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Design and Simulation of High Sensitive Capacitive Pressure Sensor with Slotted Diaphragm

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Abstract— **This paper presents a high sensitive MEMS capacitive pressure sensor for biomedical applications. Two sensor designs incorporating clamped and slotted diaphragm are implemented and compared to realize the pressure-sensitive components. The pressure sensor has been designed to measure pressures in the range of 0 to 60 mmhg that is in the range of intraocular pressure sensors. Intraocular pressure sensors are important in detection and treatment of an incurable disease called glaucoma. The capacitive pressure sensor is formed using p++ silicon diaphragm as a biocompatible material. The novelty of this method relies on p++si diaphragm includes some slots to reduce the effect of residual stress and stiffness of diaphragm. The slotted diaphragm makes capacitive pressure sensor more sensitive. That is more suitable for measuring intraocular pressure sensor. The results yield a sensitivity of 1.811×10^{-5} 1/Pa for the clamped and 5.96×10^{-5} 1/Pa for the slotted pressure sensor with a 0.55×0.55 mm^2 diaphragm. Furthermore, the pull-in voltage for the clamped pressure sensor is 51v, while the pull-in voltage of the slotted one is 38v.**

Keywords- MEMS, Capacitive pressure sensor, Sensitivity, Slotted diaphragm.

I. INTRODUCTION

Millions of people worldwide are afflicted by irreversible vision loss attributed to glaucoma [1]. 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 [2]. Normal IOP is in the range of 10–21 mmHg [3-4]. In most glaucoma patients, the IOP increases above the normal range when the aqueous outflow is lower than the inflow because of increased resistance to the fluid flow in the drainage pathway. Elevated IOP is associated with loss of optic nerve tissue, loss of peripheral vision, and leads to blindness if not treated [2]. 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 in the case of glaucoma patients [5].

An extensive review of the existing IOP pressure measurement techniques was presented by the authors in [2]. The accuracy of IOP measured by conventional techniques such as Goldmann applanation tonometry depends largely on corneal stiffness [6]. Furthermore, a visit to a physician's office is generally required. So Multiple or continuous measurement of the IOP in glaucoma patients may help in better disease diagnosis, monitoring, and management [2]. In these cases, telemetric sensing becomes a specially attractive method to meet this requirement. By means of telemetry, it is possible to capture data externally from an implanted sensing device without using wires [7].

During the design of sensor implant, the spatial constraints in the eye, surgical complexity, and reliability of the implants need to be considered. Implants placed in the anterior chamber of the eye have a larger chance of success since the implants placed in the vitreous cavity have a higher risk of infection [5]. Fig. 1 shows option for anterior chamber implants in the eye. The space available in the anterior chamber for sensor implants is found to be in a shape of hollow cylinder with 7 mm inner diameter, 8 mm outer diameter, and a height of 500 micrometer. Instead of trying to make the sensor implants as small as possible, the system should be designed to take advantage of space available to maximize performance [2].

The biotelemetric systems are classified into active sensing devices and passive sensing devices [7], [2]. Almost all the devices, both active and passive, used capacitive transducers for pressure sensing for their low power consumption, low noise, high sensitivity, low temperature drift, and good long-term stability. Advances in silicon micromachining techniques have also helped in the miniaturization of the capacitive pressure sensors [2]. 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 membrane (diaphragm) as one of the electrodes, while the other electrode is fixed beneath the membrane. Deformation of the movable part due to applied pressure is sensed and translated into an electrical capacitance change [8]. In general, the high pressure sensitivity of a capacitive pressure sensor is achieved by increasing diaphragm size, reducing diaphragm thickness, and decreasing sensing gap [9].

In this paper sensitive capacitive pressure sensor has been proposed, to measure pressures in the range of Intraocular pressure sensors. First capacitive sensor with clamped p++si diaphragm is investigated. For achieving more sensitive device and reducing the effect of residual stress and stiffness of diaphragm, slotted p++si diaphragm is proposed and compared with the clamped one. Both sensors are in the form of square diaphragm.

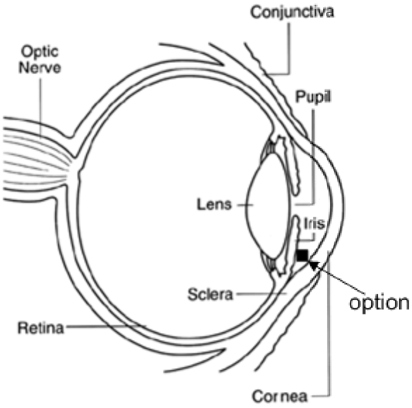


Figure 1. option for anterior chamber implant in the eye.

The paper is organized as follows. Different analysis of the clamped pressure sensor is presented in section II. In section III, pressure sensor design for both clamped and slotted diaphragm is presented. Finite element analysis of the pressure sensor is described in section IV. The simulation results are summarized in section V. Finally, section VI concludes the paper.

II. DIFFERENT ANALYSIS OF THE CLAMPED PRESSURE SENSOR

The deflection of the diaphragm due to the application of an external pressure is dependent on diaphragm's shape. There are two shapes of diaphragms that are commonly used in MEMS devices; square and round. Of course, it is possible to use rectangular shaped diaphragms. However, for the rectangular shape, non-uniform stress distributions develop due to the lack of symmetry of the structure, thus decreasing the sensitivity of the sensor. Goodall [10] demonstrates that there is no clear advantage between square and round diaphragms with the same area and under the same load. However, a square diaphragm can easily and accurately be fabricated because of anisotropic nature of the silicon crystal structure. As a result, it was decided to utilize a square diaphragm instead of a round structure.

A. Mechanical analysis of the clamped sensor

In pressure sensors, pressure is determined by the deflection of the diaphragm due to applied pressure. Fig. 2 illustrates cross-section view of the typical clamped pressure sensor diaphragm. The diaphragm sidelength is $2a$, thickness h, and the thickness of the airgap is d. When exposed to an external uniform pressure P, the diaphragm deflects causing a decrease in the airgap that results in an increase in capacitance between the diaphragm and the backplate. When pressure is withdrawn, the diaphragm moves back to its original position resulting in a decrease in capacitance. For a time-varying incident pressure, the capacitance change follows the same dynamic characteristics of the incident pressure. This change in capacitance is converted into a useful voltage signal using a bias voltage and a charge integrator.

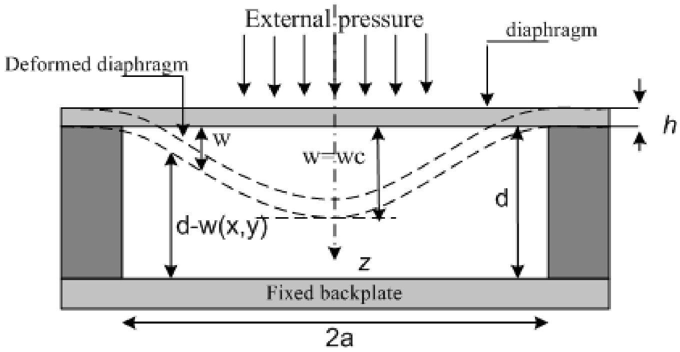


Figure 2. cross section view of typical pressure sensor diaphragm.

The deflection of a flat, clamped, square diaphragm without initial stress is given approximately [11-12]

$$P=\frac{E}{\left(1-\nu^2\right)}\frac{h^4}{a^4}\left[4.2\frac{w_c}{h}+1.58\frac{w_c^{\,3}}{h^3}\right]. \tag{1}$$

where a is the half-side length, h is the thickness, w_c is the center deflection, E is young modulus and ν is the poisson's ratio of the square diaphragm.

For large value of initial tension, the deflection of a square diaphragm can be represented by [13]

$$P=\left[\frac{4\delta w_c h}{a^2}\right] \tag{2}$$

Where δ is the initial stress of the diaphragm. The principle of superposition allows for this term to be added to the original expression given in (1).

$$P=\frac{E}{\left(1-\nu^2\right)}\frac{h^4}{a^4}\left[4.2\frac{w_c}{h}+1.58\frac{w_c^{\,3}}{h^3}+\frac{4\delta a^2}{E}\frac{w_c}{h^3}\right]. \tag{3}$$

It can be seen from (3) that if $(w_c/h) << 1$ the relation between the center deflection, and the applied pressure is approximately linear.

The mechanical sensitivity of a diaphragm is defined as

$$S_m=\frac{dw}{dP} \tag{4}$$

For a small deflection (less than 30% of its thickness), the mechanical sensitivity, S_m, of a square diaphragm, by neglecting the third-order term, can be expressed as

$$S_m=\frac{\left(1-\nu^2\right)}{E}\left(\frac{a}{h}\right)^4\left[\frac{Eh^3}{4.2Eh^2+4\delta a^2}\right] \tag{5}$$

B. Electrical analysis of the clamped sensor

The capacitance between two parallel electrodes can be expressed as

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{6}$$

where ε_0, ε_r , A and d are permittivity of free space (8.854×10^{-14} F/cm), relative dielectric constant of material between the plates (which is unity for air), effective electrode area and gap between the plates, respectively. From this relationship, increasing or decreasing the spacing between the two plates would result in a change in capacitance.

The following equation will determine the capacitance changes in a parallel plate capacitor when the electrode is deflected due to an external force [14]

$$C = \iint \frac{\varepsilon_0}{d - w(x,y)} dx\, dy \tag{7}$$

Where d is the gap height and $w(x,y)$ is the deflection of the diaphragm.

If we define an effective plate deflection as

$$s = \frac{1}{A} \iint w\ dx\, dy \tag{9}$$

where A is the diaphragm area, then the change in capacitance with pressure is

$$\Delta C = C_0 \left(\frac{s}{d - s} \right) \cong C_0 \left(\frac{s}{d} \right) \tag{10}$$

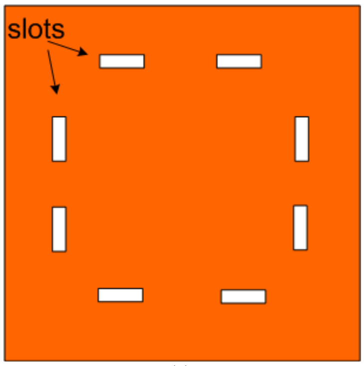
where C_0 is the zero-pressure capacitance. For deflections which are small compared with h, the effective deflection s is about one-fourth of the deflection w, and the small signal pressure sensitivity can be calculated [11].

$$S = \frac{\Delta C}{C_0 P} \tag{11}$$

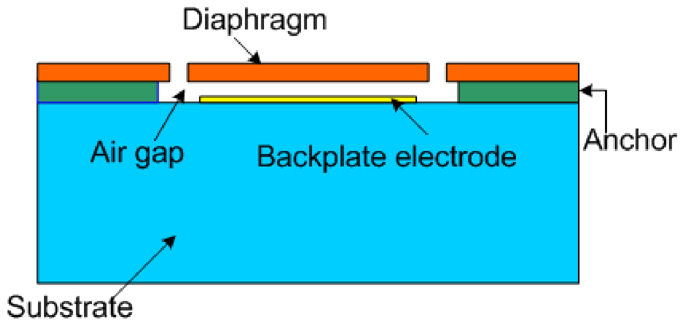
where ΔC is the capacitance change, and P is related to (3).

III. SENSOR DESIGN

The structure of the sensor for both clamped and slotted diaphragm, consists of Pyrex glass back plate, p++si diaphragm, and the backplate electrode is gold. Fig.3 shows a top view and cross section of slotted pressure sensor with slotted diaphragm. The structure parameter of the sensor includes the dimension of the diaphragm, the dimension of the backplate and the height of the air gap. In our design, the thickness of the 0.55mm×0.55mm membrane is 4 μm, and



(a)



(b)

Figure 3. Slotted pressure sensor, a) top view of slotted diaphragm, b) cross section of slotted pressure sensor.

the height of the air gap is about 1.5 μm. The residual stress for p++ silicon is around 40 MPa [15].

To reduce the effect of residual stress and stiffness of the diaphragm, we add some slots around the diaphragm. This will make the sensor more sensitive for measuring intraocular pressure.

IV. SIMULATION SETUP OF CLAMPED AND SLOTTED PRESSURE SENSOR

Intellisuite software is used for simulating of MEMS capacitive pressure sensor to optimize the design, improve the performance and reduce the time of fabricating process 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 backplate. Second, to verify the deflection and capacitance between the diaphragm and the backplate.

Fig. 4 illustrates the simulation setup of the capacitive pressure sensor with clamped diaphragm. Four faces of the p++si diaphragm are fixed. As can be seen from Fig. 4, the diaphragm, backplate electrode and the backplate are shown in green, yellow and blue part, respectively. Fig. 5 demonstrates the simulation setup of the capacitive pressure sensor with slotted diaphragm. Twelve faces of the p++ diaphragm are fixed. The Young's modulus and Poisson's ratio of p++ silicon are assumed to be 160×10^9 Pa and 0.05 respectively [16].

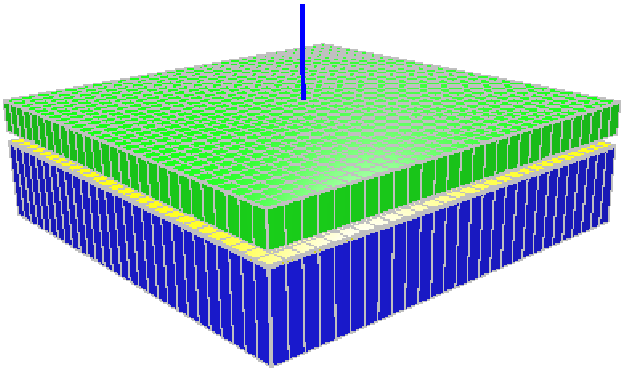


Figure 4. Simulation setup for a clamped sensor.

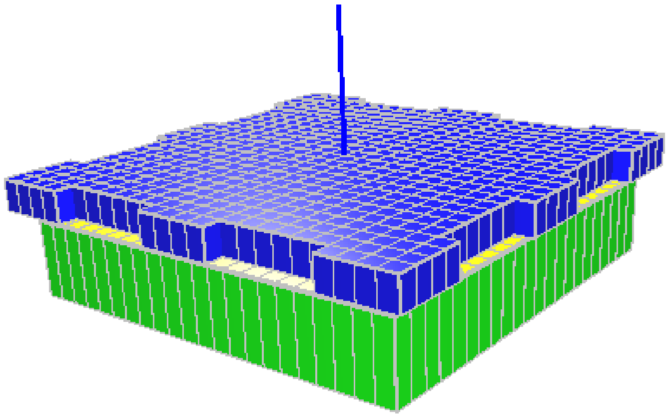


Figure 5. Simulation setup for a slotted sensor.

V. DISCUSSION AND RESULTS

A. pull-in voltage

The pull-in phenomenon causes an electrostatically actuated diaphragm to collapse on the bottom electrode if the drive voltage exceeds certain limit depending on device geometry. The electrostatic force causes the diaphragm to deflect toward the substrate. An increase of the deflection of the membrane results in a decrease of the gap spacing and thus in an increase of the electrostatic force.

Fig. 6 depicts the pull-in voltage of the clamped and slotted structure. It can be seen that the pull-in voltage of the clamped sensor is 51v while pull-in voltage of the slotted sensor is 38v. It is obvious that for slotted diaphragm, the diaphragm stiffness is decreased. Therefore, the pull-in voltage becomes smaller.

B. Displacement characterization

As can be seen from Fig. 7, for the range of pressures applied, the deflection of the center of the diaphragm has been found to vary linearly with pressures. By applying slots, the effect of residual stress and stiffness of diaphragm reduce. So for the maximum applied pressure, the center deflection of the slotted diaphragm becomes approximately double.

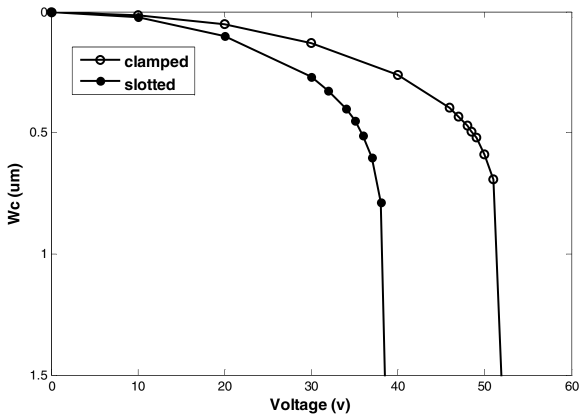


Figure 6. Central displacement of clamped and slotted diaphragm versus voltage.

Fig. 8 shows the central deflection versus thickness of the clamped and slotted diaphragm. From the observation of Fig. 8, it can be concluded that as the sensor thickness is reduced, the pressure sensor deflection for a given pressure load (4kpa) is increased, due to the relative decrease in stiffness of the membrane.

Fig.9 shows the central deflection versus gap height of the clamped and slotted diaphragm. As can be seen for the gap height values more than 1 µm, the deflection of the diaphragm, approximately has no change.

Fig. 10 depicts the central deflection of a clamped and slotted diaphragm with the range of values of initial stress. It can be seen that for a given pressure load (4kpa) the central deflection is decreased when the initial stress is increased.

C. Capacitance characterization

The capacitance is a nonlinear function of the pressure since it varies inversely with w_c, diaphragm center deflection. Fig. 11 shows the simulated relation between capacitance and pressure for clamped and slotted pressure sensor with p++si diaphragms under 4% of pull-in voltage.

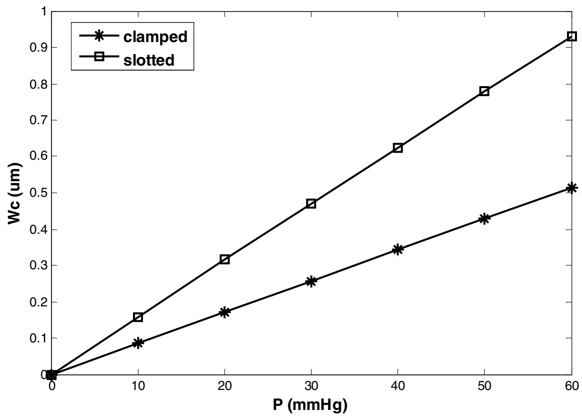


Figure 7. Central displacement of clamped and slotted diaphragm versus pressure.

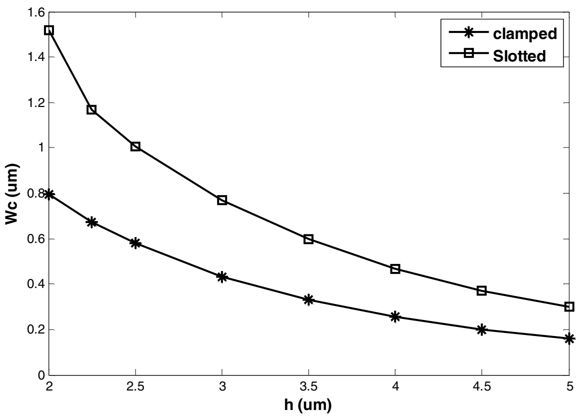


Figure 8. Central displacement of clamped and slotted diaphragm versus diaphragm thickness.

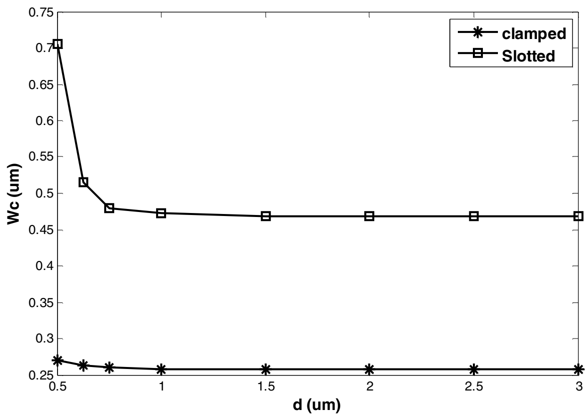


Figure 9. Central displacement of clamped and slotted diaphragm versus diaphragm air gap.

It can be seen from figure that the initial capacitance for both clamped and slotted diaphragm is about 1.81 pF. As pressure applies from 0mmhg to 60mmhg, the capacitance varies from 1.81pF to 2.07pF and 2.7 pF for clamped and slotted diaphragm respectively, so the total variation of the capacitance for slotted diaphragm is 0.89 pF. The results yield a sensitivity of 1.811×10^{-5} 1/Pa for the clamped and 5.96×10^{-5} 1/Pa for the slotted pressure sensors. By introducing the slots in the diaphragm, the sensitivity increased 3.2 times.

Fig. 12 depicts the simulated relation between capacitance and thickness for a given pressure load (4kpa) for clamped and slotted pressure sensor. The capacitance varies inversely with w_c, diaphragm center deflection. Furthermore, the center deflection varies inversely with thickness of the diaphragm (Fig. 8). So we can conclude from (7), the capacitance is decreased when the diaphragm thickness is increased.

Fig. 13 demonstrates the simulated relation between capacitance and gap height for a given pressure load (4kpa) for clamped and slotted pressure sensor. Again from (7), we can see that when the gap height is increased, the capacitance is decreased.

Fig. 14 illustrates the simulated relation between capacitance and initial stress for a given pressure load (4kpa) for clamped and slotted pressure sensor. As we can see, for the clamped diaphragm, no significant capacitance change occurs for initial stress values more than 30 MPa. For both slotted and clamped diaphragm, the capacitance decrease when the initial stress increase.

VI. Conclusion

A high sensitive MEMS capacitive pressure sensor has been designed, and simulated. The device used a slotted p++silicon diaphragm as a biocompatible material. This capacitive pressure sensor is suitable for measuring intraocular pressure sensor that is designed in the range of intraocular pressure sensor (0 to 60 mmhg).

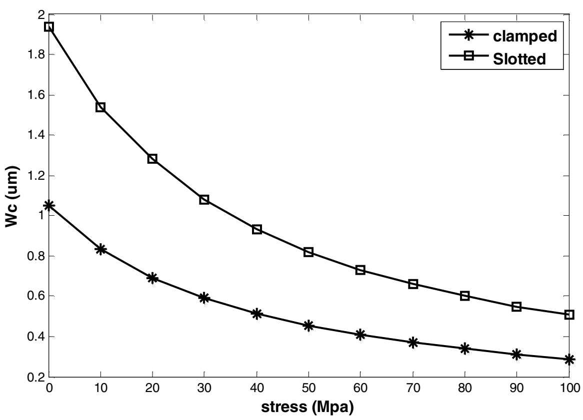


Figure 10. Central displacement of clamped and slotted diaphragm versus diaphragm initial stress.

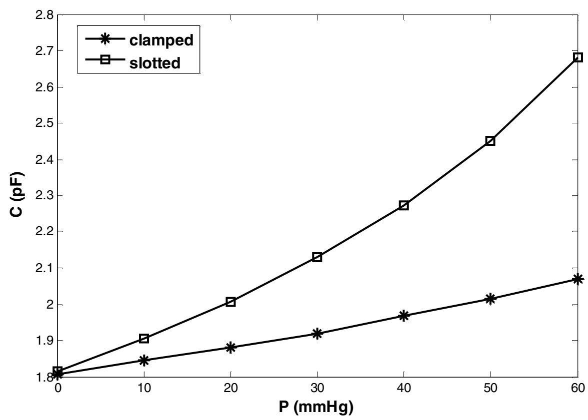


Figure 11. Capacitance versus pressure for the clamped and slotted pressure sensor.

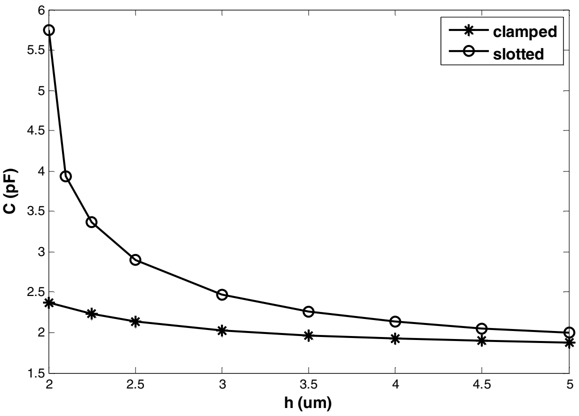


Figure 12. Capacitance versus diaphragm thickness for the clamped and slotted pressure sensor.

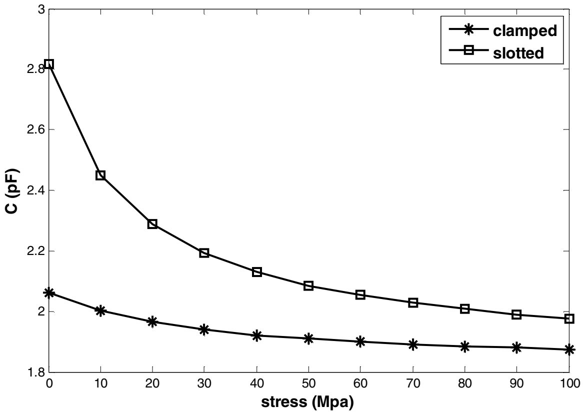


Figure 14. Capacitance versus diaphragm initial stress for the clamped and slotted pressure sensor.

The pressure sensor uses square p++si diaphragm with a thickness of 4 µm, an air gap of 1.5 µm and a $0.55 \times 0.55\ mm^2$ diaphragm. By adding slots to the clamped pressure sensor, improvement in sensitivity of the slotted pressure sensor, has been achieved. The results also yield a sensitivity of 1.811×10^{-5} 1/Pa for the clamped and 5.96×10^{-5} 1/Pa for the slotted pressure sensor. Furthermore, the pull-in voltage for the clamped pressure sensor is 51v, while the pull-in voltage of the slotted one is 38v.

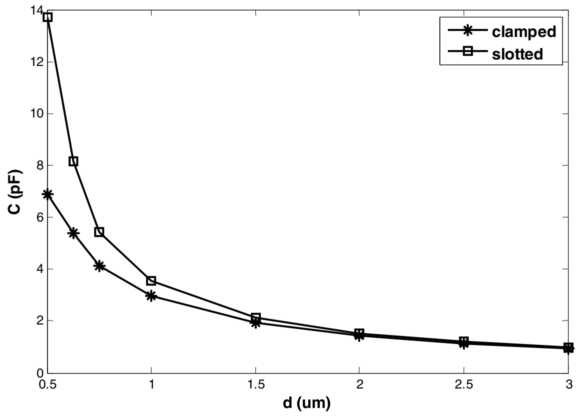


Figure 13. Capacitance versus air gap for the clamped and slotted pressure sensor.

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