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Performance Optimization of Silicon Capacitive Pressure Sensor

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Abstract—*Today sensors are used in many fields of life such as defense, medical purposes, automobiles, oceanography, domestic purposes, etc. Sensors are available in many shapes and sizes ranging from metal strain gauge pressure sensors to thin film diaphragm pressure sensors. According to the requirement, different sensors are available for different fields. In this paper capacitive pressure sensor using Silicon diaphragmhaving rectangular cavityis discussed and simulated using COMSOL Multiphysics. Siliconhas good electrical and mechanical stability as well as it is chemically inert, which is adequate for harsh environment. The stress and capacitance variation due to diaphragm deflection is observed with and without thermal stress. This paper provides the analytical solution for a rectangular diaphragm deflectionthat is variation of the stress at the edges of the diaphragm and capacitance variation as the load pressure is applied with the help of COMSOL Multiphysics.*

Keywords*: Sensors; diaphragm; Si; COMSOL Multiphysics.*

1. INTRODUCTION

As the IC fabrication techniques for silicon (Si) are developed so Si is used in MEMS pressure sensors. But in harsh conditions silicon is not preferred instead wide bandgap semiconductors such as SiC is used. In this paper silicon is taken as diaphragm and silicon carbide base because it has better stress analysis thanSteel. The cost of the MEMS pressure sensors are also economical as thousands of silicon sensors are fabricated on the single chip(Batch Fabrication).The capacitive pressure sensor shows nonlinear characteristics till the touch pressure point(TPP). After this point the linear characteristics is observed [1].The stress experienced by the diaphragm at the edges should not exceed the fracture stress of Si which is 7GPa[3].

The scaling of MEMS devices is in progress and the power consumption has reduced but at the same time the SiO_2 have to be replaced with high dielectric materials due the leakage current and quantum mechanical tunneling current in SiO_2.

In this paper different shapes of cavities are discussed. This paper includes Section 2,diaphragm mechanical analysis. The simulation results are inSection 3. Finally, Section 4, the conclusions.

2. DIAPHRAGM MECHANICAL ANALYSIS

In this paper three shapes of cavities are discussed. The vacuum cavity is taken to avoid temperature drift due to thermal expansion of gases trapped inside the cavity. When the pressure is applied the diaphragm deflects. The deflection of the diaphragm depends upon the young's modulus of the material used. High young's modulus reduces the deflection of device layers which can experience high load force(as in Silicon carbide)[5].

In plate theory, the minimum deflection should be less than 20-25% of the diaphragm thickness and the maximum deflection can be up to three times of the diaphragm thickness[5]. If the edges of the diaphragm are clamped in x-y plane, the deflection is observed in z direction as shown in Fig. 1.

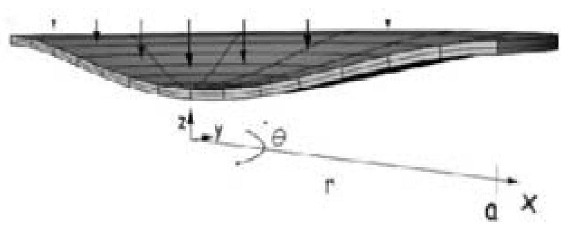

Fig. 1: Deflection of circular cavity diaphragm[5]

A. Square Diaphragms

The square diaphragm pressure sensors are mostly preferred because it has high induced stress. The high induced stress by the load pressure increases sensitivity.

For the Square plate clamped at the edges:

At the middle of the each edge of the diaphragm the maximum stress is given as[1].

$$\sigma = \frac{0.308 \mathrm{P} a^2}{h^2} \quad (1)$$

Now, the maximum deflection in the membrane (diaphragm) for a given pressure is[1].

$$w = \frac{0.0138 \mathrm{P} a^4}{h^3} \quad (2)$$

Here *P*is the applied pressure, *a*the side length, *h*is the

diaphragm's thickness and *Y*the Young's modulus.

B. Circular Diaphragms

The circular diaphragms are preferred when the deflection of the diaphragms is required large. The stress at the edges of the circular diaphragms is less as compared to square diaphragms.

For the Circular plate clamped at the edges:

The deflection in circular diaphragm is the function of radial distance from the centre and is given as[1,2].

$$W(r) = \frac{Pa^4\left[1-\left(\frac{r}{a}\right)^2\right]^2}{64D} \quad (3)$$

Where *P* is the applied pressure,*a*is the radius of diaphragm, *r* the radial distance from the centre, *D* the flexural or bending rigidity[2].

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

$$Wmax = \frac{P(1-\mu^2)a^4}{4.13Yh^3} \quad (5)$$

Here$\boldsymbol{\mu}$ is the Poisson'sratio.

C. Rectangular Diaphragm

For the Rectangular plate clamped at the edges:

The equations for the rectangular diaphragmdeflection and the stresses are given by[3].

$$\sigma_x = \frac{2Pb^2}{h^2}\frac{\pi^4 a^4}{256\left(b^4+\frac{\pi^4 a^4}{256}\right)} \quad ; \quad \sigma_y = \mu\sigma_x \quad (6)$$

Here *P* is the applied pressure, *a* and*b* are the sides of the rectangle, *h* is the diaphragm thickness, μ is the Poisson's ratio.

The sensitivity of the sensors can be increased thickness of the diaphragm should be thin; this will maximize the load deflection responses. Now when the load pressure is increased on this diaphragm large deflections results in nonlinear effects which are not desirable[1].

3. SIMULATION RESULTS

The comparison has been made using different base that is steel and silicon carbide. The diaphragm is taken silicon and the vacuum cavity in both. The properties such as thermal expansion coefficient, Poisson's ratio, stress holding capacity of steel and Si are different due to which the deflection of the diaphragm and the base varies. Table 1 shows the properties of Si used in the simulation of the capacitive sensor. Table 2 shows the parameters used while simulation.

Table 1: Properties of Si

Property	Expression	Unit
Coefficient of Thermal Expansion	2.6e-6[1/K]	1/K
Relative permittivity	4.5	1
Density	2320[Kg/m3]	Kg/m3
Poisson's ratio	0.22	1
Young's modulus	170e9[Pa]	Pa

Table 2: Parameters

Parameter	Value	Description
Pressure(p0)	20[KPa]	Differential Pressure
Temperature(T0)	20[degC]	Operating Temperature
Temperature(Tref)	70[degC]	Die Bonding Temperature

The diaphragm acts as the one electrode plate of the capacitance. When the load pressure is applied range from 0kPa to 25kPa in this paper, the deflection and capacitance variations are shown with the help of COMSOL Multiphysics. The results are simulated with and without thermal stress. The results are shown in Fig. 2-12. Fig. 2and Fig. 3 shows the total Displacement versus Load pressure of Si without and with thermal stress respectively. Fig. 4 and Fig. 5 shows the total Displacement versus load pressure of Si with SiC base without and with thermal stress respectively.

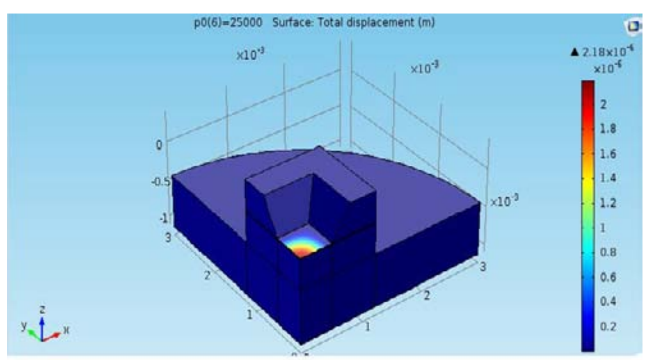

Fig. 2: Total Displacement vs Load pressure of Si without thermal stress.

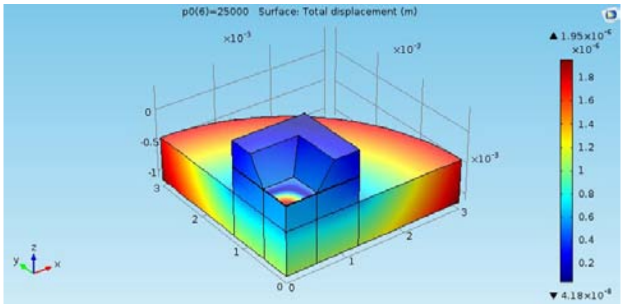

Fig. 3: Total Displacementvs Load pressure of Siwith thermal stress.

From the above simulated results the maximum diaphragm deflection is at the center. As the distance from the center increases the deflection decreases. But in Si with SiC base the diaphragm displacement is less as compared to Si at same load pressure as shown in Fig. 2-5. Therefore the Si with SiC base can experience high load force.

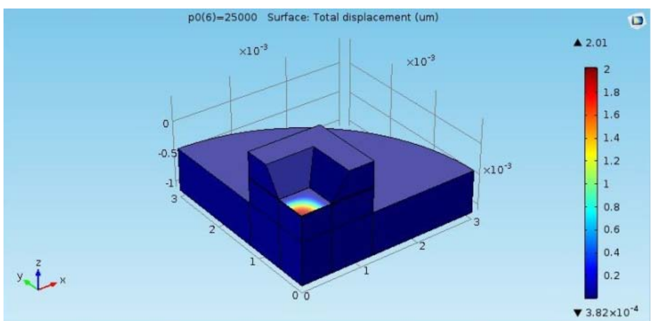

Fig. 4: Total Displacement vs Load pressure of Si with SiC base without thermal stress.

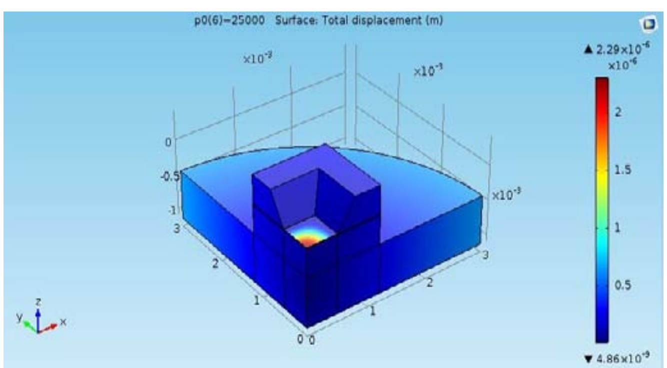

Fig. 5: Total Diaphragm Displacement vs Load pressure of Si withSiC base with thermal stress.

From the above results the deflection is more significant near the center in Si with SiC base under thermal stress whereas in Si deflection is present at the outer part also of the sensor which makes it less sensitive.

3.1 Displacement(Diaphragm deflection) vs Load Pressure:

The results are taken Sias a diaphragm. Above the defection comparison can be made on the color contrast on the diaphragm. Here the characteristics are drawn on COMSOL Multiphysics where the deflection comparison can be made more accurate at any pressure ranging from 0KPa to 25KPa. Clearly below in Fig. 6 and Fig. 7,the average and the maximum diaphragm deflection in the Si with SiC baseis less as compared to Si with steel. The Si with SiC base therefore can withstand high load force.

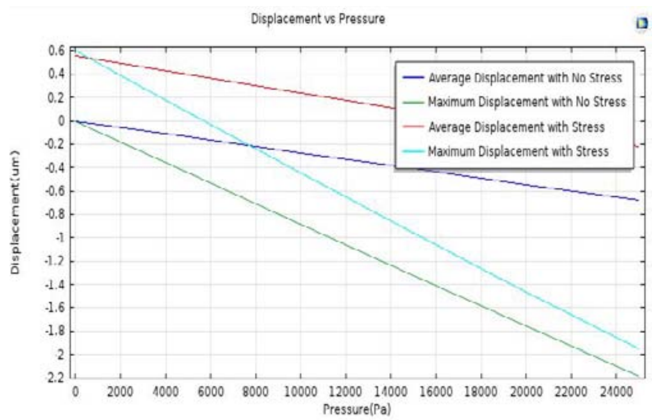

Fig. 6: Diaphragm displacement vs Load pressure of Si with and withoutthermal stress.

But in case when thermal stress is considered and no load pressure is present,the deflection in Si is in positive Z direction that is above the X-Y plane (if the diaphragm is clamped in X-Y plane) but in case of Si with SiC base the initial deflection when no load pressure is applied is approximately zero or in negative Z direction.This help MEMS capacitive pressure sensor to be well calibrated under thermal stress.

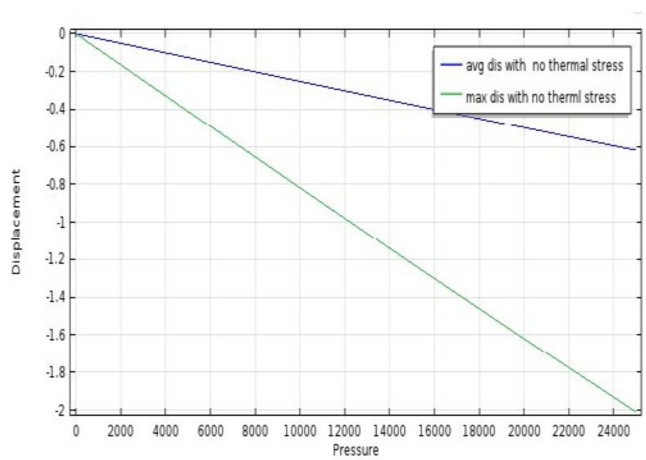

Fig. 7: Diaphragm displacement vs Load pressure of Si with SiC base without thermal stress

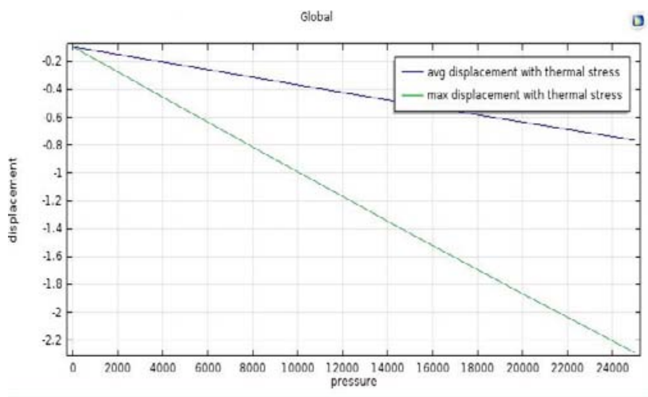

Fig. 8: Diaphragm displacement vs Load pressure of Si with SiC basewith thermal stress.

3.2.Capacitance vs Load Pressure:

The capacitance of the MEMS capacitive sensor increases with the increase in load pressure. The capacitance variations are nonlinear as shown in Fig. 9 and Fig. 10. The rate of change of capacitance with applied pressure is slightly slow in Si with SiC base as compared to Siwith steel base due to which the final value of the capacitance decreases in Si with SiC base.

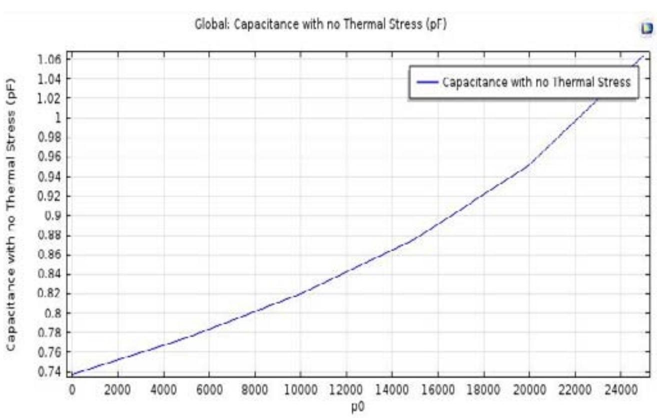

Fig. 9: Capacitance vs Load pressure of Si without thermal stress.

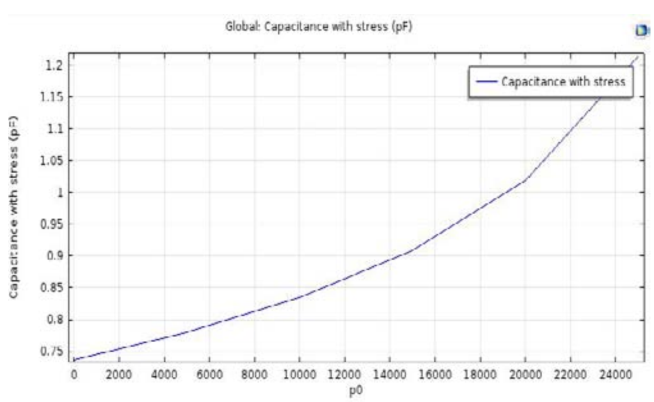

Fig. 10: Capacitance vs Load pressure of Si with thermal stress.

Now the capacitance variation of Si with SiC base is as shown.

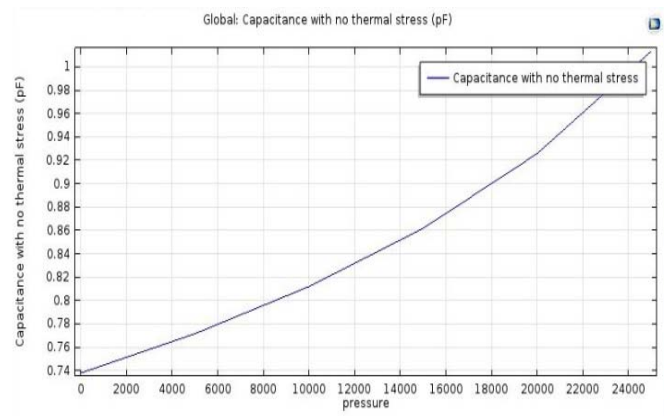

Fig. 11: Diaphragm capacitance vs Load pressure of Si with SiC base without thermal stress.

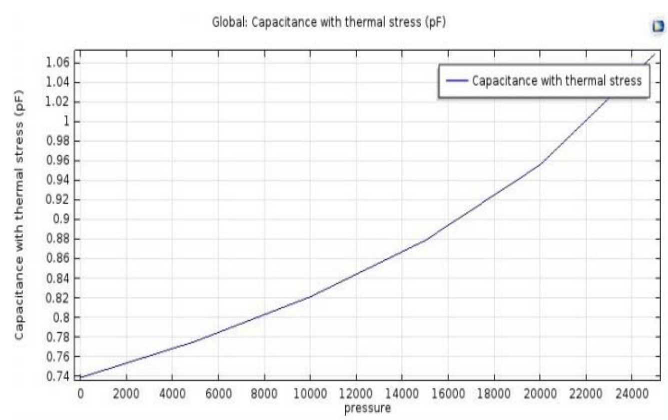

Fig. 12: Diaphragm capacitance vs Load pressure of Si with SiC base with thermal stress.

4. CONCLUSION

The diaphragm deflection of the device layers at the outer portion of the sensor can be reduced if material of high Poisson's ratio is used. Therefore the capacitive sensors with less deflection can experience high load force.On COMSOL Multiphysics, with the increase in poison's ratio the deflection distribution is uniform as shown in the total diaphragm displacement (Fig. 2 and Fig. 3). The other characteristic such as capacitance variation has no significant effect with the change in the poison's ratio value when the thermal stress are not considered. But when thermal stresses are considered the deflection has some significant effect.

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