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Design and Simulation of PDMS and PMMA Based Touch Mode Capacitive Pressure Sensor: A Comparative Study

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Authors' contributions

This work was carried out in collaboration between both authors. Author MSM designed the mathematical model and simulation of this work and wrote the first draft of the manuscript. Author HSS managed the analyses of the study and wrote the second draft of the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: In this research work, a design method and a comparative of a touch mode capacitive pressure sensor (TMCPS) using poly-dimethyl-siloxane (PDMS) and poly-methyl methacrylate (PMMA) is the done. A novel method is proposed to linear the output characteristics of the sensor because planer type capacitive sensors are non-linear.
Study Design: This method uses a mechanical coupler to convert the deflection of the diaphragm into a linear displacement that helps to linear the output characteristics. The mathematical model of the sensor is designed and simulated the 3D model to validate the mathematically calculated values.
Place and Duration of Study: This study is done in the Department of Electronics and Communication Engineering, Rajiv Gandhi University, Arunachal Pradesh at COMSOL Simulation Laboratory during 2021 to 2023.

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Methodology: The mechanical and electrostatic components of the sensor are represented mathematically model in two separate parts. For this study, a square diaphragm was used since it exhibits greater deflection than circular or rectangular diaphragms. In order to validate the model equation, a 3D model of a sensor is created in the COMSOL Multiphysics simulator and simulated. For the pressure range of 0.1 [MPa] to 10.1 [MPa], the identical 3D model of the sensor construction with a square diaphragm thickness of 20 µm is simulated for PDMS and PMMA. The different elements influencing the sensor's sensitivity are discovered, and the effects of the materials PDMS and PMMA on the output characteristic are discussed.

Results: The simulated and calculated sensitivity of the sensors based on PDMS are 0.03685 [fF/MPa] and 0.03467 [fF/MPa] respectively. And the simulated and calculated sensitivity of the sensors based on PMMA are 0.03929 [fF/MPa] and 0.03748 [fF/MPa] respectively. It is observed that the PDMS based TMCPS has more sensitivity then the PMMA based TMCPS.

Conclusion: The PMMA based TMCPS has higher sensitivity than the PDMS based TMCPS. The various parameters that affect the sensitivity of the sensor are diaphragm shape, size, Poisson’s ratio and Young’s modulus, area covered by the dielectric material, dielectric constant of the polymers dielectric and surface are of the electrode plate.

Future Scope: Future research for TMCPS can be conducted using composite polymer dielectric materials and new polymer dielectric materials to improve the sensitivity. One can optimize the sensor using different tools as the mathematical model is developed.

Keywords: Linear; mechanical coupler; planer; touch-mode; sensitivity.

1. INTRODUCTION

There are different types of pressure sensors based on the physical sensing mechanisms, they are piezoelectric, piezoresistive, inductive, capacitive, untrasonics etc [1-5]. All these sensor also used in different application like turbulence flow sensing, mass colloidal flow sensing, wearables sensor, electronics skins [5-8,9].There are three main types of capacitive pressure sensors. They are planar capacitive pressure sensors, comb structure capacitive pressure sensors, and touch mode capacitive pressure sensors [10-13,9,14]. In planar capacitive pressure sensor, the diaphragm structure does not come in contact with the bottom electrode plate, which is fixed. Such sensor is having lower sensitivity than the touch mode capacitive and they are nonlinear output with the input pressure. In touch mode capacitive pressure sensor, the diaphragm structure comes into contact with the dielectric which is attached to the bottom electrode plate. Such sensors provide a number of benefits, including a nearly linear output to input pressure relationship, a broad input range, and a robust design that can endure harsh environments. Polymers are employed as the dielectric in touch mode capacitive because they may bend under increased pressure and restore their original shape after the pressure is released. Polymers are widely used in touch mode capacitive pressure sensor. Not all polymers are ineligible for use in touch mode capacitive pressure sensors because some polymers also exhibit thermoplastic, pyroelectric, and piezoelectric properties, such as PVDF and PVDF composite [15-17]. With the proper packing, this sensor can be used to measure fluid flow, acceleration, and force. In comb structure capacitive pressure sensor, this sensor structure has interdigitated fingers that resemble two combs interlocking. This sensor structure had a larger surface area than the planar and touches mode structure, which enhanced the sensor capacitance. The comb structure capacitive pressure sensor has two modes of operation, transverse and longitudinal. This kind of sensor has high sensitivity by nonlinear output characteristic.

The output of a simple touch mode capacitive pressure sensor is nonlinear because the diaphragm deformed parabolically their structure while applying the pressure [8][12][17], therefore a modified touch mode capacitive pressure sensor with a mechanical coupler is proposed as shown in Fig. 1. The mechanical coupler will transform the nonlinear deformation of the diaphragm plate into a linear displacement which will produce linear output characteristic.

The proposed structure has a diaphragm, mechanical coupler, movable plate, polymer dielectric and fixed plate. In the diaphragm, the pressure is applied and deflects. This deflection is converted in linear displacement by mechanical coupler which is attached between the diaphragm and movable plate. The movable plate moves toward the fixed plate which is separated by polymer. This polymer dielectric keeps the moveable plate away from touching the fixed plate.

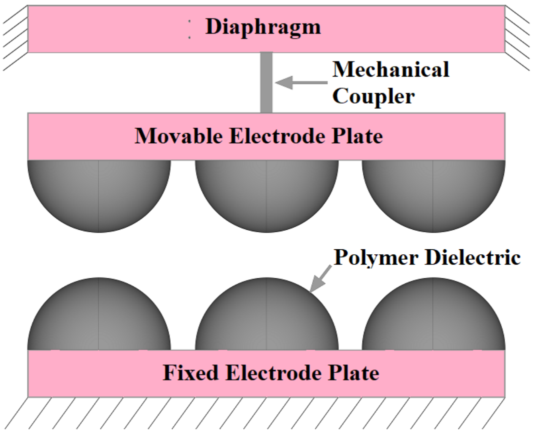

Fig. 1. Modified structure of TMCPS

2. METHODOLOGY

The suggested approach measures the deflection of square diaphragms over a pressure range of 0.1 [MPa] to 10.1 [MPa] with step size 1 [MPa] in order to calculate the output capacitance of the modified TMCPS. The 3D modelsof TMCPS are proposed with the following specifications: the hemispheres ofPDMS and PMMA dielectric polymers with a radius of 40 [µm], the square diaphragm with a length of 300 [µm] and a thickness of 20 [µm], and the square capacitor plates with a length of 300 [µm] and a thickness of 20 [µm]. The deflection of the square diaphragm is calculated for the applied pressure then the output capacitances of the TMCPS based on PDMS and PMMA based TMCPS is calculated. The proposed 3D model is simulated with two different types of polymer dielectrics i.e., PDMS and PMMA. The verification of simulated and calculated values is done twice, one with the PDMS based sensor and another is with the PMMA based sensor.

A comparative study is carried out between the two sensors, one with the PDMS based sensor and another with the PMMA based sensor. After conducting a comparison analysis, a number of significant findings were drawn from the various observations. The proposed methodology of design flow is shown in Fig. 2.

The touch mode capacitive pressure sensor is similar to other Micro-Electro-Mechanical systems. This typically consists of two parts: the mechanical and electrostatic parts. Hence, mechanical and electrostatic components are mathematically calculated in accordance with their respective operating principles.

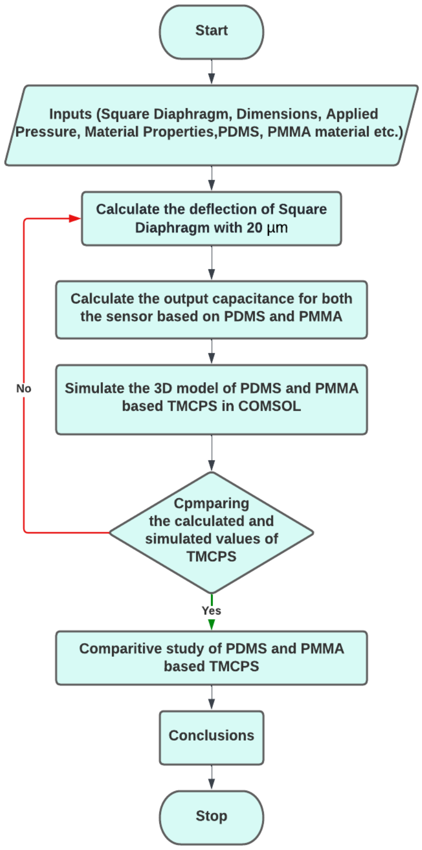

Fig. 2. The proposed methodology of design flow

In mechanical model, the diaphragm converts the applied pressure into the deflection. This deflection is converted into linear displacement by the mechanical coupler. For calculating the deflection of the square diaphragm, let us consider a rectangular diaphragm with a length of *2b* which is in *y*-direction and breadth of *2a* which is in *x*-axis. The total energy *Ω* of the rectangular diaphragm for applied pressure *P* is given as follow [18-20].

$$\Omega = \frac{D}{2}\int_{-b}^{b}\int_{-a}^{a}\left\{\left(\frac{\partial^2\psi(x,y)}{\partial x^2}+\frac{\partial^2\psi(x,y)}{\partial y^2}\right)^2-(1-\nu)\left\{\frac{\partial^2\psi(x,y)}{\partial x^2}\frac{\partial^2\psi(x,y)}{\partial y^2}-\left(\frac{\partial^2\psi(x,y)}{\partial x\partial y}\right)^2\right\}\right\}dxdy-\int_{-b}^{b}\int_{-a}^{a}\psi(x,y)P\,dxdy, \tag{1}$$

Where, *Ψ*(*x,y*)= deflection function, *D*= flexural rigidity and *v*= Poisson's Ratio. The value of *D* is given by

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

Where, *h*= thickness of the diaphragm and *E*= Young's Modulus. The deflection function *Ψ*(*x,y*) of a rectangular diaphragm is given by [15-16]

$$\psi(x, y) = \omega(a^2 - x^2)^2(b^2 - y^2)^2, \quad (3)$$

Where *ω* = constant. From Eq.1 and Eq. 3and applying the condition $\frac{\partial \Omega}{\partial \omega} = 0$, we get

$$\omega = \frac{49P}{128(7a^4 + 4a^2b^2 + 7b^4)D} \quad (4)$$

Putting the value of *ω* into Eq. 3, The Eq. 3 becomes

$$\psi(x, y) = \frac{49P}{128D(7a^4 + 4a^2b^2 + 7b^4)}(a^2 - x^2)^2(b^2 - y^2)^2 \quad (5)$$

The side length of the square diaphragm is equal i.e., *a*=*b*, then Eq. 5 becomes

$$\psi(x, y) = 0.02126\frac{Pa^4}{D}\left(1 - \frac{x^2}{a^2}\right)^2\left(1 - \frac{y^2}{a^2}\right)^2. \quad (6)$$

Eq. 6 is the deflection function at (*x,y*) point of a square diaphragm. At the centre of the diaphragm i.e. (*x,y*)=(0,0), the maximum deflection of a square diaphragm is occurred and is given by

$$\psi(x, y)_{max} = \psi(0,0) = \psi = 0.02126\frac{Pa^4}{D}$$

$$\psi(x, y)_{max} = \psi(0,0) = \psi = 0.25512\frac{Pa^4}{Eh^3}(1 - v^2) \quad (7)$$

From Eq. 7, the maximum deflection of the diaphragm is depending on the Poisson's ratio, Young's modulus, thickness of the diaphragm, length of the square diaphragm, and applied pressures.

In electrostatic modeling, Fig. 1 displays a design model for the TMCPS using PDMS or PMMA as the polymer dielectric material. Hemispherical polymers are used to coat portions of the electrode plates, but not all of them. The surfaces of the electrodes are separated into two sections: One section is the portion of the electrodes covered in dielectric polymers, and the other section is the remainder of the electrode surface that is uncoated.

As a result, the sum of capacitances C_1 and C_2 can be used to compute the overall capacitance *C*. Where C_1 denotes the capacitance of the dielectric polymer-covered area and C_2 denotes the capacitance of the uncovered area.

$$C = C_1 + C_2, \quad (8)$$

Now, the value of C_1 and C_2 can be calculated by

$$C_1 = n\frac{\varepsilon_0\varepsilon_r}{(g - \psi)}\pi r^2, \quad (9)$$

$$C_2 = \frac{\varepsilon_0(\alpha - n\pi r^2)}{(g - \psi)}, \quad (10)$$

Where, *r* = radius of the hemisphere, *n* = number of hemispherical polymer dielectric, ε_0 = absolute permittivity, ε_r = relative permittivity, *α* = surface area covered of the electrode plate and *g* = gap between the electrodes. Now, the total capacitance of the TMCPS is

$$C = \frac{\varepsilon_0(\alpha + n\pi r^2(\varepsilon_r - 1))}{(g - \psi)},$$

(11)

The sensitivity of the sensor *S* is ratio of change in the output to the change in input. Mathematically the sensitivity can be express for TMCPS is

$$S = \frac{\varepsilon_0(\alpha + (\varepsilon_r - 1)n\pi r^2)}{P(g - \psi)}. \quad (12)$$

From Eq. 12, the sensitivity of the sensor is depending on the total area covered by the of the polymer dielectric hemisphere, surface area of the electrode, gap between electrodes, relative permittivity and all the parameters that affect the deflection i.e., Poisson's ratio, Young's modulus of the diaphragm's materials, thickness of the diaphragm, length of the square diaphragm, and applied pressures.

Tables should be explanatory enough to be understandable without any text reference.

Double spacing should be maintained throughout the table, including table headings and footnotes. Table headings should be placed above the table. Footnotes should be placed below the table with superscript lowercase letters.

3. RESULTS AND DISCUSSION OF SIMULATED 3D MODEL OF TMCPS

The COMSOL Multiphysics simulator was used to simulate the 3D model of the TMCPS based on PDMS and PMMA, which is depicted in Fig. 1. This model contains a square diaphragm, mechanical coupler, moving electrode plate, fixed electrode plate, and a numbers of hemisphere-shaped dielectric polymers. The mechanical coupler is used to transform the deflection into linear displacement. Table 1 tabulates the physical dimension of the various TMCPS components, while Table 2 tabulates the material properties of TMCPS components.

After designing the 3D model of the TMCPS in the COMSOL simulator, the material properties of the various components are defined in the simulator. The mechanical and electrostatic are configured and the applied pressure is also defined in the global variable. A parametric swap is done in COMSOL for input pressure starting from 0.1 [MPa] to 10.1 [MPa] with a step size of 1 [MPa].

In Table 3, the deflection values that were calculated and simulated for both PDMS and PMMA based TMCPS are listed. The deflection is same for all both the sensors as the diaphragm is of same material for both the sensor. Also, it has been found that as increases in applied pressure, the deflection increases also increase.

The simulated and calculated capacitance values for the proposed TMCPS are shown in Table 4.

Table 1. Physical dimension of the TMCPS's components

TMCPS components	Material	Dimensions		
		Length	Breath	Thickness/ Radius
Diaphragm	Gold	300 [µm]	300 [µm]	20 [µm]
Mechanical Coupler	Silicon-dioxide	20 [µm]	20 [µm]	20 [µm]
Electrode Plates	Gold	300 [µm]	300 [µm]	20 [µm]
Polymer Dielectric	PMMA/PDMS	-	-	40 [µm]

Table 2. Material properties of the TMCPS components

Material	Young's modulus	Poisson's ratio	Dielectric constant
Gold	70 [GPa]	0.425	-
Silicondioxide	70 [GPa]	0.17	-
PDMS	-	-	2.4
PMMA	-	-	3

Table 3. Calculated and simulated values of deflections

Pressure [MPa]	Sim [µm]	Cal [µm]
0.1	0.01742	0.0186
1.1	0.19167	0.2046
2.1	0.3658	0.3906
3.1	0.5398	0.5766
4.1	0.7136	0.7625
5.1	0.8872	0.9485
6.1	1.0611	1.1345
7.1	1.2339	1.3205
8.1	1.4076	1.5065
9.1	1.5791	1.6924
10.1	1.7516	1.8784

Table 4. Calculated and simulated values of capacitance

Pressure [MPa]	PDMS-TMCPS [fF]		PMMA-TMCPS [fF]	
	Sim	Cal	Sim	Cal
0.1	16.7187	16.4263	17.1025	17.7623
1.1	16.7546	16.4603	17.1408	17.7991
2.1	16.7908	16.4945	17.1793	17.8360
3.1	16.8272	16.5288	17.2181	17.8731
4.1	16.8638	16.5632	17.2571	17.9103
5.1	16.9006	16.5978	17.2963	17.9477
6.1	16.9376	16.6326	17.3357	17.9853
7.1	16.9747	16.6674	17.3753	18.0230
8.1	17.0120	16.7025	17.4152	18.0609
9.1	17.0496	16.7377	17.4552	18.0989
10.1	17.0872	16.7730	17.4954	18.1371

The output capacitance is in the fF range, as can be observed from the data. The values also increase as the applied pressure is increased. The PMMA sensor has higher capacitance values than the PDMS sensor, the reason is PMMA has higher dielectric values than PDMS.

The graphic representations of Table 3 are shown in Fig. 4. The simulated and calculated deflections are seen to linearly change with the applied pressures.

Additionally, it has been noted that although the calculated values and simulated values are practically identical and the calculated values are slightly higher than the simulated values. So the mathematical model of the deflection can be used for further study. This linearly deflection at the center of the diaphragm is translated to linear displacement by the mechanical coupler. Because of this linear translation the output capacitance of the senor is linear in characteristics.

Fig. 5 illustrates is the graphical representation of Table 4. The simulated and calculated values of output capacitance are also linear with those of input pressure. The simulated output values are less than the calculated values but they are much closed. The PDMS based sensor has less sensitive then the PMMA based sensor. This is because the dielectric coefficient of the PDMS is lower than the dielectric coefficient of the PMMS. As the output values are much closed we can used the proposed mathematical model of the sensor in future application. The proposed improved model of the touch mode capacitive pressure sensor is very linear compared to the nonlinear planar touch mode capacitance pressure sensors. From the mathematical model, the various factor affecting the sensitivity of the sensor can be found.

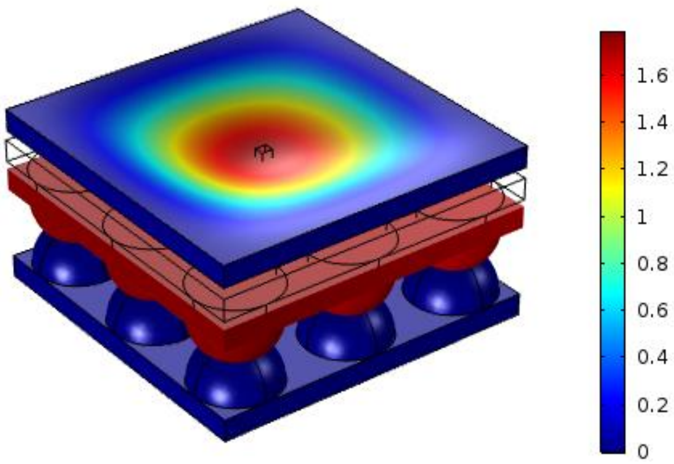

Fig. 3. COMSOL simulation output showing the deflection and shifting of movable electrode plate

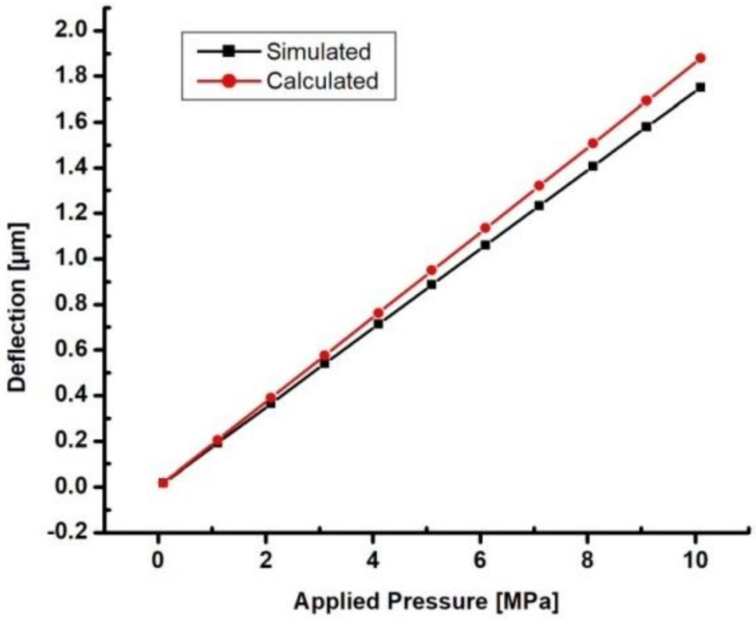

Fig. 4. Calculated and simulated deflections values for the applied pressures

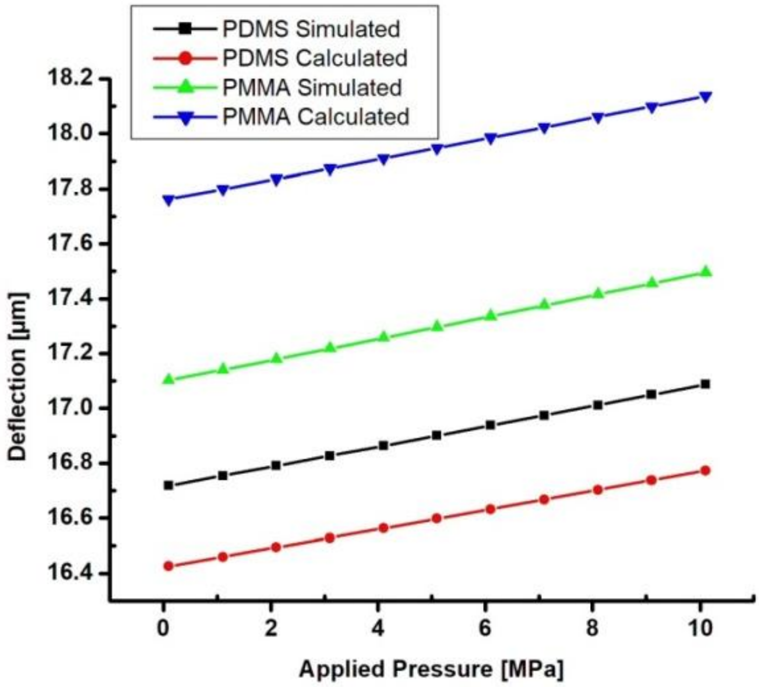

Fig. 5. Calculated and simulated output capacitances values for the applied pressures

4. CONCLUSION

This research study focuses on the mathematical modeling and simulation of the touch mode capacitive pressure sensor for pressure ranges of 0.1 [MPa] to 10.1 [MPa]. A design method based on PMMA and PDMS is presented and realized for a touch mode capacitive pressure sensor. Due to the strong agreement between the simulated and calculated values, the mathematical expression can be used to find the various factors impacting on the sensitivity of the sensors. The deflection if the diaphragm is increases with the applied pressure and surface area of the diaphragm. The deflection of the diaphragm is decrease with increase in Young's modulus, thickness of the diaphragm and Poisson's ratio as it has negative values. The output capacitances are increase with increase in deflection, area covered by the dielectric materials and relative permittivity of the dielectric but decrease with increase in the gaps between the two electrode plates. The non linear deflection is finally converted into linear displacement by a mechanical coupler to produce a sensor with a linear output characteristic. The sensitivity of the PDMS-based touch mode capacitive pressure for simulated and calculated data for a 20 [µm] diaphragm thickness is 0.03685 [fF/MPa] and 0.03467 [fF/MPa], respectively. The sensitivity of the PMMA-based touch mode capacitive pressure is 0.03929 [fF/MPa] for simulated pressure and 0.03748 [fF/MPa] for calculated pressure for a 20 [µm] thick diaphragm. The sensitivity of the PMMA based TMCPS is higher than the PDMS based TMCPS.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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