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A Novel Packaging Structure and Process for High Temperature Silicon Piezoresistive Pressure Sensor

Xin Li[1,2], Xiuxiu Liang[1*], Qin Liu[2], Peishan Wu[1] and Bo Liu[2]

[1]*School of Information Science and Engineering, Shenyang University of Technology, Shenyang 110870, China*
[2]*National Sensor Engineering Research Center, Shenyang 110043, China*

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Abstract

The performance of the usual diffused silicon piezoresistive pressure sensors for pressure measurement in high temperature environments is affected by the failure of PN junction isolation, the expansion of silicon oil in packaging structure, and other factors. This study proposed an all-solid-state packaging structure based on silicon/glass/kovar alloy bonding to modify the poor temperature tolerance of silicon oil in the conventional packaging structure of high temperature silicon piezoresistive pressure sensors. Micro-electromechanical system processes, including etching, oxidation, and sputtering, were applied to prepare a high-temperature pressure-sensitive chip based on the smart-cut silicon on insulator wafer. The interconnection of piezoresistors was realized with Ti/Pt/Au multilayer metallization composite electrodes. Silicon/glass, glass/kovar alloy pressure pipes were sealed through the electrostatic bonding process. The electron beam welding process was used to realize the solid-state connection between pressure pipes and sockets, and the sealing condition and performance of the sensor were verified by scanning electron microscope and experiments. Results show that the bonding interfaces between silicon wafer/glass/pressure pipes are good, when a pressure from 0 to 6.0 MPa is applied from 0 °C to 300 °C, the sensitivity is approximately 200 mV/MPa, the non-linearity is less than 0.59‰FS, the repeatability is less than 0.04‰FS at 300 °C, and the sensitivity temperature drift is less than -0.133 mV/(MPa·°C). This study provides a certain reference for the pressure measurement of silicon piezoresistive pressure sensors in harsh high-temperature environments.

Keywords: Solid-state package, Electrostatic bonding, Silicon piezoresistive pressure sensor, High temperature

1. Introduction

Silicon piezoresistive pressure sensors have several advantages, including small volume, high sensitivity, good reliability, fast dynamic response, and mature processes, and are among the most widely used pressure sensors in fields, such as aerospace, biomedicine, weapons, petrochemical industry, geological exploration, and flow and liquid level measurement [1,2]. In high-temperature environments, pressure measurement is required in various fields, such as aircraft engines, heavy gas turbines, and spacecrafts [3]. Now, most high-precision diffused silicon pressure sensors and transmitters are designed with a solid-state isolation diaphragm structure. Tianjin University of China studied and developed a small solid-state isolation packaging technology of high-temperature polysilicon pressure sensors based on the internationally advanced packaging technology and achieved a high working temperature for the oil-filled sensor of 220 °C [4].

On the basis of the above analysis, scholars have conducted numerous explore on the influence of the material and packaging design of high-temperature silicon piezoresistive pressure sensors on the performance of sensors [5–8]. The electrical leakage of the PN junctions between the piezoresistors and the substrate increases when the working temperature exceeds 125 °C, seriously deteriorating or even invalidating the characteristics of sensors [9]. The pressure sensor with a silicon on insulator (SOI) was proposed in a previous study, and electrical isolation between the piezoresistors and the substrate was achieved by SiO_2, addressing the failure of PN junction isolation when the working temperature of pressure sensors exceeds 125 °C [10,11]. The diaphragm isolation structure is usually adopted in the packaging structure of pressure sensors, and silicon oil fills the closed chamber formed by an oil chamber and a ripple structured diaphragm [4]. However, silicone oil causes thermal expansion and eventually exerts additional pressure on the pressure-sensitive chip in high working temperatures, seriously affecting the measurement accuracy of sensors.

Thus, an all-solid-state packaging structure was developed in this study. Micro-electromechanical system (MEMS) processes were adopted to prepare a high temperature pressure-sensitive chip based on the smart-cut SOI wafer, and the sensor was assembled with the electrostatic bonding process and the electron beam welding process to solve the poor temperature tolerance problem of silicon oil in the oil-filled packaging of high-temperature pressure sensors, providing a reference for the packaging structure design of silicon piezoresistive pressure sensors for precise pressure measurement in high temperature environments.

2. State of the art

To address the problems in pressure measurement in high-temperature environments, scholars have conducted

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numerous explore works on piezoresistive pressure sensors. Yang et al. adopted an island membrane structure to improve the stress distribution on the sensitive membrane surface, improving the sensitivity and linearity of the sensor, but the maximum test temperature was 200 °C [12]. Wang et al. designed a high-temperature silicon piezoresistive SOI pressure sensor chip based on MEMS technology, optimized the structure of the movable diaphragm of the pressure chip, and determined the size and shape of the movable diaphragm and varistor strips, but the chip was not fabricated, packaged, and tested [13]. Li et al. designed a leadless reverse packaging pressure chip with an E-type membrane structure based on the SOI material. Compared with the traditional C-type membrane structure, the E-type membrane structure could satisfy the sensitivity and linearity requirements simultaneously. The design requirements of sensors, including miniaturization and lightweight, were satisfied by the leadless reverse packaging process, but the thermal mechanical stress must be strictly controlled [14]. Rahman et al. prepared a high-temperature piezoresistive pressure-sensitive chip using MEMS and SOI technologies. The mechanical packaging structure adopted a flush-type design to avoid the attenuation of the sensors' dynamic performance caused by the channeling effect and improves the dynamic response frequency of sensors. However, the influence of temperature change on the performance of sensors was not analyzed [15]. Wu et al. designed a monocrystalline silicon high-temperature piezoresistive pressure sensor chip and packaging structure based on an separation by implanted oxygen SOI wafer. The manufactured high-temperature pressure sensor had good performance in the temperature range of 50 °C – 300 °C. However, when an oil-filled packaging is adopted, the thermal expansion of silicon oil would produce thermal stress at high temperatures [16]. Li et al. designed and prepared a piezoresistive pressure sensor based on the SOI material with a range of 5 Pa to 1.8 MPa. The wire bonding process was used to ensure electrical interconnection between the sensitive chip and the outside. Meanwhile, the temperature compensation and signal conditioning circuits were assembled to reduce the temperature drift and ensure the output of the sensor. The sensor had good precision in the designed range and could steadily work at -50 °C to 205 °C, but the electrical performance of the piezoresistor was not optimized [17]. Guo et al. studied and fabricated a high-temperature piezoresistive SOI pressure sensor chip based on MEMS technology. The oil-filled core body case of the kovar alloy material was selected to package the high-temperature SOI pressure sensor chip. To minimize the stress caused by the package, silica gel with a shore hardness less than 50 was used as the adhesive, with the gluing amount strictly controlled. The gold wire with a diameter of 1.2 mil was used for the interconnection between the chip and the case. To eliminate the influence of package, the welding process of the ripple diaphragm and the silicone oil-filling process did not do. The chip had good working characteristics and stability in the temperature range of -55 °C to 150 °C, but reliability analysis and long-term stability test were not performed [18]. Balavalad et al. designed a micro piezoresistive SOI pressure sensor, which uses the double Wheatstone bridge pressure measurement mechanism for temperature compensation. Thus, the sensor had higher sensitivity but had a high SOI bias voltage [19]. Täschner developed a silicon-based pressure sensor with an application temperature of up to 300 °C and the associated manufacturing technology. The sensor was packaged through the optimized silicon fusion bonding process and has a stress-insensitive sensor with high linearity, excellent offset stability, low hysteresis, and low sensitivity changes over the entire temperature range [7]. Kumar et al. designed a polysilicon pressure sensor, which uses a silicon dioxide layer for isolating the silicon piezoresistor. For high-temperature applications, the sensor was more cost-effective than SOI sensors but had not be subjected to the high-temperature performance test above 55 °C [20]. Guo et al. established a model for extending the operating temperature range through the doping and minority-carrier exclusion effects. For a low-doped SOI sensor, the maximum temperature could be increased by decreasing the film thickness for a fixed current. For a heavily doped SOI sensor, the maximum temperature could be increased by improving the doping level, but the continuous working performance change of the sensor at 500 °C was not analyzed [21]. Ngo et al. designed a liquid-free, piezoresistive high-temperature pressure sensor based on SOI. The sensor used a steel membrane to separate media, and the applied pressure was directly transferred to the SOI chip through a push rod. The sensor could measure pressure at temperatures up to 400 °C with an accuracy of 0.25% full scale output (FSO) [22]. Giuliani et al. revised the liquid-free, piezoresistive high-temperature pressure sensor of Ngo H D. The revised sensor adopted digital correction to compensate for the offset and the sensitivity thermal drift. The sensor could measure pressure up to 1000 bar at 400 °C with an accuracy of ± 0.50% FSO [23]. Brinkfeldt et al. conducted a comparative study on different electrical interconnection methods for super high operation temperatures (500 °C – 800 °C). Their thermo-mechanical simulation results showed that stresses are low in a connection system based on liquid interconnection, but the system was difficult to realize. The interconnection model based on mechanical pressure without any solder or metallic bond showed high stress [24]. Sheeparamatti et al. introduced the preparation of a micro pressure sensor based on polysilicon on insulator. Nano-piezoresistors were connected by a Wheatstone bridge. In the 0 – 1 MPa range, the sensitivity of the sensor was 14.7 mV/bar. The chip was cheaper than the SOI chip, but they had not been compared intensively in terms of performance [11].

The above studies mainly focus on high-temperature piezoresistive SOI pressure sensors, which have a simple process and are high-temperature tolerant and low cost. However, the study on high-temperature piezoresistive SOI pressure sensors mainly focuses on the size of piezoresistors, the material, the packaging structure, and the compensation algorithm, while the study on mitigating the influence of silicone oil's thermal expansion is limited, especially on eliminating the poor temperature tolerance of silicone oil. In this study, MEMS processes are used to prepare high-temperature SOI pressure-sensitive chips based on the smart-cut SOI wafer, and the interconnection of piezoresistors is realized with Ti/Pt/Au multilayer metallization composite electrodes. Silicon/glass, glass /kovar alloy pressure pipes are bonded through the electrostatic bonding process. The electron beam welding process is adopted to realize the solid-state connection between the pressure pipes and the sockets, and the sealing condition and performance of the sensor are verified by scanning electron microscope (SEM) and experiments.

The remainder of this study is organized as follows. Section 3 presents the working principle of the sensor, the chip design and process, and the packaging structure design and process. Section 4 discusses the performance parameters of the sensor. Section 5 summarizes the conclusions.

3. Methodology

3.1 Working principle

The reverse side of the silicon wafer is designed with a cup structure, and the bottom is a square stress diaphragm which deforms under outside pressure, the pressure signal is transmitted to the piezoresistors on the diaphragm, and the resistance of the piezoresistors changes with the strain on the diaphragm. The Wheatstone bridge powered by a constant current source is composed of four piezoresistors. If a pressure difference exists between the two sides of the diaphragm and R_1 / R_3 and R_2 / R_4 have positive increments and negative increments respectively, then $R_1 \to R_1 + \Delta R_1$, $R_3 \to R_3 + \Delta R_3$, $R_2 \to R_2 - \Delta R_2$, $R_4 \to R_4 - \Delta R_4$, which can be achieved through an appropriate design. The output voltage applied pressure is as follows [25]:

$$V_p = \frac{(R_1 + \Delta R_1)(R_3 + \Delta R_3) - (R_2 \text{-} \Delta R_2)(R_4 \text{-} \Delta R_4)}{R_1 + \Delta R_1 + R_2 - \Delta R_2 + R_3 + \Delta R_3 + R_4 - \Delta R_4} I_0 \tag{1}$$

If $R_1 = R_2 = R_3 = R_4 = R$,then $\Delta R_1 = \Delta R_2 = \Delta R_3 = \Delta R_4 = \Delta R$ is guaranteed, and the output voltage can be calculated as

$$V_p = \Delta R * I_0 \tag{2}$$

Thus, the pressure signal is converted into the output voltage signal of the circuit.

3.2 Chip design

The P-type silicon (doped with B) is selected for the piezoresistors. The doping concentration not only affects the value of piezoresistive coefficient but also the intensity that varies with temperature of the piezoresistive coefficient [26,27]. The longitudinal and transverse piezoresistive coefficients of the resistors mainly depend on the shear piezoresistive coefficient (π_{44}). The higher the doping concentration is, the smaller the π_{44} is, but the temperature coefficient is also small. The piezoresistive coefficient has a negative temperature coefficient, while the piezoresistors have a positive temperature coefficient. When the Wheatstone bridge is excited by a constant current source, the negative piezoresistive coefficient can be compensated by the positive temperature coefficient of the resistors with an appropriate doping concentration [28]. The dopant surface concentration of the P-type piezoresistors is controlled at $2 \times 10^{20} cm^{-3}$ to obtain the self-compensation effect, and the resistivity is approximately $3.24 \times 10^{-2} \Omega cm$ [29].

The sensor core body adopts a square diaphragm structure [29]. The four piezoresistors are placed along the <110> axis at the edges of the silicon cup as shown in Fig. 1. The longitudinal piezoresistive coefficient of the <110> asis direction is approximately one half of π_{44}, where π_{44} is the shear piezoresistive coefficient. However, the transverse piezoresistive coefficient is approximately minus one half of π_{44}. The two piezoresistors (R_1 and R_3) are the longitudinal gauge resistors, the other piezoresistors (R_2 and R_4) are the transverse gauge resistors, and the relative variation of the four piezoresistors can be calculated as follows [25]:

$$\frac{\Delta R_1}{R_1} = \frac{\Delta R_3}{R_3} = \pi_{l[110]}\sigma_{[110]} + \pi_{t[1\bar{1}0]}\sigma_{[1\bar{1}0]} \approx \frac{1}{2}\pi_{44}\sigma_{[110]} \tag{3}$$

$$\frac{\Delta R_2}{R_2} = \frac{\Delta R_4}{R_4} = \pi_{l[110]}\sigma_{[110]} + \pi_{t[1\bar{1}0]}\sigma_{[1\bar{1}0]} \approx -\frac{1}{2}\pi_{44}\sigma_{[1\bar{1}0]} \tag{4}$$

In Formulas (3) and (4), π_l , π_t , and π_{44} are the longitudinal, transverse, and shear piezoresistive coefficients, respectively. σ is the stress.

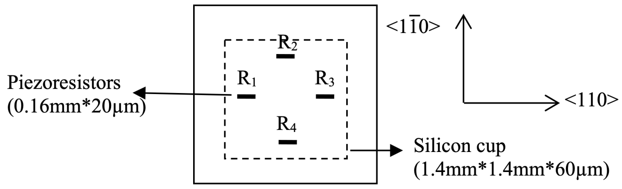

Fig. 1. Piezoresistors arrangement on the square diaphragm [25]

3.3 Smart-Cut SOI

The SOI wafer is the key to manufacturing high-temperature silicon piezoresistive pressure sensor chips. The SOI wafer is prepared with the smart-cut technology, and the process is shown in Fig. 2 [30]. (1) In ion implantation, a certain amount of H^+ is injected into silicon wafer A with a certain energy at room temperature. (2) In bonding, silicon wafers A and B are cleaned thoroughly and bonded. The SiO_2 layer grows on the surface of silicon wafer B through the thermal oxidation method, acting as a buried insulating layer in the SOI structure, and the B-wafer will be the support wafer in the SOI structure. (3) During heat treatment, the bonded silicon wafer forms a bubble layer, where H^+ is injected with high-concentration, and breaks. The left silicon layer serves as the top silicon layer in the SOI structure. Meanwhile, high-temperature heat treatment is used to improve the bonding strength of the bonding interface and eliminate the ion implantation damage in the SOI layer. (4) The surface roughness is reduced in the chemical mechanical polishing process. The top silicon layer's thickness of the smart-cut SOI wafer can be controlled by the ion implantation process parameters (approximately 5000 Å). The quality of the top silicon layer is equivalent to that of the polished silicon wafer, and the buried layer is complete.

3.4 Chip process

The sensitive resistors are made of the monocrystalline silicon of the thin layer in a SOI wafer. The cross-sectional diagram of the fabrication processes of the chip is shown in Fig. 3. The chip fabrication processes mainly include silicon wafer cleaning→oxidation→resistor strips photolithography →ion implantation→annealing→deposition of Si_3N_4→lead holes and silicon cup photolithography→preparation of multilayer composite electrodes→alloy→etching of silicon cup→anodic bonding of the chip and glass→ chip dicing.

Given their simple process and low cost, Al electrodes are adopted in conventional silicon piezoresistive pressure sensors. However, for high-temperature pressure-sensitive chips, the good ohmic contact between the resistors of the bridge circuit is the critical factor guaranteeing the electrical performance parameters reliability of the sensitive chips.

The working current of the pressure sensors is mA level, and the electrodes are usually wide. When the working temperature is lower than 200 °C, the Al electrodes can ensure reliable operation. However, when the working temperature exceeds 200 °C, the Al/Si interface degenerates and forms solution pits because of thermoelectric stress, which easily forms voids at the contact place and causes debonding [16]. Meanwhile, the thermoelectric migration from Al to Si causes the deterioration of ohmic contact. Thus, pressure sensors with Al electrodes cannot operate reliably. High-temperature composite electrodes should be applied as the electrode lead of high-temperature pressure sensors. Ti/Pt/Au multilayer metallization electrodes are applied with Ti as the contact and adhesion layers, Pt as the barrier layer, and Au as the conductive layer. The Ti/Pt electrode patterning is realized by the cut process. First, the photoresist pattern is formed by spin coating, soft baking, exposure, development, and post-baking, and the thickness of the photoresist film is 1.2 μm. Then, the Ti and Pt electrodes are sputtered successively with a radio frequency sputtering equipment, and the Ti and Pt film thicknesses are 500 and 2000 Å, respectively. The Ti/Pt electrodes are obtained by dipping into acetone and alcohol, peeling the mask layer and the upper metal layer. After cleaning and baking the Ti/Pt electrodes, the Au electrode is sputtered, etched with KI_3 solution, and annealed (520 °C, 15 min) in vacuum environment.

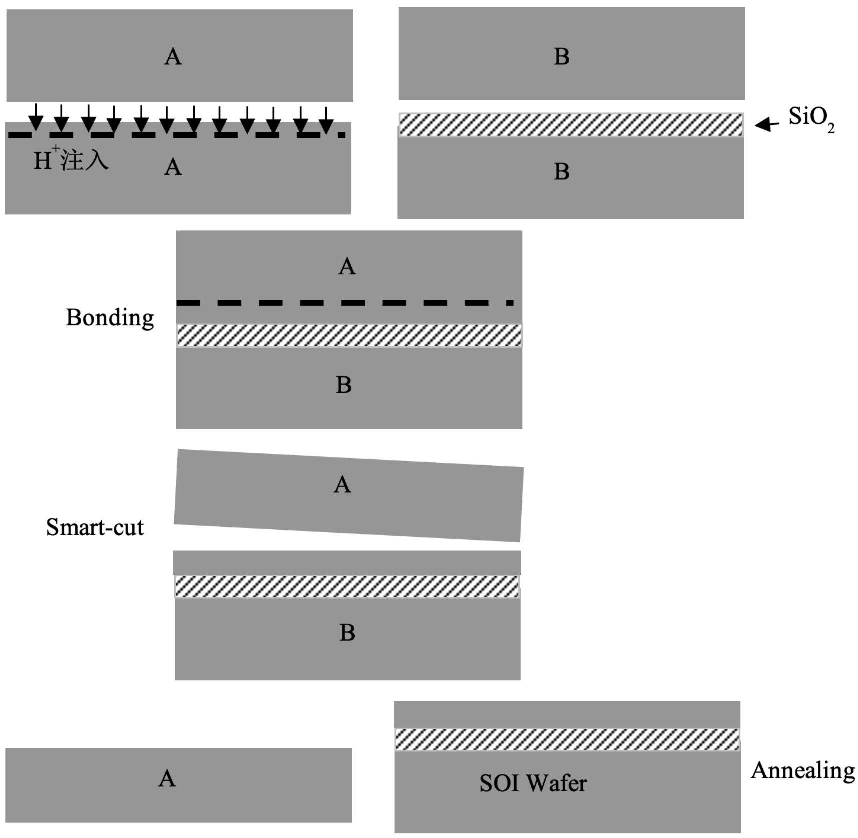

Fig. 2. Smart-cut process for SOI wafer

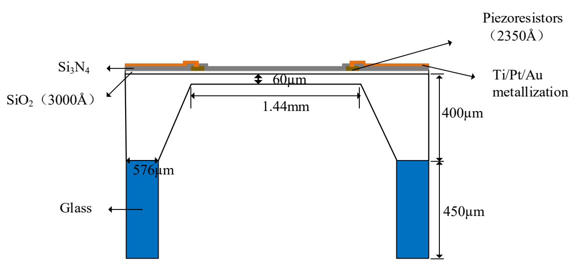

Fig. 3. Cross-sectional schematic describing the fabrication process of sensors

3.5 Sensor package

The package forms of silicon piezoresistive pressure sensors are mostly with an oil-filled isolation structure to isolate the pressure medium from the pressure-sensitive chip and protect the chip, and the sensor chips are usually glued on sockets with glue. However, the oil-filled isolation structure is big and performs poorly in high temperature. The performance of sensors in high-temperature environments is difficult to ensure and affected by the process. Therefore, a novel solid-state packaging structure based on silicon/glass/kovar alloy bonding is proposed to effectively solve the reliability problems caused by the glue connection and oil-filled.

(1) Principle of electrostatic bonding

Electrostatic bonding technology was proposed by Wallis and Pomerantz in 1969. Metal, alloy, or semiconductor can be directly bonded with glass by this technology [31]. The schematic of the electrostatic bonding equipment developed by Shenyang Instrument Research Institute is shown in Fig. 4. The equipment has a vacuum system. During electrostatic bonding, the surfaces of the prepared sensor chip/glass, glass/pressure pipes are closely in contact, placed between the two copper plate electrodes, and heated by a heater. The glass is connected to the cathode terminal, while the silicon chips or pressure pipes are connected to the anode terminal.

(2) Packaging structure and process

The all-solid-state packaging structure based on silicon/glass/kovar alloy bonding is shown in Fig. 5. The picture on the right is a sample (die/glass/pressure pipes) photo. The solid-state connection between the kovar alloy pressure pipes and the sockets, and the cover and the sockets are accomplished by the electron beam welding process. The process flow of packaging is shown in Fig. 6.

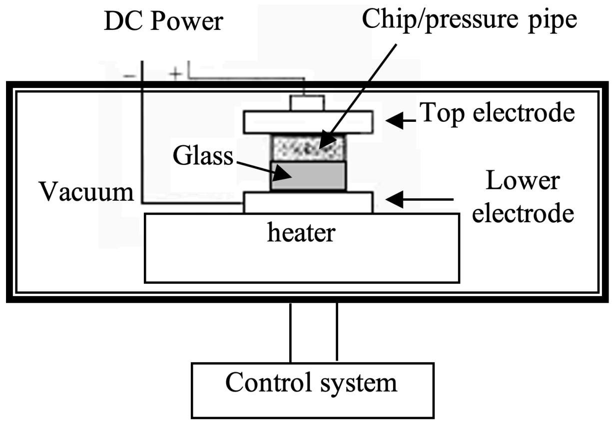

Fig. 4. Schematic of electrostatic bonding equipment

4 Result Analysis and Discussion

4.1 Result and analysis of electrostatic bonding

Glass is known as an insulator and a non-conductive material at room temperature. However, after heating and supplying high direct current (DC) voltage to glass, the positive ions (such as Na, K, and Ca ions) in a Pyrex 7740 glass will move toward the negative electrode in the strong electric field. Meanwhile, the dipoles produce a polarization orientation. The glass also shows conductivity in the process of forming a depletion layer on the surface of the glass adjoining Si. The thickness of the negatively charged depletion layer is approximately a few microns. Similarly, the electrons in the silicon in the applied voltage move toward the positive electrode of the power source and are devoured on the adjacent glass-silicon surface. Thus, the Si–glass interface generates a depletion region with positive silicon and negative glass surfaces. Most of the applied DC voltage falls on this depletion region, forming a strong electric field near the contact surface, producing a strong electrostatic attraction force, and bonding the flat Pyrex 7740 glass and the silicon chip together. Meanwhile, given that electrostatic bonding occurs at a relatively high temperature, the following electrochemical reactions occur at the closely bonded silicon/glass interface [32].

Silicon surface:

$$Si + 2H_2O \rightarrow SiO_2 + 4H^+ + 4e^- \quad (5)$$

$$Si + O - Si - OH \rightarrow Si - O - Si + H^+ + e^- \quad (6)$$

Glass surface:

$$Na_2O \rightarrow 2Na^+ + 1/2O_2 + 2e^- \quad (7)$$

$$Na_2O + H^+ \rightarrow 2Na^+ + OH^- \quad (8)$$

At the anode, silicon is oxidized and loses electrons. At the cathode, Na^+ will be reduced, and Si-O-OH bonds transform solid Si-O bonds at the interface to form strong bonds, such as S-O-S. Bonding temperature: 350 °C. Bonding pressure: 30 g of uniform force to maintain close contact between two materials. The DC voltage is controlled at the range of 400 V. When voltage is applied, a current pulse is generated soon. After a period, the current drops near zero, and the bonding is finished. The system cools naturally to reduce the effect of thermal stress on the bonding strength.

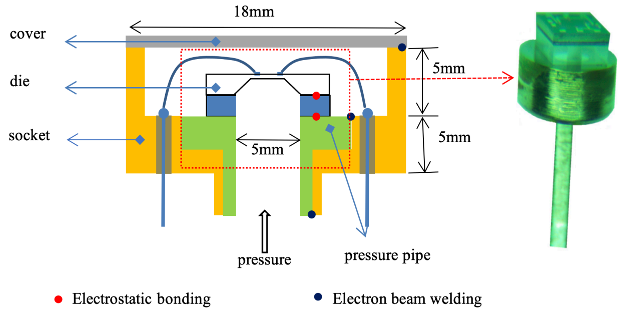

Fig. 5. All solid-state packaging structure based on silicon/glass/kovar alloy bonding

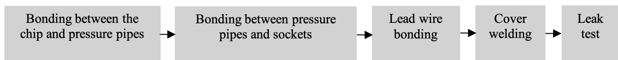

Fig. 6. Process flow of packaging

Kovar alloy is a Fe-Ni-Co alloy mainly composed of Fe, and its thermal expansion coefficient is similar to that of Pyrex 7740 glass. The bonding interface between Pyrex 7740 glass and kovar alloy is shown in Fig. 7. A light transition layer can be seen at the bonding interface. Under the effect of electrostatic field and temperature, the interface between Pyrex 7740 glass and kovar alloy will polarize and produce ions migration. Iron, Co, and Ni diffuse into the glass, and the negative non-bridge oxygen ions in the depletion layer will accumulate on the surface near the anode, and iron is oxidized, forming chemical bonds. The anodic oxidation of anodic metal occurs rapidly once glass and metal come in close contact.

$$Fe^{2+} + O^{2-} -> FeO \quad (9)$$

Anode metal forms metal ions through electrochemical reaction, and the half-cell reaction is

$$Fe -> Fe^{2+} + 2e^- \quad (10)$$

In addition to the crystalline oxides which is formed by the direct reaction of Fe ions with oxygen ions, the other part of Fe ions enters the depletion layer of the glass under the external high electric field and forms Fe-Si-O amorphous compounds with glass, which accelerate the formation of the interface transition layer. When an anodic oxide layer is formed, the solid phase reaction between the metal oxides at the interface begins to occur. Combined with the oxidation reaction at the interface, the solid-state ions exchange reaction is reproduced in high temperature.

$$XFe + Na_2Si_2O_5 -> XFeO + Na_{2-2x}Si_2O_{5-x} + 2XNa \quad (11)$$

$$XFeO + Na_{2-2x}Si_2O_{5-x} -> Fe_xNa_{2-2x}Si_2O_5 \quad (12)$$

During the bonding process, the migration of ions results in the surface vacancy of cathode, which provides power for the reaction and promotes the reaction, forming a transition layer connecting the glass and the metal.

The electrostatic bonding process has strict requirement on the bonding surfaces of silicon wafer, glass, and kovar alloy pressure pipes. The bonding surfaces must be polished, which is the key to successful sealing. Meanwhile, the thermal expansion coefficient of the bonding material should match to avoid introducing stress and ensure temperature characteristics and long-term stability. Table 1 provides the coefficients of thermal expansion (CTE) of the sensor materials.

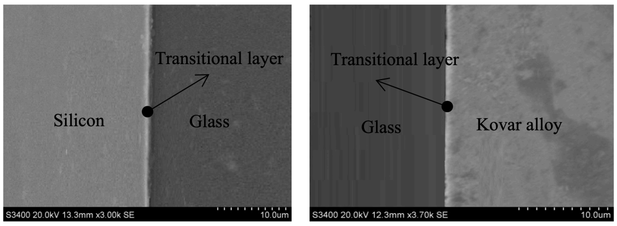

Fig. 7. Bonding interface between silicon and glass, glass and kovar alloy

Table. 1. CTE of the sensor materials

Items	Temperature (℃)	CTE (ppm/℃)
Silicon	20/250/500	2.46/3.61/4.15
Pyrex 7740 glass	0~300	3.25
4J32 kovar alloy	-20~300	3.2

4.2 Result and analysis of sensor test

Electrical aging (10 V DC, 72 h), temperature aging (-45 °C low temperature, 400 °C high temperature, 3 h of constant temperature, 3 cycles), and mechanical aging (0 – 2 MPa, 3000 cycles) experiments are carried out to obtain high-quality sensors.

The performance test in high-temperature involves the problems of nondestructive accurate measurement and safety. Both the high-temperature tolerance of the operating media of a pressure calibration device and the matching technology of the thermal expansion coefficients of a sensitive device and fixture by designing a special fixture shall be resolved, and thus the system error would not be imported by the leakage and random interference of the applied pressure in testing. The electron beam welding process is used to weld the sensor and fixture to ensure the safety test in high-temperature.

The sensors are placed in a high temperature oven using a GE sensing 7350 style high-pressure controller to obtain different pressures. The samples of the sensors are measured with an applied pressure from 0 to 0.6 MPa at different temperatures (i.e., 0 °C, 50 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C). The measured results at high temperatures (300 °C) are shown in Table 2. The sensitivity is approximately 200 mV/(mA MPa). When the least mean square method is used for the linear fitting of the measured results, the non-linearity is less than 0.59‰FS, and the repeatability is less than 0.04‰FS. The sensitivity temperature drift is less than -0.133 mv/(MPa·°C), and the sensitivity remains stable in a wide temperature range.

Table 2. Measurement results of pressure sensors with an applied pressure of 0－0.6 MPa at 300 ℃

300 ℃ Pressure (MPa)	Output (mV)						Conclusion
	Forward(1)	Reverse(1)	Forward(2)	Reverse(2)	Forward(3)	Reverse(3)	
0.0	3.716	3.721	3.721	3.722	3.722	3.724	Zero-point output 3.721 mV
0.1	23.484	23.489	23.488	23.490	23.489	23.491	Full scale output 119.383 mV
0.2	43.410	43.414	43.412	43.415	43.413	43.415	Non-linearity 0.059 %F·S
0.3	63.335	63.339	63.336	63.338	63.337	63.339	Hysteresis 0.003 %F·S
0.4	83.243	83.245	83.242	83.244	83.242	83.243	Repeatability 0.004 %F·S
0.5	103.150	103.151	103.149	103.150	103.148	103.150	Precision 0.064 %F·S
0.6	123.045	123.045	123.043	123.043	123.041	123.041	
Least square straight line Y=3.6510+198.9708X							

4.3 Analysis of relationship curve

The relationship curve of the sensitivity and temperature of the sensor is shown in Fig. 8. The curve shows that the output sensitivity of the sensor decreases with temperature in the range of 0 °C – 300 °C. The output of the pressure sensor powered by a constant current source mainly depends on the piezoresistive coefficient, stress and resistance of force sensitive resistors. Compared with the increased value of the force sensitive resistance with temperature, the effect of the piezoresistive coefficient decreasing with temperature on the output is more obvious. The relationship curve of the zero-point output and temperature of the sensor is shown in Fig. 9. The curve shows that the zero-point output changes little with temperature. The relationship curve of the non-linearity and temperature of the sensor is shown in Fig. 10. The curve shows that the non-linearity of the sensor has a decreasing trend with temperature, which is consistent with the literature [33]. The non-linearity of the piezoresistive effect has a decreasing trend with temperature, and the deep reasons need to be studied in the future. The relationship curve of the resistance of the power sensitive resistors and temperature is shown in Fig. 11. The curve shows that the resistance is 4.6kΩ at 50 ℃. The resistance increases linearly with temperature in the range of 0 °C – 300 °C, which is the result of the high doping concentration of the resistors. In the temperature range of 0 °C – 300 °C, the sensor for pressure and temperature measurement at the same time can be designed and prepared, and the temperature-measuring signal can be used on compensation of the sensitivity, improving the performance of high-temperature pressure sensors. The study shows that the high-temperature piezoresistive pressure sensors with a solid-state packaging structure based on silicon/glass/kovar alloy bonding could reliably work at the temperature range of 0 °C to 300 °C.

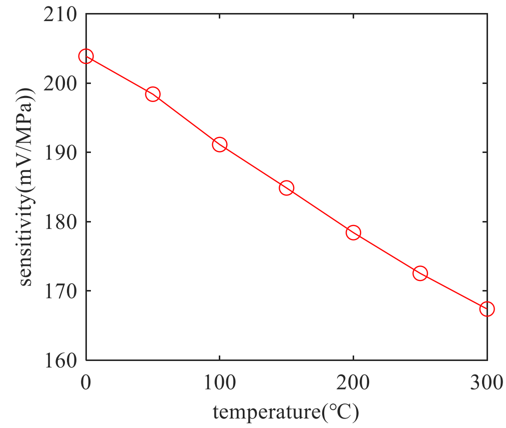

Fig. 8. Sensitivity vs temperature of the sensor

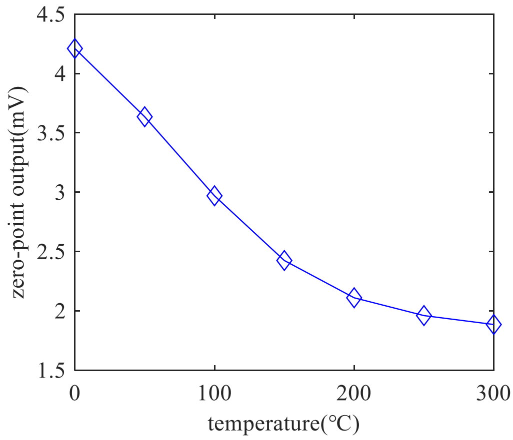

Fig. 9. Zero-point output vs temperature of the sensor

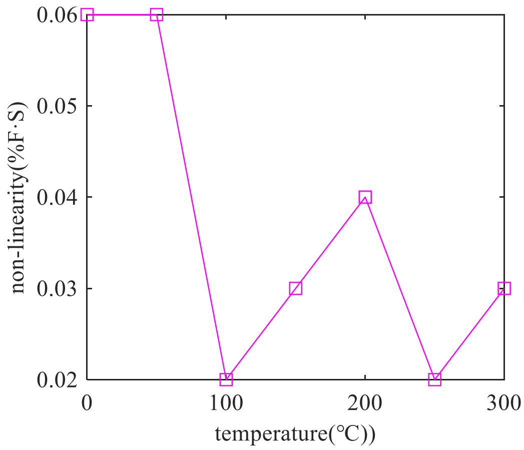

Fig. 10. Non-linearity vs temperature of the sensor

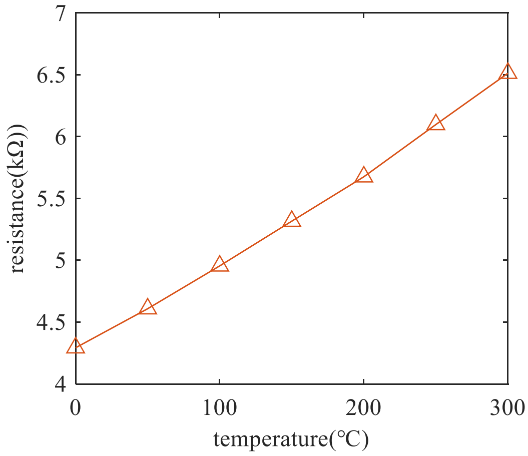

Fig. 11. Resistance vs temperature of the sensor

5. Conclusions

To improve the performance of high-precision piezoresistive pressure sensors and eliminate the poor temperature tolerance of silicone oil in common packaging structures, the performance of the prepared high-temperature piezoresistive pressure sensor was analyzed by designing the chip and packaging structure of the sensor. The following conclusions could be drawn:
(1) For the sealing between silicon wafer and glass, when the operating temperature of the sensor is high, the electrostatic bonding process is a good choice. The bonding speed is fast and the bonding quality is high when the bonding parameters are as follows: 350 °C, 400 V DC voltage for 2 minutes.
(2) For the sealing between glass/kovar alloy, when the working temperature of the sensor is high, the electrostatic bonding process is a good choice. The bonding speed is fast and the bonding quality is high when the bonding parameters are as follows: 420 °C, 600 V DC voltage for 2 minutes.
(3) The electron beam welding process is one of option for the welding between kovar alloys.

This study proposes a silicon oil-free, all solid-state packaging structure based on silicon/glass/kovar alloy bonding. The structure provides a certain reference for the pressure measurement of silicon piezoresistive pressure sensors in harsh high-temperature environments. In future study, the degradation of the bonding interface performance and graphics in high temperatures will be further analyzed, and the packaging structure of the sensor will be improved to enhance the high-temperature performance of sensors.

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