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Research Article

Study and Analysis of the Effective Geometries for the Piezoresistive Pressure Sensors

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ABSTRACT:THE REPORTED WORK IS ON THE DESIGN AND SIMULATION OF MICROELECTROMECHANICAL SYSTEMS (MEMS) BASED SILICON PIEZORESISTIVE PRESSURE SENSOR DEPLOYED TOSENSE PRESSURE IN THE RANGE OF 0 TO 1.1 BAR. THE PRESSURE IS APPLIED ON THE DIAPHRAGM CONSISTING OF FOUR PIEZORESISTORS CONNECTED IN THE WHEATSTONE BRIDGE CONFIGURATION. THE INDUCED STRESS AS A RESULT OF THE PRESSURE CAUSES CHANGE IN RESISTANCE OF PIEZORESISTORS DUE TO PIEZORESISTIVE EFFECT. THE DESIGN AND SIMULATION OF THE SENSORS PRIOR TO FABRICATION HELPS US TO OPTIMIZE THE DIAPHRAGM THICKNESS AND SIZE. MEANDER SHAPED PIEZORESISTORS WITH DIFFERENT NUMBER OF TURNS ARE STUDIED IN ORDER TO FIND OUT THE BEST CONFIGURATION FOR HIGH SENSITIVITY AND LINEARITY. THE DESIGN AND SIMULATION IS CARRIED OUT USING FEM (FINITE ELEMENT METHOD) BASED COMSOLMULTIPHYSICS. BASED ON THE SIMULATION RESULTS, THE TWO-TURN CONFIGURATION IS FOUND TO HAVE THE BEST SENSITIVITY OF 4.181 MV/V/BAR AND THE ONE TURN CONFIGURATION GIVES THE LEAST NON-LINEARITY OF 0.5051 %

Keywords: MicroElectroMechanical Systems; Piezoresistivity; Pressure sensor; Finite element method.

I. INTRODUCTION

Pressure sensing has become an integral part of various applications such as chemical processing, biomedical instrumentation, automotive industry, aviation engineering, oil fields, industrial measurement and control system [1]. MEMS based pressure sensors have replaced the traditional pressure sensors because of their small size and enhanced sensor characteristics. There are various sensing principles which can be employed for measurement of pressure namely piezoresistive, capacitive, resonant and piezoelectric sensing [2]. Out of these different sensing principles, the piezoresistive sensing is preferred in pressure sensors because of ease of fabrication, high reliability, high linearity in output of sensor and simple compensation circuitry [3].

Piezo resistance is the phenomenon of change in resistivity of certain materials (like silicon, polysilicon, SiC etc.) on application of stress/strain. Piezoresistive pressure sensors employ this principle to measure the applied pressure. Piezoresistive sensors also have much higher sensitivity than the metal strain gauges which work on the basis of change in resistance due to geometrical deformation[4]. Pressure sensors for barometric applications constitute an important part of pressure sensor market. These types of sensors are used to measure the ambient atmospheric pressure and are generally used in weather forecasting, altimeters and in aviation sector.

Piezoresistive pressure sensors employing the use of silicon as a piezoresistive element are very popular due to advantages like high sensitivity and repeatability of output [5]. Polysilicon based pressure sensors have the advantage in high temperature applications due to the presence of an insulating layer under the sensing polysilicon piezoresistors.[6,7,8] But these sensors have the disadvantage of low sensitivity and difficulty in controlling the characteristics of polysilicon. Pressure sensors employing the use of other materials like SiC and diamond for piezoresistors are not very popular for commercial usage because the fabrication technology is not mature for such materials.[9,10,11,12] Also, silicon based piezoresistors can be easily fabricated using ion implantation where in the sheet resistance of the resistors can also be carefully controlled.[13,14] In this work, we will discuss the design and simulation of a piezoresistive pressure sensor based on piezoresistance in silicon.

This paper is organized as follows. First, we describe the working of a silicon piezoresistive pressure sensor. This is followed by the specifications and design parameters of a barometric pressure sensor, based on different

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design and fabrication considerations. Finally, we give the results of simulation of various designs of pressure sensor using COMSOL.

II. SILICON PIEZORESISTIVE PRESSURE SENSOR

A piezoresistive pressure sensor consists of a diaphragm with four piezoresistors on top of it connected in a Wheatstone bridge arrangement. The diaphragm is generally formed by dry etching using Deep Reactive Ion Etching (DRIE) or though wet bulk micromachining using alkali hydroxides like Potassium hydroxide (KOH) or Tetramethylammonium hydroxide (TMAH). The diaphragm is sealed from back side using anodic bonding in vacuum in order to measure the absolute value of pressure. The applied pressure causes diaphragm deflection and stress in diaphragm, which is sensed by the piezoresistors on top of the diaphragm. The piezoresistors are placed in regions of diaphragm where high stress is generated when a pressure is applied. The size, shape and thickness of the diaphragm and the shape and placement of piezoresistors are important factors which affect the output of the pressure sensor. Sensitivity and linearity of pressure sensors are the two most important specifications of a pressure sensor and these must be optimized before fabrication.

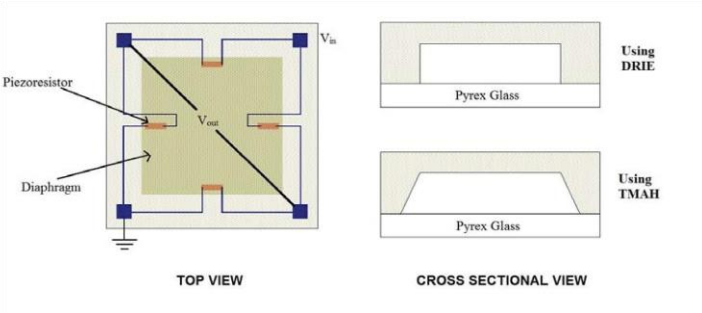

Fig1. Arrangement of piezoresistors in wheat stone bridge configuration

The change in resistance of a piezoresistive material under stress in given by

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho}$$

The first two terms correspond to geometrical deformation in length and cross section of the resistors, respectively. For piezoresistors under stress, these terms are negligible compared to the last term, which corresponds to change in resistivity. Hence, the equation reduces to,

$$I. \quad \frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} = \pi_1 \sigma_1 + \pi_T \sigma_T$$

Where, π_l and π_t correspond to longitudinal and transverse piezoresistive coefficients. σ_l and σ_t are the longitudinal and transverse stresses acting on the piezoresistor. In the present design, the piezoresistors are oriented along [110] directions on (100) wafer in order to maximize the piezoresistive effect. For this orientation,

$$\pi_{1,110} = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44})$$

Where, π_{11}, π_{12} and π_{44} are the three independent nonzero piezoresistive coefficients of silicon. Two piezoresistors are subjected to longitudinal stress and their resistance increases whereas the other two resistors are subject to transverse stress and their resistance decreases. Thus, the balanced Wheatstone bridge becomes unbalanced and the sensor gives a voltage output.

A Piezoresistive pressure sensor

A. IV. DESIGN CONSIDERATIONS FOR A PRESSURE SENSOR

The typical pressure range of operation for such sensors is from 0 to 1.1 bar pressure. After estimating the pressure, the graph between pressure measured and altitude can give the estimate of altitude. Therefore, we will choose this pressure range for our design. The sections below will provide a discussion on the various design considerations and we will finalize the design parameters which would be used for simulations using COMSOL Multiphysics. Pressure sensors demand high linearity of output. Piezoresistive pressure sensors have the advantage of better linearity than capacitive pressure sensor. Therefore, we will be using piezoresistive pressure sensing in our design. Ion implantation has been chosen as the technology for fabrication of the piezoresistors because of better deflection theory for bending of thin plates assumes that the deflection of midpoint of surface of diaphragm chosen for simplicity, so that sufficient area is present for TMAH etching from the back side the diaphragm.

Results of simulation of diaphragm size vs. max displacement

Chip Size (μm^2)	**Diaphragm Thickness (μm)**	**Diaphragm Size (μm^2)**	**Maximum Displacement (μm)**
4000*4000	25	1200*1200	0.821
4000*4000	25	1400*1400	1.717
4000*4000	25	1600*1600	2.82
4000*4000	25	1800*1800	4.55
4000*4000	25	2000*2000	8.76

The total resistance of each piezoresistors is taken as 2 kΩ. The piezoresistors would be fabricated by ion implantation of silicon. P-type piezoresistors would be used as they give better sensitivity than n-type piezoresistors. The effect of implanting boron atoms with a dosage of 1.1 x 10^{15} atoms/cm^2 and energy of 80 keV on n-type substrate with resistivity 5 Ω-cm is simulated using Silvaco Athena®. This gives a sheet resistivity of 100 Ω/Sq for the piezoresistors. To obtain a total resistance of 2 kΩ we would require 20 squares in each resistor. The resistor width is chosen to be 15 μm and therefore the length of the resistors comes out to be 15 x 20 = 300 μm. For simplicity, the thickness of the resistors is assumed to be 1 μm. Therefore, the resistivity of the resistors is 10^{-4} Ω-cm.

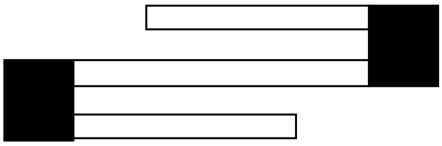

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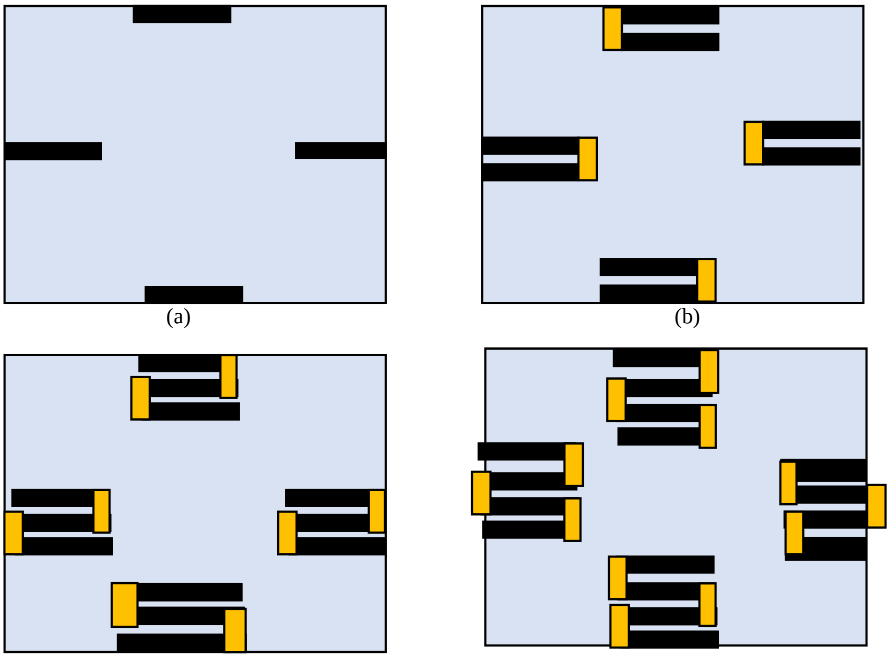
Fig.2.A typical meander shaped piezoresistor

Structure	Length (μm)
L	1800
L0 (No turn)	300
L1 (One turn)	150
L2 (Two turns)	100
L3 (Three turns)	75

Table 1. Dimensions of the Piezoresistor



(a) (b)

(c) (d)

Fig.3. Design and Structure of the piezoresistive elements
(a) No turn, (b) One turn, (c) Two turn, (d) Three turn.

The total length of the piezoresistor arms must be equal to 300 µm i.e. this length has to be distributed between the various arms of the piezoresistors. The connecting arms may be formed either using metal lines or using highly doped regions so that they do not contribute to the piezoresistive effect. In our simulations, we would consider four resistor configurations consisting of zero, one, two and diaphragm and length of resistor arms as depicted in three turns.

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VI. DESIGN SIMULATION USING COMSOL

The FEA Simulation Package, namely the Silicon structural properties Usually, silicon is considered as an isotropic material for easy analysis and calculations. But in this design, we have used the orthotropic properties of silicon (as given below) for obtaining better accuracy in results.

- Young’s modulus ($E_x = E_y = 169$ GPa, $E_z = 130$ GPa)

- Young’s modulus ($E_x = E_y = 169$ GPa, $E_z = 130$ GPa)
- Poisson’s ratio ($PR_{yz} = 0.36$, $PR_{xy} = 0.064$, $PR_{xz} = 0.28$)
- Shear modulus ($G_{yz} = G_{xz} = 79.6$ GPa, $G_{xy} = 50.9$ GPa)

COMSOL Multiphysics is one such tool. It is a powerfulinteractive environment for modeling and solving all kinds of scientific and engineering problems. It provides a powerful integrated desktop environment with a model builder where one can get full overview of the model and all its functionality. It allows us to extend conventional models of one type into Multiphysics models that solve coupled physics phenomena and do so simultaneously. No in-depth knowledge of mathematics or numerical analysis is required. Here, it is possible to build modules by defining the relevant physical quantities such as material properties, loads, source etc. rather than the underlying equations. COMSOL Multiphysics internally compiles a set of equations representing the model. Using the built-in physics interfaces, various types of studies such as stationary and time dependent, linear and non-linear, Eigen frequency, modal and frequency response studies can be performed.

Vll. SIMULATIONRESULTSAND DISCUSSION

The structure obtained after optimization of various parameters and dimensions is simulated for different values of pressures from 0 to 1.1 bar and the Pressure Vs Displacement is measured. The simulation shows some small output even at zero pressure due to limitation of mesh size that was used for simulation. The combined plot of displacement vs. pressure for all the four piezoresistor configurations. The following results are the various turns forpressure sensor.

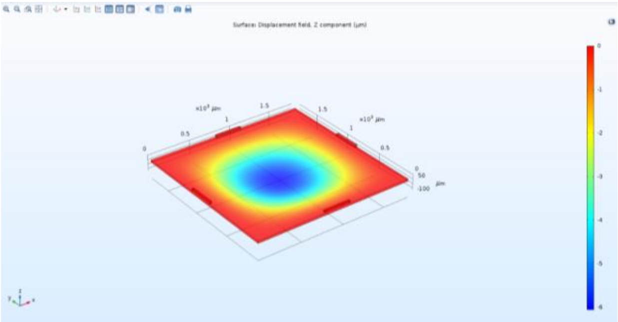

Fig 4 Pressure sensor (No turn)

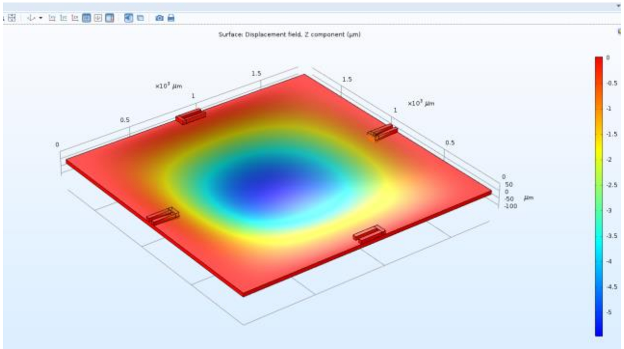

Fig 5.Pressure Sensor (One turn)

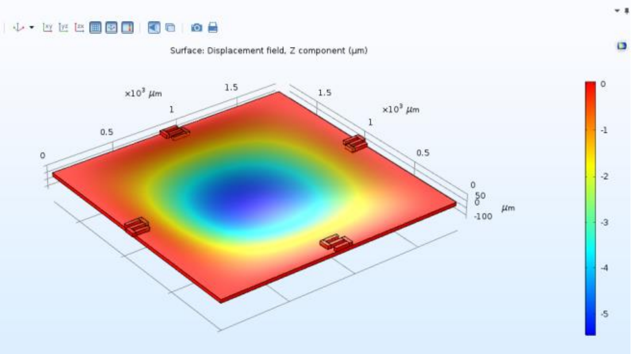

Fig 6. Pressure sensor (Two turn)

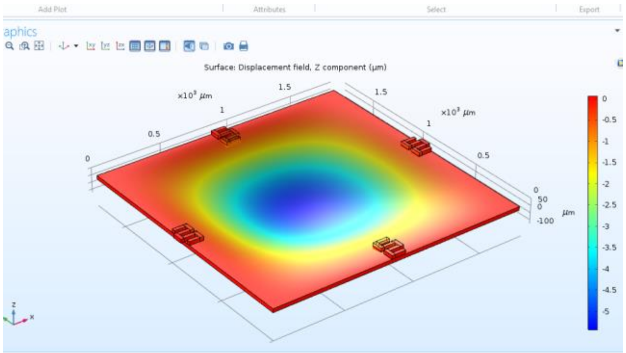

Fig 7. Pressure sensor (Three turn)

The change in displacement is simulated for different values of pressures from 0 to 1bar. From the table 5.1 we observe that the three turn pressure is found to be the best among all because of its wide range ofdisplacement values.

Table 5.1 PRESSURE Vs DISPLACEMENT

PRESSURE(MPa)	NO TURN	ONE TURN	TWO TURN	THREE TURN
0.1	0.508	0.649	1.269	1.984
0.2	1.016	1.265	1.856	2.526
0.3	1.523	1.878	2.204	2.956
0.4	2.031	2.302	2.584	3.421
0.5	2.539	2.852	3.475	3.951
0.6	3.047	3.214	4.257	4.456
0.7	3.555	3.864	4.987	5.664
0.9	4.063	4.356	5.324	5.865
1	4.571	4.869	5.554	6.309

The output graph for Pressure Vs. Displacement is shown below,

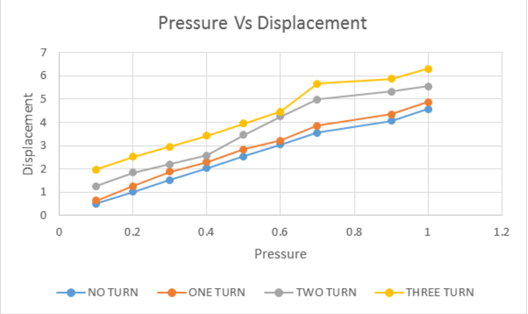

Fig.8. The output graph for Pressure vs. Displacement

5.3 CONCLUSION

Through this work, a complete design methodology has been established for silicon piezoresistive barometric pressure sensor for the range of 0 to 1.1 bar. The design principles and flow discussed here can be generalized for design of other pressure sensors having different fabrication technology and/or shape and size of different elements of the sensor.

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