The radiative properties of plasma of pulse-periodic discharge initiated with runaway electrons

M. Lomaev[1,2], D. Beloplotov[1,2], D. Sorokin[1], V. Tarasenko[1,2],

[1]Institute of High Current Electronics, Akademichesky Ave. 2/3, 634055 Tomsk, Russia
[2]National Research Tomsk State University, Lenina Ave. 36, 634050 Tomsk, Russia..

The spectral and amplitude-temporal characteristics of plasma radiation of pulse-periodic discharge in nitrogen initiated with runaway electrons are investigated experimentally. At repetitively pulsed excitation mode was found to observe the intense emission lines of copper atoms, nitrogen atoms and ions, the first and second positive system of nitrogen, NO and CN.

1. Introduction

Pulse-periodic nanosecond discharge now attract a lot of attention because of the possibility of their wide practical use for the treatment of polymeric biomaterials, metals, semiconductors, medicine, ecology and other fields [1-3]. In particular, the pulse-periodic volume (diffuse) discharge initiated with an electron beam avalanches (REP DD) was used to create point sources of spontaneous radiation in the UV region of the spectrum at the transitions of the second positive system of nitrogen, atoms of electrode material (steel, copper, niobium, tungsten) [4, 5]. Studies of radiation sources were continued in [6, 7], which used a spark discharge mode in air at atmospheric pressure, which ensures the supply of the electrode material in the gap. It is also known that the effect of the plasma REP DD can be used for modification and purification of surfaces of various metal [8, 9].

In most cases, the development of new technologies of practical importance based on the effects of plasma on a variety of materials involves the use of a repetitively pulsed discharge regime. It can provide a modification of large areas of the processed material in a relatively short time. As the working gas, it is expedient to use cheap and available nitrogen and air at atmospheric pressure. This fact also improves the interest in the study of REP DD properties in nitrogen, including, for its spectral emission characteristics.

The purpose of this work - the study of spectral and amplitude-temporal characteristics of REP DD plasma radiation in nitrogen at the repetitively pulsed regime, leading to the appearance of the emission lines of copper atoms from which the electrodes were made.

2. Experimental setup and measurement

The block diagrams of the experimental setup are shown in Figure 1. The emission spectra of the discharge plasma were registered with use of the setup, depicted on the Figure 1a. The pulser NPG-15

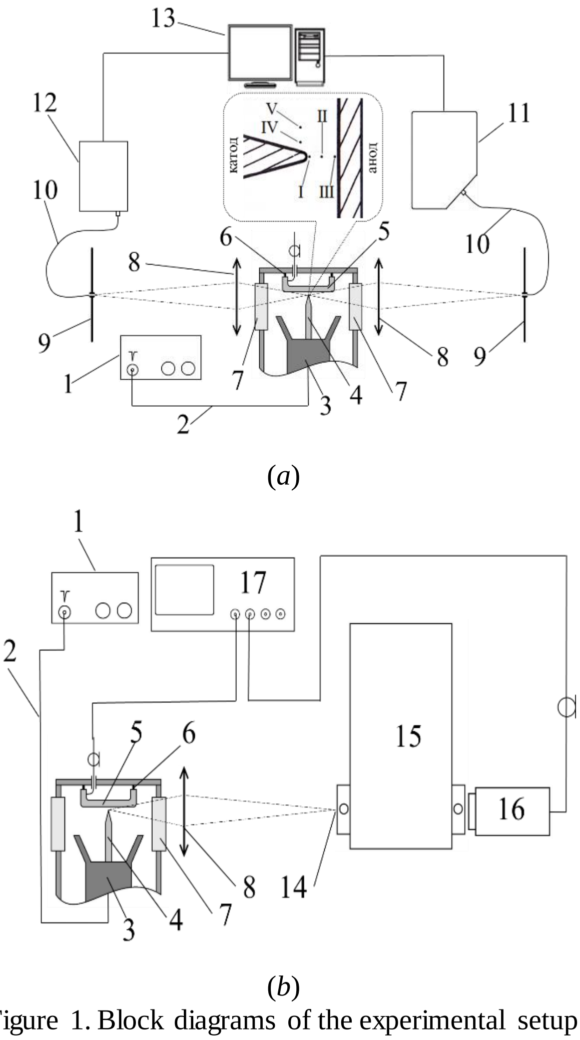

Figure 1. Block diagrams of the experimental setup for registration of spectral (a) and amplitude-temporal (b) characteristics of plasma radiation: 1 – pulser NPG-15; 2 – cable; 3 – isolator; 4 – cathode; 5 – anode; 6 – chip-resistors; 7 – side window; 8 – lens; 9 – screen with hole; 10 - optical fiber; 11 – spectrometer HR4000 (Ocean Optics B.V.); 12 – spectrometer EPP-2000C (Stellar-Net Inc.); 13 – PC; 14 - Hartmann diaphragm; 15 – monochromator MDR-23; 16 – PMT FEU-100; 17 – oscilloscope TDS3054B.

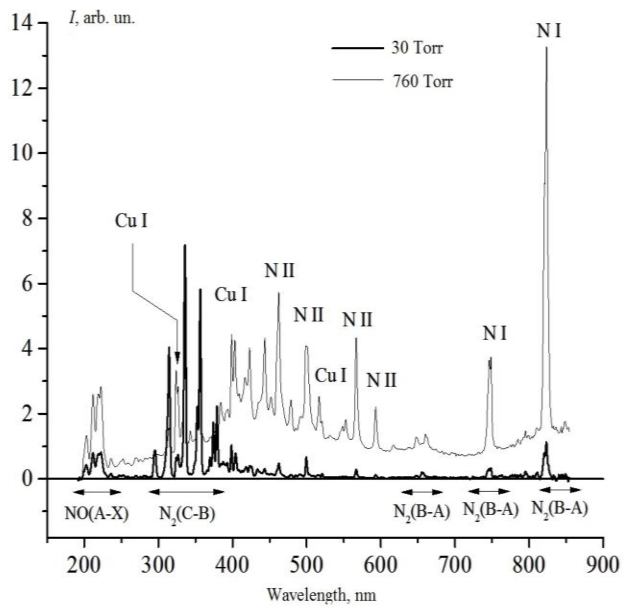

Figure 2. Emission spectra of diffuse (30 Torr) and constracted (760 Torr) discharge.

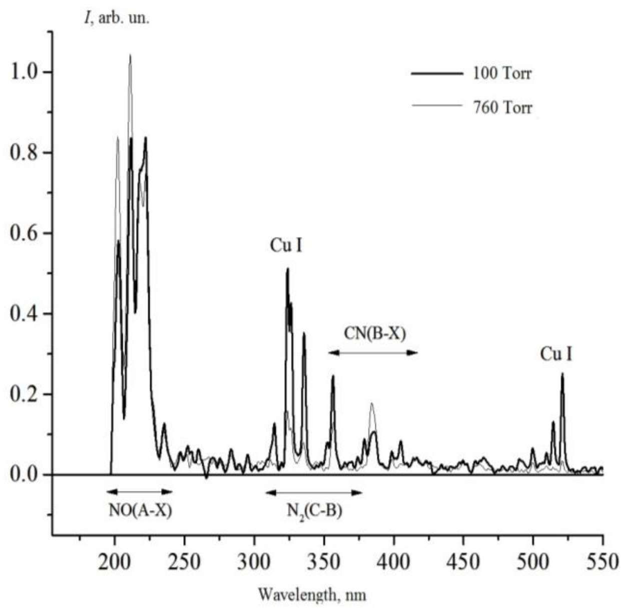

Figure 3. Emission spectra of discharge plasma from zone IV at pressure of 100 and 760 Torr.

(negative polarity voltage pulses with an amplitude up to 25 kV, front and pulse duration of 2.5 ns and 6 ns, respectively, pulse repetition rate 60 Hz) was used for discharge excitation. The needle cathode (4) and flat anode (5) made of copper located on the distance of 2 mm each other. The spectrometers HR4000, EPP-2000C and screens with holes (9) provided the registration of emission spectra of discharge plasma from different zones I – V of discharge volume (Figure 1a). The amplitude-temporal characteristics of plasma radiation were registered with the monochromator MDR-23 (15) and PMT FEU-100 (16) (Figure 1b).

3. Experimental results and discussion

During the experiments, it was found that the diffuse form of discharge (REP DD) maintained under nitrogen pressure to about 100 Torr. A further increase in pressure leads to the appearance of spark channels in the discharge gap in the background REP DD, as well as a change in the emission spectrum of a gas discharge plasma. The emission spectra of the diffuse plasma (pressure 30 Torr) and contracted (760 Torr) discharge recorded from the cathode zone I (Figure 1a) are shown on the Figure 2. The characteristic feature of the spectrum of the plasma REP DD, as in [4, 5], is the dominance of the bands of the second positive system of nitrogen N_2 (C-B) and the almost complete absence of the continuum. In the spectrum, there are also the bands of the first N_2 (B-A) and the third NO (A-X) positive systems of nitrogen, lines of copper CuI and nitrogen NI atoms, as well as lines of the atomic nitrogen ion NII.

The spectrum of the constracted discharge plasma includes a continuum from 200 to 850 nm, intensive bands N_2 (B-A) and NO (A-X), lines CuI, NI, NII, as well as relatively weak bands N_2 (C-B). As the distance from the cathode (zone II, III) the radiation intensity of the bands N_2 (C-B) and NO (A-X) is reduced due to the reduction of the electric field and the discharge current density in these areas of the discharge gap. The radiation intensity of the lines NI, NII in contracted discharge plasma is practically the same in zones I - III. The intensity of lines CuI in zone I monotonically increases with increasing pressure. Thus, the change in pressure from 30 to 760 Torr leads to ~ 4-times increase in the intensity of luminescence lines at wavelengths of 324.7, 327.3, 521.8, 515.3 nm. Note that the emission intensity of the CuI lines 510.6 and 578.2 nm, which are widely used in copper vapor laser in the visible range in the conditions of this experiment was small compared with the intensity of the lines 324.7, 327.3, 521.8, 515.3 nm.

In zones IV, V the intensity of CuI lines is nonmonotonic function of the gas pressure and reaches a maximum value at a pressure of 100 Torr. This is due, firstly, to increase the gas pressure increases, the current density and the concentration of copper vapor explosions and erosion of the cathode material. Second, with increasing pressure decreases the characteristic distance over which the copper atoms are moved by a shock wave produced by the explosion of cathode micropoints.

The emission spectra of the plasma discharge from zone IV at a nitrogen pressure of 100 and 760 Torr

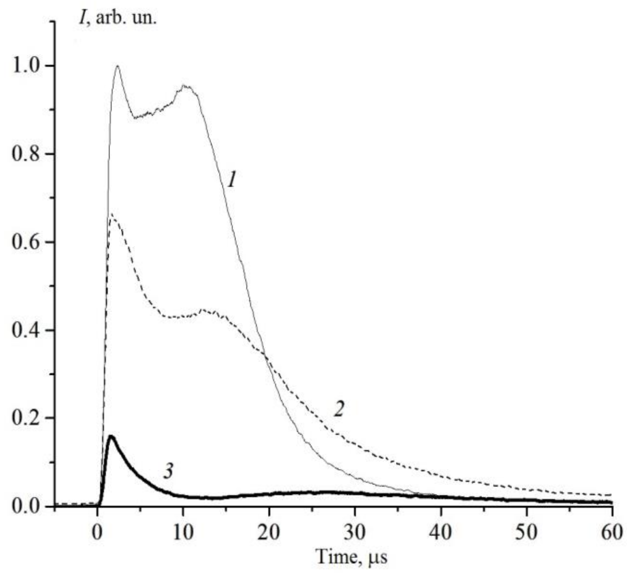

Figure 4. The time behaviour of the emission intensity at the wavelength of 521.8 nm CuI from zone II (1), and above it at a distance from the axis of the discharge gap of 1.75 mm (2) and 2.5 mm (3) at pressure of 200 Torr.

are shown on the Figure 3. As can be seen from the figure, except for emission lines CuI, NI, NII, in the spectrum emission the bands NO (A-X), N_2 (C-B), and purple bands of cyanogen CN (B-X) are observed.

The time behavior of the radiation intensity of copper atoms at the wavelength of 521.8 nm was registered in zone II, and above it at a distance from the axis of the discharge gap of 1.75 mm and 2.5 mm (Figure 4). The figure shows that as the distance from the axis of the discharge gap radiation intensity decreases.

Emphasis is placed on the availability of the second peak, as well as long duration pulses. On the curves 1, 2, 3 the first of the peaks recorded almost at the same time corresponds to the end of the excitation pulse. The delay of the second peak relative to the first one reaches ~10, ~11.5, ~25 μs in zone II and at a distance from her of 1.75 mm and 2.5 mm, respectively. Plasma emission at a wavelength of 521.8 nm after ~10 μs or more after the excitation pulse, given the fact that the radiative lifetime of the upper level of the transition CuI $^2D_{5/2}$ is ~13 ns [10] means that there is a channel of increase of population of this state at the stage of plasma relaxation. The most likely process ensuring the increase of population of the state CuI $^2D_{5/2}$ in the afterglow is the process of energy transfer from excited nitrogen molecules, which are in a metastable state N_2 $A^3\Sigma^+_u$ to the copper atoms. The lifetime of the state N_2 $A^3\Sigma^+_u$ is 13 seconds [11], which is much longer than the duration and period (16 ms) of excitation pulses. The appearance of the second peak on the curve of 1 (Figure 4), presumably due to reaching this point in time in the zone II maximum velocity of the transfer of excitation from nitrogen molecules in a metastable state N_2 $A^3\Sigma^+_u$ to the copper atoms, which increases the population of states CuI $^2D_{5/2}$ and, respectively, the radiation intensity at the wavelength of 521.8 nm. Later achieving maximum intensity of the second peak in curve 2, 3 in Figure 4 can be explained by the greater delay of the copper atoms coming in zones, remote from the axis of the discharge gap. Apparently, the main coming of the copper vapor in these area occurs when the contraction of the discharge. The appearance of the spark channel leads to the heating of the gas in the spark channel and a cylindrical shock wave formation. Under the influence of the shock wave, hot gas including a copper vapor and nitrogen molecules in a metastable state moves in a direction perpendicular to the shock wave front. Due to the aforementioned process of the excitation transfer, it leads to the re-rise of the radiation intensity at a wavelength of 521.8 nm (curves 2 and 3 in Figure 4) in zones distant from the longitudinal axis of the discharge gap.

4. Conclusion

The conducted studies showed that at nitrogen excitation with the pulse-periodic discharge initiated with runaway electrons in the gap with the needle cathode and flat anode made of the copper intense emission lines of CuI, NI and NII, the bands of second and the first positive systems of nitrogen, NO and CN are observed. It was established that in the area above the potential electrode (zone IV) luminescence intensity of copper vapor at wavelengths of 324.7, 327.3, 521.8, 515.3 nm is maximal at a pressure of 100 Torr. This pressure corresponds to the formation REP DD. As the pressure increases on the background REP DD on the axis of the discharge gap appears spark channel. The emission intensity of the copper atoms in the discharge channel increase monotonically with increasing nitrogen pressure. This is due to the pressure dependence of the rate of appearance and transport of copper vapor along the axis of the discharge gap.

The duration of radiation at a wavelength of 521.8 nm CuI on the order exceeds the duration of the excitation pulse. The appearance of repeated peaks on curves of the radiation pulses on this line and a large pulse duration are the result of an effective mechanism of excitation transfer from the nitrogen molecules in the metastable state N_2 $A^3\Sigma^+_u$ to copper atoms with the population of the state CuI $^2D_{5/2}$.

Acknowledgment

The work was supported by the grant from the Russian Science Foundation, project №14-29-00052.

5. References

[1] *Low Temperature Plasma Technology*, Edited by Paul K. Chu, XinPei Lu, CRC Press, Taylor & Francis Group, 2014.

[2] *Low Temperature Plasma. Fundamentals, Technologies, and Techniques*, Edited by R. Hippler, H. Kersten, M. Schmidt, K.H. Schoenbach, WILEY-VCH Verlag GmbH&Co. KGaA, Weinheim, 2008.

[3] Van der Horst R. M., Verreycken, van Veldhuizen and P.J. Bruggeman, *J. Phys. D: Appl. Phys.* **45** (2012) 345201.

[4] M. Erofeev, E. Baksht, V. Tarasenko, Yu. Shut'ko, *Quantum Electronics*, **40** (2010) 561.

[5] E. Baksht, V. Tarasenko, Yu. Shut'ko, M. Erofeev, *Quantum Electronics*, **42** (2012) 153.

[6] A. Shuaibov, G. Laslov, A. Minya, Z. Gomoki, *Technical Physics Letters*, **40** (2014) 943.

[7] A. Shuaibov, G. Laslov, and Ya. Kozak, *Optics and Spectroscopy*, **116** (2014) 552.

[8] E. Baksht, A. Burachenko, I. Kostyrya, M. Lomaev, D. Rybka, M. Shulepov and V. Tarasenko, *J. Phys. D: Appl. Phys.* **42** (2009) 185201.

[9] M. Shulepov, V. Tarasenko, I. Goncharenko, N. Koval', I. Kostyrya, *Technical Physics Letters*, **34** (2008) 296.

[10] A. Kramida, Yu. Ralchenko, J. Reader, and NIST ASD Team (2014). *NIST Atomic Spectra Database* (ver. 5.2), [Online]. Available: http://physics.nist.gov/asd [2015, February 4]. National Institute of Standards and Technology, Gaithersburg, MD.

[11] A. Radcig, B. Smirnov, *Handbook of atomic and molecular physics*, Moscow.: Atomizdat, 1980.