Design and Analysis of MEMS High Sensitive Capacitive Pressure Sensor

1Muslihah Ali, 2Norhayati Soin, 1Abdullah C.W. Noorakma, 1Norlana Yusof and 2S.F. Wan Muhamad Hatta
1Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, 21300 Kuala Terengganu, Terengganu, Malaysia
2Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Abstract: In this study, MEMS high sensitive capacitive pressure sensor based on poly-silicon diaphragm have been designed and analysed by using COMSOL Multiphysics Software. Three sensor designs: clamped, 8 slotted and 4 slotted with and without Teflon (polytetrafluoroethylene) coating were tested and compared to understand the sensitivity and deflection of the sensors. The pressure sensor was designed to evaluate the pressure in ranges of 0-60 mmHg which is in the range of Intracocular Pressure (IOP) for glaucoma. The capacitive pressure sensor is design using different structures of the diaphragm and it is identified that 4 slotted square diaphragms gives the highest sensitivities amongst the presented design. By coating the diaphragm and adding slots into the diaphragm, the displacement improves while mechanical and capacitance sensitivities increase.

Key words: MEMS, sensitivity, capacitive pressure sensor, clamped and slotted diaphragm, glaucoma, intracocular pressure

INTRODUCTION

Glaucoma is a group of eye diseases causing optic nerve damage and vision loss (Meng et al., 2005; Smedt, 2015). In glaucoma, eye pressure plays a role in damaging the delicate nerve fibres of the optic nerve. When a notable number of nerve fibers are damaged, blind spots develop in the field of vision. Once nerve damage and visual loss occur, it is permanent. Various studies show that a major risk factor for optic nerve damage is the increasing pressure in the eye. The main cause of damage to the optic nerve is Intracocular Pressure (IOP), excessive fluid pressure within eye which can be due to various reasons including blockage of drainage ducts and narrowing or closure of the angle between iris and cornea (Arsalan et al., 2013). The fluid inside the eye known as aqueous humour is flow behind the iris and through the pupil. The aqueous flows out of the eye through a structure known as the drainage angle which is the angle, formed inside the anterior chamber between the iris and the peripheral cornea. IOP can increase when there is a disruption of this outflow of aqueous including from certain eye injury. Normal eye pressure ranges from 12-22 mmHg. In most glaucoma patients, the IOP rises above normal range which is higher than 22 mmHg when the trabecular mesh-work of the eye gradually becomes less efficient at draining fluid. Figure 1 shows the fluid pathway. A clear fluid (aqueous humour) flows endlessly in and out of the chamber and nourishes nearby tissues. The fluid, then, leaves the anterior chamber at the open angle where the cornea and iris meet. After that, it flows through a spongy mesh-work, like a drain and leaves the eye.

Fig. 1: Intracocular fluid flow path for a normal eye

Corresponding Author: Muslihah Ali, Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, 21300 Kuala Terengganu, Terengganu, Malaysia

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Figure 2 shows the development of glaucoma. The blocked drainage canals increased the eye pressure and causing optic nerve damage.

Since, glaucoma can be treated if the increased in eye Pressure (IOP) and the amount of fluid (aqueous fluid) in the eye are known, it is necessary to measure the Intracocular Pressure (IOP). A detailed review of IOP measurement methods was given by Katuri et al. (2008).

Tonometry is one of the method that used in detecting IOP (Kirstein et al., 2011). Tonometry is a tool that measures IOP by recording the resistance of your cornea to pressure. A few type of tonometry have been used nowadays. Tonometry that’s often used is application (Goldmann) tonometry and it is very accurate. To measure eye pressure, a small probe is used to gently flatten part of the cornea. The pressure is measured by how much force is needed to flatten the cornea.

Tonometry accuracy affects the cornea (Moraes et al., 2008). So, it is required to know the cornea thickness first before started measuring the IOP. In this study, sensitive MEMS capacitive pressure sensor has been proposed in which can be operated in the IOP range for glaucoma. The sensor is designed with poly-silicon diaphragm and analyzed the sensitivity of its mechanical and capacitance. In order to increase sensitivity, the diaphragm is designed with slots.

**MATERIALS AND METHODS**

**Mechanical analysis of square diaphragm**: The mechanical analysis of square diaphragm on deflection, the capacitance of the sensor and sensitivity of the diaphragm are presented.

**Diaphragm deflection under applied pressure**: The load deflection method is used for elastic properties measurement of thin films (Ganjii and Tabarestani, 2013; Nava and Rivera, 2006; Timoshenko and Woinowsky-Krieger, 1959). In this method, the deflection of a fixed edge diaphragm is studied according to the applied pressure. The square diaphragm will be firmly clamped at its edge as shown in Fig. 3.

When pressure is applied, the diaphragm will deflect. The central deflection of a 4 slotted square diaphragm (Timoshenko and Woinowsky-Krieger, 1959; Latha and Khanna, 2015) is given by:

\[
w_c = \frac{0.12P a^4 (1-v^2)}{Eh^3}
\]

Where:
- \(w_c\) = Central deflection
- \(P\) = Pressure applied
- \(a\) = Half-side length
- \(v\) = Poisson’s ratio
- \(E\) = Young’s modulus
- \(h\) = Diaphragm thickness

**Capacitance of the sensor under applied pressure**: The sensor for IOP measurement is a pressure dependent capacitor. The principle used in designing capacitive pressure sensor is the principle of parallel plate capacitor (Timoshenko and Woinowsky-Krieger, 1959). The structure of the sensor consists of a movable top electrode and a fixed bottom electrode. The electrodes separated by a dielectric layer. According to
Eq. 2, capacitance increases as the distance between parallel plate decreases and the displacement of the diaphragm increases when the pressure applied increases:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$  \hspace{1cm} (2)

Where:
- $C$ = Capacitance
- $\varepsilon_0$ = The permittivity of free space ($8.854 \times 10^{-14}$ F/cm)
- $\varepsilon_r$ = The relative dielectric constant of material between the plates (which is unity for air)
- $A$ = Effective electrode area
- $d$ = A gap between plates

**Sensitivity of diaphragm:** The mechanical Sensitivity ($S_m$) and capacitance Sensitivity ($S_c$) are calculated using Eq. 3 and 4, respectively (Tabarestani, 2012):

$$S_m = \frac{\Delta w_c}{\Delta P}$$  \hspace{1cm} (3)

$$S_c = \frac{\Delta C}{C_0 \Delta P}$$  \hspace{1cm} (4)

Where:
- $\Delta w_c$ = A change in central displacement of diaphragm
- $\Delta P$ = Pressure change
- $\Delta C$ = Change in capacitance between parallel plates
- $C_0$ = Capacitance value for zero pressure, respectively

**Sensor design:** In our design, the sensor consists of poly-silicon as a diaphragm, gold as bottom electrode and air gap in between them. The structure parameter of the design for the sensor is $550 \times 550$ $\mu$m with thickness of 4 $\mu$m of electrodes and 50 $\mu$m for air gap. To increase mechanical sensitivity, we reduce the circumferential suspension by cutting slots into the diaphragm (Tabarestani et al., 2012). Therefore, we designed three types of diaphragm which are clamped, 8 slotted and 4 slotted and optimum design for high sensitivity was analyzed.

**Finite element analysis of iop sensor:** Finite Element Analysis (FEA) Software COMSOL Multiphysics is used to design and simulate MEMS capacitive pressure sensor. The objectives of the analysis are to verify the deflection of the diaphragm due to pressure applied to the diaphragm and the capacitance between the diaphragm and back plate. The displacement of the diaphragm and capacitance between electrodes consistent with displacement was computed using Electromechanics Module.

Fig. 4: Simulation setup for; a) clamped square diaphragm, b) 8 slotted diaphragm and c) 4 slotted diaphragm

The simulation setup for three designs is shown in Fig. 4. As seen from Fig. 4, the top plate is a diaphragm, middle plate is air gap and the bottom plate is bottom electrode. The slot has dimension of $120 \times 25$ $\mu$m with the thickness of 4 $\mu$m. The Young’s Modulus and Poisson’s ratio for the diaphragm are 169 GPa and 0.22, respectively. Then, the poly-silicon diaphragm was coated with Teflon (PTFE) with Young’s Modulus of 0.5 GPa and Poisson’s ratio of 0.46.

**RESULTS AND DISCUSSION**

The deformation of the diaphragm with applied pressure with a range of 0-60 mmHg was investigated. The displacement and capacitance for all diaphragms were obtained using simulation results.
Capacitance characterization: Figure 6 demonstrates the capacitance of parallel plates for Teflon coating against pressure applied. The capacitance of parallel plates varies linearly to the pressure applied. From Fig. 6, it can be seen that square diaphragm with Teflon coating has deflection value compared to the square diaphragm without Teflon coating. The capacitance values for clamped edge, 8 slotted edges and 4 slotted edges with maximum pressure applied are 54.55, 93.08 and 56.10 fF, respectively. From Eq. 4, the highest capacitance sensitivity is 4 slotted edges with a value of $5.50 \times 10^{-6}$ 1/Pa while the capacitance sensitivity for clamped edge and 8 slotted edges are $2.23 \times 10^{-6}$ and $5.15 \times 10^{-6}$ 1/Pa. It can be observed that the slope of capacitance change for 4 slotted diaphragms is steeper compared to other design shapes. The steeper the graph, the better the sensitivity it has.

CONCLUSION

A MEMS high sensitive capacitive pressure sensor was designed and presented. The poly-silicon and Teflon materials are used for coating the diaphragm. A comparison was done between with and without Teflon coating and realized that diaphragm with Teflon coating gives higher sensitivity because of Teflon's low Young's Modulus increased the sensitivity of poly-Si diaphragm. From the simulation, the structure with 4 slotted square diaphragms with Teflon coatings was identified gives the highest mechanical and capacitive sensitivities amongst the presented designs. Therefore, by coating the diaphragm and adding slots to the diaphragm will improve the deflection of the diaphragm thus, increase the mechanical and capacitance sensitivity. These results would be useful to find the most effective and optimum design of a MEMS high sensitive capacitive pressure sensor.

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