Journal of University of Babylon for Engineering Sciences, Vol. (26), No. (7): 2018.

High Sensitive MEMS Intraocular Capacitive Pressure Sensor (Glaucoma)

Tania Mohammed Abbas **Qais Kareem Al-Gayem**

Department of Electrical Engineering, University of Babylon, Babylon-Iraq

Taniamohammed86@gmail.com qaiskareem@yahoo.com

Abstract

Micro Electro Mechanical Systems (MEMS) are a small-scale technology that was largely adopted by the IC industry and applied to miniaturize of all systems (electrical systems, mechanical, optical, fluidic, magnetic, etc.). Minimization has been accomplished with small manufacturing processes. A Capacitive pressure sensor is simply a diaphragm-type device in which the diaphragm displacement is determined by measuring the capacitance change between the diaphragm and a metal plate that is close to it.

For this purpose, intraocular pressure sensors are important in detection and treatment of an incurable disease called glaucoma. To improve the sensitivity of the capacitive pressure sensor, low stress doped polysilicon material is used as a biocompatible material. Glaucoma is a group of eye diseases that occurs by high intraocular pressure (IOP). IOP is the pressure exerted by the ocular fluid called aqueous humor (the clear fluid inside the eye) that fills the anterior chamber of the eye

The results Shows the simulated relation between capacitance and pressure for clamped ++silicon and polysilicon clamped. It can be seen from figure that the initial capacitance for clamped p++ silicon is about 1.81 pF the capacitance varies from 1.81 to 2.162 pF for clamped p++silicon and clamped polysilicon diaphragm, respectively, so the total variation of the capacitance. This result shows the use of poly silicon material in diaphragm is high sensitivity than the p++ silicon.

Keywords: - Capacitive pressure sensor (Glaucoma), Polysilicon material, P++ silicon.

1. Introduction

Many people throughout the world are suffering from irreversible vision loss called glaucoma [1]. Glaucoma is a group of eye diseases that occurs by high intraocular pressure (IOP). IOP is the pressure exerted by the ocular fluid called aqueous humor (the clear fluid inside the eye) that fills the anterior chamber of the eye [2]. Normal intraocular pressure is in the range of 10–21 mmHg [3][4]. In glaucoma patients, when there is no balance between the aqueous outflow and aqueous inflow, then the IOP increases above the normal range. High IOP leads to loss of optic nerve tissue, loss of peripheral vision, and finally blindness if not treated [2]. The condition is painless and direct or indirect pressure measurement is necessary for vision loss detection. Therefore, it is important to have an accurate measurement of the IOP for glaucoma patients [5]. The accuracy of IOP measured by conventional techniques such as Goldman application tonometry depends largely on corneal properties such as central corneal thickness [6]. Another technique called dynamic contour tonometer (DCT) has been introduced [7] that is not affected by central corneal thickness. Different portable to no meters such as Tono-Pen [8], noncontact tonometer have been introduced [9] over the years. However, by the techniques it is not possible to measure the IOP continuously reported large fluctuation in diurnal IOP in glaucoma patients that is an important risk factor. Therefore, continuous IOP measurement in glaucoma patients may provide more accurate. For sensor implantation, there are some spatial restrictions in the eye that need to be considered. Different parts of the eye can be used for implants. Implants placed in the anterior chamber of the eye have an additional advantage while the implants placed in the vitreous cavity have a higher risk of infection [4]. Considering the available space in the anterior chamber of the eye, it is better to take advantage of available space to optimize the design [2]. Figure 1 shows option for anterior chamber implants in the eye. The bio telemetric systems are classified into active sensing devices and passive sensing devices [8]. 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.

MEMS passive intraocular pressure sensor with p++silicon diaphragm. The sensor is a simple R-L-C resonant circuit. The resonant circuit consisted of a pressure variable capacitor and an inductor. The capacitor is comprised of a thin flexible diaphragm exposed to the pressure exerted by the eye fluid. 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 [9].

The paper mainly deals with the capacitive sensor proposed. The main goal is to develop the sensitivity of the capacitive pressure sensor. The future implant will consist of a capacitive pressure sensor connected to a micro coil. Passive LC resonance technique will be used for the continuous wireless monitoring of intraocular pressure. In this paper, first capacitive sensor with clamped P++silicon diaphragm is investigated and simulated as a main structure. For achieving more sensitive device and reducing the residual stress and stiffness of diaphragm, two steps have been proposed and implemented in the main structure. First low stress doped polysilicon material is used as a biocompatible material instead of p++silicon.

2. Pressure sensor structure

In pressure sensors, pressure is determined by the deflection of the diaphragm due to applied pressure. Figure 1 illustrates cross-section view of the typical pressure sensor with clamped diaphragm. The diaphragm side length is 2a, thickness h, and the thickness of the air gap is d. When exposed to an external uniform pressure P, the diaphragm deflects causing a decrease in the air gap that result in an increase in capacitance between the diaphragm and the back plate. 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.}

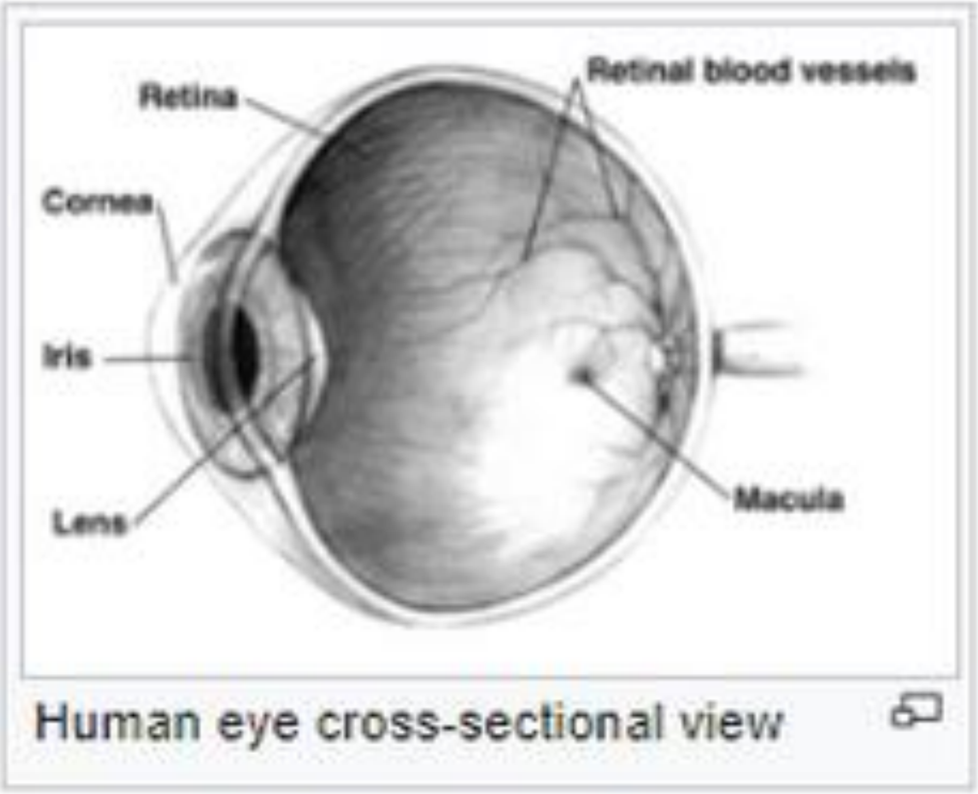

Fig. 1 Option for anterior chamber implant in the eye

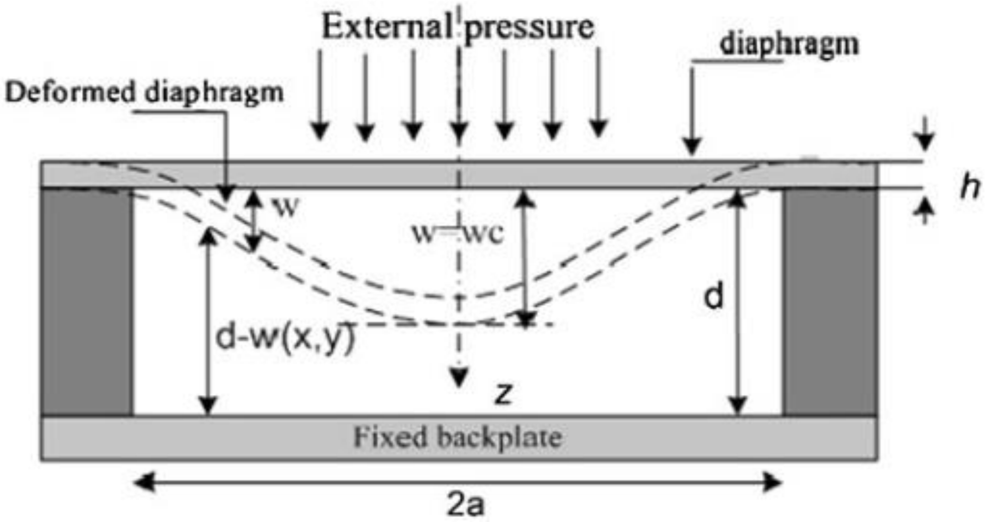

Fig. 2 Cross section view of typical pressure sensor

The Young’s modulus and Poisson’s ratio of p++silicon are assumed to be 160*10^9 Pa and 0.05, respectively, the thickness of the 0.55 mm * 0.55 mm membrane is 4 µm, and the height of the air gap is about 1.5 µm

3. Capacitive Pressure Sensor

The subject of research is a sensitive membrane of capacitive pressure sensor. Capacitive sensors use an elastic pressure-sensing element in the form of a variable capacitor gap due to displacement or deflection under pressure of membrane-electrode movable relative to the fixed electrode. It means that design of capacitive pressure sensors is flat and cylindrical capacitor. The principle operation of these pressure sensors is based on the change in capacitance of the capacitor, depending on the applied load on one of the electrodes [10].

It is known that the capacity of flat capacitor is directly proportional to the square cover and inversely proportional to the distance between them [11].

$$\mathrm{C}= \varepsilon 0\varepsilon \frac{s}{\delta} \tag{1}$$

Where:

ε0 is electric constant of the medium between the plates

ε is dielectric constant

S / δ are the area and the distance between the plates.

Sensitive elements of capacitive pressure transducers are membranes and diaphragms, which convert the measured pressure in the movement [12]. The relative capacitance changing in diaphragm membranes is proportional to the measured pressure

$$\frac{\Delta \mathrm{C}}{\mathrm{C}} = \frac{R^{\wedge}2}{8\delta W} Px \tag{2}$$

Where:

R – Radius of the membrane;

W – The magnitude of the deflection of the membrane;

δ – The distance between the membrane and the movable cover in the absence of pressure.

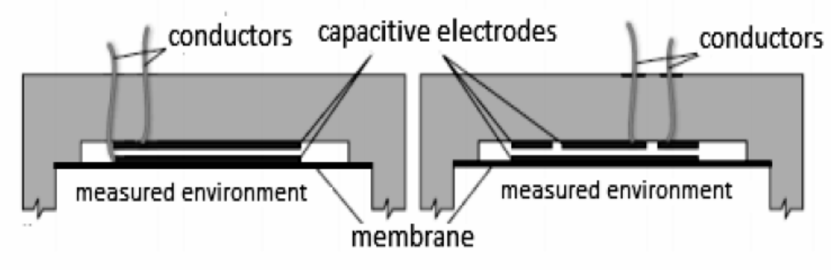

Figure (3): Capacitor pressure sensor [12]

Therefore, to improve properties such as sensor accuracy and increasing the range of measurements necessary to produce sensitive membrane of this size for maximum distance changing between the plates.

In addition, it necessary to keep in mind the potential dielectric breakdown, when a significant approximation capacitor plates to one another and while appearance of the large stress, which can damage membrane.

The simulation of the MEMS capacitive pressure sensor in touch mode achieves good linearity and large operating pressure range. Intellisuite software is used for modeling and simulating of MEMS capacitive pressure sensor to optimize the design, improve the performance and reduce the time of fabricating process of the device.

Recently MEMS capacitive pressure sensors have gained advantages over piezo resistive pressure sensor due to high sensitivity, low power consumption, invariance of temperature effects. As theses sensors application range is increasing, it is essential to review the technological developments and future scope of MEMS capacitive pressure sensor. [12]

4. MEMS Capacitive Pressure Sensor Design for High Pressure Applications

Two plates that can store an electric charge form a capacitor. The charge generates a potential difference, which may be maintained using an external voltage. A capacitive pressure sensor measures a pressure by detecting an electrostatic capacitance change. At least one electrode of the capacitor is on a moving structure. Capacitive sensors have the advantage over the piezo resistive type as they consume less power. However, have a nonlinear output signal and are more sensitive to electromagnetic interference. Capacitive sensors are compatible with most mechanical structures, and they have high sensitivity and low temperature drift. Capacitive pressure sensors have the problem that, they exhibit non-linear relationship between capacitance and displacement. Hence, linearization is an issue in such kind of sensors [12][14].

5. Performance Parameters

1. Burst Pressure: This is the maximum pressure that may be applied to the sensor without causing the sensor catastrophic failure [15].

2. Temperature Compensation: The temperature ranges across which the specification values of the pressure sensors are guaranteed, i.e., the measurement error of the pressure sensor will be within a certain bond.

3. Supply Voltage/ Supply Current: The constant supply voltage or constant supply current required to drive pressure sensors.

4. Zero Offset: Zero Offset is the output of a pressure sensor when no pressure is applied. Zero offset is either expanded as percentages of full-scale o/p.

Zero offset can be easily eliminated during calibration step.

5. Linearity: The maximum deviation of measured output. The non-linearity is addressed by using the best-fit straight-line (BFSL) method.

6. Sensitivity: Sensitivity of a capacitive pressure sensor can be defined as Electrical and mechanical sensitivity. Electrical Sensitivity is defined as the ratio of change in the capacitance to change in the pressure $Sc = \frac{\Delta C}{\Delta P}$ terms of voltage it will be the ration of change in voltage to change in pressure.

7. Mathematical Equations to Measure Diaphragm Deflection.

Typically, the geometries used for the diaphragm design are square, rectangular and circular configurations. In all cases, maximum deflection is observed at the Centre of the plate/diaphragm.

According to the theory of Plates [16, 17-18] by Krigger the equations governing the deflection of plates with pressure acting normal to the plate/diaphragm surface is given by (3)

$$\frac{\partial{}^{\wedge}4w}{\partial x\ {}^{\wedge}4}+2\alpha\frac{\partial{}^{\wedge}4w}{\partial x{}^{\wedge}2\partial y{}^{\wedge}2}+\frac{\partial{}^{\wedge}4w}{\partial y{}^{\wedge}4}={}^{P}\!/_{D} \qquad (3)$$

For maximum deflection at the center of a square plate is given by Equation (4) & (5)

$$Wmax=0.00674\frac{pa}{D} \qquad (4)$$

$$D=\frac{Eh{}^{\wedge}3}{12(1-\gamma^2)} \qquad (5)$$

For circular diaphragm

$$Sc=\frac{\Delta v}{\Delta p} \qquad (6)$$

Mechanical sensitivity is defined as the ratio of change in displacement to change in pressure applied

$$Sm=\frac{\Delta W}{\Delta P} \qquad (7)$$

$$W(r)=\frac{Pa{}^{\wedge}4}{64D}[1-\left(\frac{r}{a}\right)^2] \qquad (8)$$

For rectangular diaphragm

$$Wmax=\alpha\frac{Pa{}^{\wedge}3}{D}\text{ For a>b or a<b} \qquad (9)$$

Where

$$\alpha=1.26*10^{-3}*12(1-v^2) \qquad (10)$$

1) For Square/rectangular diaphragm: W – is deflection at (x, y) coordinates, P – is differential pressure, D - is flexural rigidity, a - is the length of diaphragm, E - is young modulus, V – is Poisson’s ratio and h - is the thickness of the diaphragm.
2) For circular diaphragm: W(r) is deflection at radial distance r from the Centre of diaphragm, a - is radius of the diaphragm, r - radial distance.
3) For Rectangular diaphragm: a - Length of plate, b – width of the plate, α – numerical factor depending on the ratio b/a or a/b.

6. Specifying physics

After producing the 3-D structure of the capacitive pressure sensor, the boundary conditions of electromechanical system have been specified for the next the physics feature settings and added to the model. These include the pressure forces acting on the sensor, the applied sense voltage, and other appropriate boundary conditions.

In the electro mechanics interface, the Linear Elastic Material is used to solve the equations of structural mechanics only.

Apply a boundary load is needed to represent the pressure acting on the top surface of the diaphragm. The moving mesh boundary conditions need to be applied on boundaries where the air domain deforms and where the default electromechanical interface boundary condition does not apply. Three material were used in the design, the first martial was silicon

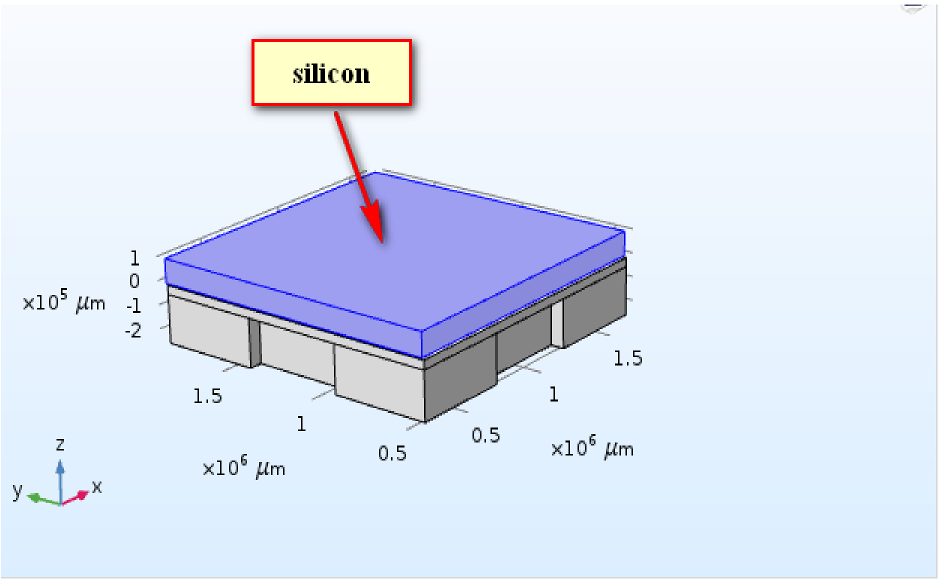

Figure (4): shows the silicon layers in the model

Table (1) silicon specification

Property	Name	Value	Unit
Young modelu	E	170	Gpa
Passion ratio	nu	.06	1
Density	rho	2330	Kg/m^3
Coefficient of thermal expression	elpha	11.7	1

The second material used in model is polysilicon in table (2)

Property	Name	Value	Unit
Relative permittivity	epsilon	4.5	1
Electric conductivity	Sigma	Sigma	S/m
Coefficient of thermal expansion	alpha	Alpha	1/k
Heat capacity at constant pressure	Cp	678	J/(K.Kg)
Dencity	Rho	2330	Kg/m^3
Thermal conductivity	K	T	W(m*k)
Young modelu	E	169e9	Pa
Passion ratio	nu	0.22	1
Reference resistivity	rho0	2e-5	Ω.m
Resistivity temperature coeffiecient	alpha	1.25e-3	1/k
Reference temperture	Tref	298.15	K

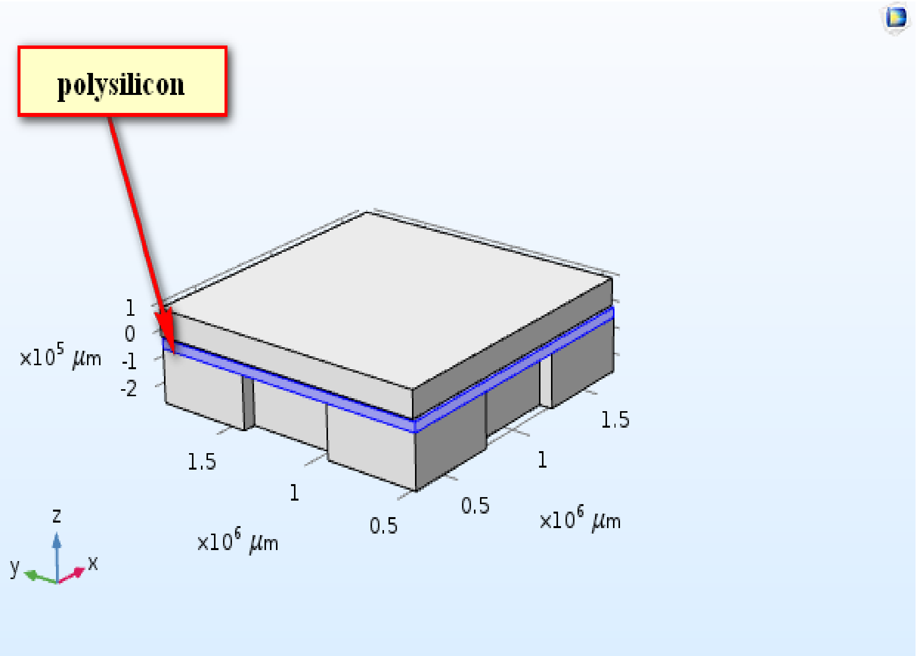

Figure (5) polysilicon layer

The last material used is Steel AISI 4340.1 and it is specification illustrated in table (3)

Table (3) Steel AISI 4340.1specifications

Property	Name	Value	Unit
Coefficient of thermal expansion	alpha	12.3e^-6	1/k
Density	rho	7850	Kg/m^3
Young modulus	E	205e^9	pa
Passion ratio	nu	0.28	1
Relative permittivity	mur	1	1
Electric conductivity	sigma	4.023e^6	S/m
Heat capacity and constant pressure	cp	475	J/(Kg.K)
Relative permittivity	epsilon	1	1
Thermal conductivity	k	44.5ta	w/(m.k)

7. Meshing

After defining the electromechanical system with their constants and the physical constraints, the next process called meshing. Table (4) specifies the number of mesh elements at different meshing and figure (6) shows the model after meshing.

Table (4) Number of mesh elements on different meshing

Mesh	Normal	Finer	Extra coarse
Number of mesh element	7971	25642	1070

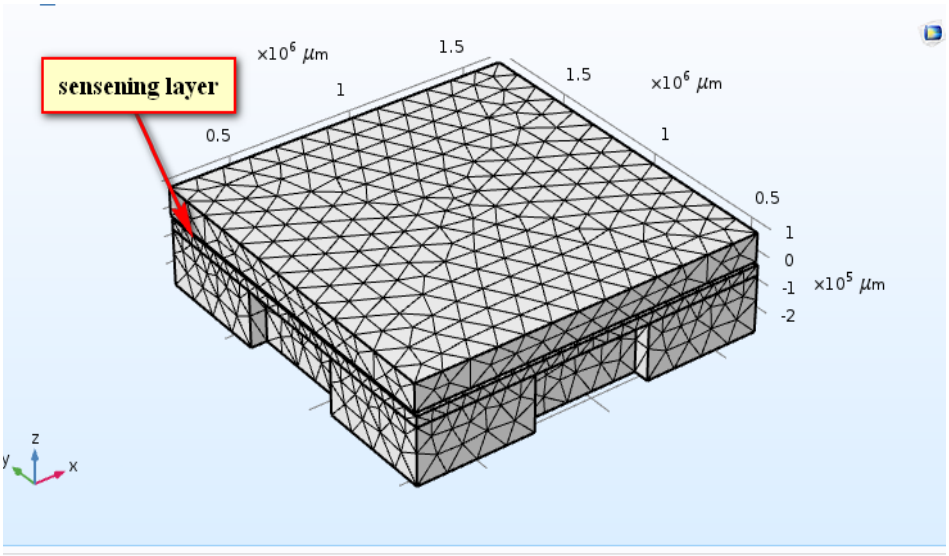

Fig (6): The model after meshing

The darker section is the sensing part of model

8. Results and discussion

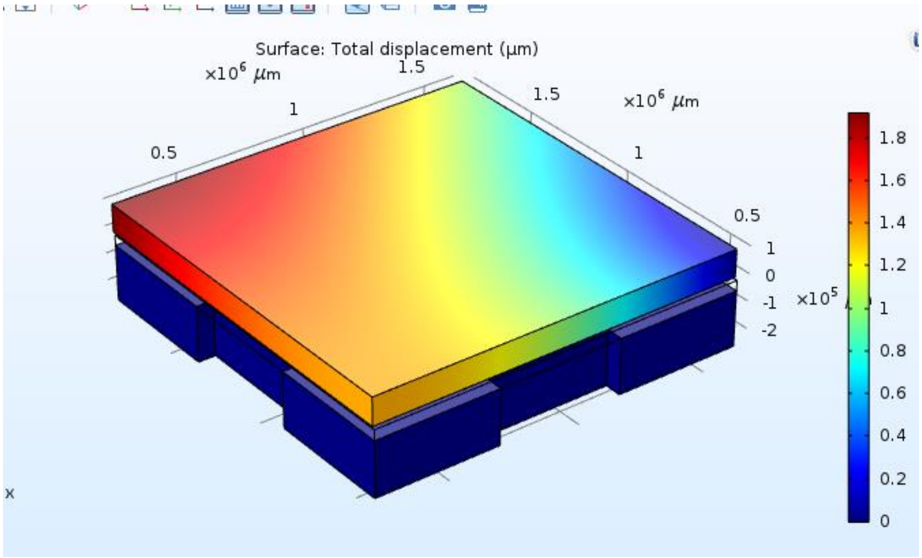

Fig (7) Total displacement of model

After the meshing, the model was computed where figure (7) shows the displacement of the structure distributed due to an applied pressure when packaging stresses are also included in the model. In addition, reach high displacement is 1.8 μm

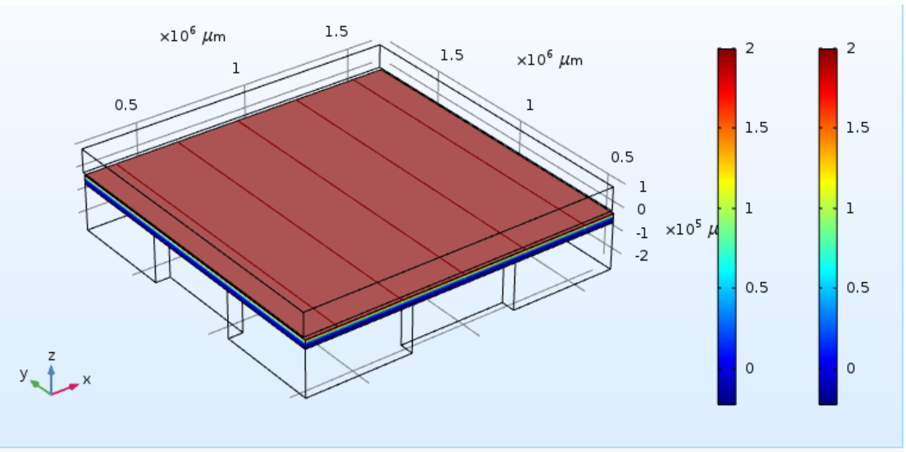

Fig (8): The electric potential of sensor

Fig (8) shows the electrical potential distributed the potential has become uniform as a result of the pressure-induced deformation of the diaphragm.

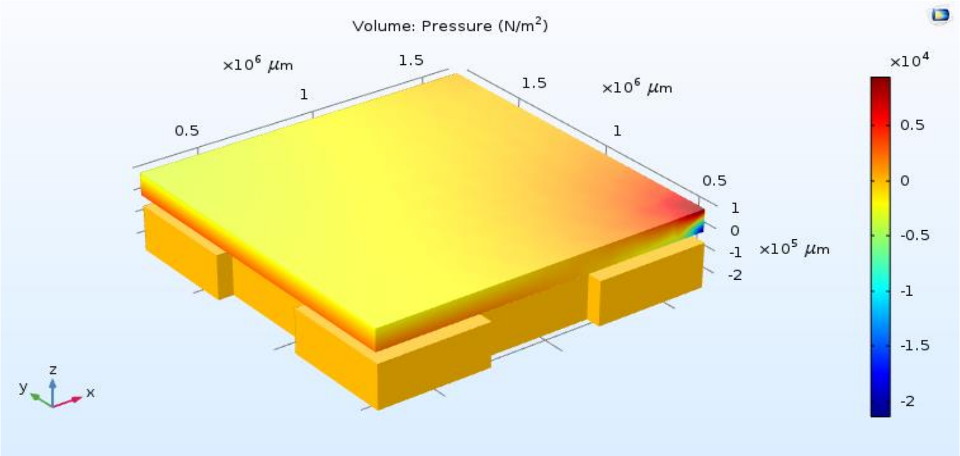

Fig (9) pressure of sensor

In figure (9) the pressure distribution is shown where the high level at the diaphragm, reach 5kPa because the polysilicon material has strong influence on the mechanical sensitivity, low stress compared to other materials. High-temperature annealing of a low-pressure chemical vapor deposition (LPCVD) of polysilicon thin film that is ion implanted with phosphorous can confine the residual stress

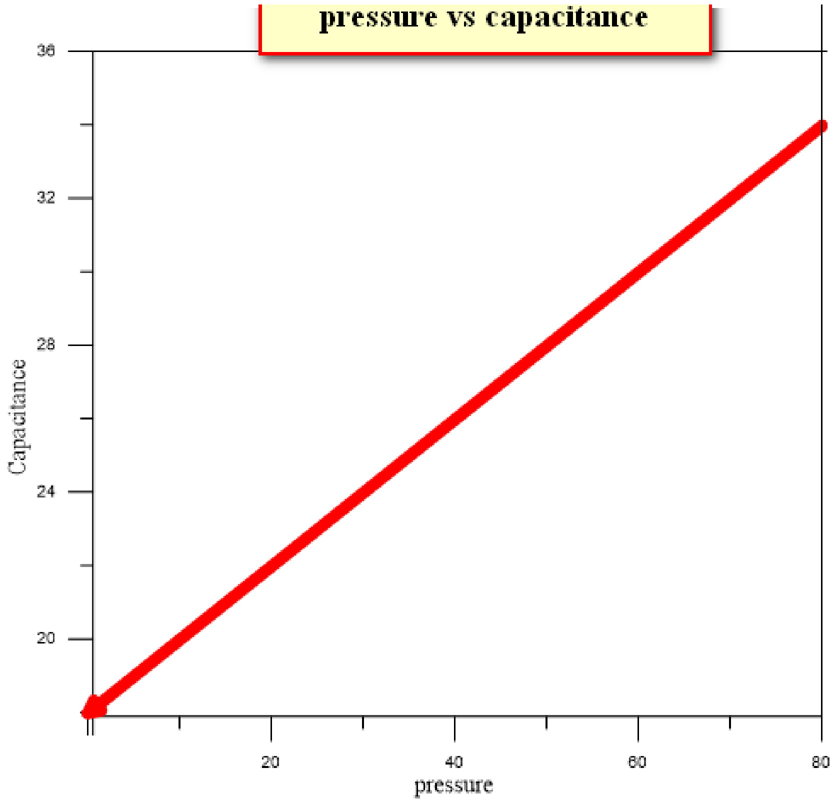

Fig (10): Pressure vs capacitance

In fig (10) shows the simulated relation between capacitance and pressure for polysilicon clamped. It can be seen from figure that the initial capacitance for clamped diaphragms are about3.1 pF. As pressure applies from 0 to 80 mmHg, the capacitance varies to 3.1pF from 1.81 pF The sensitivity of capacitive pressure sensor can be calculated using Eq.

$$S=\frac{\Delta C}{C0P} \qquad (11)$$

Where ΔC is the capacitance changes, C0 is initial capacitance and P is applied pressure. Using Eq. (3.21), the slope of the curve shows the sensitivity of the pressure sensor. in this case if the diaphragm is replaced by the silicon ++ the sensitivity of poly silicon is the best sensitivity

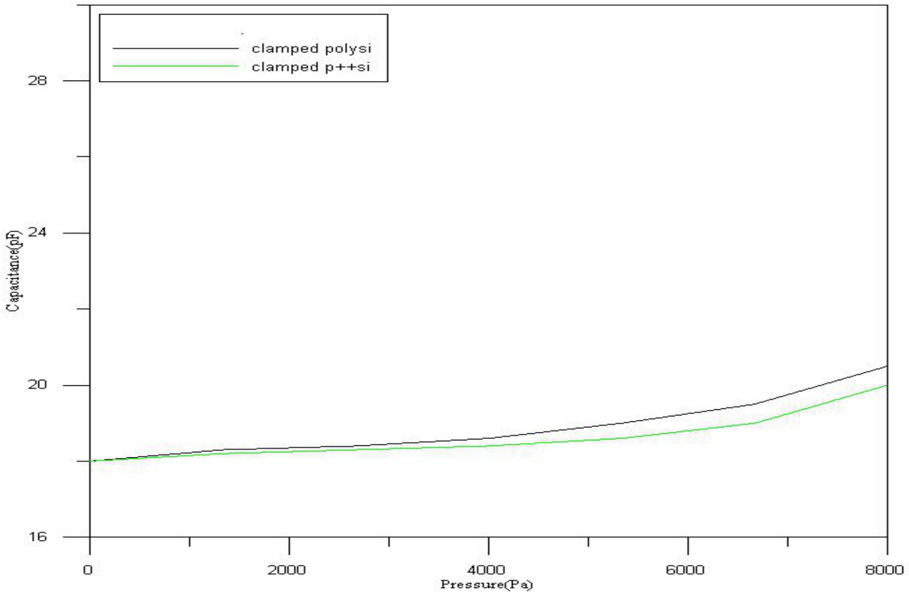

Figure (11) capacitive vs pressure compare between poly silicon and p ++silicon

Shows the simulated relation between capacitance and pressure for clamped p++silicon and polysilicon clamped. It can be seen from figure that the initial capacitance for clamped p++ silicon is about 1.81 pF the capacitance varies from 1.81 to 2.162pF for clamped p++silicon and clamped polysilicon diaphragm, respectively, so the total variation of the capacitance

8. Conclusions

3D capacitive pressure sensor is designed simulated to monitor the eye pressure. Increase the eye pressure causes damaging the optic nerves, which sometimes lead to the blind (glaucoma). In the model design, the polysilicon has been used as a material in the diaphragm to increase the sensitivity of the sensor. The result have been compared with a model that silicon ++ in the diaphragm material where a significant increase in sensitivity has been obtain when the polysilicon was employed in the diaphragm.

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الحساسية العالية للأنظمة الالكترونية والكهربائية للضغط داخل العين حساس الضغط السعوي (مرض زرق العين)

تانيا محمد عباس **قيس كريم القيم**

قسم الهندسة الكهربائية، كلية الهندسة، جامعة بابل، بابل، العراق

Taniamohammed86@gmail.com qaiskareem@yahoo.com

الخلاصة

الأنظمة الميكانيكية الكهرو ميكانيكية الدقيقة(MEMS) هي تقنية صغيرة الحجم تم تبنيها بشكل كبير من قبل صناعة الدوائر المتكاملة (IC) وتطبيقها على تصغير جميع الأنظمة (الأنظمة الكهربائية والميكانيكية والضوئية والموائع والمغناطيسية وغيرها). تم تحقيق الحد الأدنى من خلال عمليات التصنيع الصغيرة. مستشعر الضغط السعوي هو ببساطة جهاز من نوع الحجاب الحاجز يتم فيه تحديد إزاحة الحجاب الحاجز عن طريق قياس تغير السعة بين الحجاب الحاجز ولوحة معدنية قريبة منه.

لهذا الغرض، وأجهزة استشعار الضغط داخل العين مهمة في الكشف عن وعلاج مرض عضال يسمى الجلوكوما. لتحسين حساسية مستشعر الضغط بالسعة، يتم استخدام مادة البولي سيلكون منخفضة التوتر المخدر كمادة متوافقة حيويا. الجلوكوما هو مجموعة من أمراض العيون التي تحدث بسبب ارتفاع ضغط العين .(IOP) IOP هو الضغط الذي يمارسه سائل العين يسمى الفكاهة المائية (السائل الواضح داخل العين) الذي يملأ الغرفة الأمامية للعين

تظهر النتائج العلاقة المحاكاة بين السعة والضغط لـــ ++ clamped silicon وpolysilicon. يمكن أن نرى من الشكل أن السعة الأولية لسيليكون p ++ المشكل هي حوالي 1.81 pF تتراوح السعة من 1.81 إلى 2.162 pF للسليكون p ++ المشدد والحجاب الحاجز polysilicon، على التوالي وبالتالي فإن التغير الكلي للسعة. هذه النتيجة تبين استخدام مادة البولي سيليكون في الحجاب الحاجز حساسية عالية من السيليكون p + +.

الكلمات المفتاحية: – مرض الزرق العين (الكلوكوما)، ارتفاع ضغط اداخل العين، بولي سيليكون المادة الأولى وسليكون ++.