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Modelling and Simulation of Pressure Sensor based on square diaphragm with ZnO as piezoelectric material

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Abstract: MEMS is generally considered as a micro-system, which is an integration of sensors, actuators and micro-electronic circuits on silicon substrate ranging from sub-micron level to few millimetre levels by using micro-fabrication technology. These compact, cost effective and highly sophisticated devices are found to replace the bulky counterparts efficiently in many traditional applications. Now-a-days, MEMS has been getting wide popularity in various fields of research such as aero-space, bio-medical, consumer electronics, communication, automation etc. and so is becoming an interdisciplinary field of engineering research. The most adorable feature of MEMS is the ability to integrate sensing, controlling and actuating functions on a single chip.

Here, an attempt has been made to cover the application of MEMS in pressure sensor system, where diaphragm is observed to play a vital rule. The efficiency of a pressure sensor mostly depends on the design of the diaphragm and location of sensing materials. We have investigated the effect of size and thickness of the Si-diaphragm and ZnO piezoelectric material blocks on pressures sensors constituting of Si-diaphragm, SiO2-insulator and ZnO-piezoelectric blocks. The effects have been measured in terms of three vary important parameters of pressure sensors viz. stress experienced, voltage induced and deflection taken place. The values for these three parameters are calculated via mathematical modelling and computational simulation using COMSOL Multiphysics software. Two sets of values thus obtained for every parameter are found to approximate closely and so vindicate our method of study in COMSOL Multiphysics software.

From the study, it is observed that stress experienced by the pressure sensor is directly proportional to the size of the diaphragm, while it is inversely proportional to the thickness of the diaphragm as well as the piezoelectric material layer. Voltage induced at the pressure sensor is directly proportional to the size of the diaphragm as well as the thickness of the piezoelectric material, while it is inversely proportional to the thickness of the diaphragm. Deflection taken place of the pressure sensor system is nearly independent of the thickness of the piezoelectric material, but it increases gradually with increase in the size of the diaphragm.

Thus for an effective design of a pressure sensor system, the diaphragm and the piezoelectric materials should be of low thickness, while the area of the diaphragm should be sufficiently high.

Keywords: Micro Electro Mechanical Systems (MEMS), Zinc Oxide (ZnO), Aluminum Nitrite (AlN), Lead Zirconate Titanate (PZT).

1. Introduction:

MEMS is the acronym of ‘Micro-Electromechanical System’. It refers to machines with moving parts in micro-scale range that contain miniaturized electrical and mechanical components generally based on silicon wafer. MEMS is generally consisting of mainly four parts: micro-mechanical sensors, actuators and micro-electronic circuits and micro-structures. The most notable elements are the micro-sensors and micro-actuators. Micro-sensors and micro-actuators are appropriately categorized as ‘transducers’, which are defined as devices that convert energy from one form to another. In the case of micro-sensors, the device typically converts a measured mechanical signal into an electrical signal [1-4].

MEMS devices are manufactured by using micro-fabrication techniques as those used to create integrated circuits. The results are some of the smallest machines ever made, capable of being built on a silicon wafer alongside the circuits that control them. Most MEMS devices are still experimental, but they are already being used in cars to deploy airbags, bio-medicals, consumer products, telecommunication, aerospace and actuate antilock brakes, in integrated optical switches to handle internet traffic, and in many other areas.

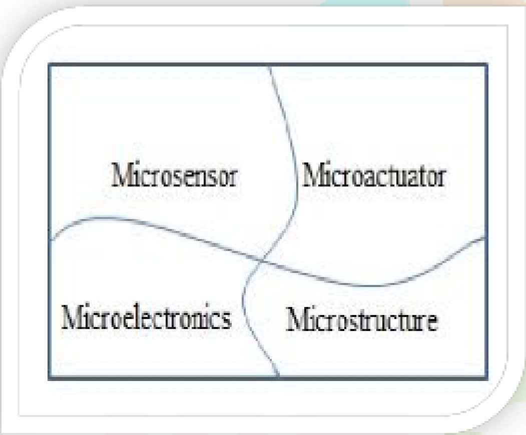


Fig.1. Components of MEMS

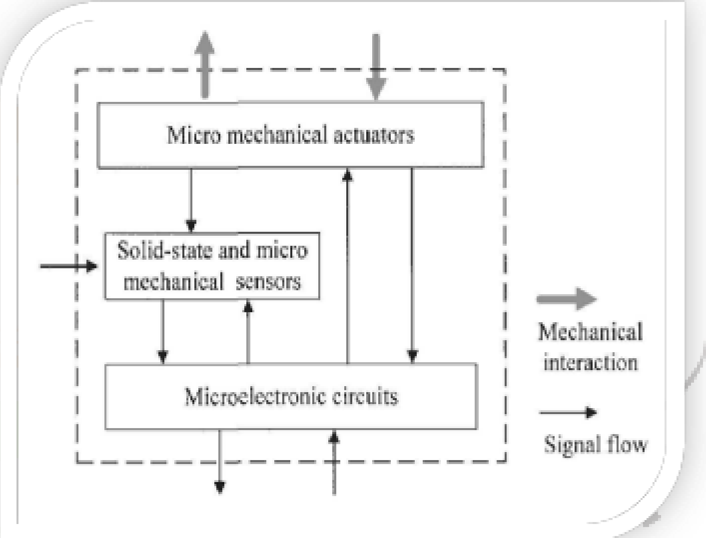


Fig.2. Basic configuration of a MEMS device

The bold arrows in the **Fig.2** indicate the mechanical interaction between the device and the outside world and the thin arrows indicate the electrical or other non-mechanical signals among the components of the device and between the device and the outside world. Not every MEMS device makes use of all the components and operations indicate in the **Fig.2**, but each involves a micromechanical structure of some kind [5-8].

The micro-actuator is an important component of MEMS, which is responsible for moving or controlling of micro-structures. The movement of this micro-structure is detected by micro-sensors. The sensors can also sense the temperature, pressure, acceleration and so on. The micro-electronics circuits are widely used for signal detection, signal processing, the control of the system and providing electro-static driving force for mechanical actuators.

Micro-dynamic is the most significant field of research in MEMS technology. It includes the basic principle of mechanics of beam and diaphragm structures, air damping and its effect on the motion of mechanical structures and electro-static driving of mechanical structures [9-15].

1.1. Pressure sensor

Pressure sensors are devices that can sense and measure the pressure of gases or liquids of any system. Pressure is an expression of, force stated in terms of force per unit area. Pressure sensors are also be called as pressure transducer, it can generates signal when pressure is imposed on it. Diaphragms play the most important and unavoidable role in them. They have wide utility such as in microphones, pressure gauge, pressure transmitter etc. Pressure sensors are used to control and monitoring of thousand applications in everyday life.

1.2. Diaphragm

Diaphragm has resemblance with membrane and it exhibits elasticity property so it is affected by external force. When an external force acting on a diaphragm produce internal forces between the portions of the body and cause deformation so stress and strain are induced in the diaphragm. If the external forces do not exceed a certain limit, the deformation disappears once the forces are removed.

There are two different ways of classification of diaphragms. Depending on their shapes, diaphragms are classified into three different types: square, circular and rectangular diaphragms while based on surface smoothness; they are classified as flat and corrugated type.

Square diaphragms are square in shape and can withstand maximum stress with high sensitivity and so is the preferred geometry for pressure sensors. Moreover, it is easy to dice the diaphragm from standard wafers and the resulting diaphragms are found to have proper crystal orientation.

Circular diaphragms are circular in shape and possess lowest stress on its edges in comparison to square diaphragm, and have largest deflection in the chanter. So, applications where maximum deflection plays the prime role, circular diaphragms are expected to work well. However, due to lack of proper crystal orientation, circular diaphragms are generally avoided.

Rectangular diaphragms are rectangular in shape and of little use as the deflection here is negligible in comparison to square diaphragm.

1.3. Objective of the work

Felling the increasing demand and utility of MEMS based pressure sensor system and the challenges therein to develop an effective design, the prime objective of our project work is to study the effect of constituting components on the overall efficiency of the pressure sensor. We have planned to design a pressure sensor system composing of a square Si- diaphragm, a SiO_2 insulator layer and ZnO piezoelectric material blocks. We have targeted to carry out the study by considering three very important parameters of pressure sensors viz. stress experienced, voltage induced and deflection taken place to measure the effect in changing the size and thickness of constituting components. The reasons behind considering square diaphragm are known to exhibit better tolerance than rectangular and circular diaphragms.

1.4. Scope of the work

The potential existence of MEMS will establish a second technological revolution of miniaturization that may create an industry which may exceed the IC industry in both size and impact on society. Micromachining and MEMS technologies are powerful tools for enabling the miniaturization of sensors, actuators and systems. The basic and unavoidable element of MEMS pressure sensor is diaphragm and its sensitivity depends on their structural and location, where square shaped diaphragm gives the best performance. In aerospace, the required noise floor of microphone is high generally 120dB - 160dB, so those are built in special manner with piezoelectric material for the higher sensitivity and noise floor. Plethora of literature reports have been found studying the effect of size, shape and thickness of the diaphragm towards their stress tolerance as well as the effect of monolayer fabrication of piezoelectric material on diaphragms towards the sensitivity of them. Couple of MEMS pressure sensor systems have been found developed and a few of them have been of practical applicability. However, the field is yet to explore completely and so has enough space to accommodate newer studies in this area.

2. Modeling of pressure sensor

Thin plates have been considered for the mathematical modelling of diaphragms as diaphragm bears fair resemblance with thin plates. Basically plates are flat structural elements and their thicknesses are much smaller than other dimensions. Plates can be classified into three groups: thin plates with small deflections, thin plates with large deflections and thick plates. It is considered that the plate material is homogeneous and isotropic. Homogenous materials show identical properties throughout and isotropic materials display same properties in all directions.

The fundamental assumptions of the small-deflection theory of bending or so-called classical theory for isotropic, homogeneous, elastic, thin plates is based on the geometry of deformations. They may be stated as follows:

A. The deflection of the mid-surface is very small as compared to the thickness of the plate. The slope of the deflected surface is very small and its square is negligible in comparison with unity.

B. The mid-plane remains unstrained subsequent to bending.

C. Plane sections initially normal to the mid-surface remain plane and normal to that surface after the bending. This means that the vertical shear strains are negligible. The deflection of the plate is thus associated principally with bending strains. It is deduced therefore that the normal strain resulting from transverse loading may also be omitted.
D. The stress normal to the mid-plane is small compared with the other stress components and may be neglected. This supposition becomes un-reliable in the vicinity of highly concentrated transverse loads.

The above assumptions are known as the Kirchhoff's hypotheses and it is associated with the simple bending theory of beams. Now, if we consider a load free plate in which the XY-plane coincides with the mid-plane of the plate, its deflection in Z-direction will be zero. When the plate is loaded with external stress or force then it will be deflected from its original position and suppose, the deflected components in X, Y, Z- direction are u, v and w respectively.

Strain-curvature relations

From the above assumptions, the strain-curvature relation can be expressed as follows.

$$\varepsilon_x = \frac{\partial u}{\partial x} \qquad \text{………eq. no (1)}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \qquad \text{………eq. no (2)}$$

$$\varepsilon_z = \frac{\partial w}{\partial z} = 0 \qquad \text{……….eq. no (3)}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \qquad \text{……..eq. no (4)}$$

$$\gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} = 0 \qquad \text{……eq. no (5)}$$

$$\gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = 0 \qquad \text{……eq. no (6)}$$

Here ε_x, ε_y, ε_z are the normal strains in X, Y and Z directions respectively and γ_{xy}, γ_{yz}, γ_{xz} are the shear strain in X, Y and Z directions.

After lots of literature survey we have used square diaphragm for modelling purpose which can withstand maximum stress with maximum sensitivity over its all shapes. The simplest expression of displacement for a pressure 'p' of a square diaphragm with a side length 2a as shown in **Fig.3.** [8]. We take the simplest displacement expression for pressure 'p' is given below [8]:

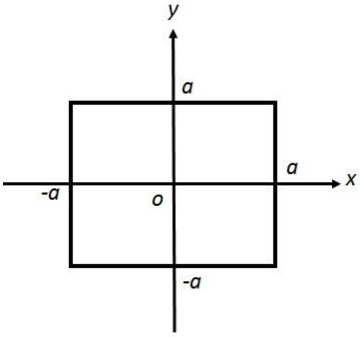


Fig.3. Structure geometries of a square diaphragm [8]

From reference [8], we take the simplest displacement expression for pressure ‘p’ is given below: $w(x,y) = 0.0213p\frac{a^4}{D}\left(1-\frac{x^2}{a^2}\right)^2\left(1-\frac{y^2}{a^2}\right)^2 \cong \frac{1}{47}p\frac{a^4}{D}\left(1-\frac{x^2}{a^2}\right)^2\left(1-\frac{y^2}{a^2}\right)^2 \ldots\ldots \text{eq. no } (7)$

The maximum displacement of the square diaphragm is at the centre of the diaphragm with the value as described by eq. no (8).

$$W(0,0) = \frac{pa^4}{47D} \ldots\ldots \text{eq. no } (8)$$

3. Materials and Software used

3.1 Piezoelectric Material

Some materials that had developed voltages when tension and compression generated voltages of opposite polarity and proportional to the applied load. This effect was popular as piezoelectric effect. Piezoelectric Effect is the ability of certain materials to generate an electric charge across that material in response to applied mechanical stress or force. This effect is reversible also, i.e., conversely, if a varying potential is applied across the crystal, then it will produce mechanical stress or force on it. It is derived from the Greek ‘piezo’ which means to squeeze or press, and elektron, which means amber, an ancient source of electric charge. Piezoelectric materials are available in the form of crystals, ceramics and polymers.

In modern technology the piezoelectric effect is very demanding in many applications that involve the production and detection of sound, electronic frequency generation, generation of high voltages, ultra-fine focusing of optical assemblies and microbalances etc. here are many piezoelectric materials, both natural and man-made, that exhibit a range of piezoelectric effects. Some naturally piezoelectric occurring materials include berlinite (structurally identical to quartz), cane sugar, quartz, Rochelle salt, topaz, tourmaline, and bone (dry bone exhibits some piezoelectric properties due to the apatite crystals, and the piezoelectric effect is generally thought to act as a biological force sensor). An example of man-made piezoelectric materials includes barium titanate ($BaTiO_3$), Lead zirconate titanate (PZT), Potassium niobate ($KNbO_3$), Sodium tungstate (Na_2WO_3), Zinc oxide (ZnO)and lead zirconate titanate. The most popularly use used piezoelectric materials in pressure sensor are ZnO, AlN, PZT, PVDF, the selected for their good piezoelectric and dielectric properties. Advantages of piezoelectric devices: High frequency response, Compact size, High output, Rugged construction, Negligible phase shift etc.

3.2 Finite Element model

Finite element analysis is also called finite element method, is a computational method which is used to predict reactions between objects and real world physical affects like mechanical stress, vibration, fatigue, heat transfer, motion, electrostatics, fluid flow etc. Products break, wear out, work way are designed in finite element analysis. Element analysis helps to breaking down a real object into a several number of finite elements, such as little cubes. Mathematical equations predict the behaviour of each element and then computers adds up all the individual behaviours' of each element to show the overall behaviour of the actual object.

There are several types of finite element method which are compatible with Windows, Mac OS X, linux, Web broswe, Unix, FreeBSD., Agros2D,CalculiX, Code_Saturne, DIANA FEA, deal.II, DUNE,Elmer, FEBio, FEniCS Project, COMSOL Multiphysics, CosmosWorks, ANSYS etc. In our project we have used COMSOL multiphysics software as simulator which is compatible with windows operating system. A brief description about COMSOL multiphysics is given below.

3.3 COMSOL Multiphysics

Now a days the demand of COMSOL multiphysics software as creating model and as simulator is very high in interdisciplinary engineering tasks. The reaction between most of the objects and the real world problems are based on multiphysics phenomena. Thus to study those objects, it's necessary to fuse two or more physics domains at one time. COMSOL multiphysics software is used for solving these complex problems. The program offers very efficient unique user-friendly working environment and it has also a wide range of tools for the effective and fast analysis. In COMSOL multiphysics we can also minimize the needs for physical prototypes, development times, shorten product and achieve substantial savings in the development process. The COMSOL modelling approach helps to develop better and cost effective products and bring them faster to the commercial market.

COMSOL multiphysics is a general-purpose software platform and one type of finite element method which is compatible Linux, Mac OS X, and Windows. It is based on advanced numerical methods, for modelling and simulating physics-based problems for single or multiphysics phenomena. COMSOL software provides powerful integrated environment which can be used in many interdisciplinary product development with an incorporated workflow, regardless of their application area. The add-on modules help to merge any physics and materials very efficiently with COMSOL multiphysics. The model tree in the Model Builder gives a full overview of the model and access to all functionality to the user as geometry, physics settings, mesh, fixed constrains, boundary conditions, studies, solvers, post processing and evaluation record etc. By using this COMSOL multiphysics we can easily extend conventional models from single physics into multiphysics models and it can also solve coupled physics phenomena simultaneously. The main advantage of COMSOL multiphysics is to accessing this power does not require in-depth knowledge of mathematics or numerical analysis.

4. Simulation and results

The proposed model of diaphragm based pressure sensor for our study is shown in the **Fig. 4.**

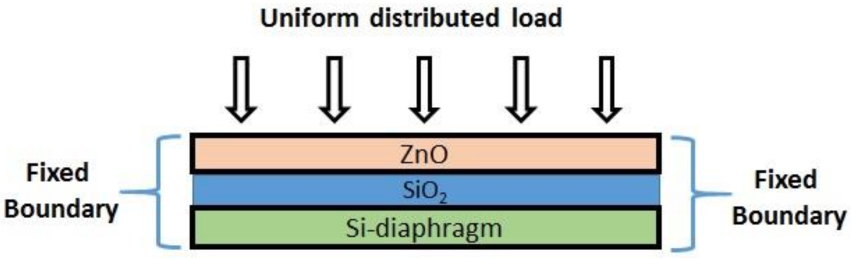


Fig.4. The proposed model of pressure sensor

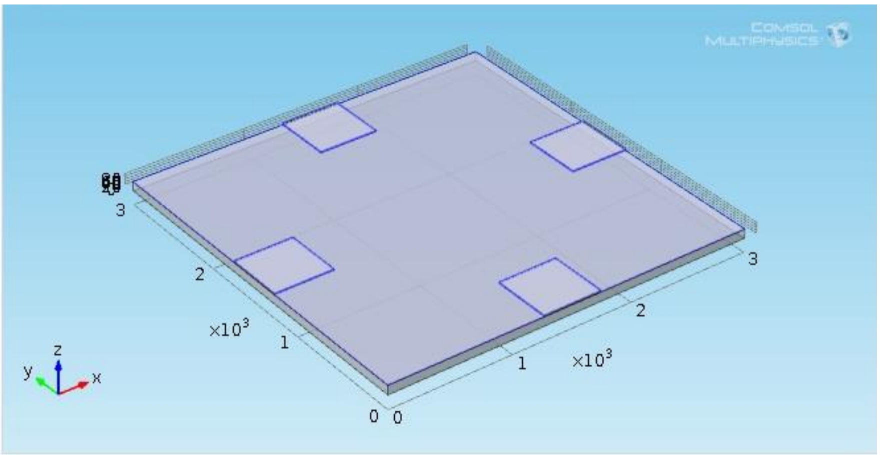


Fig.5. A model of pressure sensor system with ZnO as piezoelectric material, SiO_2 as insulator over Si-diaphragm

After successful mathematical modelling of the pressure sensor systems of our study, simulation of the same were carried out using COMSOL multiphysics software. **Fig.5.** depicts one such model with ZnO as piezoelectric material, SiO_2 as insulator over a Si-diaphragm. SPL (sound pressure level) for human is found to be 0 dB (at the threshold of hearing) to 120 dB (at the threshold of pain). In logarithmic scale SPL can be defined as

$$SPL = 20\log_{10}\frac{p_{rms}}{p_{ref}} \text{.....eq. no (9)}$$

Where ρ_{rms} is the rms pressure and ρ_{ref} is the reference pressure. In air, standard value for ρ_{ref} is considered to be 20 μPa. By putting the value of 0 dB and 120 dB in the above equation then we can define the range of p_{rms}

$$0 = 20\log_{10}\frac{p_{rms}}{20\times10^{-6}}$$

$$\Rightarrow p_{rms} = 0\ Pascal$$

Again

$$120 = 20\log_{10}\frac{p_{rms}}{20\times10^{-6}}$$

$$\Rightarrow p_{rms} = 20\ Pascal$$

So, the pressure level varies from 0 to 20 Pascal for human in air. For our study, we considered 5 N/M^2 uniform load to carry out the experiments.

In pressure sensor the most and unavoidable element is diaphragm. The quality of pressure depends on various parameters such as size, shapes of diaphragm. As we know from various research paper square diaphragm can exhibit maximum stress among all other shapes of diaphragm. So we chose square diaphragm for experimental purpose. To optimize the pressure sensor's sensitivity we used piezoelectric materials on above of the diaphragm. The piezoelectric coefficients of ZnO material has significant effects on the pressure sensor. Among various coefficients voltage constant g_{31} is directly used in calculating the analytical value of voltage of the sensor.

$$V(x,y) = \sigma(x,y).t.g_{31} \text{.....eq. no (10)}$$

Where voltage constant of ZnO g_{31} is -4.85×10^{-2} Vm/N [7].

In COMSOL multiphysics, we have simulated the stresses, voltages and deflections of diaphragm under differently fixed parameters. **Fig.6**, **Fig.7**, **Fig.8** and **Fig.9** are some of the representative images of our study collected at different point of time of the study.

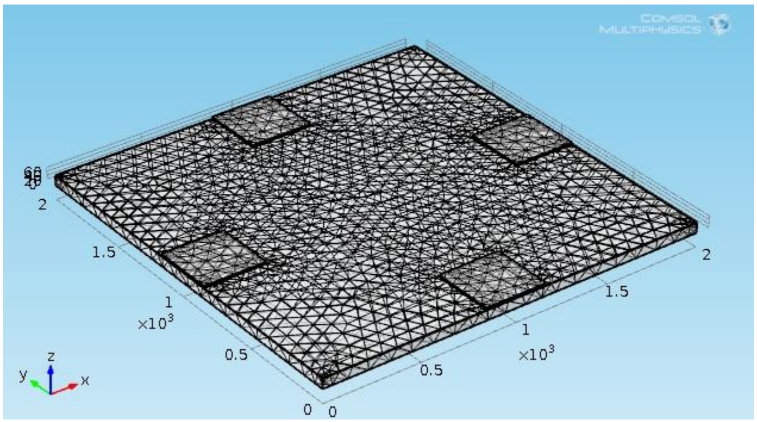


Fig.6. A meshed model of pressure sensor

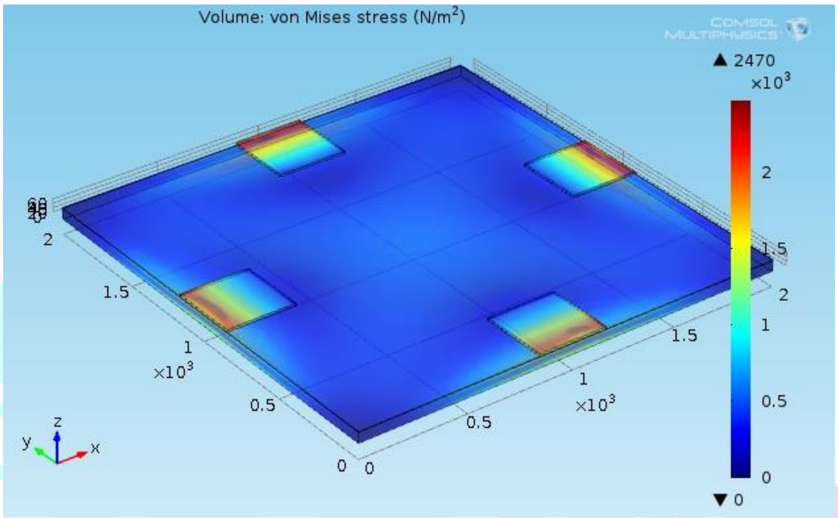


Fig.7. Stress on a pressure sensor model

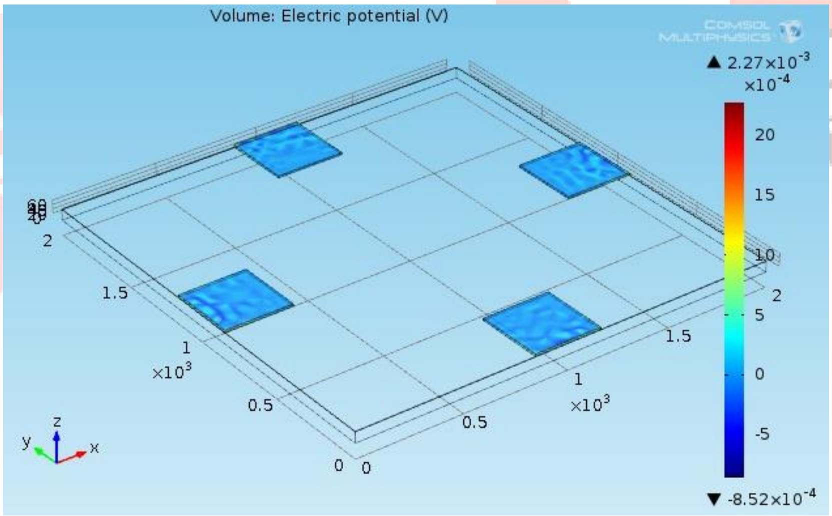


Fig.8. Voltage on a pressure sensor model

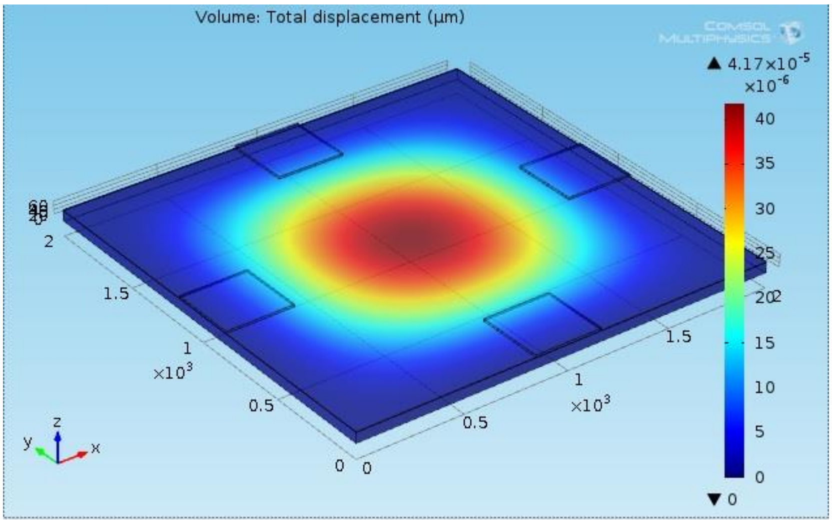


Fig.9. Deflection on a pressure sensor model

Case 1:

Here, we studied the effect of thickness of ZnO on the pressure sensor system. The dimension of silicon diaphragm was fixed at 3000 µm x 3000 µm x 50 µm, while that for SiO_2 was fixed at 3000 µm x 3000 µm x 3 µm. Four blocks of piezoelectric ZnO materials of identical sizes (480 µm x 480 µm) were taken for the experiment and their thickness were varied for all the blocks at a time. Various parameters of the component materials under **Case 1** have been summarized in **Table.1**.

Table.1. Various parameters under **Case 1**

Parameters	**Si- Diaphragm**	**SiO_2 insulator**	**ZnO piezoelectric**
Young's Modulus (GPa)	170	70	210
Poisson ratio	0.28	0.17	0.33
Length x width (µm)	3000 x 3000	3000 x 3000	480 x 480
Thickness (µm)	50	3	Varied

For this model, we carried out the simulation to determine stress, voltage and deflection and the simulated values have been compared with the analytical values [8]. The results have been summarized in **Table.2**. Comparisons of the analytical and simulated values obtained are also expressed graphically and are shown in **Fig.10**, **Fig.11** & **Fig.12**.

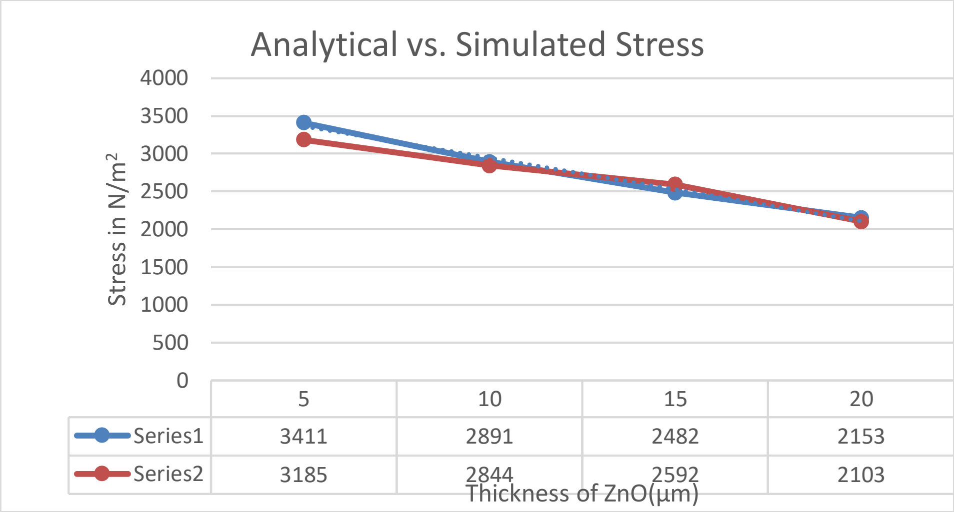
Table.2. Effect of thickness of ZnO layer in pressure sensor system

Case 1		**Thickness of ZnO material (µm)**			
		5	10	15	20
Stress values in N/m^2	**Analytical**	3411	2891	2482	2153
	Simulated	3185	2844	2592	2103
Voltage values in volt	**Analytical**	0.00083	0.00140	0.00180	0.00208
	Simulated	0.00088	0.00157	0.00174	0.00170
Deflection values in µm	**Analytical**	$2.79x10^{-4}$	$2.78x10^{-4}$	$2.70x10^{-4}$	$2.59x10^{-4}$
	Simulated	$2.20x10^{-4}$	$2.05x10^{-4}$	$1.961x10^{-4}$	$1.79x10^{-4}$

Fig.10 shows the comparison of analytical vs. simulated stress in N/m^2 of pressure sensors at different ZnO thicknesses. It reveals that the stress exhibited by the system decreases with increase in thicknesses of ZnO, i.e. stress experienced is inversely proportional to the thicknesses piezoelectric material.

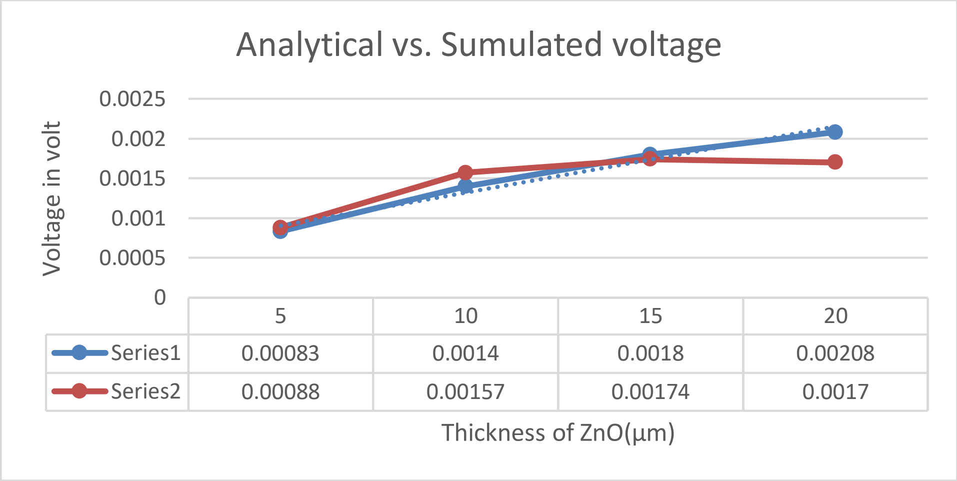
Comparison of analytical vs. simulated voltages at different thickness of the piezoelectric material ZnO have been shown in **Fig.11** and it reveals that the induced voltage increases with increase in thicknesses of the ZnO layer. So, we conclude that induced voltage is directly proportional to thicknesses of the piezoelectric material.

Fig.12 shows the comparison of analytical vs. simulated deflections (in µm) of pressure sensors at various thickness of ZnO. From the figure, it is observed that there is no significant changes in deflection with change in thickness of ZnO layer. It may be attributed to the fact that deflection is maximum at the centre of the square diaphragm (eq. no.(8)) and we imposed ZnO material only on the maximum stress area i.e. the edges of diaphragm, virtually keeping the thicknesses of the pressure sensors almost same at the centre. As a result, there is little change in thickness of the pressure sensor in the centre with change in thickness of the ZnO layer and consequently there is no significant change in deflection of the pressure sensor.



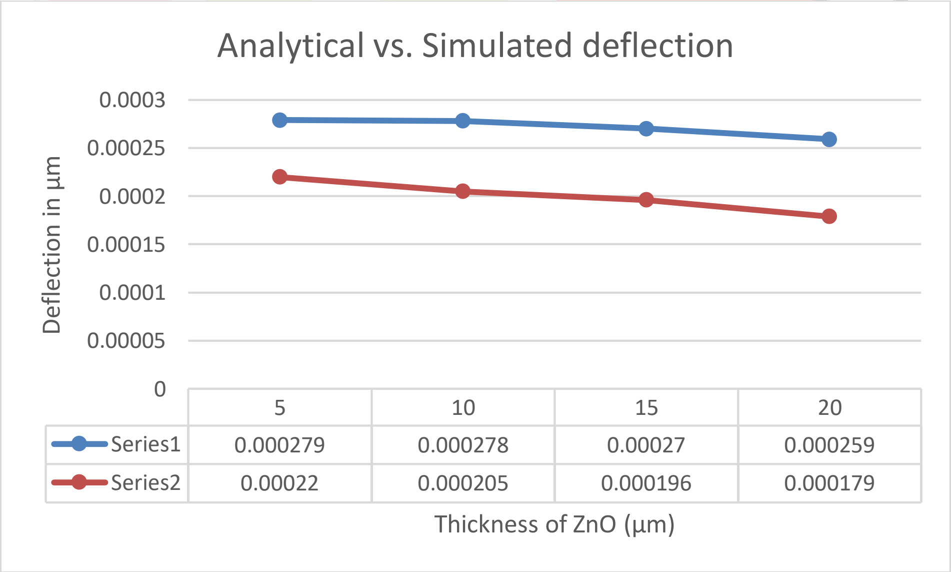
	5	10	15	20
Series1	3411	2891	2482	2153
Series2	3185	2844	2592	2103

Fig.10. Analytical vs. simulated stress at different ZnO thickness



	5	10	15	20
Series1	0.00083	0.0014	0.0018	0.00208
Series2	0.00088	0.00157	0.00174	0.0017

Fig.11. Analytical vs. simulated voltage at different ZnO thickness



	5	10	15	20
Series1	0.000279	0.000278	0.00027	0.000259
Series2	0.00022	0.000205	0.000196	0.000179

Fig.12. Analytical vs. simulated deflection at different ZnO thickness

Case 2:

Here, we studied the effect of the size of the Si-diaphragm on the pressure sensor. For this, the thickness of the Si-diaphragm, SiO_2 insulator layer and the piezoelectric ZnO blocks were fixed at 50, 3 and 10 µm respectively. The size of the Si-diaphragm was taken as the primary variable here, however the sizes of the SiO_2 insulator and ZnO blocks were also changed accordingly. Various parameters under **Case 2** study have been summarized in **Table.3**.

Table.3. Various parameters under **Case 2**

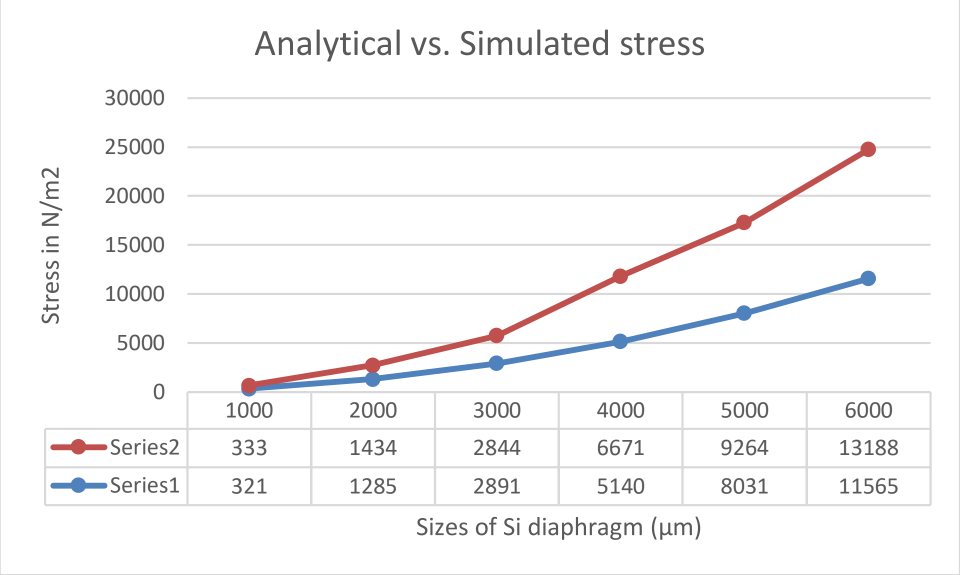
Parameters	**Si- Diaphragm**	**Sio$_2$ insulator**	**ZnO piezoelectric**
Young's Modulus (GPa)	170	70	210
Poisson ratio	0.28	0.17	0.33
Thickness (µm)	50	3	10
Length x width (µm)	Varied		

Table.4. Effect of size of Si diaphragm on pressure sensor system

Case 2		**Sizes of Si diaphragm (µm)**					
		1000x1000	2000x2000	3000x3000	4000x4000	5000x5000	6000x6000
Stress values in N/m^2	**Analytical**	321	1285	2891	5140	8031	11565
	Simulated	333	1434	2844	6671	9264	13188
Voltage values in volt	**Analytical**	0.00018	0.00062	0.00140	0.00249	0.00390	0.00560
	Simulated	0.00019	0.00061	0.00157	0.00303	0.00319	0.00436
Deflection values in µm	**Analytical**	3.43x10^{-6}	5.48x10^{-5}	2.78x10^{-4}	8.77x10^{-4}	2.14x10^{-3}	4.43x10^{-3}
	Simulated	2.62x10^{-6}	4.16x10^{-5}	2.05x10^{-4}	6.55x10^{-4}	1.57x10^{-3}	3.21x10^{-3}

Table.4. continues….

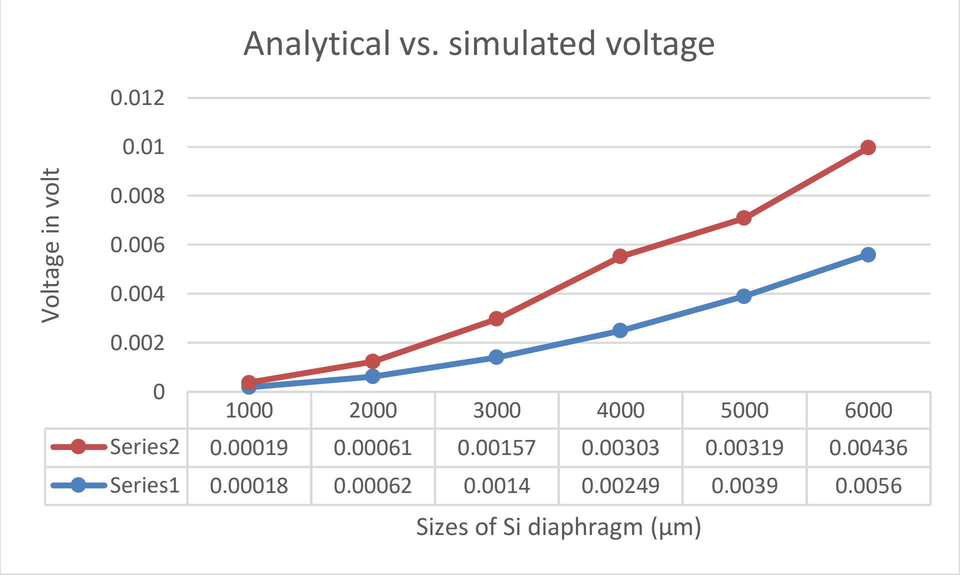
Similar to Experiment no. 1, we carried out the simulation to determine stress, voltage and deflection and the simulated values have been compared with the analytical values calculated. The results have been summarized in **Table.4**. Comparison of the analytical and simulated values obtained for different parameters are also expressed graphically and are shown in **Fig.13**, **Fig.14** & **Fig.15**.



	1000	2000	3000	4000	5000	6000
Series2	333	1434	2844	6671	9264	13188
Series1	321	1285	2891	5140	8031	11565

Fig.13. Analytical vs. simulated stress at different size of Si-diaphragm used

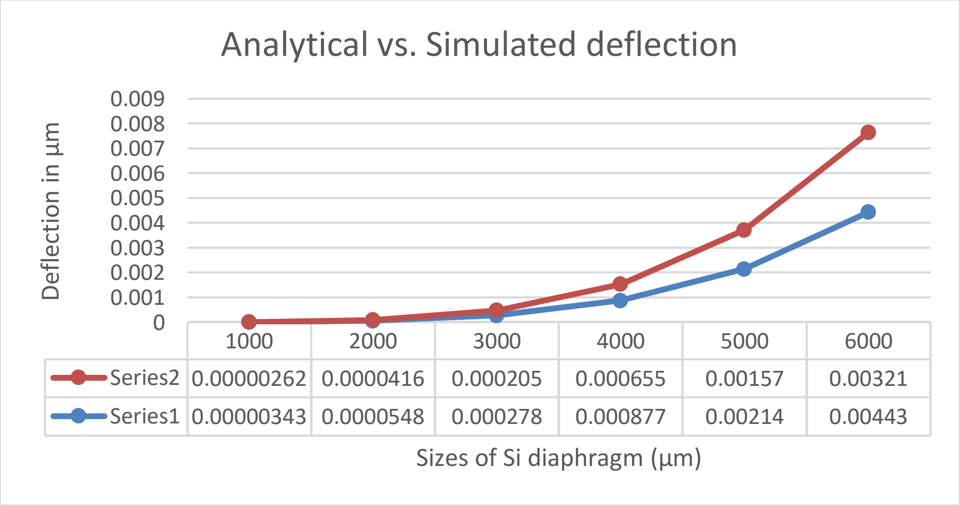
Fig.13 shows the comparison of analytical vs. simulated stress in N/m^2 of pressure sensors at varying size of the Si-diaphragm. From this figure, it can be seen that the stress experienced by the sensor is increased with increase in the area of Si diaphragm.



	1000	2000	3000	4000	5000	6000
Series2	0.00019	0.00061	0.00157	0.00303	0.00319	0.00436
Series1	0.00018	0.00062	0.0014	0.00249	0.0039	0.0056

Fig.14. Analytical vs. simulated voltage at different size of Si-diaphragm used

Fi.14. shows the comparison of analytical vs. simulated voltage (in volt) of pressure sensors with different diaphragm size. The induced voltage increases with increase in size of the Si-diaphragm and so is directly proportional to the area of diaphragm.



	1000	2000	3000	4000	5000	6000
Series2	0.00000262	0.0000416	0.000205	0.000655	0.00157	0.00321
Series1	0.00000343	0.0000548	0.000278	0.000877	0.00214	0.00443

Fig.15. Analytical vs. simulated deflection at different size of Si-diaphragm used

Fig.15 summarizes the comparison of analytical vs. simulated deflection in µm of pressure sensors at varying size of diaphragm. From the figure, it is clear that the deflection gradually increases with increase in size of Si-diaphragm.

Case 3:

Here, we studied the effect of the thickness of the Si-diaphragm on the pressure sensor system. For this, we considered a pressure sensor system constituting of a Si-diaphragm of size 3000 µm x 3000 µm, SiO_2 insulator layer of thickness 3 µm and four identical fixed blocks of piezoelectric ZnO material of dimension 480 µm x 480 x 10 µm. Simulation and calculation to determine stress, voltage and deflection of the system were carried out by simply varying the thickness of the Si-diaphragm. Various parameters under **Case 3** are shown in **Table.5**, while the results have been summarized in **Table.6**. Comparison of the simulated and analytical values have been depicted graphically in **Fig.16** and **Fig.17**.

Table.5. Various parameters under **Case 3**

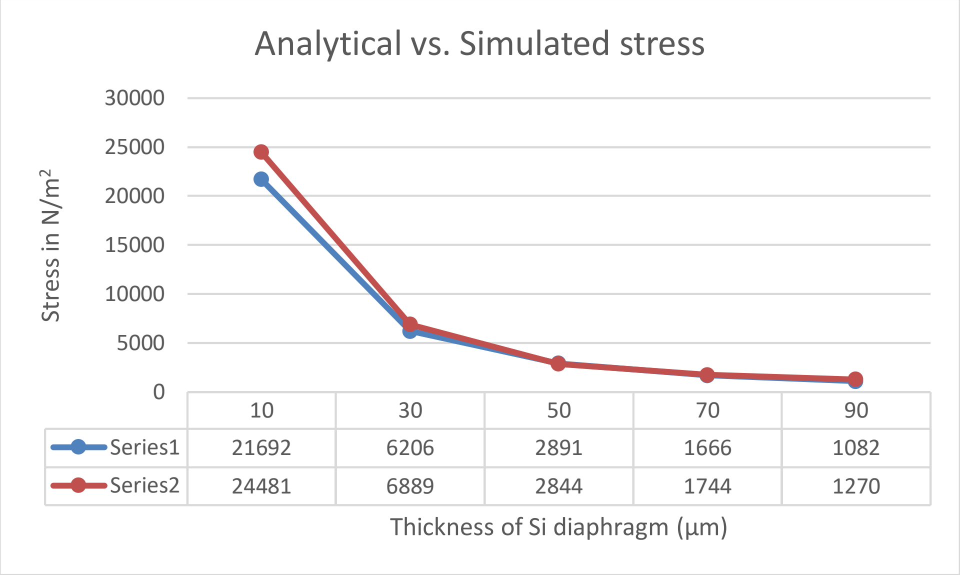
Parameters	**Si- Diaphragm**	**Sio_2 insulator**	**ZnO piezoelectric**
Young's Modulus (GPa)	170	70	210
Poisson ratio	0.28	0.17	0.33
Length x width (µm)	3000 x 3000	3000 x 3000	480 x 480
Thickness (µm)	Varied	3	10

Table.6. Effect of thickness of Si diaphragm on pressure sensor system.

Case 3		**Thickness of Si diaphragm (µm)**				
		10	30	50	70	90
Stress values in N/m^2	**Analytical**	21692	6206	2891	1666	1082
	Simulated	24481	6889	2844	1744	1270
Voltage values in volt	**Analytical**	0.01052	0.00301	0.00140	0.00081	0.00052
	Simulated	0.00353	0.00245	0.00157	0.00057	0.00052

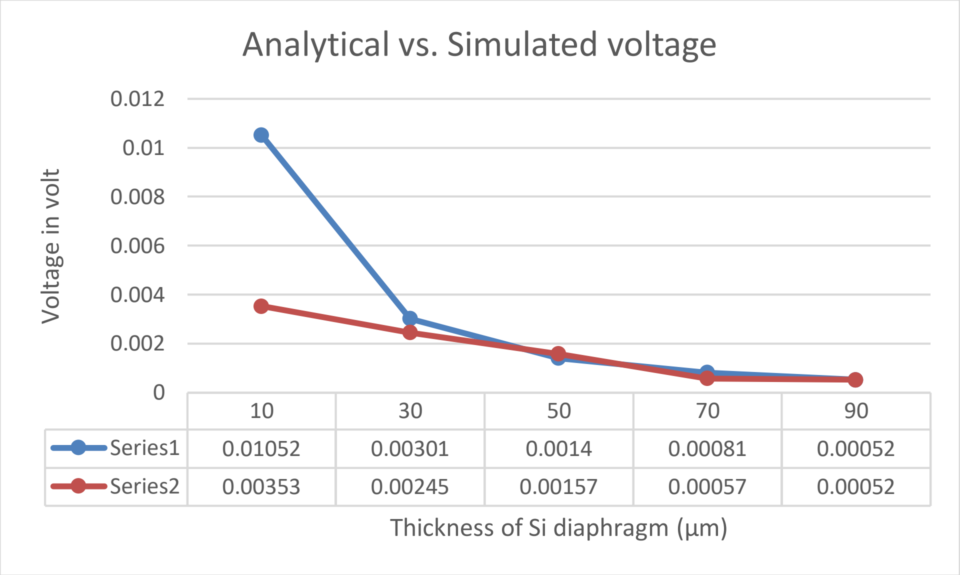
Fig.16 shows the comparison of analytical vs. simulated stress (in N/m^2) of pressure sensors with variation of Si diaphragm thicknesses. It is observed that the stress exhibited by pressure sensor is decreased with increase in thicknesses of the Si-diaphragm and so is inversely proportional to the thickness of diaphragm.

Fig. 17 depicts the comparison of analytical vs. simulated voltage in volt of pressure sensors at varying Si-diaphragm thicknesses. From this graph, it can be seen that the induced voltage decreases with increase in thicknesses of diaphragm. Thus, the induced voltage of the pressure sensor is inversely proportional to the diaphragm thicknesses.



	10	30	50	70	90
Series1	21692	6206	2891	1666	1082
Series2	24481	6889	2844	1744	1270

Fig.16. Analytical vs. simulated stress at different thickness of Si-diaphragm



	10	30	50	70	90
Series1	0.01052	0.00301	0.0014	0.00081	0.00052
Series2	0.00353	0.00245	0.00157	0.00057	0.00052

Fig.17. Analytical vs. simulated voltage at different thickness of Si-diaphragm

From the above study, it can be concluded that area and thickness of the diaphragm material and the thickness of the piezoelectric material used have significant effects on the stress, voltage and deflection experienced by the pressure sensor. The study reveals that to design an efficient pressure sensor system, the diaphragm and the piezoelectric materials should be of low thickness, while the area of the diaphragm should be sufficiently high. In most of the cases, the simulated values approximate the analytical value and thus authenticate the method of our study.

CONCLUSION

In this study, we have investigated the effect of size and thickness of diaphragm and thickness of the piezoelectric material blocks on pressure sensor. We have carried out the study by taking a pressure sensor system constituting of a square Si-diaphragm, SiO_2 insulator and ZnO piezoelectric material. Three very important parameters viz. stress, voltage and deflection are considered to measure the effect on the pressure sensor system. Values for these parameters have been calculated via mathematical modelling and use of COMSOL Multiphysics software. The simulated values have been compared to the analytical values and are found to be in good agreement, and thus authenticate our method of study. The major observations of our study are summarized below.

A. Stress experienced by the pressure sensor system is directly proportional to the size of the diaphragm, while it is inversely proportional to the thickness of the diaphragm as well as the piezoelectric material layer.

B. Voltage induced at the pressure sensor is directly proportional to the size of the diaphragm as well as the thickness of the piezoelectric material, while it is inversely proportional to the thickness of the diaphragm.

C. Deflection taken place of the pressure sensor system is nearly independent of the thickness of the piezoelectric material, but it increases gradually with increase in the size of the diaphragm.

From these outcomes, it can be concluded that to design an efficient pressure sensor system, the diaphragm and the piezoelectric materials should be of low thickness, while the area of the diaphragm should be sufficiently high.

FUTURE WORK:

Due to time constrained and other limitation we have investigated the effect of size and thickness of the diaphragm and the thickness of piezoelectric layer only on the pressure sensor system. However, the study can be extended to carry out similar studies by trying multilayer piezoelectric material and with their different sizes. Studies can also be carried out to test other piezoelectric materials like AlN, PZT etc. in lieu of ZnO.

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