# Development of Capacitive Pressure Sensor for Weather Balloon Satellite: COMSOL Multiphysics


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***Abstract*—The proposed electrostatic capacitive pressure sensor is intended for measuring atmospheric pressure, on weather balloons at the -73°C to -33°C required by us. The sensor is operated in the pressure range of 1 Pa to 90 KPa. Below the ozone layer, the sensor obtains pressure measurements up to the designated altitude. It can measure pressure using this capacitive pressure sensor, which works by monitoring changes in capacitance and diaphragm movement. The diaphragm of the sensor moves lower in response to a boundary load, shortening the distance between it and the die's grounded portion and raising capacitance. By altering the dielectric material and geometry, the sensor is optimized. The sensor is made up of a silicon die, a steel base (Steel AISI 4340), and ceramic (Nextel 480 mullite fibers), as the dielectric material. To ensure uniform application of the boundary load around the circle, the geometry of the die changed from a cuboidal shape to a cylindrical one. Based on the broad range of pressure values the diaphragm, dielectric medium, and base thicknesses have been adjusted. The diaphragm is thickened to strengthen the sensor's resistance, to greater pressures. Compared to the prior model (cuboidal die), the sensitivity has increased in our newly optimized model (cylindrical die)..**



***Index Terms*—COMSOL Multiphysics, Capacitive Pressure Sensor, Weather Balloon Satellite.**


## I. Introduction

Frequent monitoring of modern devices requires the use of MEMS-based pressure sensors for a number of applications in space, industry, biomedical, electronics, public health and security, etc. There are three main categories for pressure sensors: capacitive pressure sensor, piezoelectric, and piezoresistive.[1] These sensors are utilized in several applications and are based on the theory of sensing and ranges of pressure and capacitance.

Compared to higher altitudes, the regions below the ozone layer are not developed or used, although conventional aircraft will still operate there. As a result, more detection and observation are required at altitudes below the ozone layer. One of them is a weather balloon satellite, which reaches ozone and provides us with various meteorological characteristics, including temperature, pressure, humidity, and signal bandwidth, that can be used by any aircraft operating at those altitudes.[2,3]

This paper describes the design and modeling of a capacitive pressure sensor for a weather balloon satellite using COMSOL Multiphysics software. The fundamental components of the electronic world are capacitors. Capacitors are commonly comprised of a pair of conducting plates that are arranged in parallel. The dielectric material, which can be any suitable insulating material such as air or ceramic, is what keeps these plates apart because it is not conductive.

A pair of plates that serve as electrodes and are separated by an insulating material usually make up a MEMS capacitive pressure sensor. The structure consists of an upper plate that is a thin, elastic, electrically conducting membrane called a diaphragm, which serves as a single electrode as well as the stationary plate. The dielectric material known as ceramic fiber separates these electrodes. This makes use of the electromechanical interface, in which the diaphragm deflects in response to an externally applied uniform pressure, decreasing the space between the two electrodes and raising capacitance. Therefore, the higher the capacitance changes, the higher the sensitivity; capacitance changes caused by membrane deformation are used for pressure sensing. Therefore, the diaphragm's deflection caused by external pressure is measured and converted to a change in electric capacitance based on the principle of electromechanics.

This essay looks at the performance of a MEMS-based capacitive pressure sensor that consists of a circular diaphragm using COMSOL Multiphysics simulation. MEMS technology is used in capacitive sensors because of its tiny size, inexpensive and effective. MEMS tech further enables an implanted sensor to be combined to architectural elements to provide constant device surveillance in space.

## II. Sensor Geometry

A gap of air separates the two parallel plates that serve as the electrodes of capacitors in a capacitive pressure sensor. A device's optimal performance and required specifications depend on a number of factors, including material type, size, shape, and structure. Figure 1 shows a schematic of a capacitive pressure sensor. This study used silicon as the diaphragm material, with a Poisson's ratio of 0.07, a Young's modulus of 180 GPa and density of 2343 kg/m3. The circular diaphragm's radius is 560µm.

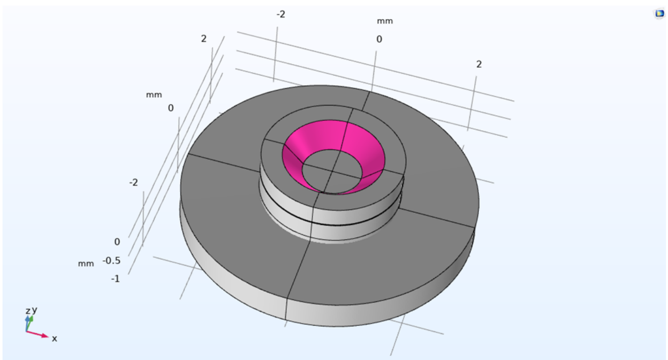

Fig. 1. Capacitive pressure sensor prototype model

Because of its low coefficient of thermal expansion (2.6 ppm/°C), high melting point, and reduced mechanical instability, silicon is the most suitable material. Because of these characteristics, asymmetric etching of bulk silicon produced the circular diaphragm. At 70°C, a metal plate made of steel has been attached to the silicon die. Only one-fourth of geometry is modelled using a symmetry boundary due to the symmetric aspect of geometry, as indicated in Figure 2 in COMSOL Multiphysics.

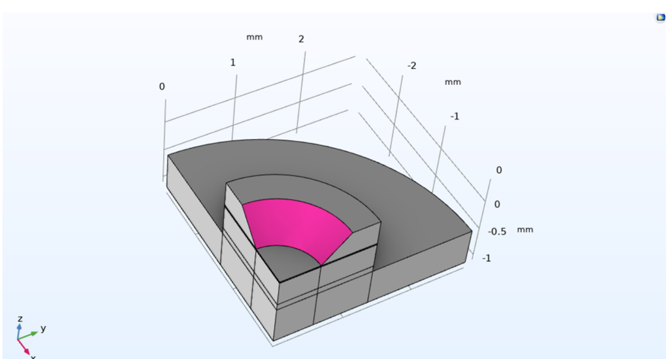

Fig. 2. one-fourth part of model geometry for symmetry

Figure 3 depicts a 2-dimensional cross-sectional view of the capacitive pressure sensor that has been designed. A voltage of 1V is applied to the diaphragm with respect to the ground.[4] The sensor consists of a silicon substrate as diaphragm material, ceramic (Nextel 480 mullite fibers) as dielectric material, which is between the the diaphragm i.e., the thin membrane, and the grounded portion of the die, which is provided for the connection between diaphragm and ground. The base of the sensor is made up of the AISI 4340 alloy, which consists of nickel, chromium and molybdenum. Due to its high strength, machinability and heat treatability, it can be used at high pressure and temperatures. Poisson's ratio ranges from 0.27 to 0.30, its density is 7850 $kg/m^3$, and its coefficient of thermal expansion is 12.3 ppm/°C.

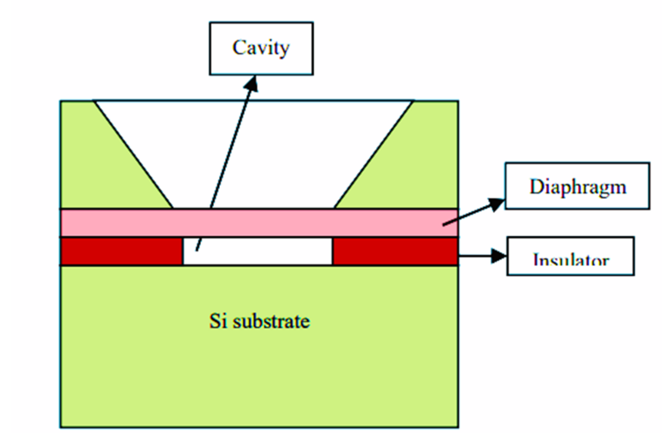


Fig. 3. one-fourth part of model geometry for symmetry

## III. Methodology

In this section, we'll get into greater detail about the capacitive pressure sensor's design, modeling, and COMSOL Multiphysics simulation. COMSOL Multiphysics is such a strong tool that doesn't require a deep analysis and calculation of mathematics. So in the project, the main concentration is on design and simulation.

### A. Working principle

Electromechanics is the underlying principle of operation for this MEMS capacitive pressure sensor. Applying pressure to the narrow diaphragm of the sensor causes the diaphragm at the center to move towards the grounded portion of the die, resulting in maximum displacement. Due to this, the gap between the diaphragm and the grounded portion of the die will be non-uniform.

The distance will reduce between the two mediums, which in turn will increase the capacitance of the sensor.

### B. Capacitive pressure sensor Physics

To examine the deflection of a circular-shaped diaphragm, sensitivity, capacitance vs. pressure analysis, and temperature vs. capacitance are carried out using COMSOL Multiphysics for this sensor with and without packing stress.

The capacitance among two identical planes in the failure of outside forces is expressed as eq(1) [5],

$$C = (\epsilon_0 * \epsilon_r * A)/d \tag{1}$$

In this equation, the symbol $\epsilon_0$ represents the permittivity of the vacuum, the symbol $\epsilon_r$ represents the relative dielectric coefficient of the substance that is placed in between the separation of the plates, the symbol A represents the surface area of the electrode, and the symbol d represents the distance of separation between the two electrodes.

But equation (1) is insufficient as we are using elastic material which has non uniform displacement instead of parallel plate which has uniform displacement. For circular shaped diaphragm the maximum displacement at the center of diaphragm is given as eq(2) [6],

$$w_{max} = 0.0206(1-\mu^2) * \frac{(PR^4)}{Eh^3} \tag{2}$$

Let R represent the radius of the diaphragm, h represent the thickness of the diaphragm, E represent Young's Modulus (in GPa), $\mu$ represent Poisson's ratio, P represent the applied external pressure, and $w_{max}$ represent the maximum deflection of the diaphragm. Changes in the diaphragm's external pressure cause the electrode spacing to alter, which alters capacitance. This deflection-related variation in capacitance is provided by eq(3) [6],

$$C = \int\int \frac{\epsilon_0}{(d - w(x,y))} * dxdy \tag{3}$$

where w(x, y) represents the diaphragm's movement and d is the separation among the pads.

The ratio of the evaluated property to the resultant signal is the definition of sensitivity. The amount that a sensor's output fluctuates in response to changes in the input quantity it is measuring is known as its sensitivity. Therefore, the pressure sensitivity is provided by eq(4) [7],

$$S_p = \frac{\partial C}{\partial P} \tag{4}$$

where P is the external pressure imposed and $\partial C$ is the variation in capacitance.

The proportion of diaphragm bending movement at a given pressure yields the mechanical sensitivity, which is expressed as eq(5),

$$S_w = \frac{\partial w}{\partial P} \tag{5}$$

where P is external applied pressure and $\partial w$ is displacement

### C. Multiphysics Study with COMSOL

Multiphysics in COMSOL offers a robust, complete PCs ecosystem. With a model builder that offers a comprehensive model overview and full capabilities, in this case, the built-in physics module is chosen to do stationary study analysis using the Structural Mechanics with Electromechanics interface.[8]

The sensor is operated at an external pressure ranging from 1 Pa to 90 KPa and within a temperature range of -73 °C to -33 °C [9][10]. Implementing the equal boundary rules to the sensor because of its symmetry. Additionally a border load is imposed to observe how uniformly the membrane is under pressure. The membrane is configured to only shift in the plane of Z, to accurately measure the capacitance outcomes [11]. The sensor's membrane is maintained at a constant voltage of 1 V in relation to the bottom [12][13]. The material properties of ceramic, silicon, and steel are described in the sensor structure. The change in pressure doesn't deform the whole diaphragm uniformly, so a plot is given for the diaphragm bending in relation to pressure. [14]

## IV. Output and Results

The following part shows the outcomes of the simulation as an estimate of pressure for diaphragm movement, linear analytic capacitance, capacitance change, pressure sensitiveness, and temperature dependence for a circular-shaped diaphragm.

### A. Pressure vs. Diaphragm displacement

Both findings with and without packing stress are displayed below. Figure 4 illustrates the movement of the silicon membrane as a result of 90 KPa of external pressure. This demonstrates that the diaphragm's middle is where maximal displacement happens.

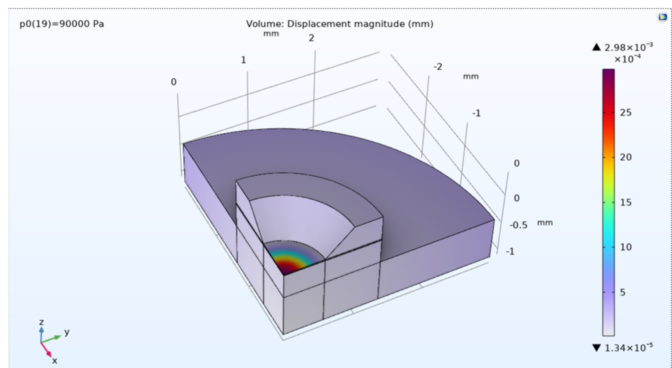


Fig. 4. Displacement of the diaphragm at 90 KPa external pressures

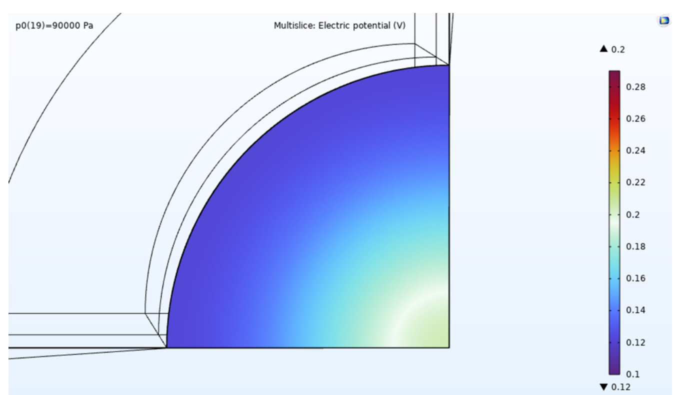


Fig. 5. Electric potential between plates of capacitor

| Pressure (Pa) | Max Disp ($\mu m$) | Avg Disp ($\mu m$) |
|---|---|---|
| 0 | -0.14353 | -0.14352 |
| 2000 | -0.78369 | -0.35837 |
| 4000 | -1.4208 | -0.35837 |
| 6000 | -2.0519 | -0.78468 |
| 8000 | -2.6727 | -0.99406 |
| 9000 | -2.9803 | -1.098 |

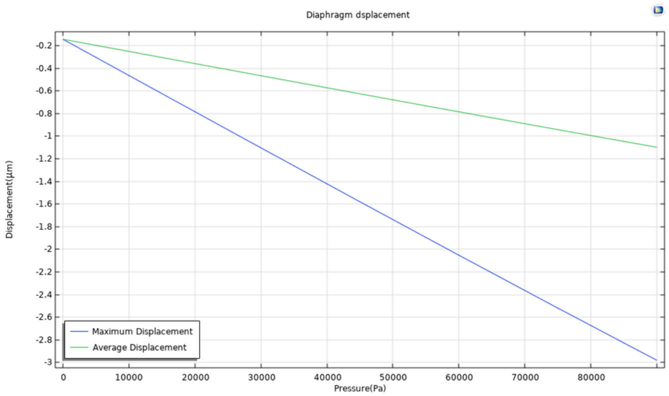


Fig. 6. Pressure vs. Diaphragm displacement

As seen in Figure 5, this causes an uneven potential between the capacitor's plates. The membrane's maximum and average displacements on a circular diaphragm with and without packaging stress, respectively, are shown as a function of external pressure in Figures 6 and 7.

### B. Displacement of the diaphragm under packaging stress

Figure 7 displays the maximum displacement as a function of package stress relative to pressure change. As shown in the figure, the plots for maximum displacement and maximum displacement with package stress coincide with each other. This means the mechanical forces that are exerted on the sensor due to packaging materials are negligible.

| Pressure(Pa) | Disp with stress($\mu m$) | Avg Disp($\mu m$) |
|---|---|---|
| 0 | -0.14353 | -0.14352 |
| 2000 | -0.78369 | -0.35837 |
| 4000 | -1.4208 | -0.35837 |
| 6000 | -2.0519 | -0.78468 |
| 8000 | -2.6727 | -0.99406 |
| 9000 | -2.9803 | -1.098 |

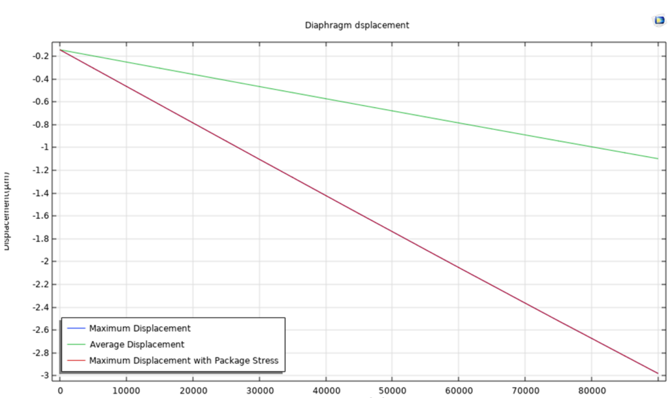


Fig. 7. Displacement vs. Pressure with packaging stress

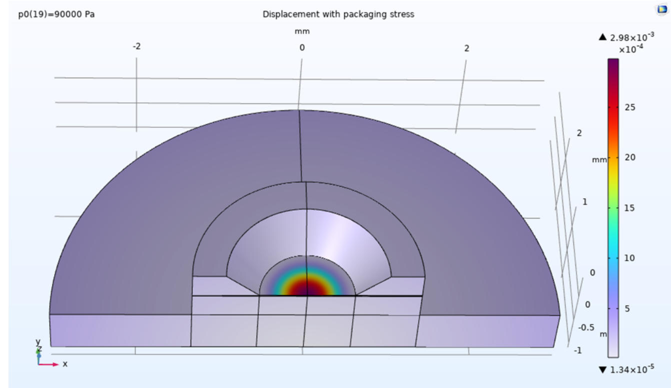


Fig. 8. Movement under the stress of packaging

### C. Pressure vs. Capacitance

The raise in capacitance is the outcome of pressure being exerted causing the diaphragm to bend. It is because the decrease in the distance between the die's bottom portion and diaphragm, will lead to an increase in capacitance, as capacitance is inversely proportional to the distance between plates. The capacitance of the sensor will increase linearly in relation to the pressure that is being supplied, as shown in Figure 8.

| Pressure(KPa) | Capacitance(pF) | Linear capacitance(pF) |
|---|---|---|
| 1.5575 | 1.5575 | 0.738 |
| 1.6074 | 1.6074 | 0.86892 |
| 1.6634 | 1.6634 | 0.99984 |
| 1.7268 | 1.7268 | 1.1308 |
| 1.799 | 1.799 | 1.2617 |
| 1.8391 | 1,8391 | 1.3271 |

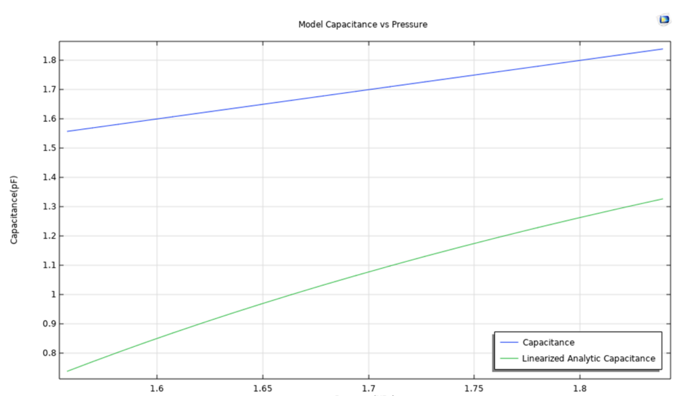


Fig. 9. capacitance vs. pressure for circular diaphragm

### D. Capacitance vs. operating temperature

This result demonstrates how the sensor reacts when packaging stress is present. The device operates within the scope of -73°C to -30°C, while the bonding temperature is 20°C. The mismatch in the thermal coefficients of expansion of silicon and steel base, two distinct materials, results in the introduction of thermal strains. Because thermal stress depends on temperature, its output is temperature-dependent. Figure 9 illustrates how displacement is increasingly pressure-dependent owing to thermal stresses. Figure 10 depicts the capacitance vs. operational temperature relationship and shows that the capacitance value decreases at a uniformly applied external pressure as the temperature increases. Sensor responsiveness is dependent on temperature because of thermal stress, which is the cause of the dependency.

| capacitance (pF) | Operating Temperature (K) |
|---|---|
| 1.8394 | 200 |
| 1.8387 | 220 |
| 1.8388 | 240 |
| 1.8389 | 260 |
| 1.839 | 280 |
| 1.8391 | 300 |

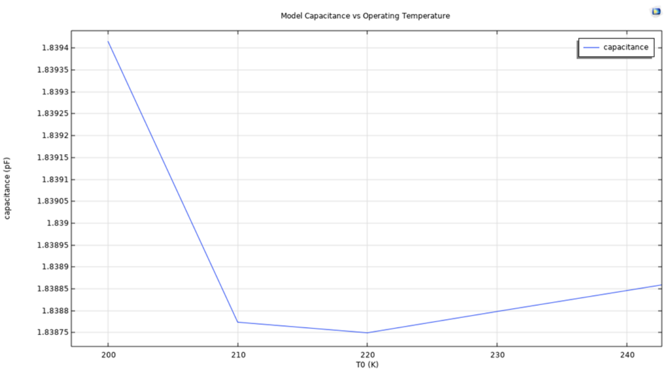


Fig. 10. Capacitance vs. operating temperature

### E. Analysis of Sensor Sensitivity

The outcomes of the simulation demonstrate that the model's sensitivity is at zero applied pressure when $S_P$ is 2.7444×$10^{-6}pF/Pa$ (one-fourth of sensor) . The pressure sensitivity at 90KPa is approximately 4.08×$10^{-6}pF/Pa$. For the purpose of determining the overall sensitivity of the sensor, multiply the sensitivity of one quadrant by four using the formula,

$S_w = S_P$ × number of quadrants. The pressure sensitivity of whole sensor is 16.32×$10^{-6}pF/Pa$

## V. Conclusion

This paper analyses the working principle, design, and simulation specifics of a MEMS-based capacitive pressure sensor. It also shows modelling includes the circular capacitive pressure sensor's diaphragm relocation, measurement of capacitance, and measurement of sensitivity with and without package stress. Due to the diaphragm circular geometry there happens to be the greatest deflection at the middle of the diaphragm. This paper also includes the effect of package stress on capacitance. As the maximum displacement and maximum displacement with package stress are the same.

The sensitivity value remains unchanged regardless of package stress. However, thermal stress makes the device dependent on operating temperature and changes in temperature. The capacitive pressure sensor finds its use in space applications, submarines, weather balloons, aircraft, and for use in construction because of its inexpensiveness, low temperature coefficient, and minimal energy use.


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