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Investigation of the plasma uniformity in an internal linear antenna-type inductively coupled plasma source by applying dual frequency

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ABSTRACT

A large area inductively coupled plasma source with an internal linear-type antenna was operated in dual frequency mode (2 MHz/13.56 MHz), and the electrical/plasma characteristics of the ICP source were examined as a function of the relative rf power ratio. When the source was operated in single frequency mode (13.56 MHz only), approximately 8.5% plasma uniformity was observed at 5 kW of 13.56 MHz rf power for the substrate size of 880 mm × 660 mm. The plasma uniformity improved with increasing rf power. However, a further improvement in plasma uniformity to approximately 6.3% could be obtained using the dual frequency mode by applying 0.9 kW of 2 MHz rf power in addition to 5 kW of 13.56 MHz. For 15 mTorr Ar, the plasma density at a dual frequency rf power of 0.9 kW 2 MHz/5 kW 13.56 MHz was $1.6 \times 10^{11}/\text{cm}^3$ and the electron temperature was approximately 3 eV. The addition and increase in 2 MHz rf power to the 13.56 MHz power increased the plasma density without increasing the electron temperature.

1. Introduction

The development of a uniform high-density plasma source is a major issue in plasma processing for a variety of microelectronic devices. In particular, for flat panel displays, the substrate is increasing in size every few years, and in the case of thin film transistor liquid crystal displays, the substrate size is as large as 2.2 m × 2.5 m. Therefore, obtaining good uniformity is the most important factor in the plasma processing of flat panel displays.

High density plasma sources have been investigated widely for the plasma processing of various microelectronic devices, such as semiconductor integrated circuit devices, solar cells, light emitting diodes, etc. in addition to flat panel display devices. This is not only due to the increased processing rates but also due to the possibility of the processing at lower temperatures, particularly for plasma enhanced chemical vapor deposition.

Of the variety of high density plasma sources, inductively coupled plasma (ICP) sources are promising candidates for the fabrication of microelectronic devices from semiconductor devices, such as flat panel displays, on account of the relatively simple antenna and source structure, and easier scalability to a large area source, etc. [1] Although the ICP source is easily scalable to a large area, when the source size is larger than a meter, the standing wave effect due to the length of the ICP source antenna and capacitive coupling to the plasma due to the increase in antenna voltage become significant. Therefore, in order to overcome these problems, many researchers have studied internal-type ICP sources with various ICP source antenna configurations. [2] Wu et al. and Setsuhara et al. examined the effect of the various antenna shapes on the large area plasma uniformity using internal linear antennas connected in series and loop-type internal antennas connected in parallel. [3–7] In the case of Wu et al. a traveling wave was introduced to overcome the standing wave problem caused by the long internal antenna length connected in series as well as to obtain uniform plasma. In the case of Setsuhara et al. a separate power source was connected to each antenna to control the power uniformity and plasma uniformity.

In this study, an internal linear-type ICP source called a “double comb-type ICP source” was used and a dual frequency mode composed of 2 MHz and 13.56 MHz sources was introduced to the ICP source antennas to improve the plasma characteristics, such as plasma uniformity, plasma density, etc. In general, dual frequency mode has been applied to capacitive coupled plasma source systems to control the ion energy effectively. [8–10] In this study, the dual frequency mode was applied to the internal linear-type ICP source and its effect on the electrical and plasma characteristics of the ICP source was examined as a follow-up experiment of a previous study. [11].

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2. Experimental setup

Fig. 1 shows a schematic diagram of the experiment setup and internal linear-type antenna array used in this study. The ICP source used in this experiment was a rectangular shape with a size of 1020 mm × 830 mm. A substrate holder with a size of 880 mm × 660 mm was installed below the ICP source and the distance between the antenna array in the ICP source and the substrate holder was maintained at 9 cm. As the ICP source antenna, five internal liner antennas were installed in parallel in the chamber, where each antenna consisted of an inner conductor made from a copper tube (10 mm diameter) and a quartz tube surrounding the inner conductor coaxially (33 mm diameter) to isolate the inner conductor from the plasma. The inside of the inner conductor tube was cooled with chilled water. One side of the antennas was connected alternatively to the rf power through an L-type matching network, while the other side of the antennas was grounded to form a "double comb-type antenna". As shown in Fig. 1(b), in the case of the dual frequency mode configuration, the left power connection side of the comb-type antenna composed of three linear antennas was connected to a 1 kW 2 MHz power supply. On the other hand, the right power connection side of the comb-type antenna composed of two linear antennas was connected to a 5 kW 13.56 MHz power supply. In the case of operation of the ICP source in single frequency mode for comparison with the dual frequency mode, both power connection sides of the comb-type antennas (left three antennas and right two antennas of Fig. 1(b)) were connected to a single 5 kW 13.56 MHz power supply.

The plasma characteristics, such as plasma density, ion saturation current, and electron temperature, were measured using a Langmuir probe (Hiden Analytical Inc., ESP) installed 7.5 cm below the ICP source antenna at a pressure of 15 mTorr of Ar. In addition, the electrical characteristics, such as the rf current on the ICP source antenna and the phase angle between rf voltage and rf current, were measured using an impedance probe (MKS Inc.).

3. Results and discussion

The characteristics of the ICP source with the internal linear-type antennas have been measured previously as a function of the rf power by connecting the five antennas to a single 13.56 MHz power source in 15 mTorr of Ar. [12] Fig. 2 shows the plasma uniformity measured as a function of the rf power with a Langmuir probe installed 7.5 cm below the ICP source antenna as shown in Fig. 1(a) and by scanning from the center (0 cm) of the chamber towards the side (33 cm). The plasma uniformity was estimated by measuring the ion saturation current by biasing the probe at -60 V and by calculating the uniformity using the formula of $[(I_{\max} - I_{\min})/(\text{average} \times 2)] \times 100\%$. As shown in Fig. 2, an increase in rf power from 2 kW to 5 kW improved the plasma uniformity

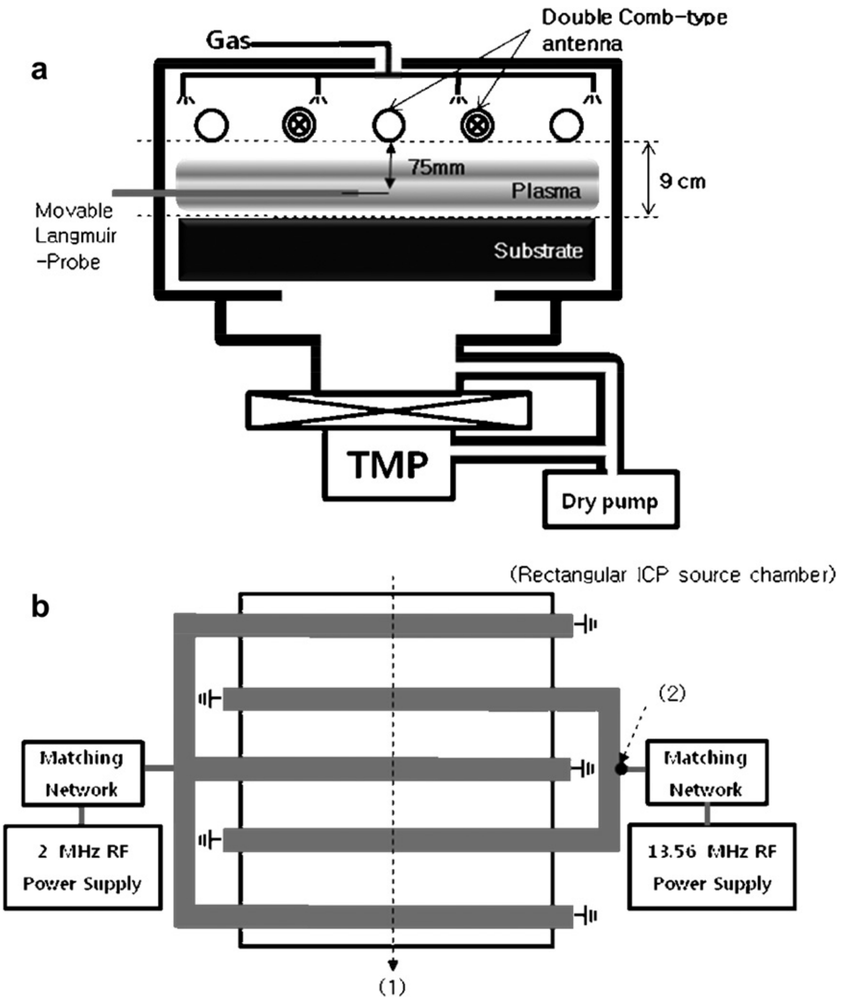

Fig. 1. (a) Schematic diagram of the linear internal-type ICP system used in this experiment. (b) Configuration of the ICP antenna connection in dual frequency mode. Dotted line (1) is the direction measured with the Langmuir probe and the node (2) is the point at which the power factor is measured.

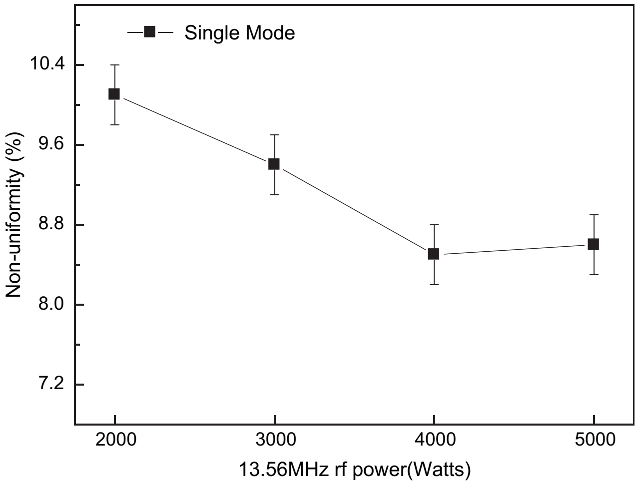

Fig. 2. Plasma uniformity as a function of the 13.56 MHz rf power in single frequency mode at 15 mTorr of Ar.

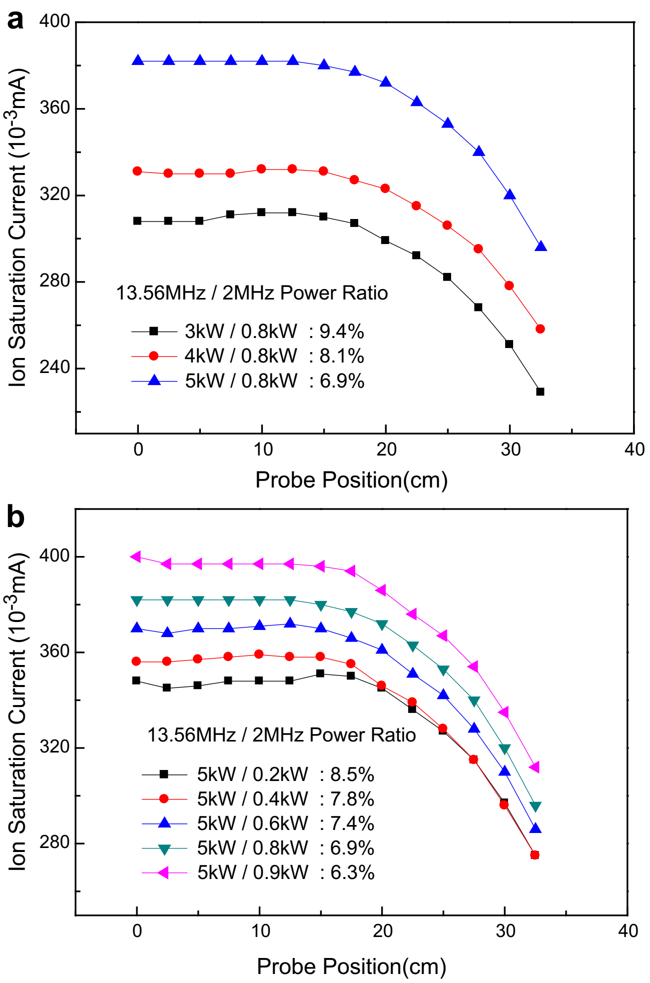

Fig. 3. Ion saturation current measured along the probe position as a function of the 13.56 MHz power/2 MHz power ratio in dual frequency mode at 15 mTorr of Ar. (a) as a function of 13.56 MHz rf power at 0.8 kW of 2 MHz rf power and (b) as a function of 2 MHz rf power at 5 kW of 2 MHz rf power.

from approximately 10%–8.5%. In addition, an increase in ion current density with increasing rf power was observed indicating an increase in plasma density with increasing rf power (not shown). Therefore, the increase in rf power not only increased the plasma density but also improved the plasma uniformity. The improvement of the plasma uniformity with increasing rf power is believed to be related to the spreading of the plasma from the center area to the edge of the substrate holder by increasing the plasma density. That is, for the single mode operation at 13.56 MHz, the better uniformity obtained at the high density plasma up to 4 kW of rf power is believed to be related to the expansion of high density plasma region closer to the wall sides with the increase of rf power. Because the substrate holder size is smaller than the plasma source size, if the high density plasma region spreads over the substrate holder area, then, the further increase of high density plasma region by the further increase of rf power may not be effective in improving the plasma uniformity further as shown in Fig. 2 for the increase of rf power from 4 kW to 5 kW.

A dual frequency mode composed of 2 MHz and 13.56 MHz sources was introduced to improve the plasma uniformity further. 2 MHz power in the range of 0.1–0.9 kW was applied to the three linear antennas located on the left side of the chamber and 13.56 MHz rf power in the range of 3–5 kW was applied to the two linear antennas located to the right side of the chamber, as shown in Fig. 1 (b). The Langmuir probe was located 7.5 cm below the antenna lines and was scanned from the center of the chamber to the edge along the dotted line (1) as shown in Fig. 1(a). The chamber pressure was maintained at 15 mTorr of Ar. Fig. 3 shows the ion saturation current measured on the Langmuir probe biased at −60 V as a function of the probe position (a) for different 13.56 MHz rf powers while keeping 2 MHz rf power at 0.8 kW and (b) for different 2 MHz rf powers while keeping 13.56 MHz rf power at 5 kW. The probe was located 7.5 cm below the antenna lines and was scanned from the center of the chamber to the edge along the vertical direction of the antenna line. The chamber pressure was maintained at 15 mTorr of Ar. As shown in Fig. 3, in all cases, the ion saturation current decreased near the side wall due to the diffusion of ions towards the chamber wall by the consumption of the charged particles by the wall. In addition, as shown in Fig. 3(a), when the 13.56 MHz power was increased from 3 to 5 kW while keeping the 2 MHz power at 0.8 kW, the uniformity of the ion saturation current was improved from 9.4 to 6.9% while the ion saturation current was increased even though the 13.56 MHz rf power was only applied to the right two antennas. Therefore, the plasma uniformity and plasma density increased with increasing 13.56 MHz rf power similar to the case shown in Fig. 2. Moreover, the improvement of the plasma uniformity with increasing 13.56 MHz rf power is also believed to be related to the increase of the plasma density near the chamber inner wall [13]. When 2 MHz rf power was varied from 0.1 to 0.9 kW whilst maintaining the 13.56 MHz at 5 kW, as shown in Fig. 3(b), the uniformity of the ion saturation current was again improved from 8.5 to 6.3% with increasing 2 MHz power from 0.1 to 0.9 kW. Therefore, significant improvement in plasma uniformity could be achieved using the dual frequency mode composed of 13.56 MHz at 5 kW and 2 MHz at 0.9 kW.

For the single mode operation at 13.56 MHz shown in Fig. 2, the improvement of the plasma uniformity was saturated from about 4 kW and no further improvement of plasma uniformity could be observed when the rf power was increased to 5 kW (We did the same experiment repeatedly but obtained similar results). But, as shown in Fig. 3(b), the addition of small 2 MHz rf power less than 1 kW further improved the uniformity. In addition, as shown in Fig. 3(a) and (b), the increase of small 2 MHz rf power was more effective in improving the plasma uniformity (3% improvement per kW) than increasing 13.56 MHz rf power (1% improvement per kW). Therefore, it is believed that the use of dual frequency mode composed of small 2 MHz and 13.56 MHz is effective in improving

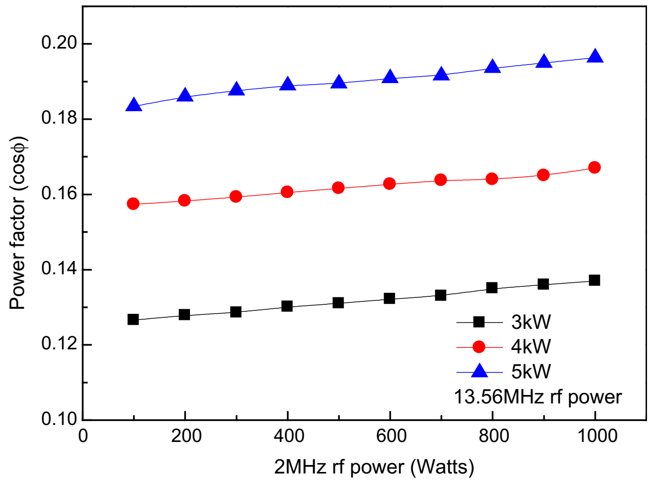

Fig. 4. Power factor(cosφ) as a function of the 2 MHz rf power in dual frequency mode at 15 mTorr of Ar.

the plasma uniformity. The reason for the improvement of plasma uniformity by using the dual frequency mode composed of 2 MHz and 13.56 MHz instead of the single frequency mode at 13.56 MHz is not clear at this time. It could be related to the generation of complicated electric field in the plasma by the dual frequency operation,which enhances the diffusion of charged particles in the plasma. Further investigation is underway.

The increase in plasma density with increasing rf power at both 13.56 MHz and 2 MHz is related to the increased power transfer to the plasma. Fig. 4 shows the power factor (cosφ) measured using an impedance probe as a function of the 13.56 MHz rf power at a fixed 2 MHz rf power and as a function of the 2 MHz rf power at a fixed 13.56 MHz rf power. The power factor is measured at the node as shown the point (2) in Fig. 1(b) to monitor the change of the characteristic of 13.56 MHz rf power feeding antennas by increasing the 2 MHz rf power. As shown in Fig. 4, an increase in both rf powers resulted in an increase in the power factor. An increase in power factor to ≈1 showed more effective power transfer to the plasma and higher plasma density [14,15]. Therefore, higher power transfer efficiency and higher plasma density could be expected by increasing both rf powers through more inductive coupling to the plasma.

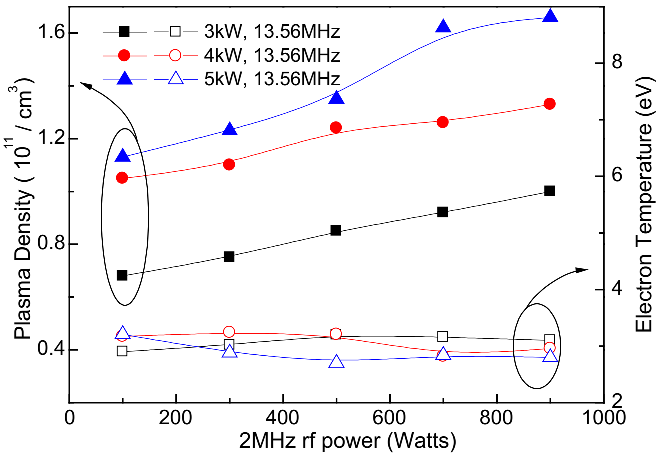

Fig. 5. (a) Plasma density and (b) electron temperature as a function of the 2 MHz rf power in the dual frequency mode at 15 mTorr of Ar.

Fig. 5 shows the plasma density and electron temperature of the internal linear-type ICP source operated with the dual frequency mode measured as a function of the 13.56 MHz rf power and 2 MHz rf power. The experimental conditions were the same as those in Fig. 3(a). The probe was located at the center of the chamber and 7.5 cm below the antenna. As shown in Fig. 5, the measured plasma density increased with increasing 13.56 MHz rf power and 2 MHz rf power in a similar manner to the ion saturation current shown in Fig. 3. A plasma density of approximately $1.6 \times 10^{11}/cm^3$ could be obtained at 0.9 kW of 2 MHz rf power and 5 kW of 13.56 MHz rf power. In the case of the electron temperature, an increase in rf power did not significantly alter the electron temperature and an electron temperature of approximately 3 eV was maintained under these experimental conditions.

4. Conclusions

A dual frequency mode composed of 2 MHz (to the three antennas on the left side) and 13.56 MHz (to the two antennas on the right side) was applied to an internal ICP source composed of five linear internal-type antennas. The effect of the respective rf powers applied to the each side of the ICP source antennas on the plasma characteristics was investigated. The effect of the respective rf powers on the plasma uniformity on the substrate area (880 mm × 660 mm) was examined and compared with that of the ICP source connected to a single 13.56 MHz rf power. When a single 13.56 MHz rf power was applied to all of the five linear antennas of the ICP source, the plasma uniformity improved from approximately 10–8.5% by increasing the rf power from 3 to 5 kW. This was attributed to the increased spread of the plasma to the edge of the substrate holder towards to the chamber wall. A further improvement of the plasma uniformity could be obtained using the dual frequency mode where one side of antennas was connected to a 1 kW 2 MHz rf power source and the other was connected to a 5 kW 13.56 MHz rf power source. Further improvement in plasma uniformity up to 6.3% could be obtained by the addition of 0.9 kW 2 MHz rf power to the 5 kW 13.56 MHz rf power. The improvement in plasma uniformity with increasing 2 MHz rf power to 5 kW of 13.56 MHz rf power was related not only to the increased spreading of the plasma towards to the chamber wall, which is similar to the case with the increase of the single 13.56 MHz rf power, but also probably to the generation of complicated electric field in the plasma by the dual frequency operation which enhances the diffusion of charged particles in the plasma. A plasma density of approximately $1.6 \times 10^{11}/cm^3$ could be obtained above the substrate area (880 mm × 660 mm) at 15 mTorr of Ar using 0.9 kW of 2 MHz rf power and 5 kW of 13.56 MHz rf power.

Acknowledgments

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References

[1] Hong GD. J Korean Phys Soc 2004;44:1000.
[2] Intrator T, Menard J. Plasma Sources Sci Technol 1996;5:371.
[3] Park SG, Kim C, Beom-hoan O. Thin Solid Films 1999;355:252–5.
[4] Wu Y, Lieberman MA. Appl Phys Lett 1998;72:777.
[5] Setsuhara Y, Miyake S, Sakawa Y, Shoji T. Jpn J Appl Phys 1999;38:4263.
[6] Kanoh M, Suzuki K, Tonotani J, Aoki K, Yamage M. Jpn J Appl Phys 2001;40:5419–23.
[7] Kim KN, Yeom GY. Jpn J Appl Phys 2006;48(3):422–6.
[8] Gianci G, Schina A, Minotti A, Quaresima S, Foglietti V. Sens Actuators, A 2006;127:28.
[9] Booth JP, Corr CS, Curely GA, Jolly J, Guillon J, Foldes T. Appl Phys Lett 2006;88:151502.

[10] Gans T, Schulze J, O'Connell D, Czarnetzki U, Faulkner R, Ellingboe AR, et al. Appl Phys Lett 2006;89:261502.

[11] Kim KN, Lim JH, Yeom GY. Appl Phys Lett 2006;89:251501.

[12] Kim KN, Lee YJ, Jung SJ, Yeom GY. Jpn J Appl Phys 2004;43(7A):4373–5.

[13] Lieberman MA, Lichtenberg AJ. Principles of plasma discharges and materials processing. 2nd ed. New jersey: Wiley; 2005. pp. 97.

[14] Murata M, Takeuchi Y, Nishida S. Vacuum 1997;48(l):1–6.

[15] Kim KN, Lim JH, Yeom GY. Thin Solid Films 2007;515:5193–6.