Plasma Chem Plasma Process (2008) 28:147–158
DOI 10.1007/s11090-007-9112-0

ORIGINAL PAPER

Plasma Characteristics and Antenna Electrical Characteristics of an Internal Linear Inductively Coupled Plasma Source with a Multi-Polar Magnetic Field

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Received: 2 November 2006 / Accepted: 9 April 2007 / Published online: 5 December 2007

Abstract The development of a large-area plasma source with high density plasmas is desired for a variety of plasma processes from microelectronics fabrication to flat panel display device fabrication. In this study, 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 3.2×10^{11} 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 5,000 W with good plasma stability. The plasma uniformity <3% could be also obtained within the substrate area. When SiO_2 film was etched using the double comb-type antenna, the average etch rate of about 2,100 Å/min could be obtained with the etch uniformity of 5.4% on the substrate area using 15 mTorr SF_6, 5,000 W of rf power, and −34 V of dc-bias voltage. The higher plasma density with an excellent uniformity and a lower rf antenna voltage obtained by the application of the magnetic field are related to the electron confinement in a direction normal to the antenna line.

Keywords Plasma · Large area · Display · Impedance

Introduction

Trends in industry of semiconductor devices and flat panel displays (FPD) toward larger substrate size and higher throughput require the development of large-area plasma sources with higher plasma density [1–4]. Also, due to the increase of substrate sizes and need for

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the higher processing rates in both microelectronics and FPDs, high density plasma processing tools that can handle larger area substrate uniformly are more intensively studied. In the case of FPD processing, the current substrate size ranges from 880 mm × 660 mm (fourth generation) to 1,850 mm × 2,250 mm (seventh generation), and the substrate size is expected to increase further within a few years [5].

Among the various high density plasma tools, inductively coupled plasma (ICP) systems are widely studied because of their simple physics and scalability compared with other high density plasmas sources such as electron cyclotron resonance (ECR) plasma sources and helicon-wave-excited plasma sources, therefore, uniform large-area plasmas can be produced relatively easily [6–9]. Inductively coupled plasmas 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 [10]. 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 FPD 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 [11–13].

To resolve these difficulties, in this article, an internal-type linear inductive antenna arrangement referred to as "double comb-type antenna" having a multi-polar magnetic field near the antenna was studied to maximize the plasma characteristics and its mechanism was investigated.

Experiment

Figure 1(a) shows the schematic diagram of the experimental apparatus used in the experiment. As shown in the figure, the plasma-processing chamber was designed as a rectangular form for FPD applications and the inner size of the chamber was 1,020 mm × 830 mm. The substrate holder size was 920 mm × 730 mm (the substrate size was 880 mm × 660 mm). The linear antenna was made of 10 mm diameter copper tubing covered by quartz tubing of 15 mm diameter and 2 mm thickness. Five linear antennas were embedded in the process chamber, and each antenna was connected to the RF power supply (13.56 MHz, 0–5 kW) through a L-type matching network alternatively from the opposite ends to form a "double-comb antenna". Multi-polar magnetic fields were applied by inserting permanent magnets having 3,000 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). The electrical characteristics of the antenna were investigated by an impedance probe (MKS Inc.). This impedance probe located between matching box and antenna. The etch characteristics of the SiO_2 film deposited on sodalime glass substrates having the size of 880 mm × 660 mm (fourth generation glass size) were investigated using a water-cooled

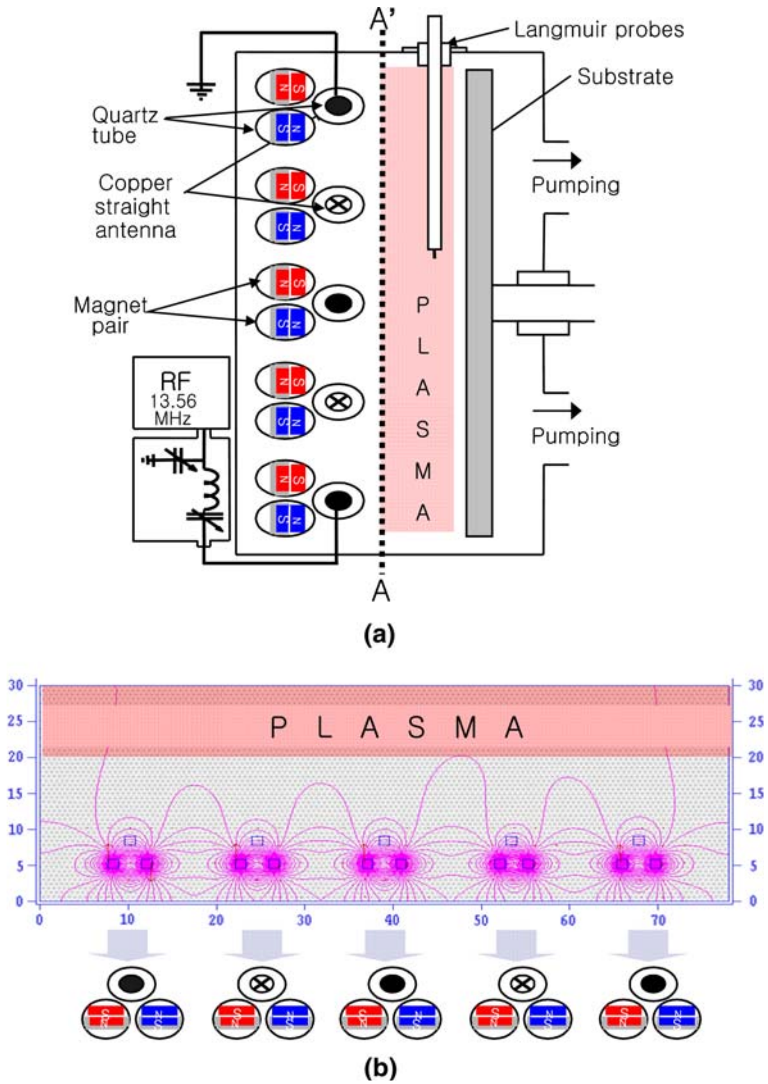


Fig. 1 (**a**) Schematic diagram of the linear internal-type inductively coupled plasma system used in the experiment. (**b**) Magnetic field line geometry by a multi-polar magnetic array used in this study (simulation by F2L code)

substrate holder installed 5 cm below the source and connected to a separate RF power supply (12.56 MHz, 0–2,000 W) through a separate matching network to supply bias voltages to the substrate.

Results and Discussion

Figure 2 shows plasma density 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

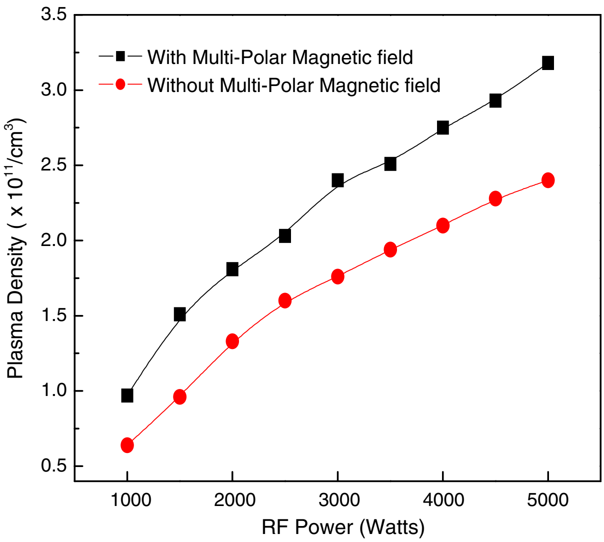


Fig. 2 Ar^+ ion density measured by a Langmuir probe at 4 cm below the antenna as a function with/without multi-polar magnetic fields. The operation pressure was maintained at 15 mTorr

Langmuir probe. As shown in the figure, the increase of RF inductive power from 1,000 to 5,000 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 5,000 W, the plasma density with the multi-polar magnetic field was $3.2 \times 10^{11}/cm^3$. The higher plasma density with the magnetic field is believed to be related to the confinement of the electrons in the plasma. With the increase of RF power, the plasma potential and electron temperature were decreased slowly for both with/without magnetic field as shown in Fig. 3, and the use of multi-polar magnetic field showed a lower plasma potential and electron temperature. At 5,000 W, the plasma potential and the electron temperature with the magnetic field were 17 V and 2.26 eV, respectively; therefore, lower damage and contamination to the substrate could be expected by using the magnetic field.

The higher plasma density with the magnetic fields is believed to be related to the confinement of the electrons in the plasma. In general, electrons and ions moving in a magnetic field are forced to have gyromotion and their gyrofrequencies and gyration radii can be represented by the following equations.

For singly charged ions,

$$f_{ci} = \frac{\omega_{ci}}{2\pi} \approx \frac{1.52 \times 10^3 B_0}{A_R}\ \text{Hz}\ (B_0 \text{ in Gauss}) \tag{1}$$

$$r_{ci} \approx \frac{1.44 \times 10^2 \sqrt{\varepsilon A_R}}{B_0}\ \text{cm} \tag{2}$$

For electrons,

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

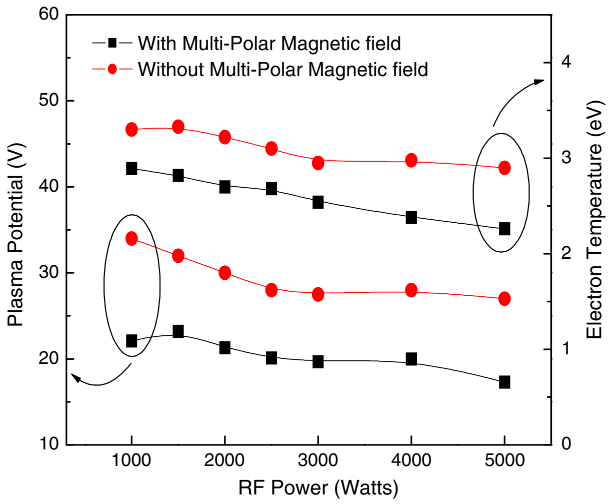


Fig. 3 Plasma potentials and electron temperatures as a function with/without the multi-polar magnetic field measured using a Langmuir probe as a function of RF power at 15 mTorr Ar

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

where B_0 is the applied magnetic field (Gauss), ε is the energy of the charged particle (in eV) and Ar is the ion mass in atomic mass units (amu). The multi-polar magnet field strength used in this study is about 3,000 G on the magnet surface and the magnetic field strength measured at 4 cm below the antenna was about 10 G. For 10 G of magnetic field strength, the gyrofrequency and gyration radius of 15 eV electron are $f_{ce} = 28$ MHz and $r_{ce} = 13$ mm, respectively. In the case of singly charged ion having the energy of 0.05 eV, $f_{ce} = 0.38$ MHz and $r_{ce} = 20$ mm. Therefore, electrons having the ionization energy of neutrals will be effectively confined and can ionize more neutrals in the plasma. Especially, at the locations near the permanent magnets, the magnetic field is stronger; therefore, the charged particles can be more effectively confined in the plasma. But, this effect decays exponentially with distance from multi-polar magnetic field.

Figure 4 shows RMS antenna voltage and RMS antenna current 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. 4, 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;

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

Therefore, the increase of plasma density by the addition of the multi-polar magnetic field in the ICP source shown in Fig. 2 decreases the rf antenna voltage and increases the rf antenna current due to the decrease of plasma impedance [14]. And the RMS voltage was generally lower for the antenna with the magnetic field. The RF voltage on the antenna induces the DC bias voltage on the quartz-tubing surface surrounding the antenna and the bias voltage is proportional to the RF voltage on the antenna. Higher bias voltage increases

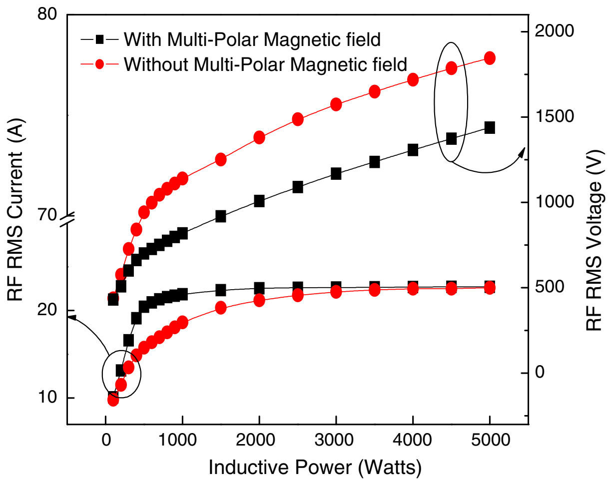


Fig. 4 RF RMS voltage and current of the internal-type ICP measured by an impedance analyzer on the antenna located close to the RF power input for the condition with/without the multi-polar magnetic field. 15 mTorr of Ar was used

the sputtering of quartz tubing and increases the contamination of the substrate. Therefore, the application of the multi-polar magnetic field to the antenna was beneficial in decreasing contamination by lowering the RF RMS voltage on the antenna.

Figure 5 shows the power factor (cos θ) representing the phase relationship between the voltage and current induced on the antenna line as a function of RF power at 15 mTorr Ar for the antennas with/without the magnetic field. The RF RMS voltage and the phase angle between the voltage and current were measured using an impedance probe installed at the power output of the matching network. Also, as shown in Fig. 5, even though the power factor estimated with the impedance probe was increased with increasing RF power for both antennas with/without the magnetic field, the antenna with the magnetic field showed a higher power factor compared to that without the magnetic field. The higher power factor at the same RF power indicates the increased resistance component of the plasma and

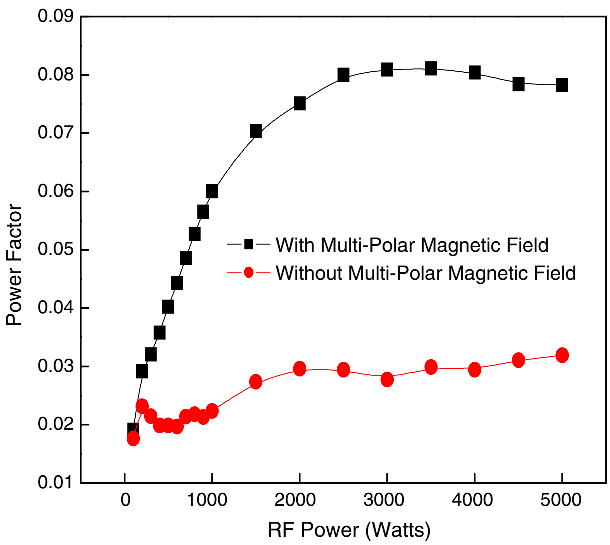
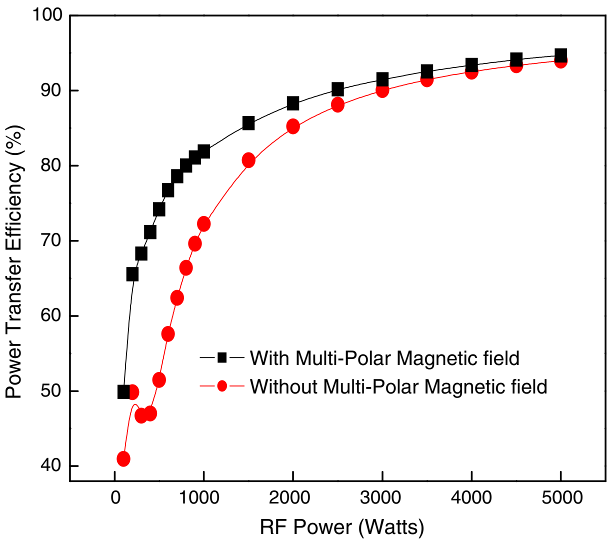


Fig. 5 Power factor calculated by the phase angle between current and voltage on the internal-type ICP antenna measured using the impedance probe data for the condition with/without the multi-polar magnetic field at 15 mTorr Ar

shows the more efficient power transfer to the plasma, and which generates higher plasma density at the same pressure or enables lower pressure operation of the plasma. In addition, as shown in Fig. 6, 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 ((Input power $- I_{rf}^2 R$)/Input power) $\times$ 100, where $I_{rf}^2 R$ is the Joule loss by the antenna resistance R ($P_{\text{Joule Loss}} = I_{rf}^2 \times R$), and by assuming that the 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 5,000 W with the magnetic field, the power transfer efficiency of about 95% could be obtained.

Figure 7 shows the resistance component of the plasma system (load resistance) calculated from the impedance probe data. As shown in the figure, the increase of RF inductive power from 100 to 5,000 W increased the load resistance almost linearly for both with/without the magnetic field, however, the load resistance with the magnetic field was higher at the same RF inductive power. Generally, the increase of plasma density by the addition of the multi-polar magnetic field in the ICP source increase the plasma conductivity (σ) and decrease the electric field component of plasma at the same input rf power. The increase of RF current with the decrease of electric field component of plasma cause the increase of load resistance. Figure 8 shows the inductance component of the plasma system (load inductance) calculated from the impedance probe data. As shown in the figure, the increase of RF inductive power from 100 to 5,000 W increased the load inductance almost linearly for both with/without the magnetic field, however, the load inductance with the magnetic field was lower at the same RF inductive power. The decrease of load inductance with multi-polar magnetic field is due to the increase of coupling coefficient. Coupling coefficient is dependent on the current distribution of inside plasma and increases as the current path of plasma becomes closer to the antenna. By applying the multi-polar magnetic field, electron and ion are confined by the multi-polar magnetic arrays, that region of high density plasma moves closer to the antenna and increases the coupling coefficient.

Fig. 6 Power transfer efficiency calculated with the impedance probe data as a function of inductive power at 15 mTorr Ar



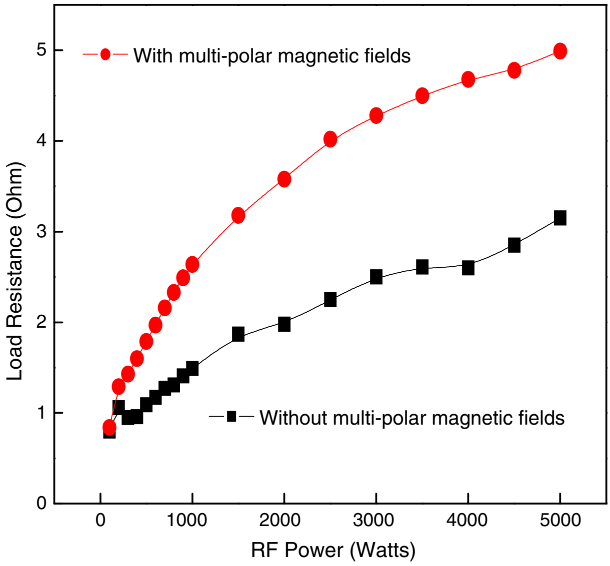


Fig. 7 Load resistance measured by an impedance probe as a function of RF power at 15 mTorr Ar

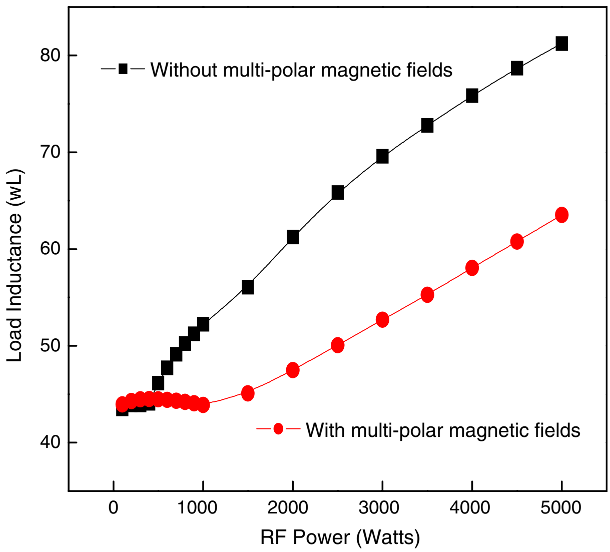


Fig. 8 Load inductance measured by an impedance probe as a function of RF power at 15 mTorr Ar

Using the impedance probe data obtained for Figs. 7 and 8, the quality factor ($Q = \omega L_t/R_t$) can be also calculated and the results are shown in Fig. 9 for the antenna with/without the magnetic field. As shown in the figure, the quality factor was decreased with increasing RF power and, at high RF powers, it was nearly saturated for both antennas with/without the magnetic field. However, at the same RF power, the antenna with the magnetic field showed a lower quality factor. In general, a plasma system with a high quality factor shows difficulties in the matching for the small changes in the chamber environment such as changes of gas composition, surface temperature, operational pressure, etc. However, a plasma system with a low quality factor is stable and is easily matchable for the various changes of the chamber

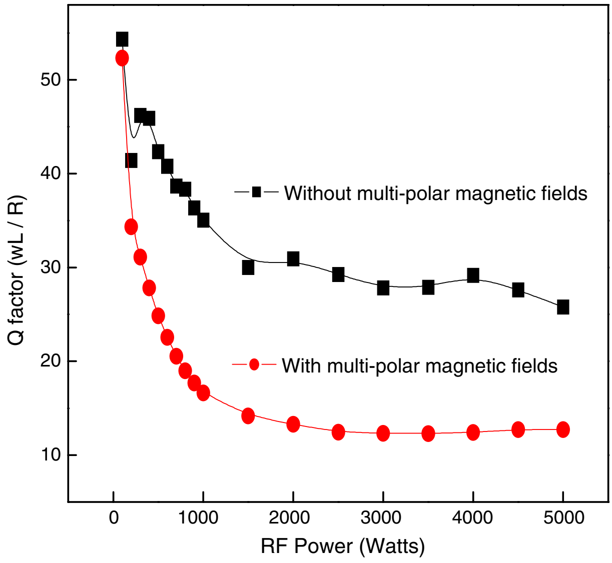


Fig. 9 Q (quality) factor calculated with the data obtained by an impedance probe as a function of RF power at 15 mTorr Ar

environment. Therefore, the antenna with the magnetic field showed more stable plasmas compared with that without the magnetic field.

Figure 10 shows the plasma uniformity along the A–A′ in Fig. 1 calculated by the two-dimensional fluid code (F2L code) simulation for 1,000 W Ar. As shown in the figure, by the application of the permanent magnet, the uniformity of the plasma along the sidewall was improved due to the decrease of diffusional loss near the wall in addition to the increase of plasma density.

Figure 11 shows the ion saturation current measured as a function of chamber position across the antenna line (A–A′) shown in Fig. 1(a) for various RF inductive powers at 15 mTorr Ar with/without the magnetic field using the Langmuir probe to estimate the

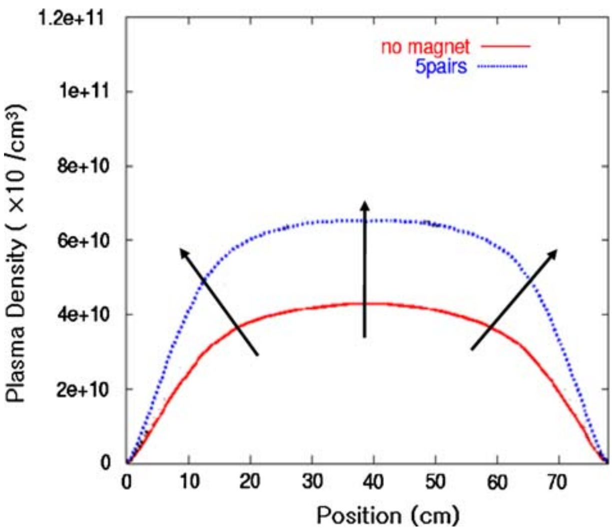


Fig. 10 Plasma uniformity along the A–A′ calculated by the two-dimensional fluid code (F2L code) simulation for 1,000 W Ar

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. [15] reported that the use of magnetic field can effectively confines hot electrons and limits diffusion of the charged particles to the chamber wall. The diffusion of the charged particles to the wall causes the nonuniformity of the plasma due to the severe density gradient near the wall, therefore, limiting the diffusional loss of the charged particles to the wall can improve the plasma uniformity [16]. When a magnetic field ($\mathbf{B}_o$) 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 [15]:

$$0 = qn\mathbf{E} - \nabla p - mnv_m\mathbf{u} \tag{4}$$

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

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 pressure gradient, and v_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:

$$\mu_\parallel = \frac{|q|}{mv_m}, \quad D_\parallel = \frac{kT}{mv_m} \quad T\text{: temperature of charged particle} \tag{6}$$

$$\mu_\perp = \frac{\mu_\parallel}{(1+\omega_{\mathrm{ce}}\tau_m)^2}, \quad D_\perp = \frac{D_\parallel}{(1+\omega_{\mathrm{ce}}\tau_m)^2} \quad \left(\omega_{\mathrm{ce}} = \frac{qB_0}{m}, \tau_m = \frac{1}{v_{\mathrm{m}}}\right) \tag{7}$$

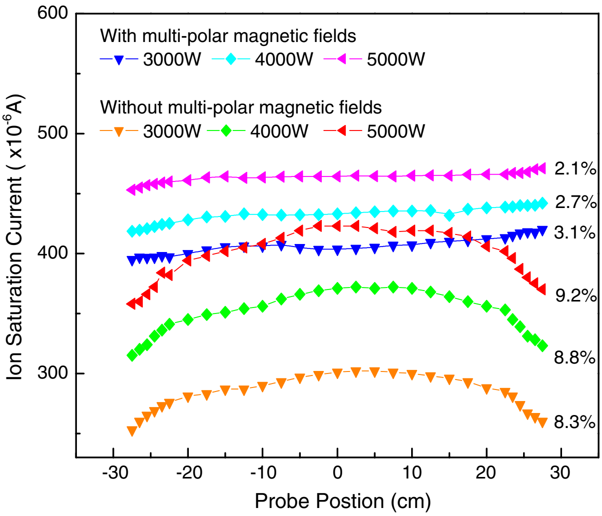


Fig. 11 Plasma uniformity of the double comb-type antenna with/without the multi-polar magnetic field measured at 4 cm below the antenna as a function of RF inductive power from 3,000 to 5,000 W at 15 mTorr Ar. Ion saturation current measured using a Langmuir probe biased at –60 V was used as the estimation of the plasma density

Therefore, from Eqs. 6 and 7, the mobility and diffusion constant normal to the magnetic field line are decreased with the ratio of $\frac{1}{1+(\omega_c \tau_m)^2}$ compared with those parallel to the magnetic field line. In our ICP source with the multi-polar magnetic field, the direction normal to the magnetic field line is the direction vertical to the antenna 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. The increase of plasma uniformity with the magnetic field is also related to the change of plasma density near the edge of the wall.

Figure 12 shows the SiO_2 etch uniformity measured on the substrate area (880 mm × 660 mm) for 15 mTorr SF_6 gas, 5,000 W of 13.56 MHz inductive power, and 2,000 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%. Therefore, an excellent etch uniformity could be obtained with the ICP with the multi-polar magnetic field.

Conclusions

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 application of the multi-polar magnetic field to the antenna increased the plasma density, lowered the antenna voltage, which resulted in the decreased possibility of contamination, and increased the stability of the plasma during the operation. Especially, the application of the magnetic field improved the plasma uniformity significantly. As a result, by the application of the multi-polar

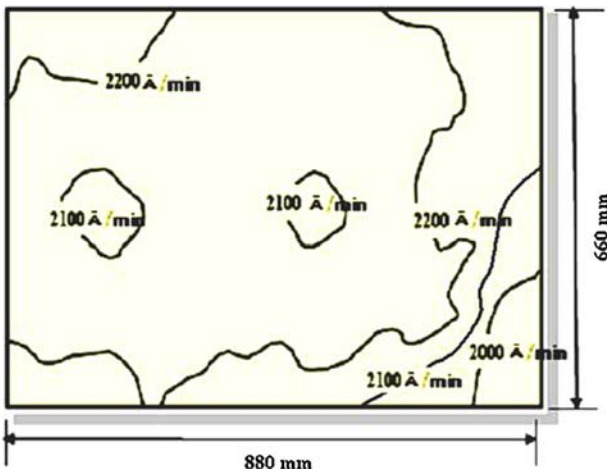


Fig. 12 Etch uniformity of SiO_2 film on the substrate area of 880 mm × 660 mm measured at 5,000W of RF power, −34 V of dc-bias voltage, and 15 mTorr of SF_6 for the double comb-type antenna with the multi-polar magnetic field

magnetic field to the double comb-type internal ICP antenna, a high plasma density of 3.2×10^{11} cm^{-3} with the plasma uniformity <3% could be obtained at the pressure of 15 mTorr Ar and at the inductive power of 5,000 W with good plasma stability. 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 effective plasma confinement by the application of the magnetic field appears related to the increased ionization and the decreased loss of the electrons to the chamber walls or to the direction vertical to the antenna line by the helical motion of the electrons.

Acknowledgements This work was supported by National Research Laboratory (NRL) Program of the Korea Ministry of Science and Technology.

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