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Study of ICP Production Mechanism by an Alternative Magnetic Field Measurement

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Abstract: In order to study the plasma production mechanism, the profiles of the inductive electromotive forces (IEMF) penetrated in the inductively coupled plasma (ICP) are discussed. Magnetic probe measurements were performed in the high dense argon ICP using different types of antenna. The IEMF is an important factor to heat the electrons in the ICP production and is closely related to the ICP production efficiency. The edge type antenna gave the deep IEMF penetration, which showed a high plasma production efficiency at the same discharge power. The deep IEMF penetration could introduce the energy in the deeper region of the plasma and contributed to the efficient ICP production due to the suppression of the heated electron extinction at the quartz wall. The 100mm wide antenna showed that the IEMF attenuation coefficient at the antenna center level was higher than that at the antenna bottom-edge level, and it was the same as the IEMF attenuation coefficient of the edge type antenna. This result implied that the antenna bottom-edges were an important part of the ICP production.

Keywords: ICP, Plasma, Production efficiency, Inductive electromotive force, Alternative magnetic field

1. Introduction

Inductively coupled plasma (ICP) mechanism can realize a more efficient plasma production than that of the capacitively coupled mechanism, which is widely used for the application of the material plasma processing, such as a reactive ion etching and so on. Recently, the ICP sources have been examinined to apply to these processing, and an investigation for the ICP production mechanism is an important subject to achieve an advanced plasma processing.

We have investigated the ICP production mechanism using a simple ICP structure equipped the single loop antenna[1)2)]. The simple structure could lead us to understand the plasma production mechanism physically with ease. We evaluated the plasma characteristics for several types of antennas using a Langmuir probe, which had different antenna facing areas to the plasma.

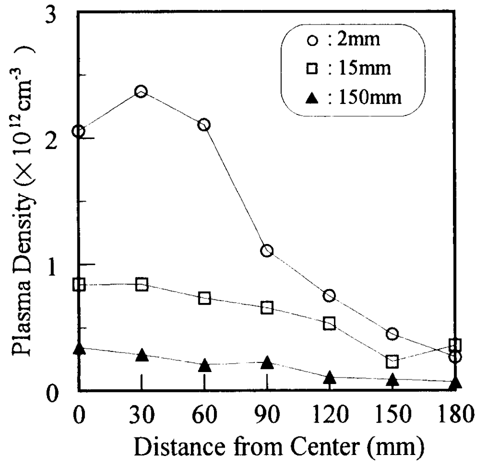

Fig.1 Plasma density distribution dependence on antenna geometry using discharge vessel(266mm inner diameter) (Discharge power: 2000W, Gas: Ar, Pressure: 1.3Pa, Measurement position: in evacuated vessel) [reference 1)]

It was proved that the plasma production efficiency depended on the antenna geometry as shown in **Fig.1**[1)]. In the ICP sources, the antenna coupled inductively with the plasma, however we could not eliminate the the capacitive coupling. The antenna with a small facing area to the plasma could reduce the capacitive coupling between the antenna and the plasma and improved the plasma production efficiency. When the inner side of the 2mm wide antenna was sharpened like a knife-edge, the plasma production efficiency was about 50% higher as shown in **Fig.2**[1)].

In the ICP, it is thought that the electrons in the plasma are heated mainly by the inductive electromotive force (IEMF), which is induced by the alternative magnetic field in the plasma. The objective of this study is to find how the plasma production efficiency shown in **Fig.1** depends on the electro-

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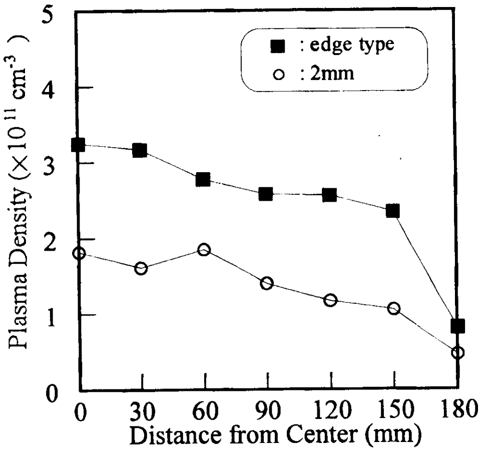

Fig.2 Plasma density distribution dependence on antenna geometry using discharge vessel(362mm inner diameter) (Discharge power: 1000W, Gas: Ar, Pressure: 1.3Pa, Measurement position: in evacuated vessel) [reference 1)]

magnetic field produced by varying the antenna geometry. In this paper, we have measured the alternative magnetic field profile in the discharge cylindrical vessel using a magnetic probe, whose output corresponds to the IEMF amplitude induced by the alternative magnetic field in the plasma. The study is also focused on the IEMF profile parameters at the antenna level, especially, the extrapolated IEMF amplitude at the quartz window and the IEMF attenuation coefficient. The former is the maximum IEMF amplitude produced in the plasma by the antenna, and it will show the relation between the absolute IEMF amplitude and the plasma production. The latter is the profile parameter, which characterizes the IEMF attenuation in the plasma. The low attenuation coefficient means the capacity to supply the energy into the deep region of the plasma due to the IEMF penetration. Moreover, we have evaluated the energy introduced into the plasma by using these parameters.

2. Experimental Setup

Fig.3 shows a schematic view of the experimental setup. A cylindrical quartz tube (266mm inner diameter and 220mm height) was used as a discharge vessel. One terminal of the cylindrical quartz tube was sealed by a grounded endplate. The another terminal was connected to a processing chamber. This chamber was evacuated to the background of 10^{-3}Pa by using the exhaust system. Ar gas was introduced into the discharge vessel and was controlled at the pressure of 1Pa. The discharge power (13.56MHz) was supplied to a single loop antenna

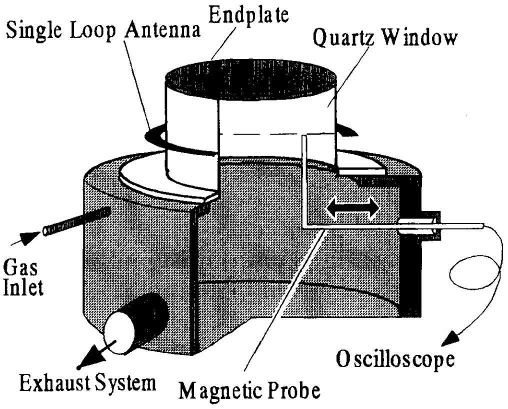

Fig.3 Schematic diagram of experimental setup

through a π type-matching network. Various antennas which have different cross sections were arranged coaxially to the quartz discharge vessel.

Fig.4(a)∼(c) show the details of the single loop antennas used in the experiment. The inner diameters of all antennas were standardized to be 300mm. These antennas were made of Cu. The cooling water lines were installed on the periphery of the antennas to prevent from an antenna impedance change during the discharge.

Fig.4(a) shows a 2mm wide antenna as the first antenna. This antenna was having a 2×20 mm^2 rectangle section. One of the 2mm sides of the antenna section was facing to the plasma, and therefore it had a small facing area to the plasma. In the electrostatical sense, this antenna geometry realized a small capacitance between the antenna and the plasma. The total surface area of this antenna was not so small, and a Joule loss at the antenna was low.

Fig.4(b) shows an edge type antenna as the second antenna. The 2mm wide antenna is worked upon this antenna, whose inner side facing to the plasma was sharpened like a knife-edge. Its facing area to the plasma was smaller than the 2mm wide antenna. But, this antenna geometry had an almost same surface area as the 2mm wide antenna. Therefore, the Joule loss of this antenna is almost equal to that of the 2mm wide antenna, for the skin depth of several μm for 13.56MHz.

Fig.4(c) shows a 100mm wide antenna as the third antenna. This antenna was a cylindrical plate (1mm thickness and 100mm width) wound around the discharge vessel. The facing area to the plasma was 50 times larger than that of the above antennas discussed in **Fig.4(a),(b)**.

The IEMF profiles were evaluated by maesuring

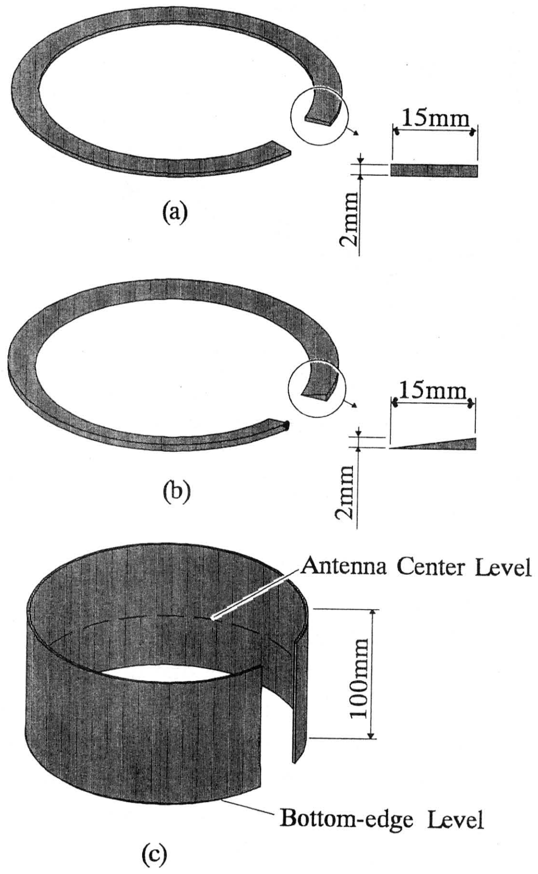

Fig.4 Details of different types of antennas
(a): 2mm wide antenna
(b): edge type antenna
(c): 100mm wide antenna

an alternative magnetic field in Ar plasmas using a magnetic probe. The measuring point was at the antenna level, at which the antennas could produce the largest alternative magnetic field. The magnetic probe was composed of a single loop (2.5mm inner diameter) at the end of a 50Ω coaxial transmission line. A core wire was welded to an external line of the coaxial transmission line. This magnetic probe was sealed by the ceramic tube to prevent it from exposing the detector part to the plasma, and could be swept radially across the vessel. The oscilloscope was connected to the another transmission line terminal to monitor the IEMF amplitude. To detect the maximum alternative magnetic field normal to the antenna plane, the single loop plane set to be parallel to the antenna plane. The output induced at the probe was proportional to the IEMF amplitude produced by the alternative magnetic field in the plasma. In this case, the discharge power frequency was a constant at 13.56MHz and the outputs of the probe were verified to be a sinusoidal wave. It was confirmed by the reflected discharge power that the magnetic probe did not affect to the matching network. Further, the sensitivity to the electric field was checked in the known capacitive state, which was produced by the connecting the only one terminal of the the 100mm wide antenna to the matching network. The output of the electric field was confirmed to be less than 1% of the total output. The IEMF was not calibrated in this experiment.

3. Experimental results

3.1 IEMF Measurement

Fig.5 shows the IEMF amplitude dependence on the distance from the quartz window at 400W. The IEMF amplitudes were measured at the antenna bottom-edge level and near the antenna center level for the 100mm wide antenna. The IEMF amplitude decreased exponentially as a function of the distance from the quartz window. But, it is evident that each IEMF amplitude produced by these antennas attenuated at different rates. In order to characterize these attenuating curves, a curve fitting was performed by the following equation,

$$V(r) = \alpha \cdot exp(-\beta r) \tag{1}$$

where V is the IEMF amplitude, α is the extrapolated IEMF at quartz window, β is the attenuation coefficient, and r is the distance from the quartz window. The comparison with these coefficients will be given in the following sections.

3.1.1 Extrapolated IEMF (α factor)

If the absolute IEMF amplitude were proportional to the ICP production efficiency, it would be valid to compare the maximum IEMF amplitudes for the plasma production efficiency. In the cyrindrical ICP, the maximum IEMF amplitudes of each antenna correspond to extrapolated values at the quartz window.

The dependence of the extrapolated IEMF amplitude at the quartz window on the discharge power is shown in **Fig.6**. The extrapolated IEMF amplitudes of all antennas increased as a function of the discharge power. The extrapolated IEMF amplitude of the 2mm wide antenna was greater than that of the edge type antenna at the same power. This result indicates that the absolute IEMF amplitude at the quartz window is not directly consistent with the ICP production efficiency.

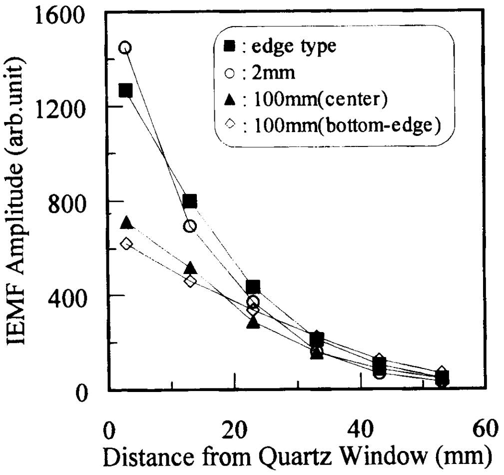

Fig.5 IEMF amplitude dependence on distance from quartz window at 400W

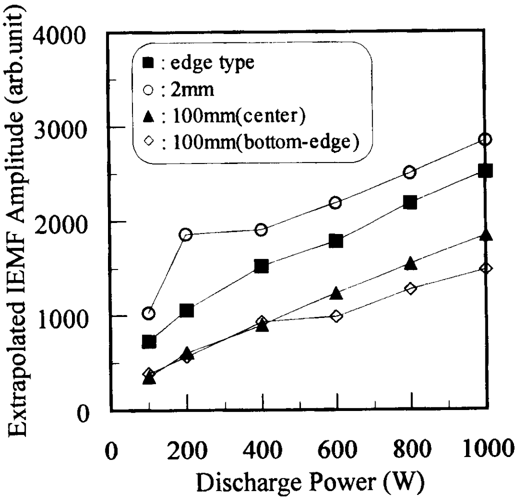

Fig.6 Extrapolated IEMF amplitude at quartz window on discharge power

The extrapolated IEMF amplitude of the 2mm wide antenna changed drastically at around 200W. This drastic change corresponds to the plasma production mode transition in this setup. The plasma production mechanism of the edge type antenna has been transited into the inductive power coupling in the region lower than 100W. Therefore, there is not a drastic extrapolated IEMF amplitude change. It is likely that the plasma production mode transition is reflected in the extrapolated IEMF amplitude.

On the other hand, the 100mm wide antenna did not produce the same IEMF amplitude at every antenna level. The extrapolated IEMF amplitude at the antenna bottom-edge level had a smaller value than that at the antenna center level at over 600W. But there were not drastic changes on the plasma characteristics at this power. A further discussion will be needed.

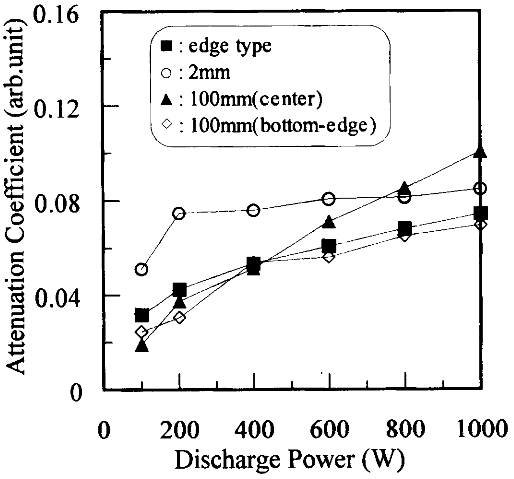

Fig.7 Attenuation coefficients dependence on discharge power

3.1.2 Attenuation Coefficient (β factor)

The attenuation coefficient is one of the important factors for the ICP production. The IEMF performs the electron heating in the ICP production and maintains the plasma. The low attenuation coefficient of the IEMF means that it is easy for the IEMF to penetrate deeply into the plasma and the energy can be supplied to the deep region of the plasma. The electrons near the quartz window have a high probability to extinguish at the quartz window. Therefore, the low attenuation coefficient can realize the high plasma production efficiency by a suppression of the energy loss at the quartz window.

The attenuation coefficient dependence on the discharge power is shown in **Fig.7**. This result showed that the attenuation coefficient of the edge type antenna was lower than that of the 2mm wide antenna. Considering the extrapolated IEMF amplitudes, the energy introduced by the 2mm wide antenna was localized at the plasma surface.

The attenuation coefficients of each antenna increased at quite different rates on the discharge power. The attenuation coefficient of the 2mm wide antenna changed drastically at 200W, which agreed with the plasma production mode transition. The plasma production mechanism is also reflected in the attenuation coefficient.

The attenuation coefficients of the 100mm wide antenna varied with the antenna levels in the same antenna. The attenuation coefficient at the antenna bottom-edge level did not agree with that of the antenna center level at over 400W and was same as that at the edge type antenna. It suggests that the IEMF produced at the antenna bottom-edge level may be dominant for the ICP production.

It is clear that the low attenuation coefficient at the antenna bottom-edge means the large energy introduction in the deep plasma region at the same discharge power. These results show that the attenuation coefficient of every antenna increased with the discharge power and it became difficult for the IEMF to penetrate into the plasma at high discharge power. In the next section, we will estimate the energy using these parameters mentioned above.

4. Discussions

In the cylindrical ICP sources, the maximum IEMF amplitude is produced at the antenna level, and the energy introduced into the plasma is estimated by the parameters at the antenna level. We estimated the energy introduced into the plasma by the surface integration at the antenna level. The energy of the electric field (E) is proportional to the square of the electric field E^2. Therefore, the surface integration of the squared IEMF amplitude (W_{0-63}) can be expressed in the following equation,

$$W_{0-63} = \int_{r=0}^{r=63} 2\pi(d-r)V(r)^2\,dr \qquad (2)$$

where r is the distance from the quartz window, d is the inner diameter of the discharge vessel and V(r) is the IEMF amplitude shown in the Eq.(1). The integration region was decided to be within 63 mm from the quartz window, for the IEMF amplitudes for the each antenna were almost same in the over 63mm region as shown in **Fig.5**.

Fig.8 shows the dependence of W_{0-63} on the discharge power. This result indicates that W_{0-63} introduced into the plasma increased monotonically as a function of the discharge power regardless of the type of antennas. W_{0-63} of the 2mm wide antenna was larger than W_{0-63} of the edge type antenna. Considering the plasma density shown in **Fig.2**, this result clearly indicated that the energy introduced into the plasma in this region is not directly proportional to the plasma production efficiency. Moreover, W_{0-63} of the 2mm wide antenna did not indicated a drastic change around the plasma production mechanism transition power.

On the other hand, W_{0-63} of the 100mm wide antenna were below 30% that of the other antennas. The parameters discussed in the above sections was different with the antenna levels, however, W_{0-63} at the antenna center level is same as that at the antenna bottom-edge level.

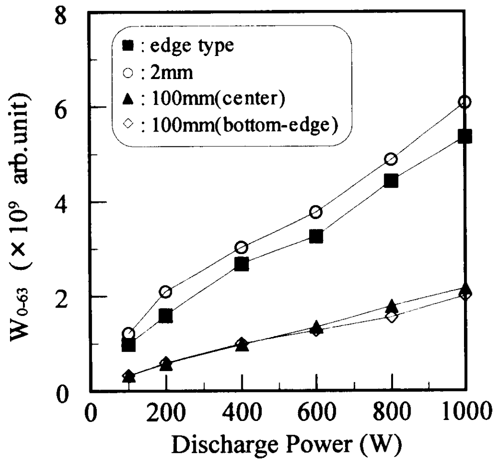

Fig.8 Dependence of W_{0-63} on discharge power in integration region within 63 mm from quartz window

Next, the energy in the different integration region was estimated. The IEMF amplitudes of the edge type antenna and the 2mm wide antenna were reversed at around 10mm from the quartz window as shown in **Fig.5**. Therefore, the integration region between 13mm and 63mm from the quartz window was considerd. We defined the surface integration of the squared IEMF amplitude in this integration region as W_{13-63}, and it was expressed in the following equation,

$$W_{13-63} = \int_{r=13}^{r=63} 2\pi(d-r)V(r)^2\,dr \qquad (3)$$

W_{13-63} dependence on the discharge power in this region is shown in **Fig.9**. From **Fig.9**, W_{13-63} of the edge type antenna is apparently greater than that of the 2mm wide antenna. Although, W_{13-63} values correspond to only 10% of W_{0-63} shown in **Fig.8**, W_{13-63} values agree with the relation of the plasma production efficiencies qualitatively. The actual plasma production is decided by the difference between the plasma production and the extinction at the quartz window. Therefore the electrons near the quartz window have a high probability to extinguish at the quartz window. It is likely that the IEMF away from the quartz window is the dominant factor for plasma production efficiency. So that, an efficient plasma production need such an antenna geometry that the IEMF can penetrate deeply into the plasma.

Secondly, W_{13-63} at the antenna center level of

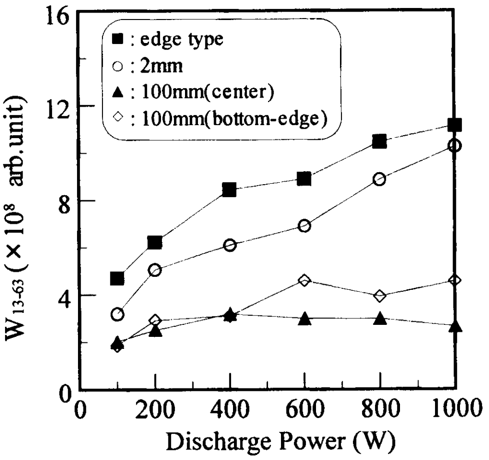

Fig.9 Dependence of W_{13-63} on discharge power in integral region between 13mm and 63mm from quartz window

the 100mm wide antenna decreased at over 400W. On the other hand, W_{13-63} at the antenna bottom-edge level increased slightly at over 400W. We could not have observed this behavior in the narrow wide antennas whose edges are not distant. It is difficult for us to distinguish where the alternative magnetic field is mainly produced at the antenna, because the IEMF produced in the plasma is the composite of the magnetic fields produced at the whole antenna level. But, the bottom-edges of the 100mm wide antenna is so distant that the difference of the IEMF produced at each antenna level could be clear. The deep IEMF penetration into the plasma is efficient for the ICP production as shown above. Therefore, it is likely that the IEMF penetration at the antenna edge levels may play an important role to the ICP production.

5. Summary

We have reported the experimental evidence that the IEMF produced in the plasma is related to the antenna geometry. The edge type antenna showed the low attenuation coefficient of the IEMF in the plasma and could penetrate the IEMF into the deeper region of the plasma. Considering the plasma production efficiency, the deep IEMF penetration into the plasma could contribute to the efficient ICP production. The main reason for the efficient ICP production would be the suppression of the heated electrons extinction at the quartz window. The 100mm wide antenna indicated that the IEMF at the bottom-edge level has a low attenuation coefficient, which is the same value as that of the edge type antenna. Based on this result, the antenna bottom-edges may also be playing an important role to the ICP production. Therefore, an antenna geometry for the high plasma production efficiency is required to penetrate the IEMF into the deeper region of the plasma. We will also need to discuss the relation between the IEMF attenuation and the plasma characteristics, since the electromagnetic field penetration into the plasma is restricted by the parameters as the function of the plasma characteristics, such as the skin depth.

In this paper, we paid attention to the only IEMF on the basis of the assumption that the plasma production was derived from only the IEMF. But, we should consider other contributing factors to the ICP production, such as E×B. A detailed analysis including the these effects will be the subject of our next paper.

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