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Design Analysis and Sensitivity Enhancement of Piezoresistive Micro Pressure Sensors

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Abstract**:** *Piezoresistive micro pressure sensors are widely used for pressure measurement. There are a few design issues need to be addressed like temperature sensitivity, placement of piezoresistive element on the membrane, design of element size, etc. For better sensitivity the length of piezoresistor needs to be increased whereas the thickness needs to be reduced. For a square membrane, the maximum stress value occurs at the center of the edge and decreases rapidly towards the center of the membrane. Increase in length of the piezoresistor beyond a limit will develop huge design error, since the localized stress variations are not considered in the design. The solution could be breaking down the resistance into smaller pieces and connecting them in series and positioning them in the maximum stress region. This paper discusses about the design of such a piezoresistive micro pressure sensor with optimized position placement and element size.*

Initially, a square diaphragm piezoresistive pressure using classical governing equations is designed. Since, three of the physics such as structural mechanics, piezoresistive physics and electrical physics are involved in the design; Comsol Multiphysics 4.3 is used to make a comparative study of the model with analytical design. The stress variation over the diaphragm is analyzed and the length of the piezoresistive element is designed by restricting the element in the maximum stress region. A Matlab code is written to find the optimum element size, and number of elements to be connected in series. The material properties, dimensions of the membrane, initial resistance and sheet resistance of the piezoresistor are considered as variables and obtained as user inputs.

Keywords: *micro pressure sensors, piezoresistive design, Comsol Multiphysics, Position optimization*

1. Introduction

Piezoresistance is defined as a change in electrical resistance of solids when subjected to stress fields. Silicon piezoresistors that have such characteristics are widely used in microsensors and actuators. Piezoresistors have high gain and exhibit a good linear relationship between the applied stress and the resistance change output. But these sensors suffer on account of temperature dependence of the piezoresistive coefficients. This piezoresistive nature of silicon makes the use of diffused or implanted resistors an obvious and straightforward technique for measuring the strain in a micromachined silicon diaphragm [1,2].

The schematic of a packaged pressure sensor is shown in figure 1. The top view of the silicon die shows four piezoresistors (R_1, R_2, R_3 and R_4) implanted beneath the surface of the silicon die. These piezoresistors convert the stresses induced in the silicon diaphragm by the applied pressure into a change of electrical resistance, which is then converted into voltage output by a Wheatstone bridge circuit[1].

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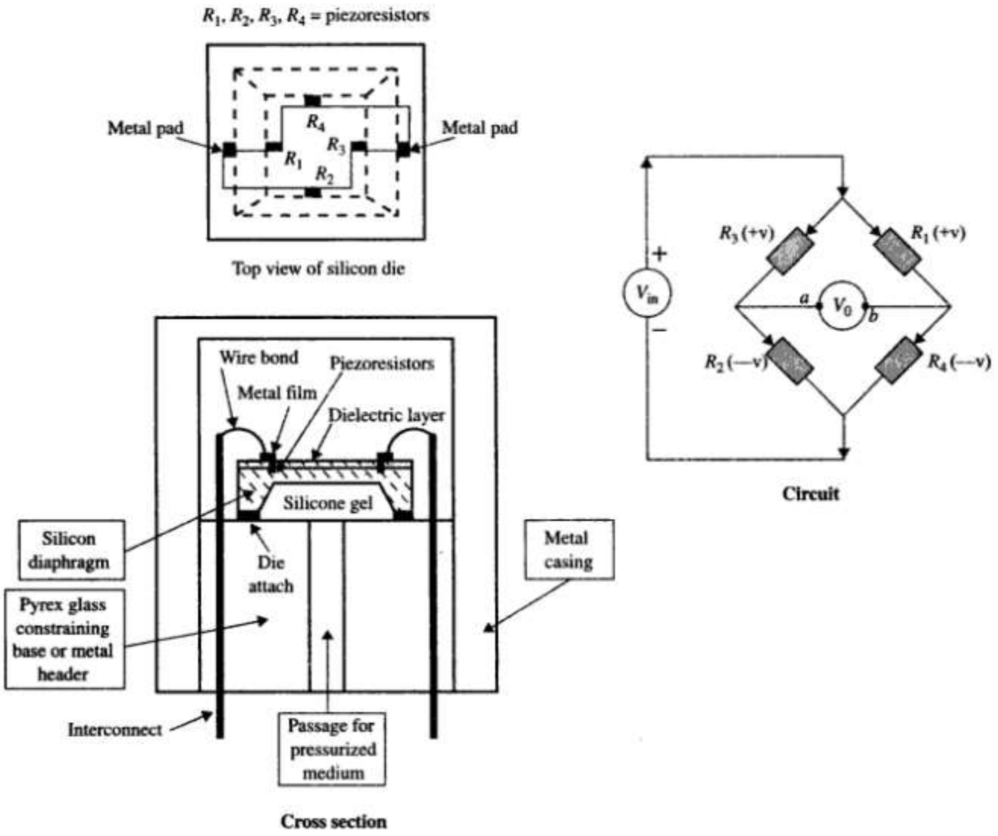


Fig. 1: Typical Piezoresistive Pressure Sensor Assembly [1]

2. Design of piezoresistive micro pressure sensors

2.1. Analytical Design

A square diaphragm with a side length 2a as shown in Fig. 2 is considered in this work [3].

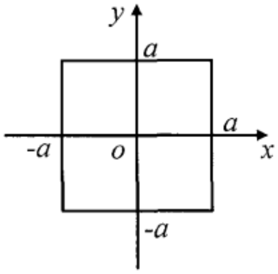


Fig 2: Structure geometries of a square diaphragm

The stresses on the surface of the diaphragm for a pressure ‘p’ is found to be [3]

$$\sigma_{xy} = 2.045(1-\nu)\, p \frac{a^2}{h^2}\left(1-\tilde{x}^2\right)\left(1-\tilde{y}^2\right)\tilde{x}\tilde{y} \quad (1)$$

Where $\tilde{x} = \frac{x}{a}$ and $\tilde{y} = \frac{y}{a}$

The equations for maximum stress in a square diaphragm are given by [3]

$$\sigma_{\max} = \frac{0.308}{h^2} P a^2 \quad (2)$$

The change of electric resistance in a silicon piezoresistance gage can thus be expressed as:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \qquad (3)$$

where the value of π_l and π_t in the <100> orientation are equal to $0.02\pi_{44}$, σ_l is the stress in the longitudinal direction and σ_t is stress in tangent direction. R can be calculated by the length l, the cross-sectional area A and resistivity (ρ) of the material as

$$R = \frac{\rho l}{A} = \frac{\rho l}{wt} \qquad (4)$$

The resistors used in micro pressure sensor applications are generally thin films and are considered as two dimensional entities. Thus, it is implied that the current flow is along the plane of the sheet, not perpendicular to it. Hence, the resistance considered is sheet resistance of the material. In a regular three-dimensional conductor, the resistance can be written in terms of sheet resistance which is the ratio of 'ρ' and 't' as

$$R = R_s \frac{l}{w} \qquad (5)$$

where, $R_s = \frac{\rho}{t}$ is the sheet resistance. A Wheatstone bridge is used to convert the change in resistance into appropriate voltage signal. The output of a wheatstone bridge can be given as

$$V_0 = V_s \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \qquad (6)$$

2.2. Finite Element Design

In order to simulate the structure with Comsol Multiphysics, the sheet resistance of the piezoresistor is considered as 150 Ω/□ (Ohms per Square) and the initial resistance is considered as 2kΩ as suggested in the reference [4]. A width of 1.5μm is considered with an initial resistance of 2kΩ. The length is calculated using eqn. 5 as 20μm. The structure proposed in [5] as shown in fig 3 is used to make a comparative study between analytical design and finite element based piezoresistive pressure sensors design. In this model, positions of the resistors are near the edges of the membrane (dashed line) because the piezoresistive effect depends on stress (respectively on strain) which is high near the fixed boarders. Considering the resulting distribution of stress, resistors R_1 and R_4 are arranged transversally and sensors R_2 and R_3 are arranged longitudinally. Because the strain decreases from the boarders to the center of the membrane, the longitudinal arranged resistors are divided into two shorter parts which are connected in series and positioned in a manner that a higher average strain is applied on the resistors in order to enforce the piezoresistive effect. An electric potential of 9V is applied between the metal pads A and C. The measured device output is the potential difference between the absolute values of the voltages at the metal pads B and D.

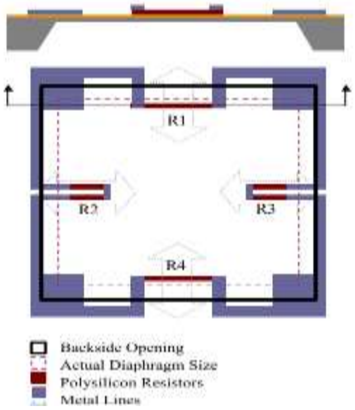


Fig 3: Piezoresistive sensor proposed by Lynn Fuller [5]

The sensor geometry and dimensions listed in the Table I are used for the initial analysis.

TABLE I: Geometry and dimensions of silicon pressure sensor

Diaphragm geometry and wafer thickness	Flat square silicon(100) and 500µm
Edge length of the diaphragm (a)	783µm
Thickness of the diaphragm (h)	63µm
Maximum central deflection of the diaphragm (wmax)	17µm (limited to h/4)
Young's modulus (E)	131 GPa
Poisson's ratio (γ)	0.27
Yield strength of silicon(100) (Sy)	7GPa
Input pressure range (P)	0 - 100MPa
Density of silicon (ρ)	2330kg/m3

3. Modelling Using Comsol Multiphysics:

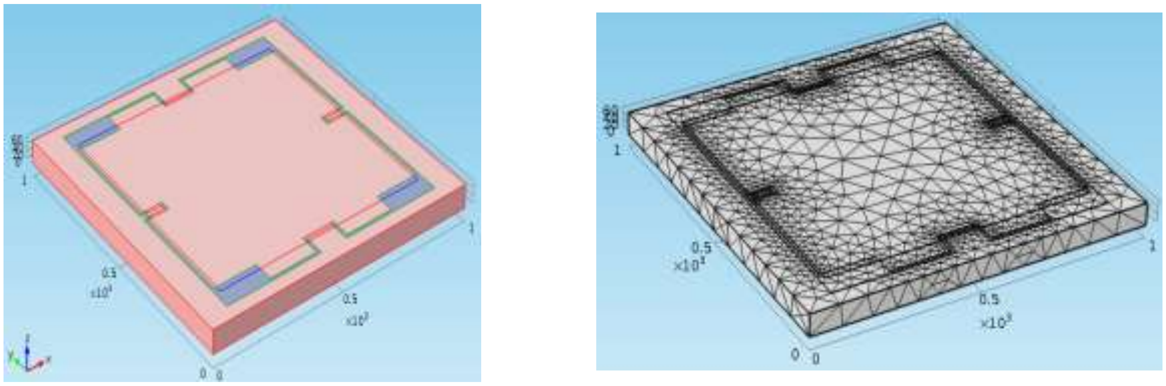
The sensor geometry as mentioned above is modelled using Comsol Multiphysics 4.3, piezoresistive physics for boundary currents module [6]. The geometry is created using a block (the membrane) with the given values for width, depth and height. Two work planes are defined on the top and bottom side of the block to define the boarders of the membrane. This also defines the frame at the same time. The dimensions of the resistors and the connections are defined by a 2D drawing on the upper work plane. The material of the membrane and frame is defined as single crystal, lightly doped n-silicon. The piezoresistive material is defined as lightly doped p-silicon. Aluminium is used as metal strip to connect between resistors. The material properties like Young’s Modulus and Poisson Ratio are set according to the given literature.

After this, the structural, electrical and piezoresistive properties of the model were defined. The lower side of the frame is defined as fixed and a pressure is applied on the upper side of the membrane as boundary load. The area within the boundaries of the connections are determined as thin conductive layers with a thickness of 400nm and the area bordered by the geometry of the resistors are defined as thin piezoresistive layers, also with a thickness of 400nm. The electrical properties are determined by defining the ground and a terminal at the edges of two connection pads. The virtual prototype of the piezoresistive pressure sensor without load is shown in figure 4(a).

The mesh for the FEM analysis is built by the software on the basis of physics controlled meshing option. The element size is defined as “finer”. Because of the simple geometry and the consideration of only a few physical effects, the computer generated mesh is sufficient and does not have to be optimized by user controlled settings. The mesh details are listed in Table II. The structure without load and its meshed 3D view are shown in figure 4(b).

TABLE II: Mesh Details Of The Piezoresistive Configuration

Parameter	Values
Element Physics	Piezoresitive (Boundary Currents)
Element Type	Free tetrahedral
Predefined Mesh Size	Normal
Maximum Element Size	100µm
Minimum Element Size	18 µm
Maximum Element Growth Rate	1.5 µm
No. Elements	8836
Discrietization Method	Quadratic
Solver	MUMPS



(a) (b)

Fig 4: Piezoresistive Pressure Sensor using Comsol Multiphysics (a) Virtual Prototype and (b) meshed structure

4. Results and Discussion

The FEM design of a piezoresistive sensor presented in earlier section is virtually prototyped using Comsol Multiphysics. The 3D stress plot and its stress variation over the arc length are shown in fig. 5 (a) and (b) respectively. It can be observed that there is a drastic change in the stress profile over the arc length. So, it is advisable to position the piezoresistors in the maximum stress region, which restricts the length of the piezoresistor. The potential distribution overt the piezoresistors for an applied potential of 9V is shown in figure 6. A comparison between analytical results and FEM results of the output voltage is listed in Table III and also plotted in figure 7. From these results it can be concluded that the analytical values are closely matching with the simulated model. It ensures that even for multiphysics analysis, these analytical equations could be used with acceptable error tolerance.

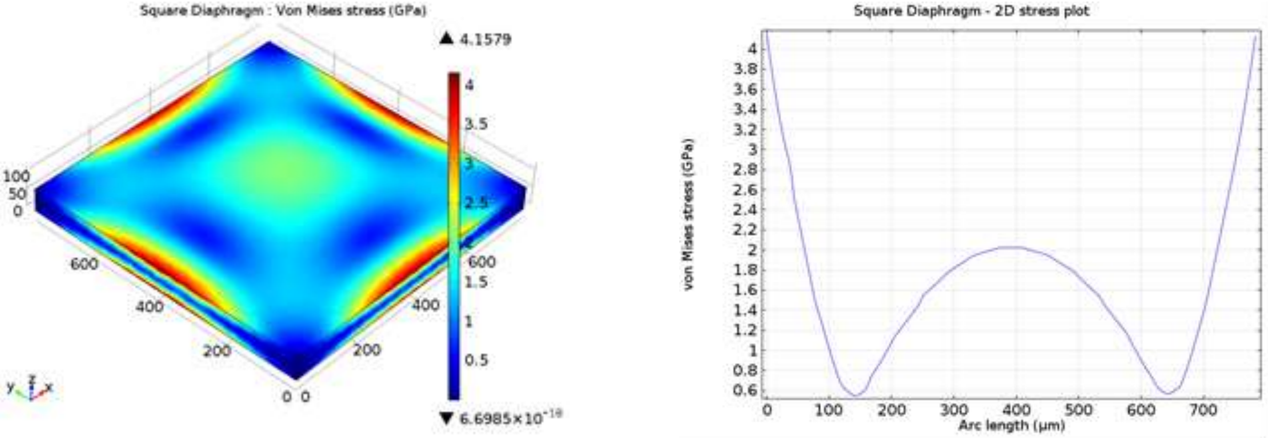
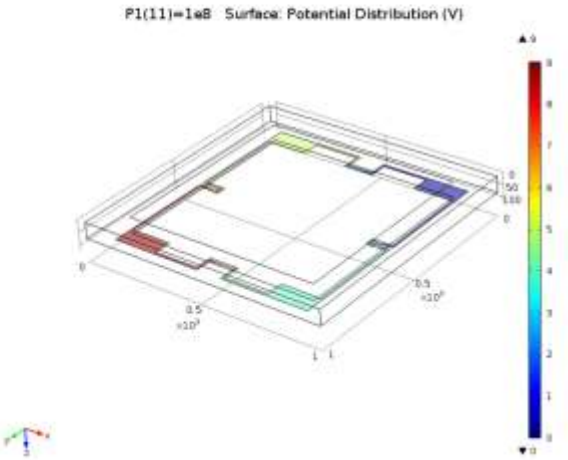


Fig 5: Stress plot of piezoresistive sensor for a pressure of 100MPa (a) 3D Plot (b) Stress distribution over arc length

The work is extened to achieve position optimization of piezoresistive element and element size calculation. Dimensions of the membrane, maximum applied pressure, tolerance on localized stress variations allowed in terms of percentage are consiered as user inputs. A Matlab code is written to do the back end calculations using the formule already presented. The output is presented in terms of optimum piezoresitive element size and the number of elements to be connected in series to achieve the total resistance value. A snapshot of the interface for a typical case is shown in figure 8.



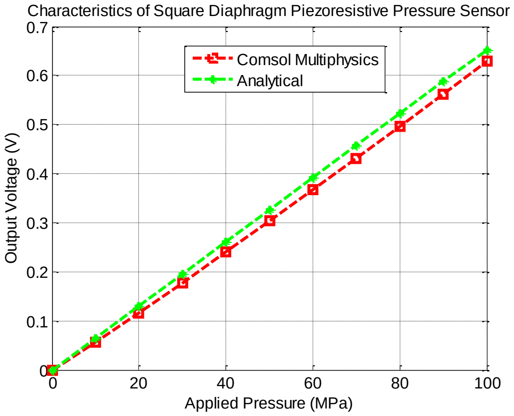


Fig 6: Potential distribution of piezoresistive sensor

Fig 7: Output voltage comparison of analytical and FEM model

TABLE III: Analytical stress values and Wheatstone bridge output voltage

Pressure (MPa)	Analytical		Simulation	
	Maximum Stress (GPa)	Output Voltage (V)	Maximum Stress (GPa)	Output Voltage (V)
10	0.4757	0.0654	0.3942	0.05562
20	0.9515	0.1307	0.7961	0.11644
30	1.4273	0.1961	1.205	0.17795
40	1.9031	0.2614	1.621	0.24018
50	2.3788	0.3268	2.042	0.30311
60	2.8546	0.392	2.469	0.36676
70	3.3304	0.4573	2.9	0.43114
80	3.8061	0.5225	3.335	0.49625
90	4.2819	0.5877	3.774	0.56208
100	4.7577	0.6529	4.217	0.62865

```
enter side length of diaphragm =783
enter height =63
enter the % pressure range =15
enter pressure to be applied on the diaphragm =1e5
enter the poissons ratio of the diaphragm material=0.27
enter the youngs modulus of the material chosen as the diaphragm=131e9
Enter the required resistance of the piezoresistor=2000
enter the given sheet resistance of the polysilicon piezoresistor=150
Enter the edge of the square of the polysilicon material=1.5



The Max stress developed =3529501.2058
The stress developed at the Max tolerance limit =3000076.0249
The min stress developed =720275.3616
the maximum piezoresistor length =11
the required length of piezoresistor as per the given specifications =20

Therefore for the best configuration of the most optimised output we need 1.8182
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Fig 8: Typical user interface for position optimization and to find number of piezoresistive elements

From the figure 8, it can be concluded that, for a structure with the dimensions provided above, the maximum stress developed at the middle of the edge is 3.5 GPa and the minimum stress is 0.72MPa. If the piezoresistors are broken into 20 elements with a length of 11µm each, then the stress at the other end of the piezoresistor is around 3GPa, which allows a stress variation of only 0.5 GPa and in turn results in better stress harvesting and yields better sensitivity.

5. References

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