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Plasma and Electrical Characteristics of a Novel Internal Linear Inductively Coupled Plasma Source for Flat Panel Display Applications

Kyong Nam Kim* and Geun Young Yeom
Department of Materials Science & Engineering, Sungkyunkwan University, Suwon 440-746

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In this study, using two different linear internal-type inductively coupled plasma sources with a serpentine-type antenna and a novel double-comb-type antenna having the size of 1,020 mm × 830 mm, are compared the characteristics of plasmas for the application to the flat panel display manufacturing. The use of the double-comb-type antenna instead of the serpentine-type antenna showed a higher plasma density, a higher radical density, and more plasma stability when an inductive power higher than 2000 W was applied to the source. By the application of a 5000 W inductive power with 15 mTorr Ar, a high plasma density of 2.2 × 10^{11}/cm^3 with a plasma uniformity of 8 % could be obtained for the double-comb-type antenna. The increases in the plasma density, the radical density, and the plasma stability for the double comb-type antenna compared to the serpentine-type antenna are due to its higher inductive coupling and lower standing wave effect.

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I. INTRODUCTION

For the etching of TFT-LCD (Thin Film Transistor - Liquid Crystal Device), and especially for next-generation TFT-LCD device processing, dry etching methods are replacing wet etching methods due to better control of the critical dimension, better repeatability, less environmental impact, easier automation, *etc.* Also, for the dry etching plasma sources of the improve the throughput of TFT-LCD device processing is to be improved high-density plasma etching sources due to their higher processing speed are preferred compared to conventional capacitively coupled plasma sources.

For the TFT-LCD device processing to be applied to extremely large-area substrates, various high-density plasma sources have been recently studied by using an array of helicon sources [1], an inductively coupled plasma (ICP) source composed of a large loop [2], ICP sources composed of internal antennas [3, 4], *etc.* Among these sources, internal-type ICP sources do not require a huge dielectric window on the wall of the processing chamber, which is prerequisite for transmitting the electromagnetic field to the plasma from the source antennas. Therefore, these internal-type ICP sources can be more easily applied to next-generation TFT-LCD substrate sizes and to easier and cheaper fabrication of the processing chamber.

Currently, various internal-type ICP sources utilizing serpentine-type antennas have been reported for applications to large-area TFT-LCD processing [5–9] and semiconductor processing [10]. However, in the case of TFT-LCD processing, due to the long length of the serpentine-type antenna close to the operating rf wavelength and its high impedance, removing the standing wave effect and the plasma instability become more difficult as the chamber size gets larger and larger.

For the operation of serpentine-type antennas, a traveling wave can be launched to remove the standing wave effect; however, matching the source to the input power is known to be difficult due to the various capacitors used to launch the traveling wave [3]. Therefore, in this research, we used a novel internal-type antenna (double-comb-type antenna) to remove the standing wave and to achieve a low impedance, and we compared the characteristics of the source, such as the plasma density, the uniformity, and the etch characteristics with those of a conventional serpentine-type antenna for application to next-generation large-area TFT-LCD processing.

II. EXPERIMENTS

Figure 1 shows a schematic diagram of the experimental apparatus. As the figure shows, the plasma processing chamber was designed in a rectangular form for flat panel display (FPD) applications, the inner size of the chamber was 1,020 mm × 830 mm, and the substrate size was 880 mm × 660 mm. As Figure 1 shows, in the case of a serpentine antenna, five linear antennas con-

*E-mail: knam1004@skku.edu; Fax: +82-31-299-6562

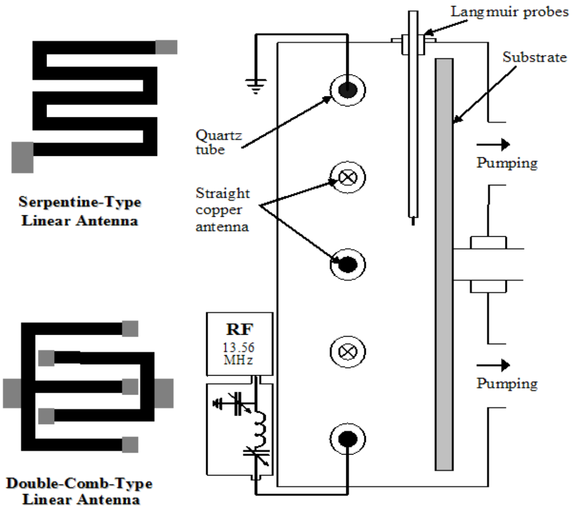

Fig. 1. Schematic diagram of the inductively coupled plasma system and the two types of internal linear antennas used in the experiment.

nected in series were embedded in the vacuum chamber. However, in the case of the novel antenna (double-comb-type antenna), five parallel antennas were connected to the rf power supply alternatively from opposite ends, as shown in the figure. The other end of each antenna was connected to ground, so double-comb-type internal antenna was formed. The linear antenna was made of 10 mm-diameter copper tubing with the outside shielded by quartz tubing. The outside diameter of the quartz tubing was 15 mm and the thickness was 2 mm. RF power at 13.56 MHz (0 $\sim$ 5 kW) was fed to the antenna through a conventional L-type matching network.

Ar plasma characteristics, such as the plasma density and the plasma uniformity of the internal-type ICP sources were measured using a Langmuir probe (Hiden Analytical Inc., ESP) located 7.5 cm below the antenna and along the vertical centerline of the chamber. The RF rms voltages on the antenna conductor and the dc voltages induced on the insulator surface covering the antenna conductor were measured on a oscilloscope by using a high voltage probe (Tektronix, P6015A). The rf currents and the power transfer efficiencies of the two antenna configurations were measured using an impedance analyzer (V-I probe, MKS Inc.). The optical emission intensity from oxygen atoms (775 nm) was measured using an optical emission spectrometer (OES, SC Tech. PSM-403) for inductive powers from 600 to 5000 W and at 15 mTorr of oxygen. Ar actinometry was used to estimate the relative densities of atomic oxygen by adding 5 % of Ar to the plasma and by taking the ratio of the intensity of oxygen atoms at 775 nm to that of Ar at 425 nm.

Photoresist etching characteristics were investigated using a 3-um-thick photoresist (AZ-GXR601) deposited on glass and using O_2 instead of Ar. The etch rate was measured at the center of the substrate. For the photoresist etching, the substrate was located 6 cm below

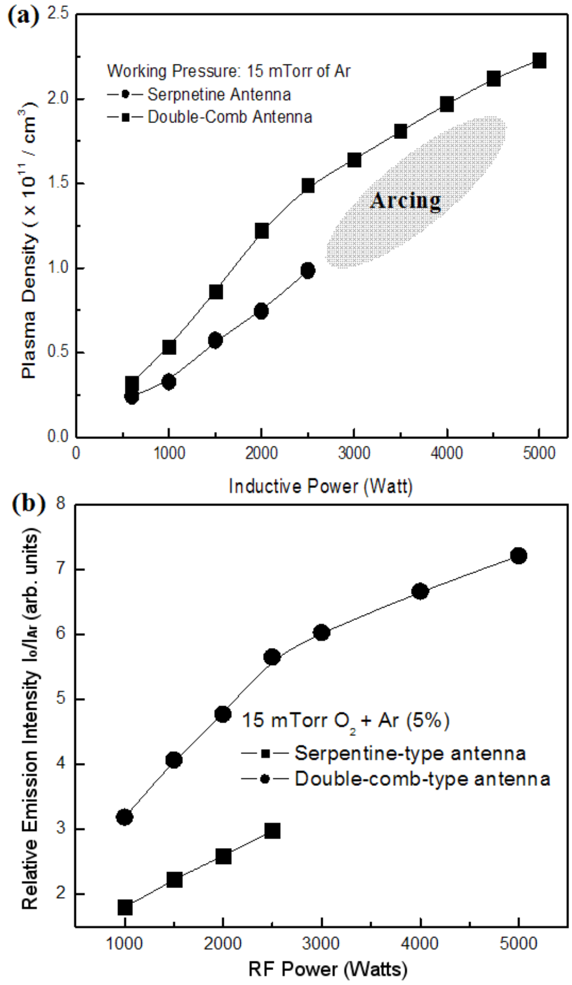

Fig. 2. (a) Ar ion density measured by using a Langmuir probe at 7.5 cm below each antenna as a function of the inductive power from 600 to 5000 W at 15 mTorr of Ar. (b) Relative oxygen atomic density estimated by using Ar actinometry for the serpentine-type antenna and the double comb-type antenna as functions of the inductive power from 1000 to 5000 W at 15 mTorr of O_2.

the antenna, and bias voltage of –35 V was applied to the substrate through a separate rf power supply (12.56 MHz, 0 – 2 kW; where, a 12.56 MHz rf power supply was used to minimize the interference between the source power and the bias power) and a matching network. The substrate temperature was kept at room temperature. The photoresist etch rate was estimated by using with a stylus profilometer (Tencor Alphastep 500) measure the step heights of the photoresist before and after the etching.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the effect of inductive power on the Ar plasma density for the serpentine-type antenna and the double comb-type antenna. The inductive power was varied from 600 to 5000 W at 15 mTorr of Ar. The plasma density was measured using a Langmuir probe located at the center of the chamber and 7.5 cm below the antenna. As the figure shows, when the serpentine antenna was used, the plasma density increased with increasing inductive power, and a plasma density of about 1×10^{11} /cm^3 could be obtained at an inductive power of 2500 W. However, when the applied power was higher than 2500 W (shaded area in the figure), the plasma became unstable by showing arcing was possibly due to the high electrostatic coupling between the antenna and the plasma. When the double-comb-type antenna was used instead of the serpentine-type antenna, a plasma density of about 1×10^{11}/cm^3, which is higher than that obtained by using the serpentine-type antenna, could be achieved. Also, until an inductive power of 5000 W had been applied, the plasma density increased almost linearly with increasing of inductive power, and the plasma remained stable. Inductive powers higher than 5000 W could not be applied due to the power limit of the rf power supply. At the 5000 W, as the figure shows, a plasma density of 2.2×10^{11}/cm^3 was obtained. Therefore, the use of the double-comb-type antenna instead of the serpentine-type antenna increased the plasma density and stability.

Using oxygen instead of Ar, we compared the differences in the radical density between the serpentine-type antenna and the double comb-type antenna. Figure 2(b) shows the relative density of atomic oxygen estimated by using Ar actinometry for 15 mTorr of O_2 measured as a function of the inductive power from 1000 to 5000 W for both the serpentine-type antenna and the double-comb-type antenna. As the figure shows, the measured density of atomic oxygen was 76 % $\sim$ 90 % higher for the double-comb-type antenna; therefore, a higher atomic oxygen density, as well as a higher ion density, can be obtained due to the higher ionization and dissociation of oxygen at the same inductive power by using the double-comb-type antenna. Therefore, the use of the double-comb-type antenna instead of the serpentine-type antenna should increase both the plasma density and the radical density.

Using 15 mTorr of oxygen and applying a dc-bias voltage of –35 V to the substrate, we investigated the photoresist etch rate for both of antenna types as functions of the inductive power from 600 to 5000 W, and the results are shown in Figure 3. As the figure shows, the photoresist etch rates were generally low due to the low dc-bias voltage used in this experiment; however, an increase in the inductive power to the antenna increased the photoresist etch rate almost linearly for both antenna types. The double-comb-type antenna showed photoresist etch rates two times higher than those of the serpentine-type antenna at the same inductive powers due to its higher plasma density and radical density. Also, the photoresist etch rate for the serpentine-type antenna could not be measured due to arcing at inductive powers higher than 2500 W (shown as the shaded area for arcing).

To find the differences between the two types of antennas, we measured the rf rms voltages induced along the antenna line on the sidewall of the chamber for 15 mTorr of Ar and 2000 W of inductive power, and the results are shown in Figure 4(a). The rf voltage was measured using a high-voltage probe (Tektronix P6015A). As the figure shows, the rf rms voltage measured for the serpentine-type antenna varied significantly along the antenna line while the voltage measured for the double-comb-type antenna did not show any significant variation. Also, the rf rms voltages measured for the serpentine-type antenna were generally higher than those measured for the double comb-type antenna. The higher rf voltage and any significant variation of the voltage for the serpentine-type antenna appear to be from its higher impedance and a possible standing wave-effect due to the longer length of the antenna line from the power input to the ground. At the same input power, due to the low impedance, a higher rf current will flow to the double-comb-type antenna and will induce more efficient inductive coupling to the plasma.

When an inductively coupled plasma source was used with a dielectric cover, due to the rf voltage on the antenna line, capacitive coupling, in addition to the inductive coupling, is induced. To measure the degree of capacitive coupling, the dc voltage induced on the dielectric surface was measured at a location close to the power input as a function of the inductive power for power from 250 to 2500 W at 15 mTorr of Ar, and the results are shown in Figure 4(b). As the figure shows, the dc voltage induced on the surface of the dielectric covering the antenna increased with increasing of inductive power up to about 1250 W and remained similar with further increases in the inductive power for both antenna types. However, the induced dc voltage was about four times higher for the serpentine-type antenna, indicating more significant capacitive coupling. The higher dc voltage

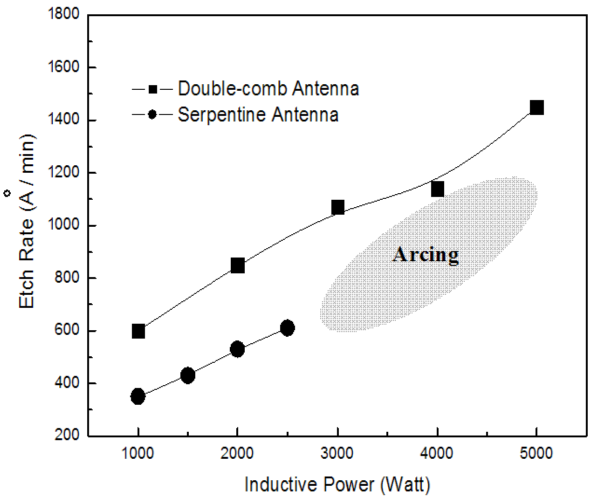

Fig. 3. Photoresist etch rates as a function of inductive power for 15 mTorr of O_2 at a dc bias of –35 V for the two types of antennas.

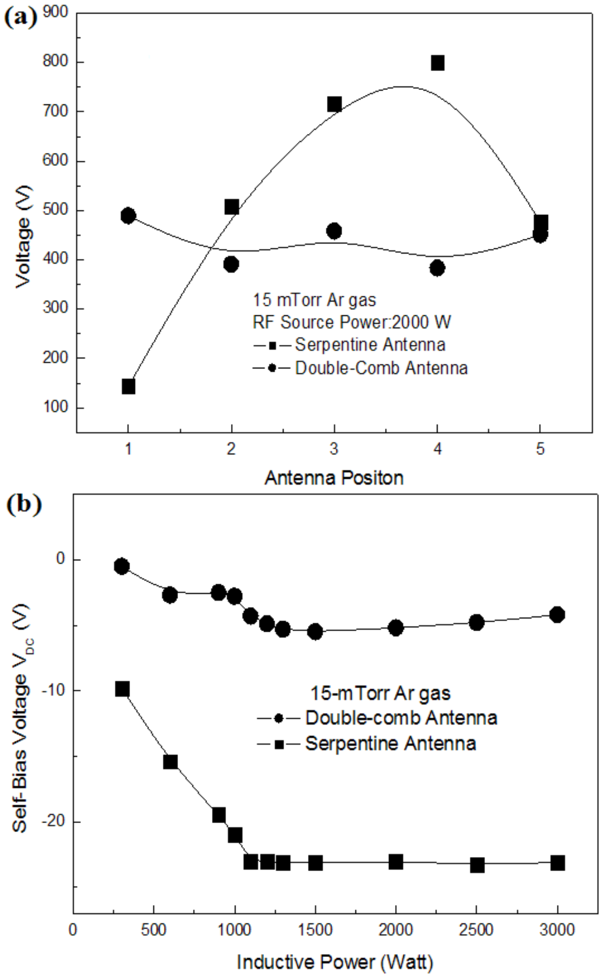

Fig. 4. (a) RMS voltage measured on the antenna line along the sidewall of the chamber for the double-comb-type antenna and the serpentine-type antenna for 15 mTorr of Ar and 2000 W of inductive power. (b) DC voltages induced on the dielectric surface covering the antenna line measured at a location close to the power input as a function of the inductive power at 15 mTorr of Ar for the two types of antennas.

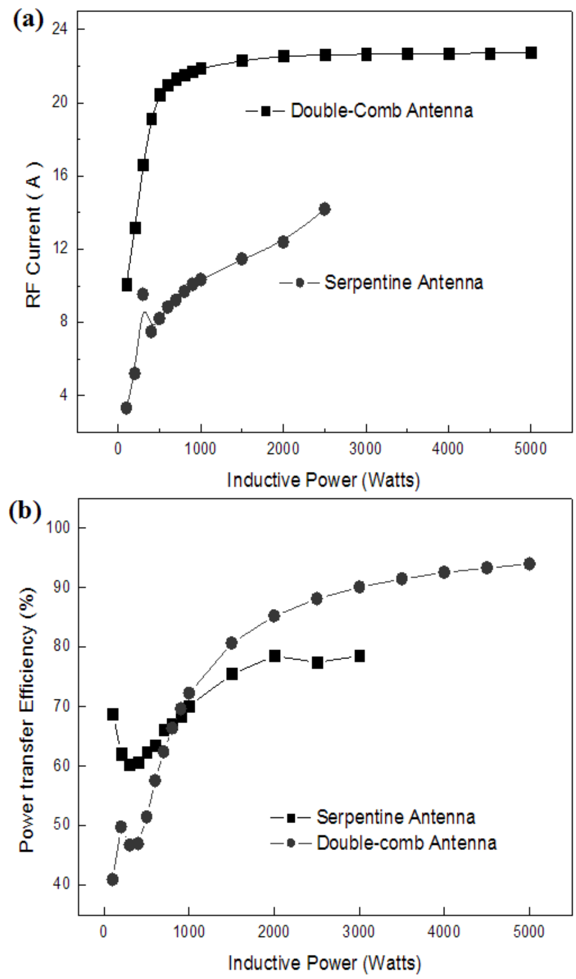

Fig. 5. (a) RF rms current of the antenna at the matching network position for the serpentine-type and the double-comb-type antennas as determined by using an impedance probe as a function of the inductive power from 100 to 5000 W at 15 mTorr of Ar. (b) Power transfer efficiency calculated for the two types of antennas as functions of the inductive power from 100 to 5000 W at 15 mTorr of Ar.

induced on the surface of the dielectric covering the antenna line could result in higher sputtering loss of the dielectric surface and more contamination by the sputtered dielectric material.

Figure 5(a) shows the rms current (I), measured by using an impedance probe, for the double comb-type antenna and the serpentine-type antenna. As the figure shows, the rf rms current increased from 10 A at 100 W to 23 A at 5000 W for the double-comb-type antenna and from 8 A at 100 W to 14 A at 2500 W. Also, when the purely resistive component of the antenna impedance was measured, the resistance (R) of the double-comb-type antenna increased from 0.76 Ω at 100 W to 3.15 Ω at 5000 W while that of the serpentine-type antenna increased from 8.38 Ω at 100 W to 13.44 Ω at 2500 W(not shown). At a given inductive power, the double-comb-type antenna had a greater rf rms current and showed less resistance compared to the serpentine-type antenna. The higher resistance of the serpentine-type antenna compared to that of the double-comb-type antenna suggests an increased power loss during power transfer to the plasma. Figure 5(b) shows the power transfer efficiency (%) calculated for both types of antennas by using the equation; Power transfer efficiency (%) $=\frac{InputPower-I^2R}{InputPower}\times 100$. As the figure shows, the power transfer efficiencies of both types of antennas generally increased with the inductive power; however, at inductive powers higher than 1000 W, the efficiency was higher for the double-comb-type antenna than it was for the serpentine-type antenna. At 2500 W of inductive power, the power transfer efficiency of the serpentine-type antenna was about 77 % while that of the double-comb-type antenna was about 88 %.

One of the most important requirements for the

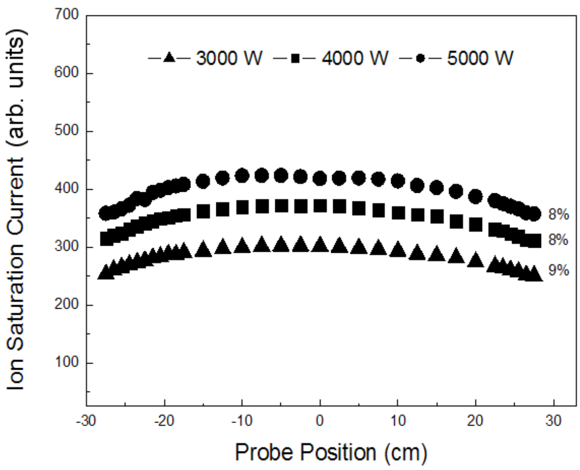

Fig. 6. Plasma uniformity measured 7.5 cm below each antenna as a function of the inductive power from 3000 to 5000 W for 15 mTorr of Ar. The ion saturation current measured using a Langmuir probe was used to estimation of plasma density.

plasma sources for flat panel display is plasma uniformity, and it is known that the plasma uniformity for processing should be equal to or less than 10 %. In this study, the ion current density was measured using a Langmuir probe over the substrate area to estimate the plasma uniformity. Figure 6 shows the ion currents measured 7.5 cm below the double-comb-type antenna by using a Langmuir probe along the vertical line of the chamber for inductive powers from 3000 to 5000 W and at 15 mTorr of Ar. The ion currents were measured as estimates of the plasma density. As the figure shows, the uniformity of the plasma measured along the chamber was about 9 % for a 3000 W inductive power and was about 8 % for inductive powers higher than 4000 W. In addition, when the photoresist was etched using a photoresist-coated glass substrate covering a substrate area of 660 mm × 880 mm with the condition of 15 mTorr oxygen, 5000 W of inductive power, and –35 V of dc-bias voltage, the photoresist etch uniformity of about 7 % could be obtained for the double-comb-type antenna (not shown).

IV. CONCLUSIONS

In this study, the effects of two different types of linear antennas for internal inductively coupled plasma sources, that is, a serpentine-type antenna and a double comb-type antenna, on the plasma characteristics were compared, and the possibility of using these antennas for applications to large-area (660 mm × 880 mm) TFT-LCD processing was investigated. For inductive powers higher than 2500 W, plasma densities higher than 1 $\times\ 10^{11}/cm^3$ could be obtained for both antenna types. However, use of the double-comb-type antenna instead of the serpentine-type antenna produced a higher plasma density, a higher radical density, and more plasma stability. When 15 mTorr of oxygen was used with a dc-bias voltage of –35V, the double-comb-type antenna showed photoresist etch rates two times higher than two times than those of the serpentine-type antenna at the same inductive powers due to its higher plasma density and radical density. By applying 5000 W of inductive power at 15 mTorr of Ar, we could obtain a high plasma density of 2.2×10^{11} / cm^3 with a plasma uniformity of 8 % for the double comb-type antenna. At the same inductive power, the rf voltages along the antenna line and the dc voltages induced on the dielectric covering the antenna were lower for the double comb-type antenna. Therefore, increases in the plasma density, the radical density, and the plasma stability for the double-comb-type antenna, compared to the serpentine-type antenna, appear to be related to a higher inductive coupling and a lower standing-wave effect, compared to the serpentine-type antenna, due to the shorter length of the antenna.

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