Japanese Journal of Applied Physics **48** (2009) 116006 **REGULAR PAPER**

Plasma Characteristics of Large Area Inductively Coupled Plasma System Using Ferrite-Module-Enhanced U-Type Antenna

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Received August 3, 2009; accepted September 4, 2009; published online November 20, 2009

A ferrite-module-enhanced internal-type linear inductively coupled plasma (ICP) source having multiple U-type antennas operated at 2 MHz has been proposed as a promising candidate to serve as an efficient high-density plasma source for plasma processing areas larger than 2,000 × 2,300 mm^2. When the ICP source was operated at 2 MHz RF power with the ferrite module, high density plasmas on the order of 2.9×10^{11} cm^{-3} were obtained at 10 mTorr Ar by applying 4 kW RF power/one U-type antenna; this is 1.5 times higher than the densities obtained at 13.56 MHz without the ferrite module. The higher plasma density obtained with the ICP source operated at 2 MHz with the ferrite module compared with that operated at 13.56 MHz without the ferrite module is related to the magnetic field enhancement caused by the ferrite module. The etch uniformity on a substrate of 2,300 × 2,000 mm^2 at 15 mTorr Ar/O$_2$ (7 : 3) and about 2.3 kW/U-type antenna was about 11%. © 2009 The Japan Society of Applied Physics

DOI: 10.1143/JJAP.48.116006

1. Introduction

Recently, there has been increasing interest in large-area high-density plasmas for materials processing at high rates and low temperatures, including the fabrication of microelectronic materials and devices, material surface modification, thin film deposition and etching, and plasma-assisted synthesis of novel materials.[1,2] Among the various high-density plasma sources, inductively coupled plasma (ICP) sources are known to be the most promising tool to fulfill various process requirements for a large-area high density plasma source because of their ability to generate high-density plasma over a wide range of pressure and to scale up to a larger size relatively easily.

Nevertheless, the scale up of the ICP source to a large size is not an easy task.[2–8] When a conventional ICP source with an external coil-type antenna is applied to the processing of very large area substrates, such as next-generation flat-panel display substrates, the antenna length and antenna impedance are significantly increased. The long antenna length increases the possibility of a non-uniform and unstable plasma because of the standing wave effect, and the large antenna impedance caused by the long antenna length increases the capacitive coupling to the plasma because of the high voltage on the antenna.[8–11] So, many researchers have investigated alternative approaches to generating uniform high-density plasmas for the large area processing, such as the use of multiple external or internal-type antennas.[12–14] Ferrite modules, such as bulk magnetic poles and ferromagnetic cores, have also been used in the ICP source antenna in order to increase the power transfer efficiency to the plasma and to increase plasma uniformity.[1,7]

In this study, we used a ferrite module enhanced internal-type linear ICP source with multiple U-type antennas operated at 2 MHz to obtain a uniformly high plasma density, and the result was compared with the ICP source operated at 13.56 MHz without the ferrite module. (13.56 MHz RF power is generally used as the RF power supply for the flat panel display industry, semiconductor processing, etc. Therefore, in this study, we compared the data operated at 2 MHz with that obtained using 13.56 MHz for the comparison with a conventional source operation case.) We used multiple U-type internal antennas operated at 2 MHz instead of conventional coil-type external antennas operated at 13.56 MHz in order to decrease a possible standing wave effect, and we employed the ferrite module to increase the efficiency of the power transfer to the plasma.

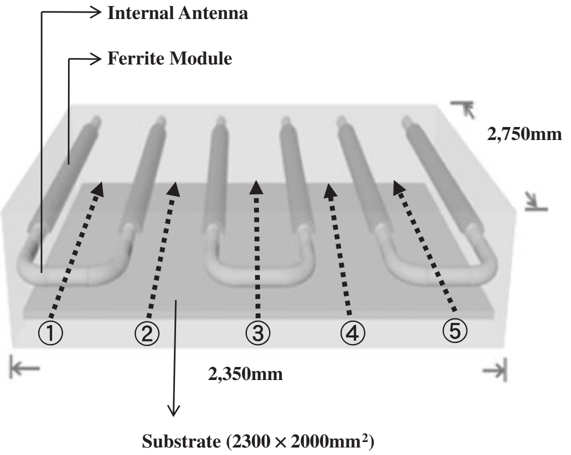

Fig. 1. Schematic diagram of the internal-type ICP system with three U-type antennas used in the experiment. For 2 MHz, as shown in the figure, half-circle-type Ni–Zn ferrite modules were installed between the antenna and the chamber top wall.

2. Experiment

Figure 1 show the schematic drawing of the large area ICP system used in this work, which had a chamber size of 2,350 × 2,750 mm^2, and of the multiple internal U-type linear ICP antenna arrangement used in the experiment. As shown in the figure, the processing chamber was made in a rectangular shape for flat panel display processing, and the substrate size was 2,000 × 2,300 mm^2. The ICP source consisted of three 6.5-m-long U-type antennas connected in parallel, with the antennas located to have an equal spacing of 240 mm. One end of each U-type antenna was connected to the power supply, while the other end was connected to the ground. The antennas were made of 10-mm-diameter copper tubing and were covered with 33-mm-diameter quartz tubing to prevent the copper tubing being directly exposed to the plasma. RF power of 2 or 13.56 MHz was

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connected to the antenna through respective L-type matching networks. When using the 2-MHz RF power to improve the plasma characteristics, a ferrite module (Ni–Zn) was placed between the U-type antenna line and the quartz tubing, so that the 33-mm-diameter quartz tubing covered not only the antenna line but also the ferrite module.

The plasma characteristics such as plasma density, plasma potential, and electron temperature were measured using a commercial Langmuir probe (Hiden Analytical ESP) which has a compensation circuit in front of the probe tip to remove possible RF noise from the RF plasma. We measured the electrical characteristics of the antenna, such as the root-mean-square (rms) voltage and the joule loss, using a voltage–current probe (MKS). The etch uniformity of the photoresist film deposited on $2{,}000 \times 2{,}300\,\mathrm{mm}^2$ sodalime glass substrates was measured using a 15-mTorr Ar/O_2 (7 : 3) mixture at 7 kW of 2-MHz RF power (about 2.3 kW per U-type antenna).

3. Results and Discussion

We measured the RF rms voltage between the U-type antenna and the matching network as well as the Joule loss on one U-type antenna as a function of the RF power per U-type antenna for 13.56 MHz and for 2 MHz with a ferrite module at 10 mTorr Ar. The results are shown in Fig. 2. When 13.56 MHz was used with the Ni–Zn ferrite module, the high impedance of the Ni–Zn ferrite when operated at 13.56 MHz (as shown in Fig. 3.) caused the ferrite module to heat up, and the operating conditions of the plasma source were unstable in time. On the other hand, when the U-type antenna was operated at 2 MHz without the ferrite module, it was difficult to initiate the plasma and the plasma showed instabilities. However, by operating the source at 2 MHz with the ferrite module, the low impedance of Ni–Zn ferrite at 2 MHz made it possible to obtain very stable plasmas without heating the ferrite module. Therefore, we compared the plasma characteristics of the source operated at 13.56 MHz without the ferrite module and with the plasma characteristics of the source operated at 2 MHz with the ferrite module. As shown in the figure, RF rms voltage increased with RF power both for 13.56 MHz without the ferrite module and for 2 MHz with the ferrite module; when the same RF power was applied to the antenna for the two cases, the operation at 2 MHz with the ferrite module showed the lower RF rms voltage. Joule loss increased with increasing RF power for both 13.56 MHz without the ferrite module and 2 MHz with the ferrite module; when operated at the same RF power the loss was higher for the operation at 13.56 MHz without the ferrite module, and the difference was higher at higher RF power. Therefore, by operating the source at the lower RF frequency with the ferrite module, it was possible to obtain a more stable plasma with a higher power transfer to the plasma.

The fact that a lower RF rms voltage was obtained at 2 MHz with the ferrite than at 13.56 MHz without the ferrite module is believed to be related to the lower impedance of the source operated at the lower RF frequency as well as to the low impedance of the ferrite module operated at 2 MHz, as shown in Fig. 3. Furthermore, the fact that a more stable plasma with a lower Joule loss was obtained for 2 MHz with the ferrite module is believed to be related to the ferrite used in the experiment. The ferrite module covered the top of the U-type antenna, so in the area between the antenna and the chamber top wall the magnetic field induced by the current flowing on the antenna was blocked by the ferrite. Instead, the magnetic field in the area between the antenna and the substrate was reinforced by the magnetic field generated by the ferrite in addition to the magnetic field induced by the current flowing on the antenna. The magnetic field induced between the antenna and the chamber top wall decreased the efficiency of power transfer to the plasma through the loss of power to the top wall of the chamber. Therefore, blocking the magnetic field between the antenna and the chamber top wall and reinforcing the magnetic field between the antenna and the substrate increased the efficiency of power transfer to the plasma by decreasing the Joule loss. Furthermore, when the power factor was estimated, the U-type antenna operated at 2 MHz with the ferrite module showed power greater by about a factor of three when compared to operation at 13.56 MHz without the ferrite module (not shown).

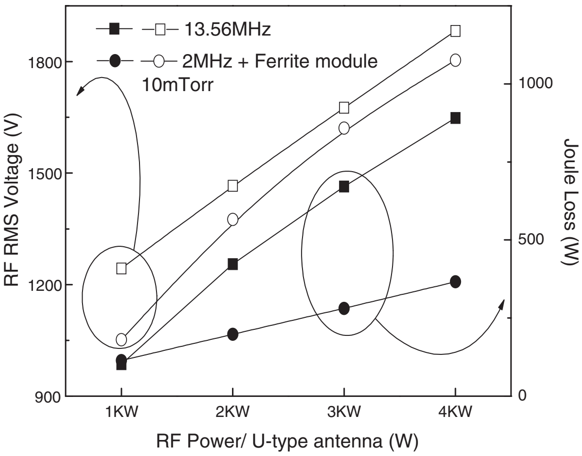

Fig. 2. The RF rms voltage and Joule loss measured as a function of RF power for the U-type ICP antenna operated at 2 MHz with the ferrite module and at 13.56 MHz without the ferrite module at 10 mTorr Ar using the *V–I* probe installed at the power output of the matching network.

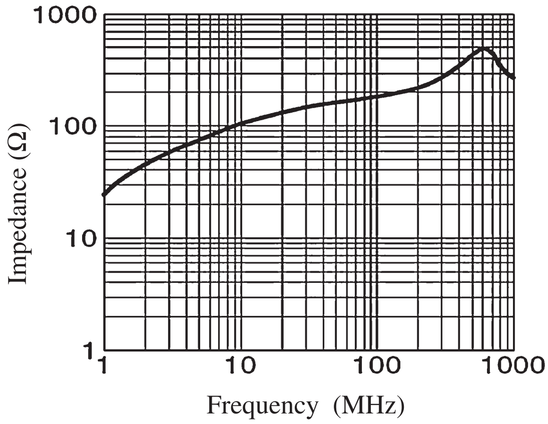

Fig. 3. The impedance of the Ni–Zn ferrite module (TDK ZCAT 3035-1330) measured as a function of operating RF frequency.[15]

We measured plasma characteristics, such as plasma density, plasma potential, and electron temperature, with a

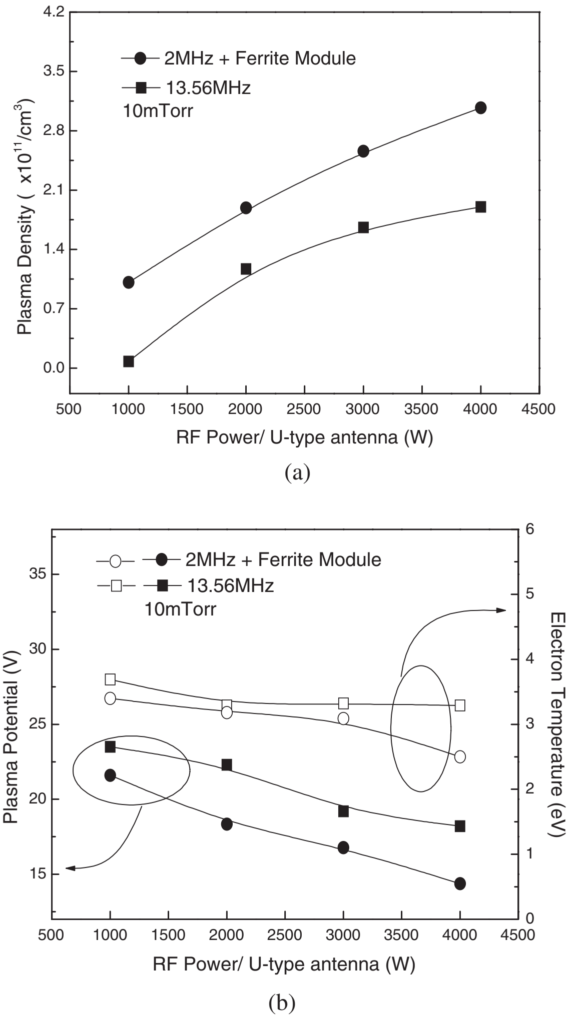

Fig. 4. (a) Plasma density and (b) plasma potential and electron temperature measured by a Langmir probe at 10 cm below the antenna and at the center of the chamber as a function of RF power for the U-type ICP antenna operated at 2 MHz with the ferrite module and at 13.56 MHz without the ferrite module at 10 mTorr Ar.

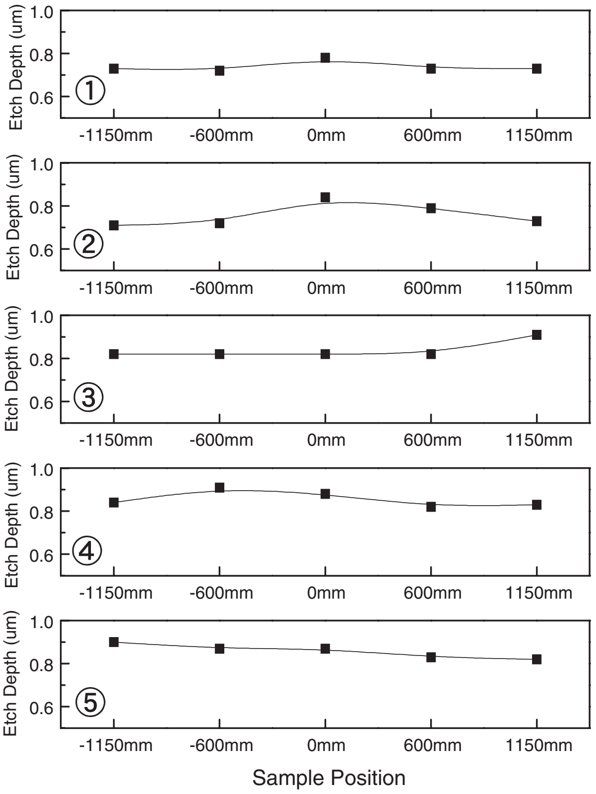

Fig. 5. Etch depth of the photoresist over the substrate area of 2,300 x 2,000 mm^2 measured with the ICP source shown in Fig. 1 operated at 2 MHz with the ferrite module. 7 kW of RF power (2.3 kW/U-type antenna) and 15 mTorr Ar/O$_2$ (7 : 3) mixture were used.

Langmuir probe located at the center of the chamber and 10 cm below the antenna. Figure 4(a) shows the plasma density measured as a function of RF power for 10 mTorr Ar with the U-type antenna operated both at 13.56 MHz without the ferrite module and at 2 MHz with the ferrite module. As shown in the figure, increasing the RF power led to an increase in the plasma density for the operation of the source at both operating frequencies, although the plasma density was higher when the source was operated at 2 MHz with the ferrite module. As can be seen in the figure, at 4 kW/U-type antenna and for 10 mTorr Ar, a plasma density of about $1.9 \times 10^{11}/\mathrm{cm}^3$ was obtained at 13.56 MHz without the ferrite module, while a plasma density of about $2.9 \times 10^{11}/\mathrm{cm}^3$ was obtained when the source was operated at 2 MHz with the ferrite module, or about 1.5 times higher than density at 13.56 MHz without the ferrite module.

Figure 4(b) shows the plasma potential and the electron temperature measured for the conditions shown in Fig. 4(a). As can be seen in the figure, increasing the RF power decreased the plasma potential and the electron temperature for both RF frequency conditions; this may possibly be due to the increased inductive coupling to the plasma at the higher RF power conditions. (Currently, it is just a speculation and needs further investigation.) Also, as shown in the figure, operating the source at 2 MHz led to a lower plasma potential and lower electron temperature compared with operation at 13.56 MHz without the ferrite module. For operation at 2 MHz with the ferrite module at 4 kW/U-type antenna and 10 mTorr, the plasma potential and the electron temperature were about 14 V and 2.5 eV, respectively. A lower plasma potential and a lower electron temperature can decrease the possibility of physical damage to the substrate and also decrease the likelihood of contamination.

On a $2{,}300 \times 20{,}000\,\mathrm{mm}^2$ substrate we placed a photoresist-covered glass substrate, and the photoresist etch depth was measured in order to estimate the plasma uniformity of the U-type source operated at 2 MHz with the ferrite. Three U-type antennas were connected in parallel to cover the substrate area, and 7 kW RF power, or about 2.3 kW/U-type antenna, was applied to the source with a gas mixture of Ar/O$_2$ (7 : 3) at 15 mTorr. Etch depths were measured after etching for 10 min along the center of each U-type antenna and between the antennas as shown in Fig. 1, and the result is shown in Fig. 5. As can be seen in the figure, the etch depth measured along the centerline of the U-type antenna and the etch depth measured between the U-type antennas were not significantly different, which implies good uniformity. The measured etch uniformity on the substrate size of $2{,}300 \times 2{,}000\,\mathrm{mm}^2$ was about 11%, which is acceptable for flat panel display processing, such as etching and deposition.

4. Conclusions

In this study, we investigated the electrical characteristics and the plasma characteristics of a large area U-type internal ICP source operated at 2 MHz RF power with a Ni–Zn ferrite module, and the characteristics were compared with those when the source was operated at 13.56 MHz without the ferrite module. The U-type ICP antenna operated at 2 MHz with the ferrite module showed a lower RF antenna voltage and lower Joule loss because of the lower impedance of the source compared with operation at 13.56 MHz without the ferrite module; this indicates a higher power transfer efficiency for the source operated at 2 MHz with the ferrite module. Because of the higher power transfer efficiency, the U-type ICP source operated at 2 MHz with the ferrite module showed a higher plasma density, a lower plasma potential, and a lower electron temperature. The source operated at 2 MHz with the ferrite module produced a density of about 2.9×10^{11}/cm^3 with 4 kW/U-type source, and, when the plasma uniformity was estimated by etching a photoresist using Ar/O_2 (7 : 3) with about 2.3 kW/U-type antenna, we found that a photoresist etch uniformity of about 11% could be obtained on the substrate area of $2{,}300 \times 2{,}000$ mm^2. The high plasma density and the good etch uniformity over the large substrate area obtained at 2 MHz with the ferrite module are believed to be related to the ferrite module concentrating the power dissipation between the antenna and the substrate without losing RF power between the antenna and the chamber top wall.

Acknowledgement

This work was supported by New and Renewable Energy R&D program under the Korea Ministry of Knowledge Economy (MKE).

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