Control of Magnetic Field in Neutral Loop Discharge Plasma for Uniform Distribution of Ion Flux on Substrate

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Abstract **– The production and transport of ions in a neutral loop discharge plasma under a quadrupole magnetic field were investigated using a Monte Carlo method. The ion production occurred around the separatrices of the quadrupole magnetic field and decreased as the neutral loop shrunk. The ion flux on the substrate had its peak near the foot of a separatrix. It was demonstrated that the time-averaged ion flux on the substrate can be distributed uniformly by controlling the magnetic field so that the foot of the separatrix sweeps over the substrate.**

Index Terms **– Neutral loop discharge plasma, quadrupole magnetic field, separatrix, etching, ion flux, uniformity, Monte Carlo method.**

Neutral loop discharge (NLD) plasma is a type of inductively coupled plasma generated along a ring of a zero magnetic field, the so-called neutral loop (NL). The NL is formed by superposing magnetic fields induced by currents flowing through three coaxial coils surrounding a chamber (Fig. 1(a)). The NLD plasma can maintain a high plasma density at low gas pressures. Therefore, it is suitable for dry etching [1]. In this work, we investigated the transport of CF_3^+, an ionic etchant species, in a CF_4 NLD plasma. The spatial distribution of the ion production and the distribution of ion flux on the substrate surface were evaluated at various NL radii, R_{NL}. We demonstrated that the time-averaged ion flux can be distributed uniformly by the dynamic control of R_{NL}.

We used a cylindrical chamber with a 40-cm diameter and a 40-cm height. The substrate was placed at the bottom of the chamber. A quadrupole magnetic field and an rf (13.56 MHz) electric field were applied to drive the NLD plasma. The currents through the top and bottom coils (60 turns each), I_{top} and I_{btm}, were fixed at 95.6 A, and that through the middle coil I_{mid} was varied from 81.5 to 131.5 A to vary R_{NL} in the range 0–18.7 cm. The number density of CF_4 molecules was set at 1.77×10^{13} cm^{-3} (0.5 mTorr at 273 K).

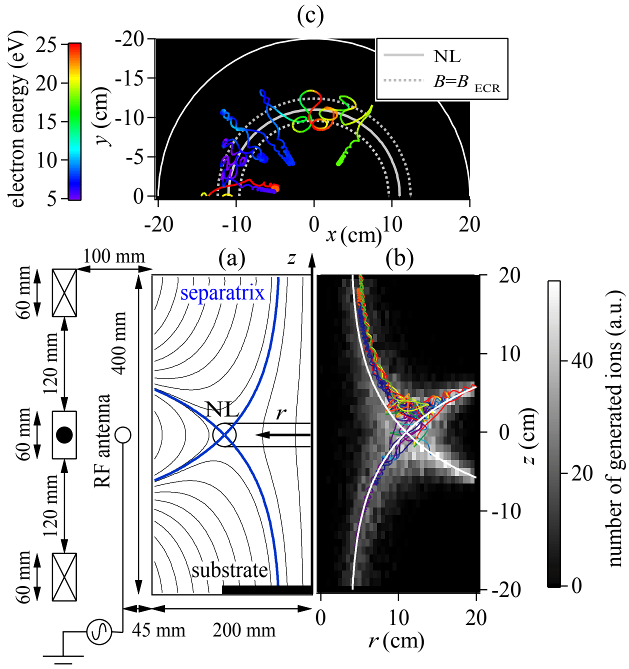

Fig. 1. Schematic of the neutral loop discharge reactor and an example of electron locus at I_{mid} = 111.5 A and R_{NL} = 11 cm: (a) the geometry and magnetic field, (b) side view of the locus and distribution of ion generation, and (c) top view of the locus.

The electron motion starting from the NL region was traced by a Monte Carlo method for 1000 rf periods and the positions of ionization collisions that produced CF_3^+ were sampled. The electron collision cross sections of CF_4 were taken from ref. [2]. We omitted the effect of the space charge field and focused on the essential function of the magnetic field that governs the electron and ion behaviors. We assumed the electron reflectivity at the chamber wall to be 99%.

After the simulation of the electrons, the flight of the produced CF_3^+ ions was traced. The initial ion velocity was chosen at random from a Maxwellian distribution at 273 K. The ion flight was treated to be collisionless because the ion mean free path estimated from the radius of the CF_4 molecule was of the order of tens of centimeters. The positions on the substrate surface where the ions reached within 50000 rf periods were sampled.

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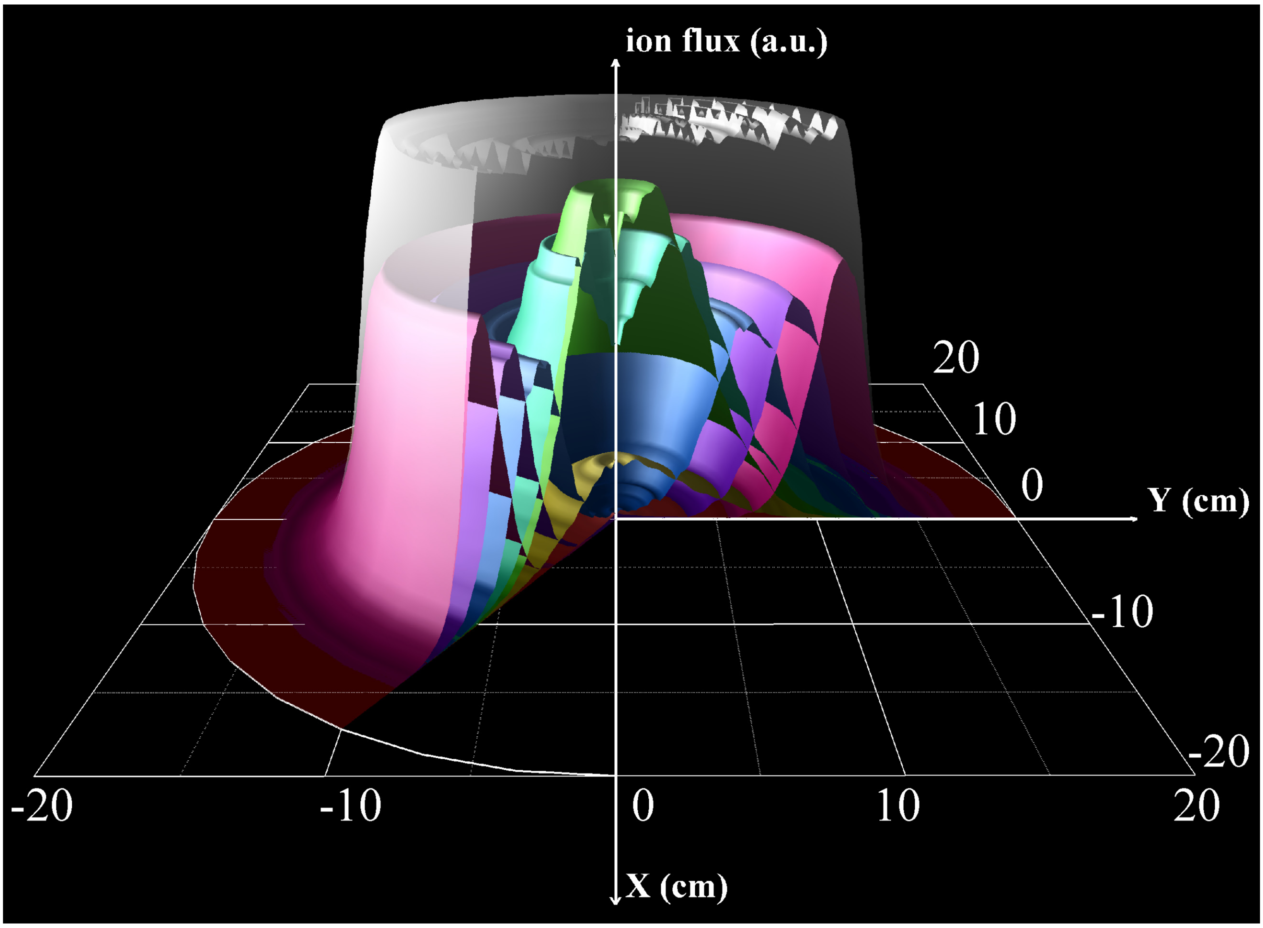

Fig. 2. Distributions of CF_3^+ flux on the substrate at I_{mid} = 81.5–131.5 A increased in steps of 10 A (from red to yellow). Their peaks appeared near the foot of the separatrix. The distribution shown in white is an ensemble of the distributions with chosen weights. Its trapezoidal cross section indicates that uniform ion irradiation is possible within a 20-cm diameter by allowing the separatrix to sweep over the substrate.

Figs. 1(b) and 1(c) show a typical example of an electron motion in the quadrupole magnetic field. The electron gained energy in the NL region when it moved along the NL, and gyrated under the guide of a magnetic field line along the separatrices. Here, we defined the NL region as the region in which the magnetic field strength is less than the rf-resonant magnetic field, B_{ECR}, which is equal to 0.48 mT. Owing to this energy transport along the separatrices, ionization occurred not only in the NL region but also along the separatrices (Fig. 1(b)).

The ion production was dependent on R_{NL}. When the NL approached the rf antenna, the ion production increased because of a tight electromagnetic coupling between the NLD plasma and the antenna. In contrast, the ion production decreased with shrinking NL and vanished when the NL degenerated into a point.

Fig. 2 shows the distributions of ion flux on the substrate at various R_{NL} values. The distribution peaks appeared near the foot of the downward separatrix. This was because CF_3^+ ions were produced near the separatrix and guided to the substrate by the magnetic field lines along the separatrix in the same manner as the electrons. By changing I_{mid}, we can allow the foot of the separatrix to sweep over the substrate surface [3]. The distribution shown in white in Fig. 2 is a superposition of the ion flux distributions at different R_{NL} values with chosen weights corresponding to the ion irradiation time. This distribution gives an estimation of the time-averaged etching rate distribution on the substrate. Its flatness, which spans a diameter of 20 cm, represents the uniformity. A possible method of achieving uniform etching by dynamic control of the separatrix in the NLD plasma has been demonstrated.

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