Linear internal inductively coupled plasma (ICP) source with magnetic fields for large area processing

Y.J. Lee, K.N. Kim, B.K. Song, G.Y. Yeom*

Department of Materials Engineering, Sungkyunkwan University, Jangan-Gu Chunchun-Dong 300, Suwon 440-746, South Korea

Abstract

A large-area (830×1020 mm) inductively coupled plasma source with internal straight antennas was developed for large area flat panel display (FPD) etch process applications and the effects of magnetic fields employing permanent magnets on the plasma characteristics were investigated. Using straight antennas connected in series without the magnetic field, high-density plasmas on the order of 10^{11} cm^{-3} could be obtained by applying 1500 W of r.f. power to the antennas. By employing the magnetic fields perpendicular to the antenna currents using permanent magnets, improved plasma characteristics such as increase of ion density and decrease of both electron temperature and plasma potential could be achieved in addition to the stability of the plasma possibly due to the reduction of the electron loss. However, the application of the magnetic field decreased the plasma uniformity slightly even though the uniformity within 10% could be maintained in the 800 mm processing area.
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1. Introduction

In order to achieve the performance required for high resolution flat panel display (FPD) devices, especially for TFT-LCD of next generation, improved dry etch processes currently indispensable technology for semiconductor industry are required for volume manufacturing and precise control of critical dimension [1–3]. The plasma sources developed to date for the production of high-density and large-area plasmas are mainly focused on external planar inductively coupled plasma (ICP) sources [4–6]. However, due to their large impedance accompanied by the large antenna size, in addition to the cost and thickness of the dielectric material required to transmit electromagnetic field to the plasmas, the conventional ICP systems using external spiral antennas show problems in extending the process area.

To solve these problems, studies on internal ICPs including both loop and straight antenna configurations, where the antenna is inserted into the plasma, have been reported [7–9]. However, the internal-type plasma sources show other practical problems such as antenna sputtering [10,11] and unstable arcing resulting from high plasma potential. And the application of the internal straight or loop antenna configurations, were mainly focused on the 300 mm diameter silicon wafer processing and only a few studies have been reported on the application of internal straight antenna plasma sources to the FPD for the substrate size less than 360 ×450 mm [7].

Therefore, in this study, to investigate a possibility of extension of these internal-type straight antenna plasma sources to larger area, FPD process applications, an 830 ×1020 mm square plasma process chamber with an internal-type linear inductively coupled plasma source was constructed and, to improve plasma characteristics such as plasma density, plasma uniformity, and plasma potential, magnetic fields employing permanent magnets have been used and the characteristics of the plasmas have been investigated and compared with those obtained without the magnets.

2. Experiment

Fig. 1 shows the schematic diagram of the internal-type linear inductively plasma source used in the experiment. The processing chamber was rectangular shape and was made of stainless steel with the size of 830×1020×400 mm for the application of large-area

*Corresponding author. Tel.: +82-31-270-7395; fax: +82-31-277-6505.

E-mail address: minjae@mail.skku.ac.kr (G.Y. Yeom).

FPD panel processing. Straight antennas were embedded in the vacuum chamber and each linear antenna was connected in series as a serpentine type at the outside of the vacuum chamber. The distances between the neighboring antennas were varied from 8 cm (the corresponding total length of the antenna was 13.48 m) to 16 cm (the corresponding total length of the antenna was 7 m). The antenna was made of 10 mm diameter copper tubing and the outside of the copper tubing was covered with quartz tubing. The outer diameter of the quartz tubing was 15 mm and the thickness of the quartz was 2 mm. One end of the connected antenna was grounded and the other end was connected to 3 kW 13.56 MHz r.f. power to generate inductive discharges.

Magnetic field was applied perpendicular to the current carrying antennas by inserting the magnets in the separate quartz tubing located parallel to the linear antenna using permanent magnets having 3000 G on the magnet surface. Plasma characteristics such as plasma density and plasma uniformity of the internal straight antenna inductively coupled plasmas were measured using a Langmuir probe (Hiden Analytical Inc., ESP) located on the sidewall of the chamber. The Langmuir probe was installed 17 and 5 cm below the straight antenna. Ar gas was used to study the plasma characteristics.

3. Results and discussion

Fig. 2 shows Ar ion densities measured as a function of 13.56 MHz r.f. power to the linear internal antenna and operational pressure. The antenna shape was serpentine types with seven copper tubes were connected as shown in Fig. 1. The length of the each copper tube was 1.14 m, therefore, the total length of the antenna
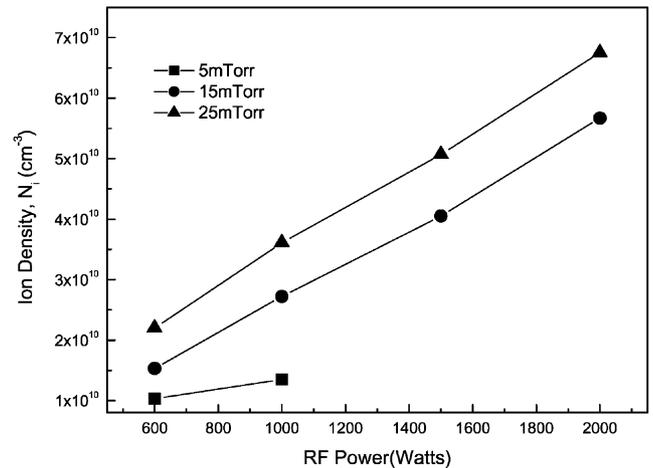

Fig. 2. The effect of r.f. power to the antenna and operational pressure on the ion density measured by a Langmuir probe using Ar from 5 to 25 mTorr and r.f. power from 600 to 2000 W. Seven internal linear antennas were connected in series as a serpentine type. The total length of the antenna was 9.57 m and the distance between the adjacent linear antennas was 12 cm. The ion density was measured at 17 cm below the antenna.

was approximately 9.57 m. One end of the antenna was connected to the r.f. power and the other end was grounded. The applied r.f. power was in the range from 600 to 2000 W and the operational pressure was from 5 to 25 mTorr. The gas used in the experiment was Ar. Ion densities were measured using a Langmuir probe located 17 cm below the antenna. As shown in the figure, the increase of r.f. power to the antenna increased the ion density almost linearly and the higher operational pressure showed the higher ion density. At 2000 W and 25 mTorr, the obtained ion density was $7 \times 10^{10}/cm^3$,
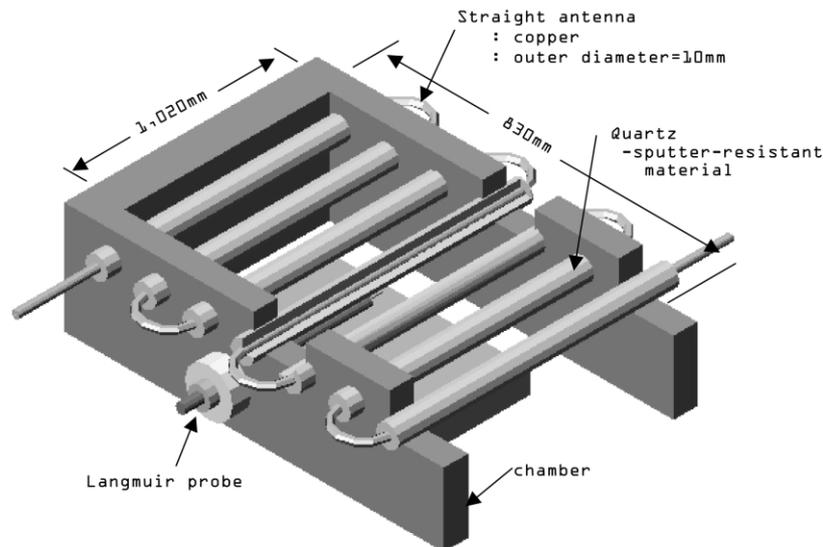

Fig. 1. The schematic diagram of the linear internal type inductive plasma source used in the experiment.
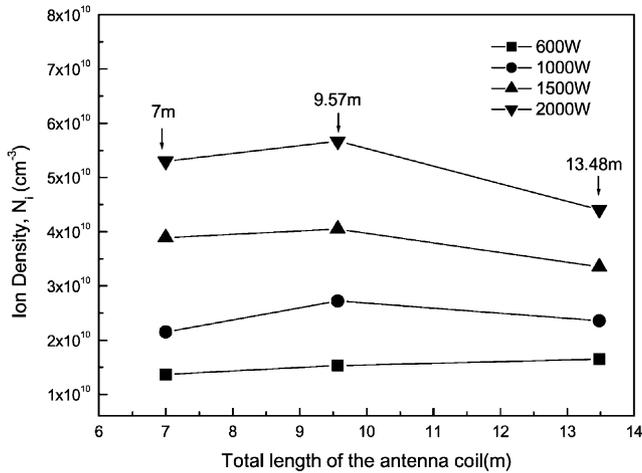
Fig. 3. The effect of the distance between the adjacent linear antenna on the ion density measured by a Langmuir probe using r.f. power from 600 to 1500 W at 15 mTorr of Ar. The ion density was measured at 17 cm below the antenna.

therefore, the operational condition appears to be in the range of high-density regime. In some experiments, the ion densities were measured 5 cm below the antenna, and the ion densities measured 5 cm below the antenna were above 2 times higher than those measured 17 cm below the antenna (not shown). Therefore, it is believed that ion density higher than $1 \times 10^{11}/cm^3$ can be obtained by applying r.f. power higher than 1500 W with 25 mTorr at 5 cm below the antenna. Even though the plasmas generated at the pressure higher than 15 mTorr showed uniform and stable plasmas, those generated below 5 mTorr showed unstable plasmas, therefore, the operation at higher r.f. powers more than 1000 W were impossible. In the unstable range of operational pressure, arcing between the plasma and chamber wall was observed possibly due to the increased electron loss to the wall and the increase of plasma potentials to compensate the loss of electrons at low pressures. Even though the antenna showed unstable plasmas at the low pressure region, the formation of uniform and stable high density plasmas at the pressure above 15 mTorr with the linear internal source, showed the possibility to apply to the flat panel display device processing larger than 830×1020 mm in size.

One of the important issues of the serpentine source used in the experiment is the interference between adjacent line antennas, therefore, the distance between the line antennas could change the ion density and uniformity of the plasmas in addition to the power transfer efficiency of the source. Therefore, the effect of the change in the distance between the line antennas was studied. Fig. 3 shows the effect of the distance between the line antennas on the ion density as a function of antenna length and r.f. power to the antenna at 15 mTorr of Ar. The distance between the line

antennas was varied from 8 to 16 cm and the corresponding total antenna length was from 13.48 to 7 m, respectively. As shown in the figure, the increase of r.f. power to the source increased the ion density regardless of the distance between the line antennas. At a given r.f. power, the decrease of distance between the line antennas from 16 to 12 cm also increased the ion density, however, further decrease of the distance from 12 to 8 cm decreased the ion density. The highest ion density obtained was approximately $5.5 \times 10^{10}/cm^3$ at the distance of 12 cm (i.e. 9.57 m) and 2000 W of r.f. power. The increase of ion density by decreasing the antenna distance from 16 to 12 cm appears to be related to the increased inductive field fed to the plasma by increasing length of the antenna. However, the decrease of ion density by further decreasing the antenna distance from 12 to 8 cm is possibly due to the increase in the destructive interference of electromagnetic fields between the line antennas. In addition, the plasmas are found to be uniform over 800 mm processing area except for the case with the antenna distance of 8 cm. In the 800 mm processing area, the plasma uniformity was maintained within 10% for the distances of 12 cm (i.e. 9.57 m) and 16 cm (i.e. 7 m) between the antennas, but in case of the distance of 8 cm (i.e. 13.48 m) 19% at the conditions of 1000 W of r.f. power and 15 mTorr of operation pressure (not shown). Therefore, it is believed that there is an optimum length of the antenna minimizing the destructive interference between the antennas and increasing the ion density.

In general, the application of magnetic field (**B**) perpendicular to the current flowing to the line antenna can effectively confine the electrons accelerated by the electric field (**E**) induced by the line antenna using the force given by **E** × **B**, and therefore decreases the electron loss to the wall [12,13]. Therefore, in this experiment, permanent magnets were installed alternatively between the line antennas as shown in Fig. 4 and the effect of the application of the magnetic field on the ion density was investigated.

Fig. 5 shows the ion density measured as a function of r.f. power and operational pressure with the magnets installed. The operational conditions were the same as those in Fig. 2. The ion density was measured at 17 cm
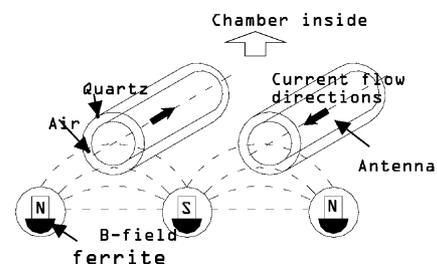

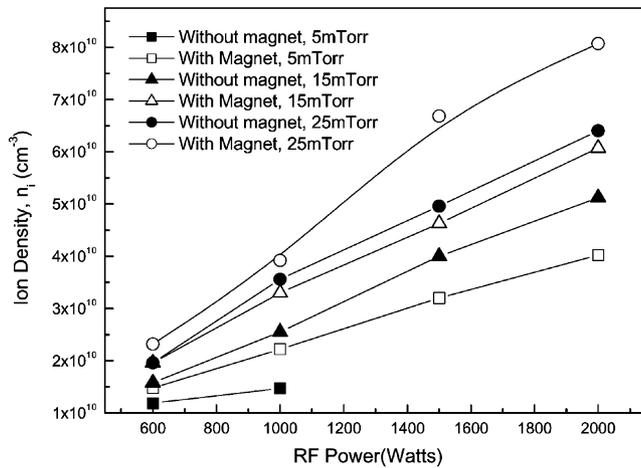Fig. 4. Arrangement of the permanent magnets used in the experiment.

Fig. 5. The effect of r.f. power to the antenna, operation pressure, and the magnetic field on the ion density measured by a Langmuir probe using Ar from 5 to 25 mTorr and r.f. power from 600 to 2000 W. Seven internal linear antennas were connected in series as a serpentine type. The total length of the antenna was 9.57 m and the distance between the adjacent linear antennas was 12 cm. The ion density was measured 17 cm below the antenna.
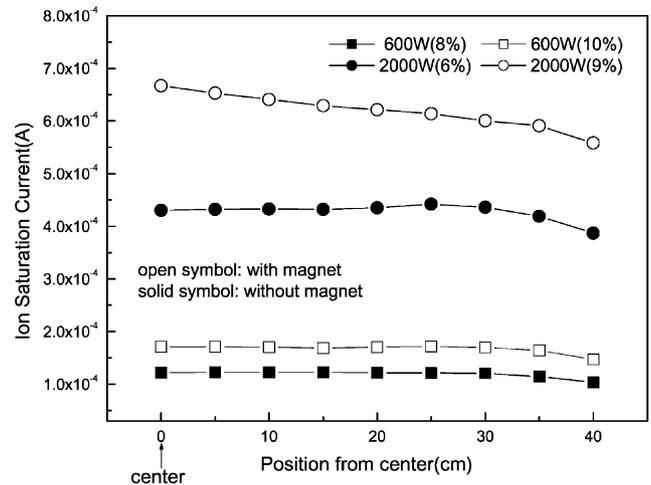

Fig. 6. Ion saturation current measured by the Langmuir probe at 5 cm below the antenna as a function of position of the chamber along the antenna line and with/without magnetic field, 600 and 2000 W of r.f. powers and 15 mTorr of Ar were used.

below the antenna. To compare the ion densities with and without the magnetic field, the ion densities measured without the magnetic field in Fig. 2 were also shown in Fig. 3. As shown in the figure, the application of the magnetic field increased the ion density for all the r.f. power and pressure conditions possibly due to the decrease of electron loss by the magnetic field. In the case of 2000 W and 25 mTrorr, the ion density measured at 17 cm below the antenna increased approximately 25% from 6.5×10^{10} to $8.1 \times 10^{10}/\text{cm}^3$ by the application of the magnetic field. Also, as shown in the figure, the application of the magnetic field made it possible to operate the source without showing any instability of the plasmas at the pressure lower than 15 mTorr even at the r.f. powers higher than 1000 W. Therefore, the application of the magnetic field shown in Fig. 4 improved the ion density and stability of the plasmas.

Fig. 6 shows the ion current density measured using the Langmuir probe as a function of position from the center of the chamber to estimate the uniformity of the plasmas generated by the internal linear inductive source with and without the magnetic field. The uniformity was calculated from the data using the equation as $\{(\text{max-min})/2 \times \text{average}\} \times 100\%$. Ion current densities were measured at 600 and 2000 W of r.f. power and 15 mTorr of Ar with the antenna of 9.57 m. The Langmuir probe was installed 5 cm below the antenna. As shown in the figure, the application of the magnetic field decreased the uniformity from 8 to 10% for 600 W and from 6 to 9% at 2000 W of r.f. power. Therefore, even though the application of the magnetic field increased

the stability and ion density of the plasmas, it decreased the uniformity of the plasmas slightly. However, the uniformity of the plasmas for all of the conditions was equal to or less than 10% and more study is under way to improve the uniformity of the plasmas with the magnetic field by rearranging the antenna and magnets.

4. Conclusions

To investigate the possibility in the application of the internal linear inductive plasma sources for the large-area FPD process applications, a large-area (830×1020 mm) internal linear type inductively coupled plasma source has been developed and the effects of r.f. power to the antenna, operation pressure, and static magnetic field on the plasma characteristics were studied. The magnetic field generated by permanent magnets was applied perpendicular to the induced electric field by the antenna current to confine the electron motion. The increase of r.f. power and operation pressure increased the ion density. Using the developed source, the plasma density higher than $10^{11} \times \text{cm}^{-3}$ at 5 cm below the antenna could be obtained by applying above 1500 W of r.f. power. The application of the magnetic field increased ion density approximately 25% and increased the stability of the plasma, however, the plasma uniformity was slightly decreased even though the uniformity was maintained within 10%.

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