Implicit and electrostatic particle-in-cell/Monte Carlo model in two-dimensional and axisymmetric geometry: II. Self-bias voltage effects in capacitively coupled plasmas

Wei Jiang\textsuperscript{1}, Hong-yu Wang\textsuperscript{1,2}, Zhen-hua Bi\textsuperscript{1} and You-nian Wang\textsuperscript{1}

\textsuperscript{1} School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian, 116024, People’s Republic of China
\textsuperscript{2} Department of Physics, Anshan Normal University, Anshan, 114007, People’s Republic of China

E-mail: ynwang@dlut.edu.cn

Received 17 December 2009, in final form 17 July 2010
Published 19 April 2011
Online at stacks.iop.org/PSST/20/035013

Abstract

With an implicit particle-in-cell/Monte Carlo model, capacitively coupled plasmas are studied in two-dimensional and axisymmetric geometry. Self-bias dc voltage effects are self-consistently considered. Due to finite length effects, the self-bias dc voltages show complex relations to the electrode areas. Two-dimensional kinetic effects are also illuminated. Compared with the fluid model, PIC/MC model is numerical-diffusion-free and more detailed properties of the plasmas can be shown.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Capacitively coupled plasma (CCP) processing is a mainstream technology for etching and deposition of devices in the semiconductor industry [1–3]. With their applications in the semiconductor industry, many physical processes involved in CCP are still not fully understood and therefore attract many researchers who are from both academic and industrial backgrounds. While there are many analytical models to understand the physics in CCP qualitatively, there are two kinds of methods [4, 5] to study the plasma process in the reactors quantitatively: the fluid or hybrid method and the particle-in-cell/Monte Carlo (PIC/MC) method.

The PIC/MC model is widely adopted in academic research because it has fewer assumptions. However, PIC/MC modeling is very computationally expensive. As a result, most PIC/MC simulations for CCP have only been done in 1D geometry up to now [6–12]. There are only a few open reports about standard 2D simulations. Vahedi [13] presents the first 2D results based on direct implicit PIC/MC model, but in planar (X–Y) geometry. Recently, Kawamura [14] has studied the dc/rf discharges with Vahedi’s model in the same geometry. The first 2D axisymmetric analysis was given by Nanbu [15], the code of which is executed on their supercomputers. Recently we have also conducted 2D axisymmetric simulations for CCP [16] in a very small size. Although 1D PIC/MC simulations can reveal most of the physics in CCP, such as plasma density, sheath thickness and heating rate, some characteristics of CCP are inherently two dimensional. For example, magnetized CCP [17–19] and very high frequency CCP [20, 21] are both two dimensional. Of course, the most general dimensional effect is the self-bias dc voltage [22, 23].

Due to the inequality of the electrode surface areas, most CCPs are asymmetric. Because of the blocking capacitor applied, negative self-bias dc voltage will build up on the rf powered electrode. Self-bias dc voltage is mainly determined by the geometric factors, namely, the ratio of powered-to-grounded electrode area $A_a/A_b$, where $a$ denotes the rf driven electrode and $b$ denotes the grounded electrode. Lieberman
first proposed an analytic spherical shell model for the self-bias dc voltage, and obtained good agreements with the experimental results. This method is expanded to the low-frequency case by Kawamura [26]. Boswell [27] first adopted 1D PIC/MC spherical simulations and investigating the evolution of the bias voltage. With a similar model, Yonemura [28] studied the self-bias voltage systematically, and the simulation results are quite consistent with the experimental measurements and Lieberman’s theory. This method is also adopted by many other researchers. In addition, self-bias dc voltage effects in CCP have also been included and studied by the fluid model [29, 30]. However, for 2D geometries, the voltage ratio does not only scale as a power of the area ratio but also depends on many other effects in complicated ways. In addition, finite plasma length and non-local effects [31] have been shown to play essential roles in understanding the low pressure plasmas, where the electron mean free path is comparable to or even larger than the electrode spacing. Electron heating and energy dissipating mechanisms could be significantly modified in these cases. Nevertheless, theoretical and numerical investigations of such effects are only carried out in 1D, so one can anticipate that finite radius may produce similar effects. Therefore more 2D PIC/MC simulations are highly desired to give more insights into this problem, especially for the kinetics and non-local effects.

This is the second one of our two serial papers. In the first, we developed an implicit and the electrostatic PIC/MC model in two-dimensional and axisymmetric geometry, and analyzed the benefits and shortcomings of several possible algorithms, see part I [32]. In this paper, we study the self-bias dc voltage’s dependence on the radius of the rf powered electrode with this model. We will present the physical and numerical parameters in section 2. Simulation results are given and compared with some fluid results in section 3. Finally, discussions and a brief summary are presented in section 4.

2. Computational parameters

The schematic of the simulation for CCP is shown in figure 1. The numerical and physical parameters of the present problems are similar to our benchmark problems in part I, except that the external circuit model is included here. The frequency of rf source $f_{\text{rf}}$ is 13.56 MHz. Voltage source is applied to the electrode at $z = 0$ cm with waveform of $V_d = 200 \sin \omega_{\text{rf}} t$, through a blocking capacitor of $C = 300 \text{ pF}$. Since the capacitor is large, the discharge is essentially voltage driven [26]. Argon gas is used at the pressure of 100 mTorr and temperature of 300 K. We include elastic, excitation and ionization collisions for electrons and include elastic and charge transfer collisions for Ar$^+$ ions in the Monte Carlo model.

The electrodes spacing is $L = 2$ cm, the radius of the outer cylinder is $R = 8$ cm and the gap between the lower powered electrode and the grounded outer cylinder is $G1 = 1$, $G2 = 2$, $G4 = 4$ cm, respectively.

The self-bias dc voltages are calculated with Vahedi’s [33] method. In the gaps, we interpolated the potential logarithmically. The particles would flow freely out of the gap, but need not be considered in calculating the self-bias voltage. It is a particle sink boundary, similar to many other previous works [13, 15].

Square cells are used, thus the simulation area is uniformly divided into 64 cells in $Z$ and 256 cells in $R$. The space and time steps are fixed for all simulations, $\Delta x = 0.02/64 \text{ m}$, $\Delta t_e = 1 \times 10^{-10} \text{ s}$ and $\Delta t_i = 10 \Delta t_e$. In the null collision method, the collision probability is normally less than 0.1. Because we have adopted large time steps for the ions, the ion collision probability can be about 0.15 if the MC process is also sub-cycled. In order to avoid this, we conduct ion collisions in every electron step and thus allow one ion to collide more than once between two moves. In fact, this collision probability exists only in theory because the ion collision probability is determined by the velocity, and the velocity of the ions only becomes large after being accelerated in the sheath. In simulations, we often set a large voltage upper limit (about 1000 V) and cause a large probability limit. But in practical simulations, the sheath voltage is limited by the rf voltage, so the real collision probability is much less than the upper limit. Then multi-collisions seldom take place in one step.

The initial density is uniform $5 \times 10^{13} \text{ m}^{-3}$ for all cells and 200 particles are placed randomly within one cell. The initial electron and ion temperatures are 3 eV and 300 K, respectively. During the simulations in total about $(5–7) \times 10^6$ particles are traced. One simulation will take about 40–60 h for 1000 rf periods before convergence with 8-way parallelization in 4 nodes of our cluster. The ions bombarding the lower electrode are accumulated for 100 rf periods to calculate the ion flux and the ion energy distribution functions (IEDFs), and all other results are given by averaging over four rf periods after the simulations have reached equilibrium.

A fluid simulation is also performed for comparison. The hydrodynamic equations for the electron equations include electron continuity equations

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = k_i N_n e. \quad (1)$$

Here $n_e$ stands for the electron density, $N$ is the background gas density and $k_i$ is ionization rate coefficient. The electron number flux $\Gamma_e$ is given by the drift–diffusion approximation

$$\Gamma_e = - \frac{D_e}{T_e} \nabla (n_e T_e) - \mu_e n_e E, \quad (2)$$

where $D_e$ and $\mu_e$ are the electron diffusion coefficient and mobility. $T_e$ is the electron temperature, which could be calculated through the electron energy equation

$$\frac{\partial \left( \frac{2}{3} n_e T_e \right)}{\partial t} = - \nabla q_e - e E \cdot \Gamma_e - \frac{1}{e} k_i N n_e, \quad (3)$$

Figure 1. Schematic of the simulation for CCP.
where \( q_0 \) is the flux of energy and \( \varepsilon \) is the threshold energy of ionization.

In addition to the electron equations, we also need to solve the ion continuity equation, ion momentum equation and Poisson’s equation. We assume that the electron flux at the boundary is

\[
\Gamma_e = \frac{n_e v_i}{4} (1 - \Theta),
\]

(4)

\( v_i = \sqrt{8T_e/\pi m_e} \) is the thermal velocity and a reflection of \( \Theta \) at a value of 0.25.

In discretized form, the ion equations are solved by the FCT method [34] and the electron equations are solved by the finite volume method [35]. The detailed descriptions of the equations, boundary conditions and the reaction coefficient can be found in our previous work [36]. The chamber geometry and discharge parameters are chosen exactly the same as the PIC/MC simulation, except the dc bias, which is directly taken from the PIC/MC results. The advantage of the fluid model is its running speed. A typical fluid simulation will take only about 18 h on a single core of Intel E2160 CPU.

According to extensive study over very broad parameters with the 1D model, we have found that the fluid model always gives smaller density compared with the explicit PIC/MC model by a factor of about 0.6–0.8, when the pressure is about 50–400 mTorr. Since we adopted the implicit scheme and large steps here, not all high frequencies have been solved here. As the theoretical analysis and the benchmark results show, the implicit PIC method commonly causes self-cooling effect. Here we have underestimated the density by a similar factor in the implicit PIC/MC simulations, as we have shown in part I. However, the exact value of plasma density is not essential here as it can be scaled nearly linearly. The essential properties are sheath thickness, potential drop and density profiles. They are all well predicted.

3. Simulation results

3.1. Self-bias dc voltage

The calculated voltages on the rf powered electrode are plotted in figure 2 and it is very clear that the voltages are in \( V = V_0 \sin \omega t V_{dc} \) form. Where \( V_0 \) is 188 V, 191 V and 195 V, \( V_{dc} \) is –49 V, –74 V and –117 V for the G1, G2 and G4 cases, respectively. Due to the impedance of the capacitor, \( V_0 \) is slightly smaller than \( V_{dc} \), and \( V_{dc} \) increases with decreasing \( R_f \) electrode radius. No higher harmonics are observed in our simulations.

For clarity, \( z \)-direction cross-sectional profiles of \( \Phi \) at \( R = 2 \text{ cm} \) for different gap lengths are shown in figure 3. The potential drop near the rf electrode \( V_a \) and the potential drop near the grounded electrode \( V_b \) can be readily read from the figure. Here we have the electrode surface area ratio \( A_b/A_a = 1.3, 1.8 \) and 4, for the G1, G2 and G4 cases, respectively. \( V_a/V_b \) and \( A_b/A_a \) have the relation

\[
\frac{V_a}{V_b} = \left( \frac{A_b}{A_a} \right)^q.
\]

(5)

We plotted \( V_a \), \( V_b \) and \( q \) as a function of gap length in figure 4. We can see that \( V_a \) increases and \( V_b \) decreases with increasing \( A_b/A_a \). The \( V_a \) from the fluid model is smaller than that from the PIC/MC model, while the \( V_b \) is larger. The \( q \) is also smaller from the fluid model.

For the \( G = 1 \text{ cm} \) case (\( A_b/A_a = 1.31 \)), the gap is much smaller than the electrode radius, and the side wall has little effect on the bulk plasmas. The 1D spherical infinite-radius model [24] gives \( q = 2.21 \) and the simulation gives \( q = 2.08 \). For the \( G = 2 \text{ cm} \) case (\( A_b/A_a = 1.77 \)), the gap length is moderate and the finite-radius effects should be considered. Both the finite radius model by Lieberman [25] and the simulation give \( q = 1.45 \). For the \( G = 4 \text{ cm} \) case (\( A_b/A_a = 4 \)), the electrode radius is comparable to the electron mean free path, so that the local effect will be significant and we have \( q = 0.95 \). We can conclude that \( q \) always decreases with increasing area ratio.

The period average potential and field \( \Phi \), \( E_z \) and \( E_r \) from the PIC/MC model are depicted in figure 5, while corresponding results from the fluid model are shown in
Figure 4. (a) Average potential drop near the rf electrode $V_a$ and potential drop near the grounded electrode $V_b$; (b) $V_a/V_b$ and power $q$ as a function of $A_b/A_a$. The solid line is from the PIC/MC model and the dashed line is from the fluid model.

Figure 5. 2D average (a) $\Phi_1(V)$, (b) $E_z(V \text{ m}^{-1})$ and (c) $E_r(V \text{ m}^{-1})$ profiles from the PIC/MC model. The gap length is 2 cm.

Figure 6. 2D average (a) $\Phi(V)$, (b) $E_z(V \text{ m}^{-1})$ and (c) $E_r(V \text{ m}^{-1})$ profiles from the fluid model. The gap length is 2 cm.

3.2. Plasma density

The electron densities for different gap lengths from the PIC/MC model are shown in figure 7, while corresponding results from the fluid model are shown in figure 8. It can be clearly seen that both the fluid model and the PIC/MC model give similar results for the peak plasma density and the profiles. The axial cross sections of the density are very similar to the 1D results except in the region near the gap, where the radial field is large.

In fluid results, the density profiles are much flatter and smoother. This phenomenon comes from the well-known numerical diffusion effect. In Eulerian simulations, the discrete equations always give larger diffusive coefficients than the original differential equations in general, even if the flux-corrected transport (FCT) method is often used. As a result, the fluid model tends to smooth out all the short wavelength oscillations and to decrease the density gradients. There is only one peak in the profiles just near the gap for all three cases. The reason is that all electron heating occurs locally in the fluid model, then the density only has peaks near the region where both $E_r$ and $E_z$ are large.

In PIC/MC results, since the kinetics effects are included, the cases are much more complicated. For the G1 case, there is only one peak near $r = R_{rf}$ and the radial density is nearly constant at $r < R_{rf}$, which is like what many other fluid
Figure 7. Average electron density profiles from the PIC/MC model. The gap lengths are (a) 1 cm, (b) 2 cm and (c) 4 cm.

Figure 8. Average electron density profiles from the fluid model. The gap lengths are (a) 1 cm, (b) 2 cm and (c) 4 cm.

3.3. Electron kinetics

We can estimate that the electron mean free path length is about 3 cm. Because the electrode distance is only 2 cm and the gaps are 1–4 cm, we should expect that kinetics effects play an important role in the discharges.

We depict the 2D average electron temperature profiles from the PIC/MC model and the fluid model in figure 10, for a gap length of 2 cm. The differences are significant. For the PIC/MC model, the profile is saddle-like in the axial direction. For the fluid model, the temperature only varies slightly around 4 eV over a very large area. This phenomenon has also been observed in many other fluid simulations [19, 38]. The reason is that, in the conventional fluid model, many kinetic effects of the electrons are disregarded. This problem can be partially solved by the revised fluid model [38]. The most significant difference is near the gap corner, where the fluid model predicted an enhanced electron temperature, while the PIC/MC model gives zero temperature because there are no electrons as we have discussed.

For clarity, we also plotted the axial cross-sectional profiles at $R = 2$ cm of the electron temperature for different gap lengths in figure 11. Again, the profiles are very similar to 1D results, that is of saddle-like form. The temperature given by the fluid model is nearly constant and higher than those given by the PIC/MC model. At larger self-dc voltage, the peak will tend to move towards the grounded electrode.

The electron power density $\mathbf{E} \cdot \mathbf{J}$ is shown in figure 12. For the PIC model, electron density heating rate is very small over most of the area, and positive electron density heating mostly occurs in a very narrow region near the sheath edge. For the G1 case, the maximum power density is near $r = R_{rf}$. For the G2 case, the positive heating rate peaks have similar values at small radius, but have smaller values near the gaps. The G4 case has a peak heating rate about 1.7 times larger than the former two cases, mostly occurring at $0 < r < R_{rf}$.
Figure 9. (a) The axial cross-sectional profile at $R = 2$ cm of electron and ion density and for $G = 2$ cm; (b) the radial cross-sectional profile of electron density at $Z = 1$ cm for different gap lengths, both from the PIC/MC model. We also plotted the same results from the fluid model with $G = 2$ cm for comparison.

Figure 10. 2D average electron temperature profiles from the PIC/MC model (a) and the fluid model (b). The gap lengths are 2 cm.

Here we have smoothed the results on the axis for better contrast.

There are two negative power regions for all three cases. The first one is located in the sheath near the rf powered electrode with the same length as the length of the electrode radius. The second one is located in the upper right corner of the discharge zone. A similar phenomenon has also been found in 1D symmetric PIC/MC simulations, but the negative power region exists in both sheaths, close to the rf and dc electrodes. As we can see, the negative self-bias voltage has eliminated the region near the dc electrode and has broadened the region near the rf electrode.

For the G2 and G4 case, a third region of negative power absorption exists near $r = R_{ef}$ in the gap center. For the G4 case, the negative power absorption rate can be high. At $r > R_{ef}$, $E_r$ can be much larger than $E_z$. When an electron enters this region, it will be decelerated and bounced back, then the current and electric field have opposite directions. The greater the gap is, the greater $E_r$ is accordingly. This region will trap some electrons and thus decrease the electron side wall loss significantly. As a result, the electron heating rate at $r < R_{ef}$ will be significantly enhanced.

The negative power absorption region caused two density peaks in the G4 scheme. We should note that two peaks exist in the G2 scheme also, but they are too weak to be recognized. Here the major movement of electrons is bouncing between the $z$-electrodes. In the region with $r > R_{ef}$ (except for the small region in the right lower corner), there exists positive $E_r$. While a long range electron is moving in the $z$-direction in this region, the positive $E_r$ pushes the electrons and acts as a focusing mechanism. So if the positive region of $E_r$ is large and the electron mean free path length can be compared with the bulk region ($E_r$ close to 0), there will be some high energy electrons focused on the axis region and causing a peak near the axis. This peak appears in the G4 case. A qualitatively similar axis peak appears in the large gap and small electrode radius discharges, which has been observed in experiments [39].

The electron kinetics and heating rates have explained the facts that there are several peaks in the density profiles. These peaks are inherently kinetic effects, and all are smoothed out in...
Figure 12. Electron power density for different gap lengths from the PIC/MC model with gap lengths of (a) 1 cm, (b) 2 cm and (c) 4 cm. We also plotted the electron power density from the fluid model with \( G = 2 \) cm for comparison.

Due to small volume factor in the axis, the field near the axis is considerably noisier. The particle numbers can be less than 20 per cell. This may heat the plasma non-physically. From the electron temperature and the electron heating rate profiles, we can see a small zone of radius less than 3 mm, just near the axis, where the electrons are non-physically heated. This has little effect on the final results, because the particle weighting is very small near the axis, thus is negligible for the total electron heating and this non-physical effect can be effectively suppressed by the particle splitting method, as we have discussed in part I.

Electron energy probability distributions are shown in figure 13. Here all electrons in the simulation zone are counted over four rf periods. For the G1 and G2 cases, both give the standard two-temperature distributions at energy below 15 eV. The temperature of high energy group electrons is similar, but the temperature of low energy group electrons for the G2 case is larger than the G1 case, which implies additional heating for the low energy electrons. For the G4 case, the EEPF temperature is higher than the temperature of high energy group electrons for the G1 and G2 cases, which is a result of enhanced electron heating as we have discussed.

3.4. Ion flux and energy distributions

Figure 14(a) shows the radial distribution of ion flux onto the rf powered electrode for three gap lengths. Here we have showed all lower side fluxes, including the flux flowing out from the region of the gap, but only the flux inside the radius of the rf powered electrode is meaningful. As we can see, although the G4 case gives the largest flux, the flux is not very uniform. In contrast, for the G1 and the G2 cases the flux is uniform over the rf powered electrode. It should be noted that the ion flux is larger for the G2 case than the G1 case, although the density is smaller. It seems that the larger side wall sheath tends to increase the flux to the electrode. The fluid model gives much larger flux than that from the PIC/MC model, although profiles are very similar.

Figure 14(b) shows the IEDFs on the rf powered electrode. Here we have considered all the ions flowing to the rf powered electrode. If the sheath is collisionless, the IEDF will be a bimodal form with two symmetrical peaks [1], and the two peaks can be seen in the IEDFs. The two peaks shift to higher energy with a decrease in the electrode radius. Larger gaps give larger average ion energy, because the self-bias dc voltage is larger. Since the ion mean free path is about 0.03 cm and the sheath thickness is about 0.5 cm, the ions can experience many collisions in passing the sheath. Therefore, the IEDFs decrease exponentially with energy.

4. Discussions and summary

In this paper, we have studied the self-bias dc voltage with the 2D PIC/MC model. At small gap length, the dc voltage can be well estimated by the 1D spherical shell model [24]. At moderate gap length, the dc voltage can be well estimated by the infinite-radius model [25]. At large gap length, the dc voltage cannot be estimated by the analytic model, as electron non-local behavior will dominate. Electron power absorption is also significantly enhanced at large gap length.
Due to the numerical diffusion effect, although it can give reasonable density values and profiles, the fluid model tends to smooth out all the short wavelength oscillations and decrease the density gradients. The density and electron temperature profiles given by the PIC/MC model are steeper. Due to the non-local and kinetic effects, there are several peaks in the density profiles. The simulations validate both the PIC/MC model we have adopted and the fluid model.

However, the PIC/MC model still has many shortcomings compared with the fluid model, which may severely constrain the applications of this model. For example, the PIC/MC model is computationally expensive, and is very hard or even practically impossible to couple with the chemical reaction model. In addition, we adopted the implicit PIC simulation and this method commonly causes self-cooling effects [37], thus the plasma density will be underestimated and high frequency phenomena will not be fully resolved. Nevertheless, through the PIC/MC model, detailed plasma behavior can be predicted, and kinetics effects can be preserved. We are trying to gain more insights into the physics of CCP with this model.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No 10635010) and the Research Fund for Doctoral Program of Higher Education of China (No 2009041110026).

References

[1] Lieberman M A and Lichtenberg A J 2005 Principles of Plasma Discharges and Materials Processing 2nd edn (New York: Wiley)
[2] Makabe T and Petrovic Z L 2006 Plasma Electronics: Applications in Microelectronic Device Fabrication (New York: Taylor and Francis)
[3] Kushner M J 2009 J. Phys. D: Appl. Phys. 42 194013
[4] Kim H C, Iza F, Yang S S, Radmilovic-Radjenovic M and Lee K K 2005 J. Phys. D: Appl. Phys. 38 R283–R301
[5] Dijk J, Kroesen G M W and Bogaerts A 2009 J. Phys. D: Appl. Phys. 42 190301
[6] Georgieva V, Bogaerts A and Gijbels R 2003 J. Appl. Phys. 93 2369
[7] Boyle P C, Ellingboe A R and Turner M M 2004 Plasma Sources Sci. Technol. 13 493
[8] Kim H C and Lee J K 2004 Phys. Rev. Lett. 93 085003
[9] Kawamura E, Lieberman M A and Lichtenberg A J 2006 Phys. Plasmas 13 053506
[10] Bronold F X, Matyash K, Tskhakaya D, Schneider R and Fehske H 2007 J. Phys. D: Appl. Phys. 40 6583
[11] Donko Z, Schulze J, Heil B G and Czarnetzki U 2009 J. Phys. D: Appl. Phys. 42 025205
[12] Jiang W, Wang H Y, Zhao S X and Wang Y N 2009 J. Phys. D: Appl. Phys. 42 102005
[13] Vahevi V, Birdussell C K, Lieberman M A, DiPeso G and Rognlien T D 1993 Fluids. Phys. Sci. B 5 2719
[14] Kawamura E, Lieberman M A and Lichtenberg A J 2008 Plasma Sources Sci. Technol. 17 045002
[15] Wakayama G and Nanbu K 2003 IEEE Trans. Plasma Sci. 31 638
[16] Wang H Y, Jiang W and Wang Y N 2009 Comput. Phys. Commun. 180 1305–14
[17] Lee S H, You S J, Chang H Y and Lee J K 2007 J. Vac. Sci. Technol. A 25 455
[18] Kim D H and Ryu C M 2007 J. Phys. D: Appl. Phys. 41 015207
[19] Leray G, Chabert P, Lichtenberg A J and Lieberman M A 2009 J. Phys. D: Appl. Phys. 42 194020
[20] Chabert P, Rainhaudoil J L, Levil P, Rax J M and Lieberman M A 2005 Phys. Rev. Lett. 95 205001
[21] Lee I, Graves D B and Lieberman M A 2008 Plasma Sources Sci. Technol. 17 015018
[22] Yonemura S and Nanbu K 2006 Thin Solid Films 506 517
[23] Bulitnick E, Kolev I, Bogaerts A and Depla D 2008 J. Appl. Phys. 103 013109
[24] Lieberman M A 1989 J. Appl. Phys. 65 4186
[25] Lieberman M A and Savas S E 1990 J. Vac. Sci. Technol. A 8 1632
[26] Kawamura E, Vahevi V, Lieberman M A and Birdussell C K 1999 Plasma Sources Sci. Technol. 8 485
[27] Smith H B, Charles C, Boswell R W and Kuwahara H 1997 J. Appl. Phys. 82 561
[28] Yonemura S, Nanbu K and Iwata N 2004 J. Appl. Phys. 96 127
[29] Rauf S and Kushner M J 1998 J. Appl. Phys. 83 5087
[30] Rauf S and Kushner M J 1999 IEEE Trans. Plasma Sci. 27 1329
[31] Kaganovich I D 2002 Phys. Rev. Lett. 89 265006
[32] Wang H Y, Jiang W and Wang Y N 2010 Plasma Sources Sci. Technol. 19 045023
[33] Vahevi V and DiPeso G 1997 J. Comput. Phys. 131 149
[34] Boris J P, Landsberg A M, Oran E S and Gardner J H 1993 LCPFCT – Flux-Corrected Transport Algorithm for Solving Generalized Continuity Equations Naval Research Report NRL/MR/6410-93-7192

[35] Hammond E P, Mahesh K and Moin P 2002 J. Comput. Phys. 176 402

[36] Xu X, Ge H, Wang S, Dai Z L, Wang Y N and Zhu A M 2009 Prog. Nat. Sci. 19

[37] Brackbill J U and Cohen B I 1985 Multiple Time Scales (London: Academic)

[38] Chen G and Raja L L 2004 J. Appl. Phys. 96 6073

[39] Kitajima T, Izawa M, Nakano N and Makabe T 1997 J. Phys. D: Appl. Phys. 30 1783

[40] Takekida H and Nanbu K 2006 IEEE Trans. Plasma Sci. 34 973