HEATING OF NITROGEN IN A SELF-MAINTAINED GLOW DISCHARGE

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Data on the distribution of the Joule energy of electrons over the various degrees of freedom of the neutral components of a discharge plasma are of great interest for a whole series of practical applications of the glow discharge (plasma chemistry, gas discharge lasers, and so on). The presence of such data offers the possibility of more intelligently selecting conditions for maintaining a glow discharge which ensure the maximum efficiency of a specific gas discharge device. In addition the appearance of additional information on the energy balance of the electrons in the discharge can facilitate the advance of new models or a narrowing of the circle of contraction models under consideration at present for the phenomenon which restricts the limiting possibilities of gas discharge devices.

However, due to diagnostic difficulties a detailed energy balance in a discharge has for the time being been obtained only by computational means (for example, see [1] and [2]). The heating of nitrogen in a glow discharge is accomplished in two heat liberation channels [3] — a rapid one, which is associated with elastic energy losses of the electrons and losses to excitation of rotations, and a slow one, which is associated with relaxation of the energy of vibrational and electronic states of N_2 molecules. The fraction of the Joule power η_r, which determines the rapid heating of the gas, has been experimentally investigated in most detail up to the present time for nitrogen. This fraction has been measured in a glow discharge in the region $E/N = (0.1\text{–}4)\cdot10^{16}$ W·cm^2 in [3-5]. Here E is the intensity of the electric field in the discharge, and N is the gas density.

In this paper the value of η_r in a self-maintained discharge in nitrogen of special purity (impurity content $\leqslant 0.01\%$) has been determined from interferometric measurements for pressures p = 20–80 mm Hg in the range $E/N = (4\text{–}8)\cdot10^{-16}$ W·cm^2. The experimental facility, which incorporates equipment for the production of a quasisteady discharge with a duration $\approx$0.6 msec and a current density $\approx$(10–100) mA/cm^2, a Mach–Zehnder interferometer with a pulsed He–Ne-laser, and a system for recording the interferograms based on a streak camera, has been described in detail in [6]. The volume of the discharge zone is 40 × 2, 5 × 3, and 5 cm^3, which was less than 1% of the chamber volume.

The construction of the electrodes, the dimensions of the chamber, the length of time a quasisteady discharge exists, and the specific Joule powers ($\approx$30 W/cm^3) selected in this paper have permitted achieving quasiequilibrium heating conditions of the gas for which the pressure in the discharge region remained constant and equal to the initial value in the chamber. In addition under the conditions of our experiments one can neglect the effect of slow heating of the gas, since the times of V–T- and V–V–T-relaxation for nitrogen [7] are much longer than the duration of a discharge pulse for the selected gas pressures and specific energy contributions $\leqslant$ 250 J/g. In this case the equation which describes the temporal variation of the nitrogen temperature in a quasisteady discharge is of the the form

$$c_p N_0 \frac{dT}{dt} = j_i E + \eta_r j_e E, \tag{1.1}$$

where c_p is the specific heat at constant pressure of nitrogen, N_0 is the initial density of the gas, T is the gas temperature, j_iE is the power of heat generation produced by the ionic component of the gas, and $\eta_r j_e E$ is the part of the Joule power of the discharge which determines the rapid heating of the nitrogen. The heating produced by ions $j_iE = (\mu_i/\mu_e)j_eE$, where μ_i and μ_e are the mobilities of ions and electrons, amounts to $\approx$0.4% of the Joule power of the electrons j_eE.

Equation (1.1) permits determining the value of η_r if the heating of the gas ΔT during a time Δt for a specified and time-independent discharge power j_eE is known. We found

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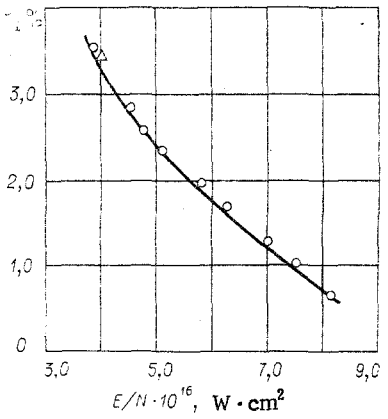

Fig. 1

this heating from the interferometric measurements which determine the variation of the gas density in the interval by using the condition of pressure constancy in the discharge zone. In addition constancy of the pressure during the discharge pulse significantly facilitates the processing of the interferograms, since in this case the shift of the interference bands at a given point of the interferogram is simply related to the variation of the gas density by the Gladstone–Dale relationship:

$$\frac{N}{N_0} = 1 - \frac{\lambda}{L}\frac{A}{p_0}K, \tag{1.2}$$

where N_0 and p_0 are the density and pressure of the gas in the initial state before the discharge was switched on, λ = 0.63 μm is the wavelength of the probe laser, L = 40 cm is the length of the discharge along the beam, A is a constant determined by the index of refraction of nitrogen under normal conditions, and K is the number of shifted bands at a given point on the interferogram. (We note that the applicability of this formula for times $\leqslant 10^{-4}$ sec under conditions of a very powerful energy contribution to the discharge [8] is doubtful. In this case the pressure in the discharge zone does not have time to equalize with the pressure in the chamber, and the energy contribution calculated from (1.2) which has gone into heating of the gas is understated.) Under the conditions of our experiments the electron concentration in the discharge was at the 10^{10} cm^{-3} level; therefore, one can neglect their contribution to the variation of the index of refraction.

It follows from the procedure described above for finding the value of η_r that the accuracy of its determination is directly related to the measurement accuracy of the value of the shift of the interferometric bands on the interferograms. Notwithstanding the rather long extension of the discharge along the beam, an inappreciable shift of the bands on the interferogram occurred in our experiments during a discharge pulse, amounting to several tenths of a band in all. Therefore in order to raise the accuracy of measurements of the value of the shift of the interference bands, we have applied special processing of the interferograms using a computer. It consisted of the input and matching in the computer of interferograms of the interelectrode gap unperturbed and perturbed by the discharge, filtering of noise on the interferograms, isolation of the lines of interference minima, and measurements of the shift between corresponding lines of the input interferograms.

Input of the interferograms is accomplished with the help of a Photomation photo-input device. The raster and aperture during input were 15 and 25 μm, respectively. The matching of the interferograms was performed for four reference points. The algorithms and programs described in [9] were used for the tie-in and geometrical matching. Filtering of the high-frequency (in comparison with the frequency of the interferograms) noise was done by a filter with a constant pulse reaction in the rectangular region. The size of the filter aperture and its orientation were chosen on the basis of a measurement of the distance between lines of the interferograms which pass through the average values and an analysis of the orientation of these lines [10]. Filtering of the low-frequency additive noise was not performed in connection with the fact that the difference in the levels of low-frequency noise on the two interferograms was small. The minima of the intensity of the interferograms on a segment located along the phase gradient and equal to the halfwidth of the interferogram

band were taken as the coordinates of the lines of the interference minima. An estimate of the width of the band and the direction of the phase gradient was made on the basis of an analysis of the distance between lines of the interferograms which pass through the average value and their orientation.

The experiment has shown that the measurement accuracy of the coordinates of the interference extrema is determined by the aperture of the input device after filtering of the noise. These coordinates lie within the limits of the discretization step, which is 3% of the band. With equally probable arrangement of the extrema within the discretization step the mean square deviation of the coordinates of the extrema is 1% of the band width. We note that in the absence of filtering the mean square deviation of the coordinates reaches 10-12% of the band with a difference between corresponding extrema on two input interferograms of ~10% of the band.

The value of η_r calculated from the measured shifts of the interference bands is represented in Fig. 1 as a function of the reduced field intensity of the discharge E/N. We have taken account of the contribution to the heating by the ionic component of the current, which amounts to 0.4% of the total energy contribution, in connection with the calculation of the fraction of the Joule energy of the electrons η_r, which determines the rapid heating of the nitrogen. The results in Fig. 1 show (in agreement with the calculations of [1] and [2]) a continuing decrease for $E/N > 4\cdot10^{-16}$ W·cm^2 of η_r in nitrogen as the reduced intensity of the electric field increases, as well as agreement (the point Δ) of the value obtained for $E/N = 4\cdot10^{-16}$ W·cm^2 with the results of [3].

It is well known that the stability of a discharge worsens as E/N increases; therefore, the decrease obtained for η_r as E/N increases indicates that direct heating of the gas is not decisive in the development of the contraction of a self-maintained discharge in nitrogen. Evidently, other secondary heat liberation channels or the creation of active particles affecting the increase in the ionization rate are important in this process. In addition it follows from the results obtained that in nitrogen in the region $E/N = (4-8)\cdot10^{-16}$ W·cm^2 and with specific energy contributions ≈300 J/g the relaxation times of its electronic states exceeds 0.6 msec by far.

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