Langmuir probe measurements of an RF driven high-density inductively coupled argon plasma

Weiyuan Ni1,2, Guicai Song1,,*, Dongping Liu2,*

1School of Science, Changchun University of Science and Technology, Changchun, China
2School of Electrical Engineering, Dalian University of Technology, Dalian, China
*Corresponding author e-mail: songcust@163.com; dpliu@dlut.edu.cn

Abstract: In this paper, a high-density inductively coupled argon plasma was generated by an RF power supply, and the plasma density, electron temperature, and plasma potential were measured by a Langmuir probe. It was found that the plasma density, electron temperature, and plasma potential along the quartz glass tube axial direction increased in the range of 0.37×10^19-6.75×10^19 m^-3, 3.44-5.91 eV , and 11.92-20.09 V respectively, when the incident RF power increased from 3 kV to 8 kV at a gas pressure of 25 Pa. The maximum values of the plasma density and plasma potential appear in the position of coil center and the electron temperature in the coil region almost unchanged.

1. Introduction

It has been reported that low pressure Radio frequency (RF) driven inductively coupled plasmas (ICPs) have many advantages compared to conventional capacitively coupled plasmas, such as high plasma density [1-3], reduction in ion damage [4] and independently controllable ion energy [5-6]. Typically, the RF driven ICP sources are capable of producing dense low-noise uniform plasmas in a large volume and the plasma density might vary within a wide range: 10^15-10^18 m^-3 at electron temperature which could be a few electron volts [7-10]. Therefore, the RF driven ICPs are widely used to plasma processing of materials, such as etching [11, 12], sputtering [13, 14], deposition of thin films [15, 16], and irradiation damages of fusion energy materials [17]. It was clear that the use of highly plasma density ICPs increases the ratio of ions to neutral radicals reaching the substrate, enhancing etching anisotropy, sputtering rate, and deposition efficiency.

The information about fundamental plasma parameters, such as electron temperature, electron/ion/plasma density, etc., are essential, because the properties of treated materials have a strong relationship with their processing plasma characteristics. There are several diagnostic techniques employed for the determination of electron density and temperature which includes plasma spectroscopy [18], Langmuir probe [19], microwave and laser interferometries [20], and Thomson scattering [21]. Among such techniques, the Langmuir probe method is widely used diagnostic techniques. A number of studies using for Langmuir probe measurements have been undertaken in order to provide reliable characterization of ICPs [22-25].

For these reasons, the RF driven high plasma density (as high as 6.75×10^19 m^-3) ICP source was developed with argon gas, and the plasma density, electron temperature, and plasma potential were measured by the Langmuir probe.
2. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup and the discharge photograph. The main body of ICP source is a quartz tube with the inner diameter, outer diameter, and length of 80, 90, and 150 mm, respectively. The antenna consists of 12-turn water-cooled copper coil placed on the quartz tube outside, which is connected to the 2 MHz RF power via a Γ-type matching network. In order to prevent a direct plasma contact with the inside surface of quartz tube, an water-cooled Faraday screen (stainless steel material) is placed on the inside of quartz tube. The Faraday screen has slits in axial direction and is therefore permeable for the RF, so that an inductive coupling to the plasma is possible. A pair of ring permanent magnets, which create the magnetic field for enhancing the plasma confinement, are positioned in dedicated grooves on the outside of the water-cooled front plate. The chamber is evacuated by a turbo-molecular pump backed by a rotary pump giving a base pressure of $1 \times 10^{-5}$ Pa. The discharge pressure is maintained by the flow rate of argon gas (99.9999%) controlled with mass flow meters and the vacuum flapper valve placed under the vacuum chamber bottom, and it is monitored by a resistance gauge equipped on the front plate. The experiments were conducted under the Ar flow rate of 20 slm and the discharge pressure of 25 Pa, and the applied RF powers in the range of 3-8 kW. The reflected power is continuously monitored, and which remained below 1%. An RF-compensated Langmuir probe (Hiden ESP400) is inserted to the region of discharge along the quartz tube axial direction from the KF(Klein Flange )-25 interface in the center of front plate in order to measure the ion density, electron temperature and plasma potential. This probe uses a cylindrical tungsten tip of 1.5 mm diameter and 4 mm length, and the probe current is measured for bias voltages in the range of $-30$ to $+45$ V. All calculations of plasma parameters are performed through a PC by using suitable software (ESPionSoft).

![Fig. 1. Experimental setup and discharge photograph](image)

3. Experimental results and discussions
Fig. 2. I-V curve recorded at 5 kW RF power and 25 Pa

A typical Langmuir probe I-V characteristics for an input power of 5 kW is shown in Fig. 2. To enable analysis, the I-V characteristic is divided into three regions - the ion saturation, electron transition, and electron saturation regions [26]. This division is useful from the point of view of understanding the shape of the I-V characteristic and more importantly in analysing the data.

Typically, the electron current $I_e$ for any Maxwellian plasma can be expressed by [26, 27]

$$I_e \propto \exp\left(-\frac{eV}{KT_e}\right)$$

(1)

Where $V$ is the probe voltage and $K$ is the Boltzmann constant. Therefore, one can find the electron temperature $T_e$ by fitting $I_e$ versus $V$ on a semi-log plot in the electron transition region.

The ion saturation portion of the characteristics is used to determine the ion density $n_i$, which can be expressed by [26, 28]

$$n_i = \frac{4\pi m_i}{3e} \left(\frac{e}{A}\right)^{\frac{1}{2}} \left(-\frac{\partial I_i}{\partial V}\right)^{\frac{3}{2}}$$

(2)

where $A$ is the surface area of the probe, $m_i$ is the ion mass and $I_i$ is the ion saturation current. So, the ion density $n_i$ can be calculated using the slope that is obtained fitting $I_i^2$ versus $V$ plot in the ion saturation region.

The plasma potential is the probe voltage corresponding to the intersection of the two lines that are obtained by fitting $I$ versus $V$ plot in the electron saturation and transition regions [26, 28].

Fig. 3. (a) Ion density vs axial distance at different RF incident power, (b) Electron temperature vs axial distance at different RF incident power, (c) Plasma potential vs axial distance at different RF incident power

Figs. 3(a), (b), and (c) show the variations of the ion density, electron temperature, and plasma potential along the quartz tube axial direction under different incident RF power at a gas pressure of 25 Pa. It can be seen from Fig. 3(a) that the ion density increases proportionately when the incident RF power is increased. This is because the increase in incident RF power provides more energy to be transferred to create more ionization in the discharge. As the incident power increases from 3 kW to 8 kW, the ion density increases to $6.75 \times 10^{19}$ m$^{-3}$. Under the constant incident RF power, the ion density
increases gradually along the quartz tube axial direction and the maximum values of ion density appear in the position of coil center. As presented in Fig. 3(b), the electron temperature slightly increases with the incident RF power, which is because the increase in the incident RF power results to higher electron density. The maximum value of electron temperature reaches to 5.91 eV at incident RF power of 8 kW. When the incident RF power is constant, the electron temperature increases quickly in the range of 0-3 cm and is unchanged nearly in the range of 3-8 cm along the quartz tube axial direction. As regarding the results shown in Fig. 3(c), the plasma potential increases with the incident RF power. It is well in agreement with the results reported by M. A. Naveed et al [18]. As the incident RF power increases from 3 kW to 8 kW, the plasma potential increases from 11.92 V to 20.09 V. The plasma potential also increases along the quartz tube axial direction and the the maximum values of plasma potential appear in the position of coil center when the incident RF power is constant.

4. Conclusion
An RF driven high density ICP source was developed with argon gas. Using the Langmuir probe, the plasma density, electron temperature, and plasma potential were measured. It was found that the the plasma density, electron temperature, and plasma potential increased with incident RF power, and the maximum values of the plasma density and the plasma potential appears in the position of coil center along the quartz tube axial direction. When the incident RF power is 8 kW, the plasma density, electron temperature, and plasma potential can reach to $6.75 \times 10^{19}$ m$^{-3}$, 5.91 eV, and 20.09 V, respectively.

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References
[1] Park, J. C., Kim, S. H., Kim, T. G., Kim, J. K., Cho, H., Lee, B. W. (2015) High density plasma etching of ultrananocrystalline diamond films in O$_2$/CF$_4$ and O$_2$/SF$_6$ inductively coupled plasmas. Phys. Lett. B, 29: 1540022.
[2] Hwang, S. M., Garay A. A., Lee, W. I., Chung. C. W. (2015) High density plasma reactive ion etching of Ru thin films using non-corrosive gas mixture. Thin Solid Films, 587(31): 28-33.
[3] Seo, B. H., Kim, J. H., You, S. J. (2015) Effects of argon gas pressure on its metastable-state density in high-density plasmas. Phys. Plasmas, 22: 053514.
[4] Seo, S. H., Chung, C. W., and Chang, H. Y. (2000) Review of heating mechanism in inductively couple plasma. Surface & Coating Technol., 131(1-3): 1-11.
[5] Bogdanov, E. A., Eliseev, S. I., and Kudryavtsev, A. A. (2015) Effect of the electron energy distribution on total energy loss with argon in inductively coupled plasmas. Phys. Plasmas, 22: 044701.
[6] Logue, M. D. and Kushner, M. J. (2015) Electron energy distributions and electron impact source functions in Ar/N$_2$ inductively coupled plasmas using pulsed power. J. Appl. Phys., 117: 043301.
[7] Seo, M. W., Bae, M. K., and Chung, T. H. (2014) Comparison of various interpretation methods of the electric probe measurements in inductively coupled Ar and O$_2$ plasmas. Phys. Plasmas, 21(2): 023514.
[8] Kim, Y. C., Kim, J. Y., Lee, H. C., Kim, Y. S., Kim, J. Y., Cho, S. W., and Chung, C. W. (2015) Experimental verification of the Boltzmann relation at the wall in inductively coupled plasmas. Appl. Phys. Lett., 106(16): 074103.
[9] Zhou, L., Chen, J., Ma, J., and Li, Y. (2015) Spatial distribution study of argon radio-frequency inductively coupled plasma in inverse hysteresis transition area [J]. Vacuum, 119: 209–213.
[10] Liu, F. X., Guo, X. M., and Pu, Y. K. (2015) Electron cooling and plasma density decay in early afterglow of low pressure argon plasmas. Plasma Sources Sci. Technol., 24:034013.

[11] Hotovy, I., Hasčík, S., Gregor, M., Rebacek, V., Predanocy, M., and Pleceni, A. (2014) Dry etching characteristics of TiO2 thin films using inductively coupled plasma for gas sensing. Vacuum, 107:20-22.

[12] Cao, M., Li, X., Missous, M., Thayne, I. (2015) Nanoscale molybdenum gates fabricated by low damage inductively coupled plasma SF6/C4F8 etching suitable for high performance compound semiconductor transistors. Microelectron. Eng., 140: 56–59.

[13] Khatir, S., Hirose, A., Xiao, C. (2014) Coating diamond-like carbon films on polymer substrates by inductively coupled plasma assisted sputtering, Surf. Coat. Techno., 253: 96–99.

[14] Ni, C. J, and Hong, F. C. N. (2014) Low-temperature growth of gallium nitride films by inductively coupled-plasma-enhanced reactive magnetron sputtering. J. Vac. Sci. Technol. A, 32: 031514.

[15] Liua, B. H., Huang, H. J., Huang, S. H., Hsiao, C. N. (2014) Platinum thin films with good thermal and chemical stability fabricated by inductively coupled plasma-enhanced atomic layer deposition at low temperatures. Thin Solid Films, 566: 93-98.

[16] Li, D., Carette, M., Granier, A., Landesman, J. P., Goullet, A. (2015) Effect of ion bombardment on the structural and optical properties of TiO2 thin films deposited from oxygen/titanium tetraisopropoxide inductively coupled plasma. Thin Solid Films, 589: 783-791.

[17] Shu, X., Huang, B., Yang, J., Liu, D., Fan, H., Liao, J., Yang, Y., Liu, N., and Tang, J. (2014) Fabrication and Helium Irradiation of Potassium-Doped Tungsten. Fusion Sci. Techno., 66(1): 278-282.

[18] Naveed, M. A., Rehman, N. U., Zeb, S., Hussain, S., and Zakaullah, M. (2008) Langmuir probe and spectroscopic studies of RF generated helium-nitrogen mixture plasma. Eur. Phys. J. D, 47: 395–402.

[19] Lee, H. C., Oh, S. J., and Chung, C. W. (2012) Experimental observation of the skin effect on plasma uniformity in inductively coupled plasmas with a radio frequency bias[J]. Plasma Sources Sci. Technol., 21:035003.

[20] Wan, A. S., Barbee, T., Cauble, R., Celliers, P., Da Silva, L. B., Moreno, J. C. (1997) Electron density measurement of a colliding plasma using soft-x-ray laser interferometry. Phys. Rev. E, 55(5), 6293-6296.

[21] Seo, B., You, S., Kim, J. (2015) Analysis of uncertainty of electron density and temperature using laser Thomson scattering in helicon plasmas. Jpn. J. Appl. phys.,54(8): 086102.

[22] Son, J., Kim, M. S., Lee, H. W., Yu, J. S., Kwon, K. H. (2014) Surface Modification of Polypropylene Separators in Lithium-Ion Batteries Using Inductively Coupled Plasma Treatment. J. Nanosci. Nanotechno., 14: 9368.

[23] Naz, M. Y., Shukrullah, S., Ghafar, A., Rehman, N. U. (2014) Development of simple designs of multitip probe diagnostic systems for RF plasma characterization. Scientific World Journal, 1: 279868.

[24] Mishra, A., Lee, S., Yeom, G. Y. (2014) Plasma dynamics in a discharge produced by a pulsed dual frequency inductively coupled plasma source[J]. J. Vac. Sci. Technol., 32(6): 061303.

[25] Jan, F., Khan, A. W., Saeed, A., Zakaullah, M. (2013) Comparative Study of Plasma Parameters in Magnetic Pole Enhanced Inductively Coupled Argon Plasmas. Plasma Sci. Technol., 04(4): 329-334.

[26] Chen, F. F. ( 2009) Langmuir probes in RF plasma: surprising validity of OML theory. Plasma Sources Sci. Technol.,18(3): 510-514.

[27] Paosawatayong, B. (2004) Compensating langmuir probe studies on the production of high-density plasma in RF transformer coupled discharge. J. Sci. Res. Chula. Univ., 29(2): 199-212.
[28] Nisha, M., Saji, K. J., Ajimsha, R. S., Joshy, N. V., and Jayaraj, M. K. (2006) Characterization of radio frequency plasma using Langmuir probe and optical emission spectroscopy. J. Appl. Phys., 99, 033304.