

Direct current discharge with microparticles: The electrical characteristics and the plasma trap parameters

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Abstract. The electrical characteristics of the positive column of glow discharge were measured and simulated in pure neon and in plasma with micron size particles. The increment of the longitudinal electric field strength caused by the presence of dust structures was measured. Simulation was based on the diffusion–drift model of the positive column of glow discharge. Simulation was carried out using the measured values of dusty structure parameters and discharge characteristics. It was shown, that a dust structure maintained in a dc discharge represents a plasma trap for ions with ion concentrations more than three times higher than in a free discharge. The results can be used to calculate the traps for confinement of ions and dust particles in gas-discharge plasma.

1. Introduction

Dusty (complex) plasma is an intensively developing branch of plasma physics [1] and is widely used in the fields of applied researches and plasma technologies [2]. The interactions of plasma component with dust particles self-consistently determine the concentration of plasma particles and the concentration of sustained in a discharge dust particles. Also, these interactions affect the electrical parameters of the gas discharge. These influences have the numerous experimental confirmations.

Changes in the electric field strength and the voltage of dc glow discharge caused by the presence of dust particles, was observed in experiments with various gases and microparticles [1–6]. Changes in the electrical parameters of the discharge caused by the presence of dust particles are used for the diagnostics of the growth of dust particles in the plasma-chemical reactors [7–9].

In dusty plasmas in inert gases the metastable atom concentrations may be by few orders higher than the ionization degree. In the analysis of the processes in a dusty plasma in inert gases, one should take into account the step-wise ionization, an additional channel of quenching of metastable states on dust particles and chemi-ionization of metastable atoms [5, 10–14]. The quenching processes on dust particles and chemi-ionization of metastable atoms may increase the portion of free electrons. Typically, the increase in concentration of metastable atoms and of plasma radiation are associated with an increase in electron temperature and in the electric field strength. Such observations are carried out in discharges with dust particles [15–22].



In this article, we present experimental results on the change in the longitudinal electric field strength under the introduction of micron-size dust particles in the plasma of the positive column of a glow discharge in neon, and the results of simulations in frames of the diffusion-drift model. Also we analyze the dust particle charge that helps to explain the interaction of microparticles with a plasma. The correct simulation of electric field and the dust particle charge is the basis for adequate simulations of different types of plasma or dynamic traps for dust particles [23,24].

2. Experimental

Experiments were carried out in a cylindrical discharge tube of 20 cm length and 1.65 cm i.d. with two ring electrodes, glued into the tube walls in front of the region of formation of dust structure for measuring the voltage drop in the positive column with and without dust particles, at neon pressure of 47 Pa. Dust structures were formed from melamine formaldehyde particles of $2.55\ \mu\text{m}$ in diameter. The dust cloud size and dust particle concentration were determined using the microscope equipped with high resolution camcorder and diagnostic laser. For more details concerning the experimental setup, see [3,4].

The longitudinal size of dust structure could be less than the discharge gap between the measuring electrodes, or even longer than the measuring section. In some cases, there were formed an extended dust structures, their length was several times greater than the distance between the gap. The number of dust particles in such structures exceeded 1.5×10^6 pcs. The measurements of voltage between the ring electrode and the concentration of the dust particles were carried out at a discharge current 0.1–1 mA. The increment of the longitudinal electric field strength caused by the presence of dust structures was calculated as the difference between the voltage drop in the discharge with and without dust particles divided by the total length of the dust structure situated between the rings.

3. Model formulation

The basic points of diffusion–drift model were described in [3] in application to the glow discharge in air. Following [3], we use diffusion–drift approximation for the solution of the problem for the homogeneous positive column of a glow discharge in neon. In neon plasma, the metastable atom production and consumption, including step-wise ionization, should be considered adequately in plasma balance equations. We consider the neon plasma consisting of neutrals, electrons, ions and metastable atoms with the excitation energy of 16.62 eV (1s configuration in Paschen's notation), neglecting the presence of diatomic ions in the studied pressure range. The model formulation and the list of important collisional processes in neon discharge at a given pressure are represented in [14]. In this study, we use the collision enhanced collection (CEC) model for particle charging [25]. The energy accommodation coefficient in interaction with dust particles was taken as 100%. It was assumed that in a quenching of plasma particles on the surface of dust particles, the energy release to the particle surface does not cause the electron emission. It was supposed also that the ultraviolet radiation of the plasma discharge does not cause any photo emission from the surface of dust particles.

The simulations were carried out using the appropriate experimental parameters of dust structures (the radius of the dust structures r_d and dust particle concentration n_d) and the corresponding values of the discharge current I and the longitudinal electric field strength E_l . The distribution of dust particles inside the dust structure and its boundary $r \leq r_d$ was assumed as homogeneous: $n_d(r) = n_{d,0}$, where $n_{d,0}$ is a dust particle concentration on the discharge axis. On the edge of the dust structure ($r > r_d$) the dust particle distribution was taken as exponentially blurred: $n_d(r) = n_{d,0}e^{10(r_d-r)/R}$, where R is a radius of discharge.

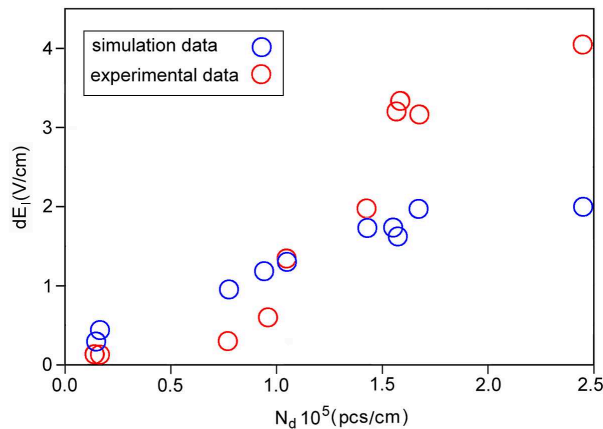


Figure 1. The increment of the longitudinal electric field strength dE_l versus the reduced number of dust particles N_d at pressure 47 Pa.

4. Results and discussion

All over range of the investigated parameters, the measured in the discharge with dust particles the longitudinal electric field strength $E_l(n_d)$ was higher than in dust-free discharge $E_l(0)$, with the same value of the discharge current. In figure 1 the comparison of simulated and experimental values of the increment of the longitudinal electric field strength $dE_l = E_l(n_d) - E_l(0)$ versus the reduced number of dust particles N_d , is represented, where N_d is the number of particles in a dust structure of 1 cm length. Red circles represent the experimental data, blue circles are the corresponding simulations. Simulations were carried out using the measured values of n_d and r_d . Below, the values n_d and N_d relate as $N_d = \int_0^{r_d} 2\pi r n_d(r) dr$. Every point in figure 1 represents the dust structure with specific size and dust particle concentration obtained at specific value of discharge current.

The increment of the electric field strength reflects the increase in the losses of plasma on the surface of dust particles. It is evident that dE_l is related to the number of particles nonlinearly and has an asymptotic character with increasing N_d . This is due to the fact that N_d in dust structure increases mainly due to increase in the dust particle concentration n_d . In the same time there proceeds a redistribution of concentration of free electrons in the cross section of discharge tube and their displacement in the discharge free of dust particles, so that the area occupied by dense dust structure becomes less conductive. In the limiting case of completely non-conductive dust structure (where the ionization and electron diffusion rates can only compensate the electron losses), the discharge current will be completely dislocated beyond. The dense dust structure will behave as a solid rod, located in the center of the discharge tube.

Figure 1 shows quite good agreement between the calculated and experimental data in the range of not too high values of N_d . At high N_d the model underestimates dE_l apparently due to the limited accuracy of the model of dust particle charging in a dense dust structures with a significant deficit of the electron density.

To analyze the dependence of the increment of the electric field strength on the discharge parameters we have simulated the situation with higher pressure and neon discharge current with a variable value of n_d . The radius of the dust structure $r_d = 4$ mm, was taken equal to the radius of experimentally observed dust structure.

In figure 2, the longitudinal electric field strength E_l is represented versus the reduced number of dust particles N_d . Figure 2 shows that the electric field strength in the discharge with dust structure depends on the parameters of the discharge, which reflects the self-consistent nature of the interaction of the gas-discharge plasma with dust structures. One can see that at pressure of 47 Pa in a discharge with $N_d = 4 \times 10^5$ pcs/cm, E_l increases by a factor of about 1.4 while at pressure of 120 Pa by a factor of about 1.8. At higher gas pressure appear the higher losses of

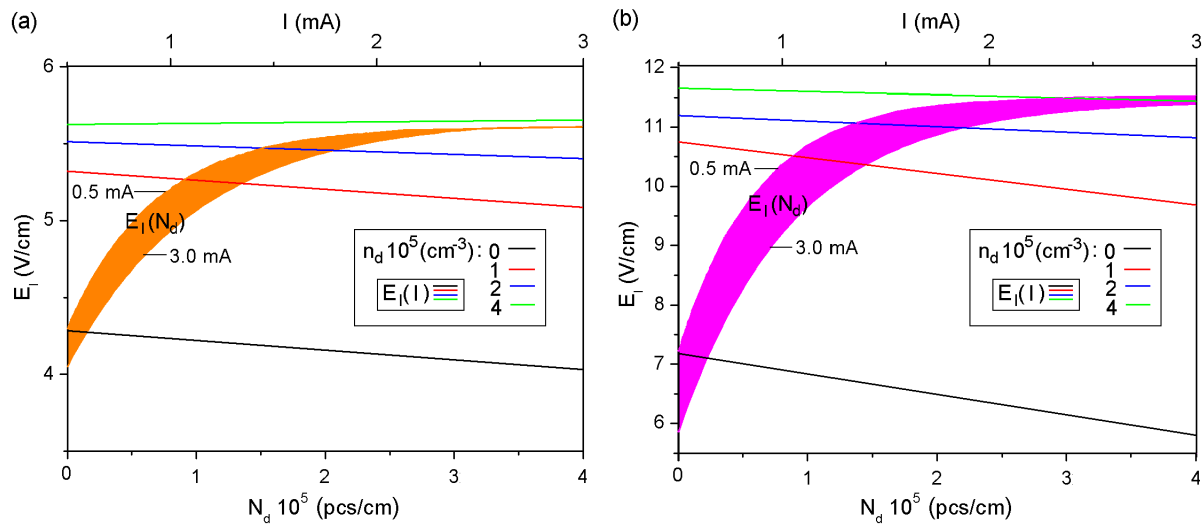


Figure 2. The longitudinal electric field strength E_l versus the discharge current I for various values of dust particle concentration n_d (lines), at neon pressure: 47 Pa (a) and 120 Pa (b). The colored zones—surfaces formed by the values $E_l(N_d)$ limited by the discharge current from 0.5 to 3 mA: 47 Pa (orange) and 120 Pa (magenta).

plasma energy on the surface of dust particles that are the sum of the losses of charged particles and the losses of excitation energy of metastable atoms. This requires a greater increase in the longitudinal electric field strength required to maintain the discharge current.

In figure 2, one can see a linear increase in the electric field strength at a low $N_d < 4 \times 10^4$ pcs/cm in the discharge and a saturation at high $N_d > 2 \times 10^5$ pcs/cm. For small N_d the dust particles actually work as an individual objects, absorbing particles within the plasma discharge, without affecting the distribution of electron density. At high N_d particles affect the plasma collectively as a structure. At the location of dust structure the gas conductivity decreases causing a redistribution of the electric current density over the cross section of the discharge. The increment of dE_l per particle is reduced, which is reflected in the decrease of the particle charge with increasing dust particle concentrations in dust structure.

With the growth of N_d up to values giving the distances between the dust particles comparable to the Debye ion radius, the screening begins of the flows of charged particles inside the dust structure, resulting in the displacement of charged particles beyond the outer boundary of the dust structure. In the limiting case, as indicated above, one may consider the dust structure as a continuum medium of a material of the dust particles. In this case the discharge current passes between the outer border of dust structure and the wall of discharge tube. The electric field strength is saturated and independent of the dust particle concentration. The value of the electric field strength approximates to the value determined by diffusional losses in a problem with a solid core, placed inside the central part of the discharge [26].

In figure 3a, the radial distribution of the dust particle charge Z_p for various values of the dust particle concentration is represented. One can observe that with the increase in dust particle concentration and related redistribution of electron density in the discharge, the dust particles located near the boundary of the dust structures obtain the higher charge. This leads to a stronger mutual repulsion of the dust particles near the boundary of the structure and to changes in the conditions of equilibrium on its borders. The dust particle charge self-consistently depends on the discharge parameters, as well as dust particle concentration. The

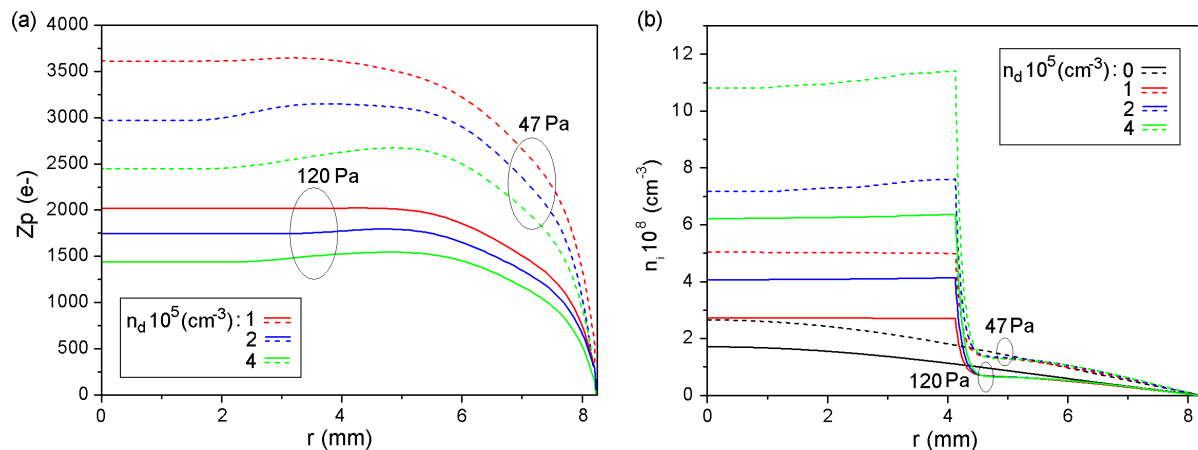


Figure 3. Radial profiles of dust particle charge Z_p (a) and ion concentration n_i (b) simulated for two values of neon pressure for discharge current 0.5 mA at different values of dust particle concentration.

depletion of the electron density inside the dust structure leads to lower particle charge with increasing n_d . However, in our case the volume charge density equal to $Z_p n_d$ increases with the growth in n_d . The increase of the volume charge density within the dust structure causes the dramatic redistribution of free charged particles in plasma. In figure 3b, the radial profiles of ion concentration in a positive column of glow discharge in neon for two values of neon pressure and four values of dust particle concentration are represented.

One can see that in dense dust structures the ion concentration may be about 3 times higher than in discharge without dust particles. Consequently, a dust structure maintained in a dc discharge may be considered as an effective plasma trap for ions able to create their concentrations few times higher than in a free discharge. Such strong excess in ion concentration over the electron one sets the high requirements to the theoretical model of dust particle charging. This is why the CEC model, considering the ion-neutral collisions, was used in our simulation. One should also note that the strong influence of ion concentration within the dust structure versus its parameters should be adequately considered in simulations of plasma chemical reactors and plasma traps for dust particles.

5. Conclusion

The values of the increments of the longitudinal electric field in the positive column of a dc glow discharge in neon with dust particles were experimentally measured and simulated using the diffusion-drift model considering the interaction of dust particles with electrons and metastable atoms.

The increase in the electric field strength in the discharge with a small number of dust particles in the structure is proportional to the the number of dust particles per unit length of the discharge, and at large number of dust particles in a dust structure does not depend on it. The relative increase in the value of the longitudinal electric field strength in the presence of dust particles increases with increasing pressure, due to the increase in the contribution of process of step-wise and chemi-ionization in a total plasma ionization balance.

The dust particle charge decreases with increasing concentration of particles in the dust cloud and neon pressure, however, the charge volume density and the ion concentration within the dust structure increases with increasing concentration of the dust particles. Dust structure may be used as a way to organize a trap for the positively charged ions, wherein the concentration

of the ions can be several times higher than in the discharge without dust particles under the same discharge current.

The results can be used to calculate the traps for confinement of ions and dust particles in gas-discharge plasma.

Acknowledgments

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