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Design and Analysis of MEMS High Sensitive Capacitive Pressure Sensor

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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 Intraocular 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, intraocular 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 Intraocular 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.

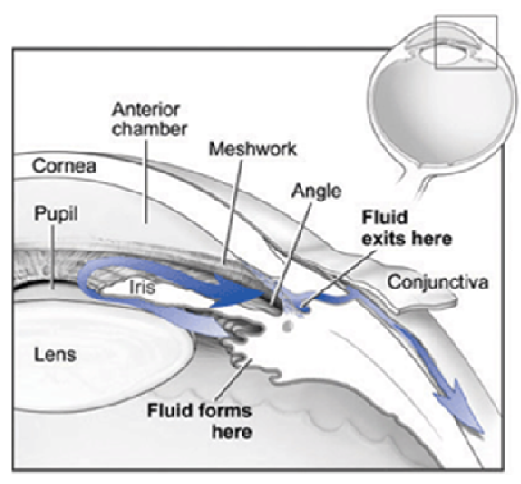

Fig. 1: Intraocular fluid flow path for a normal eye

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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 Intraocular 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 applanation (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.

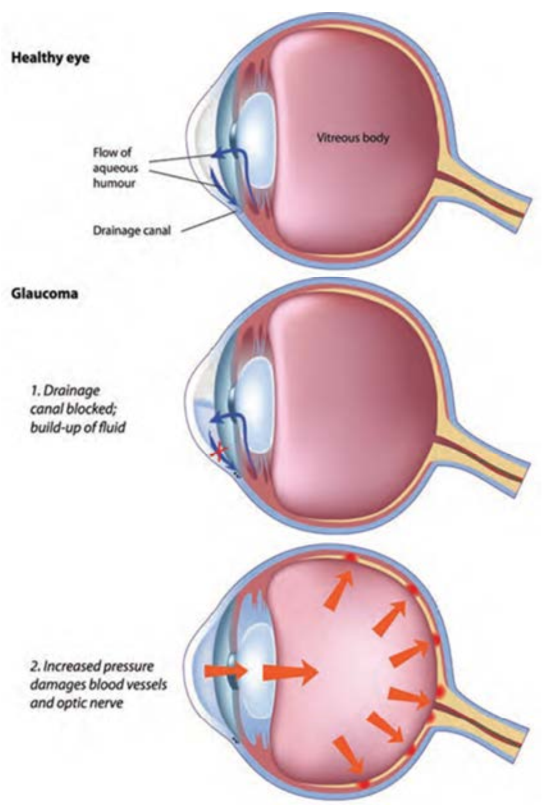

Fig. 2: Development of glaucoma

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 (Ganji 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:

$$w_C = \frac{0.12Pa^4(1-\nu^2)}{Eh^3} \qquad (1)$$

Where:

w_c = Central deflection
P = Pressure applied
a = Half-side length
ν = 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

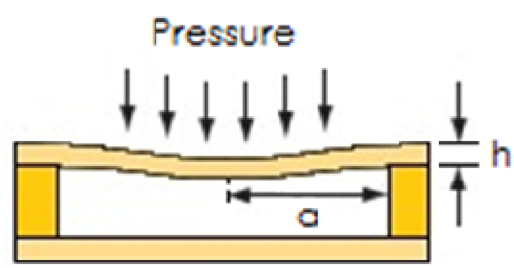

Fig. 3: Structure model for square diaphragm

Eq. 2, capacitance increases as the distance between parallel plate decreases and the displacement of the diaphragm increaseswhen the pressure applied increases:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (2)$$

Where:
C = Capacitance
ε_0 = The permittivity of free space (8.854×10^{-14} F/cm)
ε_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):

$$S_m = \frac{\Delta w_C}{\Delta P} \quad (3)$$

$$S_C = \frac{\Delta C}{C_0 \Delta P} \quad (4)$$

Where:
Δw_C = A change in central displacement of diaphragm
ΔP = Pressure change
ΔC = 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 550×550 μm with thickness of 4 μm of electrodes and 50 μm 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.

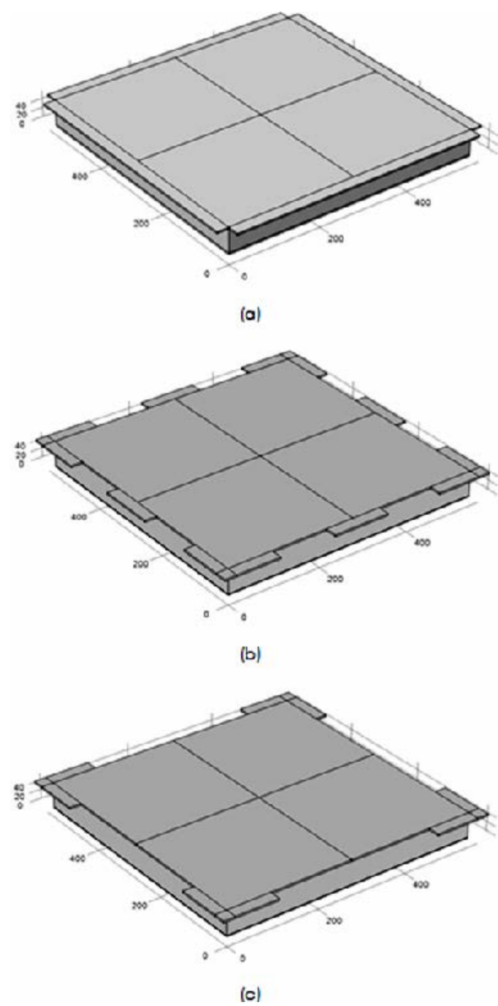

Fig. 4: Simulation setup for; a) clamped square diaphragm, b) 8 slotted diaphragm and c) 4 slotted diaphragm

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 120×25 μm with the thickness of 4 μm. 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.

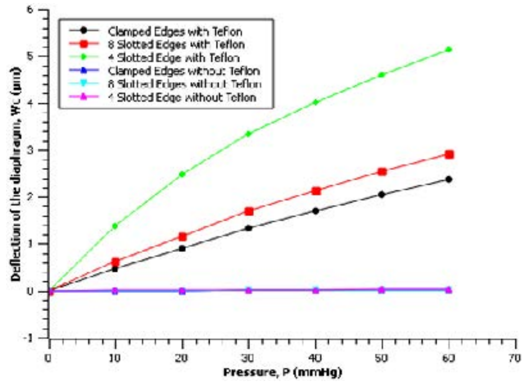

Fig. 5: Pressure vs. deflection of diaphragm

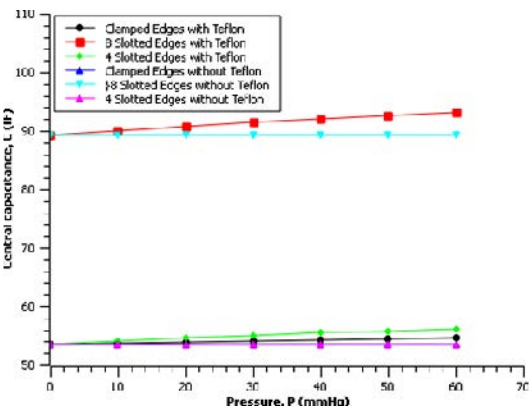

Fig. 6: Pressure vs. capacitance with Teflon coating of parallel plates

Displacement characterization: Figure 5 illustrates the deflection of the diaphragm against pressure applied. The deflection of the diaphragm is directly proportionally with the pressure applied. From Fig. 5, it can be seen that square diaphragm with Teflon coating has greater deflection compared to the square diaphragm without Teflon coating. The utmost central displacement of all design shape is the square diaphragm 4 slotted edges with Teflon coating. It has deflection of 5.13 μm for maximum pressure applied which is the highest compared to other design shapes which are only for 2.36 μm for clamped edge and 2.90 μm for 8 slotted edges. It followed Eq. 1 as deflection of the diaphragm will increase when pressure applied to the diaphragm increase. From Eq. 3, the mechanical sensitivity of this shape is 5.626×10^{-4} μm/Pa while the mechanical sensitivity for clamped edge and 8 slotted edges are 2.835×10^{-4} and 3.435×10^{-4} μm/Pa, respectively. The 4 slotted edges have the highest sensitivity compare to clamped edge and 8 slotted edges. This shows that, design with 4 slotted edges has better sensitivity compared to other design shape.

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 5.50×10^{-6} 1/Pa while the capacitance sensitivity for clamped edge and 8 slotted edges are 2.23×10^{-6} and 5.15×10^{-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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REFERENCES

Arsalan, M., M.H. Ouda, L. Marnat, T.J. Ahmad and A. Shamim *et al*., 2013. A 5.2 GHz, 0.5 mW RF powered wireless sensor with dual on-chip antennas for implantable intraocular pressure monitoring. Proceedings of the 2013 IEEE MTT-S International Conference on Microwave Symposium Digest (IMS), June 2-7, 2013, IEEE, Thuwal, Saudi Arabia, ISBN:978-1-4673-6176-7, pp: 1-4.

Ganji, B.A. and S.M. Tabarestani, 2013. A novel high sensitive MEMS intraocular capacitive pressure sensor. Microsyst. Technol., 19: 187-194.

Katuri, K.C., S. Asrani and M.K. Ramasubramanian, 2008. Intraocular pressure monitoring sensors. IEEE. Sens. J., 8: 12-19.

Kirstein, E.M., A. Elsheikh and P. Gunvant, 2011. Tonometry-Past, Present and Future. In: Glaucoma-Current Clinical and Research Aspects, Kirstein, E.M., A. Elsheikh and P. Gunvant (Eds.). In Tech Open Access Publisher, Pomona, California, ISBN:978-953-307-263-0, Pages: 388.

Latha, Y.M.A. and G. Khanna, 2015. Design and simulative analysis of a batteryless Teflon coated capacitive pressure sensor for glaucoma diagnosis. Proceedings of the 19th International Symposium on VLSI Design and Test (VDAT), June 26-29, 2015, IEEE, Hamirpur, India, ISBN:978-1-4799-1743-3, pp: 1-5.

Meng, E., P.J. Chen, D. Rodger, Y.C. Tai and M. Humayun, 2005. Implantable parylene MEMS for glaucoma therapy. Proceedings of the 2005 3rd IEEE-EMBS Special Topic Conference on Microtechnology in Medicine and Biology, May 12-15, 2005, IEEE, Los Angeles, California, USA., ISBN:0-7803-8711-2, pp: 116-119.

Moraes, C.G.V.D., T.S. Prata, J. Liebmann and R. Ritch, 2008. Modalities of tonometry and their accuracy with respect to corneal thickness and irregularities. J. Optometry, 1: 43-49.

Nava, R.A. and L.N.D. Rivera, 2006. Intraocular pressure sensor design. Proceedings of the 2006 3rd International Conference on Electrical and Electronics Engineering, September 6-8, 2006, IEEE, Mexico City, Mexico, ISBN:1-4244-0402-9, pp: 1-4.

Smedt, D.S., 2015. Noninvasive intraocular pressure monitoring: Current insights. Clin. Ophthalmol., 9: 1385-1392.

Tabarestani, S.M., B.A. Ganji and S.R. Nadooshan, 2012. Design and simulation of high sensitive capacitive pressure sensor with slotted diaphragm. Proceedings of the International Conference on Biomedical Engineering (IcoBE), February 27-28, 2012, IEEE, Tehran, Iran, ISBN: 978-1-4577-1990-5, pp: 484-489.

Timoshenko, S. and S. Woinowsky-Krieger, 1959. Theory of Plates and Shells. 2nd Edn., McGraw-Hill Book Co., New York, pp: 580.