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用于恶劣环境的耐高温压力传感器

赵立波，赵玉龙
（西安交通大学 机械工程学院 机械制造系统工程国家重点实验室，陕西 西安 710049）

摘要：为了解决如高温 200℃等恶劣环境下的压力测量问题，基于微机电系统（MEMS）和高能氧离子注入（SIMOX）技术，研制了一种量程为 0～120 kPa 的压阻式压力传感器。该传感器芯片由硅基底、薄层二氧化硅、惠斯登电桥结构的硼离子注入层、氮化硅应力匹配层、钛-铂-金梁式引线层和由湿法刻蚀形成的空腔组成。在氧剂量 $1.4\times10^{18}/\mathrm{cm}^2$ 和注入能量 200 keV 条件下，由高能氧离子注入技术形成厚度为 367 nm 的埋层二氧化硅层，从而将上部测量电路层和硅基底隔离开，解决了漏电流问题，使得传感器芯片可以在高温 200 ℃以上的环境下使用。为了提高传感器在宽温度范围内的稳定性，对温度补偿工艺进行了研究，补偿后的传感器灵敏度温度系数和零位温度系数很容易控制在 1×10^{-4}/℃ · FS。实验标定结果表明：在 200 ℃下，研发的耐高温压力传感器具有很好的工作性能，其线性度误差达 0.12%FS、重复性误差为 0.1%FS、迟滞误差为 0.12%FS，精度达0.197%FS，满足油井、风洞、汽车和石化工业等现代工业的应用需求。

关　键　词：压力传感器；微机电系统；氧离子注入；恶劣环境；高温
中图分类号：TP212.12　　**文献标识码：**A

High temperature pressure sensor for harsh environment

ZHAO Li-bo, ZHAO Yu-long

(*State Key Lab for Manufacturing Systems Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an* 710049, *China*)

Abstract: In order to solve the pressure measurement problem in harsh environments, such as high temperature above 200 ℃, a special piezoresistive pressure sensor with the ranges of 0～120 kPa is developed based on the Micro Electro-mechanical System (MEMS) and Separation by Implantation of Oxygen (SIMOX) technology. The piezoresistive pressure sensor chip consists of a silicon substrate, a thin silicon dioxide layer, an optimized boron ion implantation layer photolithographically patterned on a Wheatstone bridge configuration, a stress matching layer with silicon nitride, a Ti-Pt-Au beam lead layer for bonding gold wires, and a cavity fabricated by the wet etching. A special buried silicon dioxide layer with a thickness of 367 nm is fabricated by the SIMOX technology with the oxygen ion dose of $1.4\times10^{18}/\mathrm{cm}^2$ and an implantation energy of 200 keV. The buried SiO_2 layer is used to isolate the upper measuring circuit layer from the silicon substrate to avoid the leak-current influence, so the fabricated sensor chip can be used in a high temperature above 200 ℃. In order to improve the stability in the wide temperature range, the temperature compensation methods are studied and carried out, so the Temperature Coefficient of Sensitivity (TCS) and Temperature Coefficient of Offset (TCO) of the

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compensated sensor are easily obtained to be less than $1\times10^{-4}/℃\cdot$ FS. The calibration results show that the developed high temperature pressure sensor has good performances under 200 ℃ for a linearity error of 0.12%FS, a repeatability error of 0.1%FS, a hysteresis error of 0.12%FS, and the sensor's accuracy of 0.197%FS. which shows it is able to meet the requirements of modern industry, such as oilcans, wind tunnels, mobiles, petrochemical industry, *etc.*.

Key words: pressure sensor; MEMS; SIMOX; harsh environment; high temperature

1 Introduction

Along with the development of industry technology, the pressure sensor must be able to work in harsh environment, such as high temperature and high impact. In some fields, like petroleum and chemistry, aviation and mobile industry, the pressure of the fluid must be measured above 200 ℃. And in some other fields, for example, rocket engine, the pressure sensor must be also able to endure high temperature and instantaneous impact, for instance, 1 000 ℃ lasting 1 s.

Some kinds of high temperature pressure sensors based on different theories, such as SOI (Silicon on Insulator)[1], SOS (Silicon on Sapphire)[2], optical fiber[3-4], sputtering film[5], etc., were developed in the world. For example, the piezoresistive sensitive element based on the SOI technology had been researched in the 1980's, but its performances were not fine because the limitation of SOI material preparation. Now, the Ibis Technology Corporation with SIMOX (Separation by Implantation of Oxygen) technology[6] and Soitec company with Smart-Cut process[7] can provide the fine SOI material with different parameters according to the custom's requirements. Although there are many researches about the pressure sensor based on the SOI technology, the applied high temperature pressure sensor is few.

In order to solve the pressure measurement problems in the above fields, one kind of high temperature piezoresistive pressure sensor based on SOI technology has been developed and produced in batch, which can be used to measure the pressure of the fluid under high temperature of above 200 ℃ and has fine performances.

2 Design and fabrication process of sensor sensitive element

It is known that the SOI single silicon materials are popular in IC (Integrated Circuit) manufacture and sensor chip fabrication for high temperature application. The buried SiO_2 isolation layer in the SOI material guarantees little leakage current occur at the temperature up to 350 ℃.

The SIMOX technology is an important method to fabricate the SOI material. In the SIMOX process, it is important to control the dose of oxygen and the annealing process. In the case of the common SOI structure of top Si layer with thickness of 200 nm and buried SiO_2 layer with thickness of 367 nm, the 200 keV implanting energy accompanied with the oxygen dose of at least $1.4\times10^{18}/cm^2$ is necessary to produce an obviously buried SiO_2 layer[8]. And then, the subsequent annealing step is carried out at temperatures close to the melting point of silicon (1 300 ℃) under argon with 0.5%−2% oxygen, so an atomic craggedness in the top Si/buried SiO_2 interface is formed. The oxygen protects the superficial silicon layer from pitting during the high temperatures. By the SIMOX, the top silicon layer's thickness is only 200 nm. In order to meet the requirements of piezoresistive theory for the sensor's sensitive chip, the top silicon layer's thickness should be about 1.5 μm which generated by the LPCVD (Low Pressure Chemical Vapor Deposition). The sensor chip has been developed with size 5 mm×5 mm ×0.5 mm by the MEMS technology and microfabrication technique[9-10]. The layout of sensor's piezoresistive sensor chip is designed to square diaphragm with four piezoresistors at the each edge centers of the diaphragm, and the resistor R_1-R_4 are all alone with the crystal orientation $[1\bar{1}0]$ or [110], as shown in Fig. 1. When the pressure applied on the chip, the two resistors mainly endured maximum compressive stress, and the other two resistors mainly endured maximum tensile stress, which simulated by the ANSYS software as shown in Fig. 2. Based on the piezoresistive theory, the four piezoresistors with the same resistance value of RB will compose a Wheatstone full bridge in a five-terminal version[11], as shown in Fig. 3, and the series resistor R_Z is used to compensate the zero offset voltage[12].

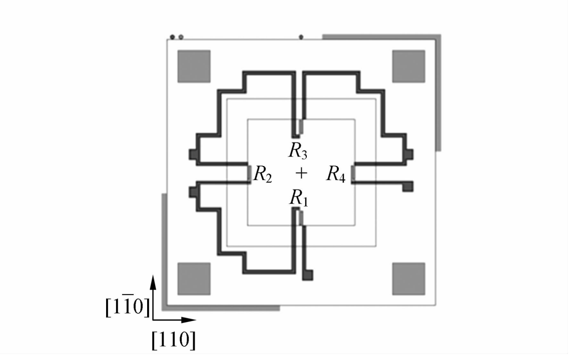

Fig. 1 Layout of sensor chip

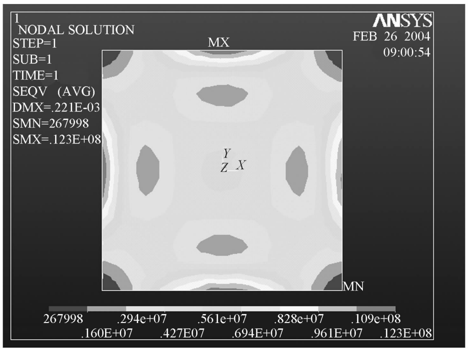

Fig. 2 ANSYS simulation result

The main fabrication processes of the piezoresistive sensor chip are introduced as follows[13-14]:

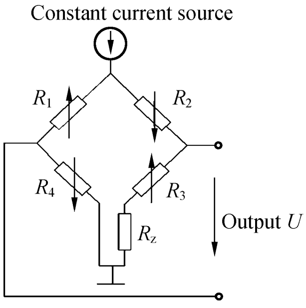

Fig. 3 Wheatstone full bridge

Firstly, the n-type (001) single-crystal silicon material was fabricated by SIMOX technology to form the SOI material. Secondly, the epitaxy crystal silicon was grown by LPCVD, and then, the implantation and diffusion of boron was performed from a B_2O_3 constant source in the top silicon layer. Subsequently, annealing and activation process was carried out in N_2 for 30 min at 1 100 ℃ to eliminate some crystal lattice defects and improve the conducting power of the top silicon layer. The top measuring circuit silicon layer was obtained with the boron concentration of $2\times10^{20}/\mathrm{cm}^3$. Then, the SiO_2 layer was formed onto the top silicon layer with the oxidation process in the O_2 for 30 min at 1 100 ℃. And a Si_3N_4 layer was fabricated onto the top SiO_2 layer by LPCVD, which was used to resist the diffusion of contaminant ion and improve the thermal stability of the sensitive chip. Next, the Wheatstone bridge resistors with three-fold structure were fabricated by RIE (Reactive Ion Etch). The single resistor's width size is 12.5 μm and the total length is 750 μm. The resistor's structure was shown in Fig. 4. The sheet resistance of the four piezoresistors is 20 Ω/□. As seen in Fig. 4, the resistors are designed and fabricated to rilievo-type, in other words, the piezoresistors are embossed from the substrate. And outer region of the resistors, such as redundant implanted silicon, top SiO_2 and Si_3N_4, were all etched in order to decrease the residual stress induced by the mismatch of thermal expansion coefficient of different membrane material. According to the piezoresistive theory, when some pressure applies on the chip, the change of the four piezoresistors can be calculated as:

$$\begin{cases} \left(\dfrac{\Delta R_1}{R_1}\right)=\left(\dfrac{\Delta R_3}{R_3}\right)\approx-\dfrac{1}{2}\pi_{44}\sigma_{[110]} \\ \left(\dfrac{\Delta R_2}{R_2}\right)=\left(\dfrac{\Delta R_4}{R_4}\right)\approx\dfrac{1}{2}\pi_{44}\sigma_{[1\bar{1}0]} \end{cases}, \quad (1)$$

Where, $\sigma_{[110]}$ and $\sigma_{[1\bar{1}0]}$ are the stress along crystal direction [110] and $[1\bar{1}0]$, respectively. π_{44} is the shear piezoresisitive coefficient.

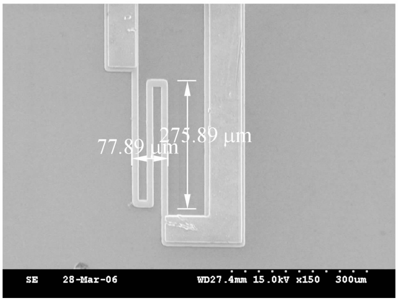

Fig. 4 SEM photo of single resistor's structure

The resistor holes were etched by the RIE or ICP (Reactive Ion Etch or Inductively Coupled Plasma) in order to form the inner lead. In order to make the chip work under high temperature of above 200 ℃, the Ti-Pt-Au multi metal layer were grown by sputtering with the thickness of 50 nm, 50 nm, 500 nm, respectively. And, the metal layers were etched to the beam lead for connecting the four resistors to form the Wheatstone Bridge, as shown in Fig. 5. Afterward, the cavity like cup structure was fabricated by wet etching to form the sensitive membrane with the different height ratio to the pressure measurement range. The developed chip's sensitive membrane height is 20 μm. Finally, the wafer was diced to dies by the scribing technology. Fig. 6 is the SEM photo of the piezoresistive sensitive chip in the cross view.

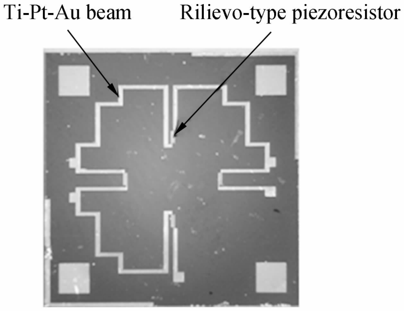

Fig. 5 Microphotograph of sensor chip in top view

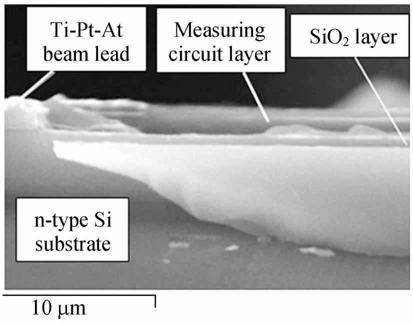

Fig. 6 SEM photo of sensor chip in cross view

3 Design and packaging process for microsensor

The detailed illustration of the mechanical structure for the high temperature pressure sensor is shown in Fig. 7. Firstly, the anodic bonding was used to package the piezoresistive sensor chip on the Pyrex glass ring[15], as shown in Fig. 8. The glass ring's height is 2 mm, it's inner and outer diameter are 1 mm and 5 mm, respectively. Fig. 9 shows the pressure sensor's photo.

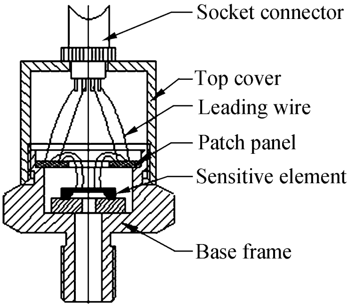

Fig. 7 Mechanical structure of sensor

The 316L stainless steel was selected as the

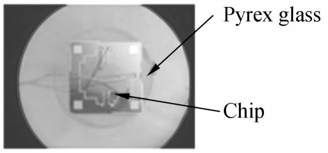

Fig. 8 Sensor chip bonded on pyrex glass

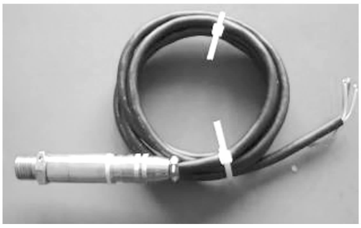

Fig. 9 Pressure sensor photo

chip base's material. The sensor chip bonded on the Pyrex glass was packaged on the base frame by the glass frits sintering technology. The sintering process was carried out in the vacuum oven or other over with N_2 environment[16]. The sintering temperature is 575 ℃ for 15 min, then cooling down along with the oven. The glass frits sintering process can obtain good packaging strength for the microsensor and ensure it competent for high temperature (up to 200 ℃) application. Then, gold wires with width of 40 μm were packaged on the bonding pads of sensor chip by the thermocompression bonding technology and soldered on the high temperature polyethylene PCB (Printed Circuit Block). Finally, the high temperature PTFE (Polytetrafluoroethylene) cable was soldered on PCB and clasped by the mechanical fasten element.

In order to eliminate the residual stress effect, some heat treatment will be carried out. Firstly, the sensor was placed under the high temperature of 180 ℃ for 4 h, then cooled down to −40 ℃ for 2 h. This process should be performed for four cycles. It is necessary to control the temperature changed moderately in the heating-up and cool-down processes in order to prevent some small cracks occuring[17].

4 Experiments and results

A high temperature pressure sensor with range of 0−120 kPa has been developed. The static calibration for the sensor was carried out with 3 mA constant current powered under 200 ℃. The test data were obtained as shown in the Tab. 1. Fig. 10 shows the output data curves under 200 ℃. According to the test data, the static performance index will be calculated with the least square method[18], such as linearity error of 0.12%FS, repeatability error of 0.1%FS, hysteresis error of 0.12%FS, and the sensor's accuracy is 0.197%FS. After the temperature compensation, the TCS (Temperature Coefficient of Sensitive) and TCO (Temperature Coefficient of Offset) of the sensor are calculated as 0.6×10^{-4}/℃ · FS and 0.8×10^{-4}/℃ · FS, respectively.

Tab. 1 Test data under 200 ℃

Pressure (kPa)	Upstroke output (mV)		Downstroke output (mV)	
	(1)	(2)	(1)	(2)
0	−0.72	−0.70	−0.70	−0.72
20	7.91	7.92	7.95	7.94
40	16.51	16.54	16.52	16.58
60	25.12	25.13	25.14	25.15
80	33.82	33.87	33.85	33.86
100	42.51	42.48	42.50	42.51
120	51.12	51.12	51.15	51.15

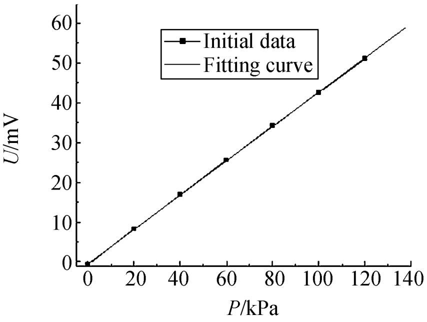

Fig. 10 Curve of output data under 200 ℃

The dynamic characteristic of the sensor was tested with the shock tube. The sensor's dynamic response curve was recorded by oscillograph, as shown in Fig. 11, and the sensor's output signal was amplified. In Fig. 11, each square value of the transverse coordinate represents 10 ms, and each square value of the lengthways coordinate represents 50 mV. It can be seen that the period of the curve is about 7.4 ms, which can be measured between the two peaks along transverse direction. And the natural frequency can be calculated as about 135.1 kHz, which is the reciprocal of the value of measured period.

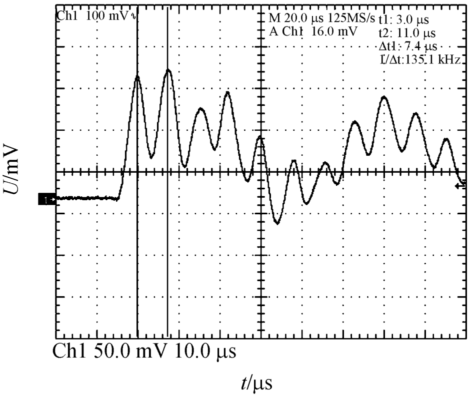

Fig. 11 Dynamic response curve

5 Conclusions

Due to the sensor chip based on SIMOX technique and high temperature packaging adopted, the developed high temperature piezoresistive pressure sensor is able to work successfully under temperature of 200 ℃. From the calibration results, the sensor's static accuracy is 0.197% FS and dynamic reponse frequency is about 135.1 kHz. The characteristics of the sensor are satisfactory to meet the requirements of many application fieds, such as oilcan, wind tunnel, mobile petrochemical industry, *etc.*.

References:

[1] FRENCH P J, MURO H, SHINOHARA T, *et al.*. SOI pressure sensor [C]. *International Conference on Solid-State Sensors and Actuators*, 1991:24-27.

[2] STUCHEBNIKOV V M. SOS strain gauge sensors for force and pressure transducers [J]. *Sensors and Actuators A: Physical*, 1991,28:207-213.

[3] ABEYSINGHE D C, DASGUPTA S, JACKSON H E, *et al.*. Novel MEMS pressure and temperature sensors fabricated on optical fibers [J]. *Journal of Micromechanical and Microengineering*, 2002,12:229-235.

[4] XIAO S R, ZHU P, BEN F L. Analysis on characteristics of optical fiber sensor for atmospheric pressure [J]. *Opt. Precision Eng.*, 2008,16(6):1042-1047. (in Chinese)

[5] WITT G. The electromechanical properties of thin films and the thin film strain gauge [J]. *Thin Solid Films*, 1974,22:133-156.

[6] BLAKE J. SIMOX (Separation by Implantation of Oxygen) [J]. *Encyclopedia of Physical Science and Technology*, 2001:805-813.

[7] BRUEL M, ASPAR B, ANDRE-JACQUES A H. Smart-Cut: A new silicon on insulator material technology based on hydrogen implantation and wafer bonding [J]. *Jounal of Applied Physics*, 1997,36:1636-1641.

[8] PLOBL A. Silicon-on-insulator: materials aspects and applications [J]. *Solid State Electron*, 2000, 44:775-782.

[9] EICKHOFF M, MOLLER H, KROETZ G, *et al.*. A high temperature pressure sensor prepared by selective deposition of cubic silicon carbide on SOI substrates [J]. *Sensors and Actuators A*, 1999,74:56-59.

[10] OBIETA I, CASTAFIO E, CRACIA F J. High-temperature polysilicon pressure microsensor [J]. *Sensors and Actuators A*, 1995,46-47:161-165.

[11] BAO M H. *Micro Mechanical Transducers: Pressure Sensors, Accelerometers and Gyroscopes* [M]. Amsterdam: Elsevier, 2000:257-262.

[12] TANDESKE D. *Pressure Sensors: Selection and Application* [M]. New York: M. Dekker, 1991:30-48.

[13] ZHAO Y L, ZHAO L B, JIANG Z D. A novel high temperature pressure sensor on the basis of SOI layers [J]. *Sensors and Actuators A*, 2003, 108:108-111.

[14] WENG Z Y, WENG Z Q, XU S L, *et al.*. Vacuum microelectronics pressure sensor [J]. *Opt. Precision Eng.*, 2004, 12(6): 603-607. (in Chinese)

[15] Integrate Circuit Edit Committee of China. *Integrate Circuit Package* [M]. Beijing: National Defence Industry Press, 1993: 193-204, 226-269. (in Chinese)

[16] ZIERMANN R, VON B J, OBERMEIER E, *et al.*. High temperature piezoresistive β-SiC-on-SOI pressure sensor with on chip SiC thermistor [J]. *Materials Science and Engineering B*, 1999, 61-62:576-578.

[17] BRIAND D, PATRICK W, NICOLAAS F, *et al.*. Bonding properties of metals anodically bonded to glass [J]. *Sensors and Actuators A*, 2004, 114:543-549.

[18] YUAN X G. *Handbook of the Sensor Technology* [M]. Beijing: National Defence Industry Press, 1989:84-114. (in Chinese)

Authors' biographies:

ZHAO Li-bo (1978－), male, Ph. D. candidate, lecturer of the School of Mechanical Engineering, Xi'an Jiaotong University, his research interests are microsensors, micro&nano technology, test measurement technology and instruments, and so on. **E-mail**: libozhao@mail. xjtu. edu. cn

ZHAO Yu-long (1968－), male, Ph. D. candidate, professor of the School of Mechanical Engineering, Xi'an Jiaotong University, his research interests are microsensors, micro&nano technology, test measurement technology and instruments, and so on. **E-mail**: zhaoyulong@mail. xjtu. edu. cn

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●下期预告

电液动力微泵微电极的不同制作工艺的比较

于　翮[1]，张　强[1]，乔大勇[2]，俞　坚[1]

（1. 北京工业大学 传热强化与过程节能教育部重点实验室及传热与能源利用北京市重点实验室，北京 100022；
2. 西北工业大学 陕西省微纳米系统实验室，陕西 西安 710072）

基于MEMS加工技术的的电液动力微泵，在微流体冷却系统和解决微电子行业中高热流器件的冷却问题中占有重要地位。电液动力微泵的核心部分是通过MEMS加工工艺制作的微电极，微电极由成对的发射极和集电极组成。在电极对间的强电场作用下，电介质流体中的离子、极子以及微粒同电场相互作用来驱动流体流动。本文系统地讨论了微电极的设计和制作中有电极材料的选择方针，多种形状的电极形状设计的问题，对两种电极加工工艺—电镀法和剥离法进行了对比。实验结果表明：贵金属有更好的抗电化腐蚀能力；同普通平行电极结构相比，带有尖锐结构的电极更能提高微泵的性能；相比电镀法，剥离法能更好地提高电极的制作质量。