Large volume radio frequency plasma source with a magnetic line-cusp field

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A large-volume cylindrical radio frequency(rf) plasma source with a magnetic line-cusp field has been developed for large-scale plasma processing. In this type of plasma source, a capacitively-coupled 13.56 MHz rf plasma is produced in the presence of a magnetic line-cusp field. Three versions of the plasma source have been designed and tested. The first version has peripheral rf electrodes placed outside the ionization chamber, and is suitable for preparing a large-volume uniform plasma. The second version features doughnut-sharped parallel plate electrodes which form part of the chamber wall and serve as high-current source. The third version is a slab-plasma source, which has a rectangular ionization chamber, a pair of rectangular rf magnetic coils and a pair of rectangular rf electrodes.

I. Introduction

Recently many industries, such as integrated-circuit fabrication, ion milling and reactive etching techniques, and ion implantation,[1] have required a plasma source having much larger volume than the conventional ones. The ECR(electron cyclotron resonance) type plasma source seems to be the most suitable for high current and large-area irradiation;[2] however, it requires a relatively high magnetic field of about 1 kG. In this plasma source, a plasma produced in the central area of the ionization chamber must cross the magnetic lines in order to diffuse into the circumferential area; accordingly, this device is unfavorable for obtaining a uniform ion distribution.

We have thus investigated the possibility of a rf plasma source with a circular magnetic line-cusp field.[3-5] This plasma source can produce a plasma in the circunferential region of the chamber, allowing it to diffuse into the center and hence to attain a highly uniform density distribution. This new type of rf plasma source aims to increase the ability for uniform ion beam irradiation over a large area. We have constructed and tested three versions of this plasma source. In what follows, their structures, operational principles, and test results are described. In all measurements reported here, discharge gases employed are argon(Ar) and helium(He).

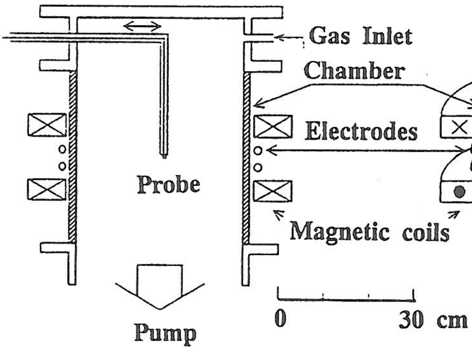

Fig.1 Schematic diagram of rf plasma source with a circular magnetic line-cusp field.

II. Structure and characteristics of the version I plasma source

A. Structure of the version I plasma source. The structure of the version I plasma source is schematically shown in Fig.1. The plasma source consists of cylindrical ionization chamber, a pair of magnetic coils, and a pair of peripheral rf electrodes. The inner diameter of the ionization chamber, made of Pyrex, is 35 cm and the length 40 cm. Around the chamber is mounted a pair of magnetic coils, which are used for producing a magnetic line-cusp field in the chamber. A discussion on the role of the cusp field will be given in Sec. IV. The coils are movable to find their most suitable positions and are usually separated by about 10 cm, giving a magnetic field of about 400 G in the vicinity of the chamber wall. The peripheral rf electrodes are placed between the magnetic coils. Both of these also can be moved, and typically placed at an interval of 5 cm. Because the coils and the electrodes are placed outside the ionization chamber, they are free from corrosion even when a chemically active discharge gas is used. The rf power usually supplied was around 500 W with a frequency of 13.56 MHz and coupled to discharge through an impedance matching network. The discharge gas is fed to the ionization chamber through a mass flow controller. The chamber is pumped by 10 in. oil diffusion pump and the ultimate pressure reached was 10^{-6} Torr.

B. Characteristics of the plasma source

As a first step of the development, we studied key issues in the production of a large-volume uniform plasma; in order to examine the plasma characteristics, a movable asymmetrical coaxial double probe(area ratio=1:600)[6] and a computer-coupled analyzing system were prepared. We examined electron density distributions for various discharge gas pressures to find the optimum pressure for a uniform plasma density distribution. Figure 2 shows radial profiles of the electron density distribution obtained for Ar in the central area of a magnetic line-cusp field. In this

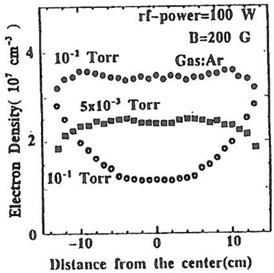

Fig.2 Radial profiles of the electron density distribution in the central area of a magnetic line-cusp field for various pressures in the ionization chamber. The working gas is Ar; the magnetic field is 200 G in the circumference of the chamber and the rf power is 100 W.

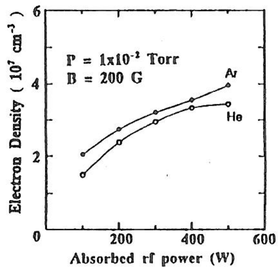

Fig.3 The electron density in the center of the chamber as a function of the rf power. Pressures of Ar and He are $1x10^{-2}$ Torr, the magnetic field is 200 G in the circumference of the chamber.

plasma source, the pressure most suitable for obtaining a uniform plasma is found to be around 10^{-2} Torr, where we can obtain a useful area of plasma with 10 % uniformity over a 30-cm-diameter region. For pressures equal to or higher than 10^{-1} Torr, the electron density near the wall was found to be much higher than that in the center. This reflects the fact that the plasma cannot easily diffuse into the central area because of the high pressure. In contrast, for pressures equal to or lower than 10^{-3} Torr, the density in the center is higher than that near the wall, showing that effective diffusion is taking place in order to reduce the density difference between circumferential region and central region, however, the electron density of plasma remains quite small.

The electron density in the center of the chamber is shown in Fig.3 as a function of the rf power. It increase with increasing rf power, but the increase rate is smaller than expected; it only reaches 10^7 cm^{-3} at 500 W. The rf electric field thus does not work enough to produce a high electron density so long as the structure of rf electrodes taken here is used; to obtain a high current source, therefore, a new design will be necessary.

III. The version II plasma source: A high density plasma source

In order to increase the electron density, we designed an improved version of the plasma source, version II, whose structure is schematically shown in Fig. 4. The ionization chamber consists of one large and two small Pyrex cylinder, and between each of the smaller ones and the larger one intervenes a piece of stainless-steel doughnut plate; the two piece of plate serve together as parallel-plate electrodes. The larger cylinder is 20 cm in inner diameter and 4 cm in height and the smaller one is 10 cm in inner diameter and 10 cm in height. Each magnetic coil is arranged around each of smaller cylinders. In order to secure zero magnetic field in the

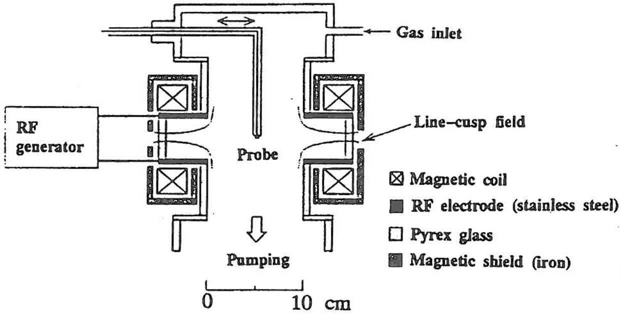

Fig.4 Schematic diagram of the high current rf plasma source.

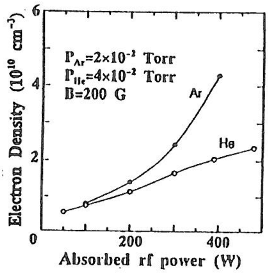

Fig.5 The electron density in the center of the chamber as a function of the rf power. Pressures of Ar and He are 2x10^{-2} and 4x10^{-2} Torr, respectively; the magnetic field is 200 G in the circumference of the chamber.

central area of the chamber, the coils are covered with an iron magnetic shield plate except their electrode sides. The electron density measured in the center of the chamber is plotted against the rf power in Fig.5. The electron density is proportional to the rf power, being equal to 10^{10} cm^{-3} at 400 W. It is also found that the electron density of Ar plasma exceeds that of He plasma, and the rate of increase of plasma density is higher in Ar plasma than that of in He plasma, and the rate of increase of plasma density is higher in Ar plasma than in He plasma. The reason for such a difference is considered to be that their ionization potential play an important role. A sharp rise in the plasma density for Ar has been observed. We considered that at low rf power, ionization is provided by plasma electron and the discharge is in the α mode,[7] being similar to the positive column of a dc discharge, while at high rf power ionization is maintained by fast electrons initiate at the rf electrodes and the discharge is in the γ mode,[7] being similar to the negative glow region of a dc glow discharge.

IV. Role of the magnetic fields

From the viewpoint of obtaining a uniform plasma profile, it was highly important to know which works better: the cusp or the mirror field. We cite in Fig.6 test results which were obtained using a small device similar to both version I and II developed for the purpose of producing an oxygen plasma source. In this device, a pair of magnetic coils are mounted around the chamber and a pair of peripheral rf electrodes are placed between the magnetic coils inside the chamber. Uniformity of the plasma density distribution in the chamber was checked through the intensity of the O_2 I–558.5 nm spectral line detected with a spectroscope. When a magnetic line-cusp field was used, an almost uniform intensity distribution in the central area

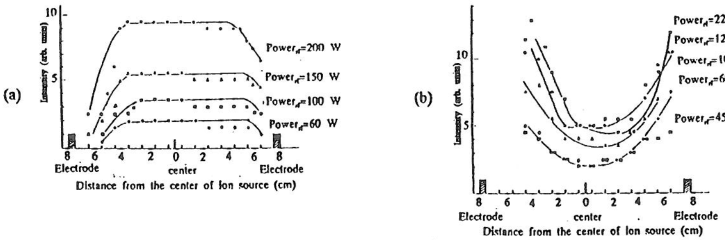

Fig.6 Radial intensity profiles of the O_2 I-558.5 nm line intensity for various pressure in (a) cusp and in (b) a mirror field. Oxygen pressure is $3x10^{-3}$ Torr. The magnetic field in the circumference of the chamber are 90 and 140 G, respectively, for cusp and mirror field.

was obtained{Fig.6(a)}. In contrast, when a mirror field was used, the intensity of the central area was much lower than that near the chamber wall and the distribution is far from uniform{Fig.6(b)}. These results show that the cusp field is far favorable than the mirror field for obtaining a uniform distribution.

When a magnetic line-cusp field is established along the circumference of the ionization chamber and an electric field perpendicular to it is applied in addition, the charged particles, i.e., ions and electrons undergo the drift motion along the chamber wall to the same direction. The velocity **v** is expressed as

$$\mathbf{v} = \mathbf{E} \times \mathbf{B}/\mathbf{B}^2$$

where **E** is the electric field and **B** is the magnetic field.[8] Besides this drifts, there exists the polarization drift for a time-varying electric field, and the curvature and gradient drifts arising from magnetic field configurations.[9] The magnetron motion and these drifts drive charged particle by a highly complicated manner to generate a high density plasma in the circumferential area of the ionization chamber; the plasma is allowed to diffuse into the central zero-field area of the cusp field. This is caused by a magnetic mirror-like effect in the line-cusp field area of the circumference of the chamber.[9] If the cusp field is replaced by a mirror field, a high magnetic field in the central area prevents the plasma from diffusing there.

V. Structure and characteristics of the version III plasma source: A slab-plasma source

A cylindrical plasma source is not suitable for high current and high energy ion implantation owing to difficulty in removing heat rapidly from the central part of an irradiated area. We have thus started on the development of a slab-plasma source for large-area irradiation. The structure of the plasma source is schematically shown in Fig.7. This plasma source consists of a rectangular ionization chamber, a pair of rectangular magnetic coils, and a pair of rectangular rf electrodes. The length of the chamber, made of Pyrex, is 15 cm and its cross-sectional dimensions are 3 cm and 8 cm. Around the chamber are mounted rectangular coils. They were separated by about 10 cm and the magnetic field strength in the circumference of

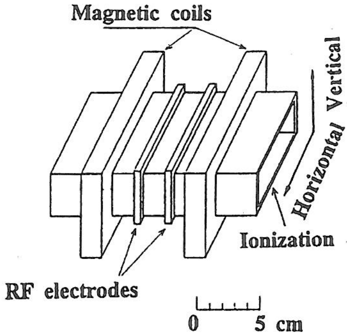

Fig.7 Schematic diagram of the slab rf plasma source with a rectangular magnetic line–cusp field.

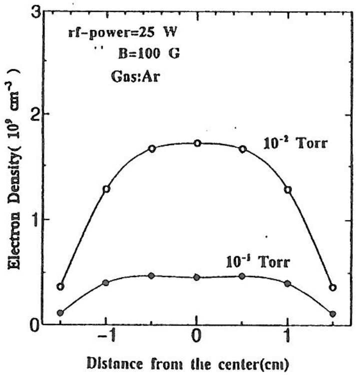

Fig.8 The electron density distribution in the center of the rectangular chamber in the vertical direction for two pressures. The working gas is Ar; the magnetic field is 100 G in the periphery of the chamber and the rf power 25 W.

the chamber wall was about 100 G. The electrodes are placed between the coils at an interval of 5 cm. The electron temperature and electron density were determined from the velocity distribution function to be about 10 ev and 10^9 cm^{-3} respectively, for a power of 25 W. Uniformity of the electron density in the chamber was checked with a movable probe. The electron density distribution in the vertical direction in the center of the rectangular chamber is shown in Fig.8 for two pressures. The suitable pressure for a uniform plasma distribution was found to be around 10^{-1} Torr, where we can obtain a useful area of plasma with 10 % uniformity over a 2–cm–long region. These results indicate that the rectangular rf plasma source with the magnetic line–cusp field is suitable for uniform slab–plasma production.

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