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

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Abstract—The electron energy distribution function (EDF) in a hollow-cathode glow discharge in nitrogen–sulfur hexafluoride (N_2–SF_6) gas mixture has been studied by experimental and theoretical methods. On adding a small amount of SF_6 to N_2, the density of electrons in the energy interval (2–4 eV) of the EDF inversion increases by approximately one order of magnitude. © *2005 Pleiades Publishing, Inc.*

The phenomenon of inverse electron energy distribution in low-temperature plasma is of considerable interest because such media can be used for obtaining inverse populations of the atomic and molecular electron levels (see, e.g., [1] and references therein). The results of our previous experimental and theoretical investigations [2] showed that such distributions can be realized in hollow-cathode glow discharge in nitrogen. In such cases, the region of inversion of a stationary electron energy distribution function (EDF) occurs in the interval from 2 to 4 eV, which corresponds to characteristic thresholds of the electron excitation of gas molecules. The EDF inversion in pure nitrogen is related to certain features of the interaction of N_2 molecules with electrons. Indeed, electrons with the energies $\varepsilon = 4$–7 eV exhibit no inelastic collisions with N_2 molecules and rather slightly lose energy via inelastic collisions with these molecules. As a result, the density of electrons with energies in the indicated interval tends to increase. In the region of 2–4 eV, electrons quite rapidly lose their energy for the excitation of vibrational levels of N_2 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 energies ($\varepsilon < 2$ eV), and their density in the region of EDF inversion is rather insignificant.

Previously [1], we theoretically predicted the possibility of increasing the fraction of electrons in the region of EDF inversion by adding a small amount of an electronegative gas (SF_6 of CCl_4) to 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 electrons with higher energies including those corresponding to the interval of inversion. Other inelastic interactions of electrons with the electronegative admixture do not significantly affect the EDF because of the low concentration of this gas.

This paper presents the results of experimental investigations of the EDF in a mixture of N_2 and SF_6 and theoretical calculations using parameters corresponding to the experimental conditions. It will be shown that adding a small amount of SF_6 to N_2 significantly increases the fraction of electrons in the interval of the EDF inversion.

The EDF was experimentally determined using a setup described in detail elsewhere [2]. The setup was based on a cylindrical vacuum chamber with a diameter of 280 mm and a height of 400 mm, which also played the role of a hollow cathode for the glow discharge. The chamber was evacuated with a mechanical pump to a minimum residual pressure of $\approx 2 \times 10^{-3}$ Torr. Since the pumping rate was virtually independent of the residual pressure in the interval from 2×10^{-3} to 2×10^{-1} Torr, the working mixture of N_2 and SF_6 in the chamber was prepared using the following procedure. Initially, the chamber was evacuated to the minimum residual pressure. Then, the necessary amount of SF_6 was introduced and the chamber was filled with nitrogen to a 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 the total gas pressure. The plasma density and the EDF were measured with the aid of Langmuir probes, which were made of a tungsten wire with a 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 the chamber. In order to eliminate the influence of surface contaminations on the current–voltage (*I*–*V*) characteristic of the probe, it was cleaned after each measurement by heating to 800°C in vacuum.

The *I–V* curves were measured using an automated system controlled by a personal computer provided with 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 the anode), the anode voltage, and the discharge current. The current increment at each step was automatically calculated using a special algorithm so as to optimize the signal-to-noise ratio in the entire experimental range (the number of steps used for the measurement of each *I–V* curve was 1500–2000). The measurements in a stroboscopic regime were performed at a frequency of 100 Hz and synchronized with the power supply variations in order to eliminate their influence on the experimental results. The measured signals were gated over a 1-μs period of time. The delay of this period relative to the onset of the power supply voltage halfwave was selected so as to optimize the signal-to-noise ratio. The results of measurements were digitized and stored in the computer memory in the form of an *I–V* curve for a given discharge current and voltage. The measurements at a fixed set of parameters were repeated up to 30 times and the obtained data averaged. The plasma potential was determined as corresponding to the point where the second derivative of the probe current with respect to the voltage is zero, and the electron density in the plasma was calculated using the value of the saturation current of electrons to the probe. The density of negative ions in the plasma was determined using the method described in [3].

During the EDF measurements, the systematic error in the region of small electron energies (≤0.2–0.3 eV) was decreased using a method based on the combination of the first and second derivatives of the electron current to the probe [4]. In this case, the EFD had the following form:

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

where C_0 is the normalization constant, j_e is the density of the electron current to the probe, V is the probe 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 determining the derivatives, we used the total current to the probe instead of the electron current, because estimates showed that the contribution of ion current to the total probe current can be ignored in the range of electron energies up to ~10 eV.

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 10^2 to 10^5 Hz, which hindered correct measurements of the plasma characteristics.

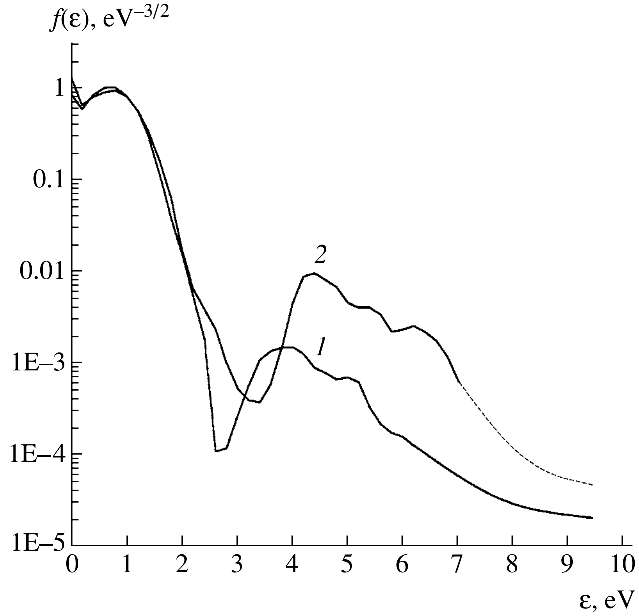

Fig. 1. The experimental EDFs measured in hollow-cathode glow discharge in (*1*) pure nitrogen and (*2*) an N_2–SF_6 mixture with the ratio of components 1 : 0.057 at a total pressure of 0.1 Torr.

The introduction of SF_6 into nitrogen led to an increase in the discharge voltage. In pure nitrogen, the voltage drop across the discharge was 520–540 V at a discharge current of 1 A. In a mixture of nitrogen with SF_6 at a partial pressure of 6×10^{-3} Torr, the discharge voltage for this current reached 700–800 V. The plasma density at this SF_6 pressure was about 2×10^{10} cm^{-3}, and the longitudinal inhomogeneity of this value did not exceed 10%. The density of negative ions in this case was several times greater than the electron density. The presence of SF_6 also led to an increase in the electric field strength in the plasma: at a partial pressure of SF_6 on the level of (5–6) × 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 nitrogen. The radial electric field strength E_r also exhibited an increase, and the radial field profile became more complicated as compared to that in the pure nitrogen plasma. The maximum radial field strength (0.4–0.7 V/cm) was observed in the paraxial region and at the periphery of the discharge, whereas in the intermediate region this value did not exceed 0.1–0.2 V/cm.

Figure 1 (curve *2*) shows the EDF measured with a probe occurring at a distance of 70 mm from the chamber axis for a discharge in N_2–SF_6 mixture with an SF_6 partial pressure of about 5.7×10^{-3} Torr. For comparison, we also present an EDF measured under otherwise

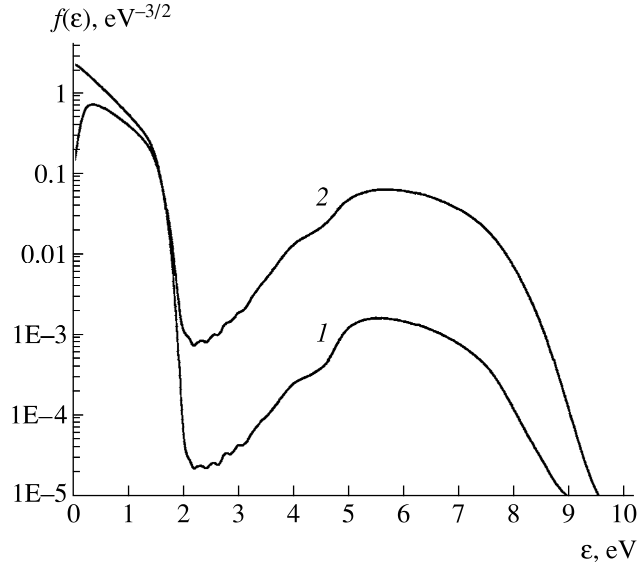

Fig. 2. Theoretical EDFs numerically calculated for a hollow-cathode glow discharge in (*1*) pure nitrogen and (*2*) an N_2–SF_6 mixture with the ratio of components 1 : 0.05 at a total pressure of 0.1 Torr.

identical conditions in pure nitrogen plasma (curve *1*). As can be seen from these data, the presence of the electronegative additive in the mixture leads to a significant increase in the electron density in the region of inversion, so that the number of electrons with energies in this interval increases by approximately one order of magnitude.

For a numerical calculation of the EDF, we solved the Boltzmann equation in a two-term approximation with allowance for the elastic and inelastic collisions of electrons with neutrals, the electron–electron scattering, and the gas ionization by a beam of high-energy electrons. Detailed description of the scheme of calculations and the interaction of electrons with molecules of the working gas mixture was presented in [1, 2]. The EDF was calculated for N_2–SF_6 mixtures with various ratios of components and a total pressure of 0.1 Torr. In agreement with experimental data, the electric field strength in the discharge region was set equal to 0.1 V/cm and the electron density was taken equal to ~10^{10} cm^{-3}. Figure 2 shows the EDFs calculated for pure nitrogen and an N_2–SF_6 mixture with the ratio of components 1 : 0.05. As can be seen from a comparison of Figs. 1 and 2, the results of calculations qualitatively agree with the experimental data, according to which adding several percent of SF_6 to N_2 significantly increases the density of electrons in the energy interval of the EDF inversion.

REFERENCES

1. A. G. Kalyuzhnaya, A. V. Ryabtsev, and A. I. Shchedrin, Zh. Tekh. Fiz. **73** (1), 42 (2003) [Tech. Phys. **48**, 38 (2003)].
2. V. Yu. Bazhenov, A. V. Ryabtsev, I. A. Soloshenko, *et al.*, Fiz. Plazmy **27**, 859 (2001) [Plasma Phys. Rep. **27**, 813 (2001)].
3. M. Shindo, S. Uchino, and R. Ichiki, Rev. Sci. Instrum. **72**, 2288 (2001).
4. N. A. Gorbunov, A. N. Kopytov, and F. E. Latyshev, Zh. Tekh. Fiz. **72** (8), 7 (2002) [Tech. Phys. **47**, 940 (2002)].

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