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Design, Simulation and Analysis of MEMS Parallel Plate Capacitors for Pressure Measurement

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Abstract:- In this paper, an analytical and simulation solution for Micro-electromechanical systems (MEMS) capacitive pressure sensor operating in harsh environment is proposed, The principle of the paper is to design, obtain analytical solution and compare the results with the simulation using MEMS SOLVER software for a circular diaphragm deflection. The material is considered to be used for harsh environment is SiC (Silicon Carbide), Because of SiC owing excellent electrical stability, mechanical robustness, and chemical inertness properties and the application of pressure sensors in harsh environments are, such as automotive industries, aerospace, oil/logging equipments, nuclear station, and power station. We are using MEMS SOLVER software for modeling and simulating of MEMS capacitive pressure sensor to optimize the design where a properly doped poly silicon diaphragm as a moving plate and one electrode fixed to the substrate as a fixed plate. The device achieved a linear characteristic response and consists of a circular clamped-edges poly-SiC diaphragm suspended over sealed cavity on a poly-Sic substrate. The proposed Parallel Plate MEMS capacitive pressure sensor demonstrated with diaphragm of 300 μm in diameter, with the gap depth of 10μm.
With the above design parameters the sensor exhibits a linear response with pressure from 0 Mpa to 1 Mpa. With a maximum deflection of 0.226 μm at the radially centre of the diaphragm. However, the nonlinearity due to gap variation is about 9.46%. This Can Be minimized by adopting several techniques discussed in this paper.

Keywords:- MEMS, Parallel plate capacitor, Sensors, Pressure and MEMSolver 3.0

I. INTRODUCTION

The Application of MEMS to the measurement of pressure is a mature application of micro machined silicon mechanical sensors, and devices have been around for more than 3 decades. It is without doubt one of the most successful application areas, accounting for a large portion of MEMS market. Pressure sensors have been developed that use a wide range of sensing techniques, from the most common piezo resistive type to high performance resonant pressure sensors.

The suitability of MEMS to mass-produced miniature high-performance sensors at low cost has opened up a wide range of applications. Examples include automotive manifold air and tire pressure, industrial process control, hydraulic systems, microphones, robotic applications, and intravenous blood pressure measurement. Normally the pressurized medium is a fluid, and pressure can also be used to indirectly determine a range of other measurands such as flow in a pipe, Volume of liquid inside a tank, altitude and air speed (Weather monitoring station).

II. BACKGROUND

Pressure measurement is a most important parameter in most of the processes. This paper will first introduce the basic physics of pressure sensing and discuss the influence of factors such as static and dynamic effects as well as media compressibility. Following that is a section on the specifications of pressure sensors, which serves to introduce the terms used and the characteristics desired in a pressure sensor. Before describing the many MEMS developments that have occurred in the field of pressure sensing, there is brief discussion on traditional pressure sensors and diaphragm design. The MEMS technology pressure sensor in section 3 then looks at silicon diaphragm fabrication and characterization, applied sensing technologies, and example applications [2].

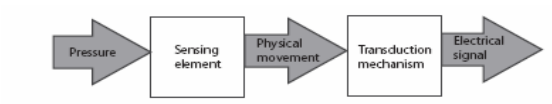

Figure 1 Block Diagram of Pressure sensor

2. a Manometer [2]:

This is a simple yet accurate method for measuring pressure based upon the influence of pressure on the height of a column of liquid. The best-known form is the U-tube manometer is shown in Figure 2. If pressure is exerted to one side of the U-tube as shown, the liquid is displaced, causing the height in one leg to drop and the other to rise. The difference in height h between the fluid-filled legs indicates the pressure.

The measurement is usually taken visually by reading the height from the scale incorporated into the instrument. Resolution can be improved by inclining one leg, allowing more precise reading of the scale. Often a liquid reservoir is incorporated onto one side, making the drop in fluid height on that leg negligible. The unit of pressure will depend upon the liquid (e.g., inch of water, inch of mercury). Manometers can be used both as a gauge sensor with one side vented to atmosphere and as differential sensors with pressure applied to both legs. The disadvantages associated with manometers include their slow response (they are not suitable for dynamic applications) and the limited range of pressures for which they are suitable. The pressure is measured in manometer using

$$p = h\rho g$$

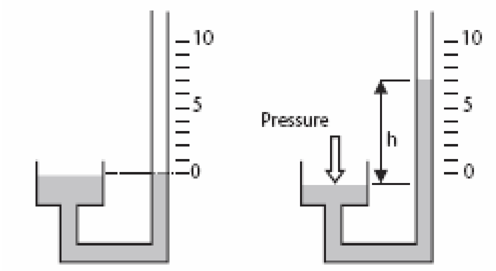

Figure 2: U-tube Manometer

2.b Bourdon Tube[2]:

Bourdon tubes operate on the same principle as the aneroid barometer, but instead of an evacuated capsule or bellows arrangement, a C-shaped or helical tube is used (see Figure 3). The tubes are closed at one end and connected to the pressure at the other end, which is fixed in position. The tube has an elliptical cross-section, and when pressure is applied, its cross-section becomes more circular, which causes the tube to straighten out until the force of the fluid pressure is balanced by the elastic resistance of the tube material. Different pressure ranges are therefore accommodated by using different materials such as phosphor bronze or stainless steel. Changes in pressure move the closed end of the tube to which a linkage arm and a gear and pinion assembly are attached. These rotate a pointer around a graduated scale, providing visual reading of the pressure.

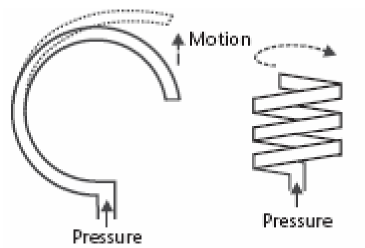

Figure 3 Bourdon Tube

Bourdon tubes are usually used by gauge pressure sensing applications, but differential sensing is possible by connecting two tubes to one pointer. By correctly arranging the linkages, the pointer can be made to measure the pressure difference between the tubes. Helical tubes are more compact, reliable, and offer performance advantages over the more traditional C-shaped devices. Bourdon tubes are used throughout the industry and are available in a wide range of pressure specifications. Various pressure measurements sensors are developed by exploiting the electrical, mechanical and thermal properties of various materials. Capacitance type gauges, piezo resistive and piezo electric properties of certain ceramics and crystals are examples for electrical properties based pressure sensors while bellows, diaphragms are examples for exploiting the mechanical (elastic) properties of the materials for pressure measurement.

Application point, ambience and environmental conditions, range, measurement characteristics, size of sensor and excitation required are the parameters mostly considered for the selection of suitable pressure sensors. For measurement requirements like wide pressure range, small size sensors, and low power consumption and for a measurement profile is required rather than a point measurement and yet at a low cost MEMS based pressure measuring sensors are ideally preferred. These type of pressure sensors are widely used in robotic arm and hand pressure control and measurement, atmospheric pressure measurement at high altitudes, automotive applications (safety & security features like proper door closure, seat belt fastening etc), patient health monitoring systems, and bio-medical applications.

MEMS based pressure sensors are gaining preference in the measurement world as they are useful in any environment, tiny in size (low space occupying), and low cost due to bulk production. Most of bulk devices like differential pressure transmitters and pressure switches are getting replaced by the MEMS based pressure measuring devices.

III. MATHEMATICAL MODELING OF SMALL DEFLECTION DIAPHRAGM

Capacitive pressure sensors have been designed for variety range of applications in measuring both absolute and differential pressures because of their high pressure sensitivity, low temperature drift, and good DC response and low power consumption [1]. Typically a capacitive pressure sensor contains three modules. One is polysillicon circular diaphragm which acts as a pressure sensing element and the range of the sensor is the design key for selecting the material for the diaphragm (Range of the sensor must be with the elastic limits of the diaphragm) and the second module is a variable plate capacitor element whose capacitance will change inversely and linearly with the distance between the plates. ($\Delta C=\in 0 \in r*A/g$). The third module is the electronic section which will give the electrical output (Voltage/current) proportional to the pressure signal input.

Metal diaphragms are typically circular and may incorporate corrugations to modify diaphragm characteristics. However, For MEMS based pressure measurement applications we can also use silicon based material as silicon compounds found to have equal or superior mechanical and thermal properties of metals like aluminum and Stainless steel.(Refer Table.1). The behavior of a diaphragm will depend upon many factors, such as the edge conditions and the deflection range compared to diaphragm thickness. The Cross sectional view of Capacitive Pressure sensor is shown in Fig. 3(a).

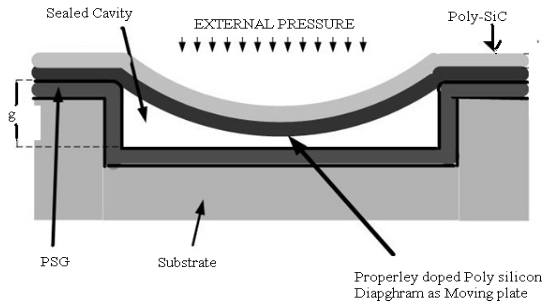

Fig. 3(a) Cross section View of Capacitive Pressure Sensor

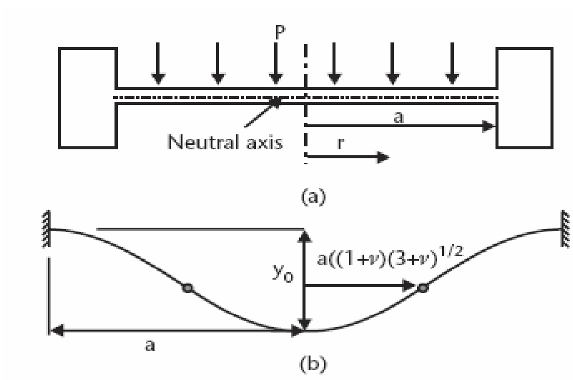

Figure 4 (a) Rigidly clamped diaphragm and (b) its associated displacement under uniform

The edge conditions of a diaphragm will depend upon the method of manufacture and the geometry of the surrounding structure. It will vary between a simply supported or rigidly clamped structure, as shown in Figures 4(a) and 5(a). Simply supported diaphragms will not occur in practice, but the analytical results for such a structure may more accurately reflect the behavior of a poorly clamped diaphragm than the rigidly clamped analysis. At small deflections (<~10% diaphragm thickness) the pressure-deflection relationship will be linear [3, 6].

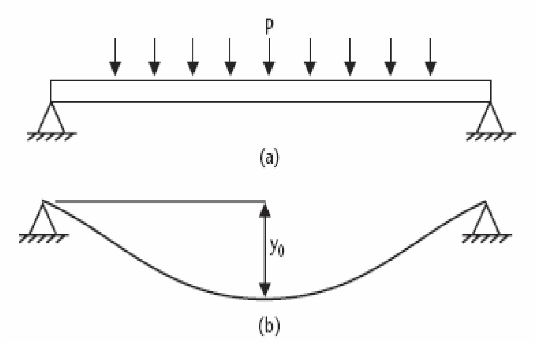

Figure 5 (a) Simply supported diaphragm and (b) its associated displacement under uniform

As the pressure increases, the rate of deflection decreases and the pressure-deflection relationship will become nonlinear. As a rule of thumb, a deflection of 12% of diaphragm thickness will produce a terminal nonlinearity of 0.2%; a deflection of 30% produces a nonlinearity of 2%. The suitability of the deflection range will depend upon the desired specification of the sensor and the acceptable degree of compensation [2]. For small deflection diaphragms the maximum deflection is 30% of diaphragm thickness. The deflection y at radial distance r of a round diaphragm under a uniform pressure P, rigidly clamped as shown in Figure 4(a), is given by [2]

$$y = \frac{3(1-v^2)P}{16Et^3}(a^2 - r^2)^2 \quad \rightarrow (1)$$

Where t is the diaphragm thickness, E and ν are the Young’s modulus and Poisson’s ratio of the diaphragm material, respectively, and a is the radius of the diaphragm. The maximum deflection y0 will occur at the diaphragm center where r = 0.

Considering a common value for poly Silicon of υ = 0.22 and Young’s modulus 170 Gpa, the maximum deflection is given by [2]

$$y_0 = \frac{0.1784*P}{Et^3}a^4 \quad \rightarrow (2)$$

The deflection of a rigidly clamped diaphragm is shown in Figure 4(b). As mentioned previously, the measurement of the deflection associated with diaphragm pressure sensors typically requires the use of electromechanical transducers rather than mechanical linkages. Electromechanical effects can be used to measure displacement directly or to measure the stress/strain induced in the diaphragm material. Therefore, it is also useful to provide an analysis of the stress distribution across a pressurized diaphragm. For a circular shaped pressure sensor, the change in capacitance due to deflection is given by [3]:

$$\Delta C = 3(1 - v^2)R^4 * \frac{\epsilon_0 \, \epsilon_r A_{sense}}{16ET^3 \, g^2} * P \rightarrow (3)$$

Where ΔC is the change in capacitance, P is the pressure difference across the diaphragm, R and T are the radius and thickness of the diaphragm, E and μ are Young’s modulus and Poisson’s ratio of the diaphragm material, A_{sense} is the area of the moving plate, and g is the sensing gap between the moving plate and the fixed plate [3].

IV. SENSOR MEASUREMENT RESULTS

For the considerations taken in this work, we have come across many observations. We have considered a round diaphragm which is fixed along the circumference and the Pressure being applied at the center. This Pressure sensor is simulated for its deflection and by applying 1Kg (0.9806mpa) Pressure at the center of the diaphragm (See fig. 10).

It is observed after the calculation that the deflection of the free end of the diaphragm is almost linear to the pressure applied at the center (refer Eq.2). It is shown in Fig 6. The applied pressure causes stress on the material (radial and tangential). We have considered the radial stress and the Maximum radial stress at the center of the diaphragm is given by

$$\sigma_r = \mp\frac{3}{8} * Pa^2 \left\lfloor (3 + v)\left(1 - \frac{r^2}{a^2}\right) \right\rfloor \rightarrow (4)$$

From the above equation the radial stress is linear to the applied pressure if all the other parameters are kept constant. It is observed that the radial stress on the diaphragm is also linear to the applied pressure (see fig.7).

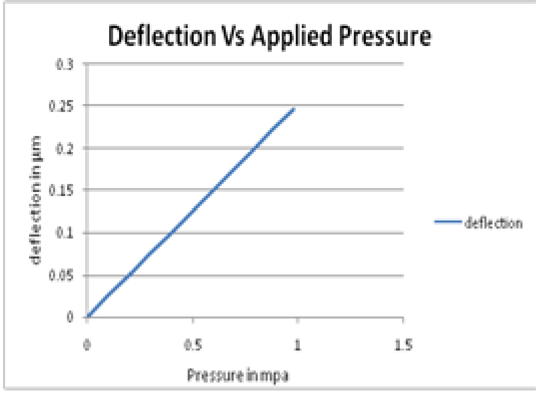

Figure 6 Deflection Vs Pressure

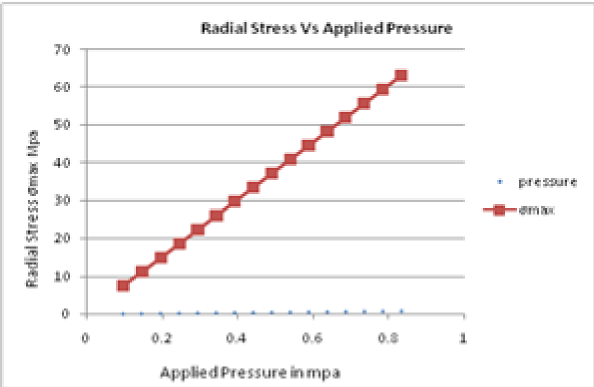

Figure 7 Radial Stress Vs Pressure

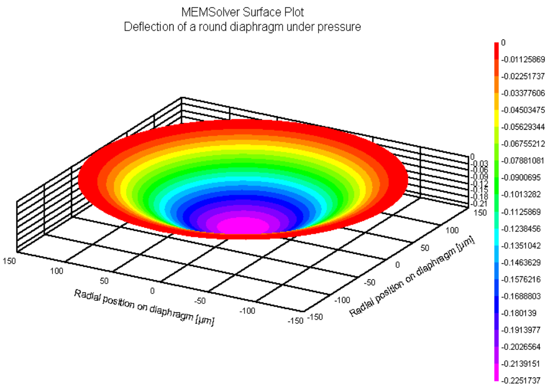

Figure 6 a. Deflection Vs Pressure

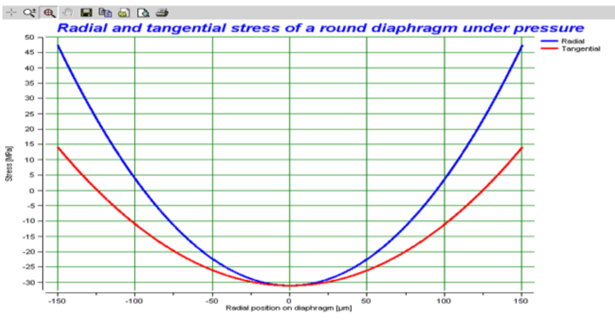

Figure 8.b Stress Vs Pressure

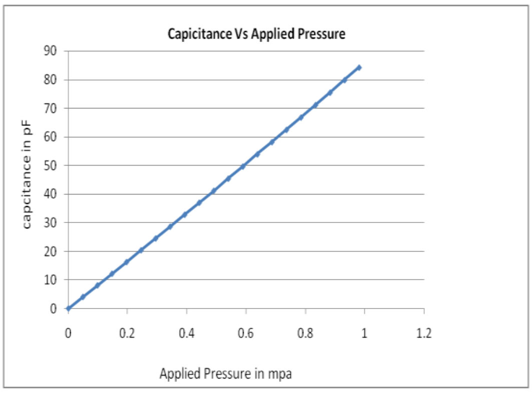

Figure 7 Capacitance VS Applied pressure

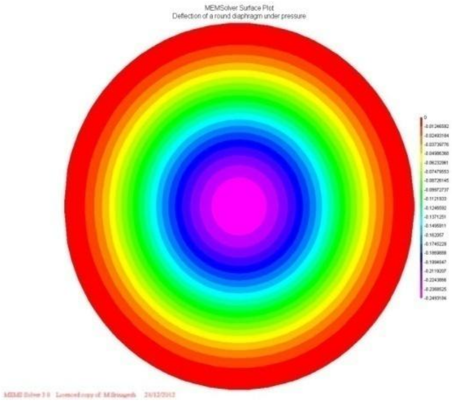

Figure 8 Deflection of the diaphragm

Property	Si {111}	Stainless Steel	Al	Al2o3 (96%)	sio2	Quartz
Youngs modulus	190	200	70	303	73	107
Poisson's Ratio	22	0.3	0.33	0.21	0.17	0.16
Density(g/cm^3)	2.3	8	2.7	3.8	2.3	2.6
Yeild strength(Gpa)	7	3	0.17	9	8.4	9
Thermal Cofficeint of Expansion(10/K)	2.3	16	24	6	0.55	0.55
Thermal Conductivity at 300K(W/cm.K)	1.48	0.2	2.37	0.25	0.014	0.015
Melting Tempararture	1414	1500	600	2000	1700	1600

Table 1 Mechanical & Thermal Properties of Silicon

The same study is taken out using MEMS Solver 3.0. And the Results for the Assumed round diaphragm of small deflection with radius of 150µm are stated below. They are shown in fig 8.a and 8.b.
Due to the Change in the gap between the plates, due to deflection of the diaphragm, of the capacitive pressure sensor there is a change in the capacitance as described in Eq. 3 So we have observed that as the Pressure applied has increased the capacitance of the sensor. It is shown in fig. 9.

V. CONCLUSION

We have designed, simulated and analyzed the capacitive pressure sensor with small deflection diaphragm. The reason for taking small deflection diaphragm is to minimize the non linearity in the gap between the plates and to have better sensitivity and linearity of the sensor. The range of the sensor is limited to 1kg (far below the elastic limits).

Due these two considerations it is observed that, the capacitance is linearly increasing with the pressure applied at the center of the diaphragm. And hence, these pressure sensors show reliable pressure readings.
The linearity of the sensor can be increased by:

- Keeping a flat plate electrode as a moving plate to which this diaphragm is attached at the center which is mechanically coupled and electrically isolated (Hermitically sealed).
- Using a microcontroller based switching capacitor module in the measuring electronics where we can develop a look up table to remove the non linearity.

This study gave a hope for developing capacitive pressure measuring devices using MEMS, which could be used for automobile industry, for measuring the pressure of the lubricating oil in the engines etc. We have considered a properly doped poly-silicon diaphragm as a moving plate whose mechanical properties are well comparable to the aluminum and aluminum based alloys which are used in automobile engines. As the parameters involved in the sensitivity are independent of temperature variations these pressure sensors have a wide scope of adoptability for automobile engine oil (Hot fluid) pressure sensing throughout the temperature range of the engine.

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REFERENCES

[1]. Y. Zhang, R. Howver, B. Gogoi* and N. Yazdi Evigia Systems, Inc., Ann Arbor, Michigan, USA "A High-Sensitive Ultra-Thin MEMS Capacitive Pressure Sensor"

[2]. Stephen Beeby and et.al. "MEMS Mechanical Sensors" pp 113-145.

[3]. Oosterbroek, R. E., et al., "Designing, Realization and Characterization of a Novel Capacitive Pressure/Flow Sensor," Proc. Transducers, Chicago, IL, 1997, pp. 151–154

[4]. Berberig, O., et al., "The Prantl Micro Flow Sensor (PMFS): A Novel Silicon Diaphragm Capacitive Sensor for Flow-Velocity Measurement," Sensors and Actuators, Vol. 66, 1998, pp. 93–98.

[5]. Prasad N Acharya Sujata Naduvinamani , "Design and Simulation of MEMS based Micro Pressure Sensor"

[6]. Y. Hezarjaribi, M.N. Hamidon and et.al "Analytical and Simulation Evaluation for Diaphragm's Deflection and its Applications to Touch Mode MEMS Capacitive Pressure Sensors"

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