Journal of the Korean Physical Society, Vol. 52, No. 2, February 2008, pp. 308∼312

Comparison of the Electrical Characteristics of Serpentine-Type and Double-Comb-Type Antennas for Large-Area Plasma Generation

Jung Kyun Park,* Kyong Nam Kim, Jong Hyeuk Lim and Geun Young Yeom
Department of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 440-746

(Received 22 November 2007)

The characteristics of a large-size internal-type inductively coupled plasma (ICP) source having a "double-comb-type" antenna have been investigated for the processing of a large-area flat-panel display substrate having a size of 2,300 mm × 2,000 mm, and its characteristics were compared with those for an ICP source having a "serpentine-type" antenna. The ICP source with the "double-comb-type" antenna showed a lower impedance, a higher plasma uniformity, and a higher plasma density compared to the ICP source with the "serpentine-type" antenna. The measured plasma density and uniformity of the ICP source with the "double-comb-type" antenna were higher than $8.5 \times 10^{10}/cm^3$ and lower than 14 %, respectively, at a 10 kW rf power and 15 mTorr of Ar. The etch uniformity of the photoresist within the substrate was about 12.5 % at a 8 kW rf power and 15 mTorr Ar/O_2 (7 : 3).

PACS numbers: 52.40.F, 52.75.R, 52.50.D
Keywords: Large-area plasma source, Inductively coupled plasma, Double-comb-type antenna

I. INTRODUCTION

Even though flat panel displays (FPDs) are currently being successfully applied to various display applications such as TVs, PC monitors, cell phones, game machines, *etc.*, for application to next-generation displays, the FPDs fabricated with lower price, lower weight, higher definition, and lower temperature processing are required. If display devices are to be fabricated at a lower price, larger substrate size is essential, and if they are to be fabricated with a higher throughput or at a lower temperature with the substrate having a lower weight such as plastic substrates, a high-density plasma source may have to be applied if a uniform plasma on a large-area substrate can be obtained.

Currently, for applications to FPDs, a low-density plasma source, such as capacitively coupled plasma (CCP), is used due to the easier physics of the plasma and ease in obtaining a uniform plasma over the large area substrate even though high-density plasmas are preferred due to the high production rate, *etc.* However, as the substrate area is increased further and further, maintaining the uniformity is found to be difficult due to the advent of standing wave effects during the operation of the CCP using an rf power [1–3]. For the processing of FPDs with large-area substrates, some high-density plasma sources have been found to be applicable by distributing the source power or antennas over the substrate area, and among those high-density plasma sources, inductively coupled plasma (ICP) sources have been most widely investigated due to their easier scalability to a large area [4,5].

Even though the ICP sources can be more easily extended to large-area plasma sources, they also show problems in extending to extremely large size, especially when a conventional external spiral-type planar ICP source is used, due to their large impedance, large antenna size, cost, and thickness of the dielectric material required to transmit the electromagnetic field to the plasma. In addition, the increase in the physical separation between the antenna and the plasma due to the increase in the thickness of the dielectric material decreases the mutual inductance and tends to have a low power efficiency [6, 7].

Many researchers have studied ICP sources using internal-type antenna for large-area plasma processing to remove the problem related to the dielectric material for the transmission of electromagnetic field. However, even with the internal-type ICP source, with increasing processing area, the length of the increased antenna becomes comparable to the rf wavelength and standing wave effects what cause a non-uniform power distribution, make the unstable electrical properties of the antenna [8, 9]. In this article, internal-type ICP sources with two different antenna lengths, "double-comb-type" and "serpentine-type" antennas [8, 10], were used, and their antenna characteristics and plasma characteristic were compared to investigate their possible use in appli-

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

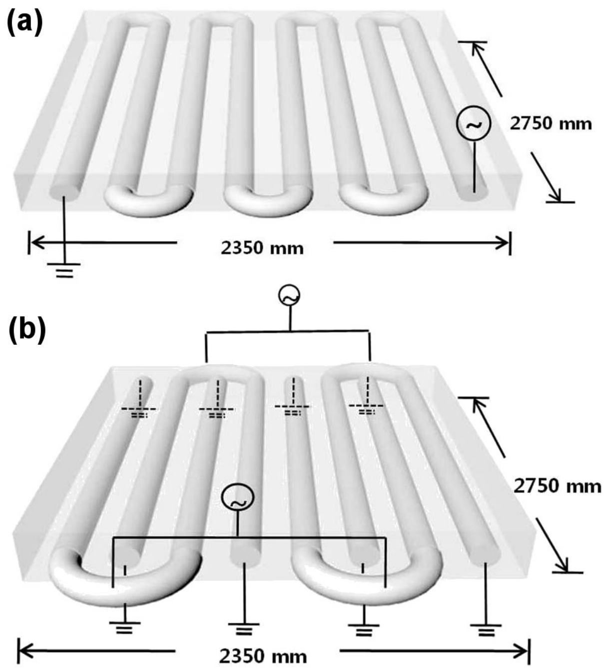

Fig. 1. Schematic diagrams of (a) serpentine-type antenna and (b) double-comb-type antenna used in the experiment.

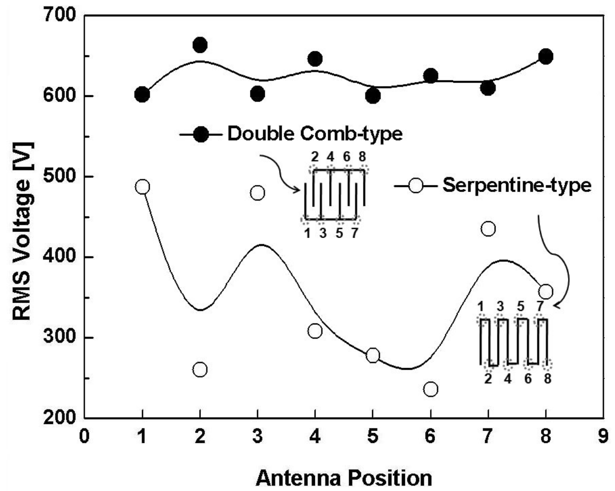

Fig. 2. Rf rms voltage distribution of the serpentine-type antenna and the double-comb-type antenna along the antenna line measured by using a high-voltage probe at 15 mTorr of Ar and rf powers of 4.5 kW for the serpentine-type antenna and of 6 kW for the double-comb-type antenna.

cations to extremely large-area FPD processing having a substrate size of 2,300 mm × 2,000 mm.

II. EXPERIMENTS AND DISCUSSION

Figure 1 shows the schematics of the ICP sources used in this experiment to compare the two different types, double-comb-type antenna and serpentine-type antenna. The size of the processing chamber was 2,750 mm × 2,350 mm, and the size of the substrate was 2,300 mm × 2,000 mm. In the case of the serpentine-type antenna, eight linear antennas inserted inside the vacuum chamber were connected in series at the outside of the chamber as shown in Figure 1(a). However, in the case of the double-comb-type antenna, for the eight internal linear antennas, one end of each of the eight antennas was alternatively connected to a 10 kW, 13.56 Mhz rf generator through a L-type matching network while the other end of each of the eight antennas was connected to ground, as shown in Figure 1(b).

To observe the electrical characteristics of the internal antennas, were installed an rf plasma impedance analyzer (V-I probe, MKS Instrument, Inc.) between the matching network and the internal antenna, and we measured the root-mean-square (rms) current and impedance. The rf rms voltage distributions of the serpentine-type antenna and the double-comb-type antenna along the chamber side line were measured using a high voltage probe (Tektoronix, P6015). The plasma densities of the internal-type ICP sources were measured using a Langmuir probe (ESP, Hiden Analytical, inc). The plasma uniformities of the ICP sources were investigated using a homemade movable electrostatic probe system consisting of 12 tips located above the substrate. The probe system, biased at –65 V, was scanned along the substrate plane to measure the distribution of the two-dimensional ion saturation current above the substrate area to estimate the plasma uniformity of the ICP sources. Finally, using a gas mixture of Ar/O_2 (Ar : O_2 = 7 : 3) at 15 mTorr, we etched a glass substrate covered with a photoresist, and we measured its etch depth by using a step profilometer (Alpha Step 500) to estimate the etch uniformity.

Figure 2 shows the rms voltage measured using a high voltage probe as a function of the antenna position along the antenna line for the serpentine-type antenna (a) and the double-comb-type antenna (b). The measured locations along the antenna line are also shown in the figure. For the operation of the sources, 6 kW of rf power was used for the double-comb-type antenna while 4.5 kW of rf power was used for the serpentine-type antenna due to the instability of the plasma with increasing rf power for the serpentine-type antenna. As the operating pressure, 15 mTorr Ar was used for both cases. As the figure shown, the rms voltage measured along the antenna line for the serpentine-type antenna varied significantly from 240 to 490 Volts along the antenna line while the voltage for the double-comb-type antenna remained similar between 600 and 660 Volts. The significant variation of the rms voltage observed for the serpentine-type antenna is believed to be from the long length (23 meter) of the antenna line corresponding to one wavelength at 13.56 MHz; therefore, due to the standing wave effect, a non-

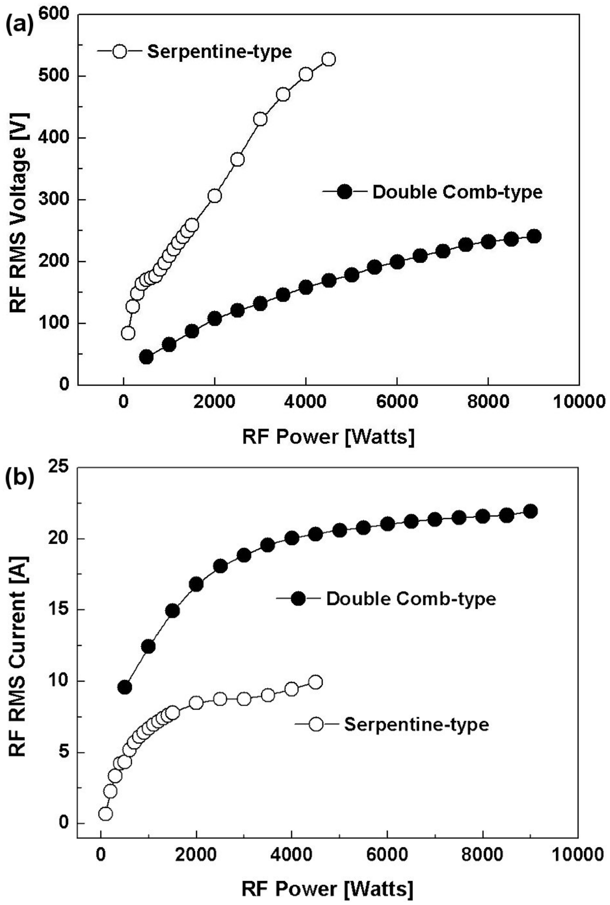

Fig. 3. (a) rf rms voltage and (b) rf rms current on the serpentine-type antenna and double-comb-type antenna measured as a function of the rf power at 15 mTorr Ar.

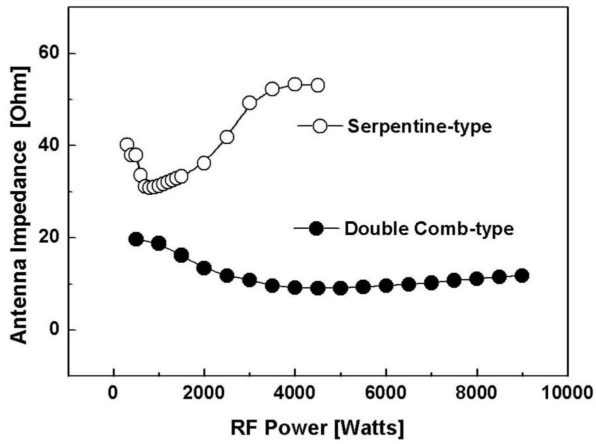

Fig. 4. Impedance measured as a function of rf power at 15 mTorr Ar by using an impedance analyzer for the serpentine-type antenna and double-comb-type antenna.

uniform plasma was generated in the system, and the instability of the plasma caused arcing. However, in the case of double-comb-type antenna, due to the short antenna length of about 3 meter, no significant variation of antenna voltage was observed along the antenna line because of no significant standing wave effect; therefore, a stable and more uniform plasma could be observed [8, 10].

Figure 3 shows the rf rms (a) voltage and (b) current of the double-comb-type antenna and the serpentine-type antenna measured as functions of the rf power at 15 mTorr Ar by using a high-voltage probe and an impedance analyzer, respectively. As Figure 3(a) shown, the increase in the rf power increased the antenna voltage for both antennas. In the case of the serpentine-type antenna, the antenna voltage increased from 90 V to 520 V with increasing of rf power from 100 W to 4.5 kW while the double-comb-type antenna showed about 230 V when the rf power was increased to 9 kW, which is close to the voltage obtained at 1.8 kW for the serpentine-type antenna. Therefore, a significantly lower voltage could be obtained for the double-comb-type antenna. The high rms voltage induced on the antenna increases the electrostatic coupling between the antenna and the plasma, and the increase in the electrostatic coupling increases the erosion of the quartz tubing enclosing the antenna and increases possible contamination during the processing [11]. Therefore, by using the double-comb-type antenna, which shows a lower rf rms voltage, we can achieve a lower quartz erosion and less contamination. In the case of the rf rms current, as Figure 3(b) shown, the increase in the rf power increased the rf current for both cases even though the rf current was saturated at about 2 kW for the serpentine-type antenna and at about 4 kW for the double-comb-type antenna. An increase in the rf power to 3 kW resulted in a rf rms current of about 20 A for the double-comb-type antenna and of about 10 A for the serpentine-type antenna. Therefore, the double-comb-type antenna showed a higher rms current compared to the serpentine-type antenna at a given rf power. The higher current and lower voltage shown for the double-comb-type antenna at a given rf power increase the inductive coupling and decrease the capacitive coupling to the plasma compared to the serpentine-type antenna.

The higher current and the lower voltage obtained for the double-comb-type antenna also show lower impedance. Figure 4 shows the impedance measured as a function of rf power for the double comb-type antenna and the serpentine-type antenna at 15 mTorr Ar by using an impedance analyzer. As the figure shown, the serpentine-type antenna had an antenna impedance in the range from 30 to 50 Ohms while the double comb-type antenna had an impedance in the range from 10 to 20 Ohms. Therefore, the serpentine-type antenna showed a higher impedance compared to the double-comb-type antenna. In general, a high plasma impedance of a plasma system causes an inefficient and unstable plasma operation and tends to decrease the power transfer efficiency. Especially, for an the extremely-large-area plasma source, the plasma system tends to show a high

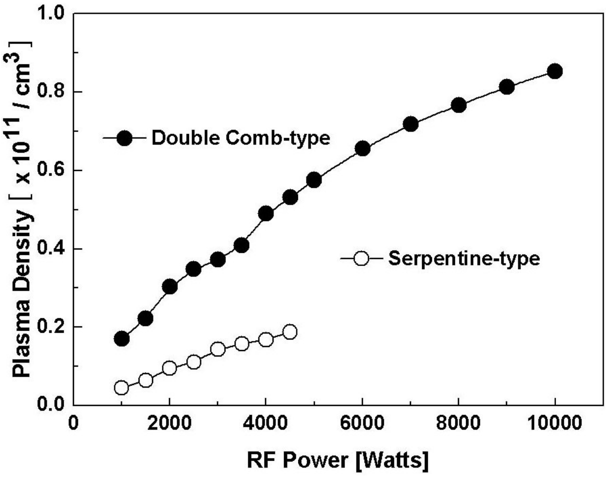

Fig. 5. Plasma density of the serpentine-type antenna and the double-comb-type antenna measured using a Langmuir probe as a function of rf power at 15 mTorr Ar.

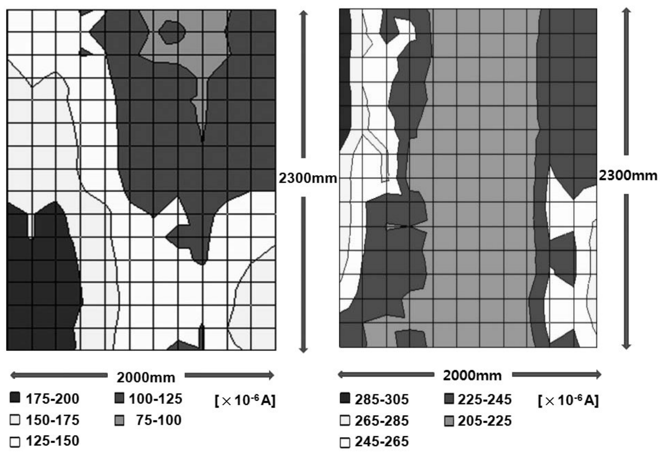

Fig. 6. Uniformity of the ion saturation current of the serpentine-type antenna and the double-comb-type antenna over a substrate area of 2,300 mm × 2,000 mm measured by using a movable electrostatic probe having 12 tips biased at –65 V for 15 mTorr of Ar and the rf power of 4.5 kW.

impedance due to the extremely large antenna size and, in this case, the selection of an antenna with a lower impedance is very important [12–14]. When the power transfer efficiency was calculated after the consideration of the Joule loss on the antenna itself at the condition of a 4.5 kW rf power and 15 mTorr Ar, the serpentine-type antenna showed a power transfer efficiency of about 69 % while the double comb-type antenna showed a power transfer efficiency of 87 % [6,15]. Therefore, the double-comb-type antenna showed higher power transfer efficiency compared to the serpentine-type antenna. (not shown)

Figure 5 shows the plasma density measured using a Langmuir probe as a function of rf power at 15 mTorr Ar for the double-comb-type antenna and the serpentine-type antenna. As the figure shown, the increase in the rf power increased the plasma density almost linearly for both antennas. An increase in the rf power to 4.5 kW increased the plasma density to about $2 \times 10^{10}/\text{cm}^3$ for the serpentine-type antenna and to $5.5 \times 10^{10}/\text{cm}^3$ for the double-comb-type antenna while an increase in the rf power further to 10 kW for the double-comb-type antenna showed a plasma density of about $8.6 \times 10^{10}/\text{cm}^3$. Even though, it is difficult to say that a high-density plasma can be obtained for the serpentine-type antenna, it is believed that, by increasing the rf power further, a high-density plasma can be obtained for the double-comb-type antenna because the power density per unit area of the plasma source is still as low as 1/3 compared to conventional ICP sources. The low rf rms voltage, high rf rms current, and low impedance shown for the double-comb-type antenna also support the possibility of obtaining a high plasma density through the efficient inductive coupling.

In the case of a large-area plasma source, it is extremely important to have a uniform plasma over the substrate surface. Figure 6 shows the ion saturation current over a substrate area of 2000 mm × 2300 mm measured using a homemade movable electrostatic probe biased at –65 V and having 12 tips under the condition of 15 mTorr Ar and 4.5 kW rf power for (a) the serpentine-type antenna and for (b) the double comb-type antenna as estimates of the uniformity of the plasma density over the substrate area. For the serpentine-type antenna, as Figure 6(a) shown, the ion saturation current was measured to be in the range from 0.075 mA to 0.2 mA over the substrate area, so the uniformity of the plasma was estimated to be 35 %. However, for the double-comb-type antenna, as Figure 6(b) shown, the current measured was in the range from 0.205 mA to 0.305 mA, and a uniformity of about 14 % could be obtained; therefore, a more uniform plasma over a large-area substrate area could be obtained for the double-comb-type antenna. The etch uniformity was also estimated by etching a photoresist covering a glass substrate with 15 mTorr Ar/O_2 and at a 4.5 kW rf power for the serpentine-type antenna and at an 8 kW rf power for the double-comb-type antenna. The result showed about a 30 % etch uniformity for the serpentine-type antenna and about 12.5 % etch uniformity for the double-comb-type antenna, similar to the trend of the ion saturation current uniformity measured in Figure 6 (not shown).

III. CONCLUSION

The electrical characteristics of the antenna and the plasma characteristics were investigated for the serpentine-type antenna and the double comb-type antenna for possible applications to an internal linear-type ICP source for the processing of a large-area flat panel display substrate having a size of 2,300 mm × 2,000 mm.

With the double comb-type antenna, a plasma density of about 8.6×10^{10} /cm^3 could be obtained at a 10 kW rf power and 15 mTorr Ar. The double-comb-type antenna showed a lower rf rms voltage, a higher rf rms current, and a lower impedance at a given rf power compared to the serpentine-type antenna; therefore, the double-comb-type antenna showed a higher power transfer efficiency close to efficient inductive coupling to the plasma. In addition, due to the lack of the standing wave effect, the variation of rf rms voltage of the antenna along the antenna line was small, and not only a stable plasma but also a uniform plasma of about 14 % over the substrate area could be obtained for the double-comb-type antenna. The etch uniformity estimated by etching a photoresist with $Ar/O_2(Ar : O_2 = 7 : 3)$ at 15 mTorr and an 8 kW rf power was about 12.5 % for the double-comb-type antenna. Therefore, by using a double comb-type antenna, we believe that a uniform and stable high-density plasma applicable to FPD processing at a substrate size of 2,300 mm × 2,000 mm, can be obtained.

ACKNOWLEDGMENTS

This work was supported by the National Program for Tera-Level Nanodevices of the Korea Ministry of Science and Technology as a 21st Century Frontier Program.

REFERENCES

[1] M. Surendra and D. B. Graves, Appl. Phys. Lett. **59**, 2091 (1991).
[2] Y. Ohtsu and H. Fujita, Appl. Phys. Lett. **85**, 21 (2004)
[3] J. P. Booth, C. S. Corr, G. A. Curely, J. Jolly, J. Guillon and T. Foldes, Appl. Phys. Lett. **88**, 151502 (2006).
[4] K. Takech and M. A. Lieberman, Appl. Phys. Lett. **89**, 869 (2002).
[5] Y. Setsuhara, S. Miyake, Y. Sakawa and T.Shoji, Jpn. J. Appl. Phys. **38**, 4363 (1994).
[6] J. Hopwood, Plasma Sources Sci. Technol. **3**, 460 (1994).
[7] H. Deguchi, H. Yoneda, K. Kato, K. Kubota, T. hayashi, K. Ogata, A. Ebe, K. Takenaka and Y. Setsuhara, Jpn. J. Appl. Phys. **45**, 10B (2006).
[8] Y. Wu and M. A. Lieberman, Appl. Phys. Lett. **72**, 777 (1998).
[9] M. A. Lieberman, J. P. Booth, P. Chabert, J. M. Rax and M. M. Turner, Plasma Sources Sci. Technol. **11**, 283 (2002).
[10] K. N. Kim and G. Y. Yeom, J. Korean Phys. Soc. **48**, 442 (2006).
[11] K. N. Kim and G. Y. Yeom, J. Korean Phys. Soc. **48**, 256 (2006).
[12] S. J. Jung, K. N. Kim and G. Y. Yeom, Thin Solid Films **506**, 460 (2006).
[13] J. Hopwood, Plasma Sources Sci. Technol. **1**, 109 (1992).
[14] K. N. Kim, S. J. Jung and G. Y. Yeom, J. Appl. Phys. **97**, 063302 (2005).
[15] K. N. Kim and G. Y. Yeom, Jpn. J. Appl. Phys. **45**, 11 (2006).