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Evaluation of diamond gauge factor up to 500 °C

Akira Yamamoto *, Nawachi Norio, Tsutsumoto Takahiro

Western Industrial Research Institute of Hiroshima Prefecture, 2-10-1 Agaminami Kure 737-0004, Japan

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Abstract

Gauge factors of boron-doped polycrystalline diamond films were investigated in the ranges from room temperature to 500 °C and from 0 to 0.07 MPa of applied pressure. A VCR fitting was used as a package for a measurement at high temperature. Undoped and boron-doped polycrystalline diamond films were deposited on a Si substrate by hot filament chemical vapor deposition (CVD) method. A chip was fabricated with bulk micro machining technique. The gauge factors were evaluated in the ranges from room temperature to 500 °C in furnace. The calculated values of the gauge factors were found to vary in a range of 5–241. The gauge factors decreased with increased temperature from room temperature to around 100–300 °C. However, with higher temperature up to 500 °C, it increased.

Keywords: Sensors; p-type doping; Strain; Hot filament CVD

1. Introduction

Semiconductor diamond has a possibility of high speed and power devices at high temperature. Piezoresistive effect of p-type semiconductor diamond is very useful for pressure sensors, accelerometers, and vibration sensors. Furthermore, the diamond has many excellent properties such as large piezoresistive effect, hardness, chemical stability and thermal conductivity. These properties are useful in realizing a sensor in a harsh environment. Piezoresistive properties of the boron-doped diamond film and the sensors constituted by boron-doped diamond film were studied by a lot of researchers. Aslam et al. [1] first reported the piezoresistive effect of boron-doped diamond films and showed gauge factors increase with temperature from room temperature to 60 °C. Dorsch et al. [2] and Wang et al. [3–5] also studied the piezoresistive properties of various boron-doped polycrystalline diamond films. They showed the same trend of temperature dependence of gauge factors. However, Deguchi et al. [6] reported a degradation of gauge factors from room temperature to 200 °C. Adamschik et al. [7] also reported the relationship between the diamond film quality and gauge factor, and the temperature dependence of the gauge factor from room temperature to 350 °C. The gauge factor in each paper showed various changes: increase, decrease, constant or mountain like.

As mentioned above, well explanation was not proposed on the temperature dependence of the piezoresistive effect of a boron-doped diamond film. Especially, packaged sensor was not evaluated over a wide temperature range yet. Davidson et al. [8,9] tested the diamond pressure sensor from room temperature to 300 °C, and the sensor output decreased with increasing temperature.

In this work, in order to investigate a possibility of the pressure sensor using boron-doped polycrystalline diamond film

Table 1
Conditions for diamond film deposition

	Undoped diamond	Boron-doped diamond
Substrate temperature	900 °C	900 °C
Filament temperature	2500 °C	2500 °C
Filament–substrate distance	5 mm	5 mm
Gas composition	H_2–5% CH_4	1.8–3.1% C–O/H)
Pressure	4 kPa	4 kPa
Deposition time	180 min	50–120 min
Gas flow rate	300 sccm (CH_4+H_2)	H_2: 300 sccm (main), 30–60 sccm (bubbling) [a]

[a] Solution of H_3BO_3 to methanol (CH_3OH) was diluted to 1/3 with acetone ($(CH_3)_2CO$), and vaporized by hydrogen bubbling.

* Corresponding author. Tel.: +81 823 74 0050; fax: +81 823 74 1131.
E-mail address: aki-kayo@hh.iij4u.or.jp (A. Yamamoto).

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Table 2
Fabrication conditions of the sensor chips

Sample No.	Resistance (Ω)	Diaphragm thickness (μm)[a]	C–O/H (%)	B/C[b] (ppm)	Undoped diamond layer (μm)	Boron-doped diamond layer (μm)
2210	1720	32	3.1	5792	10	2 (deposition time 50 min)
2227	5270	45	3.1	1448	10	3 (deposition time 90 min)
2236	75,200	25	1.8	5792	10	3 (deposition time 120 min)

[a] Diaphragm thickness is a total thickness of unetched silicon layer and undoped diamond layer.
[b] B/C shows a boron to carbon ratio in liquid solution.

at high temperature, a prototype pressure sensor was fabricated and its gauge factor was evaluated in the ranges from room temperature to 500 °C.

2. Experimental

The boron-doped diamond was deposited on an isolation layer of an undoped diamond film. Selective diamond deposition was carried out by a metal mask. A sensor package using a VCR fitting made it possible to measure the gauge factor even at high temperature over 300 °C. Lead wires were bonded by silver brazing.

Diamond films were deposited on a Si substrate chips of size 10 mm in diameter and 0.7 mm in thickness, using the hot-filament CVD method under the conditions shown in Table 1. Boron was doped using a reaction gas containing H_3BO_3 during the deposition; the doping method was explained in Ref. [10]. Table 2 shows the fabrication conditions of the sensor chips. In the diamond deposition, film quality is significantly affected by carbon concentration in reaction gas. Therefore, boron-doped diamond film was deposited in low carbon concentration 1.8–3.1%, to keep a good film quality. The quality of the diamond films was evaluated by SEM observation and Raman measurement.

Fig. 1 shows the fabrication process of the diamond pressure sensor. The sensor chip was fabricated by bulk micro machining process. Ten μm-thick undoped diamond as an isolation layer and 2–3 μm-thick boron-doped diamond layer as a strain gauge were deposited on the silicon substrate by a metal mask.

Fig. 2 shows the chip layout of the pressure sensor. There are four boron-doped diamond resistors on the undoped diamond layer. Black painted area shows the boron-doped diamond layer and the dot line shows a diaphragm in a backside. The two resistors on the diaphragm were used for the measurements and the layout is shown in Fig. 2(b). Fabricated chip was connected to Cu wire by silver brazing in hot press reactor under 10^{-3} Pa.

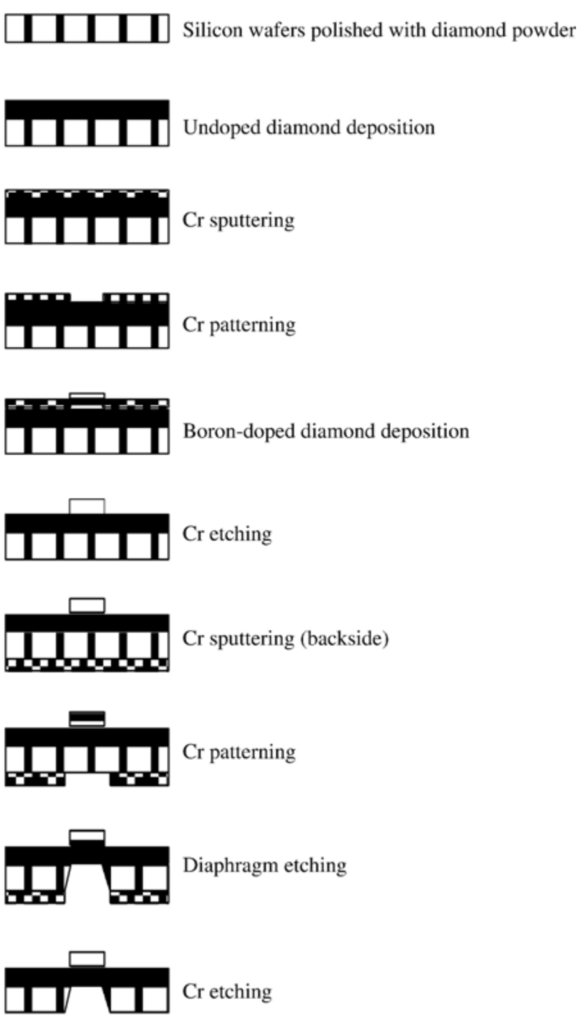

Fig. 1. Process steps for the diamond pressure sensor fabrication.

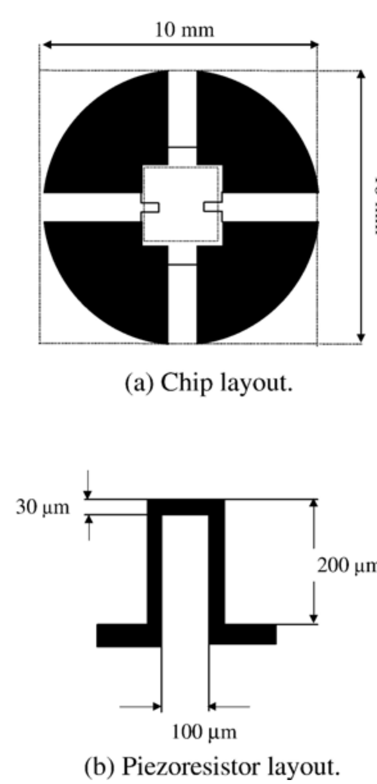

Fig. 2. Sensor chip layout.