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Fabrication of High-Temperature Silicon Pressure Sensor Using SDB-SOI Technology

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A high-temperature pressure sensor using SOI structures formed by silicon-direct-bonding (SDB) technology has been developed. This sensor consists of a thin square diaphragm and a single-element four-terminal piezoresistor produced by MEMS technology by a standard IC process. The diaphragm sizes are 700×700×40 μm^3 (D700), 1700×1700×40 μm^3 (D1700), 2200×2200×40 μm^3 (D2200) and the thickness of the diaphragm is 40 μm. The pressure sensitivity of the fabricated sensor was 16.6 μV/V·kPa (D700), 95.6 μV/V·kPa (D1700) and 183.6 μV/V·kPa (D2200) for the 100 kPa full-scale pressure range. A sensitivity shift of less than 0.097%FS/°C was obtained in the temperature range between +20°C and +370°C.

1. Introduction

A high-temperature pressure sensor, which can be used at temperatures up to 300°C(1,2) and in corrosive environments, is in demand for use in many fields, such as automobile engine control, subterranean heat exploration, as well as industrial pressure sensing instruments.

The operating temperature range of a typically diffused silicon piezoresistive pressure sensor(3) is limited to a temperature of about 120°C, due to the leakage current of the p-n junction at high temperatures. We developed a piezoresistive pressure sensor with a SOI)structure for operation at high temperatures by SDB technology. It consists of a square diaphragm with SiO_2/Si structures and a single-element four-terminal piezoresistor on the edge of the diaphragm. We investigated the relationships among the pressure sensitivity, the aspect ratio of the diaphragm and the projected piezoresistor on the

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*Corresponding author, e-mail address: ytlee@andong.ac.kr diaphragm, which was fabricated by reactive ion etching (RIE), in order to optimize the design of the piezoresistive pressure sensor using shear stress.

In this paper, we describe the structure, design, and fabrication processes of the proposed high-temperature pressure sensor, and discuss its characteristics.

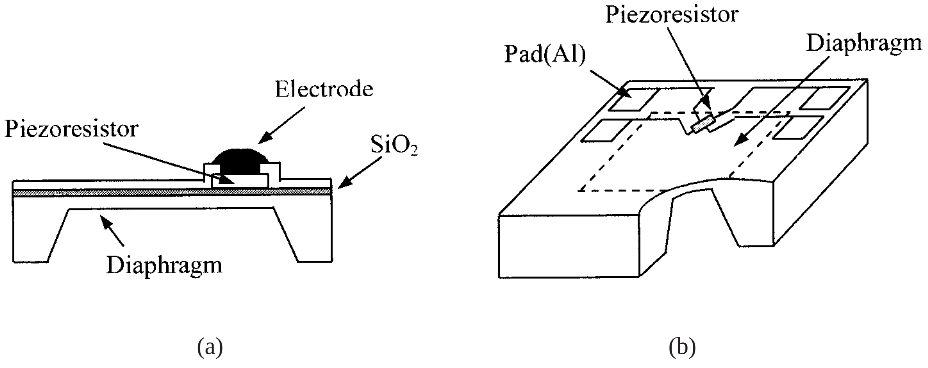
2. Design

The structure of the high-temperature silicon pressure sensor with a SOI structure proposed here is shown in Fig. 1. It consists of a thin square diaphragm with SiO_2/Si structures and a single-element four-terminal piezoresistor(4) on the diaphragm.

In the proposed sensor, the SiO_2 film on the silicon diaphragm is used for dielectric isolation of the piezoresistor from the substrate and the piezoresistor itself, respectively. The pressure sensor, with dielectric isolation of the piezoresistor, can operate at high temperatures up to 300°C.(1)

With this structure, the pressure sensor is characterized as having a higher sensitivity than conventional pressure sensors, which are generally fabricated by an ion-implant process on a flat diaphragm. As Fig. 1(a) shows, projecting-type piezoresistor was fabricated by RIE. Structural stress concentration occurred around the piezoresistor, and this heighted the sensitivity of the sensor, which is proportional to the stress. Figure 2 shows the results of the ANSYS simulation that evaluates the stress concentration which occurs around the piezoresistor. According to the results of our simulation, sensitivity rises more than 80% when the length of piezoresistor is shorter than one-tenth of the diaphragm length.

A piezoresistive-type pressure sensor using shear stress has been investigated by many researchers. It is usually realized by a single-element four-terminal piezoresistor, such as the Hall device.(5–8) It has advantages in terms of stability. It is small and is easy to produce because there is only one piezoresistor in comparison with a conventional full-bridge-type pressure sensor. Since the piezoresisitor can utilize the high piezoresistive effect of the single crystalline silicon, A high-sensitivity pressure sensor can be realized. Moreover, it is designed as a single-element four-terminal piezoresistor, which uses the shear piezoresistance effect. As such, it can be placed at the edge of the square diaphragm in the <100> direction on the (100) plane in order to achieve maximum sensitivity, as shown in Fig. 1(b).(5)



(a) (b)

Fig. 1. Structure of high–temperature pressure sensor.

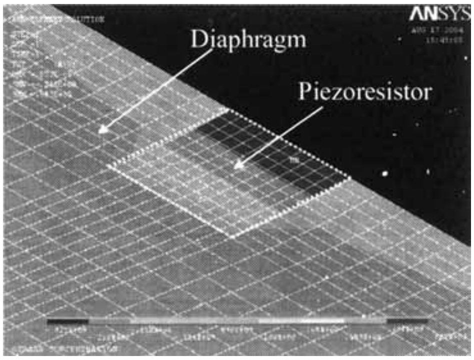


Fig. 2. Simulated shear stress concentration by ANSYS (pressure 100 kPa).

The sensitivity of the pressure sensor using the shear piezoresistance effect is proportional to the shear stress σ_{xy}. The resistive change (sensitivity) of the strain gauge, ρ_6/ρ_0, on the diaphragm can be expressed as

$$\frac{\rho_6}{\rho_0} = \pi_{44}\sigma_{xy} = \frac{1}{2}\pi_{44}\left(\sigma_x - \sigma_y\right)\sin 2\alpha . \tag{1}$$

According to this equation, the sensitivity is proportional to the shear piezoresistance coefficients, the difference between the normal stresses in the x-and y-directions, $\sigma_x – \sigma_y$, and the inclination angle of the strain gauge to the edge of the diaphragm, α.(5) Equation (1) can be rewritten as (for a strain gauge at the center of the diaphragm (x=0, y=0) with the inclination angle of 45°)(5)

$$S = \frac{\rho_6}{\rho_0} = \frac{1}{2}\pi_{44}P(1-\nu)\frac{a^2}{h^2}\left\{\frac{A^4}{1+A^4}\left[1-\frac{1}{A^2}\right]\right\}, \tag{2}$$

where P is the applied pressure, ν is Poisson's ratio, h is the diaphragm thickness, a and b represent half of the diaphragm width and length, respectively, and A is the aspect ratio of the rectangular diaphragm, $A=b/a$. It can be seen from eq. (2) that sensitivity is related to the aspect ratio of the diaphragm.(5)

In order to evaluate the dependence of sensitivity on the aspect ratio of the diaphragm, $A=b/a$, the shear stress distribution was simulated using ANSYS.(5) The shear stress distribution in a square diaphragm was simulated by ANSYS. We used solid 45 elements, which were three-dimensional, isoparametric solid elements with 8 nodes and three degrees of freedom at each node. Figure 3 shows the shear stress distribution in one-quarter of the square diaphragm, which was exposed to a pressure of 100 kPa.

Figure 4 shows the normalized sensitivies of the three positions (the center, the short edge, and the long edge of the diaphragm) as functions of b/a at a constant pressure of 100 kPa. The sensitivity at the center of the diaphragm reached its maximum value when $b/$

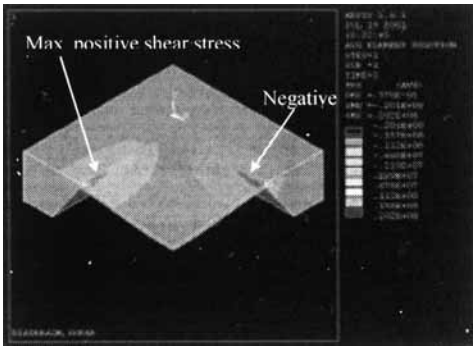


Fig. 3. Simulated shear stress distribution in one-quarter of the diaphragm obtained using ANSYS (pressure 100 kPa when b/a=1).

a=2.5, and it was close to zero percent when b/a=1 (square), because the normal stresses, σ_x and σ_y, at the center of the square diaphragm were homogeneous. The sensitivity at the long edge and the short edge of the diaphragm reached their maximum values when b/a=2 and 1.5, respectively.(5) In order to realize a small pressure sensor, it is very useful to set the strain gauge at the edge of the square diaphragm (b/a=1), because the square diaphragm is 60% smaller than the rectangular diaphragm (b/a=2.5) with a strain gauge on its center. Its sensitivity, however, reaches only 60% of that of a rectangular diaphragm with a strain gauge on its center or long edge. (b/a=2.5).

We designed square diaphragms of three different sizes, $700\times700\times40$ μm^3 (D700), $1700\times1700\times40$ μm^3 (D1700) and $2200\times2200\times40$ μm^3 (D2200). For maximum sensitivity dependent on the inclination angle, all piezoresistors are inclined at an angle of 45° to the edges of the square diaphragm.(5) As shown in Fig. 3, the positive and negative maximum shear stresses occur at the edges of the square diaphragm.

3. Fabrication

Figure 5 shows the overall fabrication process of a high-temperature piezoresistive pressure sensor. The starting material is a SOI wafer (n-Si: 1.5 μm/ SiO_2 :1 μm/ p-Si : 525 μm) formed by SDB technology. The diaphragm thickness is 40 μm. It is formed by etching in the TMAH solution at 90°C. The diaphragm thickness of the sensor was controlled by a V-groove depth control method. The upper silicon layer with 5×10^{17}cm^{-3} surface impurity concentration used to form a dielectrically isolated single-crystal silicon piezoresistor was etched by RIE. A 1-μm-thick passivation SiO_2 film was deposited by chemical vapor deposition (CVD) with SiH_4 and O_2 gases. After opening the contact holes, the aluminum film with a thickness of 1 μm for the electrodes was deposited by sputtering.

The pressure sensor chip is mounted on a glass base (SD-2 glass) by anodic bonding and is set to the package body. Au wire is used to bond the electrodes on the chip and the pins of the package. Figure 6 shows the photograph of the pressure sensor chip (Fig. 6(a)) and the packaged sensor (Fig. 6(b)).

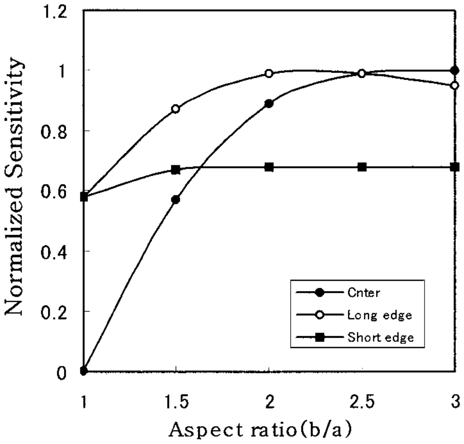


Fig. 4. Simulated sensitivites of the three positions as functions of the aspect ratio of the diaphragm (normalized).

4. Results and Discussion

Typical output voltage versus applied pressure characteristics are shown in Fig. 7. The pressure sensitivity levels, measured at the output terminal, were 16.6 μV/V·kPa (D700), 95.6 μV/V·kPa (D1700) and 183.6 μV/V·kPa (D2200) for the 100 kPa full-scale pressure range. If we used a rectangular diaphragm (b/a=2.5) for the sensor fabrication, we could get a 40% increase in pressure sensitivity, or more, in theory. The nonlinearity and hysteresis of the fabricated sensor (D2200) were less than 1.3%FS and 0.9%FS, respectively.

Figure 8 shows the temperature characteristics of sensitivity for the fabricated sensor (D2200). A sensitivity shift of less than 0.097%FS/°C was obtained in the temperature range between +20°C and +370°C. The offset voltage is 4.8 mV, and the offset shift is 0.026%FS/°C in the temperature range between +20°C and +370°C. These are acceptable values for many applications, and they enable the fabricated pressure sensor to operate in stable conditions up to a temperature of 370°C. Since performance is not seriously degraded at temperatures above 150°C because there is no leakage current in the piezoresistor owing to isolation by dielectric isolation (DI) technology using the SOI structure, the temperature drift mostly depends upon the shear piezoresistive coefficient π_{44}.(4) This is partially caused by the different thermal expansion coefficients of the silicon and silicon dioxide films.(9) The characteristics of the pressure sensor (D2200) are summarized in Table 1.

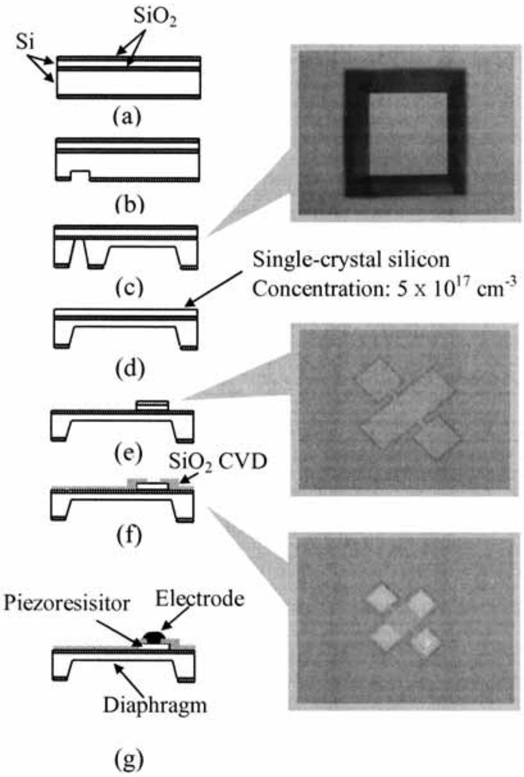
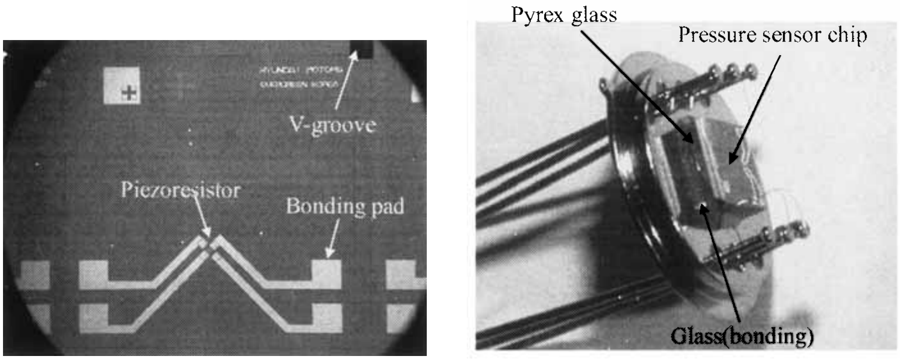


Fig. 5. Pressure sensor fabrication: (a) Initial oxidation, (b) V–groove formation, (c) Etching, (d) Ion-implantation, (e) Piezoresistor formation by RIE, (f) SiO_2–CVD and contact cutting, (g) Electrode formation by sputtering.



(a) (b)

Fig. 6. Photograph of the high-temperature pressure sensor: (a) sensor chip, (b) packaged sensor.

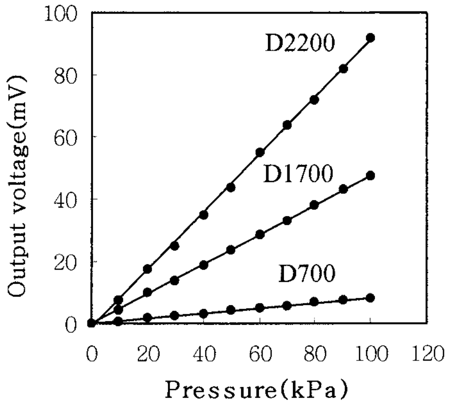


Fig. 7. Characteristics of the pressure sensors: 700×700×40 μm^3 (D700), 1700×1700×40 μm^3 (D1700), 2200×2200×40 μm^3 (D2200).

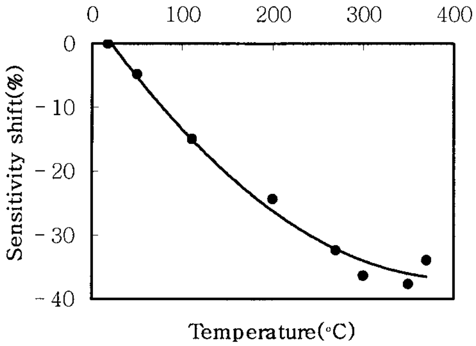


Fig. 8. Temperature effect of a full-scale span.

Table1
Specification (D2200).

Characteristics	Value
Pressure Range	100 kPa
Over Pressure	200 kPa
Supply Voltage	DC 5 V
Full Scale Span	92 mV
Sensitivity (30°C)	183.6 mV/V·kPa
Linearity	1.3%FS
Hysteresis	0.9%FS
Measured Temperature	18~370°C
Operating Temperature	–40~370°C
Temperature Effect on Full Scale Span	0.097%FS°C
Offset	4.8 mV
Temperature Effect on Offset	0.026%FS/°C

From these results, a high-temperature pressure sensor using the SOI structure seems to be especially attractive for many applications which operate at high temperatures and in corrosive environments, such as micromechanical sensors for automobile engine control and industrial pressure sensing instruments.

5. Conclusion

A high-temperature piezoresistive pressure sensor using a SOI structure formed by SDB technology, has been fabricated by MEMS technology together with standard IC process technology.

The output characteristics of the fabricated SOI structure pressure sensor showed that not only could it operate at temperatures up to 370°C, but it also had a high sensitivity.

The pressure sensitivity levels were 16.6 (μV/V·kPa(D700), 95.6 (μV/V·kPa(D1300) and 183.6 (μV/V·kPa(D2200) for the 100kPa full-scale pressure range. A sensitivity shift of less than 0.097%FS/°C was obtained in the temperature range between +20°C and +370°C.

The fabricated high-temperature pressure sensor can be applied to measure the combustion gas pressure of an automobile engine. Also, it is expected to be applicable to high temperature, high-pressure environments such as boilers.

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