# Effect of dual frequency on the plasma characteristics in an internal linear inductively coupled plasma source

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An internal-type linear inductive antenna, referred to as a "double comb-type antenna," was used as a large area plasma source with a substrate size of $880 \times 660$ mm$^2$ (fourth generation glass size). The effects of the dual frequency (2 and 13.56 MHz) radio frequency (rf) power to the antenna as well as the power ratio on the plasma characteristics were investigated. High-density plasma on the order of $1.7 \times 10^{11}$ cm$^{-3}$ could be obtained with a dual frequency power of 5 kW (13.56 MHz) and 1 kW (2 MHz) at a pressure of 15 mTorr Ar. This plasma density was lower than that obtained for the double comb-type antenna using a single frequency alone (5 kW, 13.56 MHz). However, the use of the dual frequency with a rf power ratio of approximately 1(2 MHz):5(13.56 MHz) showed better plasma uniformity than that obtained using the single frequency. Plasma uniformity of 6.1% could be obtained over the substrate area. Simulations using FL2L code confirmed the improvement in the plasma uniformity using the dual frequency to the double comb-type antenna. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2405417]

Currently, plasma processing has been used in the manufacturing of semiconductor devices and flat panel displays (FPDs) such as thin film transistor liquid crystal displays (TFT-LCD).[1–3] In the case of TFT-LCDs, the current substrate size ranges from $880 \times 660$ mm$^2$ (fourth generation) to $1850 \times 2250$ mm$^2$ (seventh generation). This substrate size is expected to increase over the next few years.[4] However, when the plasma source is scaled up to a large size that is comparable to the wavelength of the rf power supply for FPD processing, the plasma generated is inherently nonuniform due to the antenna standing wave effect, and the dielectric window that separates the coil from the plasma becomes increasingly expensive.[5] In addition, conventional ICP sources for FPD processing have many problems when being applied to the processing of extremely large area FPDs, due to the large impedance of the antennas that occurs when scaling up to larger areas. This large impedance causes a high rf voltage on the antenna over large areas, which reduces the efficiency of the power transfer to the plasma, due to the increased capacitive coupling.[6–10]

This study examined the use of an internal-type linear inductive antenna arrangement, referred to as a "double comb-type antenna." Figure 1 shows a schematic diagram of the system. In particular, a dual frequency power consisting of 2 and 13.56 MHz power supplies was applied to the antennas. The effects of the dual frequency on the plasma characteristics such as plasma density and plasma uniformity were investigated using both simulations and experiments. Figure 1(a) gives a schematic diagram of the system used in the experiment. The substrate size was $880 \times 660$ mm$^2$ (fourth generation glass size). The linear antenna was made from 10 mm diameter copper tubing with the outside shielded by quartz tubing. Five linear antennas were embedded in the process chamber, each being connected alternatively to the power supplies with the other ends of the antennas being grounded to form a double comb-type antenna, as shown in Fig. 1(b). As a dual frequency configuration (dual frequency mode), the left side comb-type antenna composed of three linear antennas was connected to a 2 MHz power supply (1 kW) while the right side comb-type antenna composed of two linear antennas was connected to a 13.56 MHz power supply (5 kW). To operate the source as a single frequency configuration (single frequency mode), both sides of the comb-type antennas were connected to a single 13.56 MHz (5 kW) power supply.

The plasma characteristics were measured using a Langmuir probe (Hiden Analytical Inc., ESP) that was located 7.5 cm below the antenna and along the vertical centerline of the chamber. The etch characteristics of the photoresist films deposited on soda lime glass were investigated using a water-cooled substrate holder that had been installed 5 cm below the source and connected to a separate rf power supply (12.56 MHz, 2 kW) through a separate matching network to supply a bias voltage to the substrate. In addition, simula-

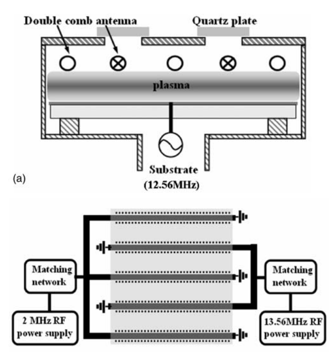


FIG. 1. (a) Schematic diagram of the linear internal-type inductively coupled plasma system used in the experiment. (b) Configuration of the double comb-type antenna when applying a dual frequency.

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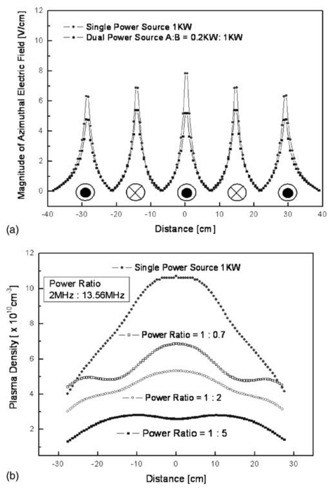


FIG. 2. (a) $E_z$ field at the each antenna position simulated by an F2L code for a single frequency and dual frequency at 5 mTorr Ar. (b) Plasma density distribution from −27.5 to 27.5 cm (chamber center: 0 cm) calculated using F2L code as a single frequency and dual frequency at a pressure of 5 mTorr Ar.

tions using FL2L code were carried out to determine the effect of the dual frequency to the internal-type linear inductive antenna on the plasma characteristics.[11,12]

The dual frequency effect has been studied in capacitively coupled plasma systems applied to semiconductor processing.[13,14] In this study, the two rf power supplies were connected alternately to the internal antenna, and the effect of the dual frequency on the plasma characteristics was examined.

The $E_z$ ($E_z$, the induced electric field in the direction parallel to the antenna line) field at each antenna position was calculated using the F2L code and by applying the dual frequency rf power feed configuration shown in Fig. 1(b). Figure 2(a) shows the $E_z$ field at each antenna center position of the antenna line, as calculated by the F2L code at 5 mTorr Ar. To operate in a dual frequency mode, a 1 kW 13.56 MHz power was fed to the right side comb-type antenna while a 0.2 kW 2 MHz power was fed to the left side comb-type antenna. As a reference, both comb-type antennas were connected to a single 1 kW 13.56 MHz power supply to operate in a single frequency mode, and the calculated result is also included in the figure. To obtain the $E_z$ field, the wave equations for the transmission line [Eqs. (1) and (2)] were solved to obtain the voltage and current to the antenna,

$$V(z) = \frac{I_L}{2}[(Z_L + Z_0)e^{\gamma(l-z)} + (Z_L - Z_0)e^{\gamma(l-z)}], \qquad (1)$$

$$I(z) = \frac{I_L}{2Z_0}[(Z_L + Z_0)e^{\gamma(l-z)} - (Z_L - Z_0)e^{\gamma(l-z)}], \qquad (2)$$

where $V(z)$ and $I(z)$ are the voltage and current along the antenna line, respectively, $Z_0$ is the characteristic impedance, $Z_L$ is the load impedance $[=(V/I)_{z=1}=(V_L/I_L)=Z_L$, where $l$ is the total antenna length], $\gamma$ is the propagation constant $(=\alpha+j\beta)$, and $I_L$ is the load current. As shown in the figure, the $E_z$ fields at the center location of the antenna line showed that, when the internal antenna was operated in a single frequency mode, the $E_z$ field at the center of the chamber was higher than that at the edges of the chamber due to interference between the adjacent antennas located in the parallel and opposite directions. Therefore, nonuniform plasma in the chamber was expected. However, in a dual frequency mode (1 kW 13.56 MHz/0.2 kW 2 MHz), there was a more uniform $E_z$ field along the chamber due to the negligible interference among the adjacent antennas caused by the significant differences in rf. Hence, more uniform plasma is expected using the dual frequency.

The more uniform $E_z$ field along the chamber obtained in the dual frequency mode operation (1 kW 13.56 MHz/0.2 kW 2 MHz) appears to be related to the different power absorptions for the different driving rf's. In general, the time-averaged power per unit volume by rf power can be expressed using the following equation:

$$P_{\text{abs}} = \frac{1}{T}\int_0^T J_T(t)E(t)dt = \frac{1}{2}R_e(\overline{J_T E_T^*}) = \frac{1}{2}R_e(\overline{J_T^* E_T}), \qquad (3)$$

where $T=2\pi/w$, $J_T$ is the total current, and $E(t)$ is the electric field, $\overline{J_T}=(\sigma_p+jw\varepsilon_0)E$ (where $\sigma_p$ is the plasma conductivity, $\omega$ is the driving frequency, and $\varepsilon_0$ is the vacuum permittivity). If $\overline{J_T}$ is inserted in Eq. (1) and rearranged, the collision (Ohmic) power absorbed by the electrons can be obtained in terms of the electric field amplitude $E$ as follows:

$$P_{\text{Ohmic}} = \frac{1}{2}|\bar{E}|^2\sigma_{\text{dc}}\frac{\nu_m}{\omega^2+\nu_m^2}. \qquad (4)$$

Equation (2) shows that $P_{\text{Ohmic}}$ (absorbed power absorbed by Ohmic heating) is proportional to $|\bar{E}|^2$ (electric field) and $E$ is inversely proportional to $w$ (driving frequency) because $E=\overline{J_T}/(\sigma_p+j\omega\varepsilon_0)$. Therefore, operation at 2 MHz produces a higher electric field than at 13.56 MHz. Hence, more uniform $E_z$ in the chamber and more uniform power absorption along the chamber can be expected at a dual frequency rf power ratio of 0.2 kW 2 MHz:1 kW 13.56 MHz. The use of a different power ratio between 2 and 13.56 MHz can change the $E_z$ at each antenna and can change the plasma uniformity along the chamber. Figure 2(b) shows the calculated plasma density along the chamber centerline using the F2L code at a pressure of 5 mTorr Ar at different dual frequency power ratios while maintaining the 13.56 MHz power at 1 kW. As shown in the figure, even though the use of a dual frequency mode showed more uniform plasma density compared with the single frequency mode, the use of a dual frequency power ratio of 0.2 kW 2 MHz:1 kW 13.56 MHz produced the most uniform plasma density due to the most uniform $E_z$ in the chamber.

To compare the results with the experiment, the internal antennas were operated in a dual frequency mode, and the rf currents on the each comb-type antenna were measured using an impedance probe (ENI Inc.) and a current probe and the plasma characteristics were measured using a Langmuir probe. 15 mTorr Ar was used. To operate the source in the dual frequency mode, the right side comb-type antenna was connected to 5 kW 13.56 MHz while the left side comb-type antenna was connected to 0.1–1 kW 2 MHz. To operate the source in the single frequency mode, both sides of comb-type antennas were connected to a 0–5 kW 13.56 MHz power supply. For the dual frequency mode, when rf currents on the each comb-type antenna were measured as a function of 2 MHz rf power while maintaining 13.56 MHz rf power at 5 kW, the rf current on the left side comb-type antenna using 2 MHz was increased from 8.9 to 33.3 A as the rf power was increased from 0.1 to 1 kW while the rf current on the right side comb-type antenna using 13.56 MHz remained at 22.3 A (not shown). The distribution of rf current

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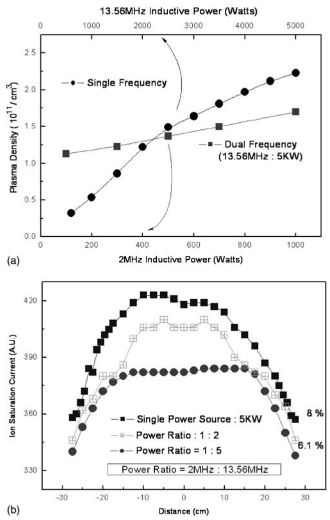


FIG. 3. (a) Plasma density in both the single frequency and dual frequency measured using a Langmuir probe as a function of the rf power of a single frequency and dual frequency at 15 mTorr Ar. (b) Plasma uniformity obtained by experiment in the double comb-type antenna as a function of the single frequency and dual frequency at 15 mTorr Ar.

to each linear antenna was investigated and the results showed that when the rf current flowing to the left side, each linear antenna using 2 MHz was about 11.1 A (total three linear antennas) by the application of 1 kW and that flowing to the right side each linear antenna using 13.56 MHz was 11.13 A (total two linear antennas) by the application of 5 kW, the best uniformity could be obtained which gives uniform $E_z$ field in the process chamber.

Figure 3(a) shows the plasma density estimated from the ion saturation current of the Langmuir probe as a function of 13.56 MHz power in the single frequency mode and that as a function of the 2 MHz power while keeping a 13.56 MHz power in the dual frequency mode. Figure 3(b) shows the plasma uniformity along the chamber for the single frequency mode at 5 kW 13.56 MHz power, and that for the dual frequency mode as a function of 2 MHz power. As shown in Fig. 3(a), when the source was operated in the single frequency mode, the increase in the rf power increased the plasma density almost linearly, and a plasma density of approximately $2.2\times10^{11}/\mathrm{cm}^3$ and plasma uniformity of approximately 8% could be obtained at 5 kW of 13.56 MHz power. When the source was operated in the dual frequency mode by varying the 2 MHz power to the left side antenna from 0.1 to 1 kW while applying 5 kW 13.56 MHz power to the right side antenna, the increase in the 2 MHz power to the right comb-type antenna increased the plasma density slightly. However, the plasma density was lower by applying 5 kW 13.56 MHz power to the right side comb-type antenna only than that obtained by applying 5 kW 13.56 MHz power to both side antennas (single frequency mode operation). A plasma density of $1.7\times10^{11}/\mathrm{cm}^3$ could be obtained with 1 kW 2 MHz power. In addition, as shown in Fig. 3(b), when the rf power ratio was 1:5 (1 kW 2 MHz:5 kW 13.56 MHz), the best uniformity of approximately 6.1% could be obtained. Therefore, the experimental results were similar to the calculation results shown in Fig. 2(b). Using the optimized dual frequency condition of 1 kW 2 MHz power/5 kW 13.56 MHz power and using 15 mTorr $O_2$, soda lime glass with a substrate area of $660\times880\ \mathrm{mm}^2$ (fourth generation) coated with a photoresist was etched. The substrate bias voltage was maintained at −40 V by applying a 12.56 MHz power to the substrate. Figure 4 shows that the etch rate was in the range of 3000–3750 Å/min and the measured etch uniformity was approximately 7%.

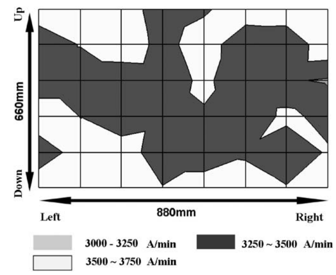


FIG. 4. Etch rate and uniformity of photoresist measured at a dual frequency power of 5 kW 13.56 MHz/1 kW 2 MHz to the double comb-type antenna, a dc-bias voltage of −40 V at 12.56 MHz, and a pressure of 15 mTorr of $O_2$ for a substrate area of $880\times660\ \mathrm{mm}^2$.

In this study, an antenna arrangement, referred to as a double comb-type antenna, was used as an internal-type linear inductive plasma source applied to FPD. The effect of a dual frequency rf power of 2 MHz/13.56 MHz to the antennas on the plasma characteristics was investigated. The use of a single frequency mode by applying a single rf power of 5 kW 13.56 MHz to the double comb-type antenna at 15 mTorr Ar showed a high-density plasma of approximately $2.2\times10^{11}/\mathrm{cm}^3$ and a plasma uniformity of approximately 8%. When a dual frequency of 2 MHz (0.1–1 kW) to the left comb-type antenna and 13.56 MHz (5 kW) to the right comb-type antenna was applied, the plasma uniformity was improved particularly at a rf power ratio of 1(2 MHz):5(13.56 MHz) to 6.1%, even though the plasma density was as low as $1.7\times10^{11}/\mathrm{cm}^3$ for 1 kW 2 MHz/5 kW 13.56 MHz. The calculation showed that the use of dual frequency power decreased the level of interference between the adjacent antennas. Moreover, at a power ratio of 1(2 MHz):5(13.56 MHz), the level of power absorption along the antenna line was uniform at each antenna due to the higher electric field at the lower rf. Therefore, similar to the experiment, the best plasma uniformity was obtained at a dual frequency with a similar power ratio.

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