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Modelling and Simulation of a Diaphragm based Touch Mode Capacitive Pressure Sensor (DTMCPS)

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***Abstract* - In this paper, the DTMCPS mathematical modelling is presented and proven using the COMSOL Multiphysics simulator. Because of the existence of the non-linear behaviors of DTMCPS, the output characteristic is linearized using noble approaches. Mechanical and electrostatic modellings are employed to investigate the maximum deflection of the square diaphragm and examine the output capacitance with its sensitivity. A 3D model of a proposed sensor is constructed and simulated using a COMSOL Multiphysics simulator to verify the output of the mathematical modelled equations. Various factors affecting the sensor's outputs are found to depend on the diaphragm thickness, length, Poisson's ratio, Young modulus, dielectric materials used, the physical dimension of the capacitor plates and the separation between the plates. Comparing the calculated and simulated outputs of the sensor, it is found that for a diaphragm thickness of 15 µm, the sensitivities of the PDMS-based TMCPS for simulated and calculated values are 0.08 fF/MPa and 0.08 fF/MPa, respectively.**

Index Terms –capacitance, coupler, deflection, sensitivity, PDMS.

1. INTRODUCTION

Recently various authors have researched the physical properties of the capacitor and the dielectric material employed between the capacitor plates to determine the capacitances of capacitive pressure sensors [1-3]. Three types of capacitive pressure sensors, namely Planar capacitive pressure sensors, comb-drive capacitive pressure sensors, and touch mode capacitive pressure sensors have been widely discussed in [4]-[7]. The capacitive pressure sensor based on a diaphragm with a nonlinear characteristic has been examined in [8]-[9].

A touch mode planar capacitive pressure sensor consists of a movable plate and a non-movable plate separated by dielectric materials. The two plates touch each other while in operation, hence the name touch mode. When the gap between the two plates becomes closer in the presence of dielectric material between the plates, the output of the touch mode capacitive pressure sensor (TMCPS) increases. As a result, the TMCPS works better than non-TMCPS. But the outputs are highly non-linear to the input pressure.

Since the output of a touch mode capacitive pressure sensor is nonlinear, a modified touch mode capacitive pressure sensor with a mechanical coupler is proposed, as shown in Figure 1. The mechanical coupler will convert the nonlinear deformation of the diaphragm plate into linear displacement.

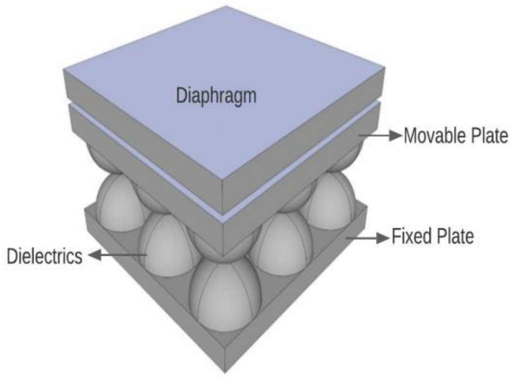


Figure 1: 3D model of modified TMCPS.

Over a pressure range of 0.1 MPa to 10 MPa, the proposed methodology quantitatively assesses the deflection of the square diaphragms and calculates the sensor's output capacitance. The sensor's 3D model is then simulated in the COMSOL Multiphysics simulator with the same input range. The dielectric materials employed in this is Polydimethylsiloxane (PDMS), and the computed and simulated capacitance values for the sensors are evaluated. The proposed design flow TMCPS based on a square diaphragm is shown in Figure 2.

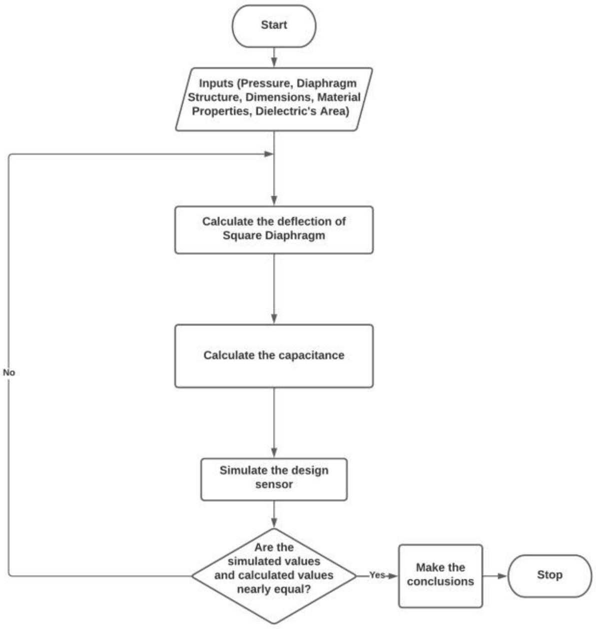


Figure 2: Design flow of a TMCPS based on a square diaphragm.

2. Mathematical Modelling of the Sensor

It is necessary to create a mathematical sensor model and run simulations to evaluate its framework before building a sensor prototype. Mechanical and electrostatic modules are included in micro electrochemical system (MEMS) devices. Hence mechanical and electrostatic modelling is needed to be done.

2.1. Mechanical Modelling

The square diaphragm is one of the most commonly used diaphragms for designing because of its higher deflection property than that of the circular diaphragm for the same applied pressure. A mechanical coupler converts this deflection of the square diaphragm into linear displacement. For the rectangular diaphragm of length *2b* along the y-axis and breath 2*a* along the x-axis, the total energy of the diaphragm under an applied pressure is given as in [10]-[12] by

$$\Omega = \frac{D}{2}\int_{-b}^{b}\int_{-a}^{a}\left\{\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)^2 - 2(1-v)\left\{\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}-\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2\right\}\right\}dxdy - \int_{-b}^{b}\int_{-a}^{a} wPdxdy, \quad (1)$$

where Ω is the total energy of the diaphragm, *w* is the deflection function of the diaphragm, *D* is the flexural rigidity of the diaphragm, *v* is the Poisson's Ratio, and *P* is the applied pressure.

The value of flexural rigidity is given by

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

where *h* is the thickness of the diaphragm and *E* is the Young's Modulus of the diaphragm material.

The displacement function of a rectangular diaphragm is given by [12]

$$w(x,y) = \lambda(a^2 - x^2)^2(b^2 - y^2)^2, \quad (3)$$

where λ is a constant.

Now substituting the equation no. (3) into equation no. (1) and imposing the condition $\frac{\partial \Omega}{\partial \lambda} = 0$, we get

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

Substituting equation no. (4) into equation no. (3), we get

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

For square diaphragm of equal dimensions, i.e., $a = b$ the above equation no. (5) reduces to

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

$$= \frac{49P}{128D(18a^4)}(a^2 - x^2)^2(a^2 - y^2)^2,$$

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

which implies the displacement of a square diaphragm at any given coordinates. The maximum displacement occurs at the centre of the diaphragm, i.e., at $x = 0, y = 0$. The maximum deflection of a square diaphragm is obtained by using equation (6) as

$$w(x,y)_{\max} = w(0,0) = 0.02126\frac{Pa^4}{D}. \quad (7)$$

2.2. Electrostatic Modelling

Touch Mode Capacitance: Figure 3 shows a touch mode capacitive pressure sensor with a polymer dielectric. The capacitance plates are coated with polymers in a hemispherical shape, while others are not. As a result, the total capacitance, C, equals the sum of capacitances C_1, covered by polymers and capacitances C_2, not covered by polymers.

The total capacitance is calculated as:

$$C = C_1 + C_2.$$

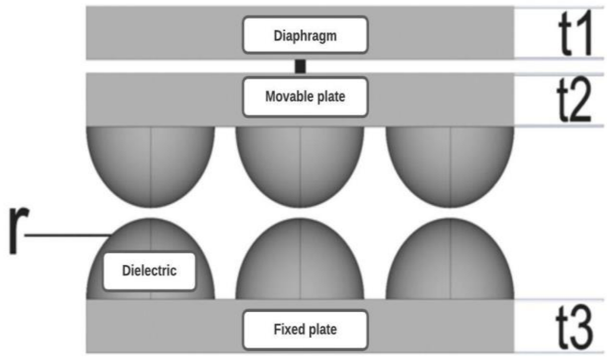


Figure 3: TMCPS with PDMS dielectric**.**

Now, the C_1 and C_2 capacitances are respectively given by

$$C_1 = n\frac{\varepsilon_0 \varepsilon_r \pi r^2}{(d - w)} \text{ and}$$

$$C_2 = \frac{\varepsilon_0 (A - n\pi r^2)}{(d-w)}.$$

Therefore, the total capacitance becomes

$$C = n\frac{\varepsilon_0 \varepsilon_r \pi r^2}{(d-w)} + \frac{\varepsilon_0 (A - n\pi r^2)}{(d-w)},$$

$$= \frac{\varepsilon_0 (\varepsilon_r n\pi r^2 + A - n\pi r^2)}{(d-w)},$$

$$= \frac{\varepsilon_0 (A + n\pi r^2 (\varepsilon_r - 1))}{(d-w)}. \quad (7)$$

Now, the Sensitivity is obtained as

$$S = \frac{\varepsilon_0 (A + n\pi r^2 (\varepsilon_r - 1))}{(d-w)P}. \quad (8)$$

The overall sensitivity is now a function of the dielectric constant, dielectric material radius, capacitance length and breadth, distance between plates, deflection, and absolute permittivity.

3. Simulation of the Sensor

A touch mode capacitive pressure sensor is designed, as illustrated in Figure 3, to measure the pressure range of 0.1 MPa to 10 MPa. A diaphragm, mechanical coupler, moveable plate, and fixed plate make up this 3D model of the sensor's structure. Both plates are made of polymers. The diaphragm is made of gold (Au), the mechanical coupler is made of Silicon dioxide (SiO_2), and both the moveable and non-movable capacitor plates are made of Au. The performance of touch mode capacitive pressure sensors is investigated using PDMS. After that, the 3D design model is simulated at pressures ranging from 0.1 to 10.1 MPa.

In the 3D model touch mode capacitive sensor design structure, the square diaphragm with the length of 300 µm and thickness of 15-20 µm, the semi-spherical dielectric polymer's radius of 40 µm, and the square capacitor plate whose length of 300 µm and thickness of 20 µm are taken to investigate. The output capacitance in planer touch mode capacitive pressure is non-linear. A mechanical coupler is linked between the diaphragm and the movable plate to avoid the non-linear character. This enables to convert the induced diaphragm deformation into a linear displacement.

4. Simulated output and calculated output of the touch mode capacitive pressure sensor.

A pressure range of 0.1 MPa to 10.1 MPa with a step size of 1 MPa was employed as input pressures for the analysis. Figures 4 and 5 show the simulated output deflection output of a sensor with a thickness of 15 m and 20 m, respectively, at 10.1 MPa.

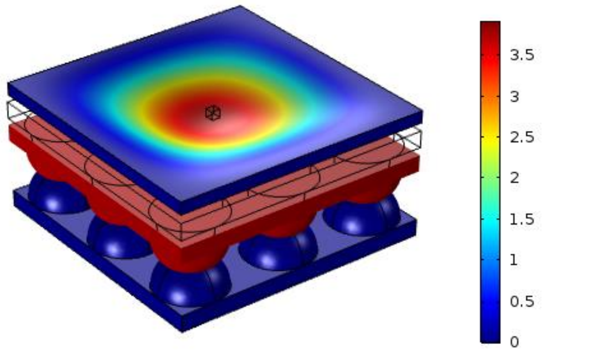
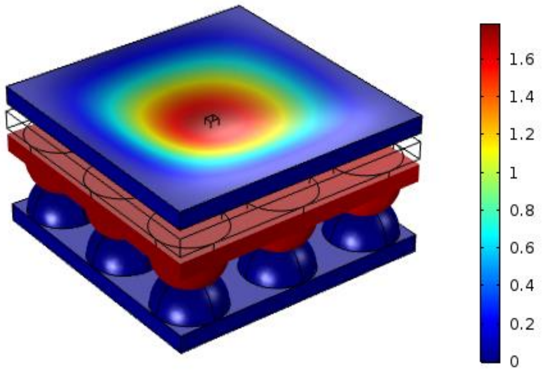


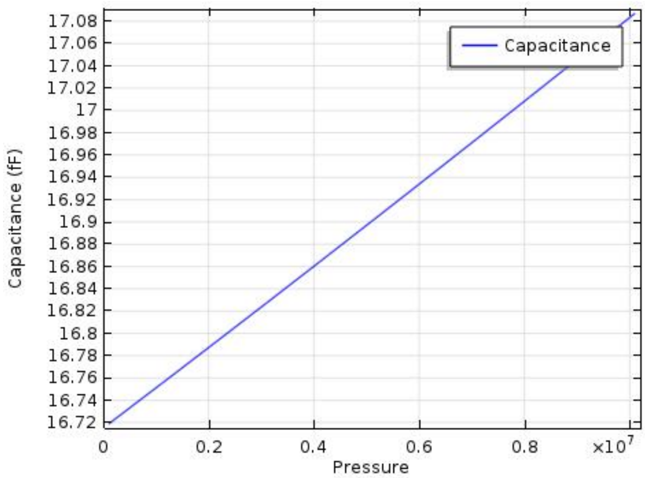
Figure 4: 15µm thick square diaphragm deflection at 10.1



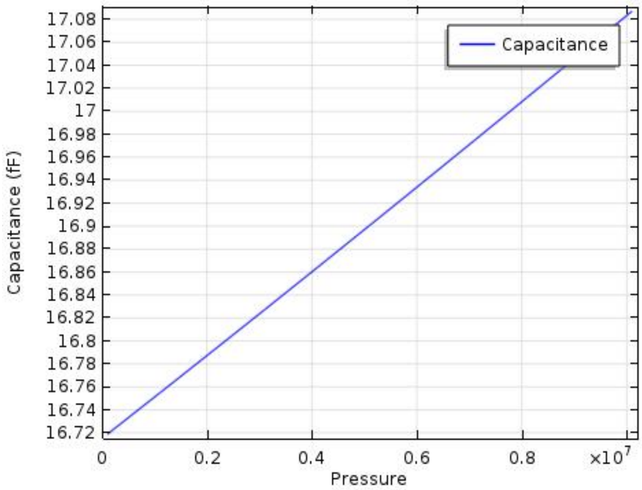
MPa.

Figure 5: 20µm thick square diaphragm deflection at 10.1 MPa.

For applied pressure ranges of 0.1 MPa to 10.1 MPa, Figure 6 shows the output capacitance of a PDMS-based sensor for square diaphragms with thicknesses of 15 µm and 20 µm, respectively.



a. Square diaphragm with 15 µm thick.



b. Square diaphragm with 20 µm thick.

Figure 6: Simulated output capacitance vs applied pressure in Pa for PDMS based sensor a. Square diaphragm with 15 µm thick and b. Square diaphragm with 20 µm thick.

Figure 6 clearly shows that the deflection linearly varies with the applied pressure. This figure also shows that lower the thickness of the diaphragm increase the deflection of the diaphragm for the same applied pressure.

The proposed touch mode capacitive pressure sensor's simulated output displacements and calculated output displacement for the applied pressure of 0.1 MPa to 10.1 MPa with a step size 1 MPa are shown in Table 1.

Table 1: Simulated vs calculated displacements for square diaphragm-based touch mode capacitive pressure sensor.

Pressure (MPa)	15 µm (µm)		20 µm (µm)	
	Sim*	Cal**	Sim	Cal
0.1	0.0396	0.04085	0.01742	0.0186
1.1	0.4358	0.4849	0.19167	0.2046
2.1	0.8307	0.9258	0.3658	0.3906
3.1	1.2233	1.3666	0.5398	0.5766
4.1	1.6132	1.8075	0.7136	0.7625
5.1	1.9994	2.2483	0.8872	0.9485
6.1	2.3818	2.6892	1.0611	1.1345
7.1	2.7558	3.1300	1.2339	1.3205
8.1	3.1285	3.5709	1.4076	1.5065
9.1	3.4904	4.0117	1.5791	1.6924
10.1	3.8514	4.4526	1.7516	1.8784

Sim*= Simulation values, Cal**= Calculated values

From Table 1, the simulated and the calculated values of deflection are very close to each other and increase their values with an increase in applied pressure.

Table 2: Simulated vs Calculated Capacitance of TMCPS

Pressure (MPa)	PDMS 15 µm (fF)		PDMS 20 µm (fF)	
	Sim*	Cal**	Sim	Cal
0.1	16.7340	16.4310	16.7187	16.4263
1.1	16.8162	16.5119	16.7546	16.4603
2.1	16.8993	16.5936	16.7908	16.4945
3.1	16.9832	16.6761	16.8272	16.5288
4.1	17.0677	16.7595	16.8638	16.5632
5.1	17.1527	16.8437	16.9006	16.5978
6.1	17.2380	16.9287	16.9376	16.6326
7.1	17.3236	17.0146	16.9747	16.6674
8.1	17.4091	17.1014	17.0120	16.7025
9.1	17.4954	17.1891	17.0496	16.7377
10.1	17.5796	17.2777	17.0872	16.7730

Sim*= Simulation values, Cal**= Calculated values

From Table 2, the simulated and the calculated values are found to be very close to each other and the output capacitance is also increased with an increase in applied pressure.

5. Conclusion

In this work, a mathematical modelling and simulation of a diaphragm-based touch mode capacitive pressure sensor for sensing pressure ranges of 0.1 MPa to 10 MPa is designed. PDMS polymers are used to develop a design technique for a touch mode capacitive pressure sensor. Since the simulated and computed values are so close, the proposed design flow can be employed in the future. It is better to employ a square diaphragm based TMCPS as it has high deflection property for applied pressure. It is observed that the sensitivity improves when the diaphragm thickness is lowered. The sensitivity of the diaphragm rises as the diaphragm gets longer. The sensitivity of the sensor is affected by Young's modulus and Poisson's ratio. The change in capacitance increases as the length, width, and dielectric of the material increases. The sensor's sensitivity improves as the distance between the plates decreases. A sensor with a linear output characteristic is created. The sensitivities of the PDMS-based TMCPS for simulated and calculated values are found at 0.08 fF/MPa and 0.08 fF/MPa, respectively for a diaphragm thickness of 15 µm.

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