Numerical study on collision-less plasma sheaths of RF-glow discharge

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Abstract

A self-consistent mathematic model for radio frequency (RF) glow discharge was proposed to investigate the spatiotemporal evolvement of collision-less plasma sheaths at different plasma characteristics, in which the influences of ion motion by instantaneous sheath electric field were considered and the present model would be suitable for describing the spatiotemporal characteristics plasma sheaths with wide RF-frequency ranges. The instantaneous relationship between the voltage on the RF-bias electrode and the sheath thickness was determined by an equivalent circuit model coupled with a fluid model. The periodic distributions of voltage on RF-bias electrode, sheath thickness, sheath electric field, density of ion and electron in sheath were obtained by numerical methods based on the present model. It was found that the distribution of electrode voltage presents non-sinusoidal waveform which is different from the sinusoidal waveform assumptions of other researches. The numerical computation results show that $\beta$, the ratio of RF frequency and ion plasma frequency, is an important parameter that affects RF plasma sheath’s features: the motion and density distribution of ion are mostly controlled by instantaneous sheath electric field if $\beta<1$; however, when $\beta>1$, the ion motion could be determined by the average field intensity of plasma sheath, and the ion density could almost not be changed.

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Keywords: RF-glow discharge; plasma sheath; numerical modeling; numerical simulation

1. Introduction

The film deposition technology based on radio frequency (RF) glow discharge plasma is used electron, superconductor, optics and mechanism fields widely. With the development of RF glow discharge film technology, it is important to know the spatial distributions and the energy distributions of the particles in plasma, the interactions between particles and the effects of the film growth. However it is difficult to attain accurate data by experiments due to the complexity of physical and chemical reactions in plasma. The numerical simulation methods such as fluid model, Monte Carlo model and Particle-in-Cell model have been important approaches in the study of plasma. Fluid model can be used to describe the electric filed, ion density and electron distributions in plasma sheath [1-3]. Lieberman[4], Godyak [5] described electron distribution in plasma sheath based on the assumption that the
motive behavior of ion is determined by the average electric field in plasma sheath; Edelberg and Aydil [6] established equations to describe sheath thickness evolutions based on the assumption that the electron distribution in sheath is obeyed the Boltzmann distribution, which is difficult to attain analytical solution as RF electrical field was added with middle or low frequency. Miller and Riley’ model [7] for ion dynamics at middle or low RF frequency was based on the assumption that the ion density is invariable in sheath; Bose et al [8] established a fluid model to study sheath features at middle RF frequency based on the assumption that the electrode voltage is given by a sinusoidal waveform.

In present study a self-consistent mathematic fluid model for radio frequency (RF) glow discharge is proposed to investigate the spatiotemporal evolvement of collision-less plasma sheaths at different plasma characteristics, in which the influences of ion motion by instantaneous sheath electric field are considered and the present model would be suitable for describing the spatiotemporal characteristics plasma sheaths with wide RF-frequency ranges.

2. Mathematical Models

The following assumptions are made in present model:

(1) all the physical variables in plasma sheath varying at one dimension due to the grades of all the physical variables along electrode axes direction are much bigger than that along other directions.

(2) neglecting the ion’ thermal movement in plasma sheath due to the temperature of ion is much lower than that of other particles in sheath.

(3) neglecting the collision process between ion with other particles in sheath due to the mean free path of ion (the order of magnitude is $10^{-3}$m) is bigger than the thickness of sheath (the order of magnitude is $10^{-4}$m) at low gas pressure.

2.1. Plasma sheath model

The density $n_i(x,t)$ and velocity $u_i(x,t)$ of charged particles in plasma sheath can be described by fluid model as below[6]:

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i u_i)}{\partial x} = 0$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} = -\frac{e}{m_i} \frac{\partial V}{\partial x}$$

where $m_i$ is the ion mass, $e$ is the elementary charge, $V(x,t)$ is the instantaneous voltage distribution in sheath, which is determined by:

$$\frac{\partial^2 V}{\partial x^2} = -\frac{e}{\varepsilon_0} (n_e - n_i)$$

where, $\varepsilon_0$ is the vacuum dielectric constant, $n_e(x,t)$ is electron number density in plasma sheath, which can be described as the Boltzmann distribution:

$$n_e(x,t) = n_0 \exp\left(\frac{eV(x,t)}{k_BT_e}\right)$$

where, $n_0$ is the plasma density, $T_e$ is the electron temperature, $k_B$ is the Boltzmann constant.

The instantaneous boundary of plasma sheath is the position where electron number density is equal to that of ion:

$$n_i(d_s,t) = n_e(d_s,t) = n_0$$
where, $d_s$ is the instantaneous thickness of sheath.

Ion moves into sheath with Bohm speed $u_B = \sqrt{\frac{k_B T_e}{m_i}}$ [9]:

$$u_i(d_s, t) = u_B$$

(6)

The voltage at the boundary of sheath is set as zero:

$$V(d_s, t) = 0$$

(7)

The electronic field at the boundary of sheath should be $\frac{k_B T_e}{2e\lambda_d}$ when the ion moves into sheath with Bohm speed[10]:

$$\frac{\partial V}{\partial x}
\Bigg|_{x=d(t)} = \frac{k_B T_e}{2e\lambda_d}$$

(8)

where, $\lambda_D$ is the Debye length of electron at sheath boundary.

### 2.2. Circuit model

The instantaneous voltage on electrode not only relies on the RF electrical source, but also relies on the instantaneous features of plasma sheath. A circuit model induced by Edelberg and Aydil [6] to self-consistent determine the relationship between instantaneous thickness of sheath and instantaneous voltage of electrode is shown in Fig.1. The sheath was equivalent as a parallel circuit which consisted of a diode, a capacitor and a current source.

The current pass through the diode denoted the electron current which can be written below:

$$I_e(t) = \frac{e n_e A}{4} \exp \left( \frac{eV_e(t)}{k_B T_e} \right)$$

(9)

where, average thermal movement speed of electron $u_e = \sqrt{\frac{8k_B T_e}{\pi m_e}}$, $A$ is the area of electrode.

The current pass through the current source denoted the ion current which can be written below:

$$I_i(t) = eu_i(0, t) n_i(0, t) A$$

(10)
The displacement current on capacitor is induced by the charges on the electrode surface:

\[ I_s(t) = \frac{dQ}{dt} = \frac{d(C_sV_s)}{dt} = C_s(t)\frac{dV_s(t)}{dt} + V_s(t)\frac{dC_s(t)}{dt} \]  \hspace{1cm} (11)

where, sheath instantaneous capacitance \( C_s(t) = \varepsilon_0 \frac{A}{d_s(t)} \).

The current equation can be described as the RF current with sinusoidal waveform:

\[ eu_i(0,t)n_i(0,t) \frac{A}{4} \exp\left( \frac{eV_s(t)}{k_BT_e} \right) - C_s(t)\frac{dV_s(t)}{dt} - V_s(t)\frac{dC_s(t)}{dt} = I_{\text{max}} \sin(\omega t) \]  \hspace{1cm} (12)

where, \( I_{\text{max}} \) is the maximum value of RF current.

The power of RF-bias can be obtained from electrode voltage and current:

\[ P = \frac{1}{\tau} \int_0^\tau V_s(t)I(t)dt \]  \hspace{1cm} (13)

where, RF period \( \tau = 2\pi / \omega \), RF current \( I = I_{\text{max}} \sin(\omega t) \).

3. Numerical method

The self-consistent fluid model proposed above based on the RF500 Chemical Vapor Deposition (CVD) coating machine, and the diameter of the electrode is 200 mm, was calculated by a numerical method based on MATLAB code.

The current equation (12) was calculated by a forth-order Runge-Kutta scheme to obtain the relationship between instantaneous voltage of electrode and sheath thickness.

The fluid equations (1)-(3) were calculated by a two-order finite-difference method to obtain the variables in plasma.

Argon plasma with plasma density \( 3.2 \times 10^{17} \text{m}^{-3} \), electron energy \( k_BT_e = 3 \text{eV} \) \( (4.8 \times 10^{-19} \text{J}) \), and the diameter of the electrode with 200mm were chosen in present study to simulate the plasma sheath characteristics.

4. Results and discussions

4.1. The influences to sheath thickness and potential drop by RF current oscillation amplitude

The cyclic variation of plasma sheath thickness and potential drop with RF current at different current oscillation amplitude are shown in Fig.2(a) and Fig.2(b). It can be found that oscillation amplitude of sheath thickness becomes bigger and electric field in sheath becomes stronger with that of current increasing, the stronger sheath electric field hindered electrons into the sheath and enhanced the thickness of sheath. The distribution of sheath potential drop presents non-sinusoidal waveform, and the frequency of sheath thickness and sheath potential drop lagged behind that of rf-electric field due to the greater inertia of ions lagged behind the responding to the transient rf-electric field.
4.2. The influences to sheath thickness and potential drop by RF plasma density

The cyclic variation of plasma sheath thickness and potential drop at different RF plasma density are shown in Fig.3(a) and Fig.3(b). It can be found that sheath potential drop, sheath thickness and their oscillation amplitude become lower as plasma density increased, the lower sheath electric field reduce the hindering effect to electrons moving to the electrode, and reduced the sheath thickness. 

Fig.3 (a) time dependent of sheath thickness at different plasma density (b) time dependent of the sheath potential drop at different plasma density 
(real line: $3 \times 10^{17}$m$^{-3}$, dashed: $3.2 \times 10^{17}$m$^{-3}$, dot line: $3.5 \times 10^{17}$m$^{-3}$) ($\beta=0.7$)
4.3. The spatiotemporal evolvement of sheath parameters

The spatiotemporal evolution of ion density is shown in Fig. 4 (a). It can be found that the variation of ion density is slow with time and acute with space due to the strong voltage and electric field (as shown in Fig. 4 (c)-(d)), which increase the velocity of ion and reduce the density of ion.

Fig. 4 The spatiotemporal evolvement of sheath parameters
(a) ion density (b) electron density (c) voltage (d) electric field (e) ion velocity ($\beta=0.7$)

The spatiotemporal evolvement of electron density is shown in Fig. 4 (b). It can be found that the variation of electron density reduced rapidly faster than that of ion density and reduces to zero near electrode action at sheath
electric field, and the reducing speed of electron density faster than that of ion density as the same results reported by YU [11].

It can be found from Fig.4 (c)-(e) that voltage, electric field and ion velocity in sheath are varied with time and space which means that it is not appropriate to describe RF-bias sheath by voltage-averaged/electrode-averaged method, and the distribution of sheath electric field had a profile approximating that of a parabola as the same results in reference [12].

4.4. The effect to the ion density by $\beta$

The frequency ratio between RF-bias frequency and plasma frequency $\beta (\beta = \omega / \omega_p)$ is an important parameter to affect RF plasma sheath’s features. The motion behavior of ion in plasma is controlled by instantaneous sheath electric field when RF-bias frequency smaller than that of plasma ($\beta<1$) (as $\beta=0.7$ shown in Fig.4 (a)) and the time of ion passing through sheath is only a part of one period, the instantaneous sheath feature of RF-glow discharge is similar to that of direct current glow discharge. The ion motion would be determined by the average field intensity of plasma sheath and the ion density would not be changed because the ion motion does not synchronous change with the variation of RF electric field as $\beta>1$ (as $\beta=2$ shown in Fig.5 (b)) and the time of ion passing through sheath needs several periods, the assumption of Lieberman [5] and Godyak [6] are only suitable for high RF frequency conditions.

5. Conclusions

(1) The sheath thickness would be changed obviously when the RF current oscillation amplitude varied, and the oscillation amplitude of sheath thickness increased as that of RF current increasing, and the distribution of electrode voltage presented non-sinusoidal waveform.

(2) The electrode voltage, sheath thickness and their oscillation amplitude become lower as plasma density increased.

(3) The motion behavior of ion in plasma is controlled by instantaneous sheath electric field when $\beta$ is smaller than 1 and the ion motion does not synchronous change with the variation of RF electric field when $\beta$ is bigger than 1, the voltage-averaged/electrode-averaged method to describe RF-bias sheath is only suitable for high RF frequency conditions.
Acknowledgment

The financial support provided by the foundation of international cooperation project (ID7440015), the doctoral foundation for returning-back scholar of Northeastern University (ID18504032) and the Australian Research Council (ID DP0877734) is gratefully acknowledged.

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