PIEZORESISTIVE MICROCANTILEVERS FROM ULTRANANOCRYSTALLINE DIAMOND

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ABSTRACT

This paper reports the temperature-dependant electrical resistivity and piezoresistive characteristics of boron-doped ultrananocrystalline diamond (UNCD), and the fabrication of piezoresistive microcantilevers using boron-doped and undoped UNCD. The devices consist of 1 μm thick doped UNCD on either 1 or 2 μm thick undoped UNCD. Over the temperature range 25-200 $^{\circ}\text{C}$, the doped UNCD has a temperature coefficient of electrical resistance of $-1.4 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$. The doped UNCD exhibits a significant piezoresistive effect with gauge factor of 7.5 and a piezoresistive coefficient of $8.12 \times 10^{-12} \text{ Pa}^{-1}$ at 25 $^{\circ}\text{C}$. The piezoresistive properties of UNCD are constant over the temperature range 25-200 $^{\circ}\text{C}$. Microcantilevers of length 300 μm have deflection sensitivity of 0.186 m Ω/Ω per μm of cantilever end deflection. These measurements of electrical and piezoresistive properties of doped UNCD could aid the design of future diamond microsystems.

INTRODUCTION

Chemical vapor deposited diamond films are an attractive material for microsystems due to their mechanical properties, chemical stability, and biocompatibility [[1], [1]]. In particular, ultrananocrystalline diamond (UNCD) is a 95% or more sp^3 -bonded polycrystalline diamond material with a high structural uniformity that results from small grain size, which gives it chemical, mechanical, and electrical properties that are close to those of bulk diamond [3-5]. The electrical properties of UNCD can range from insulating to conductor-like by varying doping concentration [6], with electrical resistivity that can be controlled over five orders of magnitude. UNCD films can be synthesized at temperatures as low as 400 $^{\circ}\text{C}$, while film thickness can vary from several nanometers to tens of microns [7-9].

The design of UNCD-based microelectromechanical devices is however impaired by a lack of understanding of the electrical, thermal, and mechanical properties of electrically conducting doped UNCD films. This paper presents electrical resistivity test structures and microcantilevers fabricated from doped and undoped UNCD heterostructures. This paper also presents characterization of the temperature-dependant electromechanical properties of these microcantilevers over the range 25-200 $^{\circ}\text{C}$.

DESIGN AND FABRICATION

Figure 1 shows a microcantilever consisting of a UNCD multilayer. The top layer is electrically conducting doped UNCD of thickness 1 μm , and the bottom layer is electrically insulating undoped UNCD of thickness either 1 μm or 2 μm . Detailed electrical resistivity measurements are reported later in the paper, however at this point we note that electrical resistivity of doped UNCD is 0.1 $\Omega\text{-cm}$ at room temperature, which is five orders of magnitude smaller than the electrical resistivity of undoped UNCD. The relatively high electrical resistivity of undoped UNCD is due to the very high sp^3 content in the UNCD. The large

difference in electrical resistivity of the doped vs. undoped UNCD layers, along with the doped UNCD offset from the cantilever neutral axis, enables the piezoresistive cantilever behavior.

Figure 1. Schematic view of an all-diamond microcantilever having doped and insulating UNCD layers.

In the present design, the UNCD layers are electrically isolated from a silicon handle wafer with a 1 μm thick silicon dioxide layer. We consider four different cantilever designs, shown in Figure 2, having overall cantilever thickness of either 2 μm or 3 μm for a total of eight device types. The cantilevers vary in length from 300 μm to 400 μm and have a notch that extends 1/3 or 2/3 of the length starting from the cantilever substrate. The notched region is referred to as the “leg”, while the rest of the cantilever is the “tip”.

The cantilever fabrication starts with silicon dioxide-coated silicon wafers. The diamond layers are deposited to the desired thickness using hot-filament chemical vapor deposition (HFCVD) with methane/hydrogen chemistry and a 5% CH_4/H_2 gas mixture. Boron-doped UNCD is synthesized by adding trimethylboron [$\text{B}(\text{CH}_3)_3$] as a source gas with a boron-to-carbon ratio of 1/330 inclusive of both carbon-containing source gasses. Both UNCD layers are then etched in oxygen plasma. Metal contacts allow for electrical access to the electrically conducting doped UNCD layer. The cantilevers are released with a through-wafer backside etch.

Figure 2 shows scanning electron micrographs of fabricated cantilevers named A, B, C, or D, followed by a number that is the cantilever total thickness. The cantilevers exhibit some curvature due to the intrinsic differential stress introduced during the growth process. For cantilevers of total length 400 μm , the cantilever deflection was about 23 μm for the 2 μm thick cantilevers and 16

μm for the $3\text{ }\mu\text{m}$ thick cantilevers. We also fabricated van der Pauw structures [10] on the same wafers for precise measurements of the UNCD sheet resistance and its temperature-dependence.

Figure 2. Scanning electron micrographs of fabricated UNCD microcantilevers.

EXPERIMENTAL SETUP

Figure 3 shows the experimental setup to measure device temperature-dependant electrical resistance and piezoresistive coefficient.

Figure 3. Schematic of the experimental setup for piezoresistivity measurements showing cantilever deflection setup and cantilever wiring diagram. The cantilever is deflected using a tungsten needle probe mounted on three-axis motorized nanopositioning stages having 7 nm resolution. The probe was moved in $13.7\text{ }\mu\text{m}$ increments with the output signal amplified 100 times before collection in a data acquisition system.

Two cantilevers were configured in Wheatstone bridge for a differential measurement and mounted on a temperature-controlled stage capable of maintaining temperature to within $0.2\text{ }^{\circ}\text{C}$ in the range of $25\text{--}200\text{ }^{\circ}\text{C}$. The cantilever electrical resistance was measured while the tip was deflected using a tungsten needle probe attached to a closed-loop nanopositioner. The location of the probe on the cantilever surface was measured under the microscope with $150\times$ total magnification.

The cantilever electrical resistance change was measured from the Wheatstone bridge voltage output when the applied bridge bias was 1 V . Probe deflection varied from $6.87\text{ }\mu\text{m}$ to $68.66\text{ }\mu\text{m}$ in $13.73\text{ }\mu\text{m}$ increments, except for the first step of $6.87\text{ }\mu\text{m}$. Sixty differential voltage measurements were made at each deflection point in 1 second intervals and were repeated three times for averaging purposes and to correct for signal drift. This procedure was repeated three times with the probe lifted off the cantilever surface and brought back into contact between subsequent trials to establish uncertainty due to the probe location.

RESULTS AND DISCUSSION

Deflection sensitivity

Figure 4 shows cantilever deflection sensitivity, S , defined by equation (1) as resistance change, ΔR , due to applied tip deflection, δ .

Figure 4. Measured cantilever electrical resistance change as a function of cantilever deflection. Deflection sensitivity, which is the slope of each curve, varies from 0.047 up to 0.186 depending on cantilever geometry.

For small deflections, the deflection sensitivity is directly proportional to the stiffness of the cantilever and depends on the location of piezoresistor with respect to the cantilever neutral axis. Thus deflection sensitivity is a strong function of geometry.

$$S = \frac{\Delta R}{R} \frac{1}{\delta} \quad (1)$$

The deflection of the cantilever free end was determined from the measured probe displacement and the measured probe-cantilever contact point combined with ANSYS structural finite element model. The measured electrical resistance change was linear over the entire range of deflections with the slope corresponding to the deflection sensitivity in the range of $0.047\text{--}0.186\text{ m}\Omega/\Omega$ per μm of deflection. The observed difference in

deflection sensitivity values between cantilevers is attributed to the stiffness variations and the distance of doped UNCD layer to the neutral bending axis of the respective cantilever. In general, short and thick cantilevers with a small notch have the highest deflection sensitivity of the cantilevers tested.

Resistivity Measurements

The electrical resistivity of UNCD was measured over the temperature range of 25-200 °C using the van der Pauw structures fabricated on the same wafers as the cantilevers. At 25 °C, the resistivity of UNCD was $(94.1 \pm 0.4) \times 10^{-3} \Omega\text{-cm}$ for the 2 μm devices and $(99.7 \pm 0.2) \times 10^{-3} \Omega\text{-cm}$ for the 3 μm devices. These values are comparable to those reported in the literature on polycrystalline and nanocrystalline diamond [11, 12]. A decrease in resistivity was observed with increasing temperature as shown in Figure 5. The negative temperature coefficient of resistance may be due to the increase in carrier concentration resulting from thermal activation.

Figure 5. Van der Pauw resistivity measurement results for 2 μm (squares) and 3 μm (circles) UNCD stacks at different temperatures.

Gauge Factor

While deflection sensitivity depends on cantilever geometry, longitudinal gauge factor, K_L , is a material property. Assuming transverse gauge factor is negligible, K_L is related to the deflection sensitivity of the cantilever through the longitudinal strain in the leg region, $\epsilon_{leg,l}$ and transverse strain in the cantilever free end $\epsilon_{tip,t}$ as

$$K_L = \frac{\Delta R}{R} \frac{1}{\epsilon} = \frac{\Delta R}{R_{leg} \epsilon_{leg,l} + R_{tip} \epsilon_{tip,t}} = \frac{S \delta}{\epsilon} \quad (2)$$

Figure 6(a) shows gauge factor for each cantilever type. Electrical resistance change was measured using the setup described above. ANSYS structural and electrical finite element simulations of cantilever structure under experimentally applied load calculated mechanical strain and three-dimensional electrical potential in the cantilever during bending, allowing precise correlation between measured electrical and mechanical behaviors. The average gauge factor value is 7.53 ± 0.32 , which is close to the measured value for microcrystalline diamond [13]. The consistency of gauge factors across all cantilever types supports the assumption that transverse gauge factor is negligible in these

cantilevers. The UNCD cantilever gauge factor is approximately 5 times smaller than polycrystalline silicon [14]. Error bars in Figure 6(a) show the variation within three measurements on the same cantilever with 10 μm uncertainty in the probe location resulting in ± 0.39 variation in K_L .

Figure 6(b) shows gauge factor over the temperature range 25-200 °C for cantilever C3. The gauge factor was constant over the measured temperature range, although a slight deviation is seen at 200 °C due to substantial increase in cantilever noise. The temperature insensitivity of UNCD piezoresistivity compares very well to highly doped silicon, in which piezoresistive coefficient decreases by 28% over the same temperature range [14].

Figure 6. a) Measured gauge factor for eight cantilever types at room temperature with inset showing zoomed in data. The average gauge factor of UNCD is 7.53 ± 0.32 . Error bars represent standard deviation of three measurements. Similarity in gauge factor values over all cantilever types indicates negligible transverse gauge factor. b) UNCD gauge factor dependence on temperature with inset showing zoomed in data. Gauge factor remains constant up to 200 °C. Data is shown for C3 type cantilever. The gauge factor in similarly doped silicon decreases by 28% over the same temperature range.

CONCLUSION

In summary, we have shown design, fabrication, and characterization of all-UNCD piezoresistive microcantilevers. The electrical and piezoresistive properties of the UNCD are determined and the cantilever characteristics are reported. This work could inform the design of future microelectromechanical devices fabricated from doped UNC.

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