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Design of Corrugated Diaphragm-Based MEMS Pressure Sensor for Biomedical Applications

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ABSTRACT

In this work we present the simulation analysis of a Micro Electro Mechanical Systems (MEMS) based capacitive pressure sensor for the measurement of blood pressure in the range 0 - 40kPa. We consider a circular corrugated silicon diaphragm and simulate the diaphragm's response to the applied pressure. Corrugations are introduced in the diaphragm in order to achieve larger displacements with improved linearity thereby increasing the sensitivity of the sensor. We consider sinusoidal corrugations and study the effect of the design parameters such as diaphragm thickness, corrugation depth, and number of corrugations on the displacement-pressure linear relation. The results are compared with that of the flat diaphragm. The deflection of the corrugated diaphragm also causes a variation in the capacitance value of the sensor with respect to the applied pressure. In order to analyze the performance of the corrugated diaphragm the capacitive response was studied for the pressure range 0 - 40kPa and compared with that of the flat diaphragm. Modeling and simulation analysis of the diaphragm deflections were carried out using the COMSOL Multiphysics software

Keywords: *blood, COMSOL, diaphragm, MEMS, pressure, sensor.*

1. INTRODUCTION

A typical capacitive pressure sensor converts the applied pressure into a capacitance variation by using a parallel plate capacitor. Capacitive pressure sensors present the advantages of simple structure, easy fabrication, high sensitivity, and low cost. MEMS (micro electromechanical systems) pressure sensor is one of the few devices that have been widely used in biomedical applications. In biomedical applications to measure the blood pressure and heart rate, pressure micro sensors are required to operate in the range 0 - 40kPa (0-300 mmHg) [1, 2]. It has been recognized for decades in the field of conventionally formed metal diaphragms that by introducing corrugations into the diaphragm structure, the linearity of a diaphragm can be increased considerably and the stiffness may also be increased by increasing the depth of the corrugations [3, 4]. Since the techniques employed for the construction of MEMS sensors are based on the manufacturing of semiconductors, silicon is highly preferred till date owing to its many special properties [5].

In this paper, design and analysis of MEMS capacitive pressure sensor with corrugated diaphragm is presented and the effect of corrugation on mechanical sensitivity and diaphragm deflection is investigated. The results obtained for the corrugated diaphragm are then compared with that of the flat diaphragm. The software COMSOL Multiphysics is selected to model and simulate MEMS capacitive pressure sensor. The model under consideration uses the Electromechanics interface to solve the coupled equations for the structural deformation and the electric field.

2. THE PHYSICS AND MATHEMATICAL MODELLING OF A CAPACITIVE PRESSURE SENSOR

In the parallel plate arrangement of the capacitive pressure sensor, the lower plate is fixed and the upper plate is flexible. When pressure is applied to the flexible plate from the top surface it deflects downwards thereby reducing the separation gap between the two plates. As a result of this the value of the capacitance increases as given by Eq. (1)

$$C = \frac{\varepsilon A}{d} \tag{1}$$

where 'A', is the area of the plates, 'd' is the separation gap and 'ε' is the dielectric constant. In the present study we consider circular plates ($A = \pi R^2$) with air gap, with the assumption that the circumference of the plates is much bigger than the air gap. The flexible plate of the capacitor acts as the diaphragm of the pressure sensor and we introduce corrugations to this diaphragm.

For the circular flat diaphragm, the capacitance is given by

$$\mathrm{C} = \iint \frac{\varepsilon\, r\, dr\, d\theta}{d - w(r,\theta)} \tag{2}$$

where, ‘w’ is the deflection of the diaphragm corresponding to the radial distance ‘*r*’ of a circular diaphragm.

Let ‘*E*’ be the Young’s modulus, ‘*R*’ be the radius of the diaphragm, ‘*ν*’ be the Poisson’s ratio and ‘*P*’ be the pressure applied on the diaphragm, the small deflection for a flat diaphragm can be defined by [6]

$$w\,(r) = \frac{P}{\frac{5.33\, h^3\, E}{(R^2 - r^2)^2\,(1-\nu^2)}} \tag{3}$$

Therefore, capacitance of the sensor can be calculated by [7]

$$C = \int_0^{2\pi}\int_0^{R} \frac{\varepsilon\, r\, dr\, d\theta}{d - \frac{P}{\frac{5.33\, h^3\, E}{(R^2 - r^2)^2\,(1-\nu^2)}}} \tag{4}$$

If A_P is the dimensionless stiffness coefficient, ‘*q*’ is the quality factor, ‘*H*’ is the corrugation depth and ‘*h*’ is the thickness of the diaphragm, then the small deflection of circular corrugated diaphragm can be defined by [1]

$$\mathrm{w\,(r)} = \frac{\mathrm{P}}{\frac{\mathrm{A_p\, E\, h^3}}{(\mathrm{R^2 - r^2})^2}} \tag{5}$$

where, $A_p = \frac{2\,(1+q)(3+q)}{3\left(1-\frac{\nu^2}{q^2}\right)}$ and $q = (1.5\,\frac{H^2}{h^2} + 1)^{1/2}$

The capacitance of corrugated pressure sensor can be calculated by [7]

$$C = \int_0^{2\pi}\int_0^{R} \frac{\varepsilon\, r\, dr\, d\theta}{d - \frac{P}{\frac{A_p h^3\, E}{(R^2 - r^2)^2}}} \tag{6}$$

The sensitivity S of the sensor can be defined by

$$S = \frac{C - C_0}{P} \tag{7}$$

where, *C* is the capacitance corresponding to the applied pressure and C_0 is the zero–pressure capacitance [2].

3. RESULTS AND DISCUSSION

The effects of design parameters on the load-deflection relation are investigated. The values of the independent design parameters and properties of silicon are summarized in Table 1.

Table 1. Tabulation of design parameters and properties of silicon

Design parameter	Symbol	Value
diaphragm thickness	*h*	15µm, 25µm, 30µm
No. of corrugations	*N*	2, 3, 4
corrugation depth	*H*	100µm, 150µm, 200µm
diaphragm radius	*R*	1000µm
separation gap	*d*	20µm, 30µm, 40µm.
density	*ρ*	2329 kg/m^3
Young’s modulus	*E*	170 GPa
Poisson’s ratio	*ν*	0.28

The sensors are designed to work in a pressure range of 0 – 40kPa which is suitable for blood pressure biomedical application. In this section, simulation results for the diaphragm deflection are analysed. Here, the parameters like diaphragm thickness, separation gap, number of corrugations, corrugation depth are varied and simulations are performed to decide the best design of the diaphragm with corrugations. Further, capacitance and capacitive sensitivity are calculated to study the performance of the sensor for both the flat and corrugated diaphragms.

3.1. Electromechanical analysis

Three designs with varied diaphragm thickness (15µm, 25µm, 30µm), three designs with varied corrugation depth (100µm, 150µm, 200µm), and three more designs with varied number of corrugations (2, 3, 4) are modelled and then compared with flat diaphragm using COMSOL Multiphysics. The simulation results are plotted in Fig.1, Fig. 2 (a) and Fig. 2 (b) respectively.

At an applied pressure of 40kPa, it is observed that the design with least diaphragm thickness (diaphragm thickness should not exceed 20% of the diameter of the diaphragm) has maximum diaphragm deflection [5]. The linear load-deflection relationship can be obtained by the varying corrugation depth (optimum depth depends on ‘*q*’ value between 5 & 15). On increasing the corrugation depth, the linearity of load-deflection relation and the stiffness of the corrugated diaphragm increases (high corrugations: q = 30 leads to rigidity) [1]. Though the number of corrugations has little effect, it is observed that highly corrugated diaphragm has more deflection when compared with flat or less corrugated diaphragm.

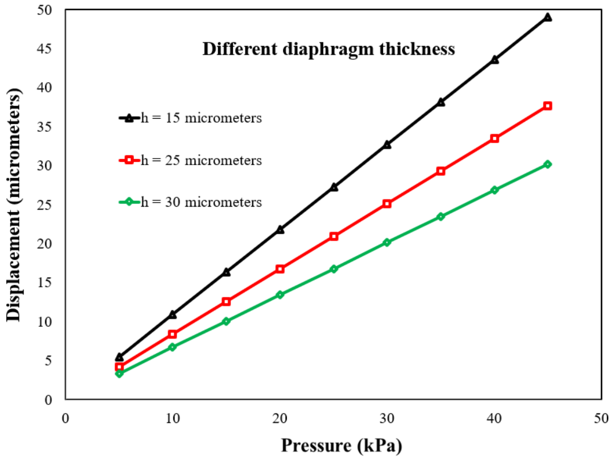

Figure 1. Load-distance relation for N = 3, H = 100µm and different values of h.

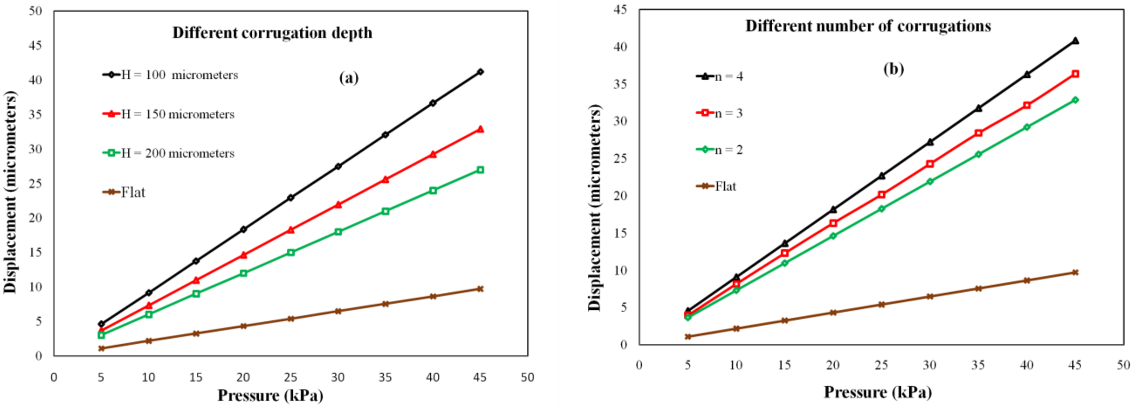

Figure 2. Load distance relation for (a) N =3, h = 15μm and different values of H and (b) H = 100μm, h = 15μm and for different values of N.

3.2. Capacitive analysis

The capacitance is dependent on the separation gap between the plates and diaphragm thickness. At the pressure value 40kPa, it is observed that for a specified separation gap between the plates, the least diaphragm thickness develops the maximum capacitance value for both flat and corrugated diaphragm (Fig. 3 (a) and Fig. 3(b) respectively). However, the corrugated diaphragm has more sensitivity and yields higher capacitance value when compared with flat diaphragm for a separation gap of 20µm.

Further, at 40kPa it is observed that for a fixed diaphragm thickness (15µm) with varied separation gap between the plates, the capacitance value decreases as the separation gap between the plates increases for both flat and corrugated diaphragm as seen in Fig. 4 (a) and Fig. 4 (b) respectively. Also, the capacitance value is high for thin corrugated diaphragm in comparison to the equivalent flat diaphragm of the same thickness. The calculation of capacitance was made using Eq. (4) for flat diaphragm and Eq. (6) for corrugated diaphragm.

3.3. Sensitivity analysis

The sensitivity of a sensor is calculated using Eq. (7) for flat and corrugated diaphragm. Table 2 summarises the sensitivity values for different separation gaps and diaphragm thickness for both flat and corrugated diaphragms.

From Table 2, it is observed that a sensor with corrugated diaphragm is more sensitive in comparison to the sensor with flat diaphragm of the same radius and thickness. Further to this, the sensitivity increases as the separation gap between the two plates increases. Also, the sensitivity is found to be high for thin diaphragms.

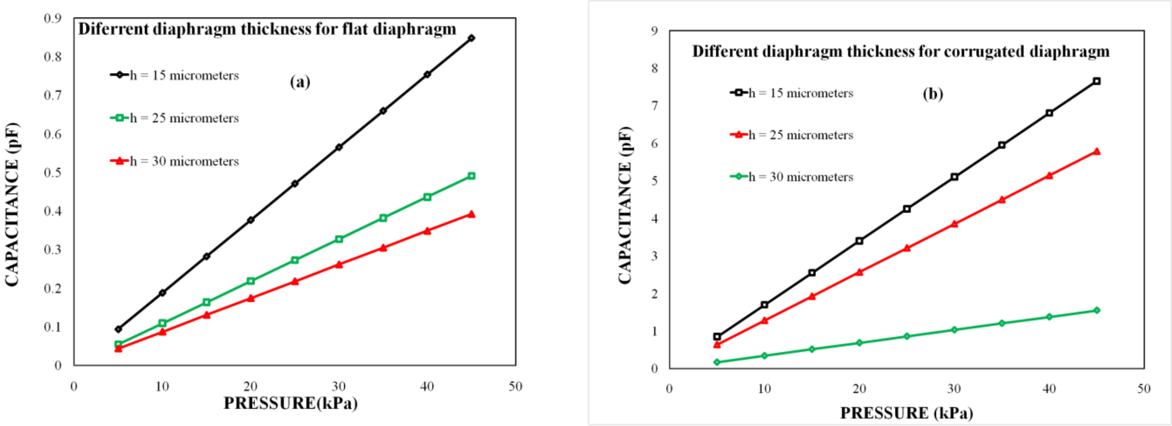

Figure 3. Capacitance as a function of pressure with d = 20μm and different values of h, for (a) flat diaphragm and (b) corrugated diaphragm with H=100μm and N=3.

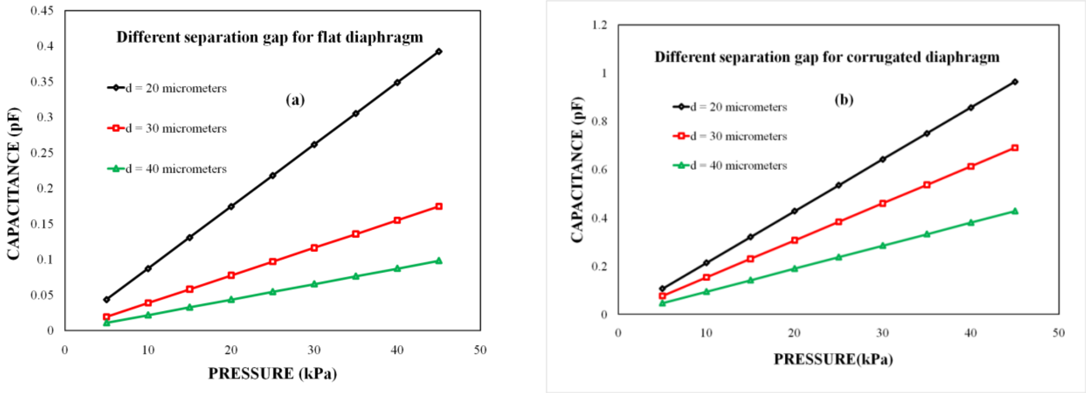

Figure 4. Capacitance as a function of pressure with h=15μm and different values of d, for (a) flat diaphragm and (b) corrugated diaphragm with H=100μm and N=3.

Table 2. Tabulation of sensitivity values for flat and corrugated diaphragms

Diaphragm thickness μm	Separation gap µm	Sensitivity (*fF/bar*)	
		Flat diaphragm	Corrugated diaphragm (100 μm)
15	20	0.017452	0.17684
	30	0.009977	0.16981
	40	0.008028	0.16686
25	20	0.003984	0.10382
	30	0.003919	0.00870
	40	0.004016	0.00849
30	20	0.002487	0.00758
	30	0.001799	0.00761
	40	0.001486	0.00735

4. CONCLUSION

In the present study, the simulation results through COMSOL Multiphysics showed the best design for the corrugated diaphragms in capacitive pressure sensors for biomedical applications. In the range of 0 - 40kPa, the corrugations played a vital role and enhanced the capacitance value and sensitivity by producing the maximum displacement. The corrugated diaphragm with least diaphragm thickness and low separation gap between the plates yields the highest sensitivity when compared with that of the equivalent flat diaphragm and highly corrugated diaphragms are generally stiffer so an optimum corrugation depth (q value between 5 & 15) is chosen for broad range of applications.

AUTHORS' CONTRIBUTION

Both authors, PRS and GG, have contributions about CONCEPT, METHOD, and ANALYSIS. GG provided feedback, discussed result and contributed to the final manuscript.

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