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# A Study of Silicon based MEMS Capacitive Sensor for Absolute Pressure Measurement of a Specific Range

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## ABSTRACT

In this paper two MEMS capacitive pressure sensor of two diffident geometries are designed for measurement of absolute pressure. Both of these sensors are designed as parallel plates where one is movable and the other is fixed. The only difference with common parallel plate structure is that one of the movable plates is supported by four anchors with respect to the fixed plate. Here we have considered two such structures, one having square shaped parallel plates whereas the other having circular shaped. The area of the diaphragms for both the sensors are equal and will perform to sense absolute pressure variations for a very specific range. This specified range of absolute pressure is 10 KPa to 100 KPa for 5 micron thick diaphragm with 3600 micrometer area. Here silicon and silicon compound (like PolySi and SiC) are chosen for diaphragm material. In this paper various factors which play a critical role for measuring absolute pressure in the performance of a MEMS capacitive pressure sensor are discussed. Factors like length, radius, thickness, distance between two plates and shape and more above the selection of diaphragm materials are taken into consideration for the efficiency of the sensor. Mechanical, electromechanical as well as material studies were performed in the Finite Element Method based Multiphysics simulation platform. In this paper two same area different shape micro sensors are designed and their comparative study is analyzed with different silicon compound. This type of absolute pressure measuring sensor can be used for pulse rate measurement.

**Keywords:** Capacitive pressure sensor, MEMS, Finite Element Method (FEM), Si, PolySi, SiC, absolute pressure

## 1. INTRODUCTION

Absolute pressure measurements are of great importance in almost all field of engineering and industrial application. Microelectronics has known very important development. Specific manufacturing techniques have been developed to reduce the cost of objects using this technology. In particular, Micro Electromechanical Systems, called by the acronym MEMS, which combine mechanical, optical, electromagnetic, thermal and fluidic in electronic semiconductor substrates drivers, have benefits widely of this development. Most absolute pressure sensors which are based on piezoresistive effect are the common type. However in the past years capacitive absolute pressure sensors have received attention due to several advantages in comparison to piezoresistive absolute pressure sensor. The main disadvantage of the piezoresistive absolute pressure sensor is the inherent temperature dependence of piezoresistive coefficients [1].Capacitive pressure sensor has lower power consumption than piezoresistive pressure sensor [2]. But piezoresistive pressure sensor most widely used than capacitive pressure sensor because of two reason. Capacitive structure is more complicated to fabricate and the capacitive sensing principle is sensitive to parasitic capacitances. The structure of the capacitive pressure sensor is more complicated, because it involves formation of a cavity that separates the two sensing electrodes from each other. Formation of such a cavity is done in two different ways. For first case multiple film depositions and etch of a buried sabscrificial layer [3–6] or in second case bonding after the cavity has been etched into one of the wafer. Wafer bonding is done by fusion bonding of two silicon wafers [7–9] or anodic bonding of a silicon wafer and a glass wafer [10, 11]. Capacitive absolute pressure sensors are required in applications including bio-medical systems, environmental monitoring and industrial process control. Capacitive absolute pressure sensors provide low noise, high sensitivity, have low temperature sensitivity and are preferred in many emerging high performance applications and can with stand a lot of vibration.

Here we have considered two such geometries, one having square shaped parallel plates whereas the other having circular plates. Both of the sensors are designed in such a manner that their areas are equal and will perform to sense absolute pressure variations for a very specific range. This specified range of absolute pressure is 10 kpa to 100 Kpa for 5 micron thick diaphragm with 3600 micrometer area. Silicon and silicon compound like PolySi (polysilicon) and SiC(silicon carbide) are chosen for diaphragm materials and performance is analyzed. It is also analyzed the effect of length, radius, thickness, distance between two plates and shape. More above the selection of diaphragm materials are taken into consideration for the efficiency of the sensor Mechanical, electromechanical as well as material studies were performed in the Finite Element Method based Multiphysics simulation platform. This paper explores the design parameters of MEMS based diaphragm type capacitive pressure sensor with anchors using FEM (Finite Element Modeling) [12] based Multiphysics software.

Mechanical and electromechanical studies are performed. Sensor designing is given on section II. The chosen materials properties are given in section III. The analyzed results are in the form of 2-D plots in section IV as results and discussion. The outcome of this designed sensors are discussed and compared against their efficiencies. Materials performance are given in section V. The concluding remarks from these analyses are described in section VI.

## 2. MATHEMATICAL MODELING

The maximum stress for circular diaphragm is given by

$$\sigma_{\max} = \frac{3\gamma W}{8\pi h^2} \qquad (1)$$

And the maximum deflection of the circular plate occurs at the centre position of the plate [15]

$$W_{\max} = \frac{3W(m^2-1)a^2}{16\pi m^2 h^2} \qquad (2)$$

The maximum stress at the middle of each edge for square diaphragm is given by

$$\sigma_{\max} = \frac{0.309Pa^2}{h^2} \qquad (3)$$

The maximum deflection for square diaphragm is given as [16]

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

Where, W = total force acting on the plate, h is the diaphragm thickness, 'a' is the radius of the circle, 'E' is the Young's Modulus, 'γ' is the Poisson's ratio and 'm' is the reciprocal of the Poisson's ratio [15]. Eq. 1- 4 are used for performing the analytical analysis of the designed MEMS based capacitive pressure sensor.

The capacitance between two parallel electric conductive plates can be written as,

$$C=\varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (5)$$

Where c is capacitance, $\varepsilon_0$ is dielectric constant of vacuum $\varepsilon_r$ is the dielectric constant of material. A is area of electrode plate and d is the gap between two electrode plate.

Based on Hooke's law, the change in thickness in the dielectric layer is the proportional to the pressure and original thickness(Eq. (6)).There for, the relationship between the applied pressure and the capacitance change can be expressed as Eqs.(6) and (7).

$$\Delta d = d_0 \frac{\Delta P}{E} \qquad (6)$$

$$\Delta C = C_0 \frac{\Delta P}{E-\Delta P} \qquad (7)$$

Where $\Delta d$ thickness change of dielectric layer is, $d_0$ is original thickness of dielectric layer. $\Delta P$ is applied external pressure,$c_0$ is original capacitance when pressure is not applied and $\Delta C$ is capacitance change when pressure is applied.

## 3. SENSOR DESIGN

### 3.1 FEM Modeling:

Finite Element Method (FEM) is used to predict mechanical response to a load, such as force or moment applied to a part of the constructed model. This part is to be simulated is broken down into small discrete element – this procedure is called meshing. Each element has a no. of nodes and its corners at which it interacts with neighboring element. Thus the system Partial Differential Equation (PDEs) is assumed to be linear element within the nodes and is solved in FEM based Multiphysics computation platform.

### 3.2 Sensor Layout

Here we have considered two such geometries, one having square shaped parallel plates whereas the other having circular plates. One of the parallel plates is suspended with four anchors with respect to the fixed plate. Both of the sensors are designed in such a manner that their areas are equal and will perform to sense absolute pressure variations for a very specific range. This specified range of absolute pressure is 10 kpa to 100 Kpa for 5 micron thick diaphragm with 3600 micrometer area. Three materials have chosen for diaphragm material like Si, PolySi and SiC. Applied pressure vs. deflection and change in capacitance is measured and graph is plotted.

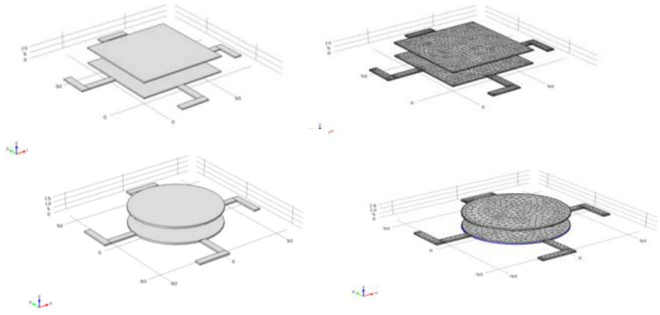


**Fig. 1.Cross-section and 3D view of the sensor geometries**

Side length of square diaphragm= 60 µm, radius of circular diaphragm= 33.84 µm, thickness of diaphragm= 5 µm, Separation gap between the plates= 30 µm.

## 4. MATERIAL ANALYSIS

The physical properties of silicon polysilicon and silicon carbide are noted in Table I. These properties are used in performing the analysis of the two designed MEMS based capacitive pressure sensor model in FEM based Multiphysics software.

**Table I. Some Physical Properties Of Silicon, Polysilicon And Silicon Carbide**

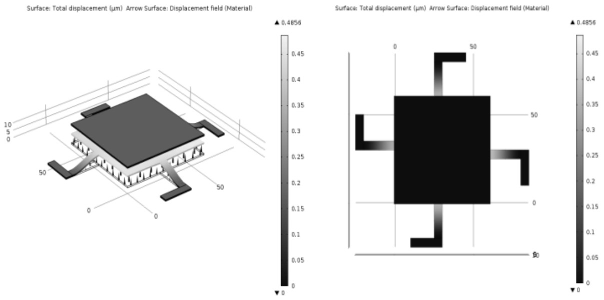
| **Materials** | **Properties** | | |
|---|---|---|---|
| Properties | ***Silicon*** | ***Polysilicn*** | ***Silicon Carbide*** |
| Young's Modulus | 170e9[Pa] | 160e9[Pa] | 748e9[Pa] |
| Poission's Ratio | 0.28 | 0.22 | 0.45 |
| Density | 2329[kg/m$^3$] | 2320[kg/m$^3$] | 3216[kg/m$^3$] |
| Thermal Expansion Coefficient | 2.6e-6[K$^{-1}$] | 2.6e-6[K$^{-1}$] | 4.3e-6[K$^{-1}$] |
| Thermal Conductivity | 130[W/(m*K)] | 34[W/(m*K)] | 490[W/(m*K)] |
| Relative Permitivity | 11.7 | 4.5 | 9.7 |

# 5. RESULT AND DISCUSSION

A wide range of mechanical and electromechanical studied along with the material analysis of the proposed two geometrical structures have been performed in the FEM Multiphysics Software platform. The detailed result of the study is presented in the below sections.

## 5.1 Mechanical and Electromechanical Study

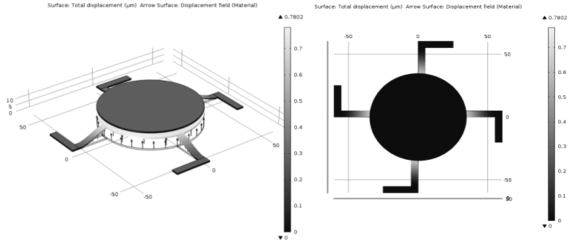
The performance is analyzed for both the designed geometries in Fig. 3(a, b) and 4(a, b). These geometries are used for special range of applied pressure 10-100Kpa. Pressure is applied on lower plate. When pressure is low there is no deflection of lower plate.



**(a)** **(b)**

**Figure 2: square shaped anchor based absolute pressure measuring MEMS capacitive pressure sensor (a) side view and (b) bottom view of sensor**

After a certain limit (10 KPa) of applied pressure lower plate is deflected towards the upper plate. If pressure increases, deflection of the plate increases. When the magnitude of the applied pressure increases, the deflection of the diaphragm is enhanced. Fig 2(a, b) and fig 3(a, b) represents the geometrical overview of square and circular diaphragm type capacitive pressure sensor. When pressure applied lower plate deflected towards the upper plate with the help of anchor. Applied pressure vs. deflection and change in capacitance are measured.



**(a)** **(b)**

**Figure 3: Circular shaped anchor based sensor (a) side view and (b) bottom view of sensor**

The effect of the variation of the distance between the two plates is also studied in Fig. 4. Thus an increase of the separation between the plate's leads to decrease of the capacitance value for both in the circular shaped as well as for the square shaped geometries. If distance between two plates is low then change in capacitance is high and sensitivity is also high. As the gap between two plates is increased the change in capacitance as well as the sensitivity is decreased.

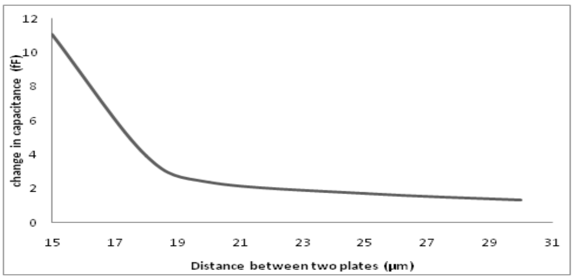


**Figure.4.Plot of capacitance with the variation of the distance between the plates**

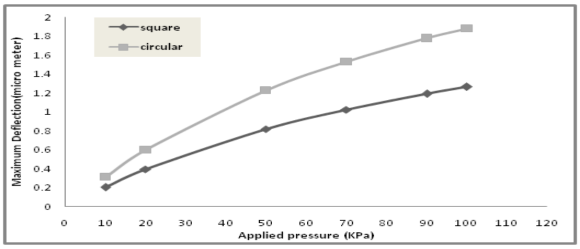


**Figure 5. Plot of maximum deflection vs. applied pressure (10 kPa-100 kPa) for both square and circular shaped diaphragm**

For equal area coverage of a circular and square shaped silicon diaphragm the applied pressure vs. maximum deflection is measured and is represented in Fig. 5. From Fig. 5 we can derive that for same amount of applied pressure circular diaphragm deflection is higher compared to that of the square diaphragm. It means that change in capacitance is also higher for circular diaphragm. As a result the sensitivity of circular diaphragm is higher than that of square diaphragm.

Thus, it is concluded that circular diaphragm is more preferable for absolute pressure measurement than the square diaphragm (for the equal area coverage of the plates of the diaphragm).

It is also concluded circular diaphragm sensitivity is also higher than square diaphragm.

Diaphragm thickness plays an important role for designing of pressure sensor. From Fig 6.it is observed that the applied pressure vs. deflection changes with the variation of the thickness of the diaphragm. When thickness of diaphragm is minimum then deflection is maximum and when deflection is maximum then change in capacitance is also maximum. It means sensor sensitivity depends upon the thickness of the diaphragm. Sensitivity decreases with increasing thickness of diaphragm. But maximum pressure handling capability can be increases by changing diaphragm thickness. Higher diaphragm thickness means it can with stand with high amount of pressure.

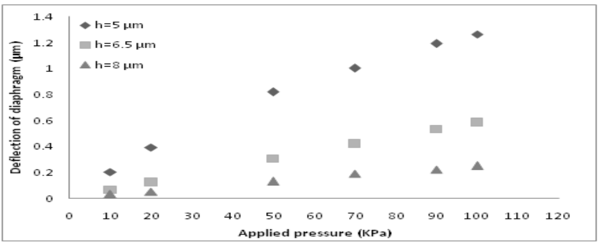


**Figure 6. Plot of the deflection with diaphragm thickness (5.0, 6.5, 8μm), with the range of applied pressure from (1-10) KPa for square shaped diaphragm**

Three materials are chosen for diaphragm material, Silicon, Polysilicon and Silicon Carbide. Applied pressure vs. diaphragm maximum deflection and change in capacitance is measured.

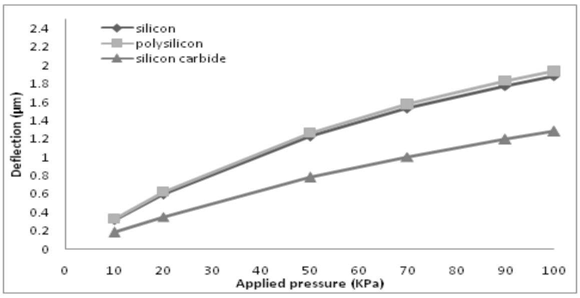


**Figure7. Measure deflection as a function of pressure (10-100KPa) for circular shaped anchor supported MEMS pressure sensor for silicon, polysilicon and silicon carbide materials**

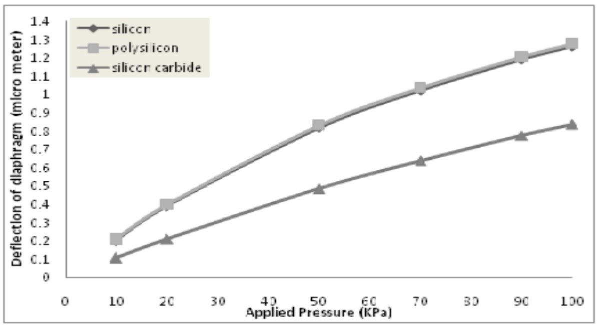


**Figure.8. Measure capacitance as a function of pressure (10-100KPa) for square shaped anchor supported pressure sensor for silicon, polysilicon and silicon carbide materials**

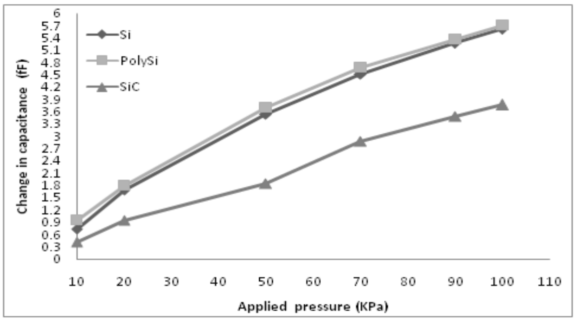


**Figure.9. Measure capacitance as a function of pressure (10-100KPa) for square shaped anchor supported MEMS pressure sensor for different diaphragm**

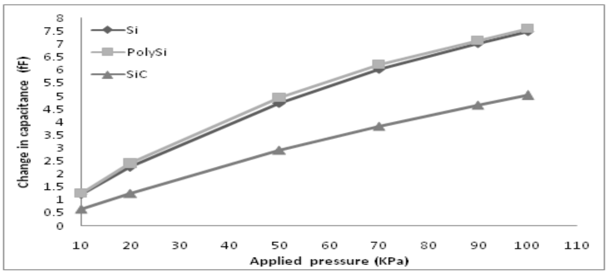


**Figure.10. Measure capacitance as a function of pressure (10-100KPa) for circular anchor suspended pressure sensor for different diaphragm materials**

Fig. 7 and Fig. 8 shows that for a particular pressure the deflection as well as the change in capacitance of polysilicon type diaphragm is greater compared to the silicon and silicon carbide. Thus polysilicon provides a higher sensivity in various applications when chosen as a diaphragm material. Silicon is more preferable than silicon carbide. Deflection of diaphragm depends on young's modulus, and young's modulus increases then deflection of diaphragm decreases. Due to this changes in capacitance also low for high Young's modulus materials. We can see applied pressure vs. deflection is higher for circular diaphragm for three diaphragm material (silicon, polysilicon and silicon carbide material) shown fig. 7, and fig. 8. Applied pressure vs. change in capacitance is plotted for three materials and that is higher for circular diaphragm, which is analyzed form Fig. 9 and Fig. 10.

# CONCLUSIONS

In this paper we have analyzed two different models of MEMS based capacitive pressure sensor for absolute pressure measurement. One having circular shaped whereas other having square shaped diaphragm. Detailed simulation based analyses on the mechanical, electromechanical as well as material studies were also performed. These types of pressure sensors are useful for measuring a particular range of pressure 10KPa to 100KPa. Circular shaped sensor is more sensitive than square one. Silicon and polysilicon and SiC is chosen for diaphragm material and applied pressure vs. deflection and change in capacitance is measured for two types of sensor . Polysilicon is more sensitive than others two materials. SiC has lower sensitivity than silicon and polysilicon. SiC can used for high absolute pressure measurement. Silicon performance in terms of diaphragm deflection and sensitivity is better than SiC as is observed from the plots. It is analyzed from the mechanical analysis that designed model can withstand a selective range of absolute pressure (10 KPa-100KPa). These types of sensor can be used for biomedical application and it is also used for pulse rate measurement. Also effect of thickness, shape, gap in between two diaphragms is analyzed. With the variation in thickness, area and gap between two plates (diaphragm) the range of measuring absolute pressure can be varied. In future, these types of pressure sensor are very efficient for medical applications for measuring respiration rate, monitoring of other physiological activities etc. and also in other micro device applications in the real world.

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