Surface & Coatings Technology 202 (2008) 5242–5245

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Scalable internal linear double comb-type inductively coupled plasma source for large area flat panel display processing

Kyong Nam Kim, Jong Hyeuk Lim, Jung Kyun Park, Geun Young Yeom *

Department of Advanced Materials Engineering, Sungkyunkwan University, Suwon 440-746, South Korea

ARTICLE INFO

Available online 13 June 2008

Keywords:
Large area
Display
Etching
Antenna

ABSTRACT

The characteristics of a large area internal linear inductively coupled plasma source of 2750 mm×2350 mm have been studied using a linear antenna with a double comb-type parallel connection. Using the ICP with the double comb-type linear antenna, a plasma density of $8\times10^{10}/\text{cm}^3$ and a power transfer efficiency of approximately 82% could be obtained at about 10 kW of rf power and with 5 mTorr Ar. Low plasma potentials and low electron temperatures decreasing from 45 to 20 V and from 3.33 to 2.78 eV, respectively, could be obtained as the operation pressure was increased from 5 to 20 mTorr at 10 kW of rf power. The measured plasma uniformity on the substrate size of 7th generation (2300 mm×2000 mm) at 5 kW of rf power and with 15 mTorr Ar was approximately 14% and the photoresist etch uniformity measured using 15 mTorr Ar/O_2 (7:3) at 8 kW of rf power was about 12.5%. Therefore, it is believed that the double comb-type parallel connection can be successfully applicable to the large area flat panel display processing.

1. Introduction

For the processing of flat panel displays (FPDs), a large area plasma processing system is required, and among the various plasma sources, for the high throughput processing and low temperature processing, large area high density plasma sources are being investigated for high rate processing or low temperature processing [1,2]. Especially, inductively coupled plasma (ICP) sources are 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 [3,4].

In the case of semiconductor processing, the ICP sources with external spiral-type antennas are generally studied, but these ICP sources show problems in the application to the processing of the extremely large TFT-LCD substrates due to the cost and thickness of the dielectric material and the large impedance of the antennas when scaling up to a larger area. The scale up of an ICP source to a large, uniform, high density plasma source is not an easy task [5–8]. It requires a carful design of antennas allowing the generation of a large-area and uniform electromagnetic field in the source. 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 [9–11].

In this letter, as the internal linear antenna for a large-area ICP source, double comb-type antenna 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

Fig. 1 shows the schematic diagram of the ICP system used in this study. To study the characteristics of ICPs with internal type antennas used for FPD applications, a rectangular shaped process chamber with an inner size of 2750 mm×2350 mm was fabricated. The substrate size was 2300 mm×2200 mm. Eight linear antennas were embedded in the process chamber, and each antenna was connected to the rf power generator (13.56 MHz, 10 kW) through the L-type matching network at alternative positions starting from opposite ends to form a "double comb-type antenna" as shown in the figure. The other ends of the antennas were grounded. In this double comb-type antenna, the distance from the matching network to the ground was about 4.2 m.

Ar plasma characteristics were measured using a Langmuir probe (Hiden Analytical Inc., ESPION), located 90 mm below the antenna and at the center of the chamber. 0.5–10 kW rf power was used with 5–20 mTorr Ar. The characteristics of the plasma uniformity were examined using a home-made movable Langmuir probe system, which is consisted of 12 tips located 110 mm above the substrate and 110 mm below the antenna. 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 as the estimation of plasma uniformity. The electrical properties of the internal linear antenna were measured using an impedance probe

---

* Corresponding author. Tel.: +82 31 299 6560.
E-mail address: gyyeom@skku.edu (G.Y. Yeom).

0257-8972/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.surfcoat.2008.06.062

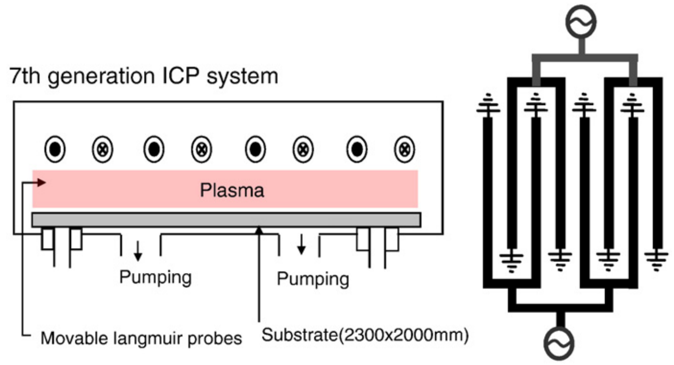


Fig. 1. Schematic diagram of the double comb-type ICP system used in the experiment.

(MKS Inc) that was located between the matching network and antenna. The etching uniformity was estimated by etching a pohotoresist covered glass substrate on the substrate area using Ar/O_2 (7:3) instead of Ar at 8 kW rf power. The photoresist etch rate was estimated by measuring the step heights of the photoresist before and after the etching with a stylus profilometer (Tencor Alphastep 500).

3. Results and discussion

Fig. 2 shows the effect of rf inductive power from 1 to 10 kW on the ion density of the plasma generated by the double comb-type linear antenna at 5 mTorr of Ar. The ion density was measured at the center of the chamber and at 90 mm below the antenna. As shown in the figure, the ion density was increased with the increase of rf power almost linearly from $1.9\times10^9/\text{cm}^3$ at 1 kW to about $8\times10^{10}/\text{cm}^3$ at 10 kW. Therefore, a relatively high density plasma could be obtained using the double comb-type antenna considering the relatively low energy input density at 10 kW (0.15 W/cm^2). The relatively high density plasma obtained in our experiment is believed to be from the effective inductive coupling to the plasma by a high rf current flowing on the antenna. To understand the coupling mode by the antenna, rf root-mean-square (RMS) current flowing on the antenna was measured as a function of rf power.

Fig. 3(a) shows the rf RMS current flowing on the double comb-type linear antenna and its first differentials as a function of rf inductive power from 500 W to 9 kW measured using an impedance probe at 5 mTorr of Ar. As shown in the figure, the increase of rf power increased the rf RMS current flowing to the antenna and, at 9 kW of rf power, the RMS current of about 22 A was observed, therefore, an increased possibility of inductive coupling to the plasma could be expected at the higher rf power. The change of rf current with rf power can be 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 observed from about 4 kW of rf power appears to show the transition of discharge mode from E-mode (capacitive coupling mode) to H-mode (inductive coupling mode) [4,10–11].

Fig. 3(b) shows the power transfer efficiency (%) calculated as a function of rf inductive power from 500 W to 9 kW at 5 mTorr Ar. To calculate the power transfer efficiency, the Joule loss at the antenna and 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:

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

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 are dependent on the power loss by the ohmic resistance of the antenna, rf cable, and

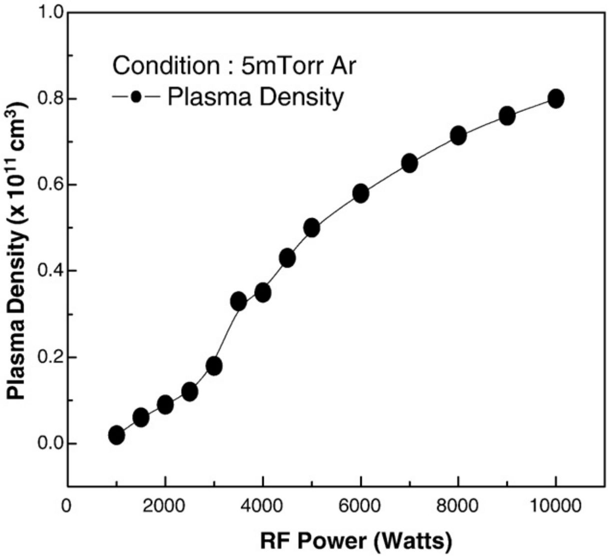


Fig. 2. Ar ion density measured by a Langmuir probe at 90 mm below the antenna for the double comb-type linear antenna as a function of rf power from 1 to 10 kW at 5 mTorr Ar.

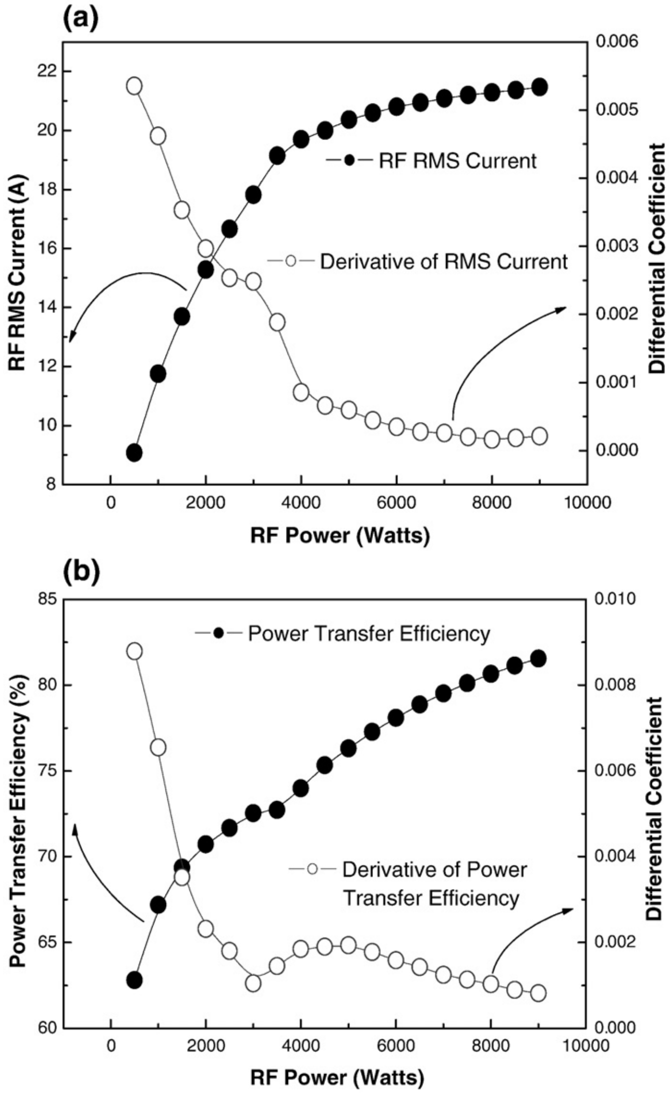


Fig. 3. (a) Rf RMS current and (b) power transfer efficiency measured by an impedance analyzer between matching box and the double comb-type linear antennas and their differentials measured as a function of rf power at 5 mTorr Ar.

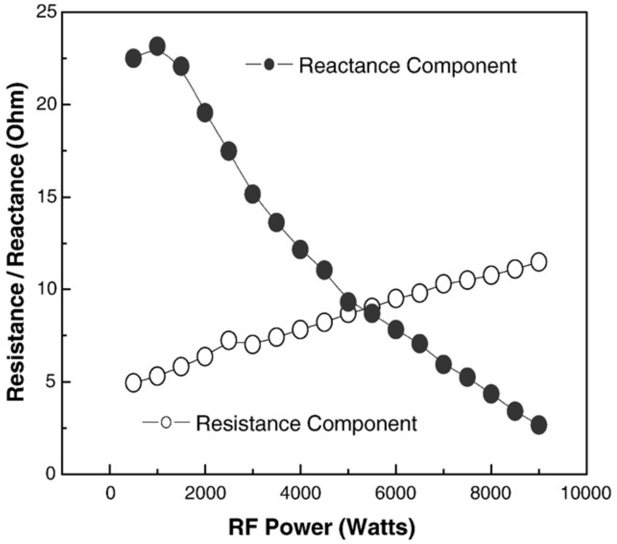


Fig. 4. Plasma resistance (Z_r) and plasma reactance (Z_i) calculated as a function of rf power at 5 mTorr Ar.

matching network. As shown in the figure, the power transfer efficiency at 5 mTorr was increased rapidly from about 62% to 81% by increasing rf power from 500 W to 9 kW. The change of power transfer efficiency with rf power can be also observed more clearly by taking the derivatives of the power transfer efficiency as a function of rf power. The slope change in the derivatives of power transfer efficiency observed from about 3–4 kW also shows the transition of discharge mode from E-mode to H-mode similar to the case of the rf RMS current.

Generally, the discharge mode transition from E-mode 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 is proportional to $1/\sigma$, is directly related to the power transfer to the plasma and the mutual coupling between the antenna and the plasma. (The increase of plasma impedance is believed to be related to the increase of time-varying electric field generated by the induced time-varying magnetic field with the increase of rf power. This time-varying electric field is formed perpendicular to the electrode direction, therefore, the increase of the electric field increases the plasma impedance). Therefore, the change in plasma operation mode can be also observed through the investigation of the impedance variation ($Z = Z_r + i\,Z_i$, Z_r : plasma resistance, Z_i : plasma reactance). Fig. 4 shows Z_r and Z_i measured as a function of rf power at 5 mTorr Ar. As shown in the figure, the increase in the rf 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 transition from a CCP mode to an ICP mode could be also observed from the result in Fig. 4.

Fig. 5 shows the plasma potential and electron temperature. The plasma potential was measured as a function of rf power at 5 mTorr Ar and electron temperature was measured as a function of operation pressure from 5 to 20 mTorr and at 10 kW of rf power. The probe was

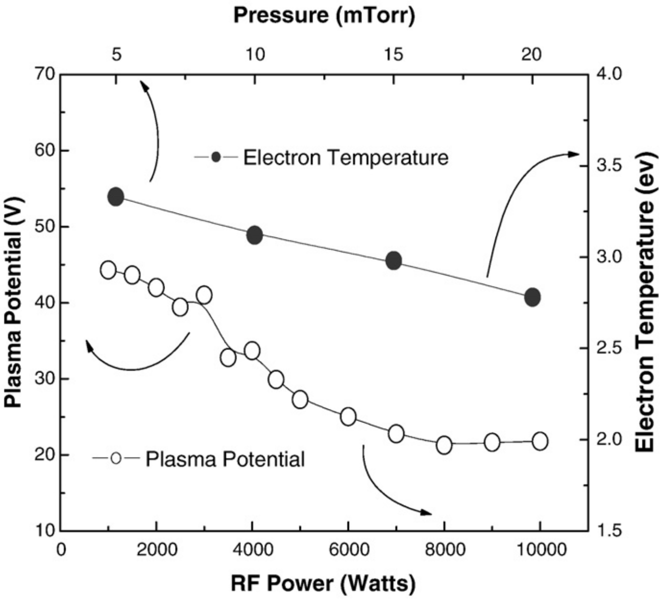
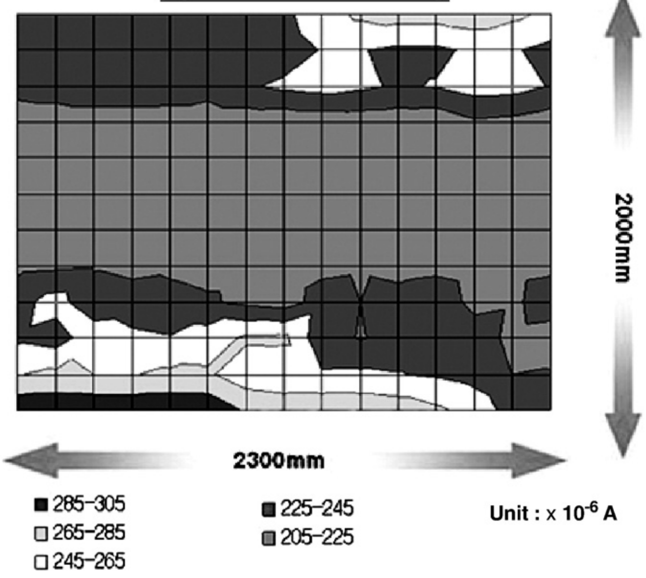


Fig. 5. Plasma potential and electron temperature measured as a function of operation pressure from 5 to 20 mTorr at 10 kW rf power using a Langmuir probe.

(a) Plasma Uniformity



(b) Etch Uniformity

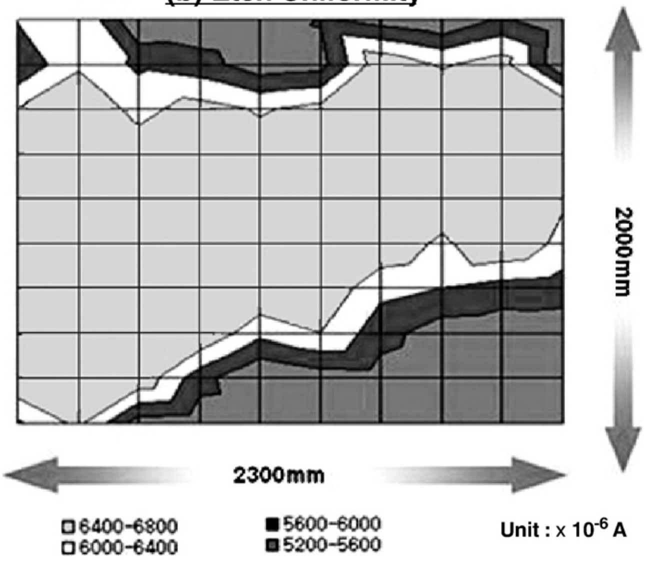


Fig. 6. (a) Plasma uniformity of the ICP with the double comb-type antenna measured using a movable Langmuir probe system biased at −65 V at 5 kW rf power and 15 mTorr Ar. (b) The etch uniformity of photoresist at 15 mTorr Ar/O_2 (7:3) and at 8 kW of rf power.

located at the same position as shown for Fig. 2. In general, the plasmas generated by the 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 FPD processing such as surface damage, contamination, etc. As shown in the figure, the measured plasma potential of Ar plasma generated by the double comb-type linear ICP antenna was decreased from 45 V to 20 V as the rf power increased to 10 kW at 5 mTorr Ar. Electron temperature was as low as 3.3 eV at 10 kW of rf power and at 5 mTorr Ar and were decreased to 2.78 eV as the operation pressure was increased to 20 mTorr.

One of the most important requirements of the plasma sources for the FPD device processing is the uniformity of the plasma on the large area substrate. Using a movable Langmuir probe system, the variation of the ion saturation current was measured above the substrate area of 2300 mm×2000 mm by biasing the probe at −65 V as the estimation of the plasma uniformity. The plasma uniformity was estimated for 5 kW of rf power at 15 mTorr Ar and the result is shown in Fig. 6(a). As shown in the figure, the ion saturation current above the substrate area (2300 mm×2000 mm) was in the range from 2.2×10^{-4} to 2.9×10^{-4} A, therefore, the estimated uniformity of the ion saturation current was about approximately 14%. In addition, photoresist covered glass was etched using $Ar/O_2(Ar:O_2=7:3)$ at 15 mTorr and 8 kW of rf power and its etch depth was measured over the substrate, and the result is shown in Fig. 6(b). As shown in the figure, the measured etch uniformity was approximately 12.5%. Most of non-uniformity of the plasma and etch rate was observed along the antenna line and, these non-uniformities appear to be related to the voltage distribution along the antenna line possibly due to the CCP mode remaining in the plasma system. If the CCP mode is still remaining in the plasma, the voltage distribution along the antenna line can affect the plasma density along the antenna line, therefore, can affect not only the plasma uniformity but also the etch uniformity. The transition of plasma mode from CCP mode to ICP mode is related to the applied rf power, and the plasma uniformity was improved with increasing rf power by transition from CCP mode to ICP mode. But, the maximum rf power used in the experiment appears not high enough to obtain a fully ICP mode. Therefore, it is believed that the double comb-type internal linear ICP source can produce a good uniformity applicable to FPD processing by supplying the sufficient rf power to the source.

4. Conclusions

In this study, plasma characteristics and electrical characteristics of an internal-type large-area ICP source (2750 mm×2350 mm) excited by the double comb-type linear antenna were investigated as an application to FPD processing. By using the double comb-type linear antenna, the plasma density of about $8\times10^{10}/cm^3$ could be obtained at 10 kW of rf power and with 5 mTorr Ar possibly indicating effective inductive coupling to the plasma using the double comb-type antenna. The change of the coupling from the capacitive coupling to inductive coupling with increasing the rf power could be observed by the change of rf current to the antenna, the change of power transfer efficiency, and the change of antenna impedance. The electron temperature and plasma potential were generally low and were in the range from 45 to 20 V and from 3.33 to 2.78 eV, respectively, when the operating pressure is varied from 5 to 20 mTorr at 10 kW of rf power. Over the substrate area (2300 mm×2000 mm), the plasma uniformity was approximately 14% at 5 kW with 15 mTorr Ar while the photoresist etch uniformity was approximately 12.5% at 8 kW rf power with 15 mTorr Ar/O_2(7:3).

Acknowledgement

This work was supported by the Postdoctoral Research Program of Sungkyunkwan University (2007).

References

[1] J. Schmitt, M. Elyaakoubi, L. Sansonnens, Plasma Sources Sci. Technol. 11 (2002) 206.
[2] P. Colpo, T. Meziani, F. Rossi, J. Vac. Sci. Technol., A 23 (2005) 270.
[3] J. Hopwood, Plasma Sources Sci. Technol. 1 (1992) 109.
[4] S.H. Seo, C.W. Chung, H.Y. Chang, Surf. Coat. Technol. 131 (2000) 1.
[5] Y.J. Lee, K.N. Kim, M.A. Lieberman, G.Y. Yeom, Appl. Phys. Lett. 85 (2004) 1677.
[6] K.N. Kim, G.Y. Yeom, J. Korean Phy. Soc. 48 (2006) 422.
[7] K.N. Kim, Y.J. Lee, S.J. Kyong, G.Y. Yeom, Surf. Coat. Technol. 752 (2004) 177.
[8] K.N. Kim, G.Y. Yeom, J. Korean Phy. Soc. 48 (2006) 256.
[9] Y. Wu, M.A. Lieberman, Plasma Sources Sci. Technol. 9 (2000) 210.
[10] M. Kahoh, K. Suzuki, J. Tonotani, K. Aoki, M. Yamage, Jpn. J. Appl. Phys. 40 (2001) 5419.
[11] Y. Setsuhara, T. Shoji, A. Ebe, S. Baba, N. Yamamoto, K. Takahashi, K. Ono, S. Miyake, Surf. Coat. Technol. 174–175 (2003) 33.