Piezoresistivity in vapor-deposited diamond films

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We report the observation of a very large piezoresistive effect in both polycrystalline and homoepitaxial chemical-vapor-deposited diamond films. The gauge factor for polycrystalline *p*-type diamond at 500 microstrains was found to be only 6 at room ambient, but increased rapidly with temperature, exceeding that of polycrystalline silicon (30) at 35 °C, and that of single-crystal Si (120) at 50 °C. For strain and current flow in the [100] direction, the gauge factor of a (100)-oriented homoepitaxial diamond film was found to be at least 550 at room temperature. Although the origins and unexpected temperature dependence of piezoresistive effect in diamond are not yet understood, these findings may suggest diamond-based sensors with performance significantly superior to that of their Si counterparts.

In principle, the high dielectric strength, high thermal conductivity, large band gap, and moderately good carrier mobilities of diamond promise electronic devices vastly superior to their silicon counterparts. Given the tremendous difficulties in developing a completely new electronic technology, it is no surprise that despite this enormous potential, no diamond-based device yet demonstrated even approaches, let alone exceeds, the performance of its conventional counterpart.[1–4] In the course of investigations of possible applications of diamond-based sensors for corrosive or high-temperature environments, we have found that the piezoresistive gauge factor of even the crudest polycrystalline diamond strain sensor is sufficient for practical devices and the gauge factor for homoepitaxial diamond films is at least 550, several times that of crystalline Si (120–170). Diamond piezoresistive pressure, acceleration, and vibration sensors can be uniquely suited to chemically harsh, high radiation, and high-temperature environments. In contrast, Si piezoresistive devices are not functional at temperatures above 300 °C,[5] and are unsuitable for chemically harsh and high radiation environments. The results described here suggest that rugged diamond-based strain and pressure sensors with excellent performance may be realizable in the near term.

In this letter, we report on what is, to our knowledge, the first quantitative study of the piezoresistive gauge factor in homoepitaxial and polycrystalline diamond films produced by chemical vapor deposition (CVD). Using both plasma and hot-filament assisted CVD,[6] *p*-type diamond piezoresistors with a thickness of 2 μm were fabricated on both diamond and oxide-coated Si substrates using the patterning techniques developed previously.[7] The quality of the films was monitored by Raman spectroscopy, scanning electron microscopy (SEM), and electrical measurements.[7,8] For the polycrystalline films with a boron doping level of $\approx 10^{18}$ cm^{-3}, the Hall mobility and carrier concentration at 300 K were 16 cm^2 V^{-1} s^{-1} and 1.2×10^{16} cm^{-3}, respectively.[8] An apparatus which produces a well-calibrated strain, developed for silicon-based sensors,[9] was used to characterize the diamond-based devices. The gauge factor, $(1/R_0)(dR/d\epsilon)$, was computed from the resistance change, dR/R_0, measured as a function of strain, ϵ, at several temperatures. The resistance change $dR=R(T)-R_0(T)$ was found at temperature T, where $R(T)$ and $R_0(T)$ represent the resistance values for strain ϵ and 0, respectively.

For polycrystalline diamond *p*-type films, the resistance change, dR/R_0, measured as a function of tensile strain, ϵ, at several temperatures is shown in Fig. 1(a). The direction of ϵ and the direction of measurement of R were the same. The contribution of any intrinsic strain to ϵ was neglected. The measurements were reproducible both for increasing and decreasing values of ϵ. The onset of nonlinearity in the dR/R_0-vs-ϵ curves moves to lower strain with increasing temperature. The gauge factor computed from the curves of Fig. 1(a) at 500 microstrains is shown in Fig. 1(b). The gauge factor shows a very strong increase with temperature, and exceeds that of poly-Si above 30 °C and that of single-crystal Si above 50 °C. (Note that the plotted value of the gauge factor at 50 °C is measured in the nonlinear region; at this temperature the gauge factor at low strain is closer to 175.) In contrast, the gauge factor of Si decreases with increasing temperature.[5]

For the study of the gauge factor of single-crystal diamond, boron-doped homoepitaxial films were grown by microwave CVD on commercially available type 2a diamond substrates (Dubbelldee Harris Corp., Mt. Arlington, NJ). The diamond samples were epoxied on a stainless-steel cantilever beam. A strain gauge could not be mounted on the surface of diamond due to the small size of the samples (4-mm disk or 3-mm squares). Instead, the strain was measured on the surface of the beam. The tensile strain on the diamond surface was estimated using the known elastic properties of the diamond and steel, and the ABAQUS finite-element modeling program (Hibbitt, Karlsson & Sorenson, Inc., Providence, RI). For the 4-mm $\times$0.25-mm disk used for this study, the strain in the surface of the diamond was found to be 31% of that in the top of the steel cantilever at the location of the sensor. The epoxy was assumed to be a perfect adhesive. Figure 2 shows the measured gauge factor as a function of strain. The gauge factor decreases with strain, suggesting that not

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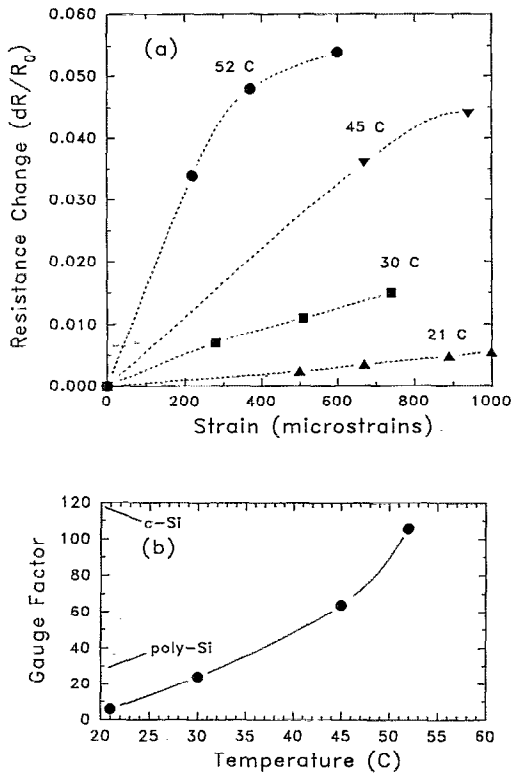

FIG. 1. (a) Fractional change in resistance of a polycrystalline diamond piezoresistor as a function of strain at several temperatures. Current flow is along the direction of the strain. Positive strain connotes tension in the film. An increase in resistance with tensile strain (positive slope) corresponds to positive gauge factor. (b) Temperature dependence of the piezoresistive gauge factor measured at 500 microstrains.

all the strain is transmitted through the epoxy film. To partially correct for this, we take the gauge factor to be the value obtained by extrapolating back to zero strain. Even this corrected value should be taken as a lower limit to the actual gauge factor. With these uncertainties, the gauge factor measured in the [100] direction in a (100)-oriented homoepitaxial p-type diamond film is at least 550 at room temperature. Studies using very thin substrates for which the adhesive is less critical are in progress.

To our knowledge, the only published study of piezoresistance in any p-type diamond is that of Latsa and Rotner,[10,11] who do not actually report a gauge factor. They compressed large, roughly cubic boron-doped synthetic diamonds using the clamps as the electrodes, and reported a decrease in resistivity with increasing force. Using the Young's modulus value of 10.5×10^{12} dyn/cm^2 for diamond, we have estimated the gauge factor from their resistance-versus-pressure curves. At strain levels of 200 and 500 microstrains, the gauge factor values were 2300 and 1400 for the [100] direction, and 3200 and 1700 for the [111] direction, respectively. These results indicate a much larger gauge factor than we find. However, we emphasize that this estimate is based on a simplistic one-dimensional model of the strain conditions and so is subject to very large errors. A more reliable estimate would entail a finite-element model requiring knowledge of the exact sample geometry and the elastic properties of the clamp materials. However, like ours, these results do show a decrease in gauge factor with increasing strain.

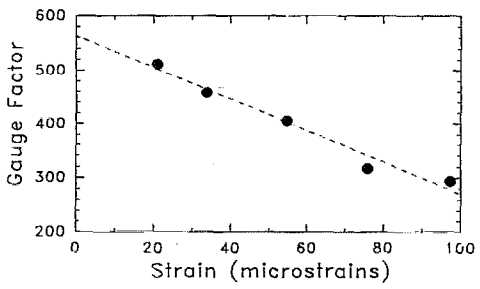

FIG. 2. Strain dependence of the piezoresistive gauge factor of a (100)-oriented homoepitaxial diamond film. Both strain and current flow are parallel to the [100] direction.

The origin of the piezoresistive effect in B-doped diamond is not understood at present. A general expression for the gauge factor, K, is given by[5]

$$K=1+2\mu+(1/\rho_0)(d\rho/d\epsilon), \tag{1}$$

where ρ is the resistivity, and μ is the Poisson ratio, which is approximately 0.1 for diamond. Thus, $K\approx1.2$ if the resistance change resulting from strain is assumed to be due only to geometrical changes, and not due to variation in ρ. The geometrical changes, therefore, cannot account for the large gauge factor observed for polycrystalline or single-crystal diamond. Piezoresistivity in p-type semiconductors is conventionally explained in terms of strain-induced separation of the light- and heavy-hole bands and the consequent change in average hole mass and mobility. It is also possible that there is a strain-induced splitting or shift of the boron acceptor level relative to the valence band. With an activation energy of 0.2–0.3 eV, only a small fraction (of order 1%) of boron acceptors are activated at room temperature. Thus the conductivity will be very sensitive to small changes in the activation energy. Latsa *et al.* explained the piezoresistive effect in diamond in terms of pressure-induced changes in the band gap. However, this last is very unlikely because the band gap of diamond is so large that very few intrinsic carriers are present. Measurements of piezoresistivity over a much wider temperature range may be required to resolve this issue. For polycrystalline films, grain boundaries may give rise to the unexpected increase in gauge factor with temperature. Further studies of the piezoresistive effect in diamond films of varying grain size, doping level, and orientation are in progress.

In summary, we have demonstrated for the first time a large piezoresistive effect in p-type CVD diamond films. At 300 K, the gauge factor is found to be at least 550 for homoepitaxial (100) films and 6 for polycrystalline diamond. The gauge factor of polydiamond shows a strong increase with temperature and exceeds that of single-crystal Si at 50 °C. While the room-temperature response of these first crude diamond piezoresistive devices is somewhat worse than their polycrystalline silicon counterparts, their high-temperature response is superior. The very large gauge factor of single-crystal diamond offers the promise of

very sensitive piezoresistive sensors. The reduction in sensitivity imposed by the stiffness of the relatively thick single-crystal substrate may be overcome by use of the near-single-crystal mosaic films produced by Geis *et al.*[12] Because of the very large gauge response of diamond and the simplicity of piezoresistors relative to active devices, it seems likely that force sensors (pressure, acceleration, etc.) for harsh environments will be the first diamond-based electronic devices to fully realize the advantages promised by the intrinsic properties of diamond.

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