Effect of Antenna Diameter on the Characteristics of Internal-Type Linear Inductively Coupled Plasma

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In this study, the antenna characteristics of an internal-type, linear, inductively coupled plasma (ICP) source were varied by changing the inner conductor diameter of the ICP antenna composed of an inner conductor enclosed by outer dielectric tubing. The effect of the varied antenna characteristics on the plasma characteristics and the electrical characteristics of the large area plasma source with a substrate area of $2300 \times 2000\,mm^2$ were investigated. The decrease of the antenna conductor diameter from 25 to 10 mm decreased the capacitance of the antenna between the conductor and the dielectric tubing, increased the plasma density, decreased the plasma potential at the same rf power, and improved the plasma uniformity. The increased plasma density and the decreased plasma potential obtained with the smaller antenna conductor diameter were attributed to the increased power transfer efficiency caused by the increased inductive coupling at the same rf power.

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1. Introduction

High density (10^{10}–$10^{12}\,cm^{-3}$) and low temperature plasma sources have been intensively studied for various kinds of device processing such as flat panel display processing (FPD), and semiconductor processing.[1,2] Among the various high-density plasma sources, inductively coupled plasma (ICP) sources have been applied to a variety of plasma processing. Generally, in most ICP reactors, the antenna conductor is placed on the dielectric material and RF power is transferred to the plasma through the dielectric material by inductive coupling with a time-varying magnetic field generated on the conducting antenna.

To increase the inductive coupling to the plasma for the FPD application, internal-type antennas have been more intensively investigated, where the inner conducting antenna with the dielectric material enclosing the conducting antenna is inserted into the vacuum chamber. In the internal-type antennas, the inner conducting antenna is generally enclosed by thin dielectric tubing that tends to increase the electrostatic coupling to the plasma due to the high capacitance of the dielectric material in contact with the plasma. Despite the requirement for electrostatic coupling for easier plasma ignition in the low density ICP, the electrostatic coupling between the antenna and plasma should be low enough to prevent non-uniform power dissipation and unstable plasma formation. A few research groups have proposed various methods to suppress the electrostatic coupling of the ICP source antenna to the plasma, such as superimposing a dc current on the antenna, and installing capacitance termination.[5–8)]

In this paper, the electrostatic coupling of the antenna for an internal-type, linear ICP source was varied by changing the conductor diameter of the ICP antenna composed of an inner conducting antenna and an outer dielectric tubing, and its effect on the plasma characteristics and electrical characteristics of a large area plasma source were investigated.

2. Experiment

The antenna configuration of the internal-type, linear ICP system used in this study is schematically shown in Fig. 1(a). The processing chamber had a rectangular shape with the dimensions of $2{,}750 \times 2{,}350\,mm^2$ for the application of large-area FPD processing and the substrate size was $2{,}300 \times 2{,}000\,mm^2$. The internal-type ICP antenna consisted of eight internal, linear antennas, and one side of each antenna was alternatively connected to a 10 kW 13.56 MHz RF power generator through an L-type matching network while the other side was connected directly to the ground. The inner conductor of the antenna was made of copper tubing (inner conducting antenna) for water cooling and was fully covered with quartz tube (dielectric tubing) for dielectric isolation from the plasma. The diameter of the inner conducting antenna was varied from 10 to 25 mm while the diameter of the quartz tube was maintained at 33 mm, as shown in Fig. 1(b).

The characteristics of the plasmas were investigated with a Langmuir probe (Hiden Analytical ESP) installed at the center of the chamber. The electrical properties of the internal-type antenna were measured by an impedance analyzer (MKS) located between the matching box and the antenna. Finally, using an RF power of 8 kW and a gas mixture of Ar/O_2 ($Ar : O_2 = 7 : 3$) at 15 mTorr, a glass substrate covered with photoresist was etched and its etch depth was measured using a step profilometer (Alpha Step 500) to estimate the etch uniformity.

3. Results and Discussion

For the large area, internal-type, linear ICP source, the plasma characteristics were measured using a Langmuir probe and the results are presented in Fig. 2 that shows the plasma density and plasma potential at 5 mTorr Ar as functions of the inner conducting antenna diameter and 13.56 MHz RF power. The diameter of the inner conducting antenna was varied from 10 to 25 mm while the diameter of the outer dielectric tubing was maintained constant and the RF power was also varied from 3 to 9 kW. The Langmuir probe was located at the center of the chamber and about 90 mm below the plasma source. As shown in the figure, the decrease of the inner antenna diameter from 25 to 10 mm increased the plasma density for all of the rf powers. The plasma density was increased from $0.76 \times 10^{11}/cm^3$ for 25 mm to $1.27 \times 10^{11}/cm^3$ for 10 mm at an RF power of 9 kW. The plasma potential decreased with increasing rf

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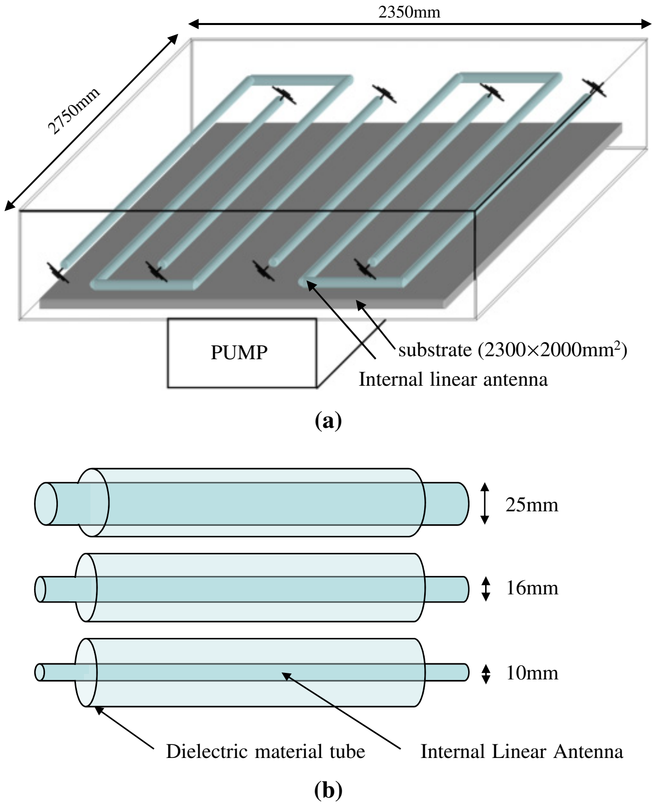

Fig. 1. (Color online) (a) Schematic diagram of the large area, internal-type, linear inductively coupled plasma source used in this study. (b) Arrangement of the internal-type linear antennas, where, 10, 16, and 25 mm inner antenna diameters were enclosed by the same size dielectric tubing.

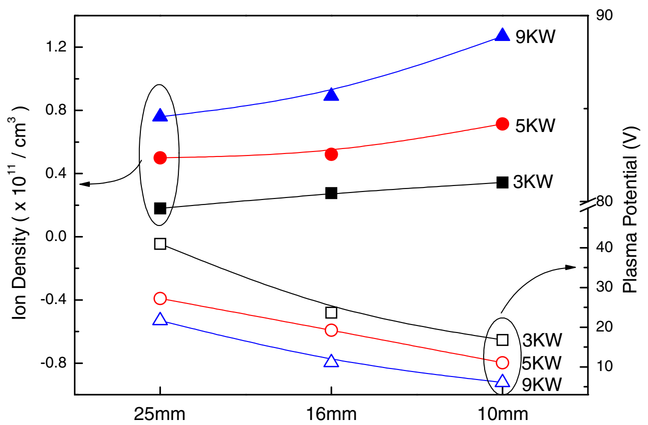

Fig. 2. (Color online) Ar^{+} plasma density and plasma potential measured using a Langmuir probe at the center of the chamber for inner antenna diameters of 10, 16, 25 mm and RF powers of 3, 5, and 9 kW at 5 mTorr Ar.

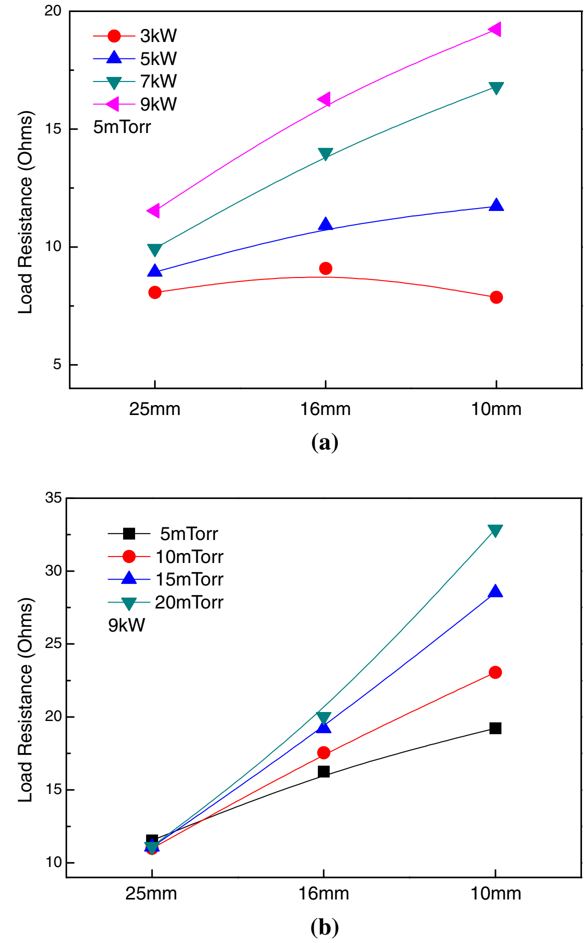

Fig. 3. (Color online) Load resistance measured as a function of (a) RF power and (b) working pressure, for inner antenna diameters of 10, 16, 25 mm, by an impedance analyzer on the antenna located close to the RF power input.

power for all of the antenna diameters, and also decreased with decreasing inner antenna diameter at each of the RF powers. Especially, at an RF power of 9 kW, the plasma potential decreased from 21 to 6 V as the inner antenna diameter decreased from 25 to 10 mm.

Figure 3 shows the load resistance of the ICP source measured as a function of inner antenna diameter (a) for different RF powers at 5 mTorr Ar and (b) for different Ar pressures at an RF power of 9 kW. As shown in Fig. 3(a), increasing RF power always increased the load resistance for all of the inner antenna diameters and decreasing inner antenna diameter increased the load resistance for all RF powers except 3 kW. When the operating pressure was increased, the load resistance was also increased for all of the inner antenna diameters but this increase was more significant for the smaller inner antenna. The increased load resistance with increasing RF power observed in Fig. 3(a) for all of the inner antenna diameters was attributed to the increased ohmic loss to the plasma by increased inductive coupling at the higher RF powers. The increased load resistance with increasing operating pressure observed in Fig. 3(b) was also attributed to the increased ohmic loss to the plasma through the increase of collision frequencies at the higher pressure.

Regarding the effect of varying the diameter of the inner antennas, the smaller inner antenna diameter tended to show less capacitive coupling and more inductive coupling to the plasma at the same RF power and operating pressure. Therefore, the increased load resistance observed with decreasing inner antenna diameter was attributed to the increased ohmic loss to the plasma by the increased inductive coupling. The capacitive coupling to the plasma is related to the sheath voltage (V_{ds}) between the quartz tube and the plasma. The ratio of V_{ds} to RF voltage (V_{rf}) applied to the inner antenna can be represented by[9)]

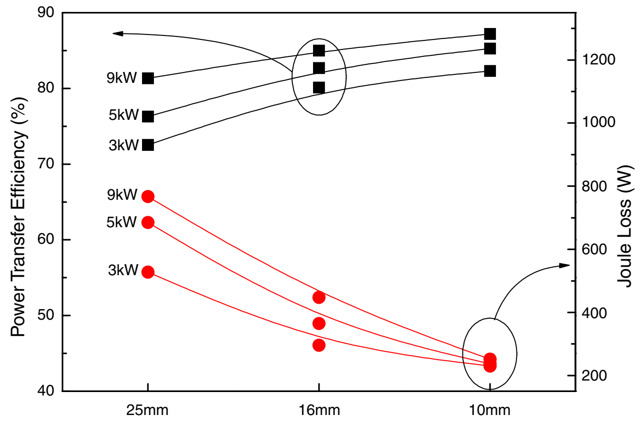

Fig. 4. (Color online) Joule loss and power transfer efficiency for antenna diameters of 10, 16, 25 mm and RF powers of 3, 5, and 9 kW at 5 mTorr Ar measured by an impedance analyzer.

$$\frac{V_{ds}}{V_{rf}} = \frac{C_{ad}C_{d}}{C_{ad}C_{d} + C_{ad}C_{ds} + C_{d}C_{ds}},$$

where C_{ad} is the capacitance between the inner antenna and the quartz tube, C_{ds} the capacitance between the quartz tube and the plasma, and C_{d} the capacitance of the quartz tube itself. As the inner antenna diameter is decreased, the capacitance C_{ad} is decreased while the other capacitance values are maintained at the same level and the decrease of C_{ad} decreases the ratio of V_{ds}/V_{rf}. Therefore, the decrease of inner antenna diameter decreases the capacitive coupling to the plasma and the power applied to the antenna is used more for inductive coupling. Therefore, in Fig. 3, the higher load resistance for the smaller antenna diameter was attributed to inductive coupling. In addition, the decrease of plasma potential observed in Fig. 2 with decreasing inner antenna diameter and with increasing RF power was also attributed to the decrease of V_{ds} and the increase of inductive coupling.

The power transfer efficiency and Joule loss were measured as a function of inner antenna diameter for different RF powers at 5 mTorr Ar and the results are shown in Fig. 4. As shown in the figure, increasing RF power increased the power transfer efficiencies and increased the Joule loss for all the inner antenna diameters. At the same rf power, decreasing inner antenna diameter increased the power transfer efficiency and decreased the Joule loss. At an RF power of 9 kW and 5 mTorr Ar, a power transfer efficiency of 87% was obtained for the 10 mm inner antenna diameter. The increased power transfer efficiency and the decreased Joule loss observed at the lower RF power and the smaller antenna diameter were attributed to the increased inductive coupling to the plasma by decreasing the power loss in the antenna itself and in the matching network and by decreasing the sheath voltages in contact with the plasma.[10,11]

The etch uniformities of the internal-type, linear ICP source were observed as a function of the internal antenna diameter by etching a photoresist-covered glass substrate using a 15 mTorr Ar/O_2 (7 : 3) gas mixture at an RF power of 8 kW. The etch time was maintained for 10 min. We used the gas mixture composed of Ar/O_2 (7 : 3) because it is known that high O_2 percentages in the gas mixture can change the plasma characteristics significantly by decreasing plasma density, by decreasing the electron temperature, etc.[12]

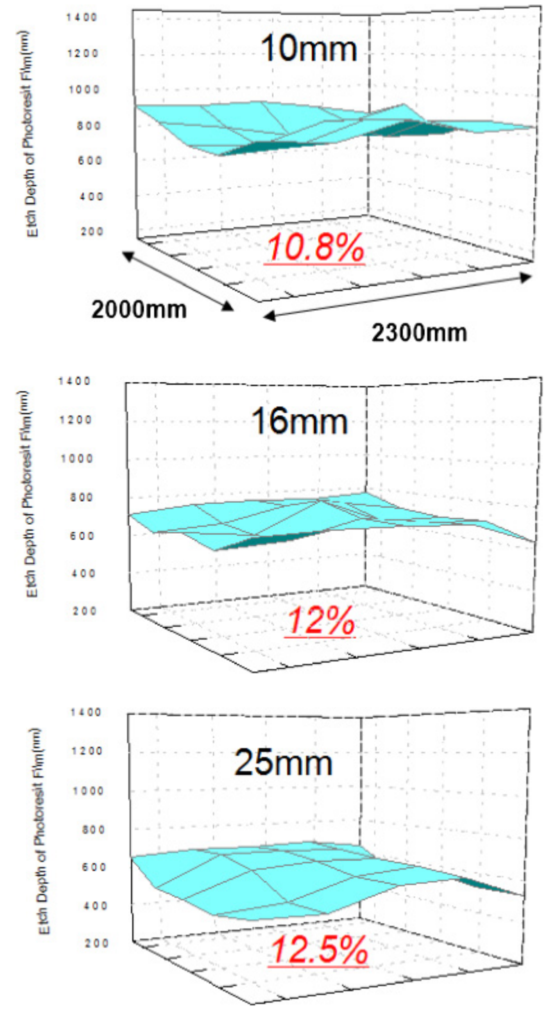

Fig. 5. (Color online) Etch uniformity of photoresist film on a substrate area of 2,300 x 2,000 mm^2 measured at an RF power of 8 kW and with an Ar : O_2 (7 : 3) mixture gas for antenna diameters of 10, 16, and 25 mm at 15 mTorr Ar.

As shown in Fig. 5, the etch uniformity of the photoresist was improved, although not significantly, from 12.5% for the 25 mm antenna diameter to 10.8% for the 10 mm antenna diameter. The photoresist etch rate was less than 100 nm/min because of the small RF power density, and lack of any dc biasing and substrate heating. Nevertheless, the internal ICP operated with the 10 mm antenna diameter exhibited an etch rate increased by about 1.8-fold compared to that operated with the 25 mm antenna diameter due to the high density plasma for the 10 mm antenna diameter.

4. Conclusions

This study investigated the effect of inner antenna diameter on the characteristics of an internal-type, linear ICP by varying the inner antenna diameter at various RF powers and operation pressures. Decreasing inner antenna diameter of the internal-type, linear ICP source decreased the capacitance between the inner antenna and the outer dielectric tubing, and thereby decreased the sheath voltage between the dielectric tubing and the plasma, which further decreased the capacitive coupling to the plasma and increased the inductive coupling to the plasma. Therefore, the effectiveness of the plasma coupling was increased by using an inner conducting antenna with a smaller diameter. By decreasing the inner antenna diameter of the internal-type, linear ICP source from 25 to 10 mm, the plasma density was increased from 0.76×10^{11} to $1.27 \times 10^{11}/\mathrm{cm}^3$ and the plasma potential was decreased from 22 to 5 V at an RF power of 9 kW and 5 mTorr Ar. When the etch uniformity was measured on a substrate of dimensions $2300 \times 2000\,\mathrm{mm}^2$ by etching photoresist using an Ar : O_2 (7 : 3) mixture gas and an RF power of 8 kW, an etch uniformity of about 10.8% was obtained for the 10 mm inner antenna diameter.

Acknowledgment

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