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A DLC/W-DLC multilayered structure for strain sensing applications

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Abstract

The strain dependence in tungsten-containing diamond-like carbon (W-DLC) film was investigated. The W-DLC film was deposited onto Si substrate by plasma enhanced chemical vapor deposition and DC magnetron co-sputtering of tungsten metal target. The strain dependence of resistance was measured by four-point bending test under well controlled temperature condition. The observed dependence was linear one and calculated gauge factor is 6.1. The high value of the gauge factor is originated from the piezoresistive effect. In addition, double layered structure of DLC/W-DLC film was fabricated. The double layerness and interface structure were investigated by transmission electron microscope. No clear boundary between DLC and W-DLC was observed. This was because of the continuous carbon matrix from the bottom layer of W-DLC to top DLC layer.

Keywords: DLC; Strain sensor; Double layered film

1. Introduction

Diamond-like carbon (DLC) films have many kinds of attractive properties such as high hardness, chemical stability, and so on. Also, DLC film is generally insulating because of the high amount of carbon sp^3 content. If we want to make sensors using DLC films, electrical functionality needs to be controlled by light element or metal doping. Recently, sensors using nickel-containing DLC (Ni-DLC) films have been studied [1] for the aim of fabrication of novel strain sensors.

Generally speaking, the strain dependence of normalized resistance is expressed as:

$$\frac{\Delta R}{R} = \frac{R(\varepsilon) - R_0}{R_0} = K \cdot \varepsilon \tag{1}$$

here, $R(\varepsilon)$ is resistance at certain strain applied to the sample, R_0 is resistance without strain, ε is strain, and K is gauge factor. The gauge factor is expressed as:

$$K = 1 + 2\sigma + \pi E \tag{2}$$

here, σ is Poisson ratio, E is Young's modules, and π is piezoresistive coefficient. The piezoresistive coefficient is constant value which represents the relationship between the variation of the resistivity and the stress applied to the sample. In the case of commercial strain gauge made of stainless steel, the πE in Eq. (2) is close to zero because the effect for the variation of resistance against the strain is so small. However, for the semiconductor materials, the last term in Eq. (2) becomes most effective.

The piezoresistive effect of the DLC film was investigated by Tibrewala et al. [2]. Their group shows the piezoresistive gauge factor of amorphous carbon film with and without the hydrogen. The gauge factor, K, represents the sensitivity of the sensor and $K \sim 50$ was obtained in a-C film and $100 < K < 1200$ in a-C:H film. Peiner et al. also show the gauge factor of 36–46 in sputtered a-C film on Si cantilever [3]. These reports suggest that amorphous carbon-based strain sensor show the high sensitivity against the strain.

In this study, tungsten-containing diamond-like carbon (W-DLC) film is investigated for the fabrication of the piezoresistive strain sensors. The strain dependence of the W-DLC film are investigated by the four-point bending test. The double layered film (DLC/W-DLC) is fabricated for the aim of the protection of

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Table 1
Substrate cleaning and deposition parameters

Initial pressure	4.0×10^{-4} Pa
Input frequency	13.56 MHz
Substrate	Single crystal Si wafer
Pretreatment of the Si substrate	
Gas	Ar=10 sccm
Substrate bias voltage	−400 V
Operation pressure	3.3 Pa
Deposition of W-DLC film on Si	
Gas	Ar/CH_4=10/2.7
Substrate bias voltage	−400 V
Operation pressure	3.3 Pa
Sputtering target	Tungsten (W)
Deposition of DLC film on W-DLC	
Gas	CH_4=2.7 sccm
Substrate bias voltage	−400 V
Operation pressure	3.3 Pa

functional W-DLC layer from mechanical load or chemical reaction. The doublelayerness and interface between the DLC and W-DLC layer are examined by transmission electron microscope.

2. Experimental

A DLC/W-DLC film was deposited onto single crystal silicon substrate using radio-frequency plasma enhanced chemical vapor deposition (RF-PECVD) and DC magnetron co-sputtering of tungsten metal target. The DC magnetron sputter locates upside of the deposition chamber. The substrate holder is at the bottom of it and the RF power is applied to the holder. The distance between the metal target and the holder is 100 mm. The inside of the deposition chamber is evacuated less than 4.0×10^{-4} Pa for all deposition. Firstly, the substrate was cleaned by RF-generated Ar plasma for 10 min. After that, W-DLC was deposited onto the substrate using RF-generated methane plasma and DC magnetron sputtering of the tungsten target for 30 min. Finally, DLC layer was deposited onto W-DLC layer using only methane plasma for 30 min. Detailed deposition parameters were summarized in Table 1.

The Raman spectroscopy was performed for the structural analyses of carbon bonding structure. The Raman spectra were acquired using Ar green laser (λ=514 nm) in dark environment by the JobinYvon T-64000 triple Raman spectrometer.

The strain dependence of resistance was measured by four-point bending tests. Temperature during the experiments was well controlled by the attached heater. All experiments were performed in dark condition in order to avoid the effect of the light. Each data point was obtained in 200 $\mu\varepsilon$ steps.

The electron micrographs in cross-section were taken using a JEOL JEM-3010 transmission electron microscope (TEM) at an acceleration voltage of 300 kV. Samples for TEM observation were prepared by mechanical polishing and Ar ion-milling (Fischione Model 1010).

3. Results and discussions

Fig. 1 shows the Raman spectrum of W-DLC film. The broaden peak derived from diamond-like carbon structure was observed. In the case of metal-containing DLC films, included metal forms nanometer-sized clusters and these are well dispersed in DLC matrix [4]. The sizes and distances of the cluster depend on the concentration of the metal. This broaden peak was profile-fitted by the Lorenz function for D peak, the BWF function [5] for G peak, and liner function for background luminescence. The positions and peak intensity ratio (I(D)/I(G)) were calculated as ω_D=1297 cm^{-1}, ω_G=1560 cm^{-1}, I(D)/I(G)=0.16, respectively. These values are agreed with the previous data reported by Ferrari et al. in non-hydrogenated amorphous carbon films [6].

The strain dependence of normalized resistance of W-DLC film was shown in Fig. 2. The linear dependence against the tensile and compressive strain was observed. The Eq. (1) was applied to the result and the gauge factor was calculated as K=6.1. Besides, temperature dependence of resistance also showed

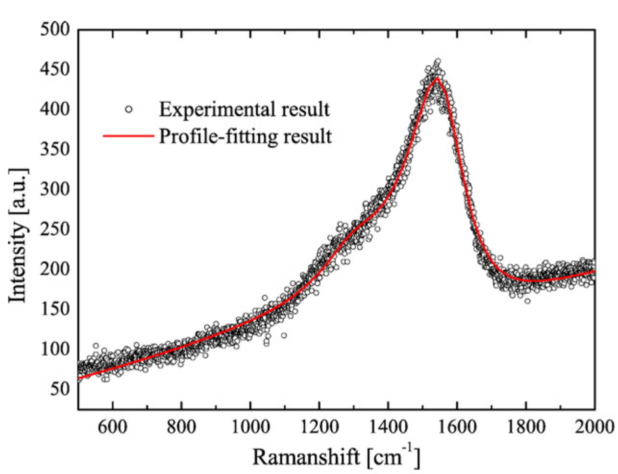

Fig. 1. The observed Raman spectrum of W-DLC film. The open-circle of this figure and solid line correspond to the experimental result and profile-fitting result, respectively.

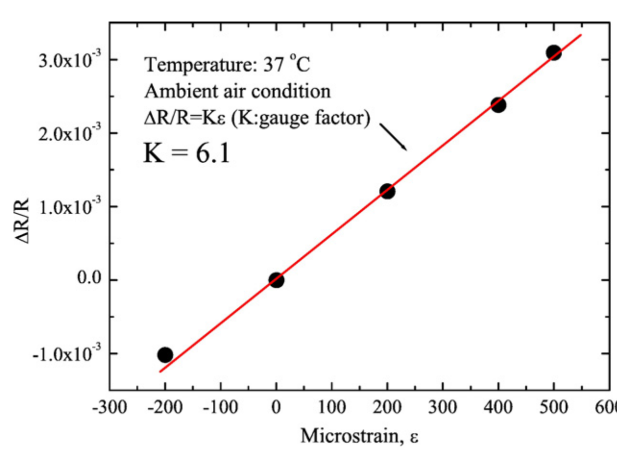

Fig. 2. The strain dependence of normalized resistance of W-DLC single layer film. The closed circle and solid line correspond to the experimental and fitting results using Eq. (1). The strain dependence measurement was performed at 37 °C and dark condition.