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ORIGINAL PAPER

Plasma Characteristics of Internal Inductively Coupled Plasma Source with Ferrite Module

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Abstract Electrical and plasma properties of a U-shaped internal inductively coupled plasma (ICP) source with/without a Ni-Zn ferrite module installed above the ICP antenna were investigated. By installing the ferrite module on the antenna, the increase of plasma density and the decrease of plasma potential could be observed. The increase of plasma density was related to the efficient inductive coupling to the plasma by concentrating the induced magnetic field between the antenna and the substrate. At 800 W of ICP power and 20mTorr Ar, a high density plasma on the order of $4.5'10^{11}/cm^3$ could be obtained.

Keywords Ferrite ICP · Inductive coupling

Introduction

Inductively coupled plasma (ICP) sources have been widely used in the last decade for high rate plasma processing such as etching and thin film deposition, because of their ability to generate high plasma density in addition to the independent control of plasma density and ion energy [1, 2]. Recently, a lot of works related to large area ICP processing have been investigated to improve the production efficiency and fabrication cost. Especially, the large area ICP sources have been investigated for the next generation display applications requiring the low temperature high rate processing such as hybrid flexible displays, organic thin film transistor-liquid crystal displays, large area solar cells, etc. [3–5] However, the extension of conventional external ICP sources to large area ICP sources shows a few problems such as a large antenna voltage, the increased thickness of dielectric window, non-uniform power deposition profile caused by standing wave, etc.

Previously, to overcome the problems related to the power coupling and standing wave, a U-shaped internal ICP source has been developed [6, 7]. In addition, by the installation of a ferrite module on the internal ICP antenna, more efficient inductive coupling by the

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increase in the coupling coefficient could be observed. However, the exact mechanism of the improved inductive coupling by the installation of the ferrite module on the ICP source antenna was not experimentally demonstrated. Therefore, in this paper, to understand the mechanism of the improved inductive coupling by the ferrite module more accurately, the plasma and electrical characteristics of the ICP source with and without the ferrite module were investigated and compared using a magnetic induction (B-dot) probe in addition to the conventional electrostatic probes.

Experimental

A schematic diagram of the internal-type ICP system used in this study is shown in Fig. 1a. As shown in the figure, the processing system was composed of an ICP source chamber and a plasma processing chamber. A U-shaped internal antenna was located on the top of the processing chamber as the internal-type ICP source. The antenna was 10 mm diameter copper tubing and was covered by quartz tubing (32 mm diameter and 2 mm thickness) for the dielectric isolation from the plasma. Only the linear part of the U-shaped antenna was located inside of the source chamber and one end of the antenna was connected to a 13.56 MHz RF power generator through a L-type matching network while the other end was connected to ground directly. The plasma processing chamber has a cylindrical shape with the size of 380 mm and the substrate holder diameter was 300 mm.

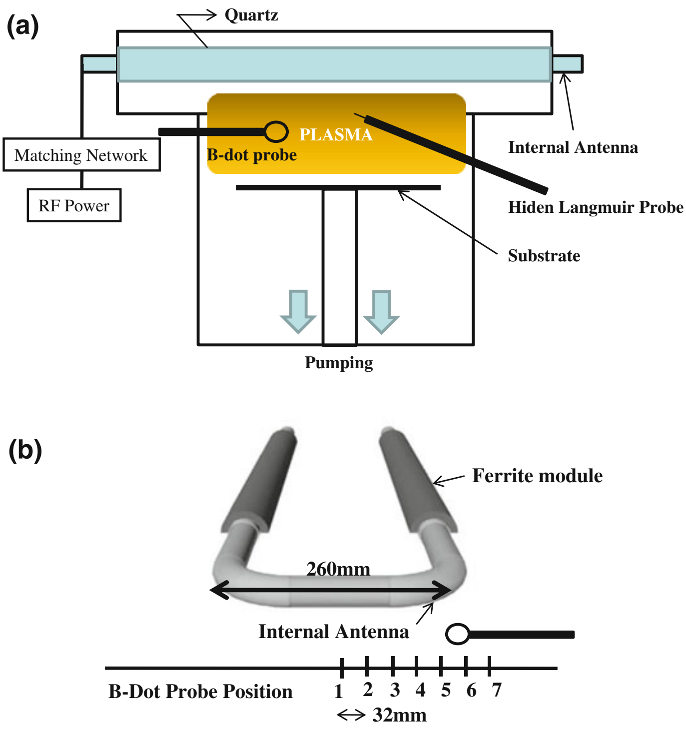

Fig. 1 **a** Schematic diagram of the ICP system with the ferrite module used in the experiment. **b** Arrangement of the internal antenna with the ferrite module used in the experiment

The half-circular ferrite module made of Ni-Zn (Ni(0.5)Zn(0.5)Fe_2O_4) was installed on the U-shaped internal ICP antenna as shown in Fig. 1b. In a previous study, the ferrite module was installed above the quartz tube covering the internal ICP antenna and, due to the heating of the ferrite, the degradation of the ferrite characteristics with increasing operation time could be observed [6]. However, in this study, the ferrite module was installed directly on the water-cooled copper internal antenna enabling the cooling of the ferrite module in addition to more efficient coupling. The ICP source was operated with 13.56 MHz of RF power from 100 to 800 W using 5 $\sim$ 20mTorr Ar.

To investigate the characteristics of the plasmas, a Langmuir probe (Hiden Analytical Inc., ESPION) was installed 4 cm below the antenna and at the center of the chamber. The probe was a cylindrical tungsten wire, which is 0.15 mm in diameter and 10 mm in length. The probe tip was supported by a ceramic tube, which was 1.2 mm in diameter and was enclosed by a compensated electrode. The electron energy probability functions (EEPF) and other plasma parameter such as plasma density (Ne) and plasma potential (Vp) were obtained using the Langmuir probe. The current–voltage (I/V) characteristics of the probe were averaged after the measurement of more than 500 times for the accurate measurement and the averaged I/V characteristics were processed numerically to obtain plasma parameters. The EEPFs are obtained from the I/V characteristics of the probe by means of double differentiation which is related to the Druyvesteyn formula :

$$g(\varepsilon) = \frac{2(2m_e)^{1/2}}{e^3 A} \frac{d^2 I}{dV^2}$$

where, V and I are the DC voltage and current on the Langmuir probe tip, e and m_e are the electron charge and mass, respectively, and A is the probe surface area. [8, 9].

The electrical properties of the internal ICP antenna were measured by an impedance analyzer (MKS Inc) installed between the matching box and the antenna. The impedance analyzer allows the measurements of the rf rms voltage, current, impedance, and phase difference between the voltage and the current. A B-dot probe was used to measure the induced time-varying magnetic field (B) inside the plasma volume under the antenna with/without the ferrite module. The B-dot probe was consisted of a conducting loop of 0.5 cm in diameter and a thin 50 ohms coaxial cable connected to the outer conductor to complete the transformer circuit. In addition, to remove the capacitive pickup caused by the ac coupling to the potential fluctuation, the balanced and unbalanced transformer measuring circuit was used. [10].

Results and Discussion

The electrical characteristics such as rf rms current, voltage, and phase angle of the internal ICP with/without the ferrite module measured by an impedance analyzer (MKS inc) installed between the matching network and the antenna are shown in the Fig. 2a as a function of rf power at 20mTorr Ar and (b) as a function of operating pressure at 800 W of rf power. As shown in Fig. 2a, the increase of rf power to the ICP source continuously increased the rf voltage and current of the antenna for both ICP sources with and without the ferrite module. However, as shown in Fig. 2b, the increase of operating pressure at a fixed rf power decreased the rf voltage and current slightly for both ICP sources. In the case of power factor, the increase of rf power and working pressure increased power factor for both ICP sources. If the ICP sources with and without the ferrite module are compared, as

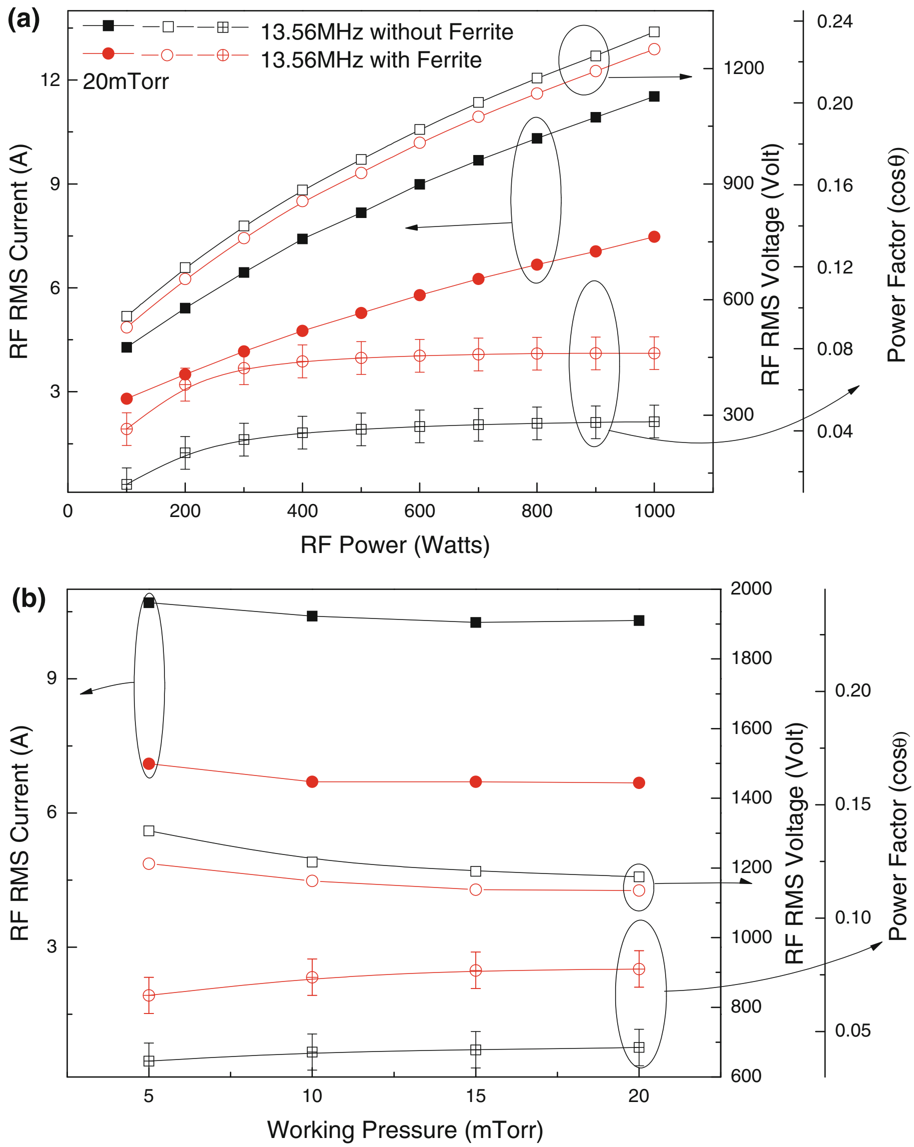

Fig. 2 Rf rms voltage and current measured **a** as a function of rf power at 20mTorr Ar and **b** as a function of operating pressure at 800 W of rf power for the internal ICP source with/without the ferrite module by an impedance analyzer on the antenna located close to the rf power input

shown in Fig. 2a, b, the ICP source with the ferrite module showed lower rf voltage and lower current while showing higher power factor. Also, the increase of power factor and the decrease of rf voltage and current was proportional to the amount of ferrite in the ferrite module installed on the ICP source (not shown) [7, 11]. Therefore, the ferrite module made the ICP source more resistive than that without the ferrite module. In addition, the ferrite module installed on the internal ICP source provides a lower joule loss at the matching network and the ICP source antenna itself due to the lower rf current [8, 12].

Even though the rf current on the ICP antenna with the ferrite module is lower than that the ICP antenna without the ferrite module, the time-varying magnetic field between the antenna and the substrate holder was reinforced by the ferrite covering top portion of the antenna shown in Fig. 1b. The time-averaged magnetic field under the antennas with and without the ferrite module was measured using the B-dot probe at 400 W of rf power and 20mTorr Ar and the results are shown in Fig. 3a as a function of probe position. Also, to

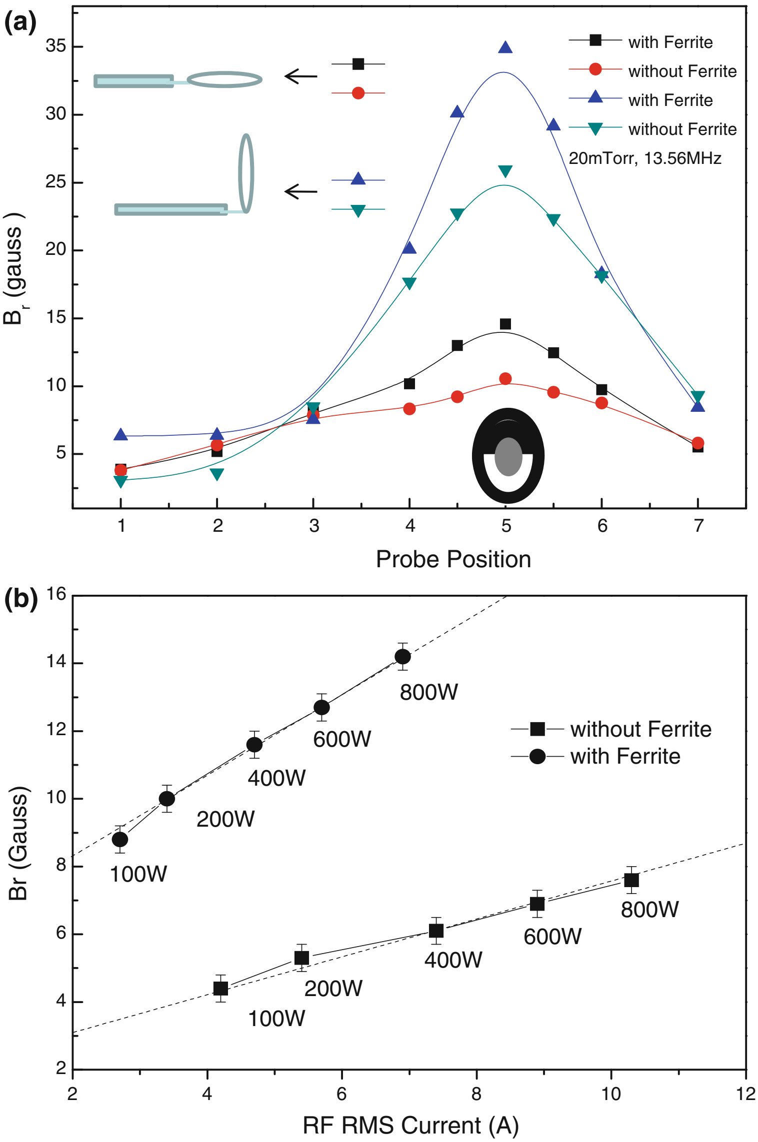

Fig. 3 **a** The induced magnetic field *B* measured by a B-dot probe at 10 mm under the antenna with/without ferrite module. **b** The magnetic field measured just below the antenna as a function of antenna current for the ICP with and without the ferrite module

investigate the dominant direction of the magnetic field, two types of B-dot probes which are consisted of parallel direction to the antenna (180°) and vertical direction to the antenna (90°) were used as shown in Fig. 3a. The induced magnetic field was the highest at the position just below the antenna for all of the cases, however, the induced magnetic field for the ICP antenna with the ferrite module was approximately two times higher than that without the ferrite module for both probes. The magnetic field of ferrite zone intensively formed at the region between 3 and 7 position (120 mm). And the half amplitude of the magnetic field peak measured along the probe position was a little smaller for the antenna with the ferrite module than that without the ferrite module indicating the concentration of the induced magnetic field near the antenna by the ferrite module.

The increase in the magnetic field caused by the ferrite module is related to the concentration of the induced magnetic field in the area between the antenna and the substrate. From the Ampere's law of$\oint_c B \cdot ds = \mu_{ferrite}\mu_0 I$ (where, s is the area measured around antenna center, μ_0: magnetic constant of free space, $\mu_0 = 4\pi \times 10^{-7} Hm^{-1}$, $\mu_{ferrite}$: the permeability of the ferrite $\sim$ 500), it can be shown that the time-varying B field measured below the antenna line is represented by the equation $B = \mu_0 I/2\pi r$ (where, r is the radius from the antenna center) when the ferrite module is not used [13]. However, by installing the ferrite module, which covers the top half of the antenna line, the magnetic field induced in the area between the antenna and the chamber wall can be diverted by the ferrite to the area between the antenna and the substrate. Therefore, as shown in Fig. 3a, after the installation of the ferrite module, the magnetic field between the antenna and the substrate was doubled from $B = \mu_0 I/2\pi r$ to$B = \mu_0 I/\pi r$.

The induced peak magnetic field was measured as a function of rms antenna current (or rf power) for the ICPs with and without the ferrite module at 20mTorr Ar and the result are shown in Fig. 3b. As shown in the figure, the induced magnetic field was increased with increasing antenna current almost linearly without saturation for both ICPs with and without the ferrite module. Also, the ICP antenna with the ferrite module showed more than two

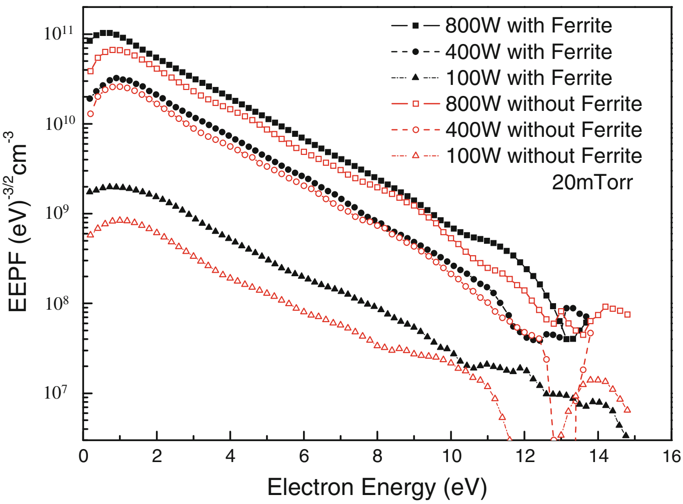

Fig. 4 EEPFs of the Ar plasmas at 20mTorr measured as a function of rf power for the ICPs with and without ferrite module

times higher induced magnetic field compared to that without the ferrite module for all of the rms current conditions indicating no significant degradation of the ferrite module. In the previous study, when the ferrite module was installed above the quartz tube covering the ICP internal copper antenna, the ferrite was easily degraded at the higher rms current conditions due to the lack of cooling of the ferrite during the operation at 13.56 MHz of rf power. [6] However, in this study, by installing the ferrite module directly on the water-cooled copper internal antenna, stable and high plasma density plasma could be obtained.

The EEPFs of the internal ICP with and without the ferrite module measured as a function of rf power at 20mTorr are shown in Fig. 4. Also, the EEPFs measured as a function of working pressure at 800 W of rf power are shown in Fig. 5a for the ICP

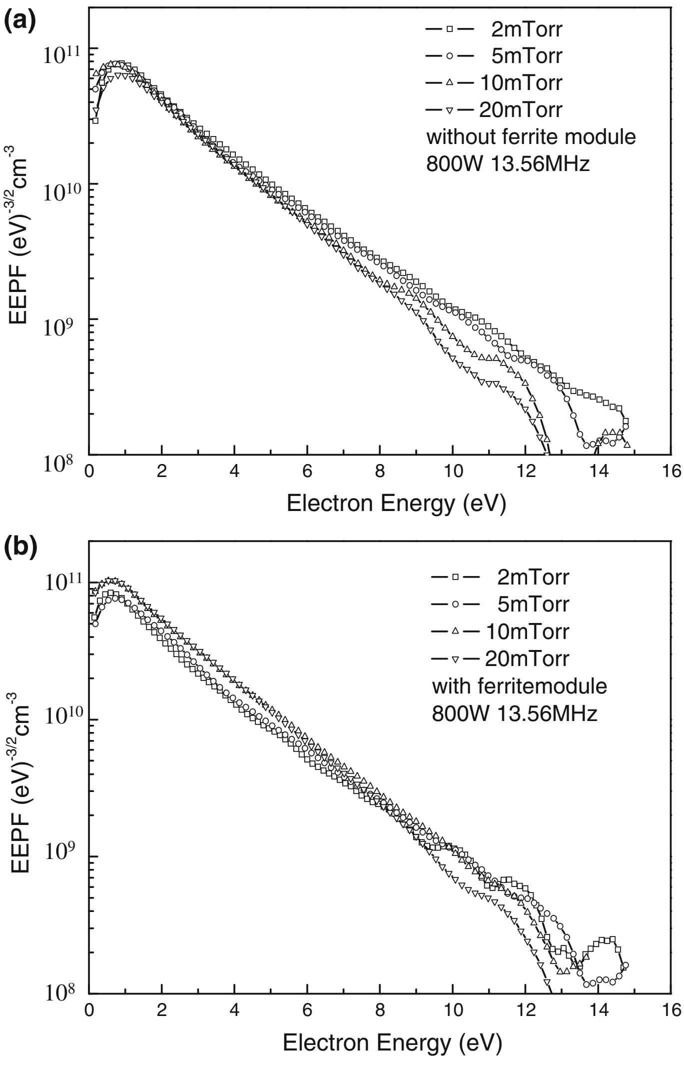

Fig. 5 EEPFs of the Ar plasmas at 800 W measured as a function of pressure for the ICPs **a** without and **b** with the ferrite module

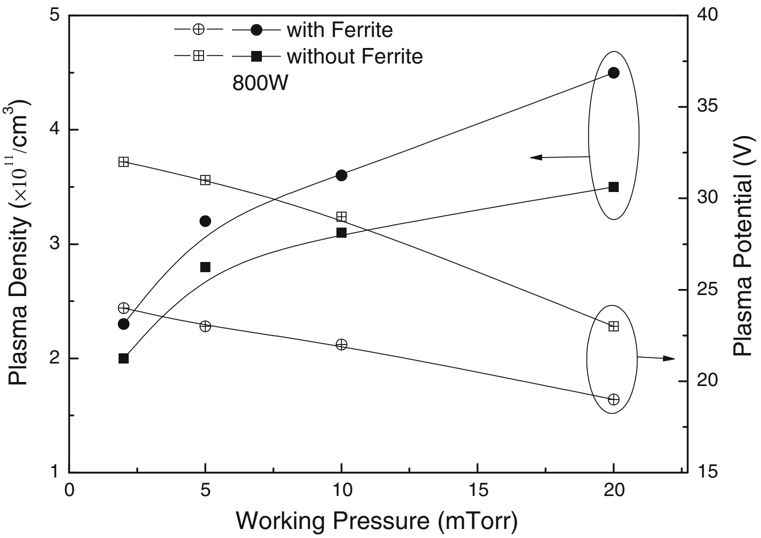

Fig. 6 Plasma density and plasma potential measured by a Langmuir probe at 4 cm below the antenna as a function of pressure at 800 W of rf power

without the ferrite module and Fig. 5b for the ICP with the ferrite module. As shown in Fig. 4, the EEPFs were Maxwellian by showing a nearly straight line even though a slight depletion of electrons from the Maxwellian distribution was observed at the energy higher than inelastic energy range ($\varepsilon < \varepsilon^*$, ε^* is the argon excitation energy (11.5 eV)) for both ICPs with and without the ferrite module. However, as shown in Fig. 4, at the same rf power, the ICP with the ferrite module showed higher electron density compared to the ICP without the ferrite module due to the enhanced induced magnetic field in the area between the antenna and the substrate. Also, as shown in Fig. 5, even though the high energy electrons were decreased as the operating pressure was increased from 2 to 20mTorr for the ICP without the ferrite module, no significant decrease of high energy electrons was observed for the ICP with the ferrite module possibly due to the supply of high energy electrons to the plasma through the enhanced magnetic field [8, 14].

The plasma density and the plasma potential of the internal ICP sources operated at 13.56 MHz 800 W rf power with and without the ferrite module were measured by a Langmuir probe (Hiden Inc.) as a function of operating pressure and the results are shown in Fig. 6. As shown in Fig. 6, the plasma density was increased with the increase of operating pressure while the plasma potential was decreased with increasing operating pressure for both ICP sources. However, the source with the ferrite module showed higher plasma density and lower plasma potential compared with the source without the ferrite module at the same pressure. And, at 800 W of rf power and 20mTorr Ar, the internal ICP with the ferrite module showed the plasma density of about $4.5 \times 10^{11}/cm^3$. The higher plasma density of the ICP with the ferrite module was related to the enhanced magnetic field between the antenna and the substrate as shown in Fig. 3a and the lower plasma potential appears to be related to the lower antenna rf voltage for the ICP with the ferrite module as shown in Fig. 2.

Conclusions

In this study, the electrical and plasma characteristics of the internal U-shaped ICPs with and without the Ni-Zn ferrite module were compared and the mechanism of enhanced inductive coupling for the ICP with the ferrite module was investigated using a B-dot probe. Installing the ferrite module which covers the top half of the ICP antenna line to the ICP source showed lower rf rms voltage, lower rf rms current, and higher power factor due to the increased resistive properties of the ICP source by the ferrite module. The B-dot probe showed that, by the installation of the ferrite module to the ICP source, the induced magnetic field between the antenna and the substrate was increased approximated two times by diverting the magnetic field between the antenna and the chamber wall. Therefore, the increased resistive properties of the ICP source with the ferrite module was related to the increased power transfer to the plasma even though there is a power loss to the ferrite itself. Due to the increased power transfer to the plasma, higher plasma density could be obtained in addition to the lower plasma potential possibly due to the lower rf rms voltage for the ICP with the ferrite module.

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