Cantilever based MEMS pressure sensor using different Piezoelectric Materials: A comparative study

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Abstract **- The micro-electromechanical systems (MEMS) has attracted many researchers since past two decades especially in micro sensors and actuators. Pressure sensors are one of the important sensors among them. These pressure sensors have been based on various physical properties like piezoresistive, piezoelectric, capacitive, magnetic, and electro-static. In this paper we have studied cantilever based MEMS pressure sensor using different Piezoelectric Materials for micro-cantilever. In this work we have chosen PZT, ZnS and $BaTiO_3$ as Piezoelectric Materials. We designed, modeled and simulated our device in COMSOL software based on finite element method. The structure consists of silicon on piezoelectric micro-cantilever with cantilever beam. In simulation we have studied displacement and voltage by varying applied pressure. It is observed that the induced voltage is almost linear with the applied force. The comparative study by simulations can be used to provide the guidelines for a design and optimization of performance of the different piezoelectric micro-cantilever pressure sensors.**

Keywords **- Micro cantilever, MEMS, Piezoelectric, Pressure Sensor, Finite Element method**

I. INTRODUCTION

The micro-electromechanical systems (MEMS) have attracted many researchers since past two decades especially in micro sensors and actuators. Pressure sensors are one of the important sensors among them. These pressure sensors have been based on various physical properties like piezoresistive, piezoelectric, capacitive, magnetic, and electro- static. But as Compared to other MEMS technologies, piezoelectric MEMS recommend great rewards [1]. A lot of researches have been proposed on the MEMS pressure sensors which have been established in the 1970's [2]. Smits and Choi [3] introduced electromechanical characteristics of a heterogeneous piezoelectric bender based on various electrical and mechanical boundary conditions: a mechanical moment at the end of the bender, a pressure applied perpendicular to the tip of the bender and a uniform load applied over the entire length of the bender. Zhang and Sun [4] outlined the relation between minimum detectable force gradients and level dimensions in noncontact scanning force microscopy using piezoelectric micro cantilever.

Finite element analysis simulations using COMSOL Multiphysics have been implemented in this work to analyze the results of the multi-layer cantilever Structures using piezoelectric materials (PZT). The geometry of a Structure is used previously, developed SiO2-based cantilevers [5]. Using this Structure the characteristics of piezoelectric material have been described. These simulation results show that displacement and electric potential are linearly increases as applied pressure increases. In this work, comparisons of simulation of various piezoelectric materials (PZT, BaTiO3 and ZnS) have been carried out using same Structure. The current design and operational principles are outlined in this paper. Future work is proposed either energy harvester or load driver.

II. BASIC THEORY

The word "Piezoelectricity" is explained as the ability of certain materials to generate electrical charge due to mechanical deformation. There is no standard method to calculate the electromechanical parameters of piezoelectric structures. Details of layer in multilayer cantilever is shown in table-1[5]

Table 1

Materials	Functions
SiO_2	Flexible basic layer of the cantilever beam
Pt , Al	Electrodes of piezoelectric layer
Si_3N_4	Used to cancel the initial charges in the cantilever beam
piezoelectric	Piezoelectric layer

In this work, two distinct approaches have been to determine the parameters of the multi-layer cantilevers. The first method explains theoretical relationship between surface stress (pressure) and tip displacement at the top layer of the micro cantilever and the relationship between the piezoelectric tip displacement and the induced voltage level is also explained. Piezoelectric materials deform then electrical charge accumulates on opposing surfaces and produces a voltage when strained by an external force [6]. This is due to the permanent dipole nature of these materials. When differential surface stress is applied on the top of the cantilever, the tip displacement z caused by the differential surface stress s can be written as [7]

$$Z = \frac{3(1-v)L^2}{T^2E}\delta s \qquad (1)$$

Where L is the length of the cantilever, T is the overall cantilever thickness, ν is the Poisson ratio, S is the differential surface stress, and E is the Young's module.

Assuming a thin piezoelectric layer on a thick elastic substrate and without the external force or moment [8], the relationship between the cantilever tip displacement and the corresponding voltage is written as

$$V = \frac{T^2E_e}{3d_{31}L^2E_p}Z \qquad (2)$$

Rearrange the equation (2) using equation (1) and written as

$$V = \frac{E_e(1-v)}{d_{31}E_p\,E}\delta s \qquad (3)$$

Where *V* is the voltage generated or applied on the piezoelectric layer, E_p is the Young's modules of elasticity for the piezoelectric, E_e is the Young's modules of elasticity elastic materials and d_{31} is the piezoelectric constant of the piezoelectric material.

In the second method, Finite Element Method simulations using COMSOL Multiphysics have been executed on multi-layer cantilevers.

III. DESIGN AND SIMULATION

Finite element analysis COMSOL Multiphysics software is opted for simulation of this Structure. COMSOL tool is a finite element analyzer, solver and Simulation software. This FEA Software has packages for various physics and engineering applications. This FEA Software has a MEMS package. Structure 1 has platinum (Pt) as an electrode but Structure 2 has aluminum (Al) as electrode. Dimension of structure 1, 2 has been shown in Table 2, 3. Structure2 side view has been shown in figure 2.

Table 2

Unit (µm)	Length	Width	SiO_2	Pt	Si_3N_4	PZT
Structure 1	500	125	0.5	0.1	0.1	0.5

Table 3

Unit(µm)	Length	Width	SiO_2	Al	Si_3N_4	PZT
Structure2	500	125	0.5	0.1	0.1	0.5

In this simulation we have some assumptions. These are following assumption.

1. All piezoelectric layers have already been polarized and the driving voltage will not change the polarization.
2. One end of the cantilever is defined as the origin of the *X*-direction. This is also consistent with the boundary conditions.
3. Fixed constraint is made in Y-Z direction at origin side.
4. All the properties of materials are taken as default properties of simulation software.

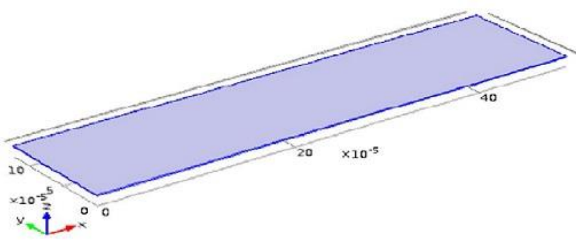

Figure 1 3D combined view of multilayer in COMSOL

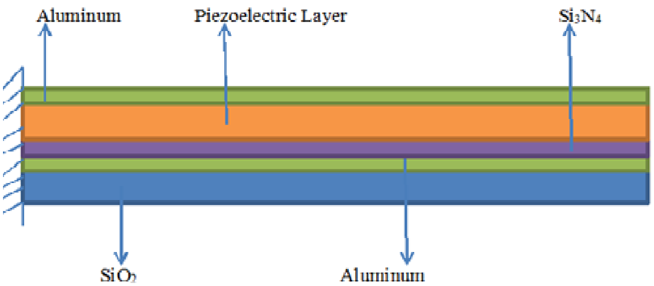

Figure 2 Side view of designed structure 2

IV. RESULTS AND DISCUSSION

Simulations of this work are done by piezoelectric devices Model of COMSOL Multiphysics. This simulation does study all the parameters related to piezoelectric materials. Piezoelectric micro cantilever Structure is made using 3D solid elements. The Structure is mashed which consists of 50,000 to 90,000 elements. Stationary type of study is chosen for simulation results. Firstly simulation results are carried out for Structure 1(table2).Surface pressure (N/m2) is applied in X-Y directions. Deformation of multilayer cantilever is achieved in Z direction. Tip displacement of multilayer cantilever is directly proportional to applied surface pressure, equation (1).

Fig 3 shows the variation of displacement with respect to length of cantilever. The end tip of cantilever has maximum deformation (1.61µm) and fixed end has minimum deformation when surface pressure is subjected.

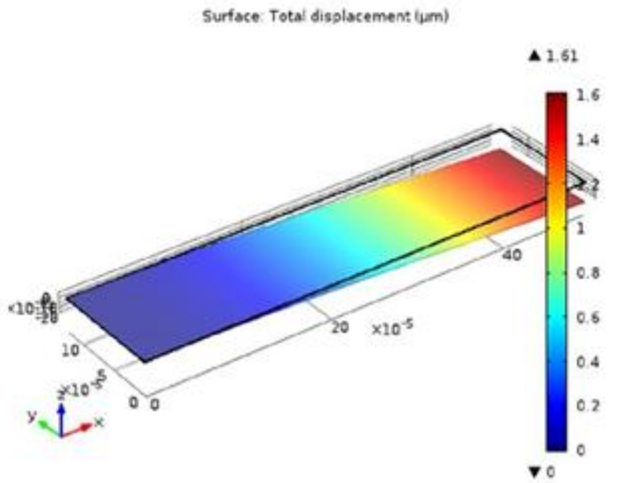

Figure 1 Deformation of cantilever when 5N/m^2 pressure is applied

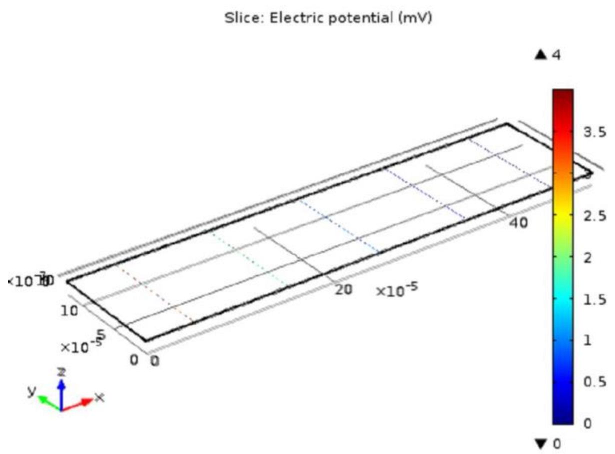

Figure 4 Induced electric potential when 5N/m^2 pressure

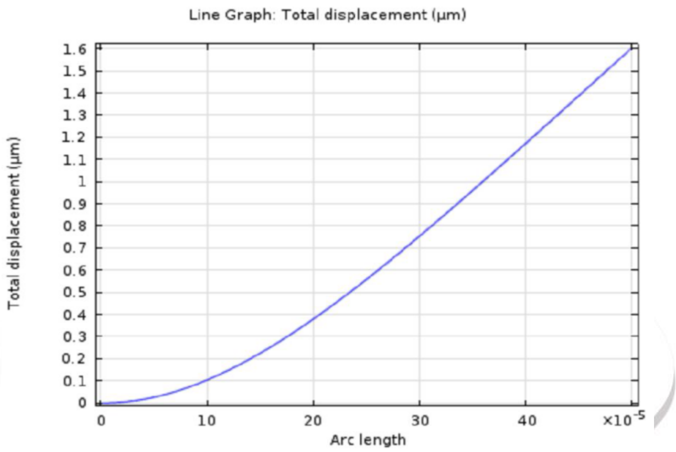

Figure 5 Displacement with increasing arc length of cantilever, for Structure 1

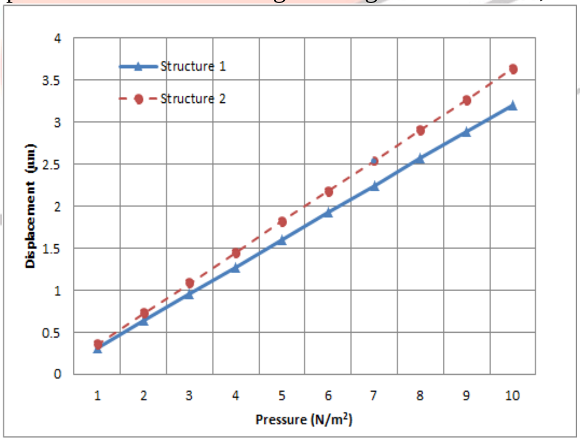

Figure 6 Displacement variations with linearly increasing pressure, Structure 1and 2

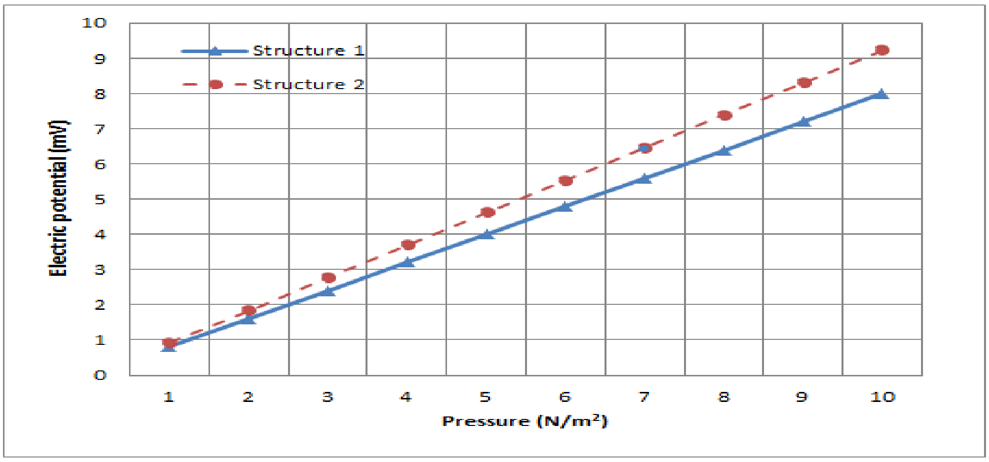

Figure 7 Electric potential variations with linearly increasing pressure, Structure1and 2.

Fig. 4 shows charge accumulation due to piezoelectric property of material when surface pressure 5N/m^2 is applied. Structure 2 has better displacement and electric potential responses rather than Structure 1 but both Structures have same piezoelectric material, Fig.6 and Fig.7 Structure 1 has platinum (Pt) as an electrode but Structure 2 has aluminum (Al) as electrode. Aluminum has low values of Poisson ratio and Young modulus.

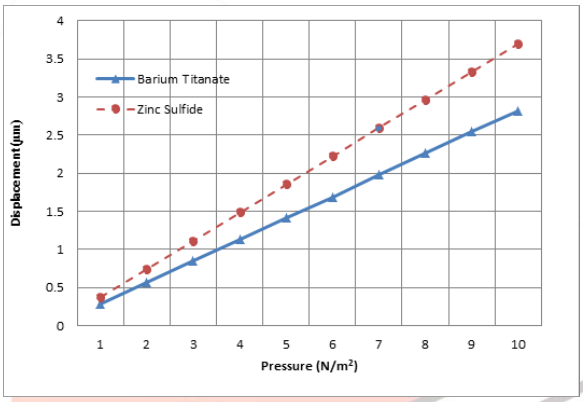

Figure 8 Displacement variations with linearly increasing pressure, piezoelectric Materials ($BaTiO_3$, ZnS).

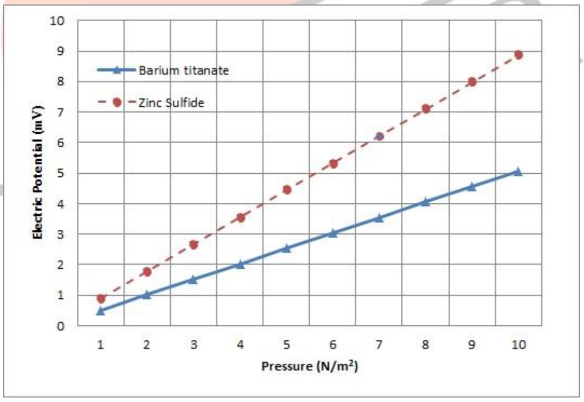

Figure 9 Electric potential variations with linearly increasing pressure, piezoelectric Materials ($BaTiO_3$, ZnS).

Fig.6 and Fig.7 have shown that Structure 2 has good response with linearly increasing pressure. So Structure 2 has chosen as further study. Fig.8 and Fig.9 are representing the comparison of piezoelectric materials (BaTiO3 and ZnS). Zinc Sulfide has better response with linearly increasing pressure due to its relatively large piezoelectric coefficient.

IV. CONCLUSION

In this paper we have studied a load driving application based multilayer MEMS cantilever piezoelectric pressure sensor using three materials namely, PZT, ZnS, and BaTiO3. Simulation results show that in these materials PZT has shown best performance. We have also studied the two electrode metals in the sensor namely platinum and aluminum Comparison shows that aluminum performs better then platinum for all three materials (PZT, ZnS, BaTiO3) due to its low values of Poisson ratio and Young modulus. The combination of aluminum and PZT produced electric potential in the range of 1-10 mV while other combinations were not able to achieve above the 8 mV.

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