Direct-current glow discharge in neon at cooling

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Abstract. The paper presents the results of the experimental measurement and the simulation of electric characteristics of dc glow discharge with the hollow cathode in neon, carried out during cooling of the discharge to the temperature of liquid nitrogen. The experiments were performed at pressure $P = 18$–$187$ Pa and discharge currents $I = 0.01$–$3.5$ mA. The behavior of the border of transition to the normal glow discharge during cooling was studied. Cooling in a subnormal discharge mode at constant current led to a change in the discharge regime. Upon cooling, the boundary of the transition to the normal glow discharge shifted to lower current, the electric field in the positive column of discharge and at the boundary of the normal glow discharge increased, but the reduced electric field decreased throughout the entire range of pressure and the discharge current.

1. Introduction

Gas-discharges cooled to a low or cryogenic temperature can be used to create a new class of cryogenic plasma-chemical technologies. The high-pressure discharge plasma is proposed to be used for the selective production of chemically active species and plasma surface treatment in micro and nanoelectronics, manufacturing of biomaterials, and also it is used in pharmaceutical and cosmetic industries [1–3]. At low gas pressure, the cryogenic cooling of reactor was used for plasma-cryogenic synthesis [4] and deposition of the high purity materials [5], as well for surface functionalization using plasma processing and plasma etching for the production of nanoporous materials [6]. Electrical discharges at cryogenic temperatures were used for the excitation of gas lasers with high efficiency [7–9].

From a basic aspect, the investigation of cryogenic plasma is relevant for the development of theories of nucleation, growth and agglomeration of nanostructures and coagulation of micro and nanoparticles in plasma at low gas temperatures [10–14]. The study of gas discharge characteristics at low temperature is also necessary for the development of concepts of elementary processes and the self-organization in the dusty and strongly nonideal plasma [14–20]. To optimize the plasma-chemical process in the gas-discharge plasma and to expand the scope of its applications, it is necessary to study the discharge properties and chemical reactions leading to the formation of new substances and compounds as well as the elementary processes involving plasma particles and particles of a new phase, types, directions, and the main stages of a plasma-chemical reactions, etc. The study of current–voltage characteristic (CVC) and the behavior of the electric field during gas cooling gives the basis for developing plasma models at low and cryogenic temperature. At the moment, there are only few experimental data on the effect of cryogenic temperature on the electrical parameters of the glow discharge in neon [21–23], that
is not enough to study the possibility of wider use of such a plasma in new technologies and to develop a radical theory. In this study we investigate the electrical parameters of the dc glow discharge in neon at temperatures 295 K and 77 K.

2. Experimental
The experiments were conducted in a glass discharge tube with inner diameter $d = 1.65$ cm and a length of about 20 cm, which have been designed for the study of processes in dusty plasma at cryogenic temperature. A feature of the design of the discharge tube were two thin annular electrodes with a distance between them of 4.2 cm. The bottom electrode was located near the hollow cathode at a distance of 1.5 cm. The electrodes were used for spatial confinement of dust particles and measurement the voltage in discharge column. The hollow cathode was closed with the insulating conical diaphragm with a central orifice disposed on the discharge axis. The discharge tube was positioned in an optical cryostat, where it could be cooled from $T = 295$ K to liquid nitrogen temperature $T = 77$ K. A more detailed description of the experimental setup is represented in [22, 24]. The voltage drop between the ring electrodes in the positive column and the total voltage of discharge tube were measured in the pressure range $P = 18–187$ Pa and discharge currents $I = 0.01–3.5$ mA. The gas pressure in the discharge tube was maintained constant in course of cooling. The gas density in a discharge corresponded to the measured temperature at given pressure, namely was proportional to the relation of 295 K to its 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.

3. Results
The behavior of the CVC of the discharge under cooling from 295 K to the temperature of liquid nitrogen at the same pressure was similar to the change in CVC observed with increasing gas pressure at $T = 295$ K [25, 26]. At constant temperature and increasing gas pressure, there was observed an increase of voltage of the discharge and an increase of electric field in the discharge column between the measuring electrodes, for all values of the discharge current. An example of electric field is presented in figure 1 at $I = 1$ mA. Figure 1 shows that the decrease in temperature at a constant pressure in the measured volume leaded to the elevated electric field $E$, which increased also with increasing pressure $P$ or the concentration of neon $N$.

Figure 1. The longitudinal electric field in the discharge column at $295$ (red circles) and 77 K (blue squares) depending on pressure of neon $P$ (a) and the concentration of neon $N$ (b) at discharge current of 1 mA.
Figure 2. The current–voltage characteristics of discharge $U(I)$ and positive column between the measuring electrodes $E(I)$ at 295 (red) and 77 K (blue) at pressure of 61 Pa (a). Transition lines (b) and the electrical parameters on the boundary of the normal glow discharge (c) at 295 and 77 K for different values of neon pressure, Pa: 1—18.7; 2—37.3; 3—61; 4—72; 5—133.3; 6—187.7.

Although the electric field increased under cooling of the discharge, the value of the reduced electric field at 77 K was lower than at 295 K over the whole discussed range of the discharge current and neon pressure [14, 22]. A decrease of a reduced electric field decreases the degree of ionization in a discharge. The decrease in the reduced electric field in neon at 295 K may be associated with a decrease of ambipolar diffusion to the walls, leading to the lower magnitude of a required electric field to maintain the ionization.

A particular point in the CVC is the point corresponding to the discharge current $I_T$ at a temperature $T$, corresponding to the transition of discharge from subnormal to normal glow mode (figure 2(a)). Hereafter this point is referred to as the transition point. At transition point, one can see a characteristic curvature of CVC of the discharge. To the right of this point CVC corresponds to the normal glow mode with a voltage weakly dependent on current. To the left of transition point, CVC corresponds to a subnormal glow mode with a voltage increasing with decrease of current. The abrupt drop in the voltage of the discharge at the transition point is due to the transitions between different types of strata, or to the change of their length in the part of positive column located between the voltage measuring section and anode. A similar behavior of the electric field was observed in a stratified discharge in neon in close experimental conditions [21]. In our case at the transition point, with the same discharge current, there is kink of the dependence of the electric field from a current, that similarly occurs in the dependences of discharge voltage versus the current. This deviation from the Schottky’s theory is determined by the influence of the hollow cathode at the measuring section of the positive column. In the subnormal glow mode near the cathode at low gas pressure, probably, there appears the change in the energy spectrum of electrons involved in the transfer of current through the discharge region, namely, there increases the fraction of fast electrons generated by a hollow cathode. The generation of low-energy electron beam from a hollow cathode has been detected earlier by the characteristic features of its impact on the dust structures [27].

Negatively charged dust particles were pushed out by electron beam. Such an effect is well observed at low gas pressures when throwing particles of micron size into the discharge. A dust cloud forms itself near the diaphragm above the hollow cathode. Figure 3 shows the CVC (a) of the discharge and the corresponding fragments of images of the dust cloud (b). The aperture opening is shown in white. An electron beam pushes out dust particles from the center to the
Figure 3. The current–voltage characteristics $U(I)$ of discharge (black squares) and positive column between the measuring electrodes (red circles) at 295 K at pressure of 19 Pa (a) and the corresponding images of a dust cloud (in axial cross section) (b) at different values of discharge current, mA: 1—0.1; 2—0.2; 3—0.3; 4—0.4.

periphery of the dust structure, resulting in the formation of a dark region (cavity), in the center of the image of the dust structure. One can see that with increasing current the cavity size increases. The observed increase in the beam scattering angle $\alpha$ (figure 3(b)) indicates an increase in its scattering due to a decrease in the fraction and energy of the beam electrons with increasing discharge current, which corresponds to a drop in the voltage of the discharge and in the cathode layer.

The formation of stable dust structures around the diaphragms and near the hollow cathode in various gases and their mixtures at pressures above 0.1 Torr (13.3 Pa) in discharges of a similar diameter was observed earlier [28]. A similar change in the shape of the dust structure from the discharge current at constant pressure and with a change in pressure at a constant current, was observed.

The discharge cooling leaded to the shift of the transition point along a hypothetical trajectory (the supposed transition line), represented in figure 3(a) with green line. One can see that in the normal glow mode, the type of CVC remains the same along the trajectory of the transition point. If cooling occurred at a current $I_1$ corresponding to a subnormal glow mode, then may be observed a change in discharge regime and a transition to the normal glow mode, because the current of transition reduced at cooling. The trajectory of the transition point is described by the ratio of change of the electric field $\Delta E$ to the change in the discharge current $\Delta I$. This value determines the angle and length of the trajectory (figure 2(b)). In the investigated range of gas pressure the slope of trajectories of transition point was negative, and the dependence of a length of trajectory versus gas pressure was non monotonous (figure 2(b)). Here, the length of the trajectory can be normalized to a linear temperature scale with the initial value equal to 295 K and the final temperature equal to the temperature of gas at the end of cooling. The value of the transition temperature to the normal discharge is different for different initial plasma parameters. The type of dependence at transformation of CVC of the positive column at cooling in the subnormal glow mode and in Townsend discharge was not persisted, and the non-linearity in the CVC of these modes leaded to non-monotonous dependence of the electric field upon the gas temperature. Figure 2(c) represents the values of the electric field and the current corresponding to the boundary of the normal glow discharge at cooling. It was found that the parameters of the transition point depended on the gas pressure, and the boundary of transition to normal glow discharge upon cooling shifted towards lower current (figure 2(a, c))
Figure 4. Discharge parameters on the boundary of the normal glow discharge at 295 (red circles) and 77 K (blue squares) temperature: discharge current $I$ versus pressure ($a$) and the reduced electric field $E/N$ versus concentration of neon $N$ ($b$).

and figure 4(a)), which was accompanied by an increase in the electric field. The decrease of the value of the reduced electric field with the gas concentration at decreasing temperature, was also observed on the boundary of the normal glow discharge (figure 4(b)). With increasing gas concentration, the dependence of the reduced electric field was observed to decay and tend to saturation.

4. Conclusion
Upon cooling, the transformation of CVC of the positive column in the region of normal glow discharge occurs with conserved type of dependence. Upon cooling were also observed transitions between the different discharge modes. It was found that in the investigated range of pressure the boundary of the transition to the normal glow discharge shifted to lower discharge current, the electric field in the positive column of the discharge increased, and the value of the reduced electric field decreased.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research, grant No. 16-02-00991.

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