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Line-type inductively coupled plasma source with ferromagnetic module

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Abstract
The characteristics of a line-type, internal antenna for an inductively coupled plasma (ICP) source installed with a ferromagnetic module were investigated for possible application to roll-to-roll processing of next-generation display devices. The use of 2 MHz instead of 13.56 MHz for the 2300 mm long ICP source improved the plasma uniformity to less than 11% along the antenna line. In addition, the use of Ni–Zn ferromagnetic material in the line-type antenna improved the plasma density to about 3.1×10^{11} cm^{-3} at 3500 W of 2 MHz radio frequency power by confining the induced, time-varying magnetic field between the antenna line and the substrate. When the photoresist-covered glass substrate was etched at 4000 W using 40 mTorr and Ar/O_2 (7 : 3), an etch uniformity of about 5–6% was obtained along the antenna line.

1. Introduction

Flexible display devices are being investigated by many researchers as a potential next-generation display. Roll-to-roll plasma processing is an important technique for flexible display processing [1–4]. For the fabrication of flexible display devices by roll-to-roll plasma processing, not only highly uniform plasma processing but also high processing rates are required to increase the throughput of the processing. In particular, the use of low-temperature substrates such as plastic substrates for roll-to-roll plasma processing enables a high processing rate to be achieved at temperatures lower than 100 °C.

As well as low-temperature processing, high-density plasma sources can be used to increase the processing rates. For this reason, plasma sources using externally applied magnetic fields such as helicon discharge and neutral loop discharge have been investigated intensively [5–9]. In recent years, several research groups have reported line-type, high-density plasma sources for the roll-to-roll processing of flexible substrates by using a microwave plasma or a capacitively coupled plasma with a very high frequency (VHF) higher than 13.56 MHz [10–12]. Although relatively high quality films can be obtained at high deposition rates and high etch processing rates through the high-density plasma sources generated by microwave plasmas and VHF plasmas, it is very hard to obtain uniform plasmas over a metre-scale-width flexible substrate in the high frequency range due to the standing wave effect [13, 14]. With the increase in the processing width larger than 1 m, the length of the plasma source becomes comparable to the wavelength of the radio frequency (rf), which leads to a standing wave effect in addition to a large rf voltage. The standing wave effect can cause a non-uniform power distribution along the line-type plasma source and the unstable plasma. Wu and Lieberman [13] proposed, developed and characterized a novel high-density plasma reactor in which standing wave effects are eliminated by launching a travelling wave on the antenna coil. To control the standing wave effect they designed a tuning network which can generate an exciting wave with any standing wave ratio. However, if lower frequency discharges are used instead of high frequency plasmas such as VHF plasma, microwave plasma, etc, they can alleviate the problems related to standing waves. However, the plasma density is decreased significantly and the rf voltage induced on the antenna of the plasma source is increased

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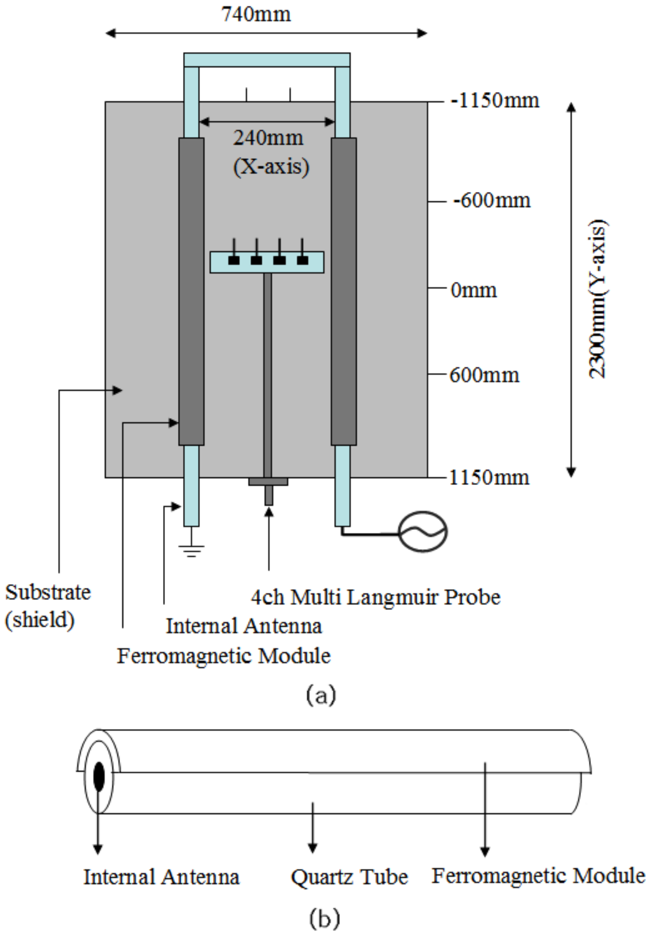

Figure 1. (*a*) Schematic diagram of line-type, internal ICP sources with a ferromagnetic module. (*b*) Arrangement of the ferromagnetic module on the internal linear antenna line.

significantly, which lowers the processing rate and can damage the substrates [15, 16].

In this work, we present a new, line-type, high-density plasma source composed of a line-type, internal antenna for an inductively coupled plasma (ICP) operated at 2 MHz and a ferromagnetic module installed on the antenna of the ICP source. Using the line-type, internal antenna, the electrical and plasma characteristics of the source were investigated for possible application to large-width, flexible substrate processing during roll-to-roll processing. The characteristics of the source were compared with the source characteristics operated at 13.56 MHz without a ferromagnetic module.

2. Experiment

Figure 1(*a*) presents a schematic diagram of the line-type, internal ICP source with a ferromagnetic module investigated in this study. The rectangular processing chamber was of size 2750 × 2350 mm^2 for flat panel display processing. The U-shaped, line-type, internal antenna, of size 240 × 2300 mm^2, was installed in the centre of the processing chamber and a shield of size 740 × 2300 mm^2 was also installed around the antenna to limit the plasma near the line-type antenna. The effective substrate size, which was limited by the shield size, was also 740 × 2300 mm^2. As shown in the figure, one end of the U-shaped internal antenna was connected to an rf power generator through an L-type matching network while the other end was connected to the ground directly. Rf characteristics of 2 MHz, 5 kW (ENI NOVA) and 13.56 MHz, 10 kW (RFPP) were used for the antenna. The operating gas for the plasma characterization was 20 mTorr Ar. In the case of 2 MHz operation, a ferromagnetic module composed of Ni–Zn with a high magnetic permeability was installed above the antenna line to confine the plasma below the antenna line, as shown in figure 1(*b*). In fact, the plasma source could not be initiated at the frequency of 2 MHz without the ferromagnetic module, while no such problem was observed for the plasma source operated at 13.35 MHz.

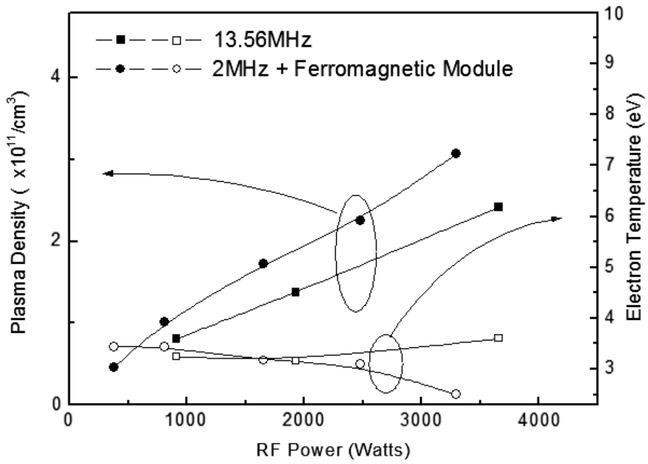

Figure 2. Plasma density and electron temperature measured by a Langmuir probe at 20 mTorr Ar as a function of rf power with the ICP source operated at 13.56 MHz and 2 MHz (with the ferromagnetic module).

The plasma characteristics of the source were measured using a Langmuir probe (Hiden Analytical Inc., ESP), and the electrical properties of the line-type, internal antenna were measured using an impedance analyzer (MKS Inc.) located between the matching box and the antenna. The characteristics of the plasma uniformity were investigated using a home-made, movable, electrostatic probe system consisting of four tips located 32 cm below the antenna and 20 cm above the substrate. The probe system, biased at −65 V, was scanned along the antenna line to measure the distribution of the two-dimensional, ion saturation current above the substrate. Using the U-shaped antenna system operated at 2 MHz with a ferromagnetic module and a gas mixture of Ar/O_2 (7 : 3) at 40 mTorr, a glass substrate covered with AZ1512 photoresist was etched and its etch depth was measured using a step profilometer (Alpha Step 500) to estimate the etch uniformity along the antenna line.

3. Results and discussion

Figure 2 shows the plasma density and electron temperature measured by a Langmuir probe (Hiden Inc.) as a function of the delivered rf power of the line-type, ICP source operated with 13.56 MHz rf power and with 2 MHz rf power (after installation of a ferromagnetic module). As shown in figure 2, the plasma density almost linearly increased with the increase in rf power for both frequencies. However, the source with the 2 MHz frequency showed a higher plasma density than that with 13.56 MHz frequency at the same rf power, while the source with the 2 MHz frequency with the ferromagnetic module showed a plasma density of about 3.1×10^{11} cm^{-3} at 3500 W. When the electron temperature was measured using the Langmuir probe, as shown in figure 2, the ICP source operated at 2 MHz frequency showed lower electron temperatures in the range 2–3 eV while the source operated at 13.56 MHz showed a slightly higher electron temperature in the range from 3 to 4 eV.

The achievement of a stable and high plasma density plasma after the installation of a ferromagnetic module was attributed to the reinforcement of a time-varying, induced magnetic field (B) which was induced by the rf current (I) flowing on the antenna just below the antenna line. The ferromagnetic module (Ni–Zn) used in this study covered the top half of the antenna line diameter, as shown in figure 1(*b*). From Ampere's law of $\oint_c B \cdot dl = \mu_0 I$ (where l is the path of integration and μ_0 is the magnetic constant of free space such that $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}), it can be shown that the time-varying magnetic field (B) measured below the antenna line is represented by the equation $B = \mu_0 I/2\pi r$ (where r is the radius from the antenna centre) when no ferromagnetic module is used. However, when the time-varying magnetic field (B) was measured after the installation of the ferromagnetic module, $B = \mu_0 I/\pi r$, which is two times higher than the source without the ferromagnetic module, was obtained below the antenna line. This result was due to the reinforcement of the induced B field below the antenna line while preventing the formation of the B field at the location above the antenna line covered by the ferromagnetic module with high permeability. Therefore, by using the antenna line covered with the half-circle-shaped ferromagnetic module, stable high-density plasmas could be obtained below the antenna line (between the antenna and the substrate) due to the reinforcement of the induced magnetic field below the antenna line and the continual presence of the magnetic field above the antenna line (which is close to the chamber top).

For the sources operated at 13.56 and 2 MHz (with the ferromagnetic module), the antenna rms voltage was measured and the Joule loss was calculated as a function of rf power using an impedance probe installed between the matching network and the antenna of the source. As shown in figure 3, the increase in rf power increased the antenna rms voltage for both sources operated at 13.56 and 2 MHz (with the ferromagnetic module), although the latter showed a lower antenna rms voltage. Even though the differences were not significant, the lower antenna voltage shown for the ICP source at 2 MHz has greater potential benefit due to its ability to decrease the electrostatic coupling between the plasma and the antenna and to decrease the possible sputtering of the quartz tube enclosing the antenna line.

The Joule loss (P_0), which is inversely related to the power transfer efficiency to the plasma, can be calculated

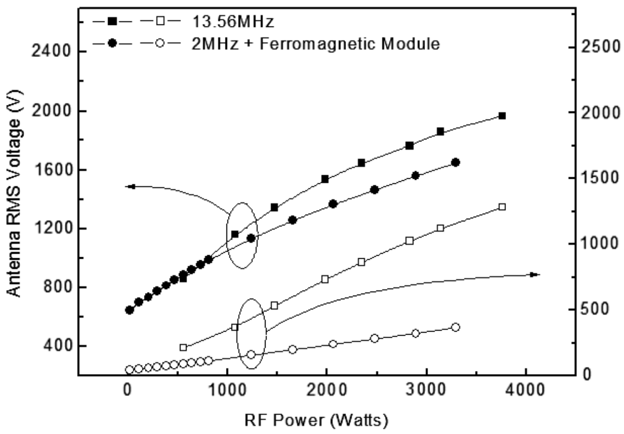

Figure 3. Rf rms voltage and Joule loss measured by an impedance analyzer on the antenna located close to the rf power input as a function of rf power with the ICP source operated at 13.56 and 2 MHz (with the ferromagnetic module) and at 20 mTorr Ar.

by measuring the antenna resistance (R_1) and the rf rms current (I) as a function of the rf power applied without generating plasmas and by calculating the ohmic loss by the equation $P_0 = R_1 I^2$. As shown in figure 3, the Joule loss of the source operated at 2 MHz with the ferromagnetic module was about 2.5 fold lower than that of the source operated at 13.56 MHz at a given rf power. Therefore, higher rf power transfer to the plasma and more efficient plasma processing were obtained with the ICP source operated at 2 MHz with the ferromagnetic module. When the rf power transfer efficiencies were calculated at an rf power of 3500 W, the ICP sources operated at 2 MHz with the ferromagnetic module and at 13.56 MHz showed power transfer efficiencies of about 88.8% and 65%, respectively.

Figure 4 shows the plasma uniformity measured along the antenna line of the ICP source operated at 13.56 and 2 MHz (with the ferromagnetic module) with a home-made, movable, four-tip, electrostatic probe system. The rf power for 13.56 MHz and 2 MHz with the ferromagnetic module was in the range from 4000 W to 8000 W and from 1000 W to 4000 W, respectively. The probe system with a width of 240 mm (80 mm distance between the tips) was scanned along the antenna line of 2300 mm. Ion saturation currents were measured at the tips biased at −65 V and the results are shown in figure 4(*a*) for 13.56 MHz and (*b*) for 2 MHz with the ferromagnetic module. At 13.56 MHz, the ion saturation current significantly varied along the antenna line of the ICP source at all the rf powers (the power input side showed a higher plasma density than the other side). However, at 2 MHz with the ferromagnetic module, the ion saturation current along the antenna line did not vary significantly with changing rf power, and neither did the uniformity. When the uniformity of ion saturation currents was compared at an rf power of 4000 W, the ICP source at 13.56 MHz showed about 35% while that at 2 MHz with the ferromagnetic module showed about 11% .

The significant variation in the ion current density measured for the ICP source operated at 13.56 MHz was attributed to the standing wave effect. When the length of the antenna line is longer than the quarter length of the rf

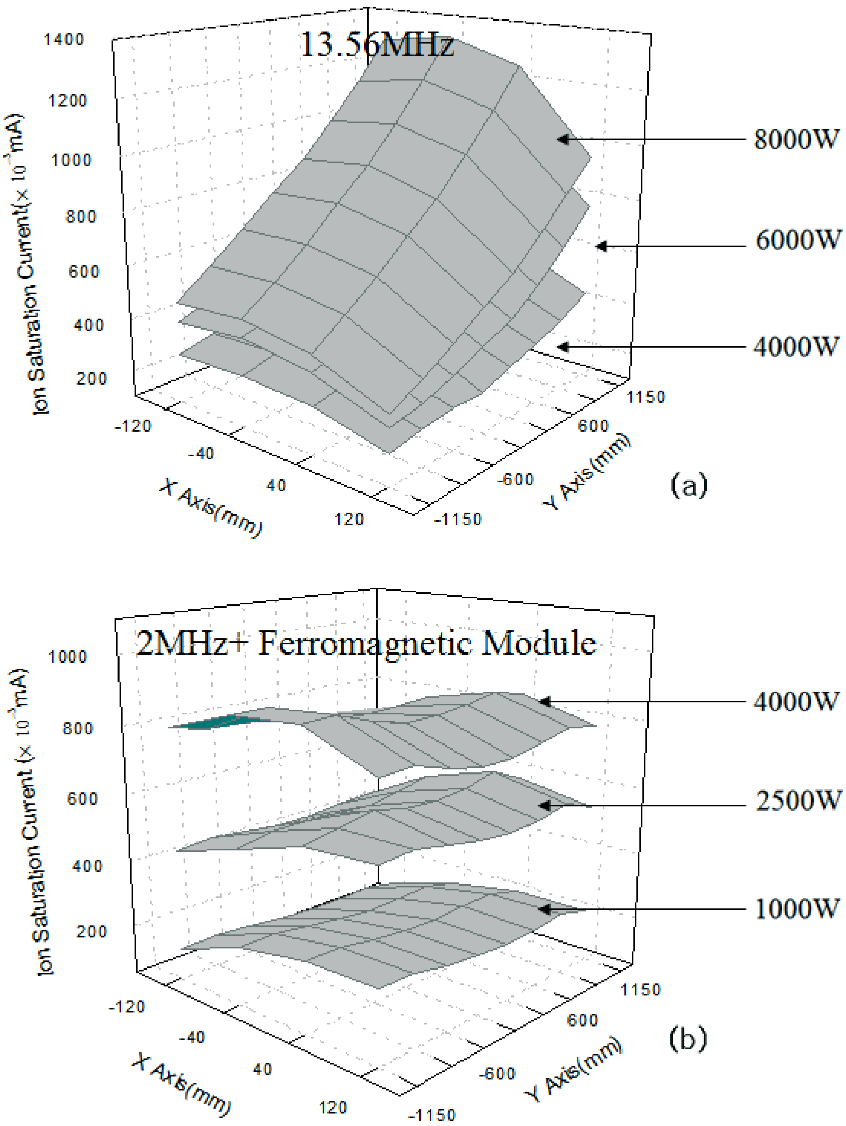

Figure 4. Plasma uniformity of (*a*) the 13.56 MHz source for an rf power of 4000–8000 W and of (*b*) the 2 MHz source with the ferromagnetic module for an rf power of 1000–4000 W measured using a movable electrostatic probe system biased at −65 V at 20 mTorr Ar.

excitation frequency, a standing wave is observed along the antenna line, which thereby induces the variation in electrical characteristics such as rf voltage, current and phase between the rf voltage and current along the antenna line [17]. As the 6 m long U-shaped antenna used in this experiment was longer than the quarter wavelength of 13.56 MHz (5.5 m), the variation of ion saturation current was observed due to the standing wave effect. However, at 2 MHz, the length of the quarter wave was approximately 38 m due to the long wavelength of 150 m at 2 MHz and no significant standing wave was observed. Considering the impact of neutral gas uniformity, generally, relatively high electron densities can lead to elevated neutral gas temperatures and depletion of the neutral gas. Also depletion of the neutral gas can result in high ionization [7–9, 18]. According to O'Connell *et al* at lower pressures neutral gas is predominantly depleted through high ionization rates and rapid transport of charged particles. Thus, non-uniform profiles of ionization can result in localized neutral gas depletion. In the case of an internal ICP source operated at 2 MHz, the profile of the ion saturation current was almost the same along the antenna line of the ICP source. Therefore, the degree of ionization and depletion of neutral gas along the antenna line was expected to be uniform.

To investigate the possibility of the line-type, internal ICP source operated at 2 MHz with the ferromagnetic module as the plasma source for in-line processing or roll-to-roll processing, photoresist-covered glass substrates were etched with an Ar/O_2 gas ($Ar : O_2 = 7 : 3$) at 40 mTorr and with an rf power of 4000 W. Ten photoresist-covered glass samples were located along the antenna line (2300 mm distance) at three different sample locations (240 mm distance), as shown in figure 5. The etch depth was similar in each location along the antenna line and the uniformity of the etch depth ranged from 5% to 6%. Of the ten samples, the first and last were separated by only about 100 mm from the chamber wall but no significant decrease in the etch depth was observed compared with that at the centre of the antenna line, possibly due to the confinement of plasma near and below the antenna line by the ferromagnetic module.

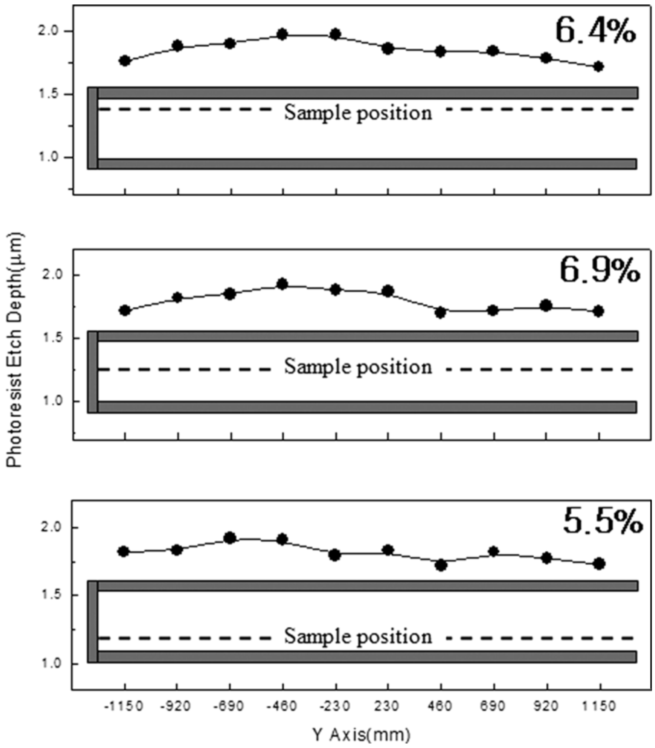

Figure 5. Photoresist etch uniformity measured at various antenna locations using the line-shaped ICP source operated at 2 MHz with a ferromagnetic module and at an rf power of 3500 W with 40 mTorr Ar/O_2 (7 : 3).

4. Conclusions

In this study, a new, line-type, internal ICP source was investigated as a possible line-type, high-density plasma source for roll-to-roll processing of next-generation flexible display substrates. The use of a line-type, ICP source with a U-shaped, internal, linear ICP antenna afforded high-density plasmas above $2 \times 10^{11}\ cm^{-3}$ at a frequency of 13.56 MHz and an rf power higher than 3000 W. However, the operation of the source at 13.56 MHz showed highly non-uniform plasma uniformity along the antenna line (about 35% at an rf power of 4000 W and 20 mTorr Ar) in addition to high Joule loss and high antenna voltage. In contrast, when the source was operated at 2 MHz after the installation of a ferromagnetic module for magnetic field enhancement and confinement below the antenna line, the source showed a higher plasma density of $3.1 \times 10^{11}\ cm^{-3}$ (at an rf power of 3500 W and 20 mTorr Ar), better plasma uniformity along the antenna line (about 11% at an rf power of 4000 W and 20 mTorr Ar), lower Joule loss and lower antenna voltage. The higher uniformity obtained at 2 MHz compared with that at 13.56 MHz was attributed to the lack of the standing wave effect, while the higher plasma density was attributed to the magnetic confinement of the plasma by the ferromagnetic module.

Acknowledgments

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