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ORIGINAL PAPER

Plasma Characteristics of a Ni–Zn Ferrite Enhanced Internal-Type Inductively Coupled Plasma Source Operated at 2 and 13.56 MHz

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Abstract Plasma and electrical characteristics of an internal-type inductively coupled plasma source with a Ni–Zn ferrite module installed near the antenna were investigated for different rf power frequencies of 2 and 13.56 MHz. Due to the lower heating of the Ni–Zn ferrite module on the antenna for the operation at 2 MHz compared to the operation at 13.56 MHz, higher plasma density and lower rf rms antenna voltage were resulted for the operation at 2 MHz in addition to more stable plasma characteristics. By the application of 500 W of rf power to the source, a high plasma density of 8×10^{11} cm^{-3} which is about four times higher than that with 13.56 MHz could be obtained at the pressure of 10 mTorr Ar. When photoresist etch uniformity was measured for the operation with 2 MHz by etching photoresist on a 300 mm diameter substrate using 10 mTorr Ar/O_2 (9:1) mixture, the etch uniformity of about 5.5% could be obtained.

Keywords Internal antenna · Ferrite inductively coupled plasma

Introduction

For the application to thin film deposition or etching, various high density plasma sources such as inductively coupled plasma (ICP) sources, electron cyclotron resonance (ECR) plasma sources, helicon-wave-excited plasma sources, etc. have been considered [1, 2]. Among the various plasma sources, ICP sources are widely studied because of their simple physics and scalability compared with other plasma sources [2, 3]. Therefore, ICP sources have been widely applied to material surface modification, thin film deposition and etching, plasma-assisted synthesis of novel materials, etc. on large area substrates [3–7].

Despite of a wide application of ICP source in various areas, there are some problems in their application to large area substrates. When the ICP is applied to large area substrates, long ICP antenna needs to be used, and, due to the high antenna voltage (∼a few kV)

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induced on the antenna, an capacitive coupling between the rf antenna and the plasma is increased [1, 2]. This can result in intensive ion bombardment of the ICP source antenna causing erosion of the dielectric material on the antenna and contamination by the sputtered dielectric materials. In addition, non-uniform rf voltage developing along the long antenna caused by a standing wave effect may also deteriorate plasma uniformity over the substrate surface [8–11].

To overcome the above problems, the ICP sources utilizing various configurations of internal-type short antennas have been proposed to obtain uniform and high density plasmas in addition to a low antenna voltage [12, 13]. Also, to increase the coupling of the ICP source to the plasma, various magnetically enhanced ICP sources such as multipolar magnetic field enhanced ICP source, ferrite enhanced ICP sources, etc. have been investigated [1, 4, 5, 15].

In this study, as an application to large area plasma processing, a “U-type” internal linear ICP source with a Ni–Zn ferrite module was used to enhance the ICP source coupling to the plasma and the effect of the different driving frequency of 2 and 13.56 MHz on the plasma characteristics and electrical characteristics of the plasma source was investigated.

Experiment

Figure 1 shows the schematic diagram of the Ni–Zn ferrite module enhanced internal-type ICP system having a “U-type” internal antenna used in the experiment. As shown in the figure, the processing system was consisted of a plasma processing chamber in Fig. 1a and a “U-type” internal-type antenna with a Ni–Zn ferrite module in Fig. 1b. The inner diameter of plasma processing chamber was 380 mm and the substrate diameter was 300 mm. On the top of the processing chamber, a rectangular shaped internal ICP source composed of two linear parallel antennas connected each other at the outside of the source chamber (U-type) was located. 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 20 cm. One side of the U-type antenna was connected to the power supply while the other end was connected to the ground. A Ni–Zn ferrite module was located between the U-type antenna line and the quartz tubing. A total of 2 or 13.56 MHz of rf power was connected to the antenna through a L-type matching network.

The plasma characteristics were measured using a commercial Langmuir probe (Hiden Analytical Inc., ESP) which has a compensation circuit in front of the probe tip to remove possible rf noise from the rf plasma (The Langmuir probe fabricated by the Hiden Analytical Inc. is reported to accurately measure the plasma characteristics for the rf frequencies 2 and 13.56 MHz with external rf filter circuit). Probe was located 4 cm below the antenna. The electrical characteristics of the antenna were investigated by an impedance probe (MKS Inc.) located between the matching box and the antenna. The substrate holder was located 8 cm below the source, and, as the estimation of plasma uniformity, the etch uniformity of photoresist (PR) film deposited on 300 mm sodalime glass substrates was measured using a 10 mTorr Ar/O_2 (9:1) mixture at 500 W of rf power.

Results and Discussion

Figure 2 shows the relative joule loss measured for the antenna with a Ni–Zn ferrite module using an impedance probe as a function of operation time with different driving

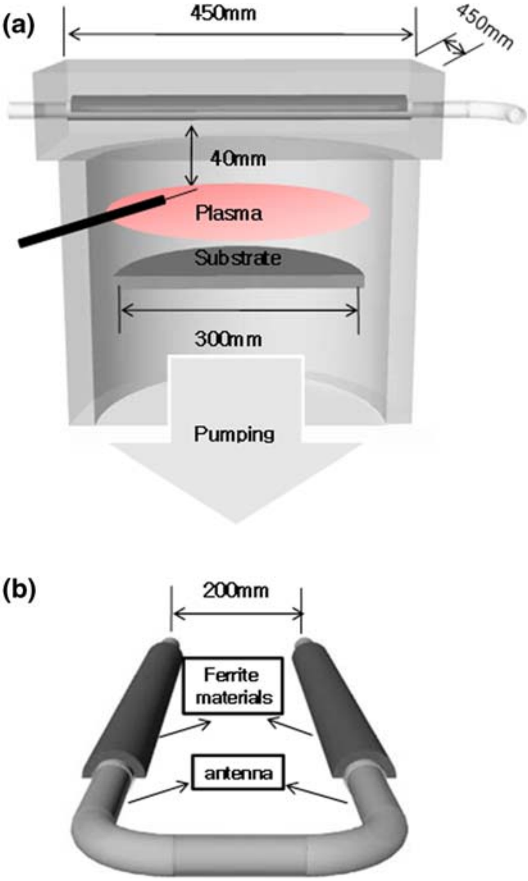

Fig. 1 Schematic diagram of a Ni–Zn ferrite enhanced internal-type ICP system used in the experiment. **a** Ferrite enhanced internal-type ICP system, **b** Ni–Zn ferrite module attached to the internal-type antenna

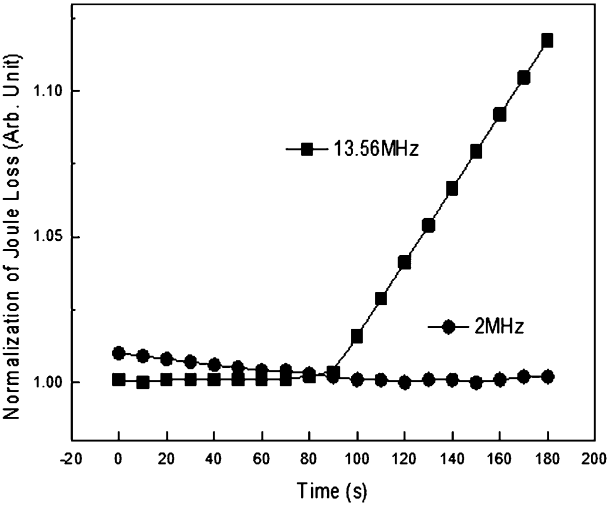

Fig. 2 Relative Joule loss obtained using an impedance probe as a function of operation time for different driving frequencies (2 and 13.56 MHz) at 10 mTorr Ar and 500 W of delivered power

frequencies of 2 and 13.56 MHz for 10 mTorr Ar and 500 W of rf power. Generally, the impedance characteristics of a ferrite material are changed sensitively to the operating frequency. As shown in the figure, in the case of the Ni–Zn ferrite enhanced internal-type ICP source operated at 13.56 MHz of rf power, the relative joule loss to the antenna was increased rapidly as the operation time elapsed about 100 s. But, in the case of the source operated at 2 MHz of rf power, the change of joule loss was negligible with increasing operation time and, therefore, improved stable plasma characteristics could be obtained. Generally, the power loss to the ferrite is divided into hysteresis loss, eddy current loss, and residual loss. Especially, hysteresis loss and eddy current loss depend on operating frequency and, at the higher operating frequency, the ferrite shows higher power loss by the increased hysteresis loss and increased eddy current loss. Therefore, when the ferrite is operated at the higher frequency, the ferrite temperature is raised further due to the increased power consumption to the ferrite. The rapid increase of Joule loss after about 90 s for the operation of the source at 13.56 MHz is believed to be related to the increased ferrite temperature which appears to change the ferrite characteristics. Due to the linear change of plasma characteristics after 90 s of operation, the antenna electrical characteristics and the plasma characteristics were measured at the operating time less than 90 s, and at this condition, reliable and repeatable electrical characteristics of antenna and the plasma characteristics could be obtained. Also, even though we did not air-cool the ICP source in this experiment, by air-cooling the ferrite enhanced ICP antenna, stable plasma characteristics which do no change with time could be also obtained.

Figure 3 shows the impedance and rf rms voltage of the Ni–Zn ferrite enhanced internal-type ICP source operated at 2 and 13.56 MHz of rf power as a function of delivered power at 10 mTorr Ar. The impedance and rf rms voltage were measured using an impedance probe installed at the power output of the matching network and they were measured within tens of seconds after the operation of the ICP source to obtain repeatable data (in the case of 13.56 MHz of rf power, the impedance and rf rms voltage start increasing with time after 90 s of ICP source operation at 500 W of delivered power). As shown in Fig. 3a, the impedance of the source was not significantly changed with the increase of rf power for both sources operated at 2 and 13.56 MHz, but the source operated at 13.56 MHz showed about nine times higher impedance compared to the source operated at 2 MHz. The high impedance of the source operated at 13.56 MHz originates partially from the high impedance of the ICP inductor itself at 13.56 MHz which increases about 6.78 times (inductive component) compared to that at 2 MHz. However, the further increase of the impedance operated at 13.56 MHz is related to the increase of resistive component operated at 13.56 MHz compared to that operated at 2 MHz, which is related to the increase of power loss to the ferrite itself. Therefore, the power transfer efficiency of the source operated at 13.56 MHz compared to that operated at 2 MHz is lower due to the power loss to the ferrite.

In the case of rf rms voltage, as shown in Fig. 3b, even though the rf rms voltage was increased with the increase of delivered power to the source for both 2 and 13.56 MHz, due to the high impedance of the source operated at 13.56 MHz, the rf rms voltage was also higher for the 13.56 MHz. Generally, the high voltage induced on the plasma source antenna increases the capacitive coupling, that is, electrostatic coupling to the plasma. The increase of electrostatic coupling of the source antenna also increases sheath voltage of the plasma source antenna [14, 16]. Therefore, the use of Ni–Zn ferrite enhanced internal-type ICP source operated at 2 MHz of rf power showed more efficient power transfer efficiency to the plasma with a lower rf rms voltage and a lower sheath voltage. Even though the use of 2 MHz instead of 13.56 MHz shows a lower sheath voltage due to the lower rf antenna

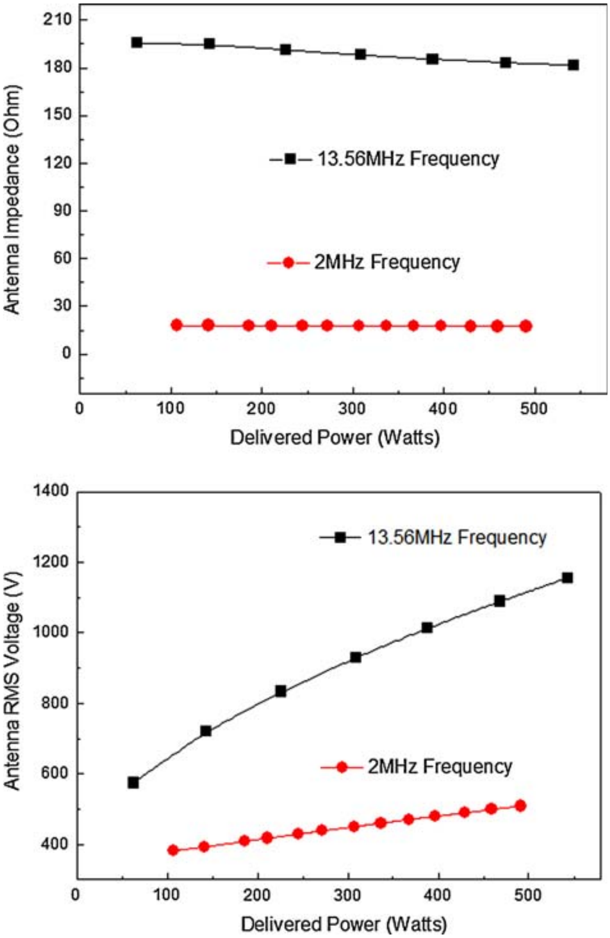

Fig. 3 **a** The impedance and **b** rf rms voltage of Ni–Zn ferrite ICP source operated at 2 and 13.56 MHz of rf power as a function of delivered power at 10 mTorr Ar

voltage, the ion bombarding the surface may show wider energy distribution at the lower frequency by reflecting the instant rf sheath voltage, and which needs further investigation.

Figure 4 shows (a) the plasma density and plasma potential and (b) the electron temperature measured using a Langmuir probe at 4 cm below the ferrite enhanced internal-type ICP source operated at 13.56 and 2 MHz as a function of the delivered power at 10 mTorr Ar. As shown in the figure, the increase of delivered power to the ferrite enhanced plasma source increased the plasma density almost linearly for both 2 and 13.56 MHz of rf power. However, the plasma density of the source operated with 2 MHz of rf power was much higher compared to that with 13.56 MHz at the same delivered power. At 500 W of delivered power, the plasma density of the source with 2 MHz of rf power was about 8×10^{11} cm^{-3}, which is about four times higher than that with 13.56 MHz of rf power. In the case of plasma potential, as shown in the figure, the increase of rf power from 50 to 500 W slightly decreased the plasma potentials and the plasma potentials were in the range of 21–23 V for 13.56 MHz and 12–17 V for 2 MHz, therefore,

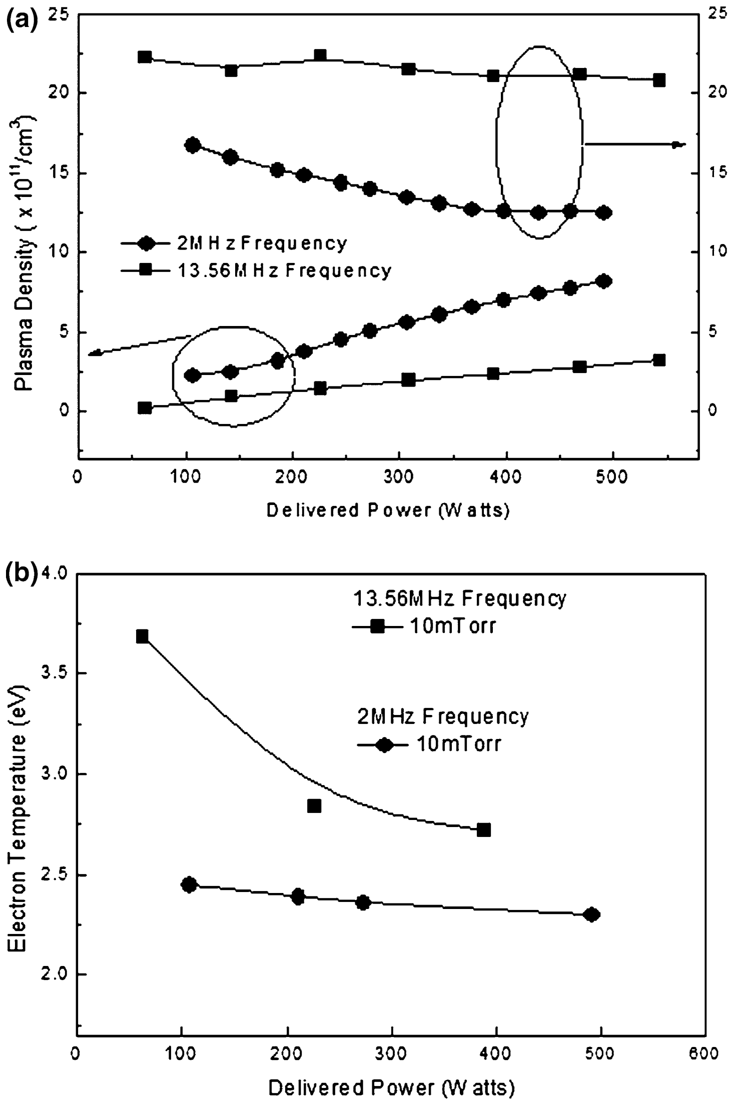

Fig. 4 **a** The plasma density and plasma potential and **b** the electron temperature measured at 4 cm below the Ni–Zn ferrite enhanced internal-type ICP source as a function of the delivered power at 10 mTorr Ar

a lower plasma potential could be observed for 2 MHz of rf power. The higher plasma density observed for the source operated at 2 MHz is believed to be related to the decreased power loss to the ferrite at the same rf power and the decreased capacitive coupling. The lower plasma potential observed for the 2 MHz operation also appears to be related to the increased inductively coupling to the plasma at 2 MHz in addition to the lower rf antenna voltage. When the electron temperature was measured using the Langmuir probe, as shown in Fig. 2b, the ICP source operated at 2 MHz rf power showed lower electron temperatures in the range of 2.3–2.4 eV while the source operated at 13.56 MHz showed a little higher electron temperature in the range from 2.7 to 3.7 eV.

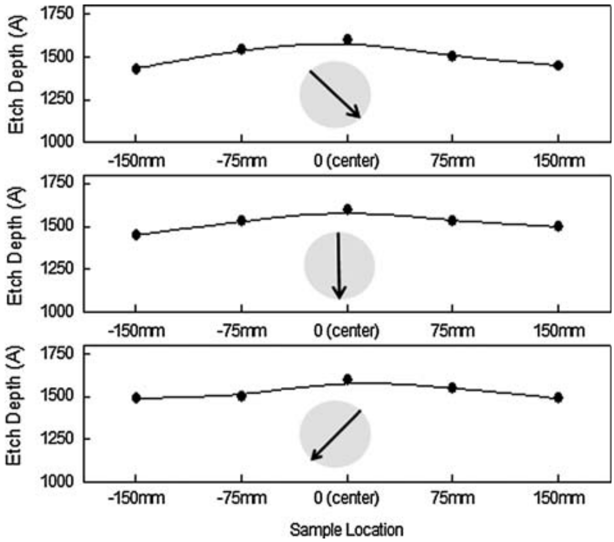

Fig. 5 Etch depth of PR on the substrate area of 300 mm wafer measured at 500 W of rf power and 10 mTorr of operating pressure in an Ar/O_2 (9:1) mixture for the source operated at 2 MHz

The PR etch uniformity of the ferrite enhanced internal-type ICP sources operated at 2 MHz 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 500 W of delivered power for 40 s and the results are shown in Fig. 5. The distance between the source and the substrate was maintained at 8 cm. As shown in Fig. 5, the PR etch uniformity of the plasma source with 2 MHz of rf power was not significantly dependent on the orientation of the substrate relative to the internal-type antenna direction of the source and was approximately 5.5%. It is believed that, through the optimization of the antenna distance between two linear antennas, the further improvement of the uniformity could be obtained.

Conclusions

In this study, plasma characteristics and electrical parameters of an internal-type linear ICP source with a Ni–Zn ferrite module installed near the antenna were investigated as a function of 2 and 13.56 MHz of rf power. The application of 2 MHz of rf power to the ICP source showed higher plasma density, lower plasma potential, and lower rf rms voltage compared to the source operated at 13.56 MHz. The improved plasma and electrical characteristics shown for the source operated at 2 MHz was related to the lower power loss to the ferrite installed near the antenna and lower impedance of the ferrite at the lower rf operating frequency. By the application of the ferrite enhanced ICP source with 2 MHz of rf power, a high plasma density of 8×10^{11} cm^{-3} which is about four times higher than that with 13.56 MHz could be obtained at the pressure of 10 mTorr Ar and at the delivered rf power of 500 W.

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