THE FEATURES OF THE ELECTRON DISTRIBUTION FUNCTION IN THE HOLLOW CATHODE GLOW DISCHARGE IN NITROGEN

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In the present paper experimental and theoretical studies of the electron energy distribution function in a stationary glow discharge with a hollow cathode in nitrogen are performed. It is shown that in such discharge in nitrogen in the energy range $\varepsilon = 2 \div 4$ eV a significant gap and respective inverse region appear on the EDF, which is due to vibrational excitation of N_2 molecules.

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1 INTRODUCTION

Due to wide use of technologies with the plasma of low-pressure gas discharges in nitrogen and its mixtures, in the last years a great attention is paid to experimental and theoretical investigations of the electron energy distribution function (EDF) with an aim of clearer understanding of the essence of plasma-chemical processes occurring in various plasma devices. It should be noted at once that EDF appearance depends essentially on the discharge kind and parameters even for the same gas mixtures. In the present work the experimental and theoretical investigations of the electron energy distribution function are performed for the system which is completely different from those studied both in [1, 2] and in [3], particularly, for the stationary glow discharge with a hollow cathode in nitrogen. As it is shown by the measurements, the electric field in the main region of such discharge is less than 0.1 V/cm at pressure ~ 0.1 Torr, that is, at field value being one order of magnitude less than that in [1, 2]. Ionization and electron heating is provided in this case by the flow of fast electrons with an energy of ~ 400 eV which are emitted from the near-cathode region.

2 EXPERIMENTAL SET-UP AND METHODS

The experiments were accomplished with a hollow cathode having a cylindrical shape with 280 mm diameter and 400 mm length. The vacuum chamber was evacuated by forevacuum pump down to a residual pressure of $5 \cdot 10^{-3}$ Torr, after that working gas was supplied to the chamber up to a pressure of $3 \cdot 10^{-2}$ - $1 \cdot 10^{-1}$ Torr. The discharge current was varied in the range 0.5 – 0.9 A; the voltage – in range 400 - 600 V. Measurements of the plasma density, electric fields and EDF were performed by means of two single Langmuire probes. The EDF was determined by numerical double differentiation of VAC by means of mathematical processing routines (with preliminary interpolation of the data, if required). For improvement precision of VAC measurements the technique based on the use of a specially developed software-hardware complex controlled by a personal computer [4] was implemented. The potential of the probe, at which the second derivative of its current on voltage crossed zero level, was taken as a plasma potential. The plasma density was calculated from the saturation current of electrons onto the probe.

3 EXPERIMENTAL RESULTS

In Fig. 1 the radial distributions of plasma density for various pressures of nitrogen are given. One can see that dependence behavior strongly depends on the working gas pressure. At p = 0.1 Torr plasma density has minimum at cathode axis, and it grows up slowly along the radius reaching its maximum at R ≈ 11 cm. At lower pressures (p = 0.03 Torr, p = 0.06 Torr) the plasma density distribution along the cathode radius possesses inverse behavior – n_e reaches its maximum at a system axis and decreases monotonously with R growth. Such peculiarity of the distribution is due to specifics of the discharge with hollow cathode. At a pressure of 0.1 Torr fast primary electrons emitted by the cathode spend almost all their energy for excitation and ionization of working gas already at a distance of several centimeters from the cathode, that is why the plasma at the system axis appears mostly due to diffusion from the region of its formation. Thus, maximum of plasma concentration is observed in the region of maximum energy losses of fast electrons (that is, maximum of plasma formation), rather than at the cathode axis. As the gas pressure decreases the length of the fast primary electron energy relaxation increases, and due to that maximum of the plasma density initially shifts to smaller radius values, and at p ≈ 0.05 Torr the plasma density distribution appears as bell-shaped curve.

Experimentally measured radial distributions of E_r electric field component at various pressures of nitrogen are presented in Fig. 2. One can see from the figure that the behavior of E_r dependence on the radius corresponds to the character of the radial plasma density dependence. At low nitrogen pressure the field has a positive sign and increases monotonously along the radius. At p = 0.1 Torr in the near-axis region of the cathode (plasma density minimum) E_r field has a negative sign, and then after crossing zero level also increases monotonously along the radius. The longitudinal electric field component (E_z) in a whole range of used nitrogen pressure does not exceed 1-2·10^{-2} V/cm. Figures 3, 4 exhibit typical EDF on energies at nitrogen pressures 0.03 and 0.1 Torr for various values of the system radius. One can see that EDF possess clearly exhibited non-maxwellian behavior with significant gap in the energy range 2÷4 eV. At the lower pressure (Fig. 3) two minima are being observed in this energy range. It has been also determined that at low pressures the EDF shape is practically independent on the radius, whereas at p = 0.1 Torr EDF shape changes significantly along the radius, and the gap depth is smaller in the center of the chamber, where E/N has its minimum value. Such behavior of an EDF radial dependence is not connected with the presence of an electric field, since its action would result in an inverse behavior of EDF dependencies on the radius (i.e., a minimum gap depth on the EDF would appear at the discharge periphery, where the field has its maximum value). Decrease of the gap in EDF near the hollow cathode axis at high pressures observed (Fig. 4) may be due to the decrease of the amount of high-energy electrons which represent the main energy source in the plasma and, consequently, due to contribution enhancement for the processes which are responsible for EDF maxwellization.

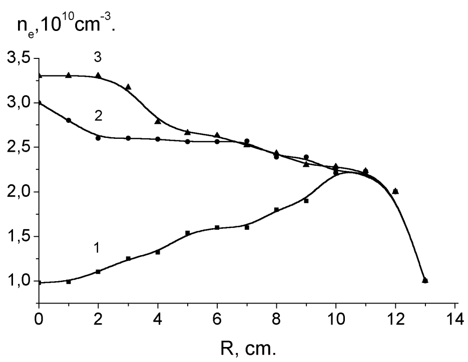

Fig. 1. Plasma density versus R for various pressures of nitrogen:
1 – p = 0.10 Torr, I_d = 0.63 A, Ud = 470 V;
2 – p = 0.06 Torr, I_d = 0.73 A, U_d = 580 V;
3 –p = 0.03 Torr, I_d = 0.77 A, U_d = 615 V.

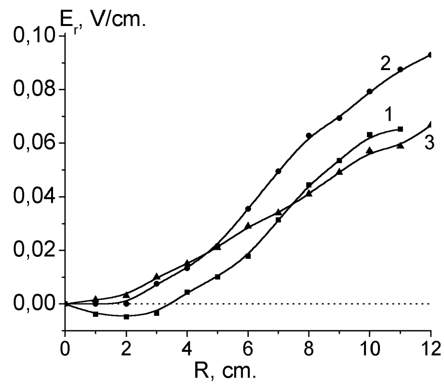

Fig. 2. Distributions of the electric field radial component for various pressures of nitrogen.
1 - p = 0.10 Torr, I_d = 0.63 A, U_d = 470 V;
2 - p = 0.06 Torr, I_d = 0.73 A, U_d = 580 V;
3 - p = 0.03 Torr, I_d = 0.77 A, U_d = 615 V.

4 RESULTS OF THE COMPUTER SIMULATION AND DISCUSSION

Calculation of the electron energy distribution function was accomplished following the Boltzman equation in the two-term approximation [5]:

$$\frac{1}{n_e N}\left(\frac{m}{2e}\right)^{1/2}\varepsilon^{1/2}\frac{\partial(n_e f_0)}{\partial t}-\frac{1}{3}\left(\frac{E}{N}\right)^2\frac{\partial}{\partial\varepsilon}\left(\frac{\varepsilon}{Q_T}\frac{\partial f_0}{\partial\varepsilon}\right)-$$
$$-\frac{\partial}{\partial\varepsilon}\left[2\frac{m}{M}Q_T\varepsilon^2\left(f_0+T\frac{\partial f_0}{\partial\varepsilon}\right)\right]=S_{eN}+S_{ee}+A(\varepsilon)\qquad(1)$$

where $f_0(\varepsilon)$ is the symmetric part of the electron energy distribution function; T is the gas temperature (eV); e = 1,602·10^{-12} erg/eV; M, N, Q_T are the molecule mass, gas concentration and transport scattering cross section, respectively; m, n_e are the electron mass and concentration; S_{eN} is the integral of non-elastic collisions; S_{ee} is the integral of electron-electron scattering; $A(\varepsilon)$ is the ionization term including the source of primary electrons. Expressions for terms S_{eN}, S_{ee}, $A(\varepsilon)$ are given in [4].

The function $f_0(e)$ was normalized by condition:

$$\int_0^\infty \varepsilon^{1/2} f_0(\varepsilon)\,d\varepsilon = 1. \qquad (2)$$

When solving equation (1) for nitrogen the electron processes presented in Table 1 [4] were taken into consideration. Hyperelastic scattering with vibrationally excited molecules was not taken into account in the calculations, because in our case the specific power introduced into the discharge and, respectively, vibrational temperature T_v was essentially less than that in [2, 3]. Cross sections of elastic and non-elastic scattering on N_2 molecules were taken as in [4]. The electric field strength and electron concentration in various regions of the discharge chamber were measured experimentally, and these values were used in the calculations. It was assumed that the energy of the primary electron beam ε_n comprised value of the order of cathode potential fall ($\varepsilon_n \approx$ 400 eV). Equation (1) was solved by numeric technique analogously to [5].

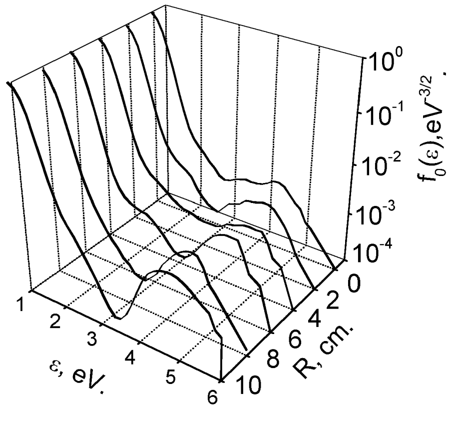

Fig. 3. Set of EDF on energies in nitrogen at p = 0.03 Torr for various R.

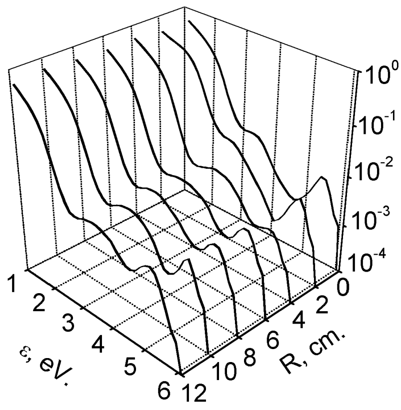

Fig. 4. Set of EDF on energies in nitrogen at p = 0.1 Torr for various R.

Fig. 5 exhibits theoretical electron distribution functions in the discharge with a hollow cathode in nitrogen. The range of EDF calculation parameters (n_e, E) corresponds to the range of n_e, E variations along the radius of the discharge chamber. At all discharge parameters two minima in the energy range $\varepsilon = 2 \div 4$ eV are clearly observed on EDF which are determined by a distinct maxima in the cross section of vibrational excitation of N_2 molecules in the above mentioned energy ranges. In case of excluding the process of N_2 vibrational excitation from the calculation EDF becomes monotonous. The gap in the electron distribution function also disappears at artificial increase of E/N value by the order up to values used in [1-4] due to maxwellizing action of electric field.

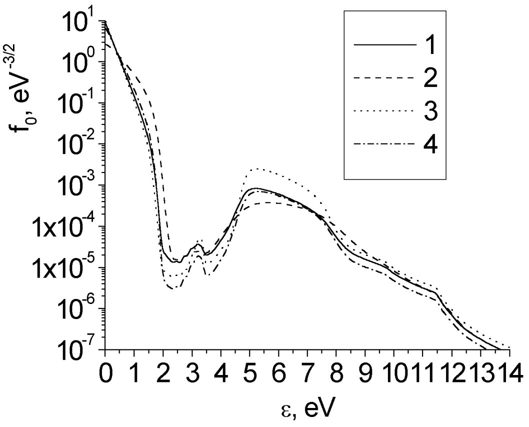

Fig. 5. Calculated EDF for nitrogen.
1 - p=0.03 Torr, n_e=$1\cdot10^{10}$ cm^{-3}, E=0.01 V/cm;
2 - p=0.03 Torr, n_e=$1\cdot10^{10}$ cm^{-3}, E=0.10 V/cm;
3 - p=0.10 Torr, n_e=$1\cdot10^{10}$ cm^{-3}, E=0.01 V/cm;
4 - p=0.10 Torr, n_e=$2\cdot10^{10}$ cm^{-3}, E=0.06 V/cm.

Comparison of measured (Fig. 3) and calculated (Fig. 5) electron distribution functions in nitrogen plasma at low pressure demonstrates not just qualitative, but quantitative agreement. Positions of experimental and theoretical minima in EDF in the energy range $\varepsilon = 2 \div 4$ eV coincide with 10-20% precision. Value of the gap depth in the measured electron distribution function (with respect to the right-side maximum) coincides with the calculation with a precision of measurement error. It should be noted that the experimental technique used does not allow correct EDF measurements in the energy range ≤ 1 eV. For this reason the measured value of $f(\varepsilon)$ decrease at $\varepsilon < 1$ eV is significantly less than calculated one. However, comparison of $f(\varepsilon)$ decrease with respect to the EDF value at 1 eV also demonstrates a good agreement between the theory and the experiment.

Somewhat worse relation of calculated and experimental electron distribution functions at higher pressures (Fig. 4) may be due to strong inhomogeneity in the energy distribution along the radius for a fast electron beam emitted from the cathode, as it was already mentioned. The calculations assumed complete spatial homogeneity of all parameters determining the electron distribution function.

5 CONCLUSIONS

Thus, investigations of EDF in the discharge with a hollow cathode, in which main source of plasma heating is represented by fast electrons formed at the cathode and accelerated by the field of near-cathode space discharge layer, have demonstrated that in nitrogen on EDF in the energy range $\varepsilon = 2 \div 4$ eV a significant gap is observed which is due to vibrational excitation of N_2 molecules.

Results of theoretical calculations are in agreement with the experiment.

6 ACKNOWLEDGEMENTS

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