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Research paper

A novel high sensitive capacitive pressure sensor for measuring intraocular pressure

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Abstract

In this paper, a new MEMS-based capacitive pressure sensor have been designed and characterized to measure pressures in the range of 0 - 60 mmHg (i.e. 0-8 KPa) that is in the range of intraocular pressure sensors. Intraocular pressure sensors are important in the early detection and treatment of Glaucoma which is an incurable disease. Two sensor designs incorporating conventional and slotted diaphragm are implemented and compared to realize the pressure-sensitive components. The novelty of this method relies on diaphragm includes some slots to reduce the effect of residual stress and stiffness of diaphragm and increase sensor sensitivity. The slotted diaphragm makes capacitive pressure sensor more sensitive, that is more suitable for measuring intraocular pressure sensor. The results yield a sensitivity of 1.113×10-4 1/Pa for the conventional and 2.375×10-4 1/Pa for the slotted pressure sensor with a 0.5 × 0.5 mm2 diaphragm. It can be seen that the sensitivity of the sensor with slotted diaphragm increased 2.13 times compared with the conventional diaphragm. Furthermore, the resonance frequency for the conventional diaphragm is 143.29 KHz while the resonance frequency for the slotted diaphragm is 128.75 KHz.

***Keywords**: Capacitive Pressure Sensor; COMSOL Multiphysics; Deflection; Displacement; Intraocular Pressure Sensor; MEMS.*

1. Introduction

This document can be used as a template for Microsoft Word versions 6.0 or later. A pressure sensor measures the pressure of the force applied across a surface in terms of force per unit area. Pressure sensors are used for control and monitoring in thousands of everyday applications involving direct measurement or even be used to indirectly measure other variables. There are two basic categories of pressure sensors: force collective type that relies completely on the pressure applied and the other type that completely relies on the other modes such as density and thermal conductivity to sense the amount of pressure being developed. Typical pressure sensors generally use a force collector to measure deflection due to applied force over an area.

Literature surveys of pressure sensors for biological development have reported Glaucoma is a group of eye diseases, characterized by elevated intraocular pressure (IOP). IOP is the pressure exerted by the ocular fluid called Aqueous Humor that fills the anterior chamber of the eye. In most glaucoma patients, the IOP increases above the normal range. Elevated IOP is associated with loss of optic nerve tissue, loss of peripheral vision, and leads to blindness if not treated; the condition is painless and cannot be detected without a pressure measurement, direct or indirect. Therefore, it is imperative to have an accurate measurement of the IOP [1]. The biomedical systems utilizing these diaphragm-based pressure sensors are classified into active and passive sensing devices. Almost all the passive and active devices used capacitive transducers for pressure sensing for their low power consumption, low noise, high sensitivity and low temperature drift. Advances in silicon micromachining techniques have also helped in the miniaturization of the capacitive pressure sensors. Capacitive pressure sensors translate a pressure change into a capacitance variation. Capacitive pressure sensors generally operate by sensing the downward displacement of a thin, flexible conductive diaphragm as one of the electrodes, while the other electrode is fixed beneath the diaphragm. Deformation of the movable part due to applied pressure is sensed and translated into an electrical capacitance change (see Figure 1). In this paper, we have designed and characterized a capacitive pressure sensor that can detect the IOP at a very early stage with an increased amount of sensitivity.

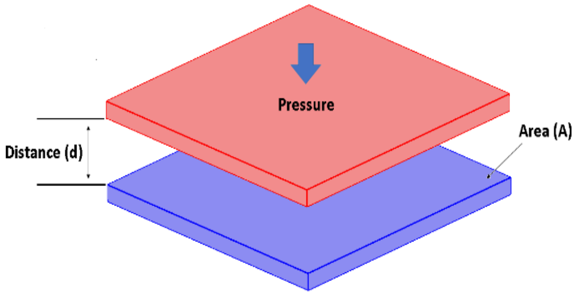

Fig. 1: Conventional Pressure Sensor Structure [2].

Microelectromechanical systems (MEMS) represent an extraordinary technology that promises to transform whole industries by helping us reduce cost, bulk and power consumption while increasing performance, production volume and functionality by orders of magnitude. MEMS is an emerging technology which uses the tools and techniques that were developed for the Integrated Circuit industry to build microscopic machines. These machines are built on standard silicon wafers. The real power of this technology is that many machines can be built at the same time across the surface of the wafer, with no assembly required. These tiny machines are quickly finding their way into a variety of commercial and defense applications. MEMS-based technology is seeing its use in the fields of automobile, electronics, biomedical and defense. MEMS-based sensors are a crucial component in automotive electronics, medical equipment, computer peripherals, wireless devices and smart portable electronics such as cell phones. Compared to the other products, MEMS capacitive sensors offer many advantages that will play a very crucial role in biomedical and healthcare applications [3].

2. Theoretical concepts

Capacitive pressure sensors measure changes in pressure by the deflection of diaphragm due to the applied pressure. Parallel plate pressure sensors typically have dielectric gas between the electrodes and the deflection in the diaphragm due to change in pressure produces a capacitance variation (Figure 1). The capacitance between two parallel electrodes can be expressed as:

$$C = \frac{\varepsilon_0 \, \varepsilon_r \, A}{d} \tag{1}$$

Where ε_0 , ε_r , A and d are the permittivity of free space (8.854×10^{-14} F/cm), relative dielectric constant of the material between the plates (unity for air), effective electrode area and gap between the electrodes, respectively. From this relationship, any variation in the spacing between the two electrodes or their effective area would result in a change in capacitance [4], [5].

The range of measurement in the capacitive pressure sensor depends on the diaphragm-substrate separation and also maximum stress the diaphragm can tolerate during operation.

The main challenge of the design is the nonlinear relationship of capacitance variation to the electrodes separation results in a nonlinear sensor operation, but in the case of small pressure variations, the relationship can be linear.

For the requirements of IOP range we need a sensor which is biocompatible and mostly the sensitivity and accuracy of the sensor can be guaranteed. For this reason, we have designed a diaphragm utilizing polysilicon which is biodegradable and compatible. The quality or condition of being sensitive is required, so that intraocular pressure based disease like glaucoma can be detected at the very early stage with greater accuracy. This study and investigation of capacitive sensor design in the next section is to be utilized it for more applications.

3. Sensor design

All paragraphs must be justified alignment. Design of a device depends on various parameters like material, structure and shape etc. All the parameters are needed to be optimized to obtain the desired specification of the device. The design started with the selection of the substrate material and its properties. In the present work, polysilicon having Young's modulus of 169 GPa and Poisson's ratio 0.22 has been used as the structural material for the sensor diaphragm because of its biocompatibility and low stress compared to other materials (i.e. 40 MPa) [6].

Based on these properties used, the shape of the diaphragm was optimized. Square shape has been chosen, due to the ease of anisotropic etching of the silicon in bulk. All the parameters necessary for the design of capacitive pressure sensors are optimized for this shape.

Figure 2 shows a top view of slotted pressure sensor. The structure parameter of the sensor includes the dimension of the diaphragm, the dimension of the fixed electrode and the height of the air gap. In our design, the diaphragm structure considered for increasing the sensitivity is L = 500 µm, w = 500 µm and thickness of 4um, the gap between two electrodes is 2 µm and the dimensions of the fixed electrode is L = 500 µm, w = 450 µm with a height of 2 µm. The slots would be placed symmetrically in the diaphragm and in practice, we can deposit a very thin polyamide layer on diaphragm to prevent the influence of the eye liquid into air gap of sensor. Seal-off technique is generally used to fabricate thin diaphragm which acts as a pressure sensor. Advances in silicon micromachining techniques have helped in miniaturization of capacitive pressure sensors and offers the possibility to reduce the size of the total system [7]. Hence the design in terms of feature size is to play a crucial role for sensitivity amplification the main goal of our sensor.

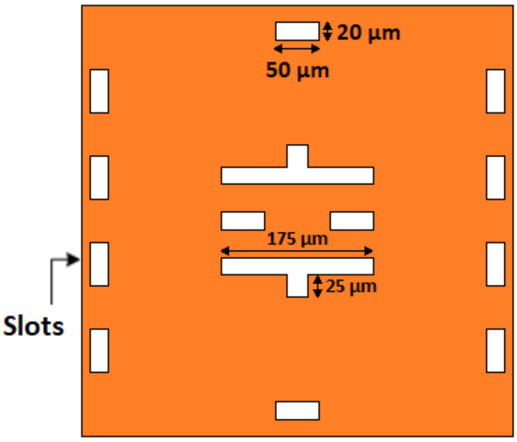

Fig. 2: Top View of Slotted Pressure Sensor Diaphragm.

4. Simulation results

For simulating MEMS capacitive pressure sensor diaphragm as specified in the previous section, finite element method (FEM) is used via COMSOL Multiphysics software to optimize the design, and analyze the mechanical properties of the device. The objectives of analysis are first, to verify the deflection of the diaphragm due to the mechanically applied force between the diaphragm and the bottom electrode. Second, is to verify the deflection and capacitance between the diaphragm and the bottom electrode to evaluate sensitivity. The standard material properties are specified in accordance with the simulation software and the literature survey [1]. Figure 3 highlights the materials used for evaluation for the plain surface as well as the slotted diaphragm.

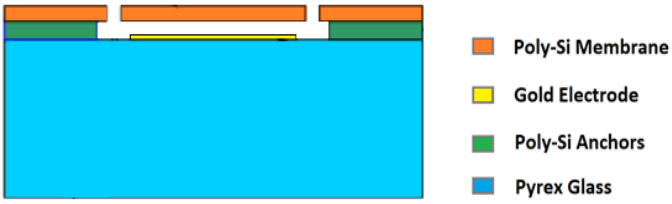

Fig. 3: Materials Evaluated During Analysis.

The deformation of the diaphragm has been achieved for the applied pressure values ranging from 0 - 60 mmHg. A change in the capacitance of the sensor was observed due to this deformation. The Displacement of the conventional and slotted diaphragm is shown in Figure 4 and Figure 5. The displacement observed for 60 mmHg pressure in conventional and slotted diaphragm is 1.47 µm and 1.86 µm respectively.

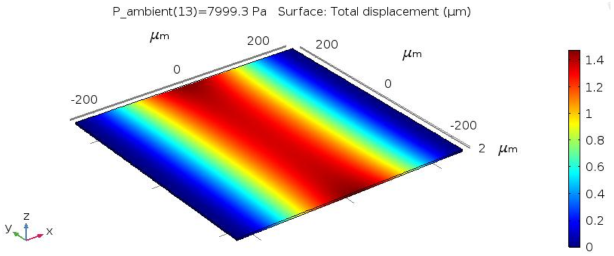

Fig. 4: Displacement of the Conventional Diaphragm.

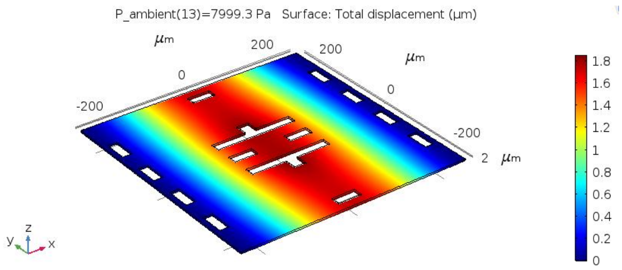

Fig. 5: Displacement of the Slotted Diaphragm.

As we can see in the figures, the slotted diaphragm has more deflection (1.86 µm) than the conventional one (1.47 µm) under the same load. So, for the maximum applied pressure, the deflection of the slotted diaphragm increases by 26.53%.

Figure 6 shows the simulated relation between capacitance and applied pressure for conventional and slotted pressure sensor. It can be seen from figure that the initial capacitance for conventional and slotted diaphragm is about 1 pF and 1.1 pF respectively. As pressure applies from 0 to 60 mmHg, the capacitance varies from 1.1 pF to 2.08 pF and 1 pF to 2.9 pF for conventional and slotted diaphragm respectively, so the total variation of the capacitance for slotted diaphragm is 1.9 pF.

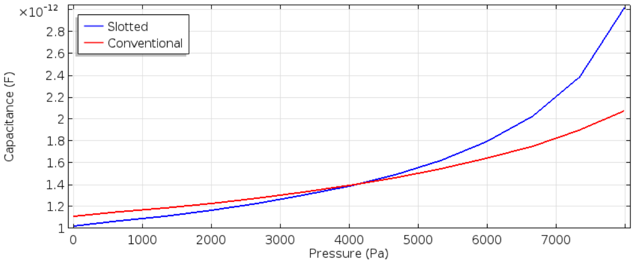

Fig. 6: Capacitance vs. Applied Pressure for the Conventional and Slotted Pressure Sensors.

The sensitivity of capacitive pressure sensor can be defined as:

$$S = \frac{\Delta C}{C_0 P} \tag{2}$$

Where ΔC is the capacitance changes, C_0 is the initial capacitance, and P is the applied pressure. Using Equation (1), the slope of the curves shows the sensitivity of the pressure sensor. The results yield a sensitivity of 1.113×10^{-4} 1/Pa for the conventional and 2.375×10^{-4} 1/Pa for the slotted pressure sensors. By introducing the slots in the diaphragm, the sensitivity increased 2.13 times.

The stress distribution in a capacitive sensor of plate size 500 µm × 500 µm is shown in Figure 7. The maximum stress amplitude on the diaphragm at a pressure load of 60 mmHg, is 145 MPa which was considerably lower than the average stress amplitude that Polysilicon can tolerate (i.e. 2 GPa) [8].

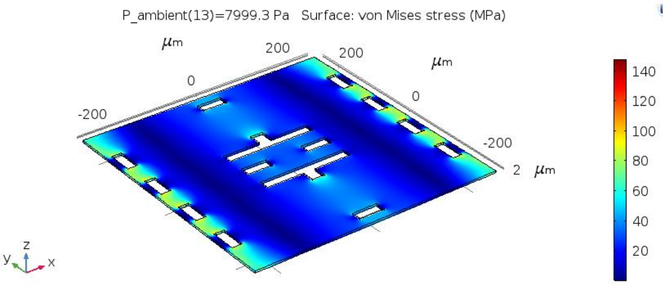

Fig. 7: Stress Distribution in A 500 Mm × 500 Mm Capacitive Sensor at A Pressure Load of 60 Mmhg (8 Kpa).

The spectrum analysis of the sensor is performed from 100 to 300 KHz. As can be seen in Figure 8, the resonance frequency of conventional diaphragm is 143.29 KHz while the resonance frequency of slotted diaphragm is 128.75 KHz. It is obvious that a slotted diaphragm will increase the deflection but we observe a reduction in frequency by 14.54 KHz that is by adding slots to the diaphragm. But still it is much bigger than the frequency of the human eye. So we can conclude that adding slots has no interference in the pressure sensor performance.

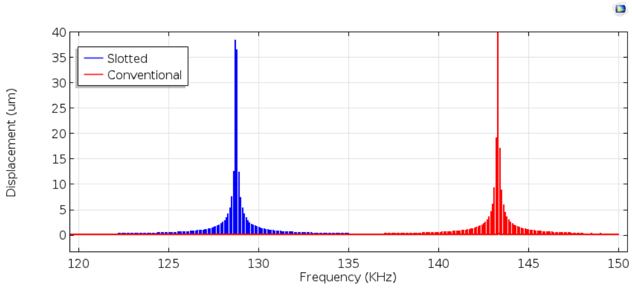

Fig. 8: Diaphragm Displacement versus Frequency for Conventional and Slotted Diaphragm.

5. Conclusion

In this paper, a novel high sensitive MEMS capacitive pressure sensor has been presented. The device used a slotted polysilicon diaphragm as a biocompatible material. This capacitive pressure sensor is optimized for measuring intraocular pressure sensor in the range of intraocular pressure sensor (0–60 mmHg). The pressure sensor uses a square polysilicon diaphragm with a thickness of 4 µm, an air gap of 2 µm and a 0.5×0.5 mm^2 diaphragm. By adding some slots in Polysilicon conventional pressure sensor, an improvement of sensitivity has been achieved. The results yield a sensitivity of 1.113×10^{-4} 1/Pa for conventional and 2.375×10^{-4} 1/Pa for the slotted pressure sensor. The results show that the sensitivity of the new structure increased 2.13 times.

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