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Finite Element Analysis of Membranes for MEMS Capacitive Pressure Sensors

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***Abstract*— In this paper the optimal properties of the following materials such as SiO_2, Si_3N_4, Poly silicon for pressure sensing applications have been discussed. The square shaped diaphragms with the dimensions of side length 500µm, thicknesses 10 µm & 15 µm of the above materials have been simulated using FEA method by Abaqus software. Maximum deflection, Mises stress and the displacement sensitivities for the different cases have been analyzed for the pressure range of 0.2 Mpa to 1.6 Mpa. In addition, the experimental design was performed and photolithography was used for fabricating the described membranes. Both the simulated and analytical details of the problem formulation and their respective observations were illustrated with the necessary results and discussion. The comparison of the simulation and the Analytical values matches closely and indicate the superior behavior of SiO_2 membrane to the prescribed pressure load.**

Keywords*— MEMS; sensors; FEA; Abaqus; photoresist; stress; displacement

I. INTRODUCTION

The urge of having Micro Electro Mechanical Systems (MEMS) based solutions are tremendously increasing in modern times as it ensures several promising features like miniaturization [1] product cost advantages, bulk processing, low power consumption [2] and reliability etc. The perception that the future of MEMS is flavored with full of commercial prospects; commissioning of billions of MEMS based sensors as ears and eyes of Internet of things (IoT) have driven the industries for employing it in creating competitive edges.

Pressure sensors have been known in the form of strain gauges over several decades. The piezoresistivity in silicon and germanium [Smith, 1954] paved a way in attempting the miniaturization of pressure sensors and other mechanical sensors. The recognition of the excellent mechanical properties of silicon [Peterson, 1982] further propelled these activities with great momentum. Carving microstructures, the expertise in manufacturing microelectronic devices and integrated circuits in silicon have triggered for the evolution of interdisciplinary area of MEMS and Microsystems. Micro machined pressure sensors are fabricated using bulk and surface micromachining techniques [3].

Among the various devices, pressure sensors using MEMS technology have received great attention because the pressure sensors find applications in everyday life involving sensing, monitoring and controlling pressure, and they therefore constitute 60 to 70 percent of the market amongst the various MEMS devices [4].

The MEMS capacitive pressure sensors are working on the basis of principle of parallel plate capacitor, wherein a thin diaphragm of the order of few microns acts as the top plate and lower plate is provided by a thin layer of suitable material patterned lithographically on a substrate. In most of the micro machined capacitive pressure sensor, silicon substrate is used as sensor structure and polysilicon or polymer materials like polymide, kapton polymide, su-8, liquid crystal polymers are used as diaphragm membrane as adopted in [5]. Such a system when encounters pressure, top plate gets deformed; distance between the plates varies and it leads to the change of capacitance that could be sensed through suitable electronic circuits.

II. FABRICATION OF MEMBRANES BY PHOTOLITHOGRAPHY

The process of lithography could be appreciated in two ways. First, due to the large number of lithographic steps needed in IC manufacturing, lithography usually accounts for about 30 percent of the cost incurred in manufacturing. Second, lithography tends to be the technical limiter for further advances in feature size reduction and thus transistor speed and silicon area. Obviously, the trade-offs between cost and capability should be given due importance in developing a lithographic process.

Optical lithography is a photographic process by which a light sensitive polymer, called a photoresist, is exposed to UV radiation normally and developed to get three-dimensional images on the substrate. In general, the ideal photoresist image will have the exact shape of the designed pattern in the plane of the substrate. Hence, the final pattern of the resist is binary i.e. partly the substrate is covered with resist while other parts are uncovered. This binary pattern is inevitable for pattern transfer since the parts of the substrate covered with resist need to be protected from etching, ion implantation, or other pattern transfer mechanism.

Normally P type oxidized (100) Silicon wafer is taken and it is diced in accordance with the size and throughput to be obtained in the batch fabrication. Standard cleaning procedures are duly applied for cleaning the wafers. Prebaking of the wafers in the oven for short span of time is adopted to make them fit for spin coating of the photoresist. The wafers coated with photoresist are exposed to UV radiation after short duration through photolithography masks for transferring the pattern on to the substrate. Development of the wafers by solvents will eliminate the unwanted portion of the photoresist layer. Further treatment with oxide etchant and bulk micromachining will release the final geometry of membrane as illustrated in Fig 1.

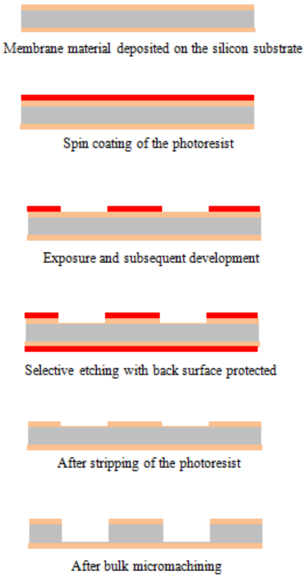

Fig. 1. Basic process of fabricating a membrane

III. MEMBRANE DEFLECTION THEORY

As far as the induced stress for a given pressure is concerned the square diaphragm has the highest induced stress and hence it is preferred geometry for the pressure sensors because the high stresses generated by the applied pressure loading result in high sensitivity. Also it is easy to dice the diaphragm from standard wafers [6].

Maximum stress calculated by centre of each edge is

$$\sigma_{\max} = \frac{0.308\,pa^2}{h^2} \qquad (1)$$

The maximum deflection at the center for a given pressure is

$$W_{\max} = \frac{-0.0138\,pa^4}{Eh^3} \qquad (2)$$

Where **p** is the applied pressure, **a** the side length, **h** the diaphragm's thickness and **E** the Young's modulus. The stress at the center of the plate can be derived as,

$$\sigma = \frac{6p(m+1)a^2}{47mh^2} \qquad (3)$$

where **m** = $1/\upsilon$, and strain at the center is

$$\varepsilon = \frac{1-\upsilon}{E}\sigma \qquad (4)$$

As a general rule, the deflection of the diaphragm at the center must be no greater than the diaphragm thickness; and, for linearity in the order of 0.3%, should be limited to one quarter the diaphragm thickness [7].

IV. FEM ANALYSIS

The Finite Element Modeling (FEM) is utilized to investigate the mechanical response to a load such as pressure, force etc. to the part of the constructed model. The geometry of the membrane is shown in Fig.2. The square shaped membranes of three materials such as silicon nitride, silicon dioxide and poly silicon have been modelled with the parameters shown in table I. Messing of the membranes is done and its response for the pressure range from 0.2 M Pa to1.6 MPa has been studied in many aspects.

Fig. 2. Geometry of membrane(500µm X500µm)

TABLE I. MATERIAL PROPERTIES

Material	Size & Thickness(µm)	Young Modulus (GPa)	Mass Density (Kg/m^3)	Poisson ratio
Silicon Nitride	500X500, 10 & 15	160	2500	0.253
Silicon dioxide	500X500, 10 & 15	73	2650	0.17
Poly silicon	500X500, 10 & 15	150	2328	0.20

V. RESULTS AND DISCUSSION

A. *Silicon Nitride*

The study of the silicon nitride membrane reveals the following facts.

Fig.3 & Fig.4 shows the response of the silicon nitride membranes of thicknesses 10 & 15 microns respectively for the pressure range from 0.2 to 1.6 MPa. It is clearly seen that the maximum deflection at the center of the membrane increases with pressure.

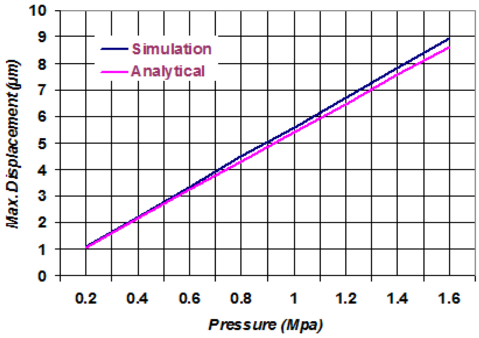

Fig. 3. Displacement of silicon nitride membrane (size: 500µmX500µm, thickness: 10µm)

Both the simulated values and the analytical values are in agreement.

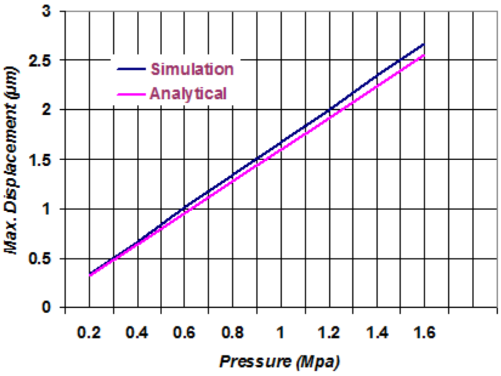

Fig. 4. Displacement of silicon nitride membrane (size: 500µmX500µm, thickness: 15µm)

As the thickness of the membrane is increased, the maximum deflection gets reduced. This fact is further confirmed from the plot of Fig. 5 which is showing the relation between the thickness and the maximum deflection.

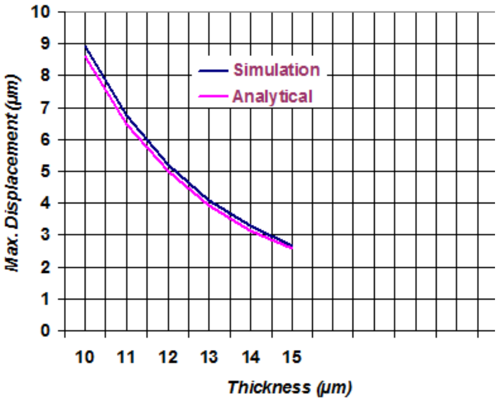

Fig. 5. Variation of Max Displacement with thickness for silicon nitride membrane (size: 500µmX500µm,pressure: 1.6 Mpa)

Fig. 6 confirms that the maximum deflection is at the center and shows the deflection produced for the silicon nitride membrane of 10 micron thickness with an applied pressure of 1.6 MPa.

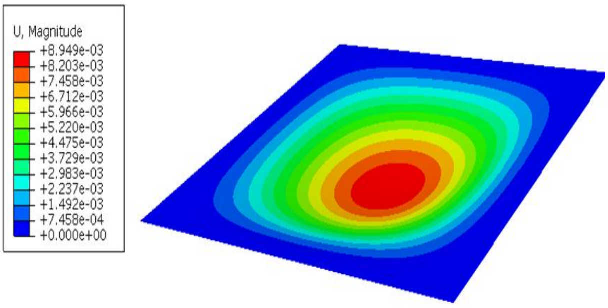

Fig. 6. Simulation of silicon nitride deformation for 1.6 MPa, thickness: 10 µm

Fig. 7 &Fig. 8 shows the Mises stress analysis of the membranes and it shows that stress is maximum at the edges and inversely related to the thickness of the membranes. This is confirmed from the plot shown in the Fig. 9

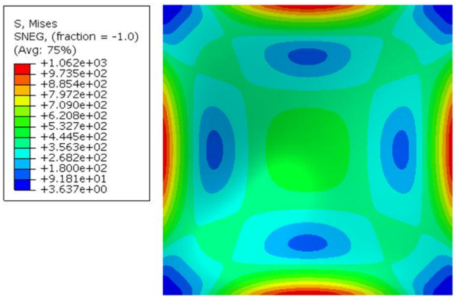

Fig. 7. Mises stress Analysis for silicon nitride (Pressure: 1.6 MPa, thickness: 10µm)

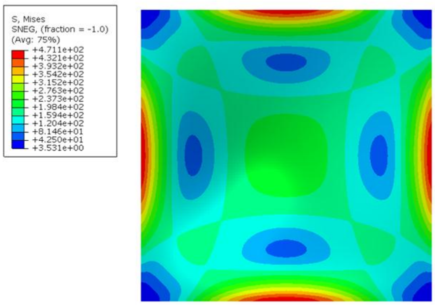

Fig. 8. Mises stress Analysis for silicon nitride (Pressure: 1.6 MPa, thickness: 15µm)

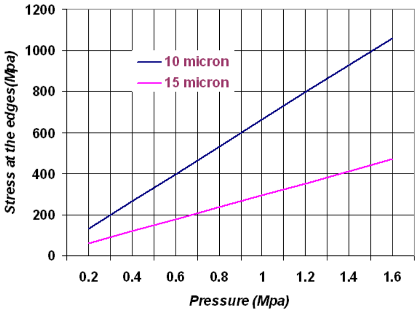

Fig. 9. Mises Stress Analysis of Silicon nitride membrane (size 500µmX500 µm)

B. *Silicon dioxide*

The results obtained in the study of silicon dioxide membrane are presented below.

Fig. 10 shows the variation of the maximum displacement with pressure for the range of 0.2 MPa to 0.7 MPa for the thickness of 10 µm. It is observed that the maximum displacement increases with pressure.

Fig. 11 shows the variation of the maximum displacement with pressure for the range of 0.2 MPa to 0.7 MPa for the thickness of 15 µm. It is also observed that the maximum displacement increases with pressure.

The deformations observed in SiO_2 membrane for the thicknesses of 10µm & 15 µm have been shown in Fig. 12 and Fig. 13 respectively for the applied pressure of 0.7 MPa.

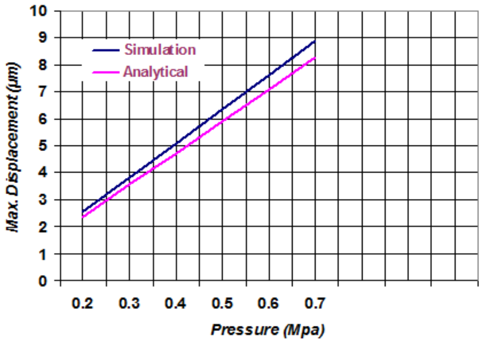

Fig. 10. Deformation of SiO_2 membrane (500µmX500µm, thickness: 10µm)

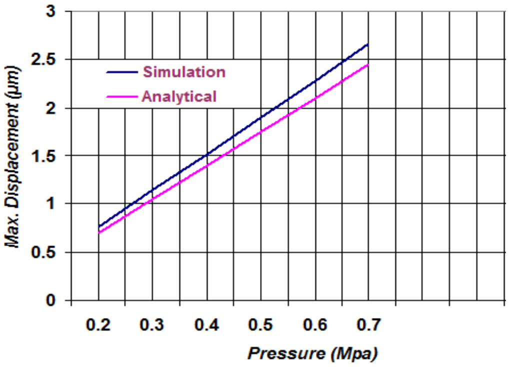

Fig. 11. Deformation of SiO_2 membrane (500µmX500µm, thickness: 15µm)

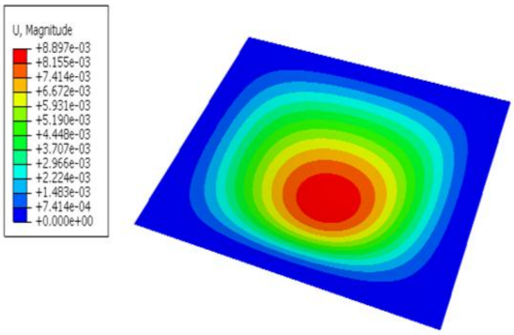

Fig. 12. Surface profile of SiO_2 membrane for 0.7 MPa (500µmX500µm, thickness: 10µm)

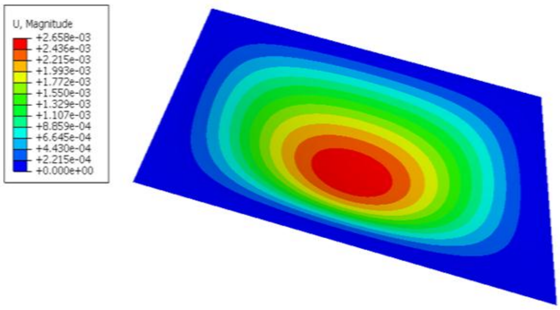

Fig. 13. Surface profile of SiO_2 membrane for 0.7 MPa (500µmX500µm, thickness: 15µm)

It is observed from the Fig. 14 that the Mises stress at the edge is 478.1 MPa for the thickness of 10 µm when the load is 0.7MPa, where as it is 212.2 MPa for the case of 15 µm as shown by Fig. 15.

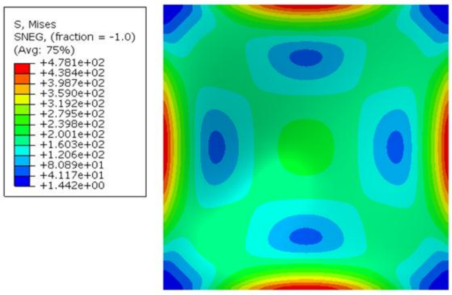

Fig. 14. Mises stress of SiO_2 membrane for 0.7 MPa (500µmX500µm, thickness: 10µm)

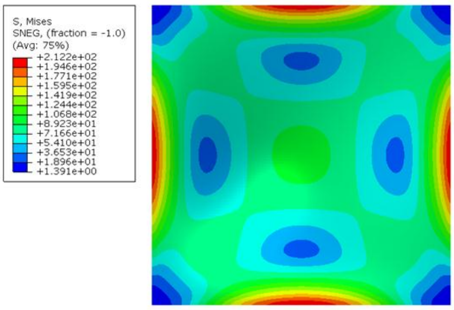

Fig. 15. Mises stress of SiO_2 membrane for 0.7 MPa (500µmX500µm, thickness: 15µm)

Fig. 16 shows the variation of the displacement with thicknesses ranging from 10 µm to 15 µm keeping the pressure at 0.7 MPa.

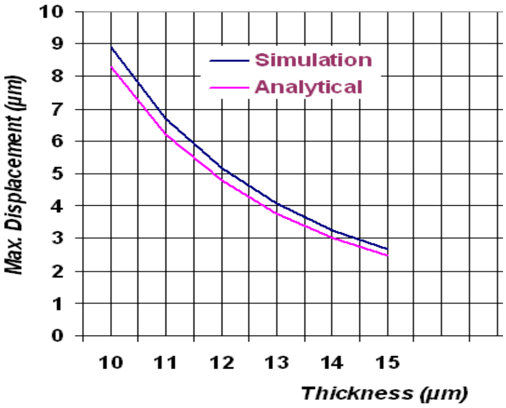

Fig. 16. Variation of Max displacement of SiO_2 membrane with thickness for 0.7 MPa

It is seen that the maximum displacement is gradually reduced as we increase the thickness.

The plot in Fig. 17 shows the variation of Mises stress with load and it shows that it is having inverse relation with thickness for a given pressure.

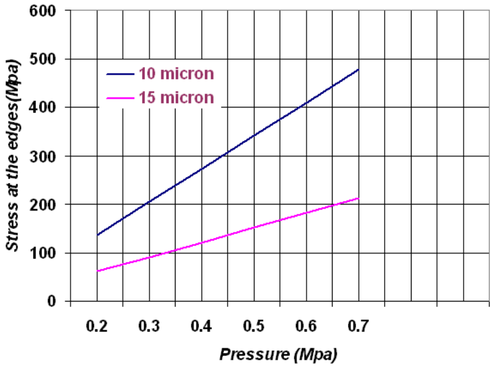

Fig. 17. Variation of Mises stress of SiO_2 membrane with load (size 500µm X 500µm)

C. *Poly Silicon*

The results of the analysis of poly silicon are presented below.

Fig. 18 &Fig. 19 shows the deformation produced in the case of Poly silicon membrane of thicknesses 10µm & 15 µm respectively for the range of pressures from 0.2 MPa to 1.6 MPa and the corresponding simulated deformations are illustrated in the Figs. 20 & 21.

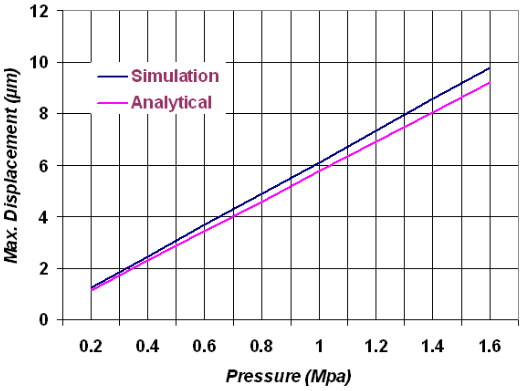

Fig. 18. Deformation of Poly silicon membrane (500µmX500µm, thickness: 10µm)

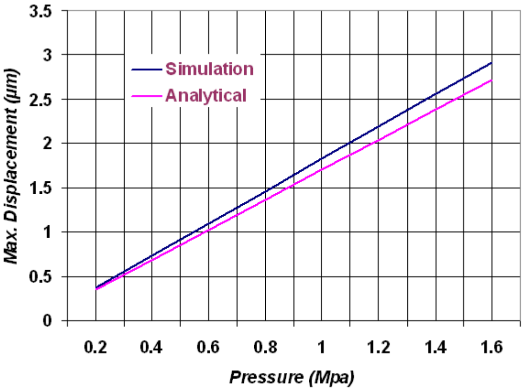

Fig. 19. Deformation of Poly silicon membrane (500µmX500µm, thickness: 15µm)

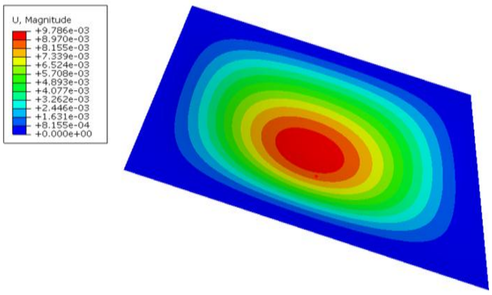

Fig. 20. Simulation of Poly silicon deformation for 1.6 MPa (thickness: 10 µm)

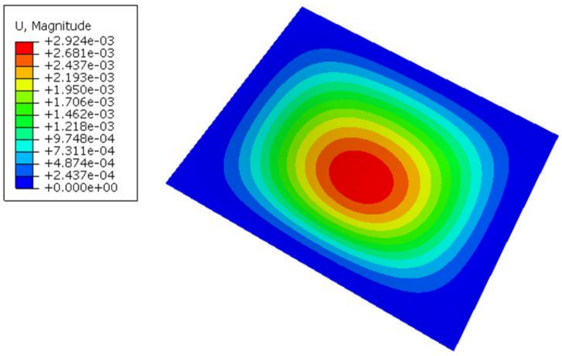

Fig. 21. Simulation of Poly silicon deformation for 1.6 MPa (thickness: 15 µm)

Fig. 22 is showing the Mises stress of Poly silicon when the load is 1.6 MPa keeping the thickness as 10 µm, whereas for 15 µm it is shown in Fig. 23.

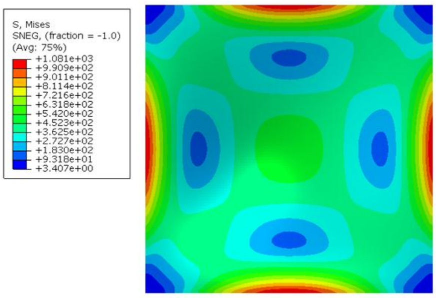

Fig. 22. Mises stress of Poly silicon membrane for 1.6 MPa (500µmX500µm, thickness: 10µm)

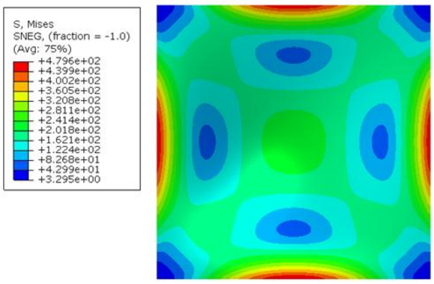

Fig. 23. Mises stress of Poly silicon membrane for 1.6 MPa (500µmX500µm, thickness: 15µm)

The plot in Fig. 24 shows the variation of Mises stress with thickness; it is observed that stress is having linear relationship with the load and stress is reduced when the thickness is increased.

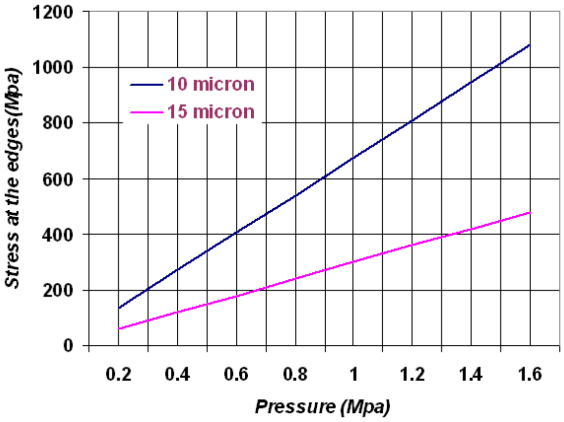

Fig. 24. Variation of Mises stress of Poly silicon membrane with load (size 500μm X 500μm)

VI. CONCLUSIONS

The displacement of all the materials simulated and compared with the Analytical data. It is seen from Fig. 25 that, specifically for the pressure of 0.2 MPa, silicon dioxide shows the maximum displacement of 2.542 μm, silicon nitride shows the minimum displacement of 1.11 μm and Poly silicon is showing 1.22 μm. Similar behavior is observed for further successive loads from 0.2 MPa to 0.8 MPa. This behavior is accounted from the material property that when Young's modulus increases, the deflection of the diaphragm decreases [8].

For the preferred geometry, the silicon dioxide diaphragm shows a displacement sensitivity of 12.43 μm/MPa, Poly silicon is showing 6.12 μm/MPa and silicon nitride diaphragm has 5.60 μm/MPa.

Hence it is concluded from the above study, the silicon dioxide diaphragm is the most sensitive when comparing with other two materials.

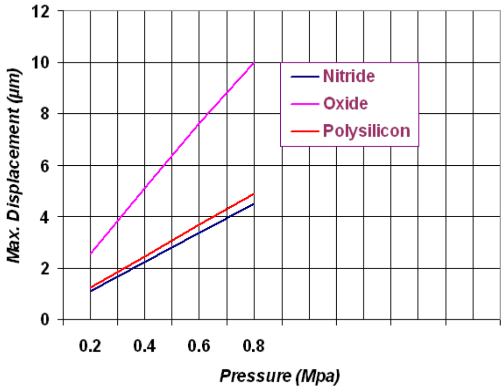

Fig. 25. Comparison of Displacements of three materials (size: 500 μmX500 μm, thickness: 10μm)

Mises Stress Analysis of the three diaphragm materials as shown in Fig. 26 reveals that, for the selected loads, it is observed that SiO_2 diaphragm is always having more Mises stress when comparing with other diaphragms and it has shown a Mises stress of 546 MPa for 0.8 MPa. This study could be the start point for the proper selection of the material and the associated parameters in designing the vital element i.e. diaphragm for MEMS pressure sensors.

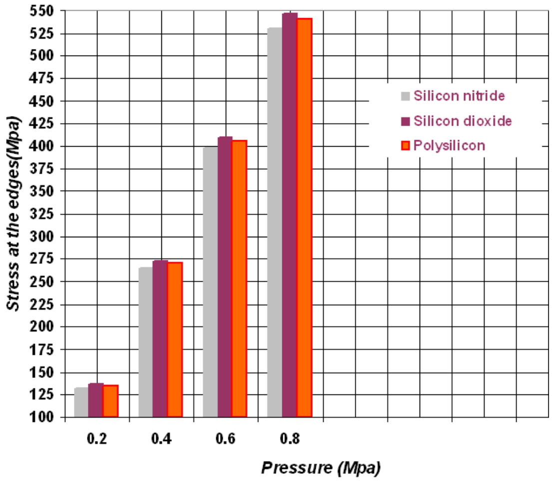

Fig. 26. Comparison of Mises stress of three materials (size: 500 μmX500 μm, thickness: 10μm)

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