Simulation study of dust particle distribution in dust plasma

Y. Y. Zhang[1] , M. Y. Duan[1],Y. F. Huang[1], W. Z. Jia[2], Y. H. Song[1]

[1] *School of Physics, Dalian University of Technology, Dalian, China*
[2] *College of Artificial Intelligence, Southwest Universitys, Chongqing, China*

Abstract: The spatial distribution of dust particles in RF capacitively coupled plasma was studied based on a 2D fluid model. The result showed that near the plates and sidewalls, the density of dust particles has a maximum peak in magnitude at the edge of the electrode, which is determined by the combined electrostatic force and ion drag force experienced on the particles. Besides, based on a 3D fluid dynamics models, the Mach cone of suspended dust particles excited by a fast-moving laser beam was simulated. It is found that laser movement speed, dust plasma coupling coefficient and air pressure can affect Mach cone shape.

Keywords: Dust plasma, Mach cone, Fluid model

1. Introduction

Capacitively coupled plasmas have important applications in thin film deposition. For example, crystalline silicon hydride (a-Si:H) films deposited on solar panels[1]. However, under extreme conditions such as high atmospheric pressure, a large number of dust particles are generated in cpacitively coupled silane discharges, which can easy to cause cavities, delamination and interconnection short circuits in the deposited film[2]. In addition to the influence on the characteristics of the plasma, the dust particles themselves have many complex physical processes in the plasma, such as dust waves, Mach cones, phase transitions, cavities[3].

2. Introduction to 2D fluid models

Electrons, ions, neutral particles, and dust particles in plasma are described by the fluid continuity equation, the momentum conservation equation, and the energy conservation equation. The electric field and potential are calculated from the Poisson equation, as follows

$$\frac{d^2V}{dx^2} = -\frac{e}{\varepsilon_0}\left(\sum n_i - n_e - Q_d n_d\right) \qquad (1)$$

$$\mathbf{E} = -\frac{dV}{dx} \qquad (2)$$

ε_0 , n_e , n_i , Q_d , n_d are vacuum permittivity, electron density, ion density, charge on the surface of dust particles, and dust density.

The dust particles in the plasma are charged by collecting surrounding electrons and ions, and the formula for charging the dust particles is

$$\frac{dQ_d}{dt} = I_e + I_i \qquad (3)$$

I_e , I_i are tream of electrons and ions flowing to the surface of dust. Electron and ion flows can be obtained by the Orbit Motion Limited theory (OML) [4].

For spherical dust particles, the ion and electron flow expressions collected on their surface are

$$I_i = \pi r_d^2 n_i e u_s\left(1 - \frac{2eV_{fl}}{m_i u_s^2}\right) \qquad (4)$$

$$I_e = \pi r_d^2 e n_e\sqrt{\frac{8k_B T_e}{\pi m_e}}\exp\left(\frac{eV_{fl}}{k_B T_e}\right) \qquad (5)$$

m_i , m_e , k_B , T_i and T_e are ion mass, electron mass, Boltzmann constant, ion temperature and electron temperature.

Dust particles in plasma are determined by several different forces, including electric field forces, gravity, thermophoresis forces, and ionic and neutral drag forces. The expression of the electric field force is as follows:

$$\mathbf{F}_E = Q_d\mathbf{E} \qquad (6)$$

The collection force and scattering force are combined to obtain the ion drag force, and the formula is as follows:

$$\mathbf{F}_I = \mathbf{F}_\mathbf{i}^\mathbf{c} + \mathbf{F}_\mathbf{i}^\mathbf{o} = \pi b_c^2 m_i u_s n_i \mathbf{u}_\mathbf{i} + 4\pi b_{\pi/2}^2 \Lambda m_i u_s n_i \mathbf{u}_\mathbf{i} = \left(\pi b_c^2 + 4\pi b_{\pi/2}^2\Lambda\right) m_i u_s \mathbf{\Gamma}_\mathbf{i} = \chi\mathbf{\Gamma}_\mathbf{i} \qquad (7)$$

Neutral particle dragging force[5]:

$$\mathbf{F_n} = -\frac{4}{3}\pi r_d^2 n_n m_n v_{th,n}\left(\mathbf{v_d} - \mathbf{v_n}\right) \qquad (8)$$

$v_{th,n} = \sqrt{\frac{8k_B T_{gas}}{\pi m_n}}$ is the thermal velocity of neutral gas molecules.

Assuming that the neutral resistance is always the sum of other forces in balance, the drift diffusion expression of the dust particle flux can be obtained[5]:

$$\mathbf{\Gamma_d} = -\mu_d n_d \mathbf{E} - D_d\frac{dn_d}{dx} + \sum\frac{n_d}{m_d v_{md}}\chi\mathbf{\Gamma_i} \qquad (9)$$

$\mu_d = Q_d / m_d v_{md}$ is the mobility of dust particles, $D_d = \mu_d k_B T_{gas} / Q_d$ is diffusion coefficient, $v_{md} = \sqrt{2}\frac{p_{tot}}{k_B T_{gas}}\pi r_d^2\sqrt{\frac{8k_B T_{gas}}{\pi m_d}}$ is frequency of momentum loss.

3. Results and discussion

The work mainly includes two parts. Firstly, the dust particle distribution is studied by using a 2D fluid model. Secondly, based on a 3D fluid model, the Mach cone excited by a laser beam is simulated. The 3D fluid model is based on the continuity equation, the momentum conservation equation, and the Poisson equation, which is not detailed description here. Please refer to [6].

3.1 Simulation study of dust particle distribution based on 2D fluid model

The simulation parameters：The dust particle radius is 100nm; The neutral gas temperature is 1Torr; RF frequency is 13.56 MHz; The voltage amplitude is 50V; The upper electrode is connected to the RF power, and the lower electrode and sidewall are grounded; Upper and lower electrode spacing is 3cm; The chamber radius is 10cm; The plate radius is 9cm.

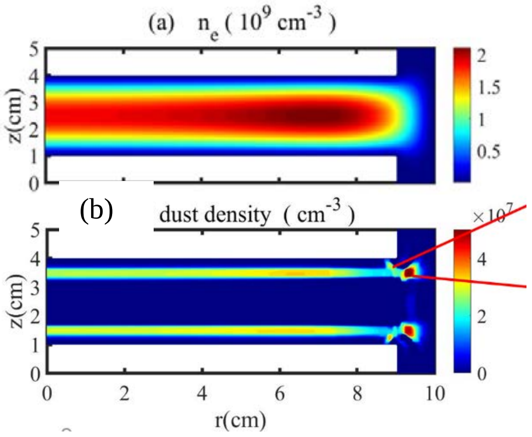

Fig. 1. Spatial distribution of plasma density and dust particle density. (a) electron density spatial distribution (b) spatial distribution of dust particle density.

Figure 1 shows the spatial distribution of electron density and dust particle density in silane plasma. The plasma density distribution shows obvious discharge characteristics of electronegative gases. By the electric field of the sheath layer, the negative ions are completely confined to the body area. Thus, the peak density of positive and negative ions is much higher than the electron density in the body region. However, dust particles are distributed near the plates and chamber side walls, which are not present in the body area. The spatial distribution of the dust particlesd density is influenced by a combination of forces, mainly electrostatic force and ion drag force. Since the background gas temperature is constant and the particles are on the nanoscale scale, thermophoresis and gravity forces are ignored.

3.2 Simulation study of Mach cone based on 3D fluid model

The simulation parameters：Plasma density is $10^9 cm^{-3}$; Ion and dust temperature is 0.03eV; Electronic temperature is 3eV; The dust particle radius is 5 micron; The charge on the surface of dust is 5000e.

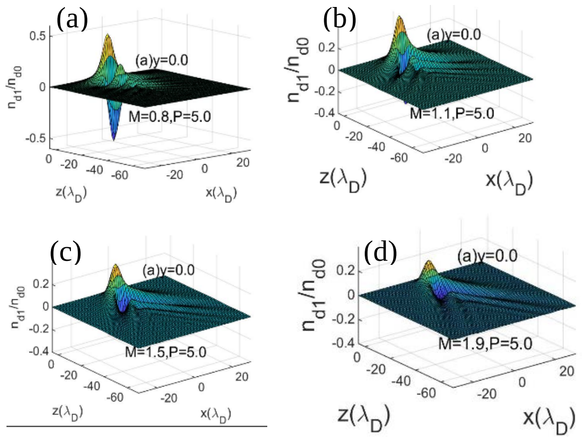

Fig. 2. The distribution of perturbed density in the Mach cone region for (a) M=0.8 (b) M=1.1 (c) M=1.5 (d) M=1.9

Figure 2 shows the spatial distribution of perturbed density for discharge pressure 5 Pa and Mach number M=0.8, 1.1, 1.5, 1.9, respectively. The V-shaped Mach cone and an oscillating wake are evident in the figure. It can be seen that these Mach cones are multi-cone structures composed of multiple “V” shaped cones, and the outermost cone is the most prominent. When the speed of the laser beam is constant, the excited Mach cone is actually a superposition of Mach cone produced by waves of various wavelengths. Besides, we found that both the disturbance density and the cone angle are constantly decreasing as the Mach number increased, which is consistent with the experimental results [7].

4. References

[1] T G. Northrop, Physica Scripta, 1992, 45(5):475-490.

[2] C. Y. Huang, C. K. Goertz, L. A. Frank, et al. Geophysical Research Letters, 1989, 16(6).

[3] A. Melzer, S. Nunomura, D. Samsonov, et al. Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Topics, 2000, 62(3 Pt B):4162-4176.

[4] A. Gallagher. Physical Review E, 2000, 62(2):2690-2706.

[5] M. R. Akdim, W. J. Goedheer. Journal of Applied Physics, 2003, 94(1):104-109.

[6] K. Jiang, L. Hou, Y. Wang, Z. L. Miskovic，Phys. Rev. E, 2004,70, 056406.

[7] A. Melzcr, S. Nunomura, D. Samsonov, et a1., Phys. Rev. E, 2000, 62, 4162.