A Design for Online Low Power Eye Pressure Measurement System Based on MEMS Capacitors Array

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Abstract -This paper proposeds a new design for online eye pressure measurement system. The proposed system is based on the array of MEMS capacitors. The energy consumption of system is optimized. The proposed design is simulated in ABAQUS version 6.14-2 in the range of 10-30 mmHg eye pressure. The simulation results are very promising. The system can be used for Glaucoma prevention. The scaled up prototype exprimetal results and simulaion results are very promising.

Key words- Glaucoma , Eye Pressure , MEMS Capacitor , Low Power

I. INTRODUCTION

The anterior chamber is a small space of the eye between cornea and iris. Figure 1.In this space there is liquid flowing called humor which helps to wash and feed the eye tissues. The humor regularly gets out of the eye and some new amount of it is produced and substituted. If, for any reason, the equilibrium between the production and of this liquid is broken, the amount of the humor in the eye changes and as a result the interior pressure of the eye changes. The natural amount of the interior pressure of the eye in adults is between 16-21 mmHg. The rise in the interior pressure of the eye harms the retina screen of the optic nerve. This disease is called Glaucoma [1]. There are some methods for eye pressure measurement as following .Tonometry is one of the method of eye pressure measurement.

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The Tonometry is useful in diagnosing Glaucoma, eye hypertension, and also the sudden increase in the eye interior pressure after the eye surgery. On the other hand, clinical signs such as the continuous hyperemia of the conjunctiva or the chronic inflammation in the eye surface shows a need for the eye pressure measurement [2-3]. This method cannot be used on line.

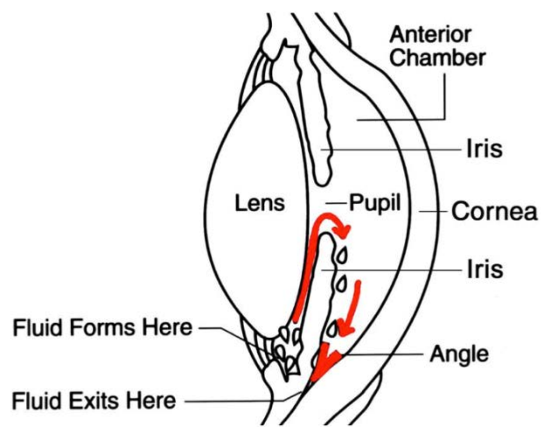

Figure 1: The anterior chamber of the eye

Another method for measuring the eye pressure is using the Imbert-Fick law. According to this law, the interior eye pressure is applied to any cross section perpendicular to the tough walls of the eye sphere and also to the other cross sections in the other points. Therefore, with the consumption that the S vector shows the cross section in the perpendicular and outward direction and the vector F shows the amount of force applied to this section, Figure 2, the interior pressure of the eye is obtained as following [4]:

$$P = \frac{F}{S} \quad (1)$$

One of the methods of measuring the interior pressure of the eye is using the micro-electromechanical sensors. An example of these sensors is Triggerfish lenses produced by SENSIMED Company, Figure a-3. The dimensions of this sensor are $2.2mm \times 2.5mm \times 50microns$ and it determines the interior pressure of the eye by calculating the deformation from the contact of the adjacent lense to the eye sphere wall, Figure b-3. This sensor includes the strain gauge, digital processor, energy receiving loops and sender [5].

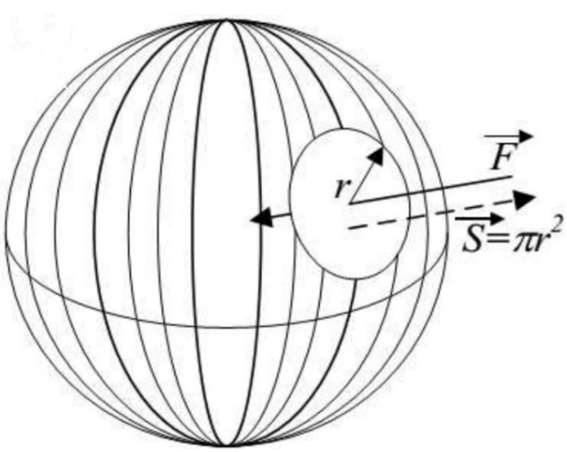

Figure 2: The cross section vector per- pendianlator to eye splane and the force applied to it

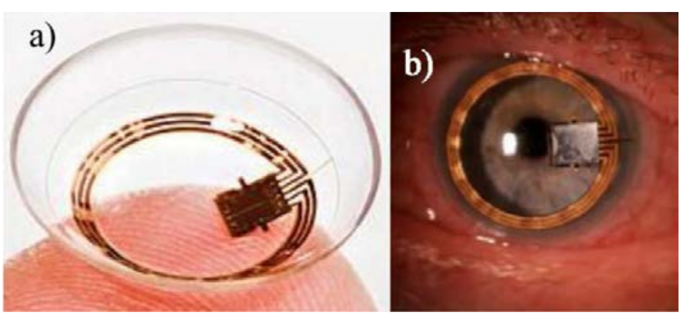

Figure 3: (a) The Triggerfish lenses sensor (b) The sensor when installed on the eye

The amount of deformation is determined by a strain gauge installed on the lense surface. This strain gauge is in a Wheatstone bridge with R=3.2KΩ±4% and the applied voltage 1.5V and converts the deformation amount to a voltage signal with the amplitude of ±35mV. This frequency after being amplified at the frequency of 25Hz is sampled by the analog to digital converter and eventually is sent by the radio with the FSK modulation in the frequency of 27MHz. The signal is received by the antenna near the eye and is recorded digitally in the recorder. Figure 4 shows the sensor parts and how the energy and data are transmitted in the Triggerfish sensor of SENSIMED Company.

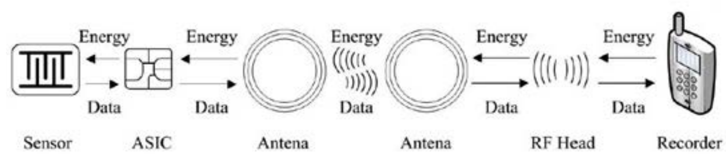

Figure 4: Schematic of Triggerfish sensor system

Although the Triggerfish sensor is easy to install, it can cause some problems for the patient. Two main problems of this sensor are:

A) The horizontal diameter of the human eye cornea is 11.75mm and the vertical one is 10.6mm, so the sensor stands against the eye cornea and prevents the light from entering cornea and at last causes reduction in the vision level of the patient.

B) The sensor design based on the strain gauge, digital converter, FSK modulation leads to an increase in energy consumption. To provide this energy, the patient need a battery with a great volume.

The new design based on MEMS capacitor sensor plan is presented in the following section.

II. MEMS BASED ONLINE EYE PRESSURE METER DESIGN

The new design based on MEMS capacitor sensor plan is presented in this section. The new design eliminates, the problems of the Triggerfish sensor. Substituting the strain gauge and the radio circuit respectively by the capacitor sensor and the resonance circuit explained in the following will result in the decrease in energy consumption.

Because the diameter of the eye pupil reaches 8mm at the most in the dark places and on the other hand the vertical diameter of cornea is 10.6mm which is the smallest cornea diameter, the only space on which the sensor can be installed on the eye without preventing the vision, is a strip with the thickness of 1mm around the cornea, Figure 5. By installing this sensor on this strip, there will be no problem for vision.

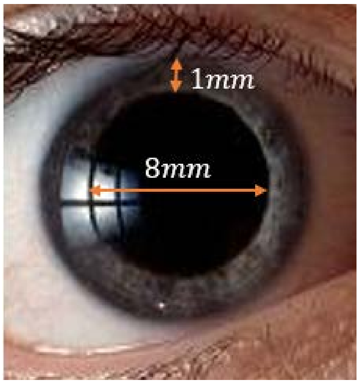

Figure 5: The eye pupil in a dark place

The MEMS capacitor sensor is designed cylindrically with the radius 0.5mm to be installed on the 1mm strip. This cylinder contains several layers. Figure 6 shows the layer structure of the MEMS capacitor sensor.

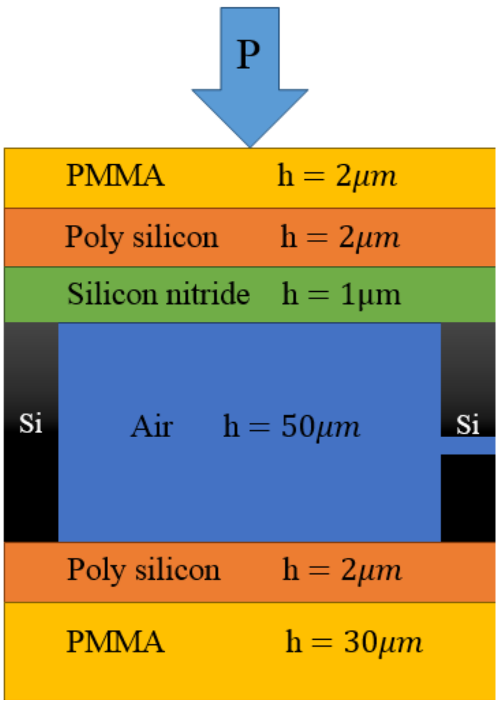

Figure 6: The layer structure of the capacitor MEMS sensor

The top and the bottom layers are made of poly methyl methacrylate. The thickness of these layers is 30µm and 2µm respectively. in fact the bottom layer is a part of the lense installed on the eye. The poly silicon layers with the thickness of 2µm at the top and the bottom act as the capacitor plates. The dielectric of this capacitor sensor is the air at 1Atm, so in the silicon strip with the thickness of 2 µm around the sensor, a hole is created so that the air pressure remains constant when the top plate is bent. The height of this dielectric layer of the capacitor is 50 µm. To avoid the capacitor breakdown outside the pressure limit, a silicon nitride layer with the thickness 1 µm is installed as the insulator between the capacitor plates.

The residual stress phenomenon is the reason to choose poly silicon and silicon nitride for the deposition process. The residual stress is caused by deposition in the manufacturing process of MEMS devices and influences the operation and the safety of these devices.

In some cases, the residual stress results in the device breakdown because of torsion, buckling, and rapture. The amount of residual stress in the manufacturing process depends on the materials and manufacturing method. Experiments in different conditions and on different materials show that the residual stress in poly silicon and silicon nitride is reduced considerably by the low pressure chemical vapor deposition (LPCVD) [7-8].

In completing the design of the eye pressure measurement system, 16 capacitors are installed in parallel. This is done to maintain the mechanical equilibrium of the contact lense in the case of installing the capacitor sensor and to increase the capacity of the capacitor sensor. Figure 7 shows the final design of the sensor on the eye.

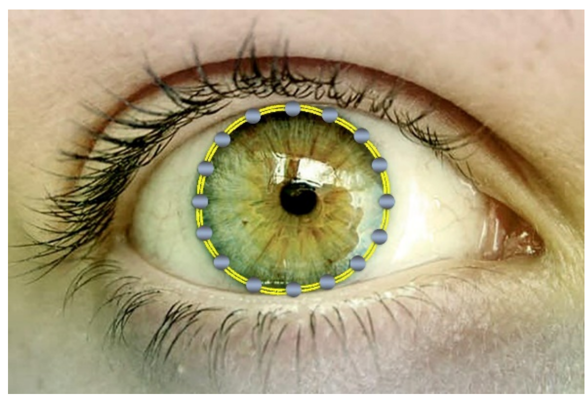

Figure 7: The sketch of MEMS the capacitor sensor for measuring the interior pressure of the eye.

The interior pressure of the eye applies vertically throughout the cornea. So the same pressure applies to each capacitor. This vertical pressure causes the bending of the top plate of the capacitor as Figure 8.

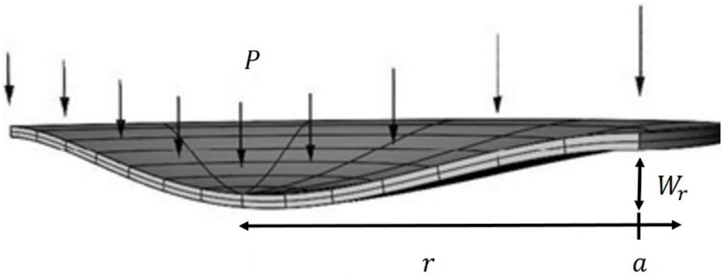

Figure 8: The deformation of the top plate of the capacitor causes by the applied pressure

The amount of the deviation of each circular section from the center of the plate with the radius r follows equation 2 [9].

$$W(r) = W_0\left(1-\left(\frac{r}{a}\right)^2\right)^2 \qquad (2)$$

In the above relation a is the radius of the plate and W_0 is the deviation of the center of the plate and $W(r)$ is the deviation of each section from the plate center and with the radius r. If it is assumed that the top plate of the capacitor is a compressed layer with the same materials, then the deviation of the plate center (W_0) follows equation 3.

$$W_0 = \frac{Pa^4}{64D+4\sigma ha^2} \qquad (3)$$

In the above relation, P is the applied pressure, h is the thickness of the plate, σ is the residual stress and D is defined in equation 4.

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad (4)$$

In the above relation, E is the Young's modulus and ν is the Poisson's ratio. Because the top plate of the capacitor sensor contains three layers with different materials, using equation 3 for calculating the amount of the deviation of the plate center analytically is difficult, so by simulating the capacitor in Abaqus software, the amount of the deviation of the plate center is obtained. Figure 9 shows the simulation of the capacitor sensor in Abaqus software by applying a 10 mmHg pressure and Figure 10 shows the output of Abaqus software which is the deviation of the plate center in the range of 10-30 mmHg.

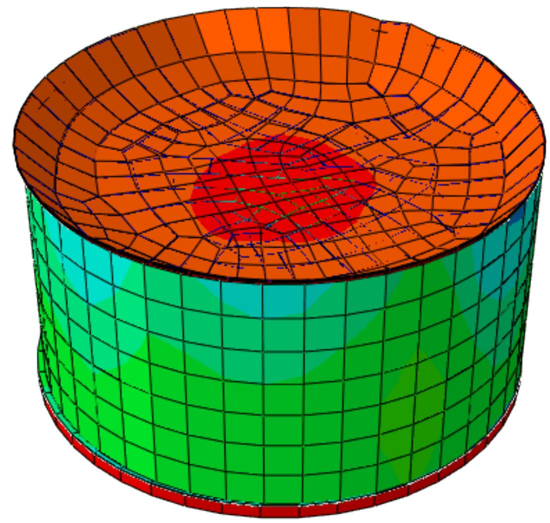

Figure 9: The simulation of the capacitor sensor by applying a 10 mmHg pressure in Abaqus software

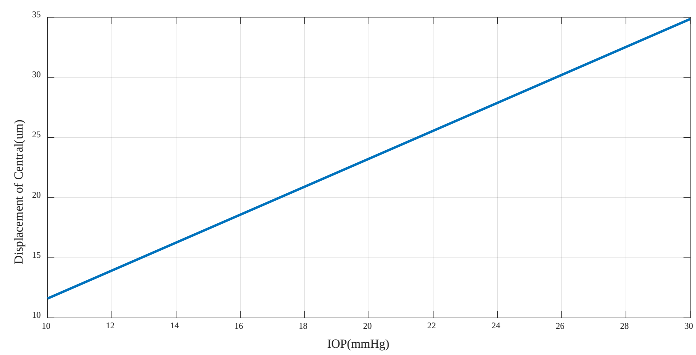

Figure 10: The center deviation of the sensor top plate cause by the applied pressure in the range 10-30mmHg

To calculate the capacity, equation 5 is used [10].

$$C = 2\pi\varepsilon \int_0^a \frac{r}{d-W(r)}dr \qquad (5)$$

In the above relation, d is the distance between the capacitor plates. Figure 11 shows the capacity of each capacitor of the sensor.

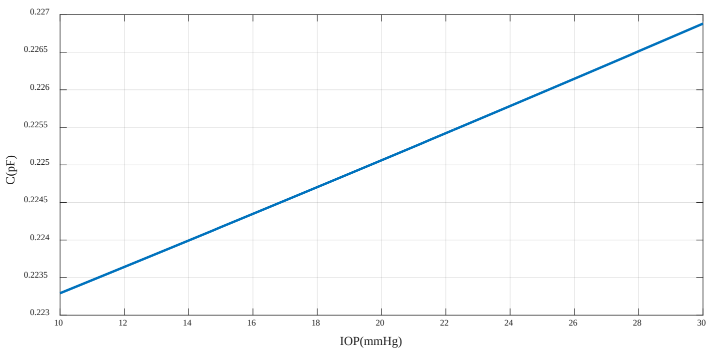

Figure 11: the capacity of one of the capacitors of the sensor in the applied pressure in the range of 10-30mmHg.

III. THE OUTPUT CIRCUIT DESIGN

The output circuit of the offered sensor contains a capacitor induction oscillator. In this circuit, the capacitor variation with the pressure determines the oscillation frequency. The changes in the resonance frequency is received by the induction antenna and is transferred to a recorder for monitoring the interior pressure of the eye, the induction antenna is in fact a circular induction whose inductance is determined using equation 6.

$$L_s = N^2 R \mu_0 \mu_r \left[\ln\left(\frac{8R}{a}\right) - 1.75 \right] \quad (6)$$

Where N is the turn number of induction coil, R is the coil radius, $\mu_0 \mu_r$ is permittivity and a is the radius of the wire section. Figure 12 indicates the electric circuit of the wireless communication with impedance reflection in the output.

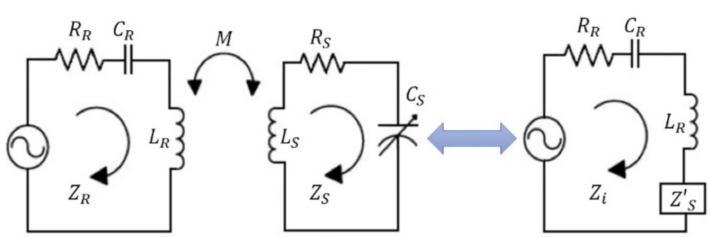

Figure 12: The equivalent circuit of the wireless communication of the sensor

The circuit impedance from the output is as equation 7:

$$Z_R = j\omega L_R + R_R + \frac{1}{j\omega C_R} \quad (7)$$

The circuit impedance from the sensor in the output is shown by equation 8.

$$Z'_S = \frac{(\omega M)^2}{j\omega L_S + R_S + \frac{1}{j\omega C_S}} = \frac{\omega^2 k^2 L_R L_S}{j\omega L_S + R_S + \frac{1}{j\omega C_S}} \quad (8)$$

Where k is the coupling coefficient which is defined as equation 9.

$$k = \frac{M}{\sqrt{L_R L_S}} \quad (9)$$

The coupling coefficient depends on the distance d between the sender and the induction receiver of the sensor. Because the sender and the receiver are co-centric and R_R is the receiver radius and R_S is the sender radius, the equation 10 indicates the relation between the coupling coefficient and the distance between the sender and the receiver [11].

$$k(d) = \left(\frac{r_S r_R}{d^2 + r_R{}^2}\right)^{\frac{3}{2}} \quad (10)$$

At last, the equation below indicates the circuit impedance from the receiver side (output side).

$$Z_i = Z_R + Z'_S \quad (11)$$

By substituting equation 7 and 8 in equation 11 we can obtain following equation [11]:

$$Z_i = j\omega L_R + R_R + \frac{1}{j\omega C_R} + \frac{\omega^2 k^2 L_R L_S}{j\omega L_S + R_S + \frac{1}{j\omega C_S}} \quad (12)$$

The parameters of the circuit (table 1) are designed so that the frequency range of the oscillator will be near the natural frequency of the sensor.

Table 1: the parameters of the sensor circuit

Parameter	Value
Reader Inductance $\boldsymbol{L_R}$	$\mathbf{1.4 \times 10^{-7} F}$
Sensor Inductance $\boldsymbol{L_S}$	$\mathbf{1.4 \times 10^{-7} F}$
Reader Resistance $\boldsymbol{R_R}$	$\mathbf{0.4\Omega}$
Sensor Total Resistance $\boldsymbol{R_S}$	$\mathbf{0.4\Omega}$
Sensor Nominal Capacitance $\boldsymbol{C_s}$ at $\mathbf{37°C}$ $\mathbf{0.87nF}$	
Coupling Factor $\boldsymbol{k}$	$\mathbf{0.97}$
Reader Radius $\boldsymbol{r_r}$	$\mathbf{2.25\ cm}$
Inductor Radius $\boldsymbol{r_s}$	$\mathbf{2.25\ cm}$
Coupling Distance $\boldsymbol{d}$	$\mathbf{3\ mm}$

When the frequency of the oscillator is equal to the natural frequency of the sensor, the circuit impedance increases suddenly from the receiver side. Figure 13 shows the results of circuit impedance simulation in different pressures via Matlab version R2015a software.

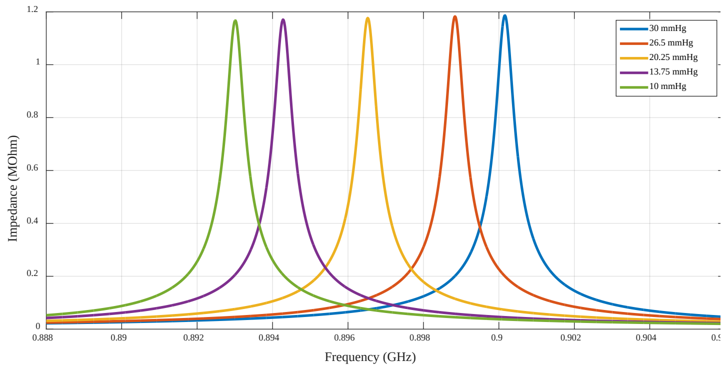

Figure 13: The output impedance in different pressures.

In this electric circuit, the change in the interior pressure of the eye causes the change in the capacity of the capacitor and this change in the capacity leads to the change in the resonance frequency. Equation 13 indicates the relation between the resonance frequency and the interior pressure of the eye.

$$f(P) = \frac{1}{2\pi\sqrt{L_S C_S(P)}} \quad (13)$$

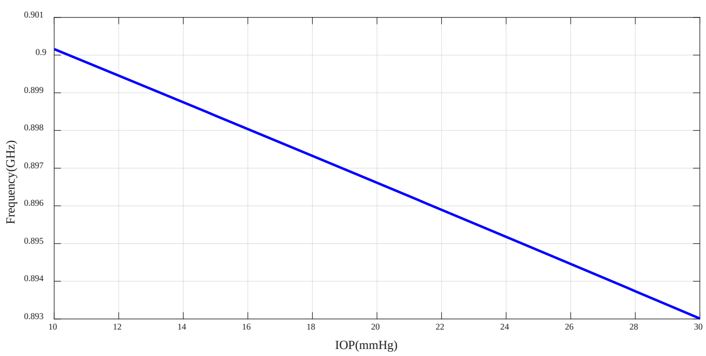

Figure 14: The changes of resonance frequency in the range of 10-30mmHg.

If we consider the Equation 13 in operation point we can see linear behavior as Figure 14. it indicates that there is a linear relation between the resonance frequency and the interior pressure of the eye and so it can be said that the sensor sensitivity in this pressure range is equal to 300KHz/mmHg. It can be consider near to operation point.

IV. CONCLUSION

The Glaucoma disease prevention needs the regular monitoring of the interior pressure of the eye and to do so, the MEMS devices are suitable choices for online eye pressure measurement. The problems of the Triggerfish lenses sensors can be eliminate using MEMS capacitor array sensor system. By analyzing and simulating, it seems that the presented MEMS capacitor sensor plan can lead to the decrease in energy consumption and so the sensor mass by using the circuit which has the wireless communication induction capacitor. It has high accuracy and linear behavior. The simulation results are promising.

REFRENCES

[1] Shen, S.Y., et al., The prevalence and types of glaucoma in Malay people: the Singapore Malay Eye Study. Investigative ophthalmology & visual science, 2008. 49 (9): p. 3846-3851
.

[2] Murawski, K., et al., An Infrared Sensor for Monitoring Meibomian Gland Dysfunction. Acta Physica Polonica, A., 2013. 124 (3): p. 2563-2570

[3] Murawski, K. and K. Różanowski, Pattern Recognition Algorithm for Eye Tracker Sensor Video Data Analysis. Acta Physica Polonica, A., 2013. 124 (3): p. 2712-2718.

[4] Murawski, K., L. Grad, and M. Rękas, Reconstruction of Lost Fragments of Signal Received from the Wireless Sensor Measuring Fluid Pressure inside the Eye Ball. Acta Physica Polonica, A., 2015. 124 (3): p. 3746-3756

[5] http://www.sensimed.ch/en/sensimedtriggersh/sensimed-trigger_sh.html, 2014.

[6] Mansouri, K., R.N. Weinreb, and J.H. Liu, Efficacy of a contact lens sensor for monitoring 24-h intraocular pressure related patterns. PloS one, 2015. 10(5): p. 1256-1264

[7] Sharma, N., M. Hooda, and S. Sharma, Synthesis and characterization of LPCVD polysilicon and silicon nitride thin films for MEMS applications. Journal of Materials, 2014. 10(5): p. 3527-3533.

[8] Jiang, W., et al., Effect of hyperthermal annealing on LPCVD silicon nitride. Materials Science in Semiconductor Processing, 2016. 43: p. 222-229.

[9] Ventsel, E., T. Krauthammer, and E. Carrera, Thin Plates and Shells: Theory, Analysis, and Applications. Applied Mechanics Reviews, 2002. 55: p. 72-75.

[10] Ha, D., et al., Polymer-based miniature flexible capacitive pressure sensor for intraocular pressure (IOP)

monitoring inside a mouse eye. Biomedical microdevices, 2012. 14(1): p. 207-215.

[11] Rodriguez, R.I. and Y. Jia, A wireless inductive-capacitive (LC) sensor for rotating component temperature monitoring. Int. J. Smart Sens. Intell. Syst, 2011. 4(2): p. 325-337.