High-sensitivity Silicon Resonant Strain Sensor

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Silicon resonant sensors, which are used in the DPharp series differential pressure transmitter, calculate pressure by measuring the strain of a diaphragm caused by the pressure with a built-in silicon resonant strain gauge. Although this gauge features higher sensitivity than metal foil strain gauges or piezo-resistance type strain gauges, measurement error is caused by temperature when its coefficient of thermal expansion is different from that of objects to be measured. To solve this, we have developed a new sensor by mounting a silicon resonant sensor on a thermal stress compensation structure and by driving the gauge electrostatically, achieving high sensitivity and less power consumption. This sensor delivers excellent affinity with wireless measurement and the Industrial Internet of Things (IIoT).

INTRODUCTION

Silicon resonant pressure sensors, which are used in Yokogawa's DPharp series differential pressure transmitters, feature excellent accuracy, repeatability, and long-term stability, and are used for a wide range of industrial measurements[(1)(2)].

Figure 1 shows a silicon resonant pressure sensor. A silicon resonant sensor chip is bonded on a glass plate, and a silicon resonator is manufactured in it using micro electro mechanical systems (MEMS) technology. A silicon resonator that functions as a strain gauge is called a silicon resonant strain gauge in this paper.

The sensor chip has a diaphragm structure on the rear surface. The pressure applied to the diaphragm causes strain in the silicon resonator and makes its resonance frequency shift. The absolute value of strain is calculated from the shifted resonance frequency and converted into the pressure value.

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The silicon resonant strain gauge used in the DPharp series differential pressure transmitters is driven electromagnetically. In contrast, a newly developed silicon resonant strain gauge is driven electrostatically and consumes little electricity. We have been studying the feasibility of a new strain sensor equipped with this gauge, which features high accuracy, high reliability, and low electric power consumption.

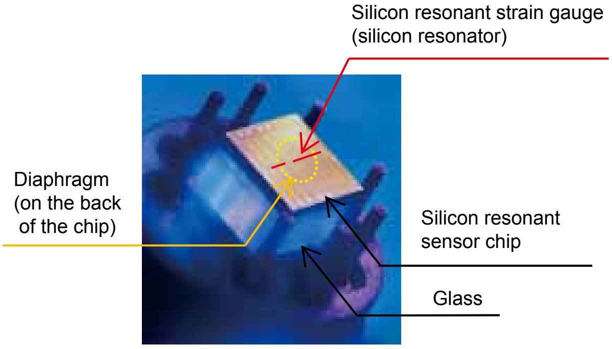

Figure 1 Silicon resonant pressure sensor

The sensitivity of strain gauges can be compared in terms of the gauge factor, G_f, which is the ratio of relative change in gauge output to the applied strain, ε. A larger gauge factor means higher sensitivity to strain. Table 1 shows the characteristics of the silicon resonant strain gauge and typical strain gauges. The resistance, R, of metal foil strain gauges and piezo-resistance strain gauges varies slightly according to expansion or contraction of the gauge. This minute change is detected by a Wheatstone bridge circuit and converted into a strain value. Metal foil and piezo-resistance strain gauges with various coefficients of thermal expansion are available, so thermal stress can be suppressed by selecting an appropriate gauge depending on the object to be measured. Since a Wheatstone bridge can also compensate for temperature effects, these gauges are stable against changes in temperature.

As shown in Table 1, a silicon resonant strain gauge has a much higher gauge factor than other strain gauges. Therefore, if a sensor chip is mounted directly on a material such as steel whose coefficient of thermal expansion is different from that of silicon, this difference causes thermal stress and this stress significantly increases thermal error in strain measurement. Thus, stable measurement is difficult with a silicon resonant strain gauge.

Table 1 Types of strain gauges and their characteristics

Type of strain gauge	Gauge factor		Applications
	Definition	Typical value	
Metal foil	$G_f \overset{\text{def}}{=} \dfrac{\Delta R / R_0}{\varepsilon}$	Approx. 2	Load cell Pressure sensor
Piezo resistance		Approx. 100	Pressure sensor
Silicon resonant	$G_f \overset{\text{def}}{=} \dfrac{\Delta f / f_0}{\varepsilon}$	Approx. 1000	Pressure sensor

For this reason, the application of silicon resonant strain gauges has been limited to pressure measurement in spite of their high gauge factor.

Yokogawa has developed a thermal stress compensation structure. By combining this structure with a silicon resonant strain sensor chip, the new silicon resonant strain sensor can stably measure minute strain. This paper describes this new sensor and the result of operation tests.

STRUCTURE AND OPERATING PRINCIPLE OF A STRAIN SENSOR

Key Structure of Silicon Resonant Strain Sensor with Thermal Stress Compensation Function

Figure 2 shows the key structure of a silicon resonant strain sensor having a thermal stress compensation function. A silicon resonant strain sensor chip is mounted on a thermal stress compensation structure. This structure transmits the strain in the measurement object to the silicon resonant strain gauge, while suppressing the thermal stress due to changes in ambient temperature.

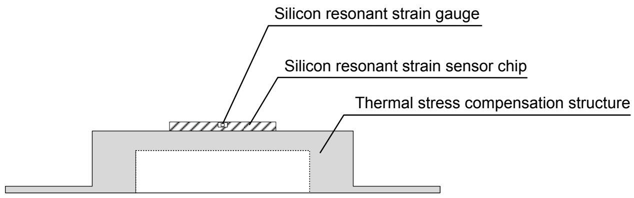

Figure 2 Sectional structure of a silicon resonant strain sensor

Mechanism of Thermal Stress Compensation Structure

Response of a strain sensor to changes in ambient temperature

Figure 3 shows the response of a silicon resonant strain sensor chip ("silicon chip") mounted directly on steel to changes in ambient temperature. Although both steel (measurement object) and the silicon chip expand as the ambient temperature rises, the thin silicon chip is stretched by the steel because the coefficient of thermal expansion of steel (approx. 12 με/K) is larger than that of silicon (approx. 3 με/K). This causes an isotropic tensile stress in the silicon chip, which affects the resonance frequency of the resonator and produces measurement error due to thermal stress.

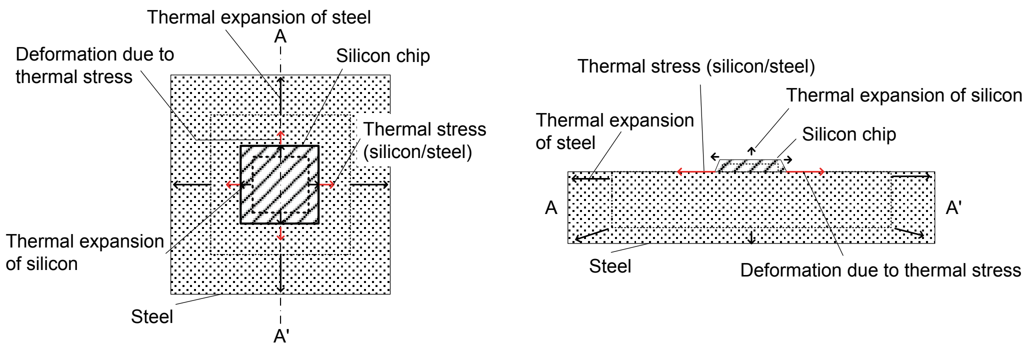

Figure 3 Deformation of a silicon chip mounted directly on steel due to rises in ambient temperature

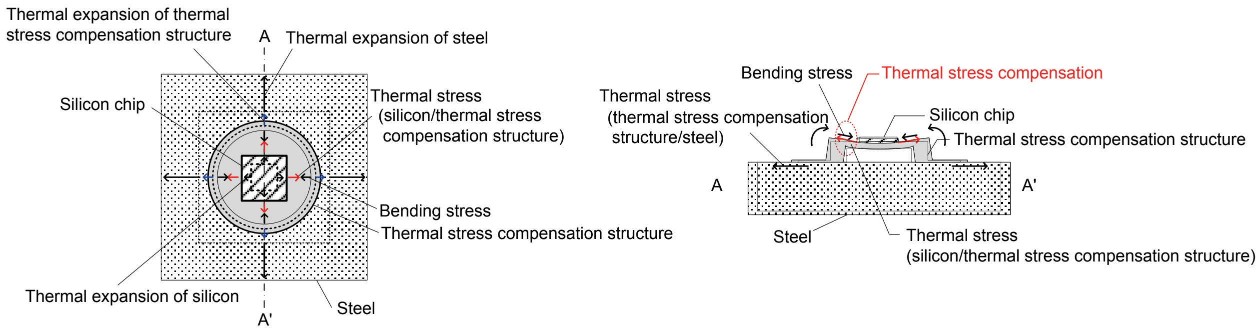

Figure 4 Deformation of a silicon chip with the temperature compensation structure mounted on steel

Figure 4 shows the response of a strain sensor with a thermal stress compensation structure to changes in ambient temperature.

When the ambient temperature rises, the steel, thermal stress compensation structure and the silicon chip expand respectively. If the coefficient of thermal expansion of the thermal stress compensation structure is lower than that of steel, the bottom of the structure is pulled outward by the steel. As a result, the bending stress bends the upper surface of the structure inward and a compressive stress is generated. This compressive stress suppresses the thermal stress generated due to the difference in coefficient of thermal expansions of the silicon chip and the thermal stress compensation structure.

Response of a strain sensor to applied tensile stress

This section describes the response of a strain sensor to applied tensile stress. Figure 5 shows the response of a silicon chip mounted directly on steel. When steel is pulled, the thin silicon chip on it deforms accordingly. Thus, the strain of steel can be determined by measuring this tensile strain applied to the silicon chip.

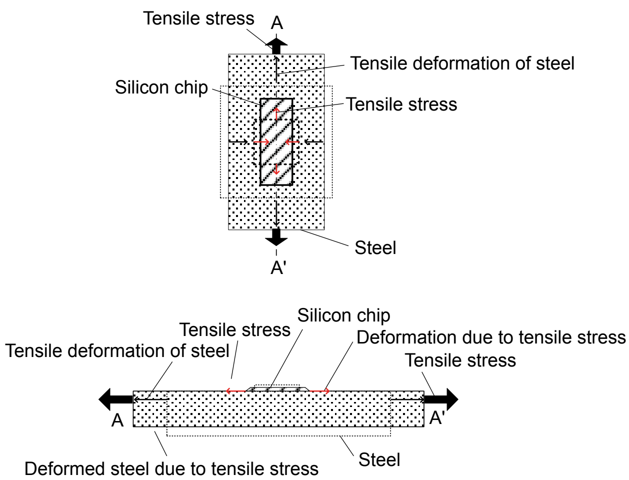

Figure 5 Deformation of a silicon chip directly mounted on steel to which tensile stress is applied

Figure 6 shows the response of a strain sensor with a thermal stress compensation structure to which tensile stress is applied. When the steel is pulled, the bottom of the structure deforms accordingly. The upper surface of the structure bends inward, and this action mitigates the stress generated in the steel. The silicon chip determines the strain of steel by measuring this mitigated stress.

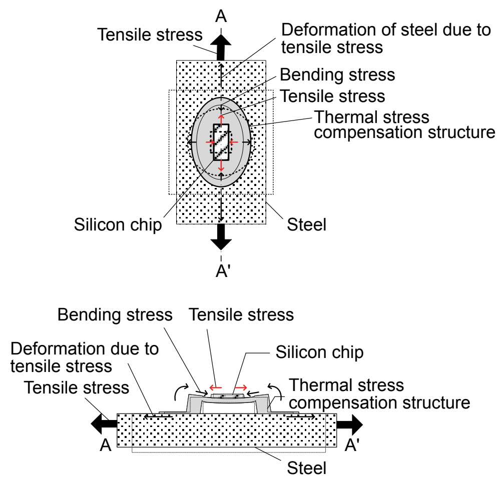

Figure 6 Deformation of a silicon chip with the temperature compensation structure mounted on steel

Thus, a thermal stress compensation structure enables a strain gauge with thermal stress compensation capability.

PROTOTYPE

The thermal stress compensation structure was designed by the finite element method (FEM). Figure 7 shows the results of simulating the thermal error and strain mitigation coefficient for various shapes of thermal stress compensation structures. We found that a structure can be designed with zero thermal error and adequate sensitivity to strain thanks to the thermal compensation effect. Figure 8 (left) shows a prototype silicon resonant strain sensor which has the characteristics shown as the red point in Figure 7. A silicon chip is mounted on a thermal stress compensation structure that has a hollow structure. The sensor signal is output via flexible printed circuits (FPC). The sensor is covered by a metal cap for electric shielding and physical protection, as shown in Figure 8 (right).

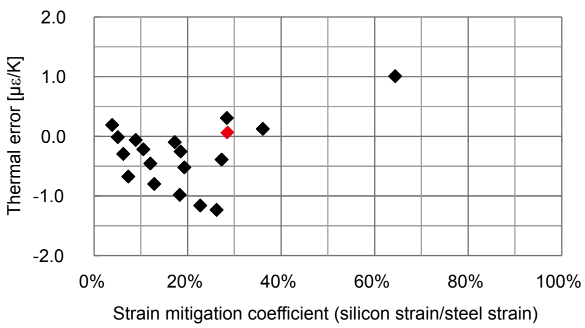

Figure 7 Simulation of thermal error and strain mitigation coefficient

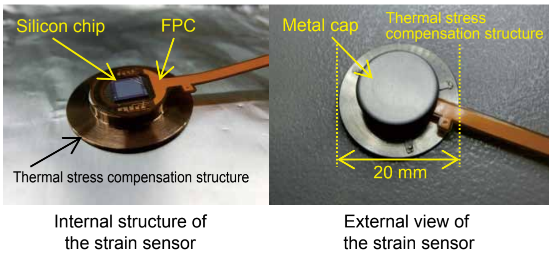

Figure 8 Photo of a prototype strain sensor

TEST RESULTS

Since a thermal stress compensation structure mitigates strain and transmits it to a silicon chip, the mitigation coefficient was measured by a tensile tester. Figure 9 shows the configuration of the tensile test. A test piece was prepared with a silicon resonant strain sensor mounted on one surface of the steel, and a commercial strain gauge on the other surface. This test piece was set on a tensile tester and tensile stress was applied to the test piece. Figure 10 shows the results of the tensile test. Nonlinearity is seen in the region under 40 με, which may be due to the initial misalignment of the test piece. As a result of the tensile test, the strain mitigation coefficient was found to be approx. 14%, and the gauge factor was approx. 107. Since the typical gauge factor of metal foil strain gauges is approx. 2, this test clearly shows that the prototype silicon resonant strain sensor has high sensitivity.

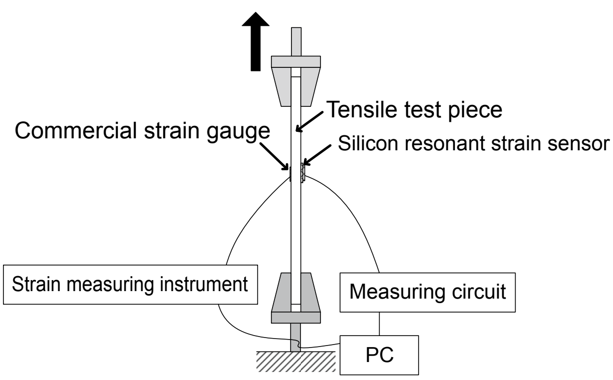

Figure 9 Evaluation system of tensile test

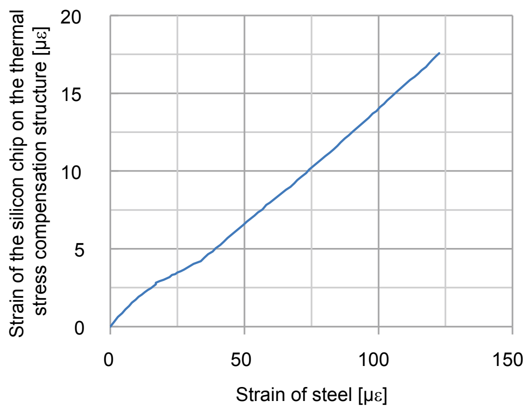

Figure 10 Tensile strain mitigation characteristic of thermal stress compensation structure

Figure 11 shows the thermal stress compensation effect measured on the prototype. A steel test piece with a silicon resonant strain sensor was placed in an isothermal bath, and the sensor output was recorded at various temperatures. When a silicon chip is glued directly on steel, the silicon chip deforms due to the thermal stress generated by the difference in coefficients of thermal expansion, as seen in Figure 3. The thermal error in strain measurement in this case was approx. 6 με/K. In contrast, the value of the prototype with the thermal stress compensation structure was within approx. ±1 με/K because the thermal stress was suppressed. This result confirmed the effectiveness of the structure.

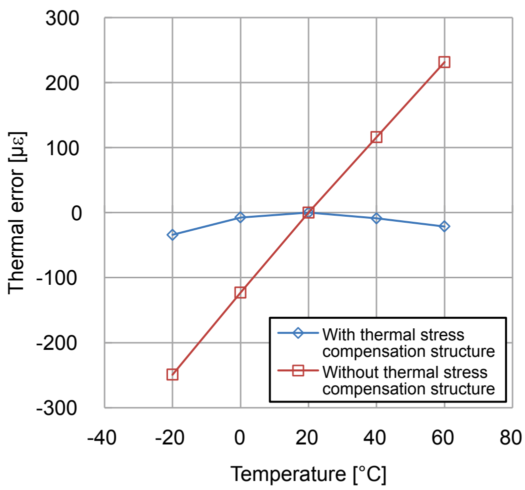

Figure 11 Thermal stress compensation effect of the prototype strain sensor

Figure 12 shows the result of measuring minute strain using a silicon resonant strain sensor on a cantilever.

A silicon resonant strain sensor was mounted on the fixed end of a cantilever, and ten weights were placed on the free end of the cantilever one by one to gradually bend the cantilever. The weight used in this test exerted a strain of 0.042 με on the cantilever. The spikes in the data were the impacts detected by the silicon resonant strain sensor upon adding a weight on the cantilever. The fluctuation in strain is approx. 10 nε at a sampling time of 100 msec, which means that strain measurement is possible with a remarkably high resolution even after the strain is mitigated by the thermal stress compensation structure.

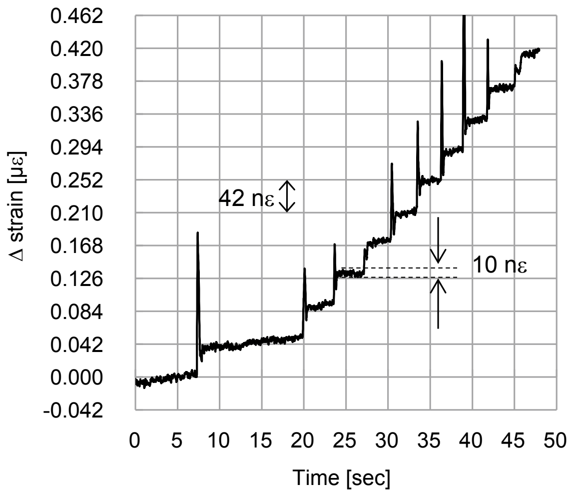

Figure 12 Resolution test with a cantilever

CONCLUSION

This paper introduced a high-sensitivity silicon resonant strain sensor under development as an application example of the new silicon resonant sensor.

The principle of the thermal stress compensation structure has been confirmed with the prototype. A strain sensor with a gauge factor of at least 100, small thermal error, and a high strain resolution of about 10 nε at a sampling time of 100 msec can be achieved by mounting a silicon chip on a thermal stress compensation structure. Since this sensor consumes little power, we believe that it is suitable for wireless measurement and the industrial internet of things (IIoT).

This study was supported by the Project to Solve Social Problems for Infrastructure Maintenance and Renewal, which is commissioned by the New Energy and Industrial Technology Development Organization.

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