The structure design of piezoresistive pressure sensor based on MEMS

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Abstract. This paper mainly designed the basic structure of the piezoresistive pressure sensor based on MEMS, analysed and optimized the structure size of the sensor, verified the rationality of the structure by finite element modelling. Through theoretical and optimization analysis, the main structural parameters of MEMS are determined.

1. Introduction

Microelectronics mechanical technology (MEMS) is the core of the micromechanical manufacturing technology. With this technology, various structures with dimensions in the um range can be manufactured. Study of MEMS sensor technology began in the 1960s. Honeywell Research Center and The Bell Laboratory designed the first silicon diaphragm pressure sensor and strain gauge [1]. The piezoresistive pressure sensor is one of the most widely used and most influential electronic devices in MEMS sensors. It is made by using the piezoresistive effect of semiconductor materials. It uses resistance to convert external pressure values into electrical signals, which has the advantages of high sensitivity, high measurement accuracy, fast dynamic response, small size, high accuracy, convenient use, and convenient mass production. It is widely used in the fields of biomedicine, aerospace control, and industrial test with good development prospects [2, 3].

China's research on MEMS technology began in the late 1980s. After more than 30 years of continuous efforts and development, although the technological level is relatively backward compared with foreign advanced technologies, it has also achieved certain results. The micro-silicon piezoresistive pressure sensor developed by the former Ministry of Machinery Industry 625 in China is used for automatic data acquisition and processing system for wind tunnel testing. The external size is 35um×72um, weight is 60g, and the accuracy can reach 0.2%-0.5% FS. Beijing University of Aeronautics and Astronautics has developed a probe for engine stall piezoresistive sensor stall detection, which has achieved good results in use [4]. This paper mainly analyses the working principle pressure sensor. At the same time, it verifies the rationality of the structural design by using the finite element analysis to ensure the normal operation of the sensor.

2. Working Principle

The piezoresistive pressure sensors use MEMS manufacturing processes such as lithography, mask, doping, and diffusion to make resistors, and uses a diffusion method or a precipitation method to make resistors on an elastic film to form the force-sensitive resistance. The four resistors are connected into
rings to form the Wheatstone bridge. Four resistors are connected in a loop to form a Wheatstone bridge. Based on the piezoresistive effect of semiconductor materials, different loads are applied to the elastic film to change the resistance value. The Wheatstone bridge is used to convert the resistance value change into a voltage signal output [5] so that the pressure measurement can be realized. Figure 1. Shows the schematic diagram of the piezoresistive pressure sensor.

![Schematic diagram of piezoresistive pressure sensor](image)

**Figure 1.** Schematic diagram of piezoresistive pressure sensor

Figure 2. Shows the Wheatstone bridge sensor sketch. Figure 3. (a) Shows the Wheatstone bridge composed of four resistances output voltage is 0 without the effect of pressure. Figure 3. (b) Shows that when the sensor is subjected to a certain pressure, the elastic diaphragm deforms. According to the piezoresistive effect of the semiconductor material, the four resistance values on the surface of the elastic diaphragm change. The output voltage difference $V_{out}$ of the Wheatstone bridge structure is: Where, $R_1$ and $R_3$ are under the compressive stress, and the resistance value changes by $\Delta R$; $R_2$ and $R_4$ are under tensile stress, and the resistance value changes are also $\Delta R$, and the resistance value becomes large, and the Wheatstone bridge structure generates output voltage $V_{out1}$ and $V_{out2}$ [5]. The output voltage difference of the Wheatstone bridge structure is:

![Wheatstone bridge diagram of the sensor](image)

**Figure 2.** Wheatstone bridge diagram of the sensor
Figure 3. Schematic diagram of the working principle of the pressure sensor

Calculated results:

\[
V_{\text{out}} = V_{\text{out}2} - V_{\text{out}1} = \frac{(R_1 - \Delta R)(R_3 - \Delta R) - (R_2 + \Delta R)(R_4 + \Delta R)}{(R_1 - \Delta R + R_2 + \Delta R)(R_3 - \Delta R + R_4 + \Delta R)} \cdot V_{DD} = \frac{\Delta R}{R} \cdot V_{DD} \tag{1}
\]

Formula (1) shows that the output voltage difference of the Wheatstone bridge structure \( V_{\text{out}} \) is proportional to the rate of resistance value change \( \frac{\Delta R}{R} \) when the constant voltage source is used for power supply. The change rate of the resistance value of monocrystalline silicon resistance is determined by the following equation [6]:

\[
\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{2}
\]

In the formula, \( \pi_l \) and \( \pi_t \) are respectively the longitudinal piezoresistive coefficient and the transverse piezoresistive coefficient of silicon, which are related to the crystal direction. \( \sigma_l \) and \( \sigma_t \) are the longitudinal and transverse stresses of the resistance along the crystal axis. Thus, in the case of the selected crystal direction, the output voltage difference of the Wheatstone bridge structure is proportional to the stress on the resistance.

3. Structure design of MEMS piezoresistive pressure sensor

3.1. Elastic diaphragm shape design

In the structure of a piezoresistive pressure sensor, an elastic film is one of the most important components, which is closely related to the sensor's sensitivity and nonlinearity. Therefore, the selection
of appropriate elastic diaphragm and the determination of reasonable diaphragm size parameters are the prerequisites to ensure the normal operation of the sensor.

The theoretical results show that when the external pressure acts on the elastic diaphragm, the greater the stress, the higher the sensor sensitivity and the better the performance. With the same chip size, packaging conditions, and applied load, the maximum stress on a square diaphragm is 1.64 times that of a circular diaphragm [7]. As far as the process is concerned, the silicon cup is prepared by dry etching, and the square film is simpler than the circular film. If the silicon cup is prepared by wet etching, it is difficult to obtain a circle due to the anisotropy of wet etching shaped silicon cup. And the smaller the cavity, the closer to the square. Therefore, the shape of the elastic diaphragm selected in this paper is square. At present, domestically, the side length of the diaphragm of a MEMS piezoresistive pressure sensor is usually 500-2000um, and the side length of the square membrane selected in this paper is 1000um.

3.2. Elastic film thickness calculation

The thickness of the elastic film can directly affect the performance and life of the sensor. When the thickness of the diaphragm is too small, it can cause the sensor to have low anti-overload capability and increase non-linearity. When the diaphragm thickness is too thick, the sensitivity of the sensor will be greatly reduced. The thickness of the elastic film is determined through the stress analysis of the elastic film, two conditions need to be considered:

1. Linear principle:
   To achieve a good linear output of the sensor, it is necessary to ensure a good linear relationship between the stress and pressure of the elastic diaphragm. According to the theory of small deflection, the maximum deformation of the elastic diaphragm of the sensor must be less than 20% of the film thickness [8]. The maximum deformation is located at the center of the elastic diaphragm:

   \[ W_{max} = 0.01518 \frac{PA(1-\nu^2)}{EH^2} \leq 20%H \]

   In the formula, the sensor range P is 2MPa, half of the edge length of the elastic diaphragm A is 500um, Poisson's ratio \( \nu \) is 0.3, and the elastic modulus of silicon E is 190GPa. The thickness of the elastic diaphragm is obtained, \( H \geq 28.9um \).

2. Overload resistance
   To ensure that the sensor has a certain overload resistance when the elastic film is subjected to a certain pressure, its stress difference should be less than 20% of the silicon failure stress. As shown in figure 4, the pressure difference distribution diagram is drawn according to the functional relationship.

![Pressure difference distribution](image)

**Figure 4. Pressure difference distribution**
As can be seen from the figure 4, the maximum stress difference lies in the middle of the diaphragm edge:

$$\left| \sigma_x - \sigma_y \right|_{max} = 1.23P \left( \frac{2A}{H^2} \right)^2 (1-v^2) \leq 0.2\sigma_m$$

(4)

The failure stress of silicon $\sigma_m$ in the formula is $4.5 \times 10^8$ N/m², substitute $H \geq 16.12\mu m$.

Based on the above factors, under the premise that the sensor can work normally, with the edge length of the elastic film at 1000um, the thickness $H$ is set as 30um.

3.3. Structural design of silicon cup

The silicon cup is the framework of the piezoresistive pressure sensor. In this paper, n-type silicon [100] wafer is selected as the substrate material. In the wet corrosion process, its size is mainly determined by the anisotropic corrosion process parameters. Figure 5. is a schematic diagram of the structure after wet etching.

![Figure 5. Schematic diagram of the structure after wet etching](image)

The calculation formula of square etching window is as follows:

$$b = a - \frac{2(H-h)}{\alpha \sin \theta} + \frac{2(H-h)}{\tan \theta} ; \alpha = \frac{R}{R(100)}$$

(5)

In the formula, $b$ is the side length of the window on the mask, $a$ is the side length of the elastic thin film, $H$ is 400um, as the thickness of the silicon wafer, $h$ is elastic film thickness, $\alpha$ is the corrosion rate ratio of the [100] plane and the [111] plane in the KOH etching solution, which is related to the type of the etching solution and the etching conditions, and is about 400. $\theta$ is 54.74°, which is the angle between the [100] plane and the [111] plane, calculated $b$ is 1480um.

4. Resistance design of MEMS piezoresistive pressure sensor

4.1. Resistance position design

To maximize the use of the piezoresistive effect and to minimize the influence of the negative piezoresistive effect on the sensor output, as shown in figure 6., the article design places the resistor strips at the edge of the film, a pair parallel to the edge of the elastic diaphragm and a pair perpendicular to the edge of the elastic diaphragm so that the Wheatstone bridge output is maximized.
4.2. Resistance bar size design

In order to avoid the influence of high temperature on the normal operation of MEMS piezoresistive pressure sensor, the maximum power consumption per unit area of the piezoresistive strip $P_{\text{max}}$ should be controlled as $5 \times 10^{-3} \text{ mw/um}^2$, the actual power consumption per unit area is [9]:

$$P = \frac{I^2 R}{bL} = \frac{I^2 R_s L}{bL} = \frac{I^2 R_s}{b^2}$$ (6)

$R_s$ is the block resistance value, $I$ is the bridge arm current, and $b$ is the width of the piezoresistive bar. The relation between the resistance value of the piezoresistive bar and dimension is:

$$R = R_s \left( \frac{L_1}{b_1} + \frac{L_2}{b_2} + 2K_1 + nK_2 \right)$$ (7)

$K_1$ is the end factor, $K_1 = 0.35 \sim 0.65$, $K_2$ is the corner factor, $K_2 = 0.5$, $n$ is the number of corners. Due to process limitations, the square resistance of the piezoresistive bar is $180 \Omega$, and the width $b$ of the piezoresistive bar is $10\mu m$. The design of the piezoresistive bar is two sections. Because the width-length ratio of the place where the piezoresistive bar is connected in the middle is 1, the resistance value is negligible. The piezoresistive bar resistance is $5K\Omega$, the piezoresistive bar length is $200\mu m$, and each section is $100\mu m$.

4.3. Determination of doping concentration

Because the resistance bar is a P-type resistor formed by the diffusion method, the doping concentration has a greater effect on the piezoresistance coefficient. When the doping concentration is about $10^{-15} \text{ cm}^3$, the piezoresistive coefficient of monocrystalline silicon varies very little with the doping concentration, when the doping concentration is increased, the piezoresistive coefficient decreases with the increase of the doping concentration, when the doping concentration is larger than $10^{20} \text{ cm}^3$, the piezoresistive coefficient decreases rapidly [10]. Therefore, the doping concentration should be reasonably selected. In this paper, the doping concentration is selected as.

Based on the above calculation, the main parameters of the sensor are shown in Table 1.
Table 1. Main parameters of the sensor

| Name of parameter         | Numerical value        |
|---------------------------|------------------------|
| Sensor size               | 2000×2000 um           |
| Elastic thin film side length | 1000 um               |
| Elastic diaphragm thickness | 30um                  |
| Length of resistance      | 200um                  |
| Resistance width          | 10um                   |
| Value of resistance       | 5kΩ                    |
| Sensor range              | 2MPa                   |

5. Structural simulation of MEMS piezoresistive pressure sensor

5.1. Pressure sensor simulation model construction
Because only the corresponding performance simulation is performed on the thin film of the sensor structure, the model established is the thin film structure of the pressure sensor. The paper first constructs the structural model through Pro Engineer 3.0 and then imports the structural model into ANSYS Workbench software. The material parameters used are shown in Table 2.

Table 2. Material parameters of pressure sensor simulation model

| Model parameter                          | Numerical value        |
|------------------------------------------|------------------------|
| Silicon substrate density (kg/m\(^2\))    | 2330                   |
| Young modulus (Pa)                       | 1.3E11                 |
| Poisson's ratio                          | 0.278                  |
| Silicon membrane size (μm\(^3\))         | 1000×1000×30           |

In the mechanical environment, multi-region meshing is adopted, and the minimum cell size is set to 25um. Figure 7. Shows a schematic diagram of the mesh structure division.

5.2. Static analysis of pressure sensor
Static analysis is used to analyze the effect of fixed loads on the structure and time-varying loads that can be approximated as equivalent static forces. To simplify the analysis, the restraint is fixed by applying a displacement constraint to make it closer to the actual device structure. Figure 8. Shows the stress distribution on the elastic diaphragm of the pressure sensor.

Figure 7. Schematic diagram of grid structure division
It can be seen from figure 9. That the maximum stress value is at the edge of the elastic film. To improve the sensitivity of the pressure sensor, the piezoresistive strip needs to be placed in the area with the highest stress, that is, it needs to be placed at the edge of the elastic film, which is in line with the calculation of the theoretical model. As a result, the accuracy of the theoretical calculation was further verified.

The ANSYS finite element simulation software is used to simulate and analyze the film deflection of the piezoresistive pressure sensor designed in this paper, as shown in figure 9. The figure shows the deformation of the entire elastic film. Under uniform pressure load, the elastic film the maximum deflection is located in the geometric center area of the silicon film and gradually decreases along the sides of the silicon film, which verifies the correctness of the theoretical model.
6. Conclusion
In this paper, a square silicon film structure of the MEMS piezoresistive pressure sensor is designed. The side length of the square film is 1000um and the thickness is 30um. The varistors are placed at the edge of the elastic film. The resistance bar composed of two sections. The length of the resistance bar is 200um, each section is 100um and the width is 10um. It ensures that the Wheatstone bridge output is maximal. At the same time, the doping concentration of the resistance bar is reasonably selected from $10^{-10}$ cm$^3$. From the theoretical analysis to simulation, the correctness of the scheme is verified. Under the premise of ensuring the normal operation of the sensor, the sensitivity and anti-overload ability of the pressure sensor are improved as much as possible, and the influence of temperature on the performance of the sensor is reduced. This research has certain guiding significance and reference value for the sensor chip structure design.

7. Author Contributions
Resources, writing—original draft preparation, methodology, data curation, Zhou Yongjun and Han Wenman contributed equally to this article.

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References
[1] Nie M, Gao Y. The Analytical Calibration Model of Temperature Effects on a Silicon Piezoresistive Pressure Sensor [J]. AIP Advances, 2017 (7): 0351201 - 7.
[2] Rochus V, Wang B, Tilmans H A C, et al. Fast Analytical Design of MEMS Capacitive Pressure Sensors with Sealed Cavities [J]. Mechatronics, 2016 (40): 244 - 250.
[3] Singh K, Joyce R, Akhtar J. Fabrication of Electron Beam Physical Vapor Deposited Polysilicon Piezoresistive MEMS Pressure Sensor [J]. Sensors and Actuators A: Physical, 2015 (223): 151 - 158.
[4] Niu Songjie. Research on piezoresistive pressure sensor technology of MEMS: [master's thesis]. Jiangsu: soochow university, 2016.
[5] Zhao, X. F., Li, D. D., Yu, Y., et al. Temperature characteristics research of SOI pressure sensor based on asymmetric base region transistor [J]. Journal of Semiconductor, 2017, 38 (7): 89—92.
[6] Y Kanda. A graphical representation of the piezoresistance coefficients in silicon [J]. IEEE Transactions on Electron Devices, 1982, 29 (1): 64 – 70.
[7] Yozo Kanda, Akio Yasukawa.Optimum design considerations for silicon piezoresistive pressure sensors,sensors and actuators, 1997, A62: 539 - 542.
[8] A. AlvinBarlian, WooTaePark, JosephR. Mallon, Jr, AliJ. Rastegar, BethL. Pruitt.Review: SemiconductorPiezoresistance for Microsystems [J], Proceedings of the IEEE Institute of Electrical & Electronics Engineers, 2009, 97 (3): 513.
[9] Yi Xuanqiang, Yuan Weizheng, Ma Binghe. design of sensitive structures for piezoresistive micro-pressure sensors journal of northwest polytechnical university, 2008.12, 26 (6): 782 – 786.
[10] GUO S W, TIAN X D, WANG W. Temperature characteristics of microcrystalline and polycrystalline silicon pressure sensor [J]. Sensors and Actuators A: Physical, 1990, 21 (1): 133 - 136.