Inversion of the Electron Energy Distribution in Hollow Cathode Glow Discharge in Nitrogen-Sulfur Hexafluoride Gas Mixture

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Abstract. Experimental and theoretical studies of the electron energy distribution function (EEDF) in glow discharge with hollow cathode in the mixture of N_2 and SF_6 are accomplished. It is shown that at adding of 5-6% SF_6 to nitrogen, electron concentration at inverse region of EEDF (2-4 eV) increases by about one order of magnitude. The reason for such effect consists in intensive adherence of low-energy electrons to electronegative molecules which promotes the decrease of their amount in the discharge and, consequently, the increase of relative amount of electrons in the inverse region.

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INTRODUCTION

The phenomenon of inverse electron energy distribution function (EDF) in low-temperature plasma is of considerable interest because such media can be used for obtaining inverse population of the atomic and molecular electron levels. The results of our previous experimental and theoretical investigations [1] showed that such distribution can be realized in hollow cathode (HC) glow discharge in nitrogen. The EDF inversion in pure nitrogen is related to certain features of the interaction of N_2 molecules with electrons. In the region 2 – 4 eV electrons quite rapidly lose their energy for the excitation of vibrational levels of nitrogen molecules, which results in the appearance of a trough in the corresponding region of the EDF. Unfortunately, the absolute majority of electrons occur in the region of lower energy (< 2 eV), and their density in the region of EDF inversion in rather insignificant. In [2] we theoretically predicted the possibility of increasing the fraction of electron in the region of EDF inversion by adding a small amount of electronegative gases (SF_6 or CCl_4) into nitrogen. It was suggested, that the attachment of low energy electrons to the electronegative molecules would lead to a decrease in the number of such electrons in the discharge and, accordingly, to an increase in the relative fraction of electron with higher energies including those corresponding to the region of inversion.

This paper presents the results of experimental investigation of the EDF in a mixture of N_2 and SF_6 and theoretical calculation using parameters corresponding to the experimental conditions.

EXPERIMENTAL SETUP AND MEASUREMENTS RESULTS

The experiments were carried out with the hollow cylindrical cathode 280 mm in diameter and 400 mm in length. A 230 mm-diameter anode was placed near one end of the cathode. The hollow cathode was evacuated by a forepump to a residual pressure of $\approx 2\times10^{-3}$ Torr. Since pumping rate was virtually independent of the pressure in the range from 2×10^{-3} to 2×10^{-1} Torr, the working mixture of N_2 and SF_6 in the hollow cathode was prepared using the follow procedure. After evacuation of HC to residual pressure, the necessary amount of SF_6 was introduced and the HC was filled with N_2 to total pressure of 0.1 Torr. The partial pressure of SF_6 in our experiments was varied within (1-10)$\times 10^{-3}$ Torr, which amounted to 1-10% of total gas pressure. The plasma density and EDF were measured with the use of Langmuir probes, which were made of a tungsten wire with diameter of 50-100 µm and had a charge collector length of 10-12 mm. The probes could be moved in the radial and axial direction. In order to eliminate the influence of surface contamination on the current-voltage (*I-V*) characteristics of the probes, they were cleaned after each measurement by heating up to 800^{0}C.

The *I-V* curves were measured using an automated system controlled by a personal computer provided with a special software. The system provided programmed variation of the probe current (which was set with an accuracy of 0.1 µA) and simultaneously measured the probe potential (relative to anode), the anode voltage and the discharge current. The results of measurements were digitized and stored in the computer memory in the form of an *I-V* curves for a given discharge current and voltage. The measurements at the fixed set of parameters were repeated up to 30 times and obtained data were averaged. The plasma potential was determined as corresponding point where the second derivation of probe current with respect to the voltage was zero.

During the EDF measurements, the systematic error in the region of small electron energies (≤0.2-0.3 eV) was decreased using the method based on the combination of the first and second derivatives of electron current to the probe [3]. In this case, the EDF had the following form:

$$f(eV) \approx \frac{1}{C_0}\left(j_e''(eV) - j'_e(eV)\frac{\Psi}{eV}\right)$$

where C_0 is the normalization constant, j_e is the density of the electron current to the probe, V is the potential relative to the plasma potential, $\Psi = ac_i/\gamma_0\lambda$ is the diffusion parameter of the probe, a is the probe diameter, λ is the electron mean free path, $c_i = \ln(\pi l/4a)$, l is the probe length and $\gamma_0 = 4/3$ (for $a \ll \lambda$). For determination of the derivatives we used the total current to the probe instead of electron current, because estimations had shown that the contribution of ion current to total probe current could be ignored in the range of energies up to ~ 10 eV.

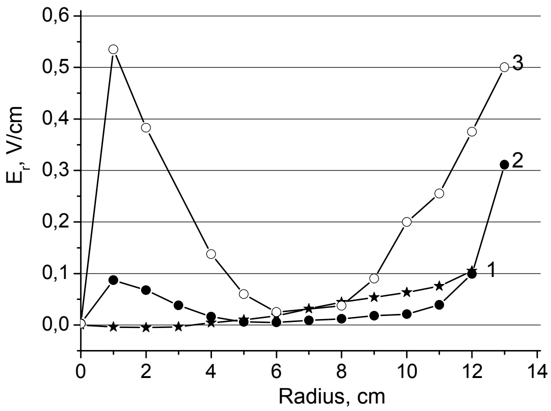

FIGURE 1. Radial profile for radial electric field for different partial pressure of SF_6. in N_2+SF_6 mixture: 1 - P_{SF6}=0 Torr; 2 - P_{SF6} ≈2$\times 10^{-3}$ Torr, 3 - P_{SF6} ≈4$\times 10^{-3}$ Torr. Total gas pressure is 0.1 Torr.

The partial pressure of SF_6 in our experiments did not exceed 6×10^{-3} Torr. Higher densities of this gas in the discharge plasma led to the excitation of intense relaxation oscillations with frequencies in the range from 10 to 10^5 Hz, which hindered correct measurements of the plasma characteristics. The introduction of SF_6 into nitrogen led to an increase in the discharge voltage. In pure N_2, the discharge voltage was 520-540 V at the discharge current 1 A. In a mixture of N_2 with SF_6 at a partial pressure of 6×10^{-3} Torr the discharge voltage for the same current reached 700-800 V. The presence of SF_6 in the gas mixture also led to an increase in the electric field strength in the discharge plasma: at partial pressure of SF_6 on a level of (5-6)$\times 10^{-3}$ Torr the longitudinal electric field strength reached ≈0.1 V/cm, which was almost ten times as strong as the value in the case of pure N_2. The radial electric field E_r also exhibited an increase and moreover the radial field profile became more complicated as compared to that in the pure nitrogen plasma (Fig.1). In this figure the dependencies of radial electric field on the system radius are presented for different partial pressures of SF_6. One can see from the figure that SF_6 adding leads to rapid growth of radial electric strength E_r in the paraxial region and at the periphery of discharge plasma, whereas in the intermediate region E_r growth is essentially smaller. At SF_6 partial pressure of 4×10^{-3} Torr, E_r reached ≈ 0.5 V/cm in paraxial region and at the periphery of discharge, but in intermediate region one did not exceed ≈ 0.05 V/cm.

Such change of the profile of E_r radial distribution is due to variation in the component content of charged particles of the plasma at SF6 adding to nitrogen. While in case of the discharge glowing on nitrogen its plasma is composed of electrons and positive ions (mainly N_2^+), at adding of electronegative gas SF_6 to nitrogen heavy negative ions SF_6^- , SF_5^- , SF_4^- etc. are supplemented to mentioned above charged components. In Fig.2 measured dependencies of concentrations of charged particles on the system radius are presented for plasma of discharges on pure nitrogen and N_2 - SF_6 mixture with SF_6 partial pressure comprising $\approx 4\times10^{-3}$ Torr. The density of negative ions in the plasma was estimated using the method described in [4]: The sense of this method is, as follows: ratio of negative ion density to positive ion one is estimated by taking ratios of the ion saturation current ratio in the negative gas mixture plasma to that in reference gas plasma. In our case, pure nitrogen plasma was used as reference one.

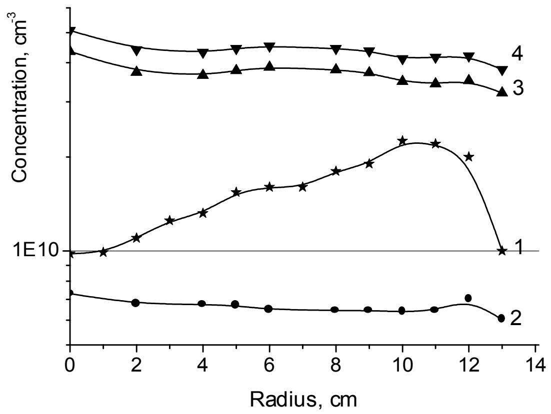

FIGURE 2. Dependence of concentrations of charged particles on radius of the system. 1- n_e, pure nitrogen; 2 – n_e, 3 – n_-, 4 – n_+, N_2+SF_6 mixture, partial pressure SF_6 $\approx 4\times10^{-3}$ Torr. Total gas pressure is 0.1 Torr.

One can see from the figure that adding of 4% SF_6 to nitrogen leads to essential changes both in densities of charge d particles, and in structure of their radial distributions: 1) density of negative ions in the plasma exceeds one of electrons by factor of $\approx$ 6; 2) plasma density distribution with minimum at the system axis is substituted by more «flat» one. Such behaviour of change of the density profile is due to accumulation of heavy negative ions in axial region of the system.

Figure 3 (curve 2) exhibits the EDF measured with a probe placed at a distance of 7 cm from system axis for the discharge in N_2-SF_6 mixture with SF_6 partial pressure of about 5×10^{-3} Torr with the total gas pressure of 0.1 Torr (i.e. with 1:0.05 ratio of the components). As one can see from Fig.1, the measurements were performed in region where electric field did not exceed 0.1 V/cm. For the comparison, we also present the EDF measured under otherwise identical condition in pure nitrogen plasma (curve 1). As it can be seen from these EDFs, the presence of negative additive in the gas mixture leads to significant increase in the electron density in the region of inversion, so that the number of electrons with energies of 2-4 eV increases by approximately one order of magnitude.

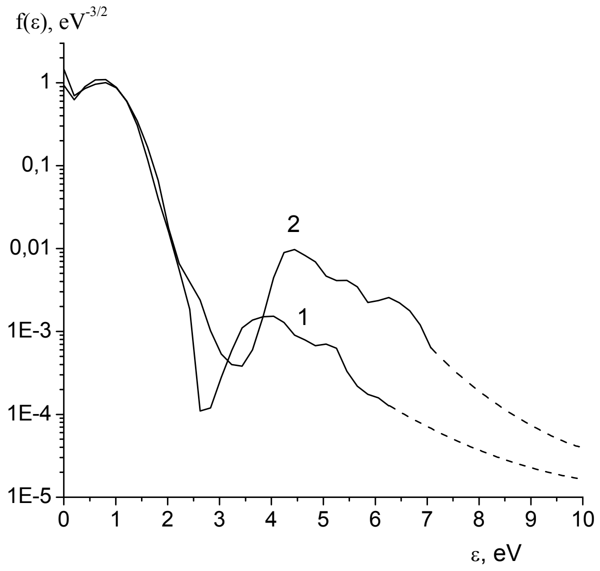

FIGURE 3. Experimental EDFs measured in HCD in pure nitrogen (1) and N_2+SF_6 mixture (2) with ratio of the components 1:0.05 at total gas pressure of 0.1 Torr. R = 7 cm.

For numeral calculation of the EDF we solved the Boltztman equation in a two-term approximation with allowance for the elastic and inelastic collisions of an electrons with neutrals, the electron-electron scattering and the gas ionization by a beam of fast initial electrons. Detailed description of a scheme of the calculations and the interaction of electrons with molecules of working gas mixture was presented earlier in [1, 2]. Parameters of the experimental setup used in [1] for EDF measurements in hollow cathode glow discharge on pure nitrogen were used in the calculations. In such discharge practically all applied voltage drops in narrow near-cathode layer. Electric field in main region of the discharge is small (~0.1 V/cm). Gas ionization and electron heating are performed by the flow of fast electrons with 400 eV energy flying out of the near-cathode layer. The EDF was calculated for $N_2 - SF_6$ mixture with various ratios of the gas components and total pressure of 0.1 Torr. In agreement with experimental data, the electric field in plasma region under calculation was varied from 0.1 to 1.0 V/cm and the electron density was taken equal to ~ 10^{10} cm^{-3}. The EDF $f(\varepsilon)$ was normalized to satisfy the condition

$$\int_0^\infty \varepsilon^{1/2} f(\varepsilon) d\varepsilon = 1$$

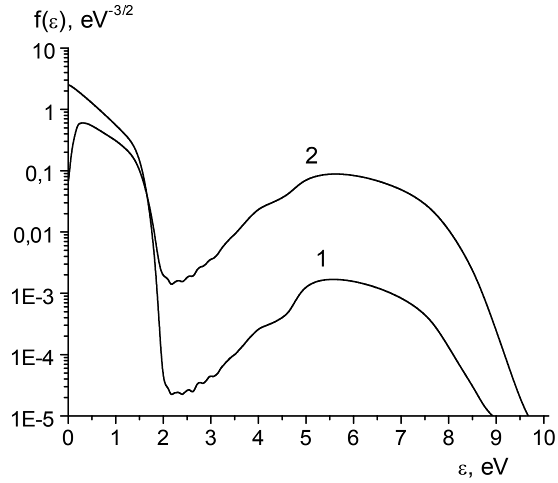

FIGURE 4. Theoretical EDFs numerically calculated for HCD in pure nitrogen (1) and N_2+SF_6 mixture (2) with ratio of the components 1: 0.05 at total gas pressure of 0.1 Torr and electric field of 0.1 V/cm.

Figure 4 shows the EDF calculated for pure nitrogen and $N_2 - SF_6$ mixture with the ratio of the components of 1:0.05 at electric field strength of 0.1 V/cm. As one can see from the comparison of Fig. 3 and Fig.4, the results of calculations qualitatively agree with experimental data, in accordance to which adding several percents of SF_6 to N_2 significantly increases the density of electrons in the energy range of the EDF inversion.

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