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A Critical Review of MEMS Capacitive Pressure Sensors

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Abstract: This paper provides an overview including developments, challenges with respect to design, modelling, simulation and analysis of MEMS pressure sensors. Recently MEMS capacitive pressure sensors have gained advantages over piezoresistive pressure sensor due to high sensitivity, low power consumption, invariance of temperature effects. As theses sensors application range is increasing, it is essential to review the technological developments and future scope of MEMS capacitive pressure sensor. This paper focuses on the review of various types of capacitive pressure sensor principles, design, modelling, parameters to consider, materials that can be used in fabrication. Few models of capacitive pressure sensors have been simulated and the results are presented. Simulation results show how the capacitance varies with increase pressure (harsh environment). The design, modelling and simulation of pressure sensors have been done using Comsol/Multphysics. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: MEMS, Pressure Sensors, Capacitive Pressure Sensors, COMSOL Multiphysics.

1. Introduction

MEMS technology combines silicon based microelectronics and micromachining technology. MEMS pressure sensors are almost covering major part of the sensor market in recent years and are fast developing with brand new capabilities. Pressure sensors are required in many applications like defence, biomedical, automobile and many more civilian & domestic applications. Primitive pressure sensors were developed using strain gauge mechanism but now there has been a rapid development both in fabrication capabilities and packaging. MEMS pressure sensors design and miniaturization changed after finding the piezoresistivity in silicon and germanium [1-2]. The combination of micromaching techniques of silicon and the advent of high expertise in silicon integrated circuits have paved way for MEMS and Microsystems concept. Several MEMS devices have been manufactured and commercialized in the recent past and have reached consumers. Amongst these, pressure sensors have gained lot of interest as they have a wide horizon of applications including automobiles, industries, defence and domestic. Automotive sector remains the biggest area for MEMS pressure sensors claiming 72 % share in revenue, medical electronics at 12 %, industry segments at 10 % and rest 6 % is split between consumer electronics and military/aerospace applications [3-4]. The current pressure sensors face challenges of to be used in applications involving high pressure ranging from few Pascal (Pa) (biomedical applications) to several Mega Pascal (MPa) (Industries, automotive). Temperature also has its part to play in the performance of MEMS pressure sensors, were these have to be used in the temperature ranges between –25 ^{0}C to 150 ^{0}C (aerospace application) and there is still growing demand for operating pressure sensors at more than 600^{0}C (harsh environments). Hence, these harsh environments require special sensing devices to adapt for the high pressure and high temperature environments.

Recently MEMS-based technologies involving silicon (Si), silicon on insulator (SOI), silicon on sapphire (SOS), silicon carbide (SiC), carbon nanotubes (CNT) and polymers have been found to be able to provide the necessary ruggedness to be able to adapt and provide better performance in harsh environments. Amongst various transduction principles of MEMS pressure sensors, piezoresistive and capacitive transduction mechanism have been used widely [4-5]. Piezoresistive pressure sensors provide high sensitivity enabling linear operation over wide range of pressure [5]. Capacitive pressure sensors are preferred as they provide high sensitivity to pressure and their performance for most part remains invariant of temperature, this makes it suitable to be used for high pressure and temperature applications [4, 6]. MEMS pressure sensors typically use a flexible diaphragm that deforms in the presence of a pressure difference and this deformation is converted to an electrical signal. In its most simple form, a MEMS pressure sensor is created by bulk micromachining to create the silicon membrane. Piezoresistors are patterned across the diaphragm. The sensor is packaged in such a way that the topside of the diaphragm is exposed to the environment (based on application). The change in pressure forces a deformation of the diaphragm, resulting in a change of resistance of the piezoresistors and in turn to voltage by on-chip electronics (Wheatstone bridge). Piezoresistive pressure sensor technology is slightly complex, including ion implantation for improved control of the piezoresistors, etch stops for better control of the diaphragm thickness [7-8]. Capacitive sensors comprises of a fixed electrode and a movable electrode (parallel plate concept), which displeases due to applied pressure and results in change in capacitance. Change in capacitance is evidence of applied pressure. Capacitive pressure sensors are less sensitive to temperature variations but have lower output signals, requiring amplifying electronics [5].

This paper aims to cover the basic design, modelling technologies of MEMS pressure sensors, following the basic classification. The paper emphasises on capacitive MEMS pressure sensors, presenting basic design and analysis for high pressure and high temperature applications. Several simulation results have been provided based on the capacitive transduction mechanism of these sensors. The design, simulation and analysis have been carried out using COMSOL.

2. Evolution and Classification of MEMS Pressure Sensors

Boron doped silicon piezoresistors have replaced the metal strain gauges and have proved to be highly sensitive. Piezoresistivity is the change of resistance of a material when it is submitted to stress [7]. The piezoresistors are diffused directly on the silicon diaphragm by implanting or diffusing boron on the selected regions of maximum stress. Then these resistors are connected in the form of Wheatstone's bridge [8-9]. Piezoresistive pressure sensors have captured major market of pressure sensors covering automobile, defense, space and biomedical applications. Fig. 1 shows model and displacement of piezoresistive pressure sensor with respect to applied pressure. Fig. 2 is a voltage distribution for applied pressure. Piezoresistive pressure sensors have been the success story because of the reason that they enable linear operation over a wide range of pressure.

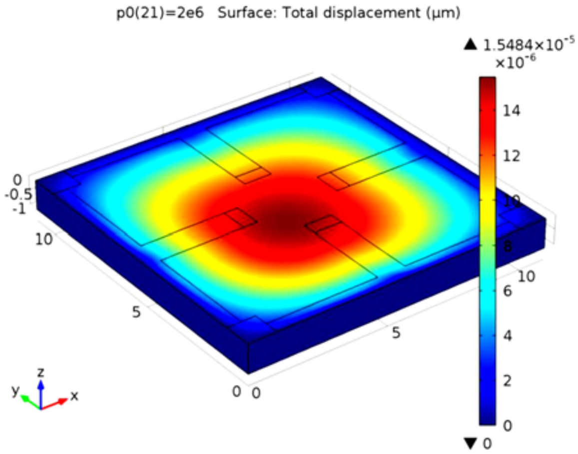

Fig. 1. Model of Piezoresistive pressure sensor showing deformation.

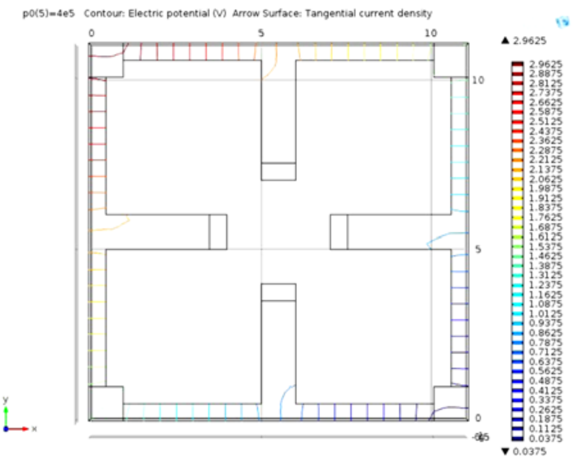

Fig. 2. The distribution of voltage for applied pressure.

2.1. Capacitive Pressure Sensors

This class of pressure sensor makes use of parallel plate capacitive transduction principle, were applied pressure creates change in the capacitance between two plates. It uses diaphragm as one electrode which is movable, with respect to the fixed electrode. The charge generates a potential difference which may be maintained using an external voltage. A capacitive pressure sensor measures a pressure by detecting an electrostatic capacitance change. The deflection of the diaphragm causes the change in capacitance, which can be readout as electrical signal using suitable mechanisms like capacitance bridge [10-12]. Capacitive sensors have the advantage over the piezoresistive type, that they consume less power, invariant of temperature but have a nonlinear output signal [13].

Capacitive sensors are compatible with most mechanical structures, and they have high sensitivity and low temperature drift. Fig. 3 shows capacitive pressure sensors model with the total displacement of the top electrode as the pressure is applied. Fig. 4 show the plot of capacitance in pF v/s applied pressure in Pa. The plot shows a liner capacitance change as a function of applied pressure.

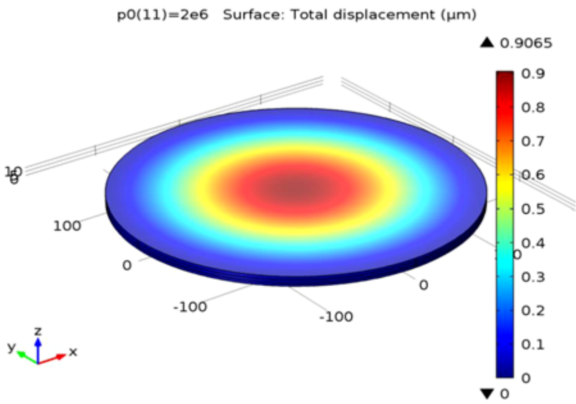

Fig. 3. Model and displacement plot of capacitive pressure sensor.

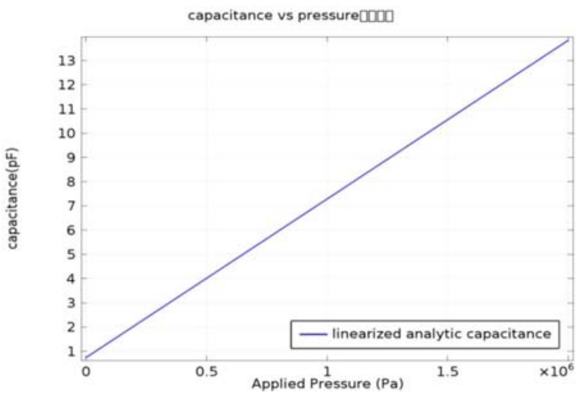

Fig. 4. Plot of capacitance variation as function of applied voltage.

2.2. Piezoelectric Pressure Sensors

Barium titanate, single-crystal quartz, leads Zirconate-Titanate (PZT) etc., can generate an electrical signal and a potential difference when they are subjected to mechanical stress or strain [14]. When pressure is applied to a material it creates a strain or deformation in the material [15]. In a piezoelectric material strain creates an electrical potential difference or voltage. Fig. 5 shows the circular diaphragm model and displacement of the piezoelectric sensor for applied pressure. Fig. 6 shows the output electrical potential in volts versus the applied pressure in Pascals.

2.3. Resonant Pressure Sensors

The pressure measurement here is based on the resonant frequency of the structures. Actually the external pressure applied will change the resonant frequency of the structure and that change is an evidence of the pressure [5, 16]. Resonant pressure sensors are widely used nowadays because of the fact that measurement of frequency is one of the robust and high precision methods available, and the resonant frequency is generally not a function of the imperfections of electronics.

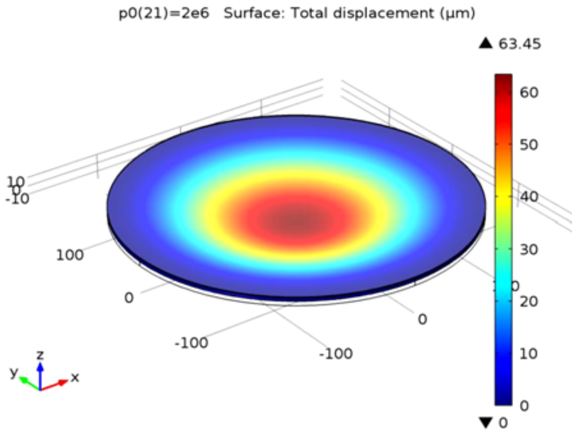

Fig. 5. Model and displacement plot of piezoelectric pressure sensor

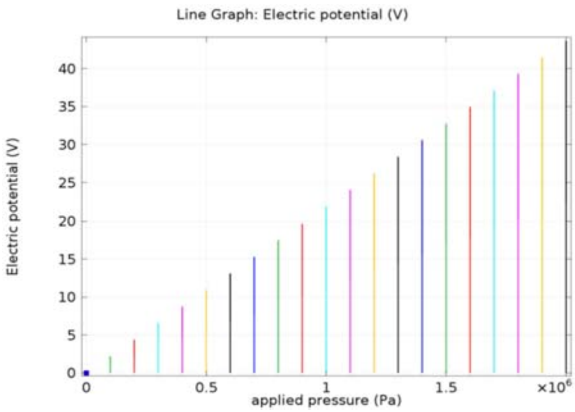

Fig. 6. Graph of Applied pressure (Pa) Vs Electric potential (V).

3. Application Requirements and Market Prospective

3.1. Application Requirements

In the Table 1, various applications and their required pressure ranges have been mentioned. The table shows the type of capacitive pressure sensors useful for measuring different parameters mentioned in the table.

Table 1. Pressure measurement applications and ranges.

No.	Measurement	Type of sensor	Value
1	Atmospheric pressure	Absolute	101.3 kPa
2	Manifold pressure in vehicles	Absolute	100 a
3	In vivo blood pressure	Absolute	80/120-mm (300 mmHg max)
4	Ex vivo blood pressure	Absolute	80/120-mm (300 mmHg max)
5	Intraocular pressure	Gauge	15 mmHg
6	Tire Pressure	Gauge	30 psi
7	Vacuum Cleaner	Gauge	100 Pa to 3 kPa
8	Ventilators	Differential	25 cm H_2O

3.2. Market Perspective

Fig. 7 show the market perspective of the pressure sensors over a period 2012 to 2018 for applications like, automotive, industrial, consumer electronics, medical etc. From the figure it can be clearly observed that pressure sensors are expected to use widely in automotive applications in coming years.

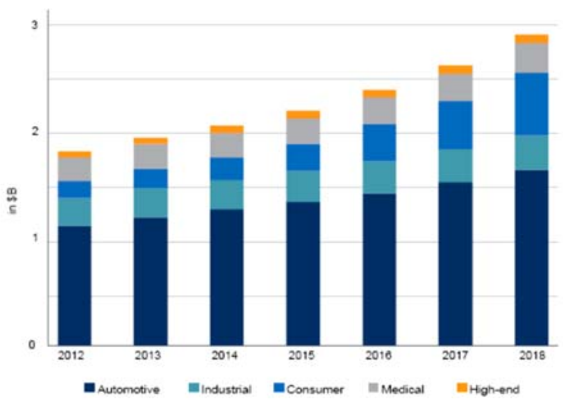

Fig. 7. MEMS Pressure Sensor market forecast by applications 2012-2018. (Reproduced from Yole MEMS pressure sensors market forecast).

The MEMS Pressure sensor technologies are quite mature and the market is big and expected to grow from $ 1.9B in 2012 to $ 3B in 2018. Due to lot of opportunities and technological advances Yole thinks that there is a huge market for MEMS pressure sensors and the market for it can hit around $ 3B in 2018 [17].

4. Simulation and Analysis of MEMS Capacitive Pressure Sensor

4.1. Materials for the Design of Pressure Sensors

Various materials are used for design of the diaphragms to achieve better sensitivity few of those are, stainless steel 17-4PH, stainless steel 316, hastelloy, monel, inconel, titanium, nispan c, quartz, silicon and sapphire. Typically 'thin plates' and 'Small deflection' concept is used for the design consideration of the capacitive diaphragms [18-19]. Thin plates refers to the condition $h \cong \frac{a}{10}$ (a-side of a diaphragm) were as small deflections refers to $W_{\max} \cong \frac{h}{4}$ and also it's a maximum central deflection [20-21]. The suitable structure for a sensor would be a case of linearity in the relation between max deflection and applied pressure for $W_{\max} \cong \frac{h}{4}$ [22].

4.2. Mathematical Equations to Measure Diaphragm Deflection

Typically the geometries used for the diaphragm design are square, rectangular and circular configurations. In all cases maximum deflection is observed at the centre of the plate/diaphragm. According to the theory of Plates [18, 23-25] by Krigger the equations governing the deflection of plates with pressure acting normal to the plate/diaphragm surface is given by (1).

$$\frac{\partial^4 w}{\partial x^4} + 2\alpha \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = P/D \tag{1}$$

For maximum deflection at the centre of a square plate is given by Equation (2) & (3).

$$W_{\max} = 0.00674 \frac{Pa^3}{D} \tag{2}$$

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \tag{3}$$

For circular diaphragm, (4)

$$W(r) = \frac{Pa^4}{64D}\left[1-(\frac{r}{a})^2\right] \qquad (4)$$

For rectangular plate, (5)
In general,

$$W_{\max} = \alpha\frac{Pa^3}{D} \text{ for a < b,} \qquad (5)$$

$$W_{\max} = \alpha\frac{Pa^3}{D} \text{ for a > b,} \qquad (6)$$

where

$$\alpha = 1.26\times10^{-3}\times12(1-\upsilon^2)\,, \qquad (7)$$

where
1) For Square/rectangular diaphragm: W - is deflection at (x, y) coordinates, P – is differential pressure, D - is flexural rigidity, a - is the length of diaphragm, E - is young modulus, V – is Poisson's ratio and h - is the thickness of the diaphragm.
2) For circular diaphragm: W(r) is deflection at radial distance r from the centre of diaphragm, a - is radius of the diaphragm, r - radial distance.
3) For Rectangular diaphragm: a - Length of plate, b – width of the plate, α – numerical factor depending on the ratio b/a or a/b.

4.3. Performance Parameters

1. Burst Pressure: This is the maximum pressure that may be applied to the sensor without causing the sensor catastrophic failure [5].
2. Temperature Compensation: The temperature range across which the specification values of the pressure sensors are guaranteed, i.e., the measurement error of the pressure sensor will be within a certain bond.
3. Supply Voltage/ Supply Current: The constant supply voltage or constant supply current required to drive pressure sensors.
4. Zero Offset: Zero Offset is the output of a pressure sensor when no pressure is applied. Zero offset is either expanded as percentages of full-scale o/p. Zero offset can be easily eliminated during calibration step.
5. Linearity: The maximum deviation of measured output. The non-linearity is addressed by using the best-fit straight line (BFSL) method.
6. Sensitivity: Sensitivity of a capacitive pressure sensor can be defined as Electrical and mechanical sensitivity. Electrical Sensitivity is defined as the ratio of change in the capacitance to change in the pressure $Sc = \frac{\Delta C}{\Delta P}$. In terms of voltage it will be the ration of change in voltage to change in pressure $Sc = \frac{\Delta V}{\Delta P}$ [26]. Mechanical sensitivity is defined as the ratio of change in displacement to change in pressure applied

$$Sm = \frac{\Delta w}{\Delta P}\,.$$

4.4. MEMS Capacitive Pressure Sensor Design for High Pressure Applications

A capacitor is formed by two plates which can store an electric charge. The charge generates a potential difference which may be maintained using an external voltage. A capacitive pressure sensor measures a pressure by detecting an electrostatic capacitance change. At least one electrode of the capacitor is on a moving structure. Capacitive sensors have the advantage over the piezoresistive type as they consume less power. But have a nonlinear output signal and are more sensitive to electromagnetic interference.

Capacitive sensors are compatible with most mechanical structures, and they have high sensitivity and low temperature drift. Capacitive pressure sensors have the problem that, they exhibit non-linear relationship between capacitance and displacement. Hence linearization is an issue in such kind of sensors. This section provides a simulated model and results of conventional, touch mode and slotted capacitive pressures [27-29]. All three design of capacitive pressure sensor includes three layers diaphragm, middle layer (Dielectric medium) and substrate with Poly-silicon, SiO_2 and Steel AISI 4340 respectively [30]. The material properties are listed in Table 2.

Table 2. Material properties for the design of Capacitive Pressure Sensors.

Name	Poly-silicon	SiO_2	Steel AISI 4340
Density (kg/m³)	2320	2200	7850
Young's modulus (GPa)	169	70	205
Poisson's Ratio	0.22	0.17	0.28
Relative permittivity	4.5	4.2	1

4.4.1. Conventional Capacitive Pressure Sensor

In conventional mode operation, the diaphragm is kept at a distance away from bottom electrode (substrate). Here the two ends of top electrode are fixed (sideways). Fig. 8 show the structure of the conventional pressure sensor along with the total displacement of diaphragm of 2 μm, for an applied pressure of 10 MPa as 0.7888 μm. Fig. 9 shows that the total displacement with applied pressure from 0 to 10 MPa. The plot shows that the total displacement achieved for an applied pressure of 10 MPa as 0.788 um. Fig. 10 is a plot of applied pressure versus capacitance. The figure shows that a conventional square diaphragm based capacitive pressure sensor provides a linear increase in the capacitance.

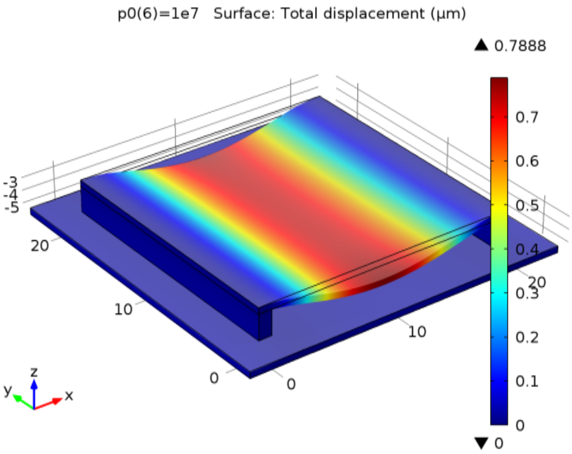

Fig. 8. Model and displacement plot of conventional pressure sensor.

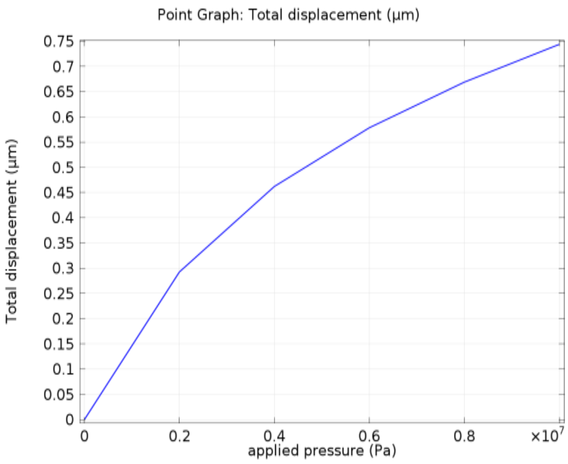

Fig. 9. Graph of Applied pressure v/s Total Displacement for Conventional pressure sensor.

4.4.2. Touch Mode Capacitive Pressure Sensor

In touch mode, when external pressure increases on the diaphragm, the diaphragm starts touching the bottom electrode (substrate) with the insulating layer. The advantage of this mode of operation is near-linear output characteristics and large over-range pressure [25, 31-32]. Fig. 11 show the simulation of touch mode capacitive pressure sensor, here the displacement of diaphragm is achieved for applied pressure ranging from 0 to 50 MPa. The total displacement for 50 MPa applied pressure was onserved as 1.1982 um.

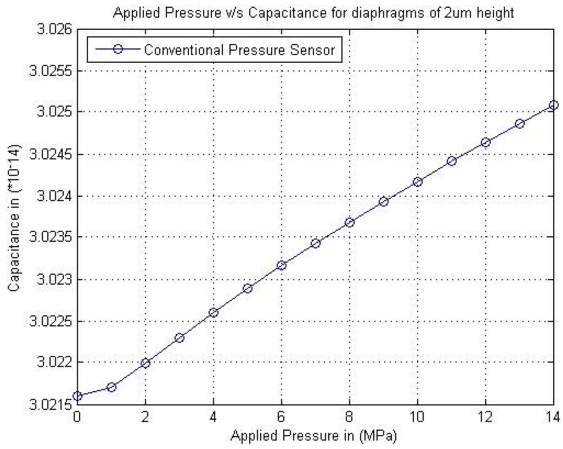

Fig. 10. Graph of applied pressure v/s capacitance for conventional pressure sensor.

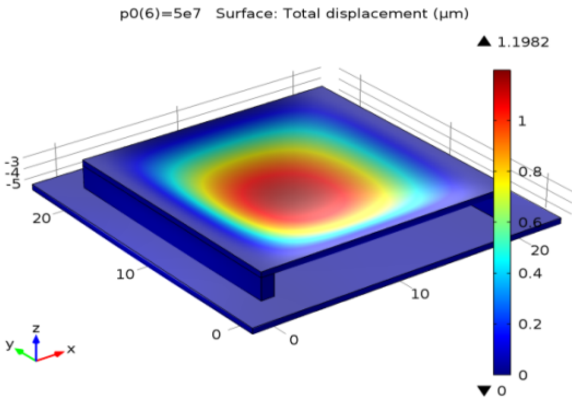

Fig. 11. Model and displacement of touch mode.

Fig. 12 shows that as applied pressure increases from 0 to 50 MPa the displacement is from 0 to 1.2 μm Fig. 13 shows the plot of Capacitance versus applied pressure in the range of 0 to 50 MPa, the plot shows that as applied pressure increases from 0 to 50 MPa the capacitance increases linearly from 30.02 fF to 30.11 fF.

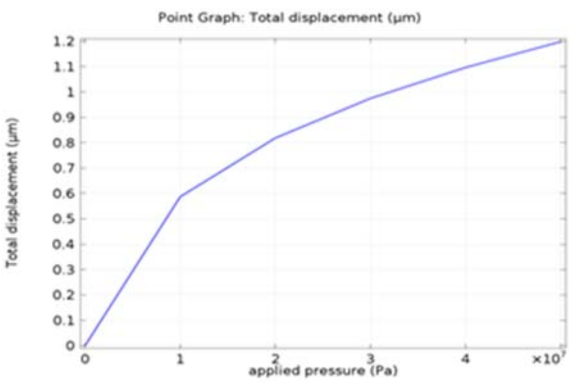

Fig. 12. Graph of Applied pressure v/s Total displacement for Touch mode pressure sensor.

4.4.3. Slotted Capacitive Pressure Sensor

In slotted pressure sensor, when external pressure increases on the diaphragm, the sensitivity of pressure sensor increases. To reduce the effect of residual stress and stiffness of the diaphragm, slots around the diaphragm are added. This will make the sensor more sensitive for measuring intraocular pressure (2 kPa). In the model, two side faces Poly-silicon are fixed. Fig. 14 shows the model and simulation of slotted capacitive pressure sensor. Pressure range applied from 0 to 10 MPa is applied to maintain uniformity with other models discussed in the paper. The above simulation shows the total displacement of 0.9396 um for the total applied pressure of 10 MPa.

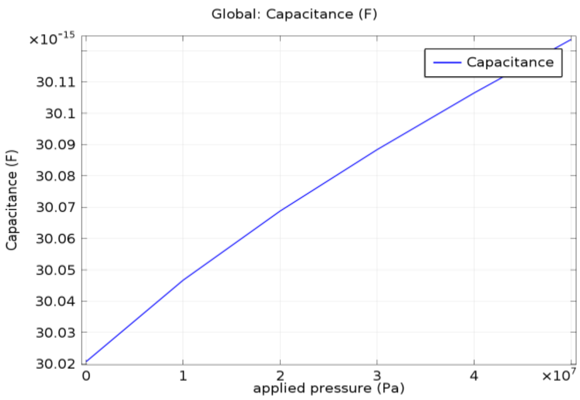

Fig. 13. Graph of Applied pressure v/s Capacitance for Touch mode pressure sensor.

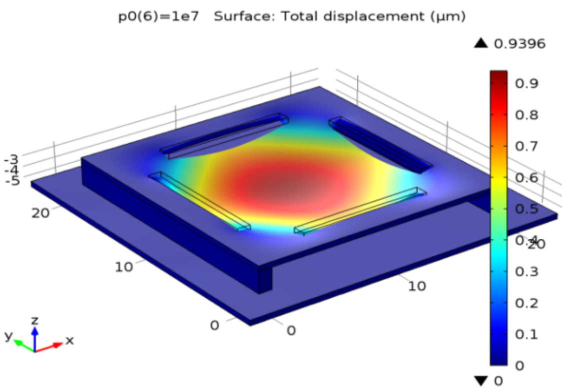

Fig. 14. Model of simulated slotted pressure sensor.

Fig. 15 shows the plot of total displacement versus the applied pressure for a slotted capacitive pressure sensor and the total displcament observed is 0.9 µm (for max applied pressure of 10 MPa). Fig. 16 shows that as the applied pressure increases from 0 to 10 MPa the capacitance increases from 26.834 fF to 26.852 fF. By providing slots around the diaphragm,the effect of residual stress and stiffness of the diaphragm can be reduced. Table 3 shows the results of conventional, touch mode, slotted capacitive pressure sensor for applied pressure from 0 to 50 MPa. The table presents the range of pressure to which the three models can be subjected to.

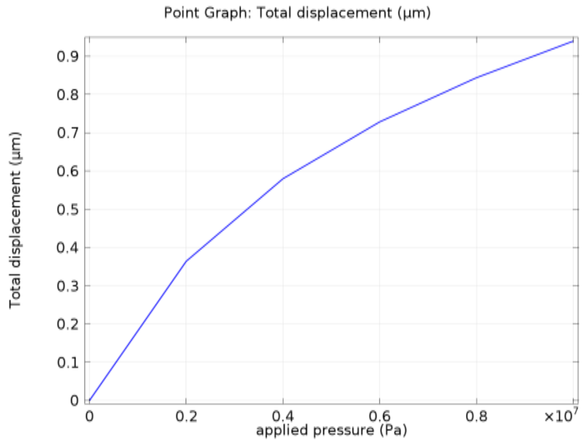

Fig. 15. Graph of Applied pressure vs. Total Displacement for Slotted pressure sensor.

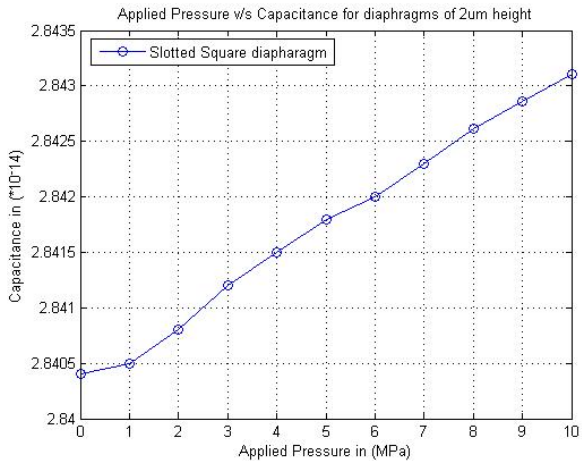

Fig. 16. Graph of Applied pressure vs. Capacitance for Slotted pressure sensor.

Table 3. Results of Conventional, Touch mode, Slotted Capacitive pressure sensor.

Types	Applied Pressure	Displacement	Capacitance
Conventional	10 MPa	0.7888 µm	30.046 fF
Touch mode	50 MPa	1.1982 µm	30.11 fF
Slotted	10 MPa	0.9396 µm	26.852 fF

The above simulation results were shown for conventional, touch mode and slotted capacitive pressure sensor (square diaphragm based). In all three cases the square diaphragm was modelled using the materials mentioned in Table 2. After many iterations of simulation the applied pressure range for conventional and slotted pressure sensor was selected to be between 0 to 10 MPa. For touch mode pressure range of 0 to 50 MPa is selected as the diaphragm should touch the bottom electrode. From the simulation results we can say that the slotted MEMS capacitive pressure sensor achieves good sensitivity where as the touch mode MEMS capacitive pressure sensor achieves good linearity and large operating pressure range. Hence, the slotted pressure sensor can be used for high sensitivity applications. The touch mode capacitive pressure sensor is used in harsh environment (50 MPa).

4.5. MEMS Capacitive Pressure Sensors for High Temperature Application

Temperature has its part to play in the performance of MEMS pressure sensors, were these have to be used in the temperature ranges between -25 ^{0}C to 150 ^{0}C (aerospace application). There is still growing demand for the pressure sensors to be able to operate at more than 600 ^{0}C. The major challenge for designing the capacitive pressure sensors for high temperature applications is on material selection and the diaphragm design. The materials to be selected should withstand high temperature, therefore materials like silicon may not be feasible for the selection. Materials like SiC (silicon carbide) are being now widely for the design of pressure sensors for high temperatures, as it offers good mechanical stability and electrical stability.

5. Conclusions

The paper presented a survey on MEMS pressure sensor types and the existing transduction mechanisms. The paper provides a brief review of typical application requirements with an overview on market perspective. Few performance parameters as per the capacitive pressure sensors are discussed. Finally design and analysis of MEMS capacitive pressure sensors has been given depicting the results of simulation. MEMS pressure sensors based on capacitance transduction mechanism has lot of scope due to its high sensitivity, stability and invariance of temperature etc. However few performance parameters like linearity, sensitivity have to be still addressed.

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