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Design and Implementation of Piezo Resistive MEMS Pressure Sensor for Spiro Meter Application

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ABSTRACT- Spirometer is an essential component in the medical evaluation of patients suffering due to shortness of breath. It takes measurement of the quantity of air inhaled and exhaled by the lungs during a certain period of time to determine the pulmonary capacity. Improved spirometers are used for estimating the severity of the airflow obstruction in the patients suffering with asthma and the impact of Chronic Obstructive Pulmonary Disease (COPD). Earlier days, volume displacing spirometers and flow sensing spirometers were used. However, volume displacing spirometers are large and bulky and hence they were less portable. The flow sensing spirometers are portable, smaller and measure flow. Undesirable characteristics of flow sensing is frequent and careful calibration checks needed for some models. Further moisture and secretions may cause problems in these devices. Nowadays low cost, portable spirometer built with pressure sensor is used for detecting airflow and pressure. In this present work, the design and analysis of MEMS pressure sensor employed spirometer has been carried out. The MEMS sensors ensure high sensing accuracy and good stability which are the essential requirements for spirometers used in advanced medical applications. This is achieved with polysilicon piezoresistors in the present work. As a part of the spirometer design the effect of diaphragm shape in the MEMS pressure sensor that is to be used in the spirometer is presented first. The circular and square diaphragms have been studied and a comparison study on the results paves the way for selecting the shape of the diaphragm to achieve very sensitive pressure sensors. Subsequently the results of the simulation studies conducted on various diaphragm sizes to design the geometries of the pressure sensor is presented. This design involves arriving at the best optimized sensitivity and linearity. IntelliSuite MEMS design tools that uses FEM analysis have been used in all the simulation studies. Finally the performance of these MEMS pressure sensors is presented.

INDEX TERMS-MEMS, spirometer, Diaphragm design, pressure sensor, Piezoresistive.

I. INTRODUCTION

MEMS or Micro-Electro-Mechanical Systems are chips that are made in semiconductor fabrications that combine electronic functions and mechanical actions to deliver extraordinary functionality and versatility. MEMS devices can sense and control making them valuable for numerous applications in automotive as well as in the medical field. Longer range preventive medicine and very early preemptive intervention are the essential strategies make health monitoring practical through continuing advances in diagnostics and wellness assessment enabled by leading-edge technology from other fields. Today, MEMS devices allows powerful and deployment of preventive and interceptive medical techniques. Sensing is the largest category in the medical field. MEMS pressure sensors work on the principle of mechanical bending of thin silicon diaphragm by the contact medium. The diaphragm is the key sensing component of a MEMS pressure sensor and hence the realization of a high – performance diaphragm is important to achieve high efficiency of the sensor. The dimensions of the diaphragm like the thickness, length, radius, shape are taken into consideration and the effects of variations in pressure on the geometry of the sensing element are analyzed using Intellisuite software tool [1]. In this paper the load-deflection and stress behavior of a diaphragm type pressure sensor (Si-frame), which is used in a spirometer, has been studied. The pressure sensing element combines resistors and an etched diaphragm structure to provide an electrical signal that change with pressure. As the diaphragm, etched to a thickness estimated by the range to be measured, moves under pressure.Stress is concentrated in specific areas of the silicon element. Four ion-implanted resistors in these areas change in value with compression. Choosing the proper location for the resistors and controlling the orientation of the resistors allows the MEMS designer to predict how the resistor will change in value for a given deflection of the diaphragm.

II. SPIROMETER

Spirometer is a noninvasive diagnostic instrument used for screening and basic testing of pulmonary function. Offering essential diagnostic insight into the type and extent of lung function impairment, spirometer tests can be performed fast at fairly low cost [2].Obstructive lung disease is a category of respiratory disease characterized by airwayobstruction. It is generally characterized by inflamed and easily collapsible airways, obstruction to airflow, problems exhaling and frequent office visits and hospitalizations. Types of obstructive lung disease include; asthma, bronchiectasis, bronchitis and chronic obstructive pulmonary disease (COPD). Although COPD shares similar characteristics with all other obstructive lung diseases, such as the signs of coughing and wheezing, they are distinct conditions in terms of disease onset, frequency of symptoms and reversibility of airway obstruction [3]. In the light of an ever-increasing prevalence of airway diseases, pulmonary function instruments have become indispensable diagnostic tools, in clinical and office settings, in industrial and preventive medicine, as well as in epidemiology.

Figure2.1 represents spirometer instrumentation. Screening of individuals at risk, basic testing of sick patients and treatment follow-up are key applications of spirometer. Spirometer has shown considerable growth in past 30 years for several reasons (a) published standards and testing guidelines, (b) improved spirometer and software, (c) evidence that both patients and physicians have inaccurate perceptions of the severity of the airflow obstruction, (d) evidence that history taking and physical examination by themselves are not helpful in identifying patterns of lung disease, (e) recommendations that spirometer be included in the assessment of patients suspected of having asthma and recommendations of objective measurements to reduce the impact of chronic pulmonary disease. The new spirometry technique is superior to existing spirometry techniques (pneumotach, ultrasound, hot wire anemometer) for the following reasons. (a)Low cost, robust design; (b) Ease of sterilization and maintenance (c) High accuracy; (d) More parameters can be measured than similarly priced devices
(e) Data transfer and storage capabilities.

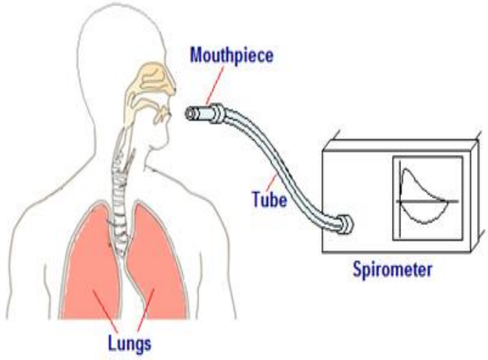

Fig.2.1 Spirometer Instrumentation

Spirometer measures the flow and volume of gas (air) moving in and out of the lungs during a breathing manoeuvre.The measured flow and volume values are plotted as graphs called the spirograms (Figure 2.2) that are used for diagnosis of the patient. The spirometer is based on the measurement of either the flow rate or the volume of gas inhaled and exhaled during respiration. The pressure measurement system is also a flow rate measurement-based method where the flow rate is indirectly determined by measuring the pressure (e.g., orifice or venturi tube meters). The flow volume curve depicts the relation between the lung volume and the maximum rate of airflow as lung volume changes during a forced expiration. The Figure 2.2 corresponds to flow volume spirograms to different levels of disabilities. Normal or healthy person; (b) fixed airway obstruction; (c) extra thoracic obstruction and (d) airflow obstruction [4].

A flow-volume loop is generated by having the patient inhale deeply to total lung capacity (TLC), forcefully exhale until the lungs have been emptied to residual volume (RV), and rapidly inhale to reach TLC. Flow is plotted on the Y axis and the volume on the X axis; a typical loop is shown in Figure 2.2. The upper portion of the curve reflects the expiratory portion of the forced vital capacity (FVC) maneuver and is also referred to as the maximal expiratory flow-volume (MEFV) curve. Depending on their location (intra thoracic or extra thoracic), they tend to behave differently during inhalation and exhalation.

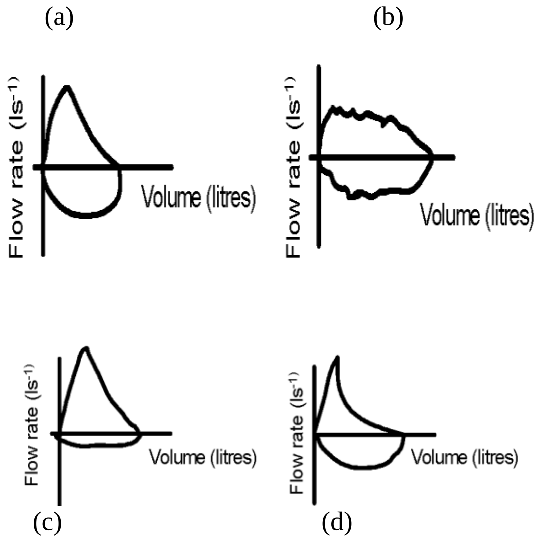

Fig.2.2 Flow Volume Spirograms

Breathing maneuvers need to be instructed clearly; especially the forced exhalation should be supported by incentive commands. For evaluation, maximum forced Flow rates (FEFs) are picked from the recording. Evaluation of spirometer testing is carried out by comparing measured data with predicted normsor reference data, derived from body weight, height, age, and gender. Predictions are calculated from equations published and recommended by scientific societies. When comparing measured with predicted values, the standard deviation, an indicator of the variation of the tested parameter in a healthy population, needs to be taken into consideration[5]. Lung volumes and lung capacities refer to the volume of air associated with different phases of the respiratory cycle. Lung volumes are directly measured; Lung capacities are inferred from lung volumes. The average total lung capacity of an adult human male is about 6 litres of air,but only a small amount of this capacity is used during normal breathing. Tidal breathing is normal, resting breathing; the tidal volume is the volume of air that is inhaled or exhaled in only a single such breath. The average human respiratory rate is 30-60 breaths per minute at birth, decreasing to 12-20 breaths per minute in adults [6].

III. MEMS PRESSURE SENSOR STRUCTURE

The silicon technology displaces older technology in traditional applications. In this paper electrical signal domain and mechanical signal domain were applied and analyzed. Sensors utilize a direct conversion of specific energy into electrical signal. This can be illustrated by a piezoresitive effect, which is used in creating pressure transducers, where pressure directly changes resistance which in turn represents the value of pressure. There are two major factors that make silicon micromachining so attractive. The first one is that silicon is almost a perfect mechanical material, especially for sensors. It is stronger than steel, it does not show mechanical hysteresis and is highly sensitive to stress. Typical structure of the silicon pressure sensor shown in Figure 2.3 is made on a silicon wafer and a membrane has been formed by anisotropic etching in KOH.

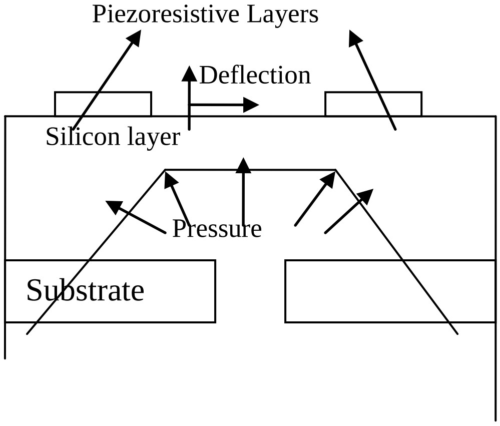

Fig.2.3 Thin Diaphragm Pressure Sensor Structure

The majority of wafers are formed from single crystalline silicon. As a semiconducting material it is easily oxidized into sio$_2$ making an excellent barrier layer for selective diffusion, and it also operates at higher temperatures than germanium.Bulk micromachining was used as it involves the removal of materials from the bulk substrates usually silicon wafers, to form the desired three dimensional geometry of the microstructures. Isotropic etching is hardly desirable in micromachining because lack of control of the finished geometry of the work piece. Since the substrate is silicon which has a diamond cubic crystal structure anisotropic etching is most preferred. Diaphragms made from material using bulk micro machining technique. For the fabrication of a polysilicon diaphragm a wet etch was used to remove a sacrificial silicon dioxide layer [7]. Boron implantation of the piezoresitive elements was performed to convert the regions from n-type to p-type and make sensitive to mechanical stress. Piezoresistors are made from a piezoresitive material and are usually used for measurement of mechanical stress. The simplest form of piezoresitive silicon sensors are diffused resistors.

The sensitivity calculations assume that the resistors act as point transducers at the edge of the diaphragm. Using anisotropic etching changes in wafer thickness will result in variations in diaphragm size. Since the diaphragm is formed by selective anisotropic etching from the back side etch mask with the front side resistor pattern is required. This alignment can be done using double-side photolithography. The alignment tolerance is independent of structural feature size; there are several ways to reduce the importance of alignment in pressure sensitivity. Increasing the diaphragm size decreases the relative misalignment if the resistors are also scaled and produces a pressure output which increases as l^2. The percentage change in Δv due to diaphragm misalignment decreases with l. Thus piezoresitive sensors utilizing thin silicon diaphragms offer high pressure sensitivity over dynamic ranges. For the piezoresitive type of device diaphragm thickness is the structural parameter requiring greatest control [8].

IV.Pressure Sensor Design Selection

The main types of pressure sensors are piezoresitive sensing and capacitive sensing. Diaphragms are the simplest mechanical structures used as a sensor element in both traditional and MEMS technology pressure sensors. Two types of diaphragms are chosen for the analysis. One is square shaped diaphragm and another is circular in shape.

A.Circular diaphragm

Finite element simulation for a pressure sensor fabricated using (100) silicon wafer has been accomplished. It is a thin sheet of a flexible material, anchored at its circumference, over which differential pressure is applied. The actual design and development process involves arriving at the best compromise (relative to the performance specifications) of sensitivity, linearity, and frequency response, as determined primarily by the diaphragm diameter and thickness.

The Figure 2.4 explains the mask layout obtained during the fabrication process, and the mask is obtained in 2-D.It gets meshed during the analysis process. The deflection of the circular diaphragm is,

$$y = \frac{3w(m^2 - 1)a^2}{16\pi E m^2 h^3} \quad (1)$$

where $w = \pi a^2 p$,
p = applied pressure [MPa],
m = 1/υ [dimensionless],
υ = poison's ratio,
a = radius of the diaphragm [μm],
E = Young's modulus [GPa],
h = length of the diaphragm [μm],
Y = displacement of diaphragm center [μm].

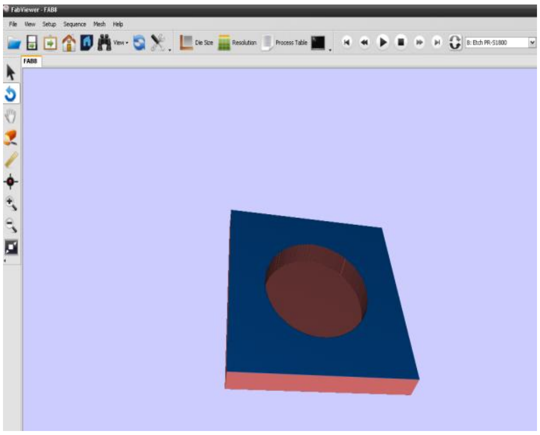

Fig.2.4 Circular Diaphragm

B. Square diaphragm

In the case of a square membrane with fixed boundaries. The maximum displacement occurs at the center of the diaphragm. The maximum stress occurs at the center points of two opposite edges and in the center of the membrane. These locations with high stress values are preferred for the placement of piezoresistive sensors for detecting membrane deformation.The maximum deflection at the centre of the diaphragm is,

$$W = \frac{0.0138\, p a^4}{E h^3} \quad (2)$$

where p = applied pressure [MPa],
a = radius of the diaphragm [μm],
E = Young's modulus [GPa] ,
h = length of the diaphragm [μm].

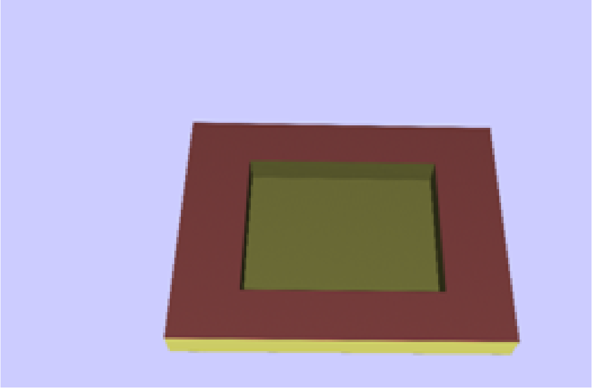

Fig.2.5 Square Diaphragm

C.Deflection Analysis

Linearity and sensitivity are the two performance parameters of the pressure sensor, which are traded off in the realization of the sensor. An analysis of the various issues involved in the performance optimization is presented in this paper.

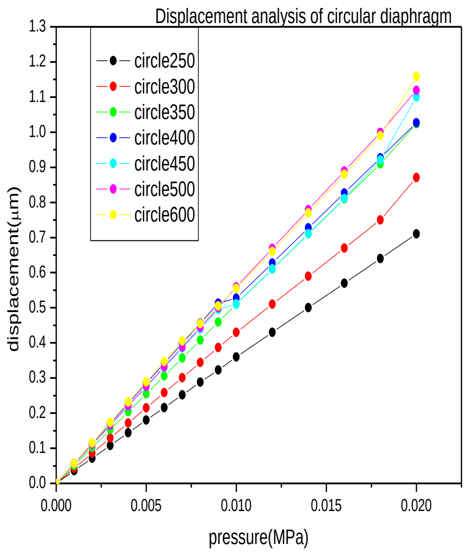

Fig.2.5 Displacement analysis of circular diaphragm

The Figure 2.5 shows the result of the relations between the sizes (radius), pressure, and deflection of a piezoresitive pressure sensor. This pressure sensor has a circular shaped silicon diaphragm 1000µmx1000µm length and in different thicknesses ranging from (4.95µm to 14.5µm) under uniform normal pressure. From the graph it can be concluded that displacement linearly changes with the pressure for the pressure of 0.00-0.02MPa and displacement from 0.0micrometer to
1.3micrometers.

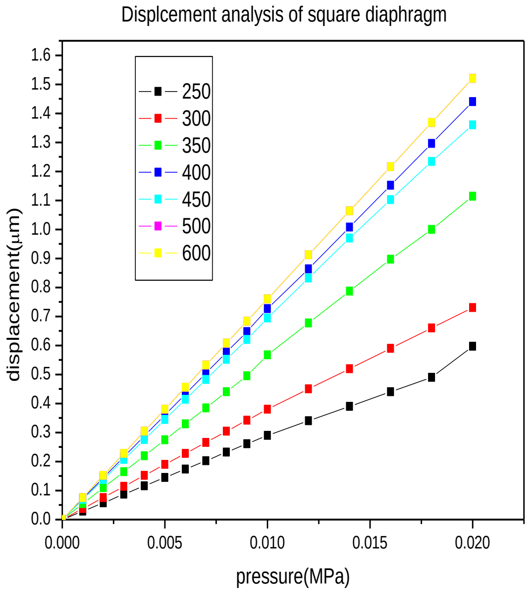

Fig.2.6 Displacement Analysis Of Square Diaphragm

A close look at Figure 2.6 shows that displacement linearly changes with the pressure for the pressure of 0.00-0.02MPa with different thickness ranging from (4.95µm to 14.5µm) and displacement from 0micrometer to 1.6micrometers.

D. Performance Comparison

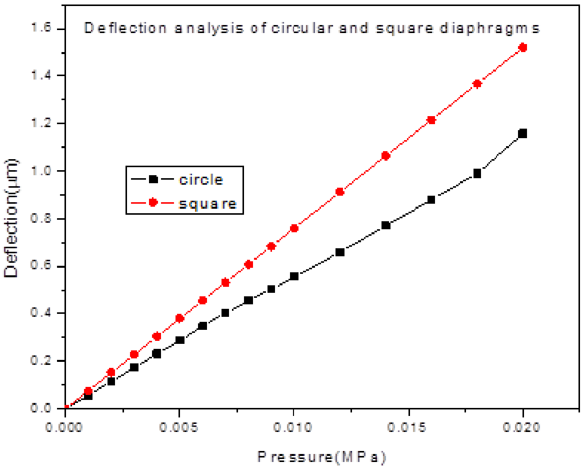

Fig.2.7 Maximum Deflection Of The Diaphragm In Micrometers As A Function Of Pressure In Mpa

The Figure 2.7 shows and explains the comparison of the deflection obtained with circular and square diaphragms at 0.02MPa. The half side length of the diaphragm is 600µm and the thickness of the diaphragm is 14.5µm. It can be inferred that square diaphragm has higher Deflection level when compared with circular diaphragm.

TABLE I

PERCENTAGE (%) IMPROVEMENT IN DEFLECTION AT 0.02MPA

S. No	Radius (µm)	Circle (µm)	Square (µm)	(%) Improvement in deflection (µm)
1.	250	0.727	0.597	17.88
2.	300	0.871	0.762	12.51
3.	350	1.024	1.119	-9.277
4.	400	1.140	1.455	-27.63
5.	450	1.100	1.388	-26.18
6.	500	1.119	1.463	-30.74
7.	600	1.158	1.52	-31.26

The table I present the percentage improvement in deflection for square and circular diaphragms of different dimensions. A close look at the deflection results show the circular diaphragm are showing better deflection in lower dimensions. But when it comes to larger diaphragm size, it is the square diaphragm that gives more deflection.

E. Stress Analysis

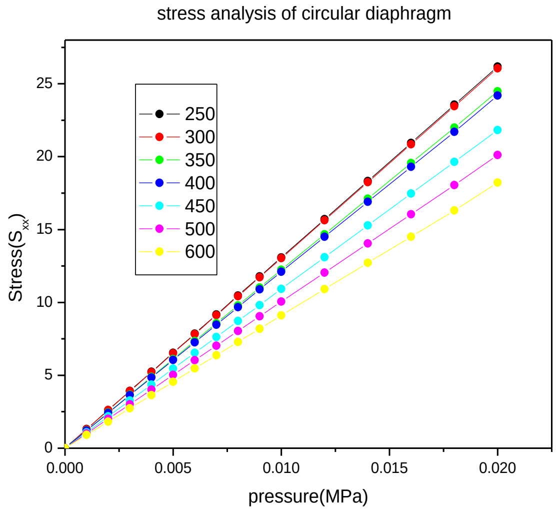

Fig.2.8 Stress Analysis Of Circular Diaphragm

The figure 2.8 shows the linear relationship between pressure and the induced stress. A close look at the stress levels shows that the circular diaphragms are showing better stress levels at lower dimensions while comparing with square diaphragms which show better deflections at higher stress levels in Figure 2.9.

TABLE II
PERCENTAGE (%) IMPROVEMENT IN STRESS AT 0.02MPA

S. No	**Radius (µm)**	**Circle (MPa)**	**Square (MPa)**	**(%)Improvement in stress (MPa)**
1.	250	26.19	7.915	69.78
2.	300	26.06	20.334	21.97
3.	350	24.49	20.568	16.01
4.	400	24.2	24.209	-0.03
5.	450	21.82	23.811	-9.11
6.	500	20.11	23.811	-18.39
7.	600	18.22	19.91	-9.27

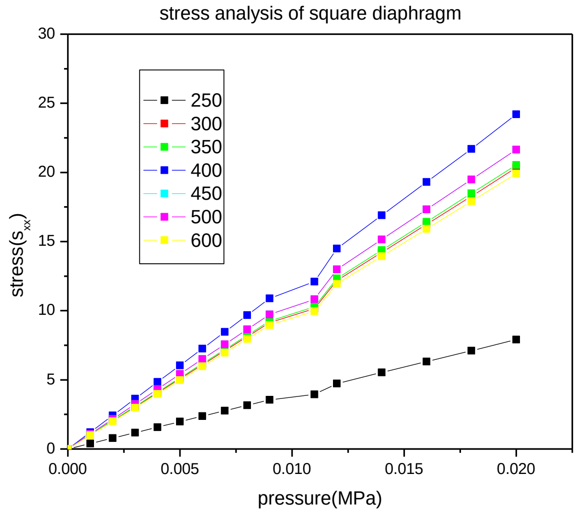

Fig. 2.9 Stress Analysis Of Square Diaphragm

As far as the induced stress and deflections are concerned square diaphragm has the highest induced stress hence it is the preferred geometry because the high stresses generated by applied pressure loading result in high sensitivity.

F. Performance Comparison

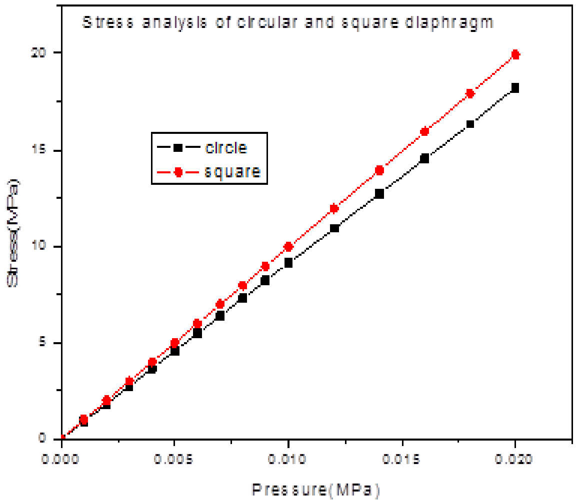

Fig.2.10 Maximum Stress Of The Diaphragm In Mpa As A Function Of Pressure In Mpa.

The figure 2.10 explains the comparison of deflection between circular and square diaphragms at 0.02MPa of a diaphragm with half side length of 600µm and thickness of the diaphragm 14.5µm. It can be inferred that square diaphragm has higher stress generation when compared with circular diaphragm.

The relationship between pressure, side length, and percentage improvement in stress can be analyzed using Intellisuite tool.

The table II summarizes the percentage improvement in stress levels in for square and circular diaphragms of different dimensions. Again it is seen that the circular diaphragm give large stress levels in smaller dimensions. But at high dimensions it is square that gives better stress generation.

V. PIEZORESISTIVE ANALYSIS

Pressure sensors employing piezoresitive effect is discussed in this work. If a strip of elastic material is subjected to tension, its longitudinal dimension will increase while there will be a reduction in a lateral dimensions. Since the resistance of a conductor is proportional to its length and inversely proportional to its area of cross section, the resistance of gauge increases with positive strain. The change in the resistance value of a conductor due to applied strain is called piezoresitive effect. Proper selection of piezoresistors i.e. orientation, shape, location, doping concentration and dose is essential. Piezoresistive pressure sensors combine the excellent mechanical properties and piezoresitive effect of single crystal silicon and related process technologies of integrated circuits. Piezoresistive pressure sensors use diffused or implanted resistors that measure the stress on a silicon diaphragm. Boron implantation of the piezoresitive elements was performed to convert the implanted regions from n-type to p-type and make them sensitive to mechanical stress.

5.1 Piezoresistive Coefficients

The piezoresitive coefficient relates the fractional change in resistance to the applied stress. In a cubic semiconductor, the matrix of piezoresitive Coefficients contains only three independent values, conventionally labeled π_{11}, π_{12}, and $\pi_{44.}$ The piezoresitive coefficients are sensitive to several quantities in addition to conductivity type and orientation, including temperature and doping level [9].The value for π_{44} is138.1x10^{-11}Pa^{-1},
π_{11} is 6.6x10^{-11}Pa^{-1} ,π_{12} are,-1.1x10^{-11}Pa^{-1}.

The mechanical stresses obtained by FEA should be transferred into output voltage thus the simulation value can be applied to predict the equivalent output electrical signal. R1, R2, R3, R4 are the parallel resistors placed on the diaphragm. The bridge output voltages of various sensors are presented in Table III.

TABLE III
PRESSURE VS BRIDGE OUTPUT:

S. No	Radius (µm)	ΔV (V)
1.	250	0.162
2.	300	0.16
3.	350	0.168
4.	400	0.17
5.	450	0.155
6.	500	0.152
7.	600	0.16

The Table III explains difference in voltage for the applied pressure.

VI.CONCLUSION

This paper first reviewed the operation of a modern spirometer that involves usage of MEMS pressure sensor for assessing the lung functions in human. Such measurement involves pressure sensors based on MEMS technology. This paper dealt with the design of the pressure sensors for spirometry application. A comparison study between pressure sensors that use square diaphragm and circular diaphragm is best suited for spirometry application.

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