Journal of Mechanical Science and Technology 24 (8) (2010) 1655~1660
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0515-0

An ultra-high pressure sensor based on SOI piezoresistive material[†]

Yulong Zhao[*], Xudong Fang, Zhuangde Jiang and Libo Zhao

State Key Laboratory for Mechanical Manufacturing System, Xi'an Jiaotong University, Xi'an 710-049, China

(Manuscript Received October 14, 2009; Revised March 12, 2010; Accepted May 17, 2010)

Abstract

This paper describes an ultra-high pressure sensor which is in urgent need and widely used in defense industry and petroleum industry. It is designed on the combination of micro Silicon on Insulator (SOI) solid piezoresistive chip based on Micro Electro Mechanical Systems (MEMS) technique and cylindrical elastic body that could successfully convert dynamic ultra-high pressure measurement in explosion to strain measurement. Performances of the sensor including size, sensitivity, and linearity are investigated with experiment data. It's proved that the dynamic ultra-high sensor in the range of 2GPa in this paper is successful in pressure measurement in explosion. The research of ultra-high pressure sensor in this paper could not only provide a reference for the improvement of explosive property, but also lay a foundation for research of pressure sensor in the range of 10GPa of the next step.

Keywords: MEMS; Ultra-high pressure; Sensor; Piezoresistive; SOI

---

1. Introduction

The measurement of high pressure is indispensable in many fields for national economy development and defense industry, especially in military production, research and experiment of strategy and tactics weapon. For instance, the applications of pressure measurements such as new materials synthesis in high pressure environment, underground nuclear weapon explosion, safety protection in highway, underwater shock wave measurement and protection in accident collision all call for high pressure sensors. The pressure to be measured in these applications reaches the level of GPa or even higher. Therefore, an ultra-high pressure sensor is not only indispensable for military departments but also has a bright application for civilian use in the future. The sensor should be capable of working in harsh environments such as high pressure and high temperature, and keeping stability and reliability. Moreover, it should meet accuracy requirements in high pressure conditions.

Sensor technologies in China have made great progress in the last twenty years. However, the sensors that are capable of measuring ultra-high pressure up to the level of GPa are very rare. Besides, most of the existent sensors that are being used are piezoelectric with a high output resistance, which must be combined with a charge amplifier for its output quantity of electricity. Simultaneously, piezoelectric crystal can only measure the pressure below its Curie Point with the restriction of piezoelectric effect. To accomplish the task of measuring ultra-high pressure, piezoresistive sensors can be taken into consideration for its character of low output resistance, large output signal, high accuracy and excellent dynamic performance. But piezoresistive sensors are abandoned on occasion because of the material of piezoresistive sensitive element [1].

In this paper, an ultra-high pressure sensor with micro solid piezoresistive chip of SOI technique and cylindrical elastic body is introduced. Its excellent dynamic performance is closely related to eutectic welding technology [2]. The sensor is capable of measuring pressure changes in explosion when explosive column explodes. After several experiments, the sensor shows good dynamic performance, high range, and high-temperature resistance that it can be used for multi times.

2. Design

The ultra-high pressure sensor is designed to meet the need of pressure measurement during explosion. The peak value can be up to 2GPa. Thus, both sensor chip and shell should be designed purposely to satisfy the pressure requirement. Because instantaneous high temperature is generated in the process of explosion, the chip must be instantaneously high temperature resistant. Traditionally, sensor chip will lose accuracy because of the leakage current in high temperature condition. It's likely that the technology of Separation by Implantation of Oxygen (SIMOX) is the best way to overcome the problem of the rising leakage current at high temperature. The silicon-

---

[†] This paper was recommended for publication in revised form by Associate Editor Yong Tae Kim

[*] Corresponding author. Tel.: +86 29 8266 8616, Fax.: +86 29 8339 9505
E-mail address: zhaoyulong@mail.xjtu.edu.cn

oxide layer, which is formed by SIMOX technique, guarantees low leakage currents for high accuracy [2].

In this paper, the sensor chip is produced from a 4 inch (100) orientation SIMOX silicon wafer. However, the thickness of the top silicon and the buried silicon-oxide layer of the wafer are about 0.2um and 0.3~0.4um, respectively. LPCVD is used to increase the thickness of silicon gauge layer to about 1.5 um to satisfy the need of piezoresistivity [3]. The ion of boron is implanted into the top silicon gauge layer, and the purpose doping density of the ion in the device layer is about $1.0\times10^{20}/\text{cm}^3$ to keep sensitivity. LPCVD is also used to extend the thickness of sealed silicon nitride layer to 0.1 um to match the internal strain and protect the silicon gauge layer. The wafer structure of the SOI layer is shown in Fig. 1.

The schematic of pressure sensor chip is shown in Fig. 2. Piezoresistive resistor stripes are arranged at the maximum stress points to improve sensitivity. The Wheatstone bridge in the silicon gauge layer is etched like this in Fig. 2(a). It's made from the surface silicon layer, and its four piezoresistors are respectively along the direction $[110]$ for the piezoresistors R1 and R3, and along the direction $[1\bar{1}0]$ for the piezoresistors R2 and R4. When the chip is compressed along the direction $[1\bar{1}0]$, the piezoresistors of R1 and R3 will increase, while the piezoresistors of R2 and R4 will reduce, and vice versa. The fabricated sensor chip under SEM is shown in Fig. 2(b). The chip is capable of measuring the strain and converting it to voltage with the Wheatstone bridge.

The mechanical structure is designed based on the piezoresistive effect of MEMS sensitive chip, as shown in Fig. 3. It consists of four parts. Part 4 is the outer shell, which is to protect the chip and cylindrical elastic body inside. Simultaneously, the top of part 4 is a circular plate, which is to sense pressure at first. The plate is a part of part 4, which is formed by taking materials out of the structure and it is 5mm thick. Part 1 is the elastic body connected to part 4 with screw thread. Besides, part 2 and part 3 are on the surface of it as shown in Fig. 3. Part 2 is a circuit diagram which is used to compensate for zero drift and drift caused by temperature changes. While part 3 is the sensor chip connected to the elastic body by welding. Meanwhile, it's connected to part 2 with gold wire to output signal precisely. After the accomplishment of assembly of the sensor, the plate will be in intimate contact with part 1, which is called cylindrical elastic body. When pressure is loaded on the plate, it will get elastic deformation and transmit the pressure to elastic body. Then the elastic body will engender compressive deformation. As a result, the compressive strain can be measured by the SOI chip with voltage signal output. In the process, the deformation and stress can be calculated with the following formulas.

In Fig. 4(a), the maximum radial stress locates at the edge of the plate, shown in Eq. (1) [4].

$$(\sigma_{rr})_{\max} = \frac{3W}{4\pi h^2} \tag{1}$$

The maximum circumferential stress locates at the edge of the plate, shown in Eq. (2) [5].

$$\left(\sigma_{\theta\theta}\right)_{\max} = \frac{3\nu W}{8\pi h^2} \tag{2}$$

The stress in the center of the plate is

$$\sigma_{rr} = \sigma_{\theta\theta} = \frac{3\nu W}{8\pi h^2} \tag{3}$$

While the maximum deflection lies in the center of the plate [6],

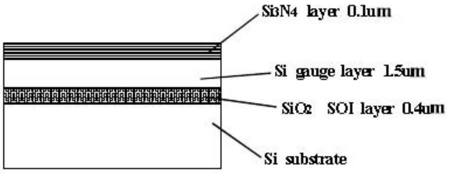
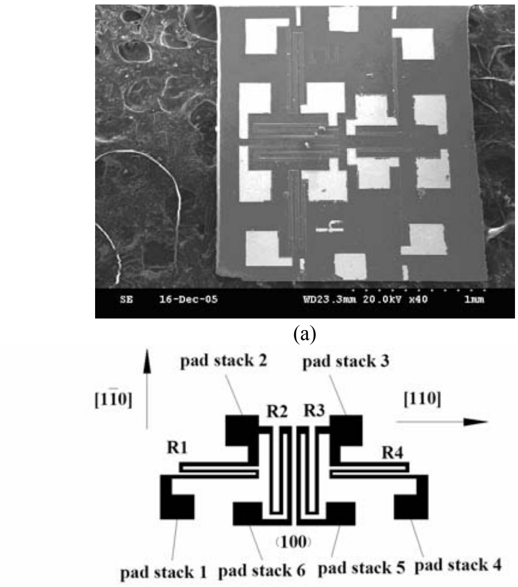


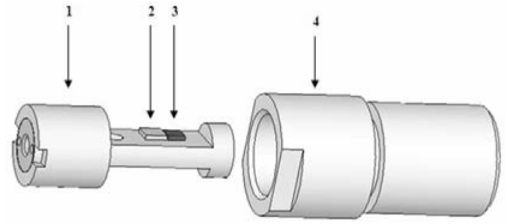
Fig. 1. Layer structure of SOI.



(a)

(b)

Fig. 2. Schematic of sensor chip.



1. cylindrical elastic body ,whose mechanical model is as shown in Fig. 4(b);
2. circuit diagram, to compensate for temperature and zero drift;
3. sensor chip;
4. outer shell ,in front of which lies circular plate whose mechanical model is as shown in Fig. 4(a)

Fig. 3. Schematic of mechanical structure.

$$\omega_{\max} = -\frac{3W(m^2-1)a^2}{16\pi E m^2 h^3} \tag{4}$$

In all the formulas, $W=(\pi a^2)p$, and $m=1/\nu$. Where E is Young's Modulus of the plate, ν is Poisson's ratio, h is the plate's thickness, a is the plate's radius, and p is equally distributed load. From the upper formulas, it can be discerned that the maximum stress lies at the edge of the plate, which is beyond the range of sensor chip if directly measured by splicing chip on it. Moreover, it is too difficult to splice chip on the edge of the plate. The stress in the center of the plate is also beyond the range of chip under the equally distributed pressure of 2GPa. Thus, the maximum deflection in the center is utilized because it transforms pressure measurement into strain measurement of the elastic body, which is obviously in the range of chip.

In the cylindrical elastic body, strain is shown in Eq. (5).

$$\xi = \frac{\sigma}{E} = \frac{F}{EA} = \frac{p\pi a^2}{EA} \tag{5}$$

Where p is equally distributed pressure on the circular plate, a is the plate's radius, and A is elastic body's sectional area. Simultaneously, the elastic body is also a compressive bar as shown in Fig. 4(b). It should satisfy the following conditions, shown as Eqs. (6)-(9).

$$F_{cr} = \frac{\pi^2 EI}{(\mu l)^2} \tag{6}$$

$$n_{st} = \frac{F_{cr}}{F} \geq \left[n_{st}\right] \tag{7}$$

F_{cr} is critical load of the bar, I is the minimum moment of inertia of the cross section, μ is length factor, in this situation μ=0.5, l is the bar's length, n_{st} is factual safe factor of the bar, [n_{st}] is the safe factor, and F is the force working on the bar [9]. σ_{cr} is the bar's critical stress. To keep the bar from buckling, it should satisfy such conditions [7, 8].

$$\sigma_{cr} = \frac{F_{cr}}{A} = \frac{\pi^2 EI}{(\mu l)^2 A} \tag{8}$$

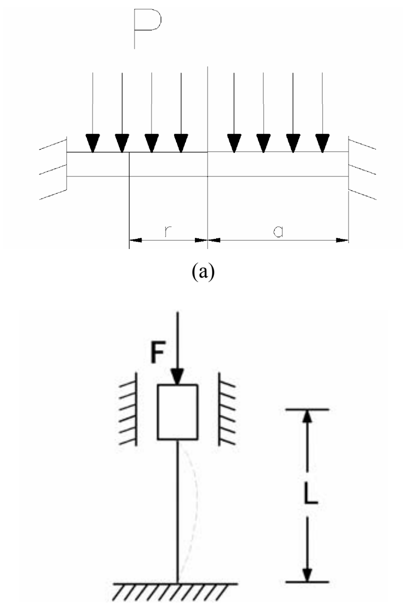
$$\sigma_{cr} \leq \sigma_p \tag{9}$$

Where σ_p is the bar's proportional limit, which is determined by the bar's material property.

It's determined from the chip's working principle that ξ is proportional to the chip's output voltage. Thus, ξ can be determined by the chip's range and then the series of parameters such as radius a, sectional area A, and plate's thickness h all can be determined by the upper formulas. The process of design is completed when all the parameters are confirmed.

3. Fabrication

The whole fabrication process is based on the SOI chip, which is made by MEMS techniques such as LPCVD, implantation and etching. After the sensor chip is fabricated, the key problem is how to realize the sensor seal. The sensor chip is fixed at the side surface of the elastic body by eutectic welding technology with 98Au/2Si as the solder under the temperature of 380℃~430℃. The reason for such welding style is that it's high temperature resistant and the thermal resistance between sensor chip and elastic body is low. The schematic of welding is shown in Fig. 5. In the process of welding, it should be guaranteed that the chip's [110] crystallographic orientation should be in accord with the elastic body's compressive axial direction aiming to keep the measurement accurate.



(a)

(b)

Fig. 4. Working principle of sensor.

The next step for sensor seal after welding is to lead wire and build up Wheatstone bridge. As shown in Fig. 6, the resistors on four arms of the bridge reflect sensitively strain changes of elastic body. The changes of four piezoresistors in the chip can be calculated with stress as follows [9, 10].

$$\begin{aligned} (\frac{\Delta R}{R})_1 = (\frac{\Delta R}{R})_3 &= \pi_{l[110]}\sigma_{[110]} + \pi_{t[1\bar{1}0]}\sigma_{[1\bar{1}0]} \\ (\frac{\Delta R}{R})_2 = (\frac{\Delta R}{R})_4 &= \pi_{l[1\bar{1}0]}\sigma_{[1\bar{1}0]} + \pi_{t[110]}\sigma_{[110]} \end{aligned} \tag{10}$$

Where π is piezoresistive coefficient, σ is stress on the corresponding orientation. Each piezoresistor of the Wheatstone bridge is about 350 Ω .

To adjust the zero drift and reduce the effect of temperature changes, it's necessary to connect the bridge to part 2. Mean while, it's indispensable to adjust pretightening force when tightening the thread to adjust the zero drift to a desirable point and guarantee close contact between circular plate and elastic body. The sensor manufactured is shown in Fig. 7.

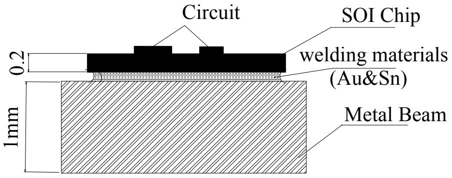


Fig. 5. Schematic of welding SOI chip with metal body.

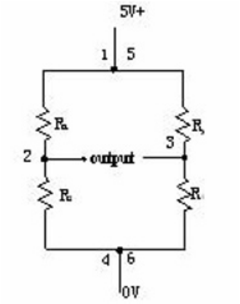


Fig. 6. Wheatstone bridge of sensor.

Fig. 7. Ultra-high pressure sensor of GPa level.

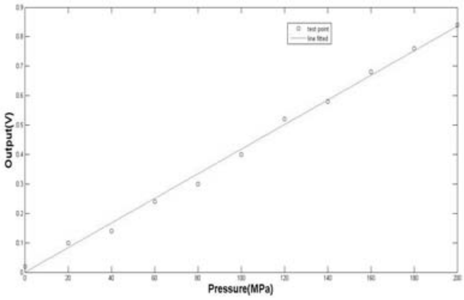


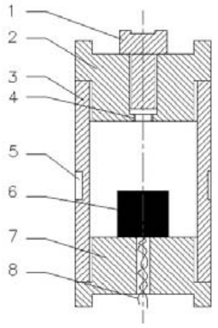
Fig. 8. Output of the sensor in calibration.

4. Experimental results

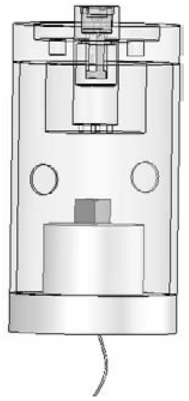
The sensor fabricated needs calibration before it's used in explosion experiments. The calibration is executed with 5V DC power supply. The static calibration is operated with Piston Pressure Gauge in the range of 0~200MPa. The experimental data is shown in Table 1 and Fig. 8, which reveals the sensitivity, linearity. Static calibration in the range of 2GPa can not be operated because of equipment limits but can be inferred from the current calibration results. In Fig. 8, the line is fitted by Least Square Method with test points. The results show that the precision is 4.09%FS in calibration experiment of 200MPa. The 4% error is not small absolutely, however, the calibration range is only 10 percent of the range 2GPa. The equipment of higher range is being sought to complete the calibration process. It's believed that the precision of total range of 2GPa will be acceptable when the calibration of full scale is completed with new equipment.

Table 1. Experiment data.

Pressure (MPa)	Output (V)
0	0.02
20	0.10
40	0.14
60	0.24
80	0.30
100	0.40
120	0.52
140	0.58
160	0.68
180	0.76
200	0.84



(a) 1-sensor; 2-front-end cover; 3-shell; 4-air intake; 5-jet hole; 6-explosive; 7-back-end cover; 8-explosive fuse



(b)

Fig. 9. Schematic of experiment facility measuring pressure changes in explosion.

The explosion experiment is executed in equipment shown in Fig. 9. The equipment's 3D model is shown in Fig. 9(b). As shown in Fig. 9(a), the sensor and explosive are fixed at the two ends separately. The jet hole 5 should be put into water so

Fig. 10. Typical figure of pressure changes in explosion.

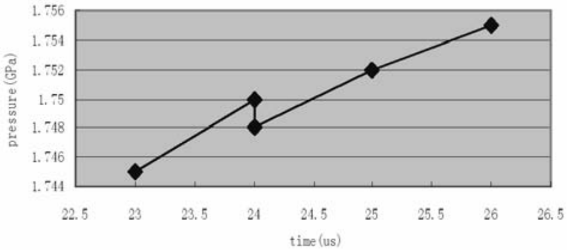


Fig. 11. Comparison of several experiments.

that the pressure could last long enough for measurement when tremendous pressure pushes out the hole in explosion. Oscilloscope is used as data acquisition equipment to record pressure changes.

Several explosive experiments have been done and the figures show very similar results. Typical figure of pressure changes is shown in Fig. 10. The maximum pressure in explosion is 1.75GPa and the total explosion process lasts for 2.66ms. The peak value is obtained in 20-40μs soon after commence of the explosion. Subsequently, it begins to decrease until nearly 1.5ms with a second peak value of second explosion of the explosive. The peak value and corresponding time of five experiments are shown in Fig. 11, from which error and repeatability can be obtained.

The tendency of pressure changes, the length of time , the peak value and corresponding time in the explosion all can be observed from the figure which are of great help to the research of explosive's performance. It not only helps improve performance of explosive but also will direct how to control detonation pressure in explosion.

5. Conclusion

The research in this paper successfully measures the pressure changes in explosion. It relies on the combination of micro SOI solid piezoresistive sensor chip and cylindrical elastic body in the mechanical structure. The curve of pressure changes has great significance in improving explosive performance, evaluating lethality of weapons and controlling initiation time of explosion. The SOI sensor chip introduced in this paper shows stable property and high temperature resistance which provides idea and method for relative applications. The research in this paper also lays foundation for research of larger range sensor.

Acknowledgment

This work was supported by Basic Scientific Research of National Defense (Grant No. XAJT2008171), China.

References

[1] W. Shanggang, G. Yanqing, D. Shunan, W. Shiying and T. Shiyou, Application of Wide Range Pressure Gauge to DDT Experiments on Energetic Materials, *J. Chinese Journal of Energetic Materials*, 15 (2) (2007) 165-168.

[2] Z. D. Jiang and Y. L. Zhao, Research and characteristic measurement of micro silicon pressure sensor, *J. Funct. Mater. Device*, 7 (4) (2001) 365-368.

[3] S. R. Yang and M. Y. Ding, Extension and Growth Technology, *National Defense Industry Press*, Beijing, China, (1992).

[4] T.-R. Hsu, MEMS & Microsystems−Design and Manufacture, *China Machine Press*, Beijing, China (2004).

[5] S. P. Timoshenko and Woinowsky-Krieger S, Theory of plates and shells, McGraw-Hill, New York, USA (1959).

[6] S. P. Timoshenko and J. M. Gere, Theory of elastic stability, McGraw-Hill, New York, USA (1961).

[7] H. C. Cai and H. Yang, Mechanics of Materials, *Xi'an Jiaotong University Press*, Xi'an, China (2004).

[8] R. J. Roark, Formulas for Stress and Strain, McGraw-Hill, New York, USA (1965).

[9] B. Tian and Y. Zhao, The analysis and structural design of micro SOI pressure sensors, Proc. of the 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Shenzhen, Guangdong, China (2009) 55-58.

[10] Avallon and T. Baumeister III, Marks' Standard Handbook for Mechanical Engineers, McGraw Hill, New York, USA (1996).

Yulong Zhao is working in the Department of Mechanical Engineering of Xi'an Jiaotong University, China. He received his B.S., M.S. and Ph.D. degree in 1991, 1999 and 2003, respectively. His research interests are MEMS sensors and micro/nano manufacturing technology.

Xudong Fang received his B.S. in Xi'an Jiaotong University in 2008.His research interests are micro sensors and MEMS technology.

Zhuangde Jiang received his B.S. and M.S. in Xi’an Jiaotong University in 1977, 1988,respectively. His research interests are MEMS and Nano manufacturing technology, Precise instrument and Sensor technology, Precise optical electric measurement technology, Precise and Super-precise manufacturing technology.

Libo Zhao, Ph.D., he received his B.S., M.S. and Ph.D. in Xi’an Jiaotong University in 2000, 2003 and 2007, respecttively. He is postdoctoral fellow of TsingHua University now, and his research interests are MEMS sensors and micro/nano manufacturing technology.