Two-Dimensional Spatial Structure of Inductively Coupled Plasma with One Internal Loop Antenna

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Inductively coupled plasmas with a radio frequency power supply are widely used as high density plasma sources. It is well known that they include not only an inductive discharge mode but also a capacitive one. The antenna support, especially, would serve as the capacitive coupling element, while the loop antenna the inductive one due to the antenna geometry. It was found that the length of the antenna support plays an important role in the plasma ignition. The antenna size is also one of the key parameters of the discharge mode, also changing the plasma structure. The radio frequency power corresponding to the discharge transition from the capacitive to inductive mode decreased with increasing the antenna size. In order to study the discharge mode transition, two dimensional spatial structures of inductively coupled plasma using an internal loop antenna have been investigated using two antennas with different sizes. The results have revealed that for the large antenna of 150 mm diameter, the uniform profile was formed even at low injected powers, whereas for the small antenna of 55 mm diameter, the spatial structure of plasma density depended on the injected radio frequency power.

Keywords: Inductively coupled plasma, high-density plasma source, spatial structure of plasma density, capacitively coupled discharge, antenna support, internal loop antenna, discharge mode transition

1. Introduction

Inductively coupled plasmas (ICP) using radio frequency (RF) power supply are widely used as in the case of capacitively coupled plasma (CCP) for plasma processing [1, 2]. In ICP systems, helical and spiral antennas are usually placed outside the discharge chamber, but immersed loop antennas are also used [2]. In order to avoid electron loss at the antenna and to suppress the anomalous rise of the plasma potential, a new-type of internal coupling system developed in which a bare metal antenna is directly immersed into the plasma [3]. On the other hand, the large-diameter RF plasmas are produced by inductive coupling of the internal –type antenna [4]. In this system, the double half-loop antenna of 360mm diameter was employed for the reduction of antenna inductance. Thus, the internal-antenna configuration to produce ICP is expected as a promising candidate for an efficient high-density source, as well as an alternative to avoid the problems associated with dielectric windows in conventional sources. In the plasma processing of the large diameter substrate for microelectronic device fabrication, uniform plasma over a large area is required. In the large diameter inductive plasma, the mode transition between CCP and ICP has been investigated with power transfer efficiency, i.e., the ratio of the net power deposited into plasma to the total power input into the matching circuits [5]. The influence of the antenna configuration and standing wave effects on the density profile has also been examined in the large-area ICP source [6]. In these studies, two-dimensional structures of plasma density for CCP and ICP have not been measured in detail although the antenna-size may also affect the spatial structure of plasma parameters.

In this work, we have investigated the spatial structure of RF plasmas, for two internal loop antennas with different diameters, using a movable needle Langmuir probe. The effect of the antenna support on the discharge mode transition has also been examined from the plasma production viewpoint.

2. Experimental procedure

Figure 1 shows the experimental vacuum vessel, 300 mm in diameter and 300 mm in length. The immersed antennas with four different diameters, in the range from 55 to 150 mm, were independently used. These antennas were covered by insulated tubes to suppress the contamination of the metal antenna and the additional

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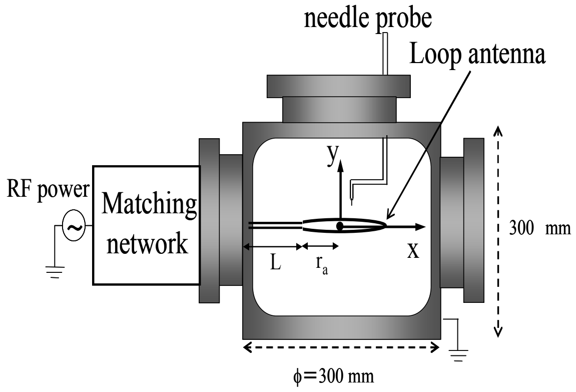


Fig.1 Experimental apparatus for inductively coupled plasma system.

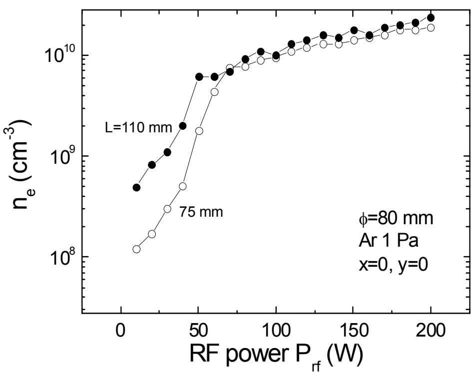


Fig.2 Plasma density n_e as a function of RF power P_{rf} for two different antenna supports, of L=75 and 110 mm. Here, the antenna size is 80 mm in diameter.

discharge with the grounded chamber wall. The inductance of antenna increased from 400 to 550 nH with increasing its diameter, while the capacitance decreased from 60 to 40 nF. Thus, a combined impedance of the antenna changed from 2.5 to 3.5 Ω. These values were measured at a fixed frequency of 1 MHz and a fixed voltage of 5 V. The lengths of radii and support of the antenna are denoted as r_a and L, respectively. The axes x and y for the two-dimensional structure of plasma density are also defined as shown in Fig.1. Ar gas was introduced at a pressure of 1 Pa. The RF power at 13.56 MHz input to generate the ICP through the matching network was in the range of 30-200 W.

The Langmuir probe filter, consisting of an LC parallel circuit with a variable capacitance C, was used to compensate the influence of RF plasma potential oscillations on the probe characteristics [7-9]. In order to remove the contamination of the probe surface, a cleaning of the probe by Ar ion bombardment was done for about one hour before every measurement. The fundamental plasma parameters, such as temperature and density of electrons were estimated from the electron current –voltage characteristic [10] measured by the Langmuir probe (a needle with 0.1 mm in diameter and 3 mm in length). On the other hand, the spatial structure of plasma density for two different antenna sizes, 55 and 150 mm in diameter, were evaluated from the ion saturation current density j_{is} detected by rotating and moving the negatively biased L-shaped Langmuir probe. This is because the plasma density is almost proportional to the ion saturation current density [10].

3. Results and discussion

The antenna support may affect the plasma production, even the ICP, because the ICP includes the CCP. Figure 2 shows the plasma density as a function of RF injected power for two different antenna support lengths of L=75 and 110 mm, respectively. Here, the measured position is at a center of the antenna, which is 80 mm in diameter. It is seen that for a short support length of L=75 mm the plasma density increases drastically with increasing RF power P_{rf} from 10 to 70 W and then gradually increases to be 10^{10} cm^{-3}. That is, in this case, the discharge mode reaches the ICP at 70 W. On the other hand, for a long support length of L=110 mm the plasma density also increases in the same manner. But, the RF power for the discharge transition to the ICP mode is 50 W, which is lower than that for the short support length. In the region of the CCP mode for P_{rf} < 70 W, the plasma density for L=110 mm is higher than that for L=75 mm. The difference of the plasma density between them decreases also with increasing P_{rf}. This indicates that the long antenna support serves to attain easily the plasma production for the CCP mode. This effect of the antenna support was dependent on the antenna size and became weak with increasing the antenna size.

The influence of the antenna size on plasma density has been examined. Figure 3 shows plasma density as a function of RF power at various antenna sizes from 55 to

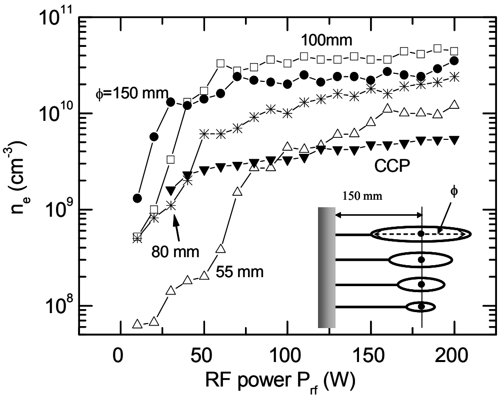


Fig.3 Plasma density n_e as a function of RF power P_{rf} for various antenna sizes of 55 - 150 mm. Here, the distance between the center of the antenna and the grounded chamber wall is fixed to be 150 mm at all antenna sizes. CCP denotes data of capacitively coupled plasma.

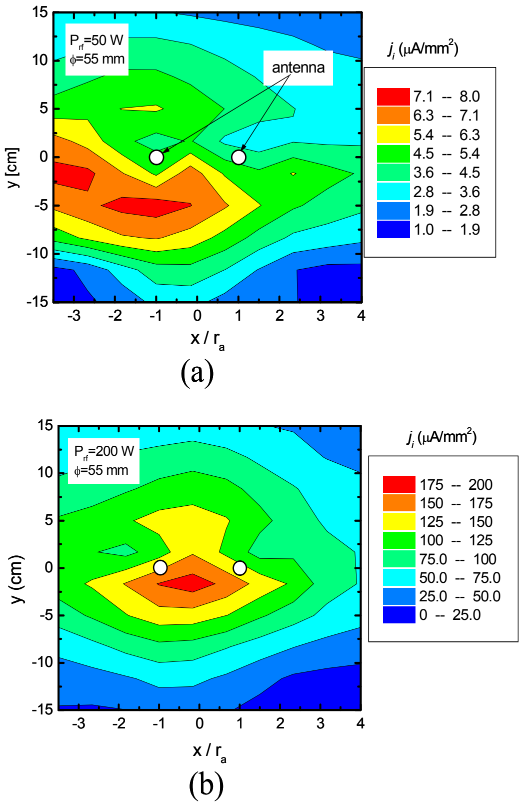
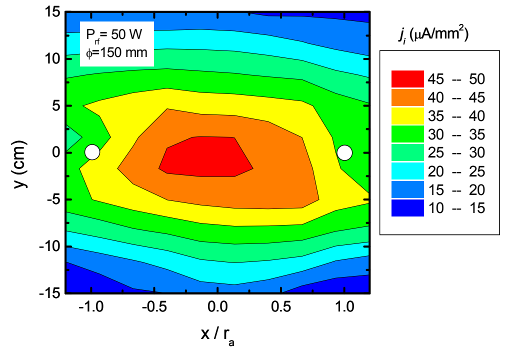


Fig.4 Two dimensional *x-y* contour maps of plasma density in the case of 55 mm diameter antenna for (a) P_{rf}=50 W and (b) 200W, respectively. Probe ion saturation current density j_{is} is used as the plasma density.

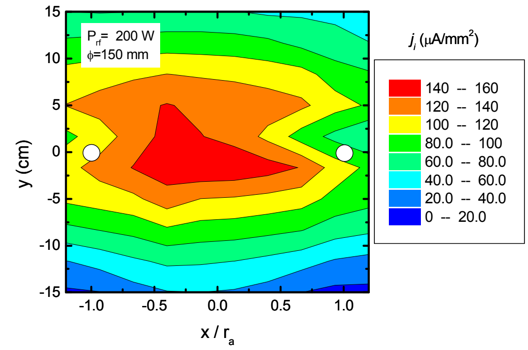
150 mm. As shown in an inset of Fig.3, at all antenna sizes the distance between the center of the antenna and the grounded chamber wall was fixed to be 150 mm. Here, the measured position is at the center of the antenna. For comparison, data of CCP with a plane electrode are also included in Fig.3. The parameters were measured at the distance of 65 mm from the plane electrode. In this case, the plasma density steadily increases with being of the order of 10^9 cm^{-3}.

For all antenna sizes, the variation of the plasma density as the discharge transited from CCP to ICP was studied. The RF power at which the discharge mode transits from the CCP to the ICP decreases with increasing the antenna size. The plasma density at a fixed RF power also increases with increasing the antenna size. This can be explained as follows. In the CCP discharge, the breakdown voltage V_B might obey the Paschen law [11]. In general, a minimum breakdown voltage $(V_B)_{min}$ is a few Torr·cm. As the pressure is about $p=10^{-2}$ Torr, it is easy for the long support rod to discharge plasma. This means that for the large antenna size the plasma is easily generated and has high density.

In these plasma discharge systems, the spatial structures of the plasma density were investigated for two sizes of the antenna. Figures 4 (a) and (b) show two-dimensional *x-y* contour maps of the plasma density for the small antenna size (ϕ=55 mm) at P_{rf}=50 and 200 W, respectively. Here, the radial position is normalized by the antenna radius r_a, x/r_a =±1 denoting the position of the antenna. For low powers, the plasma density has a maximum value at y=-5cm above the antenna and then decreases with going away from that position. The non-uniform plasma density profile observed at low powers indicates that the discharge is in the CCP mode. For high powers, the plasma density in the center of the antenna is the highest in the whole area and decreases symmetrically when the distance from the center increases. In the former case, the spatial structure of the plasma density is caused by that that the antenna acts as a powered electrode in capacitively coupling plasma. The reason why the plasma density is asymmetric along the y axis in Fig.4 (a) and (b) might be ascribed as follows.



(a)



(b)

Fig.5 Two dimensional *x-y* contour maps of plasma density in the case of 150 mm diameter antenna for (a) P_{rf}=50 W and (b) 200W, respectively.

Since a top flange which was positioned at y / r_a = 32 and 2 < x / r_a < 2 was made from an insulating material, the capacitive character of the discharge is enhanced at the region of the bottom metal flange.

Figures 5 (a) and (b) show two-dimensional *x-y* contour maps of the plasma density for the large antenna (ϕ=150mm) at P_{rf}=50 and 200 W, respectively. It is found that the spatial structure for the low power is almost the same as that for the high power. This might be ascribed to the fact that the ICP was attained at the low power of 50 W. When comparing the profile for the small antenna, the region with the uniform density is seen to expand for the large antenna. This suggests that the large antenna can produce an uniform plasma even at the low power.

4. Conclusion

Two-dimensional structures of plasma density have been investigated for two antenna sizes for large diameter plasma processing. The influences of the support length and the diameter of the antenna on plasma production were also discussed. It was found that plasma production is easily attained for the long antenna support and the large antenna diameter. In the case of the small antenna diameter, for a low power it was observed that the plasma density structure is that ascribed to the CCP mode, while for a higher power a uniform profile in the antenna loop was detected. On the other hand, in the case of the large antenna diameter, it was revealed that the uniform plasma structure could be attained even at low RF injected powers.

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