Improved Piezoresistive Pressure Sensor for Precise Blood Pressure Monitoring

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***Abstract*— Piezoresistive pressure sensors are one of the most important and oldest applications of microelectromechanical systems (MEMS). In this paper, a conventional piezoresistive pressure sensor has been simulated and thoroughly analyzed for is output characteristics using finite element method (FEM) tool COMSOL Multiphysics®. The stress distribution and displacement on the surface of the diaphragm is ascertained and the positions of the piezoresistors are optimized in order to obtain the best possible sensitivity and the linearity of the piezoresistive pressure sensor. The goal in pressure sensor design is to obtain best possible sensitivity, without compromising on the linearity. This goal can be achieved by realizing some structures on the diaphragm, where the stresses are concentrated, namely stress concentration structures (SCS). In this work, a cross beam-membrane (CBM) structure has been taken as a case study for SCS. The conventional pressure sensor structure is compared with CBM structure in terms of sensitivity and linearity using FEM analysis and the results are reported.**

***Keywords—component, formatting, style, styling, insert** (key words)*

I. Introduction

Microelectromechanical systems (MEMS) have received enormous attention in the past few decades. This is because of big strides in miniaturization and better performance of MEMS devices over their conventional counterparts [1]. Amongst all devices, MEMS-based pressure sensors have got lot of attention because pressure sensors are used in everyday life in various tasks which involve sensing, monitoring and controlling pressure. Consequently, pressure sensors cover 60 to 70 percent of the market amongst the various MEMS devices [2]. Pressure sensors were one of the first commercialized MEMS-based sensors [3]. Different transduction mechanisms are used in various pressure sensors types to measure pressure. These are: piezoresistive, capacitive, piezoelectric, optical and resonant. Each mechanism has its own set of pros and cons. However, piezoresistive pressure sensors are the favored choice in various fields due to their high sensitivity, small size, simple fabrication and low cost [3]. Silicon is the favored choice of material for piezoresistive sensors owing to silicon piezoresistors showing good sensitivity, repeatable output and high mechanical stability [4]. Silicon is also ideal material for making the diaphragm because it boasts of freedom from creep and hysteresis, outstanding mechanical properties and reproducible elastic deformations [5]. The thickness (and size/shape) of the diaphragm is dependent on the intended application. Piezoresistivity is the phenomenon in which a material's resistance changes when it is subjected to stress. Hence, a resistor realized with piezoresistive materials will change in resistance when a stress is applied on it.

A pressure sensor working on the principle of piezoresistivity has a diaphragm on which a pressure load which is to be measure is applied. Initially, resistance of all piezoresistors on diaphragm is same. However, the resistance changes when pressure is applied. The resistors are configured in Wheatstone configuration and resistance of two piezoresistors increases while resistance of other two decreases. This makes the bridge unbalanced and we get an output voltage at two ends of Wheatstone bridge, if input is given at the other two ends. To maximize the sensitivity of pressure sensor, piezoresistors are placed at high stress regions on the diaphragm. When the diaphragm thickness is reduced to increase sensitivity, the non-linearity of the sensor also increases. To circumvent this trade-off problem, stress concentration structures are created in a conventional diaphragm using a cross beam-membrane [6]. In this work, we show both sensitivity and linearity enhancement using stress concentration structure in a pressure sensor with pressure range of 0-30 bar. Such a pressure range is suited for applications such as engine control and dive computers.

II. Modelling and Simulation of Conventional Piezoresistive Pressure Sensor using FEM

The modelling of the pressure sensor is carried out for pressure range of up to 30 bar and the diaphragm dimensions are chosen accordingly. Length and width of the sensor die is 3500 μm and height of substrate is 350 μm. Diaphragm edge length is 1400 μm and thickness of the diaphragm is 50 μm. The thickness of the diaphragm is chosen as per thumb rule that the deflection of the diaphragm at full scale pressure must be is less than $1/5^{th}$ of the thickness of the diaphragm [7]. The contour plot of von-Mises stress distribution and diaphragm deflection for pressure of 30 bar is shown in Fig. 1. Firstly, in the model, four piezoresistors are placed at the edges of diaphragm. This is the conventional placement of piezoresistors because maximum stresses are present close to the edges. The length of each of the piezoresistor is 100 μm, width is 10 μm and thickness is 1 μm. All the piezoresistors are identical and are connected using aluminum line in the software. The material of the piezoresistor is single crystal, lightly doped, p-(110) silicon and diaphragm is made up of single crystal silicon with isotropic properties. When input of 3 V is supplied at two ends of Wheatstone bridge, output of 996.2 mV is observed at the output nodes, for a pressure of 30 bar. This translates to a sensitivity of 11.07 mV/V/bar. Also, in this conventional positioning of piezoresistors, we obtain a non-linearity of 0.6 %. The electric potential (voltage) in the Wheatstone bridge is shown in Fig. 1. The zoomed view of one of the piezoresistors is also shown depicting the electric potential change inside the piezoresistor. The sensitivity and nonlinearity plot are shown in Fig. 2 and Fig. 3, respectively.

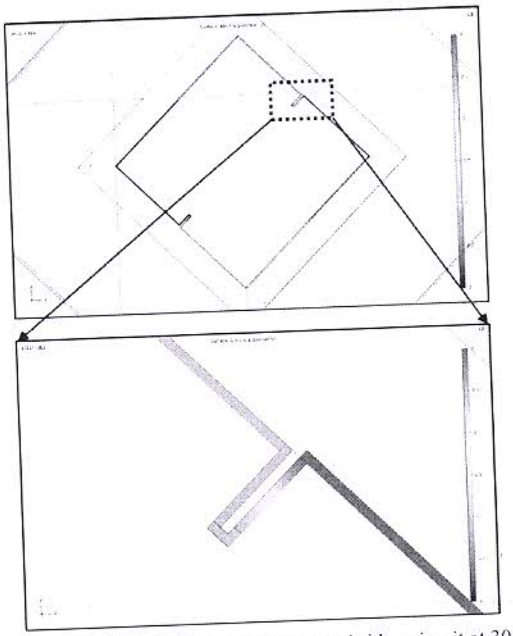

Fig. 1. Voltage distribution in Wheatstone bridge circuit at 30 bar

III. OPTIMIZATION OF PIEZORESISTOR POSITION

The piezoresistors should be placed at regions having maximum stress in order to maximize the sensitivity. As stated earlier, the high stress regions are located near the edges. We need to determine the exact optimized positions of piezoresistors which yields maximum sensitivity. This optimization was carried out by first optimizing the position of transverse piezoresistors, keeping the longitudinal piezoresistors at the edges. Then, the position of longitudinal piezoresistors is optimized, keeping the transverse piezoresistors at the edges. Through this exercise, we obtain the optimized position for both the piezoresistors. It was observed that in the optimized design, the longitudinal piezoresistors are placed slightly outside the edge of the diaphragm and the transverse piezoresistors are placed slightly inside the edges of the diaphragm as shown in Fig. 4. The optimization of piezoresistors has been carried out in terms of maximization of sensor output.

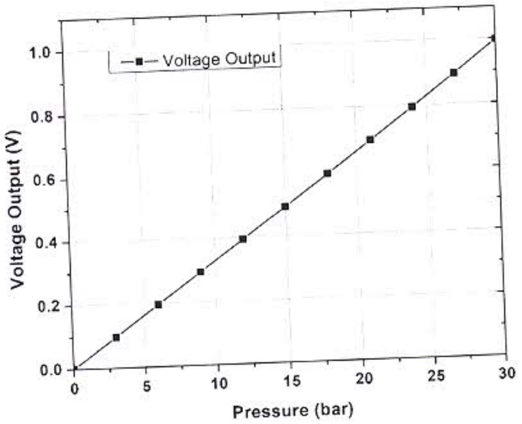

Fig. 2. Sensitivity plot

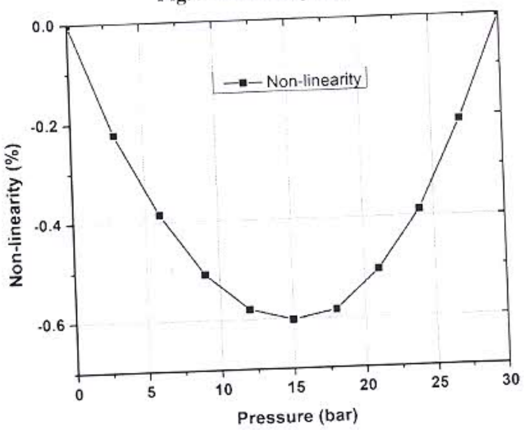

Fig. 3. Non-linearity plot

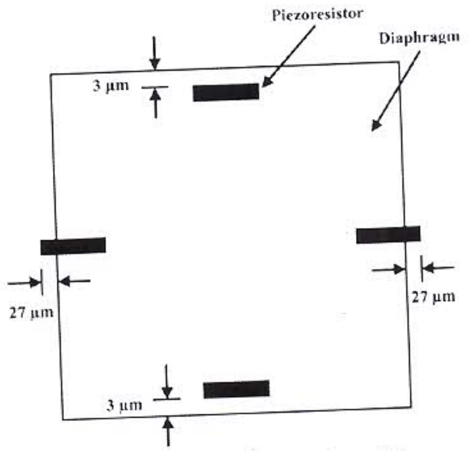

Fig. 4. Optimized position of piezoresistors

When position of longitudinal piezoresistors is optimized, while keeping the transverse piezoresistors at the edges, we obtain an output voltage of 1022.26 mV at full scale pressure and a corresponding sensitivity of 11.36 mV/V/bar. By optimizing the position of longitudinal piezoresistors, 2.6 % increase in sensitivity is achieved. When position of transverse piezoresistors is optimized, while keeping longitudinal piezoresistors at edges, voltage output of 999.5 mV and sensitivity of 11.10 mV/V/bar is obtained. In this case, the increase in sensitivity is only 0.33 %. This indicates that optimizing the position of transverse piezoresistors leads to a more pronounced enhancement in sensitivity compared to optimizing the position of longitudinal piezoresistors. When both the piezoresistors are set at their optimized positions, we get output voltage of 1025.32 mV and corresponding sensitivity of 11.39 mV/V/bar, an increment of 2.92 % in sensitivity. Before optimization, non-linearity was about 0.6 % and after optimization it is about 0.3 %. In conclusion, through optimization of position of piezoresistors, sensitivity increases by around 3% and there is a significant improvement in non-linearity, which becomes half its prior value.

IV. CBM Stress Concentration Structure

Generally, for the purpose of enhancing sensitivity, the diaphragm thickness is reduced. However, a thin diaphragm causes increase in non-linearity. Thus to achieve the aim of enhancing the sensitivity without reducing linearity, structures can be introduced on the diaphragm surface which leads to formation of stress concentration regions. In this paper, we use cross-beam membrane (CBM) structure, having 20 μm thickness on top of the conventional diaphragm having 50 μm thickness, as a representative case study to demonstrate the phenomenon of stress concentration. In the CBM structure, we introduce two beams intersecting at their mid-point on top of the diaphragm, without changing the thickness of the diaphragm. The CBM structure is shown in Fig. 5. The stress concentration regions are in areas where the cross beam meets the edges of the diaphragm.

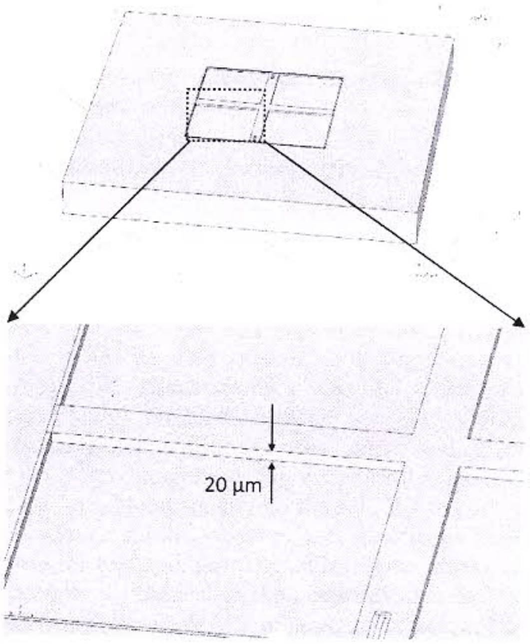

Fig. 5. CBM structure

When the piezoresistors are placed at the edge of the diaphragm in a CBM structure, we obtain a voltage output of 1067.97 mV, at 30 bar pressure and 3 V input voltage. This amounts to a sensitivity of 11.86 mV/V/bar, an increment of 7.2 % compared to a conventional pressure sensor with piezoresistors at the edges.

For further enhancement in sensitivity, the positions of the piezoresistors is optimized in the CBM structure pressure sensor in similar fashion as described earlier for conventional diaphragm pressure sensor. It is observed that if longitudinal piezoresistors are placed 23 μm outside the edges and transverse piezoresistors are placed 14 μm inside the edges, we get maximum voltage output. After optimization of position of piezoresistors, voltage output of 1136.68 mV and sensitivity of 12.63 mV/V/bar is obtained. Hence, by appending CBM structure on a simple diaphragm and optimizing the position of piezoresistors, sensitivity of the piezoresistive pressure sensor is enhanced by 14%. This is shown in Fig. 6. The non-linearity in this case is found to be 0.13 %, which is less than 1/4th of the value obtained for a simple diaphragm with conventional piezoresistor placements. The comparison is depicted in Fig. 7.

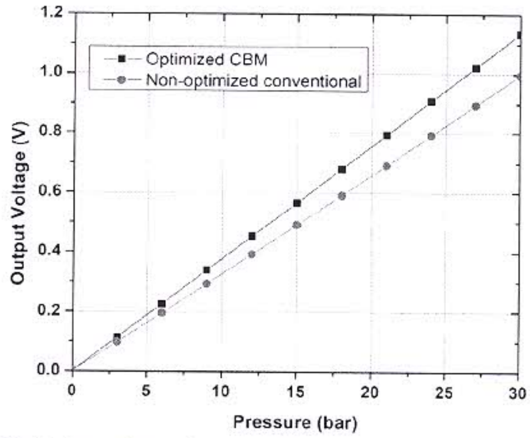

Fig. 7. Comparison of output voltage between a non-optimized conventional diaphragm structure and optimized CBM structure

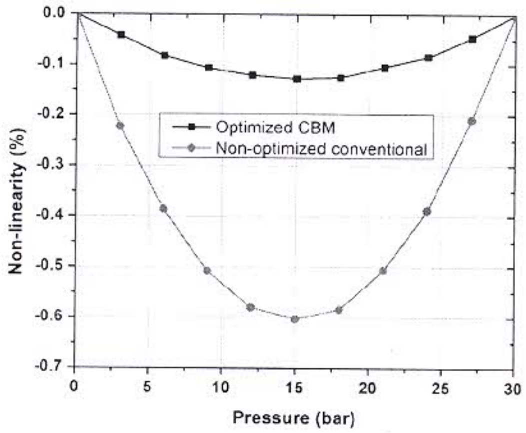

Fig. 8. Comparison of non-linearity between a non-optimized conventional diaphragm structure and optimized CBM structure

V. Conclusions

The simulation of a piezoresistive pressure sensor is performed using FEM tool COMSOL Multiphysics® to obtain its output characteristics. The position of the piezoresistors for obtaining maximum sensitivity is also determined. Furthermore, FEM simulations are carried out for a CBM structure and the output characteristics of sensor so obtained is evaluated. The position of piezoresistors is optimized for CBM structure, for high sensitivity and linearity. The results are compared for sensor with simple diaphragm and conventional piezoresistor placement and sensor with CBM structure and optimized piezoresistor placement. An enhancement of 14 % is observed in the sensitivity and the non-linearity is reduced by more than factor of 4.

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