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Effective plasma confinement by applying multipolar magnetic fields in an internal linear inductively coupled plasma system

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A novel internal-type linear inductive antenna referred to as “double comb-type antenna” was used for a large-area plasma source with the substrate area of 880 mm × 660 mm and the effect of plasma confinement by applying multi-polar magnetic field was investigated. High-density plasmas on the order of $3.18\times10^{11}\ \mathrm{cm}^{-3}$, which is 50% higher than that obtained for the source without the magnetic field, could be obtained at the pressure of 15 mTorr Ar and at the inductive power of 5000 W with good plasma stability. The plasma uniformity less than 3% could also be obtained within the substrate area. When SiO_2 film was etched using the double comb-type antenna, the average etch rate of about 2100 Å/min could be obtained with the etch uniformity of 5.4% on the substrate area using 15 mTorr SF_6, 5000 W of rf power, and −34 V of dc bias voltage. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2188037]

Trends in industry of semiconductor devices and flat panel displays (FPDs) toward larger substrate size and higher throughput require the development of large-area plasma sources with higher plasma density.[1–5] In the case of thin film transistor-liquid crystal displays, the current substrate size ranges from 880 mm × 660 mm (fourth generation) to 1850 mm × 2250 mm (seventh generation), and the substrate size is expected to increase further within a few years.[6]

Inductively coupled plasmas (ICPs) have many advantages over various other plasma sources for large-area plasma processing. Since they do not depend upon large voltages to excite the plasma, ion energies in the inductive discharges are considerably lower than those found in capacitively coupled plasma.[7] For the plasma processing of these substrates, high density plasmas are preferred due to the high production throughput and, among the various high density plasma sources, ICP sources have been the most widely investigated due to their easier scalability to large areas. However, when the ICP sources are applied to the processing of flat panel display having an extremely large substrate size, the ICP sources show many problems especially for the external spiral antenna-type ICP sources due to the cost and thickness of the dielectric material and the large impedance of the antennas that arises when scaling up to larger areas. The large impedance of the antenna causes a high rf voltage on the antenna over the large area, and it tends to lower the power transfer efficiency to the plasmas due to the increased capacitive coupling.[8–10]

To resolve these difficulties, in this letter, an internal-type linear inductive antenna arrangement referred to as “double comb-type antenna” having multipolar magnetic field near the antenna was studied to maximize the plasma characteristics and its mechanism was investigated.

To study the characteristics of ICPs with internal-type antennas used for FPD applications, a rectangular shaped process chamber with the inner size of 1,020 mm × 830 mm was fabricated. The schematic diagram of the ICP source and the multi-polar magnetic field configuration used in this study are shown in Fig. 1. The linear antenna was made of 10-mm-diam copper tubing covered by quartz tubing of 15 mm diameter and 2 mm thickness. Multi-polar magnetic fields were applied by inserting permanent magnets having 3000 G on the magnet surface in the quartz tubing located above and parallel to the linear internal antennas and the magnetic field lines simulated using a two-dimensional fluid code (F2L code) for the permanent magnet array are shown in Fig. 1(b).

The plasma characteristics were measured using a Langmuir probe (Hiden Analytical Inc., ESP) located 4 cm below the antenna and along the centerline of the chamber [A-A in Fig. 1(b)]. The electrical characteristics of the antenna were investigated by an impedance probe (MKS Inc.). The etch characteristics of the SiO_2 film deposited on soda lime glass substrates having the size of 880 mm × 660 mm.

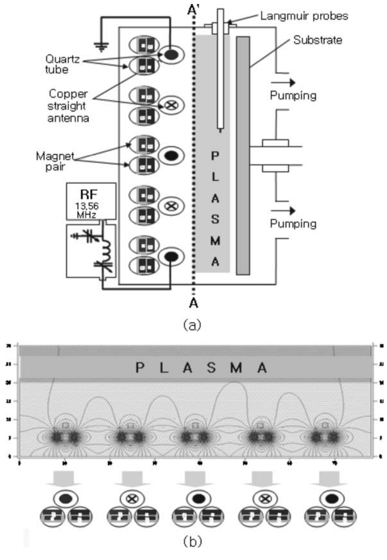

FIG. 1. (a) Schematic diagram of the linear internal-type inductively coupled plasma system used in the experiment. (b) Magnetic field line geometry by a multipolar magnetic array used in this study (simulation by F2L code).

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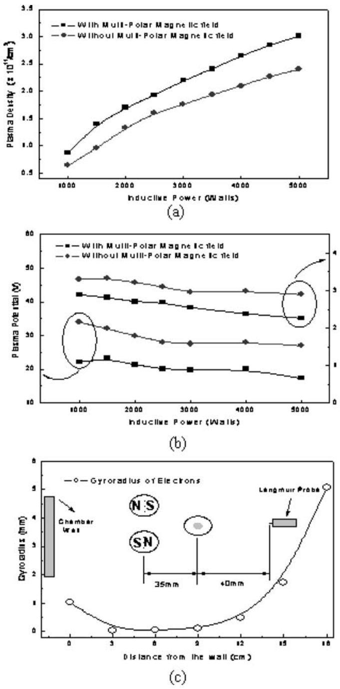


FIG. 2. (a) Ar^+ ion density measured by a Langmuir probe at 4 cm below the antenna as a function with/without multi-polar magnetic fields. The operation pressure was maintained at 15 mTorr. (b) Plasma potentials and electron temperatures as a function with/without multi-polar magnetic fields measured using a Langmuir probe as a function of rf inductive power at 15 mTorr Ar. (c) Gyroradius of electrons by the permanent magnet array from top wall to bulk plasma.

Figure 2 shows (a) plasma density and (b) plasma potential and electron temperature measured at 4 cm below the source as a function of rf inductive power with/without the multi-polar magnetic field at 15 mTorr Ar using a Langmuir probe. As shown in the figure, the increase of rf inductive power from 1000 to 5000 W increased the plasma density almost linearly for both with/without the magnetic field, however, the plasma density with the magnetic field was higher at the same rf inductive power. At 5000 W, the plasma density with the magnetic field was $3.18 \times 10^{11}/\mathrm{cm}^3$. The higher plasma density with the magnetic field is believed to be related to the confinement of the electrons in the plasma. The gyrofrequency (f_{ce}) and gyration radius (r_{ce}) of the charged particle in the magnetic field can be written as following equations:

$$f_{ce} = \frac{\omega_{ce}}{2\pi} \approx 2.80 \times 10^6 B_0 \text{ Hz} \tag{1}$$

$$r_{ce} \approx \frac{3.37\sqrt{\epsilon}}{B_0} \text{ cm}, \tag{2}$$

where B_0 is the applied magnetic field (Gauss) and ϵ is the energy of the particle (in volts). The increase of plasma density with the magnetic field is from the increased ionization of Ar by the gyration motion of the electrons in the plasma in addition to the plasma confinement in a direction normal to the antenna line. But, this effect decays exponentially with distance from multipolar magnetic field. Figure 2(c) shows this effect by calculating the gyroradius from a certain position. Gyroradius increased from 0.0116 mm to 32.380 96 mm according to the distance from antenna. In the case of plasma potential and electron temperature shown in Fig. 2(b), with the increase of rf inductive power, the plasma potential and electron temperature were decreased slowly for both with/without magnetic field, and the use of multi-polar magnetic field showed a lower plasma potential and electron temperature. At 5000 W, the plasma potential and the electron temperature with the magnetic field were 17 V and 2.26 eV, therefore, by using the magnetic field, lower damage and contamination to the substrate could be expected.

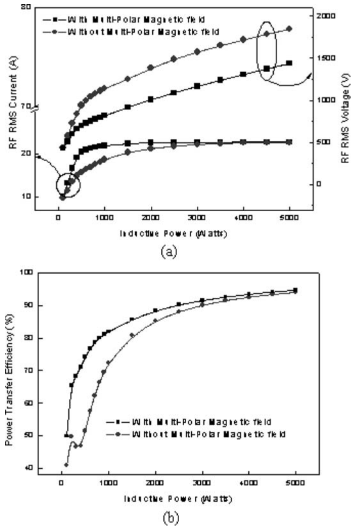


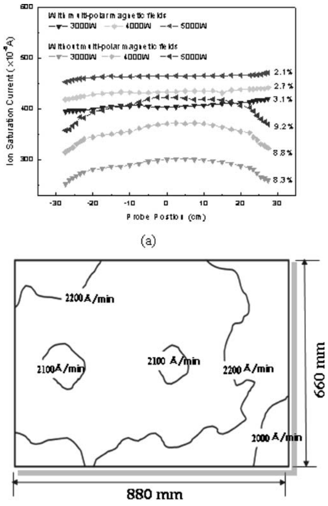
FIG. 3. (a) RF rms voltage and current of the internal-type ICP measured by an impedance analyzer on the antenna located close to the rf power input for the condition with/without the multi-polar magnetic field; 15 mTorr of Ar was used. (b) Power transfer efficiency measured by the impedance analyzer as a function of inductive power at 15 mTorr Ar.

Figure 3 shows (a) rms antenna voltage and rms antenna current and (b) power transfer efficiency measured as a function of rf inductive power with/without the multi-polar magnetic field for 15 mTorr Ar using an impedance probe. As shown in Fig. 3(a), the increase of rf inductive power increased the rf antenna voltage and current for both with/without the magnetic field, however, the use of magnetic field increased the antenna current and decreased the antenna voltage at the same rf inductive power. At a given rf inductive power, the rf voltage induced on the antenna is related to the plasma conductivity (σ) from the following equation:

$$\boldsymbol{\sigma} \propto \mathbf{n_e} \propto \frac{1}{\text{antenna voltage}}. \tag{3}$$

Therefore, the increase of plasma density by the addition of the multi-polar magnetic field in the ICP source shown in Fig. 2(a) decreases the rf antenna voltage and increases the rf antenna current due to the decrease of plasma impedance. In addition, as shown in Fig. 3(b), the use of the magnetic field increased the power transfer efficiency even though the differences are smaller at higher rf inductive powers. The power transfer efficiency was calculated using $(\text{Input Power} - I_{\mathrm{rf}}^2 R)/\text{Input Power} \times 100$, where $I_{\mathrm{rf}}^2 R$ is the Joule loss by the antenna resistance R ($P_{\text{Joule Loss}} = I_{\mathrm{rf}}^2 \times R$), and by assuming that all the power from the rf generator is consumed in the ICP source without losing power in the matching network and rf power cable. At 5000 W with the magnetic field, the power transfer efficiency of about 95% could be obtained.

Figure 4(a) shows the ion saturation current measured as a function of chamber position across the antenna line (A -A′) as shown in Fig. 1(a) for various rf inductive powers at



(a)

(b)

FIG. 4. (a) Plasma uniformity of the double comb-type antenna with/without the multi-polar magnetic field measured at 4 cm below the antenna as a function of rf inductive power from 3000 to 5000 W at 15 mTorr Ar. Ion saturation current measured using a Langmuir probe biased at −60 V was used as the estimation of the plasma density. (b) Etch uniformity of SiO_2 film on the substrate area of 880 mm × 660 mm measured at 5000 W of rf power, −34 V of dc-bias voltage, and 15 mTorr of SF_6 for the double comb-type antenna with the multi-polar magnetic field.

15 mTorr Ar with/without the magnetic field using the Langmuir probe to estimate the uniformity of the plasmas. As shown in the figure, the uniformity of the plasma estimated using the ion saturation current was about 9% for the ICP without the magnetic field, however, by the addition of the magnetic field, the uniformity was improved to 2.1%–3.1%. Leung *et al.*[11] reported that the use of magnetic field can effectively confine hot electrons and limits diffusion of the charged particles to the chamber wall. When a magnetic field ($\mathbf{B_0}$) in addition to an electric field ($\mathbf{E}$) is present, the momentum conservation equations for charged particles parallel to the magnetic field line and normal to the magnetic field line can be written as follows:[11]

$$0 = qn\mathbf{E} - \nabla p - mn\nu_m \mathbf{u}, \tag{4}$$

$$0 = qn(\mathbf{E} + \mathbf{u}_\perp \times \mathbf{B}_0) - \nabla p - mn\nu_m \mathbf{u}_\perp, \tag{5}$$

where, m is mass of the charged particles, n is the density of the charged particles, $\mathbf{u}$ is the mean particle velocity parallel to the magnetic field line, $\mathbf{u}_\perp$ is the mean particle velocity normal to the magnetic field line, q is the charge of the charged particle, ∇p is the variation of particle momentum, and ν_m is the momentum transfer frequency. From the above equations, the mobility ($\mu_\parallel$) and diffusion constant ($D_\parallel$) parallel to the magnetic field line and the mobility ($\mu_\perp$) and diffusion constant ($D_\perp$) normal to the magnetic field line are obtained as follows:

$$\mu = \frac{|q|}{m\nu_m},$$
$$D = \frac{kT}{m\nu_m} T \quad \text{:temperature of charged particle}, \tag{6}$$

$$\mu_\perp = \frac{\mu}{1 + (\omega_{\mathrm{ce}}\tau_m)^2}, \quad D_\perp = \frac{D}{1 + (\omega_{\mathrm{ce}}\tau_m)^2}$$
$$\left(\omega_{\mathrm{ce}} = \frac{qBo}{m}, \tau_m = \frac{1}{\nu_m}\right). \tag{7}$$

Therefore, from Eqs. (6) and (7), the mobility and diffusion constant normal to the magnetic field line are decreased with the ratio of $1/1 + (\omega_c\tau_m)^2$ compared with those parallel to the magnetic field line. The confinement of charged particles vertical to the antenna line at the chamber wall side can decrease the loss of the charged particles to the chamber edge, therefore, higher plasma uniformity is believed to be obtained by the application of the multi-polar magnetic field in our ICP source.

Figure 4(b) shows the SiO_2 etch uniformity measured on the substrate area (880 mm × 660 mm) for 15 mTorr SF_6 gas, 5000 W of 13.56 MHz inductive power, and 2000 W of 12.56 MHz bias power using the ICP with/without the multi-polar magnetic field. The induced bias voltage on the substrate was −34 V. As shown in the figure, the SiO_2 etch uniformity over the large area substrate area was about 5.4%.

In this study, the effect of multi-polar magnetic field on the large-area internal-type linear ICP source, referred as double-comb-type ICP source on the characteristics of plasmas, was studied and its mechanism was investigated. The use of multi-polar magnetic field to the linear internal-type ICP not only increased the plasma density but also improved the plasma uniformity significantly. The improvement of plasma characteristics obtained by the application of the multi-polar magnetic field is believed to be from the gyration of the hot electron formed in the plasma and the plasma confinement due to the magnetic field. The improvement of the plasma uniformity is also from the limitation of plasma diffusion to the chamber edge due to the decrease of mobility and diffusion to the direction normal to antenna line.

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