DUST PARTICLES DISCHARGING IN RF DUSTY PLASMA AFTERGLOW

I.I. Filatova[1], V.V. Azaronok[1], N.I. Chubrik[1], F.M. Truhachev[2]

[1]B.I. Stepanov Institute of Physics of the NAS of Belarus, Nezalezhnastsi ave. 68, 220072 Minsk, Belarus, filatova@imaph.bas-net.by
[2] Mogilev State A. Kuleshov University, 220030 Mogilev, Belarus, ftru@rambler.ru

Investigations of dust-particle dynamics in dusty plasma is of great importance for optimization of many industrial technologies related to surface modification, cleaning of plasmachemical devices, separation of macroparticles by size, synthesis of nanoparticles, and creation on nanostructured coatings [1, 2]. In this paper, the decay of dust structures is investigated in the plasma afterglow and the numerical simulations are performed taking into account balance of forces acting on dust particles for estimation of their size and residual charge after the extinction of plasma.

Figure 1 shows a schematic diagram of the setup for investigation of dusty plasma in an RF capacitively coupled discharge. The discharge was excited at a

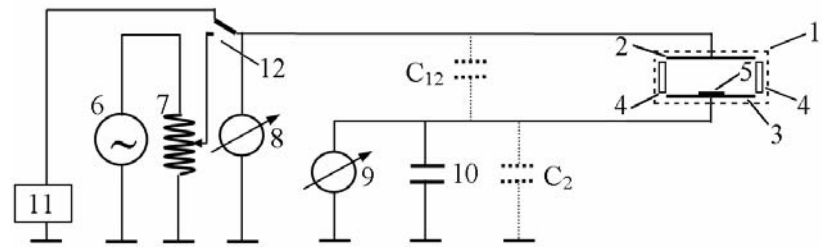

Figure 1 Schematic diagram of the experimental setup: 1– vacuum chamber, 2 – upper electrode, 3– lower electrode, 4– quartz plates, 5– acoustic radiator, 6– RF generator; 7– inductor; 8, 9– voltmeter, 10– coupling capacitor, 11– dc power supply, 12– switch, C_{12}– capacitance between the upper and lower electrodes, and C_2– capacitance between the lower electrode and the ground

frequency of 5.28 MHz between two 120-mm-diameter cooled copper electrodes separated by a distance of L = 21 mm. The plasma-forming gas was ambient air at a pressure of 100 Pa. Under the experimental conditions, the electron density and the electron and ion temperatures were n_e ~10^8 cm^3, T_e ~2 eV, and T_i ~0.03 eV, respectively. Polydisperse Al_2O_3 grains with effective dimensions of r_p ~ 0.1–20 μm were injected into the plasma by means of a piezoelectric radiator situated on the lower electrode. In order to reveal the presence of a residual charge on dust grains after the discharge was switched off, a dc voltage of U_{DC} =37 V from stabilized power supply 11 was applied through a switch 12 to the upper electrode instead of the RF voltage. It was assumed that grains having a negative residual charge would shift toward the upper electrode.

Photographs of grains illuminated by a narrow laser beam (λ = 635 nm) with a thickness of about 1 mm and height of 20 mm in the plane perpendicular to the electrode surface were taken using a standard video camera with a frame rate of 25 s^{-1}. The velocities of grains were determined from variations in their positions estimated using a series of frames, which reflected the dynamics of grains over a time interval of Δt ~ 0.4 s after switching-off of the discharge and termination of plasma recombination. The time resolution of the video camera was 40 ms. Video images of particles were analyzed for the determination of velocities of both the dust layers and individual grains.

It was found that the dust structure formed in the discharge plasma consisted of several layers. Dust particles levitated above the lower electrode. We studied the dynamics of the two upper layers (I) and (II) formed at distances of 12 and 9 mm from the lower electrode, respectively, which preserved their structure for about 1 s after the discharge was switched off (Fig. 2).

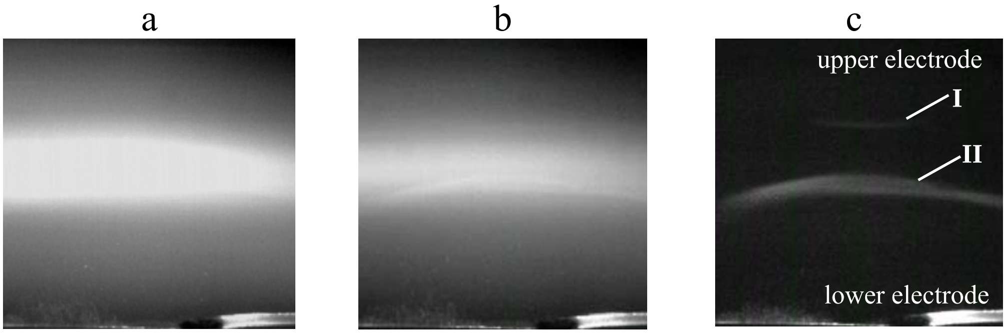

Figure 2 The dust structure formed in plasma (a) and its decay in the afterglow: in 2 ms (b), and 42 ms (c) after the discharge switching-off

It was difficult to resolve individual grains in layer I, because their number density was too high. Hence, the grain dynamics in this layer was estimated by analyzing variations in the position of the upper boundary of the layer. For layer II, we analyzed variations in the positions of both the upper boundary of the layer and individual grains. In the absence of the potential U_{DC}, grains from layers I and II moved downward with steady-state velocities of $\upsilon_{pI} \approx 2.2$ mm/s and $\upsilon_{pII} \approx 5$ mm/s, respectively. After applying a positive potential U_{DC}, grains from both layers moved upward with the same velocities $\upsilon_{IE} = \upsilon_{IIE} \approx 2.2$ mm/s.

The size and charge of dust grains were estimated from the balance of forces acting on the grains in the post-discharge phase. It was assumed that the grains were spherical. After the discharge is switched off, the grains are subject to the gravity force F_G and the neutral drag force F_{Np} [1],

$$F_G = \frac{4}{3}\pi r_p^3 \rho g \,, \tag{1}$$

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

where r_p is the effective radius of dust grains; ρ is their mass density (ρ = 2400 kg/m^3 for Al_2O_3); g is the free fall acceleration; m_n is the mass of a buffer gas (air) molecule; n_n is the density of buffer gas molecules; υ_{Tn} is their thermal velocity; and υ_n and υ_p are the drift velocities of the buffer gas and dust grains, respectively. The mean relative molecular mass of air taking into account the percentage of its chemical components was taken equal to 29. In computations, it was assumed that $\upsilon_n = 0$. Expression (2) is valid for $K_n >> 1$, where $K_n = l/r_p$ is the Knudsen parameter and l is the mean free path of neutral gas molecules. Under our experimental conditions, K_n was higher than 100.

The balance of vertical forces acting on grains after the discharge is switched off is described by the equation

$$F_G = F_{Np}. \tag{3}$$

The grain radius r_p was estimated using the following expression resulting from equations (1) – (3):

$$r_p = \frac{2m_n n_n \upsilon_{Tn}\upsilon_p}{\rho g}\sqrt{\frac{2}{\pi}}\left(1+\frac{\pi}{8}\right), \tag{4}$$

It was found that $r_{pI} \cong 0.1$ μm and $r_{pII} = 0.25$ μm for grains from layers I and II, respectively.

After applying a positive potential U_{DC}, in addition to the gravity force and the neutral drag force, the grains were subjected to the electric force F_E,

$$F_E = QE\,, \tag{5}$$

where $Q = Ze$ is the dust grain charge, e is the elementary charge, and $E = U_{DC}/L$ is the DC bias. In this case, the balance equation takes the form

$$F_G + F_{Np} = F_E. \tag{6}$$

The residual grain charge Q was estimated by the following formula obtained with allowance for Eqs. (1), (2), (5), and (6):

$$Q = \frac{4}{3}\frac{\pi r_p^2}{E}\left(r_p\rho g + 2\sqrt{\frac{2}{\pi}}m_n n_n \upsilon_{Tn}\upsilon_p\left(1+\frac{\pi}{8}\right)\right). \tag{7}$$

The values of Q for grains from layers I and II were found to be $Q_I = -1e$ and $Q_{II} = -8e$, respectively. This result agrees well with the results obtained in [3, 4].

In the absence of data on the buffer gas, the model allows to find how the grain size is related to the grain charge, provided that the dynamics of grains in both the presence and absence of an external electric field are known. We obtained such a relationship for grains from layer II. It was assumed that the residual charge varied from one elementary charge to several tens of elementary charges [3, 4].

It was obtained the following relationship for grains from layer I taking into account:

$$|\upsilon_{p\text{II}}| = 2.3\ |\upsilon_{p\text{II}E}|. \qquad (8)$$

According to expression (2), the same relationship holds for the neutral drug forces F_{Np} in formulas (3) and (6), which describe the balance of forces acted on dust grains in the absence and presence of the DC bias, respectively. Then, Eq. (6) can be written in the form $1.4{\cdot}F_G = F_E$. With allowance for expressions (1) and (5), the grain radius r_{pII} as a function of the residual grain charge Z can be represented as follows:

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

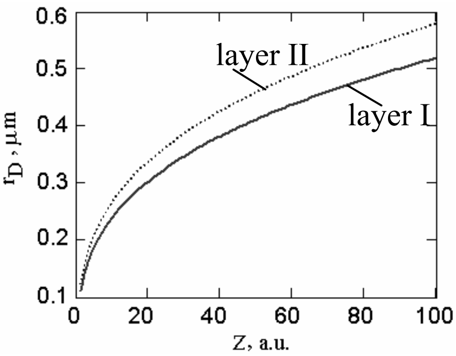

Figure 3 Radius of grains in dependence on the residual charge

The dust particle radius as a function of the residual charge is represented in Fig.3. The radii of grains with charges from $-1e$ до $-10e$ lie in the range 0.1 – 0.25 μm, which agrees with experimentally measured values of r_p.

Conclusions

It is found that, after the RF power is switched off, dust grains with radii of r_p = 0.1– 0.25 μm preserve a residual negative charge which value can vary in the range from $-1e$ to $-10e$, depending on the grain size. The property of dust grains to preserve their electric charge in the afterglow plasma offers new opportunities for the development of new nanotechnologies based on the possibility to control the motion of nanosized grains in the post-discharge phase by applying an external electric field.

References

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