The piezoresistive effect in the 3-D diamond-like carbon nanostructure fabricated by focused-ion-beam chemical vapor deposition

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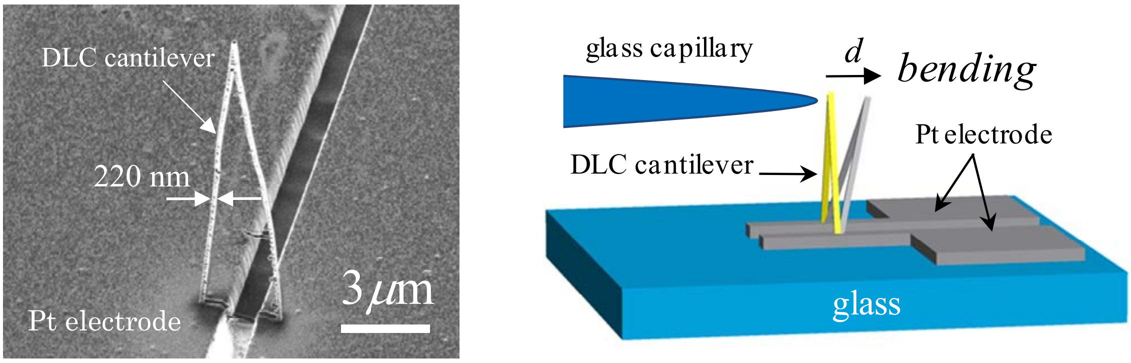
Focused-ion-beam chemical-vapor-deposition (FIB-CVD) enables us to fabricate the arbitrary three-dimensional (3-D) structures such as wine glasses, bellows, and coils. In addition, the 3-D structures made of various materials, such as diamond-like carbon (DLC), tungsten (W), and silicon oxide (SiO_x), can be fabricated by selecting the gas source. However, there have not yet been any reports concerning deposition method of the functional materials such as a piezoelectric material and a piezoresistive material. And, if the 3-D nanostructure with functional material characteristics can be fabricated by FIB-CVD, we will be able to achieve the various novel nanodevices such as sensing device with a high functionality. Therefore, the material characteristics of the 3-D DLC nanostructure fabricated by FIB-CVD were evaluated and the modification method of their material characteristics was examined to achieve the functionalization of the 3-D DLC nanostructure in this study.

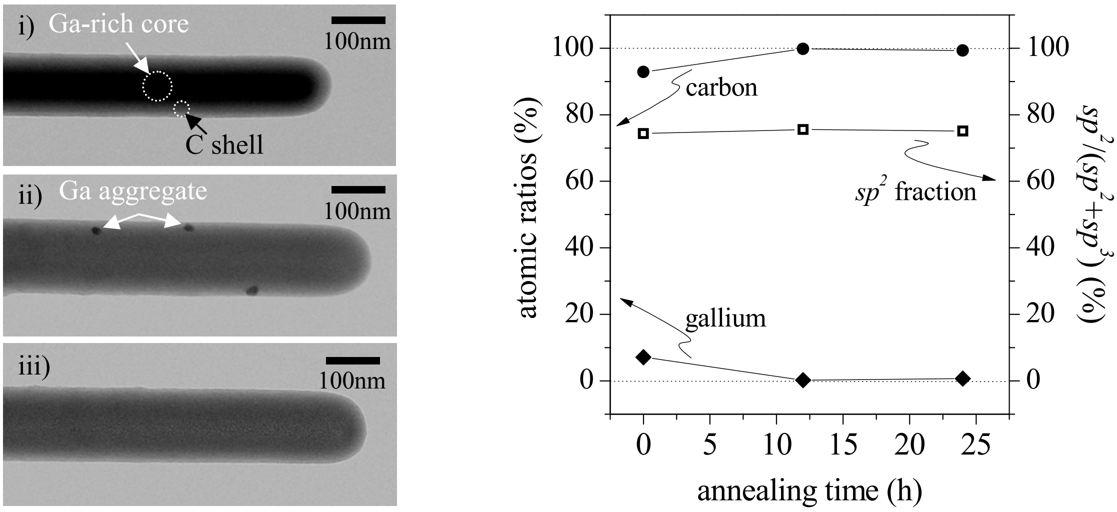
In this experiment, the DLC cantilever was fabricated on the 2-terimanal Pt electrode by FIB-CVD using *phenanthrene* ($C_{14}H_{10}$) gas as a gas source to evaluate the electrical material characteristics of DLC, as shown in Fig. 1(a). FIB-CVD was carried out using 30 kV Ga^+ FIB with a beam current of 1.6 pA. And electrical characteristics of a DLC cantilever were evaluated by a bending method using a glass capillary as shown in Fig. 1(b). As a result, the resistance of an untreated DLC did not depend on the bending strain. This indicates that the untreated DLC deposited by FIB-CVD do not have the piezoresistive property. And it seemed that the Ga implanted by Ga^+ FIB inhibited the piezoresistive effect because the piezoresistive effect in DLC is induced by the interaction between the conductive sp^2 clusters and the insulative sp^3 clusters. Therefore, we examined an annealing method to remove Ga from DLC without changing the $sp^2/(sp^2+sp^3)$ ratio, because the high temperature annealing induces the increase of $sp^2/(sp^2+sp^3)$ ratio. And, we found that the annealing treatment at a low temperature (300 deg. C) for long time (12 hours or more) is an effective method to remove Ga without changing $sp^2/(sp^2+sp^3)$ ratio, as shown in Fig. 2(a) and (b). After this, the electrical characteristics of the DLC cantilever annealed at 300 deg. C for 12 hours were evaluated by a bending method as shown in Fig. 1(b). The resistance of the DLC cantilever was changed with the increase in the bending strain as shown in Figs. 3. And the values of gauge factor were 2 – 34. These results indicate that the piezoresistive property in the 3-D DLC nanostructure fabricated by FIB-CVD could be induced by removing Ga from DLC. Furthermore, a resonant frequency detection of a mechanically vibrated DLC cantilever was achieved by the piezoresistive property added to material characteristics of DLC, as shown in Fig. 4. This indicates that the annealed DLC cantilever had a function of the self-detection.

A useful method to functionalize the 3-D DLC nanostructure fabricated by FIB-CVD was demonstrated in this study. The functional material characteristics of the modified 3-D DLC nanostructure with a piezoresistive property will be reported in detail.



(a) (b)

Fig. 1 The 3-D DLC nano cantilever fabricated by FIB-CVD: (a) SIM image, (b) Schematic of the piezoresistive effect evaluations. Strains to a DLC cantilever were applied by glass capillary. Bending distances d of DLC cantilever were 1, 2, 3, 4 and 5 μm.



(a) (b)

Fig. 2 Annealing effect of DLC nanopillar: (a) STEM images of DLC nanopillars i) before annealing treatment and after 300 deg. C annealing for ii) 12 h and iii) 24 h, (b) changes in the atomic ratios and $sp^2/(sp^2+sp^3)$ ratio.

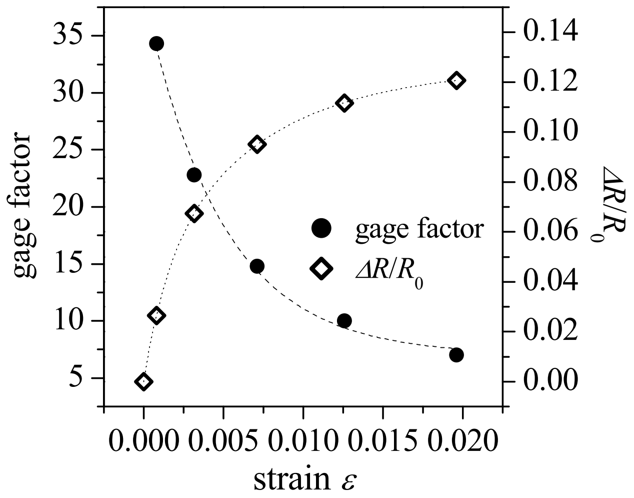


Fig. 3 Strain ε dependency of changes in the resistance and gage factor of a DLC cantilever annealed at 300 deg. C for 12 h.

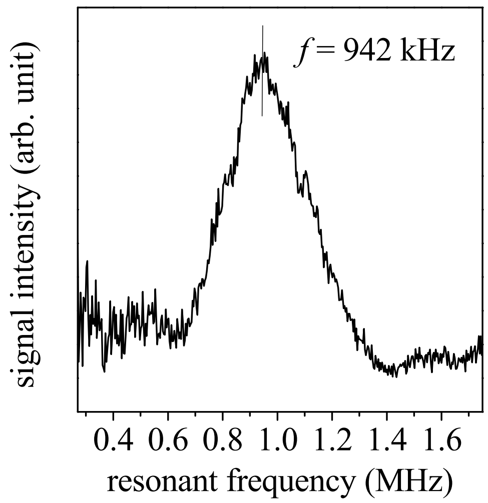


Fig. 4 Resonant frequency spectrum obtained by the self-detection function of the annealed DLC cantilever.