Plasma Chem Plasma Process
DOI 10.1007/s11090-009-9176-0

ORIGINAL PAPER

Study of Internal Linear Inductively Coupled Plasma Source for Ultra Large-Scale Flat Panel Display Processing

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Received: 11 February 2009 / Accepted: 27 April 2009

Abstract An internal-type linear inductive antenna, which is referred to as “double comb-type antenna”, was used as a large-area inductively coupled plasma (ICP) source with a substrate area of 2,300 mm × 2,000 mm. The characteristics of the ICP source were investigated for potential applications to flat panel display (FPD) processing. The source showed higher power transfer efficiency at higher RF power and higher operating pressures. The power transfer efficiency was approximately 88.1% at 9 kW of RF power and a pressure of 20 mTorr Ar. This source showed increasing plasma density and improved plasma uniformity with increasing RF power at a given operating pressure. A plasma density >1.5 × $10^{11}/\text{cm}^3$ and a plasma uniformity of approximately 11% was obtained at 9 kW of RF power and 15 mTor Ar using this internal ICP source, which is applicable to FPD processing.

Keywords Large area · Inductive antenna · Flat panel display · Impedance · Uniformity

Introduction

High density plasma sources generated at low pressures have been studied intensively for various device processes, such as flat panel display (FPD) processing, semiconductor processing, etc. In particular, among the various high-density plasma sources, inductively coupled plasma (ICP) has been applied to various plasma processing due to the easier scalability to a larger area [1, 2]. Although, ICP sources are easily extendable to large areas, they show problems when applied to extremely large areas. High voltages are

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required to drive the radio frequency (RF) current through the long length of the ICP antenna, and when conventional external-type ICP is used, a thick dielectric material separating the antenna and plasma needs to be used to transmit the electromagnetic field from the antenna. The high voltage on the antenna line causes high electrostatic coupling between the antenna and plasma. This increases the erosion rate of the dielectric material, which can contaminate the substrate during plasma processing, such as etching and deposition. In addition, the thick dielectric material between the antenna and the plasma increases the physical distance between the antenna and plasma. This decreases the inductive coupling between the antenna and plasma, which can result in a low power transfer efficiency [3].

In order to solve these problems, various internal-type ICPs have been investigated including a serpentine antenna, low inductance antenna, divided antenna, etc. [4–7]. However, with the increase in processing area to sizes greater than one meter, the length of the antenna line becomes comparable to the wavelength of the RF power, which leads to a standing wave effect in addition to a large RF voltage. The standing wave effect can cause a non-uniform power distribution along the antenna line and unstable plasma. In order to remove the standing wave effect, the configuration of the ICP antenna line is very important, and needs to be optimized in order to obtain the highly efficient power transfer to the plasma in addition to uniform power distribution along the antenna line [8].

This study examined an internal-type ICP source consisting of eight internal-type linear antennas and an extremely large-area (2,750 mm × 2,350 mm). The electrical characteristics of the antenna line and the characteristics of the plasma were studied to determine the possibility of the internal-type linear ICP source as an application to the extremely large-area plasma processing.

Experimental Apparatus

Figure 1a, b show a schematic diagram of the internal-type linear ICP source investigated in this study. The processing chamber had a rectangular shape for applications to large-area FPD processing. The size of the processing chamber was 2,750 mm × 2,350 mm and the substrate size was 2,300 mm × 2,000 mm. The antenna configuration of the internal-type linear ICP source was a "double-comb type", and as shown in Fig. 1b, eight linear antennas were used with each antenna being connected to 10 kW RF power of 13.56 MHz through a L-type matching network alternatively while the other end of the antenna was connected to the ground. The linear antenna was made from 10 mm diameter copper tubing to allow water cooling and was fully covered by quartz tubing (2 mm thick and 33 mm outer diameter) for dielectric isolation from the plasma. Between the copper tubing and the quartz tubing, there was air gap.

Ar was used as the discharge gas, and the RF power and pressure were varied from 1 to 10 kW and from 5 to 20 mTorr, respectively. The plasma characteristics were measured using a commercial Langmuir probe (Hiden Analytical Inc., ESP) which has a compensation circuit in front of the probe tip to remove possible rf noise from the rf plasma. The commercial Langmuir probe was located 90 mm below the antenna and at the center of the chamber. The electrical properties of the internal linear antenna were measured using an impedance analyzer (MKS Inc.) located between the matching box and the antenna. The uniformity of the plasma was investigated by measuring the ion saturation current of a home-made movable multi-Langmuir probe system consisting of 12 tips located 330 mm below the source, as shown in Fig. 1a, and the probe system was biased at −70 V and was

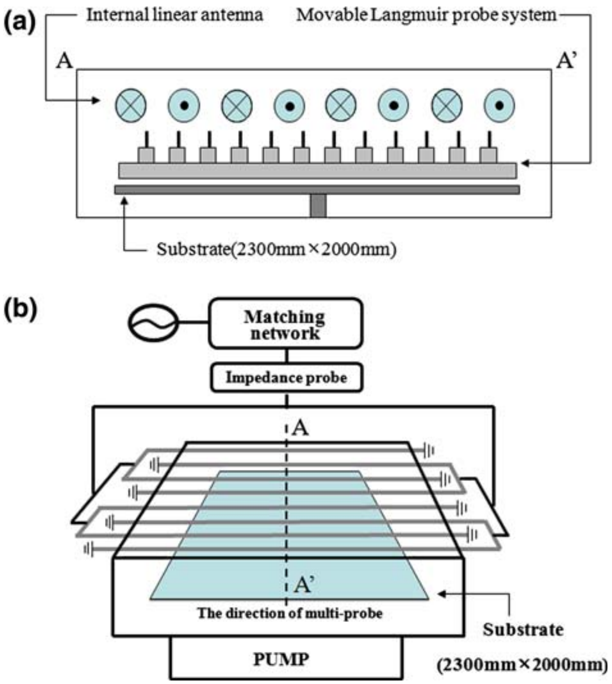

Fig. 1 **a** Schematic diagram of the internal-type linear ICP system used in this experiment. **b** Arrangement of the double comb-type antenna

scanned as a function of the chamber position across the antenna centerline as shown in Fig. 1b.

Results and Discussion

Characteristics of Double Comb-Type Antenna ICP

Figure 2a shows the plasma density of the double comb-type ICP measured as a function of the RF power using a Langmuir probe at 15 mTorr Ar. The plasma density was measured at the center of the chamber and 90 mm from the source. As shown in the figure, the increase in RF power from 1 to 10 kW (0.155 W/cm^2) increased the plasma density almost linearly from 0.23×10^{11}/cm^3 to 1.58×10^{11}/cm^3. Therefore, high density plasma, $>1 \times 10^{11}$/cm^3, could be obtained by applying RF power >5 kW (0.077 W/cm^2). The rapid increase in plasma density with increasing RF power observed in the double comb-type ICP source appears to be related to the increased power transfer efficiency as a result of the efficient inductive coupling to the plasma. In addition, although the plasma density was not measured at RF power >10 kW, it is believed that the plasma density would increase consistently at RF power >10 kW without saturation due to the almost linear increase in plasma density with RF power <10 kW.

Figure 2b shows the plasma potential and electron temperature of the double comb-type ICP measured as a function of the RF power using a Langmuir probe at 15mTorr Ar. As shown in the figure, the plasma potential decreased from 11.6 to 6 V with increasing RF

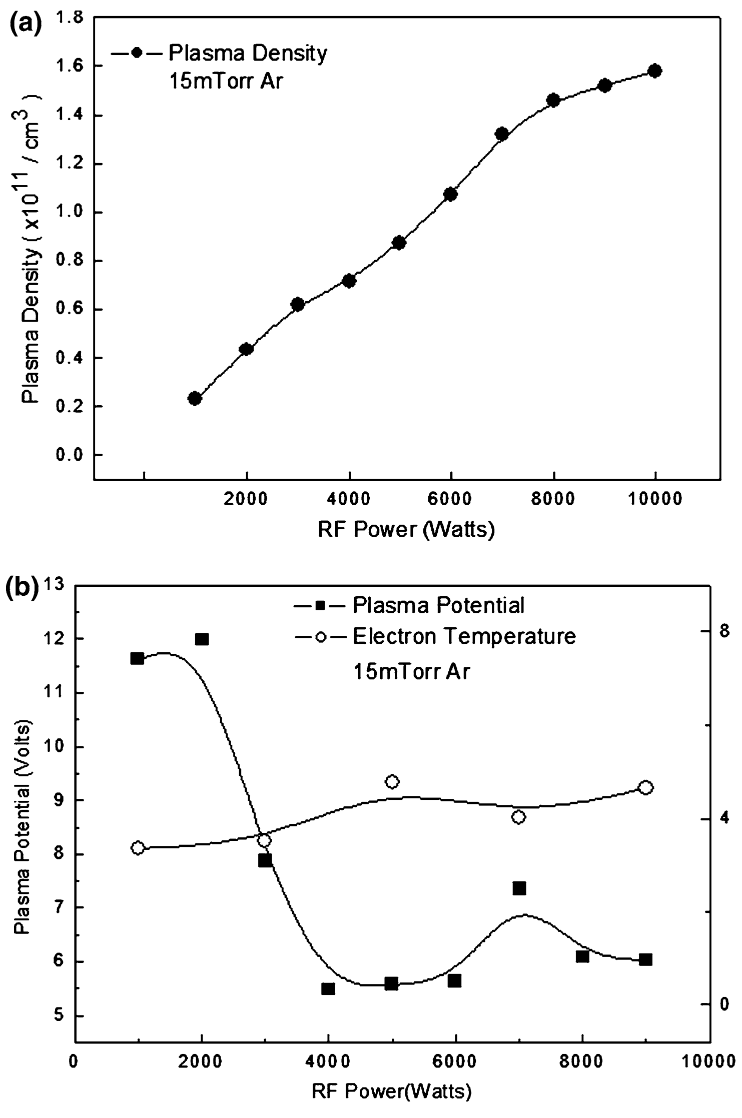

Fig. 2 **a** Ar ion density measured by a Langmuir probe at the center of the chamber for the double comb-type linear ICP source as a function of the RF power from 1 to 10 kW at 15 mTorr Ar. **b** Plasma potential and electron temperature measured by a Langmuir probe as a function of RF power from 1 to 10 kW at 15 mTorr Ar

power while the electron temperature increased from 3.3 to almost 4.7 eV. In general, a high plasma potential increases the possibility of sputtering the chamber material in contact with ground potential, and in the case of dielectric materials such as quartz tubing surrounding the copper antenna, the high potential differences between the plasma potential and the floating potential can increase the possibility of sputtering of the dielectric material. In addition, the plasma with a high plasma potential is known to show more unstable plasma compared with the plasma with a low plasma potential [9]. Therefore, it is believed that more stable and reliable processing can be expected using the double comb-type ICP generated at high RF power.

Electrical Properties of the ICP Antenna

The rf rms voltages were measured at 20 mmTorr Ar on the copper antenna using an impedance probe installed between the ICP source and the matching network and these were about 800 V for 1 kW and 1,830 V for 9 kW (not shown). However, the estimated rf rms sheath voltage was about 1.15% of the rf antenna rms voltage by showing the most of voltage at the air gap between the copper tubing (10 mm diameter) and the quartz tubing (33 mm outer diameter) of the antenna. Therefore, the rf rms sheath voltage shown between the plasma and quartz tubing which is related to the capacitive coupling to the plasma was less than 20 V. Figure 3 shows the load resistance of the double comb-type antenna line measured as a function of the RF power using the impedance probe for an operating pressure of Ar from 5 to 20 mTorr. As shown in the figure, the load resistance increased almost linearly with increasing RF power at a constant operating pressure. In addition, the load resistance increased with increasing operating pressure at a given RF power. This increase in load resistance with increasing RF power and operating pressure indicates increased power consumption by the plasma compared with the power consumption by the other electrical parts, such as matching network and the antenna line itself. Therefore, higher power transfer efficiency from the ICP antenna to the plasma is believed to be obtained with increasing RF power and operating pressure. [10].

Figure 4a shows the Joule loss of the ICP antenna calculated from the measured data using an impedance probe as a function of the RF power for the operating pressure from 5 to 20 mTorr. The operating conditions were the same as the conditions shown in Fig. 3. The Joule loss ($P_{\mathrm{Joule\ Loss}}$) was calculated using the following equation:

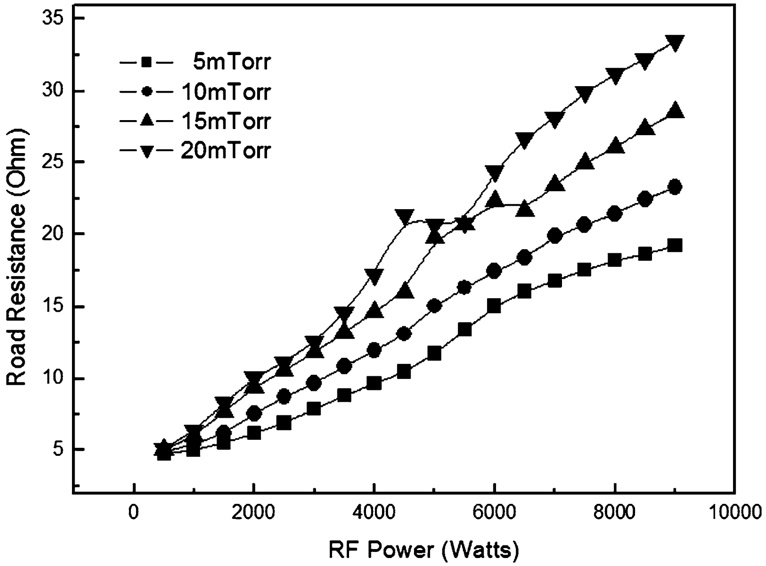

Fig. 3 Load resistance measured by an impedance probe as a function of the RF power and operating pressure

$$P_{\text{JouleLoss}} = I_{\text{rf}}^2 R$$

where I_{rf} is the RF current measured on the antenna line using an impedance probe and R is the resistance of the antenna line. As shown in the figure, the increase in RF power at a given operating pressure increased the Joule loss, and a decrease in operating pressure at a given RF power increased the Joule loss. The total rf rms current induced on the antenna between the ICP source and the matching network increased from 10.5A to 15.2A when rf power was increased from 1 kW to 9 kW at 20 mTorr Ar and, at 9 kW of rf power, the rf rms current decreased from 19A to 15.2A when the operating pressure was increased from 5 to 20 mTorr. The increased Joule loss with increasing RF power is related to the increase in RF antenna current with increasing RF power to the ICP antenna. The decrease in Joule loss with increasing operating pressure it is related to the decreased RF current to the antenna line with decreasing electric field on the antenna line at a given RF power due to the increased plasma resistivity at the higher operating pressure [3]. The change in Joule loss indirectly suggests a variation in power absorbed by the plasma, which is related to the power transfer efficiency.

Figure 4b shows the power transfer efficiency calculated by the Joule loss in Fig. 4a as a function of the RF power at various operating pressures. The power transfer efficiency ($\gamma_{\text{Power Transfer Efficiency}}$) was calculated using the following equation:

$$\gamma_{\text{Power Transfer Efficiency}} = \frac{P_{\text{Input}} - P_{\text{JouleLoss}}}{P_{\text{Input}}} \times 100$$

where the input power (P_{input}) was the RF power to the ICP source measured after the matching network by considering the power loss to the matching network. As shown in the figure, the power transfer efficiency increased with increasing RF power at a given operating pressure and increased with operating pressure at a given RF power. The increase in power transfer efficiency with increasing operating pressure at a given RF power is related to the increased RF power consumption to the plasma by decreasing the Joule loss to the antenna line at a fixed RF power. Although the increase in RF power increased the Joule loss, the increased power transfer efficiency with increasing RF power at a given operating pressure is related to the higher power consumption by the plasma compared with the power lost on the antenna line with increasing RF power. Therefore, as shown in the figure, the highest power transfer efficiency of approximately 88.1% was obtained at 20 mTorr Ar and 9 kW of RF power.

Plasma Uniformity

Using a home-made Langmuir probe system consisting of 12 tips and by biasing the probe tips at −70 V, the ion saturation current of the ICP source was measured at the center of the source and across the antenna line as a function of the RF power at 15 mTorr Ar. Figure 5 shows the ion saturation currents measured along the probe position as a function of RF power. As shown in the figure, the change in ion saturation current across the antenna line decreased with increasing RF power. Therefore, the plasma uniformity estimated by the ion saturation currents improved with increasing RF power from 18% at 1 kW to 11% at 9 kW.

The improvement in plasma uniformity with increasing RF power shown in Fig. 5 is not clear but it may be partially related to the improvement in plasma density near the chamber

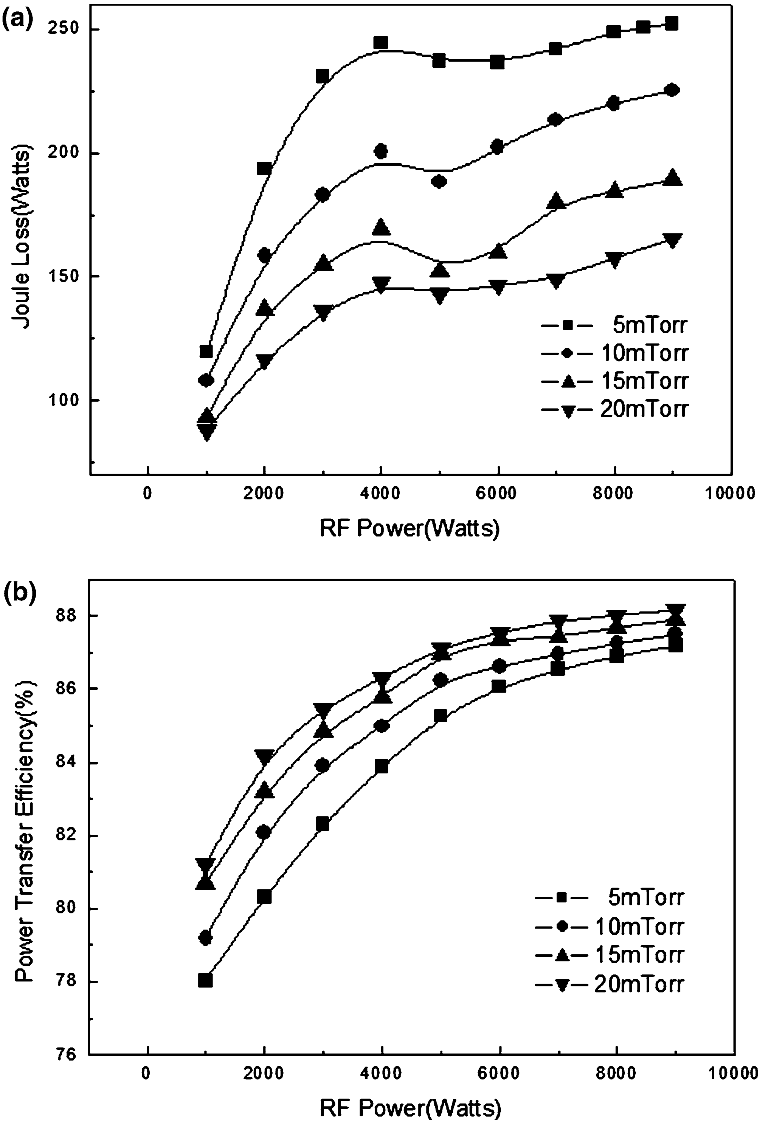

Fig. 4 **a** Joule loss on the double comb-type ICP antenna measured as a function of the RF power and Ar pressure using an impedance probe. **b** Power transfer efficiency calculated by the Joule loss on the double comb-type ICP antenna

wall by increasing the diffusion of charged particles towards the chamber wall at high RF power, in other words, by decreasing the differences in plasma density between the center and edge of the chamber. In fact, the slight increase in electron temperature with increasing RF power shown in Fig. 2b may increases the rate of diffusion of charged particles, as can be expected by the Einstein relation ($D/\mu = \mathrm{kTe}/e$, where D is the diffusion coefficient, μ is the mobility of a charged particle, kTe is the electron temperature in eV, and e is the electron charge). Therefore, it is believed that highly uniform plasma could be obtained over the entire substrate area at RF power >10 kW using the double comb-type ICP in

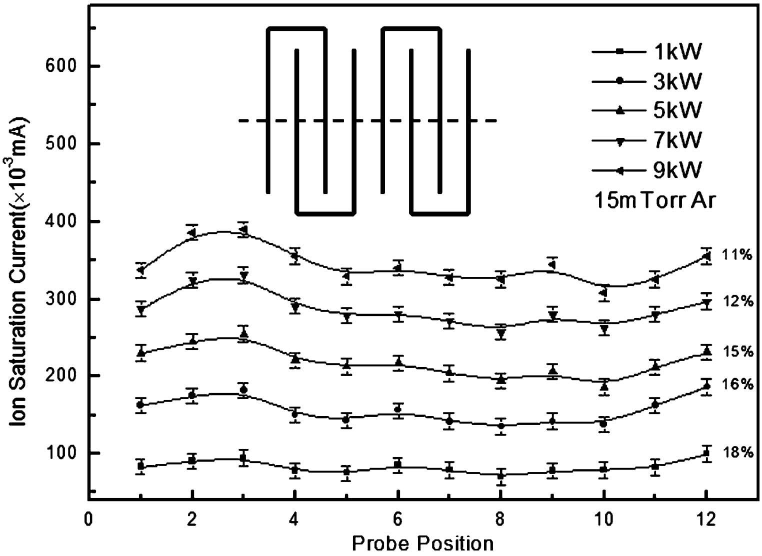

Fig. 5 Plasma uniformity of the double comb-type ICP antenna measured using a movable Langmuir probe system biased at −70 V as a function of the RF power at 15mTorr Ar

addition to the high plasma density by decreasing the differences in plasma density further between the center and edge of the chamber.

Conclusions

The characteristics of an extremely large internal-type linear ICP source (2,750 mm × 2,350 mm) with a double comb-type antenna were investigated as an application to the large area FPD processing. The application of 10 kW RF power (0.155 W/cm^2) to the source showed a plasma density of 1.58 × 10^{11}/cm^3 at 15 mTorr Ar, which demonstrates that high density plasmas can be obtained. This source showed an increase in load resistance with increasing RF power and operating pressure. Therefore, more efficient power transfer to the plasma could be obtained at higher RF power and operating pressure. The power transfer efficiency was approximately 88.1% at 20 mTorr and 9 kW. This source also showed an improvement in plasma uniformity with increasing RF power with approximately 11% at 9 kW and 15 mTorr Ar due to the more uniform plasma density between the center and edge of the chamber due to the increasing diffusion of charged particles.

Acknowledgments This work was supported by the National Program for Tera-Level Nano devices of the Korea Ministry of Education, Science and Technology (MEST) as a twenty-first Century Frontier Program and Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Strategic Technology.

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