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Meters-Scale Large-Area Plasma Sources with Multiple Low-Inductance Antenna Units for Next-Generation Flat-Panel Display Processing

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Profiles of argon plasma sustained with multiple low-inductance antenna (LIA) units in a 300-cm rectangular plasma source have been investigated by a three-dimensional plasma simulation using fluid model. Profile of 4*s* excited Ar (Ar*) density was investigated as well as plasma density profile. It is found that FWHM of the profile for Ar* density is larger than 2 factors compared to that for density of Ar plasma sustained with two LIA units were installed at the center of top plate. This difference is caused by the different diffusion for particles; i.e., Ar ions diffuse along the electric field gradient while 4*s* excited Ar particles follow the diffusion of neutral argon. With multiple LIA units, the nonuniformity of the plasma density was 5.5% while that of Ar* density was 4.9% in 230-cm rectangular area, which is equivalent to the substrate size required for next generation flat-panel display processes.

Key words: Plasma, ICP, Internal-antenna, Large area, plasma source

1. INTRODUCTION

Large-area uniform plasma processing sources have attracted much interest for manufacturing applications such as solid state microelectronic devices and flat-panel displays (FPDs) [1], due to recent trends of substrate enlargement mainly for fabrication-cost reduction. In fabrications of devices, uniform profile of radical particles as well as plasma density is strongly desired to meet the requirements for the processes not only in the deposition of silicon films, intermetal dielectrics and passivation layers for integrated circuits but also as substitutes to the presently employed wet processes including substrate cleaning, ashing and etching [2-4]. However, considering large-area plasma productions with high-frequency (HF) power sources to scale up the source size over a meter, standing wave effects and/or edge effects can limit process uniformity, which become inevitable with increasing source size when the source employs power coupling elements with a scale length equivalent to or as long as the 1/4 wavelength of the HF-power transmission [5-7]. In order to overcome these constraints, we have developed inductively coupled plasma (ICP) generation using the U-shaped low-inductance antenna (LIA) unit, as shown in Fig. 1. In our previous studies, this configuration for ICP generation allows high-density of 10^{11} – 10^{12} cm^{-3} argon plasma production with high power transfer efficiency (as high as 90%) and low plasma damage (as low as 10 V) via low-voltage operation of ICPs at only 1.1 Pa [8]. Since LIA units can be installed almost at any location of the chamber wall, this technique has another merit of wide flexibility in designing large-scale sources with high plasma density and has provided a way to produce uniform plasma in a meter-sized chamber.

In the present work, we investigated properties of argon plasma sustained with multiple LIA units in the ultra-large-area plasma sources to examine feasibility of processing plasma source with uniform plasma production larger than 2 meters, which is required for next generation FPD processes.

2. SIMULATION CODE

A plasma model developed for the present investigation is based on continuity equation of each heavy particles and energy conservation equation for charged particles using the drift-diffusion

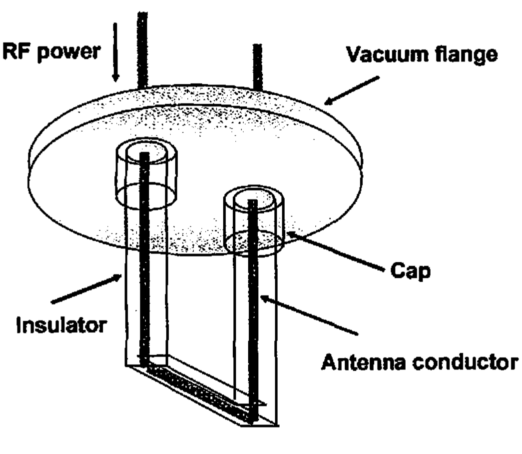

Fig. 1. Schematic diagram of LIA unit.

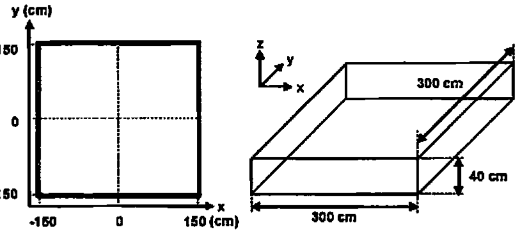

Fig. 2. Schematic illustrations of process chamber.

approximation, where it is assumed that the plasma is electrically neutral over the volume of a bulk plasma ($n_i = n_e$), and that the electron and ion fluxes to the walls balances at all time ($\Gamma_e = \Gamma_i$) [9]. Argon (Ar) plasmas sustained by 13.56 MHz RF power are simulated in the present study. Using the obtained electron temperature T_e and plasma density n_p profile, diffusion equation as well as continuity equation of neutral particles was solved to determine 4*s* excited Ar (Ar*) density n_{Ar*} profile. In this model, the simulation space is divided into rectangular numerical cells, the volume of which is fixed at 10.0 x 10.0 x 10.0 cm^3 in the *x*-, *y*- (perpendicular to axis of chamber) and *z*- (parallel to axis of chamber) directions, respectively. The amount of the absorbed power to LIA units is calculated using the electron energy equation, the value of which is input directly into the cell which includes the fraction of the antenna; i.e., the absorbed power in the cell is calculated as (total power to the antenna) x (volume fraction of the antenna included in the cell) / (total antenna volume). Electron–ion pairs and Ar* are assumed to be created by argon-electron collisions including ionization, excitation and elastic collisions of the background gas. Electron and ion are also assumed to be lost by diffusive flow to the walls.

Figure 2 shows a rectangular process chamber for which the plasma fluid simulations were carried out in this work. The chamber had an internal square area of 300 cm and an internal hight of 40 cm. Ar gas flow was introduced from the whole top of the chamber and flew through the plasma at argon pressure of 6.7 Pa. Each U-shaped LIA unit with a dimension of 40 cm in width and 16 cm in length was mounted on the top plate located at z = 40 cm and plasma profiles were examined at a substrate holder located at z = 0 cm.

We evaluated nonuniformity of plasma properties as

$$nonuniformity = \pm \frac{N_{max} - N_{min}}{Ave.} \times \frac{1}{2}$$

and

$$Ave. = \frac{N_{max} + N_{min}}{2}.$$

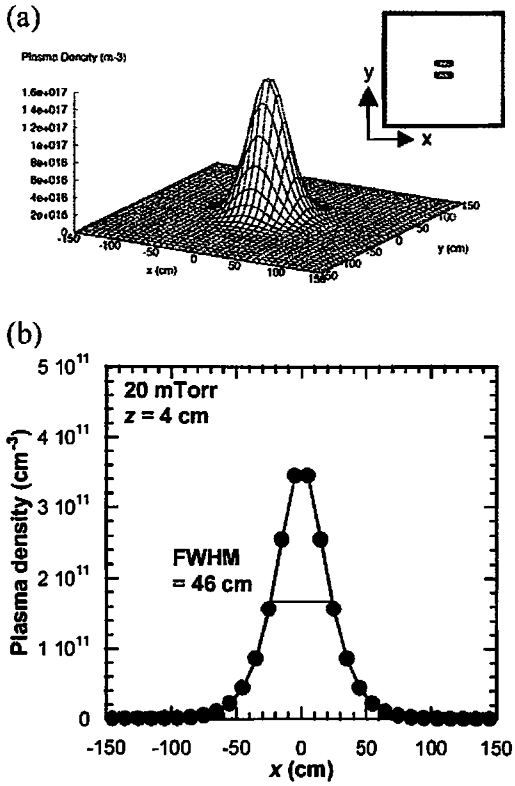

Fig. 3. Computed plasma density profile sustained with two LIA units located at the center of the top plate. The inset shows the configuration of LIA units located at the top plate of the chamber.

Here N_{max} and N_{min} are maximum and minimum values of plasma properties (n_p and n_{Ar*}) in the evaluation area.

3. RESULTS AND DISCUSSION

First, in order to reveal profiles of plasma properties sustained with LIA units localized at the center top of the rectangular process chamber, the profile of plasma sustained with two LIA units at RF power of 2000 W were installed at a center of top plate, as shown in the inset of Fig. 3, was investigated. The distance between two LIA units was kept at 20 cm.

Figure 3 shows the numerical result of (a) two-dimensional plasma density profile and (b) plasma density distribution at y = 0 cm in the 4.0 cm above the substrate. As seen in Fig. 3 (a), the profile of n_p has a peak at the center position. This result indicates that proper spacing between LIA units should be about ~ 50 cm, which is equivalent to FWHM of the profile as shown in Fig. 3 (b), for attaining large-area uniformity of plasma density in the multiple LIA configurations.

Figure 4 shows the numerical result of (a) two-

(a)

(b)

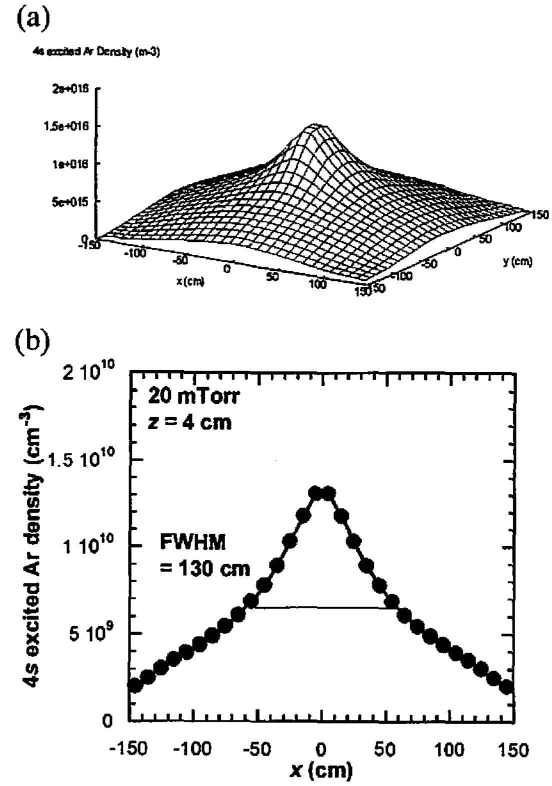

Fig. 4. Computed Ar* density profile sustained with two LIA units located at the center of the top plate.

dimensional Ar* density profile and (b) Ar* density distribution at y = 0 cm. The profile of n_{Ar^*} has a peak at the center position as well as n_p as shown in Fig. 4 (a). However, FWHM of the profile for Ar* density is larger than 2 factors compared to that for plasma density. The different profile of these particles is attributed to the different diffusion characteristics. In addition to the diffusion equation, by which the behavior of neutral particles is mainly ruled, the behavior of charged particles is also restrained to the ambipolar diffusion. We obtained the *y-z* 2D vector plot of Ar, Ar* and Ar ion (Ar^+) flux at x = 0 cm (not shown here). In these results, Ar^+ diffuses from the center of the chamber toward the chamber walls. The density of Ar^+ shows the highest value at the center of the chamber and decreases with the distance parts from the center. On the other hand, Ar and Ar* diffuse from the top plate of the chamber to the substrate and Ar* density shows the most at the center of the top plate, in which LIA units were installed. The magnitude of Ar flux is larger than 3 orders compared to that of Ar* flux. These results indicate that Ar ion diffuse along the electric field gradient while 4*s* excited Ar particles follow the diffusion of argon.

Based on the results, we designed a discharge

(a)

(b)

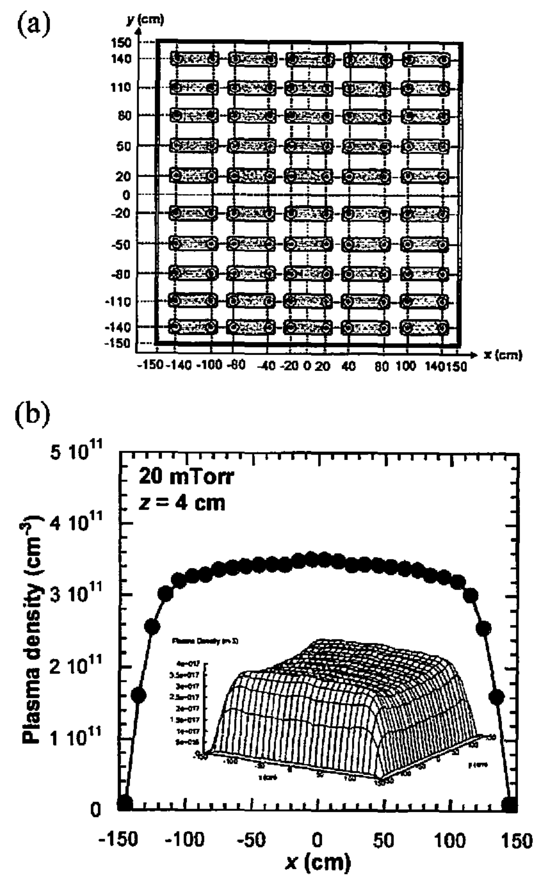

Fig. 5. The configuration of LIA units for this calculation (a). Computed plasma density profile sustained with multiple LIA units located at the center of the top plate (b).

chamber of 300 x 300 cm^2 and examined the uniformity of plasma density and Ar* density. Figure 5 (a) shows the configuration of LIA units located at the top plate of the chamber, in which RF-power inputs to each of LIA units were set in 800 or 1000 W. Figure 5 (b) presents the computed plasma density profile in the 4.0 cm above the substrate. The nonuniformity of the plasma density was 5.5% in 230-cm rectangular area. The plasma density near both sides of the chamber walls was lower than that of the uniform plasma region because of the diffusive flow of the Ar ion to the walls. The two-dimensional computed Ar* density profile and Ar* density distribution at y = 0 cm in the 4.0 cm above the substrate is shown in Fig. 6 (a) and (b). Uniform Ar* density profile with a nonuniformity of 4.9% was obtained over 230-cm rectangular area as shown in Fig. 6 (b). The Ar* density near both sides of the chamber walls was higher than that of the uniform plasma region. The increase of Ar* density is considered to be caused by the decrease of the plasma density near both sides of the chamber walls as

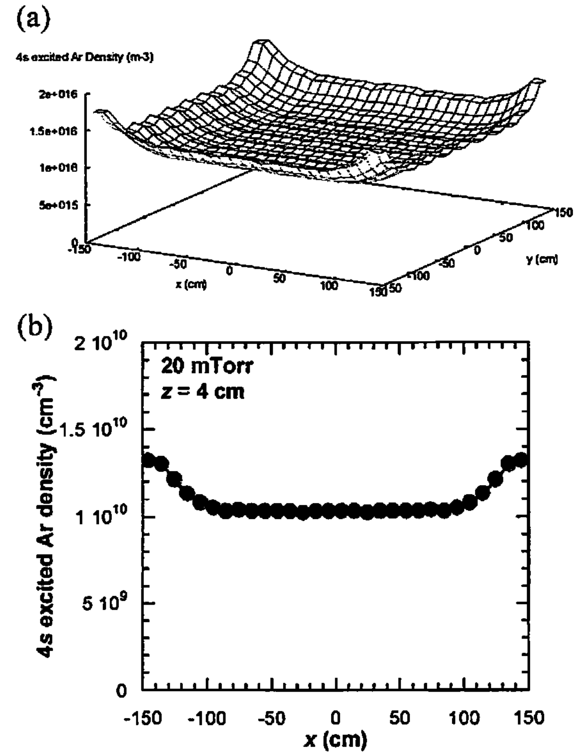

Fig. 6. Computed Ar* density profile sustained with multiple LIA units located at the center of the top plate.

shown in Fig. 5 (b). Rate constant of loss of Ar* due to Ar*-electron collision is much higher than that of excitation of Ar due to Ar-electron collision [9]. Thus the loss of Ar* drastically decreases with decreasing electron density, while the generation of Ar* slightly decreases. Therefore the difference between the generation of Ar* and the loss of Ar* is relatively large and the Ar* density increases with decreasing electron density.

4. CONCLUSIONS

Profiles of argon plasma in a 300-cm rectangular plasma source sustained with multiple LIA units have been investigated by a fluid-simulation code. Both the profile of plasma density and that of Ar* density near the substrate have a peak at the center position in the condition that two LIA units were installed at the center of top plate. However, FWHM of the profile for Ar* density is larger than 2 factors compared to that for plasma density. This difference is caused by the different diffusion for particles; i.e., Ar ions diffuse along the electric field gradient while 4*s* excited Ar particles follow the diffusion of argon. For uniform plasma production, the simulation of plasma production in the rectangular process chamber with multiple LIA units was carried out. The nonuniformity of the plasma density was estimated 5.5% while Ar* density was obtained with a nonuniformity of 4.9% in 230-cm rectangular area, which is equivalent to the substrate size required for next generation FPD processes.

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