Plasma intensification in 2 MHz RF glow discharge in carbon film plasma sputtering deposition by means of a hollow cathode

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Abstract. A hollow cathode has been one of the methods to intensify the plasma in the etching or ashing process. This work examined a number of technologies in the intensification of a 2 MHz RF glow discharge plasma to deposit carbon film by means of the hollow cathode. Three types of the cathode configurations, which were cylindrical, rectangular and a cylindrical-rectangular combination, were tested to get an optimum condition for the carbon deposition. Both carbon target and substrate were fixed inside the hollow cathode. The plasma was characterized by means of optical emission spectroscopy (OES) at the range of 200 nm – 1000 nm. The results showed that the combination where the rectangular hollow was placed inside the cylindrical one, produced the most intense glow. Ion density and electron temperature in the plasma were determined by a calculation based on the atomic data related to the specific electronic transitions of the ions. The density of ions was very high in the centre area of the rectangular hollow producing complex reactions. On the other hand, the high density of the ions decreases the electron temperature. The energy of the ions was difficult to be predicted since the spectrum showed the existence of a large number of ion states. Observations on the resulted deposit on the surface of quartz substrate suggest that the intensification needs to be further investigated related to the effectiveness of sputtering and deposition process.

1. Introduction
Carbon films have been utilized in many applications such as mechanical parts and also sensors [1]. The films have many properties depended on their microstructures and electronic structures. Hydrophobicity of the DLC film, for example, depends on the graphitic structures in the film [2].

There are many methods and techniques to deposit carbon film onto a specific surface and control its functionality. In the production of sensors, controlling the microstructure of the carbon up to the nanoscale is crucial [3]. One of the methods that can be designed to perform both deposition and functionalization of the carbon film is plasma processing. Utilization of the plasma itself is not new, but plasma deposition of carbon film with various nanoscale microstructure still is a big challenge.

This work is part of the future development of the carbon base sensor and transducers. Our laboratory utilizes a low-frequency plasma in many processes including the synthesis of the nanocarbon. A hollow cathode is normally used to intensify the plasma[4], [5]. This intensification is important for the low RF plasma since many processes can be accelerated by the higher reaction rate. This study will examine the
use of the hollow cathode and the effect of its geometrical shape on the sputtering deposition of the carbon.

2. Experiments
The experiments were carried out in a vacuum plasma reactor. The reactor is mainly an aluminium vacuum chamber equipped with a gas system and a plasma generator. The generator is basically a 2 MHz radio frequency power supply connected to a dipole antenna inside the vacuum chamber. The generator is also equipped with an automatic electronic matching impedance system to keep the plasma stable during any process. The schematic of the plasma reactor is shown in figure 1.

![Schematic of Dipole 2 MHz RF Plasma System with a hollow cathode installed](image1)

**Figure 1.** Schematic of Dipole 2 MHz RF Plasma System with a hollow cathode installed

As can be seen in figure 1, the plasma is generated between the two electrodes (dipole antenna). The electrodes are made of a stainless steel rod. The plasma is distributed in the chamber which is electrically grounded. A cathode which is a square plate, is connected to a negative DC voltage to control the distribution of the plasma. This work investigated the role of a hollow cathode in intensifying the plasma for carbon film sputtering deposition. Three kinds of hollow cathodes, a rectangular, a cylindrical and a cylindrical-rectangular combination were studied. During the experiments, the hollow cathode was fixed on the main cathode as shown in figure 2.

![Configurations of the hollow cathode for the plasma intensification: (a) rectangular, (b) cylindrical and (c) cylindrical-rectangular](image2)

**Figure 2.** Configurations of the hollow cathode for the plasma intensification: (a) rectangular, (b) cylindrical and (c) cylindrical-rectangular

All process parameters i.e. chamber pressure, RF power and gas flow rate were kept constant during the experiment. The process gas utilized in this work is a high purity grade of argon (99.999%). The chamber was pump down to 4 Pa to evacuate atmospheric gases from the system before the argon gas injected into the chamber. The flow rate of the gas was adjusted to 60 ml/min by means of a dialled flowmeter. The chamber pressure was then set to 20 Pa and kept constant during the experiment by adjusting the pumping valve. The power was fixed by adjusting the RF voltage at 120 volts. The ion in the plasma is driven to the cathode by applying -500 volts DC voltage.
An optical spectrometer Aurora 4000 was utilized to measure the emission intensity of the generated plasma at the range of 200-1000 nm. The measurements were focused on the plasma inside the hollow cathode. This is done by directing the fiber sensor to the center of the hollow from a quartz window at the front door of the chamber.

3. Results and Discussions

The results of the optical emission measurements were used to identify the plasma species and determine the plasma states in terms of electron temperature ($T_e$) and electron density ($N_e$). The plasma species were identified by matching the peaks in the spectra with the NIST database for atomic and molecule. A number of references were also used to validate the identification. The spectra measured in this work have a typical feature showed in figure 3. Two dominant species were identified which are excited atomic argon (Ar I) and ionic argon (Ar II).

![Figure 3. A typical argon plasma spectrum](image)

The peaks in the spectrum are originated from a number of reactions. Common reactions taking place in the argon plasma are shown in Table 1 below.

| No. | Process                | Reaction                      |
|-----|------------------------|-------------------------------|
| 1   | Ionization             | $e + Ar \rightarrow Ar^+ + 2e$ |
| 2   | Excitation             | $e + Ar \rightarrow e + Ar^*$ |
| 3   | Spontaneous Radiation  | $Ar^* \rightarrow Ar + h\nu$  |
| 4   | De-excitation          | $e + Ar^* \rightarrow Ar + e$ |
| 5   | Ion excitation         | $e + Ar^* \rightarrow Ar^{*+}$ |

In sputtering processes, ions can be controlled by applying an electric field. Negative DC voltage was applied to the cathode. The ion is expected to be trapped inside the hollow cathode leading to an intensification of the plasma reactions. Figure 4 shows the spectra of the argon plasma in the various hollow cathodes investigated in this work. The range of wavelength is focused on to analyze the peaks related to the ions.
The peak at 335.2 nm, 354.9 nm and 389.3 nm were strongly related to the emission of ionic argon species (Ar II). The three peaks are used to determine the plasma character ($T_e$ and $N_e$) related to the various configuration of the hollow cathode.

**Table 2.** Electron temperature and electron density inside the various configuration of the hollow cathode.

| No. | Hollow cathode             | $T_e$ (K)   | $N_e$ (cm$^{-3}$) |
|-----|---------------------------|-------------|-------------------|
| 1   | Rectangular (R)           | $1.07 \times 10^4$ | $4.3 \times 10^{17}$ |
| 2   | Cylindrical (C)           | $1.03 \times 10^3$ | $2.3 \times 10^{17}$ |
| 3   | Cylindrical-rectangular (CR) | $1.12 \times 10^4$ | $7.4 \times 10^{17}$ |

It is obvious from the figure that the combination of cylindrical-rectangular configuration resulted in the highest electron density and electron temperature. The electron density of plasma in the cylindrical is slightly less than the one in the rectangular configuration, but the difference of the electron temperature is significantly large. Since the cathode is negatively biased, the distribution and direction of the electric field inside the hollow strongly depend on the shape. The rectangular shape produced more effective plasma reactions especially the ionization of the atomic argon due to more directional motions of the electron and ions which are from the top to the bottom and vice versa. In the cylindrical hollow, the motion of charged particles can be in many directions. Placing the rectangular hollow inside the cylindrical intensifies the reactions. There is no clear explanation related to the mechanism of the intensification.

Scanning Electron Microscope (SEM) observation indicated that islands of carbon were deposited uniformly on the surface of the quartz substrate.
Figure 5 SEM image of carbon islands deposited on quartz substrate by 2 MHz RF plasma sputtering with CR hollow cathode intensification

It can be seen in figure 5 that the various shape of carbon islands was observed. The distribution and variation of the island were similar in all 60 minutes deposition under the R, C and CR hollow cathode intensification. This indicates that the intensification with various hollow cathode on the sputtering process was insignificant. The intensification was certainly increasing the density and the temperature of the electron. The density of the argon ions was also increased. Since the carbon target and the substrate were fixed inside of the hollow cathode, the ions bombarded both of the surfaces. The bombardment on the carbon target should be greater than the one on the substrate. This quasi-equilibrium condition is not effective to sputter the carbon.

4. Conclusions
Intensification of RF plasma can be implemented by the utilization of hollow cathodes. The shapes and shape combination determine the intensification. The hollow cathode obviously intensified the character of argon plasma in terms of its electron temperature and electron density. The combination of the cylindrical and rectangular hollow gave the highest electron temperature and density of the electron. Further studies are needed to investigate the mechanism of the intensification and its effect in the sputtering process.

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