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Characteristics of a Ferromagnetic-Enhanced Inductively-Coupled Plasma by an Internal Linear Antenna

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The electrical and the plasma properties of an internal linear inductively coupled plasma (ICP) source with/without a C-shaped Ni-Zn ferromagnetic module installed near the inductive antenna were investigated. The installation of the ferromagnetic module decreased the voltage and the current of the antenna at a given power while the phase angle between the voltage and the current was decreased. Therefore, the load resistance and the power transfer efficiency were increased at the same rf power for the ICP source with the ferromagnetic module. At a rf power of 800 W and 5 mTorr, the installation of the ferromagnetic material increased the plasma density from $2.9 \times 10^{11}/cm^3$ to $3.5 \times 10^{11}/cm^3$ while decreasing the plasma potential and the electron temperature slightly.

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I. INTRODUCTION

Inductively coupled plasma sources (ICPs) are widely used for microelectronics fabrication and will possibly be used for flat panel display processing in the near future because of their ability to generate a high-density plasma at low pressures [1,2]. However, for applications to large area flat panel display processing, with increasing processing area, conventional ICPs having an external spiral antenna have some problems such as a large voltage on the antenna, increased thickness of dielectric window, *etc.*. To avoid thick dielectric window and obtain more efficient processing, internal ICP sources, where the antenna is directly immersed in the chamber, can be empolyed [3, 4]. Compared to other high-density sources, internal ICP sources seem to be well suited for large-area plasma processing due to their simple antenna configuration, low operational pressure, and ease of manufacture.

Although the ICPs have potentially useful aspects, they have shortcomings related to the coupling of the antenna and the plasma and to the possible nonuniformity of the plasma caused by the standing wave effect. For example, the increases in the inductive antenna rf rms voltage, plasma potential, and electron temperature are believed to be related to an increase in the electrostatic coupling from the antenna to the plasma. The high voltage induced on the antenna will increase the electrostatic coupling to the plasma and can increase the sputtering of the dielectric material covering the antenna [5,6]. For this reason, some solutions have been investigated for more efficient and stable plasma processing by superposing a dc current on the antenna, employing a magnetic pole near the antenna, using a low inductance antenna, *etc.* [7–9]. Especially, in the case of the employing a magnetic material, the system consists of an inductor embedded within a high magnetic permeability module to enhance the magnetic coupling and, hence, to improve the density and the uniformity of the plasma [8, 10,11].

In this research, the effect of C-shaped ferromagnetic module installed near the antenna of an internal-type ICP source was investigated for the generation of a more efficient and stable plasma at a lower rf antenna voltage by enhancing the inductive coupling from the antenna to the plasma. The result shows that a positive change in the characteristics of the plasma and the electrical properties of the discharge system was obtain by installing a ferromagnetic module near an internal antenna.

II. EXPERIMENTS

The experimental setup of the internal ICP system used in this study is schematically shown in Figure 1(a). As shown in the figure, the processing system was composed of an ICP source chamber and a plasma processing chamber. The rectangular-shaped ICP source located on the top of the processing chamber consisted of two internal linear antennas connected with each other outside the source chamber. As shown in the figure, one side of the

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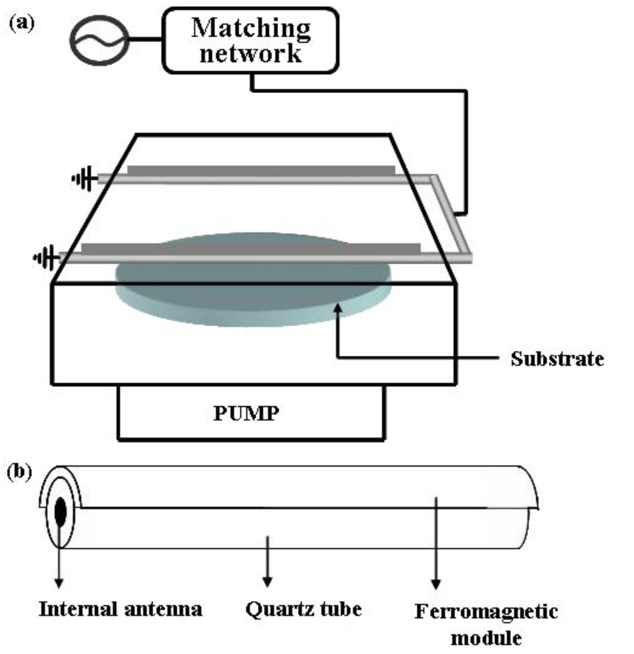

Fig. 1. (a) Schematic diagram of the ferromagnetic-enhanced inductively-coupled plasma system used in the experiment. (b) Arrangement of the C-shaped ferromagnetic module on the internal linear antenna line.

antenna was connected to a 3-kW 13.56-MHz, rf power generator through a L-type matching network while the other side was connected to ground directly. The plasma processing chamber was made of a cylindrical-shaped stainless-steel chamber having a 380-mm diameter and a substrate with a diameter of 300-mm. The ferromagnetic module used in this study was composed of Ni-Zn, and the module made of the C-shaped ferromagnetic material was installed above the antenna by enclosing the antenna line as shown Figure 1(b). The internal linear antenna was made of 10-mm-diameter copper tubing for water cooling and was fully covered by quartz tubing for dielectric isolation from the plasma. To investigate the characteristics of the plasmas, an electrostatic probe (Hiden Analytical Inc., ESP) was installed 4 cm below the antenna and at the center of the chamber. The electrical properties of the internal antenna were measured by using an impedance analyzer (MKS Inc.) located between the matching box and the antenna.

III. RESULT AND DISCUSSION

Figure 2 shows (a) the rf rms voltage and the (b) rf rms current measured as functions of rf power at various operating pressures for the linear antennas with/without the C-shaped ferromagnetic module installed near the antenna. As shown in the figure, an increase in the rf power and a decrease in the operating pressure increased the rf voltage of the antenna for antennas both with and

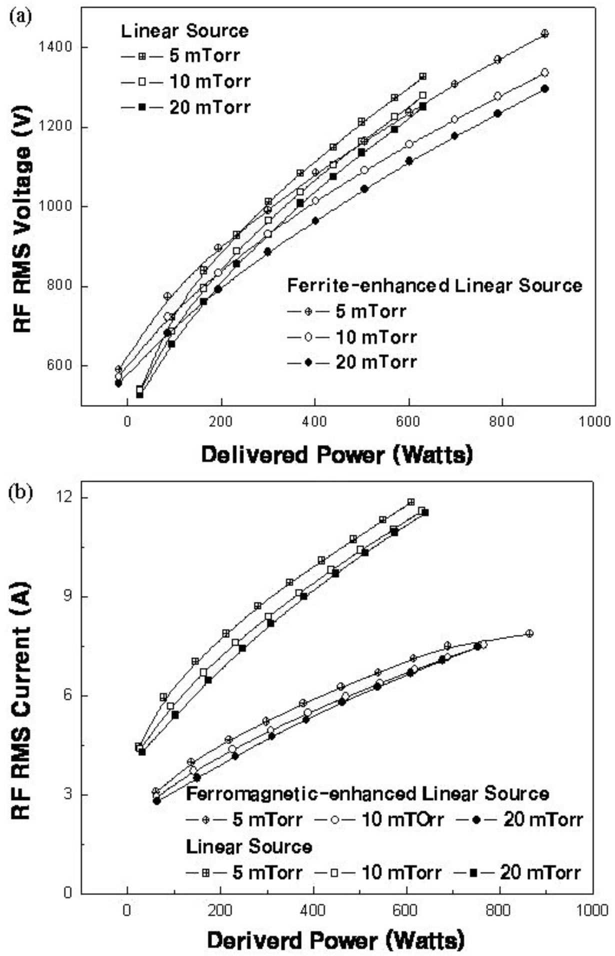

Fig. 2. (a) Rf rms voltage and (b) current measured as functions of rf power at various operating pressures for the internal linear ICP source with/without the ferromagnetic module by using an impedance analyzer on the antenna located close to the RF power input.

without the ferromagnetic module. In addition, for the same rf power and operating pressure, the antenna with the ferromagnetic module showed a lower antenna voltage compared to the antenna without the ferromagnetic module. The large rf voltage induced on the antenna line increases the electrostatic coupling to plasma and the sputtering of quartz tubing enclosing the antenna line. Therefore, the decrease in the rf voltage induced on the antenna line by using the ferromagnetic module decreases the sputtering of the quartz tubing and decreases possible contamination of the substrate [5, 12]. In the case of the rf rms current, as shown in Figure 2(b), an increase in the rf power also increased the rf rms current almost linearly, and a decrease in the operating pressure increased the current slightly for both antennas. In addition, at a given rf power of 600 W in the pressure range of 5 $\sim$ 20 mTorr, use of the ferromagnetic module with to the antenna decreased the rf rms current from 11.5 $\sim$ 11.8 A to 6.7 $\sim$ 7.1 A. The decrease in the rf rms current

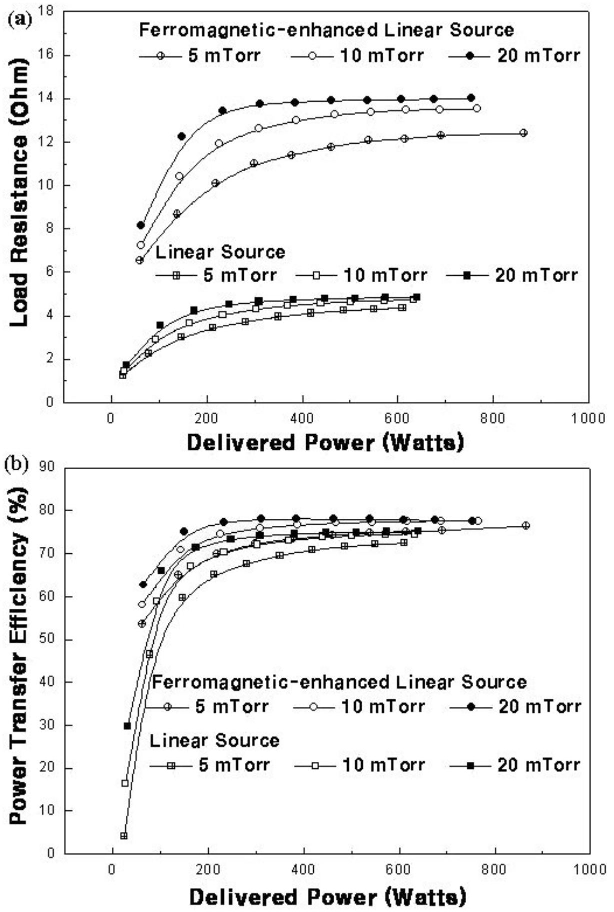

Fig. 3. (a) Load resistance and (b) calculated power transfer efficiency for the internal linear ICP source with/without the ferromagnetic module as functions of rf power at various operating pressures.

with the installation of the ferromagnetic module was accompanied by a decrease in the phase angle between the voltage and current (not shown).

Figures 3(a) and (b) show the electrical properties of the antenna of the internal ICP, that is, (a) the load resistance and (b) the power transfer efficiency, calculated as functions of rf power at various operating pressures and of the linear antennas with/without the ferromagnetic module by using an impedance probe. As shown in Figure 3(a), the load resistance which consists of the plasma and the antenna resistances increased with the increasing rf power even though it was nearly saturated at high rf powers. An increase in operating pressure also increased the load resistance. Especially, as shown in the figure, the use of the ferromagnetic module near the linear antenna increased the load resistance by about three times for all of the rf powers and operating pressures. Generally, the increase in the plasma density by the addition of the ferromagnetic module in the ICP source increased the plasma conductivity (σ) and decreased the electric field component of plasma at the same input rf power. The increase in the rf current with decreasing electric field component of the plasma causes an increase in the load resistance [13]. Therefore, at a 600-W rf power, the load resistance was increased from 4.3 $\sim$ 4.8 Ω to 12 $\sim$ 14 Ω. The increase in the load resistance with decreasing rf rms current and voltage (Figure 2) shown for the magnetic material at a given rf power and operating pressure indicates an effective power transfer to the plasma by increasing the plasma density, where is caused by the high magnetic permeability of the ferromagnetic material (Ni-Zn) installed near the antenna. In addition, the decrease in the rf rms current at a given rf power decreases the power loss on the antenna line by avoiding heating of the antenna line, therefore, higher rf power operation is possible in addition to effective rf power transfer.

The power transfer efficiency was calculated as a function of the rf power for the pressure range from 5 to 20 mTorr, and the results are shown in Figure 3(b). The power transfer efficiency was calculated from the relationship among the input power to the antenna, the RF RMS current, and the resistance ($\frac{InputPower - I_{rf}^2 R}{InputPower} \times 100$). Here, $I_{rf}^2 R$ ($P_{JouleLoss} = I_{rf}^2 \times R$) is the Joule loss consumed through the current flowing on the antenna. As shown in the figure, increasing the rf power initially increased the power transfer efficiency, however, for rf power higher than 300 W, the power transfer efficiency was almost saturated. An increase in the operating pressure increased the power transfer efficiency slightly, as expected, by the increase in the load resistance with increasing rf power, as shown in Figure 3(a). In addition, as shown in Figure 3(b), the use of a ferromagnetic module near the linear antenna increased the power transfer efficiency from 72 $\sim$ 74 % to 75 $\sim$ 78 % at a 600-W rf power for the pressure range of 5 $\sim$ 20 mTorr.

The use of a ferromagnetic module near the linear antenna, as shown in Figure 1(b), concentrates the time-varying magnetic field induced by the rf current on the area between the substrate and the antenna, which is not enclosed by the C-shaped ferromagnetic material. Also, the time-varying magnetic field induced on the area between the antenna and the substrate can be more than two times higher compared with that of the linear antenna without the ferromagnetic module at the same rf current applied to the antenna [8, 13]. Therefore, the time-varying electric field induced by the time-varying magnetic fields as estimated by Maxwell's equations is increased near the area between the antenna and substrate. In addition, the power loss to the wall located near the antenna line and the mutual interference between the antenna lines can be minimized by enclosing the antenna line with a ferromagnetic material.

The characteristics of the Ar plasma such as the plasma density, the plasma potential, and the electron temperature, were measured as a function of rf power at various operating pressures for the antenna with/without the ferromagnetic module by using an electrostatic probe, and the results for the plasma density and for the plasma potential and electron temperature

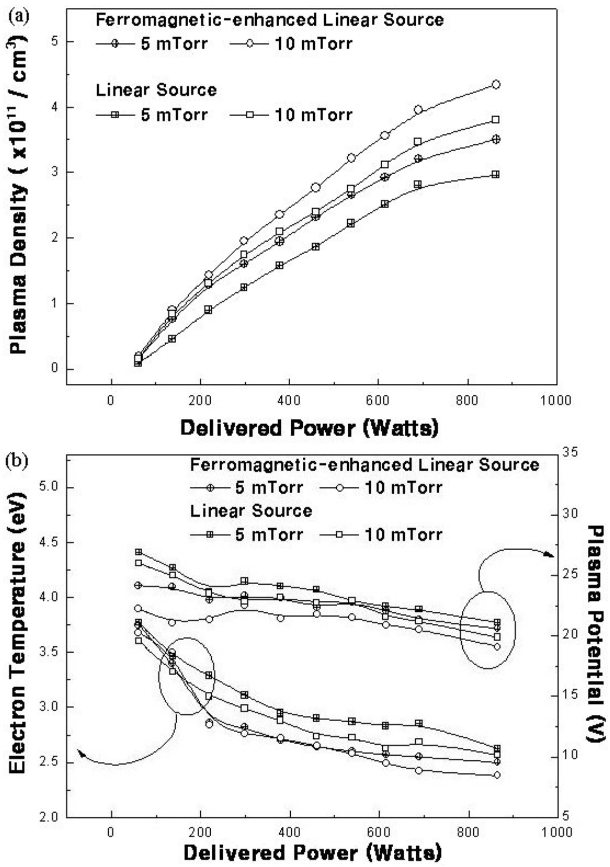

Fig. 4. (a) Ar^+ ion density and (b) plasma potential and electron temperature measured by using an electrostatic probe 4 cm below the antenna as functions of rf power at various operation pressures.

are shown in Figures 4(a) and 4(b), respectively. The electrostatic probe was located 4 cm below the antenna line. As shown in the figure, the increasing the rf power increased the plasma density almost linearly and increasing the operating pressure increased the plasma density. The increasing the rf power and the operating pressure also decreased the plasma potential and the electron temperature. However, as shown in the figure, at the same rf power and operating pressure, the installation of the ferromagnetic module near the antenna line also increased the plasma density and decreased the plasma potential and electron temperature. For example, for an 800-W of rf power and 5 mTorr of Ar, the use of the ferromagnetic module increased the plasma density from $2.9 \times 10^{11}/cm^3$ to $3.5 \times 10^{11}/cm^3$ while decreasing the plasma potential and electron temperature slightly. The increase in the plasma density and the decrease in the plasma potential and the electron temperature obtained at the same rf power and operating pressure caused by the installation of the ferromagnetic module appear to be related to more effective power transfer to the plasma from the antenna [14,15]. The more effective power transfer appears to be possible due to a more effective inductive coupling from the antenna to the plasma and to a concentration of the plasma generation between the antenna and the substrate caused by the antenna line being enclosed by the ferromagnetic module.

IV. CONCLUSIONS

In this study, the effect of a ferromagnetic module installed near the antenna line of an internal linear ICP on the electrical characteristics of the antenna and the plasma characteristics were investigated as a function of the rf power at various operating pressures. The application of the C-shaped ferromagnetic module showed a lower rf rms voltage on the antenna line; therefore, the possible contamination of the substrate by the sputter etching of the quartz tubing enclosing the antenna line could be minimized at the same rf power and operating pressure. In addition, by the installing a ferromagnetic module, a lower rf rms current and a higher load resistance were obtained at the same rf power and operating pressure, indicating a higher power transfer efficiency. The calculated power transfer efficiency also increased with the installation of the ferromagnetic module at the same rf power and operating pressure. The installation of the ferromagnetic module also increased the plasma density and decreased the plasma potential and electron temperature, possibly due to more effective inductive coupling from the antenna to the plasma and to the plasma being concentrated between the antenna and the substrate by enclosing the antenna line with a C-shaped module.

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