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Characteristics of Large Area Inductively Coupled Plasma Using a Multiple Linear Antennas with U-Type Parallel Connection for Flat Panel Display Processing

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In this study, the characteristics of large area internal linear inductively coupled plasma (ICP) sources of $1{,}020 \times 920\,\text{mm}^2$ (substrate area is $880 \times 660\,\text{mm}^2$) were investigated using a multiple linear antennas with U-type parallel connection. Using the multiple linear antennas with U-type parallel connection, a high plasma density of $2 \times 10^{11}\,\text{cm}^{-3}$ and a high power transfer efficiency of about 88% could be obtained at 5 kW of RF power and with 20 mTorr Ar. A low plasma potential of less than 26 V and a low electron temperature of 2.6–3.2 eV could be also obtained. The measured plasma uniformity on the substrate size of fourth generation ($880 \times 660\,\text{mm}^2$) was about 4%, therefore, it is believed that the multiple linear antennas with U-type parallel connection can be successfully applicable to the large area flat panel display processing.

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KEYWORDS: plasma, large area, display, Langmuir probe

1. Introduction

Inductively coupled plasmas (ICP) have been investigated for the processing of semiconductors and flat panel display devices as one of the high density (10^{11}–$10^{12}\,\text{cm}^{-3}$) and low gas pressure plasma sources.[1–3] Especially, ICP was the most attractive among the high density plasma sources due to the advantages of simple physics and a simple source structure requiring no external magnetic field.[1,4]

In the case of semiconductor processing, the ICP source with externally spiral-type antennas are generally studied, but this ICP source shows problems in the application to the processing of the extremely large size of thin film transistor-liquid crystal display (TFT-LCD) substrates due to the cost and thickness of the dielectric material and the large impedance of the antennas when scaling up to larger areas. The large impedance of the antenna causes a high RF voltage on the antenna, and it can lead a low efficient power transfer to the plasmas by the increased capacitive coupling. One of the solutions resolving the above problems is to use internal-type ICPs, which could effectively exclude the problems related to the thickness of the dielectric material when scaling to large areas.[6,7,9] Various internal-type ICPs utilizing straight antenna elements connected as serpentine shapes have been reported for the application of large-area TFT-LCD processing.[5,6] However, with the increase of the substrate size, the length of the serpentine-type antenna becomes comparable to the operating RF wavelength, and the standing wave effect that causes a non-uniform power distribution along the antenna becomes intolerable.[7,8] So, it became necessary to reduce the antenna impedance.[9]

In this study, a novel arrangement of the internal-type ICP antenna (a multiple linear antennas with U-type parallel connection) for a large-area ICP source, which has little standing wave effect and a low impedance, was studied for the application of the next generation large-area flat panel display device processing, and its plasma and electrical characteristics were investigated.

2. Experiment

Figure 1 shows the schematic drawing of the large area ICP system having the chamber size of $1{,}020 \times 920\,\text{mm}^2$ and the internal-type linear ICP antenna arrangement used in the experiment. As shown in the figure, the processing chamber was made of a rectangular shape for the flat panel display processing and the substrate size was $880 \times 660\,\text{mm}^2$ (fourth generation). The ICP antenna was consisted of three 2.3-m-long U-type antennas connected in parallel (multiple linear antennas with U-type parallel connection) and the antennas were located to have an equal spacing of 16 cm. One end of each antenna was connected to the power supply while the other end was connected to the ground. The antenna was made of 10 mm diameter copper tubing and was covered with 13 mm diameter quartz tubing to avoid direct exposure of plasma to copper tubing.

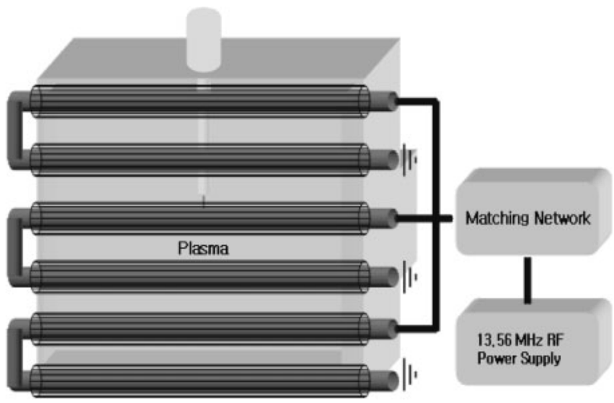

Fig. 1. Schematic diagram of a multiple U-type ICP system used in the experiment.

Radio-frequency (RF) power of 5 kW and 13.56 MHz was connected to the antenna through a L-type matching network and the Ar gas pressure in the range from 5 to 20 mTorr was used to generate the plasmas. Plasma characteristics of the ICP system such as plasma density, plasma potential, electron temperature, plasma uniformity, etc. were measured using a Langmuir probe (ESP, Hiden Analytic) at 7.5 cm below the antenna. The electrical characteristics of the antenna such as root-mean-square (rms) current and resistance were measured using an impedance probe (MKS).

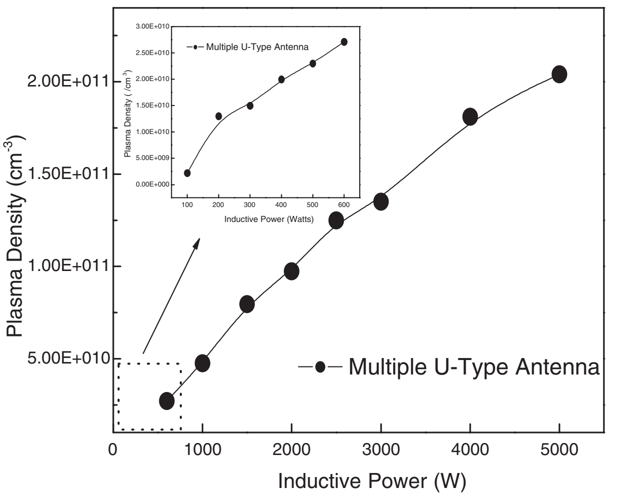

Fig. 2. Ar ion density measured by a Langmuir probe at 7.5 m below the each antenna for the multiple linear antennas with U-type parallel connection as a function of inductive power from 1 to 5 kW at 15 mTorr Ar.

3. Results and Discussion

Figure 2 shows the effect of RF inductive power from 1 to 5 kW on the ion density of the plasma generated by the multiple linear antennas at 15 mTorr of Ar. The ion density was measured at the center of the chamber and at 7.5 cm below the antenna. As shown in the figure, the ion density was increased with the increase of RF power almost linearly from $4.76 \times 10^{10}\,\text{cm}^{-3}$ at 1 kW to about $2 \times 10^{11}\,\text{cm}^{-3}$ at 5 kW. Therefore, a high density plasma could be obtained using the multiple linear antennas and by applying 5 kW of RF power. The high density plasma obtained in our experiment is believed to be from the inductive coupling to the plasma by a high RF current flowing on the antenna. To understand the coupling mode by the antenna, RF rms current flowing on the antenna was measured as a function of RF power.

Figure 3 shows the RF rms current flowing on the multiple linear antenna and its first differentials measured as a function of RF inductive power from 100 W to 5 kW using an impedance probe at 15 mTorr of Ar. As shown in the figure, the increase of RF power increased the RF rms current flowing to the antenna and, at 5 kW of RF power, the rms current of about 10 A was observed, therefore, an increased possibility of inductive coupling to the plasma could be expected at the higher RF power. When the first differential of the RF rms current was calculated, as shown in the figure, a peak at about 300 W with a rapid increase of the current in the region from 100 to 300 W could be observed. The rapid increase of the RF rms current appears to show the increase of inductive field in the plasma which is more dependent on the RF current of the antenna compared to the capacitive field. Generally, the discharge mode transition from E- to H-mode is followed by an intense increase in n_e. where, the plasma conductivity (σ) is proportional to the plasma density ($\sigma \propto n_e$). The plasma impedance, where the real part of the plasma impedance in proportional to $1/\sigma$ is directly related to the power transfer to the plasma and the mutual coupling between the coil and the plasma, the change in plasma operation mode can be

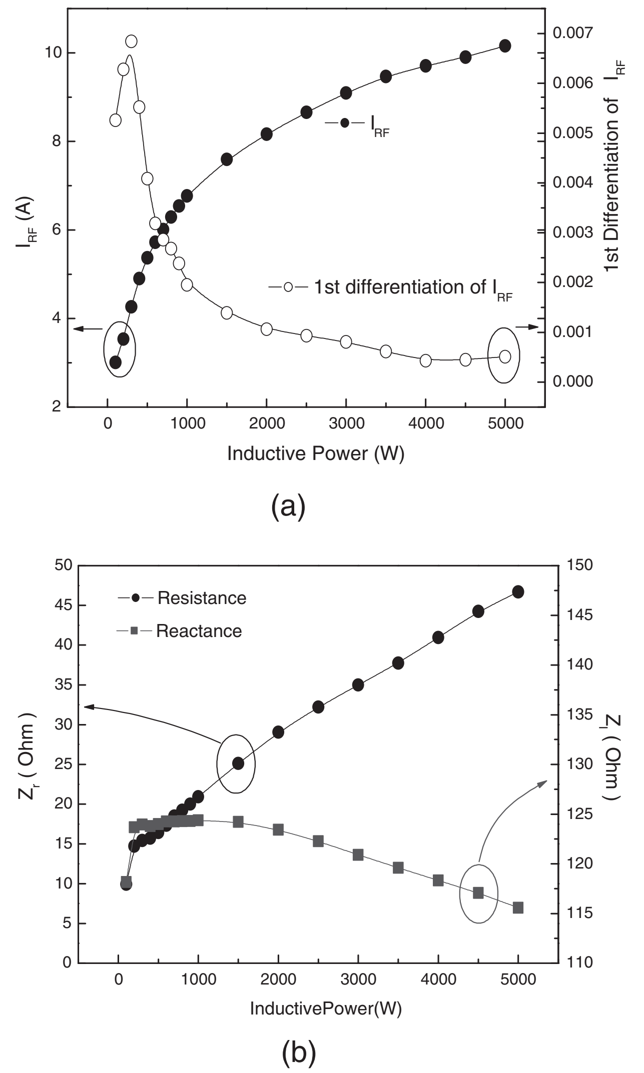

Fig. 3. (a) RF rms current measured by an impedance analyzer between matching box and the multiple linear antennas with U-type parallel connection and its differentials measured as a function of RF power at 15 mTorr Ar. (b) Plasma resistance (Z_r) and plasma reactance (Z_i) calculated as a function of RF power at 15 mTorr Ar.

observed through the investigation of the variation of the antenna impedance ($Z = Z_r + iZ_i$, Z_r: antenna resistance, Z_i: antenna reactance). The discharge impedance can be determined indirectly by measuring external parameters such as the rms antenna voltage V_{RF}, current I_{RF}, and phase shift φ (power factor, $\cos\varphi$) between the antenna voltage and current and by calculating the following equation;

$$Z_r = \left(\frac{V_{RF}}{I_{RF}}\right)\cos\varphi, \quad Z_i = \left(\frac{V_{RF}}{I_{RF}}\right)\sin\varphi$$

In our experimental data, as the inductive power was increased from 100 to 5000 W, $\cos\varphi$ was increased from 0.08754 to 0.34489 (not shown). Using the measured voltage, current, and phase shift as a function of the inductive power for an Ar pressure of 15 mTorr, Z_r and Z_i were calculated and the results are shown in Fig. 3(b). As shown in this figure, the increase in the inductive power resulted in an increase in the value of Z_r and a decrease in the value of Z_i, which corresponds to an increase in the efficiency of the power transfer from the antenna to the plasma. Therefore, the result shown in Fig. 3(a) appears to

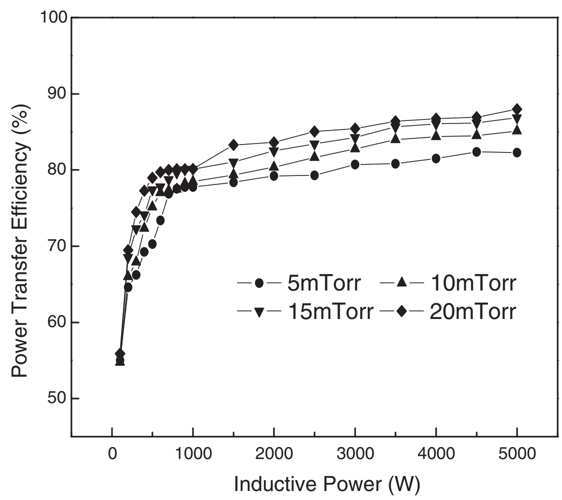

Fig. 4. Power transfer efficiency measured by an impedance analyzer as functions of inductive power from 100 W to 5 kW and working pressure from 5 to 20 mTorr Ar.

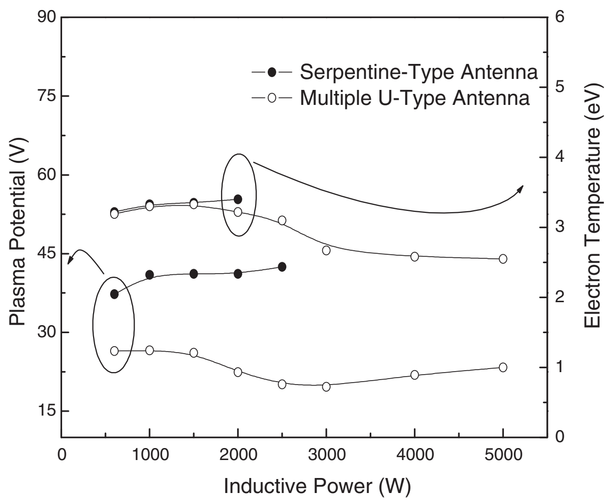

Fig. 5. Plasma potentials and electron temperatures of the multiple linear antennas with U-type parallel connection measured using a Langmuir probe as a function of RF inductive power from 600 W to 5 kW at 15 mTorr Ar. As a reference, plasma potentials and electron temperatures of a serpentine-type antenna were included.

show the transition from a CCP mode to an ICP mode from the near 100–300 W of RF power.

Figure 4 shows the power transfer efficiency (%) calculated as functions of RF inductive power from 100 W to 5 kW and Ar pressure from 5 to 20 mTorr for the multiple linear antennas. To calculate the power transfer efficiency, the Joule loss at the antenna, RF cable as well as matching network was measured using an impedance probe. And, after the measurement of the Joule loss, the power transfer efficiency was calculated using the following equation:

$$\frac{\text{Input power} - I^2R(\mathit{loss\ I} + \mathit{loss\ II})}{\text{Input power}} \times 100$$

where, *loss I* is the Joule loss at the RF cable and matching network, and *loss II* is the loss at the antenna, and which was dependent on the power loss by the ohmic resistance of the antenna, RF cable, and matching network. As shown in the figure, the power transfer efficiency at 5 mTorr was increased rapidly from about 55 to 66% by increasing RF power from 100 to 300 W, however, the further increase of RF power to 5 kW increased the power transfer efficiency slowly to 82% at 5 kW of RF power. The increase of Ar pressure from 5 to 20 mTorr further increased the RF power transfer efficiency and, at 20 mTorr of Ar and at 5 kW of RF power, the highest power transfer efficiency of 88% could be obtained. For all the Ar pressures investigated, the similar change of the slope of the power transfer efficiency as a function of RF power was observed at the RF power of near 100–300 W possibly indicating the transition of the discharge mode as described above.

Figure 5 shows the plasma potential and electron temperature measured as a function of RF inductive power from 600 W to 5 kW at 15 mTorr of Ar for the multiple linear antennas using the Langmuir probe. The probe was located at the same position as shown for Fig. 2. In general, the plasmas generated by capacitive coupling show high plasma potentials and high electron temperatures (>3–5 eV), and these can lead to an instability of the plasma and can cause problems in the processing such as surface damage, contamination, etc. The measured electron temperature of the Ar plasma generated by the multiple linear ICP antennas was low and was in the range from 2.6 to 3.2 eV and a little lower electron temperature could be obtained at the higher RF power in general. In the case of the plasma potential, the plasma potential was lower than 26 V and was not significantly varied with RF power. As a comparison, instead of the multiple U-type configuration, a serpentine-type antenna configuration was formed by connecting all the linear antennas in series as described elsewhere in details[6] and its plasma potentials and electron temperatures were compared with those by the multiple U-type configuration. For the serpentine-type antenna, the RF power higher than 2.5 kW could not be operated due to the instability of the plasma. As shown in the figure, the electron temperature and plasma potential of the plasma generated by the serpentine-type antenna was generally higher than those by the multiple linear antennas with U-type parallel connection. Therefore, it is believed that more efficient and more inductively coupled plasma could be obtained by using the multiple U-type antenna instead of the serpentine-type antenna.

One of the most important requirements of the plasma sources for the flat panel display device processing is the uniformity of the plasma on the large area substrate. Figure 6 shows the ion saturation current measured along the centerline of the substrate width of 660 mm for various RF powers and at 15 mTorr Ar using the Langmuir probe biased at −60 V. The ion saturation current of the Langmuir probe was used as the estimation of the plasma density. As shown in the figure, the plasma uniformity was about 4% and was not dependent on the RF power significantly. The etch uniformity was measured by etching 3 μm thick photoresist covered glass substrates using 15 mTorr O_2 instead of 15 mTorr Ar. Figure 6(b) shows the etch uniformity measured on the substrate area (880 × 660 mm^2). As shown in the figure, the etch uniformity on the substrate area was about 8% (not shown) which is better than the typical processing uniformity required for the flat panel display processing. Therefore, using the multiple linear antennas

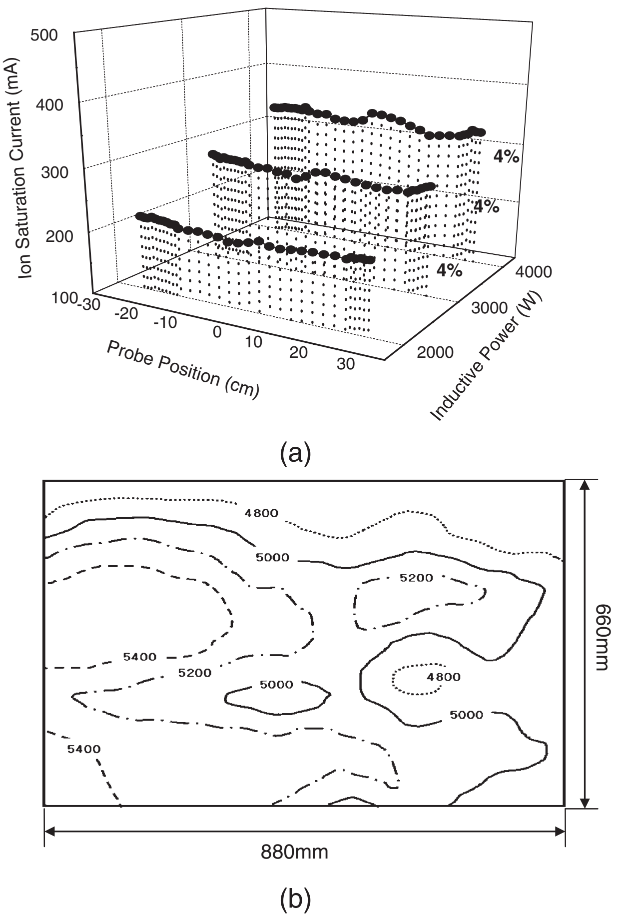

Fig. 6. (a) Plasma uniformity of the multiple linear antennas with U-type parallel connection measured at 7.5 cm below the antenna as a function of RF inductive power from 2 to 4 kW with 15 mTorr Ar. Ion saturation current measured using a Langmuir probe biased at −60 V was used as the estimation of the plasma density. (b) The etch uniformity of photoresist measured on the substrate area ($880 \times 660\,mm^2$). The etch uniformity was measured by etching 3 μm thick photoresist covered glass substrates using 15 mTorr O_2 at 5 kW of RF power and at −60 V of bias voltage.

with U-type parallel connection, a good etch uniformity required for the flat panel display device processing could be obtained.

4. Conclusions

In this study, plasma characteristics and electrical characteristics of an internal-type large-area ($880 \times 660\,mm^2$) ICP source excited by a multiple linear antennas with U-type parallel connection were investigated as an application to flat panel display processing.

By using the multiple linear antennas with U-type parallel connection, a high density plasma of about $2 \times 10^{11}\,cm^{-3}$ could be obtained at 5 kW of RF power and with 15 mTorr Ar possibly indicating inductive coupling to the plasma using the U-type antenna. The change of the coupling from the capacitive coupling to inductive coupling with increasing the RF power could be observed at the RF power of about 300 W by the change of RF current increase to the antenna and the change of power transfer efficiency. At 5 kW and 20 mTorr, the power transfer efficiency was as high as 88%. Also, using the multiple linear antennas with U-type parallel connection, the plasma potential less than 26 V and the electron temperature in the range from 2.6 to 3.2 eV could be obtained. When the plasma uniformity was measured along the centerline of the substrate, a good uniformity of about 4% could be obtained. Therefore, it is believed that the multiple linear antennas with U-type parallel connection can be successfully applicable to a high density large area plasma source required for the large area flat panel display processing.

Acknowledgments

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