Article
Journal of Nanoscience and Nanotechnology
Vol. 15, 8674–8678, 2015
www.aspbs.com/jnn

Plasma Characteristics Using Superimposed Dual Frequency Inductively Coupled Plasma Source for Next Generation Device Processing

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U-shaped inductively coupled plasma (ICP) source was investigated as a linear plasma source for the next generation roll-to-toll flexible display processing. For the radio frequency power to the source, the dual frequency composed of 13.56 MHz and 2 MHz was used and the effect of dual frequency to the U-shaped ICP source on the plasma density, electron temperature, and plasma uniformity was investigated. As the operating condition, 200 mTorr Ar was used without operating turbo pumps. The use of superimposed dual frequency composed of 13.56 MHz + 2 MHz instead the single frequency of 13.56 MHz increased the plasma density slightly at the same total power. In addition, the addition of 2 MHz rf power to 0.4 kW while maintaining 1 kW 13.56 MHz rf power not only decreased electron temperature but also improved both the plasma uniformity and the process uniformity measured by photoresist etching. Therefore, by using the dual frequency to the U-shaped ICP source, not only the plasma density but also plasma uniformity could be improved in addition to the decrease of possible damage to the substrate.

Keywords: ICP, Linear Plasma Source, Flexible Displays, Dual Frequency.

1. INTRODUCTION

These days, researches on display technology are rapidly changing to flexible display technology due to the transition of the next generation display devices to mobile and wearable devices and many researchers are working on developing materials and tools required for next generation flexible display device fabrication. One of the tools required to be developed for the next generation flexible displays is a large area high density plasma equipment that can process flexible display substrates uniformly by roll-to-roll and at a high speed.[1–4]

Previously, for the large area high density plasmas, very high frequency (VHF) power was applied for the capacitively coupled plasmas, however, due to the standing wave problem, the size of the electrodes was limited, therefore, the obtaining a uniform plasma over a large area was difficult.[5–13] In the case of Monaghan et al.,[14] by using the multiple floated push–pull type electrode tiles, the problems related to the standing wave were solved, and by increasing the number of electrode tiles, a large area plasma could be achieved using the capacitively coupled plasmas. However, even at the frequency of 162 MHz, the plasma density is still lower than $10^{11}/cm^3$ which is required as the high density plasma sources.

For the inductively coupled plasmas (ICP), Takeuchi et al. also used the VHF for maximizing the plasma density.[15] But the standing wave problem is also applied to the ICP source due to the long antenna line used to generate time-varying inductive field. To remove the standing wave problem in the ICP source, Wu et al. previously studied on the lunching traveling wave to the ICP antenna to remove the standing wave effect.[16] In the case of Setsuhara et al., the plasma uniformity over a large area was obtained by removing the problems related to the standing wave by using short bent ICP antennas instead of long helical or serpentine type ICP antennas.[17,18] In our research group, Kim et al. also used the mutilple U-shaped linear antennas to obtain the uniform plasma without having standing wave problem and, by covering the top half of the antenna

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 1533-4880/2015/15/8674/005 doi:10.1166/jnn.2015.11510

coil with ferrites, high density plasma could be obtained between the ICP antenna and the substrate.[19,20]

The above plasma sources investigated previously are generally applied to the rectangular or circular type plasma systems. For the plasma source applied to the next generation flexible display devices, a linear plasma source is believed to be required for roll-to-roll processing and, in this case, a linear type plasma source with a short width and long length needs to be developed. In this study, one U-type antenna was used as the linear-type plasma source, and to enhance the plasma uniformity and the plasma density over the linear plasma source, a dual frequency plasma composed of 13.56 MHz and 2 MHz was applied to the source and the effect of the superimposed dual frequency on the plasma density and plasma uniformity of the source was investigated. Especially, in this study, we operated the ICP source at a higher pressure to investigate the possibility to remove expensive turbo pumps for the processing.

2. EXPERIMENT SETUP

Figure 1 shows the schematic diagram of the ICP source used in the experiment. The size of the vacuum chamber was 900 mm × 1050 mm, and the size of the substrate was 660 mm × 880 mm for the 4th generation display device processing. To investigate the plasma characteristics as the linear ICP source, a U-type ICP antenna with the size of 1020 mm × 160 mm was installed in the middle of the chamber. The ICP antenna was made of oxygen-free copper tube having outside diameter of 9.7 mm and the outside of the copper tube was enclosed with alumina tubing having15 mm diameter and 2.5 mm thickness. On one side of the U-shaped antenna, a 13.56 MHz radio frequency (rf) power (RFPP, RF30S) and a 2 MHz rf power (ENI, Nova-50A) were connected in parallel after passing through matching networks for impedance matching and rf power filters for the protection of the power supplies from the other rf power. The other side of the U-shaped antenna was grounded. For the ICP operation without turbo pumps, the system was pumped only with a dry pump (Alcatel ADS602P).

Ar was used for the characterization of the plasma and, for the plasma characterization, a commercial Langmuir probe (ESP, Hiden Analytical Inc.) was used to measure the plasma characteristics such as ion density and electron temperature. In addition, a home-made electrostatic probe was used to measure ion saturation current for the estimation of the plasma uniformity in the linear ICP source area of 160 × 880 mm^2. Photoresist covered glass substrate was used to compare the plasma characteristics with the etch characteristics. The photoresist covered glass substrate was etched using an Ar/O_2 (8:2) gas at 200 mTorr of operating pressure. The photoresist was a positive PR(AZ9260) spin coated on the glass substrate followed by soft baking at 90 °C for 2 min. The photoresist thickness was about 6 μm.

3. RESULTS AND DISCUSSION

First, to find out the differences between the single frequency and the superimposed dual frequency on the ICP characteristics, the single frequency rf power of 13.56 MHz and the dual frequency rf power composed of 13.56 MHz and 2 MHz were applied to the U-type ICP antenna and the effect of dual frequency on the plasma density was investigated. Figure 2 shows the ion density as a function rf power for 13.56 MHz only and for the dual frequency composed of 13.56 MHz and 2 MHz measured using the Langmuir probe. The plasmas were generated using 200 mTorr of Ar. As shown, the increase of rf power to the ICP antenna with the single 13.56 MHz only from 0.5 to 1.4 kW increased the ion density from 6.3×10^{10}/cm^3 to about 1.0×10^{11}/cm^3, therefore, by using 1.4 kW rf power, a high density plasma could be obtained with 13.6 MHz only at 200 mTorr Ar. The ion density was

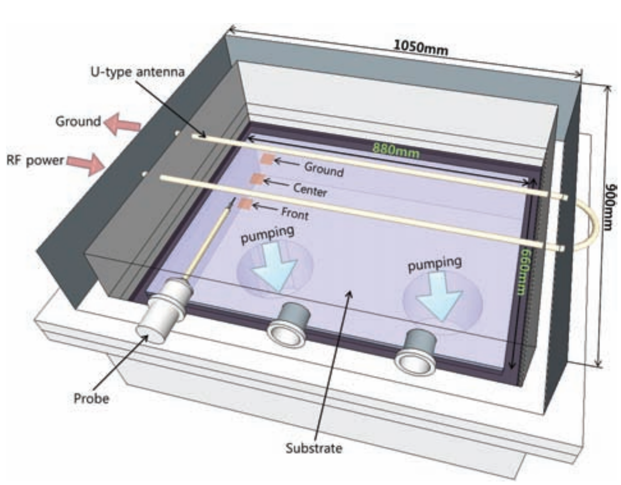

Figure 1. Schematic diagram of the ICP source used in the experiment.

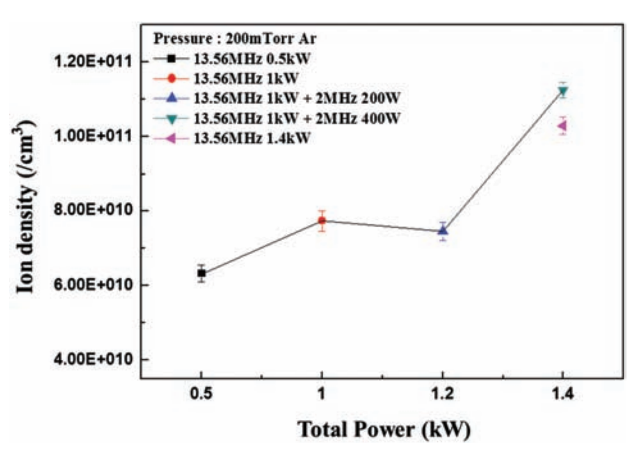

Figure 2. Ion density as a function rf power for 13.56 MHz only and for the dual frequency composed of 13.56 MHz and 2 MHz measured using the Langmuir probe. The plasmas were generated using 200 mTorr of Ar.

also measured using the dual frequency conditions by the addition of 2 MHz rf power to 0.4 kW while maintaining 1 kW of 13.56 MHz rf power. As shown in the figure, even though no significant change was observed for 0.2 kW 2 MHz + 1 kW 13.56 MHz, the increase of plasma density could be observed for 0.4 kW 2 MHz + 1 kW 13.56 MHz. When the same total power of 1.4 kW is compared for the single frequency of 13.56 MHz only and for the dual frequency of 13.56 MHz and 2 MHz, the use of dual frequency showed a little higher ion density compared to the single frequency of 13.56 MHz.

Using the Langmuir probe, in addition to the ion density, the electron temperature was measured for the dual frequency rf power as a function of 2 MHz rf power while maintaining 1 kW of 13.56 MHz and the results are shown in Figure 3. As shown in Figure 3, the increase of 2 MHz rf power from 0 to 0.4 kW decreased the electron temperature from 3.2 to 2.8 eV. The decrease of electron temperature can decrease the damage to the flexible substrate made of polymer materials. Therefore, by using the dual frequency composed of 13.56 MHz and 2 MHz, the possibility in damaging the substrate could be decreased in addition to the increase of ion density.

Using a home-made electrostatic probe, the variation of ion saturation current in the probe across the U-type antenna was measured as a function of 2 MHz rf power while maintaining 1 kW of 13.56 MHz to estimate the plasma uniformity and the results are shown in Figure 4(a). The front is the power input position, the ground is the power out position which was grounded, and the center is the location between the front and ground in the U-shaped antenna. The process conditions are the same as those in Figure 3. The electrostatic probe was biased at −30 Volts and the ion saturation current was measured using a multimeter (KEITHLEY 2000) after passing through an rf filter to remove the rf noise to the probe. As shown in

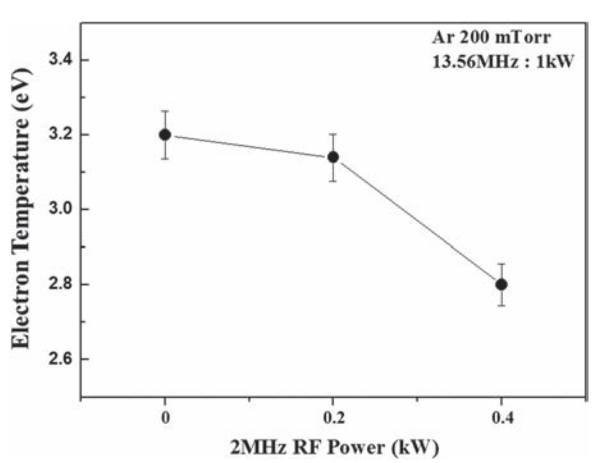

Figure 3. Electron temperature measured for the dual frequency rf power as a function of 2 MHz rf power while maintaining 1 kW of 13.56 MHz.

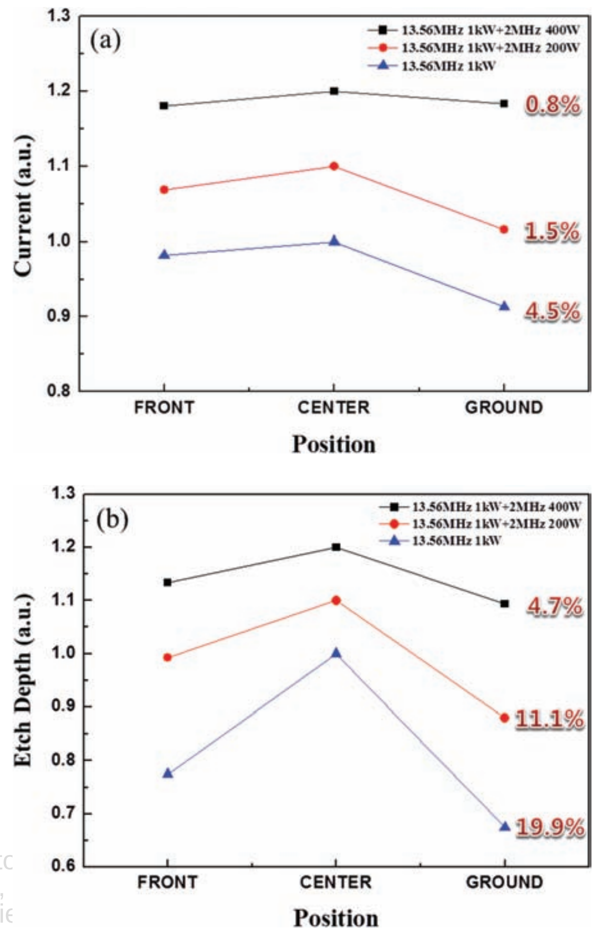

Figure 4. (a) Variation of ion saturation current measured using an electrostatic probe across the U-type antenna as a function of 2 MHz rf power while maintaining 1 kW of 13.56 MHz to estimate the plasma uniformity. Ar 200 mTorr was used. (b) Etch depth of photoresist as a function of 2 MHz rf power while maintaining 1 kW of 13.56 MHz. The photoresist was etched using 200 mTorr of Ar/O_2 (8:2).

Figure 4(a), the addition of 2 MHz rf power while keeping 1 kW 13.56 MHz increased the ion saturation currents indicating the increase of ion density as observed in Figure 2. In addition, the increase of 2 MHz rf power to 0.4 kW improved the uniformity of the ion saturation current from 4.5% for 1 kW 13.56 MHz only to 0.8% for 1 kW 13.56 MHz + 0.4 kW 2 MHz. Therefore, by using the dual frequency instead of the single frequency to the U-shaped ICP antenna, the improvement of plasma density could be obtained.

Even though the uniformity of the ion saturation current was improved by using the dual frequency, the uniformity of the ion saturation current needs to be related to the processing uniformity. For this relationship, 6 μm thick photoresist covered glass wafers were etched at the same locations as in Figure 4(a) and the etch uniformity was measured, and the results are shown in Figure 4(b). To etch photoresist, instead of pure Ar, an Ar/O_2 (8:2) gas mixture was used while keeping the operating pressure at

200 mTorr. The etch time was fixed at 7 min. As shown, the increase of 2 MHz rf power while keeping 1 kW of 13.56 MHz increased the photoresist etch depth similar to the increase of ion saturation current. In addition, the increase of 2 MHz rf power improved the etch uniformity from 19.9 to 4.7%. Therefore, even though the uniformity of plasma uniformity estimated using the ion saturation current was not exactly same as the photoresist etch uniformity, similar uniformity improvement in the process rates could be observed by the use of dual frequency instead of the single frequency to the U-type ICP source. The improvement of plasma uniformity and process uniformity observed by using dual frequency rf power to the same ICP antenna instead of the single frequency rf power is believed to be related to the electron scattering over a larger space due to the complicated electric field formed on the antenna even though more investigation is required for the exact reason.

The ion current uniformity shown in Figure 4 is the uniformity over the cross sectional direction of U-shaped antenna. To measure the uniformity over the area covered by the U-shaped antenna, ion saturation currents were measured not only along the cross sectional direction of the U-shaped antenna but also along the U-shaped antenna line, the ion saturation current was measured for the single frequency of 1 kW 13.56 MHz only and for the dual frequency of 1 kW 13.56 MHz + 0.2 kW 2 MHz and the results are shown in Figure 5. 200 mTorr of Ar was used. As shown, the uniformity of ion saturation current with the single frequency of 1 kW 13.56 MHz only was 6.74% while that with the dual frequency of 1 kW 13.56 MHz + 0.2 kW 2 MHz was 4.94%. The ion saturation current for the dual frequency was higher than that for the single frequency. Therefore, by adding the dual frequency rf power to the U-shaped ICP antenna, the overall plasma uniformity could be improved.

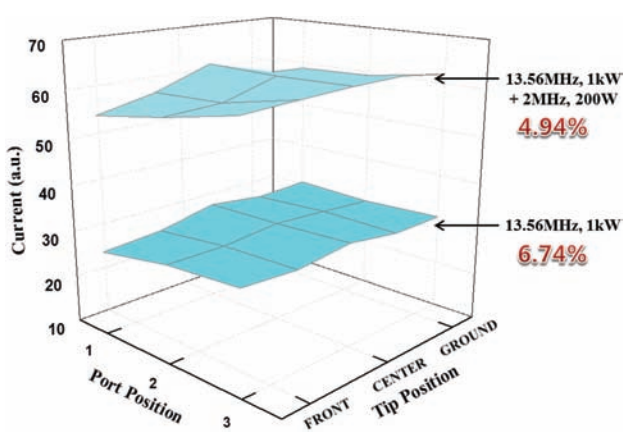

Figure 5. Uniformity of ion saturation current measured using an electrostatic probe over the area covered by the U-shaped antenna. The ion saturation current was measured for the single frequency of 1 kW 13.56 MHz only and for the dual frequency of 1 kW 13.56 MHz + 0.2 kW 2 MHz. As the operating condition, 200 mTorr of Ar was used.

4. CONCLUSIONS

In this study, as an application to next generation linear plasma source applied to roll-to-roll flexible display processing, a U-shaped ICP source was used and the effect of superimposed dual frequency rf power composed of 13.56 MHz and 2 MHz instead of the single frequency rf power of 13.56 MHz applied to the U-shaped ICP antenna on the plasma characteristics and process uniformity of the linear plasma source was investigated. The use of dual frequency composed of 13.56 MHz + 2 MHz compared to the single frequency of 13.56 MHz increased the plasma density slightly at the same total rf power applied to the ICP source. The addition and increase of 2 MHz rf power to the ICP source while maintaining 1 kW 13.56 MHz rf power generally decreased the electron temperature. The use of dual frequency rf power also improved the plasma uniformity over the U-shaped antenna area. The process uniformity estimated by the photoresist etch uniformity was similar to the plasma uniformity estimated by the ion saturation current of the electrostatic probe. Therefore, it is believed that, due to the low non-uniformity ($<5\%$) and high density plasma ($>10^{11}/cm^3$) of the U-shaped ICP antenna operated with the dual frequency, it can be applied to the next generation linear plasma source for roll-to-roll flexible display processing.

Acknowledgments: This research was supported by the MOTIE (Ministry of Trade, Industry and Energy) (10049065) and KSRC (Korea Semiconductor Research Consortium) support program which development of future semiconductor device. This work was also supported by the International Joint Research and Development Program (N009300229, Large area PECVD Equipment development for Flexible low temperature high density film deposition) founded by the Ministry of Knowledge Economy (MKE, Korea).

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Received: 8 August 2014. Accepted: 6 April 2015.