

# Performance Analysis and Simulation of MEMS Capacitive Pressure Sensor



S. Ananthi, Monica Lamba, Himanshu Chaudhary, and Kulwant Singh

**Abstract** MEMS capacitive pressure sensor has a wide application due to its less power dependency and less sensitive to temperature changes. It also has good over-pressure tolerance. This paper focuses on sensitivity analysis of capacitive pressure sensor by plotting graphs between diaphragm displacement versus applied pressure, change in capacitance versus applied pressure at different temperatures for different materials. Sensor working principle is based on electro-mechanics interface. In this paper, capacitive pressure sensor with different structure is designed, simulated and the results are analyzed using COMSOL Multiphysics 5.5.

**Keywords** MEMS capacitive pressure sensor · COMSOL multiphysics · Structure · And sensitivity

## 1 Introduction

### 1.1 MEMS Pressure Sensors

Sensors are used in modern devices for monitoring various physical parameters like temperature, pressure, humidity, etc., based on MEMS technology. Pressure sensors have wide range of applications in almost all possible areas like automobile industries, aerospace, biomedical, defense applications, etc. Pressure sensors are used to measure the applied pressure by a liquid or gas, and then the measured quantity is expressed as an electrical signal by a read circuit. Pressure sensors are based on piezoelectric, piezo-resistive, or capacitive technology. These types have their own advantages and disadvantages [1, 2]. Selection is based on application requirement like pressure range, accuracy, power consumption, and environmental condition like

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S. Ananthi (✉) · M. Lamba · H. Chaudhary  
Department of Electronics and Communication Engineering, MUJ, Jaipur, India  
e-mail: [ananthi232@gmail.com](mailto:ananthi232@gmail.com)

K. Singh  
FlexMEMS Research Centre, Department of Electronics and Communication Engineering, MUJ, Jaipur, India

temperature, etc. The piezo-resistive pressure sensors are the simplest to fabricate and provide electrical output directly [3]. In MEMS piezo-resistive pressure sensors, four resistors placed in Wheatstone bridge configuration are strained in proportion to the applied pressure [4, 5]. Change in their resistance value is a measure of applied pressure.

Capacitive pressure sensors have the capability to meet up the rising demand of specialized pressure sensors because of its high sensitivity, fast response time, less temperature dependency [6, 7], and low power requirement. They have a simple design and analysis due to the simple governing equation [8].

In MEMS capacitive pressure sensors [9], two parallel and electrically isolated conducting plates by a dielectric medium like vacuum are fabricated on a silicon substrate. The bottom plate is fixed and the top membrane bends according to the applied pressure, thereby creating a capacitance change. This change is then converted into an electrical signal as a measure of applied pressure.

## ***1.2 Comparison of Capacitive with Piezo-Resistive MEMS Pressure Sensor***

Capacitive sensors have high accuracy, low power consumption [8, 9], and long term stability. The main advantage of capacitive sensor is the over pressure tolerance. Touch mode sensors have higher burst pressures [10] commonly used in biomedical applications. It can withstand up to hundred times the rated pressure without breaking and with no plastic deformation. Sensor performance is unaffected after the release of the over pressure. Capacitive pressure sensors are more suitable for medical applications [11, 12] (where high accuracy and long term stability are required) and for industry, where the occurrence of over pressure [13] is common and sensor repair is not an option. MEMS capacitive technology can be applied in demanding environments such as absolute, gauge, and relative pressure measurement [14]. But it needs more complex signal conditioning circuit and production cost is high compared with piezo-resistive sensors. The readout circuit for the capacitive sensor can be monolithically integrated [15], based on a switched mode method using reference and sensing capacitors.

## **2 Mathematical Modeling of Capacitive Pressure Sensors**

The equation for the capacitance of a parallel plate capacitor is given by the relation indicated as

$$c = \frac{\epsilon_0 \epsilon_r A}{d} \quad (1)$$

Here,  $C$  denotes capacitance, expressed in terms of  $A$  = area between the two plates,  $\varepsilon_r$  = dielectric constant,  $\varepsilon_0$  = permittivity of free space, and  $d$  = distance between the two plates. The generalized equation for determining the maximum deflection of a square membrane whose thickness is uniform and all its edges are fixed, is given by [16] when external pressure is applied

$$w_{\max} = \frac{0.0138L^4P}{Eh^3} \quad (2)$$

In terms of poisson's ratio, central maximum deflection of the square shaped diaphragm of MEMS sensor under the applied pressure is given by [17]

$$w_{\max} = \frac{0.01512(1 - \mu^2)L^4P}{Eh^3} \quad (3)$$

Here,  $P$  = applied pressure,  $L$  = length of diaphragm,  $h$  = thickness of diaphragm,  $E$  = Young's Modulus of Elasticity, and  $\mu$  = Poisson's ratio.

Now, since the spacing between the two plates of the capacitor changes due to the applied pressure, the change in capacitance is given by

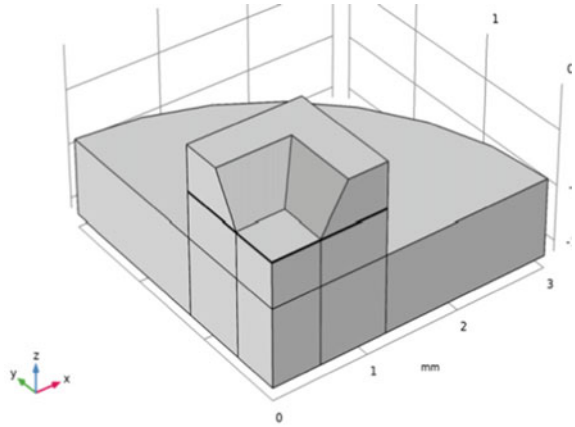
$$\Delta C = \iint \frac{\varepsilon_0\varepsilon_r}{d - w(x, y)} dx dy \quad (4)$$

### 3 Modeling MEMS Capacitive Sensor in COMSOL Multiphysics

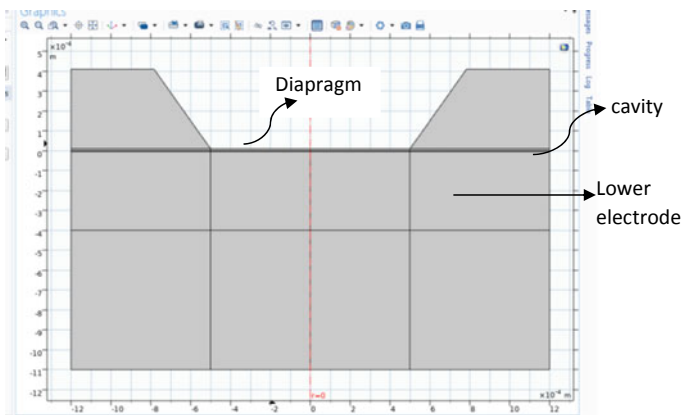
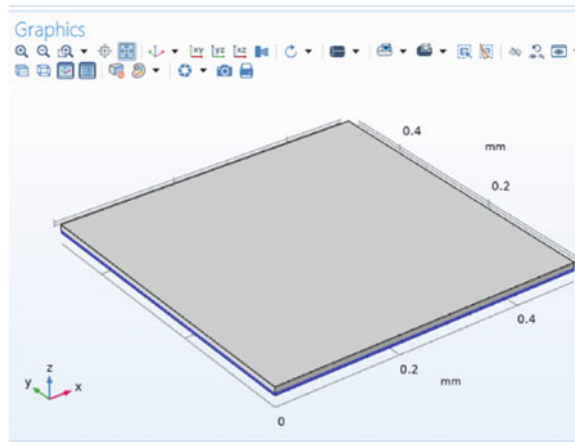
The COMSOL Multiphysics software [18, 19] provides incorporated environment in which we can build the sensor model. The pressure sensor is part of the silicon die. One fourth of the model is considered due to the geometrical symmetry of the sensor as shown in Fig. 1. This will reduce the computational time and the memory required for computation. Using an in-built model, build-in physics structural mechanics with electro-mechanics interface and stationary study is performed. Pressure ranging from 0 to 25 kPa is applied, at  $T_0 = 20$  °C and the sensor is considered to have a die bonding temperature of 70 °C.

The boundary conditions are applied to the right side ( $zx$  plane at  $y = 0$ ) and left side ( $zy$  plane at  $x = 0$ ) as indicated in Fig. 1. Simulation is carried out for three different materials defined for diaphragm (silicon, graphene, and SiC). Thickness of the diaphragm is 0.01 mm and has a square shape with length and breadth as 0.5 mm. The distance between the electrodes (the cavity blue in color) is 0.003 mm, as shown in Fig. 2. The thickness of lower electrode and substrate are 0.39 mm and 0.7 mm, respectively, relatively very low thickness of diaphragm and cavity are seen as a bold horizontal line as in Fig. 3. The cavity is sealed under high vacuum, and

**Fig. 1** Geometrical model of MEMS capacitive pressure sensor



**Fig. 2** Cavity between the two electrodes



**Fig. 3** Cross sectional view of MEMS capacitive pressure sensor

**Table1** Material property of different materials used for diaphragm

Property	Silicon	Graphene	SiC
Young's modulus (TPa)	0.170	1	0.450
Poisson's ratio	0.06	0.17	0.22
Density (kg/cubic meter)	2330	2000	3200
Coefficient of thermal expansion (per Kelvin)	$2.6 * 10^{-6}$	$8 * 10^{-6}$	$3.8 * 10^{-6}$

the sides are insulated so that there is no connection between upper diaphragm and lower electrode. The boundary load is applied on upper boundary of the diaphragm. The diaphragm is allowed to move only in the z-direction to get the correct values of the capacitance change. The upper diaphragm (domain) is seized at a fixed potential of 1 V with respect to the ground at 0 V. The ground is applied to boundary of lower electrode.

In the physics part, solid mechanics and electrostatics are added. This automatically adds the electro-mechanical forces interface. To do the finite element analysis, over the whole capacitor MEMS structure moving mesh is applied. When pressure is applied, the center of the diaphragm is more compressed, and as a result, the applied mesh over the center of the diaphragm is also compressed. Hence, moving mesh is the appropriate to apply, instead of applying physics controlled mesh.

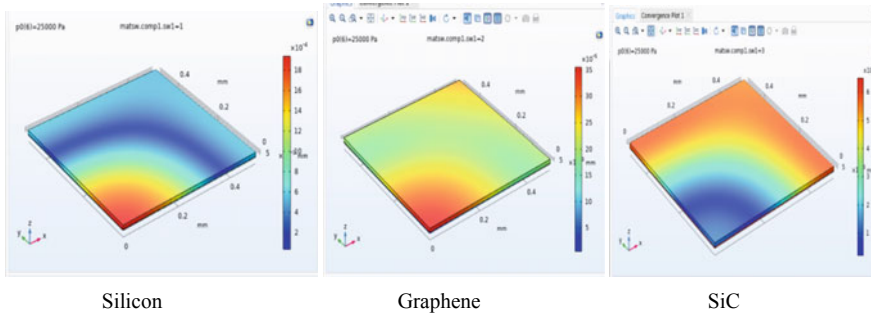
The material properties of different materials under consideration for simulation are as shown in Table.1.

Stationary study is computed with parametric sweep of different pressures ranging from 0 to 25 kPa and the t the corresponding displacement of diaphragm, capacitance is analyzed. An applied pressure originates deformation in diaphragm owing to that potential is not uniformly distributed in plane. Thus, plot for deformation of diaphragm versus pressure and plot of capacitance versus pressure are simulated separately. The analysis first carried out without any added stress due to sensor packaging stress and at a temperature of 20 °C. Then, it is analyzed with packaging stress and the operating temperature is varied from 290 to 300 K to find out the corresponding change in capacitance of the sensor.

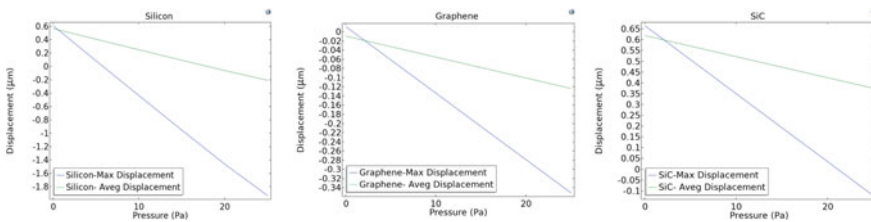
## 4 Simulation Results

### 4.1 Diaphragm Displacement in Response to an Applied Pressure for Different Materials

Using switch mode simulation displacement of diaphragm as a function of pressure is simulated. Center of the diaphragm is more deflected, as shown in Fig. 4.



**Fig. 4** Displacement of the diaphragm for an applied pressure of 25 kPa



**Fig. 5** Displacement of the diaphragm for an applied pressure range of 0–25 kPa

### 4.2 Displacement Versus Various Pressure for Square Diaphragm

The applied pressure is varied between 0 and 25 kPa. Deformation of diaphragm versus applied pressure is plotted as shown in Fig. 5.

### 4.3 Capacitance Versus Pressure for Square Diaphragm

Pressure range of 0–25 kPa is applied for which Si material shows a capacitance change from 0.75 to 1.2 pF, graphene from 0.74 to 0.77 pF, and in the case of SiC, it is 0.74–1.06 pF. Graphene material has more linear curve as compared with Si and SiC. Graphs are plotted as shown in Fig. 6.

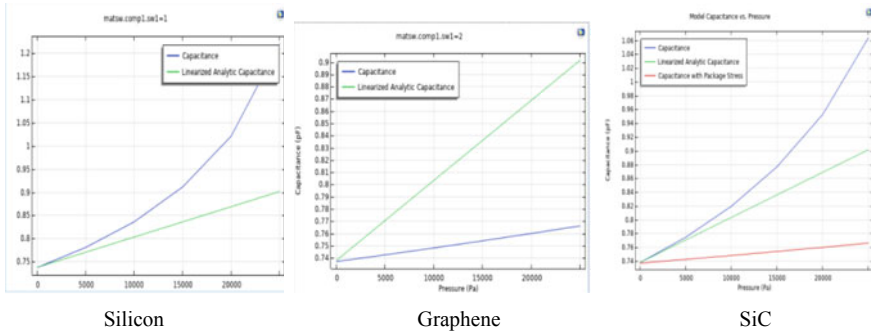


Fig. 6 Capacitance in pF versus applied pressure in  $P_a$

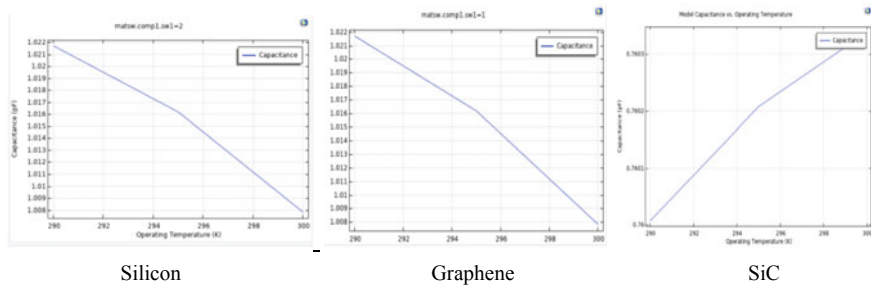


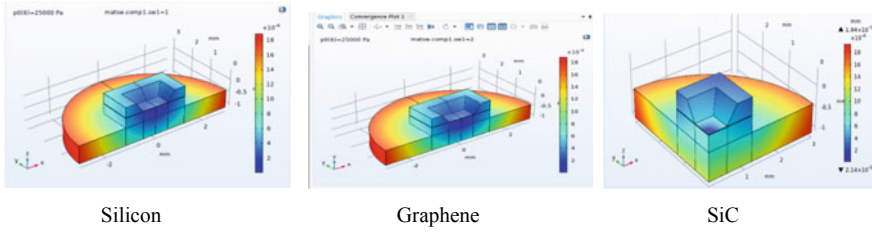
Fig. 7 Variation in capacitance with variation in operating temperature

### 4.4 Capacitance Versus Operating Temperature

To observe the effects of packaging stress on performance of device, thermal expansion is added in the model. The effect of thermal expansion is observed on entire structure as drawn in Fig. 7. The temperature is varied from 290 to 300 K.

### 4.5 Displacement of Structure with Packaging Stress

The designed structure is assumed to be operating at a temperature of 20 °C. And its bonding temperature is 70 °C. The displacement of the structure at operating temperature of 20 °C with a load of 25 kPa is simulated and plotted as shown in Fig. 8. There is an interaction between the thermal stress and stress due to applied load.



**Fig. 8** Displacement of structure with packaging stress

**Table 2** Simulation analysis

Property (for one quadrant of sensor)	Silicon	Graphene	SiC
Sensitivity (pF/Pa)	$18 * 10^{-6}$	$1.2 * 10^{-6}$	$12.8 * 10^{-6}$
Pressure sensitivity at 25 kPa	1.2 pF	0.77 pF	0.81 pF
Maximum displacement of diaphragm at 25 kPa	$-2 \mu\text{m}$	$-0.35 \mu\text{m}$	$-0.12 \mu\text{m}$
Change in capacitance due to change in operating temperature (290–300 K)	$-0.014 \text{ pF}$	$-0.014 \text{ pF}$	$0.0003 \text{ pF}$

## 5 Simulation Analysis

The simulated results are compared, shown in Table 2. Silicon has the maximum sensitivity for the pressure range 0–25 kPa, and diaphragm thickness of 0.01 mm. Sensitivity of capacitor for a change in temperature, over a range of 290–300 K is not very significant for the given pressure range proving capacitive MEMS sensor is less sensitive to temperature changes. Negligible changes are observed in the case of SiC which is widely used in high temperature application [20].

## 6 Conclusion

With the help of COMSOL Multiphysics 5.5 simulation tool, analysis and simulation of capacitive MEMS pressure sensor are carried out. The capacitor model and the physics acting upon it is studied through the simulation. Mathematical modeling is done, and the analytical value of the capacitor is compared with the simulated value by COMSOL. Geometrical shapes and diaphragm material can be changed to optimize the sensitivity and linearity of the sensor depending upon the application requirement such as pressure range operating condition, etc. Since capacitive pressure sensor are capable of measuring absolute pressure (by comparing unknown low pressure with vacuum), gauge pressure (pressure higher than atmospheric pressure), and differential pressure they find application in medical and industrial field.



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