A self-consistent hybrid model of a dual frequency sheath: Ion energy and angular distributions

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This paper presents a self-consistent hybrid model including the fluid model which can describe the characteristics of collisional sheaths driven by dual radio-frequency (DF) sources and Monte Carlo (MC) method which can determine the ion energy and angular distributions incident onto the dual rf powered electrode. The charge-exchange collisions between ions and neutrals are included in the MC model in which a self-consistent instantaneous electric field obtained from the fluid model is adopted. In the simulation, the driven method we used is either the current-driven method or the voltage-driven method. In the current-driven method, the rf current sources are assumed to apply to an electrode, which is the so-called the equivalent circuit model and is used to self-consistently determine the relationship between the instantaneous sheath potential and the sheath thickness. In the voltage-driven method, however, the rf voltage sources are assumed to apply to an electrode. The dual rf sheath potential, sheath thickness, ion flux, ion energy distributions (IEDs), and ion angular distributions (IADs) are calculated for different parameters. The numerical solutions show that some external parameters such as the bias frequency and power of the lower-frequency source as well as gas pressure are crucial for determining the structure of collisional dual rf sheaths and the IEDs. The shapes of the IADs, however, are determined mainly by the gas pressure. Furthermore, it is found that the results from the different driven methods behave in the same way although there are some differences in some quantities. © 2007 American Institute of Physics.

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I. INTRODUCTION

In plasma etching processes, a capacitively coupled plasma (CCP) driven by dual radio-frequency (DF) sources at widely different frequencies has been introduced, which makes it possible to obtain the desired independent control of plasma density in the reactor and the ion energy impinging on the substrate. In this case, a dual frequency sheath that separate the bulk plasma from the process surface will be formed near the powered electrode, similar to that in a single frequency (SF) driven plasma. The spatiotemporal variations of the sheath electric field and the collisions the ions undergo while traversing the sheath determine the motion of the ions. Thus, the time-dependent behavior of the space-charge sheath are responsible for ion energy distributions (IEDs) and ion angular distributions (IADs) bombarding the substrate which critically determine the etch rates and etch profiles. Therefore, the study on the characteristics of collisional dual rf sheaths as well as IEDs and IADs are of importance for the design of a high quality etch process.

In recent years, some works have been devoted to the physics of collisionless sheath adjacent to the dual rf powered electrode, including simplified analytical models and fluid models. When the gas pressure in the reactor is on the order of tens of mTorr, however, ion-neutral collisions play a key role in the momentum and energy transfer in a partially ionized plasma and their role on sheath formation is significant. On physical grounds, one can expect that the ion collision in the sheath may reduce the ion impact energy to the electrode. Consequently, ion dynamics must encompass the entire range of collisionality.

To the best of our knowledge, there were few studies reported on the collisional dual rf sheath characteristics. Based on an electron step model, Boyle et al. studied the collisional effects on the dual rf sheath dynamics. However, the authors neglected the time-dependent terms in the ion fluid equations and assumed that the average ion potential energy gains from the dual rf electric field dissipate fully in the charge-exchange collisions between the ions and the neutral particles. It is noted that such a collisional rf sheath model is only suitable to describe the sheath characteristics in very high-pressure and high-frequency discharges. Actually, when the bias frequency is less than or equal to the ion plasma frequency, one has to consider the time-dependent terms in the ion fluid equations. In this case, the motion of the ion is determined by the instantaneous sheath electric field, rather than the time-averaged field. In addition, although many works have been done in which the collisional effects on the IEDs and IADs have been simulated with the Monte Carlo (MC) method for single rf sheaths, few works have been reported on the collision in the dual rf sheath on how to influence IEDs and IADs. With the (particle-in-cell) PIC/MC method, Lee and Georgieva et al. investigated the influence of the external parameters on the IEDs for DF-CCP discharges. Assuming the electron density as a function of time-averaged dc potential across the sheaths, Shannon found that the IEDs bombarding the dual

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rf-powered electrode can be tuned by properly mixing the high-frequency and low-frequency rf current components.\textsuperscript{16} Because the actual spatiotemporal electric field in dual rf sheaths directly determines the forms of IEDs and IADs at the process surface, it is necessary to use the self-consistent instantaneous electric field obtained by the fluid model in simulating the IEDs and IADs with the MC method.

When simulating the spatiotemporal evolution of the rf-driven sheath, we can adopt either the current-driven method or the voltage-driven method. Whichever method is adopted, it should be noted that the current balance condition\textsuperscript{17,18} on the electrode should be satisfied by which the sheath potential can be self-consistently determined for the current-driven method and the self-bias voltage can be self-consistently obtained for the voltage-driven method. However, the amplitudes of the voltages are given in some works,\textsuperscript{15,19} which leads to inconsistencies in physics. Taking into account all time-dependent terms in the ion fluid equations and the current balance condition, Guan et al. studied the effects of the parameters of the lower frequency source on the properties and IEDs with a dual rf collisionless sheath model.\textsuperscript{7} On the other hand, despite the fact that the current- or voltage-driven method have been used in simulating the properties of sheaths for decades, we know of no direct comparisons between the results from the two driven methods.

In this paper, we will present the dynamics model of the collisional dual rf sheath including the current driven or voltage driven method. The effects of the external rf source parameters on the characteristics of the dual rf sheath can be investigated with the model. Besides, we can obtain IEDs and IADs with the MC model of the ion transport across the sheath. This paper is outlined as follows: In Sec. II the dynamic model of the collisional rf sheath is described by the ion fluid equations coupled with the Poisson equation. Some numerical results, such as the time-dependent sheath potential and the sheath thickness as well as the ion flux are shown in the section. Also, the results from different driven methods are compared. Then, in Sec. III, the spatiotemporal variation of the electric field from the last section is further used in the MC simulation of the collisional ion transport across the sheath to determine the IEDs and IADs striking the substrates. Finally, a short summary is given in Sec. IV.

II. DESCRIPTION OF THE DUAL RF SHEATH MODEL

We consider that the electrode is driven by two rf sources which are respectively the low-frequency (LF) source and the high-frequency (HF) source, as shown in Fig. 1. Thus, a dual rf sheath will be formed near the electrode surface in which we assume the elastic and charge transfer are the dominant collision mechanism. We may neglect the ion thermal motion effects since the ion temperature is much smaller than the directional kinetic energy in the sheath regions. We consider that plasma consists of single charged ions and electrons adopting a one-dimensional configuration, with the electrode placed at x=0. In the following, we describe the one-dimensional spatiotemporal variation of the ion density, $n_i(x,t)$, and the ion drift velocity, $u_i(x,t)$, with the cold ion fluid equations,

\begin{equation}
\frac{\partial n_i}{\partial t} + \frac{\partial (n_i \cdot u_i)}{\partial x} = 0,
\end{equation}

\begin{equation}
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} = -e \frac{\partial V}{\partial x} - V_n \cdot u_i,
\end{equation}

where $m_i$ is ion mass, $e$ is the electronic charge. In Eq. (2), $v_n=\nu N \sigma (u)$ is the total collision frequency for momentum loss, where $N$ is the neutral gas density, $\sigma (u)$ is the total collision cross section.\textsuperscript{20} The electric potential inside the sheath is governed by the Poisson equation,

\begin{equation}
\frac{\partial V}{\partial x} = -\frac{e}{\varepsilon_0} (n_i - n_e),
\end{equation}

where the electric potential, $V(x,t)$, is related to the sheath electric field, $E(x,t)$, by $E(x,t) = -\partial V(x,t)/\partial x$. Here $\varepsilon_0$ is the permittivity of free space and $n_e(x,t)$ is the electron density. In contrast to the previous sheath model\textsuperscript{3–6} in which the time-derivative terms in Eqs. (1) and (2) are omitted and the potential $V(x,t)$ in Eq. (2) is replaced by a time-averaged potential. In the present model, all the time-dependent terms in the ion fluid equations are retained, therefore, the model is valid over a wide range of bias frequency and the instantaneous electric field can be obtained.

Since the electron plasma frequency $\omega_p e$ exceeds the high frequency $\omega_H$ and the collision frequency $\nu_m$ between ions and neutrals, we can assume that the electrons are inertialess and respond to the instantaneous potential in the sheath. Contrary to the stepwise model,\textsuperscript{5,10} here we consider that the electron density in the sheath changes continuously and is given by the Boltzmann distribution,

\begin{equation}
n_e(x,t) = n_0 \exp \left( \frac{e V(x,t)}{k_B T_e} \right),
\end{equation}

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

The condition which a stationary collisionless sheath exists is that the ion flow velocity satisfies the Bohm criteria at the plasma-sheath boundary. Thus, the value of ion velocity at the plasma-sheath interface is usually chosen as Bohm
velocity. However, the Bohm criterion is not valid for the collisional sheath boundary according to Riemann’s theory, there are no finite locations of a sheath edge under the influence of collision. In the case, one has to consider a transition layer, i.e., a space-charge neutral pre-sheath which is of the order of mean free path of plasma-neutral interaction and in which the ions are accelerated so that they enter the sheath with the minimum energy required for a stable sheath.

Initially, at the pre-sheath-plasma boundary, \( x = d_p \), ions coming from the bulk plasma enter the pre-sheath with a very small velocity (almost equal to zero), i.e.,

\[
u_i(d_p, t) = 0.
\]  
(5)

With the time advancing, the velocity of ions at the pre-sheath-plasma boundary can be determined by the extrapolation method. The ion density at the pre-sheath-plasma boundary, \( x = d_p \), should be equal to the bulk plasma density,

\[n_i(d_p, t) = n_0.
\]  
(6)

In addition, the potential at the pre-sheath-plasma boundary is assumed as zero, i.e.,

\[V(d_p, t) = 0.
\]  
(7)

On the other hand, at the pre-sheath-plasma boundary, we assume that the ion density is equal to the electron density, i.e., the quasineutral condition,

\[n_i(d_p, t) = n_e(d_p, t).
\]  
(8)

Here we should stress that, in contrast to the pre-sheath-plasma boundary, the sheath-pre-sheath boundary varies with time.

Finally, we assume that at the electrode \( (x = 0) \) the potential is equal to an instantaneous voltage, i.e.,

\[V(0, t) = V_e(t).
\]  
(9)

When determining the instantaneous voltage \( V_e(t) \), we can adopt either the current-driven method or the voltage-driven method. For the current-driven sheath, the relationship between the instantaneous voltage \( V_e(t) \) and the instantaneous sheath thickness \( d_e(t) \) can be determined self-consistently by the equivalent circuit model,

\[I_e(t) - I_i(t) - I_H(t) = I_L \sin(\omega t) + I_H \sin(\omega_H t),
\]  
(10)

where \( \omega \) is the frequency of the rf source, \( I \) is the current amplitude of the rf source, and the suffixes \( L \) and \( H \) refer to the lower and higher frequencies, respectively. And \( I_e(t) \), \( I_i(t) \), and \( I_H(t) \) are the ion current, the electron current incident on the electrode, and the capacitive displacement current due to temporal variation of the sheath voltage,

\[I_i(t) = e u_i(0, t) n_i(0, t) A,
\]  
(11)

\[I_e(t) = e u_e n_0 A \frac{\sin(V_e(t))}{k_B T_e},
\]  
(12)

\[I_H(t) = e u_H n_0 \cos(\omega_H t),
\]  
(13)

where \( A \) is the electrode area, \( u_e = \sqrt{8k_B T_e/m_e} \) is the mean velocity of an electron with mass \( m_e \) and \( C_e(t) = e_0 A/d_e(t) \) is the time-dependent sheath capacitance.

Another choice to obtain the instantaneous voltage \( V_e(t) \) is the voltage-driven method in which the two voltage sources are assumed to apply to an electrode and the voltage on the electrode can be expressed as

\[V_e(t) = V_{dc} + V_L \cos(\omega t) + V_H \cos(\omega_H t),
\]  
(14)

where \( V_L \) and \( V_H \) are, respectively, the voltage amplitudes of the low- and high-rf source, and the \( V_{dc} \) is the self-bias voltage. In contrast to choosing constant self-bias voltage \( V_{dc} \), we consider that the dc self-bias \( V_{dc} \) is a function of applied voltage and can be obtained self-consistently by using the current condition as follows.

Considering the integral of the sum of the ion current \( I_e(t) \), electron current \( I_i(t) \), and displacement current \( I_H(t) \) should be zero in one low frequency cycle, i.e.,

\[\int_0^{T_L} (I_e(t) - I_i(t) - I_H(t)) dt = 0
\]  
(15)

where \( T_L \) is the low-frequency cycle, which can determine self-consistently the self-bias \( V_{dc} \) in Eq. (14).

In plasma processing, the power of the rf source is an important parameter, therefore, we keep the power value at some constant values in simulating the properties of the dual rf sheath. For the current-driven method, the powers of low- and high-frequency source \( P_L \), \( P_H \) can be determined as follows:

\[P_L = \frac{1}{T_L} \int_0^{T_L} dI_L \sin(\omega t) V_e(t),
\]  
(16)

\[P_H = \frac{1}{T_L} \int_0^{T_L} dI_H \sin(\omega_H t) V_e(t).
\]  
(17)

In order to obtain the desired power value, we need to adjust the current amplitudes of low- and high-frequency source \( I_L \) and \( I_H \) repeatedly until the powers reach the specific values. Then, \( I_L \) and \( I_H \) can be fixed and used in Eq. (10) to obtain the voltage \( V_e(t) \). On the other hand, for the voltage-driven sheath, the power of the low-frequency source \( P_L \) and the high-frequency source \( P_H \) can be calculated,

\[P_L = \frac{1}{T_L} \int_0^{T_L} (I_e(t) - I_i(t) - I_H(t)) V_L \cos(\omega t) dt,
\]  
(18)

\[P_H = \frac{1}{T_L} \int_0^{T_L} (I_e(t) - I_i(t) - I_H(t)) V_H \cos(\omega_H t) dt.
\]  
(19)

Similar to the current driven method mentioned above, we adjust the voltage amplitudes of low- and high-frequency sources \( V_L \) and \( V_H \) repeatedly until the powers reach the specific values.
Now we get a set of closed nonlinear equations that determines the spatiotemporal dependence of the collisional dual rf sheath. The above equations with the boundary conditions will be solved numerically by using a finite difference scheme with an iterative process. In the following simulations, we take an argon discharge as an example in which all the base values of the input parameters, such as $k_B T_e = 3$ eV, $n_0 = 5 \times 10^{10}$ cm$^{-3}$, and $d = 30$ cm (the electrode diameter), are given. Furthermore, for convenience in the calculations, we use the Debye length $\lambda_D$, the ion plasma frequency $\omega_{pi}$, the Bohm velocity $u_B$, the plasma density $n_0$, and the electron temperature $V_0 = k_B T_e / e$ to nondimensionalize the position $x$, the time $t$, the ion velocity $u_i$, the ion density $n_i$, and the potential $V$, respectively.

Theoretically and experimentally, it is shown that the lower frequency source mainly determines the sheath parameters while the higher frequency source mainly controls the bulk plasma parameters. According to Lieberman’s viewpoint, the condition of the independent control of the ion energy bombarding the dual rf powered electrode and the ion density in the reactor should be

$$\omega_{hi}^2 |V_h| \gg \omega_{li}^2 |V_l|, \quad (18)$$

$$|V_l| \gg |V_h|. \quad (19)$$

Thus, the frequency and power of the low- and high-frequency sources can be chosen at 2 MHz, 60 MHz, 300 W, and 100 W, respectively. Meanwhile, it is reasonable to investigate the characteristics of a dual rf sheath and IEDs by just adjusting the parameters of the low-frequency source while fixing the parameters of the high-frequency source.

With the current-driven method, the time dependence of (a) the sheath potential, (b) sheath thickness, and (c) ion flux impinging on the dual rf powered electrode is shown in Fig. 2 for different values of the frequency of the low-frequency source, where the power of the low- and high-frequency sources are, respectively, fixed at 300 W and 100 W, the frequency of the high-frequency source at 60 MHz, and the gas pressure at 20 mTorr. It is can be seen that both the higher frequency and the lower frequency affect the time dependence of the dual rf sheath parameters: the slow oscillation outline is modulated by the lower frequency while the rapid oscillations are modulated by the higher frequency, and the number of rapid oscillations is the ratio of the higher frequency to lower frequency, which is similar to the results in the collisionless situation.

The effects of the pressure on (a) the sheath potential, (b) sheath thickness, and (c) ion flux are shown in Fig. 3, where the frequency and power of the low- and high-frequency sources are, respectively, fixed at 2 MHz, 60 MHz, 300 W, and 100 W. One can observe from Figs. 3(a) and 3(b) that, as the pressure is increased, the amplitudes of the sheath potential and the sheath thickness increase. In addition, contrary to the collisionless case in which the ion flux oscillates around the constant ion flux $n_i u_B$, the ion flux decreases obviously and the phase-shifting increases with the pressure increase. The reason for this is that the stronger the pressure is, much more collisions occur between the ions and neutrals. Therefore, the increasing gas pressure would decrease the etch rates.

Figure 4 displays the effects of the power of the low-frequency source on (a) the sheath potential, (b) sheath thickness, and (c) ion flux, where the lower and higher frequency...
are, respectively, fixed at 2 MHz, 60 MHz, the power of the high-frequency source at 100 W, and the gas pressure at 20 mTorr. It is clear that the amplitudes of the sheath potential and the sheath thickness as well as the ion flux increase as the power is increased.

The results mentioned above are obtained by using the current-driven method in which the instantaneous voltage $V_p(t)$ is self-consistently determined by Eq. (10). In order to compare the current-driven method with the voltage-driven method in which $V_p(t)$ is determined by Eq. (14), we utilize the voltage-driven method to calculate (a) the sheath potential, (b) sheath thickness, and (c) ion flux as shown in Fig. 5 with the same input parameters as in Fig. 3. In the simulation, the power of the low- and high-frequency source are...
calculated with Eq. (17). From Fig. 5, it is clearly that the sheath parameters varies with the gas pressure in the same way as those in Fig. 3 although there are some differences in the amplitude of them, which indicates that the two methods are useful for simulating the properties of the rf sheath. However, the current-driven method should be more reasonable than the voltage-driven method because the nonlinear results from the current-driven method embody the nonlinearity of the sheath.

### III. ION ENERGY AND ANGLE DISTRIBUTIONS

It is necessary to study the effects of the input parameters on the IED arriving at the dual rf powered electrode due to the importance of IEDs in etching processes. In this section, with the spatiotemporal variation of the electric field obtained in the last section, we simulate the ion transport across the presheath and sheath region by the MC method and further determine the IEDs and IADs impinging on the electrode. For the collisionless sheath, an ion is accelerated only by the electric field and its trajectory is a line normal to the electrode surface. For the collisional sheath, besides the electric field acceleration, the ion will collide frequently with neutrals which results in momentum and energy transfer. Thus, one may expect that ion-neutral collisions in the sheath can alter the IEDs and IADs in the collisional case.

The motion for the ions due to the electric field acceleration is determined by the equation

$$m_i \frac{d^2 x(t)}{dt^2} = eE(x,t).$$

(20)

Here the electric field is calculated from the simultaneous solution of the fluid model in Sec. II. We assume that the ion enters the presheath from the bulk plasma with an initial velocity which is picked randomly from a Boltzmann velocity distribution with temperature $T_i$, where $T_i = 300$ K.

When simulating collisions, we consider the two major collisional processes between ions and neutrals, i.e., the charge-exchange collisions and elastic collisions. Each of these processes has its own collision cross section which is dependent upon energy. For elastic scattering, the hard sphere model is adopted:

$$\epsilon_i = \epsilon \cos^2(\theta_i/2),$$

(21)

where $\epsilon_i$ and $\epsilon$ are the energy of the incident and scattered ion, respectively. The scattering angle $\theta_i$ in the center of mass can be obtained by

$$\theta_i = \cos^{-1}(1 - \xi_1),$$

(22)

where $\xi_1$ is a random number from 0 to 1. According to the theory of the elastic two-body collision, the scattering angle $\theta_i$ in the laboratory can be written as,

$$\tan \theta_i = \sin \theta_i / (1 + \cos \theta_i).$$

(23)

Thus, the deflection angle of the ion velocity after the $i$th collision is determined by the formula,

$$\cos \phi^{(i)} = \cos \phi^{(i-1)} \cos \theta_r^{(i)} + \sin \phi^{(i-1)} \sin \theta_r^{(i)} \sin \Psi^{(i)}$$

(24)

where $\Psi = 2\pi \xi_2$ is the azimuthal angle of the ion velocity and $\xi_2$ is also a random number from 0 to 1.

After charge-exchange collisions the original ion becomes an Ar atom which continues along its previous trajectory but will no longer experience any acceleration under the
electric field, while the original atom becomes an ion with an initial velocity chosen randomly from a Maxwellian distribution. The scattering and azimuthal angle for the new ion can be randomly determined.

\[ \theta_i = 2\pi \xi_3, \quad \Psi = 2\pi \xi_4, \]  

where \( \xi_3 \) and \( \xi_4 \) are two random numbers (between 0 and 1).

In the simulation, the cross sections for the elastic (el) scattering and the charge-exchange (cx) collisions between Ar\(^+\) and Ar are shown as follows:

\[ \sigma_{el} = 40.04(1.0 - 0.0563 \ln \varepsilon)^2 \]

and

\[ \sigma_{cx} = 47.05(1.0 - 0.0557 \ln \varepsilon)^2, \]

where cross sections are in \(10^{-16}\) cm\(^2\) and the ion kinetic energy, \(\varepsilon\) in eV. Thus, the total cross section is given by

\[ \sigma_{total} = \sigma_{el} + \sigma_{cx}. \]

The ion passage distance \(\Delta x\) in the sheath during the time interval \(\Delta t\) can be obtained by solving Eq. (20). Ions will suffer either an elastic collision or a charge-exchange collision when the passage distance \(\Delta x\) is smaller than the distance between collisions, \(l = -\lambda \ln \xi_5\), where \(\lambda = 1/(N\sigma_i)\) is the mean-free path and \(\xi_5\) is a random number (between 0 and 1). The collisional type is randomly determined by \(\sigma_{el}/\sigma_i\) and \(\sigma_{cx}/\sigma_i\). After the collision, one can calculate the ion’s trajectory and the new velocity. This process is continued until the ion strikes the electrode. At this point, we store its energy and angle of incidence. We typically use \(5 \times 10^5\) ion trajectories to obtain the IEDs and IADs with a reasonable signal to noise level. The input parameters in the following simulations are the same as those used in the last section.

Figure 6 shows the lower frequency dependence of the IEDs with the same input parameter as in Fig. 2. It is can be seen that the IEDs present multiple peaks and as the lower frequency increases, the width of the IED becomes narrow, which is similar to the results in the collisionless circumstance.

The pressure dependence of the IEDs is shown in Fig. 7 with the same input parameter as in Fig. 3. We observe that the maximum ion energy increases as the pressure increases. From Fig. 3(a), one can discover that the sheath potential is increasing as a function of pressure, therefore, the energy of the ions also increases with the pressure increasing.

Figure 8 displays the effects of the power of the lower frequency source on the IEDs with the same input parameter as in Fig. 4. It is observed that as the power is increased the maximum ion energy increases.

In Fig. 9 we plot the IADs at the dual rf powered electrode for different discharge pressures. It is noticed that higher pressure results in that the IADs spread to large angle regions, which can potentially lead to poor anisotropic etching behavior. Because larger pressure would lead to higher density of the neutral and the ions would undergo much more collisions with neutrals in the sheath, more ions would arrive at the electrode with larger angle normal to the surface.
Utilizing the electric field obtained from the fluid model with the voltage-driven method, we calculate the IEDs and IADs shown in Figs. 10 and 11 for the same input parameters as in Fig. 5. Comparing them with Figs. 7 and 9 from the current-driven method, it is observed that they have a same trend in despite of existing some quantitative differences. Finally, we obtain the IED shown in Fig. 12 with the voltage driven-method where the amplitudes of voltages of the high- and the low-frequency source are fixed, respectively, at 450 V and 150 V. In the simulation, the self-bias \( V_{dc} \) in Eq. (14) is determined self-consistently by the current balance condition Eq. (15) instead of being given as in Refs. 4 and 5. In contrast to the results in Fig. 10, the maximum ion energy decreases somewhat with the increasing pressure although the voltages applied to the electrode remain constant. Therefore, it can be conclude that there would be different results if the calculating conditions are different although the same driven method is used.

IV. CONCLUSIONS

In this paper, we have used a self-consistent hybrid fluid model to obtain the parameters of the dual rf sheath and the IEDs as well as IADs impinging on the dual rf powered electrode. Because the Bohm criterion is not valid for the collisional sheath boundary, we simulate the region including presheath and sheath as a whole, rather than only considering the sheath region as in a collisionless case, which avoids inconsistencies in physics while adopting the Bohm velocity as the plasma-sheath boundary condition. In order to draw a comparison between the results from the two kinds of driving method, we used either the current-driven method or the voltage-driven method to simulate the spatio-temporal evolution of the rf sheath. Moreover, the instantaneous electric field obtained by the fluid model is used in the MC model for gaining IEDs and IADs at the dual rf powered electrode.
For a collisional dual rf sheath, we conclude that the time dependence of sheath parameters is composed of two parts: the slow oscillation outline part is modulated by the frequency of the lower frequency source while the rapid oscillations part is modulated by the frequency of the higher frequency source, similar to the results in the collisionless situation. Apart from the frequency, the power of the low-frequency source, similar to the results in the collisionless cillations part is modulated by the frequency of the higher frequency of the lower frequency source while the rapid oscillations part: the slow oscillation outline part is modulated by the time dependence of sheath parameters is composed of two nonlinearity.

It has been found that the frequency and power of the low-frequency source, especially the gas pressure are critical for IEDs. And the gas pressure is also crucial for IADs. We obtain IEDs with the current-driven method or the voltage-driven method when the power keeps the constant values, and also to calculate the IEDs with the voltage-driven method when the amplitude of the voltages is kept at constant values. By comparison, the similar trends have been found in the constant power situations although the different driving methods are used. However, the results in the case of the constant powers behave differently from those in the case of the constant voltages even if the same voltage-driven method is used, which indicate that the calculating conditions are important in the simulation.

In practical plasma processing, mixture gases including chemical active particles are used, in which many kinds of chemical reactions occur. Therefore, in the future work, we will extend the present model to study the chemical reaction and the effects of the active particles on the characteristics of the rf sheath.

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