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Characteristics of Plasma Using a Ferromagnetic Enhanced Inductively Coupled Plasma Source

Kyong Nam Kim, Jong Hyeuk Lim, Jung Kyun Park, Jong Tae Lim, and Geun Young Yeom

Department of Advanced Materials Engineering, Sungkyunkwan University, Suwon, Gyunggi-do 440-746, Korea

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Plasma characteristics and electrical parameters of an internal linear inductively coupled plasma (ICP) source with a U-type antenna with/without a Ni–Zn ferromagnetic material installed near the antenna were investigated. The application of the ferromagnetic material to the antenna increased the plasma density, improved the plasma uniformity, lowered the antenna voltage, and increased the stability of the plasma during the operation. For the U-type ferromagnetic enhanced internal linear ICP source, a high density plasma on the order of 4.5×10^{11} cm^{-3} which is about three higher than that obtained for the source without the ferromagnetic material could be obtained at the pressure of 10 mTorr Ar and at the RF power of 600 W at 13.56 MHz. [DOI: 10.1143/JJAP.47.7339]

KEYWORDS: large area, impedance, internal antenna, inductively coupled plasma, ferromagnetic

1. Introduction

Recently, there has been an increasing interest in large-area high-density plasmas for material processing at low temperature, which include the fabrication of microelectronic materials and devices, material surface structuring and modification, thin film deposition and etching, and plasma-assisted synthesis of novel materials.[1,2] Among the various high density plasma sources, inductively coupled plasma (ICP) sources are known to be the most promising tools to fulfill various process requirements. In fact, due to their capabilities in generating high density plasma for a wide range of pressure and in scaling up the plasma source to a larger size relatively easily, the ICPs are widely used as the well-established tools for various material processing. Nevertheless, the scale up of the ICP source to a large size is possible while keeping uniform and high-density plasma is not an easy task.[2–8)]

When the ICP sources are applied to the processing of very large area substrates such as next generation silicon substrates ($\geq$450 mm), flat panel display substrates, etc., the ICP sources show some problems due to the scale up to a large size plasma. Especially, the external spiral antenna-type ICP sources show more problems due to the cost and thickness of the dielectric material and the large antenna impedance caused by long antenna length. The thick dielectric material and the large antenna impedance tend to decrease the power transfer efficiency. In addition, the large antenna impedance increases capacitive coupling to the plasma due to the high radio-frequency (RF) voltage on the antenna and the long antenna length increases the possibility of a non-uniform and unstable plasma due to the standing wave effect.[8–11] To overcome the above problems, the ICP sources utilizing various configurations of internal-type antennas have been proposed to obtain uniform and high density plasmas over large area substrates.[11]

In this study, an internal-type linear inductive antenna referred to as "U-type antenna" has been used for an ICP source and, to improve its plasma characteristics, a ferromagnetic material was attached near the antenna and the effect of the ferromagnetic material on the plasma characteristics and electrical characteristics of the antenna were investigated.

2. Experiment

Figure 1 shows the schematic diagram of the ICP source having the U-type internal antenna enhanced by ferromagnetic material (FE-ICP) used in the experiment. As shown in the figure, the processing system was composed of an ICP source chamber and a plasma processing chamber. The plasma processing chamber was a cylindrical shape having the inner diameter of 380 mm and the substrate diameter was 300 mm. The rectangular shaped ICP source chamber located on the top of the processing chamber contains the internal-type ICP source composed of two linear parallel antennas connected each other at the outside of the source chamber (U-type). The antennas were made of 10 mm diameter copper tubing covered by a quartz tube of 20 mm diameter and the distance between the two antennas was 18 cm. One side of the U-type antenna was connected to the power supply while the other end was connected to the ground. A ferromagnetic material (Ni–Zn) was located between the U-type antenna line and the quartz tubing, therefore, the antenna line and the ferromagnetic material were covered by the quartz tubing. RF power of 5 kW 13.56 MHz was connected to the antenna through a L-type matching network and the Ar gas pressure in the range from 5 to 20 mTorr was used to generate the plasmas.

The plasma characteristics were measured using a Langmuir probe (Hiden Analytical ESP) located 4 cm below the antenna. The electrical characteristics of the antenna were investigated by an impedance probe (MKS) located between the matching box and the antenna. The etch uniformity of the photoresist (PR) film deposited on sodalime glass substrates having the size of 300 mm was measured using a substrate holder installed 8 cm below the source and using 10 mTorr Ar/O_2 (9 : 1) mixture at 600 W of RF power.

3. Results and Discussion

Figure 2 shows (a) the RF root mean square (rms) voltage and (b) the Joule loss representing relative power transfer efficiency as a function of RF power at 10 mTorr Ar for the ICP source with/without the ferromagnetic material installed on the antenna along the antenna line. The RF rms voltage and the Joule loss were measured using an impedance probe installed at the power output of the

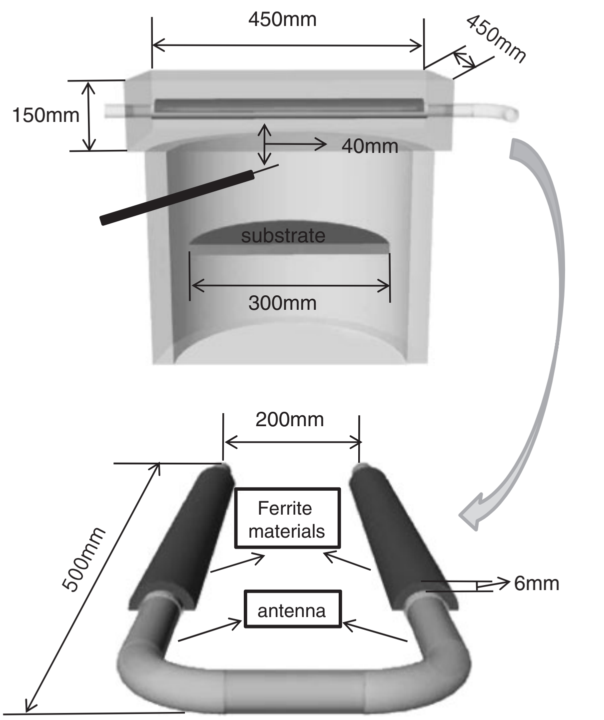


Fig. 1. Schematic diagram of FE-ICP system used in the experiment.

matching network. As shown in Fig. 2(a), the RF rms voltage was increased with increasing RF power for both of the ICP sources with/without the ferromagnetic material. However, the rms voltage was generally lower for the ICP source with the ferromagnetic material. The RF voltage on the antenna induces the DC voltage on the quartz tube surface surrounding the antenna and the induced DC voltage is proportional to the RF voltage on the antenna. Higher DC voltage increases the sputtering of quartz tubing and increases the possibility of substrate contamination. Therefore, the installation of the ferromagnetic material to the antenna was beneficial in decreasing the possibility of contamination by lowering the RF rms voltage on the antenna.[8] Also, as shown in Fig. 2(b), the Joule loss estimated with the impedance probe was increased with increasing delivered power for both of the ICP sources with/without the ferromagnetic material. In the ICP source without the ferromagnetic materials, Joule loss originates from the ohmic loss at the antenna line by RF current flowing on the antenna. But, in the ICP source with ferromagnetic materials, Joule loss originates not only from the antenna line but also from the heating of the ferromagnetic material by induced eddy current to ferromagnetic material. However, as shown Fig. 2(b), the ICP source with the ferromagnetic material showed a lower Joule loss compared to that without the ferromagnetic material possibly due to the smaller current flow at the same RF power which results in lower Joule loss at the antenna line. The lower Joule loss at the same delivered RF power indicates 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. The ferromagnetic material of Ni–Zn used in this study is a material with high magnetic permeability. Due to the high magnetic permeability of the ferromagnetic material, the

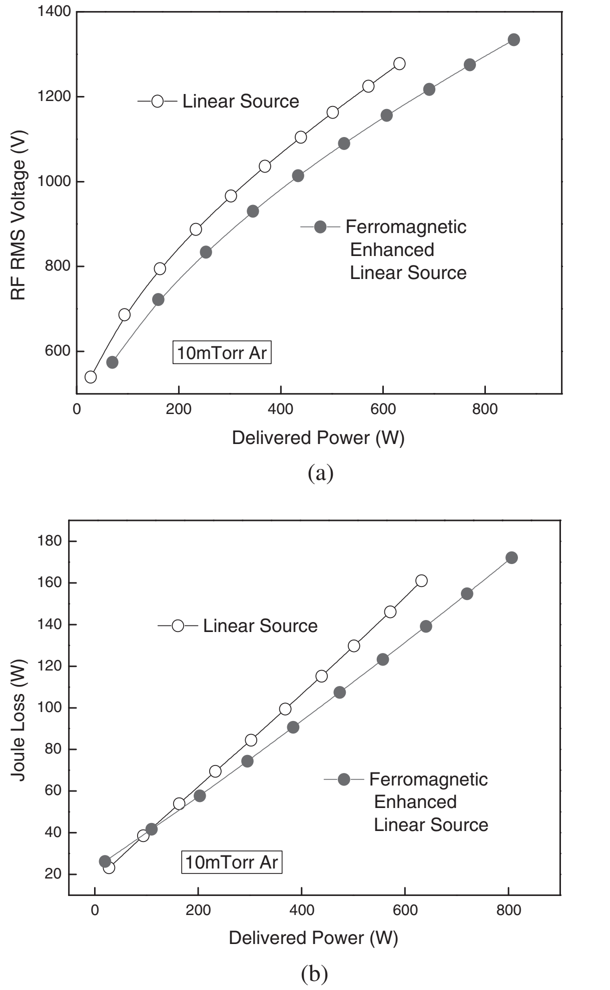


Fig. 2. (a) RF rms voltage and (b) Joule loss measured as a function of RF power for the ICP source with/without the ferromagnetic material at 10 mTorr Ar by an impedance probe installed at the power output of the matcher.

magnetic field becomes to zero in the ferromagnetic material. Therefore, by using the ferromagnetic material as shown in Fig. 1, the magnetic field changes to $B = \mu_0 (I/\pi r)$. (μ_0: the magnetic constant of free space I: the current, r: the effective antenna radius) from $B = \mu_0 (I/2\pi r)$ which is the magnetic field induced on the antenna in free space without ferromagnetic field. Consequently, the use of ferromagnetic material shown in Fig. 1 concentrates the magnetic flux to plasma side and reduces the power loss to the wall side located near the antenna line, and, the magnetic induction towards plasma side is increased by approximately a factor of 2. These effects obtained by the installation of the ferromagnetic material near the antenna improved plasma density, quality factor, uniformity, etc.

Figure 3 shows the plasma density measured at 4 cm below the ICP source as a function of the RF rms current on the antenna installed with/without the ferromagnetic material at 10 mTorr Ar using a Langmuir probe. As shown in the Fig. 3, the increase of RF rms current to the ICP source increased the plasma density almost linearly for both with/without the ferromagnetic material. However, the plasma density of the ICP source with the ferromagnetic material was much higher at the same RF rms current. At 8 A of RF rms current, the plasma density of the ICP source with the

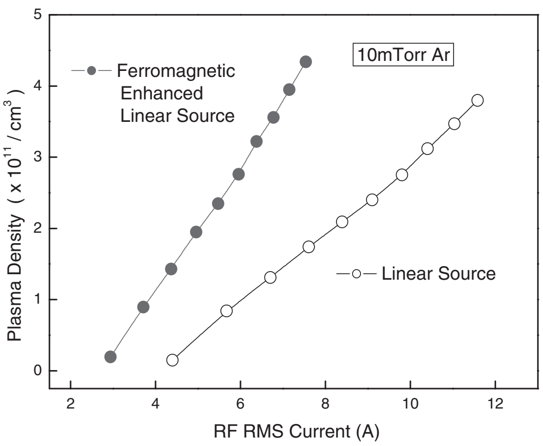
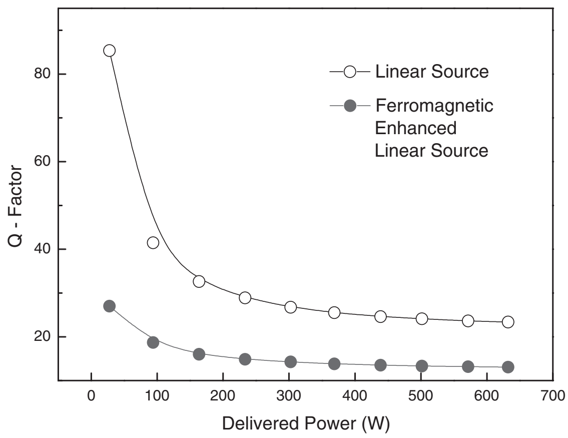


Fig. 3. Ar^+ ion density measured by a Langmuir probe at 4 cm below the antenna as a function of RF rms current for the ICP source with/without the ferromagnetic material. The operation pressure was maintained at 10 mTorr.

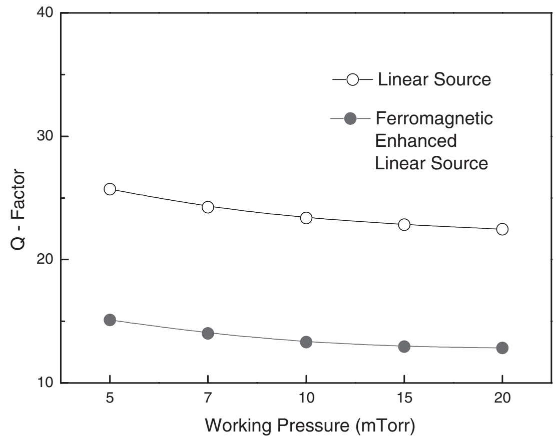
ferromagnetic material was about $4.5 \times 10^{11}/\mathrm{cm}^3$. The plasma density of the ICP source with the ferromagnetic material was about 3 times higher than that without the ferromagnetic material. The higher plasma density obtained for the ICP source with the ferromagnetic material is believed to be related to the increased energy absorption of the electrons in the plasma by the enhanced time-varying magnetic field induced by the ferromagnetic material. Due to the enhanced time-varying magnetic field generated by the ferromagnetic material, higher time-varying electric field is induced in the plasma and it increases the energy absorption of the electrons in the plasma through the electric field, and which causes the increased plasma density at a same RF rms current on the antenna.

Using the impedance probe, the quality factor ($Q = \omega L_t/R_t$) of the ICP source was measured and the results are shown in Fig. 4(a) for the ICP sources with/without the ferromagnetic material. As shown in the figure, the quality factor was decreased with increasing RF power and, at high delivered RF powers, it was nearly saturated for both of the ICP sources with/without the ferromagnetic material. However, at the same RF power, the ICP source with the ferromagnetic material showed a lower quality factor. Figure 4(b) shows the quality factor measured as a function of the working pressure from 5 to 20 mTorr at 600 W of RF power for the ICP sources with/without the ferromagnetic material. As shown in the Fig. 4(b), the increase of working pressure decreased the quality factor slowly for both of the ICP sources with/without the ferromagnetic material. However, the quality factor of the ICP source with the ferromagnetic material was significantly lower than that without the ferromagnetic material.

In general, a plasma system with a high quality factor shows difficulties in the impedance matching for small changes of the chamber environment such as changes of gas composition, RF power, operational pressure, etc. due to the high selectivity of the circuit to the environment. Therefore, if there are small changes in operating environment, matching point is distorted significantly, therefore, plasma becomes unstable. However, a plasma system with a lower quality factor is more stable because the matching point is



(a)



(b)

Fig. 4. Quality factor calculated with the data obtained by an impedance probe (a) as a function of RF power at 10 mTorr Ar and (b) as a function of working pressure at 600 W of RF power for the ICP system with/without the ferromagnetic material.

not changed significantly for the various changes of the chamber environment. Therefore, it is believed that the ICP source with the ferromagnetic material tends to show more stable plasmas compared with that without the ferromagnetic material.

The etch uniformity on the 300 mm diameter substrate area was estimated by etching a PR covered glass substrate using 10 mTorr Ar/O_2 (9 : 1) mixture at 600 W of RF power for 3 min. The PR etch uniformity of the ICP source without the ferromagnetic material was 16.6% (not shown). However, as shown in Fig. 5, the PR etch uniformity of the source with the ferromagnetic material was approximately 10.8%. It is believed that, through the optimization of the antenna distance between two linear antennas, the further improvement of the uniformity could be obtained for the ICP source with the ferromagnetic material.

4. Conclusions

In this study, the effect of the ferromagnetic material installed to the U-type antenna of the linear internal ICP source on the electrical characteristics of the antenna and the plasma characteristics was investigated. The application of the Ni–Zn ferromagnetic material to the internal linear antenna improved the plasma uniformity, lowered the

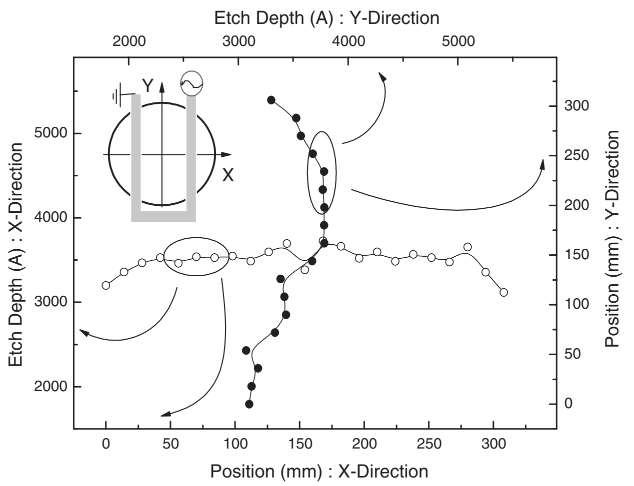


Fig. 5. Etch depth of the PR over a substrate area of 300 mm wafer measured at 600 W of RF power and 10 mTorr of operating pressure in an Ar/O_2 (9 : 1) mixture.

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 ferromagnetic material improved the plasma density significantly. As a result, by the application of the ferromagnetic material to the U-type antenna of the ICP source, a high plasma density of $4.5 \times 10^{11}\,cm^{-3}$ which is about three times higher than that without the ferromagnetic material could be obtained at the pressure of 10 mTorr Ar and at the delivered RF power of 600 W with good plasma stability. The improvement of plasma properties by the application of the ferromagnetic material appears related to the increased ionization through the enhanced time-varying magnetic field in the plasma and the decreased loss of the power to the chamber wall near the antenna line by concentrating the magnetic flux around the antenna line.

Acknowledgment

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