Stable and Corrosion-Resistant Sapphire Capacitive Pressure Sensor for High Temperature and Harsh Environments

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ABSTRACT

This paper describes a capacitive pressure sensor utilizing sapphire as a structural material with a novel sapphire micromachining technology. It features high corrosion resistance, an oil-free structure, and high temperature usage. The fabricated sensor is confirmed to be a high accuracy pressure sensor having high pressure sensitivity in the temperature range covering from room temperature to 250°C with small thermal zero shift. The sensor is an absolute pressure sensor which is designed for a range of 0-350 k Pa. A thermal pressure sensitivity shift of a 0.03 % of full scale per degree (%F.S./℃) and a thermal zero shift of a 0.02 %F.S./℃ are obtained.

Keywords: capacitive pressure sensor, sapphire, corrosive & high temperature application

INTRODUCTION

In order to meet the demands of low cost and downsized products, the trend of pressure sensors shifted from mechanical sensors to silicon sensors utilizing micromachining technology. In terms of durability under industrial environments, silicon has poor corrosion resistance. For this reason, an oil-filled structure is commonly employed to isolate the silicon sensor from the medium to be measured. This oil-filled structure not only forms an obstacle to meet the lower costs and smaller sizes but also limits the uses in high temperature environments, high vacuum, etc.

Recently, in such fields like semiconductors and fine-chemicals industries, the pressure measuring demands in corrosive and/or in high temperature (150°C or more) atmosphere have been increased. In order to satisfy these demands with lower cost and smaller in size, the chip itself must be highly resistant to corrosion. Today, various pressure sensors have been reported where the chip itself is resistant to corrosion, but the chips have different issues as follows. In one type of silicon based sensors, pressure sensing diaphragm is coated with a corrosion-resistant film [1,2], but the formation of a corrosion-resistant film might results in a large hysteresis and insufficient long-term stability. In another type, alumina is used as the chip material [3], but the chip is large in size and the corrosion resistance of alumina itself is insufficient due to the fact that sintering promoters exist in grain boundaries. Piezo resistive type sensor that utilizes silicon on sapphire technology has difficulty in satisfying a high accuracy in a low-pressure range [4,5].

Our final goal is to realize an oil-free pressure sensor that has high corrosion resistance and is capable to precisely measure low to high pressure range even in high temperature region. For this goal, all sapphire-based capacitive pressure sensor has been proposed utilizing sapphire-to-sapphire direct bonding technology. It was confirmed that the first prototype model which was designed for a range of 0-5 kPa had small thermal zero shift in the temperature range between 0°C and 50°C and excellent long-term stability [6].

In this paper, the experimental measurement results of the sensor in a relatively high temperature ranging from room temperature to 250°C are reported.

SENSOR DESIGN

A photograph of the sensor chip and its cross section are shown in figure 1 and figure 2 respectively. The sensor chip consists of a diaphragm and a base, which are composed of sapphire and two pairs of electrodes, which form two sets of capacitors arranged on the opposite surfaces in the cavity. The one pair of electrodes forms sensing capacitor (Cx) that varies with an applied pressure and the other pair of electrodes forms compensating capacitor (Cr). The chip size is 9.0 mm by 9 mm and the diaphragm diameter is 3.0 mm. Figure 3 shows the packaged sensor.

The sensor chip is fabricated in the same process of the first model utilizing the novel sapphire micromachining technology [6].

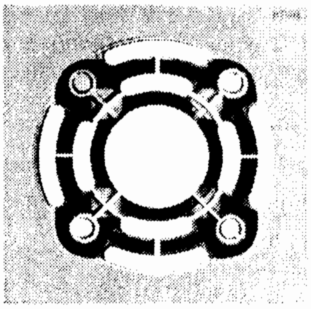

Figure 1: Photograph of the sensor chip

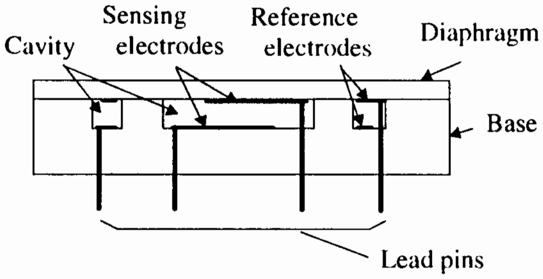

Figure 2: Schematic cross section of the sensor chip

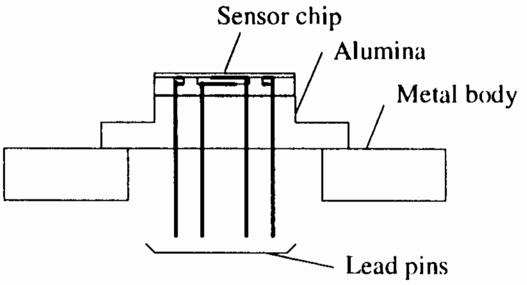

Figure 3: Schematic cross section of the packaged sensor

RESULTS AND DISCUSSION

Ratiometrical value of (Cx-Cr)/Cx that can offset the variation of dielectric constant between electrodes of Cx is used for the sensor characteristic measurement. In this paper, however, only Cx is used to understand the basic characteristics. All the measurements are conducted on the packaged sensor as shown in Figure 3.

Pressure characteristics

Figure 4 shows the relationship between applied pressure and the output of the sensor at the temperatures of 30, 100, 200 and 250°C with the output at 0 kPa normalized to zero. The thermal pressure sensitivity shift is only 0.03 %F.S./℃ in a temperature range from 30℃ to 250℃.

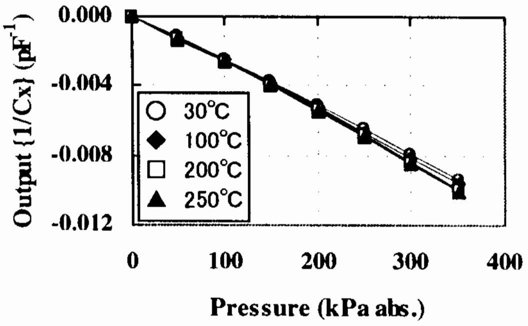

Figure 4: Pressure characteristics of the sensor

The cause of the thermal pressure sensitivity shift has been considered. Thermal variations of mechanical characteristics (expansion, Young's modulus) that are inherent factors of sapphire diaphragm itself are estimated as follows. For the circular diaphragm with a clamped edge, the relationship between applied pressure P and Cx is represented by equations (1) through (3) [7]. The thermal variation of the pressure sensitivity shift is estimated by applying the coefficient of linear expansion and thermal coefficient of Young's modulus of sapphire to the equations. The coefficients are assumed to be constant.

$$Cx=\sqrt{\frac{4\pi\,\varepsilon R^2}{64W_0L}}\ln\left[\frac{\frac{L}{W_0}+(\frac{r}{R})^2\sqrt{\frac{L}{W_0}}+(\frac{r}{R})^2-1}{\frac{L}{W_0}-(\frac{r}{R})^2\sqrt{\frac{L}{W_0}}+(\frac{r}{R})^2-1}\right] \quad (1)$$

$$W_0=\frac{PR^4}{64D} \quad (2)$$

$$D=\frac{EH^3}{12(1-\nu^2)} \quad (3)$$

W_0 : deflection at the center of the diaphragm
R : radius of the diaphragm
r : radius of the electrode of Cx
L : gap between the electrodes
E : Young's modulus of sapphire
ν : Poisson's ratio of sapphire
ε : dielectric constant between the electrodes

Values of E =3.36×10^5 MPa, ν =0.25, and ε =8.85 × 10^{12} F/m are used. The coefficient of linear expansion of sapphire and thermal coefficient of Young's modulus of sapphire are 8.0×10^{-6}/℃ and –44 MPa/℃ respectively.

Figure 5 shows measured and calculated values of the thermal pressure sensitivity shift with the pressure sensitivity at 30°C normalized to zero. The figure shows that the effect of the thermal variations of linear expansion and Young's modulus is 46 % of the pressure sensitivity shift. It is considered that the factor of the remainder of the shift is thermal variation of diaphragm's internal stress. The cause of the internal stress is assumed to be thermal stress from joint area between chip and packaging, temperature gradient within chip, mismatching of coefficients of linear expansion between electrode thin film and diaphragm, and so on.

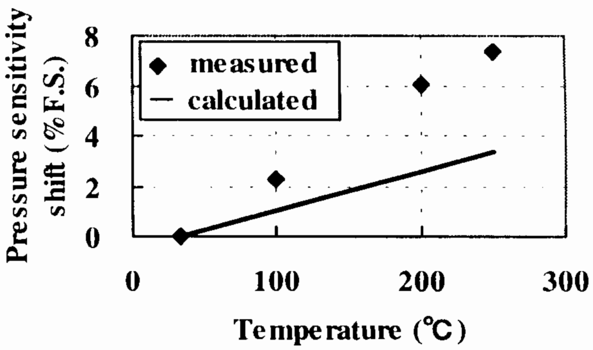

Figure 5: Pressure sensitivity shift of the sensor

To realize a high accuracy sensor, it is required to compensate the pressure characteristics using a proper approximation formula. Figure 6 shows deviation of the output (1/Cx) in the figure 4 from the cubic polynomial approximation at 30, 100, 200 and 250°C. From the figure 6, the deviation is less than 0.2 %F.S. when the pressure characteristics is compensated using the cubic polynomial approximation. As the pressure characteristics can be compensated at multi-points in short period of time and it is possible to apply digital processing inexpensively, the cost increase related to polynomial approximation on pressure characteristics is rather small and therefore, it is generally implemented in industrial applications.

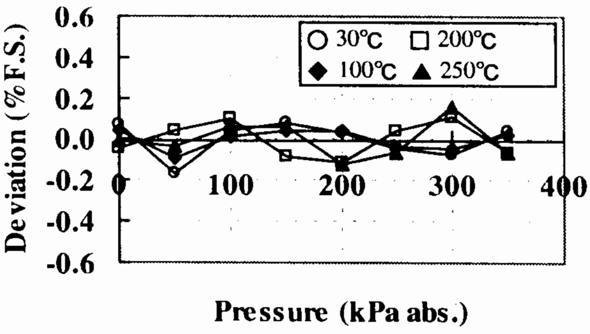

Figure 6: Deviation of the pressure characteristics from cubic polynomial approximation

Thermal zero shift

Figure 7 shows the thermal zero shift of the sensor. From the figure, the thermal zero shift in the temperature range between 50°C and 250°C is

0.02 %F.S./℃. It can be analyzed that the thermal influence on the pressure measuring accuracy while measuring pressure of the sensor is 0.1 %F.S. even the temperature varies ±5°C, showing the robustness against temperature variations.

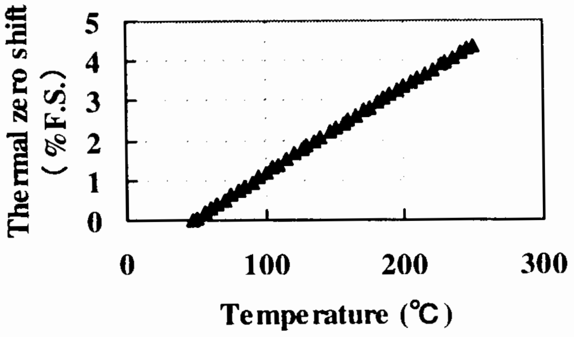

Figure 7: Thermal zero shift of the sensor

Summary of the performance

The summary of evaluation results on the packaged sensor has been shown in Table 1 in the temperature range from room temperature to 250℃. It has been proved that the sensor has the high accuracy with total performance within 0.2 %F.S.

Table 1: Summary of the performance

Pressure sensitivity	22 % of base capacitance at 30°C
	24 % of base capacitance at 250°C
Pressure hysteresis	<0.03 %F.S. (30, 100, 200, 250°C)
Deviation of the pressure characteristics from cubic polynomial	<0.2 %F.S. (30, 100, 200, 250℃)
Thermal pressure sensitivity shift	0.03 %F.S./°C (before thermal compensation)
Thermal zero shift	0.02 %F.S./°C (before thermal compensation)

CONCLUSION

All sapphire-based capacitive pressure sensor has been developed. The sensor features oil-free structure, highly corrosion resistant and high temperature usage. An absolute pressure sensor for the range of 0 – 350 kPa was fabricated and it was proved that the sensor has an excellent characteristics in the temperature range from room temperature to 250°C with small thermal zero shift. With this sensor, advanced pressure sensors for harsh and high temperature usage, such as semiconductor and fine-chemicals processing can be realized.

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