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Spatial distribution of electron characteristic in argon rf glow discharges*

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The spatial distributions of the electron density and the mean electron energy of argon radio frequency (rf) glow discharge plasma in a plasma-enhanced chemical vapour deposition (PECVD) system have been investigated using an established movable Langmuir probe. The results indicate that in the axial direction the electron density tends to peak at midway between the two electrodes while the axial variation trend of mean electron energy is different from that of the electron density, the mean electron energy is high near the electrodes. And the mean electron energy near the cathode is much higher than that near the anode. This article focuses on the radial distribution of electron density and mean electron energy. A proposed theoretical model distribution agrees well with the experimental one: the electron density and the mean electron energy both increase from the centre of the glow to the edge of electrodes. This is useful for better understanding the discharge mechanism and searching for a better deposition condition to improve thin film quality.

Keywords: spatial distribution of electron characteristic, a movable Langmuir probe, radio frequency glow discharge
PACC: 0630C, 5270, 5280H

1. Introduction

Plasma processing is an important branch of materials science, largely due to its applications in etching, sputtering, especially in glow discharge deposition. Plasma-enhanced chemical vapour deposition (PECVD) is being investigated as a potential technique for the deposition of crystalline films such as polycrystalline silicon and epitaxial silicon.[1,2] The charged-particle concentration and spatial distribution are very important characteristics used in thin film deposition process, especially when spatial uniformity is considered. The spatial distributions of charged particle concentrations are also the fundamental parameters for analysing the spatial reaction process. In order to understand the thin film deposition mechanism and improve deposition conditions, it is necessary to study the spatial distribution of plasma characteristics in the PECVD system.

There are many models to simulate the behaviour of electrons and ions in a glow discharge.[3−8] Most models[7,8] indicate that the peak value of the electron concentration occurs at the midway between the two electrodes. However, the results about the radial distribution of electron density are inconsistent with this even for the similar system. Some results[9,10] revealed that the electron concentration peak lies in the centre of the glow, but others[11,12] showed that an increase of electron density occurs near the edge of the electrodes. The difference perhaps originates from the different reactors used.

The electron density and the electron energy distribution functions have been studied frequently. However, the spatial distributions, especially the radial distributions of the electron density and the mean electron energy have rarely been studied experimentally.[7,13,14] To the author's knowledge, only Schwabedissen *et al*,[9] and Overzet and Hopkins[12] have studied the radial distribution of the electron density in experiment using Langmuir probe. Schwabedissen *et al* indicated that the electron concentration peaks in the centre of the glow in planar-inductively-coupled plasmas. Overzet *et al* pointed out that the charge density increases toward the ra-

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dial edge of the electrodes, and reaches a maximum, approximately 1cm inside the actual electrode edge in the reactor.

After the improvements in many aspects,[15–19] such as tuned filtration, mitigation of radio frequency interference and contamination of the probe, etc, Langmuir probe measurements have become a powerful and experimentally simple means for determining key internal discharge parameters. In this work, we have designed and established a position movable Langmuir probe to measure the spatial distributions of the electron concentration and the mean electron energy in the PECVD system. In this paper we focus on studying the radial distribution of electron characteristics. We propose a model to simulate the radial distribution of the electron density and compare the experimental results with the theoretical ones.

2. Experiment and analysis

A schematic of the experimental apparatus is shown in Fig.1. The discharge is sustained between two asymmetric parallel plate stainless steel electrodes with a diameter of Φ88 mm for the bottom one and Φ120 mm for the upper one, the distance between them is kept at 30mm. The probe is formed by a tungsten wire, 155 mm in length and 0.35 mm in diameter, fitted snugly inside a thin glass tube, except a 5 mm length of the probe tip which is exposed to the plasma. It is noted that the probe can be moved along the axial direction from the bottom (powered) electrode to the upper (grounded) electrode. Making use of it, we measured the axial distributions of the electron density and the mean electron energy. The radial distribution of electron characteristics was obtained by changing the probe length in the direction parallel to the electrodes.

In order to alleviate the radio frequency (rf) interference, the Langmuir probe was tuned. The probe tuning circuit consisted of L1 and C1 as shown in Fig.1. By adjusting the variable capacitor C1, the floating potential corresponding to $I = 0$ in the probe $I-V$ curve could be maximized at the point the probe circuit was tuned.

The parameters, such as the electron energy distribution function (EEDF) $f(E)$, the mean electron energy $\bar{E}$, the electron density n_e, can be determined by the equations as follows:[15,16]

$$[f(E)]_{(E=-eV_\mathrm{p})} = -\frac{4}{A_\mathrm{p}e^2}\sqrt{\frac{-m_\mathrm{e}V_\mathrm{p}}{2e}}\frac{\mathrm{d}^2I}{\mathrm{d}V_\mathrm{p}^2}\,, \quad (V_\mathrm{p} < 0)\,, \tag{1}$$

$$\int_0^\infty \sqrt{E}f(E)\mathrm{d}E = 1\,, \tag{2}$$

$$\bar{E} = \int_0^\infty E^{3/2}f(E)\mathrm{d}E\,, \tag{3}$$

$$n_\mathrm{e} = 4I_{\mathrm{e,sat}}/(eA_\mathrm{p}c_\mathrm{e})\,, \tag{4}$$

$$c_\mathrm{e} = (2\bar{E}/m_\mathrm{e})^{1/2}\,. \tag{5}$$

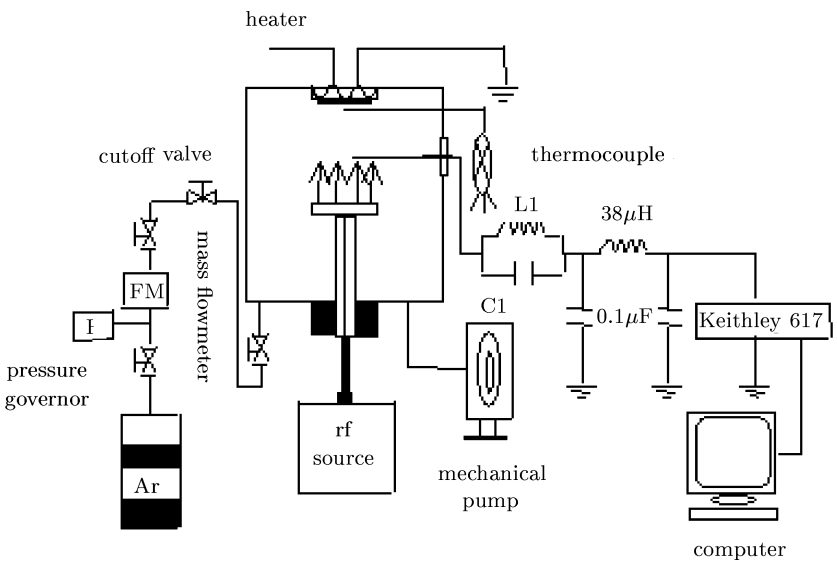


Fig.1. A schematic diagram of the experimental system.

In these equations, E is the electron energy, V_p is the probe voltage, I is the current collected by the probe, c_e is the mean electron velocity, $I_{e,sat}$ is the electron saturation current and A_p refers to the plasma contact area of the probe.

3. Results and discussion

Figures 2(a) and 2(b) depict the axial dependences of the electron density and the mean electron energy under (a) pressure = 10 Pa, rf power = 20 W and (b) pressure = 30 Pa, rf power = 10 W. The spatial distribution profiles of the electron density and the mean electron energy in Figs.2(a) and 2(b) are similar, only there is a little difference in both values of the corresponding density and energy because of the different pressure and discharge power. The mean electron energy is largest near the cathode sheath, afterwards decreases rapidly in the bulk plasma regions and increases slightly until being adjacent to the anode. This is related to the axial field distribution between the two electrodes. At the interface between bulk plasma and sheaths, where exists a large voltage fall, only fast electrons can overcome the ambipolar potential and reach the electrode, while slow electrons are excluded and localized in the bulk regions. Because there is a much larger voltage drop close to the cathode than that near the anode, the mean electron energy at the plasma interface close to the cathode is much higher than that near the anode. However, in bulk plasma regions, there is a smaller voltage fall, usually it can be thought no voltage fall there. So diffusion is the main behaviour of electrons. The electron energy that gained from rf field is smaller than that lost by frequent collisions. Thereby the mean electron energy decreases with the distance increasing from the plasma interface to the bulk internal regions. On the other hand, the axial distribution of the electron density appears reverse variation tendency as compared with that of the mean electron energy. In the neighbourhood of the cathode, the mean electron energy is the maximum and the electron density is least. But at the middle between the two electrodes, the electron density peaks obviously while the mean electron energy reduces in a saddle. The cause is that high-energy electrons lose their energy through various collisions and make ionization rate increase.

The axial dependence of the electron density on gas pressures of 10, 20 and 30Pa is depicted in Fig.3. It is obvious that the maximum electron density always occurs at about the midway between the two electrodes. This result agrees with the previous reports.[20]

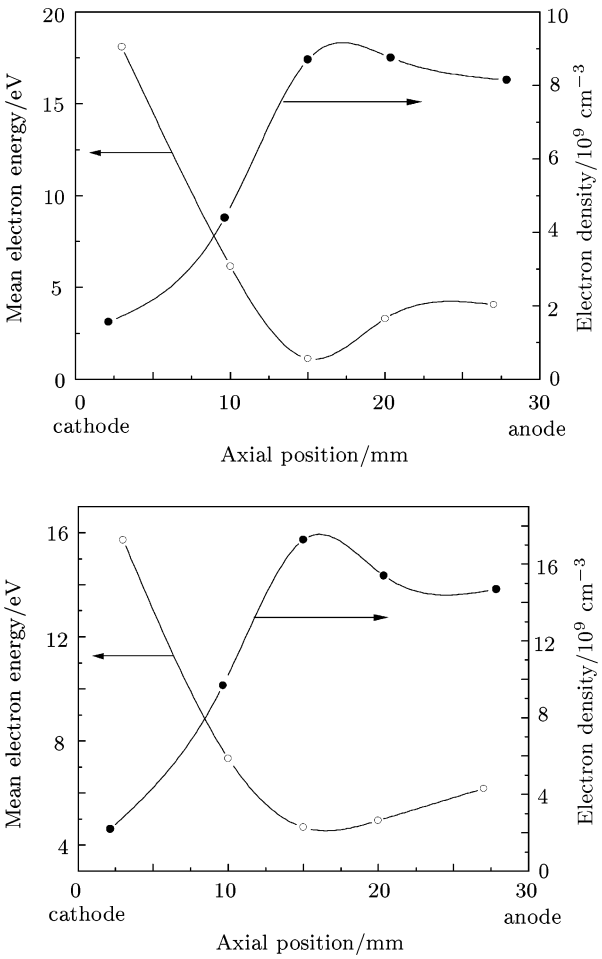


Fig.2. Axial distributions of the electron density and the mean electron energy. ○: mean electron energy, ●: electron density. (a) gas pressure = 30 Pa, rf power = 10 W, and (b) gas pressure = 10 Pa, rf power = 20 W.

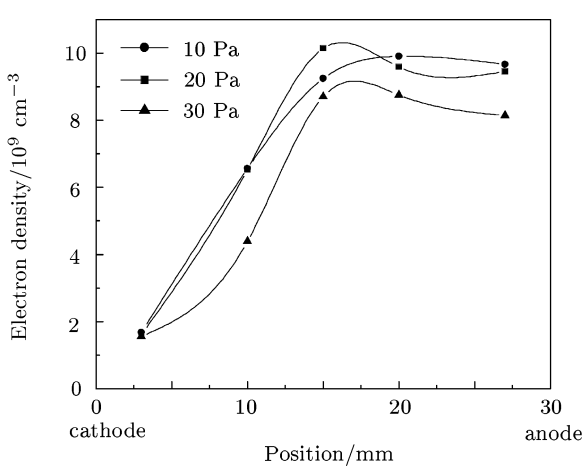


Fig.3. The axial dependences of the electron density on various pressures. rf power = 10 W

Figures 4(a) and 4(b) show the radial distributions of the electron density and the mean electron

energy under (a) pressure = 20 Pa, rf power = 20 W and (b) pressure = 30 Pa, rf power = 30 W. It is obvious that the electron density and the mean electron energy both increase almost by the same factor of 2 from the centre to the edge of electrodes under above different discharge conditions. The results indicate that the deposition films will be nonuniform if using this PECVD system. The radial spatial nonuniformity of plasma may be related to the structure of the reactor. It is important to study the radial spatial distribution of the plasma charged particle characteristics and improve its uniformity.

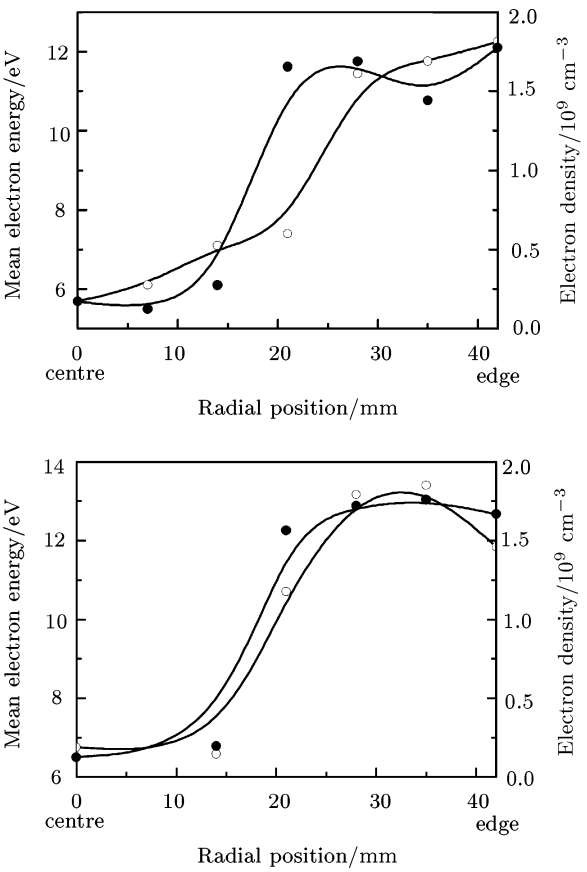


Fig.4. Radial distributions of the electron density and the mean electron energy. ○: mean electron energy, •: electron density. (a) gas pressure = 20 Pa, rf power = 20 W and (b) gas pressure = 30 Pa, rf power = 30 W.

4. Theoretical model of electron radial distribution

A theoretical model is proposed to depict the radial distribution of the electron density in the positive column region. The basic assumptions of the model are as follows: (1) The gas is mainly ionized by electron collisions. (2) The charged particles are depleted at the wall of reactor due to the ambipolar diffusion. (3) The electron density equals the positive ion density. (4) Volume recombination is considered.

As shown in Fig.5, a unit length of cylinder with internal radius r and thickness dr between the centre between and the edge of electrodes is investigated.

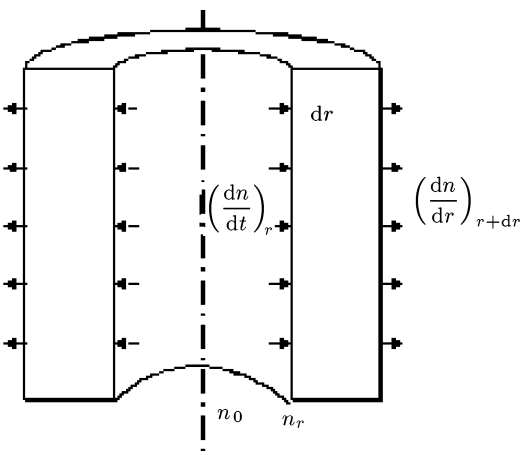


Fig.5. The cylindrical shell configuration.

Due to the ambipolar diffusion, the velocity of charged particles (electrons or positive ions) toward the wall of reactor is:

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_r = -2\pi r D_\mathrm{a}\left(\frac{\mathrm{d}n}{\mathrm{d}r}\right)_r , \tag{6}$$

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{r+\mathrm{d}r} = 2\pi(r+\mathrm{d}r)D_\mathrm{a}\left(\frac{\mathrm{d}n}{\mathrm{d}r}\right)_{r+\mathrm{d}r} = -2\pi D_\mathrm{a}(r+\mathrm{d}r)\left[\left(\frac{\partial n}{\partial r}\right)_r + \left(\frac{\partial^2 n}{\partial r^2}\right)_r \mathrm{d}r\right] , \tag{7}$$

where n is the density of the charged particles, r is the radial distance away from the centre between electrodes, and D_a is the ambipolar diffusion coefficient.

In our PECVD system, due to the aperture of influent gas at the centre of the reactor and the aperture of effluent gas at one side of the reactor (see Fig.1), the radial velocity of gas and the charged particles is largest at the centre between electrodes. Therefore, the increment of the number of charged particles in the cylindrical shell (thickness dr) per unit time is approximately

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_r - \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{r+\mathrm{d}r} = 2\pi D_\mathrm{a}\left[r\frac{\partial^2 n}{\partial r^2} + \frac{\partial n}{\partial r}\right]\mathrm{d}r . \tag{8}$$

From the equilibrium equation of the generation and loss rates of the charged particles in stationary discharge, we can obtain the following equation

$$Fn2\pi r\mathrm{d}r = 2\pi D_\mathrm{a}\left[r\frac{\partial^2 n}{\partial r^2} + \frac{\partial n}{\partial r}\right]\mathrm{d}r + Zn2\pi r\mathrm{d}r , \tag{9}$$

where F and Z represent the number of electrons participating in the recombination and the ionization per unit volume per unit time, respectively.

Equation (9) can be transformed to

$$\frac{\mathrm{d}^2 n}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}n}{\mathrm{d}r} - \frac{(F-Z)}{D_\mathrm{a}} n = 0\,. \tag{10}$$

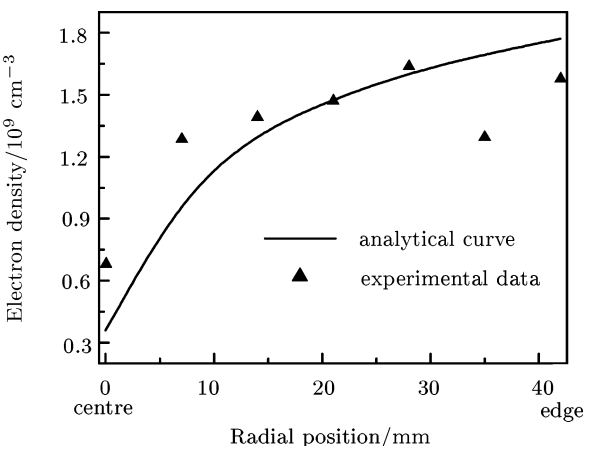


Fig.6. Radial variation of the measured electron density. "测" represents the experimental data.

Let $r = \sqrt{D_\mathrm{a}/(F-Z)}\,x$, we can obtain

$$\frac{\mathrm{d}^2 n}{\mathrm{d}x^2} + \frac{1}{x}\frac{\mathrm{d}n}{\mathrm{d}x} - n = 0\,. \tag{11}$$

Equation (11) is a zero-order Bessel equation of the second kind, its solution is

$$n(r) = n_0 J_0\left(r\sqrt{\frac{(F-Z)}{D_\mathrm{a}}}\right)\,, \tag{12}$$

where $n(r)$ is the density of the charged particles, n_0 is the density of the charged particles at the centre of electrodes. J_0 is the zero-order Bessel function of the second kind. It is well known that J_0 is a monotonically increasing function. Therefore, it is clear that the charged particles density profile has its maximum value at the edge of the electrode. Figure 6 shows the experimental radial distribution of the electron density under the discharge pressure $P = 30$ Pa and rf power $P_\mathrm{rf} = 20$ W and that of the theoretical model, both distribution profiles agree well with each other. The experimental results manifest the veracity and credibility of the theoretical analyses. This theoretical model is useful for better understanding of the discharge mechanism and for searching for a better discharge parameter to improve the radial spatial distribution uniformity of the electron characteristics.

5. Conclusions

An established movable tuned probe has been used successfully to measure the spatial distributions of the electron density and the mean electron energy in a capacitively coupled rf glow discharges.

The experimental results indicate that the electron density peaks at the midway between the two electrodes, and this profile is in accord with most models' predicted and measured results. We also find that the axial spatial variation trend of the mean electron energy is just opposite to that of the electron density, and the mean electron energy near the cathode is much higher than that near the anode.

The measured radial distributions of the electron density and the mean electron energy increase from the centre to the edge of the electrode. A proposed theoretical model is used to predict this radial spatial variation profile, it agrees well with the measured one.

These measured and the theoretically modelled spatial distributions of the electron density and the mean electron energy are useful for better understanding of the discharge mechanism and for searching for a better deposition condition to improve thin film quality.

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