# Ferrite-Enhanced U-Shaped Internal Antenna for Large-Area Inductively Coupled Plasma System

Kyong Nam Kim, Jong Hyeuk Lim, Woong Sun Lim, and Geun Young Yeom

***Abstract*—A Ni–Zn ferrite-enhanced U-shaped internal inductive antenna (240 mm × 2300 mm) operated at 2 MHz was used as a linear plasma source for an ultralarge-area plasma, and its plasma and electrical characteristics were investigated and compared with those of the antenna operated at 13.56 MHz without the ferrite. By the magnetic field enhancement, the operation of the source showed higher power transfer efficiency, lower antenna impedance, and lower RF rms voltage compared to that operated at 13.56 MHz without the ferrite. When photoresist etch uniformity was measured by etching the photoresist using a 40-mtorr $Ar/O_2$ $(7:3)$ mixture at 2 MHz by locating three U-shaped antennas in parallel, the etch uniformity less than 11% could be obtained on the substrate size of 2300 mm × 2000 mm.**

***Index Terms*—Flat panel display processing, inductively coupled plasma (ICP), internal antenna.**

## I. INTRODUCTION

THE FLAT PANEL display industry has been experiencing an impressive growth for the last decade and moving to ultralarge generation sizes such as 2200 mm × 2500 mm (eighth-generation glass size) for reducing manufacturing cost. Therefore, for the processing of the ultralarge-area substrate, ultralarge-area plasma processing systems are required, and to increase the throughput, high-density plasma sources are preferred [1]–[4].

Among the various high-density plasma sources, inductively coupled plasmas (ICPs) are known to have advantages in scaling over various other plasma sources for large-area plasma processing due to simple physics of operation [5]–[10]. However, even for the ICP source, when the plasma source is scaled up to an ultralarge size, the standing-wave effect along the ICP antenna line may significantly deteriorate the plasma uniformity over the processing area in addition to a poor power transfer efficiency by high power loss to the ICP antenna line [5].

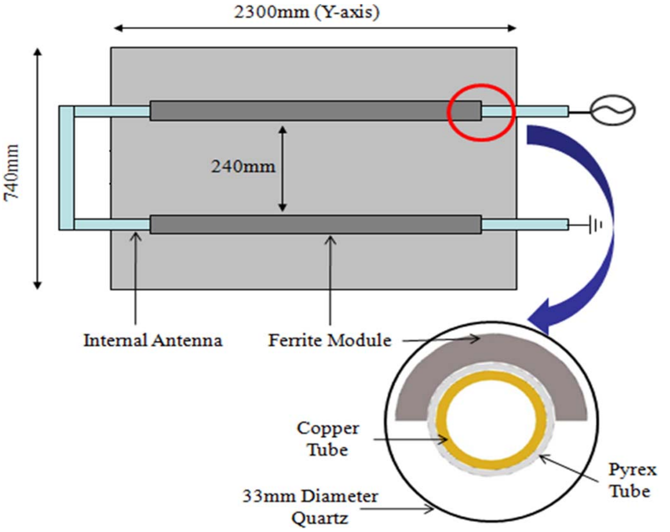

Fig. 1. Schematic diagram of a Ni–Zn ferrite-enhanced internal U-shaped ICP antenna used in the experiment.

To improve the RF power transfer efficiency from the ICP source to the plasma, ferrite-enhanced ICP sources have been investigated by a few researchers [5], [8]. Meziani *et al.* installed a ferrite plate over a meter-size (800 mm × 800 mm) external serpentine coil-type ICP antenna operated at 13.56 MHz, and Godyak and Chung used a series of ferrite cores in the chamber, and 400-kHz power was inductively coupled to the distributed ferrite cores. These research results showed the enhanced RF power transfer efficiency to the plasma. However, when the substrate size is larger than 2000 mm × 2000 mm, internal-type ICP sources are more efficient, and to remove possible standing-wave effects, short antennas, together with the RF power frequency lower than 13.56 MHz, may need to be used.

In this study, an internal U-shaped antenna operated at 2 MHz and enhanced by a Ni–Zn ferrite was used as the application to the ultralarge-area ICP source, and its plasma and electrical properties were investigated and compared with those of the source operated at 13.56 MHz without the ferrite.

## II. EXPERIMENTAL APPARATUS AND METHOD

Fig. 1 shows the schematic diagram of the internal U-shaped ICP antenna with the ferrite used in the experiment. The ICP antenna was composed of a U-shaped 10-mm-diameter

Manuscript received September 5, 2009; revised November 25, 2009. First published January 15, 2010; current version published February 10, 2010. This work was supported by the IT R&D Program of MKE (2009-S-007-1, Development of 300 mm wafer backend processing equipments for 32 nm node semiconductor devices).

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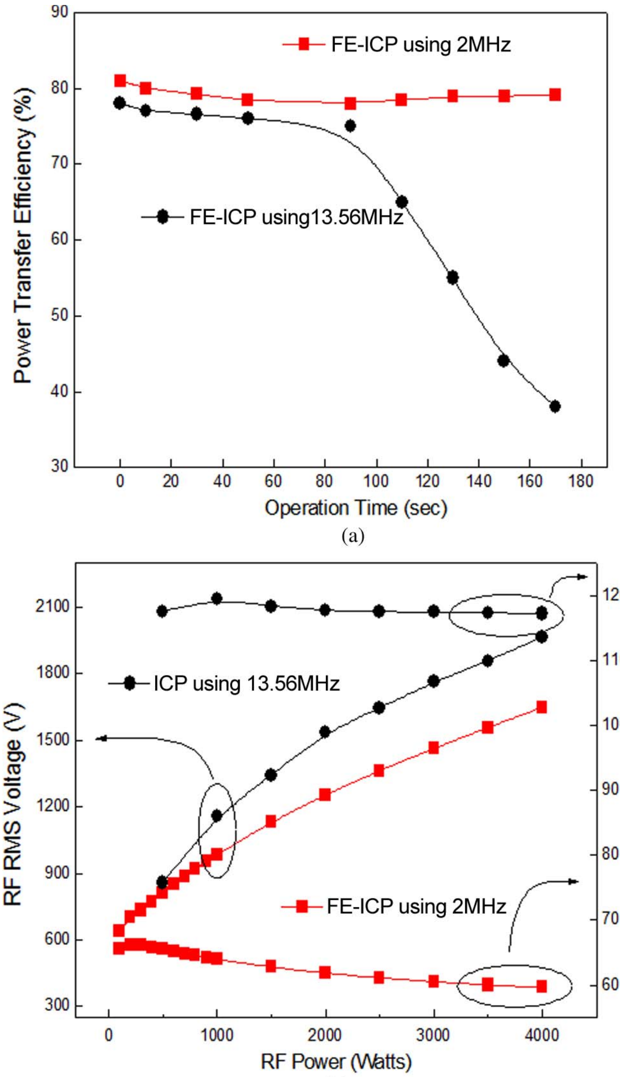
Digital Object Identifier 10.1109/TPS.2009.2037966

copper tubing and a 33-mm-diameter quartz tubing enclosing the antenna in the vacuum chamber area, and a ferrite module (Ni–Zn) was located between the U-type antenna and the quartz tubing, as shown in Fig. 3; therefore, the 33-mm-diameter quartz tubing was covering not only the antenna line but also the ferrite module in the chamber. The size of the U-shaped antenna was 740 mm × 2300 mm. One end of the antenna was connected to the RF power, while the other end was grounded. The plasma characteristics were measured using a Langmuir probe (Hiden Analytical Inc., ESP) below the antenna. The electrical characteristics of the antenna were investigated by an impedance probe (MKS Inc.) located between the matching box and the antenna.



(a)

(b)

Fig. 2. (a) Relative power transfer efficiency measured using an impedance probe as a function of operation time for the ferrite-enhanced internal U-shaped antenna operated at different driving frequencies (2 and 13.56 MHz) at 20-mtorr Ar and 500 W of RF power. (b) RF rms voltage and impedance of the internal U-shaped ICP source antenna operated at 2 and 13.56 MHz as a function of RF power at 20-mtorr Ar (the ICP source at 2 MHz with the ferrite and the source at 13.56 MHz without the ferrite).

## III. RESULTS AND DISCUSSION

As the RF power frequency to the antenna, both 2 and 13.56 MHz were used to study the effect of RF on the characteristics of the plasma. RF of 2 MHz has about seven times longer wavelength compared to conventional 13.56 MHz. Therefore, for the ICP antenna length longer than a few meters required for the ultralarge-area ICP system, any possible standing-wave effect that may occur along the antenna line can be removed by using 2-MHz RF. The ferrite module installed above the ICP antenna line decreases the induced time-varying magnetic field above the antenna line (between the antenna line and the chamber wall) to zero during the RF operation to the antenna due to the high magnetic permeability of the ferrite located above the antenna line. On the other hand, the time-varying magnetic field below the antenna line (between the antenna line and the substrate) is doubled by the enhanced time-varying field from the ferrite in addition to the time-varying magnetic field by the antenna, as shown in the following equation [8]:

$$B_{\text{without-ferrite}} = \mu_0 \cdot \frac{I}{2\pi r} \rightarrow B_{\text{with-ferrite}} = \mu_0 \cdot \frac{I}{\pi r}$$

where $\mu_0$ is the magnetic constant of free space, $I$ is the current, and $r$ is the effective antenna radius. Therefore, by using the ferrite-enhanced ICP antenna, enhanced plasma characteristics could be obtained in addition to the removal of possible contamination due to the plasma between the ICP source antenna and the chamber wall for the internal ICP source. However, depending on the operating frequency, the ferrite shows different impedance characteristics, and the use of a ferrite above a critical frequency can cause ohmic heating of the ferrite and can degrade the ferrite characteristics which result in the degradation of plasma characteristics by decreasing the power transfer efficiency. The ferrite-enhanced internal U-shaped antenna was operated using 500-W RFs (2 and 13.56 MHz) at 20-mtorr Ar, and the variation of power transfer efficiency to the plasma with time was measured using an impedance probe installed between the matching network and the antenna, and the result is shown in Fig. 2(a). As shown in Fig. 2(a), the power transfer efficiency of the ICP source operated at 13.56 MHz decreased significantly at the time higher than 90 s due to the loss of magnetic permeability by the heating of the ferrite, while that operated at 2 MHz did not change significantly with operating time, showing a saturated power transfer efficiency of about 80% due to the low impedance of the ferrite at 2 MHz.

Fig. 2(b) shows the RF rms voltage and impedance of the internal U-shaped ICP source measured as a function of RF power using the probe at different frequencies of 2 and 13.56 MHz with 20-mtorr Ar. The ferrite module was installed on the ICP source for the 2-MHz operation; however, due to the degradation of plasma characteristics for the 13.56-MHz operation with the ferrite, the characterization for the 13.56 MHz shown in Fig. 2(b) was measured without the ferrite module. As shown in the figure, with increasing the RF power up to 4 kW, the antenna impedance remained similar at 60 Ω for the 2-MHz operation with the ferrite and at 120 Ω for the 13.56-MHz operation without the ferrite. Therefore, higher antenna impedance was observed at the 13.56 MHz without the ferrite. In the case of the RF rms voltage measured on the

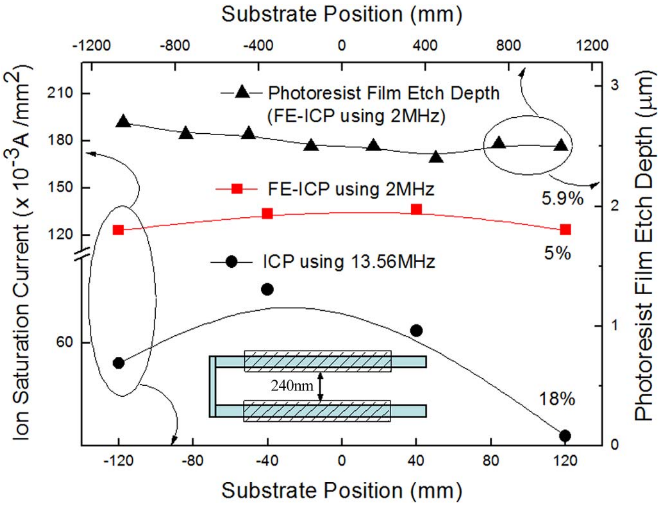


Fig. 3. Plasma uniformity of the U-shaped ICP source measured using an electrostatic probe biased at −60 V for 4-kW RF power and 20-mtorr Ar (the ICP source at 2 MHz with the ferrite and the source at 13.56 MHz without the ferrite). The photoresist etch uniformity along the antenna line direction measured by etching the photoresist using 40 mtorr $(\mathrm{Ar{:}O_2} = 7:3)$ for the ferrite-enhanced ICP source operated at 4 kW and 2 MHz is also shown.

antenna line, the RF rms voltage on the antenna was increased with the increase of RF power for both cases; however, the RF rms voltage was lower for the 2 MHz with the ferrite at a given RF power possibly due to the lower antenna impedance observed for the 2 MHz with the ferrite. Therefore, for the operation of the internal U-shaped ICP antenna, the operation at 2 MHz with the ferrite showed better antenna characteristics such as low RF rms voltage and low antenna impedance compared to that operated at 13.56 MHz without the ferrite. The lower RF rms voltage on the antenna induces a lower dc bias on the quartz tubing, and it decreases the additional possibility of contamination by sputtering of the quartz surface [7].

The plasma uniformity of the ICP source operated at 20-mtorr Ar and 4 kW of RF powers (2 MHz with the ferrite and 13.56 MHz without the ferrite) was estimated by measuring the ion saturation current of an electrostatic probe biased at −60 V and by scanning the probe vertically across the antenna line below 10 cm from the source. As shown in Fig. 3, the ICP source operated at 2 MHz with the ferrite showed 5% of plasma uniformity, while that operated at 13.56 MHz showed about 18% by showing significantly high ion saturation current between the two antenna lines. The improved plasma uniformity at the 2-MHz operation appears to be related to the increased diffusion of the plasma due to the longer RF period compared to that operated at 13.56 MHz. As shown in the figure, the ICP source operated at 2 MHz with the ferrite showed higher ion saturation current, indicating higher plasma density compared to that at 13.56 MHz due to the magnetic field enhancement between the antenna and the substrate by the ferrite. The plasma densities measured at the center of the source were $2 \times 10^{11}$ cm$^{-3}$ for the 2 MHz with the ferrite and $1 \times 10^{11}$ cm$^{-3}$ for the 13.56 MHz at 7 kW of RF power (not shown). For the ferrite-enhanced ICP source operated at 2 MHz, the plasma uniformity along the antenna line direction was also estimated by etching the photoresist using 40 mtorr $(\mathrm{Ar{:}O_2} = 7:3)$ and by measuring the etch uniformity along the antenna line. As shown in the figure, the uniformity of about 5.9% could be obtained along the 2300-mm antenna line due to the lack of standing-wave effect at the operation of 2 MHz.

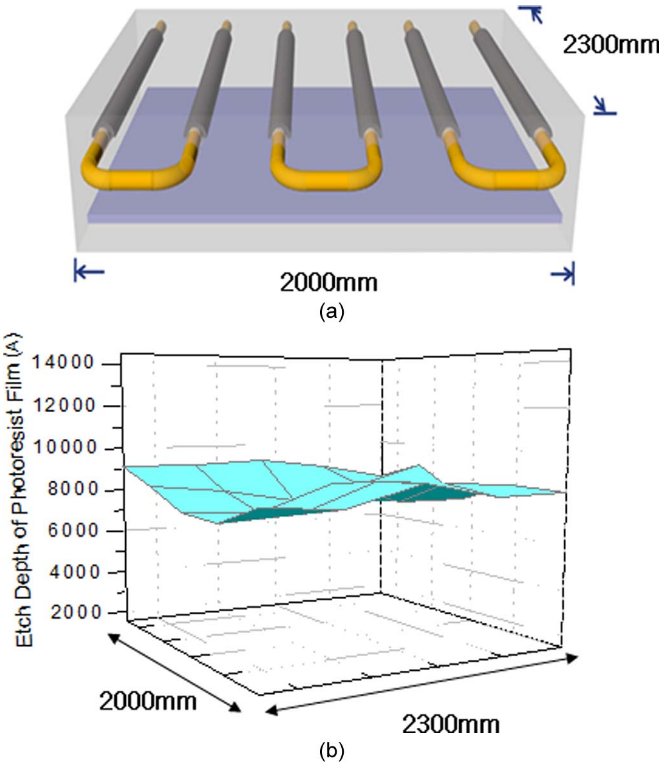


Fig. 4. (a) Large-area ICP processing system having a substrate size of 2300 mm × 2000 mm composed by locating three Ni–Zn ferrite-enhanced U-shaped ICP antennas in parallel. (b) Etch depth of the photoresist on the substrate size of 2300 mm × 2000 mm by operating the source operated at 2 MHz and 7 kW of RF power and 40-mtorr $\mathrm{Ar/O_2}$ $(7:3)$ mixture.

The U-shaped ICP antenna shown in Fig. 3 can be extendable for a large-area plasma processing system having a substrate size of 2300 mm × 2000 mm (seventh generation) by locating three U-shaped ICP sources in parallel as shown in Fig. 4(a) to apply for the dry etch and cleaning process of larger area thin-film transistor liquid crystal display processing. Using three U-shaped ICP sources in parallel and by operating the source at 7-kW 2-MHz RF power with 40 mtorr $(\mathrm{Ar{:}O_2} = 7:3)$, the photoresist etch uniformity over the substrate size of 2300 mm × 2000 mm was measured as an initial application to the photoresist removal and glass cleaning process, and the result is shown in Fig. 4(b). As shown in the figure, the photoresist etch uniformity of about 11% could be obtained. Therefore, by locating the ferrite-enhanced U-shaped ICP source in parallel, uniform high-density plasmas could be obtained over the ultralarge-area substrate.

## IV. CONCLUSION

In this study, as the application to ultralarge-area high-density plasma sources, the electrical and plasma characteristics of a Ni–Zn ferrite-enhanced U-shaped ICP source operated at 2 MHz were investigated. The use of 2 MHz instead of conventional 13.56 MHz as the RF power to the long ICP source antenna removed possible standing-wave effects along the antenna line which degrade the stability and uniformity of the plasma. In addition, due to the rapid increase of the impedance with increasing RF for the Ni–Zn ferrite, no significant loss of power was observed for the 2 MHz, while a significant power loss due to the eddy current was observed for the 13.56 MHz when the ferrite-enhanced ICP was used. The use of the ferrite-enhanced U-shaped ICP antenna at 2 MHz showed a lower RF antenna voltage, a lower antenna impedance, and higher plasma density and uniformity compared to that operated at 13.56 MHz without the ferrite. By locating three ferrite-enhanced U-shaped ICP antennas in parallel, a uniformity of about 11% could be obtained over a large-area plasma system with a substrate size of 2300 mm × 2000 mm.

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