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Axial uniformity of diamond-like carbon film deposited on metal rod by using microwave–sheath voltage combination plasma

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ABSTRACT

We developed a novel method for the deposition of diamond-like carbon (DLC) films at high deposition rates (over 100 μm/h) using microwave–sheath voltage combination plasma. This method was applied for depositing a DLC film on a three-dimensional metal substrate, but we found that the film thickness was not uniform along the direction of microwave propagation. Hence, we investigated the factors affecting the axial uniformity of DLC film deposited on long metal rods (1 cm in diameter). Since the axial distribution of plasma was observed to affect the uniformity of DLC, we evaluated the axial distribution of ion density using a Langmuir Probe in Ar plasma that was generated along both DLC-coated and non-coated rods. The results showed that the ion density along the axis of the DLC-coated rod decayed at a shorter distance than that along the axis of the uncoated one. The voltage of the ion sheath presumably decreased owing to the voltage drop in the DLC film with high resistivity, in accordance with the short microwave decay. The uniformity considerably improved by using a duty ratio of 50% for the pulsed operation of both the microwaves and the substrate bias at −200 V. When the substrate voltage was increased to −500 V, the hardness of the DLC film measured by the nano-indenter was about 25 GPa, uniformly distributed along the rod axis. Raman results show that the film is typical DLC structure, and the structure shows good uniformity along the rod axis.

1. Introduction

Diamond-like carbon (DLC) films are widely used as protective coatings and have many applications because of their excellent mechanical properties such as high hardness, low friction, and high wear resistance [1]. However, in conventional DLC-film preparation techniques, the deposition rate is too low, which constrains the mass production of these films. Previous works have investigated the deposition rate by various methods and all have reported low values. For example, Mansano et al. reported a deposition rate of 2.16 μm/h by magnetron sputtering [2], Garrelie et al. reported 3.6 μm/h by laser deposition [3], and Wei reported 5 μm/h by plasma-based ion implantation and deposition [4]. The relatively low deposition rate of DLC films in these techniques could be attributed to the low plasma density (electron density $N_e < 10^{10}$ cm^{-3}) near the substrate. However, Kousaka et al. developed a new technique that enables generation of higher density plasma ($N_e > 10^{11}$ cm^{-3}) adjacent to the metal substrate [5]. In their work, 2.45-GHz surface waves were guided along a negatively biased conductive rod to generate high-density Ar plasma ($N_e > 10^{11}$ cm^{-3}) along the rod shape. The plasma therein obtained is called microwave-excited high-density near plasma because it is generated as if the plasma has been stuck to the adjacent metal surface [5–7].

As shown in Fig. 1(c), the aforementioned plasma is sustained by microwave surface waves [8] along the plasma–sheath–metal interface [5–7]. Without the sheath expansion, microwaves exhibit a short decay distance and as such, plasma does not spread along metal surfaces. For practical applications, it is essential to expand the sheath width by increasing the sheath voltage using an external DC power supply [6,7]. In other words, an external power supply and the injection of microwaves are both essential to take advantage of the microwave-excited, high-density near plasma for use in coating applications. This method of plasma generation is called the microwave–sheath voltage-combination plasma (MVP) method. Note that similar high-density plasma generated adjacent to a metal surface cannot be obtained by any other method that gives glow-type discharge. For example, capacitively coupled plasma (CCP) using RF bias results in much less electron density than MVP (Fig. 1(a)), and a remote-type high-density plasma such as conventional surface wave-excited plasmas (SWP) significantly decays from the generation region to the substrate (Fig. 1(b)). Therefore, the MVP method is a novel technique to obtain high-density plasma ($N_e > 10^{11}$ cm^{-3}) that can be sustained along an adjacent metal surface.

A high deposition rate can be achieved by using the MVP method in plasma-enhanced chemical vapor deposition (PECVD), because plasma

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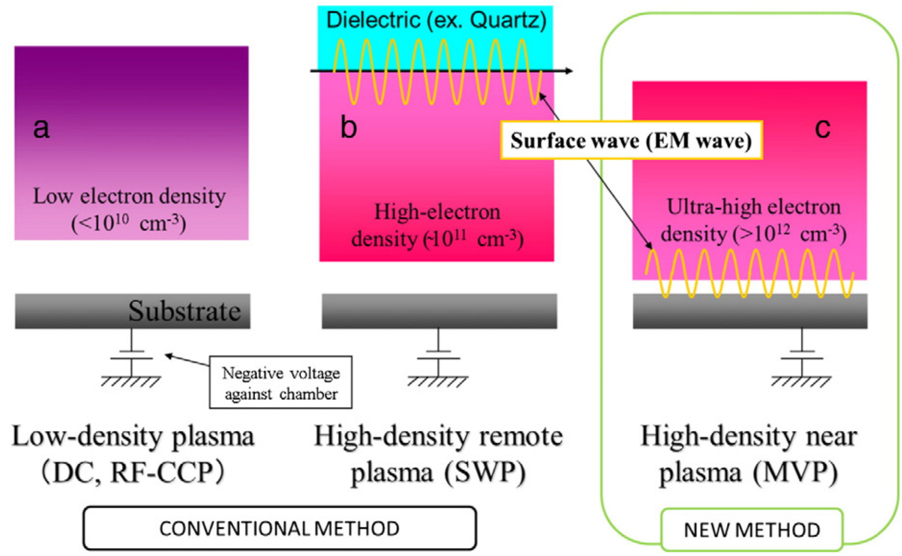

Fig. 1. Schematic illustration of plasma generation methods: (a) CCP: capacitively coupled plasma, (b) SWP: surface wave-excited plasma (high-density remote plasma), and (c) MVP: microwave–sheath voltage combination plasma (high-density near plasma sustained along an adjacent metal substrate). All substrates are inside a grounded metal chamber.

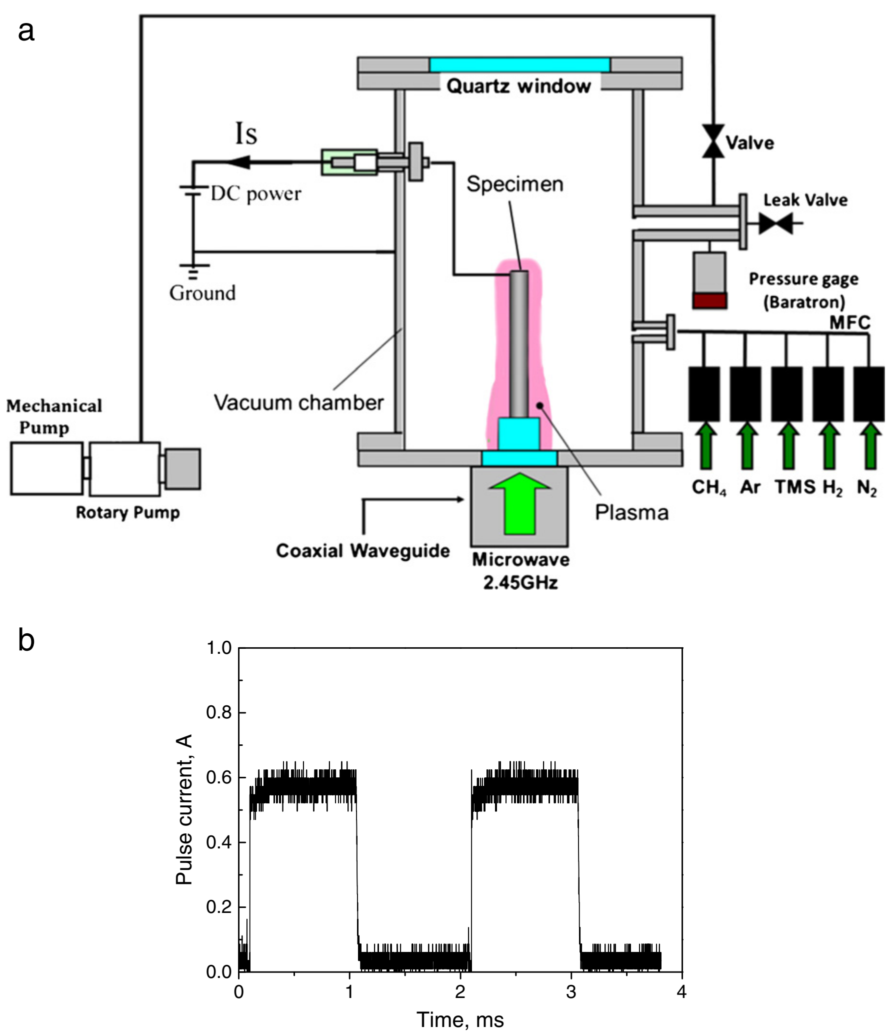

Fig. 2. (a) Schematic of the DLC coating equipment for a three-dimensional metal substrate employing high-density near plasma, which is sustained by microwaves propagating along plasma–sheath interface surrounding the adjacent surface of a metal substrate. (b) The pulse current through the substrate monitored in the deposition process.