Parametric optimization and analysis of pressure sensor chip membrane using design of experiments (DOE)

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MEMS, Piezoresistive, Sensitivity, Membrane, DOE.

ABSTRACT

MEMS offers the uses of the membrane in various applications such as pressure sensors and micro-pumps. The working principle of all these devices is based on the deflection of the membrane due to the application of force. Piezoresistive pressure sensors are simpler to integrate with electronics, and they are inherently more linear than capacitive pressure sensors. The parameter optimization of the membrane is the prime challenge for achieving the best performance of the device. In this paper, the parametric optimization is incorporated for aspect ratio in terms of excellent sensitivity and linearity with the help of the design of experiments (DOE) and ANSYS. It is observed that the aspect ratio of 0.04 gives the maximum deformation with the elastic behaviour, among other sample points of the design.

1. Introduction

The demand for sensors increased monotonically after introducing industry 4.0. In essence, industry 4.0 is the subset of the fourth industrial revolution towards automation in industry. Pressure sensors have become an integral part of various applications like the automotive industry, oil & gas processing, and aerospace applications, etc. MEMS pressure sensors enhanced the application by size and cost reduction. This type of sensors has replaced the traditional pressure sensors because of better sensor characteristics and small size. Different sensing principles could be employed for the measurement of pressure. Piezoresistive principles are employed here due to good sensitivity and linearity.

2. Piezoresistive Pressure Sensor & Pressure Sensor Membrane

2.1 Piezoresistive pressure sensor

Silicon has proven to be an excellent material for fabricating small pressure sensors. Nowadays, pressure sensors contribute to the largest market share of mechanical MEMS devices [1]. Typically, the technique involves deformation at the center by applying measuring pressure on one side of a membrane and a reference pressure to the other side. The reference pressure is the pressure present on the reverse or negative side of a pressure sensing element. Reference pressure takes absolute zero pressure for absolute pressure measurements, which is employed here. The principle of piezoresistive pressure sensors is based on a silicon property called piezoresistance, where the resistance changes with stress/strain. The resistivity of the material directly depends on the crystallographic structure of semiconductors. The ion implantation [3] enhanced the piezoresistivity effect of silicon, which has replaced the traditional strain gauge technique.

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2.2 Pressure sensor membrane

The application of pressure to the sensor causes a deflection of the membrane, and this leads to a change in resistance of the piezoresistive elements. As a result, the calculation of stress distribution and deflection in accordance with the applied pressure becomes pivotal [4]. There are various shapes of the MEMS pressure sensor membrane, i.e., Square, circular, and rectangular. In this paper, the square membrane is employed because this type of membrane gives higher vibration frequency and stress at the midpoint of an edge [2], which leads to the easy implantation of piezoresistors.

3. Mathematical Relations

This paper incorporates an absolute pressure sensor condition. Therefore, the thin membrane is subjected to pressure on one side and vaccum on the other side. The thickness of the membrane defines the dimensions of the etch hole [5]. The etch hole width w depends on wafer thickness H, the membrane thickness h, the membrane width l, and angle of membrane sidewall θ.

$$w=1+2(H - h) \tan \theta \quad (1)$$

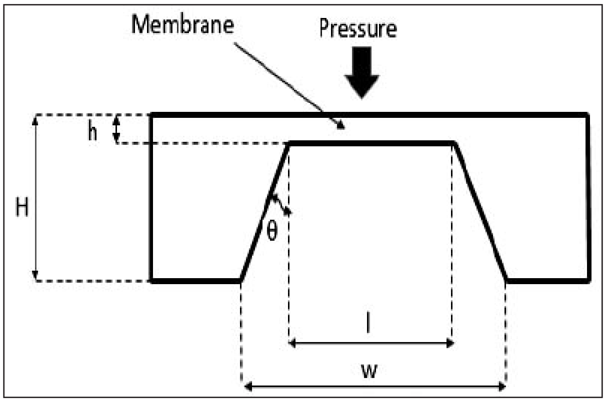

Fig. 1. Cross-sectional schematic view of the pressure chip.

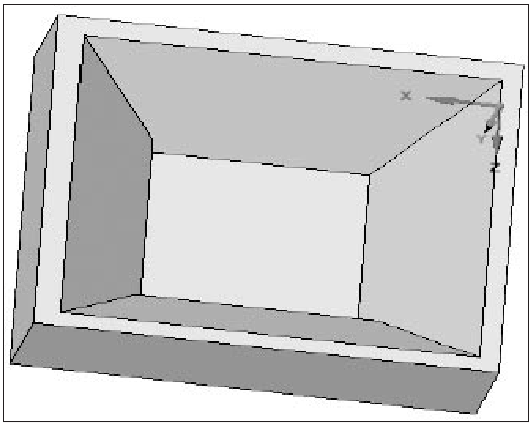

Fig. 2. A CAD model of the sensor chip.

In order to illustrate the deflection of the membrane due to pressure applied on its top surface, the equation of membrane for maximum deformation and stress at the center is given as [2] [6]:

$$y = c_w(1-\mu^2)\frac{pl^4}{Eh^3} \quad (2)$$

$$\sigma_c = 6c_c p\left(\frac{l}{h}\right)^2 \quad (3)$$

Where p is pressure applied on the membrane, E is Young's modulus, μ is Poisson ratio and C_w & C_c are the empirically selected optimization constant for different aspect ratios (refer to Table 1 and Table 2).

4. Design Considerations

In this section, we demonstrated the essential design considerations for a silicon pressure sensor chip. To find the correlation of the parameters for the design of a sensor plays a vital role in MEMS devices. This sensor chip is designed with considerations of following specifications, i.e., rated pressure = 10 bar, proof pressure = 15 bar, and burst pressure = 50 bar. We used parametric optimization in Ansys to find the best aspect ratio (h/l). The design points (h/l) are considered for the design of experiments (DOE) that vary with 36 µm to 44 µm. Silicon with standard anisotropic properties is referred for the sensor chip due to the typical behaviour for MEMS devices. The parameters have taken from the analytical equation of the membrane. The parameter optimization conducted to find the best aspect ratio for the maximum deformation, where stress must be under the elastic limit.

Fig. 3 and Fig. 4 represent the parameter correlation scatter plot in a quadratic and linear polynomial fit of the maximum equivalent stress

Table 1
Optimization constants for membrane deflection (y) model for different aspect (h/l) ratios.

Aspect ratio (h/l)	0.001≤(h/l)≤0.01	0.01<(h/l)<0.03	0.03≤(h/l)<0.05	(h/l)=0.05	0.05<(h/l)≤0.1
Constant (c_w)	0.0155	0.0166	0.0179	0.0189	0.0235

Table 2
Optimization constants for membrane stress at center corresponding to aspect ratio (h/l).

Aspect ratio (h/l)	00.001≤(h/l)≤0.01	0.01<(h/l)<0.05	0.0.05≤(h/l)<0.1
Constant (c_c)	0.02263	0.02363	0.02799

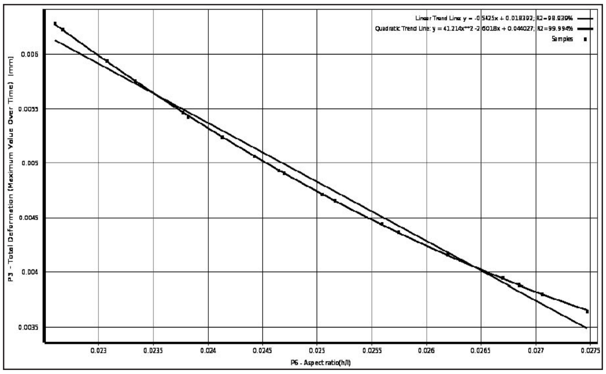

Fig. 3. Correlation scatter of maximum total deformation.

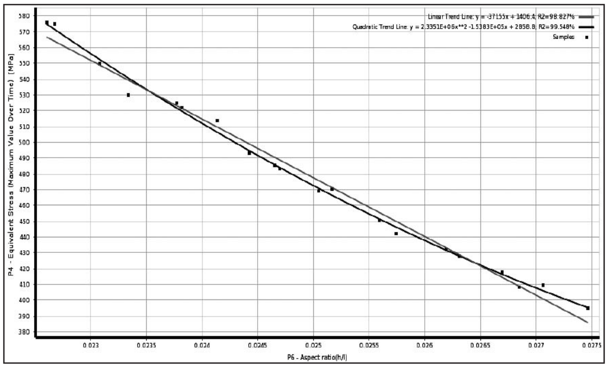

Fig. 4. Correlation scatter of equivalent stress.

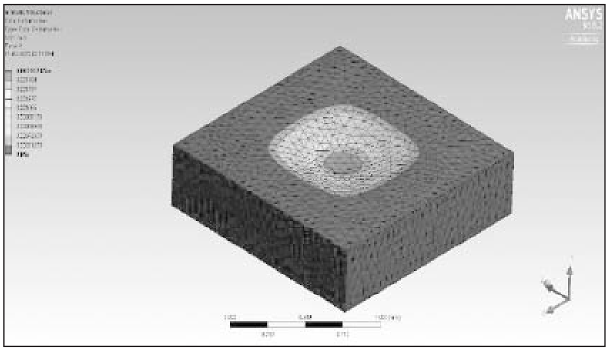

Fig. 5. Contour plot of Max. total deformation.

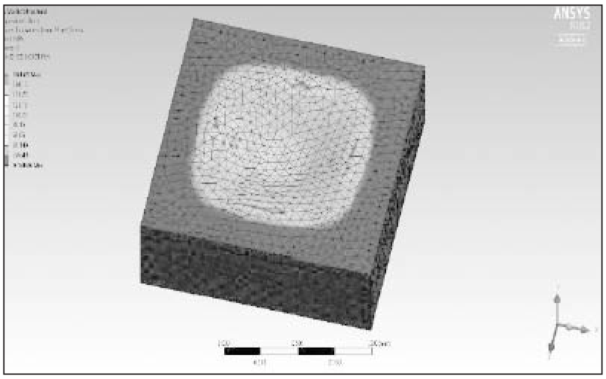

Fig. 6. Contour plot of von mises stress.

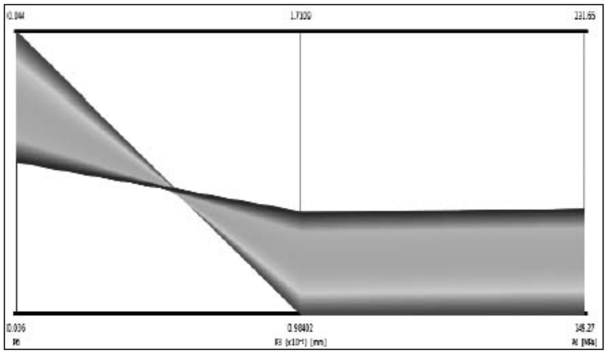

Fig.7. The response of sample points after optimization.

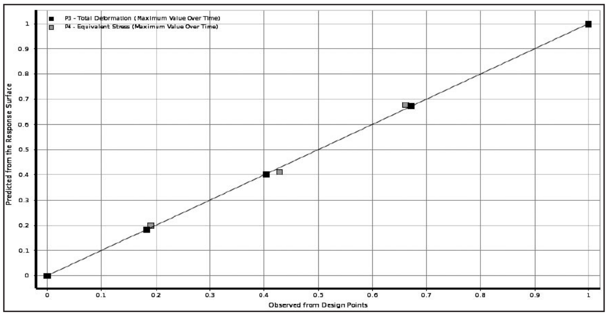

Fig. 8. The goodness of fit for predicted from response surface vs. observed from design points.

and maximum total deformation. The aspect ratio considered as an objective variable, and deformation & Von-Mises stress as a constraint variable.

5. Result and Analysis

In this work, a MEMS- based piezoresistive pressure sensor was designed with 3D modeling and mapped grid meshing using Ansys software. Structural analysis is carried out for calculating deformation and Von-Mises stress (refer to Fig.5 & Fig.6), and results validated with the goodness of fit (Fig.8). The design points for the design of experiments (DOE) have been considered for parametric optimization (Fig.3 & Fig.4). The optimized aspect ratio is found in fig.7, and points are summarized in table 3.

The DOE has considered random points for scattering as per instruction of a given range of the sample points. Table 3 shows the optimized candidate points in terms of aspect ratio, which gives the best aspect ratio (h/l) in terms of Von-Mises stress and deformation.

The response of optimized sample points is represented through this plot (Fig.7). The extremes of this response show the upper and lower bound of objective and constraint variables.

Table 3
Optimized candidate points.

	Candidate Point-1	**Candidate Point-2**	**Candidate Point-3**
Aspect ratio (h/l)	0.040356	0.040724	0.041092
Total Deformation at center (micron)	1.2469	1.2164	1.1869
Max. Von-Mises stress (MPA)	179.94	176.64	173.41

6. Conclusion

This paper focused on parametric optimization and design techniques for the piezoresistive pressure sensor chip. The parameters of the pressure sensor chip membrane were selected for optimization by the analytical equation of the membrane. This work has modeled and optimized a MEMS sensor chip in order to enhance the sensitivities and linearity with the help of the best aspect ratio. Based on the results obtained, the aspect ratio of 0.04 is found to be the best in terms of maximum deformation within the elastic limit. The validation of this work is done by using the goodness of fit.

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