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Plasma states and carbon film deposition in glow discharge connected to dielectric barrier discharge

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ABSTRACT

We developed a plasma source by connecting a direct current glow discharge (GD) with a dielectric barrier discharge (DBD) via a ground mesh (DB-GD). Based on the Langmuir probe measurements, the electron density of the DB-GD increased and the electron temperature decreased compared with those of the GD. Calculations of the electron energy distribution functions revealed that the DB-GD possessed a lower density of high-energy electrons and higher density of low-energy electrons than the GD did. We also confirmed that the DB-GD generated with methane gas was capable of producing an amorphous carbon film.

Direct current glow discharge (GD) has been applied to a wide range of industrial fields, such as semiconductors and tribology for film deposition, etching, tool coating, and hydrophilic/hydrophobic treatment, because the structure of the electrode is simple and advantageous for treating large surface areas, and high-quality film can be obtained. Plasma-enhanced chemical vapor deposition (PECVD) is of great importance as a method capable of coating various films, such as diamond, diamond-like carbon, nitrides, and oxides, to impart additional functions to a material surface [1]. However, from an industrial viewpoint, there is a need to further improve the productivity of PECVD, which has motivated our studies on the densification of GD plasma. The increase in electron density is possibly a way to improving productivity because a small electron density ($< 10^{10}\,\mathrm{cm}^{-3}$) has been recently reported to cause a decrease in deposition rate [2]. Using DC discharge regime, an electron density of $6.5 \times 10^{10}\,\mathrm{cm}^{-3}$ has been achieved under a relatively low pressure, reduced discharge potential, and high current condition based on an electrical model employing pressure, potential, and current as parameters [3].

The fundamental plasma states of GD have been studied in detail [4]. Hollow cathode discharge [5] is a type of GD that produces high-density plasma using a cavity-type cathode, whose densification mechanism has been analyzed in detail [6] and reportedly applied to amorphous carbon (a-C) film deposition [7]. The generation of micro-hollow cathodes at a high pressure has also been demonstrated [8]. However, further utilization of the electrode structure, such as arraying the cavity [9], is required to produce uniform plasma in a large area using hollow-cathode discharge.

Dielectric barrier discharge (DBD) [10] has attracted attention in recent years because it can be generated even at atmospheric pressure to produce high-density plasma in a non-equilibrium state, where the gas temperature is lower than that of thermal equilibrium plasma, resulting in a lower substrate temperature [10,11] and higher electron temperature, which can potentially promote gas decomposition. In addition, the electrode of the DBD has a simple structure, where the dielectric material is inserted between the parallel-plate electrodes, which is advantageous for generating discharge in a large area.

In the present work, we connected the DBD to the GD to develop a plasma source, which was abbreviated as DB-GD, to increase the electron density without compromising the advantage of large-area production in GD. In addition, we revealed a unique effect of suppressing the electron temperature while simultaneously increasing the electron density of the DB-GD.

A schematic of the DB-GD circuit is illustrated in Fig. 1. The DB-GD electrode consists of a DBD region and GD region. The DBD region is the space between the ground electrode and upper electrode, which is layered by a 2-mm-thick dielectric alumina plate. A mesh weave of stainless steel wire with a diameter of 0.4 mm and pitch of 1.2 mm was used as the ground electrode, and a 0.1-mm titanium plate was used for comparison. The distance between the upper electrode and ground electrode was 14 mm, and that between the ground electrode and lower electrode was 78 mm. An AC voltage of 1 kV at 15 kHz was applied to the upper electrode using a low-frequency, high-voltage power supply (TE-HFVE5V1520K-0400, Tamaoki Electronics Co., Ltd.). The GD region is the space between the ground electrode and the lower metal electrode. A voltage of −400 V was applied to the lower electrode using a DC high-voltage power supply (LQ5N4.0, Glassman Japan High Voltage Ltd.). In this approach, the DBD region and GD region have a common ground mesh electrode, whereas their circuits are independent, enabling their operation either individually or simultaneously. While DB-GD was generated by simultaneously applying AC

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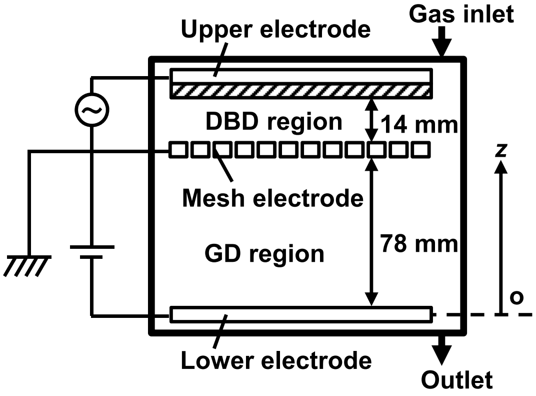

Fig. 1. Schematic of DB-GD generator.

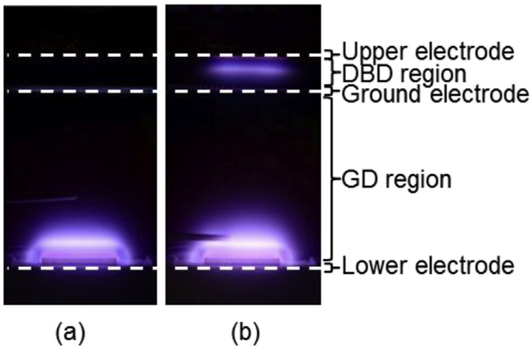

Fig. 2. Photographs of plasma produced using (a) GD and (b) DB-GD.

voltage to the upper electrode and DC voltage to the lower electrode under the aforementioned conditions, GD for comparison was generated by applying only a DC voltage of −400 V to the lower electrode using the same scheme.

The plasma was produced from argon gas, which was introduced from the upper part of the chamber after the chamber was evacuated to a pressure below 10 Pa using a rotary pump and a mechanical booster pump. During plasma production, the pressure inside the chamber was maintained at 50 Pa by introducing argon at a constant flow rate of 300 sccm and controlling the evacuation rate with a butterfly valve.

The electron density and electron temperature were measured using a Langmuir probe (LPM-100 R B, ARIOS Inc.) [12]. Measurements were conducted at five positions whose distances from the lower electrode were $z = 7.8$, 23.4, 39, 54.6, and 70.2 mm. Among the obtained IV curves from these positions, we analyzed the curves that were measured accurately, as explained in the caption of Fig. S1. The electron energy distribution functions (EEDFs) of both the DB-GD and GD were obtained from the probe analysis results using the commercial software (LMP-100SCAN, ARIOS Inc.) [13], which employs the Druyvesteyn method [14].

Fig. 2a and b shows the photographs of the plasma produced using GD and DB-GD, respectively. For the GD, light emission from the plasma is observed only near the lower electrode of the GD region. For the DB-GD, light emission is observed both in the DBD region and near the lower electrode in the GD region, excluding the vicinity of the upper electrode and ground mesh electrode. The light emission near the lower electrode in the GD region is brighter for the DB-GD than that for the GD, which is possibly due to the higher density of argon luminescent species in DB-GD compared to GD.

Fig. 3 presents the results of Langmuir probe analysis of the GD and DB-GD. The electron density (Fig. 3a) is 7–8 × 10^{10} cm^{-3} for the GD,

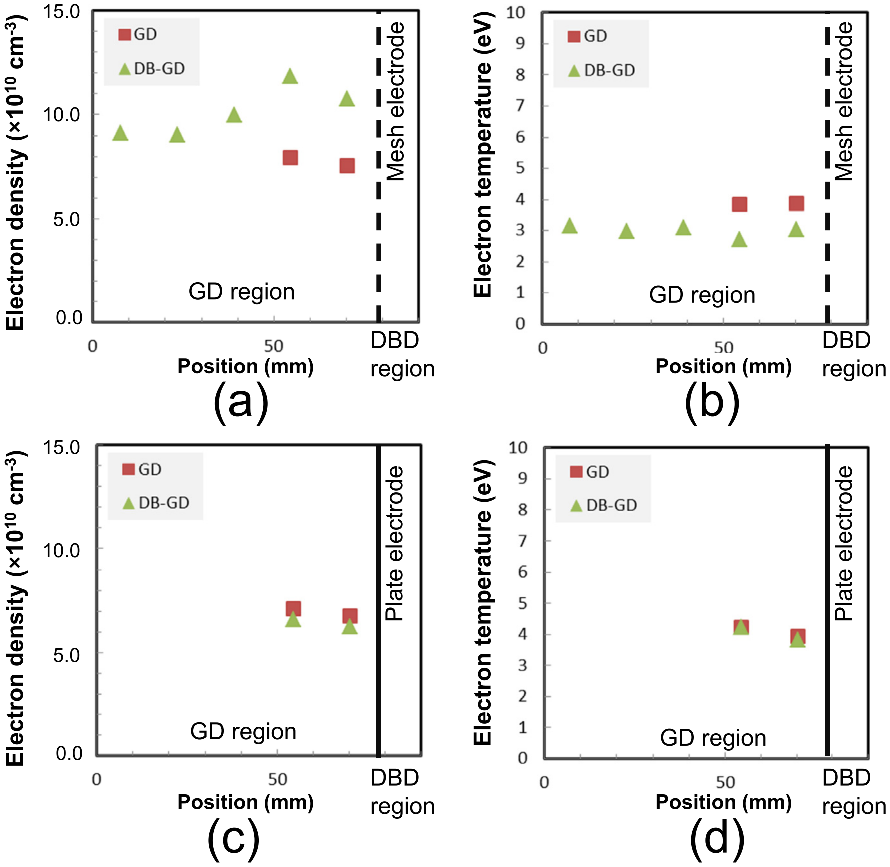

Fig. 3. Distribution of electron density and electron temperature: (a),(b) mesh ground electrode; (c),(d) plate ground electrode.