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ELECTRIC FIELD ON THE DIAGRAM OF PHASE TRANSITIONS IN CRYOGENIC DUSTY PLASMAS*

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Abstract. Phase diagram of dusty plasma in neon at 89 K with the isolines of the reduced values of longitudinal electric field is represented. The regions of existence of structured dust clusters and structural transition are shown to be characterized by higher values of reduced electric field than the regions of their melting and the regions with a homogeneous dust structures.

Key words: cryogenic dusty plasma, phase diagram, longitudinal electric field.

1. INTRODUCTION

The study of dusty plasma cooled to cryogenic temperatures is of fundamental interest for low temperature plasma physics, including for studies of strongly coupled systems [1] and for the development of the nucleation theory [2]. While the plasma with melt grains in a gas discharge was discovered by Irving Langmuir *et al.* in 1924 [3], the cryogenic plasma with dust particles was experimental obtained for the first time by the authors of this article comparatively recently [4–7]. Cryogenic dusty plasma has been investigated at the boiling point of liquid nitrogen (77 K) in rf and in glow discharge plasmas in air. There were found the dense dust structures consisting of dust particles of micron sizes, with distances between dust particles close to the Debye ion radius (10–30 microns). Cryogenic dusty plasma in neon was first obtained experimentally at 77 K [8]. There was found that the distance between the dust particles, the types and of forms dust formations have a complex dependence on temperature of the heavy component, gas pressure and discharge parameters [9].

One of the principal features of cryogenic plasma is a significant influence of metastable atoms and molecules accumulated in the discharge, on the characteristics of the plasma and the associated processes of ionization. Metastable atoms are intense source of free electrons. These extra electrons interacting with

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the dust particles change the direction of the processes of self-organization of charged dust particles that is accompanied by structural transitions in dusty formations [9]. The structural transitions characterized, for example, by a change in density of the dust particles, lead to self-consistent changes in the properties of the background plasma [10–12].

The strength of electric field is one of the fundamental characteristics of plasma that determine the value of electron temperature and accordingly, the intensity of ionization processes in plasma. The electron temperature in turn determines the charge of dust particles that defines the internal structure of dust formations, their geometrical shape and size. Hence, the study of change of an electric field in plasma is the important tool in understanding of the dusty plasma properties and in the analysis of processes of its self-organizing.

This paper presents the results of experimental study of the current-voltage characteristics of cryogenic dusty plasma in neon and of the nature of self-organization of dust particles depending on the plasma parameters.

2. EXPERIMENTAL SETUP

Dusty plasma was produced in the glow discharge in neon, where the 4.14 micron size melamine formaldehyde particles were injected. The glow discharge was initiated in a discharge tube (1) by means of a high-voltage source (2) operating in a current stabilization mode (Fig. 1a). Dust structures in discharge with current in the range of 0.01–3.5 mA, at pressures of 0.14–1.4 torr (at $T = 295$ K) were studied. The glass discharge tube was of 16.5 mm *i.d.* and the distance between the hollow cathode (3) and the ring anode (4) was 200 mm. Dust particles (5) were injected in the discharge from the container (6) located above the top electrode. After ignition of the glow discharge, the emission of a portion of particles from the container was organized, and a formation of dust structure (7) followed. The optical registration of a discharge luminescence and images of dust structures were carried out. The temperatures of a discharge tube wall and the values of gas pressure and electric characteristics of a positive column of discharge where dust structures appeared were measured in experiments. For the governing and maintenance of desired gas temperature, the discharge device was enclosed in optical cryostat (8) (Fig. 1b), where the discharge tube was cooled from the temperature of external air $T = 295$ K down to 89 K in a stream of evaporating liquid nitrogen. The temperature of a discharge tube wall was measured in three points: on half of its length, and near to the cathode and the anode. Signals from thermocouples (9) were outputted (Fig. 1a) to the measurement block, located in the block of cryostat management. The accuracy of maintenance of temperature was ± 0.5 K at the peak heat generation in the discharge. The accuracy of heat stabilization without a heat generation was ±0.05 K in a temperature range of

4.2–50 K and ± 0.1 K in a temperature range of 50–295 K. The average temperature gradient along a discharge tube at temperature of the cathode 77.4 K was 5.3 K/cm at the maximum value of a discharge current. The difference of temperatures between points where the electric measurements in a positive column were carried out didn't exceed 20 K. The deviation of temperature on the maximal length of dust structures was less than 2.5 K. The temperature of gas was accepted to equal to the wall temperature. This temperature was considered as an average over the length of electric measurements. The current voltage characteristics (CVC) of the glow discharge and CVC of a positive column with the dust structures were measured. For the measurement of voltage drop in a positive column of the glow discharge in a discharge tube, the ring electrodes (10) were located. The ring electrodes were in a galvanic contact with the plasma. For exception of influence of a measuring circuit on discharge plasma, a voltage on the discharge was measured using the two-channel voltmeter with high input resistance. For preventing of the cathode contamination by dust particles and for the fixing of the discharge strata between the ring electrodes, the dielectric shield (11) was located over the cathode.

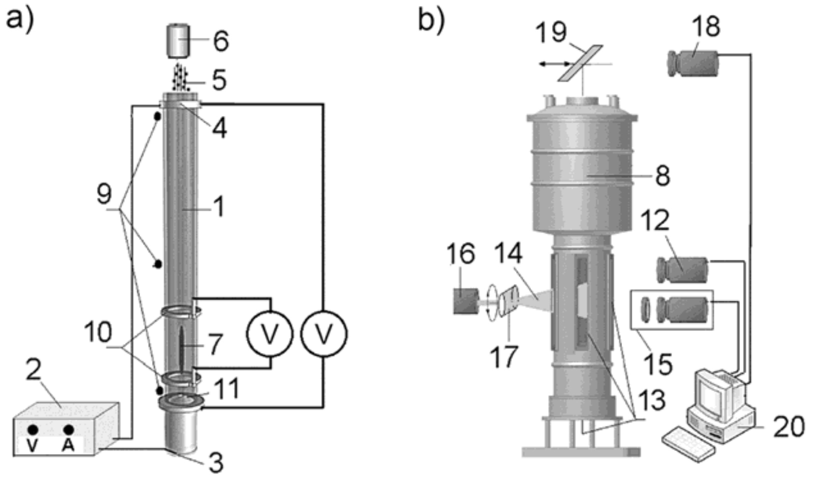

Fig. 1 – Reconstruction of experimental setup: discharge tube and scheme of electrical measurements (a) optical cryostat and scheme of the optical measurements (b).

The registration of an integrated luminescence of the discharge plasma in an optical range was carried out by means of video camera (12). For optical measurements of dust structure sizes and the discharge luminescence in the longitudinal and cross sections, the cryostat have been supplied with flat quartz windows (13) at end surface of the discharge device and along the cryostat length (at angle of 90^{o}). The obtained images of dust structures were registered in a reflected light of a flat laser beam (14) with the help of a microscope and video camera (15). The flat laser beam was formed after a passage of radiation from laser (16) through the optical system consisting of two cylindrical lenses (17). The images of dust structures in cross section were registered by a video camera (18) by rotating of the image by a mirror (19). The vacuum jacket of the cryostat and the discharge tube were evacuated to 10^{-3} torr and $5\cdot 10^{-7}$ torr, respectively. Electric and optical measurements were carried out with time synchronization, by means of recording of images of dust structures, a luminescence and parameters of the discharge in a video file on a computer (20). Video cameras and diagnostic lasers were settled down on a uniform platform which allowed to carry out 3D scanning of dust structures.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

The dependence of the reduced electric field E/N in the positive column of a discharge at $T = 295$ K and 89 K was experimentally obtained. It was found that at presence of dust particles the longitudinal electric field strength increases while maintaining the total discharge current at all temperatures of gas. While the density of dust particles in cryogenic plasma increased, their total quantity N_D, maintained in a discharge, was small. It was determined by the fact that dust structures forming at cryogenic temperatures, have smaller sizes than that forming at room temperature. The influence of dust structures witht such quantity of particles on the CVC is minor [10, 12]. Still, the discharge voltage drop ΔU related to the total quantity of dust particles N_D measured on identical length of discharge, is much higher at cryogenic temperature, than at room temperature: $(\Delta U/N_D)_{295\text{K}} \approx 10^{-5}$ V/particle, $(\Delta U/N_D)_{89\text{ K}} \approx 10^{-3}$ V/particle.

The reduced values of E/N in a positive column of free discharge, *versus* the reduced pressure P_r (at the fixed value of discharge current I) are represented in Fig. 2 for conditions where in our experiments the cryogenic dust plasma was observed. The arrow shows the border of dust plasma existence (the thick line marked in Fig. 2). Over the values of P_r, this border exists in all investigated range of discharge current at $T = 89$ K, and at $T = 295$ K it shifts to $P_r = 1.9$ torr cm (for MF particles with a size less than 4 microns). Such dependence is obvious, as well the value of reduced longitudinal electric field E/N depends on P_r and sets the value of gradient of an electric field necessary for maintenance of dust particles in balance in a vertical direction [13].

In Fig. 2 one can see the decrease of the reduced electric field with decreasing temperature of gas. Such dependence on temperature may be explained by reduction of ambipolar diffusion of the charged particles towards the walls of a discharge tube [14]. In this case the maintenance of the discharge needs the smaller concentration of charged particles and proportionally the smaller value of an electric field, necessary for compensation of diffusional losses.

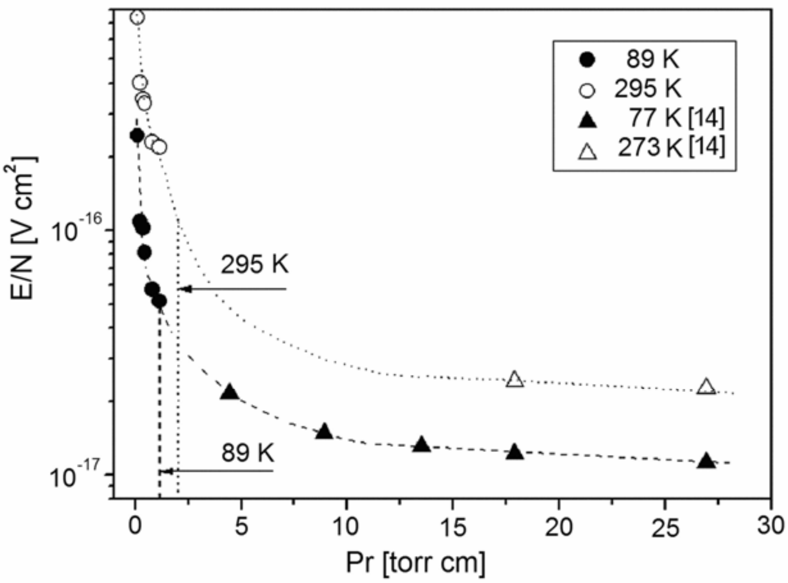

Fig. 2 – The reduced electric field *E/N* in a positive column *versus* the reduced pressure P_r, at cryogenic and room temperature at a discharge current $I = 0.5$ mA. The arrow shows the border of dust plasma existence.

In Fig. 3 the data for free discharge in comparison with data from [15] extrapolated to values of a discharge current of 3 mA are represented. One can see the agreement of data over the experimental values of *E/N*, and on extrapolation of our data to the data received in work [14] with higher values of P_r (Fig. 2). This agreement indicates that the developed in this work the methodical approach to the measuring the plasma parameters at presence of a longitudinal temperature gradient in a positive column, was correct. One can conclude also that the electric field change caused by this temperature gradient, is negligible.

It was found that at the transition from the room temperature of the heavy plasma component to the temperature of liquid nitrogen, the transition area to the normal glow discharge shifts to smaller discharge currents for the same values of the reduced pressure, and approximately coincides with the boundary of the melting of structured clusters. It was revealed, that distances between dust particles and shapes of dust structures have complex dependence on plasma temperature, gas pressure and parameters of the discharge. The initial distance between dust particles in structure at $T = 295$ K and pressure of 0.63 torr was 140–310 microns, depending on discharge current and varied along the dust structure. The maximum distances between the dust particles 310 microns were observed along the edges of structures in the top or bottom parts. The minimum distances between dust particles 140 microns were observed inside the dust structure. When the temperature diminishes down to 200 K, the structural phase transition began. In the center of dust structure the formation of a dense nucleus was observed, similarly to the processes of self-organizing of dust structures around the center of crystallization [16].

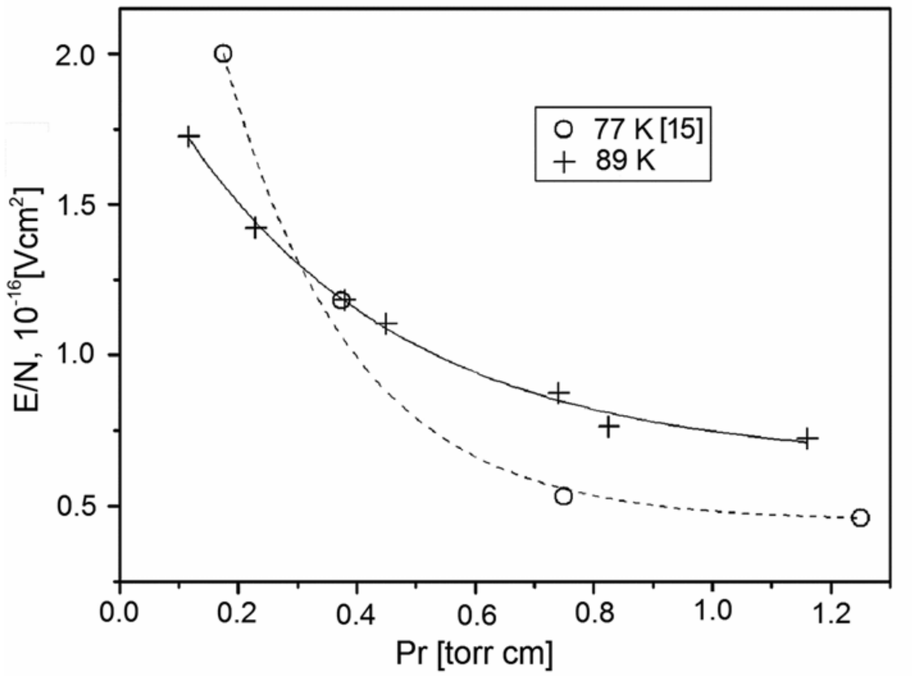

Fig. 3 – The reduced electric field *E/N* in a positive column depending on reduced pressure P_r, at cryogenic temperature at a discharge current I = 3 mA.

At temperatures less than 200 K the processes of self-organizing could proceed in two directions. This area limited by the value of discharge current and gas pressure, corresponds to two structural phase conditions [8, 9]. The regions of transition from chain-ordered clusters to homogeneous structures and regions of clusters melting are registered. The process of reduction of temperature is accompanied by the reduction of inter-particles distances to values of 10–40 microns. The distance between chain (threadlike) clusters was of 100–150 microns.

New experimental data and their analysis demonstrate that the self-organization of dust structures at cryogenic temperatures is more complicated than we assumed earlier. In this work, it was discovered for the first time the formation of complex cluster structures consisting of a simple clusters. Smallest clusters, which can be regarded as elementary 1D clusters are vertically oriented threadlike clusters, consisting of two dust particles. Threadlike clusters under certain conditions, form more complex 2D structure consisting of several ranked elementary 1D clusters. In Fig. 4 (1) the 2D structures formed by several threadlike clusters are encircled. In turn, these complex 2D clusters form a large dust structure. The various phase transitions can occur in this dust structure. Depending on the plasma parameters, there may be transformations from the second order transitions up to melting and the transition to a state of vapor cloud with the random motion of individual particles. For example, depending on the gas pressure and the electric field strength there were observed the structural second order transitions from 2D structures formed out of threadlike clusters to structures consisting of flat clusters (Fig. 4 (4)).

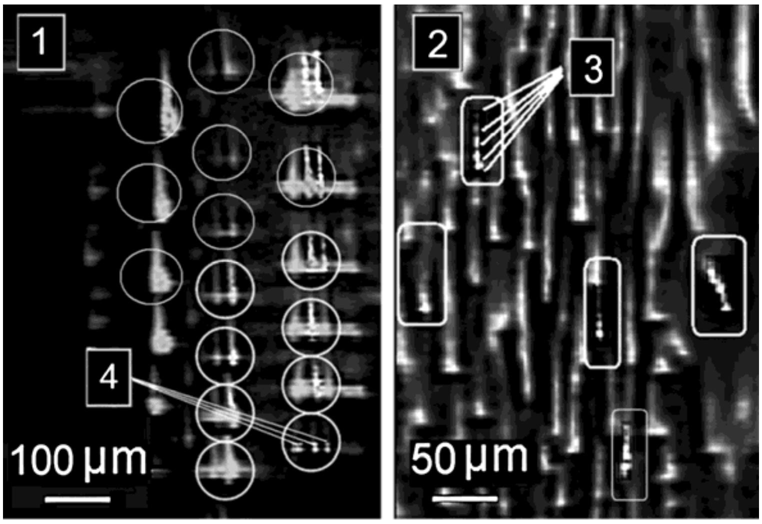

Fig. 4 – Fragments of images of dust structures (axial section) in cryogenic plasma: ordered clusters (1), the homogeneous structures formed out of threadlike clusters (2), single particles in threadlike cluster (3), flat cluster (4).

Upon melting there appear homogeneous structures, that are in a liquid state and consist of 1D threadlike clusters. The fragment of this structure is shown in Fig. 4(2). In Fig. 4(1) the ordered structures formed out of ordered clusters, which formed a hexagonal lattice are shown with circles. The distance between dust particles in threadlike clusters was about 10 microns (Fig. 4(3)).

The phase diagram of dusty plasma in neon at a temperature of 89 K with the isolines of the reduced values of the longitudinal electric field strength is presented in Fig. 5. It has been found that the phase transition depends on the value of the longitudinal electric field strength. The higher is the field strength, the higher is the order of dust structures. It was found that the regions of existence of structured clusters and structural transition were characterized by higher value of the reduced longitudinal electric field strength than the regions of their melting and the region of homogeneous structure formed out of threadlike clusters.

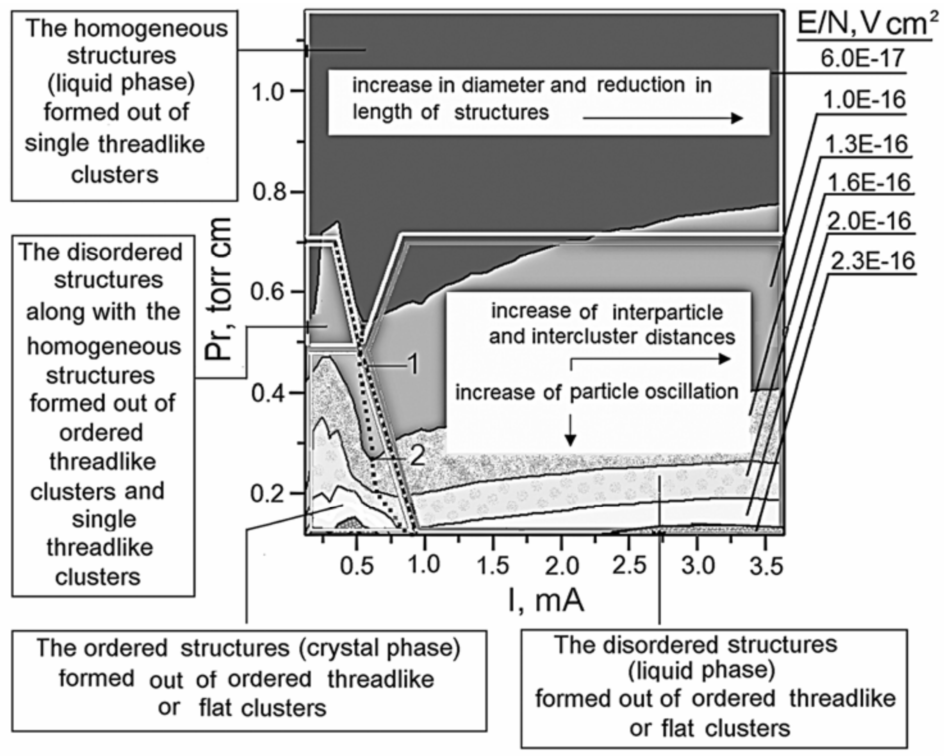

Fig. 5 – The diagram of state of dusty plasma in neon at $T = 89$ K with isolines of the reduced longitudinal electric field strength: border of melting (1), border of the transition to the normal glow discharge (2).

At low currents, *i.e.* to the left from the vertical border of melting (Fig. 5(1)), the horizontal phase borders on the axis of reduced pressure are determined by the value of the electric field strength. To the right from this border the melting is defined by the discharge current (Fig. 5). It is worth to note that the vertical border of melting coincides with the border of the transition to the normal glow discharge (Fig. 5(2)), where the electric field strength slightly depends upon the discharge current. To the left from the vertical border of melting, ordered structures consist from ordered 2D threadlike clusters or flat clusters. The structural transition proceeds with the change of gas pressure. Under pressure increase the flat clusters were reconstructed into ordered threadlike form and then their melting occurred. At increase of the discharge current the melting of the ordered structures and increase of the distances between dust particles and between of clusters was observed.

Thus the inversion of the border of the melting of dust structure in a direction of change of gas density was found out at cryogenic temperature. There are also different types of structural forms. At room temperature the dusty structures consist out of single dust particles, while at cryogenic temperature the dusty structures consist out of clusters.

4. CONCLUSIONS

When reducing the gas temperature, a change in directions of structural phase transitions in dusty plasma was observed. The clustering of the dust cloud was predominantly observed. At room temperature, the border of the structural transition is mainly determined by the discharge current, while at cryogenic temperatures, this border is determined by gas pressure. At cryogenic temperature the melting of clusters and changes of their structures was observed at change of gas pressure. At cryogenic temperature phase borders are determined not only by the discharge current and the gas pressure, but also by the value of the electric field strength. The electric field strength determines the degree of ordering of dust structures at such values of discharge currents, where their melting is not observed.

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