Optimization of stacked diaphragms for MEMS Piezoresistive pressure sensor

Santo Mathew, Suja K J, Rama Komaragiri
Department of ECE
National Institute of Technology Calicut, Kerala
rama@nitc.ac.in

ABSTRACT-Micro Electro Mechanical System (MEMS) based silicon pressure sensors have undergone a significant growth in the last few years. In most of the cases, pressure sensors are manufactured by bulk micromachining or surface micromachining and square diaphragms of constant thickness in the order of microns are used. The sensitivity and linear deflection of pressure sensor highly depends upon the diaphragm structure. In this work, optimisation of the thickness of various layers for stacked silicon on insulator(SOI) diaphragms is studied. Also a study of the bulk micro machined silicon piezoresistive pressure sensor and a surface micro machined SOI pressure sensor are simulated and compared with respect to output voltage and deflection

Index terms-MEMS, Piezoresistive Pressure Sensor, SOI diaphragm, Silicon diaphragm, Sensor output voltage, Sensitivity analysis, Deflection analysis

1. INTRODUCTION

Pressure sensors are one of the most common MEMS devices. The MEMS fabrication technology enables minimization of complex systems by integrating the sensing, controlling and actuating functions on a single chip. Diaphragm dimensions are determined by the pressure range and maximum pressure that needs to be measured. MEMS based pressure sensors are characterized into piezoresistive and capacitive type based on pressure sensing principle. The piezoresistive pressure sensor utilises the piezoresistive property of silicon to measure applied pressure. The piezoresistive device works on the principle of change in resistance with the deflection of the diaphragm due to applied pressure. Generally Wheatstone bridge configuration is formed by using four different resistors.

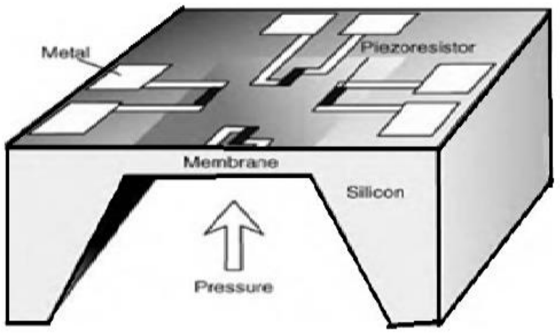

Figure 1. Structure of a piezoresistive silicon pressure sensor.

Figure 1 shows the cross section of a bulk micro machined square diaphragm with diffusedpiezoresistors. The substrate is silicon and the cavity is produced by anisotropic etching on one side. Piezoresistors are implanted on other side of the substrate to sense the induced stress due to applied pressure. The performance of the piezoresistive pressure sensor depends on the dimensions of the diaphragm and the position of the resistors on the diaphragm. In order to obtain high deflection diaphragm should be thin. A very thin diaphragm results in non linear effects. P-type diffused resistors with large piezoresistive coefficients on an N type layer are used in pressure sensors.

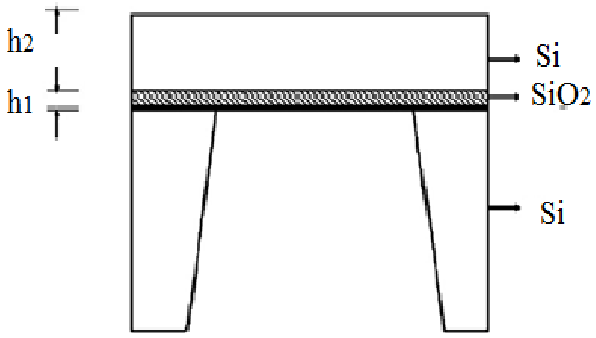

Figure 2. Structure of a SOI MEMS pressure sensor.

Figure 2 shows the schematic cross section of a SOI pressure sensor implemented by surface micromachining process. The insulator material can be SiO_2, Si_3N_4 or any other dielectric. The total thickness h of the diaphragm is the sum of insulator thickness h_1 and top silicon layer thickness h_2.

2. THEORY AND DESIGN

The diaphragm can be modelled as a well known thin-plate problem [1].Analytical model for burst pressure and sensitivity are reported [2]. The load deflection method that describes the relation between displacement and applied pressure for a flat square diaphragm is given by [3]eqn(1)

$$\frac{Pa^4}{Eh^4} = \frac{4.2}{(1-\nu^2)}\left(\frac{y}{h}\right) + \frac{1.58}{(1-\nu)}\left(\frac{y}{h}\right)^3 \qquad (1)$$

Where *E* is Young’s modulus, ν is Poisson’s ratio of the diaphragm material and *h* is diaphragm thickness. Accordingto the load-deflection method, the deflection range is divided into two regions: a small deflection region where deflection less than 25% of the diaphragm thickness described by the linear term in eqn(1) and a large deflection region described by the non-linear, cubic term in eqn (1).The square diaphragm has the highest induced stress with the application of a given pressure [4] and thus a square diaphragm is preferred for the design of pressure sensor in these studies. For a square plate clamped at the edges, the maximum stress σ_{max} at the middle of each edge is given byeqn (2)

$$\sigma_{\max} = \frac{0.308\,P\,a^2}{h^2} \quad (2)$$

Where P is applied pressure,and "a" is side length of the square diaphragm under consideration.

The maximum deflection for a square diaphragm with a given side length and thickness is given by eqn (3)

$$Wmax = \frac{0.00126Pa^4}{D} \quad (3)$$

Where D is the bending rigidity of the diaphragm material and is given by eqn (4).

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (4)$$

The maximum deflection is inversely proportional to bending rigidity. As thickness of diaphragm increases rigidity increases which in turn decreases the deflection.The output voltage and sensitivity of the diaphragm depends on the stress induced which in turn is a function of deflection.

3. RESULTS AND ANALYSIS

The structure was created and simulated using Coventor Ware® tool. Diaphragms with a side length of 500 µm, 600 µm and 700 µm with various thicknesses are simulated. Deflection, stress and output voltage are noted. The maximum pressure applied is 0.9MPa which is less than one tenth of the burst pressure used for calculating the minimum diaphragm thickness. The maximum stress induced is one tenth of the fracture stress as expected.

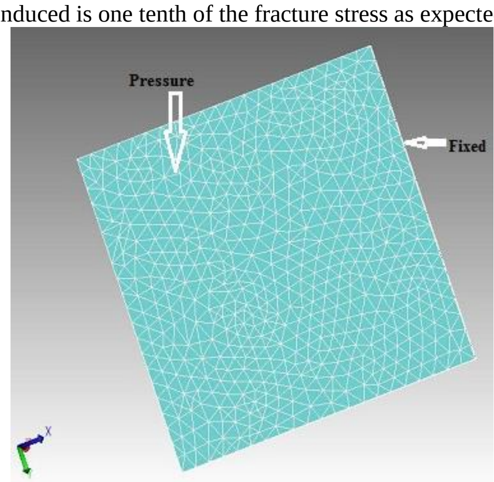

Figure 3. Simulation structure of a square diaphragm

Figure 3 shows the simulation structure of a diaphragm with meshes. The edges of the diaphragm are fixed. Figure 4 shows the deflection of a square diaphragm when a uniform load is applied. The deflection is maxima at the centre of the diaphragm. Figure 5 shows the induced stress with the application of pressure. Stress induced is maxima at the middle of the edges. An applied pressureresults in bridge unbalancewhich results in an output.

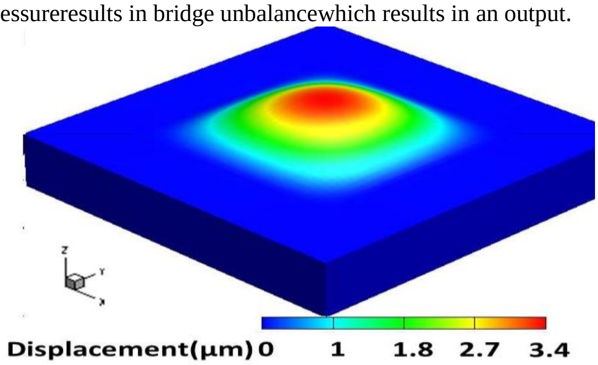

Figure 4. Deflection of the square diaphragm with the application of pressure

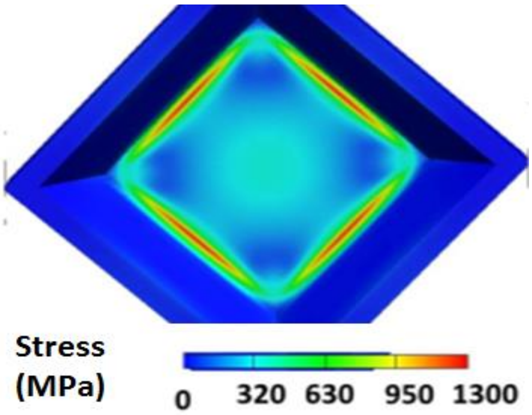

Figure 5. Stress in the diaphragm with respect to maximum applied pressure

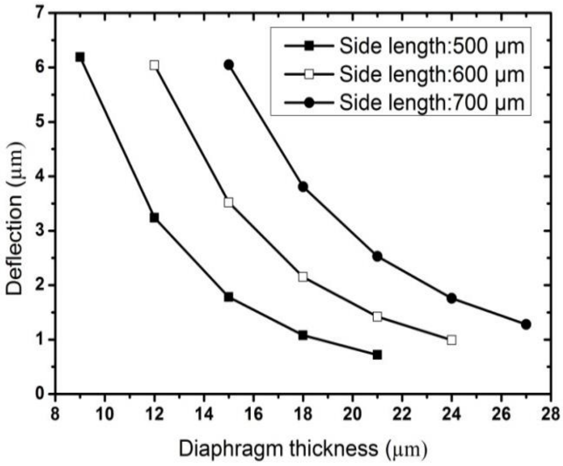

Figure 6. Deflection of silicon diaphragm for different diaphragm dimensions

Figure 6 and 7 respectively show the deflection of silicon and SOI diaphragms for different diaphragm dimensions for an applied pressure of 0.9 MPa. As the thickness of the diaphragm increases, the bending rigidity which is proportional to the thickness increases and deflection decreases. For a particular thickness, as side length increases, deflection increases. For a given side length and thickness SOI diaphragm gives better deflection than silicon diaphragm.

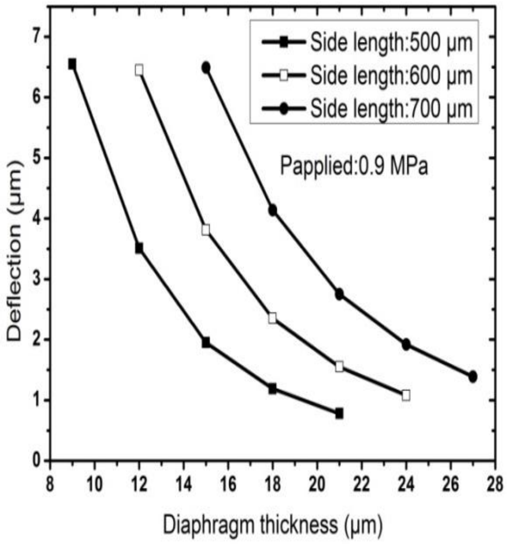

Figure 7. Deflection of SOI diaphragm for different diaphragm dimensions

The silicon diaphragm is realized by conventional bulk micromachining and the horizontal and vertical edges of the diaphragm are essentially integral part of the substrate. In contrast to this, the SOI diaphragm is realised by surface micromachining where the edges of the diaphragm are not integral part of the substrate. Hence deflection is more for SOI than silicon diaphragm with same dimensions.

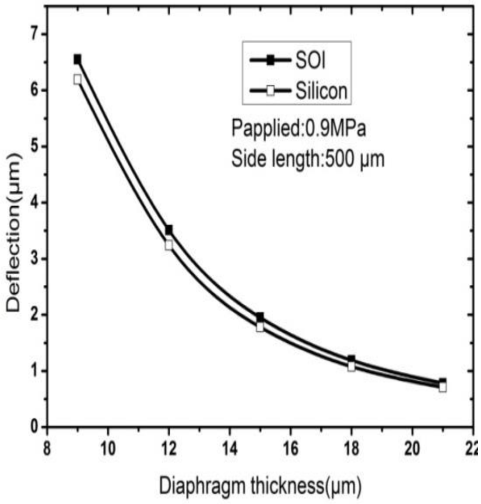

Figure 8. Comparison of diaphragm deflection for silicon and SOI diaphragm

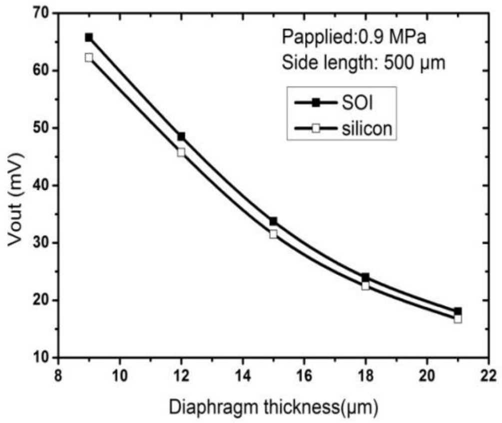

Figure 9. Comparison of output voltage of silicon diaphragm and SOI diaphragm

Figure 8 shows the deflection of SOI and silicon diaphragms for same dimensions and same pressure. Diaphragm deflectionismore for SOI diaphragm than silicon diaphragm with same dimensions. Figure 9 shows a comparison of output voltage of silicon diaphragm and SOI diaphragm for a given dimension and applied pressure. The output voltage of SOI diaphragm is greater than that of silicon diaphragm since the deflection obtained is greater for SOI diaphragm.

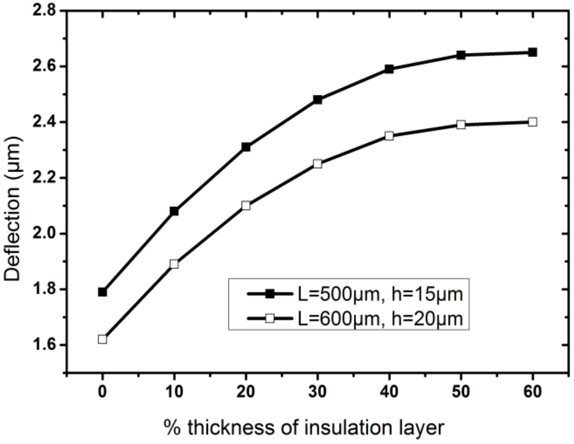

Figure 10. Deflection of SOI diaphragm for various insulation layer thicknesses. (Pressure applied = 0.9MPa)

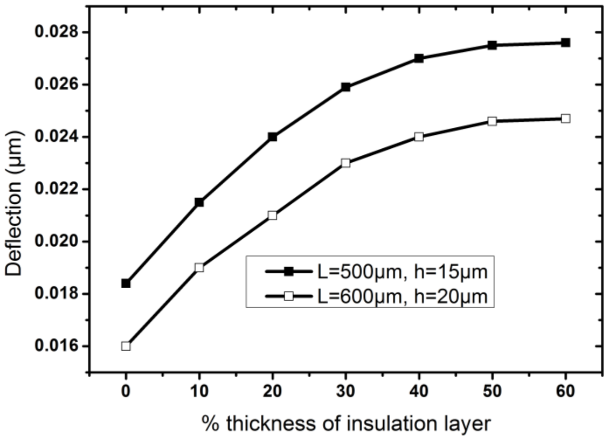

Figure 11. Deflection of SOI diaphragm for various insulation layer thicknesses. (Pressure applied = 9kPa)

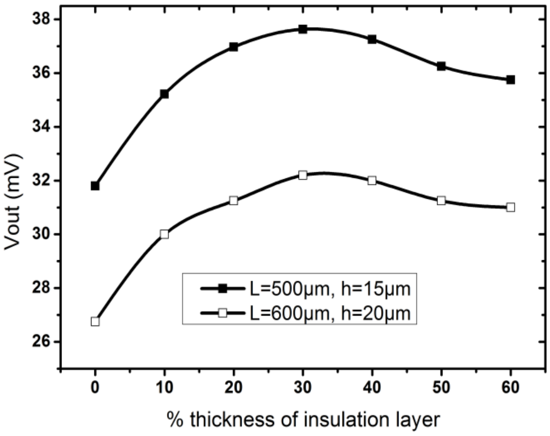

Figure 12. Output voltage of SOI diaphragm for various insulation layer thicknesses. (Pressure applied = 0.9MPa)

Figure 10 and 11 respectively show the deflection of SOI diaphragm when the insulation layer thickness is varied from 0% to 60% of the total thickness for two different applied pressures. The deflection shows an increasing trend with an insulation layer thickness up to 30% of total diaphragm thickness and beyond that, it is found to be almost saturating due to rapid increase in flexural rigidity.

The device is simulated for two diffrent pressure ranges. The range of pressure applied are 0.1 MPa to 0.9 MPa and 1 to 9 kPa. In both pressure ranges the change in deflection shows the same trend. It shows an increasing trend with insulation layer thickness up to 30% of total diaphragm thickness and beyond that it is found to be almost saturating.

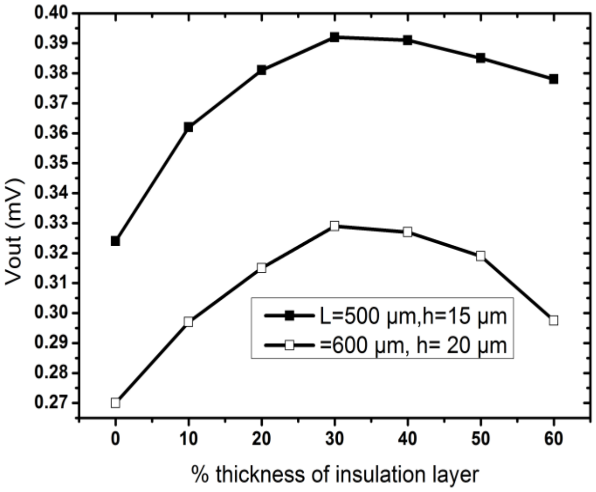

Figure 13. Output voltage of SOI diaphragm for various insulation layer thicknesses.(Pressure applied = 9kPa)

Figure 12 and 13 respectively show the variation in sensor output voltage (V_{out}) when thickness of the insulation layer changes. Vout increases initially, reaches a maximum when insulator layer thickness is 30% of total diaphragm thickness and then decreases. As the oxide layer thickness increases, the stress relaxation become more and stress at the top silicon layer where the piezoresistors are integrated which is applied to the piezoresistor decreases. So V_{out} decreases as the insulatorlayer thickness increases. V_{out} shows the same trend for any applied pressure.

4. CONCLUSION

For a stacked diaphragm, the deflection and V_{out} are higher compared to silicon diaphragm with same dimensions. Deflection shows an increasing trend with insulation layer thickness up to 30% of total diaphragm thickness and beyond that it is found to be almost saturating due to rapid increase in flexural rigidity. V_{out} initiallyincreases and reaches a maximum when insulation layer thickness is 30% of total diaphragm thickness and then decreases because of the stress relaxation at higher insulation layer thickness.

5. ACKNOWLEDGEMENT

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