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# Characteristics of Inductively Coupled Plasma using Internal Double Comb-type Antenna for Flat Panel Display Processing

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This study examined the electrical and plasma properties of an internal linear inductive antenna for flat panel display processing. An internal linear antenna, which is referred to as a "double comb-type antenna", with a substrate area of 2,300 × 2,000 mm$^2$ was used as a large-area inductively coupled plasma (ICP) source. This extremely large area ICP source showed a transition from E-mode to H-mode near 3 kW. At 9 kW, a power transfer efficiency of approximately 81% was obtained. The plasma uniformity measured by a Langmuir probe was approximately 14% over the substrate area at 15 mTorr Ar and 5 kW of RF power. [DOI: 10.1143/JJAP.46.L1216]

KEYWORDS: inductively coupled plasma, flat panel display, large area plasma, low impedance, uniformity

Inductively coupled plasma (ICP) sources have been the subject of many experimental and theoretical studies owing to the fact that high-density plasma can be generated easily under a low pressure without an external magnetic field.[1,2] In particular, applications that require large area plasma processing such as processing for thin film transistor-liquid crystal displays are very demanding the these sources. However, the high impedance that occurs with scale-up to a larger area, the cost and thickness of the dielectric material, has made the scale-up of conventional ICP sources using an external spiral antenna a difficult task. The antenna impedance as well as the cost and thickness of the dielectric material required to transmit electromagnetic field to the plasma increases significantly with increasing antenna size. Moreover, the increase in physical separation between the antenna and plasma through the increase in dielectric thickness results in a low power transfer efficiency.[2,3] For this reason, many large area high density plasma sources have been produced using internal ICP antenna-types such as parallel antenna type, low inductance antenna module, loop type, serpentine type, etc.[4–7]

For applications of internal ICP antennas, the electrical properties of the antenna should be uniform and the electrostatic coupling between the antenna and plasma should be low enough to prevent non-uniform power dissipation and unstable plasma formation. If a long antenna is used, the antenna length becomes comparable to the RF wavelength with increases in the plasma source, resulting in standing wave effects, which can cause a non-uniform power distribution and unstable electrical properties of the antenna. A previous study used an internal linear inductive antenna, which was referred to as a "double comb-type antenna", for a large-area plasma source with a substrate area of 880 × 660 mm$^2$, and investigated the electrical properties, plasma characteristics, etc.[8] The use of a double comb-type internal antenna not only balanced the power dissipation to each antenna but also eliminated the standing wave effect. In addition, the double comb-type antenna showed a higher antenna current, higher plasma density, and lower antenna resistance compared with the other types of internal ICP antenna, such as a serpentine-type antenna.

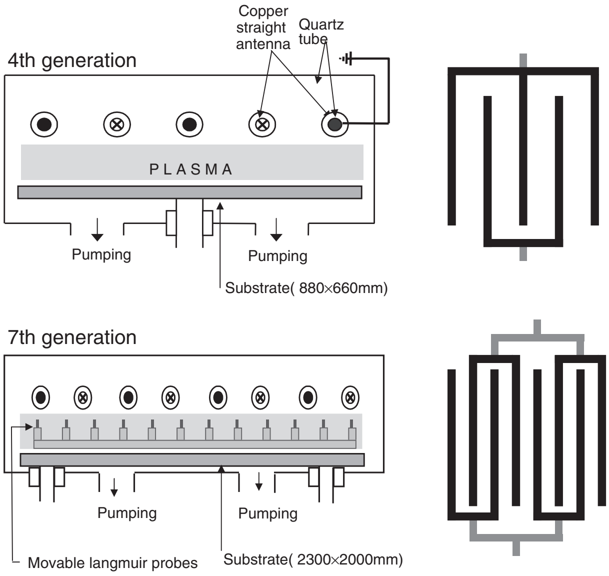

Fig. 1. Schematic diagram of the 4th and 7th generation ICP sources with the double comb-type antennas.

In this study, a larger sized double comb-type internal linear ICP source with a substrate area of 2,300 × 2,000 mm$^2$ was developed. The voltage distribution, electrical properties, etch uniformity, power transfer efficiency, etc. The potential of this double comb-type internal linear antenna source for application to the extremely large-area plasma processing (7th generation glass substrate) was examined.

Figure 1 shows a schematic diagram of the linear antenna arrangement of the double comb-type ICP sources used in this study. The top of the figure shows the double comb-type antenna, which was used in a previous study, with a substrate area of 880 × 660 mm$^2$ (4th generation), where each end of the five linear antennas are connected alternatively to a 5 kW 13.56 MHz RF power generator and the ground. The bottom of the figure shows the double comb-type antenna with a substrate area of 2,300 × 2,000 mm$^2$ (7th generation). The size of the processing chamber was 2,750 × 2,350 mm$^2$. The double comb-type antenna arrangement used for the size of this source consisted of eight linear internal antennas, where one end of each antennas was connected to a 10 kW 13.56 MHz RF power generator through a L-type matching network while the other end was grounded. The linear antenna for a substrate area of 2,300 × 2,000 mm$^2$ was made from 25.5 mm diameter copper tubing to allow for water cooling, and was covered by quartz tubing

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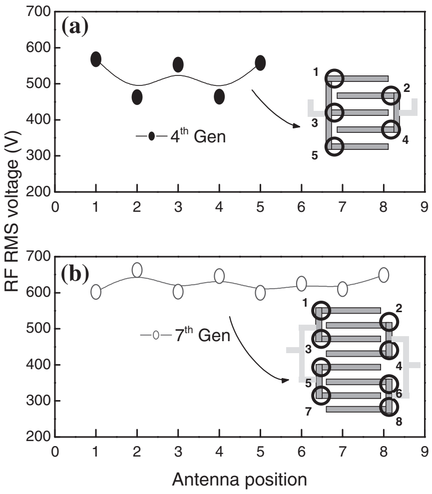

Fig. 2. RF RMS voltage distribution of the (a) 4th and (b) 7th generation systems along the antenna line measured using a high voltage probe at 5 kW of RF power and a pressure of 15 mTorr Ar.

that was 33 mm in diameter and 1.5 mm thick for dielectric isolation from the plasma.

The characteristics of the plasma uniformity were examined using a home-made movable Langmuir probe system, which consisted of 12 tips located above the substrate. The probe system was biased to −65 V and scanned along the substrate plane to measure the distribution of two-dimensional ion saturation current above the substrate area. In addition, the plasma density at the center of the processing chamber was measured using a commercial electrostatic probe (Hiden Analytical Inc., ESPION). The electrical properties of the linear internal antenna were measured using an impedance probe (MKS Inc.) that was located between the matching network and antenna.

For the 7th generation system, the voltage distribution on each antenna was measured using a high voltage probe (Tektronix P6015A) as a function of the chamber position at 15 mTorr Ar and 5 kW 13.56 MHz RF power. The results are shown in Fig. 2. For comparison, the voltage distribution on each antenna measured in a previous experiment for the 4th generation system at the same condition[8] is also included in the figure. As shown in the figure, the voltage on each antenna for both the (a) 4th and (b) 7th generation systems were similar at 450−550 and 550−650 V, respectively. In the ICP system, the antenna length of the inductive coil increased with increasing chamber size. The long length of the antenna can results in a standing wave effect, which causes non-uniform power absorption, unstable discharge, etc. Previous studies reported that the use of a long ICP antenna known as a "serpentine-type antenna" had a non-uniform voltage distribution, and a non-uniform plasma density, etc. when the plasma source size was increased.[5,8] The use of a double comb-type antenna examined in this study resulted in a shortening of the antenna length from the power input to ground. Therefore, no significant variation of the input voltage was expected along the chamber wall, even for a chamber size larger than the 7th generation. Therefore, the lack of significant variation of voltage along the chamber wall results from the lack of a standing wave effect.

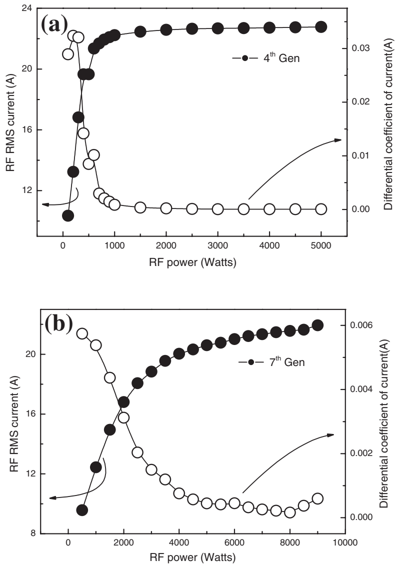

Fig. 3. RF RMS current measured using an impedance probe between the matching network and the (a) 4th and (b) 7th generation ICP antennas and its 1st differentials measured as a function of RF power at a pressure of 15 mTorr Ar.

Figures 3(a) and 3(b) show the RF RMS current between the matching network and the antenna measured as a function of RF power at 15 mTorr of Ar for the 4th and 7th generation ICP source using an impedance probe. As shown in the figure, an initial increase in RF power rapidly increased the RF current flowing to the antenna for both systems. However, the RF current became almost saturated after approximately 500 W and 3 kV for the 4th and 7th generation ICP source, respectively. The change in RF current with RF power was observed more clearly by showing the derivatives of the RF current as a function of RF power, as shown in the figure. Saturation of the RF current tends to show a transition of discharge mode from E-mode (capacitive coupling mode) to H-mode (inductive coupling mode).[9–11] Therefore, both 4th and 7th generation ICP source showed a transition to more efficient H-mode from E-mode with increasing RF power, and the transition power showed an approximately 6 fold difference, which is similar to the differences in the discharge area (6−7 times).

The load resistance/reactance of the 7th generation ICP sources were measured using the impedance probe, as a function of the RF power at 15 mTorr Ar. The results for the load resistance and load reactance are shown in Fig. 4. As shown in the figure, the load resistance generally increased with increasing RF power and the load reactance decreased with increasing RF power. For a transformer model of the power transfer mechanism from the ICP antenna to the plasma, the ICP antenna and plasma are regarded as the primary and secondary coils, respectively. The rf current along a primary coil induces the plasma current through mutual coupling in a secondary coil having the plasma resistance, geometrical inductance and the electron inertia inductance. The increase in load resistance and the reduction in load reactance with increasing RF power indicate the increase in mutual inductive coupling between the antenna and plasma, and are related to the efficient power transfer to the plasma.[12,13] Therefore, a decrease in load reactance with increasing RF power and increasing the load resistance suggests an increase in the inductive coupling coefficient. Indeed, the increase in RF power to the ICP coil increased

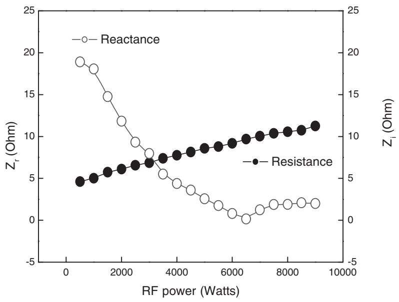

Fig. 4. Load resistance and reactance measured of the 7th generation ICP source using an impedance probe as a function of the RF power at a pressure of 15 mTorr Ar.

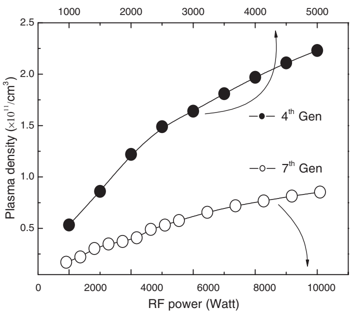

Fig. 5. Ar$^+$ ion density of the 4th and 7th generation ICP sources measured using an electrostatic probe as a function of the RF power.

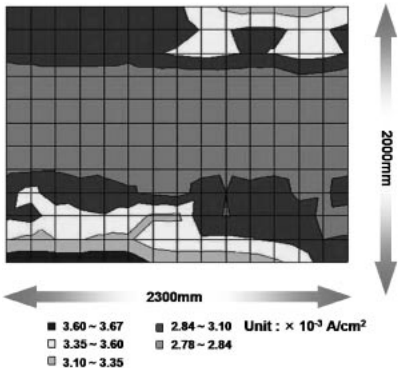

Fig. 6. Plasma uniformity of the double comb-type antenna measured using a movable Langmuir probe system biased at −65 V at 5 kW RF power and 15 mTorr Ar.

the power transfer efficiency. An approximate 81% RF power efficiency could be obtained at approximately 9 kW of RF power to the 7th generation ICP source. (not shown)

Using an electrostatic probe, the plasma density at the center of the chamber was measured as a function of the RF power for the 7th generation ICP source and the plasma density was compared with that measured for the 4th generation ICP source in a previous study.[8] As shown in Fig. 5, an increase in RF power increased the plasma density almost linearly for both the 4th and 7th generation ICP sources, showing approximately $2.2 \times 10^{11}$ cm$^{-3}$ at a 5 kW RF power for the 4th generation ICP source, and $8.5 \times 10^{10}$ cm$^{-3}$ at 10 kW RF power for the 7th generation ICP source. The 7th generation ICP source was approximately 1/4–1/5 times lower than that for the 4th generation ICP source at the same RF power due to the lower power density at the 7th generation ICP source. The discharge area of the 7th generation ICP source was approximately 6–7 times larger than that of the 4th generation ICP source, as mentioned above. Therefore, it is believed that if the RF power to the 7th generation is increased to 30 kW, the high plasma density of approximately $2.2 \times 10^{11}$ cm$^{-3}$, which is close to that of the 4th generation ICP source, could be easily obtained at the same power density.

Using a movable Langmuir probe system, the ion saturation current was measured above a substrate area of 2,300 × 2,000 mm$^2$ by biasing the probe at −65 V. Its uniformity for 5 kW of RF power at 15 mTorr Ar was estimated. Figure 6 shows that the ion saturation current above the substrate area ranged from $2.78 \times 10^{-3}$ to $3.67 \times 10^{-3}$ A/cm$^2$, and the estimated uniformity of the ion saturation current was approximately 14%. Therefore, it is believed that the double comb-type internal linear ICP source could produce good uniformity applicable to flat panel display (FPD) processing for both the 4th and 7th generation ICP sources.

In this study, an ICP source was fabricated using an internal linear-type antenna for a large-area ICP source called "double comb-type antenna" for a substrate size of 2,300 × 2,000 mm$^2$ (7th generation glass size), and its electrical properties were investigated to determine its potential as a double comb-type ICP source for producing a high density and uniform ICP source suitable for the 7th generation substrate. The use of the double comb-type antenna to the 7th generation ICP source showed a uniform antenna voltage along the chamber wall that is similar to the 4th generation ICP source with no standing wave effect. The plasma density increased linearly with increasing RF power in a similar manner to the 4th generation ICP source, even though the plasma density was about 1/4–1/5 times lower due to the approximately 1/6–1/7 times lower power density at the same RF power. The change from E-mode to H-mode occurred at approximately 3 kW while it occurred at approximately 500 W for the 4th generation ICP source. For the 7th generation ICP source, the plasma uniformity at 5 kW with 15 mTorr Ar was approximately 14%. Therefore, it is believed that the double-comb type ICP source is suitable for producing larger sized FPDs such as 7th generation FPD processing.

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