Analysis of Geometry Influence on Performances of Capacitive Pressure Sensor

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***Abstract*—In this work analysis of performances of a capacitive pressure sensor is performed, using COMSOL software tool. The basic sensor structure is composed of two cavities separated with a thin membrane. One cavity contains reference pressure (vacuum) and the other is connected with the measured pressure. When this pressure is changed, membrane is deformed depending on several factors such as applied pressure, used materials mechanical properties and geometry of the sensor structure. Influence of these parameters on sensor characteristics is analyzed and capacitance as a function of applied pressure plots is presented. It is demonstrated that COMSOL is a powerful software tool for successful prediction of performances of capacitive pressure sensors with different geometries, even in the cases with dynamics such as when sensor membrane is deformed.**

***Index Terms*—Capacitive pressure sensor, COMSOL, geometry influence.**

I. Introduction

Most electrical sensors usually use membranes as primary elastic element. Applied membranes are suitable for measuring the pressure from its lowest values to the highest. Measurement range, operating frequency and the sensor sensitivity depend on the characteristics of the primary element. Deformation of elements that occurs due to effects of pressure (differential pressure), is further converted into electrical output signal. According to that, sensors can be divided into: electromagnetic, capacitive, resistive and piezoelectric sensors.

Principle of the capacitive sensor operation is that it uses a membrane as movable capacitor electrode. Typical measurement range of this sensor is from 100 Pa to 10^8 Pa, and the accuracy is ± 0.25-0.05%. Some disadvantages of capacitive pressure sensors are: the capacity and the movement of outer lines affect the output signal distortion; high output impedance must be balanced, the sensitivity on the change of temperature and required shielding of the connection cables. On the other hand, good features are: high frequency permeability, manufacturing process simplicity, low costs, the possibility of measuring static and dynamic changes, the small membrane mass, small volume and continual resolution [1].

Pressure sensors are used in various automotive, biomedical and other industrial applications [2]. Since 1980, a great number of publications has appeared having silicon capacity pressure sensors as the topic. Thus, for example, blood pressure measurement sensors were developed [3, 4], a different forms of membrane geometry were discussed (circular, rectangular, square) [5], and also the characteristics of differential pressure sensors were considered [6].

In this work, the analysis of the capacitive pressure sensor that measures the static pressure in the range from zero to atmospheric was performed. Performance analysis of the proposed sensor was carried out using COMSOL [7] software tool for different geometry of the sensor structure and different membrane thicknesses.

II. Capacitive Pressure Sensor Structure

The basic sensor structure is composed of two cavities separated with a thin membrane. One cavity contains reference pressure (vacuum) and the other is connected with the measured pressure. When the pressure changes, the membrane is deformed and the magnitude of the deformation depends on several factors: the pressure amount, the mechanical properties of material, and the structure shape [7].

Any initial stress in the material also affects the deformation. Therefore, the manufacturing process and the selected materials directly affect the sensor operation. In some structures the membrane and cavities are engraved into silicon and sealed with glass layers. Because the materials are bonded together at a high temperature, cooling them down to the sensor's normal operating temperature produces undesirable stress in the material that affects device performance.

A common way of detecting the membrane deformation is the capacitance measuring. The surface of the deforming membrane and the opposite side of one of the cavities are coated with metal. Thus they form a capacitor whose value depends on the distance of the plates and on the system geometry. Hence, deflection of the membrane results capacitance changes between movable and fixed electrodes.

COMSOL software tool has been used for electric parameters and simulation analysis as a function of the applied pressure. COMSOL Multiphysics is a powerful interactive

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environment for modeling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs), and its use does not require a deep knowledge of mathematics or numerical analysis, but the models are built on the basis of adequate physical characteristics equations. For a capacitive pressure sensor analyzed in this work the model first computes the initial stresses from device construction; then it accounts for the structure's mechanical deformation resulting from an applied pressure. It finally calculates the sensor's capacitance for the deformed shape from the electric field. Often the deforming membrane is a circular or rectangular diaphragm fixed at all boundaries. But viewing this structure in 2D, a bridge type structure results, which is fixed only at the two edges. Fig. 1 and Fig. 2 illustrate the analyzed model's geometry.

As shown on Fig. 1 and Fig. 2 the model consists of three layers. The active silicon structure sits between two blocks of glass. The following list provides descriptions of the different structures in the sensor:

- Top and bottom layers
  - Rectangular
  - Material: Glass, HOYA, SD-2
  - Width: 2.5 mm
  - Height: 0.5 mm

- Middle layer
  - Complex structure: a rectangle in which cavities needed for sensor operation are engraved
  - Material: Silicon
  - Width: 2.5 mm
  - Height: 0.5 mm
  - Membrane width: 1.5 mm or 1.9 mm
  - Membrane height (thickness of membrane): 10, 20 or 30 μm

- Cavity with a vacuum
  - Symmetric trapezoid or rectangular
  - Material: Vacuum
  - Width at the top: 1.9 mm
  - Width at the bottom: 1.5 mm
  - Height: 0.475 mm

- Cavity with ambient pressure
  - Rectangular
  - Material: Air
  - Width: 1.5 mm or 1.9 mm
  - Height: 5 μm

- Capacitance measurement
  - Done with two metal plates at the top and bottom of the cavity with ambient pressure
  - Top plate potential: 1 V
  - Bottom plate potential: Ground
  - Plate width: 1.0 mm

The thickness of all parts is 2.5 mm.

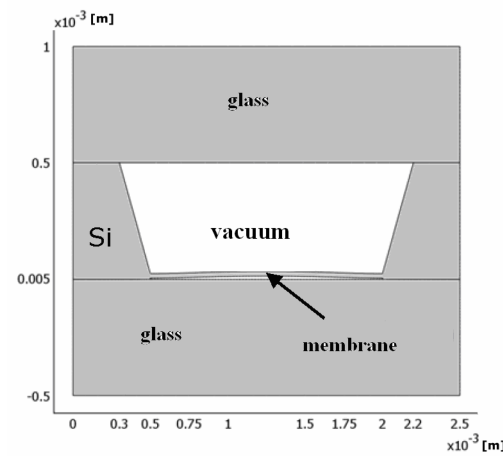

Fig. 1. 2D view of a pressure sensor (geometry: symmetric trapezoid).

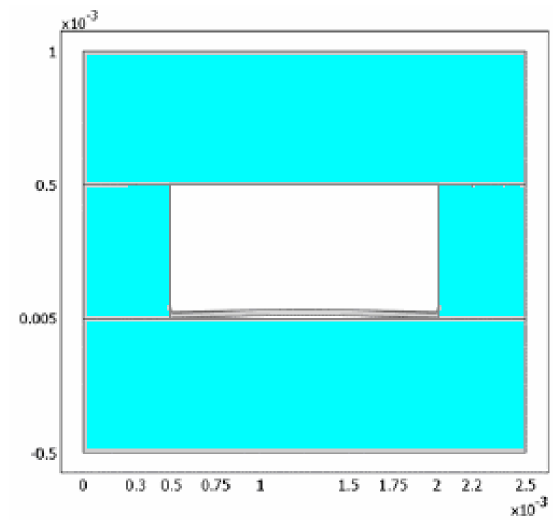

Fig. 2. 2D view of a pressure sensor (geometry: rectangular).

III. Stress and Deformation

Mechanical deformation is a change of shape and volume of the body under the action of external forces (or pressure).

During manufacturing, the sensor is bonded together in a vacuum and at a high temperature and is then cooled down. Therefore, during this process no external forces act on the sensor's boundaries, but internal stresses appear because the two materials have different coefficients of thermal expansion. This process also produces a vacuum in the upper cavity, and it serves as the reference pressure.

During normal operation, the sensor is fixed on a solid surface, and ambient pressure pushes on all outer boundaries. The temperature also changes, which produces extra stresses due to thermal expansion.

For a linear elastic material, the stress-strain relationship including the initial stress (σ_0), initial strain (ε_0) and thermal effects (ε_{th}), is:

$$\sigma = D\varepsilon_{el} = D(\varepsilon - \varepsilon_{th} - \varepsilon_0) + \sigma_0 \tag{1}$$

where D is the elasticity matrix.

Initially only thermal expansion is active, and it comes from the relationship:

$$\varepsilon_{th} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{bmatrix} = \alpha_{vec}\left(T - T_{ref}\right) \tag{2}$$

where α_{vec} are the coefficients of thermal expansion, T is the ambient temperature, and T_{ref} is the reference temperature.

This model assumes that after manufacturing the sensor is close to its initial geometry and thus the initial strain is zero.

For calculating large deformations, strain values come from the expression:

$$\frac{\gamma_{ij}}{2} = \varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i} \cdot \frac{\partial u_k}{\partial x_j}\right) \tag{3}$$

For the case of large deformations, the model solves the problem using the principle of virtual work, which states that the sum of virtual work from internal strain is equal to work from external loads.

IV. Modeling in COMSOL Multiphysics

In COMSOL Multiphysics this problem can be solved using four application modes: two Plane Stress application modes, one Moving Mesh (ALE) application mode, and one Electrostatics application mode. The latter two are defined in a frame to allow the mesh to move.

Because the structure's deformation can be large, a large deformation analysis for both Plane Stress application modes must be used. The electric field was solved only in the small air gap where the ambient pressure is applied to the sensor (Fig. 3).

The solution process takes place in four steps:

1. The first Plane Stress application mode represents the sensor's fabrication, and it computes the initial stresses that result from thermal expansion using static solver.
2. The second Plane Stress application mode solves the deformation and stresses that result when the sensor is exposed to ambient temperature and pressure. It uses the initial stresses and deformation from the first plane stress application mode. This is solved with a parametric solver for different values of ambient pressure.
3. The ALE mesh for each ambient pressure can be solved using a parametric solver.
4. Finally, electric field for each ambient pressure can be solved using a parametric solver.

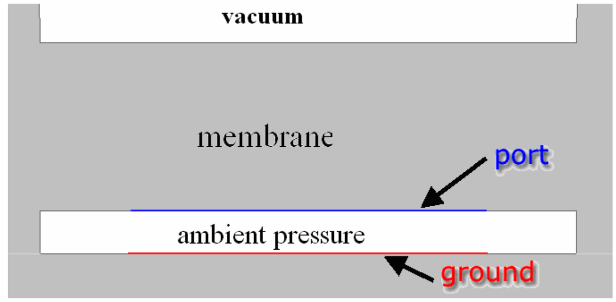

Fig. 3. Position of capacitors plate.

V. Results and Discussion

Fig. 4 shows the results after the bonding phase, where bonding took place at 400 °C and the sensor is then cooled down to 22 °C. In the image the x- and y- axes have different scales, and the structural deformation is scaled by 20.

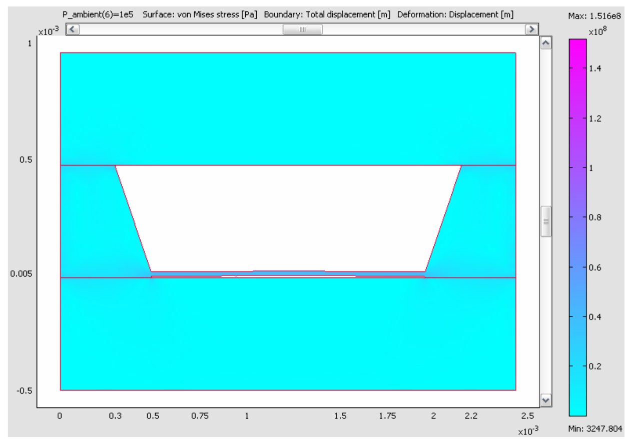

Fig. 4. Initial stresses of the materials in the pressure sensor (geometry: symmetric trapezoid).

It appears that the membrane slightly pulls towards the larger cavity even though there are no applied loads. Stresses appear near the boundaries of the different materials and in the silicon membrane, which is narrower than other parts of the sensor. The maximum appears at the lower left corner of the smaller cavity.

Fig. 5 shows the results when the sensor is in operation: it is exposed to a pressure of one atmosphere at 22 °C. The figure is arbitrarily scaled and is focused on the left half of the lower cavity. The membrane deforms toward the vacuum with maximum deformation at the middle. Maximum stresses appear at the upper corners of the lower cavity where the membrane attaches to the silicon boundaries. The streamlines show the electric field in the lower cavity. The lines are vertical between the two electrodes. Some field lines appear outside of the electrode region, but the field strength is very small there (dark blue color).

The capacitance change as a function of the ambient pressure for different membrane thicknesses is presented in Fig. 6, from the model shown in Fig. 4.

As can be seen from Fig. 6 capacitance change as a function of the pressure is slower for thicker membrane. This is a consequence of lower resilience of higher membrane and

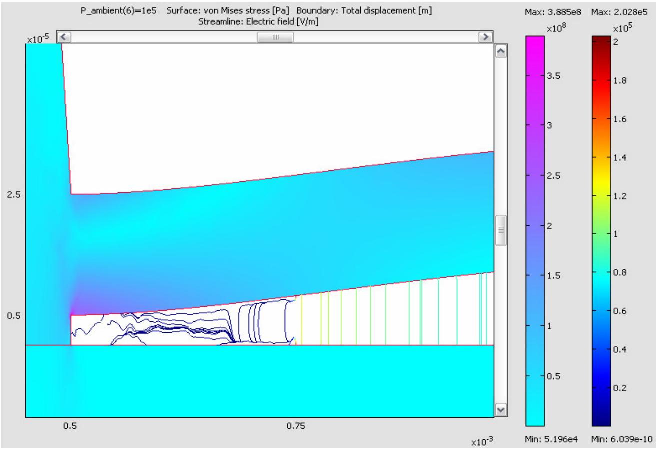

Fig. 5. Sensor deformation, stresses (left color bar: von Mises Stress) and electric field (right color bar: Electric field strength) when exposed to ambient pressure.

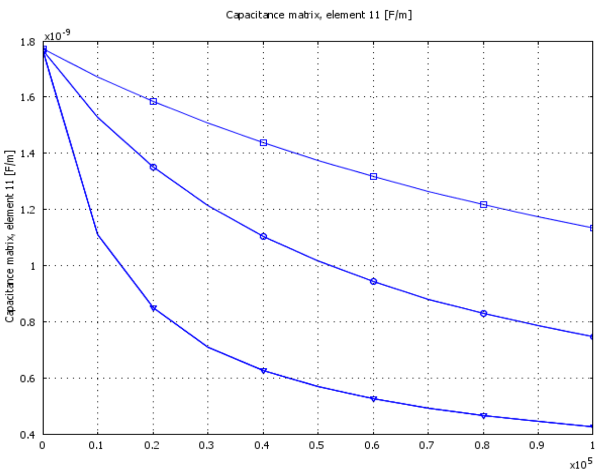

Fig. 6. Computed capacitance vs. ambient pressure for three different values of membrane thicknesses: (membrane thickness =10 μm, ∇; membrane thickness =20 μm, ○; membrane thickness =30 μm, □).

smaller influence on the capacitance change at the same applied pressure.

Fig. 7 illustrates geometry of the upper cavity of the middle layer: rectangular (width 1.5 mm).

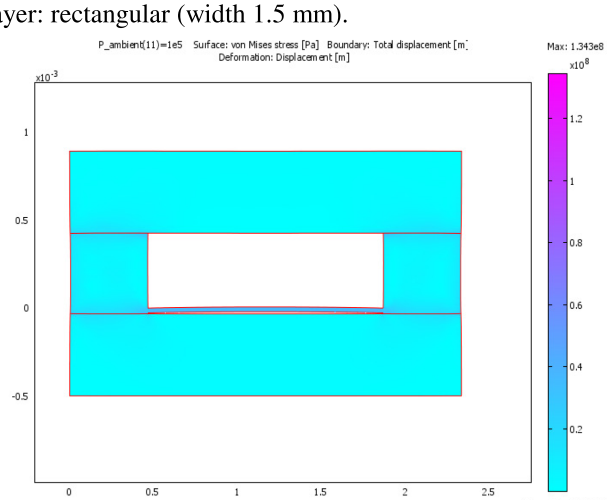

Fig. 7. Initial stresses of the materials in the pressure sensor (geometry: rectangular (width 1.5 mm)).

For this geometry, computed capacitance vs. ambient pressure for three different values of membrane thicknesses is almost the same as in Fig. 6. So, it can be noticed that the change of cavity geometry from the symmetric trapezoid into rectangular, with a width equal to the shorter base of the symmetric trapezoid (membrane width is not changed) is not significantly influenced on computed capacitance.

In the next step, geometry of upper cavity and the geometry of lower cavity have been changed. Geometry is now rectangular with width of 1.9 mm, as it shown in Fig. 8.

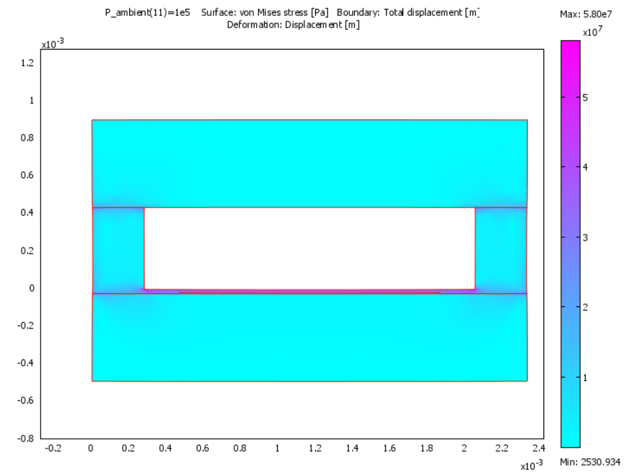

Fig. 8. Initial stresses of the materials in the pressure sensor (geometry: rectangular (width 1.9 mm)).

Fig. 9 presents the capacitance change as a function of applied pressure, C=f(P), from model shown in Fig. 8 for different membrane thicknesses.

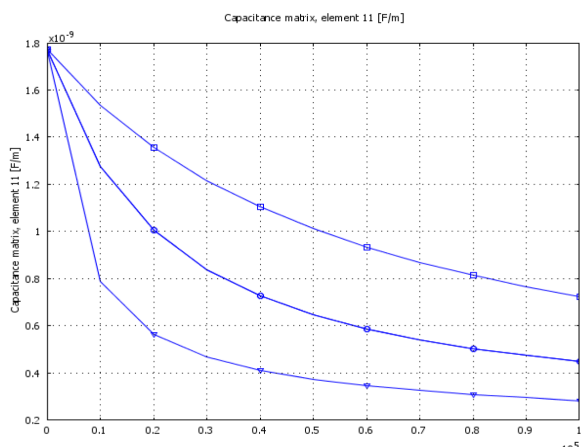

Fig. 9. Computed capacitance vs. ambient pressure for same temperature conditions and three different values of membrane thicknesses: (membrane thickness =10 μm, ∇; membrane thickness =20 μm, ○; membrane thickness =30 μm, □). Membrane width is 1.9 mm.

Fig. 9 plots C=f(P) for sensor structure with constant membrane width (1.9 mm) and variable membrane thickness (10 μm, 20 μm, 30 μm). Fig. 9 as the previous plots shows that thicker membrane causes slower change of capacitance in a function of applied pressure. However, increasing the membrane width from 1.5 mm to 1.9 mm resulted lower capacitance values at the same values of pressure compared with results shown in Fig. 6.

The rate of capacitance change in a function of applied pressure can be changed choosing a different membrane material (with more or less elasticity). Material with higher modulus of elasticity (Young's modulus - E) has a higher rigidity, and lower elasticity. In Fig. 10, except for silicon, is shown computed capacitance vs. ambient pressure for materials with twice and four times higher Young's modulus of silicon membrane.

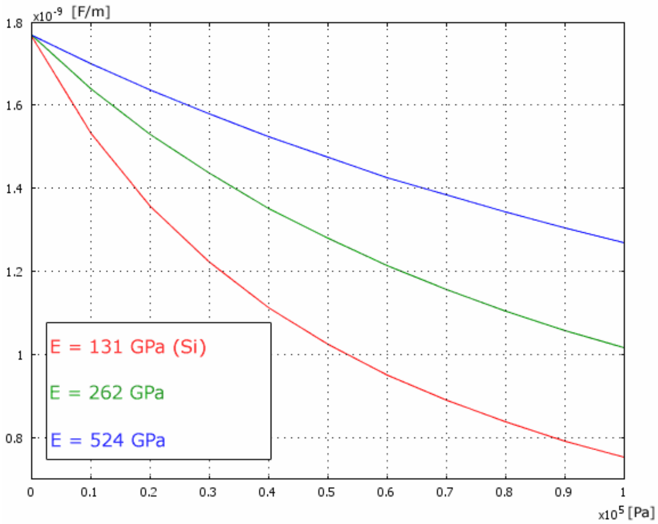

Fig. 10. Computed capacitance vs. ambient pressure for three different values of Young's modulus of membrane material.

VI. Conclusion

Capacitive deformation detector can be realized as the differential capacitive sensor with movable membrane as electrode. The membrane is engraved in the middle layer of sensor structure. Fixed electrode is the metal coated opposite side of one of the cavities. Deflection of the membrane due to pressure differences results in changes in capacitance between movable and fixed electrodes. Results showed that if the membrane was thicker, capacitance values were higher and capacitance change as a function of applied pressure was slower. The capacitance as a function of pressure is not significantly changed when the symmetric trapezoid geometry at the larger cavity of the middle layer is replaced with rectangular (membrane width and geometry of smaller cavity are not changed). But, when the symmetric trapezoid geometry at the larger cavity of the middle layer is replaced with rectangular whose width is equal to wider base of symmetric trapezoid and with wider membrane in smaller cavity, obtained capacitance values at the same values of applied pressure were lower compared with previous results.

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