Effect of Capacitor Installed in Series With a Ferrite-Enhanced Internal Linear-Type Antenna on the Properties of an Inductively Coupled Plasma

Gwang Ho Gweon, Jong Hyeuk Lim, Seung Pyo Hong, and Geun Young Yeom

***Abstract*—In this paper, the effect of the capacitance of a variable capacitor connected on the ground side of a ferrite-enhanced internal U-type inductively coupled plasma (ICP) source on the electrical characteristics of an ICP antenna and the plasma characteristics is investigated. When the capacitance of the variable capacitor satisfies $C = 2/\omega^2 L$ (where ω is the angular power RF frequency and L is the antenna inductance), the highest plasma density of $2.74 \times 10^{11}/\text{cm}^3$ and the lowest plasma potential of about 19.5 eV are obtained at a 13.56-MHz RF power of 400 W and 10-mtorr Ar. In addition, under these conditions, the best plasma uniformity of about 6% over a substrate area of 300 mm and the most stable operating conditions, due to the lowest heating of the ferrite installed on the ICP antenna, are obtained. The capacitance condition of $C = 2/\omega^2 L$ is related to the minimization of the capacitive coupling to the plasma due to the lowest peak RF voltage being obtained along the antenna line. It is also related to the maximization of the power-transfer efficiency to the plasma by minimizing the power loss to the ferrite installed on the ICP antenna, due to the lowest peak RF current being obtained along the antenna line.**

***Index Terms*—Capacitance, ferrite, inductively coupled plasma (ICP), internal antenna.**

I. INTRODUCTION

THE DEVELOPMENT of high-density plasma sources is one of the major issues in the plasma processing for a variety of microelectronic devices. Combined with the high-density plasma, obtaining good plasma uniformity over the substrate surface is the most important factor in large-area plasma processing.

Of the diverse high-density plasma sources such as the electron cyclotron resonance plasma, helicon wave plasma, inductively coupled plasma (ICP), etc. [1]–[3], ICP sources have been recognized as the most promising candidate for the fabrication of microelectronic devices, ranging from semiconductor devices to flat-panel displays, due to their merits, such as their relatively simple source structure, easier scalability to large-area sources, etc. [4]. However, as the substrate and the processing-area size increase to a larger scale, ICP sources result in high voltages on the antenna, due to the latter's high impedance, which results in an increase of the capacitive coupling between the antenna and plasma. In addition, the power-transfer efficiency from the antenna to the plasma decreases, due to the increased capacitive coupling.

To improve the characteristics of ICP sources for large areas, techniques such as the use of capacitors connected in series with ICP antennas [5]–[7], the use of an internal-type short antenna to decrease the impedance of the source, etc., have been investigated [8]. A study by Suzuki *et al.* [5] showed the improvement of plasma characteristics, such as an increase of the plasma density, decrease of the plasma potential, etc., by connecting a variable capacitor in series with a one-turn circular internal-type antenna and by inducing a resonance condition which minimizes the capacitive coupling to the plasma. In the study of Kim *et al.* [6], a more uniform plasma was obtained by connecting a variable capacitor in series with one of the parallel antennas connected to an RF power supply and by controlling the current flowing to each antenna. Terai *et al.* [7] also reported that they could reduce the capacitive coupling in an ICP system by using a capacitor combined with divided antennas.

In this study, a variable capacitor was connected in series with an internal-type ICP source in a similar manner to the research by Suzuki *et al.* [5], but using a U-shaped internal antenna installed with a ferrite module. In addition, the effect of the capacitance of the variable capacitor on the electric characteristics of the internal antenna of the ICP source and the plasma characteristics was investigated for the ferrite-enhanced internal ICP source. In our experiment, the ICP antenna was partially covered with a high-permeability ferrite to generate high-density plasmas near the substrate by concentrating the magnetic field induced by the antenna current between the antenna and the substrate [9].

II. EXPERIMENTAL SETUP

The schematic diagram of the experimental ICP system and the electrical connection of the internal linear U-type ICP antenna used in this study are shown in Fig. 1(a) and (b), respectively. The diameter of the chamber was 380 mm, and the substrate diameter was 300 mm. The U-type antenna module consisting of two internal linear antennas connected in series was installed above the substrate. Each internal linear antenna

Manuscript received January 23, 2010; revised March 10, 2010; accepted March 10, 2010. Date of publication April 19, 2010; date of current version June 9, 2010. This work was supported by the National Program for Tera-Level Nanodevices of the Korea Ministry of Education, Science and Technology as a 21st Century Frontier Program.

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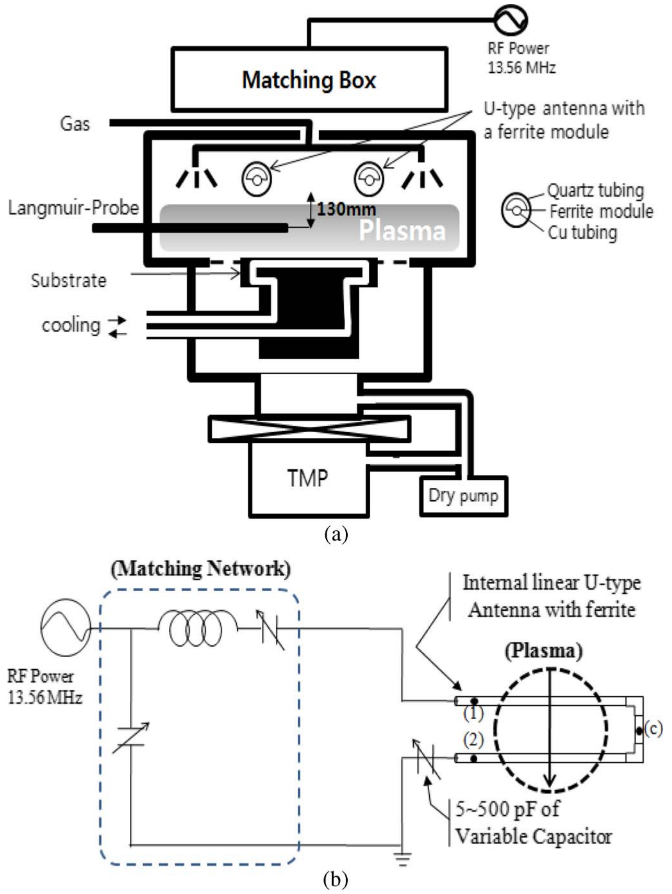
Digital Object Identifier 10.1109/TPS.2010.2045905



(a)

(b)

Fig. 1. (a) Schematic diagram of the internal U-type ICP system used in this experiment. (b) Equivalent circuit of the ICP source with an internal linear antenna connected with a variable capacitor in series. (1), (2), and (C) are the measurement points for $V_1(I_1)$, $V_2(I_2)$, and $V_c(I_c)$, respectively. The arrow in the circle indicates the scan direction of the ion density measured by using a Langmuir probe.

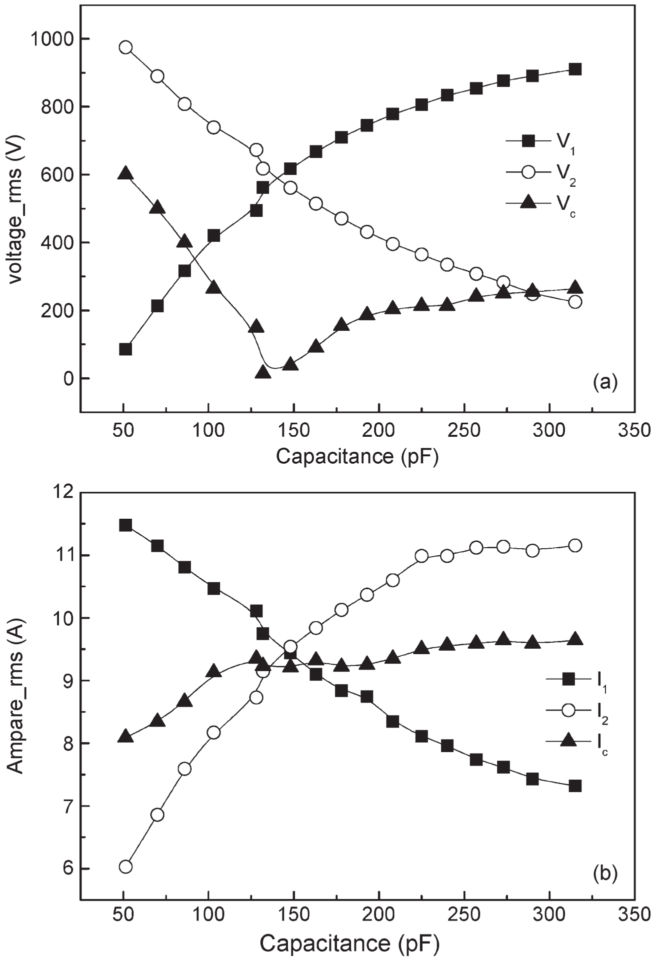


Fig. 2. (a) RF rms voltage and (b) RF rms current on the U-type antenna measured as a function of the capacitance of the capacitor connected in series to the ground position of the ICP antenna.

was composed of an inner copper tube (10-mm diameter) and a quartz dielectric tube (33-mm diameter) enclosing the copper tube to isolate it from the plasma. In addition, for the enhancement of the magnetic field between the antenna and the substrate, half-circle-shaped Ni–Zn ferrite was installed between the top portion of the copper tube and the quartz tubing, as shown in Fig. 1(a). As shown in Fig. 1(b), one end (position 1) of the U-type antenna module composed of two linear antennas was connected to a 13.56-MHz RF power supply through an L-type matching network. The other end (position 2) of the antenna module was connected to the ground through a variable capacitor in the range from 4 to 500 pF connected in series, which was used to investigate the effect of the additive capacitance on the plasma properties.

The plasma characteristics such as the plasma density, ion saturation current, and electron temperature were measured using a Langmuir probe (Hiden Analytical, Inc., ESP) installed 130 mm below the ICP source antenna and at the center of the antenna line at an RF power of 400 W and 10 mtorr of Ar. In addition, the electrical characteristics, such as the RF voltage and RF current, and the phase angle between the RF voltage and RF current, at the power input position after the matching network (position 1) and the ground position before the variable capacitor (position 2), were measured using an impedance probe (MKS, Inc.), a high-voltage probe (Tektronix, P6015A), and a current probe (Pearson electronics, 6600). Finally, using an RF power of 400 W and a gas mixture of Ar/O_2 (Ar:$O_2 = 7:3$) at 10 mtorr, a photoresist (PR)-covered glass substrate was etched, and its etch depth was measured using a step profilometer (Alpha Step 500) to estimate the PR etch uniformity. The etch uniformity was estimated using the following formula:

$$\text{Uniformity}(\%) = \frac{\text{Maximum value} - \text{Minimum value}}{2 \times \text{Average value}} \times 100.$$

III. RESULTS AND DISCUSSION

The RF rms voltage and RF rms current flowing at the power input position (position 1; V_1 and I_1), the center of the U-type antenna (position C; V_c and I_c), and the ground position (position 2; V_2 and I_2) of the U-type antenna module were measured as a function of the capacitance of the variable capacitor using the impedance probe, high-voltage probe, and current meter, and the results are shown in Fig. 2(a) for the RF rms voltage and Fig. 2(b) for the RF rms current. An RF power of 400 W at 13.56 MHz was applied at 10-mtorr Ar. As shown in Fig. 2(a), as the capacitance of the variable capacitor was increased from 50 to 315 pF, the RF rms voltage V_1 measured at the power input position increased from about 85 to 910 V, while the RF rms voltage V_2 measured at the ground position decreased from 975 to about 225 V, and at a capacitance of 148 pF, V_1 showed the same voltage as V_2 of about 580 V. In addition, at 148 pF, the phase relation between V_1 and V_2 was 180°, and the RF rms voltage at the center of the U-type antenna V_c was close to 0 V. For the RF rms current, contrary to the RF rms voltage, as the capacitance was increased from 50 to 315 pF, I_1 measured at the power input position decreased from 11.5 to 7.3 A, while I_2 measured at the ground position increased from 6 to 11.2 A. Similar to the RF rms voltage, at the same capacitance of 148 pF, I_1 and I_2 showed the same RF rms current of 9.5 A. At 148 pF, the phase relation between I_1 and I_2 was near 0°, and the RF rms current I_c at the center of the U-type antenna was equal to I_1 or I_2.

Therefore, the voltage and current at the various antenna positions varied with the capacitance installed at the ground position. In particular, at a capacitance value of 148 pF, the lowest RF peak voltage and the lowest RF peak current were obtained along the U-type antenna line, and the same RF current was obtained along the antenna line. Therefore, at this capacitance, the capacitive coupling is minimized, and the highest power-transfer efficiency is obtained due to the efficient inductive coupling [5]. In addition, due to the RF current being the same at each section of the antenna line, the power absorption to the plasma along the antenna line is uniform, and therefore, a uniform plasma distribution can be expected. The capacitance corresponding to equal values of the rms voltage and current can be obtained from the research by Suzuki *et al.* [5].

In general, the voltages at position 1 (V_1) and position 2 (V_2) can be written as follows:

$$V_1 = \left(j\omega L + \frac{1}{j\omega C} + R_l + R_f\right) I_1 \tag{1}$$

$$V_2 = \left(\frac{1}{j\omega C}\right) I_2 \tag{2}$$

where L and C are the inductance of the internal antenna and the capacitance of the capacitor, respectively. R_1 and R_f are the resistances of the antenna and the ferrite installed on the antenna in our experiment, respectively. R_1 and R_f are generally smaller than the impedances caused by the inductance L and the capacitance C, and therefore, they can be ignored, and V_2/V_1 can be written as follows:

$$\frac{V_2}{V_1} = \frac{1}{1-\omega^2 LC}\left(\frac{I_2}{I_1}\right). \tag{3}$$

When $I_1 \approx I_2$ and $V_1 \approx -V_2$ (due to the 180° phase relationship)

$$C_{I_1 \approx I_2} = 2/\omega^2 L. \tag{4}$$

The inductance value of the U-type antenna line measured using an LCR meter (Nicety LC802) was 1.71 μH, and the capacitance $C_{I_1 \approx I_2}$ was calculated to be 161.3 pF which is close to 148 pF. The discrepancy between the measured and calculated capacitance values could be related to the differences in R_l and R_f in (1).

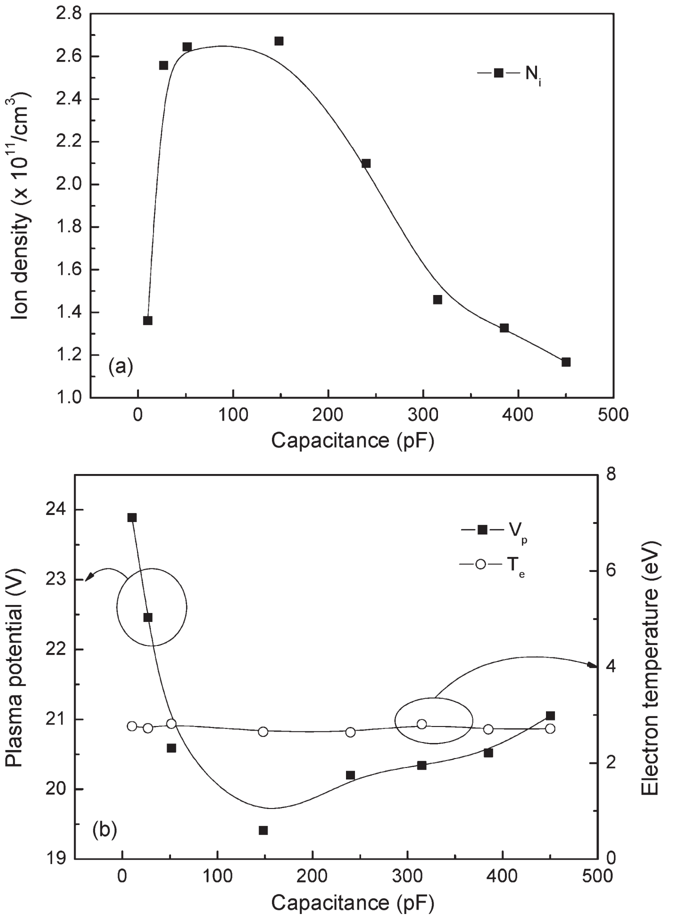


Fig. 3. (a) Plasma density and (b) plasma potential and electron temperature measured as a function of the capacitance of the variable capacitor using a Langmuir probe for the conditions shown in Fig. 2.

Fig. 3 shows the variation of the plasma characteristics such as the (a) plasma density and (b) plasma potential and electron temperature measured as a function of the capacitance of the variable capacitor using a Langmuir probe for the conditions shown in Fig. 2. The Langmuir probe was installed 130 mm below the antenna and at the center of the antenna line. As shown in Fig. 3(a), as the capacitance was increased from 4 to 500 pF, the plasma density rapidly increased from about $1.3 \times 10^{11}/\text{cm}^3$ at 4 pF to about $2.7 \times 10^{11}/\text{cm}^3$ at 148 pF, and further increasing the capacitance to 500 pF decreased the plasma density significantly to $1.1 \times 10^{11}/\text{cm}^3$. Therefore, the plasmas obtained under our experimental conditions were in the high-density plasma regime but showed the highest plasma density at a capacitance of 148 pF, $C = 2/\omega^2 L$, as shown in Fig. 2. In the case of the plasma potential, as shown in Fig. 3(b), as the capacitance was increased, it showed a minimum of about 19 eV at 148 pF and then slowly increased as the capacitance was further increased. The electron temperature did not vary significantly with the capacitance and was in the range of 2.6–2.8 eV.

As mentioned earlier, the highest plasma density obtained at a capacitance of $C = 2/\omega^2 L$ was believed to be related to the efficient inductive coupling to the plasma afforded by the power

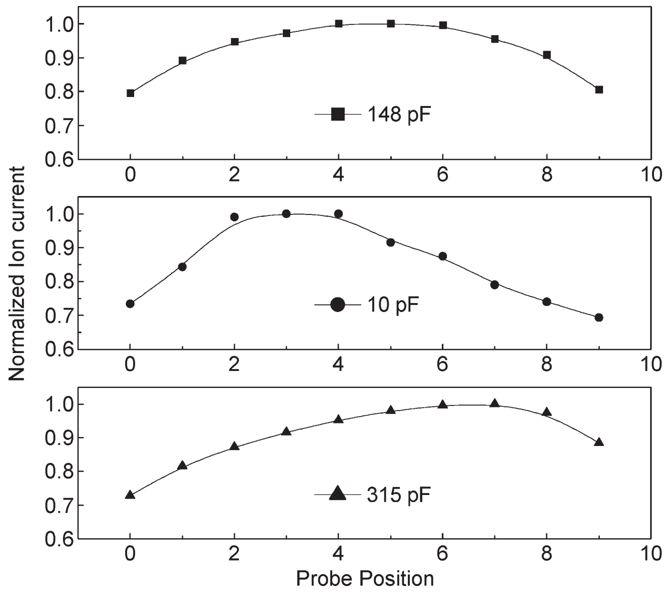


Fig. 4. Plasma uniformity measured along the chamber centerline and vertically to the linear antenna for different capacitances of the variable capacitor at an RF power of 400 W and 10-mtorr Ar using the Langmuir probe biased at −40 V.

transfer to the plasma being the highest. The minimum plasma potential at the capacitance condition of $C = 2/\omega^2 L$ was also related to the lowest capacitive coupling being obtained under these conditions. In the case of capacitive coupling, the plasma is sustained by the potential at the sheath, whereas in the case of inductive coupling, the plasma absorbs the power from the time-varying magnetic field near the electrode induced by the antenna current, and therefore, the plasma potential is generally lower when the plasma is operated by inductive coupling [10].

The plasma uniformity was measured along the chamber centerline and vertically to the linear antenna, as shown in Fig. 2(b) [along the arrow direction in Fig. 2(b)], for different capacitances of the variable capacitor at an RF power of 400 W and 10-mtorr Ar using the Langmuir probe, and the results are shown in Fig. 4. The Langmuir probe was biased at −40 V to measure the ion current in order to estimate the plasma density. The measurement was carried out from the power input side (position 0) to the ground side (position 9) along the chamber centerline. As shown in Fig. 4, when the capacitance of the variable capacitor was 148 pF, the peak ion current was at the center of the chamber, and the ion current was generally uniformly distributed along the chamber centerline. However, when the capacitance was 10 pF, the peak ion current was inclined to near the power input position, and when the capacitance was 315 pF, it was inclined to near the ground position.

The ion current distribution observed along the centerline of the chamber was related to the distribution of the RF voltage and RF current on the antenna line. When the capacitance was 10 pF, the RF antenna current was the highest and the RF antenna voltage was the lowest near the power input position, while when the capacitance was 315 pF, the RF antenna current was the highest and the RF antenna voltage was the lowest near the ground position. The RF voltage is related to the capacitive coupling to the plasma, while the RF current is related to the inductive coupling to the plasma, and the inductive coupling tends to transfer power to the plasma more efficiently. Therefore, the observation of the highest ion current being observed near the power input position at 10 pF and near the ground position at 315 pF is related to the highest power transfer being obtained at this portion of the antenna line due to the increased inductive coupling to the plasma. When the capacitance was 148 pF, the RF voltage was generally low along the antenna line, and the RF antenna current was the same throughout the antenna line. Therefore, not only the highest power transfer to the plasma but also the most uniform power transfer along the antenna line, which causes a uniform plasma over the chamber area, is believed to be obtained under the conditions of $C = 2/\omega^2 L$. To demonstrate the variation of the plasma uniformity with the capacitance of the variable capacitor, PR on the glass substrate was etched using an RF power of 400 W and 10 mtorr of Ar/O_2 gas mixture ($\mathrm{Ar{:}O_2} = 7:3$), and the PR etch uniformity was measured. The size of the glass substrate was 300 mm in diameter, and the distance between the antenna and the substrate was 90 mm. The result showed PR uniformities of 13.1%, 6.0%, and 16.6% for capacitances of 10, 148, and 315 pF, respectively. Therefore, under the capacitance condition of $C = 2/\omega^2 L$, the most uniform plasma was obtained due to the uniform inductive power transfer along the antenna line afforded by the uniform RF current.

In our ICP antenna, Ni–Zn ferrite is located on the internal ICP antenna to concentrate the induced magnetic field between the antenna and the substrate. The magnetic field induced between the antenna and the chamber top can decrease the power-transfer efficiency by heating the chamber wall due to resistive heating. By locating the half-circle-shaped ferrite above the antenna line, the magnetic field induced above the antenna line can be transferred to the magnetic field between the antenna and the substrate and effectively used to transfer power to the plasma [11]. However, due to hysteresis loss, eddy current loss, etc., which result in the increased heating of the ferrite at a higher frequency and a higher RF current [12], [13], the ferrite itself can lower the power-transfer efficiency, particularly at higher frequencies and higher RF currents. Fig. 5 shows the temperature of the ferrite on the internal ICP antenna measured as a function of the operating time for different capacitances of the variable capacitor at an RF power of 400 W and 10-mtorr Ar. The ferrite temperature was measured and averaged at the centers of the two internal linear antennas of the U-type antenna module. As shown in Fig. 5, the ferrite temperature generally increased with increasing operating time, even though it tends to saturate after a long operating time. However, compared with the ferrite installed on the ICP antenna without the capacitor (grounded), the ferrite installed on the ICP antenna with the capacitor showed a lower ferrite temperature. In addition, when the capacitance of the capacitor was 148 pF, the lowest ferrite temperature was observed, which indicates that the power-transfer efficiency to the plasma is increased due to the decreased power loss to the ferrite. This lowest ferrite temperature is believed to be related to the lowest peak RF current observed for the capacitance of 148 pF in Fig. 2. That is, the power loss to the ferrite (P_{loss}) is proportional to

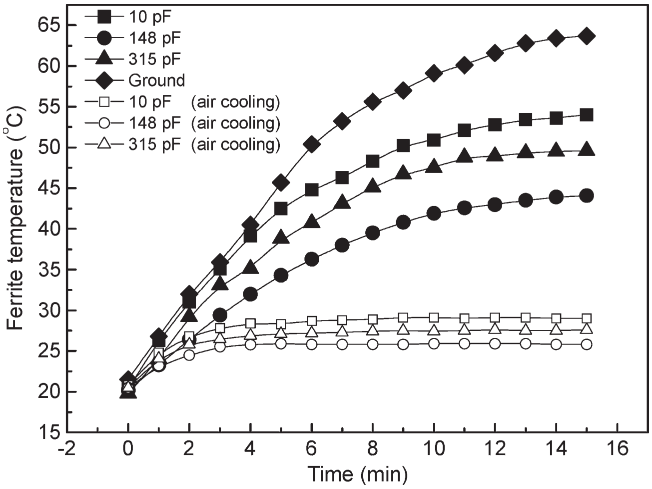


Fig. 5. Temperature of the ferrite on the internal ICP antenna measured as a function of the operating time for different capacitances of the variable capacitor at an RF power of 400 W and 10-mtorr Ar.

$P_{\text{loss}} = I^2 R_f$, and therefore, a higher peak current means a higher power loss. When the capacitance is 148 pF, the lowest peak current is observed, and therefore, the lowest power loss to the plasma can be expected for the capacitance condition of 148 pF. Meanwhile, when the ferrites were air cooled by flowing air through the internal quartz tube of the ICP antenna, as shown in Fig. 5, all of the ferrites of the ICP antenna with the different capacitors showed the lowest saturation temperature of less than 30 °C. However, the ferrite of the ICP antenna with a capacitance of 148 pF still showed the lowest temperature and provided the most stable operating conditions.

IV. CONCLUSION

A variable capacitor has been installed on the ground side of a Ni–Zn ferrite-enhanced internal U-type ICP source, and the effect of the capacitance of the variable capacitor on the electrical characteristics of the ICP antenna and the plasma characteristics has been investigated. The increase in the capacitance of the variable capacitor increased the RF rms voltage and decreased the RF rms current measured at the power input position while simultaneously decreasing the RF rms voltage and increasing the RF rms current measured at the ground position of the U-type antenna. When the capacitance of the variable capacitor satisfied $C = 2/\omega^2 L$, which is 148 pF under our experimental conditions, the RF rms voltages at the power input position and ground position were the same with a phase difference of 180°, and also, the RF rms currents were the same, which indicates that the lowest capacitive coupling to the plasma was observed, due to the lowest peak RF voltage being obtained along the antenna line. Under these conditions of $C = 2/\omega^2 L$, the highest plasma density and lowest plasma potential were obtained, in addition to the best plasma uniformity over the substrate area and the most stable operating conditions, due to the lowest heating of the ferrite installed on the ICP antenna being obtained. At a 13.56-MHz RF power of 400 W and 10-mtorr Ar, a plasma density of $2.74 \times 10^{11}/\text{cm}^3$ was obtained, and on the 300-mm-diameter substrate, the PR etch uniformity of 6% could be obtained with 10 mtorr of an Ar/O_2 gas mixture (Ar:$O_2 = 7:3$). It is believed that the use of a capacitor with the condition of $C = 2/\omega^2 L$ is applicable to all ICP antennas, including the ferrite-enhanced internal ICP antennas used in this study, for the purpose of improving the plasma properties and the electrical properties of the antenna by minimizing the capacitive coupling and by maximizing the power-transfer efficiency to the plasma.

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