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Design and preparation of a high immunity piezoresistive pressure sensor

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Abstract: To eliminate the complex interference encountered by pressure sensors in practical applications, we designed and fabricated a piezoresistive pressure sensor featuring wide-temperature-range adaptability to harsh environments and high anti-interference characteristics. A circuit integrating conditioning compensation function with signal conversion function was proposed to compensate and convert pressure signals, and an integrated encapsulated housing was designed and fabricated to connect the pressure sensor chip with the PCB circuit for real-time processing of pressure signals. Its anti-interference performance was primarily reflected in reducing interference to the sensor caused by environmental temperature, voltage noise, and long-distance transmission. The thermal zero drift of the pressure sensor was reduced by 88.95%, and thermal sensitivity drift by 76.17% across the temperature range from −40 ℃ to 105 ℃. When subjected to voltage noise, the signal fluctuation was reduced by 99.7% after circuit processing. When subjected to long-distance transmission, the signal degradation after circuit processing was reduced by 89.9%. The results show that the sensor's anti-interference performance in complex real-world applications has been enhanced, resulting in more reliable output of the sensor.

Key words: micro-electro-mechanical systems (MEMS); silicon-on-insulator (SOI); pressure sensor; anti-interference; compensation circuit

0 Introduction

Pressure sensors are among the most widely used devices in industrial applications[1-4]. In recent years, silicon piezoresistive pressure sensors have gained widespread applications in aviation, aerospace, and marine engineering due to their high sensitivity and excellent stability[5-8]. In these application scenarios, sensors are frequently exposed to extreme temperatures and unstable voltage inputs, significantly impacting the measurement accuracy of pressure sensors. Therefore, it is necessary to develop a pressure sensor capable of stable operation and maintaining measurement accuracy in complex environments.

Recently, some researches have focused on pressure sensors facing complex environments such as high and low temperatures. For example, Giuliani et al.[9] investigated a pressure sensor with a pressure range from 0 MPa to 100 MPa and a temperature range from −50 ℃ to 400 ℃, and the test accuracy could reach ±0.5% of full scale. Yao et al.[10] proposed a pressure sensor with an integrated regulating circuit. The voltage output is amplified through an amplifier circuit, reducing transmission loss over long distances and improving the signal-to-noise ratio by 20 dB. Belwanshi et al.[11] made the sensor's sensitivity drop by only 9% at 200 ℃ via the oxide-isolated polycrystalline silicon resistor method. Xu et al.[12] designed a leadless package structure pressure sensor, with the upper limit operating temperature of 300 ℃, the lower limit operating temperature of −40 ℃, high temperature repeatability error of 0.77% at 300 ℃, low temperature repeatability error of 0.85% at −40 ℃, thermal zero drift of 4.9% per 100 ℃, and thermal sensitivity drift of 5.1% per 100 ℃.

The aforementioned research primarily focuses on the measurement errors generated by pressure sensors when exposed to high and low temperature environments. However, traditional piezoresistive pressure sensors rely on a Wheatstone bridge to convert a pressure signal into a voltage signal for output[13]. Due to Wheatstone bridge's inherent sensitivity to resistance changes, sensor output is affected when connecting wires are excessively long or when uneven contact resistance occurs. Additionally, voltage noise poses a significant challenge to practical engineering applications. Therefore, research on a silicon piezoresistive pressure sensor that not only withstands harsh high and low temperature environments but also exhibits high immunity to voltage noise and long-distance transmission is highly necessary. This paper presents the fabrication of a silicon piezoresistive pressure sensor using a complete process as well as a circuit that integrates conditioning compensation function and signal conversion function. This method successfully enhances the testing accuracy of the sensor, ensuring the measurement precision and anti-interference performance of the pressure sensor in complex environments.

1 Design and manufacturing of piezoresistive pressure sensor

1.1 Design of pressure sensitive chip

The design of piezoresistive pressure sensors is based on the piezoresistive effect of silicon resistors[14]. The general piezoresistive pressure sensor consists of four resistors that are placed in the diaphragm stress concentration area, respectively. When an external force acts on the diaphragm, the diaphragm deforms. Then, deformation signals are transmitted to the piezoresistor to cause its own resistance changes, thus converting the change in resistance into a voltage output through the measurement circuit[15], as shown in Fig.1.

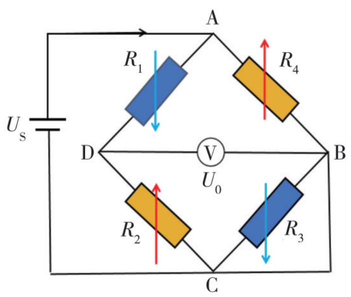


Fig. 1 Schematic diagram of pressure sensor

According to the Wheatstone bridge principle, when the applied excitation voltage is U_s, the output voltage U_o is expressed as

$$U_0=\frac{R_1+\Delta R_1}{R_2+R_1+\Delta R_2+\Delta R_1}-\frac{R_4+\Delta R_4}{R_3+R_3+\Delta R_4}U_s, \quad (1)$$

where U_s is the input voltage; U_0 is the output voltage; and R_1, R_2, R_3 and R_4 are the bridge arm resistors.

The simulation operates on COMSOL Multiphysics to find the balance between sensitivity and overload resistance. Stress concentration zones are identified for placing varistors to ensure that the sensitive membrane deformation complies with thin-plate theory[16-17]. The deflection and differential stress distribution diaphragm of the sensor when the force is 2 MPa are shown in Fig.2.

We also use COMSOL Multiphysics to carry out electrical simulation analysis to calculate the sensor' s full-scale output and COMSOL finite element analysis software to analyze the structure of the sensitive chip. Under a 5 V supply voltage and a 2 MPa load, the potential distribution of the piezoresistor is shown in Fig.3, with the corresponding full-scale output voltage of 101 mV.

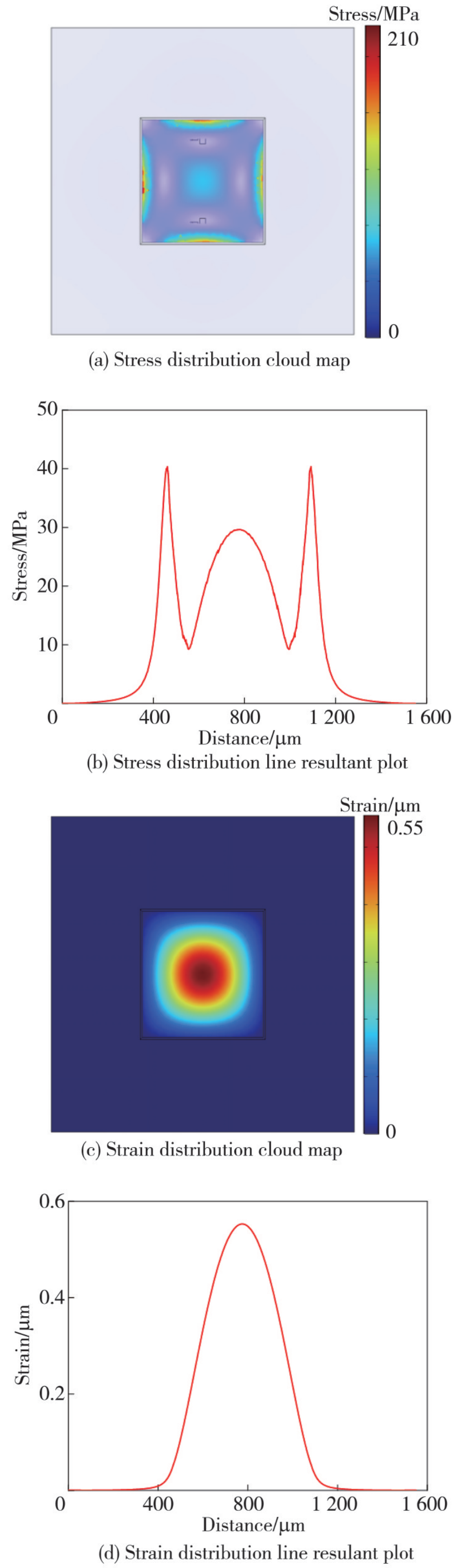


Fig. 2 Deflection and differential stress distribution of sensor diaphragm

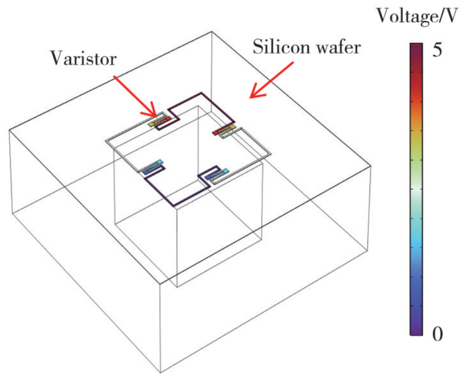


Fig. 3 Sensor potential distribution

1.2 Pressure-sensitive chip manufacturing

The piezoresistive pressure sensor sensitive chip in this study was prepared by MEMS process[18-19]. The specific preparation process flow is shown in Fig.4.

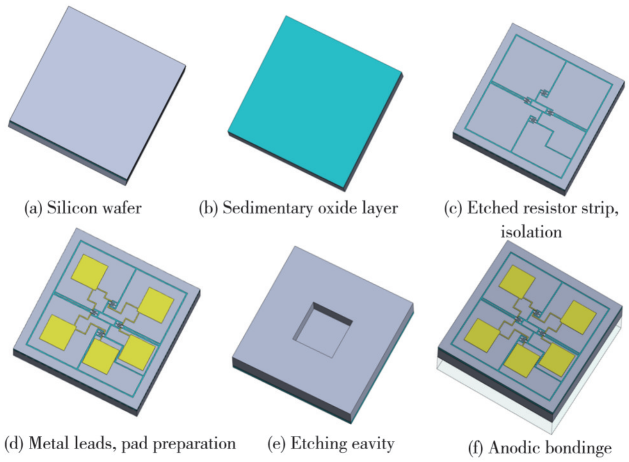


Fig. 4 Process flow diagram

a) Wafer preparation: silicon-on-insulator (SOI) wafer, double-sice polished, N-type, B-doped.

b) 1.5 μm silicon oxide is deposited on the SOI wafer via inductively coupled plasma enhanced chemical vapor deposition (ICPECVD) to serve as a masking layer for ion etching and resistor patterning.

c) Ions were injected into element B with a doping concentration of about 8.0×10^{17} cm^{-3} and a junction depth of 1.5 μm, followed by an annealing process to electrically activate the dopants and the use of reactive ion etching (RIE) to etch the resistor strips and electrical isolation grooves.

d) Titanium, platinum, and gold are deposited sequentially on the SOI wafer using a magnetron sputterer, and then excess metal is ultrasonically stripped to form patterned metal leads and bonding pads, which are heat-treated in a vacuum annealing furnace to form Ohmic contacts.

e) After deep silicon etching of the back cavity, the sensitive film is released.

f) The backsside of the SOI wafer is anodically bonded to a borosilicate glass substrate in a vacuum chamber to form a hermetically sealed reference cavity.

The pressure chip after preparation is shown in Fig.5.

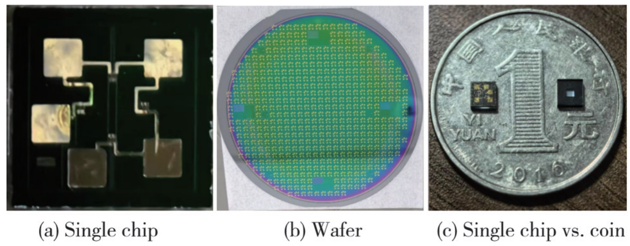


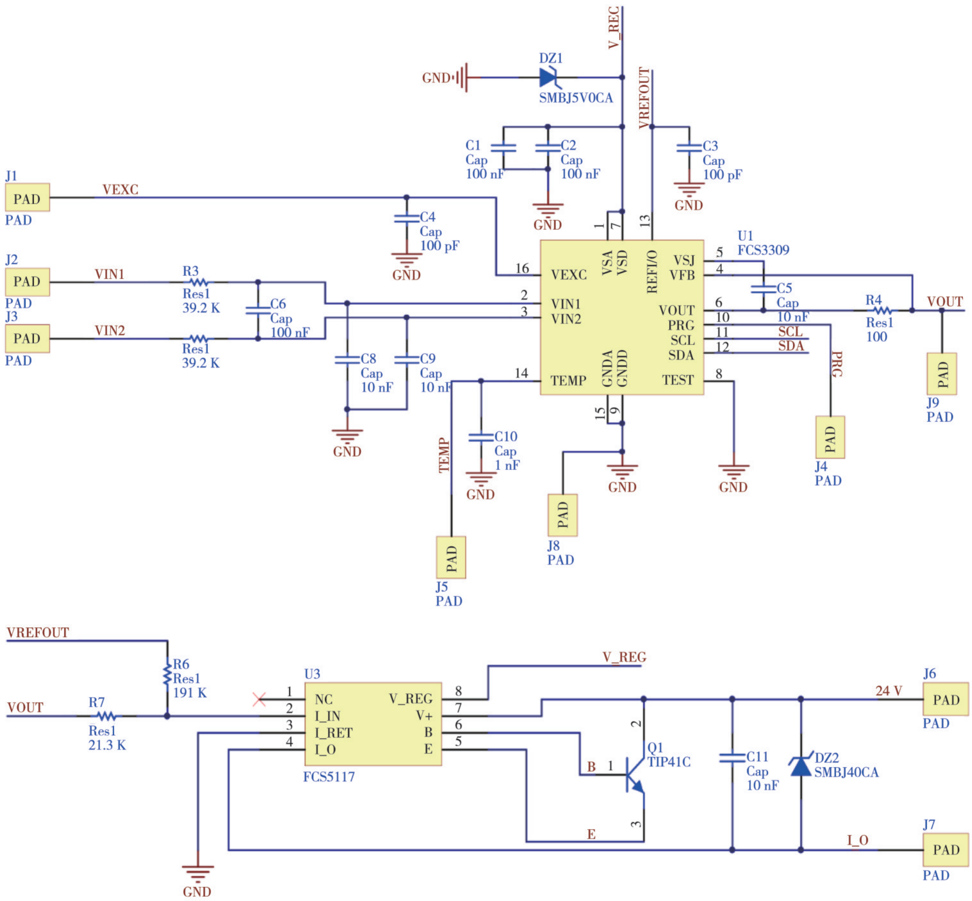
Fig. 5 Pressure chip

1.3 Circuit design

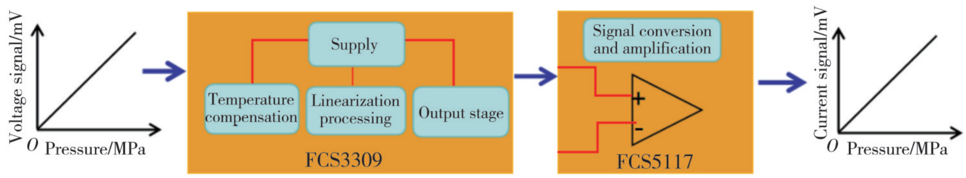
The signal compensation conversion circuit proposed in this study is designed based on signal conditioning chip FCS3309 and signal transmission chip FCS5117. The core of the temperature compensation conditioning section is FCS3309 chip, a programmable analog DC-DC converter specifically designed for pressure bridge sensors. The analog voltage signal output from the sensor undergoes digital calibration to adjust for zero drift, linearity error, and measurement range, thereby achieving linear amplification of the voltage signal. By sampling the external temperature sensor with the internal ADC, the impact of temperature on the sensor can be monitored in real time. The data are used to perform temperature compensation and conditioning on the pressure sensor. Based on the raw output data from the pressure sensor, the microcontroller can modify its internal registers via the PRG pin to perform specific compensation adjustments on the sensor. Communication with an external EEPROM via the SCL and SDA pins is used to save and load relevant temperature coefficients and other parameters.

For signal conversion and transmission, its core component is FCS5117 chip, a 4—20 mA current loop transmitter designed for industrial control applications. It accepts a conditioned and compensated voltage signal as its input. Powered by an external 24 V supply, it converts the voltage signal into a proportional 4—20 mA current output, thereby effectively eliminating signal degradation caused by voltage drops over long distances. Additionally, it generates a fixed 5 V voltage to power the pressure sensor.

The proposed signal compensation conversion circuit works as follows: The pressure sensor outputs a voltage signal via a Wheatstone bridge. Then, the FCS3309 acquires this voltage signal, performs temperature compensation and linearization processing, and outputs the processed signal. Finally, the voltage signal processed by the FCS3309 is acquired by the FCS5117, which converts the voltage signal into a standard 4—20 mA current signal. The circuit schematic diagram is shown in Fig.6.



(a) Circuit schematic



(b) Circuit operation diagram

Fig. 6 Schematic diagram of compensation conversion circuit

1.4 Pressure sensor packaging

The overall sensor packaging is shown in Fig.7. The package housing is made of stainless steel. Inside the housing, an oil-filled pressure core is encapsulated, the signal from which is connected to an internal PCB-based conditioning and compensation circuit for processing, and then is output from the front end of pressure sensor. The rear of the sensor features an M20 threaded interface, which is connected to a pressure application device that supplies the pressure signal.

1) Signal lead-out connector. It is threaded into the housing of the sensor to output the signal processed by the compensation conversion circuit.

2) Compensation conversion circuit. It is responsible for collecting the pressure sensing core signal for compensation conditioning and then converting it to 4—20 mA current signal.

3) Sensor housing. It is made of stainless steel and is responsible for protecting the pressure sensing core and compensation conversion ircuit.

4) Pressure sensing core. The prepared chip is embedded into a ceramic substrate and secured with adhesive. Bonding wires connect the pads on the chip to their corresponding pads on the substrate to route the signals. The assembly is the filled with silicone oil to protect the sensitive elements from harsh environments. A schematic of the core package is shown in Fig.8.

5) M20 pressure connector. It fixes the pressure core in place and ensures hermetic sealing through welding.

Its threaded interface at the rear is connected to the pressure testing device to introduce the pressure signal.

Fig. 7 Pressure sensor package schematic and physical drawing

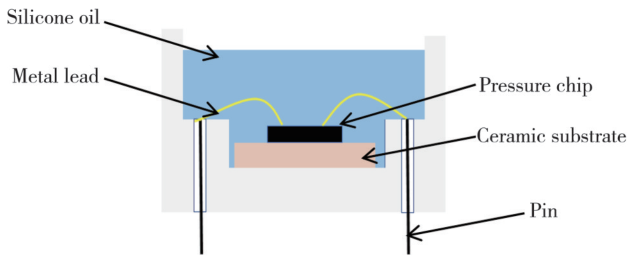


Fig. 8 Pressure core package schematic

2 Test results and discussion

The test platform consists of a pressure pump, a high-precision multimeter, a high-precision power supply, and a high-/low-temperature oven, as shown in Fig.9.

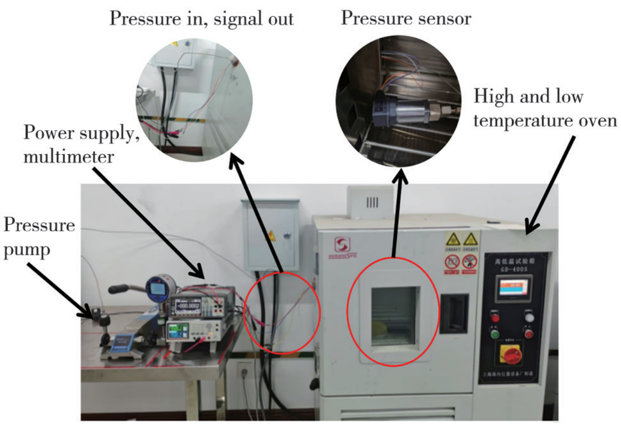
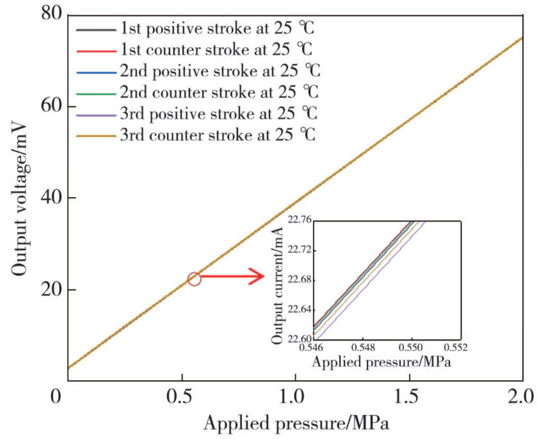


Fig. 9 Sensor test platform

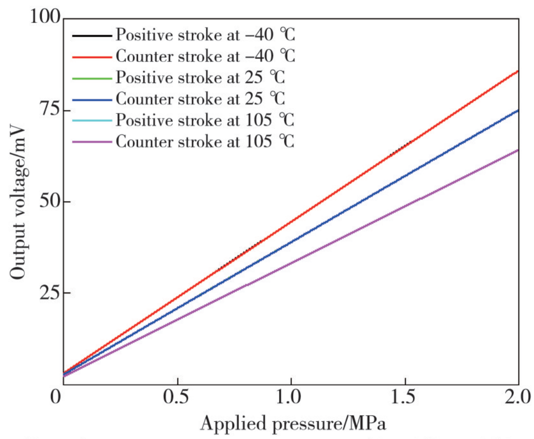
The sensor is placed in high- and low-temperature oven that provides different working temperatures . The pressure-conducting tube introduces the pressure into the sensor as a pressure source. The pressure sensor signal is led by a wire and connected to a high-precision multimeter for signal collection[21].

2.1 Temperature test

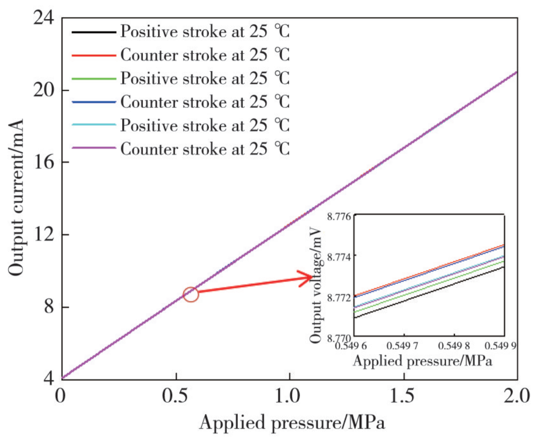
Under test conditions of −40 ℃, 25 ℃, and 105 ℃, the pressure of 0 − 2 MPa was applied to the sensor through linearly increasing (positive stroke) and linearly decreasing (negative stroke) sequences, respectively. The resulting variations in the sensor's current and voltage are shown in Fig.10.



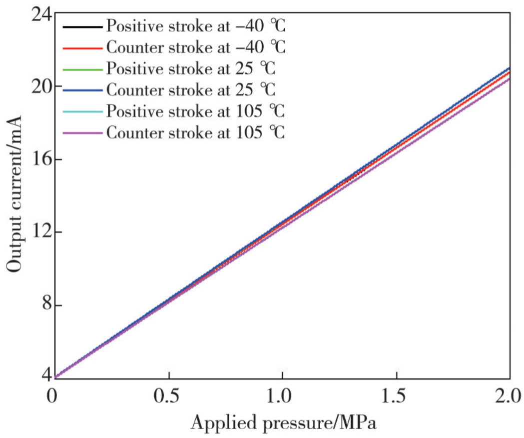
(a) Without compensation circuit, at 25 ℃



(b) Without compensation circuit, at −40 ℃, 25 ℃, 105 ℃



(c) With compensation circuit, at 25 ℃



(d) With compensation circuit, at −40 ℃, 25 ℃, 105 ℃

Fig. 10 Test results

Theoretically, the performance of a piezoresistive pressure sensor is closely related to the temperature-dependent behavior of its silicon resistors. As temperature increases, the piezoresistive coefficients of the silicon resistors decrease, leading to reductions in sensor sensitivity. Furthermore, due to variations in the manufacturing process of the silicon resistors, their temperature coefficients also differ. This results in inconsistent changes in resistance with temperature, which induces a zero shift in the sensor output under varying temperature conditions. To address this, a compensation conversion circuit is designed to acquire external temperature variation signals and perform temperature compensation on the sensor, thereby resolving the issues of zero shift and loss of sensitivity. According to the results of Figs. 10 (a) and (c) , we can calculate the linearity, hysteresis, and repeatability of the sensor before and after temperature compensation. According to the single-test results at different temperatures in Figs.10 (b) and (d) , we can determine the temperature characteristics of the sensor, including zero-point drift and loss of sensitivity. The calculated static performance and temperature characteristics of the sensor are listed in Table 1.

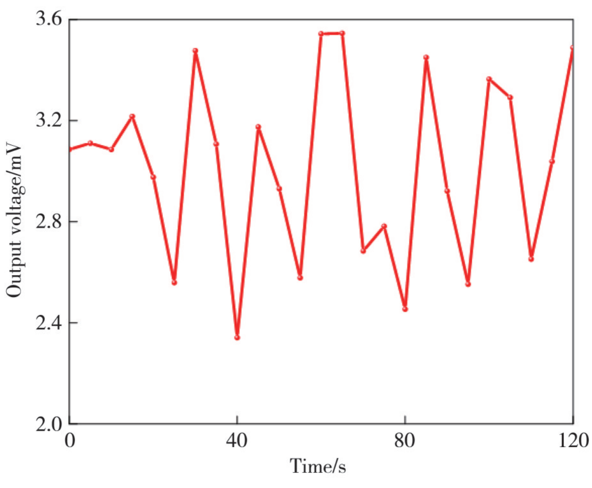
Table 1 Comparison of pressure sensor performance before and after compensation

Test	Linearity in full scale/%	Hysteresis in full scale/%	Repeatable in full scale/%	Zero drift in full scale/(%/℃)	Sensitivity drift in full scale/(%/℃)
Without compensation circuit	0.048 8	0.044 7	0.097 7	0.008 900	0.180 1
With compensation circuit	0.109 3	0.022 3	0.018 8	0.000 983	0.042 9

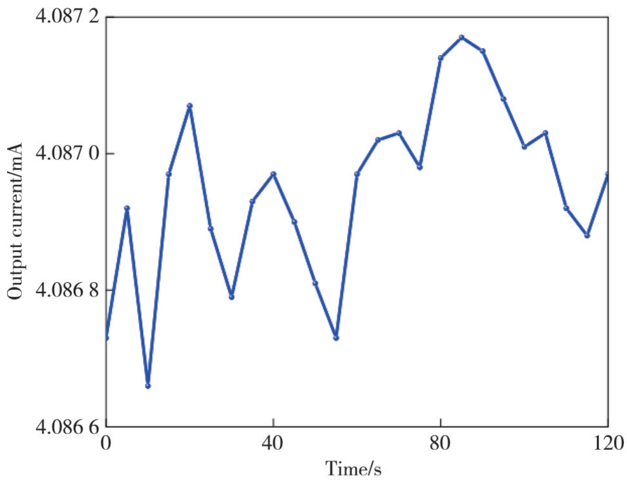
It can be seen from the test results that the compensation circuit reduces the zero drift by 88.95% and improves the sensitivity of the sensor by 76.17% without reducing its static performance. It also improves the measurement accuracy of the sensor in high-/low-temperature environments and expands the application scenarios of the sensor.

2.2 Voltage noise test

In practical applications, the power supply providing voltage for the pressure sensor inevitably experiences fluctuations, thereby generating voltage noise and affecting the output of the pressure sensor. In this study, signal transmission chip can generate a fixed 5 V voltage to power the pressure sensor although external voltage fluctuates, effectively eliminating the impact of voltage noise on sensor output. By adjusting the power supply voltage within a 15% range of its rated value to simulate voltage noise and recording the readings from a high-precision multimeter every 5 s, the tests on the pressure sensor without and with compensation circuit were conducted to evaluate its immunity to voltage noise. The test results are shown in Fig.11.



(a) Before circuit processing



(b) After circuit processing

Fig. 11 Test results of voltage noise

The pressure sensor output is subject to voltage noise interference up to 0.873 5% of full scale before the circuit compensation, while 0.002 6% of full scale after the compensation circuit, reducing the voltage noise interference by 99.7%. Therefore, the compensation conversion circuit enhances the voltage noise resistance of the pressure sensor, and improves the measurement accuracy of the pressure sensor in environments with voltage noise interference.

2.3 Long-distance transmission test

In practical applications, problems may arise where sensor signals need to be transmitted over long distance. Traditional piezoresistive pressure sensors rely on a Wheatstone bridge to convert pressure signals into voltage signals. However, the Wheatstone bridge is highly sensitive to changes in resistance. During long-distance transmission, voltage drop will result in signal loss. Additionally, if the contact resistance between the two wires of the differential signal is uneven, it will cause significant offset in the sensor's output signal. Here, converting the voltage signal to a current signal via a signal transmission chip can effectively prevent these issues.

This study simulated two signal transmission scenarios for the pressure sensor under test: one involving long-distance transmission, where 1 or 2 resistor was connected in series between the pressure sensor output terminal and the multimeter; and the other involving normal-distance transmission, where no resistor was connected. For these two transmission scenarios, the output signals with and without the compensation circuit were tested respectively, and the results are shown in Table 2.

Table 2 Test results of long-distance transmission

Test	General case output/mV	Long-distance analog test output/mV	Degree of impact in full scale/%
Without compenation circuit	3.086 2	3.058 5	0.038 20
With compensation circuit	4.086 7	4.087 3	0.003 84

It should be noted that, in the absence of the compensation circuit, the output signal was a differential voltage, with 20 Ω and 30 Ω resistors connected in series to the positive and negative terminals of the multimeter, respectively. In the case of using the compensation circuit, the output signal was a direct current, and a 30 Ω resistor was connected in series between the pressure sensor and the multimeter to simulate the long-distance transmission scenario.

It can be seen from the test results that using the compensation circuit to convert the voltage signal into the current signal reduces the influence of long-distance transmission by 89.9%. It effectively enhances the measurement accuracy of the pressure sensor during the long-distance transmission.

3 Conclusions

This study employs COMSOL to perform simulation analysis on a silicon-based pressure sensor, verifying its piezoresistive effect. A circuit integrating conditioning compensation and signal conversion functions was proposed. An integrated encapsulated package was designed and fabricated to connect the pressure sensor chip with the PCB circuit, enabling real-time processing of pressure signals. Experimental verification has demonstrated that the sensor's anti-interference performance has been improved. In high-/low-temperature testing, the zero drift and sensitivity drift of the pressure sensor decreased from 0.008 9% and 0.180 1% to 0.000 983% and 0.042 9% in full scale, respectively; In noise interference testing, the impact of voltage noise on signal output decreased from 0.873 5% to 0.002 6% in full scale; in long-distance transmission testing, the effect of long-distance transmission on signal output decreased from 0.038 2% to 0.003 84% in full scale. The sensor demonstrates strong resistance to interference when subjected to temperature variations, voltage noise, and long-distance transmission.

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Declaration of conflicting interests

The authors declare that they have no competing interests.

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高抗干扰压阻式压力传感器设计与制备

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摘　要: 为应对实际应用中压力传感器面临的复杂干扰情况, 设计并制备了一种具有宽温域恶劣环境适应性及高抗干扰特性的压阻式压力传感器: 调理补偿与信号转化一体的电路实现了对压力信号的补偿和信号转化, 集成化封装管壳实现了压力芯片与PCB电路的连接以实时处理压力信号。该传感器可减少环境温度、电压噪声和长距离传输的干扰: 在−40～105℃范围内, 其热零点漂移降低了88.95%, 热灵敏度漂移降低了76.17%; 对于电压噪声干扰, 经电路处理后的信号波动降低了99.7%; 长距离传输时, 经电路处理后的信号改变降低了89.9%。实验结果表明, 所设计的传感器应对复杂情况的抗干扰性能获得显著提升, 输出结果可靠性高。

关键词: 微机电系统; 绝缘体上硅; 压力传感器; 抗干扰; 补偿电路

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