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Piezoresistive Effect of Diamond Films Produced by dc Plasma CVD

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The piezoresistive effect of polycrystalline p-type diamond films formed by dc plasma chemical vapour deposition has been investigated. The gauge factor is about 116 at 500 microstrains at room temperature, and strongly increases with increasing temperature, exceeding that of polycrystalline- and single-silicon. The origin of the piezoresistivity in boron doped polycrystalline diamond films may be ascribed to strain-induced shift of the boron acceptor level and grain boundaries.

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Diamond can be considered as a semiconductor with a very wide band gap (≈5.4 eV) and has a variety of useful physical and chemical properties, such as good thermal conductivity, high carrier mobility and breakdown voltage, large drift velocity. Therefore, it is expected to be an attractive material for high frequency and high-power devices.[1-4] Recently, Aslam *et al.* first reported the piezoresistive effect in both polycrystalline and homoepitaxial chemical-vapor deposited diamond films.[5] Their experimental results have shown that the piezoresistive gauge factor of homoepitaxial diamond films was at least 550 at 500 microstrain at room temperature, exceeding that of crystalline silicon (120–170), but that of polycrystalline p-type diamond films was only 6. Dosch *et al.* presented double-layer structures with a nominally undoped diamond film and an overlying boron-doped diamond film on silicon to investigate the piezoresistive effect of polycrystalline diamond films.[6] Their experiments demonstrated that the maximum longitudinal gauge factor at room temperature is 5.4, and increases to 13.7 with increasing temperature from 27 to 60°C. Davidson *et al.* studied the piezoresistive effect of free-standing polycrystalline diamond films which exhibited the gauge factor between 10 and 100.[7]

In this work, we investigated the piezoresistive effect in boron-doped polycrystalline diamond films. Experimental results have shown that the gauge factor of p-type polycrystalline diamond films is about 116 at room temperature, and increases to 316 at 75°C at 500 microstrains. Diamond films used in study were synthesized by dc plasma chemical vapour deposition (CVD). The diamond films were doped p-type using a nontoxic saturated solution of boron trioxide (B_2O_3) powder in CH_3OH mixed with acetone. The typical growth conditions for polycrystalline p-type diamond films are listed in Table 1.

The quality of the diamond films were characterized by Raman spectroscopy, scanning electron microscopy, and electrical measurements.[8] The boron concentration in the films was measured by secondary ion mass specroscopy and capacitance–voltage measurements, and shown in Table 2.

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Table 1. Growth conditions for polycrystalline p-type diamond films.

Gases	H_2+CH_4
CH_4/H_2	0.5–2 vol.%
Flow rate	100–500 (Standard cm^3/min)
Substrate temperature	700–850°C
Applied voltage	700–1200 V
Discharge current	0.5–2A cm^{-2}
Total pressure	26600 Pa

Table 2. Boron concentration in p-type diamond films.

Sample number	Boron concentrations (cm^{-3})
DF1	2.5×10^{18}
DF2	2.2×10^{20}
DF3	1.5×10^{17}

For the measurement of the relative changes in the resistance with the strain, the diamond films were epoxied on the middle region of a free-standing stainless-steel beam. The thickness of stainless-steel beam and epoxy resin is about 50 and 30 μm, respectively. A mixture of hydrofluoric and nitric acids was used to remove the silicon substrate materials, and only remnant diamond films with a thickness of 7–10 μm and 4×7 mm area were glued to the stainless-steel beam that was protected using teflon tape. A tensile stress was applied to the films while the micrometer was screwed toward to the steel substrate. The deflection of the films with tensile stress can be obtained from the micrometer. The tensile strain on the diamond films was estimated using known elastic properties and geometry of the diamond and steel. The strain value obtained can be calibrated by a standard strain gauge and the calculation from the computed simulation. The direction of the strain and the direction of the resistance measurement were the same. The intrinsic strain of the films was neglected. The resistance of the films can be got from four point measurement. A schematic diagram of the piezoresistive effect is shown in Fig. 1.

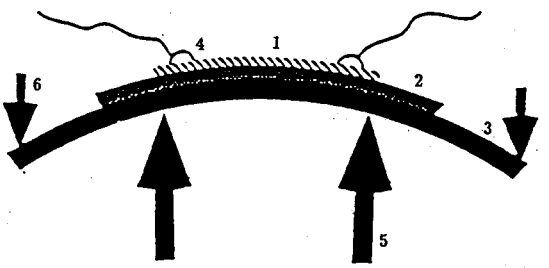

Fig. 1. Schematic diagram of the piezoresistive experimental arrangements. 1. Diamond films; 2. Epoxy layer; 3. Stainless-steel beam; 4. Nickel contact; 5. Micrometer; 6. Frame.

Figure 2 shows the relationship between the relative changes of the resistance, dR/R_0, and tensile strain, ε, for polycrystalline p-type diamond films at room temperature. The resistance changes, $dR = R(T) - R_0(T)$, was measured at temperature T, where $R(T)$ and $R_0(T)$ are the resistance values for strain ε and 0, respectively. The variation of dR/R_0 with strain ε is quite different at various doping level in the films. Much more heavily and lightly doped polycrystalline diamond films have less resistance changes with strain than that of moderately doped films. Figure 3 shows the dependence of the gauge factor K on the strain ε. The gauge

factor K is defined by the relationship:

$$K = \frac{dR}{R_0}/d\varepsilon = 1 + 2\nu + \frac{d\rho}{\rho_0}/d\varepsilon \,, \tag{1}$$

where ν is Poisson's ratio, ρ and ρ_0 are resistivity for strain ε and 0, respectively. The gauge factor is slightly decreased with increasing ε. The gauge factor is about 116 at 500 microstains at room temperature for sample DF1 (boron concentration $2.5\times10^{18}\,\mathrm{cm}^{-3}$), much larger than Aslam's results.

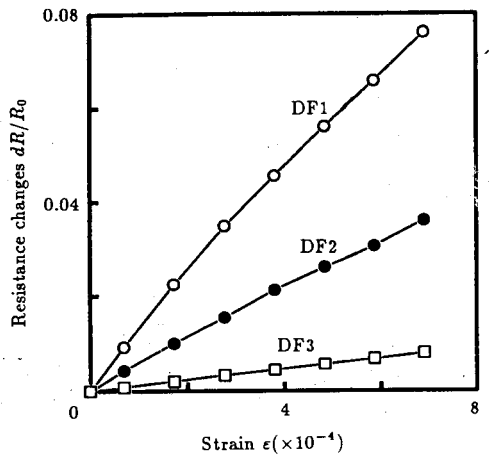

Fig. 2. Relationship between relative changes in the resistance and strain for polycrystalline diamond films with different boron-doped level at room temperature.

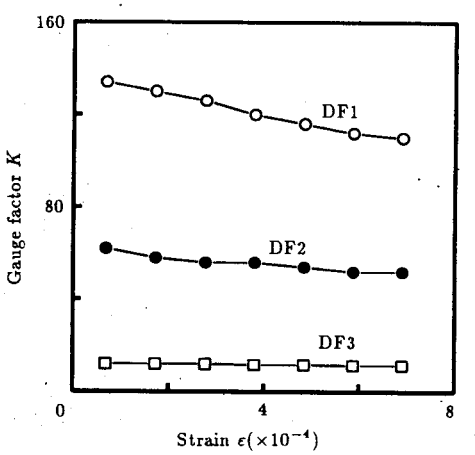

Fig. 3. Changes of the gauge factor with strain at room temperature.

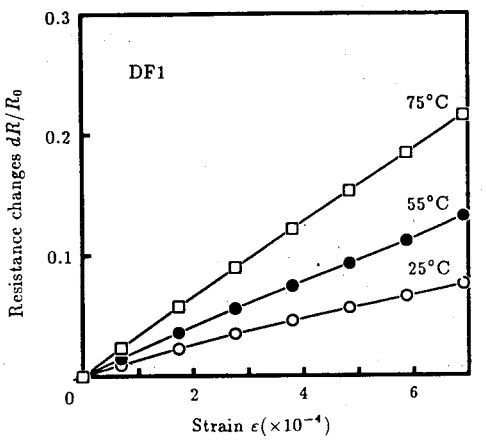

Fig. 4. Relative changes in the resistance with the strain for polycrystalline diamond films with boron concentration of $2.5\times10^{18}\,\mathrm{cm}^{-3}$ at various temperatures.

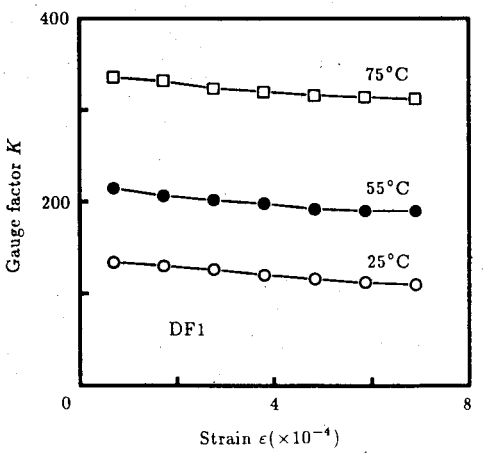

Fig. 5. Correlation between gauge factor and strain for polycrystalline diamond films with boron concentration for $2.5\times10^{18}\,\mathrm{cm}^{-3}$ at different temperatures.

A typical correlation between the relative changes of resistance and the strain at different temperatures for sample DF1 is shown in Fig. 4, where a linear relation exists. The measurement

must be at very stable temperature because the resistance of diamond films is much more sensitive to temperature. In our experiment, the variation of the measurement temperature is about $\pm 0.05°C$. Figure 5 shows the gauge factor with the strain at various temperatures for sample DF1. The gauge factor exhibits a very strong increase with increasing temperature. The gauge factor of polycrystalline diamond films with doped level of $2.5\times10^{18}\,cm^{-3}$ at 500 microstrains at 75°C is about 316, exceeding that of polycrystalline and single silicon. The gauge factor of single-silicon was decreased with increasing temperature.

The piezoresistivity of p-type semiconductor is ascribed to strain-induced separation of the light- and heavy-hole bands and the consequent change in the average hole mass and mobility. The piezoresistive effect in boron-doped diamond films may be also caused by a strain-induced shift of the boron acceptor level relative to the valence band. On the other hand, for polycrystalline diamond films, grain boundaries play an essential part in piezoresistive effect. The intergrain geometry and radius of curvature will be changed as tensile stress is applied on the films, which may enhance electron scattering.

In conclusion, we have studied the piezoresistive effect of polycrystalline p-type diamond films formed by dc plasma CVD. The gauge factor is about 116 at room temperature, and extremely increased with increasing temperature at 500 microstrains. Experimental results have shown that the diamond-based sensor is sufficient for practical devices in corrosion or high-temperature environments.

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