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Simulation based Analysis of Capacitive Pressure Sensor with COMSOL Multiphysics

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***Abstract*— Sensors are omnipresent, being embedded in our bodies, aircrafts, cellular telephones, automobiles, radios, bridges and other innumerable applications such as safety related areas, public and health security systems, smart systems, monitoring applications, biomedical systems, submarines, for underground oil exploration, etc. This paper describes performance analysis of a capacitive pressure sensor working on electro-mechanics interface. Capacitive pressure sensors are advantageous over their counterpart piezoresistive sensors as they consume less power, low sensitivity to temperature, high overpressure capability and high resistance to pressure shocks, improved long term stability, high operating temperature and ease of packaging. In this paper, simulation and performance evaluation of electrical and mechanical effects of MEMS based capacitive pressure sensor with square diaphragm using COMSOL Multiphysics is described. This includes diaphragm deflection, sensitivity and linearity analysis, capacitance vs. pressure analysis and thermal considerations. The values of diaphragm displacement and capacitance are plotted under uniform external pressure 25kPa. The simulation results compare the capacitance values with linearized analytical capacitance under same external pressure. The effect of packaging stress on MEMS design process is also emphasized in the paper. It also describes comparison of sensitivity of capacitive pressure sensor with and without packaging stress.**

Keywords*— *Capacitive pressure sensor, COMSOL Multiphysics, Diaphragm displacement, Packaging stress, Sensitivity

I. INTRODUCTION

Continuous monitoring of modern devices are critically needed using MEMS (Micro-Electro Mechanical Systems) based pressure sensors for numerous applications such as automobile industries, airplanes, submarines, biomedical devices, radios, civil applications, public and health security systems, smart systems, cellular telephones, underground oil exploration, etc [10]. The three different types of pressure sensors are piezoresistive, piezoelectric and capacitive pressure sensors used extensively for automation. Capacitance pressure sensors have gained attention and importance over other is due to their high pressure sensitivity, less temperature sensitivity, less consumption of power and have low fundamental noise floor. In addition to these, it has features like thin membrane, small volume, can measure static and dynamic changes, continual resolution, low costs, simple manufacturing and high frequency permeability [3].

Capacitors are basic building blocks of electronic world. Capacitors are generally composed of two conducting parallel plates separated by a non-conducting substance called dielectric which can be air, ceramic or any other suitable insulating material.

In general, MEMS capacitive pressure sensor is made up of two parallel plates which act as an electrode separated by an insulating material. It consists of upper plate, which is thin flexible conductive membrane called diaphragm as one of the electrodes and the lower plate is fixed. These electrodes are separated by dielectric substance called vacuum. This uses electromechanics interface i.e. when the diaphragm is exposed to an external uniform pressure, it deflects causing decrease in gap between two electrodes resulting in an increase in capacitance. As a result, capacitance change due to deformation of membrane is used for pressure sensing, higher the capacitance change, higher the sensitivity. Hence, deflection of diaphragm due to external pressure is sensed and translated to electrical capacitance change based on electromechanics principle.

This paper describes simulation results and performance analysis of MEMS based capacitive pressure sensor with square diaphragm using COMSOL Multiphysics. Capacitive sensors use MEMS technology due to benefits of small size, low cost and high performance. MEMS technology also allows an implantable sensor integrated with structures for continuous monitoring of devices in various applications.

This paper models diaphragm displacement, capacitance, sensitivity [9], linearity at different applied pressure of MEMS capacitive pressure sensor with square diaphragm using COMSOL Multiphysics [4, 9, 13]. This paper also emphasized results of thermal considerations on capacitance due to packaging stress. Thus understanding of tolerable packaging stress is required before fabrication of devices.

II. CAPACITIVE PRESSURE SENSOR STRUCTURE

Capacitive pressure sensor is made up of two parallel plates acting as electrodes of capacitors and separated by air gap. Various parameters like type of material, size, shape and structure play an important role in order to obtain optimized device with desired specification. The model geometry used as a capacitive pressure sensor is shown in Figure 1. Here single crystal silicon having Young's Modulus (E) of 170 GPa, Poisson's ratio (μ) of 0.06, density (ρ) of 2330 kg/m^3 has been used. The dimension of square diaphragm is 500 μm x 500 μm. Silicon is best suited due to its high melting point, less mechanical hysteresis and low thermal coefficient of expansion (2.6 ppm/°C). These properties led to the square diaphragm due to anisotropic etching of silicon in bulk.

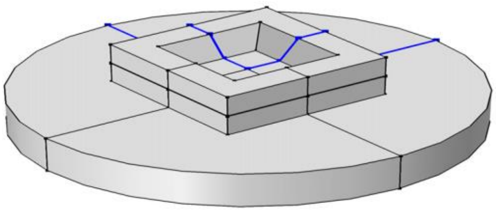

Figure1. The model geometry of capacitive pressure sensor

The silicon die has been bonded to steel metal plate at 70°C. Due to symmetric nature of geometry, only a single quadrant of geometry is modeled with symmetry boundary condition in COMSOL Multiphysics as shown in Figure 2.

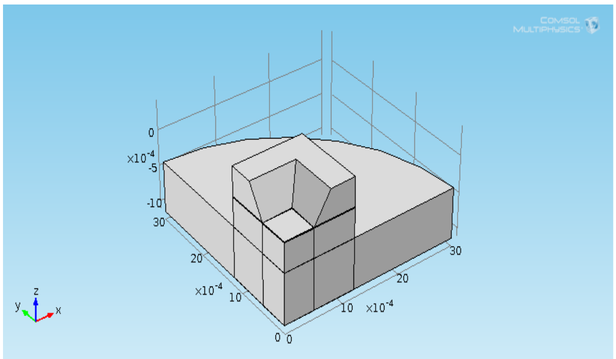

Figure2. The device geometry with one quadrant due to symmetry

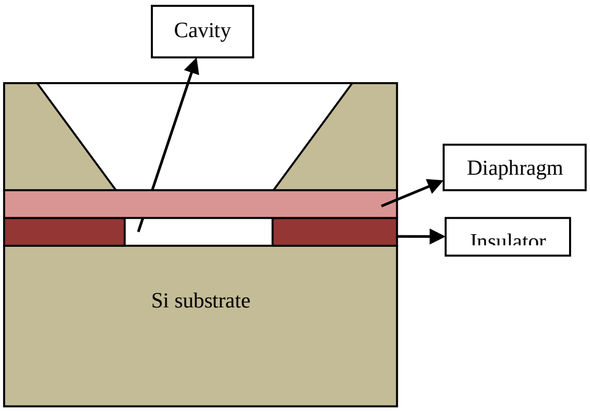

Figure3. A 2D cross-section of capacitive pressure sensor

A 2D cross-section of capacitive pressure sensor is shown in Figure 3. Fixed potential of 1V is applied to thin membrane separated from a ground plane with sealed chamber by high vacuum. The structure shows silicon substrate, a cavity and a thin membrane acting as a diaphragm. Insulation is provided at sides of chamber to prevent connection between membrane and ground plane. Steel AISI 4340 alloy which is heat treatable and low alloy steel containing chromium, nickel and molybdenum is used as a base of sensor. It has high toughness and strength in heat treated condition. It has density of 7850 kg/m^3, high melting point (1427°C), Poisson's ratio in range of 0.27-0.30 and thermal coefficient of expansion is 12.3 ppm/°C.

III. METHODOLOGY

This section describes the working principle of MEMS capacitive pressure sensor design, its mathematical background and modeling in COMSOL Multiphysics. COMSOL Multiphysics is a powerful interactive tool for modeling and solving all kinds of engineering problems and it does not require a deep knowledge of mathematics or numerical analysis but the models are built on the basis of adequate physical characteristic equations.

A. Working Principle of MEMS Capacitive Pressure Sensor

MEMS capacitive pressure sensor works on electromechanics principle. When an external pressure is applied on thin membrane, the pressure difference cavity and external applied pressure causes deformation of thin diaphragm. The thickness of air gap is not uniform but now varies across the membrane and this deflection is translated into electrical change in capacitance to ground.

B. Mathematics in Capacitive Pressure Sensor

To study the effects of diaphragm deflection for single crystal silicon, capacitance vs. pressure analysis, sensitivity and linearity analysis and thermal considerations, simulation is performed using COMSOL Multiphysics for MEMS capacitive pressure sensor with and without packaging stress for square shaped diaphragm.

The capacitance between two parallel plates without external pressure is expressed as,

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad (1)$$

where ε_0 is permittivity of free space, ε_r is relative dielectric constant of material between plates, A is effective electrode area and d is separation between plates.

Equation (1) is not sufficient when an external pressure is applied to calculate the capacitance value. For square shaped diaphragm of MEMS capacitive pressure sensor, central deflection of diaphragm is given by [4],

$$w_{max} = 0.01512\ (1 - \mu^2)\ \frac{PL^4}{Eh^3} \qquad (2)$$

where L is length of diaphragm, h is thickness of diaphragm, E is Young's Modulus (GPa), μ is Poisson's ratio, P is applied external pressure and w_{max} is maximum diaphragm deflection.

Due to external pressure on diaphragm, change in spacing between electrodes occurs resulting in change in capacitance. This change in capacitance due to deflection is given by [4],

$$C = \iint \frac{\varepsilon_0}{d - w(x,y)}\, dxdy \qquad (3)$$

where d is spacing between electrodes and w(x, y) is deflection of diaphragm.

The sensitivity is defined as ratio of output signal and measured property. A sensor's sensitivity indicates how much the sensor's output changes when the input quantity being measures changes. The pressure sensitivity is thus given by,

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

where ∂C is change in capacitance and P is external applied pressure.

The mechanical sensitivity is obtained by ratio of change in diaphragm deflection at an applied pressure and is given by,

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

where ∂w is displacement and P is external applied pressure.

The sensor is bonded together in a vacuum and at high temperature while manufacturing process and then cooled down. At this time there is no external force on boundaries but internal stress appear as two different materials have different coefficient of thermal expansion. When external pressure is applied on outer boundaries, it causes change in temperature which produces extra stresses due to thermal expansion.

The stress-strain relationship for linear elastic material with initial stress (σ_0), initial strain (ε_0) and thermal effects (ε_{th}) if given by [3],

$$\sigma = D\varepsilon_{el} = D(\varepsilon - \varepsilon_{th} - \varepsilon_0) + \sigma_0 \tag{6}$$

where D is elasticity matrix.

The thermal expansion is given by following relation [3],

$$\varepsilon_{th} = \alpha_{vec}(T_0 - T_{ref}) \tag{7}$$

Where α_{vec} are coefficients of thermal expansion, T_0 is operating temperature and T_{ref} is die bonding temperature.

C. Modeling in COMSOL Multiphysics

The COMSOL Multiphysics provides a powerful integrated desktop environment with a Model Builder that gives full overview of model and access to all functionality. Here built-in physics Structural Mechanics with Electromechanics interface is selected which performs stationary study analysis.

The sensor is exposed with uniform external pressure of 25kPa with operating temperature of 20 ℃ and die bonding temperature of 70 ℃. The symmetric boundary conditions are applied to the device due to symmetry in geometry discussed above. The boundary load is applied to represent the pressure acting on surface of diaphragm. The membrane is allowed to move only in z-direction to get the correct values of capacitance change. A thin membrane is held at fixed potential of 1V with respect to ground. The material properties are defined for silicon, cavity which is air and for steel base as described in capacitive pressure sensor structure. An applied pressure causes deformation of diaphragm due to which potential is not uniformly distributed in plane. Thus plot for deformation of diaphragm as a function of pressure across it and plot of capacitance as a function of pressure are obtained. This computed capacitance is then compared with linearized analytic capacitance derived in [5].

In next study, thermal expansion is added to the model to see the effects of packaging stress on performance of device. The thermal coefficient of expansion for silicon is 2.6 ppm/℃. The effect of thermal expansion is observed on entire structure.

IV. RESULTS AND DISCUSSION

This section shows the simulation results for diaphragm displacement, linearized analytical capacitance, capacitance change, pressure sensitivity and temperature sensitivity as a function of pressure for square shaped diaphragm.

A. Diaphragm displacement vs. pressure

The results shown here are both with and without packaging stress. The deformation of silicon membrane due to external pressure of 25kPa is shown in Figure 4. This shows that maximum displacement occurs at the centre of diaphragm. This results in non-uniform potential between plates of capacitor as shown in Figure 5. Figure 6 and 7 shows maximum and average displacements of membrane as a function of external pressure on square diaphragm without packaging stress and with packaging stress respectively.

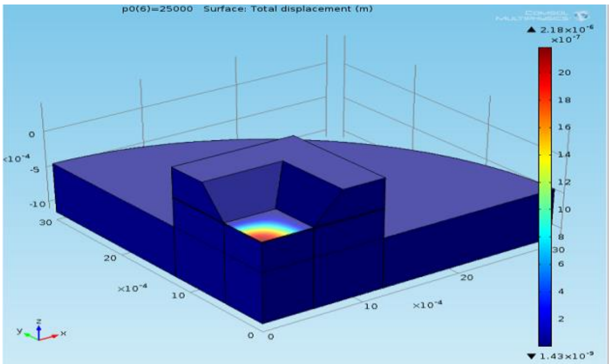

Figure4. Diaphragm displacement at 25kPa external pressure

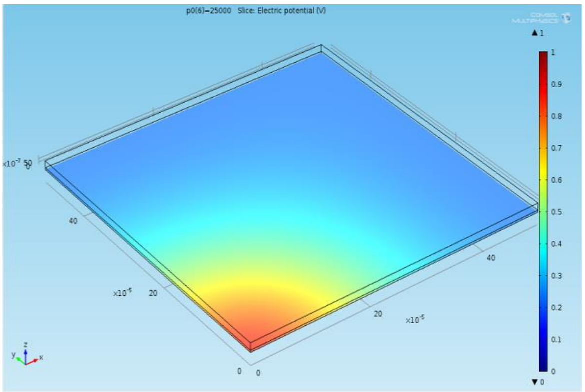

Figure5. Electric potential between plates of capacitor

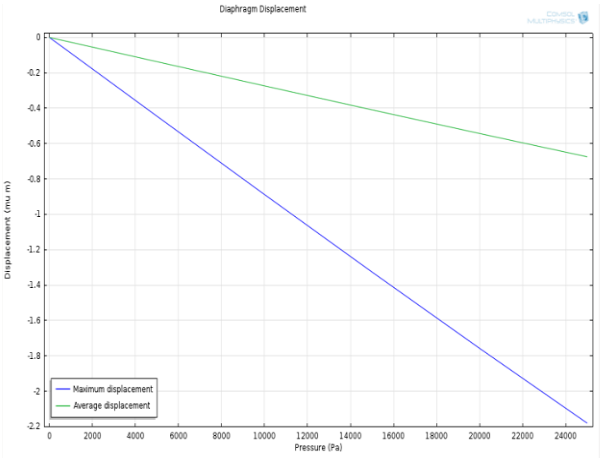

Figure6. Displacement vs. Pressure for square diaphragm

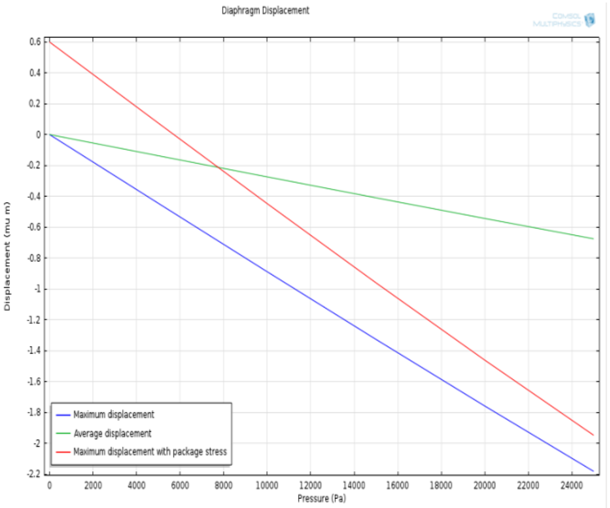

Figure7. Displacement vs. Pressure with packaging stress

B. *Capacitance vs. pressure*

The deformation of membrane due to applied pressure causes change in capacitance. The capacitance of device increases non-linearly with applied pressure as shown in Figure 8. It also compares plot of linearized analytic capacitance [Ref1]. It is clearly observed that change in capacitance increases more when packaging stress are taken into consideration as shown in Figure 9.

C. *Capacitance vs. operating temperature*

This result shows the response of device in presence of packaging stress. The operating temperature of device is 20℃ and bonding temperature is 70℃. Thermal stresses are introduced due to miss-match in thermal coefficient of expansion of two different materials, silicon and steel base. Thermal stress makes device output temperature dependent due to its dependence on temperature. Figure 10 shows that due to thermal stresses, displacement is more dependent on pressure. Figure 11 shows the capacitance vs. operating temperature analysis which shows that as temperature increases, capacitance value decreases at uniform external applied pressure. Due to thermal stress, the sensor response has become temperature dependent.

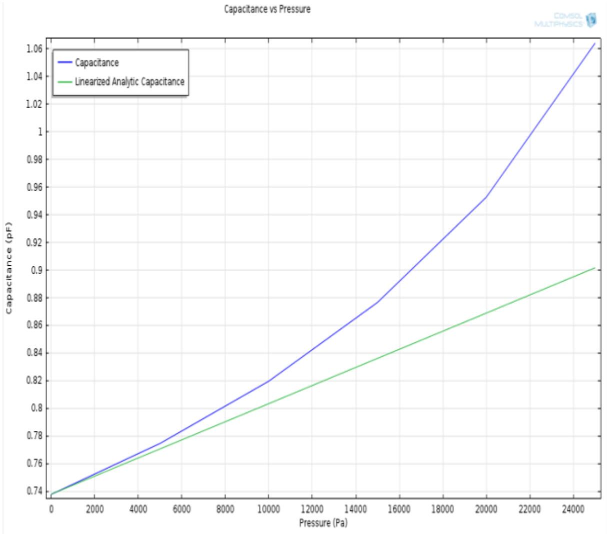

Figure8. Capacitance vs. Pressure for square diaphragm

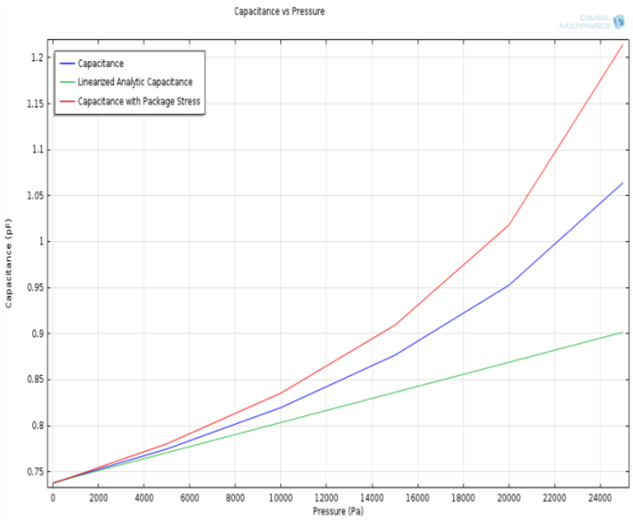

Figure9. Capacitance vs. Pressure for square diaphragm with packaging stress

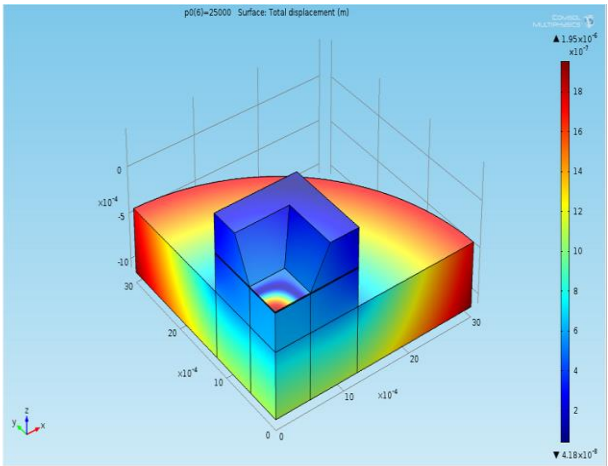

Figure10. Displacement of structure with packaging stress

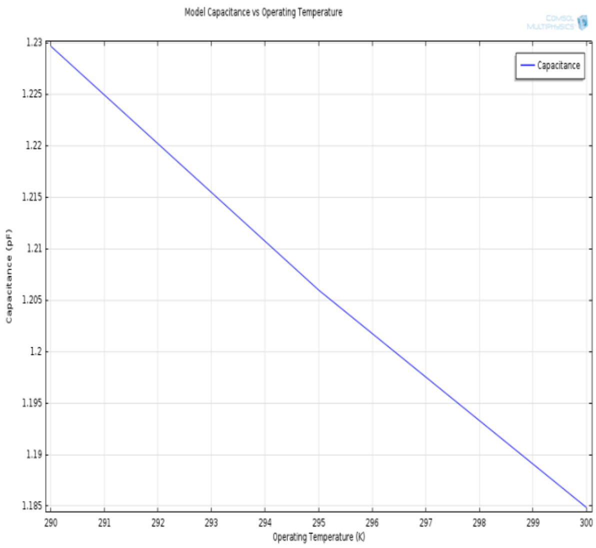

Figure11. Capacitance vs. Operating temperature

D. Sensitivity analysis

The simulation results show that at zero applied pressure, the sensitivity of model is 7.3 x 10^{-6} pF/Pa (one quadrant of sensor). The sensitivity of whole sensor is therefore 29 x 10^{-6} pF/Pa. The pressure sensitivity at 25kPa is 13.2 x 10^{-6} pF/Pa (one quadrant of sensor). The sensitivity of whole sensor is 52.8 x 10^{-6} pF/Pa.

The sensitivity response of sensor is altered due to thermal stress considerations. At zero applied pressure, the sensitivity has increased. At 25kPa applied pressure, the measured sensitivity is 19.6 x 10^{-6} pF/Pa (one quadrant of sensor). The sensitivity of whole sensor thus becomes 78.4 x 10^{-6} pF/Pa.

This shows that sensitivity increases nearly 1.5 times due to packaging stress but it also introduces temperature dependence on device. Figure 10 shows the change in capacitance at 25kPa applied pressure as a function of temperature. The temperature sensitivity obtained is nearly 3.3 x 10^{-3} pF/K (one quadrant of sensor). The temperature sensitivity of whole sensor is 13.2 x 10^{-4} pF/K.

V. CONCLUSION

In this paper, working principle of MEMS capacitive pressure sensor is analyzed. This paper shows modeling of diaphragm displacement, capacitive analysis and sensitivity analysis for square shaped diaphragm with and without packaging stress. It is observed that maximum deflection occurs at centre of diaphragm. The sensitivity depends on change in capacitance, higher the change in capacitance, higher is the sensitivity of device. This paper also included the effects of packaging stress due to thermal considerations. The sensitivity of device increased 1.5 times compared to device sensitivity without stress. However, thermal stress makes the device temperature dependent which has to be noted. This shows the importance of packaging in MEMS design process. This capacitive pressure sensor finds its use in health monitoring of airplanes, submarines and civil applications due to benefits of low power consumption, high over pressure capability, low temperature coefficient, ease of packaging, improved long term stability and low cost.

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