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# Radio-frequency magnetized ring-shaped hollow cathode discharge plasma for low-pressure plasma processing

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ABSTRACT

Influence of magnetic field configuration on ring-shaped hollow cathode discharge has been investigated in order to perform high-density plasma sources under a low gas pressure of a few tens mTorr. Three typed arrangements of permanent magnets such as (a) NS-NS, (b) NS-SN and (c) NS are examined. The NS-NS arrangement has a divergent profile with a peak in axial direction in hollow cathode. The NS-SN placement forms a cusp profile with a mirror configuration in axial direction. In final, the NS setup assigns a conventional divergent field. For the cases of (a) NS-NS and (b) NS-SN arrangements, their plasma density keeps a higher order of magnitude of $10^{11}$ cm$^{-3}$ at the wide range of gas pressure of 10–200 mTorr. On the other hand, the NS arrangement maintains only the order of magnitude of $10^{11}$ cm$^{-3}$ at the region of gas pressure more than 30 mTorr. All radial profiles of plasma density near the hollow cathode show non-uniformity like M-shaped distribution. However, it is found that the uniformity of their radial profiles depends on the arrangement of permanent magnets.



## 1. Introduction

It is well known that the hollow cathode discharge can produce high-density plasma with only a simple structure of the hollow electrode [1–15]. It is reported numerically [1] that the following two interdependent mechanisms are consistently taken into account: the creation of ions and excited atoms due to electron collisions in the dc discharge and the emission of secondary electrons on the cathode surface due to ions and ultraviolet photons. Recently, a two-dimensional particle-in-cell simulation [2] has been developed to study density enhancement of capacitively coupled radio-frequency (RF) discharges with multi-slit electrodes. The observed density increase is shown to result from the hollow cathode effect that takes place within the multi-slit electrode configuration, which forms as a result of secondary electron emission due to ion bombardment. Up to now, various hollow cathode RF discharges [6–12] have been investigated for high-density plasma production. It has been reported [7] that a square hollow cathode with a tapered shape was developed in order to produce highly uniform and dense plasmas with density on the order of $10^{10}$ cm$^{-3}$ with a wide range of operating pressures (20–200 mTorr). RF linear hollow cathodes in several arrangements [8] have been examined for operation at reduced gas pressures and suitable for scale-up. The performance of a RF powered cylindrical and linear hollow cathode with gas flowing through the cathode, in the mTorr pressure range, was reported with some linear magnets [9]. The use of hollow electrode enhanced high intensity plasma for semiconductor fabrication processes was analyzed [10]. Compound RF discharge plasmas with a tapered shape hollow cathode compared with a plane cathode were investigated for the development of plasma processing [11]. Musil et al. [12] has investigated dc magnetron sputtering with grooved target, where hollow cathode discharge is attained. The results have reported a dramatic decrease of the discharge voltage needed to sustain a certain discharge current compared to the planar target. Recently, in plasma enhanced chemical vapor deposition sources, we have developed a high-density plasma with the hollow cathode effect using multiple hollow electrodes for amorphous hydrocarbon (a-C: H) thin films [13].

In our previous studies on plasma source, we have developed the high-density plasma with the ring-shaped hollow electrode of the well-typed shape [14]. A maximum plasma density of $10^{11}$ cm$^{-3}$ was attained at Ar gas pressures of 100–350 mTorr and/or an input power density of 0.64 W cm$^{-2}$. However, as the size of hollow width $W$ is fixed, the pressure at which the hollow cathode effect is satisfied is limited. Namely, the size must be widened by reducing gas pressure. According to the criteria [15] of our proposed ring-shaped hollow cathode discharge; $W = 2d_s + \lambda_{en}$ where $d_s$ and $\lambda_{en}$ are sheath thickness and electron-neutral mean free path, respectively, the hollow width is required at approximately

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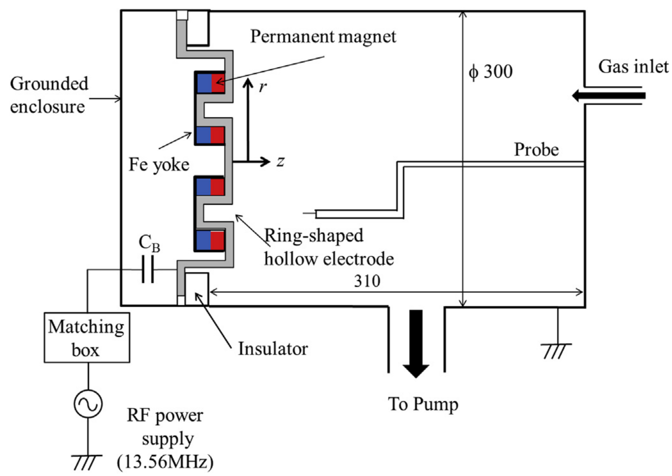


**Fig. 1.** Schematic diagram of radio-frequency magnetized ring-shaped hollow cathode discharge plasma.

100 mm at gas pressure of 10 mTorr. It is impossible for small electrode of the magnitude of 100 mm to form the hollow trench.

The addition of a magnetic field is one candidate for the solution. Electrons are easily magnetized under a lower gas pressure in general [16]. The electrons rotate around the magnetic field line so that the chance of the collision to the neutral gases increases. The electron-neutral mean free path which decides the hollow trench width at the lower gas pressure shortens effectively under the presence of the magnetic field. Therefore, it is possible to satisfy the criteria of the ring-shaped hollow cathode discharge with the use of the magnetic field under the lower gas pressure conditions.

In this paper, influence of magnetic field configuration in hollow trench on ring-shaped hollow-cathode discharge has been investigated for producing high-density plasma under lower gas pressure. The plasma density is examined by Langmuir probe at various external conditions of gas pressure and radio-frequency input power. In Section 2, experimental setup is explained in detail. In Section 3, the arrangements of permanent magnets in the ring-shaped hollow cathode electrode are explained in detail. In Section 4, results and discussions on magnetic field of their arrangements of magnets, and gas pressure dependency and radial profile of plasma density are described. In Section 5, the results obtained in this paper are summarized.

## 2. Experimental setup

The experiments are done in a stainless steel cylindrical vacuum vessel with 300 mm in diameter and 310 mm in length as shown in Fig. 1. The ring-shaped hollow electrode with 104 mm in diameter, which has a trench with 10 mm in width, 15 mm in depth and 48 mm in inner diameter and 68 mm in outer diameter, is mounted from a left side through an insulator. Permanent magnets are set around the trench as shown in Fig. 1. In detail, the setup is described in the next section later. In the experiment, a base pressure in the vessel is kept to be less than $10^{-6}$ Torr. Ar gas is introduced from 10 to 200 mTorr by regulating a flow meter. The radio-frequency (RF) power supply at 13.56 MHz which ranged from 20 to 50 W is input through an impedance-matching network and a blocking capacitor between the RF powered electrode and the grounded vessel. The gap between the RF powered electrode and the grounded vessel is fixed at 2 mm so as to avoid an additional discharge between the electrode and the grounded chamber. The discharge voltage is measured by the high-

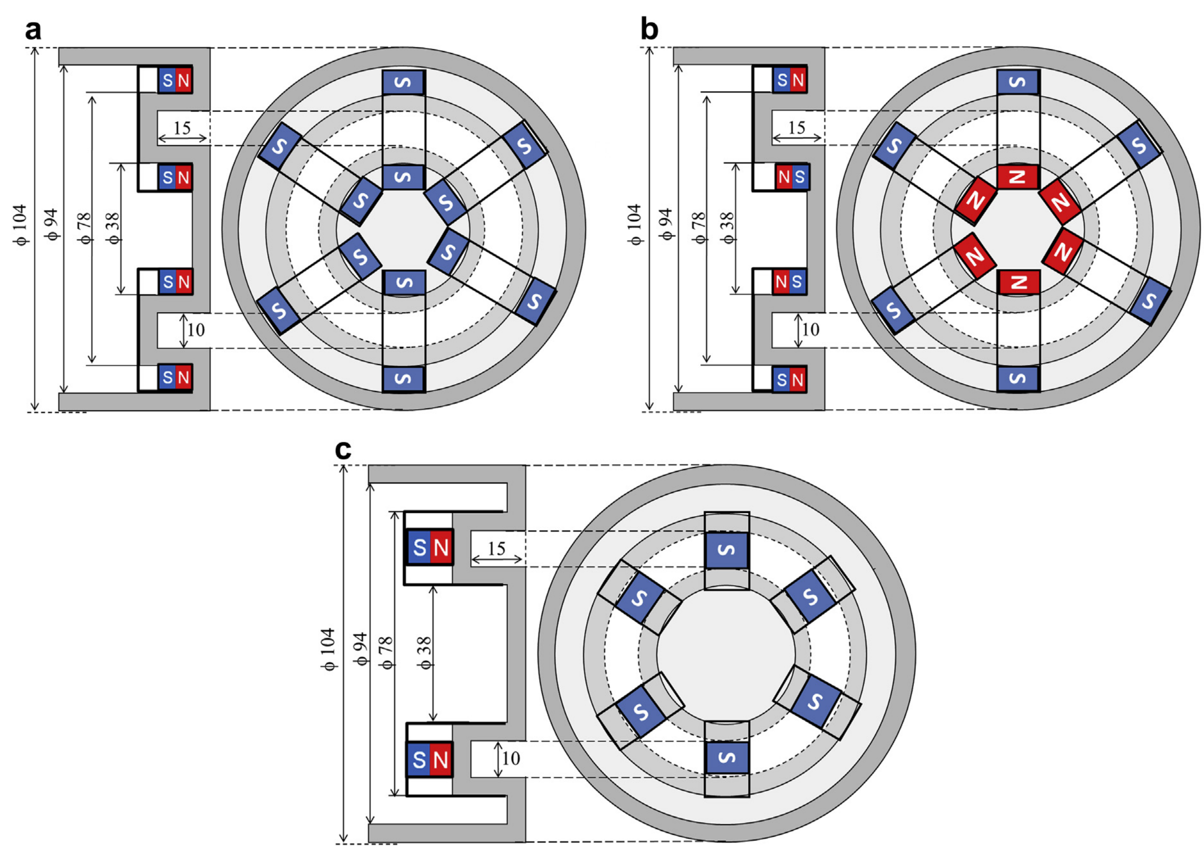


**Fig. 2.** Constructions of ring-shaped hollow cathode for (a) the NS-NS arrangement, (b) the NS-SN arrangement and (c) the NS arrangement of permanent magnets. The neodymium magnets were used.