COMPUTER SIMULATION OF DUST TRANSPORT PHENOMENA IN A RF DISCHARGE

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Using computer simulation we study the dynamics of dust particles in an rf discharge considering the mutual influence of the dust component and plasma. Simulation of the discharge is carried in the frame of the two-dimensional model by PIC/MCC method. To describe the motion of particles it is used molecular dynamics method, which takes into account the main factors influencing the behavior of dust particles (electric and gravitational forces, the forces of friction with the ions and neutrals). The simulation results have shown that dust particles are trapped in locations where the forces acting on them are balanced. The equilibrium configuration of particles studied depending on their size and different pressures of neutral gas in microgravity conditions, and under laboratory conditions. It is shown that dust particles lead to a decrease in the jump of the mean potential in the electrode layers and a sufficiently large particles can significantly alter plasma parameters in the discharge.

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1. INTRODUCTION

Particle contamination during plasma processing of semiconductors is known to be a significant contributor to reductions in product yield. Particles can charge negatively in a plasma and trap in minima of combined gravitational and electric potential fields, forming dust clouds [1]. There have been many experiments on fine particles, which have clarified various interesting features of fine particles in plasmas. Strong interactions of dust particles and the openness of the system lead to self-organization and 'structurization' of initially homogeneous dust clouds into a complex aggregate of dissipative dust structures and dust voids, with sharp boundaries between them [2]. These structures become quasi-stationary within short time scales and they are determined by a limited number of parameters controlling the structure. Here, we are interested in shape and structure of fine-particle clouds, namely the effect of particulate size on the spatial distribution of dust in a plasma environment is investigated through the simulation of a dust transport model coupled with plasma model.

2. MODEL

A two-dimensional RF discharge is considered between two plane electrodes separated by a gap of $d = 0.05\, m$ which is filled with Ar at pressure $p = 0.1\ Torr$. Dust particles of a given radius r_d are distributed uniformly at initial time in the interelectrode gap. The dust particles collect and scatter electrons and ions distributed in the discharge with density ne and ni, respectively. A harmonic external voltage $V_e(t) = V_0 \sin(\omega t)$ at a frequency f = 13,56 MHz and various amplitudes V_0 sustains the RF discharge.

The PIC/MCC method is used to describe this discharge [3]. In the frame of Monte-Carlo method we take in account elastic collisions of electrons and ions with atoms, an ionization and excitation of atoms by electrons, the charge exchange between ions and atoms.

Using a Lagrangian approach, the individual particle trajectory is tracked by solving the following force balance equations for each particle:

$$\frac{d\vec{r}}{dt} = \vec{v}_p ,$$

$$m_p \frac{d\vec{u}_p}{dt} = \vec{F}_g + \vec{F}_e + \vec{F}_i + \vec{F}_n ,$$

where $\vec{r}_p$ and $\vec{u}_p$ are the particulate position and velocity, respectively. $\vec{F}_g, \vec{F}_e, \vec{F}_i, \vec{F}_n$ are the forces acting on the dust particle due to gravity, electric field, ion drag and neutral drag, respectively [4]. In the calculation of such forces, dust particles are assumed to be spheres.

The gravitational force acting on a dust particle is given by

$$\vec{F}_g = \frac{\pi d_p^3}{6}\left(\rho_p - \rho_f\right)\vec{g} ,$$

where d_p is the particulate diameter; ρ_p and ρ_f are the densities of the particulate and neutral fluid, respectively, and $\vec{g}$ is the gravity.

Particulates in a plasma quickly become negatively charged to retard electrons which are much more mobile than ions, and then experience the electrostatic force

$$\vec{F}_e = q_d \vec{E} ,$$

where q_d is the charge of the particle.

The ion drag force results from collisions with the ions, which give rise to momentum transfer. The ion drag force has two components, the collection force and the Coulomb force. The former can be written as $F_{di}^c = n_i m_i v_i^2 \pi b_c^2$, where $b_c = \frac{d_p}{2}\left(1 - 2eq_d / am_i v_i^2\right)$ is the collection inpact parameter. The latter is given by $F_{di}^o = n_i m_i v_i^2 4\pi b_{\pi/2}^2 \Gamma$, where $b_{\pi/2} = eq_d / m_i v_i^2$ is orbital impact parameter, Γ is the Coulomb logarithm. The neutral drag force is determined by

$$F_{nd} = -\frac{2\sqrt{2\pi}}{3}\gamma d_p^2 n_n T_n \frac{u}{v_{Tn}} ,$$

where T_n, n_n, v_{Tn} are neutral temperature, density and thermal velocity correspondingly.

Dust charge q_d was obtained from the equation

$$\left(\frac{T_i m_e}{T_e m_i}\right)^{1/2} \frac{n_i}{n_e}\left(1-\frac{e\varphi_d}{k_B T_i}\right)\exp\left(-\frac{e\varphi_d}{k_B T_e}\right)-1=0,$$

which is a consequence of the condition $I_e + I_i = 0$.

Here I_e and I_i is electron and ion currents on a dust particle in the case of Maxwell distributions of electrons and ions, φ_d is the dust particle potential relative to plasmas.

Dust grains influence the potential of the electric field ϕ, which is described by Poisson equation

$$\frac{\partial^2 \varphi}{\partial x^2} = -\frac{e}{\varepsilon_0}\left[n_i - n_e + q_d n_d\right],$$

where n_d is the dust density.

3. SIMULATION RESULTS

Fig. 1 shows equilibrium distribution of dust particles with dust grain radius $r_d = 5\ \mu m$ in the discharge chamber in the presence of gravity (a) and under microgravity conditions (b).

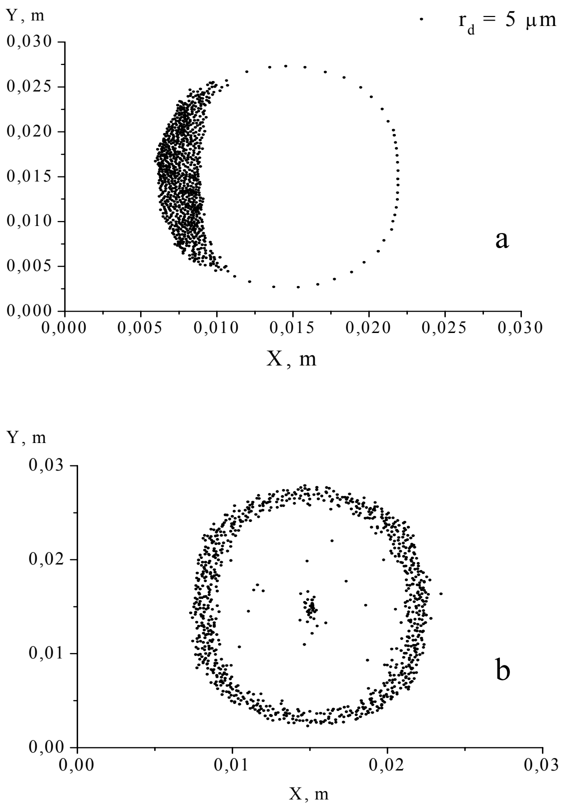

Fig. 1. Spatial distribution of dust particles in the discharge chamber at p =0.1 Torr, $V_0 = 500\ V$, $r_d = 5\ \mu m$ under laboratory conditions (a) and under microgravity conditions (b)

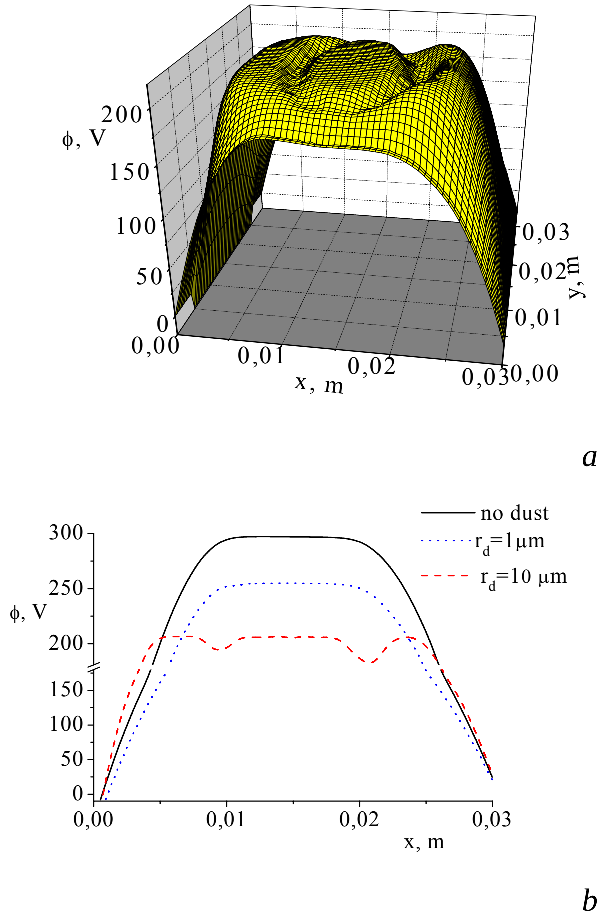

Fig. 2. Time-average two-dimensional spatial distribution of electric potential (a) and the potential distribution along perpendicular direction to the electrode (b) in the discharge chamber at p =0.1 Torr, $V_0 = 500\ V$, $r_d = 5\ \mu m$ under microgravity conditions

It is seen that dust particles form clouds in the form of a ring. In the first case (Fig. 1, a) most of them are located above the lower electrode due to the influence of gravity. However, some particles levitate under the upper grounded electrode, forming a chain of equally-spaced particles. Under microgravity conditions particles are distributed uniformly in the ring, but some particles are collected in the center of the ring. The reason for the formation of structure in the form of a ring is the ion drag force, which is due to flow of ions from the center of the discharge chamber to the electrodes and the side walls. This force balances the electric force directed from the walls, as a result dust clouds are formed represented in Fig. 1. We carried out test calculations of dust particles dynamic under microgravity conditions without taking into account the ion drag force. Results show that dust particles are collected in the center of the chamber and the void is not formed.

In Fig. 2 electric potential distribution is shown for case depictured in Fig.1,b. We can see that dust cloud disturbs the plasma potential so that the electric force pushes the dust particles. Thus dust particles oscillate at the boundary of the rf sheath. Fig. 2, b shows potential distributions along the direction perpendicular to the electrode for cases without dust particles, dust particles with $r_d = 1\ \mu m$ and dust particles with $r_d = 10\ \mu m$. We can see, that minima potential are observed only in the case of large dust particles ($r_d = 10\ \mu m$). In this case dust particles acquire large charges and their influence on potential is more significant. Note, that dust clouds reduce the potential drop in the rf sheath. Increasing the radius of dust particles also leads to a reduction of the potential drop.

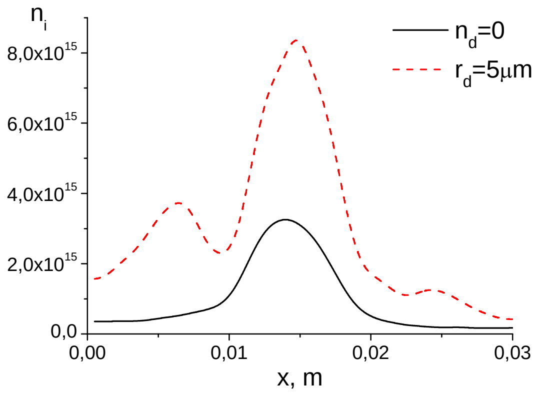

Fig. 3. Spatial distributions of the ion density along perpendicular direction to the electrode

Fig. 3 shows spatial distributions of the ion dinsity in discharge along perpendicular direction to the electrode under the center of the chamber. We can see that dust particles cause the ion density increasing in the discharge. Besides, on the dust clouds boundaries ion density peaks are formed. The reason of this phenomena is the increasing of ionization rate to support the discharge. The increasing of plasma density causes to the increasing of the discharge current

4. CONCLUSIONS

Results of simulations show that dust clouds in the form of ring are formed in the discharge chamber. The void in the center of the chamber is caused by the ion drag force.

It is shown that plasma density is increased in the presence of dust particles due to the increasing of the discharge current, but potential drop is decreased at that.

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КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ТРАНСПОРТА ПЫЛЕВЫХ ЧАСТИЦ В ВЧ-РАЗРЯДЕ

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С помощью компьютерного моделирования исследуется динамика пылевых частиц в ВЧ-разряде с учетом взаимного влияния пылевой компоненты и плазмы. Моделирование разряда проводится в рамках двухмерной модели методом PIC/MCC. Для описания движения частиц используется метод молекулярной динамики, в котором учтены основные факторы, влияющие на поведение пылевых частиц (электрическая и гравитационная силы, силы трения с ионами и нейтралами). Результаты моделирования показали, что пылевые частицы захватываются в областях, где силы, действующие на них, уравновешиваются. Исследованы равновесные конфигурации частиц в зависимости от их размера при разных давлениях нейтрального газа как в условиях микрогравитации, так и в лабораторных условиях. Показано, что пылевые частицы приводят к уменьшению скачка среднего потенциала в приэлектродных слоях и при достаточно большом размере могут существенно изменять параметры плазмы в разряде.

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ТРАНСПОРТУ ПИЛОВИХ ЧАСТИНОК У ВЧ-РОЗРЯДІ

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За допомогою комп'ютерного моделювання досліджується динаміка пилових частинок в ВЧ-розряді з урахуванням взаємного впливу пилової компоненти і плазми. Моделювання розряду проводиться в рамках двохвимірної моделі методом PIC/MCC. Для описання руху пилових частинок використовується метод молекулярної динаміки, в якому враховані основні фактори, що впливають на поведінку пилових частинок (електрична та гравітаційна сили, сили тертя з іонами та нейтралами). Результати моделювання показали, що пилові частинки захвачуються в областях, де сили, які діють на них, врівноважуються. Досліджено рівноважні конфігурації пилових частинок в залежності від їх розміру при різних тисках нейтрального газу як в умовах мікрогравітації, так і в лабораторних умовах. Показано, що пилові частинки приводять до зменшення скачка середнього потенціалу в приелектродних шарах та при достатньо великому розмірі можуть суттєво змінювати параметри плазми в розряді.