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Investigation On Sapphire Based Mems Pressure Sensor Sensitivity Through Finite Element Method

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Abstract: In this paper, a micro-electromechanical (MEMS) capacitive pressure sensor using sapphire deposited on the diaphragm is investigated by simulation using COMSOL Multiphysics Software. Typically, a diaphragm serves as the detecting element for this micro-pressure sensor, converting applied pressure into the appropriate displacement. Firstly, this study focused on the various shapes of diaphragms like circular, square, and rectangular. The model was developed with different thicknesses and materials like silicon and sapphire to get the highest level of sensitivity from the shape. In order to validate the simulation method, a comparison with the results from the previous researcher has been made first. The recommended pressure range is 0 MPa to 100 MPa. The circular shape with thickness diaphragm of 60 µm has highest sensitivity although sapphire has low sensitivity because of its properties but it is good option for high pressure.

Keywords: MEMS Capacitive Pressure Sensor, Sensitivity, Diaphragm, Displacement, COMSOL Multiphysics

1. Introduction

Sensors are a necessary component of contemporary life today, especially in electrical and mechanical applications. The first ten years of the twenty-first century have been dubbed the "Sensor Decade" [1]. Along with the Internet of Things (IoT), sensor research and development have expanded fast in recent years [2]. Piezoelectric, piezo-resistive, and capacitive technologies form the foundation of pressure sensors. The industry has determined that the capacitive pressure sensor is the optimal pressure sensor for this cutting-edge technology [3].

Capacitive pressure sensors have the ability to meet the rising demand for specialised pressure sensors because of their high sensitivity, quick reaction time, minimal temperature dependency, and

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low power needs. Due to the straightforward governing equation, they have a straightforward design and analysis [4].

Two parallel conducting plates, known as electrodes or diaphragms, are held apart by a dielectric substance to form a capacitor in a MEMS capacitive pressure sensor. The other electrode is often positioned beneath the pressure-sensitive one on a hard substrate. The top plate of the capacitive pressure sensor's parallel plate design is moveable or a diaphragm, which is maintained separated by a dielectric substance. The lower plate is fixed. The separation gap between the two plates is reduced when pressure is applied to the flexible plate from the top surface [5].

Researchers primarily employ diaphragm-based MEMS capacitive pressure sensors since the diaphragm is the primary sensing element in MEMS pressure sensors and must be appropriately built. To obtain the highest sensitivity, various diaphragm shapes, such as square, rectangular, and circular shapes, have been compared for stress distribution and displacement [3]. In the meantime, one of the researchers examined the linearity of the form and the burst strength of these three geometries using various diaphragm thicknesses [6] and [7] came to the conclusion that there was good agreement between theory and simulation for the equation for the three shapes associated to the applied pressure used to assess displacement at various pressures.

This paper compares the different shapes, thickness, and materials for diaphragm that related to sensitivity using Finite Element Method (FEM) for simulation of a MEMS capacitive pressure sensor in COMSOL Multiphysics software. The three diaphragm shapes tested were circular, square and rectangular. The sensitivity is determined by measuring the change in pressure and displacement.

2. Methodology

A moving and fixed plate, along with a diaphragm, make up a MEMS capacitive pressure sensor. The diaphragm is prone to deflecting when external pressure is applied to it. The diaphragm's deflection reduces the air gap, increasing the capacitance between the diaphragm and the backplate. If the external pressure is uniform, both the deflection and the rise in capacitance are linear. As a result of this the value of the capacitance increase as given in the Eq. 1;

$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \quad \text{Eq. 1}$$

where ε_o is the permittivity of the free space, ε_r is the material's dielectric constant between the capacitance's plates, A is the electrode's area, and d is the distance between two plates, which is a sensor component that demands a change in capacitance in response to an applied pressure load. The Figure 1 is an example of circular capacitive pressure sensor that explains how capacitive pressure sensor working in 3D image.

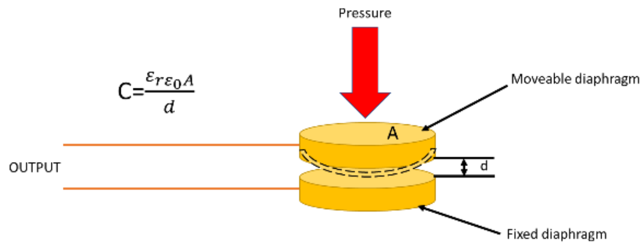


Figure 1: Deflection of circular diaphragm MEMS capacitive pressure sensor

A common material, silicon, which is frequently used by other researchers, as well as various diaphragm thicknesses before comparing the materials between silicon and sapphire, will be used in this study to obtain high sensitivity from the diaphragm, which has the result of geometry. Figure 2 depicts the capacitive pressure sensor's top diaphragm. Only the top diaphragm is used because it is moveable.

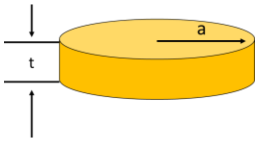


Figure 2: Schematic top diaphragm of circular capacitive pressure sensor

2.1 Modelling and Design of MEMS Pressure Sensor

2.1.1 Model of square diaphragm design in one dimension and three dimensions

For a square diaphragm with thickness, *t* and side length of $\sqrt{\pi a}$ as shown in Figure 3 for one dimension and Figure 4 for three dimensions from [3] as;

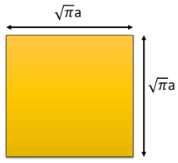


Figure 3: Square diaphragm in two dimensions

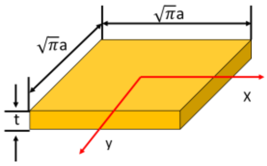


Figure 4: Square diaphragm in three dimensions

From the general differential equation of the thin plate theory, the displacement (w) at any point of the square diaphragm with fixed edges under distributed load circumstances may be deduced and written as follows [3]:

$$w(x,y) \cong \frac{1}{47} q \frac{a^4}{D} (1 - \frac{x^2}{\pi a^2})^2 (1 - \frac{y^2}{\pi a^2})^2 \quad \text{Eq. 2}$$

At the center, the greatest displacement has a value of [3];

$$w(0,0) = 0.0213 q \frac{a^4}{D} \quad \text{Eq. 3}$$

where D, is the flexural stiffness, may be expressed as follows [3]:

$$D = \int_{-t/2}^{t/2} \frac{E_z^2}{1-\vartheta^2} dz = \frac{Et^3}{12(1-\vartheta^2)}$$

where, E is Young's modulus and ϑ is Poisson's ratio. The formula for a square diaphragm's maximum deflection from [3] is;

$$W\max = 0.0151 q \frac{(1-\vartheta^2)a^4}{Et^3} \quad \text{Eq. 4}$$

The maximum stresses for the square diaphragm are at the edges' centers and may be written as [3];

$$\sigma_{xx} = 1.02 q \frac{\pi a^2}{t^2}; \sigma_{yy} = \vartheta \sigma_{xx}; \tau_{xy} = 0 \quad \text{Eq. 5}$$

2.1.2 Model of rectangular diaphragm in one dimension and three dimensions

For a rectangular diaphragm with a side length of 2a, width $\frac{\pi}{2}a$, and thickness, t as shown in Figure 5 in one dimension and Figure 6 in three dimensions;

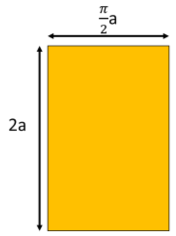


Figure 5: Rectangular diaphragm in one dimension

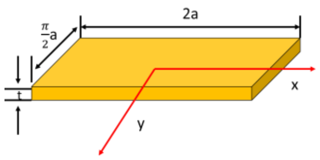


Figure 6: Rectangular diaphragm in three dimensions

A rectangular diaphragm's displacement at any location may be expressed as [3];

$$w(x,y) \cong \frac{(1-\vartheta^2)}{2Et^3} q \frac{(\frac{\pi^2}{16}a^2 - x^2)(a^2 - y^2)^2}{\frac{\pi^4}{256}a^4 + a^4} \qquad \text{Eq. 6}$$

At the center, the greatest displacement has a value of [3];

$$w(0,0)\max = 0.0188q\frac{(2a)^4}{Et^3} \qquad \text{Eq. 7}$$

The following is the equation for the stress in a rectangular diaphragm [3]:

$$\sigma_{xx} = 2\frac{qb^2}{t^2}\frac{\frac{\pi^4}{256}a^4}{b^4 + \frac{\pi^4}{256}a^4}; \sigma_{yy} = \vartheta\sigma_{xx}; \tau_{xy} = 0 \qquad \text{Eq. 8}$$

2.1.3 Model of circular diaphragm in one dimension and three dimensions

A circular plate of radius, a and thickness, t as shown in Figure 7 in one dimension and Figure 8 in three dimensions, carries a load of intensity, q uniformly distributed over the entire surface of the plate;

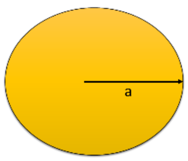


Figure 7: Circular diaphragm in one dimension

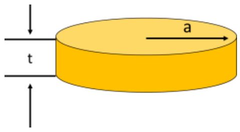


Figure 8: Circular diaphragm in three dimensions

A circular diaphragm's displacement at any location can be expressed as [3];

$$w(r) = \frac{qa^4}{64D}\left(1 - \frac{r^2}{a^2}\right)^2 \quad \text{Eq. 9}$$

At the center, the greatest displacement has a value of [3];

$$w(0)\max = \frac{qa^4}{64D} \quad \text{Eq. 10}$$

The formulae for the maximum stress and deflection in a square diaphragm are as follows [3]:

$$\sigma_r(a) = \frac{3}{4} q \frac{a^2}{t^2}; \sigma_t(a) = \frac{3}{4} \vartheta q \frac{a^2}{t^2} \quad \text{Eq. 11}$$

2.2 Simulation of diaphragm model

Modelling the three shapes using the same material silicon that used as the diaphragm’s common material by the previous researcher has been done using the COMSOL Multiphysics software. The structure, as previously explained, will translate the applied pressure into displacement. By using a secondary transduction method, this displacement might be efficiently leveraged to get an electrical amount for subsequent processing or display.

This paper considers a pressure sensor for a medium pressure range of 0 MPa to 100 MPa for diaphragms of various thicknesses. Use of COMSOL Multiphysics is made for the examination of the sensor shape and dimensions stated in Tables 1 and Table 2 for materials properties.

Table 1: Geometry and dimensions pressure sensor [4]

Si No	Parameter	Scale value
1.	Size of diaphragm	For circular diaphragm, diameter(2a) =783 µm For square diaphragm, diameter(a) for width and length=783 µm For rectangular diaphragm, diameter for width=600 µm and length=783 µm
2.	Thickness of diaphragm (t)	60 µm, 63 µm, 66 µm
3.	Maximum central deflection of the diaphragm (Wmax)	16 µm (limited to t/4)

Table 2: Parameter for silicon and sapphire properties [4]

Parameter	Silicon	Sapphire
Initial gap(g0)	19 µm	19 µm
Young Modulus	131 GPa	400 GPa

Poisson’s ratio(y)	0.27	0.24
Yield strength	7GPa	700MPa
Density	2330kg/m^3	400kg/m^3
Permittivity of free space	8.854x10^{-12}F/m	9.1
Relative permittivity	1	1

Table 3: Displacement of circular, square and rectangular diaphragm

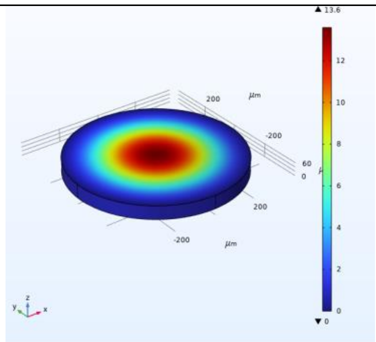
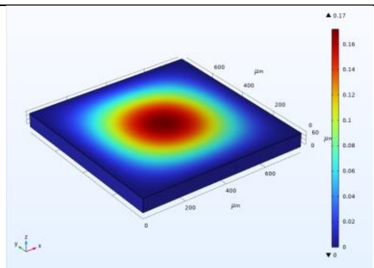
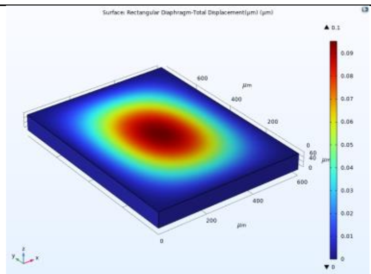
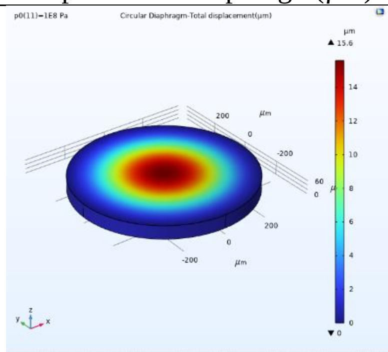
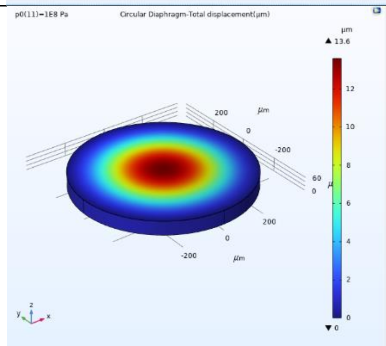
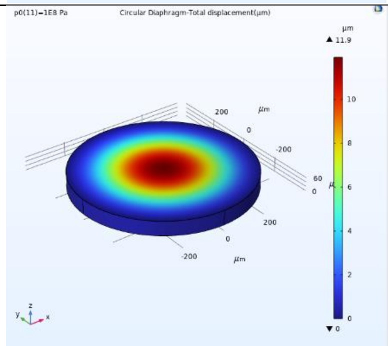
Name	Displacement (μm)
Circular diaphragm	
Square diaphragm	
Rectangular diaphragm	

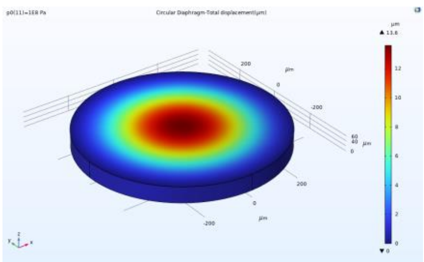
Table 3 shows the displacement plot for three shapes which are circular, square and rectangular diaphragm were simulated through COMSOL Multiphysics 6.0 software under the applied pressure. The result shows that the for these shapes, the deformation occurs maximum at center of the diaphragm and minimum at edges.

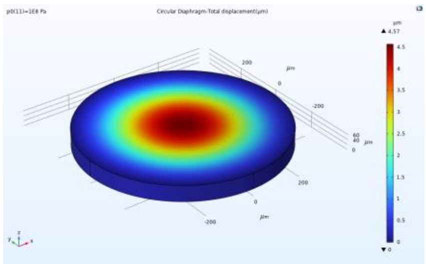
Table 4: Displacement different thickness of diaphragm in circular diaphragm

Thickness (µm)	Displacement diaphragm(µm)
60	
63	
66	

Based on Table 4, the displacement plot for different thickness of 60 µm, 63 µm and 66 µm were modelled for the circular shape diaphragm using COMSOL Multiphysics 6.0 software under the applied pressure. For all the thickness, thickness of 63 µm show that lowest displacement because of the diaphragm stiffer and more resistant to deformation.

Table 5: Different materials were applied on the circular diaphragm with same thickness

Material	Displacement diaphragm(µm)
Silicon	

Sapphire	

Based on Table 5, it shows that different materials were applied on the circular diaphragm with same thickness of 63 um. For the silicon diaphragm, the displacement is larger than of the sapphire diaphragm due to higher elasticity which is lower Young's Modulus of the silicon.

3. Results and Discussion

With regard to the length of the diaphragm, the displacement analysis results for circular, square, and rectangular diaphragms as shown in Figure 9.

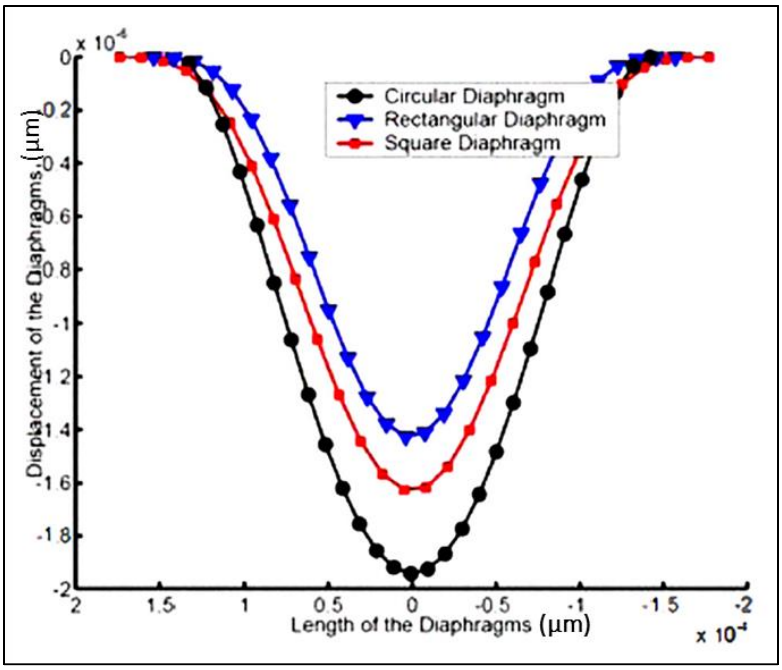


Figure 9: Displacement Vs Length of the diaphragm graph

The graph plotted in Figure 9 for three shape (circular, square, rectangular) diaphragm shows that a higher center deflection when homogenous pressure is applied by using Matlab. For the same thickness which is 63 µm, a circular diaphragm show that it has more sensitivity as compare to other shapes [3][9]. This is because circular diaphragms are symmetric shape, which means that the deflection caused by a pressure is evenly distributed around the center of the diaphragm.

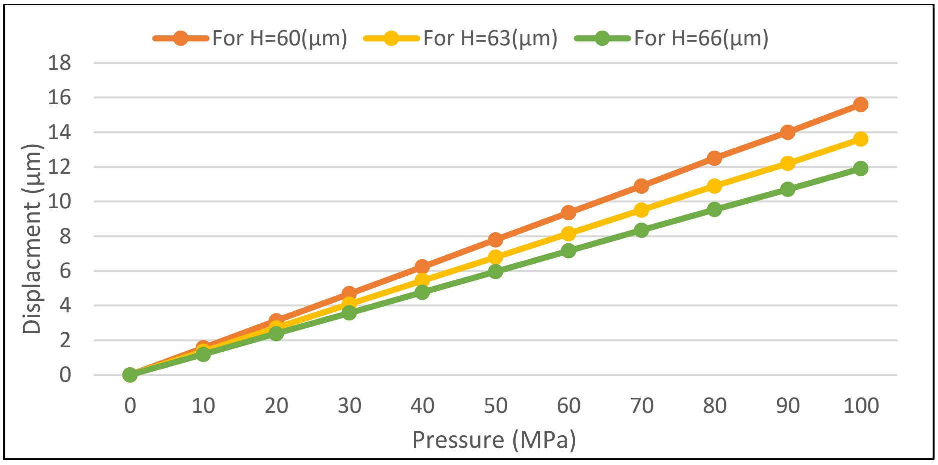


Figure 10: Displacement of diaphragm Vs Pressure graph for different thickness diaphragm

The graph plotted in Figure 10 show that thickness for 60 µm, 63 µm and 66 µm by using Excel. The range of this thickness is suitable for silicon under the pressure 0 MPa to 100 MPa that will not break this sample [10]. The depicted curve for thickness 60 µm shows that the displacement increases higher than other thickness. The thickness of the diaphragm has an inverse relationship with the displacement of the diaphragm, which is directly proportional to the applied pressure. Therefore, the displacement and sensitivity of the sensor increase as the diaphragm's thickness decreases. The thin thickness which is 60 µm have highest sensitivity because it can be more easily deflected by pressure and not breakable.

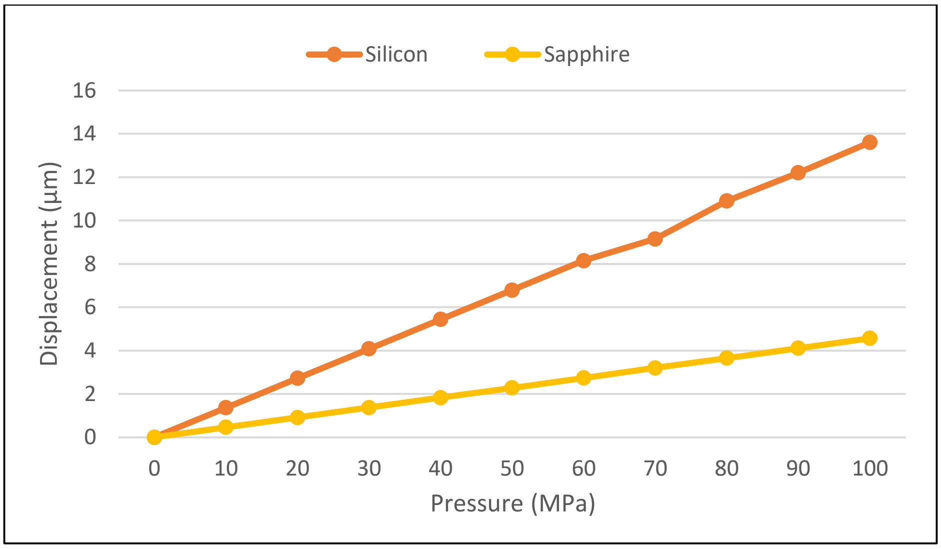


Figure 11: Diaphragm displacement(µm) Vs Pressure (MPa) graph for different materials

The graph plotted in Figure 11 by using Excel show that displacement of sapphire is lower than displacement of silicon on the same pressure in circular diaphragm [11]. This is because the sapphire material relatively brittle and has a high modulus of elasticity than silicon. This mean sapphire will have less displacement for the same applied pressure than a more elastic material such as silicon. So, the sapphire is less sensitivity to pressure changes than silicon material.

4. Conclusion

Three different diaphragm shapes (circular, square, and rectangular) are investigated in this study utilizing a simulation model with COMSOL Multiphysics under the same applied pressure. According to the study, the deflection is greatest in the middle of all three designs. It was discovered that, in comparison to other diaphragms, the circular diaphragm provides the highest deflection for an applied pressure. Due to the uniform stress distribution at the diaphragm's edges, sensitivity is higher and nonlinearity is lower in circular diaphragms. For the different thickness on the circular diaphragm, it is observed that when thickness is decreasing, the displacement and sensitivity of the sensor is increasing. For the different material on the circular diaphragm, it is observed that the sapphire is less sensitivity than silicon because of the sapphire properties which is brittle and has a high modulus of elasticity. Meanwhile, the sapphire is a good option for high pressure applications, where a high modulus of elasticity and a high durability are more important than sensitivity. While silicon is a good option for lower application where sensitivity and cost are m ore important than the high pressure.

Acknowledgement

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