Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 2, 2000

ELECTRON-BEAM DIAGNOSTICS OF RAREFIED GASES: ACTIVATION BY SHORT ELECTRON PACKETS

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UDC 533.6.011.8+537.533

The excitation of light emission of the 0–0 band of the first negative system of the nitrogen ion by activation of nitrogen molecules using short pulses of fast electrons was studied. The intensity and width of the light response were measured as functions of the duration and amplitude of the exciting current pulse and of the density of nitrogen molecules. The contribution of slow secondary electrons to the excitation of the ions increases with increase in both the gas density and the duration of the current pulse. Since the processes of excitation of ions by fast primary and slow secondary electrons are separated in time, when measuring the light-signal intensity, it is possible to determine the contribution of secondary electrons to the excitation.

Electron-beam diagnostics has been widely used in experimental studies of the gas dynamics of supersonic jets [1–3] and relaxation processes in various gas objects [4–7]. If the levels in the radiating state of an ion are populated only by fast primary electrons of the beam with the observance of the optical selection rules and emptying occurs by spontaneous radiation, there is a linear relationship between the spectral line intensities and the populations of the molecular levels in the ground state [8]. However, this scheme of the excitation–emission process is valid for most gases only at low pressures.

An increase in the gas pressure makes interpretation of measurement results difficult. First, an increase in density leads to scattering of the diagnostic electron beam. As a result, the current measured at the collector differs from the current at the point on which the optical system is focused. Second, because of the increasing number of ion–molecule collisions, the contribution from the nonradiating deactivation of the excited levels, which competes with spontaneous radiation, becomes greater, and the dependence of the light-emission intensity on the gas density ceases to be linear. Third, along with primary electrons, a cloud of low-energy secondary electrons arises in the measurement region. The cross sections for electron-impact excitation and ionization of molecules are many times larger for secondary electrons than for primary electrons, and the selection rules for the vibrational and rotational transitions differ markedly from the optical selection rules.

The first two factors can be taken into account if the fast electron scattering cross section in the gas studied and the fluorescence quenching factor are known. There have been attempts to take into account the effect of secondary electrons by including the distribution function of secondary electrons into the mathematical model describing the excitation process, by introducing new selection rules, etc. [9]. However, determining the energy distribution function for secondary electrons in the gas studied is a complicated problem.

In the present paper, we study the excitation of the radiating states of ions by short packets of fast electrons. In the case where the interval between electron pulses is sufficient for secondary electrons to migrate from the observation point, one might expect that when the light signal is recorded in a narrow

Novosibirsk State University, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 2, pp. 20–24, March–April, 2000. Original article submitted October 24, 1997; revision submitted January 28, 1999.

 0021-8944/00/4102-0220 $25.00

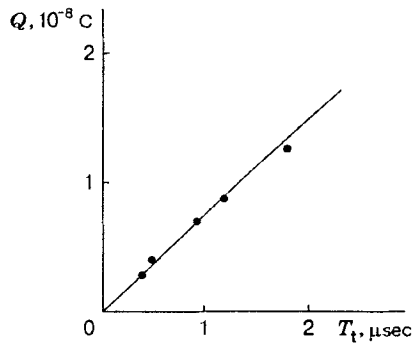

Fig. 1

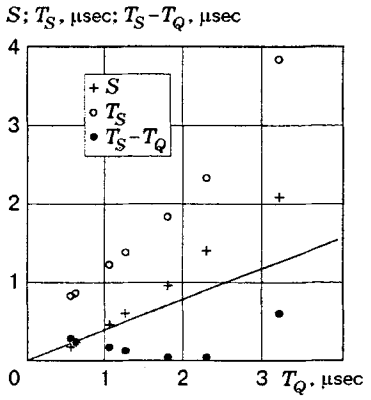

Fig. 2

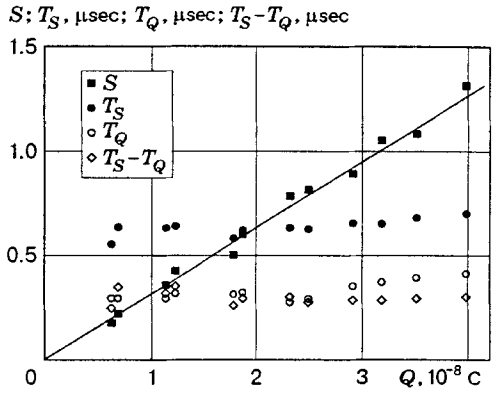

Fig. 3

time interval at the leading edge of the current pulse, the contribution of secondary electrons to the recorded signals decreases.

The experiments described here were performed on the gas-dynamic bench at the Department of Applied Physics of the Novosibirsk State University [10]. The device for shaping short electron packets with an energy of 10–20 keV and the system for recording current and light pulses with a time resolution of 50 nsec are described in [11]. Results from tests of the pulsed electron-beam system and a diagram of the apparatus are given in [12].

The pulsed apparatus smoothly varies the duration (T_Q) and amplitude (I_Q) of the current signal over wide ranges by changing the corresponding parameters of the rectangular pulse that controls the pulse modulation unit. The shape of the current signal recorded at the electron collector is a convolution of this rectangular pulse with the apparatus function of the electron source and the recording system [12]. The electron pulse has a minimum duration (at the half-height) of 250 nsec with a width of the leading edge of about 250 nsec. The increase in the current-pulse duration of the recording system is less than 20 nsec, and the spread of primary electron energy in the beam is not more than 1%, so that the signal at the collector reflects the real shape of the current pulse at the observation point. The measurements show that for triggering times T_t = 0–2 μsec, the total electronic charge in the pulse $Q = \int I_Q(t)\,dt$ depends linearly on the width of the triggering rectangular pulse T_t. Figure 1 shows this dependence for a gas pressure P = 10 Pa and an instantaneous current $I_Q(t) \approx 6$ mA. The diameter of the electron beam at the observation point was 1 mm. The choice of the gas object (nitrogen) is due to the large number of experimental data for continuous electron beams [4, 5, 9].

The light response excited by the electrons in the gas was recorded at a wavelength of 391.4 nm, which corresponds to the 0–0 band of the first negative system of N_2^+. The resolution of the monochromator was chosen so as to completely include the 0–0 band (the P and R branches). As shown in [12], the recorded leading edges of the light and current pulses coincide but the half-width of the light pulse is larger than the half-width of the current pulse: $T_S > T_Q$. The additional broadening of the light pulse is attributed to the processes occurring in the electron-beam plasma in the observation region.

The dependences of the light-pulse intensity $S = \int I_S(t)\,dt$, the light-pulse duration T_S, and the difference in duration between the light and current pulses $T_S - T_Q$ on the current-pulse duration T_Q with unchanged amplitude, obtained in nitrogen at a pressure of 10 Pa, are shown in Fig. 2. As can be seen from Fig. 2, for current-pulse times larger than 1 μsec, the dependence of the light-response intensity on T_Q departs from linearity. This departure correlates with a decrease in the difference of the durations of the light and current pulses ($T_S - T_Q$).

To verify the assumption that the nonlinearity of the light-signal intensity manifested with increase in T_Q is related to an increase in its duration and not intensity, we measured the dependences of the pulse parameters on the amplitude of the current signal with unchanged width. Figure 3 gives the light-pulse intensity S, the durations of the light T_S and current T_Q pulses, and their difference $T_S - T_Q$ versus the current-signal intensity Q. The current intensity in the pulse was varied in the range 10–80 mA by changing the current-passage coefficient [11, 12]. In this case, the current-pulse duration increased (by not more than 30%), as well as the light-response duration, but their difference remained almost constant.

Since the electron-beam diagnostic technique uses emission spectra, only the processes of emptying and pumping of the radiating states were recorded. We consider these processes for the case of a pulsed electron beam. A detailed analysis of the working mechanisms of population and emptying of the radiating states during excitation of nitrogen molecules by a stationary electron beam is presented in [4, 7].

The processes studied differ in time characteristics and in the type of dependence of the rate on the gas density and current-pulse amplitude:

— for excitation of molecules by a direct electron impact, the rate of population R_1 is proportional to the density of the molecules n and the electron-current density i: $R_1 \sim in$;

— for excitation of molecules via an intermediate electron state, the rate is proportional to the product of the population of the intermediate state into the current density: $R_2 \sim i^2 n$;

— for vibrational–rotational heating of molecules in the ground state with subsequent excitation, $R_3 \sim i^2 n^2$;

— for direct excitation by slow secondary electrons with violation of the optical selection rules, $R_4 \sim in^2$ and the time of the process is limited by the time of spread of the secondary electron cloud;

— for relaxation population, the rate of the process is proportional to the population of the higher-lying level ni into the gas density n, i.e., $R_5 \sim in^2$, and the time of the process, as for the deactivation processes, is limited by the lifetime of the excited state. The characteristic time of the first three processes is determined by the lifetime of primary electrons in the observation region.

It follows from the experiments that with increase in current, the light-pulse width does not change and its intensity increases linearly (Fig. 3). Hence, the contribution of cascade processes (R_2 is excitation via the intermediate electron state and R_3 is excitation with preliminary vibrational–rotational heating in the ground electronic state) to the population of the radiating state of the ion is negligibly small. At the same time, the behavior of the dependences shown in Fig. 2 suggests that an increase in the current-pulse duration leads to formation of a cloud of secondary electrons, which initiate emission of the ions owing to the large excitation cross section.

The process of formation of secondary electrons is determined equally by the number of ionizing electrons and the density of the ionized gas. Therefore, with increase in the gas density, effects similar to those observed with a change in the current-pulse duration should take place. The parameters of the current and optical pulses as functions of the gas density were studied in the pressure range of 2–120 Pa. Time

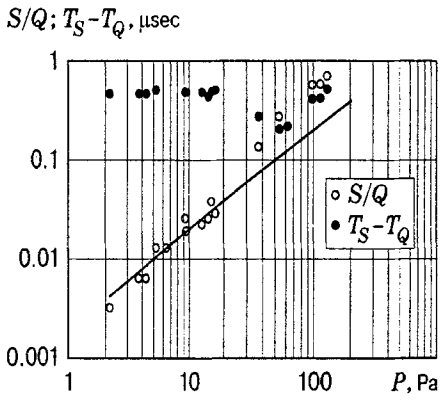

Fig. 4

characteristics and changes in the intensities of the optical and current signals were recorded with a constant duration of the current pulse (T_t = 0.5 μsec). Figure 4 shows the difference in duration between the light and current pulses and the ratio of the intensities of the light and current pulses versus pressure.

For the specified experimental conditions (electron energy 8 keV), the difference in duration between the light and current pulses at low (lower than 15 Pa) and high (higher than 75 Pa) pressures is about 0.35 μsec, and in the pressure range of 15–75 Pa, it decreases to 0.15 μsec. The plot of the ratio of the intensities of the light and current pulses is well approximated by segments of two straight lines, and the inflection point corresponds to a pressure of about 15 Pa. As a whole, there is good agreement between the dependences of the intensity and duration of the light pulse on both the gas density and the electron packet duration.

The above experimental results indicate that at small durations of the current pulse, the dependence of the emission-light intensity of the excited nitrogen ions on the current-pulse amplitude is linear, and, hence, excitation of the radiating state is performed by a direct impact of the fast electrons of the beam. For short durations of the current pulse, the width of the light pulse does not depend on the current-pulse amplitude and, for durations less than 2 μsec, it depends linearly on the width of the current pulse. An increase in both the current-pulse duration and the gas density leads to an increase in the number of secondary electrons. Therefore, to reduce the effect of excitation by secondary electrons on the recorded radiation, it is necessary to decrease the width of the primary current pulse or to perform measurements at the leading edge of the light response. This will extend the range of densities that can be used for electron-beam diagnostic and make it possible to study high-rate process in an electron-beam plasma.

This work was performed within the framework of the Program on Fundamental Natural Sciences of the Ministry of Education of the Russian Federation (Grant No. ZN-217-98) and was supported by the Russian Foundation for Fundamental Research (Grant No. 96-03-33924) and the Program of the Ministry of Science and Technical Policy of the Russian Federation on the support of unique research and experimental setups of national significance (Grant No. 06-05).

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