Design of Piezoresistive Pressure Sensors for very Low Pressure

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Abstract - *In the era where environmental and energy problems are of great concern, sensors like pressure sensor and temperature sensor play an imperative role in environmental monitoring. Out of the various types of pressure sensors available, piezoresistive pressure sensors are the most recurrently applied because they have significant advantages over other sensors, such as good linearity, high pressure sensitivity etc. This paper focuses on Micro electro mechanical system (MEMS) based design of the said sensor as they provide the ability to measure the low-pressure range and have the advantages of small size, low power requirements, good performance, and the ability to be mass produced in the micromachining process. By integrating the design of the sensor using the multiphysics software COMSOL, the optimum sensor that achieves the best possible result by yielding the highest sensitivity can be achieved. Using COMSOL, by manipulating the sensor's parameters in a user-friendly interface, the sensor can be designed and simultaneously tested, thereby saving time and money while providing the desired results that can be used for a number of applications in several domains.*

Key Words: **Piezoresistive, Linearity, Sensitivity, Micromachining**

1. INTRODUCTION

MEMS based pressure sensors are in demand in the ever evolving world due to their ability to measure extremely low pressure while also possessing advantages like miniature size, low power requirements, decent performance and the ability to be produced in large numbers. There are various kinds of MEMS based pressure sensors, out of which piezoresistive pressure sensors hold a higher regard due to their significant advantages like: good linearity, high pressure sensitivity, small size, high performance, low cost and ease of fabrication. [1]

1.1 Piezoresistive pressure sensors

Piezoresistive pressure sensors consist of a thin membrane called diaphragm, the strain on which is determined using a resistor. When the pressure is applied, diaphragm bends and causes a deformation in its crystal lattice, which ultimately modifies the band structure placed on the diaphragm, and changes the resistivity of material.

1.2 Finite element analysis using COMSOL

The Finite Element Analysis is a technique used by engineers to minimize the number of prototypes and optimize the components in order to produce better products. One of the methods employed in this is the Finite Element Method (FEM). The piezoresistive pressure sensor is designed to obtain desired sensitivity and FEM is used to predict the stresses that are induced and the deflection of the membrane. [2] Using COMSOL Multiphysics software, various kinds of engineering problems can be solved as it creates an interactive environment that mimicks the effects that are observed in reality. The software has an inbuilt MEMS module from which the piezoresistivity shell can be selected and different designs of sensors can be simulated.

2. DESIGN OF THE EXISTING MODEL

Using the MEMS piezoresistive shell in COMSOL, the results of the existing model was simulated in order to compare the results with the proposed models and determine the superior model. One main parameter to determine the sensitivity is the Von Mises stress. It determines the yielding point of a given material to an applied stress. When pressure is applied to the diaphragm of the sensor, deformation of the membrane takes place and the voltage changes according to the pressure applied.

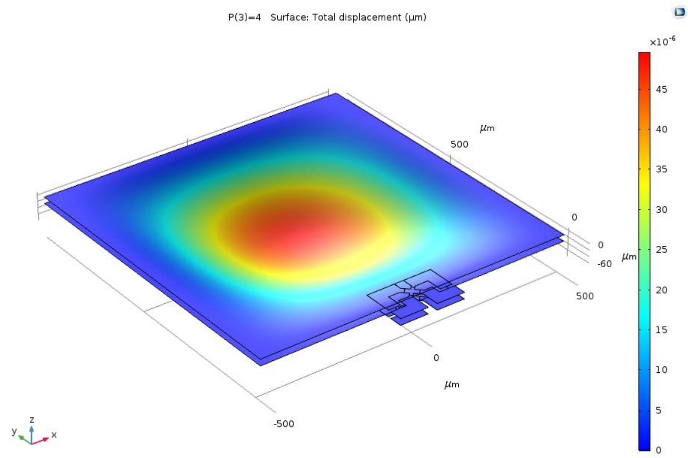

Fig -1: Displacement of the membrane

The above figure shows the displacement of the diaphragm as a result of a 100 kPa pressure applied to the membrane; at its center the displacement is 45 μm.

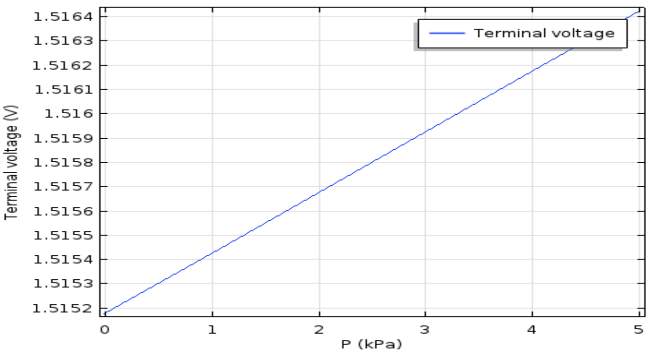

Fig-2: V vs. P graph

The above graph illustrates the sensitivity of the existing sensor model, where an output of 1.5V/KPa is obtained. The sensitivity factor calculated from the obtained voltage and the applied pressure of 5KPa, is 30mv/KPa, after taking into account the maximum threshold value of the sensor.

3. NOVEL PIEZORESISTIVE PRESSURE SENSOR WITH CBMP STRUCTURE

This structure was proposed by Anh Vang Tran, Xianmin Zhang, and Benliang Zhu. Cross-Beam membrane and Peninsula structure was designed for a better sensitivity and linearity. In this CBMP structure, a square diaphragm with a length of length of 2900µm and thickness 18µm is designed. The height and width of the cross beam µm and 210µm respectively. The resistors of length 200µm is used. The pressure sensor is arranged in a square configuration with these resistors. Polycrystalline silicon, also called as Poly-Si, has high purity and is deposited on top of the silicon substrate to make it highly doped. The pressure ranging from 0kPa to 5kPa is applied at the edges of the diaphragm.

On applying pressure within the range of 5kPa, the diaphragm gets deformed due to the stress and electrical potential is developed. The figure shows the displacement of 1.2m when pressure is applied to the membrane at its four corners. The peaks are formed at the region where the pressure is given due to the increase in the heat dissipation.

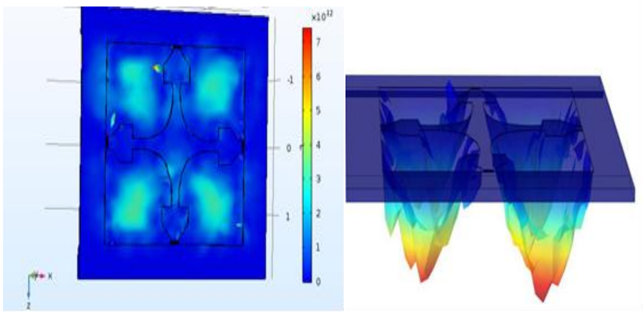

Fig-3: Displacement in CBMP structure

When the applied pressure exceeds the yield strength, it damages the membrane. Thus, the Von Mises stress must be higher than the yield point of the membrane.

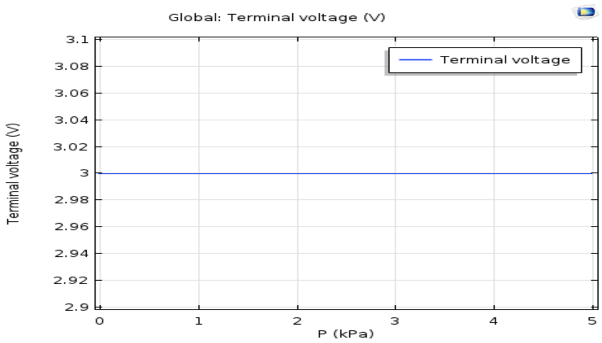

Fig-4: V vs. Graph for CBMP structure

The above graph illustrates the sensitivity of the sensor. This shows that the square diaphragm doesn't give the desired sensitivity. The terminal voltage obtained (3V/kPa*area) here is higher, so the sensitivity of the sensor is less than the existing model. The main disadvantage of this structure is the increase of Von Mises stress value than the yield strength of the membrane, which linearly increases the heat dissipation of the structure.

4. CBMP STRUCTURE WITH CIRCULAR MEMBRANE

In order to overcome the problem of peak formation due to excessive heat dissipation, an alternate model of piezoresistive pressure sensor has been proposed in this paper. The main aim of this circular diaphragm structure is to overcome the issue of heat dissipation and reduce the Von mises stress distribution, thereby providing better sensitivity and nonlinearity. Based on these considerations, the characteristics of the sensors are simulated.

4.1 Model Definition

The main design parameters include the membrane dimensions: the circular cross-beam dimensions beam height (H) 12µm and beam width (W) 210µm. The requirements under consideration include the measurement pressure range of (0–5 kPa), the sensor output voltage, sensitivity and non-linearity error. The design optimizations are made as done in the square diaphragm, and the piezoresistors with two turns are placed at the centers of the crossbeams. In the final design, a fixed resistor with a 200µm length and a 12µm width is used for all resistors.

4.2 Results

When a pressure of 0-5KPa is applied to the diaphragm region, the displacement takes place quite moderately only in the regions near the input and output terminals, as indicated by the color variation in the below figure. Similarly, the Von mises stress is accumulated only in the region near the contacts, thus showing that the issue of peaks arising due to heat dissipation in the square structure has been overcome. This indicates that the stress produced is considerably less, and does not damage the sensor in any way, meaning that it can be suitable for a large number of applications.

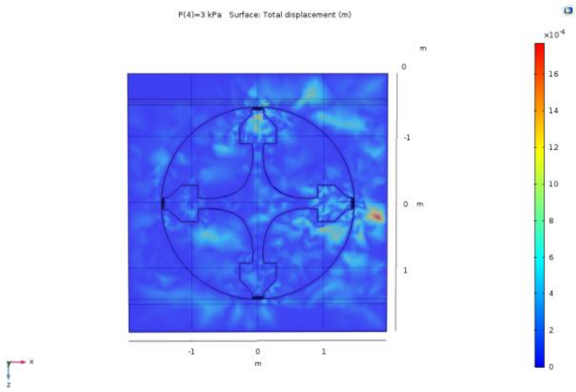

Fig-5: Displacement with Circular Diaphragm

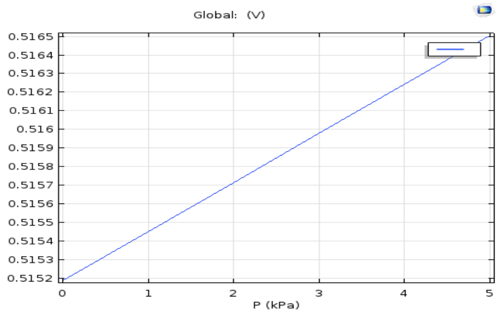

Fig-6: V vs. P graph for Circular membrane structure

The above graph illustrates the sensitivity of the proposed sensor model with a circular diaphragm, where an output of 0.515V/KPa is obtained. The sensitivity factor calculated from the obtained voltage and the applied pressure of 5 KPa is 10.3mv/KPa, after taking into account the maximum threshold value of the sensor.

5. CONCLUSION

On the objective of optimizing sensitivity, different models for piezoresistive pressure sensors were proposed. When pressure was applied, certain deflections were produced in the membrane and the induced stresses were predicted with the FEM. Initially, a conventional model named as Motorola Xducer, having a rectangular resistance network was designed and its results were simulated. Though it produced a good sensitivity of 30 mV/KPa, it had issues related to non-linearity and response time. Therefore, another model known as the CBMP model with a square diaphragm was designed. However, in this model, the heat dissipation was drastically high causing the formation of peaks in the Von Mises stress distribution.

Table-1: Results

DIAPHRAGM	SENSITIVITY (mV/KPa)	OUTPUT VOLTAGE(V)
Square	60	3
Rectangular	30	1.5
Circular	10.3	0.51

As a result, the sensitivity produced wasn't ideal and had a value of 60 mV/KPa, with higher non-linearity. Therefore, a final structure was proposed which was similar in design but having a circular diaphragm and different device physics. The circular diaphragm structure had desirable results in the Von Mises stress distribution and in displacement of the membrane. The result thus obtained had no heat dissipation issues and produced a sensitivity of 10.3 mV/KPa, which is better than the existing model.

From the below chart, it is visible that the proposed circular diaphragm structure has lesser non-linearity error when compared to the other structures.

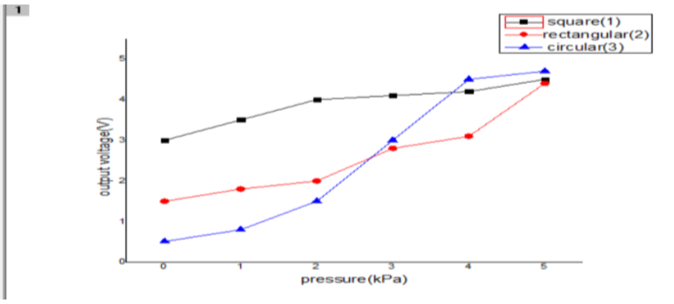

Chart-1: Sensitivity of different types of diaphragms

Thus, by using MEMS based design of piezoresistive pressure sensor a device with good linearity and maximized sensitivity can be obtained at extremely small sizes. So, this can be used in automotive industry, biomedical field and household appliances. In particular, the circular diaphragm structure is preferred as the deflection is more at the centre of circular membrane and the stress is more at the edges of the circular membrane. Due to low stress, this type of pressure sensor is used even in harsh environments.

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