Sensitivity to Shape and Membrane Thickness Variations in Capacitive Pressure Sensors

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ABSTRACT

This study describes the effect of variations in shape and membrane thickness in capacitive pressure sensors. Specifically, square, rectangular and circular shapes were considered with three different membrane thicknesses. Capacitive changes and membrane deformations with respect to pressure variation were computed using the IntelliSuite simulation software, and the sensitivity of the sensor was assessed. Square-shaped pressure sensor with least membrane thickness was found to be more sensitive than the circular and rectangular shaped sensors, with the rectangular one showing the least sensitivity.

Keywords: pressure sensors, shape, membrane thickness, capacitance.

1 INTRODUCTION

Structural elements such as diaphragms and beams are extensively used in the development of sensors in micro-electro-mechanical systems [1, 2]. As the technology of MEMS sensors is yet to achieve standardization of components, their fabrication may lead to deviations from standards in thickness and shape that influence the emanating electrical output signals [3, 4]. In parallel plate capacitors, the capacitance depends upon the gap between the plates as well as the overlapping area of the plates. If one plate is stationary and the other plate is deformable, the effective gap is determined by the shape of the deformable plate and the deformation profile under the prescribed boundary conditions in addition to the pressure in the cavity created between the plates during fabrication [5]. The dimensions of the cavity and diaphragm thickness also play an important role in defining the final device sensitivity for a given pressure range. Wise and Samaun [6] have patented a method for forming regions of predetermined thickness in silicon diaphragms. In fabrication, it is possible to encounter variations in the diaphragm thickness both intentionally and unintentionally. Intentionally when a specific sensitivity is desired, and unintentionally when fabrication errors creep into the process. For greater sensitivity of the pressure sensor, diaphragms with small thicknesses yield better load deflection response, but the nonlinearity of large deflections may lead to undesirable consequences. It is widely accepted that linear deflections of diaphragms are most desirable for high performance sensors. Tadigadapa and Massoud-Ansari [7] have developed a fabrication process to make pressure sensors with a wide range of shapes and dimensions. This work addressed the issue of sensitivity of capacitive pressure sensors from fabrication point of view, but not with regard to finite shapes such as ones we have discussed here.

With the advent of MEMS technology, capacitive pressure sensors that are accurate as well as sensitive and durable can be constructed. There are several design parameters that are important for sensor design. To understand the impact of certain parameters, such as device geometry and membrane thickness, one can use finite element analysis and other commercially available simulation software. In the present study we have used IntelliSuite software which is available under license from IntelliSense Corporation.

2 METHOD

In this study we examined three simple geometries – square, rectangular, and circular - as well as 0.1µm, 0.2 µm, and 0.3 µm membrane thicknesses. Each of the samples had approximately the same capacitive surface area 1600 um^2. The square geometry was 40µmx40µm; the rectangular geometry was 20µmx80µm, and the diameter of the circular shape was 45 µm.

With each permutation of geometry and membrane thickness, a virtual model was designed using IntelliSense 3D Builder [8]. Then, an analysis module was created for the Thermo-Electro-Mechanical (TEM) subprogram. Within TEM a voltage differential of 1 Volt was introduced between the membrane and the sensing plate. Then, pressures of 0, 0.5x10e-2, 1.0x10e-2, and 1.5x10e-2 MPa were applied to the membrane. Using a finite element analysis, deformations were calculated and capacitance was determined . A total of 36 FEA samples were analyzed. The results are tabulated below.

Table 1. Deformations in selected shapes and thicknesses.

	Square			Rectangle			Circle		
Pressure\Thickness	0.1 μm	0.2 μm	0.3 μm	0.1μm	0.2 μm	0.3 μm	0.1 μm	0.2 μm	0.3μm
0x10-e2 MPa	0	0	0	0	0	0	0	0	0
0.5x10-e2 MPa	0.715	0.102	0.031	0.07	0.0089	0.0028	0.123	0.0396	0.0167
1.0x10-e2 MPa	1.43	0.203	0.062	0.14	0.018	0.003	0.246	0.0793	0.0334
1.5x10-e2 MPa	2.146	0.305	0.094	0.21	0.027	0.00832	0.369	0.119	0.0501

Table 2. Capacitances for selected shapes and diaphragm thicknesses.

	Square			Rectangle			Circle		
Pressure\Thickness	0.1μm	0.2 μm	0.3 μm	μm 0.1	0.2 μm	0.3 μm	0.1 μm	0.2 μm	0.3 μm
0x10-e2 MPa	8.213	9.017	8.884	9.457	9.46	9.462	7.678	7.708	7.731
0.5 x10-e2 MPa	9.892	9.121	9.051	9.546	9.472	9.466	7.826	7.755	7.751
1.0 x10-e2 MPa	11.52	9.231	9.083	9.638	9.485	9.47	7.983	7.803	7.771
1.5 x10-e2 MPa	12.91	9.347	9.116	9.734	9.497	9.474	8.149	7.852	7.791

3 RESULTS AND DISCUSSION

Tables 1 and 2 above show the deformations capacitances for various combinations of applied pressure and membrane thickness. Analysis of the data shows that the square geometry with thinnest membrane (0.1um) exhibited the highest rate of capacitive change with respect to changing pressure. This means that this device is most sensitive to changing pressure. The circular geometry was second most sensitive, and the rectangular one with a 4-to-1 length to width ratio was least sensitive. A hierarchy of sensitivity is thus established. Sensitivity (from highest to least) : Square → Circle → Rectangle.

Other apparent trends included increased deformation with increased pressure, as well as increased capacitance with increased pressure. This was to be expected because capacitance for a simplified parallel capacitor is determined from

$$C = \varepsilon_o A / d \qquad (1)$$

where C is capacitance, A is area, ε_o is the permittivity of the free space, and d is the distance between plates. As d decreases, the capacitance increases. As such, one can glean that in our computational experiment, increased deformation brought on a smaller effective d. Hence, larger deformations led to increased capacitance.

Additionally, there was less deformation with increasing membrane thickness. This was to be expected as the bending modulus increases dramatically with increasing thickness.

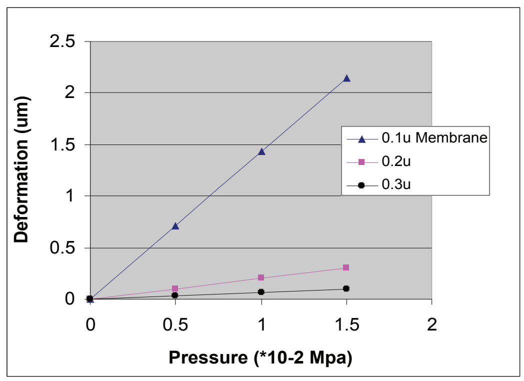

Figure 1: Maximum deformation vs. pressure for a square geometry

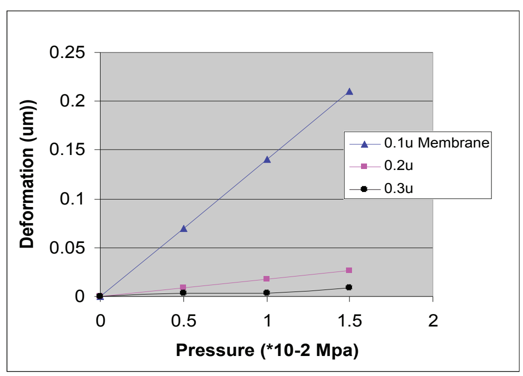

Figure 2: Maximum deformation vs. pressure for a rectangular geometry

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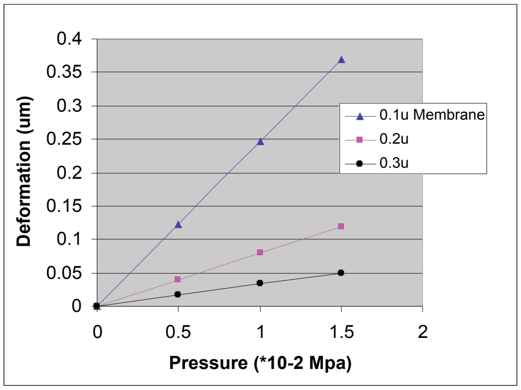

Figure 3: Maximum deformation vs. pressure for a circular geometry

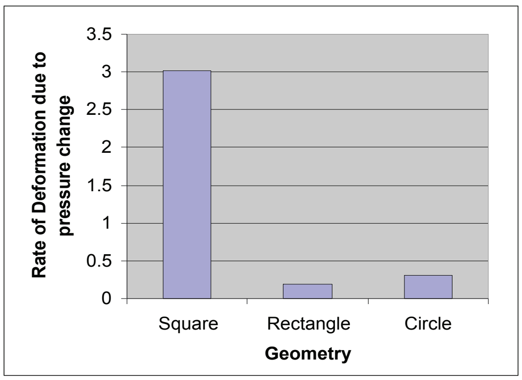

Figure 4: Rate of deformation vs. geometry

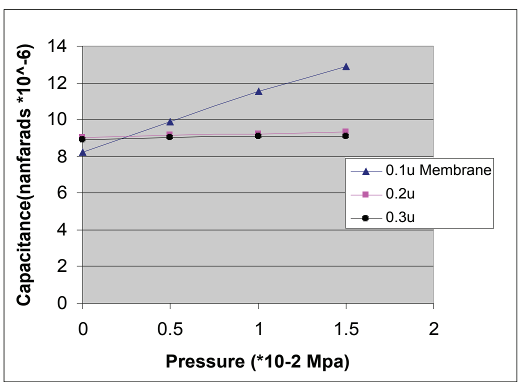

Figure 5: Capacitance vs. pressure for a square geometry

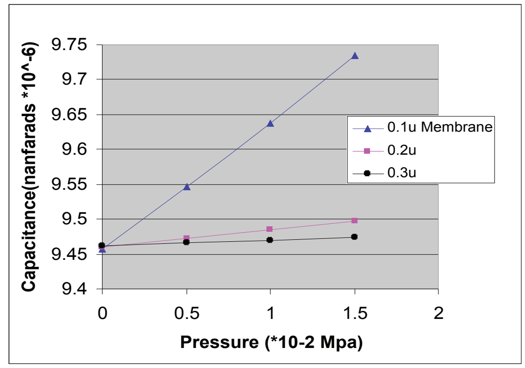

Figure 6: Capacitance vs. pressure for a rectangular geometry

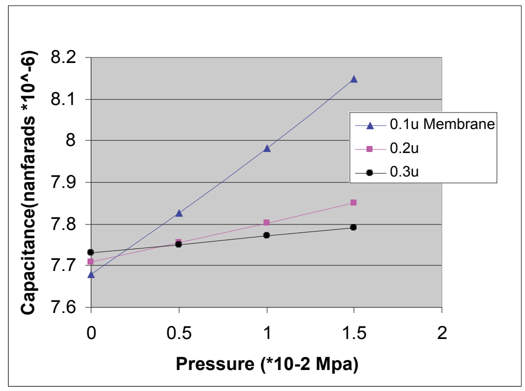

Figure 7: Capacitance vs. pressure for a circular geometry

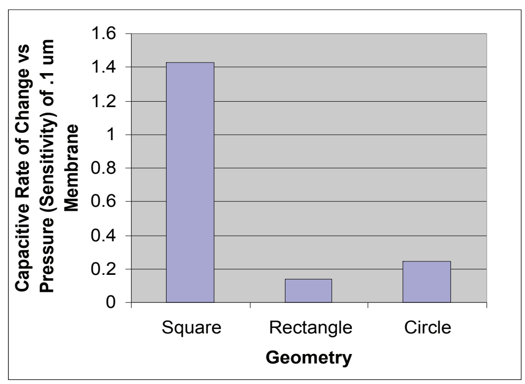

Figure 8: Capacitive sensitivity (rate change) vs. geometry

Figures 1, 2, and 3 depict pressure versus deformation for various membrane thicknesses and shapes. Figures 5, 6 and 7 depict pressure versus capacitance for the same. In these figures, the square geometry is clearly the winner. The bar heights in Figures 5 and 8 show rates of deformations and rates of capacitive change (sensitivity) with respect to applied pressure heavily in favor of square-shaped sensors. Why does a square-shaped sensor yield such superior sensitivity in comparison with rectangular and circular shaped pressure sensor? This question has Led to further investigation of the effect of various length/width ratios on the deformation and capacitance computations. Define

_ (alpha) = length / width

For values of _ = 0.25, 0.38, 0.55, 0.78 and 1.0, the deformation and capacitance as a function of pressure are calculated and displayed in Figs. 9 and 10, Note that _ = 1 implies a square shape.

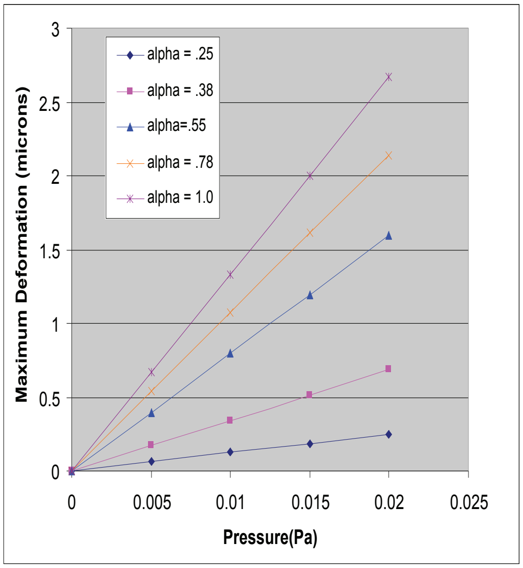

Figure 9: Maximum deformation vs. pressure

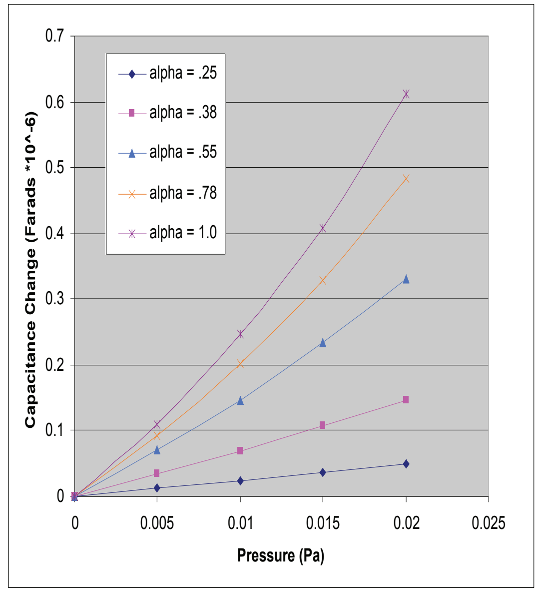

Figure 10: Capacitance change vs. pressure

The upper curves in Figs, 9 and 10 depict maximum deformation and capacitance change in a square shaped pressure sensor exhibiting higher sensitivity.

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