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Characteristics of internal inductively coupled plasma with a ferrite module

Jong Hyeuk Lim, Kyong Nam Kim, Gwang Ho Gwon, Seng Pyo Hong, Seok Hwan Kim and Geun Young Yeom[1]

Department of Materials Science and Engineering, Sungkyunkwan University, Suwon, Kyunggi-do 440-746, South Korea

E-mail: gyyeom@skku.edu

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Abstract

The electrical and plasma properties of an internal inductively coupled plasma system with and without a Ni–Zn ferrite module operated at 13.56 and 2 MHz were investigated. Installing a ferrite module covering the top half of the ICP antenna increased the inductive coupling of the antenna to the plasma by the magnetic field reinforced by the ferrite. However, because of the high impedance of the Ni–Zn ferrite operated at 13.56 MHz, a more effective coupling was achieved at the operational frequency of 2 MHz. By using the ferrite module at 2 MHz, a plasma density of $\sim 6 \times 10^{11}$ cm^{-3} and a plasma potential of ∼13 V were obtained at 500 W and 5 mTorr Ar. The plasma density was higher and the plasma potential lower than those obtained at 13.56 MHz.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Inductively coupled plasma (ICP) sources have been widely investigated for various processes, including plasma etching and thin film deposition. However, as the processing area is increased, ICP sources with an external coil-type antenna begin to experience problems, such as the high voltage on the antenna and the thick dielectric window [1–3]. In particular, as the dielectric window thickness increases, the physical separation between the antenna and the plasma must be increased as well, which leads to a decrease in the mutual inductance and the power transfer efficiency. In addition, the high voltage induced on the antenna increases electrostatic coupling to the plasma and can increase the sputtering of the dielectric materials.

A number of researchers have attempted to resolve the problems of the ICP sources caused by the increase in the source size [4–6]. Using a simple transformer model, Keller investigated the effect of varying the thickness of the dielectric window material on plasma efficiency in conventional ICP. Sugai *et al* and Kanoh *et al* have developed internal circle antenna-type ICP sources with a terminating capacitor, and by optimizing the capacitance of the floating capacitor inserted in series with the antenna, they obtained lower electrostatic coupling and higher inductive coupling to the plasma. Of particular interest are the reports of lower electrostatic coupling obtained by the use of a thin dielectric window material, internal-type ICP and a resonance condition of the ICP. Godyak *et al* reported that, by using the ferrite cores to an ICP source, they significantly decreased the electrostatic coupling, and they also removed the problems related to the transmission line effect by operating the ICP at 400 kHz [7].

The impedance of the ICP system depends not only on the type of the ICP source antenna but also on the operating frequency, and the use of a lower operating frequency decreases the ICP source impedance and can decrease the electrostatic coupling for a given antenna type. In this paper, we used an internal-type ICP source and investigated the effects of a ferrite module and operating frequencies of 2 and 13.56 MHz on the plasma characteristics in an effort to increase the inductive coupling to the plasma. In particular, we carried out this experiment to compare the plasma characteristics of a U-type antenna operated at 13.56 MHz (which is the conventional operating frequency) and 2 MHz applied to the 300 mm and larger diameter substrate and, particularly, to investigate the effect of a ferrite module installed with the antenna on the ICP characteristics.

[1] Author to whom any correspondence should be addressed.

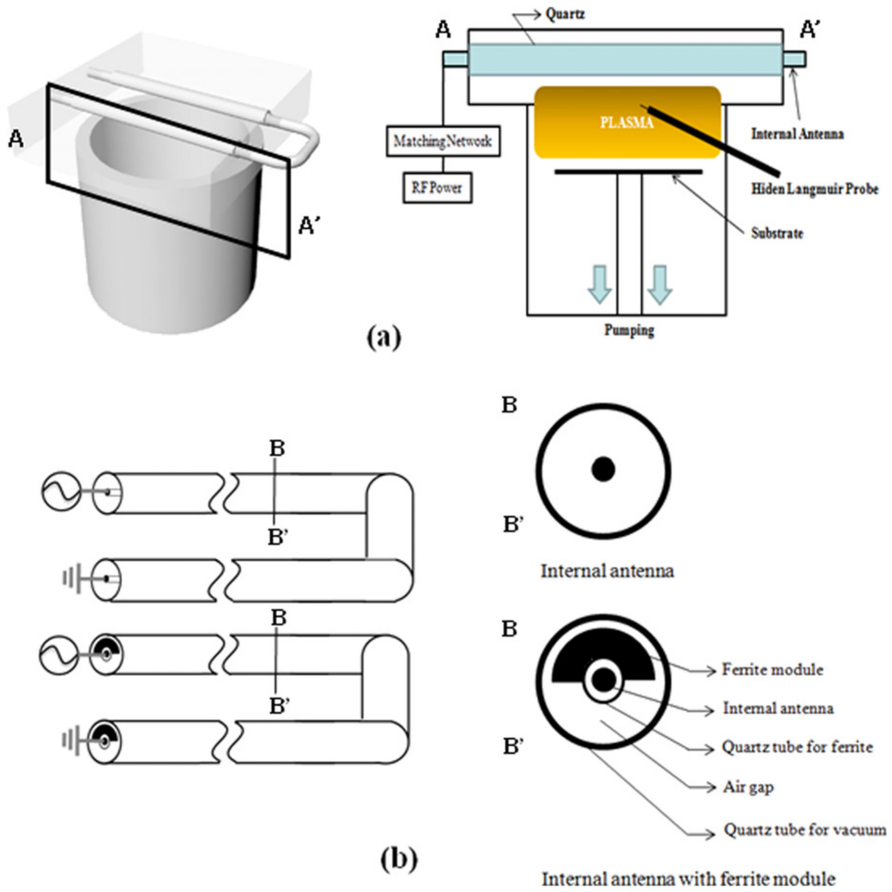

Figure 1. (*a*) Schematic diagram of the internal-type ICP system with a U-type internal antenna used in the experiment. (*b*) Arrangement of the internal antenna with/without a ferrite module used in the experiment.

2. Experiment

The experimental setup is shown in figure 1. As seen on the left-hand side of figure 1(*a*), a rectangular shaped ICP source was located on top of the 380 mm diameter processing chamber having 300 mm diameter substrate size. The source consisted of one U-type internal antenna with the two parallel legs of the U shape running through the source chamber. One end of the antenna was connected to an rf power generator (13.56 or 2 MHz) through a respective L-type matching network, while the other end was connected to a ground directly. The plasma was generated between the antenna and the substrate holder as shown on the right-hand side of figure 1(*a*). We used this U-type antenna configuration for generating a high-density plasma in this experiment because a previous experiment [8–10] which was carried out in a large area rectangular plasma source having a size of 880 mm × 680 mm showed that the plasma generated with a U-type antenna was very stable and very uniform over the substrate surface.

The antenna was made of a 10 mm-diameter copper tubing covered coaxially by a quartz tube having a diameter of 33 mm and a thickness of 2 mm as shown on the top side of figure 1(*b*). When a half-circle shaped ferrite module was installed, it was located on the upper side of the antenna between the inner copper tubing and the 33 mm-diameter quartz tubing as shown on the bottom side of figure 1(*b*). In this case, between the copper tubing and the ferrite module, another quartz tubing having a diameter of 20 mm (2 mm thick) was located coaxially as shown on the bottom right side of figure 1(*b*). For the size of the glass tubing, when we studied the effect of glass tube diameter on the plasma characteristics for the antenna without the ferrite in a previous study [6, 11], we found that a smaller diameter of the glass tubing at the same Cu antenna showed a higher plasma density due to increased magnetic flux to the plasma. In this experiment, we used a 20 mm-diameter glass tubing just above the Cu tubing (for the case with the ferrite module) because it was one of the previously optimized conditions for our antenna system which guarantees sufficient air flow between the Cu tubing and the quartz tubing in addition to sufficient water flow to the Cu antenna by using a 10 mm-diameter Cu tubing. The ferrite module used in this study was composed of Ni–Zn (ZCAT 3035-1330, TDK Inc) with a high magnetic permeability of 500. It was fabricated by compressing the ferrite particles into a half-circular shape; therefore, it did not possess any preferred orientation for magnetization.

To investigate the characteristics of the plasmas, we installed a Langmuir probe (Hiden Analytical Inc., ESP) 4 cm below the antenna at the centre of the chamber. The electrical properties, such as resistance and the reactance component of the internal antenna, were measured by an impedance analyzer (MKS Inc) located between the matching box and the antenna. An LRC meter (KC-605, Kokuyo Inc.) was used to measure the inductance and the resistance of the antenna

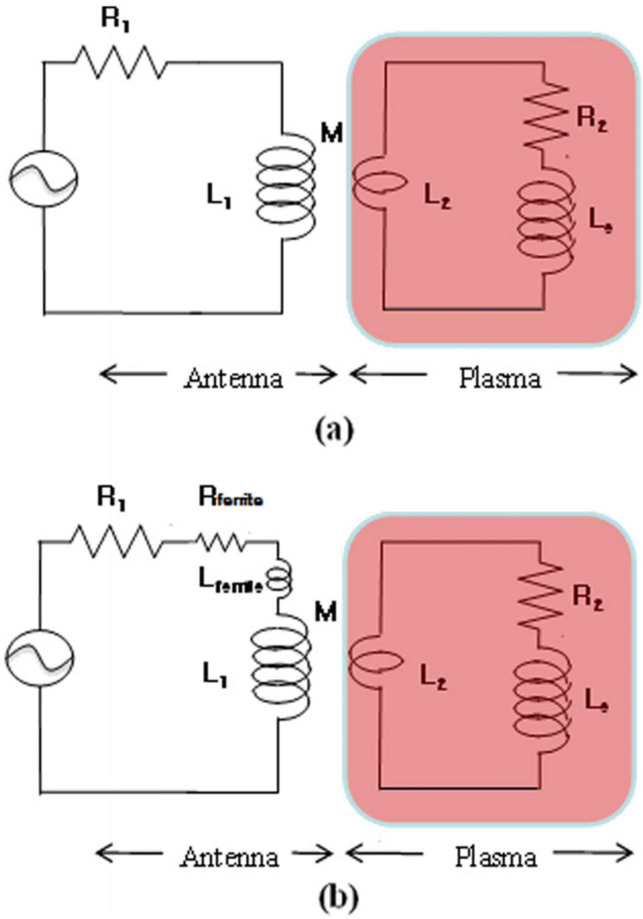

Figure 2. (*a*) Equivalent electrical circuit of an ICP system. (*b*) Equivalent electrical circuit of an ICP system with a ferrite module.

with and without the ferrite module. All the experiments were carried out under a near matched condition having a reflected power below 5%. Also, the loss to the matching network was measured during the experiment; therefore, the power value measured after the matching network was used as the delivered power which included not only the power dissipated in the plasma but also the power dissipated in the antenna by the antenna line, connectors, ferrite, etc.

3. Results and discussion

In general, the rf current flowing in the inductive antenna of an ICP source produces a time-varying magnetic field which transfers energy inductively from the rf power to the plasma via a penetrating magnetic flux. A few researchers (Piejak *et al* [12], Keller *et al* [4] and Jones *et al* [13]) have used a transformer model to explain the energy transfer to the plasma for the ICP system. As shown in figure 2(*a*), the ICP source antenna is considered to be the primary coil with an inductance of L_1 and a resistance of R_1. The plasma is regarded as the one-turn secondary coil of a transformer with a secondary coil inductance of L_2 in addition to an electron inertia inductance of L_e and a plasma resistance of R_2. L_1 and L_2 are inductively coupled through a mutual inductance M ($M = k\sqrt{L_1 L_2}$, where k is the coupling coefficient). When the electrical circuits of the antenna and the plasma are merged, the total resistance component (R_r) and the total inductance component (L_2') of the equivalent circuit can be represented as

$$R_r = \frac{V_{rf}}{I_{rf}} \cos\phi = R_1 + \frac{w^2 k^2 L_1 L_2 R_2}{R_2^2 + (wL_e + wL_2)^2}, \quad (1)$$

$$wL_2' = \frac{V_{rf}}{I_{rf}} \sin\phi = wL_1 - \frac{wk^2 L_1 L_2 (wL_2 + wL_e)}{R_2^2 + (wL_e + wL_2)^2}, \quad (2)$$

where V_{rf} and I_{rf} are the rf voltage and the rf current on the ICP antenna, w is the operating frequency and they can be measured using the impedance analyzer during the operation of the plasma [12].

The inductance L_1 and resistance R_1 of the U-shaped ICP antenna used in this study can be measured without the operation of the plasma by using the LCR meter. When the inductance and resistance were measured with and without the ferrite module, the resistance of the antenna changed from 0.8 to 1.2 Ω after the installation of the ferrite module, while the antenna inductance changed from 1.6 to 2.4 μH. Since the ICP antenna had both higher resistance and higher inductance with the ferrite module, the addition of the ferrite module led to a higher impedance as well. Therefore, we can represent the ICP source with the ferrite module as the electric circuit shown in figure 2(*b*) with an additional resistance ($R_{ferrite}$) and an additional inductance ($L_{ferrite}$) in series with those of the ICP antenna, and the total resistance and the inductance can be expressed by the following equations:

$$R_r = \frac{V_{rf}}{I_{rf}} \cos\phi = R_1 + R_{ferrite} + \frac{w^2 k^2 (L_1 + L_{ferrite}) L_2 R_2}{R_2^2 + (wL_e + wL_2)^2}, \quad (3)$$

$$wL_2' = \frac{V_{rf}}{I_{rf}} \sin\phi = w(L_1 + L_{ferrite}) - \frac{wk^2 (L_1 + L_{ferrite}) L_2 (wL_2 + wL_e)}{R_2^2 + (wL_e + wL_2)^2}. \quad (4)$$

Figure 3 shows the measured ICP system impedance, V_{rf} and I_{rf} for 13.56 MHz with and without the ferrite module and for 2 MHz with the ferrite module as a function of the delivered rf power in 5 mTorr of Ar. At 2 MHz, it was difficult to operate the ICP source without the ferrite module, so only the data with the ferrite module are shown. As shown in figure 3(*a*), the system impedance, which is represented by $Z = \sqrt{R^2 + (wL)^2}$, was not changed significantly with changes in the rf power. The system impedance was higher after the installation of the ferrite module because of the additional $R_{ferrite}$ and $L_{ferrite}$, and it was higher for 13.56 MHz than for 2 MHz because of the dependence of Z on the frequency w. As shown in figure 3(*a*), even though the rf rms voltage increased as the rf power increased for all the cases, the voltage decreased after the installation of the ferrite module and was lower at the lower frequency, possibly because of more inductive coupling to the plasma. As shown in figure 3(*b*), the rf rms current also increased with an increase in rf power, but it decreased significantly after the installation of the ferrite module because of the increased impedance. The current

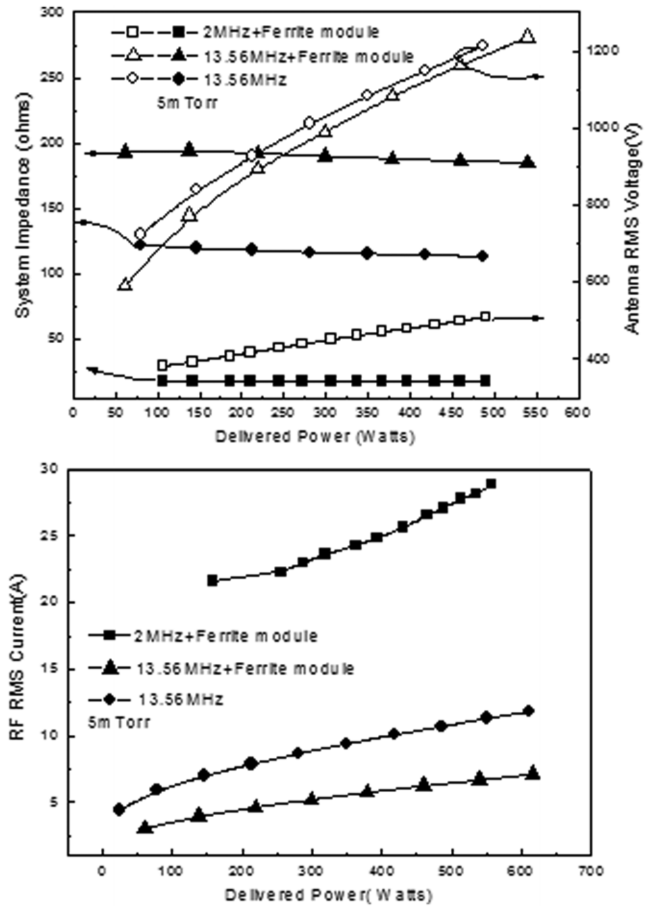

Figure 3. (*a*) System impedance and rf rms voltage and (*b*) rf rms current of the internal-type ICP with a ferrite module operated at 2 MHz and 13.56 MHz of rf power as a function of delivered power at 5 mTorr Ar.

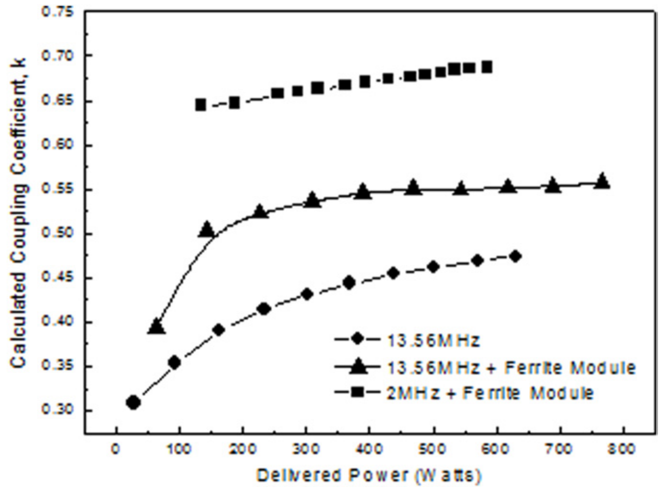

Figure 4. Calculated coupling coefficient as a function of rf power for 13.56 MHz with and without the ferrite module and for 2 MHz with the ferrite module at 5 mTorr Ar.

was highest at 2 MHz and with the ferrite module because this produced the lowest impedance, indicating that the most effective inductive coupling to the plasma occurred at 2 MHz instead of at 13.56 MHz.

The degree of inductive coupling to the plasma can be determined by calculating the coupling coefficient k between the rf antenna and the plasma by assuming that the plasma acts as a one-turn inductor, that is $L_2 = L_1/kn^2$ ($n = 1$ for the plasma). That is, equation (5) can be obtained using equations (1) and (2) while equation (6) can be obtained using equations (3) and (4) as follows [4, 12, 13]:

$$k = \sqrt{\frac{w^2(L_1 - L_2')^2 + (R_r - R_1)^2}{wL_1[w(L_1 - L_2') - \frac{w}{\nu}(R_r - R_1)]}} \quad \text{(without ferrite)}, \qquad (5)$$

$$k = [w^2(L_1 + L_{\text{ferrite}} - L_2')^2 + (R_r - R_1 - R_{\text{ferrite}})^2] \times \left[w(L_1 + L_{\text{ferrite}})\left[w(L_1 + L_{\text{ferrite}} - L_2') - \frac{w}{\nu}(R_r - R_1 - R_{\text{ferrite}})\right]\right]^{1/2} \quad \text{(with ferrite)}, \qquad (6)$$

where ν is the effective collision frequency. Figure 4 shows the calculated k as a function of rf power for 13.56 MHz with and without the ferrite module and for 2 MHz with the ferrite module at 5 mTorr Ar. The effective collision frequencies at 5 mTorr Ar used in plotting figure 4 were 0.9 MHz, 1.5 MHz and 3.5 MHz for 13.56 MHz, 13.56 MHz + ferrite and 2 MHz + ferrite, respectively. It was calculated using the average electron temperatures of 3.0 eV, 2.8 eV and 2.5 eV for 13.56 MHz, 13.56 MHz + ferrite and 2 MHz + ferrite, respectively, because the electron temperature was not significantly varied with the delivered power [14]. As shown in figure 4, the increase in rf power generally increased the coupling even though the coupling coefficient appeared to be saturated at a high rf power. At 13.56 MHz, after the installation of the ferrite module, an increase in the coupling coefficient of about 10% could be observed because of the increased inductance on the source antenna side from the installation of the ferrite. The decrease in rf frequency from 13.56 to 2 MHz further increased the coupling coefficient because of the decreased system impedance, as shown in figure 2(*a*).

Figures 5(*a*) and (*b*) show the plasma potential and the plasma density, respectively, measured as a function of rf power for 13.56 MHz with and without the ferrite module and for 2 MHz with the ferrite module at 5 mTorr Ar. As shown in figure 5(*a*), increasing the rf power led to a lower plasma potential. Furthermore, using the ferrite module and lowering the frequency both led to a lower plasma potential; at 500 W of rf power, the potential decreased from about 22 V for 13.56 MHz without the ferrite module to about 13 V for 2 MHz with the ferrite module. The decrease in the plasma potential is believed to be related to the decreased rf rms voltage due to the increased inductive coupling to the plasma. The increase in the inductive coupling increased the plasma density. As shown in figure 5(*b*), the use of the ferrite module for 13.56 MHz and the use of the lower rf frequency led to a higher plasma density. At 500 W of rf power and 5 mTorr Ar, using the ferrite module caused the plasma density to increase from about 2.1×10^{11} to about 2.9×10^{11} cm^{-3} for 13.56 MHz, and decreasing the rf frequency to 2 MHz with the ferrite module caused a further increase in the plasma density to about 6×10^{11} cm^{-3}.

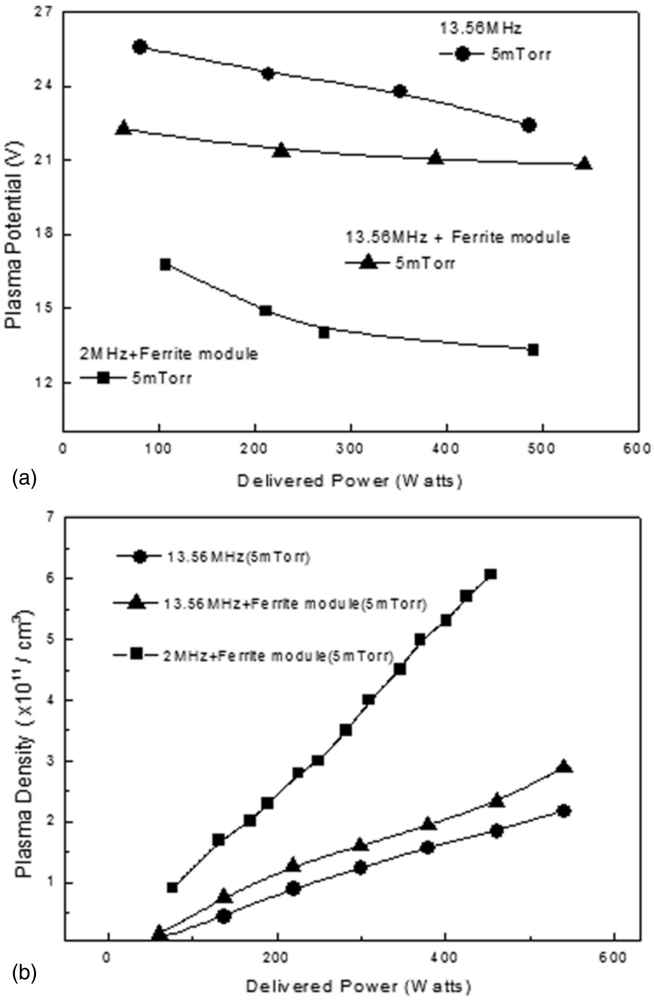

Figure 5. (*a*) Plasma potential and (*b*) plasma density measured by a Langmuir probe at 4 cm below the antenna as a function of rf power at 5 mTorr Ar.

The increase in the inductive coupling caused by the installation of the ferrite is related to the concentration of the induced magnetic field in the area between the antenna and the substrate. As shown in figure 1(*b*), when the ferrite is not installed, the magnetic field induced by the ICP antenna current ($\oint_c B \cdot \mathrm{d}s = \mu_0 I$, where B is the magnetic field, I is the antenna current and $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$) in the area between the antenna and the chamber wall will be lost as heat without transferring any power to the plasma [4, 15]. However, by installing the ferrite, 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, after the installation of the ferrite module, the magnetic field at a point r between the antenna and the substrate can be doubled from $B = \mu_0 I/2\pi r$ to $B = \mu_0 I/\pi r$. The less-than-expected improvement in the plasma density seen in figure 5(*b*) for 13.56 MHz after the installation of the ferrite is partially related to the power loss to the ferrite itself during the operation at 13.56 MHz, which is related to hysteresis loss, residual loss, etc, which are increased with the increase in rf frequency [16, 17].

4. Conclusions

We investigated the electrical and coupling characteristics of an internal-type ICP source operated with and without a Ni–Zn ferrite module and at different rf frequencies at 5 mTorr Ar. Installing the ferrite module on the ICP antenna led to a more efficient inductive coupling to the plasma at 13.56 MHz by an increase in the coupling coefficient. Decreasing the rf operating frequency to 2 MHz with the ferrite module in place further increased the coupling coefficient and led to a decreased power loss to the ferrite itself. With the ferrite module installed, when the source was operated at the lower rf frequency, the more efficient inductive coupling led to a decreases in the voltage induced on the antenna and in the plasma potential and an increase in the plasma density. At 500 W of 2 MHz rf power with the ferrite module installed, we could obtain a high-density plasma of about $6 \times 10^{11}\,\mathrm{cm^{-3}}$ at 5 mTorr Ar.

Acknowledgments

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