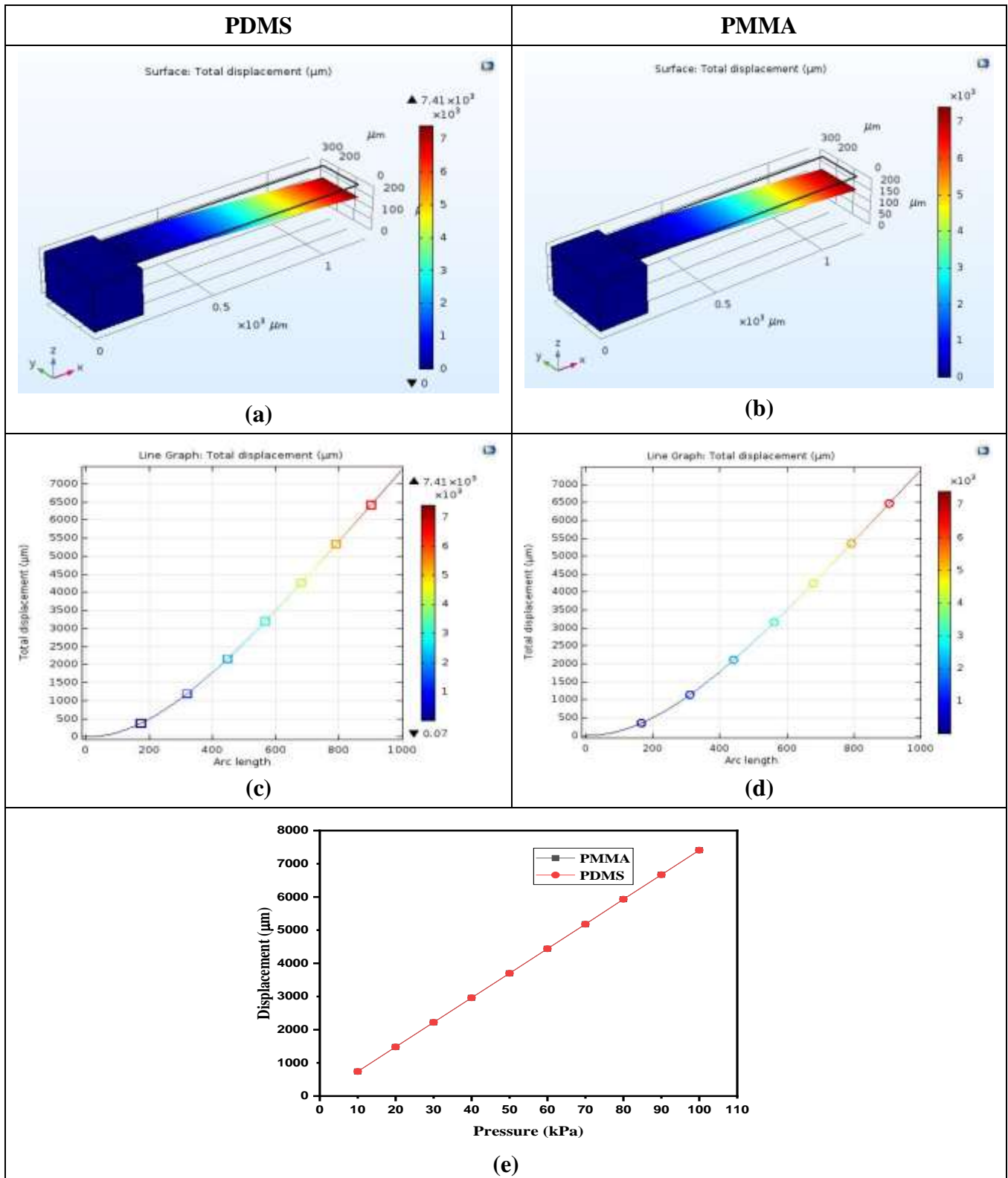| PDMS	PMMA
(a)	**(b)**
(c)	**(d)**
(e)	

Figure 6- (a) Represents Simple Piezoresistive Cantilever Structure Displacement with PDMS Material for 100kPa Applied Pressure. The Displacement is 3.79e^4 (μm) for PDMS Material. (b) Shows the Displacement for the Pressure of 100kPa. The displacement is 3.14e^4(μm) for PMMA material. (c) and (d) Graph Represents the Total Displacement for Arc Length with Two different Material. (e) Graph Represents the Displacement for different Applied Pressure (10 to 100kPa).

Structure 3
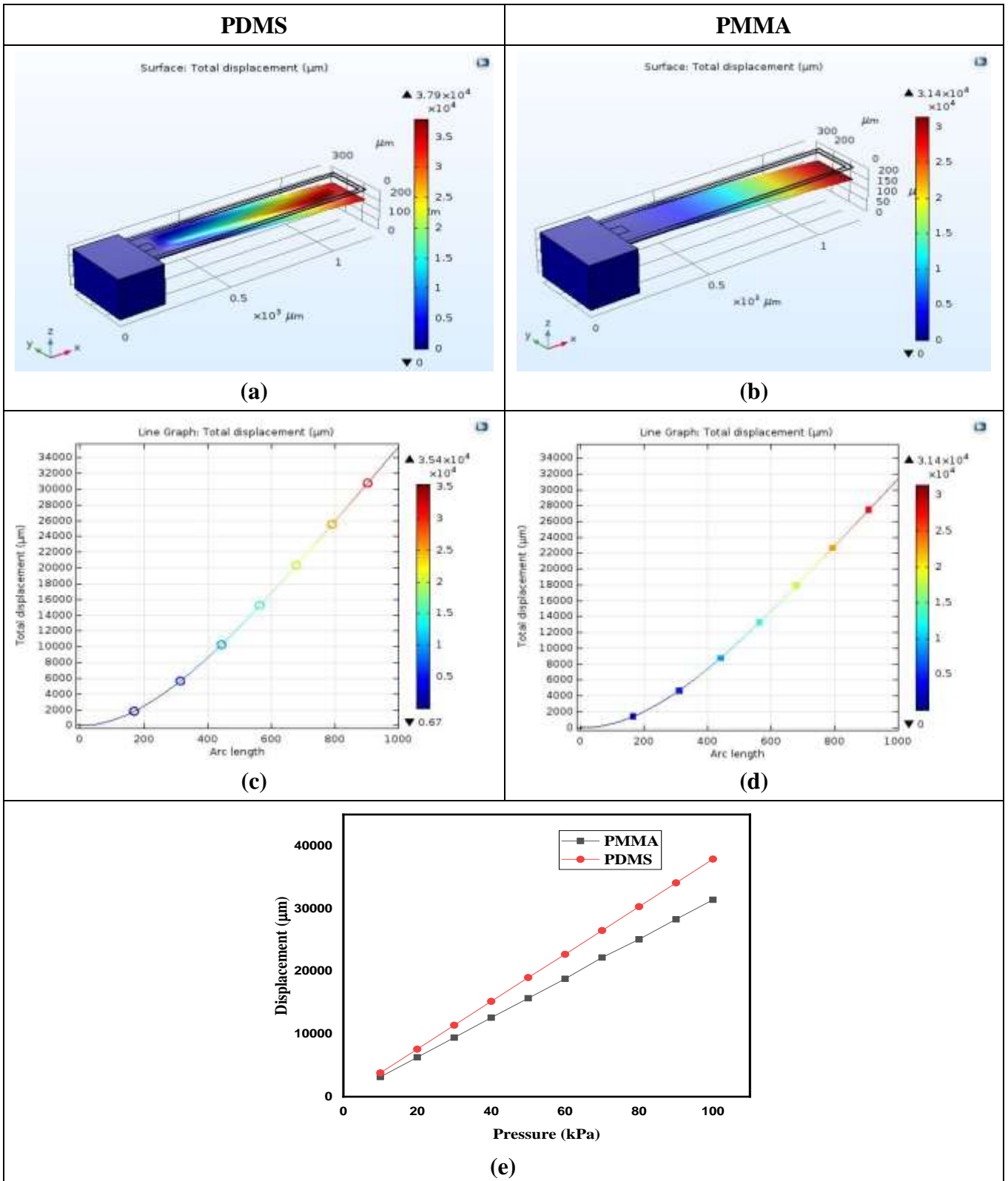
Summary

The simulation results shows that the structure 3 designed with PDMS got higher displacement compared with all other structures with PMMA and also Pdms.

5. Conclusion

The main motive of this research is to get high displacements by design and analyzing different cantilever for pressure measurements. In this paper, the three different cantilever with PMMA/PDMS materials have been compared and the simulation done by using COMSOL multiphysics. MEMS piezoresistive cantilever displacements have been analyzed by applying pressure range between 10kPa to 100kPa. The obtained simulation results represented that the cantilever with PDMS (structure 3) gives a higher displacement compared with PMMA structures. Hence, we conclude this paper that the cantilever structure 3 with PDMS exhibits better displacement. This analyzed cantilever structure could be used to fabricate a pressure sensor with linearity and better sensitivity.

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