

Plasma and antenna characteristics of a linearly extended inductively coupled plasma system using multi-polar magnetic field

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Abstract

A novel internal-type linear inductive antenna, referred to as a “double comb-type antenna”, was used as a large-area plasma source with a substrate area of 880 mm × 660 mm. This study investigated the effect of a multi-polar magnetic field on plasma confinement. High density plasma in the order of $3.2 \times 10^{11} \text{ cm}^{-3}$, which is 50% higher than that obtained for a source without a magnetic field, with good plasma stability was obtained at a pressure of 15 mTorr Ar and an RF power of 5000 W. Plasma uniformity <3% within the substrate area was also obtained.

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1. Introduction

The trends in semiconductor devices and flat panel displays (FPD) toward a larger substrate size and a higher throughput require the development of large-area plasma sources with higher plasma density [1–4]. In addition, high density plasma processing tools that can handle a larger area have attracted considerable attention due to the larger substrate sizes and the need for the higher processing rates in both microelectronics and flat panel displays. In the case of FPD processing, the current substrate size ranges from 880 mm × 660 mm (4th generation) to 1850 mm × 2250 mm (7th generation), and this substrate size is expected to increase further within a few years [5].

Among the many high density plasma tools, inductively coupled plasma (ICP) systems have been widely studied on account of their simple physics and scalability compared with other high density plasma sources such as electron cyclotron resonance (ECR), helicon-wave-excited plasma sources, etc. Therefore, uniform large-area plasma can be produced relatively easily [6–9]. However, there are many problems encountered when ICP sources are used in the processing of flat panel displays with an extremely large substrate size particularly for external spiral antenna-type ICP sources due to the cost and thickness of the dielectric material and the large impedance of

the antennas that occurs when scaling up to larger areas. An antenna with high impedance causes a large RF voltage on the antenna over a large-area, which reduces the power transfer efficiency to the plasma as a result of the increased capacitive coupling [10–12].

In order to resolve these difficulties, this study investigated an internal-type linear inductive antenna arrangement, which is referred to as a “double comb-type antenna”, with a multi-polar magnetic field near the antenna to maximize the plasma characteristics and examined its mechanism.

2. Experiment

A schematic diagram of the experimental apparatus used in the experiment is shown in Fig. 1. The plasma processing chamber was designed to be in a rectangular form for FPD applications. The inner size of the chamber was 1020 mm × 830 mm and the substrate holder size was 920 mm × 730 mm (the actual substrate size was 880 mm × 660 mm). The linear antenna was made from 10 mm diameter copper tubing covered with quartz tubing, 15 mm in diameter and 2 mm in thickness. Five linear antennas were embedded in the process chamber, and each antenna was connected to an RF power supply (13.56 MHz, 0–5 kW) through a L-type matching network alternatively from opposite ends to form a “double comb antenna”. A multi-polar magnetic field was applied by inserting permanent magnets with 3000 G on the magnet surface in the

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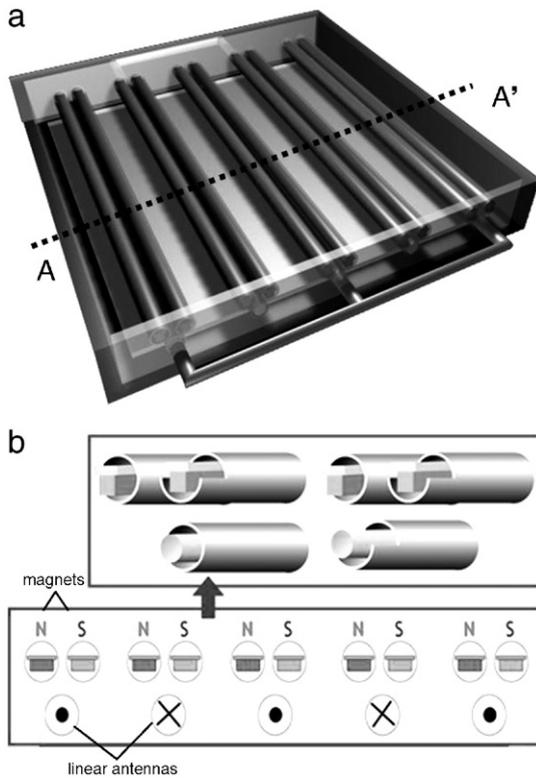


Fig. 1. (a) Schematic diagram of a linear internal ICP system used in the experiment. (b) Arrangement of the permanent magnets used in the experiment to form a multi-polar magnetic field.

quartz tubing located above and parallel to the linear internal antennas, as shown in Fig. 1.

The plasma characteristics were measured using a Langmuir probe (Hiden Analytical Inc., ESP) that was 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 examined using an impedance probe (MKS Inc.) located between the matching box and antenna. The etch uniformity of a SiO₂ film deposited on a 880 mm × 660 mm (4th generation glass size) sodalime glass substrate was investigated using a water-cooled substrate holder installed 5 cm below the source and connected to a separate RF power supply (12.56 MHz, 0–2000 W) through a separate matching network to supply a bias voltage to the substrate.

3. Results and discussion

Fig. 2(a) shows the characteristics of the plasma measured 4 cm below the source as a function of the RF power with/without a multi-polar magnetic field at 15 mTorr Ar using a Langmuir probe. The plasma density both with/without the magnetic field increased almost linearly with increasing RF power from 1000 to 5000 W. However, the plasma density with the magnetic field was higher at the same RF power. At 5000 W, the plasma density with the multi-polar magnetic field was approximately $3.2 \times 10^{11}/\text{cm}^3$. The higher plasma density was attributed to the electrons confined in the plasma by the magnetic field. Since electrons moving in a magnetic field have

gyromotion, they remain in the plasma for a longer duration that allows the ionization of more neutral particles in the plasma. The magnetic field is stronger at the locations near the permanent magnets. Therefore, charged particles can be confined in the plasma more effectively.

With increasing RF power, the plasma potential and electron temperature decreased slowly for the plasma with/without magnetic field, as shown in Fig. 2(b), and the use of a 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, less damage and contamination to the substrate is expected using the magnetic field.

Fig. 3 shows (a) the RF root mean square (RMS) voltage and (b) the power factor ($\cos\theta$) representing the phase relationship between the voltage and current induced on the antenna line as a function of the RF power at 15 mTorr Ar for antennas with/without the magnetic field. The RF RMS voltage and the phase angle between the voltage and current were measured using an

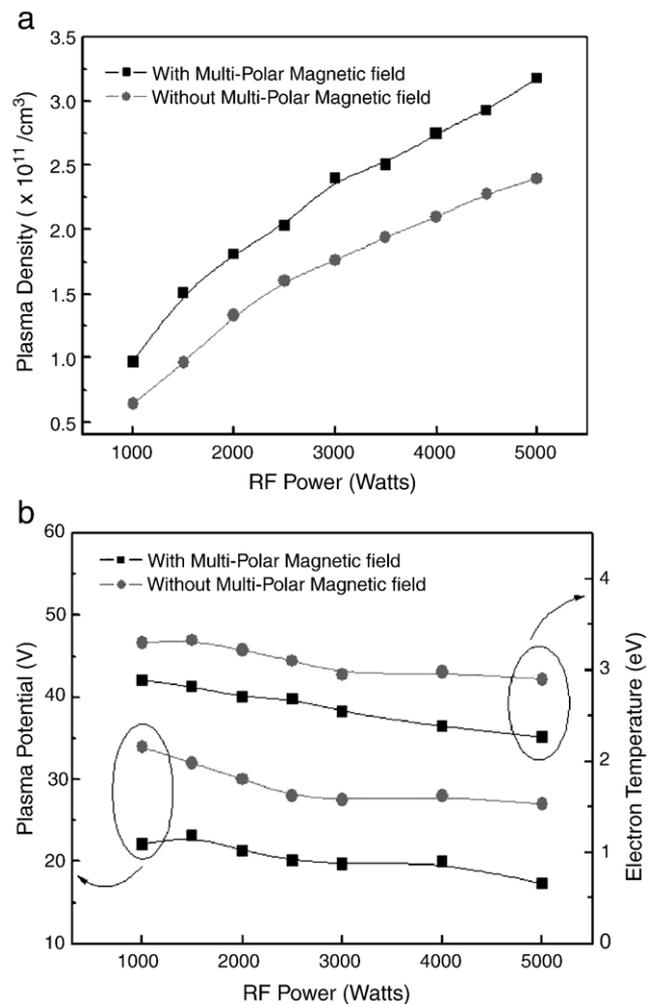


Fig. 2. (a) Ar⁺ ion density measured by a Langmuir probe at 4 cm below the antenna as a function with/without the multi-polar magnetic field. The operation pressure was maintained at 15 mTorr. (b) Plasma potential and electron temperature with/without the multi-polar magnetic fields as a function of the RF power at 15 mTorr Ar.

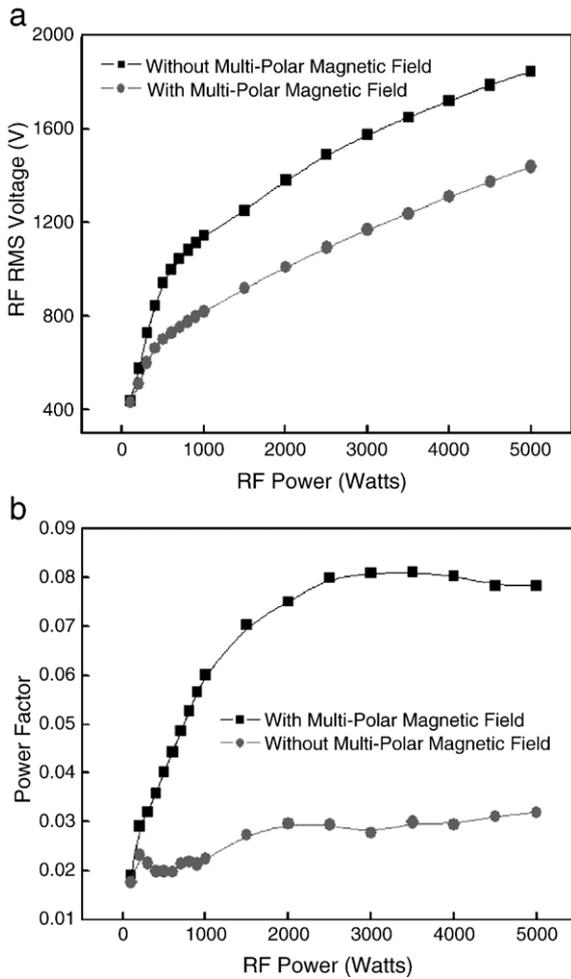


Fig. 3. (a) RF RMS voltage measured as a function of the RF power for the internal-type ICP antenna with/without the multi-polar magnetic field at 15 mTorr Ar. (b) Power factor calculated by the phase angle between the current and voltage on the internal-type ICP antenna measured under the condition with/without the multi-polar magnetic field at 15 mTorr Ar.

impedance probe that was installed at the power output of the matching network. As shown in Fig. 3(a), the RF RMS voltage increased with increasing RF power both with and without the magnetic field. However, the RMS voltage was generally lower for the antenna with the magnetic field. The RF voltage on the antenna induces a DC bias voltage on the surface of the quartz tubing surrounding the antenna that is proportional to the RF voltage on the antenna. A higher bias voltage increases the rate of sputtering of the quartz tubing, which increases the level of contamination on the substrate. Therefore, the application of a multi-polar magnetic field to the antenna can decrease the level of contamination by lowering the RF RMS voltage on the antenna. In addition, as shown in Fig. 3(b), the antenna with the magnetic field showed a higher power factor than that without the magnetic field even though the power factor estimated using the impedance probe increased with increasing RF power for both antennas. The higher power factor at the same RF power indicates an increase in the resistance component of the plasma and shows more efficient power transfer to the plasma, and

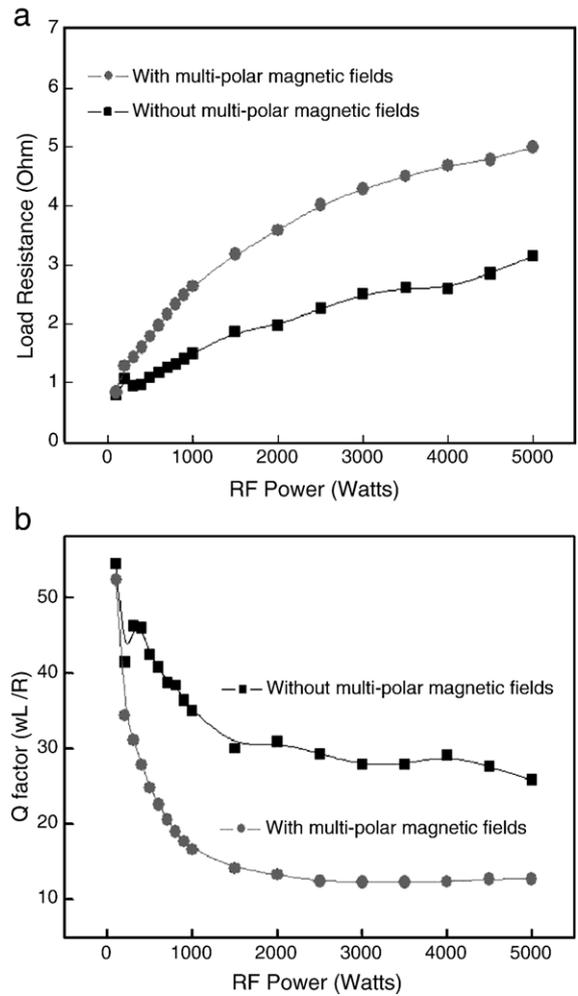


Fig. 4. (a) Load resistance measured as a function of RF power at 15 mTorr Ar. (b) Q (quality) factor as a function of RF power at 15 mTorr Ar.

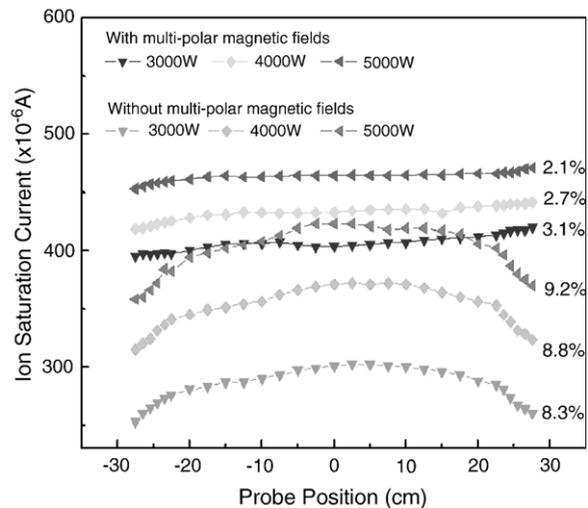


Fig. 5. Plasma uniformity of the double comb-type antenna with/without the multi-polar magnetic field measured at 4 cm below the antenna as a function of RF power from 3000 W to 5000 W at 15 mTorr Ar. Ion saturation current measured using a Langmuir probe biased at -60 V was used to estimate the plasma density.

which generates higher plasma density under the same pressure that enables lower pressure operation of the plasma.

Indeed, the resistance component of the plasma system (load resistance) can be calculated from the impedance probe data. Fig. 4(a) shows the load resistance as a function of the RF power of the antennas with/without the magnetic field calculated from the impedance probe data shown in Fig. 3. As shown in the figure, the magnetic field increased the resistivity of the plasma system. The increase in the load resistance with the magnetic field was attributed to the helical motion of the electrons, which not only decreases the effective mobility of the electrons but also increases the rate of inelastic collisions with neutrals. Using the impedance probe for the data obtained for Fig. 3, the quality factor ($Q = \frac{\omega L_s}{R_s}$) can be also calculated. The results are shown in Fig. 4(b) for the antenna with/without the magnetic field. As shown in the figure, the quality factor decreased with increasing RF power, and was almost saturated with both antennas at high RF power. However, the antenna with the magnetic field showed a lower quality factor at the same RF power. In general, it is difficult to match small changes in the chamber environment of a plasma system with a high quality factor caused by changes in the gas composition, surface temperature, operational pressure, etc. However, a plasma system with a low quality factor is stable and can be matched easily with the various changes in the chamber environment. Therefore, the antenna with the magnetic field showed more stable plasma compared with that without the magnetic field.

The ion saturation current measured by the Langmuir probe biased at -60 V as a function of the chamber position across the antenna centerline (A–A' in Fig. 1) for both antennas is shown in Fig. 5. The RF power was varied from 3000 W to 5000 W at 15 mTorr Ar. The ion saturation current of the probe was used to estimate the plasma density. As shown in the figure, when the antenna was used without a magnetic field, the plasma uniformity measured along the antenna centerline ranged from 8 to 9% for RF power ranging from 500 to 3000 W. However, when the magnetic field was applied to the antenna, the plasma uniformity improved significantly to approximately 3.1% at 3000 W and to 2.1% at 5000 W. The improvement in plasma uniformity by the magnetic field was attributed to the change in the plasma density profile at the edge of the chamber as a result the reduced loss of charged particles to the chamber wall or to the direction vertical to the antenna line by the applied magnetic field.

4. Conclusions

This study examined the effect of applying a multi-polar magnetic field to a double comb-type linear internal ICP an-

tenna on the plasma and antenna characteristics. The application of a multi-polar magnetic field to the antenna increased the plasma density, lowered the antenna voltage resulting in decreased contamination, and increased the plasma stability during operation. In particular, the application of a magnetic field improved the plasma uniformity considerably. As a result, the application of a multi-polar magnetic field to the double comb-type internal ICP antenna produced a high plasma density of $3.2 \times 10^{11} \text{ cm}^{-3}$ with a plasma uniformity $< 3\%$ at a pressure of 15 mTorr Ar and an inductive power of 5000 W with good plasma stability. The improvement in the plasma properties by the magnetic field was attributed to the increased ionization and the decreased loss of electrons to the chamber walls or to the direction vertical to the antenna line via the helical motion of the electrons.

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