IONS ENERGY DISTRIBUTION FUNCTIONS
IN THE CATHODE REGION
OF A GLOW DISCHARGE IN NITROGEN

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An experimental investigation of the ion fluxes to the cathode of the glow discharges in nitrogen has been performed and is presented in this work. These were studied in a discharge tube with flat electrodes. A hole closed by a grid was located in the cathode center. After the hole, the collector was mounted. The study was conducted in nitrogen at discharge currents of 2.5–10 mA and gas pressure 0.3–3 Torr. The dependence of the collector current on the potential difference between the collector and the cathode was determined. In all cases, the voltage blocking (the collector current is equal to zero) is much less than the total voltage across the tube, which can be taken as the value of the cathode fall. The maximum energy of ions reaching the cathode significantly depends on the gas pressure. The alteration of the discharge current at a constant gas pressure does not affect the blocking voltage and the energy distribution of ions. The ion energy distribution functions were determined from the experimental characteristics. The analysis of the ion distribution functions shows that the main process determining the ions energy distribution is charge-exchange.

The glow discharge is a classical object of studies in the field of gas electronics. Although there is a great number of investigations, some phenomena are still without a detailed theoretical description [1]. The lack of sufficient experimental data is one of the reasons of such a situation. This, especially, is the case of the cathode region of the glow discharge.

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Most of the main characteristics of glow discharges, and even their existence, are determined by the 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 [2]. Therefore, investigations of the cathode region of glow discharges are important for the industry related to the formation of various thin films. Of particular interest are the ion fluxes to the cathode as they mostly initiate different processes on its surface. The main aim of this investigation was to determine the ion energy distribution functions (IEDF) at the cathode surface.

The physical processes in the cathode region of a glow discharge were experimentally investigated in a glass tube (Fig. 1).

The layout consists of two round planar electrodes: cathode (1) and anode (2). Their diameters were $D = 42$ mm. The distance between the electrodes was $L = 150$ mm. The cathode at its center had a hole (diameter of 4 mm) which was covered by a grid. A flat analyzer-collector 3 of diameter $d_c = 4$ mm was mounted against the hole. The anode had an opening through which a cylindrical probe of diameter $d_z = 0.2$ mm and length $l = 3$ 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 current–voltage characteristics (CVC) – dependence of the collector current on the potential difference between the collector
and the cathode. The scheme for obtaining the collector characteristics is shown in Fig. 2. The measurements were performed in nitrogen at current 2.5–10 mA and gas pressures 0.3–3 Torr.

Figures 3 and 4 show typical collector CVC obtained in nitrogen at different discharge currents and pressures.

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 collector characteristics in Fig. 4. The change of the discharge current at a constant gas pressure does not affect the blocking voltage.
The expression for the ion energy distribution function has been obtained from the experimental CVC [3].

The resulting collector current can be expressed as

\[ I_c(x = 0, \varepsilon) = \int_{\varepsilon}^{\infty} f(\varepsilon) v_e S_c \, d\varepsilon. \] (1)

Here, \( dn_+ = f(\varepsilon) \, d\varepsilon \) is the determination of the distribution function \( f(\varepsilon) \) which implies \( n_+ = \int_0^{\infty} f(\varepsilon) \, d\varepsilon \) that is the ion concentration; \( v = \sqrt{2\varepsilon/M} \) is the ion velocity where \( M \) is the mass of an ion; \( S_c \) is the effective area of the hole in the cathode; \( e \) is the ion charge; and \( \varepsilon \) is the energy. Thus, from (1), it follows:

\[ \frac{dI_c}{d\varepsilon} = -f(\varepsilon) v_e S_c. \]

Then, the expression for the calculation of the real IEDF has the form:

\[ f(\varepsilon) = -\frac{1}{ve S_c} \frac{dI_c}{d\varepsilon}. \]

Figure 5 shows the IEDF obtained under various discharge conditions.

If the differential ion flux \( \Phi(\varepsilon, x) \), is known, one can obtain the distribution function of the ion energies \( f(\varepsilon) \). This was done in the following way. The value of \( \Phi(\varepsilon, x) \) was divided by the directed velocity of ions in the electric field of the cathode layer \( v \):

\[ \frac{\Phi(\varepsilon, x = 0) \, d\varepsilon}{v} = f(\varepsilon) \, d\varepsilon. \] (2)

The thermal velocity was neglected, since its value was \( 10^3 \) times smaller than the directed velocity.
Considering that the main process affecting the movement of ions is charge-exchange and assuming that the potential distribution in the layer is linear [4], one can derive the collector current from the differential flow of ions.

Finally, the expression (4) for the IEDF takes the following form:

$$f(\varepsilon) = \frac{I_{c(\varepsilon=0)}}{S_e(1 + \gamma)} \sqrt{2\varepsilon} \exp \left( - \frac{L_{sh}}{\lambda} \left( 1 - \frac{1}{1 - \frac{\varepsilon}{U_e}} \right) \right) \times \frac{L_{sh}}{2\lambda U_e \sqrt{1 - \left( \frac{\varepsilon}{U_e} \right)}}$$  \hspace{1cm} \text{(3)}$$

where $I_{c(\varepsilon=0)}$ is the collector current at $U = 0$; $\gamma$ is the coefficient of the ion-electron emission [2]; $L_{sh}$ is the length of the cathode layer; $\lambda$ is the mean free path determined by charge-exchange; and $U$ is the voltage drop across the cathode layer.

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.

The 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 6** Comparison of the experimental IEDF (nitrogen, $p = 0.3$ Torr, $I = 5$ mA, $U = 740$ V) (1) with that calculated by Eq. (3) (2)

**Figure 7** The axial potential distribution (nitrogen, $p = 0.3$ Torr, $I = 5$ mA, $U = 740$ V)
Figure 6 shows a comparison of an IEDF calculated by Eq. (3) 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 (Fig. 7).

Concluding Remarks

Thus, the complex of the electric characteristics of the cathode region of the glow discharge in nitrogen was received.

The analysis of the ion distribution functions shows that the main process determining the ions energy distribution is charge-exchange.

The presented experimental data qualitatively agree with the results of the theoretical description of the cathode region based on a kinetic analysis [4].

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References