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Sensitivity Analysis of Micro-Structured Dielectric Layer of Capacitive Pressure Sensors for Flexible Electronics Applications

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Abstract

Micro-structuring the surface of the dielectric medium that is sandwiched between the two electrodes of the capacitive pressure sensor (CPS), increases the sensitivity of the sensor compared to, without the microstructure. A thorough analysis of CPS output sensitivity, linearity and relative change in its capacitance are done by introducing micro-structure in the dielectric layer. The designed micro-pyramidal structure on the surface of PDMS dielectric layer shows good linearity over the simulated range of 0-50 k Pa and with a nonlinearity error of 1%. Different types of microstructures are designed and their performance is studied first. The simulated result also compared to dielectric layer without any micro-structure and with vacuum as dielectric layer. Further analysis done by selecting the micro-pyramidal structure and varying its base length and the inter space between the micro-structure. The designed model with surface area=400sq.µm and distance=20µm and pyramidal micro-structure gives 51.4 times increase in sensitivity when compared to the same model without any micro-structure.

Keyword: *Micro-Structure, Dielectric, Flexible, Performance, Simulation.*

1.0 Introduction

MEMS Pressure Sensors

Flexible pressure sensors have higher sensitivity compared with silicon and its compounds-based sensors and can work on non-planar surface, with good performance. A flexible capacitive sensor has a flexible substrate, very thin layer of electrode and dielectric material sandwiched between the electrodes. Capacitive pressure sensors are temperature and humidity insensitive when compared with piezo-resistive pressure sensors[1]. The functional layer in capacitive pressure sensor is the dielectric layer. Elastomeric polymers are used as substrates and also as functional layers[2]. Enhancing sensitivity of flexible can be achieved by modifying the dimensions of the sensor, by mechanical properties of dielectric, by micro-structuring the surface dielectric or electrode (increases the compressibility of the sensor)[3,4], introducing filler material into dielectric material (increases the dielectric constant of the dielectric layer)[5] or modifying dielectric layer into porous structure by curing agent (decreases the modulus of elasticity of dielectric layer)[1,6,7]. Young's modulus of dielectric elastomers can be changed by curing agent by introducing pores into its structure. When

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applied pressure increases the size of the pores reduces due to compression and as a result dielectric constant of the dielectric material increases. Pores can be introduced into the structure by sacrificial solvent method[8,9]. Micro-structures on the surface of the dielectric are more compressed than a dielectric having a flat surface. Sensors modelling were done in software and then proposed models were simulated and the results were summarized for improved sensitivity by modifying the shape, introducing slots in the diaphragm, or with center bossed diaphragm[10-14.] A model is designed with micro-structured PVDF as dielectric[15]. Simulation results help in finding optimized parameters for better performance and efficiency of the sensor. The aim of this paper is to simulate a capacitive pressure sensor with flexible substrate and diaphragm, effect of micro-structure on dielectric on sensitivity of the sensor.

Sensor Design and Mathematical Modelling

Flexible capacitive pressure sensor CPS is modelled, consisting of five different layers with micro-structured dielectric layer. Bottom most layer, the substrate is modelled with PET material because of its good mechanical strength and good flexibility. Two thin layers of copper act as top and bottom electrode. The middle layer designed with micro-structured polydimethylsiloxane PDMS material. The top most layer is designed with polyimide material serves as membrane over which pressure is applied. The schematic of the pressure sensor is as shown in Figure 1. A potential of one volt is applied to the upper electrode and the lower electrode is grounded. Capacitance denoted by ‘C’, between two parallel plates without external pressure is given in terms of the overlapping area of the parallel plate ‘A’, dielectric constant of the medium between the plates ‘ε_r’, permittivity of free space ‘ε_0’ and the distance between the two plates ‘d’:

$$c = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad \text{... (1)}$$

In presence of an external pressure, the generalized equation for determining the maximum deflection of a square membrane whose thickness is uniform and all its edges are fixed, is given by[16].

$$W_{max} = \frac{0.01512(1-\mu^2)\,L^4 P}{E h^3} \qquad \text{... (2)}$$

Here W_{max} = central maximum deflection for P = applied pressure, L = length of diaphragm, h = thickness of diaphragm, E = Young’s Modulus and μ = Poisson’s ratio. The sensitivity S and the nonlinearity error are defined by[15].

$$S = \frac{\Delta C}{\Delta P} \text{ and } r = \frac{\Delta Cmax}{C_0} * 100\% \qquad \text{... (3)}$$

2.0 Modelling and Simulating Sensor in COMSOL Multiphysics

The middle dielectric layer is micro-structured with four different shapes namely, pyramid, truncated pyramid, cylinder and cuboid. The sensitivity of the sensors modelled with different micro-structures are compared keeping its other dimensions as fixed. The COMSOL Multi-physics[17] provides integrated environment to build the sensor model. In the model building solid mechanics and electrostatics physics are selected to study stationary analysis of the model. Two very thin electrode of thickness 0.01µm and of copper material are modelled below and above the dielectric, PDMS material. Upper electrode is maintained at 1 Volt potential while lower one is grounded. One fourth of the model is considered due to the geometrical symmetry of the sensor and symmetric boundary conditions are applied as shown in Figure 1. Load is applied to the top surface of the membrane. The pressure range selected is suitable for flexible electronics and most of the biomedical applications lie within this range. Fine tetrahedral meshing is applied to do finite element analysis of modelled sensor. The dielectric material is then modelled with air and then flat panel of PDMS material. Dimensions of the sensor geometry selected are 400*400 square microns with thickness of 10 µm and the distance between the plates is taken as 20 µm. In one quarter of the sensor, totally nine pyramids are designed on the surface of the dielectric layer. The base length of all micro-structures is kept constant as 25 µm and the inter space between them as 35µm.

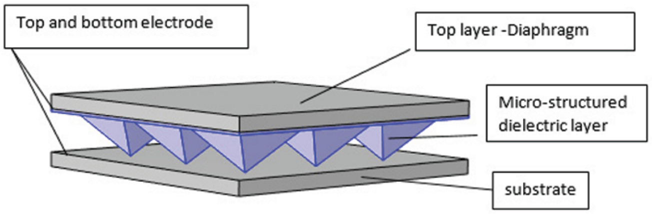

Figure 1: One quarter of the model of the designed sensor

3.0 Simulation Results and Discussion

Performance of the Sensor with Different Micro Dielectric Structure

The dielectric layer with four different micro-structures are designed and the response of the sensor for the applied pressure in the range 0-50k Pa are studied. The displacement

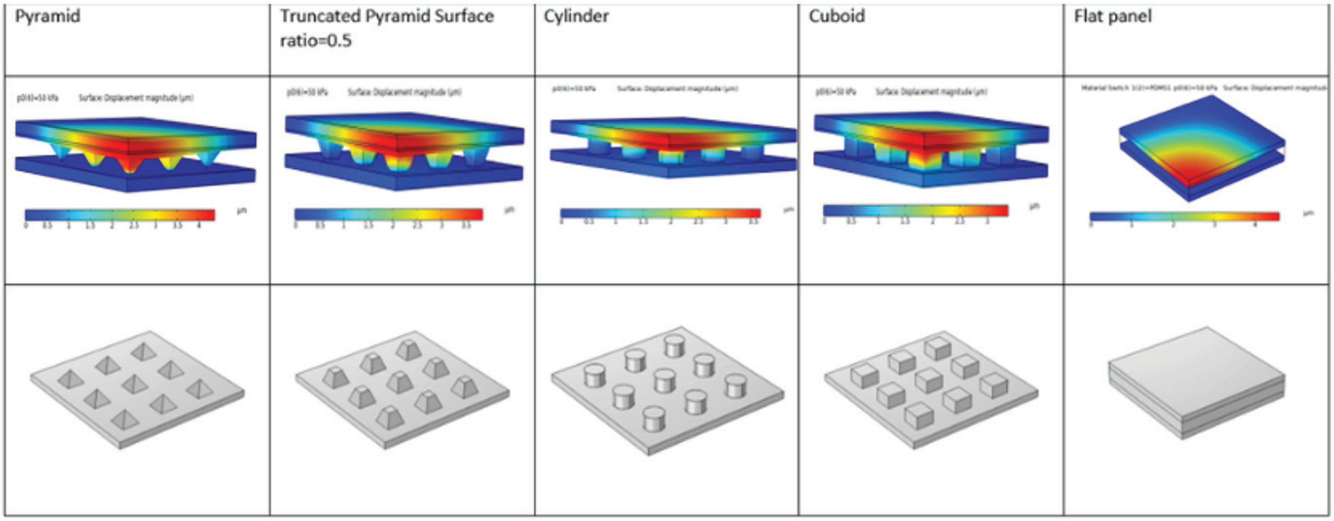

Figure 2: Types of micro-structure of the CPS with 3D-displacement for an applied pressure of 50k Pa. And the corresponding micro-structure (one quarter of the structure), modelled and simulated in COMSOL 5.6

of the diaphragm as a function of the applied pressure is simulated. The corresponding capacitance calculated by integrating the stored energy between the plates of the capacitive sensor. Surface displacement for an applied load of 50k Pa for different micro-structure is shown in Figure 2. The center part of the diaphragm gets more deflected. The relative change in the capacitance for the applied pressure calculated. Sensitivity is given by the ratio of change in capacitance to the change in applied pressure. The results show the sensor has a linear response in the simulated full range of 0-50k Pa (Figure 3). Then for the same dimension of the CPS the dielectric layer is modelled with vacuum and then with flat panel of PDMS and the response is simulated.

Diaphragm displacement of the capacitive sensor remains the same with flat panel PDMS or vacuum as dielectric material between the two electrodes at a given applied pressure. But the capacitance at any given pressure is higher for flat panel PDMS due its higher dielectric constant when compared to vacuum as dielectric material. When micro-structures are introduced at the surface of the dielectric material with space in between them, the initial capacitance when no pressure is applied, decreases and it is as comparable as that of air medium. Since air is more compressible than PDMS material, when pressure is applied over the capacitive sensor diaphragm, the relative change in capacitance is more. To have a higher sensitivity, not the initial capacitance is considered, but change in capacitance value is considered as the sensitivity is defined as change in capacitance to the corresponding change in pressure. Hence sensitivity of the CPS with micro-structure also increases compared to flat PDMS dielectric CPS. The performance of the sensor with different micro-structures is plotted in Figure 3(a) and (b) for comparison of the results. The sensitivity of the sensor for unstructured dielectric design is $3.5*10^{-5}$ kPa^{-1}. It increases to a value of $1.8*10^{-3}$ kPa^{-1} for pyramidal micro-structured dielectric CPS, 51.4 times increase in sensitivity. Sensitivity for different shapes and unstructured planer PDMS and the corresponding nonlinear error are plotted in Figure 3(c).

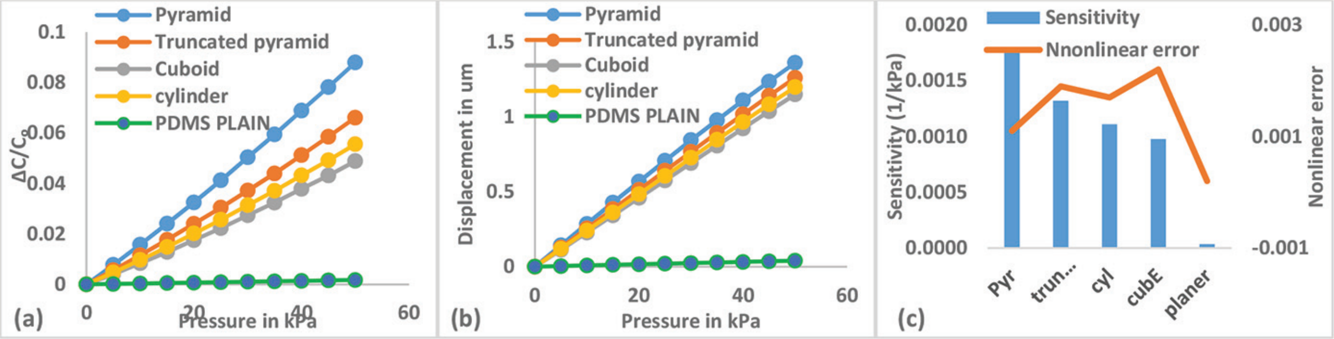

Figure 3: Comparison of (a) relative change in capacitance and (b) displacement of the membrane versus applied pressure, (c) sensitivity and percentage nonlinear error for different microstructure.

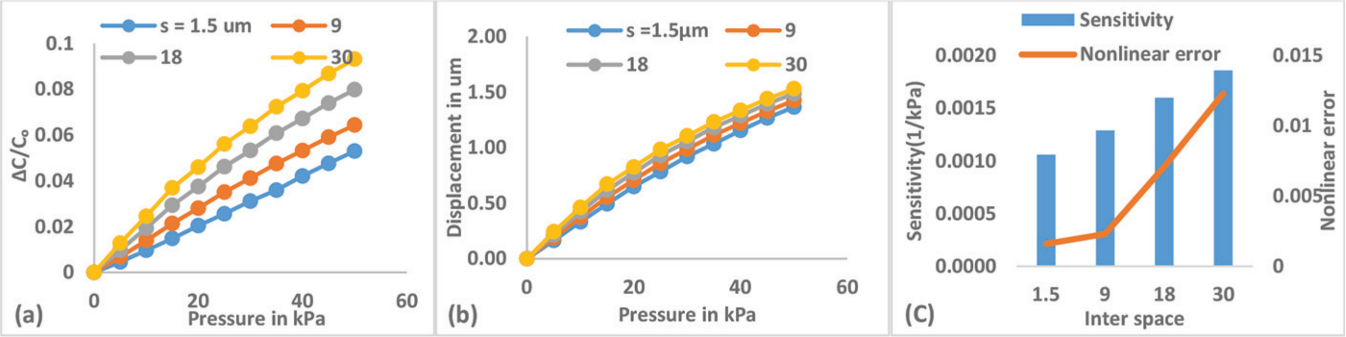

Figure 4: The simulated responses of CPS pyramidal structure with varying interspace (a) relative change in capacitance, (b) displacement of the diaphragm versus applied pressure and (c) Sensitivity and nonlinear error versus inter-space between them.

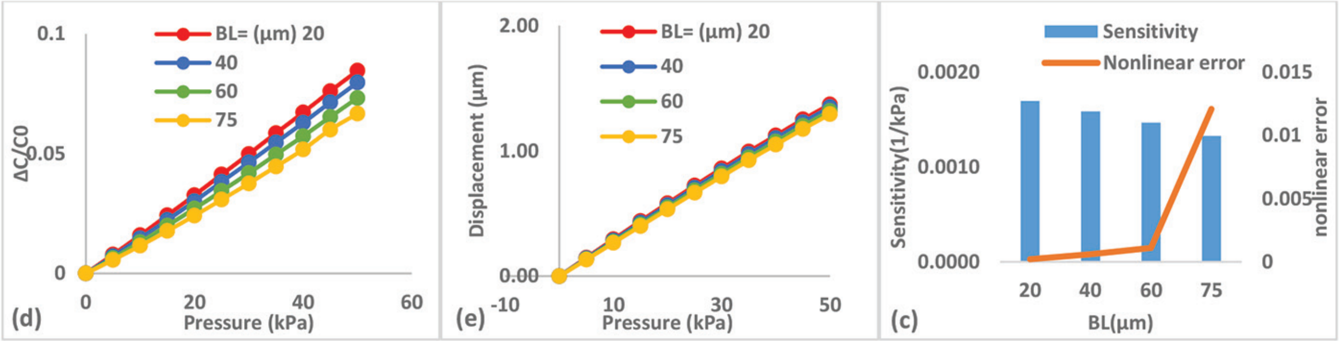

Figure 5: The simulated responses of CPS with different base length of the pyramidal structure (a) relative change in capacitance, (b) displacement of the diaphragm versus applied pressure and (c) Sensitivity and nonlinear error versus base length

To improve the sensor performance micro-structure as pyramid is considered, interspace between them (s=1.5,9,18, 30µm) and base length of the pyramids (b=20, 40, 60, 75µm) are varied one at a time while keeping other parameters as constant. Increasing the space between the pyramidal structure increases the sensitivity. The sensitivity increases from $1.1*10^{-3}$ kPa^{-1} (for s=1.5 µm) to $1.9*10^{-3}$ kPa^{-1} (for s=30µm). Lesser the length of the base higher the sensitivity. The sensitivity decreases from $1.7*10^{-3}$ kPa^{-1} (for BL=20 µm) to $1.3*10^{-3}$ kPa^{-1} (for BL=75µm). The relative change in capacitance and displacement of the membrane are plotted in Figure 4(a-b) for varying inter space. The nonlinear error also increases from 0.002 to 0.0121corresponding to roughly one per cent error at s= 30micron as shown in Figure 4(c). Plot in Figure 5(a-c) the corresponding changes for variation in base length.

4.0 Conclusion

CPS with dielectric materials having higher relative permittivity will have initial higher capacitance when no load is applied than air as dielectric material. But when pressure is applied the distance between the two electrodes of CPS decreases due to displacement of the membrane that is exposed to load and the change in capacitance value per unit pressure applied is more for air dielectric medium than materials with higher relative permittivity. By micro-structuring the surface of the dielectric material which are compressed more than a planar dielectric material between the electrodes. This increases the sensitivity. In this paper finite element method is used to show the increase in sensitivity by introducing various micro-structures on the surface of PDMS dielectric material and found micro-pyramidal structure has highest sensitivity. Varying the size and inter space between pyramidal structure are simulated and results are discussed. Increasing the inter-space and decreasing the base length increase the sensitivity. The result concludes that capacitive pressure sensor designed for low pressure measurement in particular wearable electronics with pyramidal micro structured dielectrics has the highest sensitivity, 51.4 times increase as compared with dielectric with no micro-structure.

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