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Uniformity of internal linear-type inductively coupled plasma source for flat panel display processing

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The variation in plasma uniformity over an extremely large size inductively coupled plasma (ICP) source of $2750 \times 2350\ \mathrm{mm}^2$ was examined. An internal linear-type antenna called "double comb-type antenna" was used as the ICP source. A plasma density of $\sim 1.4 \times 10^{11}/\mathrm{cm}^3$ could be obtained at 5 mTorr Ar by applying 10 kW rf power to the source at a frequency of 13.56 MHz. An increase in rf power from 1 to 10 kW improved the plasma uniformity over a substrate area of $2300 \times 2000\ \mathrm{mm}^2$ from 18.1% to 11.4%. The improvement in uniformity of the internal ICP source was attributed to the increase in plasma density near the wall. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2840997]

Capacitively coupled plasma (CCP) sources are generally used for processing flat panel display (FPD) panels on account of their scalability to large areas without sacrificing the plasma uniformity significantly. However, CCP sources have low plasma density resulting in a low throughput. In order to increase the throughput of FPD processing, i.e., increase the plasma density, a rf 13.56 MHz needs to be applied to the CCP source. However, an increase in rf frequency causes a standing wave effect that degrades the plasma uniformity.[1] Another method for increasing the throughput is to use a high density plasma source such as inductively coupled plasma (ICP),[2–4] electron cyclotron resonance plasma,[5] helicon plasma,[6] etc. Among these high density plasma sources, ICP is widely used in the fabrication of semiconductor devices on account of its geometric simplicity, low cost, and relatively easy scalability to a large area. However, as the ICP source size is increased for applications to or FPD processing, conventional ICP with external spiral antenna have some problems such as a large voltage on the antenna, increased thickness of dielectric window, etc.[7,8] Increased thickness of the dielectric window, which separates the antenna coil and plasma, attenuates the induced electromagnetic fields and decreases coupling. Various internal-type ICP sources have been examined over the last decade to overcome the thick dielectric window and obtain uniform plasma.[9–12] However, a nonuniform plasma and unstable electrical properties of the antenna can occur when the ICP antennas or substrate dimensions become comparable to the wavelength of the operating rf, as a result of a standing wave effect.[13] Therefore, the antenna configuration is very important in internal-type ICPs in order to obtain uniform and stable plasma. In this study, internal linear-type ICP antennas connected as a double comb type were used as an extremely large ICP source and the variation in plasma uniformity and density as a function of rf power was investigated.

Figure 1 shows a schematic diagram of the ICP system used in this experiment. The processing chamber had a rectangular shape with an internal size of $2750 \times 2350\ \mathrm{mm}^2$ for large-area FPD processing and the substrate size was $2300 \times 2000\ \mathrm{mm}^2$. As shown in Fig. 1, the ICP source consisted of eight internal linear antennas. One side of the antenna was connected to a 10 kW 13.56 MHz rf power generator through a *L*-type matching network while the other side was connected to the ground. The linear antenna was made from 10 mm diameter copper tubing to allow for water cooling and was covered by quartz tubing for dielectric isolation from the plasma.

The characteristics of the Ar plasma were examined by installing a Langmuir probe (Hiden Analytical Inc., ESP) and the rf rms current induced on the antenna was measured using an impedance probe (MKS Inc.). In addition, the plasma uniformity was examined using a homemade movable Langmuir probe system consisting of 12 tips located above the substrate. The probe system was biased to −70 V and scanned along the substrate plane to measure the distribution of the two-dimensional ion saturation current above the substrate area. In addition, a 2-μm-thick photoresist coated glass covering a substrate area of $2300 \times 2000\ \mathrm{mm}^2$ was etched using 15 mTorr $\mathrm{Ar/O_2}$ (7:3) at 8 kW 13.56 MHz. Its etch depth was measured as an indicator of etch uniformity. The photoresist etch depth was measured using a step profilometer (Tencor Inc., Alpha-step 500).

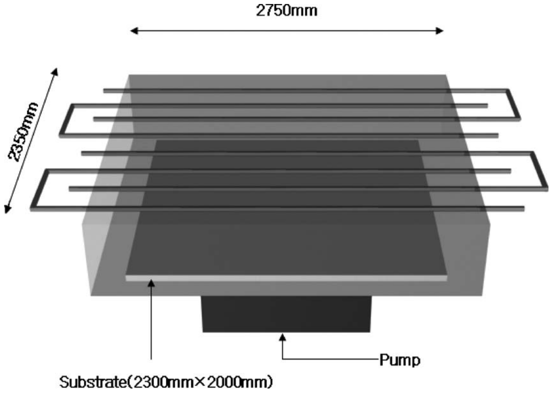

FIG. 1. Schematic diagram of the internal linear-type inductively coupled plasma source with a substrate size of $2300 \times 2000\ \mathrm{mm}^2$.

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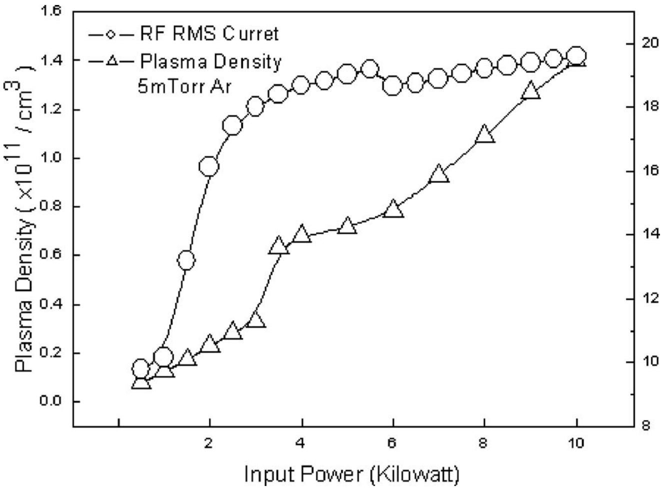

FIG. 2. Ar plasma density measured using a Langmuir probe at the center of the chamber and rf rms current measured on the antenna of the double comb-type ICP using an impedance analyzer as a function of the rf power from 500 W to 10 kW at a pressure of 5 mTorr Ar.

Figure 2 shows the plasma density measured using a Langmuir probe at the center of the chamber and the rf rms current induced on the antenna was measured using an impedance probe at 5 mTorr Ar as a function of the rf power. As shown in the figure, the plasma density increased to $\sim 1.4 \times 10^{11}/\text{cm}^3$ with increasing rf power from 500 W to 10 kW. An abrupt increase in plasma density was observed between 3 and 4 kW, which appears to indicate a transition from a capacitive mode to an inductive mode.[14,15] In addition, in the case of the rf rms current, it initially increased rapidly with increasing rf power. When the rf power approached 3 kW, the rate of increase decreased and was almost saturated at rf power <4 kW. The variation in rf rms current with increasing rf power also appears to indicate a change in the plasma mode from capacitive mode to inductive mode, similar to the change in plasma density.

Figure 3(a) shows the ion saturation current measured using the movable Langmuir probe system for 15 mTorr Ar as a function of the rf power. The probe system was located at the center of the chamber in a direction normal to the antenna line and the probe tip was biased at −70 V. From a probe system with 12 probe tips located along the centerline of the chamber and separated by an equal distance, the distribution of the ion currents along the center of the chamber was obtained instantly and the data were normalized to that of the third probe. As shown in the figure, the variation in ion current decreased with increasing rf power from 2 to 8 kW. Therefore, more uniform plasma could be observed at higher rf power with a more uniform ion current distribution. Figure 3(b) shows the plasma uniformity for 15 mTorr Ar as a function of rf power measured over a substrate area of 2300×2000 mm^2 by scanning the movable Langmuir probe system above the substrate. As shown in the figure, similar to the ion current distribution shown in Fig. 3(a), the measured uniformity of the ion current over the substrate area improved from 18.1% to 11.4% as the rf power was increased from 1 to 10 kW. The improvement in plasma uniformity was related to the increase in plasma density near the chamber wall region.

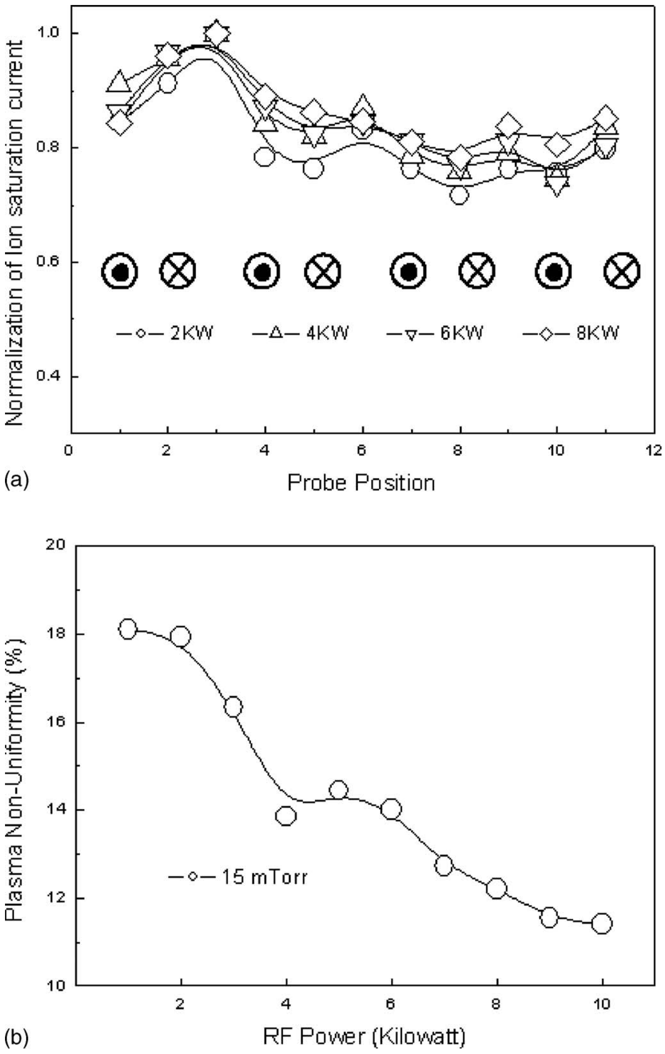

FIG. 3. (a) Ion saturation currents measured by a movable Langmuir probe system along the centerline of the chamber in a direction perpendicular to the antenna as a function of rf power at 15 mTorr Ar. (b) Plasma uniformity over a substrate area of 2300×2000 mm^2 by scanning the movable Langmuir probe system above the substrate as a function of rf power at 15 mTorr Ar.

The variation in plasma uniformity as a function of rf power can be explained from the diffusion or electron density distribution to the wall. For a plane-parallel geometry, the ion density $N(x)$ to the wall can be represented by the following:[16]

$$N(x) = \frac{G_0 l^2}{8D}\left[1 - \left(\frac{2x}{l}\right)^2\right], \qquad (1)$$

where x is the distance from the center of the chamber to the wall, l is the chamber diameter, D is the diffusion coefficient, and G_0 is a constant. D is related to the electron temperature by the Nernst–Einstein relation given by the following:

$$D/\mu = kT_e, \qquad (2)$$

where μ is the electron mobility and kT_e is electron temperature in eV. The electron temperature measured by the Langmuir probe increased from 3.5 to 4.7 eV when the rf power was increased from 3 to 9 kW. Therefore, the diffusion constant D increased with increasing rf power and the variation in plasma density decreased toward the chamber wall, which improved the plasma uniformity. The etch uniformity over a substrate area of 2300×2000 mm^2 was estimated by etching a photoresist covered glass substrate using a 15 mTorr Ar/O_2 (7:3) mixture for 10 min at 8 kW of rf power. As

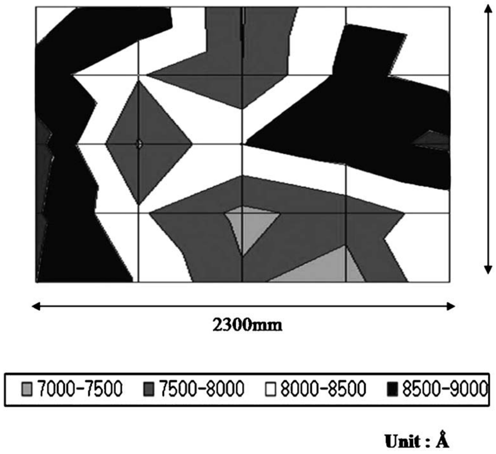

FIG. 4. Etch uniformity of the photoresist film over a substrate area of 2300×2000 mm^2 measured at 8 kW rf power in an Ar/O$_2$ (7:3) mixture.

shown in Fig. 4, the etch uniformity of approximately 10.8% could be obtained, which is similar to the plasma uniformity. In addition, when the etch uniformity was measured as a function of rf power along the centerline of the substrate, the etch uniformity was improved from 19.5% to 9.4% with increasing rf power from 1 to 8 KW (not shown). Although it is not easily seen in the figure, the edge side of the substrate showed a lower etch depth when the photoresist was etched at various rf powers (not shown), which degraded the etch uniformity in a manner similar to the uniformity data shown in Fig. 3(b).

In conclusion, this study examined the plasma uniformity of high density plasmas using an extremely large area ICP source (2750×2350 mm^2) with an internal linear-type "double comb-type antenna." The increase in rf power to the ICP source increased the plasma density to $\sim 1.4\times 10^{11}/\text{cm}^3$ at 10 kW. The increase in rf power not only increased the plasma density but also improved the plasma uniformity over the substrate area from 18.1 at 1 kW to 11.4% at 10 kW. The improvement in plasma uniformity with increasing rf power was related to the increase in plasma density near the wall.

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[1] N. Spiliopous, D. Mataras, and D. E. Rapakoulias, J. Vac. Sci. Technol. A **14**, 2757 (1996).
[2] M. Watanabe, D. M. Shaw, and G. J. Collins, J. Appl. Phys. **85**, 3428 (1999).
[3] J. Hopwood, Plasma Sources Sci. Technol. **1**, 109 (1992).
[4] J. H. Keller, Plasma Phys. Controlled Fusion **39**, A347 (1997).
[5] S. Matsuo and Y. Adachi, Jpn. J. Appl. Phys., Part 1 **21**, 4 (1982).
[6] J. E. Stevens, M. J. Sowa, and J. L. Cecchi, J. Vac. Sci. Technol. A **13**, 5 (1995).
[7] T. Meziani, P. Colpo, and F. Rossi, Plasma Sources Sci. Technol. **10**, 276 (2001).
[8] S. Park, C. Kim, and B. Oh, Thin Solid Films **355**, 252 (1999).
[9] K. Eng, K. Strohmaier, R. Palmer, B. Stoner, and S. Washburn, Rev. Sci. Instrum. **68**, 2381 (1997).
[10] D. H. Kang, D. K. Lee, K. B. Kim, and J. J. Lee, Appl. Phys. Lett. **84**, 3283 (2004).
[11] H. Sugai, K. Nakamura, and K. Suzuki, Jpn. J. Appl. Phys., Part 1 **33**, 2189 (1994).
[12] K. N. Kim, M. S. Kim, and G. Y. Yeom, Appl. Phys. Lett. **88**, 161503 (2006).
[13] K. N. Kim, S. J. Jung, and G. Y. Yeom, Jpn. J. Appl. Phys., Part 1 **44**, 8133 (2005).
[14] U. Kortshagen, N. Gibson, and J. E. Lawler, J. Phys. D **29**, 1224 (1996).
[15] G. Cunge, B. Crowley, D. Vender, and M. M. Turner, Plasma Sources Sci. Technol. **8**, 576 (1999).
[16] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (Wiley, New York, 1994).