INTRODUCTION
Dusty plasmas are an open nonequilibrium dissipative nonideal system with strong Coulomb interaction. Therefore, the dust structures can be used to simulate nonideal systems in the microcond, including those forming at low and warm cryogenic gas temperatures. The dust clouds in plasma can exist in forms analogous to the thermodynamic states of matter [1], and the phase transitions between these states can be observed. The structure of dust particles can ‘melt’ and ‘evaporate’ like a matter. In this case, the long-range order between the dust particles is violated while the short-range order is preserved. In this case, the cold dust particles can form dust slabs and dust particles can form dust particle clouds. These studies are relevant for the development of the theory of nucleation, growth and agglomeration of nanostructures and coagulation of micro- and nanoparticles in plasma [2, 3], and may promote the related sciences such as low-temperature and quantum chemistry [4, 5]. At low and cryogenic gas temperatures in some gases, the structures consisting of dust clusters can be formed [3, 6], and the Bose-condensation can occur [10]. As well as individual dust particles, these clusters can form the lattice sites similar to atoms in a solid, and also exist in a ‘liquid’ and ‘gaseous’ states.

EXPERIMENTAL
The experimental setup was similar to that presented in paper [11] and is shown in figure 1. The experiments were carried out in the vertically oriented glass discharge tube (1) with an inner diameter of 1.05 cm and a length of 20 cm, which has been designed for the study of dusty plasmas in dust plasma at cryogenic temperature. The hollow cathode (2) was located at the bottom of the discharge tube. The hollow anode (3) was located in the upper part of the discharge. A feature of the design of the discharge tube was the two thin annular electrodes (4) with 4.2 cm distance between them, which were located along the discharge tube at a distance of 1.5 cm from the cathode of the galvanic contact. The inner diameter of the discharge tube was 0.05 cm. These annular electrodes were used for measurement of voltage in the discharge tube with the help of a voltmeter (5) with a high input resistance of 1 GΩ. The hollow cathode was covered with an insulating conical diaphragm (6) with a central orifice of 2 mm in diameter, disposed on the discharge axis. The conical diaphragm was located on the cathode for the stabilization of the discharge. It prevented the hit of dust particles on the surface of the cathode with the aim to prevent changes of its emission characteristics. The discharge tube was positioned in an optical flow cryostat (7), where it could be cooled from room to liquid nitrogen temperatures [7, K]. The vacuum jacket of the cryostat (8) and the discharge tube were evacuated to $10^{-1}$ Pa and $7\times10^{-10}$ Pa respectively. The temperature of the discharge tube wall was measured in three positions: on the half of its length and in the vicinity of the cathode and anode. The signals from thermocouples (9) were outputted to the temperature measurement unit, located in the cryostat temperature controller (10). The accuracy of the temperature maintenance was $0.5\,K$ at the peak heat generation in the discharge. The accuracy of heat stabilization without a heat generation was $\pm 1\,K$ in a temperature range of 50–273K. Glow discharge was maintained in the discharge tube by means of a high-voltage source (11) operating in a current stabilization mode. The voltage drop across the measuring annular electrodes in the positive column and the total voltage across the discharge tube were measured at the pressure of 20 Pa at discharge currents of 0.01–3.5 mA. The gas pressure in the discharge tube was maintained constant in this range and corresponded to the measured temperature at a given pressure; namely, it was proportional to the ratio $29\,K$ to the measured value. The temperature was measured on the wall of the discharge tube, near the measuring electrodes. It was assumed that temperatures of the tube wall and the gas were equal. Images of dust structures were recorded in the dark room using a camera (12) focused on the discharge figure (20). The images were analyzed the composition, shape, degree of order and dynamic stability of dust structures. A more information was given in sections [7, 8].

RESULTS
In the neon dc discharge at room temperature, the dust structures were formed from individual dust particles. With decreasing gas temperatures, the individual dust particles form clusters. When clusters were formed, they were observed the typical features of a first-order phase transition at which the particle density increased sharply and continued to increase with decreasing gas temperature. The process of formation of clusters can be considered as ‘condensation’ and ‘deposition’ of dust particles at temperature of 77 K can be multicompontent [6]. Multiple-component system is a representative mixture of dust particles and clusters form dust particles (figure 2a). The composition of the dust system varies with pressure of gas and discharge current. One-component dust systems consist of simple clusters (figure2). Simple clusters are threadlike clusters consisting of several dust particles located along the axis of the discharge. Threadlike clusters consist of dust particles in liquid state, which were observed at higher neon pressures $P_{\text{Ne}}=120\,Pa$ [6]. In our case, as the gas pressure decreased, we formed the complex clusters (figure 2b), which consisted of threadlike clusters. Figure 2a represents the dependences of the dust structure volume, $V$, linear power input $Q$ and longitudinal electric field $E_{L}$ upon the discharge current. The images of dust structures (figure 2f–g) correspond to characteristic points of phase transition. From the analysis of the dust structure images and the dependence of $V$ on $Q$, one can conclude that there are the evidences of a first- and second-order phase transitions in dust structures, which follow the changes of the discharge current. When $V=0.15\,mm^{3}$ (figure 2e, region I), the dust structure is in the ‘liquid crystal’ state (figure 2f). The dust ‘crystal’ is formed by cluster chains, which consist of multi-dimensional clusters. An increase in current to $0.633\,mA$ (figure 2a, region II) is accompanied by a decrease and disappearance of the symmetry of the dust structure (figure 2c). The image of the discharge is a higher current (figure 2a, region III), the dust structure is a mixture consisting of individual dust particles and simple clusters. The unstable dynamic state of the dust particles is resembled a ‘boiling liquid’. The development of oscillations and rotations of individual dust particles was observed. The intensity of dust particle motion increased with decreasing pressure. As the discharge current increased (figure 2a, region III), the concentration of individual dust particles and the intensity of their motion decreased. The dust system in region III exists in the ‘liquid’ state. In this region, the change in the dust structure size with the change of the discharge current occurs in a manner analogous to that observed in the dust structures at room temperature.

CONCLUSION
The impact of the discharge current on the size, the shape and composition of complex Coulomb dust structures consisting of dust clusters at cryogenic temperature has been studied. The first and second-order phase transitions were found. It was found that with increasing current, the complex clusters melted, giving a mixture of components consisting of simple clusters, complex clusters, and individual dust particles.

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REFERENCES
2. Huttel Y 2017 Gas Aggregation Synthesis of Nanoparticles (Weinheim: Wiley VCH)

Figure 1. Experimental setup: discharge tube (1), cathode (2), anode (3), ten gas sources (4), thermocouple (3), pressure controller (8), vacuum jacket (8), thermocouples (9), cryostat controller (10), high-voltage dc source (11), scroll pump (12), turbo molecular pump (13) [11].

Figure 2. (a) Dust structure volume $V$ (black circles) and linear power input $P$ (blue triangles) versus discharge current $I$ (b–e) Images of dust structures at phase inversion points.