Experimental research of the cathode region of the glow discharge in nitrogen

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Abstract. The main falling of the discharge tension accounts for the cathode region where the main streams of charged particles are concentrated. The research of this region is important for receiving various coverings and processing of surfaces with gas discharge. Authors have presented results of the experimental electric and optics research of the cathode regions of the glow discharge in nitrogen. The research of the potential distribution in the cathode region is conducted; distribution functions of the various electron energy groups are measured; the research of the ions energy distribution near the cathode is executed. The model of formation of the ions energy distribution near the cathode is offered. Criteria for formation of the potential hole for electrons and its influence on a power range of electrons are experimentally defined. The theoretical analysis of the received results is carried out. Nonlocal theoretical model of the cathode region of the glow discharge is offered. Comparison of the received results to an overall picture of a luminescence of the discharge is executed. The agreement of experimental data with theoretical is shown.

1. Introduction
In spite of a large number of publications, so far physical processes in separate parts of the discharge have been insufficiently studied. In particular this holds true for the cathode regions. Two approaches to formation of the cathode region of the glow discharge are still most widespread [1-5]. There is not enough experimental data about distribution of parameters of the plasma in the cathode region and almost no analysis of these data from the point of view of nonlocal kinetics. Meanwhile it is important for the development of the theory of discharge and its practical use. Therefore complex study of physical properties of the near-cathode regions of the glow discharge and creation of the corresponding theoretical model are relevant directions of development of modern physics of the gas discharge.

2. Electrons energy distribution functions
Traditionally the description of the gas-discharge plasma builds on the basis of the hydrodynamic approach operating with average characteristics of particles. However such approach cannot fully describe many phenomena in gas discharges especially when inhomogeneity of plasma is essential [3, 6]. More exact kinetic analysis has been limited to generally homogeneous plasma; recording of its heterogeneity was generally carried out through numerical calculations [7, 8]. Significant progress in the theory of heterogeneous regions of the gas discharge is made thanks to the use of principles of nonlocal kinetics of electrons [2, 3, 5, 6].
For the purpose of determination of the near-cathode regions structure of short (without positive column) glow discharge in molecular gas (nitrogen) and check of its nonlocal model the discharge tube has been made and measurement of the near-cathode regions of the discharge parameters is executed.

The measurements were performed in a glass tube. The tube (radius 37 mm) contained a mobile flat cold cathode of diameter 56 mm, a flat anode of diameter 60 mm, and a cylindrical 3-mm-long probe with a diameter of 0.2 mm capable of moving along the tube. The anode – cathode distance was 165 mm. The research included measurement of the potential of the space, electron distribution function, concentration of the charged particles and radiation of the discharge as well as calculation of these values, their comparison with experimental data and development of nonlocal theoretical model.

The electron distribution function was determined by using the second derivative of the probe current with respect to the probe potential. The glow discharge conditions were selected so as to provide the absence of ionization waves. The plasma potential was determined at the second derivative zero.

Existence of two types of the structure of the cathode regions is revealed. For small values of the pL parameter (p – the pressure, L – the distance between electrodes) a pit is observed on the profile of the potential. At bigger value of the pL parameter the potential pit apparent experimentally isn’t registered. The site of constancy of the potential of the plasma is observed.

The reason of the existence of a potential pit for electrons at low pressure is that the density of the diffusion current exceeds the density of the discharge current. In this connection the fulfillment of the continuity equation requires an existence of a reversed field. At these pressures collisions of electrons with atoms and gas molecules are negligible. Therefore, the diffusion stream is significant. A big reversed field is needed. That is why the potential pit should be rather deep (about the temperature of electrons).

An increase of gas pressure increases the number of collisions. As a result the resistance to the diffusion stream increases. Therefore, the stream decreases. Thus, the reversed field will decrease too and the area of the reversed field be much shorter. In this case \( j_{\text{diffusion}} \geq j_{\text{discharge}} \) and the pit cannot be registered. On the condition that \( j_{\text{diffusion}} < j_{\text{discharge}} \) an existence of a pit is not necessary.

It is established that the measured electron distribution functions in the slow part are Maxwell ones with a temperature less than one eV. This fact is explained by the kinetic model of the glow discharge of a direct current based on nonlocal ionization of gas by the electrons which have gained the energy in a cathode layer. This model predicts presence of three groups of electrons: fast, intermediate and slow (locked in a potential pit). The group of slow electrons consists of the locked electrons. Their energy is lower than the potential of second point of the field address (or anode potential in the short discharge). These electrons do not participate in transfer of current and cool down up to the room temperature. The maximum concentration of the electrons corresponds to a bottom of the potential pit. Electronic current in the Faraday’s dark space is transferred by intermediate electrons with energies less than energy of excitation of atoms.

Measurement results of the intermediate electron distribution function along the discharge axis agree in nonlocal rate with the calculations based on the solution of the kinetic equation of Boltzmann with a zero boundary condition on the anode.

Fast electrons are few, therefore for their research the probe technique is ineffective. Information on this part of electron distribution function is obtained by optical methods of a research, namely discharge radiation. It is revealed that the discharge luminescence is as much as possible on border of the layer — plasma. This results from the fact that excitation and ionization in the negative glow are caused by the fast electrons accelerated by the strong field in the cathode layer. Their energy much more surpasses energy of excitation and ionization of atoms. Ionization of atoms exponential grows in process of removal from the cathode, reaching a maximum near border the layer — plasma.

The results of optical and electrical measurements agree well. There is a good recurrence of the results.
Thus, the received experimental results are good in agreement with the model of the near-cathode regions of the glow discharge based on the nonlocal ionization of the gas by the electrons which have gained the energy in a cathode layer.

3. Ions energy distribution functions

Most of the main characteristics of glow discharges, and even their existence, are determined by processes in the near-electrode regions, primarily in the cathode region. It usually accounts for the main part of the discharge voltage. There are significant flows of charged and neutral active particles from the plasma to the cathode surface here. These streams can be used for surface treatment [9]. Therefore the research of the near-cathode region of the glow discharge is important not only for theoretical creation of model of the discharge, but has also important practical application. In this regard of particular interest are the ion fluxes to the cathode, as they mostly initiate different processes on its surface and also distribution of potential in near-cathode region.

For determine of the ion energy distribution function (IEDF) in the near-cathode region of the glow discharge the second discharge tube has been made and has been performed experimental research. The physical processes in the cathode region of a glow discharge were experimental investigated in a glass tube. The layout consists of two round planar electrodes: cathode and anode. Their diameters were 42 mm. The distance between the electrodes was 150 mm. The cathode at its center had a hole (diameter of 4 mm), which was covered by a grid. A flat analyzer-collector of diameter 4 mm was mounted against the hole. The anode had an opening through which a cylindrical probe of diameter 0.2 mm and length 3 mm was inserted into the discharge gap. The probe could be moved along the tube axis. The ion fluxes to the cathode were determined by measuring the collector characteristics (CVC) – dependence of the collector current on the potential difference between the collector and the cathode.

In the same way as during EEDF research, before carrying out measurements careful cleaning of a discharge tube was carried out by its warming up by current with repeated change of working gas and polarity of electrodes.

In all cases, the blocking voltage (the collector current is equal to zero) is much less than the total voltage across the tube, which in the first approximation can be taken as the value of the cathode fall. This means that the ion on the way from the plasma of the discharge to the cathode experiences multiple collisions. This is confirmed by the estimation of the mean free path of ions, which is smaller than the cathode fall. Therefore, the increase in pressure affects the maximum energy of ions reaching the cathode. This corresponds to the received collector characteristics. The change of the discharge current at a constant gas pressure does not affect the blocking voltage.

To calculate the distribution functions of the ions the voltage drop on the cathode layer was taken equal to the voltage across the discharge tube. The molecular nitrogen ions $N_2^+$ were considerate as the dominant ions.

$$ f(\varepsilon) = \frac{I_c(\varepsilon=0)}{S_c \cdot \varepsilon \cdot (1 + \gamma)} \cdot \sqrt{\frac{M}{2e}} \cdot \exp \left( -\frac{L_{sh}}{\lambda} \left( 1 - \sqrt{1 - \frac{e}{U \cdot e}} \right) \right) \cdot \frac{L_{sh}}{2\lambda \cdot U \cdot e \cdot \left( 1 - \frac{e}{U \cdot e} \right)} $$

(1)

where $I_c(\varepsilon=0)$ is the collector current at $U = 0$, $S_c$ is the effective area of the hole in the cathode, $\gamma$ – the coefficient of the ion-electron emission [1], $M$ – mass of an ion, $e$ – energy, $e$ – the ion charge, $L_{sh}$ – the length of the cathode layer, $\lambda$ – the mean free path determined by charge-exchange, $U$ – the voltage drop across the cathode layer.

Calculations were performed for different ratios of the thickness of the cathode layer to the free path length. The comparison of the calculated and experimental functions allows to determine the optimal value of this ratio.

Figure 1 shows a comparison of an IEDF calculated by formula 1 with an experimental IEDF. The best agreement is observed with $L_{sh}/\lambda = 4$. This value is in good agreement with the estimation
made on the basis of the charge-exchange process [1]. The value $L_{sh}$ was determined from the axial distribution of the probe floating potential in the tube.

![Figure 1](image_url)

**Figure 1.** Comparison of the experimental IEDF (nitrogen, $p = 0.3$ Torr, $I = 5$ mA, $U = 740$ V) with that calculated by the formula (1).

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