DIAGNOSTICS OF PARTICLES IN RF DUSTY PLASMA

I.I. FILATOVA,[1] V.V. AZHARONOK,[1] N.I. CHUBRIK,[1]
A.A. MALEVANOVA,[2] F.M. TRUHACHEV,[2] T.S. RAMAZANOV[3]

[1]**B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus**
(68, Nezavisimosti Ave., 220072 Minsk, Belarus; e-mail: filatova@imaph.bas-net.by)

[2]**Mogilev State University**
(1, Kosmonavtov Str., 212022 Mogilev, Belarus; e-mail: ftru@mail.ru)

[3]**Institute of Experimental and Theoretical Physics, al-Farabi Kazakh National University**
(96a, Tole bi Str., Almaty 050012, Republic of Kazakhstan; e-mail: ramazan@physics.kzftru@mail.ru)

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We study the dynamics of polydisperse dust particles in a rf post-discharge plasma. The levitation of charged particles after the discharge switching-off is found, and the velocities of their fall are measured. A model of the dynamics of particles in the afterglow plasma is proposed to estimate their size and residual charge.

1. Introduction

Investigations of dust-particle parameters in dusty plasma are of great importance for the optimization of many industrial technologies based on the plasma processing such as microelectronics, nanotechnologies, and fusion [1]. Moreover, the presence of a residual charge on dust particles in the discharge afterglow that has been revealed recently opens up new possibilities for dusty plasma applications [2, 3]. In this paper, the results of optical and spectroscopic investigations of the formation of dust structures in plasma of a capacitively coupled radio frequency discharge are presented. The decay of dust structures is investigated in the post-discharge plasma, and the numerical simulations are performed with regard for the balance of forces acting on dust particles for the estimation of their size and residual charge after the extinction of plasma.

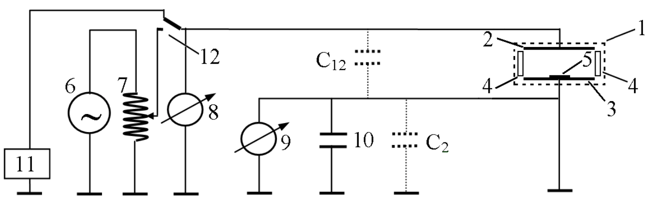

Fig. 1. Schematic view of the experimental setup: *1* – vacuum chamber, *2* – top electrode, *3* – bottom electrode, *4* – quartz plate, *5* – piezovibrator, *6* – rf generator, *7* – inductor, *8, 9* – voltmeter, *10* – capacitor, *11* – DC source, *12* – switch, C_{12} – capacity between electrodes, C_2 – capacity between the bottom electrode and the ground

2. Experimental Conditions and Results

The discharge was operated on a frequency of 5.28 MHz between two parallel plate water-cooled electrodes with a diameter of 120 mm separated by a distance $L = 21$ mm (Fig. 1).

Ambient air was used as a process gas at a pressure of 100 Pa. The specific energy input was $W_0 = 0.5$ W/cm^3. The electron concentration and the electron and ion temperatures in plasma under experimental conditions were estimated as $n_e \sim 10^8$ cm^3, $T_e \sim 2$ eV and $T_i \sim 0.03$ eV. Polydisperse Al_2O_3 particles with radii of 0.1–20 μm were injected into the plasma volume by means of a piezoelectric radiator of acoustic waves located on the bottom electrode. Dust particles were illuminated by a laser fan ($\lambda = 635$ nm) in the plane perpendicular to the electrode plane. The video images of particles were collected with a standard CCD camera (25 images per second) with a spatial resolution of 24 pixel/mm. Simultaneously, the emission spectra of plasma were recorded in the range of 300-800 nm using a spectrometer SL-100 fabricated by "Solar Laser System" [4]. For the detection of the residual charge on a dust particle in the discharge afterglow, DC bias 11 was applied to the upper electrode instead of the rf voltage by means of the commutator 12 (see Fig. 1). The bias value φ amounted 37 V, which allowed us to produce an electric field between the electrodes with the field strength $E = 1760$ V/m.

The emission spectra of plasma were presented mainly by the (2+) system of N_2. A spectral line ($I_{\rm las}$) of the scattered laser light can be observed in the spectra at 635 nm after the injection of dust particles into the plasma volume. It was analyzed to obtain information on the

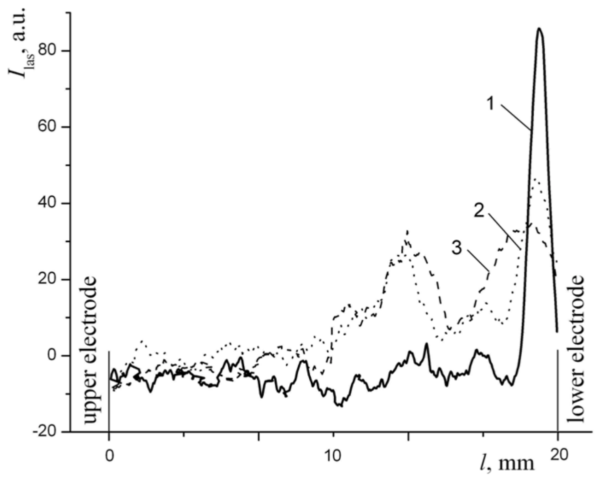

Fig. 2. Spatial intensity distribution of scattered laser light I_{las} before (*1*) and after the injection (at 3.5 s (*2*) and 12.6 s (*3*)) of dust particles into the discharge chamber

microparticles distribution in the plasma volume. The spatial intensity distribution of scattered laser radiation along the electrode gap l during the formation of dust structures in the discharge volume is presented in Fig. 2.

In the afterglow plasma, we observed a few layers of dust particles formed at different distances from the ground electrode which increased with the particle size decreasing (Fig. 3). Large particles from the lower layers fell very quickly after the discharge was switched-off. We have analyzed the decay of two upper layers of small dust particles that have kept their structure for some time (not less than 1 s) in the post-discharge period. The uppermost layer (I) was formed at a distance of $l_1 \approx 12$ mm from the lower electrode, another one (II) – at a distance of $l_2 \approx 9$ mm (see Fig. 3).

It is established that, after the discharge switching-off, the ordered structure of charged dust particles was kept during some time. The presence of the residual charge on a dust particle has been revealed from a comparative study of the particle motion in the absence of a DC bias and caused by the DC voltage application. It is shown that, in the absence of the bias, the particles from layer I moved downward with the ultimate velocity of $\upsilon_{D1} \approx 2.2$ mm/s, and the particles from the lower layer II – with the velocity of $\upsilon_{D2} \approx 5$ mm/s. In the case of the bias application, the particles from both layers moved upward with the velocity of $\upsilon_{D1E} = \upsilon_{D2E} \approx 2.2$ mm/s.

3. Theoretical Model

The main dust parameters (the particle charge and its radius) were estimated from the analysis of the balance

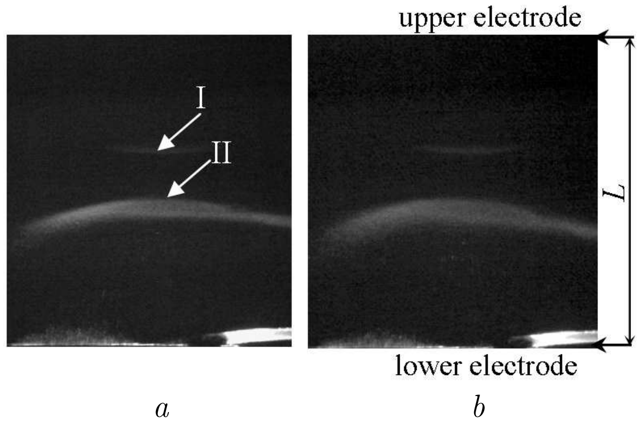

Fig. 3. The dust structure decay in the afterglow plasma: in 2 ms (*a*) and 82 ms (*b*) after the discharge switching-off

of forces acting on dust in the afterglow. We have taking two forces into consideration acting on dust particles after the discharge was switched-off: the gravity force F_G and the neutral drag force F_{ND} that can be expressed as [1]

$$F_G = \frac{4}{3}\pi r_D^3 \rho g, \qquad (1)$$

$$F_{ND} = \frac{8}{3}\sqrt{2\pi} r_D^2 m_n n_n \upsilon_{Tn}\left(1 + \frac{\pi}{8}\right)|\upsilon_D - \upsilon_n|, \qquad (2)$$

where r_D is the particle radius; ρ is the density of Al_2O_3 grains ($\rho = 2400$ kg/m^3); g is the acceleration of gravity; m_n, n_n, and $\upsilon_{Tn} = \sqrt{8T_n/\pi m_n}$ is the neutral molecule mass, its concentration, and thermal velocity; υ_D is the dust particle velocity; and υ_n is the mean velocity of a neutral gas ($\upsilon_n = 0$ under experimental conditions).

The electric force F_E appeared, when the DC voltage is switched-on, can be written as

$$F_E = QE, \qquad (3)$$

where $Q = Ze$ is the particle residual charge, e is the elementary charge, and $E = \varphi/L$ is the external electric field.

The forces acting on dust particles in the post-discharge period and the directions of their motion are schematically shown in Fig. 4.

In the absence of DC bias, the particles from layer I are levitated due to the balance between the forces F_G and F_{ND}:

$$F_G = F_{ND}. \qquad (4)$$

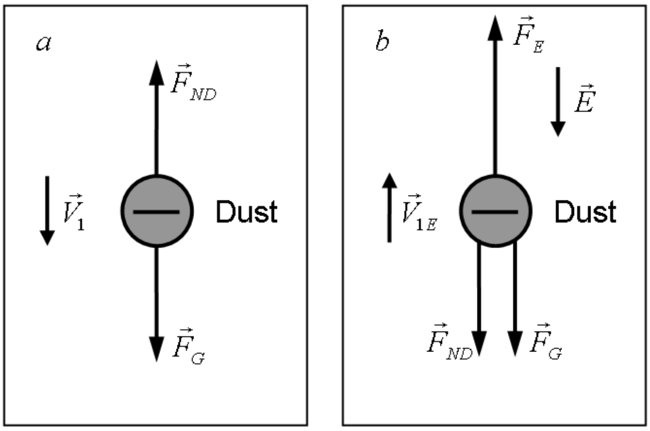

Fig. 4. Dust particles motion scheme in the afterglow plasma: the DC voltage is switched-off (*a*), voltage is switched-on (*b*)

The expression for the radius of particles from layer I deduced from (1), (2), (4) is

$$r_{D1} = \frac{2m_n n_n \upsilon_{Tn} \upsilon_{D1}}{\rho g}\sqrt{\frac{2}{\pi}}\left(1+\frac{\pi}{8}\right). \qquad (5)$$

For the experimental conditions, the radius value was estimated as $r_{D1} \cong 0.1$ μm.

In the presence of the DC voltage (Fig. 4,*b*), the force balance equation is

$$F_G + F_{ND} = F_E. \qquad (6)$$

The residual charge of particles from layer I can be deduced from (1)–(3) and (6):

$$Q_1 = \frac{4}{3}\frac{\pi r_{D1}^2}{E}\left(r_{D1}\rho g + \sqrt{\frac{1}{2\pi}}m_n n_n \upsilon_{Tn}\upsilon_{D1}A\right), \qquad (7)$$

where $A = \left(1+\frac{\pi}{8}\right)$. The charge value estimated for the experimental conditions is $Q_1 = 1e$.

By analogy, for layer II, we obtained the following values of particle parameters: $r_{D2} = 0.25$ μm and $Q_2 = 8e$, respectively. The obtained results of dust residual charge measurements are in a good agreement with data presented in the [2, 3].

In the case if the process gas is unknown and the neutral drag force is undefined, the residual charge on dust particles can be found in the following way. It was shown in [2, 3] that the value of particle residual charge under similar experimental conditions is $Q \approx 10e$. We can suppose that, for layer I, the absolute values of the forces F_{ND} in (4) and (6) (with and without DC bias) are equal, as it follows from the equality $|\upsilon_{D1}| = |\upsilon_{D1E}|$.

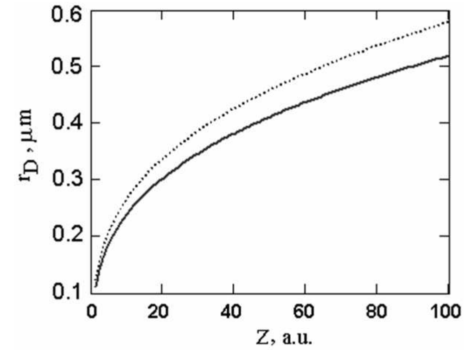

Fig. 5. Radius of a dust particle as a function of the residual charge: solid curve corresponds to layer I, dotted curve – to layer II

In this case, the particle radius can be expressed from (1)–(4), (6) as a function of the residual charge

$$r_{D1} = (3ZeE/8\pi\rho g)^{1/3}. \qquad (8)$$

For layer II, in view of expression (2) and the ratio $|\upsilon_{D2E}|/|\upsilon_{D2}| = 1/2.3$, we can suppose that the same ratio exists between the neutral drag forces with and without the DC bias. So, we obtained the following expression for the particle radius:

$$r_{D2} = (3ZeE/5.8\pi\rho g)^{1/3}. \qquad (9)$$

The dust particle radius as a function of the residual charge is represented in Fig. 5.

We could not experimentally define the concentration of dust particles n_D directly from the video images because of the insufficient resolution of a recording apparatus. In this connection, an indirect method has been proposed for the evaluation of n_D. Taking into consideration the fact that the dust cloud decays more slowly than it moves under the influence of the external forces, we suppose that the electric field E' produced by particles in the dust cloud has to be less than the external electric field E (let us assume $E' \leq E \times 10^{-2}$). The expression for the dust concentration is

$$n_D = \sigma/hQ. \qquad (10)$$

Here, σ is the surface density of the electric charge ($\sigma = 2E'\varepsilon_0$), $\varepsilon_0 = 8.85\times10^{-12}$ F/m is the dielectric constant. With regard for the cloud size measured from the experiment, we can obtain finally the following expression for the dust concentration: $n_D = 2E'\varepsilon_0/hQ$. The estimated n_D value for $Q = 10e$ is $n_D \leq 5 \times 10^5$ cm^{-3}.

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4. Conclusions

A spatially resolved spectral line I_{las} of the scattered laser light in the emission spectra of a rf dusty plasma at 635 nm was analyzed to investigate the distribution of microparticles in the plasma volume. The dust structure dynamics has been studied in the late afterglow of dusty plasma. A theoretical model has been proposed for the estimation of the particle size and its residual charge. It is shown that the particle residual charge amounts to about $-1e$ for particles with a radius of 0.1 μm and $-8e$ – for particles with a radius of 0.25 μm. The results can be used for the development of new methods of plasma diagnostics, polydisperse particles separation, and for plasma reactor clearing.

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ДІАГНОСТИКА ЧАСТИНОК У ПИЛОВІЙ RF ПЛАЗМІ

І.І. Філатова, В.В. Ажаронок, Н.І. Чубрик,
А.А. Малеванова, Ф.М. Трухачев, Т.С. Рамазанов

Р е з ю м е

Виконано дослідження динаміки полідисперсних частинок у післясвіченні плазми високочастотного розряду. Виявлено левітацію заряджених частинок і виміряно швидкості їх руху після вимикання розряду. Запропоновано модель, що описує динаміку частинок у післясвіченні плазми і дозволяє оцінити їх розмір та остаточний заряд.