Performance Evaluation of Embedded Strain Sensing Varying Thickness Polymer Micro-cantilever as Biosensor Platform

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***Abstract* - High deflection sensitivity of micro-cantilever is one of the important criteria for cantilever being used as a sensor as well as an actuator. Also resonance frequency of these sensors needs to be higher for biosensing applications. Varying thickness cantilever satisfy these desired criteria as compared to constant thickness micro-cantilever of similar length and width. Deflection sensitivity of polymer based cantilever is further enhanced by its low value of Young's Modulus. Among various techniques of detection, piezoresistive based technique is treated as the most suitable detection technique for micro-cantilever in bio-sensing applications. Taking all these aspects into consideration, this paper presents design of varying thickness micro-cantilever and its simulations.The proposed varying thickness cantilever consists of strain sensing embedded piezoresistive material. The study also presents the optimization of dimensions of multi-layer varying thickness micro-cantilever with objective of high sensitivity and resonance frequency. The paper also presents the fabrication methodology and materials for fabrication of varying thickness multilayer varying thickness micro-cantilever. The electromechanical and mechanical performance characterization of this micro-cantilever is further evaluated. This paper uses Finite Element Method (FEM) to obtain the performance of piezoresistive micro-cantilever sensor by optimizing the geometrical dimensions of both cantilever and piezoresistor. CoventorWare a commercial FEM tool for MEMS device design and simulation is used for this work. It is observed that the deflection sensitivity, change in resistance due to stress for this proposed micro-cantilever is quite higher than the normal rectangular micro-cantilever**

***Keywords*—Polymer, FEM, Biosensing,Piezo, Bulklithography, Direct Laser Write**

I. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) technology which deals with the fabrication of devices in the micron scale using a silicon processing technology has generated a noteworthy amount of attention due to the enhanced performance and cost benefit and it also covers the wide range of sensors and actuators. Like other several MEMS sensors, micro-cantilever based biosensors have also fascinated substantial importance to monitor a particular substance in applications such as chemical analysis, environmental control and industrial processes [1]. In these applications, micro cantilever either works on the principle of surface stress, bulk stress or mass changes. In first two modes micro-cantilever bends due to molecules attaching on one side of the cantilever or changes in temperature or humidity. In third mode its resonance frequency shifts due to mass loading. Among various detection techniques, piezoresistive read out has several advantages [2]. This technique is characterized by Gauge factor of the piezoresitive material. Doped Polysilicon, Gold (Ag), SU8-CB mixture, SU8-Ag nano particles mixture and Indium Tin Oxide (ITO) are some of the piezoresitive materials [2] [3] [4] [5] [6].

The conventional rectangular micro-cantilevers posses limited sensitivity to detect the small molecular mass. Typically in biological tests of concentrations of analytes in given sample having μl or pl blood serums contain few triglyceride (TG) and glucose molecules. These molecules are involved in molecular binding generating stress on the cantilever [7]. The amount of deflection due to this stress induced is measured in biological test for conclusions of investigation from sample. Hence, the deflection sensitivity of micro-cantilever need to be more for accurate determination of results [7]. In order to increase the sensitivity of the micro-cantilever several modifications are proposed by the researchers. From the simulation results it is observed that variable sectional thickness based stepped and varying thickness micro-cantilevers give improved performance in terms of higher deflection sensitivity, surface stress and resonance frequency [7] [8]. Also the varying thickness cantilever beam has uniform distribution of stress over its entire length [9]. Due to low Young's Modulus of elasticity compared to Silicon and its compounds, polymer material are preferred over them. SU-8 polymer due to its several advantages has become the choice as MEMS device material [10].

Fabrication of variable sectional thickness based stepped and varying thickness structures posed challenges using conventional micro fabrication processes due to several depositions, photolithography, masks alignment steps required and it is time consuming. But for UV pattern-able polymer materials researchers have proposed several methods for fabricating variable sectional thickness based stepped and varying thickness structures. In the proposed work for one step maskless grey scale lithography for fabrication of 3-dimensional structures in SU-8, authors used Digital Micro-mirror Devices (DMD) to modulate the light intensity across a single SU-8 photoresist layer [11]. Use of electron beam lithography (EBL) to provide high resolution sub-wavelength patterned greyscale masks is demonstrated [12]. In this paper, these greyscale masks are used to fabricate 3-dimensional tapered microstructures for micro-fluidic devices. Also unconventional lithography techniques include inclined ultraviolet (UV) exposure, back-side UV exposure, drawing lithography, and moving-mask UV lithography to create microstructures using SU-8 [13]. These techniques are reviewed in this study. Common photolithography is a widely accepted and powerful patterning technology but only produces planar structures. This restriction is not prohibitive for IC fabrication, but it is a significant limitation for MEMS technologies that may greatly benefit from three-dimensional (3-D) geometries [14]. In this paper a double-exposure greyscale photolithography technique is developed and demonstrated to produce three- dimensional (3-D) structures with a high vertical resolution. Two types of lithography techniques namely grey scale and binary optics are compatible with image processing [14]. These techniques are successfully demonstrated for fabricating 3-D structures in this paper.

Microstereolithography (MSL) is the latest technology adopted for fabricating polymer structure. This process is optimized by studying the effect of laser wavelength, laser energy, scanning speed, and photoinitiator concentration on curing width and depth of the microstructure [15]. On the similar line, author of this paper; K. S. Bhole, *et al*. have shown the experimental results of fabricating the varying thickness cantilever bulk lithography technique. This technique allows fabrication of 3-D microstructures with continuous variation in thickness as opposed to discrete variation provided by normal MSL and other VLSI process. In both these techniques, Hexanediol diacrylate (HDDA) Trimethylolpropane Triacrylate (TMPTA) and Benzoin Ethyl Ether (BEE) photoinitiator is used as a structural material [16] [17].

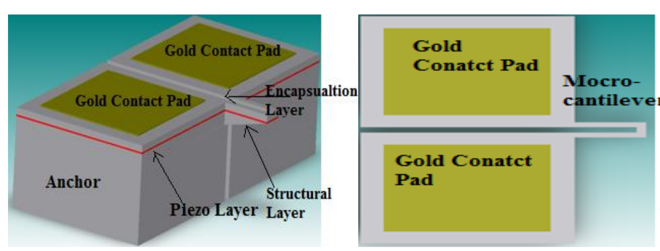
The dimensions of the structures achieved are however large as opposed to micro-cantilever structures for biosensing applications demonstrated by other researchers which are in the range of nanometers to few microns [1] [3] [4]. In order to fabricate micro-structures with the dimensions mentioned in these papers, experimental study of possibility to fabricate greyscale optical elements and structures in SU-8 is very much useful. In this study, authors have characterized SU-8 for both UV and e-beam exposure. It is found from this characterization i.e. exposure dose against cured film thickness that SU-8 film thickness ranging from 100 nm-600 nm is possible from a sample of 700 nm thick SU-8 film on Si-substrate. This is also confirmed by fabricating the 3-D structures in SU-8 [18] [9].

In order to fabricate varying thickness micro-cantilever, we propose to use 3D µ-Printing by Direct Laser Writing with backside exposure of SU-8 coated on Glass substrate [20] [21]. Flip Chip approach in fabrication of micro-cantilever has the advantage that the substrate from which the devices are released is reusable [1]. This is described in detail in Section 2 on fabrication process flow. Also backside exposure of SU-8 coated on Glass substrate is demonstrated in the work of fabricating polymer composite structures and hollow metallic micro-needle array for portable drug delivery [22] [23]. In order to release the devices from substrate, a sacrificial layer is required. Silicon dioxide (SiO_2) deposited by wet oxidation, dielectric sputter, Poly vinyl alcohol (PVA), Phosposilicate Glass (PSG), and polystyrene are used successfully as sacrificial layer [3] [1] [24] [25].

The remaining paper is organized as follows. In Section II, methodology for fabricating varying thickness micro-cantilever is described. Section III describes the design and simulation of this proposed micro-cantilever carried out in CoventorWare platform. In Section IV, the Mechanical and Elecromechanical characterization is presented. Finally the conclusion derived is illustrated in Section V and references used in Section VI.

II. METHODOLOGY

In this paper, varying thickness polymer micro-cantilever with embedded strain sensing layer is proposed for biosensing application. Fabrication of such multilayer micro-cantilever is proposed for the first time. The schematic representation of this multilayer micro-cantilever is as shown in Fig. 1. These three layers are namely encapsulation layer, piezo layer and structural layer. SU-8 negative epoxy material is used for the encapsulation and structural layers. Indium Tin Oxide (ITO) is selected as piezo layer material embedded between these two SU-8 layers [5] [6].



(a) (b)

Fig. 1 Schematic representation of proposed varying thickness multilayer micro-cantilever (a) Side View (b) Top View

A. Fabrication Process Steps

In this section, the fabrication process steps are described as shown in Fig. 2 considering the various issues like selection of material and processes. It is divided into three parts. Two inch diameter Glass wafer is selected as substrate. The masks required for front side and back side alignment are excluded and hence Part A is a three masks process. These three masks are hard masks and are aligned using double sided alignment system. The photolithography in Part B is proposed using 3D µ-Printing by Direct Laser Writing with backside exposure of SU-8 coated on Glass substrate. The mask used for this step is a soft mask (Mask4). Lastly, the photolithography in Part C is again carried out using double sided alignment system and requires hard mask (Mask5).

a. Part A: Sacrificial Layer

First, a Glass wafer is cleaned with piranha ($1:3H_2O_2:H_2SO_4$) is to be cleaned. A 200 nm thick dielectric sputter-deposited silicon dioxide is used as a sacrificial layer as shown in Fig. 2 (b). It is due to its uniform smooth interface and it can be easily etched in hydrofluoric acid. Importantly this is also transparent to UV light wavelength used in photolithography process. Even though other materials like PVA, Paralyne C are transparent to UV light, they suffer with the subsequent processes or not etched easily [1] [24].

b. Part A: Encapsulation Layer

For encapsulation layer, SU-8 2000.5 is spin coated at 3000 r/min on the substrate then soft bake at 70^0 C for 5 min, followed by UV exposure (Mask1) for 20 sec followed by post exposure bake at 95^0 C for 5 min. Then the substrate is immersed in SU-8 developer for 1 min and then transferred into isopropyl alcohol (IPA). The patterned layer is as shown in Fig. 2 (c).

c. Part A: Piezoresistive Layer

The gauge factor of ITO deposited using sputtering can be tailored by monitoring deposition conditions and also thin layer of ITO is transparent to UV wavelength of photolithography process. A thin layer 120 nm of ITO is deposited and patterned using liftoff process (Mask3). It is shown in Fig. 2 (d) and Fig. 2 (e).

d. Part B: Structural Layer

The process steps for structural layer is as described in Section 2.1.2 except that the photolithography is carried out in 3D µ-Printing by Direct Laser Writing with backside exposure of SU-8 coated on Glass substrate. SU-8 is characterized by energy dose against cured thickness [17] [18]. This data is used for patterning this layer with varying thickness using soft Mask4 as shown in Fig. 2 (f).

e. Part C: Anchor Layer

The process steps for patterning anchor layer is as described in Section 2.1.2 except that SU8 2100 is used and spin coated at 1000 rpm/min and soft bake at 65^0 C for 10 min, post exposure bake at 85^0 C for 45 min and 20 min in SU-8 developer followed by 1-2 min rinse in IPA. The patterned layer (Mask4) is as shown in Fig. 2 (g).

f. Part C: Release

Finally, the devices can be released by etching the sacrificial layer in hydrofluoric acid. The released device is as shown in Fig. 2 (h).

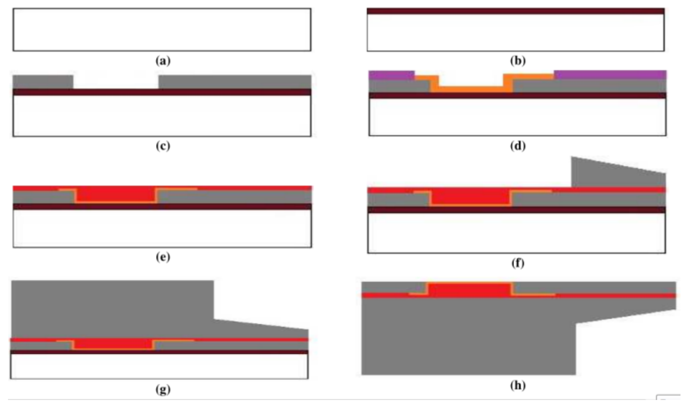
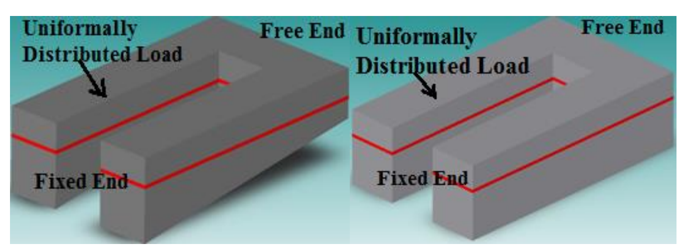


Fig. 2 Process flow for fabrication proposed varying thickness micro-cantilever: **Part A**: (a) Starting wafer (b) Deposition of dielectric sputter SiO_2 Sacrificial layer (c) Patterning of encapsulation layer SU8 2000.5 (Mask1) by front side UV exposure (d) Patterning of Gold contact pads: liftoff method by front side UV exposure (Mask2) (e) Deposition and patterning of sputtered ITO piezo layer by front side UV exposure (Mask3) (f) Patterning of structural layer SU8 2002 3D µ-printing by direct laser writing with backside UV exposure (g) Patterning of anchor layer SU8 2100 with front side UV exposure (Mask4) (h) Wet etching of sacrificial layer to release the device

III. Design and Simulation

The geometric parameters of the micro-cantilever like length, width and thickness of each layer and material properties like Young's Modulus, piezoresitive coefficients play significant role in the performance of the device. CoventorWare, a commercial Finite Element Method (FEM) analysis tool for design and simulation of MEMS device is used to evaluate and compare the performance of the proposed micro-cantilever with normal rectangular micro-cantilever. In order to simplify the design and simulation study, the anchor layer and contact pads are not included in FEM analysis. The boundary conditions are that one end of the micro-cantilever is fixed and uniformly distributed load is applied on the top surface. The 3-D models of these micro-cantilevers are as shown in Fig. 3.



(a) (b)

Fig. 3: (a) 3-D Model of proposed varying thickness micro-cantilever (b) 3-D Model of normal rectangular micro-cantilever

Since for varying thickness micro-cantilever; Manhattan bricks parabolic could not be a suitable choice of meshing, tetrahedron parabolic type meshing is used for both the models. The meshed models are as shown in Fig. 4 and Fig. 5.

Initially, both the meshed models are solved using MemMech solver to simulate the displacement and surface stress distribution of the micro-cantilevers for varying loads. In Fig. 6 and Fig. 7 respectively the displacement and surface stress distribution of the normal rectangular and varying thickness micro-cantilevers is shown for visualization. The piezoresitive layer in both the models is same and hence it is meshed using Manhattan bricks parabolic meshing style.

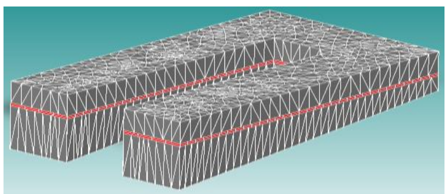


Fig. 4 Meshed 3-D models of proposed varying thickness multilayer micro-cantilever

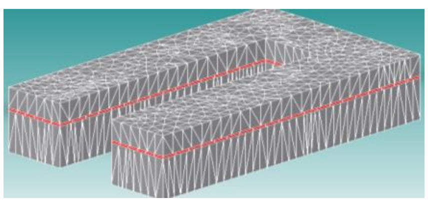
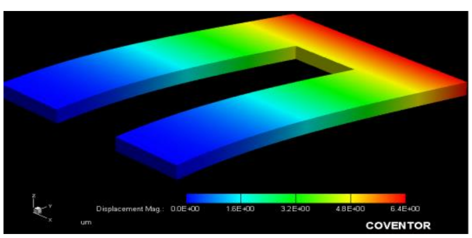
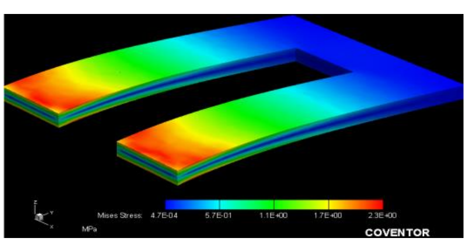


Fig. 5 Meshed 3-D Model of normal rectangular micro-cantilever

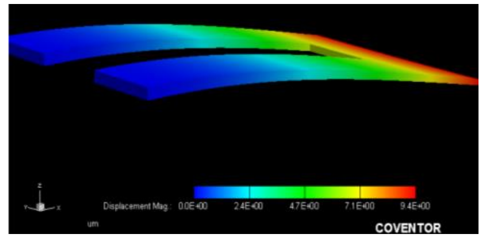


(a)

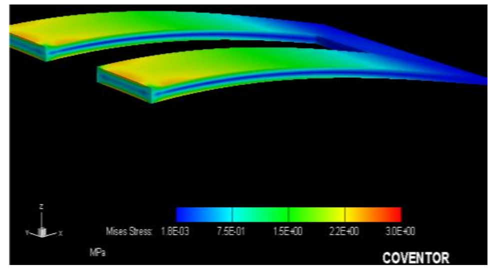


(b)

Fig. 6 (a) Displacement of normal rectangular micro-cantilevers and (b) surface stress distribution of the normal rectangular for applied load



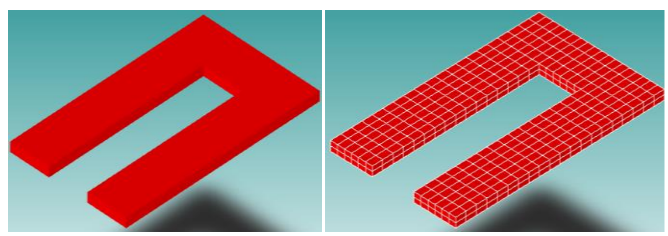
(a)



(b)

Fig. 7 (a) Displacement of varying thickness micro-cantilever and (b) surface stress distribution of the varying thickness micro-cantilever for applied load.

The 3-D model and meshed structure of piezoresitive layer is as shown in Fig. 8 (a) and Fig. 8 (b) respectively. Then, MemPZR solver is used to simulate the change in resistance of this layer for varying loads.



(a) (b)

Fig. 8 (a) 3-D Model of piezoresitive layer for proposed varying thickness multilayer and normal rectangular micro-cantilever (b) Meshed Model of piezoresitive layer for proposed varying thickness multilayer and normal rectangular micro-cantilever

IV. Dimension Variations

In order to see the effect of variations in geometrical parameters namely thickness of the structural layer on the stiffness constant, resonant frequency and change in resistance of piezo layer of the micro-cantilever for applied load, the thickness is changed in steps from 1.8 µm at fixed end to 0.2 µm at free end. The optimization of the length and the width for affinity micro-cantilever is proposed in [1] [3]. Hence, these dimensions are taken for simulation and not varied. The representative 3-D models for varying thickness from 1.8 µm at fixed end to 1 µm and 1.8 µm at fixed end to 0.2 µm is shown in Fig. 9. This is done by changing the process step parameters for structural layer in CoventorWare Designer-Process Editor. This process step represents the 3D µ-Printing by Direct Laser Writing with backside exposure of SU-8 structural layer coated on Glass substrate.

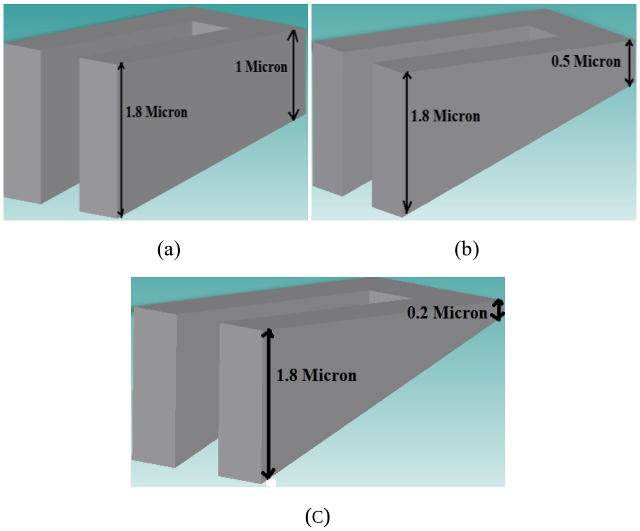


Fig. 9 Varying thickness mico-cantilever 3-D models for thickness variation from (a) 1.8 μm at fixed end to 1 μm at free end (b) 1.8 μm at fixed end to 0.5 μm at free end and (c) 1.8 μm at fixed end to 0.2 μm at free end

V. RESULTS

Simulation study is carried out for estimating the deflection sensitivity (stiffness constant), change in resistance of piezo layer and resonant frequency of the proposed micro-cantilever by varying the thickness of the structural layer. These obtained values are compared with the normal rectangular micro-cantilever model with same dimensions except constant thickness of the structural layer. A uniformly distributed forces of 1-μN to 5-μN are applied in steps for both the cases.

The deflection sensitivity, resonance frequency and the change in the piezo layer resistance of the proposed micro-cantilever for varying thickness of structural layer is as shown in Fig. 10, Fig. 11 and Fig. 12 respectively. From Fig. 10, Fig. 11 and Fig. 12, it is clear that the deflection sensitivity, resonance frequency and the change in the piezo layer resistance of the proposed micro-cantilever increases as the thickness is changed from 1 μm to 0.2 μm at its fixed end i.e. the cantilever becoming more tapered. The deflection sensitivity, resonance frequency and the change in the piezo layer resistance of the proposed micro-cantilever for varying thickness from 1.8 μm at fixed end to 1 μm and 1.8 μm at fixed end to 0.2 μm is as shown in Fig. 13. The thickness which gives these results is referred to as optimum thickness. The deflection sensitivity, resonance frequency and the change in the piezo layer resistance of the proposed micro-cantilever obtained for optimum thickness earlier are compared with deflection sensitivity and the change in the piezo layer resistance a normal rectangular micro-cantilever is as shown in Fig. 14 respectively. From Fig. 14 it is clear that the performance of the normal rectangular micro-cantilever can be increased by optimizing the tapered structure of micro-cantilever. However, as expected the resonance frequencies of all the models do not change with applied load as evident from Fig. 11.

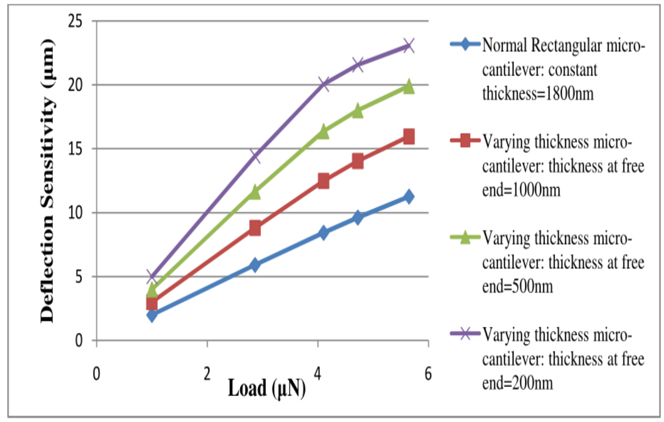


Fig. 10 Plot of maximum displacement of micro-cantilever against load

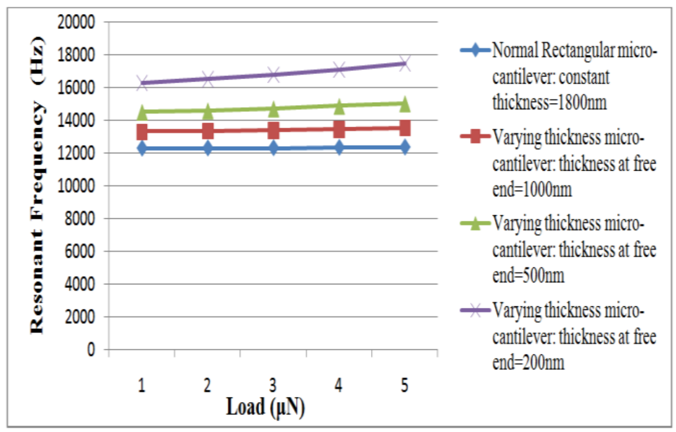


Fig. 11 Plot of change in resonance frequency of micro-cantilevers against load

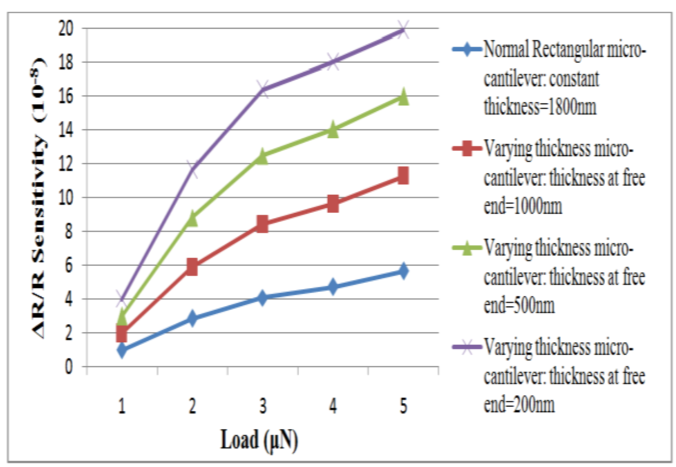


Fig. 12 Plot of the change in the piezo layer resistance of micro-cantilevers against load

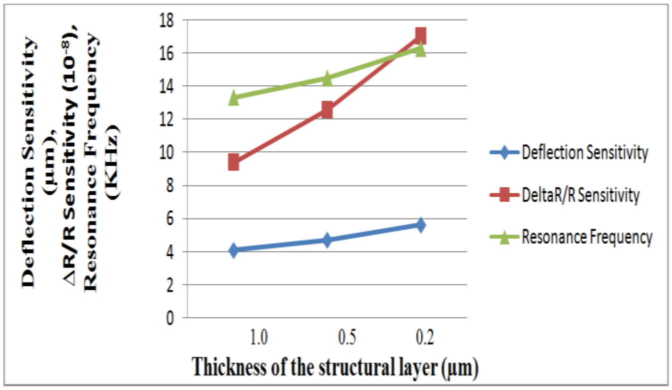


Fig. 13 Plot of maximum displacement, resonance frequency and the change in the piezo layer resistance of varying thickness micro-cantilever against different thickness

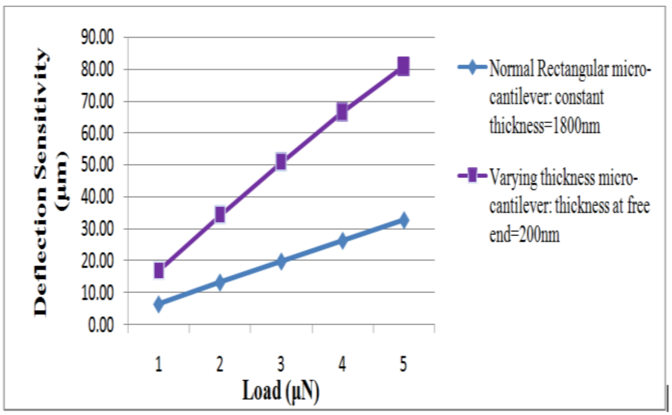


Fig. 14 Plot of maximum displacement, resonance frequency and the change in the piezo layer resistance of optimized varying thickness micro-cantilever and normal rectangular micro-cantilever

VI. CONCLUSION

In this work, the performance evaluation of polymer embedded strain sensing varying thickness micro-cantilever is done through design and simulations in CoventorWare. Through geometrical variations optimum dimensions of the micro-cantilever are obtained. This micro-cantilever has larger deflection sensitivity, resonance frequency and change in resistance of piezo layer as compared to normal rectangular micro-cantilever. Hence this is suitable for biosensing applications for detecting the small concentrations of analyte in given sample like the *µl* and *pl* blood serums contain few triglyceride (TG) and glucose molecules. These analytes would take part in molecular binding to generate stress on this cantilever to deflect it larger than normal rectangular micro-cantilever. Further it can be concluded that SU-8 polymer is a suitable material for varying thickness cantilever as it can be easily patterned with varying thickness by changing the UV exposure energy dose and it also enhances the deflection sensitivity due to its low Young's Modulus. ITO is the most suitable piezo material in this structure as it is transparent to UV wavelength. For the first time, the design, simulation results and the fabrication methodology of this novel multilayer micro-cantilever is proposed which is suitable as biosensor platform.

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