Reduction of the electrostatic coupling in a large-area internal inductively coupled plasma source using a multicusp magnetic field

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A large area (1020 mm × 830 mm) inductively coupled plasma (ICP) source has been developed using an internal-type linear antenna with permanent magnets forming a multicusp magnetic field. The large rf antenna voltages, which cause the electrostatic coupling between the antenna and the plasma in a large area internal-type linear-antenna ICP source, were decreased significantly by applying the magnetic field near and parallel to the antenna. Through the application of the magnetic field, an approximately 20% higher plasma density, with a value of close to 1.0×10^{11} cm^{-3} at a rf power of 2000 W, and about three times higher photoresist etch rates were observed, while maintaining the plasma nonuniformity at less than 9%. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1784877]

High-density and large-area plasma processing technologies are indispensable for high resolution flat panel display (FPD) devices, especially for the next generation of TFT-LCDs.[1,2] The plasma sources developed to date for the production of high-density and large-area plasmas were mainly focused on the inductively coupled plasma (ICP) sources used with external-type antennas, due to their simplicity and scalability to large areas.[3–5] However, due to the cost and thickness of the dielectric material required to transmit the electromagnetic field to the plasma, scaling these ICP sources with external-type antennas to larger sizes is very difficult. Furthermore, due to the high impedance of the antenna in large area ICP sources, a high rf voltage is induced at the antenna over a large area, and this can lead to the antenna being more capacitively coupled with low efficiency plasma production.[6,7]

Recently, internal-type ICPs, which effectively eliminate the problems associated with the thickness of the dielectric materials when scaling to large areas, have attracted more attention in the area of large area flat panel processing.[8–11] However, these internal-type ICPs suffer from a problem of capacitive coupling between the antenna and the plasma which is worse than that observed in the case of external-type antennas, due to the reduction of the distance between the plasma and the antenna. This results in sputtering of the antenna materials, together with a problem of low power transfer to the plasma and plasma instability caused by the increased loss of electrons, as reported by other researchers.[9,10] It was reported that depositing a dielectric coating on the metal antenna[9] and covering the internal straight antenna with a large diameter quartz pipe[10] could reduce this strong electrostatic coupling effect. However, low power transfer efficiency and plasma instability still pose serious problems when plasma reactors are scaled to large areas.

In this letter, experimental results are shown confirming that the large rf antenna voltages, which cause the electrostatic coupling between the antenna and the plasma, and the plasma impedance, could be effectively reduced in a large area internal-type linear-antenna ICP system (1020 mm × 830 mm) by applying a weak multicusp magnetic field instead of using a large diameter quartz pipe around the antenna as suggested by Wu *et al.*[10] This arrangement involving the use of a multipolar magnetic field in an internal ICP system employing a linear antenna coil and the results obtained using this system are described in this letter.

A schematic diagram of the internal-type linear-antenna ICP source used in this study is shown in Fig. 1. The process chamber was designed so as to be rectangular, mainly for the purpose of the FPD application, and was made of stainless
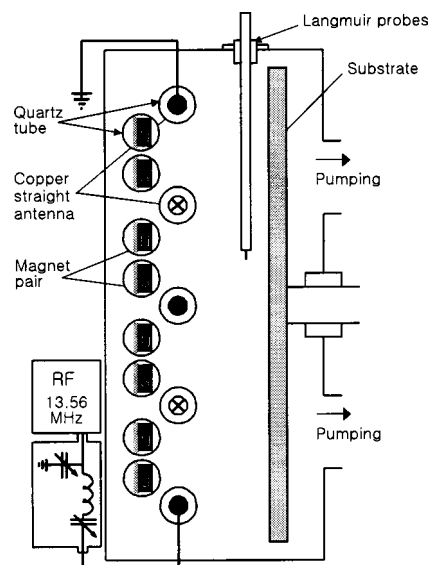

FIG. 1. Schematic diagram of the internal-type linear ICP source used in this experiment and the arrangement of the permanent magnets in the source.

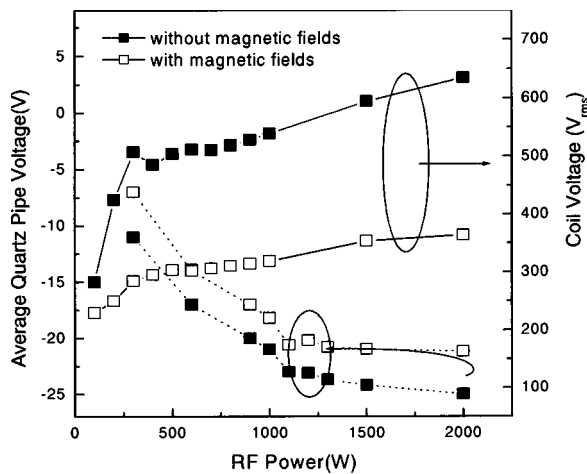[a]Electronic mail: gyyeom@skku.edu

FIG. 2. The effect of the magnetic field on the rms voltage across the coil and the dc potential shift on the insulator as a function of the rf power. The rf power was varied from 100 to 2000 W at an Ar pressure of 15 mTorr.
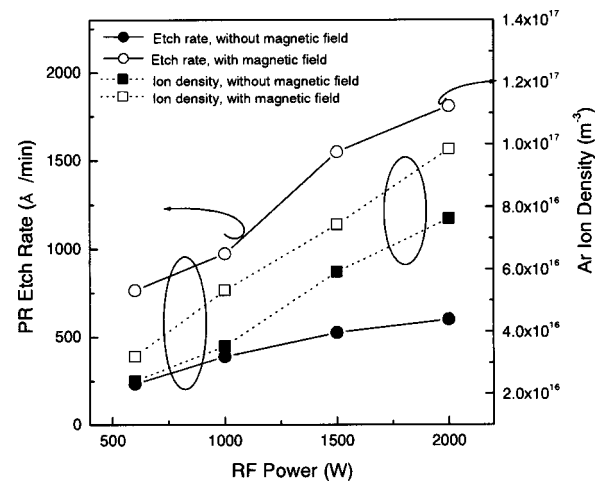

FIG. 3. The effect of the magnetic field on the Ar ion density and PR etch rate. The ion density was measured at 7.5 cm below the antenna. The rf power was varied from 600 to 2000 W at an Ar pressure of 15 mTorr.

steel. The inner size of the chamber was 1020 mm $\times$ 830 mm. Five linear antennas were equally embedded in the vacuum chamber and each linear antenna was connected in series as a simple serpentine type at the outside of the vacuum chamber. The length of the each linear antenna was 1240 mm and the distance between the neighboring antennas was 160 mm. Therefore, the total length of the antenna in our system was approximately 7 m. The antenna was made of 10-mm-diam copper tubing and the outside of the copper tubing was covered with quartz tubing with an outer diameter of 15 mm and a thickness of 2 mm. Therefore, the air gap between the quartz tube and the antenna was about 1.5 mm, while the air gap used by Wu *et al.*[8,13] was about 7.8 mm.

One end of the connected linear antenna was grounded and the other end was connected to a radio frequency power supply (13.56 MHz, 0–2.5 kW) through a conventional L-type matching network. Ar ion densities were measured using a Langmuir probe (ESP, Hiden Analytical, Inc.) located 7.5 cm below the antenna and along the vertical centerline of the chamber at Ar pressures ranging from 5 to 25 mTorr and rf power levels ranging from 600 to 2000 W. The photoresist (PR) etching characteristics were investigated using a 6-μm-thick hard baked PR film (AZ9260) deposited on a glass substrate and using oxygen instead of Ar. For the PR etching, the substrates was located 5 cm below the antenna and a bias voltage of −350 V was applied to the substrate through a separate rf power supply (12.56 MHz, 0–2 kW). Magnetic fields were applied by inserting permanent magnets with a coercive force of 3000 G at the magnet surface into the separate quartz tubing located parallel to the linear current carrying antennas, as shown in Fig. 1. By arranging the magnets, so as to create a pattern of alternating magnet poles each separated by a distance of 40 mm, a magnetic cusp was formed between the neighboring linear antennas.

Figure 2 shows the measured rms rf coil voltage and the dc potential shift on the insulator covering the antenna conductor as a function of the rf power supplied to the source, with and without the magnetic field. The rf voltage was measured using a high voltage probe (Tektronix P6015A) at the first linear antenna located close to the rf power input. As shown in Fig. 2, the rf coil voltage measured without the magnetic field increased rapidly up to 635 V when the rf

power was increased to 2000 W. However, when the magnetic field was applied, the rf voltage was much lower than that without the magnetic field. This lower rf voltage at the same level of rf power resulting from the application of the multipole magnetic field is mainly attributed to the reduction of the plasma impedance, as described by

$$\widetilde{V}_{rf} = \widetilde{I}_{rf}|Z|, \tag{1}$$

where $Z = R + j\omega L$ is the equivalent plasma impedance.

Kim *et al.*[12] reported a decrease in the rms rf coil voltage resulting from the reduction of the plasma impedance through the application of an axial magnetic field to a conventional inductively coupled plasma. The imposed multicusp magnetic field helps to confine energetic electrons, so as to increase the power transfer efficiency. Therefore, the plasma impedance can effectively be reduced through the application of the multicusp magnetic field.

The effect of the reduced rms rf coil voltage obtained with the multicusp magnetic field was also confirmed by measuring the dc potential shift on the insulator covering the antenna conductor. The rf coil voltage, V_a, and the rf voltage of the insulator covering the antenna conductor, V_s, which is proportional to the dc bias voltage, V_{dc}, on the insulator, are found to be related by the following simple equation (2) in the internal linear inductively coupled plasma:[6,13]

$$V_{dc} \propto V_s \cong \frac{C_i}{C_i + C_s} V_a, \tag{2}$$

where C_i is the capacitance between the antenna and the quartz surface and C_s is the capacitance between the quartz surface and plasma. From this equation, it was clarified that the electrostatic coupling which results in quartz pipe etching was strongly dependent on the rms coil voltage, V_a and the distance between the antenna and quartz pipe. As shown in Fig. 2, the amount of the dc potential shift induced on the insulator covering the antenna conductor which was directly responsible for the quartz pipe erosion was reduced with the magnetic field as predicted by the above equation.

Figure 3 shows the effect of rf power supplied to the internal source with and without the magnetic field on the ion density and PR etch rates. In both cases, increasing the rf power increased the ion densities linearly, however, the ap-

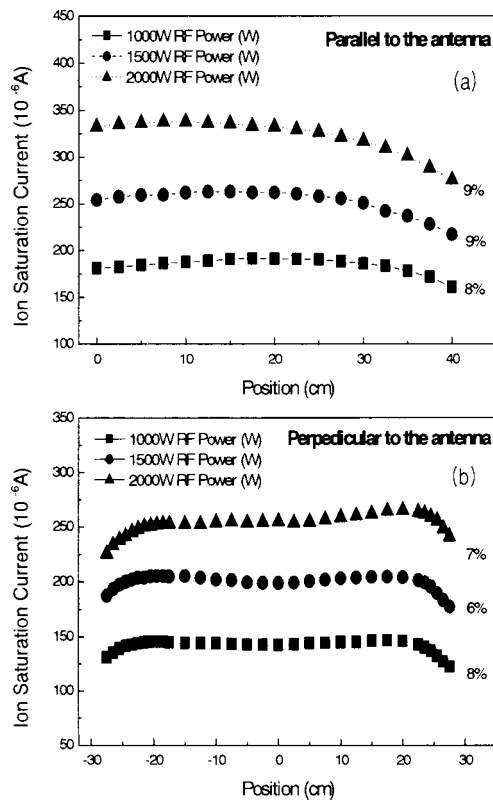Appl. Phys. Lett., Vol. 85, No. 10, 6 September 2004

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FIG. 4. Ion saturation currents measured by a Langmuir probe (a) perpendicular to the antenna and (b) parallel to the antenna at 7.5 cm below the antenna as a function of the position of the chamber in the presence of a multipole magnetic field. The rf power was varied from 1000 to 2000 W at an Ar pressure of 15 mTorr.

tenna (a) and parallel to the antenna (b) for various rf power levels for the substrate size of 820 mm × 630 mm. The plasma uniformity was calculated from the experimental data using the equation, plasma uniformity = {(max − min)/2 × average} × 100%, where max and min refer to the maximum and minimum ion current densities, respectively. As shown in Fig. 4, the nonuniformity of the plasma within the substrate was less than 9%, regardless of the rf power.

In summary, in a large area internal-type linear-antenna ICP system (1020 mm × 830 mm) the capacitive coupling between the antenna and the plasma could be effectively reduced by applying an asymmetric magnetic field. Also, higher plasma densities of up to 10^{11} cm^{-3} and higher PR etch rates were observed in the presence of the magnetic field. This increase in plasma density and decrease in rf antenna voltage in the presence of the magnetic field were attributed to two main factors, namely the formation of an $E \times B$ field near the antenna and decreased diffusional loss of the plasma to the chamber wall near the antenna. The application of the magnetic field also increased the stability of the plasma, while maintaining the plasma uniformity at less than 9% in the case of a substrate size of 820 mm × 630 mm.[16]

plication of the magnetic field resulted in higher ion densities of close to ~10^{11} cm^{-3} at a rf power of 2000 W. There was a significant increase in the PR etch rates in the presence of the magnetic field, possibly due to both the increased ion density and the increased number of dissociated oxygen atoms. The increase in the ion density observed in the presence of the magnetic field is believed to result from the decreased diffusional loss of the charged particles to the chamber wall,[13,14] as well as from the effective ionization of high energy electrons by the $E \times B$ field near the antenna, where the E field is formed parallel to the antenna and the B field is produced across the antenna by the magnets. Therefore, in our case, by arranging the multipolar magnets near and parallel to the antenna, instead of using the conventional magnet arrangement wherein polarized magnets are alternatively placed all around the chamber wall,[13–15] an effective increase of plasma density and PR etch rates could be obtained.

Figure 4 shows the uniformities of the plasmas, as measured by the ion current densities of a Langmuir probe as a function of the chamber position perpendicular to the an-

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