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# Design of Piezoresistive MEMS Pressure Sensor Chip for Special Environments

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**Abstract:** To meet the pressure sensors used in special harsh environments, the MEMS piezoresistive pressure sensor design is proposed that the technology is more mature and more extensive used. The research of Piezoresistive sensor chip is done based on the analysis of sensor principle. The chip substrate material is selected combine with the special environment. The range sensor chip design is done based on small deflection theory and silicon material diaphragm piezoresistive effect theory. In order to avoid resonance modal analysis of the diaphragm is done. The force-sensitive resistor strip and its layout in the diaphragm is designed combine with the round diaphragm stress distribution. Semi-open-loop mode bridge is choice based on the comparison of advantages and disadvantages of three bridge modes. Given the special environment of vibration, acceleration sensitivity calculations must be done to adapt vibration environments for pressure sensor. Theory basis in sensor design is full, design projects and parameters combine with special environmental closely, and the research will have important significance for further study of special environmental pressure sensor. *Copyright © 2014 IFSA Publishing, S. L.*

**Keywords:** Special environment, Piezoresistive, MEMS, Pressure sensor, Force-sensitive resistor strip, Diaphragm.

## 1. Introduction

Piezoresistive pressure sensor has some advantages such as small size, fast response, simple structure, the output voltage signal is easy handle, the technology of piezoresistive pressure sensor is more mature, sensor products are reliable, and the research of piezoresistive pressure sensor is more than others [1-3]. So special pressure sensors for harsh environments generally are used piezoresistive design. The design of special piezoresistive MEMS pressure sensor uses small deflection theory, the piezoresistive effect theory, and finite element theory combined with the special environmental requirement.

## 2. Principle of Piezoresistive Pressure Sensor

When a force acts on the single crystal silicon, the resistivity of the single crystal silicon will be significant changed. The diffusion method of manufacturing a force-sensitive resistor strip on the silicon wafer can make the piezoresistive pressure sensor. The P-type silicon impurity is diffused into the N-type silicon to form four force-sensitive resistor strips which connect with each other to constitute a Wheatstone bridge on the diaphragm. The bridge will be imbalance when the pressure is taken onto diaphragm and the output voltage signal will be changed proportional to the pressure [4]. Sensor principle of piezoresistive pressure sensor is shown as Fig. 1.

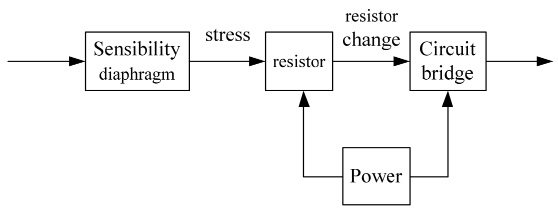



**Fig. 1.** Sensor principle of piezoresistive pressure sensor.

Design four force-sensitive resistor strips on the substrate diaphragm form Wheatstone full bridge detection circuit shown as Fig. 2. Suppose the resistance of four force-sensitive resistor strips of the bridge arm is equal, R1 = R2 = R3 = R4 = R, when there is no pressure, the bridge output voltage Vout=0. When the pressure acting on the sensitive diaphragm, the resistance will be change, so that the bridge out of balance, wherein R1, R3 are reduced ΔR, R2, R4 are increased ΔR. The output voltage of bridge is Vout=ΔR•I, when the power is current source I, wherein ΔR is proportional to the pressure. The pressure can be detected through the measurement of the change of the output voltage of the bridge.

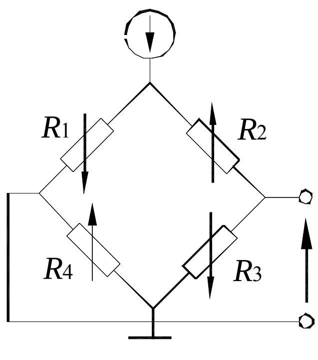



**Fig. 2.** Wheatstone full bridge circuit.

## 3. Design of Sensor Chip

### 3.1. Substrate Choice

The material of silicon does not appear plastic deformation or creep when the temperature below 500 °C, so silicon material sensor is not prone to fatigue failure. Silicon sensors are no fatigue after loading 100 million times as the test shown [5]. The reason of the material of silicon not prone to fatigue failure is the process of grain or slip dislocations does not appear, from the analysis of the physical principle.

Under certain conditions of temperature, the piezoresistive coefficient of P-type Si is bigger than N-type Si, and the sensitivity is higher, further, the linear of resistance change with the pressure and temperature characteristics of P-type Si are better than the N-type Si, so, N-type silicon is selected as substrate.

Different orientation of silicon has different piezoresistive coefficient. The larger piezoresistive coefficient, the greater change of resistance at the same pressure, the greater output of the pressure sensor, and the more sensitive of the sensor. So, designating orientation of silicon is the first step to choice silicon die. The cross section of cracking or breaking of the [110] orientation silicon are order than other orientation silicon. So a 4-inch (100) silicon die is selected as substrate, the thickness of silicon die is 500 μm. The density of (100) orientation silicon is $\rho$ =2.32×103 kg/m$^3$, the elastic modulus is E = 129.5 GPa, Poisson's ratio is $\mu$ = 0.22, the elastic limit is $\sigma_e$ = 8 × 107 Pa.

### 3.2. Range Design

The active research diaphragm structure of MEMS pressure sensor is island structure. But the structure reduces the sensitivity of the sensor to improve the linearity of the sensor output. So the island structure diaphragms enhance sensitivity of the output by increasing the size of the diaphragm usually, but also increase the size of the sensor. Further, the quality of the part of island structure cannot be ignored compared to the diaphragm. When the sensor is subjected to impact or vibration, the interference signal generated by the acceleration of the island mass can affect the pressure output signal, so the island structure of the pressure sensor is not suitable for special harsh environment applications. So the circular diaphragm is designed for special pressure sensor used in harsh environment. Two assumptions must be used in the design calculations, the first is the maximum deflection of the diaphragm no greater than 1/5 of the thickness, so the small deflection theory can be used to calculate, and the second is that the pressure is evenly applied to the diaphragm.

Under the two assumptions, the deflection of the diaphragm can be obtained with the small deflection theory the following equation:

$$y = \frac{3p(1-\mu^2)}{16Eh^3}(R^2 - r^2)^2, \quad (1)$$

The center deflection is shown as equation (2):

$$y_{\max} = \frac{3p(1-\mu^2)R^4}{16Eh^3}, \quad (2)$$

The lowest level natural frequency of vibration of the diaphragm is shown as equation (3).

$$f_0 = \frac{10.17h}{2\pi R^2}\sqrt{\frac{E}{12(1-\mu^2)\rho}}, \quad (3)$$

where $p$ is the uniform pressure (Pa), $h$ is the diaphragm thickness (cm), $R$ is the diaphragm radius (cm), $r$ is the radius of any part of the diaphragm (cm), $\mu$ is the Poisson's ratio of the material of the diaphragm, $E$ is the elastic modulus of the material of the diaphragm (Pa), $\rho$ is the density of the material of the diaphragm (kg/cm$^3$).

It can be seen that from equation (2), the smaller the diaphragm thickness and the greater the radius, the higher the sensitivity of the sensor, and it can be seen that from equation (3), the greater the diaphragm thickness and the smaller the radius, the higher the natural frequency. Therefore, it is necessary to consider the sensitivity and the natural frequencies of the diaphragm, and also consider the sensor size requirements and processing technology level in the design. As the smaller diaphragm radius will affect the sensitivity of the sensor, the diaphragm radius of the sensor is designed as 2 mm according to the range and experience.

In order to ensure linearity and overload protection of force-sensitive resistor strip, make the absolute value of the maximum strain of piezoresistive diaphragm not more than 500 micro-strains usually as equation (4). The corresponding maximum stress is much smaller than the allowable stress, so there is no need to consider the allowable stress of the diaphragm itself.

$$\max\left(\varepsilon_r, \varepsilon_\theta\right) \le 500\mu\varepsilon = 500\times10^{-6},$$

$$\varepsilon_r = \frac{3p(1-\mu^2)}{8Eh^2}(R^2-3r^2) \le 500\mu\varepsilon = 500\times10^{-6},$$

$$p \le \frac{4Eh^2\times10^{-3}}{3\left|\left(1-\mu^2\right)\left(R^2-3r^2\right)\right|}, \quad (4)$$

To meet the small deflection theory equation (5) must be build.

$$\frac{h}{2R} \le 0.2, \quad (5)$$

Simultaneous equation (4) and (5) can calculate the maximum pressure which the diaphragm can withstand and center deflection of the diaphragm with different thickness of the diaphragm shown as Table 1. The center deflection is calculated by finite element simulation software to verify the results shown as Fig. 3.

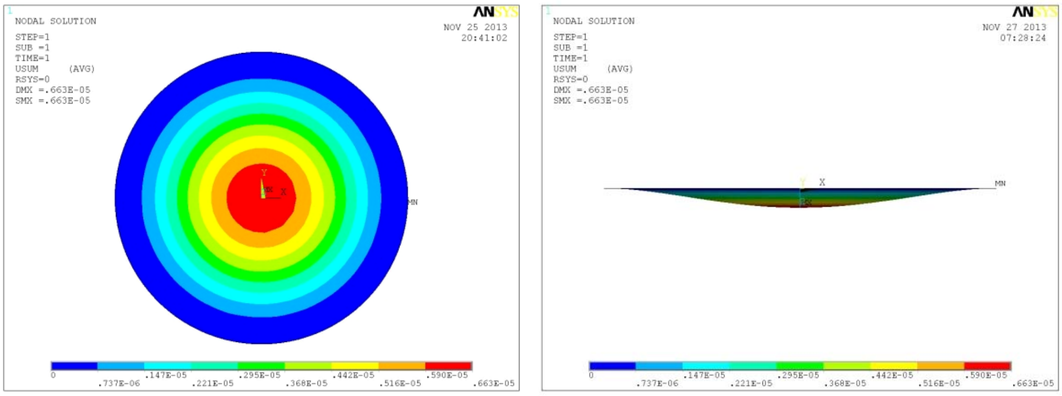
**Table 1.** Calculate results of different thickness of the diaphragm.

| **Thickness of the diaphragm (mm)** | **Maximum pressure (MPa)** | **Center deflection ($\mu m$)** | **Simulation result of center deflection ($\mu m$)** |
|---|---|---|---|
| 0.1 | 0.301 | 6.635 | 6.632 |
| 0.2 | 1.206 | 3.317 | 3.322 |
| 0.3 | 2.713 | 2.211 | 2.214 |
| 0.4 | 4.523 | 1.555 | 1.557 |

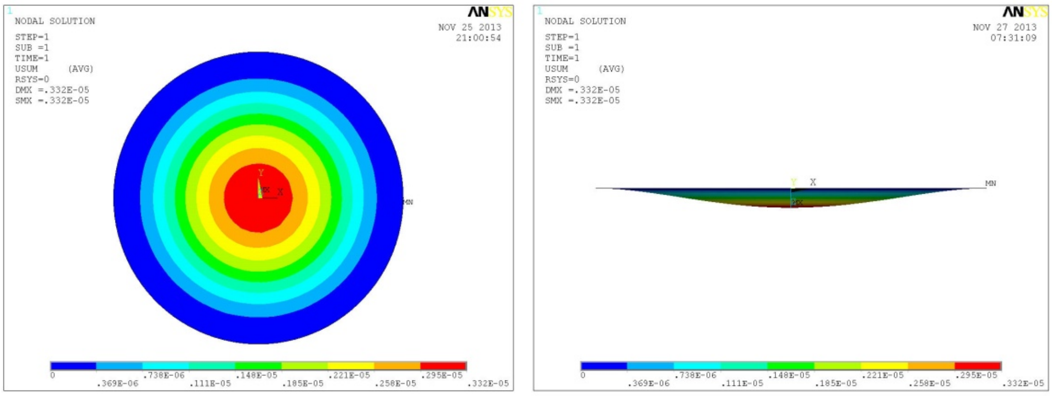
From above calculation can obtained the result that 0.2 mm thickness of the diaphragm is suitable for 1.0 MPa range sensor, and the 0.3 mm thickness of the diaphragm is suitable for 2.0 MPa range sensor.

### 3.3. Modal Analysis of Diaphragm

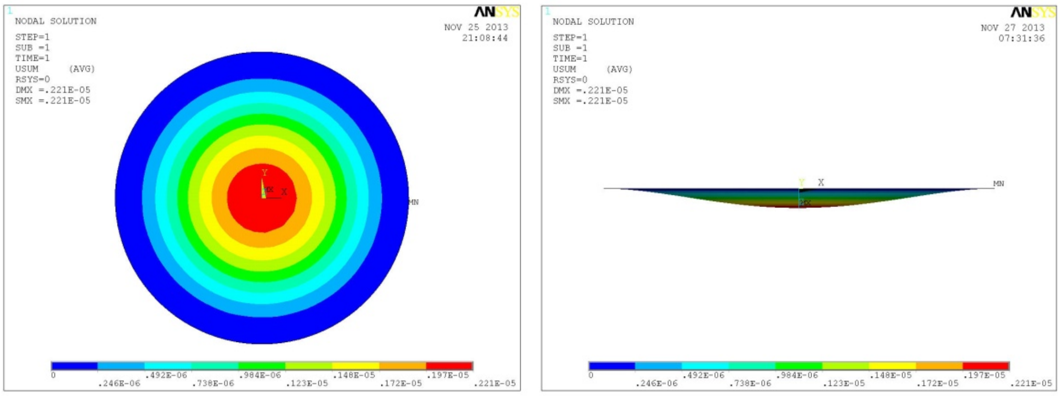
The natural frequency is 0.267 MHz which be calculated according to equation (3). The natural frequencies and mode shapes of the diaphragm can be calculated by the software of ANSYS [8] and the simulation results shown as Fig. 4. From the result of first-order mode shape it is can be seen that the diaphragm move to the perpendicular direction of the diaphragm and its first order natural frequency is 0.256 MHz. From the result of second-order mode shape it is can be seen that the diaphragm individual move to the two perpendicular directions of the diaphragm and its second order natural frequency is 0.511 MHz. From the result of third-order mode shape it is can be seen that the two side of diaphragm individual move to the two different perpendicular directions of the diaphragm and its third order natural frequency is 0.512 MHz. From the result of forth-order mode shape it is can be seen that both the two side of diaphragm move to the two different perpendicular directions of the diaphragm and its forth order natural frequency is 0.802 MHz. According to the results of modal analysis, including natural frequencies and mode shapes, the dynamic performance of the diaphragm can be evaluated. The results have guiding significance for the design of the operating frequency. The operating frequency should be required away from each modal frequencies, specifically the operating frequency does not fall in each modal half-power bandwidth.



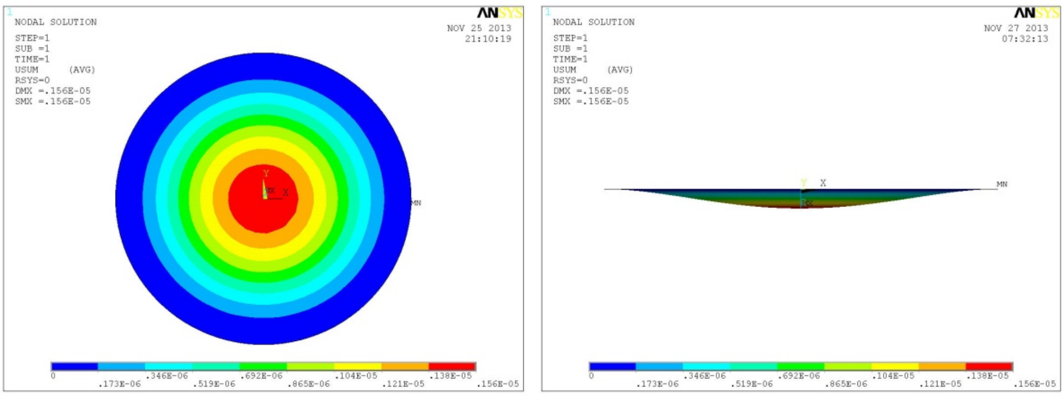

h=0.1 mm




h=0.2 mm

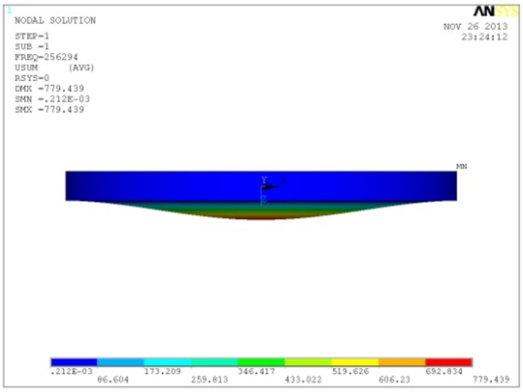



h=0.3 mm

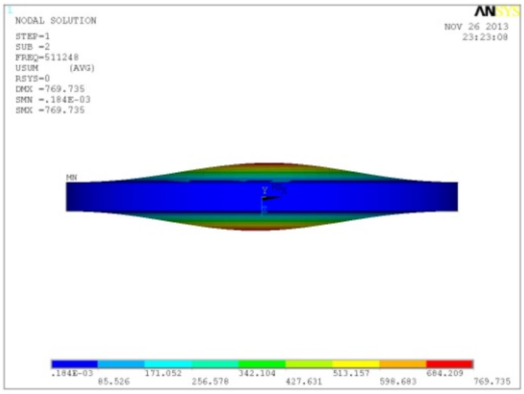



h=0.4 mm

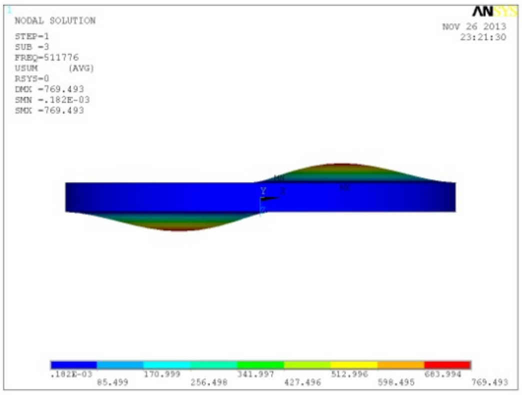
**Fig. 3.** Strain cloud of the diaphragm with different thickness.



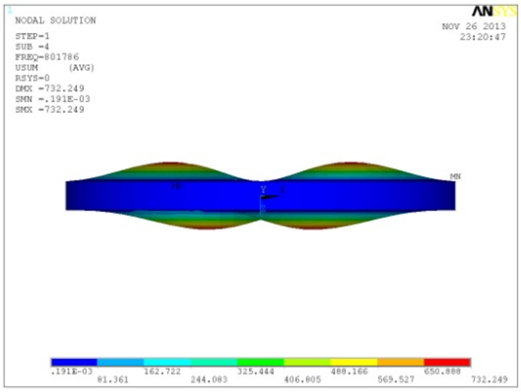
(a) first-order mode



(b) second-order mode



(c) third-order mode



(d) forth-order mode

**Fig. 4.** Diaphragm modes.

### 3.4. Design and Layout of Force-sensitive Resistor Strip

Although SOI technology can be used for sensitive diaphragm to adapt the application of high temperature environment, but in the case of the force-sensitive resistor strip is electrified the force-sensitive resistor strip also powered heat itself, and the heat temperature will cause the sensor temperature drift, therefore, in order to reduce the self-heating of force-sensitive resistor strip, the bridge arm current should not too large [9]. If a 3 V supply is used, the bridge arm resistance should be greater than 1 kΩ.

In order to reduce the heat from the force-sensitive resistor strip itself, the power per unit area must be controlled below $P_{\max} = 5\times10^{-3}\,\mathrm{mW}/\mu\mathrm{m}^2$. The equation of power per unit area is shown as equation (6).

$$P = \frac{I^2 R}{LW} = \frac{I^2 \rho_D L}{W\delta LW} = \frac{I^2 R_S}{W^2}, \qquad (6)$$

where L, W, $\delta$ apart are the length, width and thickness of the force-sensitive resistor strip, $R_S$ is the sheet resistance which ally doping content.

Combined with design calculation of the force-sensitive resistor strip, and considering the current technology level of production process, the width of the force-sensitive resistor strip is selected generally 10 to 20 μm. If the width of force-sensitive resistor strip is too wide, the length of the force-sensitive resistor strip will be too long to achieve the same value of resistance, it will be negative for layout design and doping uniformity. If the width of force-sensitive resistor strip is too narrow the value error of resistance is too large, so the zero output of bridge increases. It is necessary to take full advantage of the area of maximum stress to adapt the sensor with high sensitivity. So the force-sensitive resistor strips structure using the 3 fold structure, and widening the corner to suppress the negative resistance phenomenon [10]. The designed force-sensitive resistor strip width is 12.5 μm, the pitch is 15 μm, the effective length is 750 μm, and the thickness is 1.35 μm, shown as Fig. 5.

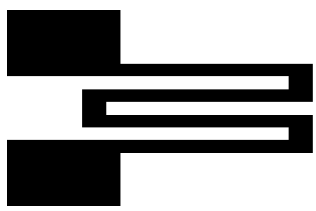


**Fig. 5.** Single force-sensitive resistor strip.

The larger the piezoresistive coefficient, the greater change the resistance, at the same stress, and the pressure sensor is more sensitive. Therefore, the layout of the force-sensitive resistor strips must rational use the piezoresistive coefficient in order to get good results. Fig. 6 is the curve of piezoresistive coefficient of a (100) crystal plane. It is can be seen that from Fig. 6, concerned the (100) crystal plane, $[0\bar{1}1]\perp[011]$ or $[01\bar{1}]\perp[0\bar{1}\bar{1}]$ is the best crystal orientation for sensor. The layout design of (100) plane is shown as Fig. 7.

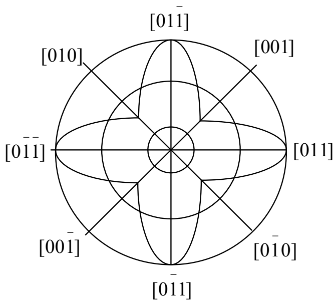



**Fig. 6.** The curve of piezoresistive coefficient of (100) crystal plane.

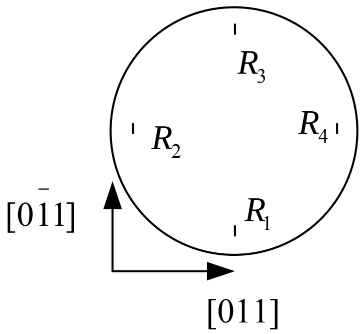



**Fig. 7.** Layout of force-sensitive resistor strips.

Fig. 8 is the X direction stress distribution of the diaphragm which is clamped along its edge and withstands the uniformly distributed loads.

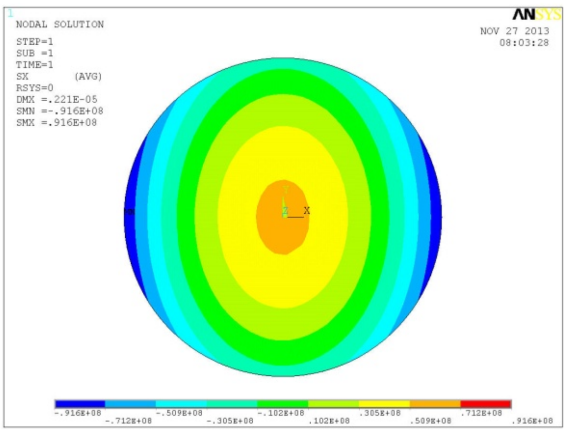



**Fig. 8.** The X direction stress distribution of diaphragm.

The stress of the point along X-axis in Fig. 8 is radial stress and the stress display tangential stress for the point along Y axis. Fig. 9 is drawled though the result of Fig. 8, it denotes the radial stress and the tangential stress distribution of the diaphragm which is clamped along its edge and withstands the uniformly distributed loads. It can be seen from Fig. 9 that it is necessary to layout four force-sensitive resistor strips on the edge of the diaphragm in order to get the maximum output. Resistive layout on the diaphragm is shown as Fig. 10.

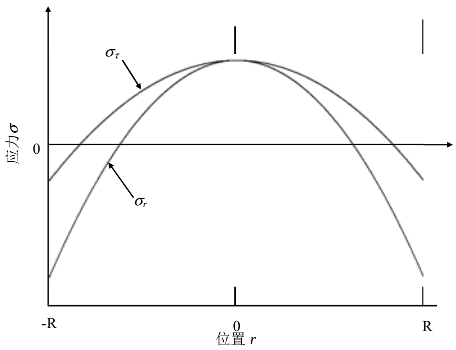



**Fig. 9.** The stress curve of the diaphragm surface.

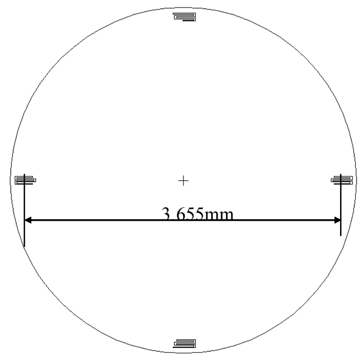
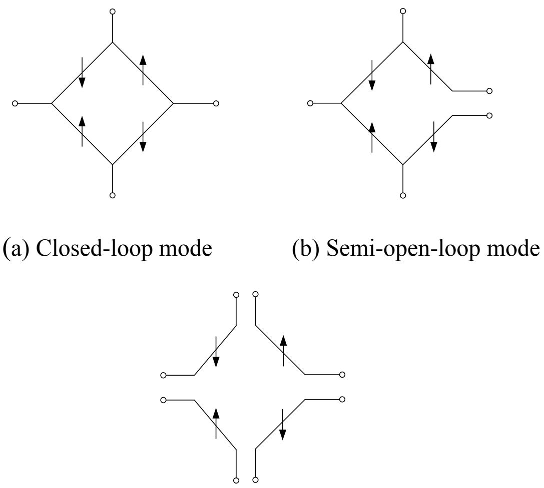



**Fig. 10.** Layout of force-sensitive resistor strips.

## 3.5. Bridge Circuit Design

Depending on the connection of four force-sensitive resistor strips, the bridge can be divided into three modes, closed-loop mode, semi-open-loop mode and open-loop mode. Fig. 11 (a) is the closed loop bridge, the design can reduce leads, but the circuit can only use the parallel resistance bridge arm to adjust the balance of the bridge. And it will be affected from other bridge when measuring resistance with a MultiMate. Fig. 11 (c) is the open loop mode, although it is very convenient to measure the resistance of each arm, and can easily compensate for the sensor, but too much leads will have some difficulty for the packaging process. If the design use the form of semi-open loop mode shown as Fig. 11 (b), although adding one lead, but the balance adjusting can use parallel resistance and series resistance method, and it is convenient to compensate thermal zero drift and sensitivity drift. Semi-open-loop form is chose though considering the lead and compensation issues.



(a) Closed-loop mode (b) Semi-open-loop mode

(c) open-loop mode

**Fig. 11.** Three modes of Wheatstone bridge

### 3.6. Acceleration Sensitivity Calculation

If the sensor response caused by the acceleration is the same to the sensor response caused by the pressure, in this case the ratio of acceleration to pressure is the acceleration sensitivity. Special environment including shock and vibration and other harsh environments, the acceleration response of the pressure sensor will reduce the accuracy of the measurement, so the design of acceleration sensitivity to reduce the acceleration response of the sensor is an effective way to improve the measurement accuracy of the pressure sensor. For a circular diaphragm the acceleration sensitivity as follows [11]

$$\frac{p}{a} = \frac{m}{A} = 0.618\rho h,$$

where *m* is the equivalent mass of the pressure sensor, $A$ is the effective working area of the diaphragm. So it is can be seen that reducing the ratio of quality to area can reduce acceleration sensitivity of the sensor.

## 4. Summarizes

In this paper, the design scheme of the MEMS piezoresistive pressure sensor for special environmental is proposed combined special environmental requirements for pressure sensor. And structural of sensor diaphragm is designed based analysis of the working principle of the sensor, the design comprise substrate selection, range design, modal analysis, force-sensitive resistor strip design and layout, bridge design and acceleration sensitivity calculations. The research has important implications for pressure sensor using in special environmental.

## References

[1]. H. Eriksen, S. Guo, Pressure Sensor, *US Patent* No. 6,928,878, 2004.

[2]. R. Beach, R. P. Strittmatter, T. C. McGill, Semiconductor Nitride Pressure Micro Sensor and Method of Making and Using The same, *US Patent* No. 6,647,796, 2003.

[3]. S. Guo, H. Eriksen, K. Childress, A. Fink, M. Hoffman, High Temperature High Accuracy Piezoresistive Pressure Sensor Based on Smart-Cut SOI, in *Proceedings of 21st IEEE International Conference on Micro Electro Mechanical Systems (MEMS'08)*, Tucson, Arizona, USA, January 13-17, 2008, pp. 892–895.

[4]. C. Shan, Y. Niu, C. Zhang, et al., Sensor Design Basis, *National Defense Industry Press*, Beijing, 2007.

[5]. M. Gad-el-hak, MEMS Design and Fabrication, *China Machine Press*, Beijing, 2010.

[6]. Z. Liu, X. Tan, J. Yang. Research On A Micro Piezoresistive Pressure Sensor, *Machinery Design and Manufacture*, Issue 1, 2012, pp. 103-105.

[7]. Z. Jiang, B. Tian, Y. Zhao, et al., Special Micro-Electro-Mechanical Systems Pressure Sensor, *Journal of Mechanical Engineering*, Vol. 49, Issue 6, 2013, pp. 187-197.

[8]. L. Zhang, Modal Analysis and Experiment, *Tsinghua University Press*, Beijing, 2011.

[9]. X. Yi, W. Yuan, B. Ma, et al., Designing The Sensing Structure of A Certain Micro Piezoresistive Pressure Sensor, *Journal of Northwestern Polytechnical University*, Vol. 26, Issue 6, 2008, pp.782-786.

[10]. H. Shan, Z. Song, X. Wang, et al., Piezoresistive Pressure Sensors for Harsh Environments , *Optics and Precision Engineering*，Vol. 20, Issue 3, 2012, pp. 550-555.

[11]. M. Zhu, Kinetic Pressure Measurement, *National Defense Industry Press*, Beijing, 1983.