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Improvement of piezoresistance properties of silicon carbide ceramics through co-doping of aluminum nitride and nitrogen

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Abstract

The piezoresistance coefficient was measured on co-doped silicon carbide ceramics. Evaluation samples of α-silicon carbide ceramics were first fabricated by glass capsule HIP method using powder mixture of silicon carbide and aluminum nitride with various ratios. The resultant aluminum nitride added silicon carbide ceramics were doped with nitrogen by changing the post-HIP nitrogen gas pressure. The lattice parameter increased with the amount of adding aluminum nitride indicating that the incorporated aluminum substituted smaller silicon atoms. After post-HIP treatment, lattice parameter then decreased with nitrogen gas pressure. The piezoresistive coefficient increased with the addition of aluminum nitride, it further increased with the nitrogen doping pressure.

Keywords: HIP; Co-doping; Donor; Acceptor; Silicon carbide; Strain sensor

1. Introduction

A resistivity change accompanied by the strain of a solid is called a piezoresistivity effect, which is utilized for the direct strain sensing or stress sensing within its elastic deformation range. Silicon single crystal is almost always used as strain sensing element. This is because it has a favorable sensitivity (piezoresistivity coefficient). Furthermore, sophisticated semiconductor technologies such as processing and joining can easily be transferred.

On heating as low as 200 °C, however, its elastic deformation range becomes narrow considerably. As a result, residual strain would remain after releasing the stress needed for sensing. Another problem on high temperature operation is oxidation leading to a soar in electric resistance. In these reasons, pressure sensor available over 200 °C has not been practicably realized yet.

Silicon carbide ceramics is expecting a high temperature structural material since it has an excellent thermal durability or maintained mechanical strength at elevated temperature. Silicon carbide also attracted much attention as an electronic material for high power devices and high temperature operation, because they possess a wide band gap of 2–3 eV. It has already been reported that silicon carbide single crystals exhibit the piezoresistive effect similar to the silicon single crystal [1]. There has been no practical application of silicon carbide single crystal for strain sensor because of its relatively small sensitivity and expensive fabrication cost.

On silicon carbide polycrystal which is advantageous for fabrication cost and mechanical strength, we have already reported a piezoresistivity coefficient comparable to that for single crystal [2–7]. Based on these data, we proposed a direct strain or pressure sensing at elevated temperature using silicon carbide ceramics of which sensitivity is barely feasible [4–6]. For sensing near room temperature, however, silicon single crystal is suitable due to its favorable sensitivity and fabrication cost. If the sensitivity of silicon carbide ceramics were enhanced to beyond that for silicon single crystal, it could substitute the strain or pressure sensing elements even near the room temperature, in addition to elevated temperature.

Compared with the exploring for a new material, it is advantageous to modify silicon carbide ceramics by incorporating variety of additives. This is because the high temperature property of silicon carbide ceramics would be maintained with the latter route. Another merit using polycrystal is a facile examination of doping effect.

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We have already examined the effect of dopant on the practically advantageous silicon carbide ceramics to improve the piezoresistive effect. The piezoresistivity coefficient is suggested to increase with increasing the doping amount within the solid solution limit in both group III and group V elements doping, e.g., 1.5 mol% in the case of aluminum [5,6,8]. We have also examined the co-doping of Al metal and atmospheric nitrogen. The effect of both dopants counteracted each other, resulting in degrading in piezoresistance coefficient [9].

In the present study, the piezoresistance coefficient was measured on co-doped silicon carbide ceramics. Evaluation samples of α-silicon carbide ceramics were first fabricated by glass capsule hot isostatic pressing (HIP) method using powder mixture of silicon carbide and aluminum nitride with various ratios. The resultant aluminum nitride added silicon carbide ceramics were doped with nitrogen by changing the post-HIP nitrogen gas pressure. The piezoresistive coefficient increased with the addition of aluminum nitride, it further increased with the nitrogen doping pressure.

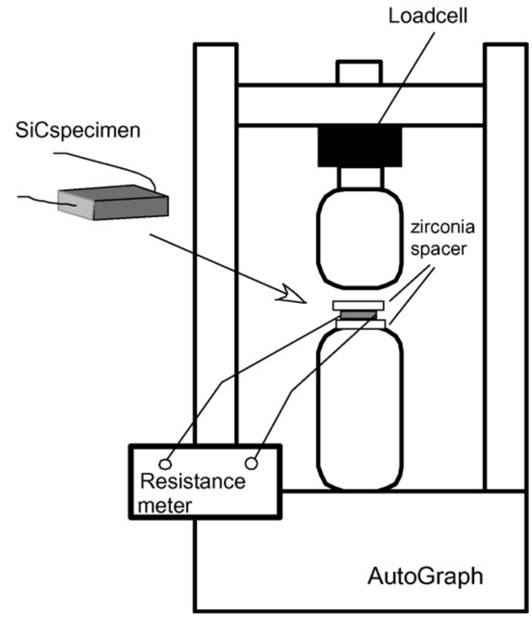

Fig. 1. Schematic set-up to measure the piezoresistivity property.

2. Experimental procedure

The α-type silicon carbide powders (Yakushima Dendo Co. Ltd., Yakushima, Japan) and aluminum nitride (Tokuyama Co. Ltd., Tokyo, Japan) were mixed with a predetermined ratio (0.2, 0.4, 0.6, 0.8, 1.0, 3.0 and 5.0 wt.% of AlN). Powder mixture of SiC and AlN were ball-milled in ethanol with zirconia balls for 2 h. The milled slurry was dried and subsequently sieved through a 280 μm mesh. About 0.7 g of this powder mixture was uniaxially pressed in a Ø 10 mm die under a pressure of 60–100 MPa. Resultant cylindrical powder compact was packed in a polyethylene bag, followed by cold isostatic pressing under 350 MPa.

The green compacts were then coated with BN powder (GP; Denka Co., Tokyo, Japan) to prevent reactions with the capsule glass during HIP process. The BN-coated specimens were put into a borosilicate glass tube to be used as the capsule. The tube was evacuated and heated to the softening temperature of the glass, then sealed and cut with a as flame burner, closely enveloping the specimen in a glass capsule. The encapsulated specimens were HIP-sintered under argon gas at a pressure of 195 MPa at 1950 °C for 30 min. After breaking the capsule glass, once HIP-sintered specimens were post-HIPed at 1950 °C for 30 min under various nitrogen pressure (50–195 MPa).

The resultant sintered specimens were subjected to density measurement by Archimedes method using deionized water as the immersion medium. The crystalline phases were analyzed by X-ray diffraction (XRD) with Cu Kα radiation.

The sintered bodies were cut into rectangular bars with a precision diamond saw (Step Cutter, Maruto Co. Ltd., Japan), and then surface polished with diamond paste (9 μm). The resulting test pieces with dimension of 3 mm × 4 mm × 6 mm were used to estimate the applied stress dependency of electronic resistance. The electronic resistance was measured by a two-probe direct-current (DC) method using a digital high-resistance meter (Model R8340A, Advantest Co., Ltd., Tokyo, Japan) with a constant voltage supply. Silver paste was attached to two of the parallel planes (3 mm × 4 mm planes) to form electrodes. These test pieces were placed on a mechanical test machine (AutoGraph AGS-5kNG, Shimadu Co., Ltd., Kyoto, Japan), and the compressive stress was applied to the plane of 4 mm × 6 mm which was perpendicular to the plane of the electrodes, increased at a constant rate. During this process, the electric current change, corresponding to the stress, was measured. From the effect of compressive stress perpendicular to the electric field on the change in electric current, the piezoresistance coefficient with application of perpendicular stress was calculated. The sample set-up is shown in Fig. 1.

In any case, resistance changes almost linearly with applied load. The piezoresistance coefficient, π, was obtained form the following relationship between the applied stress (σ), resistance without load (R) and change in resistance (ΔR).

$$\pi = \frac{(\Delta R/R)}{\sigma}$$

The Hall effects of silicon carbide ceramics with aluminum nitride and nitrogen were evaluated using a Hall effect evaluation system (Resitest 8300, Tokyo Technica Co. Ltd., Tokyo, Japan).

3. Results and discussion

3.1. Change in piezoresistive coefficient with AlN doping

First, we examined sample doped with only aluminum nitride (AlN), a group III and group IV compound. Obtained silicon carbide ceramics doped up to 5 wt.% of AlN have favorably densified with relative density over 92% of their theoretical ones. Density dependency of piezoresistance coefficient can be negligible with these samples [3].