

Plasma Density Distribution in Asymmetric Geometry Capacitive Coupled Plasma Discharge System

Yinchang Du, and Yangfang Li

Abstract—In this work, we used the single Langmuir probe to measure the plasma density distribution in an geometrically asymmetric capacitive coupled plasma discharge system. Because of the frame structure of powered electrode, the plasma density was not homogeneous in the discharge volume. It was higher under the frame, but lower in the centre. Finite element simulation results showed a good agreement with the experiment results. To increase the electron density in the central volume and improve the homogeneity of the plasma, we added an auxiliary electrode, powered by DC voltage, in the simulation geometry. The simulation results showed that the auxiliary electrode could alter the potential distribution and improve the density homogeneity effectively.

Keywords—Capacitive coupled discharge, asymmetric discharge, homogeneous plasma.

I. INTRODUCTION

CAPACITIVE coupled plasma (CCP) is widely used in film deposition, etching and flat panel display industry [1]–[3]. One can have large scale and homogeneous plasma by using the symmetric CCP discharge. By varying the gas pressure, discharge voltage, frequency and phase, the plasma parameter can be easily manipulated [1].

It is however a big challenge to control the ion flux and ion energy independently in CCP discharges [4]. A lot of research on the geometrically asymmetric and electrically asymmetric discharges has been carried out to control the ion flux and energy respectively. In geometrically asymmetric discharge, a DC self-bias develops to balance the charged particle flux on the powered and grounded electrodes [5]–[7]. The self-bias voltage V_s is given in equation 1 and 2 [4]

$$V_s = -\frac{\phi_{\max} - \varepsilon\phi_{\min}}{1 + \varepsilon} \quad (1)$$

$$\varepsilon = \frac{|\phi_{sg}|}{|\phi_{sp}|} \approx \left(\frac{A_p}{A_g}\right)^2 \frac{\overline{n_{sp}}}{\overline{n_{sg}}} \left(\frac{Q_{mg}}{Q_{mp}}\right)^2 \quad (2)$$

where ϕ_{\max} and ϕ_{\min} are the maximum and minimum radio frequency (rf) voltage. ε is the discharge geometric parameter. ϕ_{sg} and ϕ_{sp} are the cross sheath voltage on the grounded and powered electrodes, respectively. $\overline{n_{sp}}$, $\overline{n_{sg}}$, Q_{mp} , and Q_{mg} are the mean ion density and maximum charge at the sheath edge of the powered and grounded electrode, respectively. The self-bias

Yinchang Du is with the University of Science and Technology of China, Department of Modern Physics, 230026, Hefei, Anhui province, China (email: ycd@mail.ustc.edu.cn).

Yangfang Li is with the Max-Planck institute for extraterrestrial physics, 85748 Garching bei Muechen, Germany (email: yfli@mpe.mpg.de).

can change the ion bombardment energy. And there is a strong gradient of the plasma parameters, observed at the periphery of the electrodes [8]. There is an electrode area ratio law of the CCP discharge. Salem et al. used a cylindrical apparatus to sort out the theoretical models [9]. Schulze et al. [10] found that the electrically asymmetry effect could make the geometrically asymmetric CCP discharge electrically symmetric. By tuning the phase shift between the driving frequencies, they could switch the discharge mode from etching mode to a clean mode or a deposition mode.

For geometrically asymmetric discharge, the plasma electrical potential and electron density distribution are not homogeneous, because of the configuration of the electrodes. Since thermal velocity of electrons is much faster than that of ions, an ambipolar field is established [11].

In this paper, we used a single Langmuir probe to measure electron density distribution along the axis of the geometrically asymmetric CCP discharge apparatus. The distribution of the electron density was influenced by the structure of the powered electrode. The simulation results showed a good agreement with experimental measurement. To improve the homogeneity of the plasma, we added an auxiliary electrode, powered by DC voltage, in the simulation geometry. By increasing the potential in the low density volume, the density of the volume was increased. More homogeneous plasma can be produced by applying the auxiliary electrode in the geometrically asymmetric discharge apparatus.

II. EXPERIMENT SETUP AND RESULT

In our experiment, the vacuum chamber was 400 mm high and 800 mm in diameter, the detail of the discharge system can be found elsewhere [12]. The experiment setup was shown in Fig.1. The upper-framed electrode was powered with 13.56 MHz rf voltage while the lower-planar electrode was grounded. The size of the electrodes was a 500 mm × 500 mm stainless steel board. The interval of the two electrodes was fixed at 60 mm. The powered electrode, power supply and the match unit were cooled by the cooling water.

A single Langmuir probe was inserted into the discharge volume. The probe was made of tungsten, with the size of 10 mm long and 0.15 mm in diameter. The probe tip was set at a height of 20 mm from the lower CCP electrode to avoid the influence of the plasma sheath. As the probe moved along the axis of the discharge volume, the plasma density distribution was obtained. Given the limit moving of the probe, the diagnostic range was only 12 cm, with 1 cm interval of two diagnosis points.

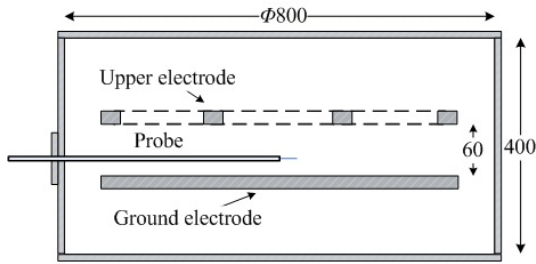


Fig. 1 The experiment setup (unit: mm)

We used the argon as the working gas, with pressures of 10 Pa, 30 Pa, 50 Pa, and 100 Pa respectively. The input rf power from the rf generator was 80 W and it was delivered into the discharge chamber by using a matching unit with less than 1% of reflecting power. The probe data were analyzed by the orbital-motion-limit (OML) theory, which gave us more accurate ion density [13], [14]. Plasma is normally quasi-neutral in the bulk plasma, so the ion density is always equal to the electron density. We can get the electron density from the ion density which was calculated by the OML theory. The electron density (n_e) is shown in Fig. 2.

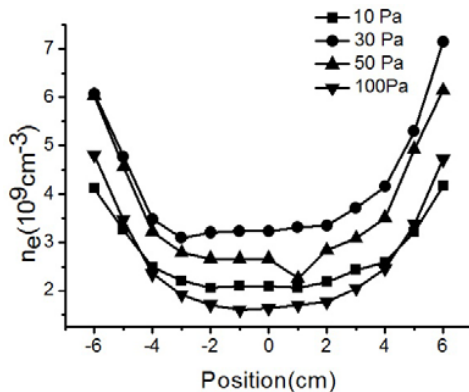
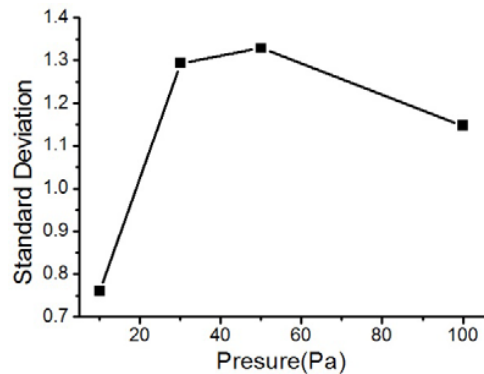


Fig. 2 The n_e varied with the pressure and position. The measurement was conducted for four different gas pressures, 10 Pa (square), 30 Pa (circle), 50 Pa (uptriangle), 100 Pa (downtriangle), respectively

We set the centre of the vacuum chamber at 0 cm, and -6 cm and 6 cm were the positions under the two stripes of the powered electrode respectively. We can see from the Fig. 2 that the density is higher at -6 and 6 cm than that at 0 cm. Because of the frame structure of the rf electrode, the parabolic density profiles gave lowest density in the centre. The n_e of 6 cm reached the top, about $7 \times 10^9 \text{ cm}^{-3}$, at 30 Pa. And the minimum density was $1.6 \times 10^9 \text{ cm}^{-3}$, when the gas pressure was 100 Pa at 0 cm. The n_e was inhomogeneous in the discharge volume.

For easy comparison of the diagnostic results, the standard deviations (SD) of the density distribution were shown in Fig. 3. We can see from the figure, there was a lowest SD of density when the pressure was 10 Pa. The lower SD value meant that we could get the more homogeneously density distribution at low gas pressure. As the pressure increased, the SD value increased, and reached the maximum when the pressure was 50 Pa. The inhomogeneity was caused by the increasing collision

frequency of the electron-neutron collision. When the pressure reached 100 Pa, the SD slightly decreased because of the lower plasma density.

Fig. 3 The standard deviation of the n_e varied with pressure

III. FINITE ELEMENT SIMULATION RESULT AND DISCUSSION

For further study of the geometrically asymmetric discharge system, we used the finite element simulation program COMSOL to calculate the plasma parameter of this discharge system. This was a 2D simulation geometry, and the profile of the geometry was almost the same as the discharge chamber. The sketch of the simulation geometry is shown in Fig. 4.

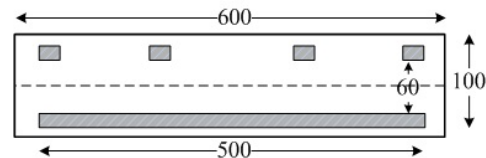


Fig. 4 The geometry of the simulation (unit: mm)

In the simulation, the upper four stripes were powered by 150V 13.56MHz rf signals. The lower electrode and the wall were connected to the ground. The working gas was the argon, with the pressure 10 Pa, 30 Pa, 50 Pa, 100 Pa respectively. After 10 rf periods, the electron density, temperature and electric potential along the dash line in Fig. 4 were shown in Fig. 5.

We can see from Fig. 5 that the electron density increased as the pressure increased, when the input voltage was 150V. The electron density was approximately $1 \times 10^{13} \text{ m}^{-3}$, when the pressure was 10 Pa. When the gas pressure raised up to 30 Pa or more, the maximum electron density raised up to $1.5 \times 10^{14} \text{ m}^{-3}$. The distribution of the electron density became more inhomogeneous as the density rising up. The electron density had a parabolic distribution, the same as the experimental result. The electron temperature was about 4 to 5 eV, when the gas pressure was 10 Pa. As the pressure increased, the electron temperature decreased significantly. When the pressure raised up to 30 Pa, the electron temperature was about 2.5 eV, and did not change much as the pressure increased.

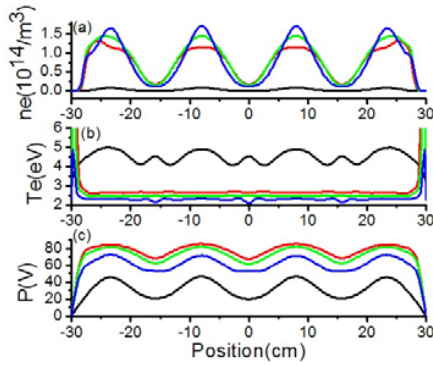


Fig. 5 This is the results of the finite element simulation. The curves in figure (a), (b), (c) are the electron density, electron temperature, and electric potential varying with the position respectively. The different colors mean the differential pressure, black, red, green, blue for the pressure of 10Pa, 30Pa, 50Pa, 100Pa respectively

The distribution of electric potential was the same profile as the electron density distribution. The electric potential raised as the pressure raised up, but slightly decreased when the pressure was higher than 30 Pa. In the inhomogeneous plasma, the electron density and electric potential obey the Boltzmann equation [15]. The equation is shown in 3.

$$n_e = n_0 \times \exp\left(\frac{eV_p}{kT_e}\right) \quad (3)$$

Where n_e is the electron density where the potential is V_p . n_0 is the electron density where $V_p = 0V$. T_e is the electron temperature. We can see from 3, when the electric potential is changed, the electron density distribution will be changed too. The homogeneity can be improved by increasing the potential of the low density volume.

To improve the homogeneity of the electron density distribution, we added a small electrode, with the size of 1mm \times 1mm, in the simulation geometry with the centre at position (0 cm, 1 cm), and set the potential of the electrode to 100 V. The small electrode could change the potential profile of the simulation. The gas pressure was set to 30 Pa, with 150 V 13.56 MHz rf signal. After 10 rf periods, the electron density, temperature, and electric potential are shown in Fig. 6.

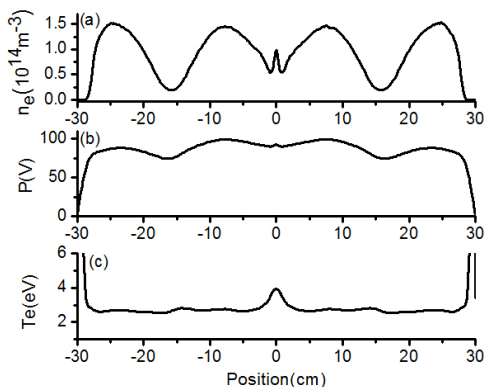


Fig. 6 The simulation results after mounting a small electrode. The curves in figure (a), (b), (c) are the electron density, electric potential, and electron temperature varying with the position respectively.

The electron density of 0 cm had been increased significantly by raising the electric potential of 0 cm. There was a maximal value of electron density and electron temperature at 0 cm. At the same time the electric potential distribution was almost flat in the central volume.

The electron density distribution was changed by applying the auxiliary electrode. The homogeneity was improved by raising the electric potential of the lower density volume. The plasma parameter of other discharge volume, which was far away from the auxiliary electrode, did not change a lot when the auxiliary electrode was applied. This method is very useful for improving the homogeneity of the geometrically asymmetric discharge system.

IV. CONCLUSION

In the capacitive coupled plasma discharge, there is a self-bias, caused by the different area of the powered and grounded electrodes, which can alter the ion bombardment energy. In our experiment, the powered electrode was a steel frame, while the grounded electrode was a 500mm \times 500mm steel board. The geometrically asymmetric discharge could cause the self-bias as well as the inhomogeneous electron density distribution. The single Langmuir probe diagnosis results showed that there was a higher n_e right below the stripes of the powered electrode, while the n_e in the central discharge volume was lower. There was a parabolic distribution profile of the n_e in the discharge volume. The n_e increased as the gas pressure increased from 10 Pa to 30 Pa, and the density distribution became more inhomogeneous. When the pressure was higher than 30 Pa, the density slightly decreased, but the homogeneity did not change so much.

The finite element simulation results showed a good agreement with the single Langmuir probe diagnosis results. As it is shown in Fig. 5, the distribution profile of electric potential was almost the same as that of the electron density. The high electron density was accompanied by the high electric potential.

To improve the homogeneity of the plasma, we added a small auxiliary electrode, which was applied 100 V DC voltage, in the simulation geometry. The auxiliary electrode altered the potential distribution profile of the discharge volume. The electron density in the discharge centre was raised up by applying the DC voltage on the auxiliary electrode. The simulation results gave us a method to improve the homogeneity of the geometrically asymmetric CCP discharge apparatus.

ACKNOWLEDGMENT

This work is supported by the MPG-CAS Doctoral Training program as agreed by the presidents of Chinese Academy of Science and Max Planck Society.

REFERENCES

- [1] M. A. Lieberman and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, (Wiley, New York), 2005, pp.327-328.

- [2] T. Makabe and Z. Petrovic, Plasma Electronics: Applications in Microelectronic Device Fabrication, (Taylor & Francis, Boca Raton, FL) 2006, pp.255-272.
- [3] E. Kawamura, M. A. Lieberman, and A. J. Lichtenberg, "Capacitive discharges driven by combined dc/rf sources", J. Vac. Sci. Technol. A. vol. 25, 2007, pp.1456-1475.
- [4] B. G. Heil, U. Czarnetzki, R. P. Brinkmann and T. Mussenbrock, "On the possibility of making a geometrically symmetric RF-CCP discharge electrically asymmetric", J. Phys. D: Appl. Phys. vol. 41, 2008, pp.165202.
- [5] J. W. Coburn and E. Kay, "Positive-ion bombardment of substrates in rf diode glow discharge sputtering", J. Appl. Phys., vol.43, 1972, pp.4965-4972.
- [6] K. Köhler, J. W. Coburn, D. E. Horne, E. Kay, and H. Keller, "Plasma potentials of 13.56-MHz rf argon glow discharges in a planar system", J. Appl. Phys., vol.57, 1985, pp.59-67.
- [7] M. A. Lieberman and S. E. Savas, "Bias voltage in finite length cylindrical and coaxial radio-frequency discharges", J. Vac. Sci. Technol. A., vol.8, 1990, pp.1632-1642.
- [8] K. Radouane, B. Dapsax M. Yousfi, J. P. Couderc, E. Klusmann, H. Meyer, R. Schulz, and J. Schulze, "Two-dimensional electrical modeling of asymmetric radio-frequency discharges for geometry effect analysis. Comparison with experiments" J. Appl. Phys., vol.90, 2001, pp.4346-4354.
- [9] M. Mohamed Salem, and J. F. Loiseau, "Experiments to sort out theoretical models concerning the area ratio law for plasma reactors", J. Phys. D: Appl. Phys., vol.29, 1996, pp.1181-1187.
- [10] Julian Schulze, Edmund Schngel, Uwe Czarnetzki, Markus Gebhardt, Ralf Peter Brinkmann, and Thomas Mussenbrock, "Making a geometrically asymmetric capacitive rf discharge electrically symmetric", Appl. Phys. Lett., vol.98, 2011, pp.031501.
- [11] V. A. Godyak, and R. B. Piejak, "Paradoxical spatial distribution of the electron temperature in a low pressure rf discharge", Appl. Phys. Lett., vol.63, 1993, pp.3137-3139.
- [12] Y.F. Li, W.G. Zhang, J.X. Ma, K. Jiang, H.M. Thomas and G.E. Morfill, "Traveling electric field probed by a fine particle above voltagedmodulated strips in a striped electrode device", Phys. Plasmas, vol.17, 2010, pp.033705.
- [13] F.F. Chen, "Langmuir probes in RF plasma: surprising validity of OML theory", Plasma Sources Sci. Technol., vol.18, 2009, pp.035012.
- [14] F.F. Chen, "Time-varying impedance of the sheath on a probe in an RF plasma", Plasma Sources Sci. Technol., vol.15, 2006, pp.773-782.
- [15] J. M. Kriesela, and C. F. Driscoll, "Electron plasma profiles from a cathode with an r^2 potential variation", Phys. Plasmas, vol.5, 1998, pp.1265-1272.

Yinchang Du was born in Hefei Anhui province, China, April 30th 1986. He got his Bachelor degree in Physics from the Northwest Polytechnic University (NWPU), majoring in optical information science and technology, in July 2008. He is currently a PhD candidate at department of Modern Physics, University of Science and Technology of China, Hefei, Anhui province, majoring in plasma physics. His research field mainly focuses on the radio-frequency discharge plasma.

He worked as a teaching assistant at the Department of Optic and Atom Physics.. From November 2011, he has been supported by the co-educated program of China Academy of Science and Max- Planck Society. He is now working on the homogeneity of the geometrically asymmetric CCP discharge system in the Max Planck Institute for Extraterrestrial Physics, Garching, Germany.