Dynamic Mathematical Modelling of Capacitive Pressure Sensors using Different Materials for Healthcare Applications

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Abstract

This paper discusses the principle, design and theoretical dynamical modelling of MEMS capacitive pressure sensors with different material properties results that have been simulated as well as compared. The properties of the material ensure that sensor performance analysis for operating pressure range 0-25kPa. This work discusses Timoshenkos plate deflection theory and follows the pull-in phenomenon. One important factor that could influence the performance of a MEMS capacitive pressure sensor is the structure of the diaphragm. The active area of this sensor is made up of 0.5 mm0.5 mm and the cavity size are 2m. According to the simulations, the optimized parameters have higher linearity and greater sensitivity than the initial parameters. The comparison of results shows that Aluminium material gives the highest deflection and better capacitance sensitivities which is about 88 pF/pa and is more linear with the applied pressure than other materials. The behaviour of the touch mode capacitive pressure sensor in terms of the temperature dependence of capacitance is analysed and repeatability error has been reduced. This configuration of touch mode pressure sensor is promising for the use in health monitoring devices like patient blood pressure due to small pressure fluctuation.

Keywords— Capacitive pressure sensor, Linearity, Sensitivity, Range of Blood pressure, Deflections

1 Introduction

Nowadays CPS (Capacitive pressure sensor) is one of the popular MEMS pressure sensors due to their fast dynamic range and less sensitivity to temperature in comparison with piezoresistive pressure sensors and is widely applied in high-performance applications [4, 27, 5, 13] . The capacitive pressure sensor comprises the thin elastic diaphragm and a sealed cavity between the elastic diaphragm and substrate. The thin diaphragm is allowed to contact the substrate and a pair of plates behave as parallel plate capacitors.

Micromachined MEMS CPS can be classified in different ranges such as low, medium, ultra-low and high. Different ranging of pressure can work for different applications like gentle touches use low- a pressure range (1kPa- 10kPa) [3, 24] ,medium pressure range (10kPa -100kPa) can be used for some pressure or movement of the object that is operated by hands [21] . Ultra-low pressure ranging ($< 1Pa$) is used in the progress of the microphone, and touch screen and finger-print recognition. Above these sensors, the range is also used in commercial products like wearable touch keyboards [29, 30] and household appliances. High-pressure ranges ($> 100kPa$) are used in special applications such as industrial robots, colonoscopes [26], etc. MEMS capacitive pressure sensor has a fast-developed product range with brand-new features in contemporary years and covers the foremost part of the sensor market. With the increasing requirements of some sensing applications, great efforts are devoted to the exploration in the direction of the application range of pressure sensors. The main motive of this studies is to find out suitable material for better sensitivity and good linearity. Sensitivity is the most important parameter to judge the quality of pressure sensors [34]. To achieve good sensitivity, conductivity, stability, reproducibility and resolutions. the main aim is to enhance these performance parameters of capacitive pressure sensors. Particularly these parameters are dominantly determined by different two critical factors which are 1) the materials used for conductive electrodes [15, 31] and 2) the shape and structure of the dielectric layer [22, 20, 7, 8, 6, 19] . But there have some limitations of micromachined capacitive pressure sensors have non-linear output and low sensitivity in terms of capacitance [28] . To address this problem, one way is increasing the diaphragm thickness and another way is to expand the middle of the diaphragm membrane in such a way that the output will be more linear concerning the input but capacitive sensitivity reduces due to increasing the stiffness [25, 17].

Many materials have been used as active and non-active components in pressure design applications because the properties of materials play a very significant role in the behaviour of capacitive pressure sensors. Still, one of the main concerns is Material selection for the diaphragm, with rapid development in the world of research, it is not impossible to discover a new material that can compete with the existing materials. In this paper, firstly different capacitive pressure sensors using different diaphragm membrane materials with their different application are investigated and simulated in the same model. Detailed mathematical modelling and simulation results on various characteristics are presented.

2 Design of Pressure Sensors

The diaphragm and substrate are used as mechanical components in many sensors and are the most important part of the system. The size of the thin diaphragm, material

S.NO	Types of pressure sensors	Measurement	Range
1	Absolute	Atmospheric pressure	101.3 kPa
2	Absolute	In-vivo Blood Pressure	80/120 mm
3	Gauge	Intraocular Pressure	15mm Hg
4	Gauge	Tire pressure	30 Psi
5	Differential	Ventilators	25cm H_2O

Table 1: Types of Pressure Sensors with Specific Range and their Applications [2]

selection of the diaphragm, and substrate depend upon the required applications. Some types of pressure sensors along with their application and their pressure range are given in table 1. The deflection of the diaphragm and sensitivity of the sensor is depending upon according to properties of the materials and pressure mounted on the thin membrane.

The design of the diaphragm membrane and structure of MEMS pressure sensor by using finite element simulation software (FEA). MEMS pressure sensors are generally used to measure one parameter at a time, but the value of parameters changes when they operate in complex environments which create a major task for designing a MEMS pressure sensor to achieve good sensitivity with operational precision and speed in harsh environments.

3 Principle and Mathematics background Modelling of the Capacitive Pressure Sensor

MEMS capacitive pressure is work on the principle of the electromechanics interface. By changing applying the pressure to the top of the diaphragm, the membrane moves towards the direction of the substrate. Then performance occurs in terms of diaphragm deflection with thermal considerations. Due to the symmetric nature of the geometry, only a single geometry is used for the analysis [18, 10]. this model contains a thin membrane that is held at a fixed potential of 5V.

$$\frac{\partial^4 w(x,y)}{\partial x^4} + 2\alpha \frac{\partial^4 w(x,y)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y)}{\partial y^4} = \frac{p}{Dh^3} \tag{1}$$

To avoid any connection between substrate and diaphragm membrane insulation connection is provided. Basically, for designing diaphragm capacitive pressure sensors uses the theory of thin plate and small deflection, where the condition of theory plates uses a $h \approx \frac{a}{10}$ and deflection is $w_{max} \approx \frac{h}{4}$ [32] but in case of circular diaphragm r is taken as radius and where h is the thickness and the rectangular diaphragm is taken a is length and b is width. The mathematical expression for calculating diaphragm deflection with a clamped edge due to applied pressure P are governing the fourth-order differential equation in x-y planes (1).

Where w (x, y) is deflection of diaphragm supported with boundary edge condition, a is side of diaphragm, h is the thickness. The following mathematical expression can be used to determine the capacitance of this structure [12].

$$c_0 = \frac{\varepsilon k A}{d_0} \tag{2}$$

Where ε is absolute dielectric permittivity of, k is the relative permittivity of the plates, A is the area of the plates on a squared meters and d0 is the separation between the parallel conducting plates. However, the capacitance cannot be calculated using equation (2) above when the diaphragm's pressure has changed. As a result of uniform pressure being applied, the diaphragm deflects. As can be seen, the deflection with a uniformly loaded square shape plate is utmost at the diaphragm's centre.

$$w_{max} = 0.00126 \frac{L^4 P}{D} \tag{3}$$

Where w_{max} is the maximum deflection, α is the length of the diaphragm membrane, P is the differential pressure, D is the flexural rigidity can be computed by the expression [16, 9, 11] .

$$D = \frac{Eh^3}{12(1-v^2)} \tag{4}$$

Where h is thickness of membrane, E is modulus of elasticity, ν is Poissons ratio [23]. When above equation number 3 is insert in equation number 2 then, maximum deflection occurs.

$$w_{max} = 0.01512(1-v^2)\frac{PL^4}{Eh^3} \tag{5}$$

3.1 Measurements of Capacitance

The mentioned relation (6) can use to find out the change in capacitance and sensitivity of the moving diaphragm towards the cavity after changing the load on the top of the diaphragm.

$$c_f = \varepsilon \int\int \frac{dx.dy}{d - w(x,y)}, \tag{6}$$

$$c_f = \frac{\varepsilon}{d} \int\int \frac{dx.dy}{d - w(x,y)}, \tag{7}$$

Taylor series expansion is given in the following equation,

$$\frac{1}{1+x} = 1 + x + x^2 + x^3, for - 1 < x < 1 \tag{8}$$

Since in this case(w/d=1), therefore formula (8) can be written in the equation (9),

$$c_f = \frac{\varepsilon}{d} \int\int_{-a}^{a} (1 + \frac{w(x,y)}{d} + \frac{w^2(x,y)}{d} + ..) \tag{9}$$

As long as the sensor works with less deflection then, the capacitance, neglecting the higher-order factors, can be calculated by,

$$c_f = \frac{\varepsilon}{d} \int\int_{-a}^{a} (1 + \frac{w(x,y)}{d}) dx.dy \tag{10}$$

By using the binomial expression, the change in capacitance of square shape membrane can be written as [1].

$$c = c_0(1 + \frac{12.5Pa^4}{2015dh}) \tag{11}$$

Where c is the final calculating capacitance, c_0 is initial capacitance, P is uniform (constant) pressure applied, d is the spacing between the plates and a is the length (size) of the diaphragm. As the zero-pressure capacitance, is given in equations (12),

$$c_0 = \frac{4\varepsilon a^2}{d} \tag{12}$$

Capacitive pressure sensitivity of the square membrane is given by (9).

$$S_A = \frac{49\varepsilon a^6}{2025 d^2 D} \tag{13}$$

3.2 Measurement of Sensitivity

Therefore, Sensitivity of above diaphragm depend upon thickness of membrane and distance between electrodes, influence by applied load and sensitivity of membrane can be expressed as (15).

$$S_c = \frac{dc}{dp} \tag{14}$$

The mechanical sensitivity of a diaphragm is defined as

$$S_M = \frac{dW}{dp} \tag{15}$$

For small deflection, square diaphragm sensitivity is,

$$S_m = \frac{a^2}{3.14h[\frac{4.2Eh^3}{3.14a^2(1-v^2)}]} \tag{16}$$

Thus, the low capacitance will make the device more sensitive. As a result, high displacement will lead to nonlinearity. The segmented or mesh model was created using the FEM (Finite element method) as depicted in figure 2.

4 Simulation Result and Discussion

In this analysis, Diaphragm deflection, capacitance and mechanical sensitivity vary according to the properties and characteristics of materials explained and simulated results of each material are also presented, as well as the equation used for the modelling of pressure to calculate and verify results. The shape of a diaphragm can be square, elliptical and circular but in this paper, the shape of the diaphragm is taken as square and dimensions are $0.5mm \times 0.5mm \times 10\mu m$ made up of different diaphragm material has been examined under the uniform pressure range is 0 to 15kPa, the dimensions of the cavity is 2 m filled with vacuum, silicon is taken substrate is shown in the figure 1 and FEM is used to create the segmented model is depicted in figure 2 and mesh parameter is shown in table 2 and as seen in the diagram boundary condition for the diaphragm deflection of this structure is limited in the z-direction only.

The result shown here in figure 3 is the simulation profile of deformation of the Aluminium membrane at external pressure 15 kPa. The given results proves that maximum deflection is occur at the centre and displacement reduces as moves away from the centre as shown by the vertical line and in order to sustain the linearity moving diaphragm/ plate should not move more than of the distance between the plates. Figure 4. Shows the simulation profile of applied boundary load at 10kPa. The maximum and mean deformations of the square diaphragm membrane at 10 kPa, 3.21 μm and 1.21 μm respectively.

S.NO	Parameter	Size
1	Maximum element size	0.3
2	Minimum element size	0.054
3	Element Growth rate	1.5
4	Curvature factor	0.6
5	Resolution of the regions	0.5
6	Number of iterations	4

Table 2: Mesh Parameter of the Model

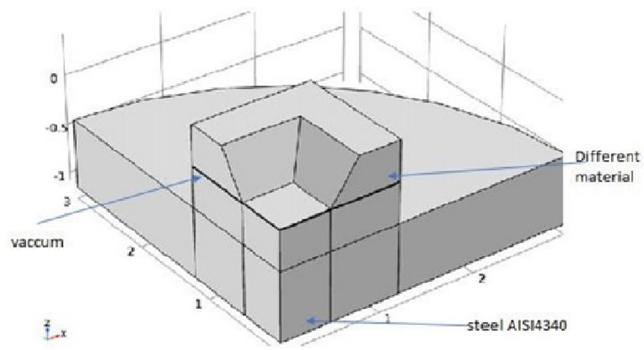

Figure 1: Three -dimensional view of Capacitive Pressure Sensor with different Material

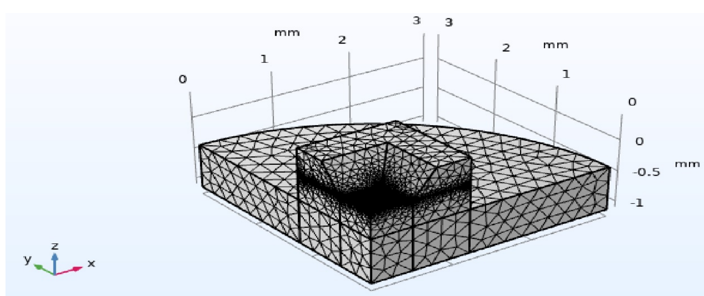

Figure 2: Mesh Model of Capacitive Pressure Sensor

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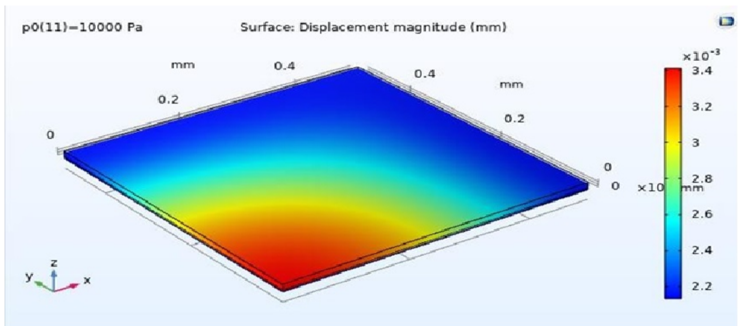

Figure 3: Quadrant Simulation Profile of Deformation of Diaphragm for 0.5mm at 10 kPa pressure

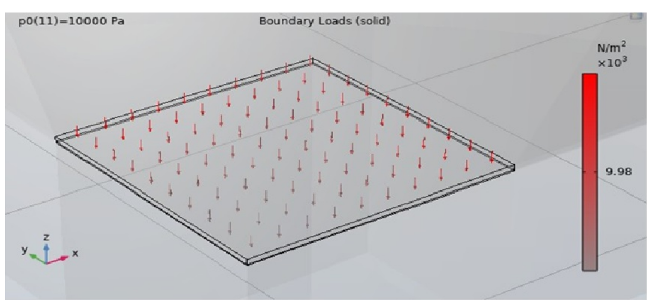

Figure 4: Simulation profile of applied boundary load when applied pressure at 10 kPa

Parameter Name	Value	Units
Youngs modulus	170	GPa
Poissons ratio	0.06	1
Density	2330	Kg/m^3
Relative permittivity	11.7	1
Coefficient of thermal expansion	2.6×10^{-6}	PPM/ $^{\circ}C$

Table 3: Material properties of Si

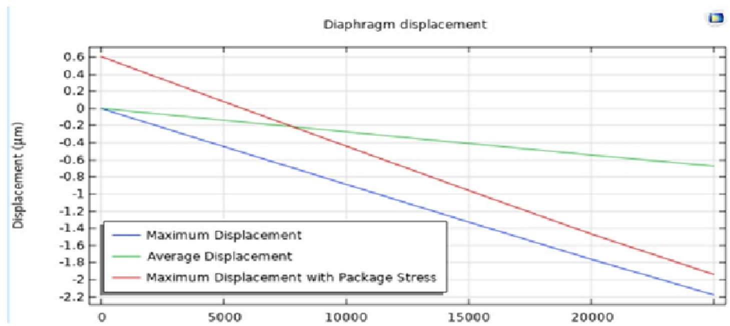

Figure 5: Diaphragm Displacement with Applied Pressure

5 Analysis of Pressure Sensor Performance using Different Materials

Only a few materials are being investigated for capacitive pressure sensors in order to achieve the required application. As three basic requirements of material defined by Mc Donald [33] (a) good electrical and mechanical properties (b) compatible with the fabrication device (c) good intrinsic properties that prevent high stress from developing during processing. Here simulated result of all material is presented.

5.1 Silicon

Silicon material is used as diaphragm material in capacitive pressure sensors due to high melting points and low hysteresis and low thermal expansion. Due to thermal expansion added to the devices, the response of this device is more dependent on the temperature and the capacitive response of the device is nonlinear with gradually increasing the pressure range. the simulated result of capacitance sensitivity is 52.8×10^{-6} pF/Pa and computation time calculated for the whole sensor is 23s. The properties used for the device are shown the table 3 and the graph between diaphragm deflection under applied uniform pressure with and without packaging stress is shown in figure 5.

Parameter Name	Value	Units
Youngs modulus	169	GPa
Poissons ratio	0.22	1
Density	2320	Kg/m^3
Relative permittivity	4.5	1
Coefficient of thermal expansion	2.8×10^{-6}	PPM/$^{\circ}C$

Table 4: Material Properties of Silicon Nanowires

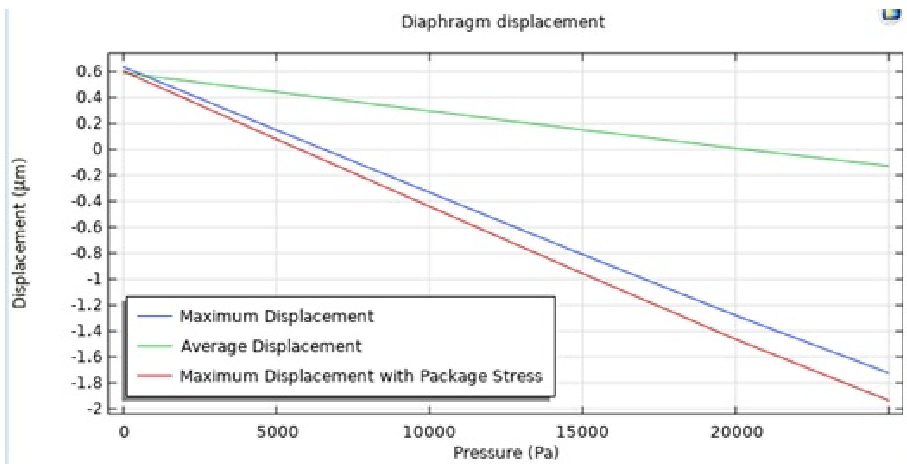

Figure 6: Diaphragm Displacement with Applied Pressure

5.2 Silicon nanowires

Silicon nanowires are used as diaphragm material in capacitive pressure and used low range pressure sensing application that is suitable for blood flow monitoring applications [14]and the simulated result of capacitance sensitivity is 2.3×10^{-6} pF/kPa. The properties used for the device are shown the table 4 and the graph between diaphragm deflection under applied pressure with and without packaging stress is shown in figure 6.

5.3 Titanium

Titanium metal is used as diaphragm material in capacitive pressure and titanium thin films deposited in conjunction with other materials onto a single crystal substrate is being used to create the micro devices. Due to strongest and high fracture toughness, this element is more promising metal substrate. The properties used for the device is shown the table 5 and graph between diaphragm deflection under applied pressure with and without packaging stress is depicted in figure 7.

Parameter Name	Value	Units
Youngs modulus	115.7	GPa
Poissons ratio	00.321	1
Density	4506	Kg/m^3
Relative permittivity	89.1	1
Coefficient of thermal expansion	8.5×10^{-6}	PPM/$^{\circ}C$

Table 5: Material Properties of Titanium

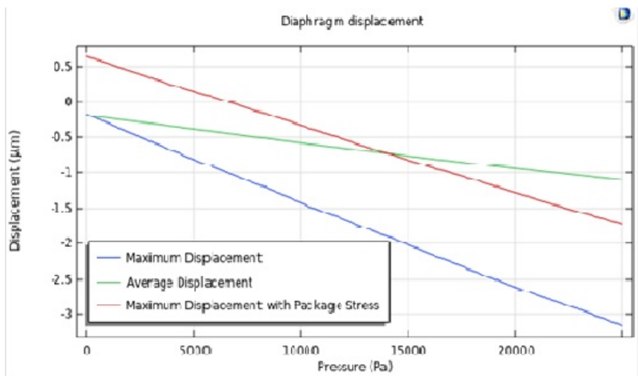

Figure 7: Diaphragm Displacement with Applied Pressure

5.4 Aluminium

Aluminium metal is used as diaphragm material in capacitive pressure and used in IC microelectronics through the integration of CMOS (complementary metal oxide semiconductor) Technology. Capacitive pressure on-chip signal circuitry with aluminium metal gives the highest sensitivity in square shape diaphragms under different pressure ranges. The properties used for the device are shown the table 6 and the graph between diaphragm deflection under applied pressure with and without packaging stress is shown in figure 8.

Parameter Name	Value	Units
Youngs modulus	70	GPa
Poissons ratio	0.35	1
Density	2700	Kg/m^3
Relative permittivity	11.5	1
Coefficient of thermal expansion	25×10^{-6}	PPM/$^{\circ}C$

Table 6: Material Properties of Aluminium

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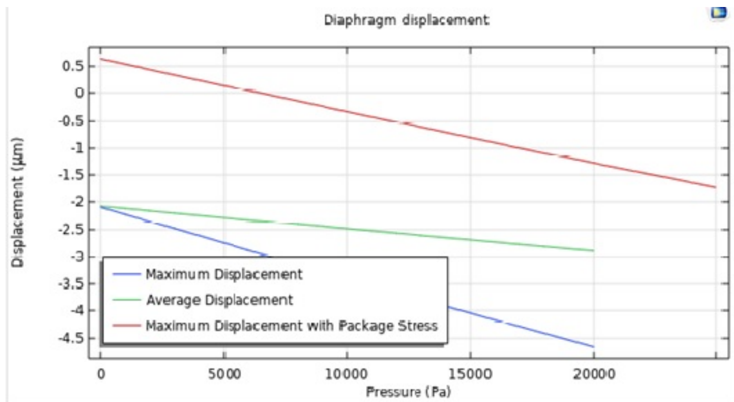

Figure 8: Diaphragm Displacement with Applied Pressure

Parameter Name	Value	Units
Youngs modulus	120	GPa
Poissons ratio	0.34	1
Density	8960	Kg/m^3
Relative permittivity	11.5	1
Coefficient of thermal expansion	25×10^{-6}	PPM/$^{\circ}C$

Table 7: Material properties of copper

5.5 Copper

Copper metal is used as diaphragm material in capacitive pressure. Although it has good electrical conductivity and high malleable as compared to other materials. it cannot be used in high-pressure applications due to the weak nature of the metal. The properties used for the device are shown in the table 7 and the graph between diaphragm deflection under applied pressure with and without packaging stress is shown in figure 9.

5.6 Comparative Analysis of all Materials

In this paper, different membrane materials were used on the same model and a comparative analysis of touch mode capacitive pressure sensor for different pressure range 0 to 25kPa has been investigated at $10\mu m$ thickness. The average diaphragm deflection and capacitance varied according to the used material properties. The average diaphragm deflection of different membrane materials to different pressure ranges is shown in the figure 10. In, the plots represent that the average deflection of all material is increases with increasing the pressure range in a linear or non-linear manner. On the other hand, among all materials Aluminium material has the highest deflection and more linearity as compared to other materials.

Figure 11. depicts the relationship between the relative capacitance and applied pressure in case of a square diaphragm. This plot represents that the aluminium material has the highest capacitances when compared to other materials. At zero

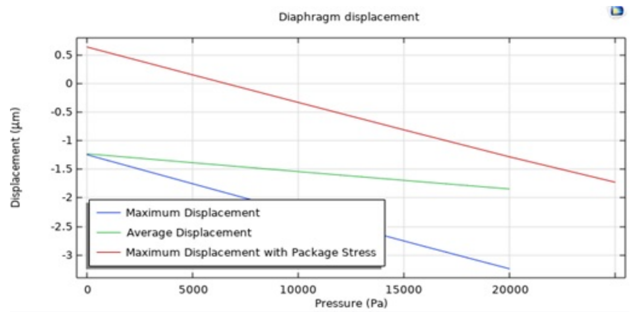

Figure 9: Diaphragm Displacement with Applied Pressure

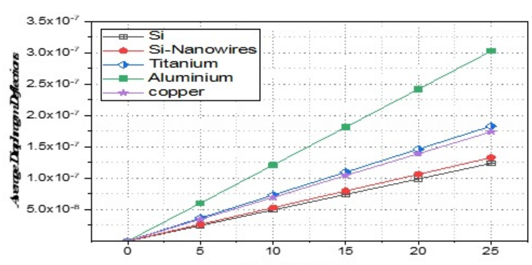

Figure 10: Diaphragm Displacement with Applied Pressure

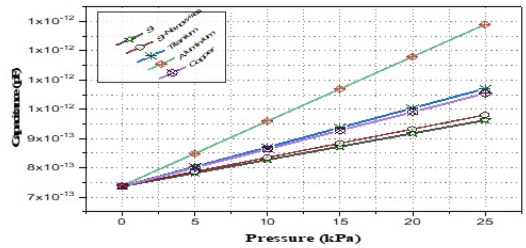

Figure 11: Capacitance changes with Applied Pressure

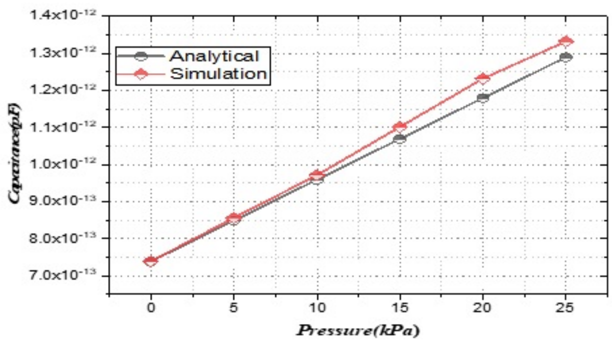

Figure 12: Analytical and Simulation Capacitance with Pressure

applied pressure, the value of capacitances for all the materials is same and gradually increases with applied pressure, but as is shown in the graph, Aluminium material provides better linearity than others materials over the range 0 kPa to 25 kPa

Figure 12 shows the comparison of analytical and simulation results of capacitance with applied pressure of a square diaphragm. This plot indicates that aluminium material provides more accurate and promising result of analytical with simulation result. At 10kPa, the value of capacitance is 9.69×10^{-13} F.

5.7 Sensitivity Analysis

Sensitivity is an important factor for the analysis of the capacitive pressure when membrane deflection and capacitance changes. Here table 8 shows a comparative analysis of the capacitance sensitivity of all Materials of the square diaphragm in which aluminium material provides the highest sensitivity at 10 kPa externally applied pressure is 22×10^{-6} pF/pa (one fourth part of the model) and the overall sensitivity of the model is 88×10^{-6} pF/pa with and without packaging stress.

Material Name	Sensitivity-Quadrant part (pF/pa)	Overall Sensitivity(pF/pa)
Si	9×10^{-6}	36×10^{-6}
Si- Nanowires	9.6×10^{-6}	38.4×10^{-6}
Titanium	13.2×10^{-6}	52.8×10^{-6}
Aluminium	$22.0 \times 1^{0-6}$	88.0×10^{-6}
Copper	12.6×10^{-6}	50.4×10^{-6}

Table 8: Comparative Sensitivity of all Material

6 Conclusion

This paper has described the dynamical modelling of highly sensitive normal and touch mode capacitive pressure sensor was analytically designed and simulated using the finite element method. This sensor comprises of moving top membrane, fixed bottom plate and cavity. In this investigation, the results show that the analytical result is in good agreement with the simulated result. Based on the observed performance its characteristics, accuracy and resolution are improved while repeatability error and computation time are reduced. Aluminium has been found to be more compatible and sensitive than other materials, making it more suitable for the measurement of blood pressure measurement. It also discussed how the reduced cavity size enhanced the sensitivity but this approach is restricted due to pull-in the phenomenon that faces inaccuracies in response time. In addition, these findings open a new route for other medical applications like ICP, IOP.

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