Design and Simulation of Sensor for Acquisition of Arterial Pulse Detection

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Abstract

The work presented in this paper describe the design and simulation of a MEMS (Micro Electro Mechanical System) system based piezoelectric sensor for detecting arterial pulse in biomedical application. The study is done through the analysis of square and circular diaphragm made out of piezoelectric and MEMS material. In this work, piezoelectric material is used which work on the principle of piezoelectric effect. In piezoelectric effect, diaphragm reorients under stress, form an internal polarization which result in crystal charge on the crystal face that is proportional to applied pressure. When pressure is applied on diaphragm deformation occurs which converts physical energy into output electrical voltage. For selecting the appropriate geometry and material for sensor design different parameter were checked such as deformation, output voltage, Stress and linearity. FEM analysis is done for circular and square diaphragm on COMSOL Multi-Physics. Comparison of square and circular diaphragm is done on the basis of deformation and Electrical potential. Piezoelectric sensor is designed and simulated with lithium-Niobate and poly-si. Sensitivity obtained for the designed sensor is about 4mV/Kpa.

Keywords— Traditional Indian Medicine (TIM), MEMS, FEM (Finite element analysis), COMSOLE Multiphysics

Language: English

Date of Submission: 05-08-2018

Date of Acceptance: 20-08-2018

Date of Publication: 03-09-2018

DOI: 10.24297/ijct.v17i2.7574

ISSN: 2277-3061

Volume: 17 Issue: 02

Journal: International Journal Of Computers & Technology

Publisher: CIRWORLD

Website: https://cirworld.com

INTRODUCTION

In ancient time, Nadiparikasha is done in ayurveda for diagnosis of disease. Nadipariksha is done by applying pressure on redial artery of left hand wrist. The pulse obtained from radial artery are due to contraction and relaxation of blood vessel, moment of blood through the artery due to that change in diameter occurs[1]. In an ancient technology, Nadiparikshan is done by ayurvedic experts. Accuracy of diagnosis is depends on the expertise. To improve accuracy of diagnosis electronic devices are made. In electronic system, to detect the pulse from radial artery different sensor were used and that detected signal carry information of health and disease in the body.

Pressure sensors such as piezoelectric, piezoresistive, capacitive, ultrasonic, IR sensor, FSR were used for detecting arterial pulse. For human pulse detection strain guage transducer is not used as it required power supply for operation and output waveform are noisy. Whereas piezoelectric sensor has good dynamic response and it does not show dc shift when pressure is applied. Therefore piezoelectric sensors were used for arterial pulse detection. The word is getting digitalized and smaller so MEMS technologies were recently used for sensor design. MEMS systems are smaller in size and light in weight.

2. RELATED WORK

Radial pulse pressure signals are utilize in ancient TIM and TCM for health diagnosis. These approaches give importance to three distinct pulse points over radial artery for the assessment of health status. A survey of piezoresistive pressure sensor has been done by Shwetha Meti [25] including their pressure sensing mechanism. This paper provides survey of piezoresistive pressure sensor including their pressure sensing mechanism, evolution, materials, design considerations, performance parameter that to be considered and the fabrication process used Jae J. Im [5] designed blood pressure monitoring system using piezoelectric sensor. In this work, author worked on intra-arterial pressure pulse, radial artery pulse, and FSR output from patients during surgery. It was observed that, 0.010 volts is maximum value of for radial artery pressure pulse, when the output of the FSR was set at 1.6 volts. Philippe Renevey [6] developed a wrist-located pulse detection system. In this paper, author uses IR signals for detection of pulse signal. The method was based on optical infra-red (IR) signal which was emitted on the surface of the body tissue.

Piezoelectric membrane sensor was developed [7] which consist of piezoelectric ceramic film, metal foil and top electrode. In this paper, corona discharge poling method was used to achieve piezoelectricity. Highly flexible sensor was realized because of porosity in the piezoelectric film. Thick PZT film was fabricated onto SS foil. This sensor was tested by directly attaching sensor onto the wrist and corresponding wave signal was obtained. This sensor was also used for taking breathing curves from human belly. Sol-gel composite spray method used for fabrication. Lu Wang [8] developed arterial pulse detecting system using nc-Si: H/c-Si heterojunction MOSFET pressure sensor. Fabrication of MOSFET pressure sensor was done by MEMS technology. This developed system was used to detect, display, store and analyze pulse signals simultaneously. MEMS Based Piezoresistive Pressure Sensor was developed to improve Sensitivity [9]. Silicon nitride diaphragm was used in this work. Principle of the sensor was dependant on the deflection of the silicon nitride diaphragm. By analyzing different dimension of square and circular diaphragm, author found that square diaphragm had highest induce stress compared to circular diaphragm as high stresses generate high sensitivity which was in range of 0 to 1MPa. Gatkin [10], developed a low-cost arterial pulse analyzer using piezoelectric ceramic plate sensors for recording dynamic pressure waves at radial and brachial arteries non-invasively. This analyzer provides run-time display of arterial pulse waveforms during test.

Pulse Pressure Sensor Based designed with PZT thick film [11]. PZT thick film had good piezoelectric property and mechanical flexibility and for this reason it was used in designing of flexible diaphragm pressure sensor. PZT film had good frequency accuracy and linearity. PZT thick film had good piezoelectric property and flexibility therefore it was used in human pulse pressure monitoring system. Piezoresistive MEMS Pressure Sensors was developed using Si, Ge, and SiC diaphragms [12]. The piezoresistive property such as output voltage, deflection, stress was used to decide the shape of diaphragm. Here, Circular, Square and Rectangular shapes were considered for study. In this work they observe that, for deflection value of the circular diaphragm is better and for stress rectangular diaphragm is better. Author concluded that from mechanical and electrical point of view the square diaphragm is better.

MEMS Piezoresistive Pressure Sensor was developed by Wang Lijing [13] to enhance sensitivity. The Sensitivity of MEMS piezoresistive pressure sensor was improved by selecting proper membrane geometry and piezoresistor location. As it is piezoresistive sensor, applied pressure is converted into voltage through wheatstone bridge. It is observed that effective use of the sensor deflection area increases the sensitivity of the sensor. MEMS silicon piezoresistive pressure sensor was developed for barometric application [14]. Wheatstone bridge configuration was used for sensitivity measurement. In this paper designing and simulating various parameter of silicon was considered such as fabrication technology of silicon, diaphragm thickness, size and orthotropic properties of silicon. Linearity and sensitivity of the silicon piezoresistive pressure were checked.

3. Piezoelectric Pressure Sensor

In ayurveda, Nadipariksha is done for diagnosis of disease and body condition. Nadiparikshsa is done by ayurvedic expertise and so accuracy of the result is depend on his expertise knowledge. So, to make a step towards making the diagnosis by nadi-pariksha objective, science based system is need to be developed for human pulse detection which will be accurate & intelligent enough to take decision. Almost seventy years ago infrared optical sensors have been used as in photo-plethysmography (PPG) [17] for cardiovascular pulse detection to measure the optical power variation which is due to absorption or scattering when the amount of blood in the measurement volume varies. IR sensors do not measure the pressure directly. Dupuis et. al. [18], describe use of a strain gauge differential pressure sensor in a measurement system, where a low pressure cuff was wrapped around the wrist and then the pressure modulation in the cuff caused by the pressure pulse was measured with strain gauges. But strain gauge requires power source for its operation. Also waveforms may be noisy and there was dc shift due to holding pressure and shift varied as holding pressure changed. Sorvoja et. al. and Ruha et al.[19, 20], describe utilization of new pressure sensitive materials like electromechanical film (EFMi) and polyvinylidene fluoride (PVDF) in sensors for pulse detection in the radial artery. Gagnadre et. al. [21], describe the use of fiber optic sensors to detect heart rate. A multimode optical fiber was placed between two aluminum plates. The force generated by the pressure pulse caused variation in the modal distribution in the fiber and the pulse is detected using a photodetector.

Recently piezoelectric sensors [22, 23, 24] are widely used measuring pulse pressure directly where the mechanical stimulus generated by the pressure pulse in converted to an electrical signal for further signal processing. A piezoelectric sensor for pulse detection has good dynamic response. Piezoelectric material does not show dc shift also it has dynamic response. In the present research work, the designing and simulation of the MEMS piezoelectric pressure sensor is carried out for acquisition arterial pulse data. The analysis of square and circular diaphragm is done with comparison in the deformation and electrical potential to select appropriate diaphragm. Stationary analysis is done to calculate the sensitivity of designed sensor. Finally time dependent study is done on real time database.

4. Piezoelectric Effect

Piezoelectric sensor works on the principle of piezoelectric effect. Electrical potential is generated under mechanical stress is direct piezoelectric effect [3]. Piezoelectric sensors are active sensors and produce electrical potential (charge) under applied stress [4]. Electrical potential is develop due to polarization of crystal under stress. Mechanical stress occurs on applying electrical potential is called inverse piezoelectric effect. Constitutive equation for piezoelectric effect is given below.

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^{d} \sigma_m$$

Where D is electrical displacement, E is applied electric field, σ is stress, e_{ij}^{σ} is piezoelectric constant permittivity & d_{im}^{d} is piezoelectric coefficient. These all are matrix of different dimension. The above equation describes the principle of piezoelectric effect.

The relation between electric displacement D abd generated charge is given below in equation form.

$$q = \iint D_1 \quad D_2 \quad D_3 \begin{bmatrix} dA_1 \\ dA_2 \\ dA_2 \end{bmatrix}$$

From above equation, it shows charge q is dependent on electrode area normal to the displacement, where dA1, dA2, dA3 are electrode area. The charge q and voltage generated across sensor electrode Vc by following equation where Cp is capacitance.

$$Vc = q / Cp$$

So electric voltage generated in sensor determine by using above equations.

5. Piezoelectric MEMS Design consideration

In present wok, circular and square shape of diaphragm is analyzed for deformation and electrical potential. Select appropriate diaphragm for further work.

5.1.1 Square diaphragm

Square shape diaphragm is designed having length and breadth of 100um and height is 5um as shown in Fig1. Corner square block is of length 10um and height is 1um. Piezoelectric material lithium niobate is placed at the corner block of designed diaphragm. Poly Si is placed at other part of sensor.

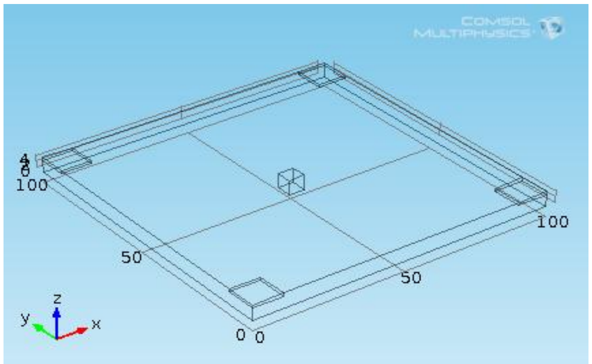


Fig 1 Design for square diaphragm

The force of 1uN is applied at the center of the diaphragm. Central block has length 5um and width is 5um and height is 5 um. On applied force diaphragm gets deform under the stress electrical potential is developed. Displacement and electrical potential obtained is shown in Fig 2.a. and Fig 2.b respectively. Applying 1uN force on square diaphragm, as length increases the output voltage and deformation goes on increases but when height is increases then output voltage and deflection goes on decreasing. From the result of different size it can conclude that for better result design of sensor should be thinner and length should be more. Therefore for design of sensor select max length and minimum height. The comparative table for square diaphragm with different length & breadth is shown in Table 1.

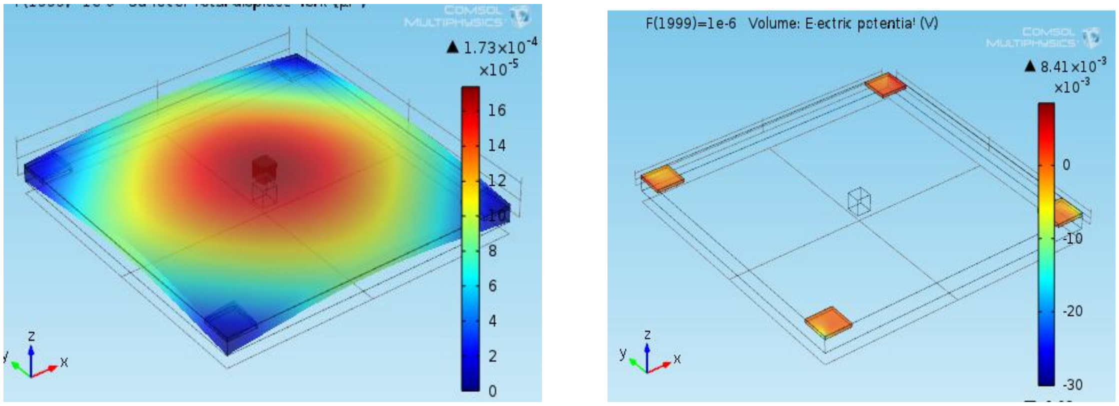


Fig 2.a Displacement

Fig 2.b Electrical potential

Fig 2 Displacement and electrical potential for circular diaphragm

Sr. No.	LENGTH	BREATH	HEIGHT	DEFORMATION	ELECTRICAL POTENTIAL
1	80um	80um	5um	1.11*10^-9 um	5.43*10^-6 V
2	100um	100um	5um	1.73*10^-9um	8.41*10^-6V
3	120um	120um	5um	2.5*10^-9um	11.03*10^-6V
4	80um	80um	10um	1.498*10^-11um	1.18*10^-7V

Table 1: Comparative table for square Diaphragm

5.1.2. Circular diaphragm

Circular Shape diaphragm is designed with radius of 40um and height is 5um as shown in Fig3. Similar to the square diaphragm, in circular diaphragm piezoelectric material is placed at the four blocks as shown in Fig4 which is length 10um and height 5 um. At other part of design poly si material is placed.

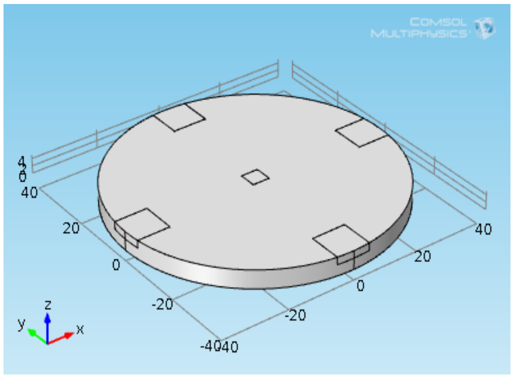


Fig 3 Designed for Circular diaphragm

Force of 1 uN is applied on the center block of design. The middle block having length of 5um, width of 5um and height is of 5um. On applying pressure design gets deform and induces deformation and electrical potential shown in Fig 4.a. and Fig 4.b. respectively. The comparative table for circular diaphragm with different radius & height is shown in Table 2.

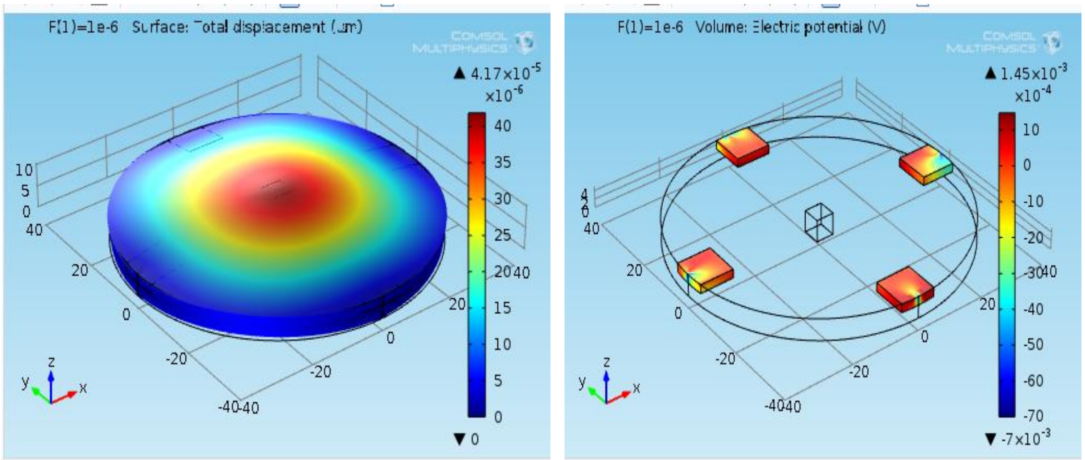


Fig 4.a Displacement

Fig 4.b Electrical potential

Fig 4 Displacement and electrical potential for circular diaphragm

SR. NO.	RADIUS	HEIGHT	DEFORMATION	ELECTRICAL POTENTIAL
1	40um	5um	4.178*10^-11um	1.45*10^-7V
2	20um	5um	2.39*10^-11um	2.79*10^-7V
3	40um	10um	6.69*10^-13um	1.37^10^-7V

Table 2: Comparative table for circular Diaphragm

From the results shown in Table 1 & Table 2, deformation as well as electrical potential of square diaphragm is better than circular diaphragm when applied force is 1 uN. Fig 2 and Fig 4 shows the electrical potential and deformation of square and circular diaphragm respectively on applied of pressure of 1uN. So for further analysis & for design of sensor, square diaphragm is used.

5.2 Modified Piezoelectric Sensor

To increase the electrical potential on applied force of 1uN modified geometry is designed. In designed sensor, piezoelectric material lithium niobate is placed in zig-zag at the corner shown in Fig 5. At other part of the sensor poly si material is placed.

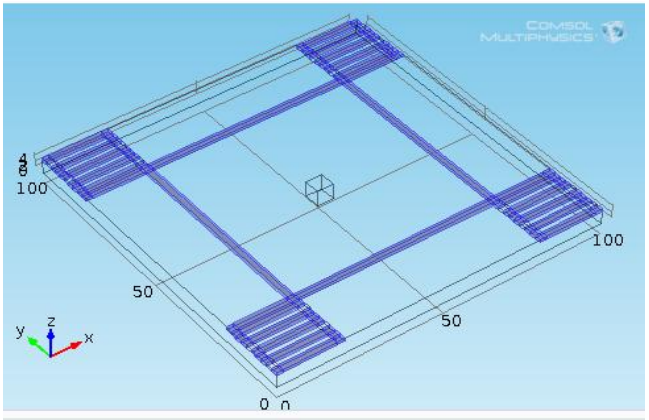


Fig 5. Modified design of square diaphragm

The force of 1uN is applied at the centre of diaphragm of size 5um*5um*5um. Simulation result for deformation and electrical potential of modified design sensor is shown in Fig 6.a and Fig 6.b respectively. Electrical potential of this designed sensor is better than previous designed.

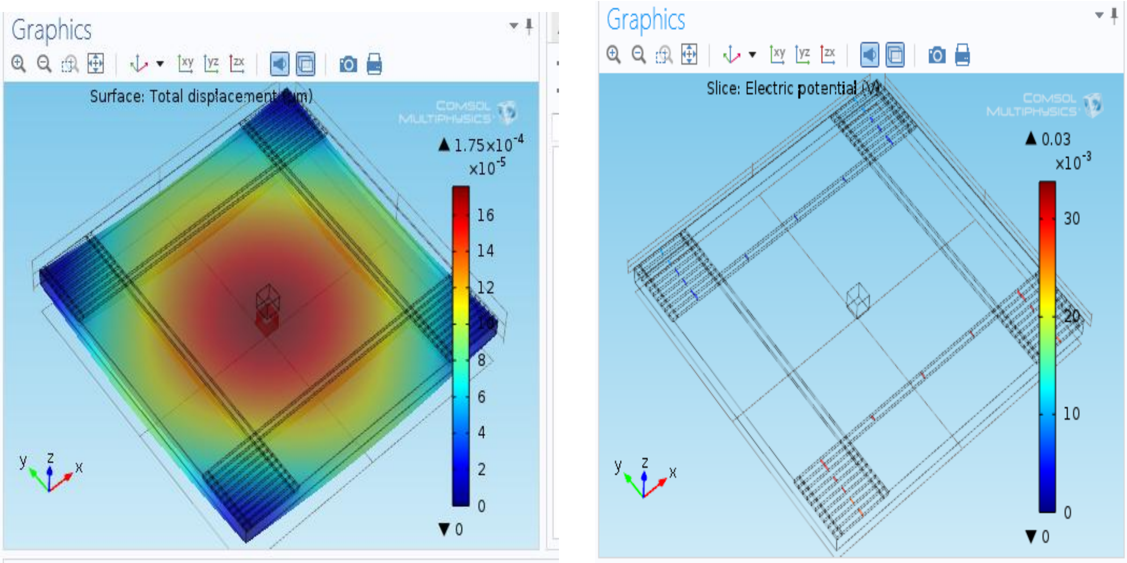


Fig 6.a Displacement

Fig 6.b Electrical potential

Fig 6 Displacement and electrical potential for modified design

5.3 Analysis for material selection

To select the appropriate material which gives better for electric potential depend on stress developed on applying force. The stress developed in sensor is dependent on the different properties of material. Analysis for different material is done. Analysis is done by applying 1uN force on square diaphragm of length 100um and height 5um as shown in Fig7.a Comparison for developed electric potential for different material is done which is given in Table 3.

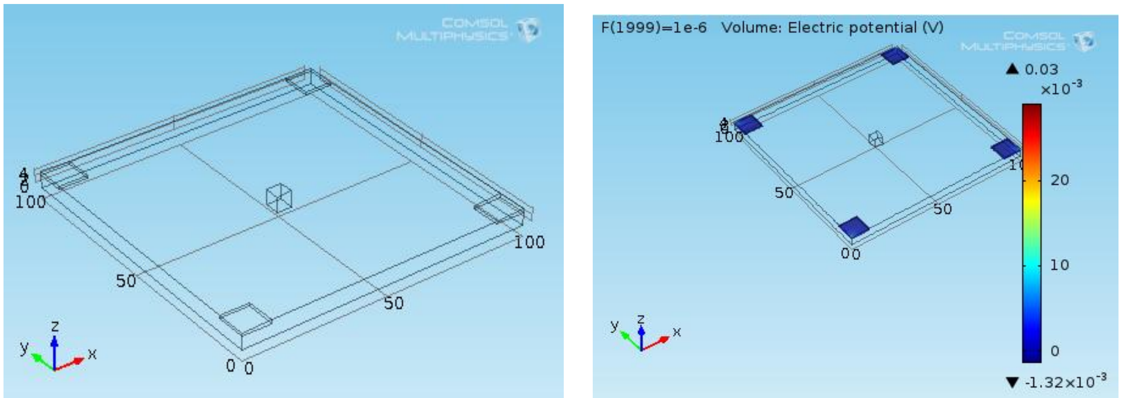


Fig7.a Design of square diaphragm Fig7.b Electrical potential

Fig.7. Square diaphragm and its electrical potential with lithium niobate

Material	**Electrical Potential(V)**
Barium Sodium Niobate	1.43*10^-7
Barium Titanate	2.528*10^-7
Lithium Tantanate	5.34*10^-6
Lithium Niobate	8.41*10^-6
Lead Zirconate Titanate PZT-2	3.63*10^-8
Lead Zirconate Titanate PZT-4D	2.2*10^-8
Lead Zirconate Titanate PZT-5H	2.33*10^-9
Quartz	0.02*10^-3
Zinc oxide	0.03*10^-3
Zinc sulphide	7.96*10^-7

Table 3. Comparative table for electric potential for different material

From above comparative table for piezoelectric material & observed electrical potential, zinc oxide has better result as compare to other material.

5.3.1 Properties of Zinc oxide

Zinc oxide is piezoelectric material which works on the piezoelectric effect. Zinc oxide has formula ZnO which is inorganic compound. Zinc oxide is II-IV group compound semiconductor. Zinc oxide has high transparency, high electron mobility and wide band gap. Properties of zinc oxide are given in Table 4

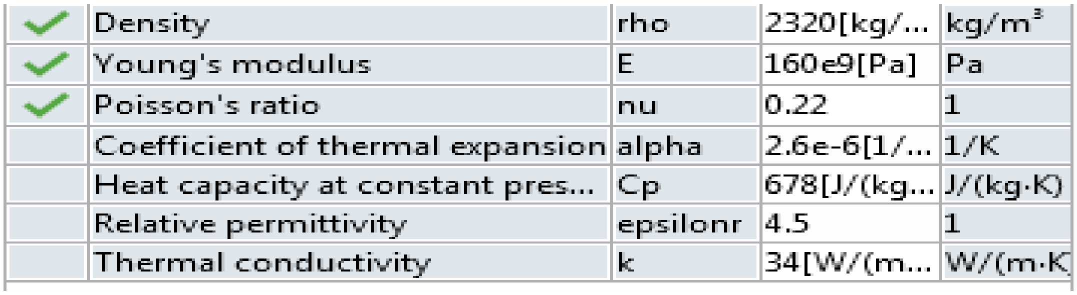
Density of zinc oxide is 5680 Kg/m. Elasticity matrix of zinc oxide of designed sensor is order of matrix 6*6. For presented work coupling matrix is also order of 6*6 for zinc oxide. Relative permittivity is 8.544. All factors which affect the results are mentioned in Table 4.

	Property	Name	Value	U
✓	Density	rho	5680[kg/...	kg
✓	Elasticity matrix (Ordering: xx,...	cE	{2.09714...	Pa
✓	Coupling matrix	eES	{0[C/m^...	C/
✓	Relative permittivity	epsilon...	{8.5446,...	1
	Compliance matrix (ordering: x...	sE	{7.86e-01...	1/
	Coupling matrix (ordering: xx,...	dET	{0[C/N],...	C/
	Relative permittivity	epsilon...	{9.16, 9.1...	1
	Loss factor for compliance ma...	eta_sE	0	1

Table 4 Properties of zinc oxide.

5.3.2 Properties of polycrystalline Silicon:

Polycrystalline silicon is also called as poy-si which has high purity. It is in crystal form. Polysilicon is also called crystallite, which is a material having metal fake. Poly silicon is collection of single crystal silicon randomly. It is deposited on top of the silicon substrate. It is nothing but highly doped silicon. One of the major advantages of poly silicon over silicon crystal is that, it is randomly oriented & has strong bonding in molecule. Density of poly silicon is 2320 kg/m3 whereas Young’s Modulus is 160*109 Pa. Purity of poly silicon can be as high as 99.9999% property. Properties of poly-si is given in Table 5.



✓	Density	rho	2320[kg/...	kg/m^3
✓	Young's modulus	E	160e9[Pa]	Pa
✓	Poisson's ratio	nu	0.22	1
	Coefficient of thermal expansion	alpha	2.6e-6[1/...	1/K
	Heat capacity at constant pres...	Cp	678[J/(kg...	J/(kg·K)
	Relative permittivity	epsilonr	4.5	1
	Thermal conductivity	k	34[W/(m...	W/(m·K

Table 5. Material properties of Poly Si

5.4 Modified piezoelectric sensor with zinc oxide

In analysis of material, zinc oxide has better result as compare to other piezoelectric material so here modified piezoelectric sensor is design and simulated with zinc oxide instead of lithium niobate. In designed sensor, piezoelectric material zinc oxide is placed in zig-zag at the corner shown in fig 8. At other part of the sensor poly si material is placed.

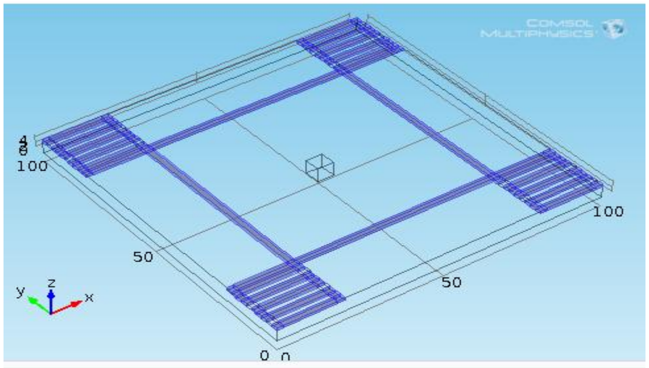


Fig 8. Modified design of square diaphragm

The force of 1uN is applied at the centre of diaphragm of size 5um*5um*5um. Simulation result for deformation and electrical potential of modified design with zinc oxide is shown in fig 9.a and fig 9.b respectively. Electrical potential of this designed sensor is better than previous designed.

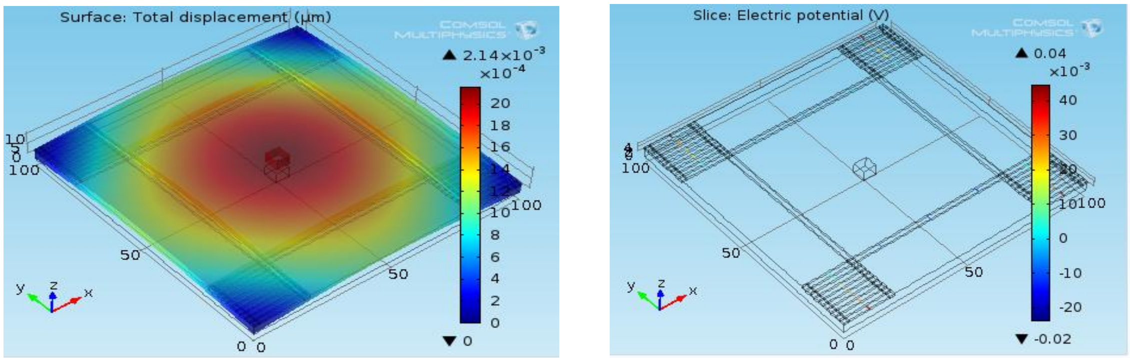


Fig 9.a Design of square diaphragm Fig9.b Electrical potential

Fig 9 Square diaphragm and its electrical potential with zinc oxide

5.5. Design of piezoelectric arterial pulse Sensor

5.5.1 Design, deformation and electrical potential

Diameter of radial artery is 2.4mm. Pressure in radial artery is in the range of 70mmhg to 120mmhg. To detect pulses from radial artery sensor have length and width in mm. So the sensor is designed with 5mm length and width and height is 0.2mm which is shown in Fig 10. Pressure of arterial pulse is 70mmhg to 120mmhg therefore 9kpa to 15kpa pressure is applied. On applying pressure, displacement and electric potential is as shown in Fig. 11. As shown in Fig.10 piezoelectric material zinc oxide is placed at the corner of zig-zag shape. Poly-si material is placed in other portion of the geometry.

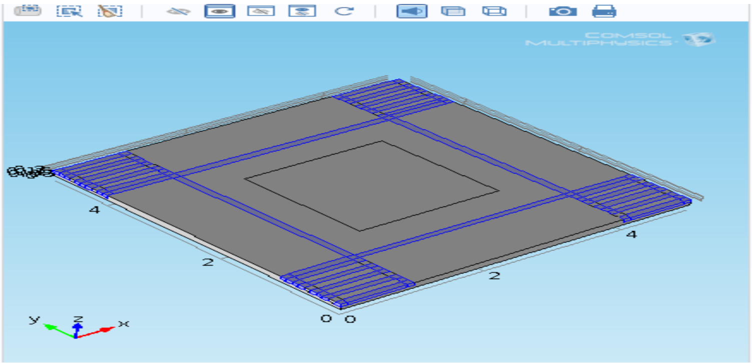


Fig 10 Design of piezoelectric arterial pulse sensor

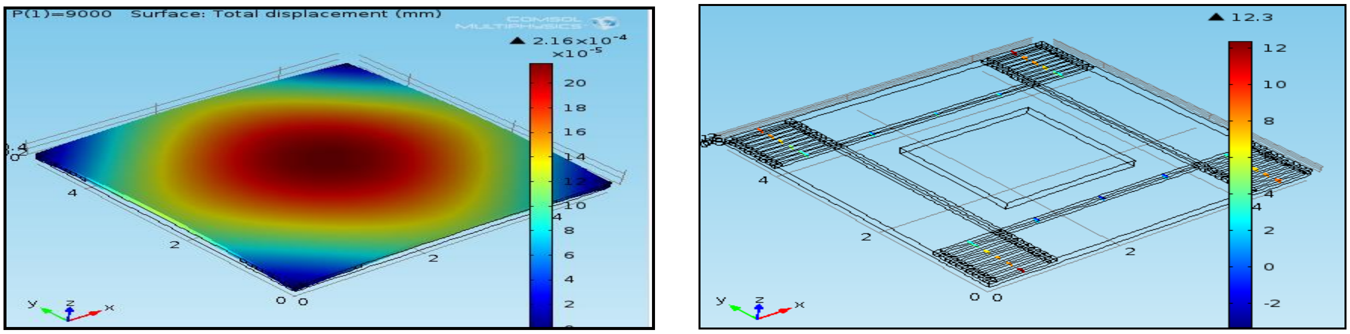


Fig 11.a Displacement

Fig 11.b Electrical potential

Fig 11. Displacement and electrical of arterial pulse sensor.

Designed Piezoelectric arterial pulse sensor is as shown in Fig 10. Stationary analysis is done for piezoelectric arterial pulse sensor which gives maximum displacement of 2.16*10^-9mm as shown in Fig11.a.On applying pressure from 9Kpa to 15Kpa, electrical potential of 0 to 12 V occurs at various stages as shown in Fig11.b

5.5.2 Sensitivity of piezoelectric arterial pulse Sensor

Sensitivity is defined as the ratio of change in output to change in measured quantity. Therefore for piezoelectric MEMS pressure sensor, sensitivity is ratio of change in output voltage to the change in applied pressure or stress. Sensitivity is one of the parameter used to determine accuracy of the sensor

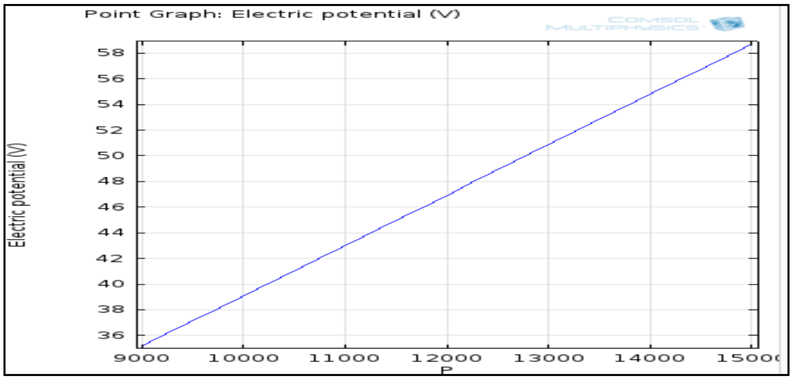


Fig12 Graph of pressure vs electrical potential

Sensitivity of designed sensor is calculated from graph of applied pressure verses output electrical potential shown in Fig12. Sensitivity obtained of designed piezoelectric MEMS arterial pulse sensor is 4 mV/pa

5.5.3 Sinusoidal waveform as input to sensor

Time dependent analysis is done for designed square diaphragm to check dynamic response. In this study, 100 Hz sinusoidal wave is given as input force shown in Fig.13.a.

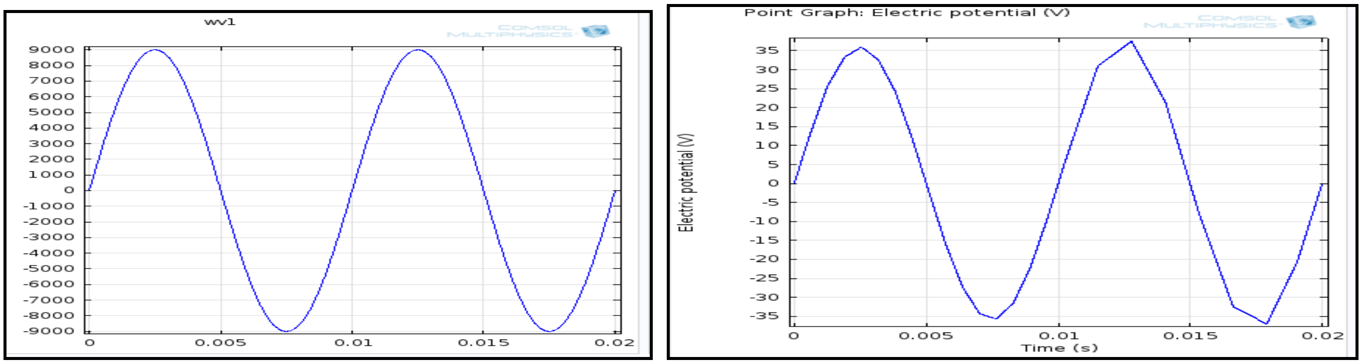


Fig 13.a Input sine waveform

Fig 13.b Output electrical voltage

Fig13 Input sinusoidal waveform and Output waveform for electrical voltage

Electric potential is generate on applying of sinusoidal input. Input sinusoidal wave of 100Hz and output electric potential shown in Fig13.b. The designed piezoelectric sensor is linear upto10KHz as the frequency response is good up to Kilo Hertz.

5.5.4 Real time input data

The designed sensor is checked with real time signals taken from database. Waveform of real time database is shown in Fig. 14.a. This waveform is applied at the centre of sensor.

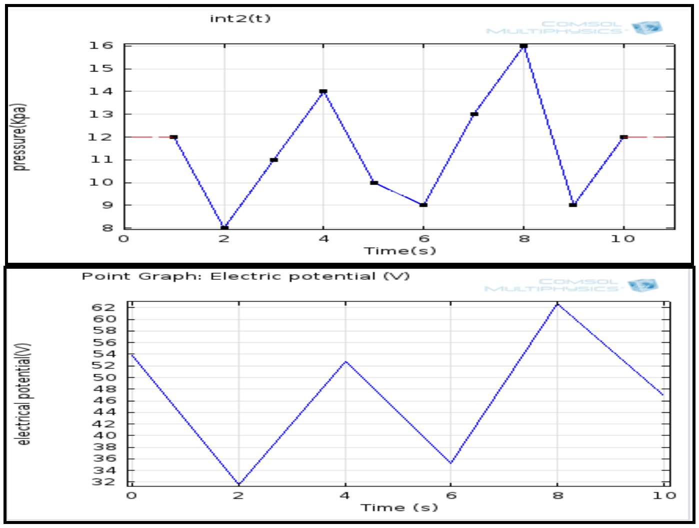


Fig 14.a Input data input

Fig 14.b Output electrical potential

Fig.14 Input waveform Output waveform of electrical potential

Electrical potential develop on applying that waveform is shown in figure 14.b. That shows the output voltage on applied waveform form database

6. CONCLUSION

In the present research work, a complete design of piezoelectric pressure sensor for arterial pulse detection is done. By simulating square diaphragm and circular diaphragm on COMSOL multiphysics, it is found that square diaphragm has better result in deformation and electrical potential as compare to circular diaphragm and the Zinc oxide has better result than other piezoelectric material. Therefore mechanically and electrically square diaphragm is better for fabrication. Time depended analysis is done for designed sensor and found that designed sensor is linear in frequency range of 10Hz-10KHz and so can be very well used for arterial pulse detection. Sensitivity obtained for designed piezoelectric pressure sensor for arterial pulse detection is about 4mV/pa.

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