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Blue and green jets in laboratory discharges initiated by runaway electrons

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Abstract. Spectral and amplitude-temporal characteristics of plasma radiation of nanosecond pulse-periodic discharge in air, nitrogen and argon in pressure range of 30–760 Torr were investigated. Discharge gap geometry was a “point-to-plane”. Voltage pulses of negative polarity (amplitude, FWHM and risetime was 13 kV, 10 ns and 4 ns, respectively) were applied to a pointed cathode made of different metals (stainless steel, aluminum and copper). Jets of different colour were observed near a cathode tip. They are formed due to explosive emission. Colour of jets depends on the cathode material. Intense lines of the atoms and ions of iron in the wavelength range of 200–600 nm, aluminum with $\lambda = 394.4, 396.15$ nm, including multiply charged ion Al VI with $\lambda = 360.39$ and 361.65 nm, copper with $\lambda = 324.8, 327.3, 510.6, 515.3, 521.8, 522$ nm were registered. The resonance energy transfer from metastable $A^3\Pi_u^+$ level of nitrogen molecule to $3d^{10}4p$ level of Cu I was found. As a result a luminescence duration of Cu I was about 1.5 ms at duration of discharge current of 1.5 μ s. During constriction of the diffuse discharge the sputtering of material occurs in the direction perpendicular to the longitudinal axis of the discharge gap.

1. Introduction

Great attention has been given to study of pulse-periodic nanosecond discharges for the wide possibilities of their application in different fields of science and technologies [1, 2]. For example, a plasma of such discharge can be used for modification of different materials (metals, semiconductors, polymers) [1–3] as well as a point source of spontaneous radiation [4–7]. Depending on a discharge burning mode lines and bands of the different transitions can dominate in radiation spectrum. In diffuse discharge in nitrogen or air the radiation of the second positive (2^+) nitrogen system dominates [4, 5]. In a spark discharge a radiation of a cathode material vapour can become dominant in the emission spectrum. In paper [5] radiation of the atoms and ions of the iron was obtained at the interelectrode distance of 0.5 mm when the cathode made of a stainless steel was used. In paper [6] radiation of the atoms and ions of copper in discharge at atmospheric air pressure when the cathode made of a copper was obtained. In addition, bands of NO in a wavelength range of 200–300 nm were observed. Note that one of the features of the nanosecond discharge in “point-to-plane” gap is generation of the runaway electrons (REs) at the breakdown stage. REs are registered with collector behind the anode made of foil in both single and repetitive modes [8]. REs preionize gas in the gap and provide the diffuse discharge burning at high pressure.



The objective of the present work is study of spectral and amplitude-temporal characteristics of radiation of the pulse-periodic nanosecond discharge in air, nitrogen, argon at pressure range of 30-760 Torr with using different metallic cathodes (stainless steel, aluminum, copper).

2. Experimental setup

In experiments a repetitive pulser, a discharge chamber, spectrometers, a monochromator and a photomultiplier were used (figure 1). Voltage pulses of negative polarity with an amplitude of 13 kV, FWHM of 10 ns and risetime of 4 ns produced by the NPG-15/2000N pulser were applied to an electrode (cathode) made of different metals (stainless steel, aluminum, copper). Pulse repetition rate was 60 Hz. The cathode had a cone form. Diameter of cone base was 6 mm, and curvature radius of tip was about 0.2 mm. Grounded electrode (anode) was a disc with diameter of 38 mm. Interelectrode distance was 2 and 3 mm. Discharge current was registered with a shunt composed of low inductance chip-resistors. Spectra of the optical radiation of the discharge plasma from different regions of the discharge gap (shown in the red dashed frame in figure 1) were registered with the spectrometers HR4000 (Ocean Optics B.V., 1st: $\Delta\lambda = 330\text{--}425$ nm; 2nd: $\Delta\lambda = 200\text{--}305$ nm) and EPP-2000C (Stellar-Net Inc., $\Delta\lambda = 192\text{--}850$ nm). Waveforms of the discharge plasma radiation intensity from different regions of the discharge gap were registered with the MDR-23 monochromator and PMT-100 photomultiplier. Discharge chamber was filled with air, nitrogen and argon at pressure range of 30–760 Torr.

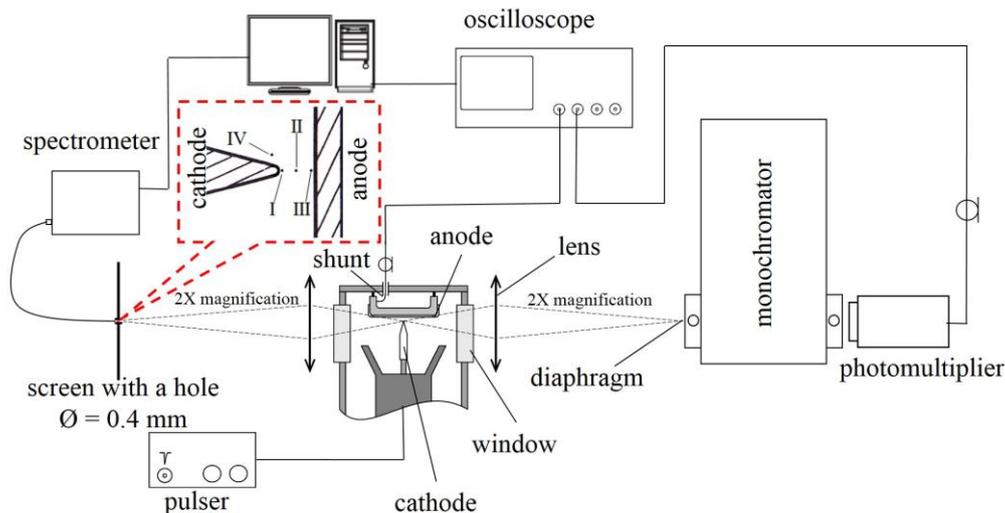


Figure 1. Scheme of experimental setup. Regions of spectrum registration are shown in red dashed frame.

3. Results

Let's consider results of experiment for each metal individually.

3.1. Stainless steel

The diffuse discharge was formed at pressure of gases up to 100 Torr. In this case radiation of (2^+) nitrogen system dominated in emission spectrum of discharge plasma. Subsequent pressure increasing led to formation of a spark discharge on the background of the diffuse discharge. Under these conditions, blue jets on the cathode surface around the one's tip were observed (figure 2). At gas pressure of 200 Torr and higher the blue jets were observed on the cathode tip only (figure 2b). The blue jets originate from bright spots (explosive emission centers) on the cathode surface. It indicates that the blue jets are a glow of metal vapor formed as a result of explosion of microinhomogeneities on the cathode surface and spark-erosion of the one.

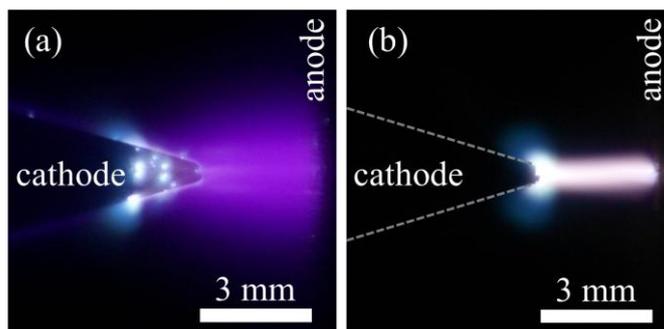


Figure 2. Image of the discharge plasma glow in air at pressure of 100 (a) and 200 Torr (b). Exposure time is 1 s. Pulse repetition rate is 60Hz. Cathode made of a stainless steel.

Increasing pressure leads to brightening of blue jets, but their size decreases. It's most likely that pressure increasing leads to reduction of injection distance of the metal vapor. The blue jets on the flat electrode surface were not observed. Spectrum of the discharge plasma radiation from regions IV and II at air pressure of 100 Torr and interelectrode distance of 2 mm are presented on figure 3. As is seen, radiation of (2^+) nitrogen system as well as the one of the nitrogen and oxygen atoms (N I, O I) and ions (N II, O II) dominates in the emission spectrum of the discharge plasma from the middle of the discharge gap, while near the cathode tip (region IV) a radiation of the iron atoms (Fe I) and ions (Fe II) dominates. There are about 12500 lines of Fe I and Fe II in the wavelength range of 200–600 nm [9].

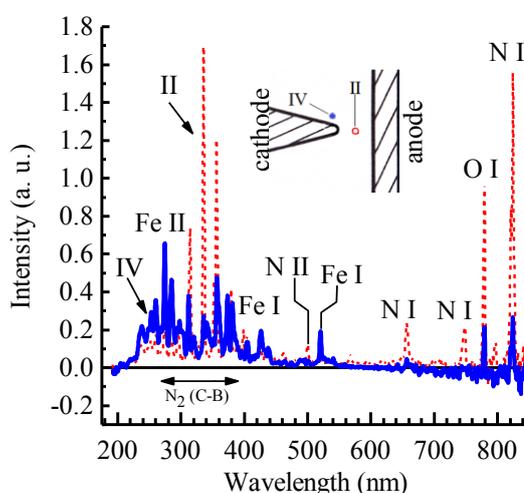


Figure 3. Spectrum of discharge plasma radiation in air at pressure of 100 Torr. Interelectrode distance is 2 mm. Cathode made of a stainless steel.

Dependence of discharge plasma radiation intensity from different regions of the discharge gap on gas pressure has a complex character. Spectra of the discharge plasma radiation from region I at argon pressure of 100 and 760 Torr and dependence of Fe I ($\lambda = 404.58$ nm) and Fe II ($\lambda_1 = 259.84$ nm, $\lambda_2 = 259.94$ nm) radiation intensity in different regions of the discharge gap on pressure of argon are shown in figure 4. It is seen that the radiation intensity of Fe II from regions I, II, III, IV (figure 4c) increases with pressure increasing up to about 400 Torr, but then it decreases. The radiation intensity of Fe I from region I (figure 4d) increases with pressure increasing up to 760 Torr, while one of regions II, III, IV reaches a maximum at pressure of about 400 Torr.

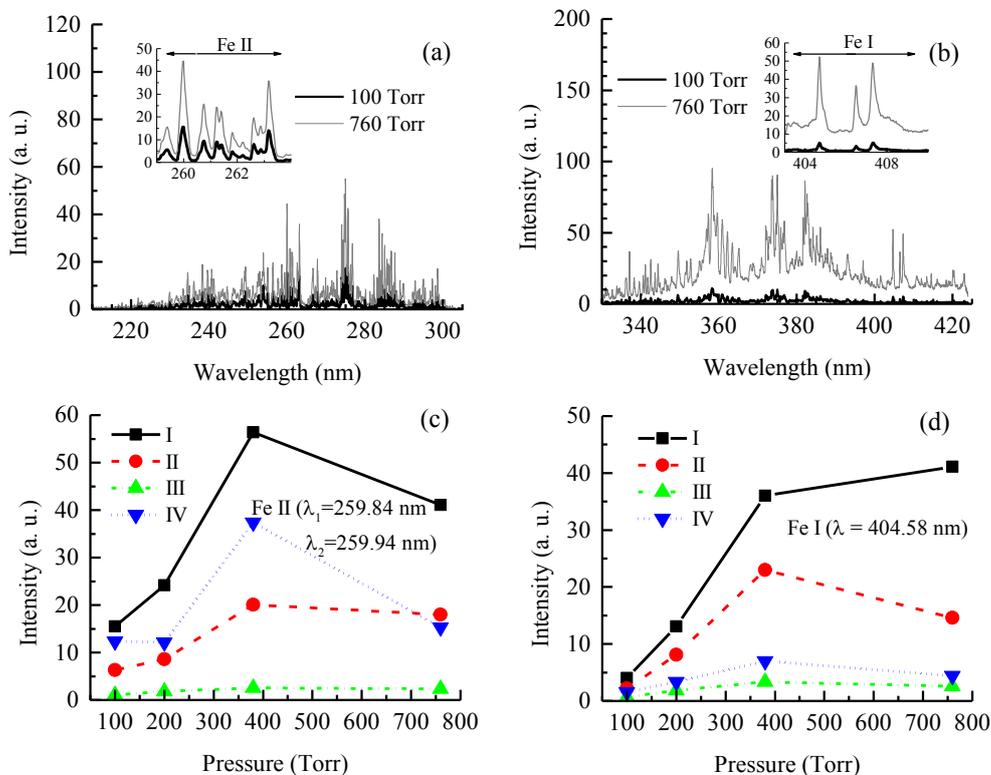


Figure 4. Spectra of the discharge plasma radiation from region I (a, b) and dependence of Fe I ($\lambda = 404.58$ nm) and Fe II ($\lambda_1 = 259.84$ nm, $\lambda_2 = 259.94$ nm) radiation intensity in different regions of the discharge gap on the argon pressure (c, d). Interelectrode distance is 2 mm.

As it was noted above, increasing of gas pressure leads to constriction of diffuse discharge. The discharge current density increases respectively. It contributes to erosion of the cathode and formation of the metal vapor. However, high pressure of gas reduces the injection distance of the metal vapor.

3.2. Aluminum

In the same way as for stainless steel the blue jets were observed on the cathode surface but not only near the cathode tip. At gas pressure of 30 and 50 Torr the discharge occupies whole volume of discharge chamber and the blue jets are observed on a cylindrical surface of the cathode. It is known that aluminum is more fusible as compared with stainless steel. Hence, the explosive emission centers on the aluminum cathode surface are formed at lower density of discharge current than on the stainless steel cathode surface. At gas pressure of 100 Torr and higher the blue jets were observed near the cathode tip only. In this pressure range the discharge formed between the cathode tip and the flat anode (like in figure 2b).

Spectral investigation with high-resolution spectrometers HR4000 shown that there are intensive radiation of the aluminum atoms (Al I) and ions (Al II) in emission spectrum of the discharge plasma. Radiation of Al I with $\lambda = 394.4, 396.15$ nm that impart blue colour of jets (upper level is $3s^24s$ ($^2S_{1/2}$) (3.14 eV), lower levels are $3s^23p$ ($^2P^0_{1/2}$) (0 eV) and $3s^23p$ ($^2P^0_{3/2}$) (0.014 eV) respectively [9]) as well as the one of Al II with $\lambda = 280.12, 280.55, 281.62$ nm are registered. Further still radiation of multiple charged ion Al VI with $\lambda = 360.39$ and 361.65 nm (upper levels are $2s^22p^3$ ($^2D^0$) $3p$ (3D_2) (127.84 eV) and $2s^22p^3$ ($^2D^0$) $3p$ (3D_1) (127.82 eV) respectively, lower level is $2s^22p^3$ ($^2P^0$) $3s$ ($^1P^0_1$) (124.4 eV) [9]) were registered. Dependence of the radiation intensity of Al I on pressure of gases is similar to the one of Fe I (figure 4b). However maximum of the radiation intensity in region II, III, IV is observed at pressure of about 200 Torr. Waveforms of the radiation intensity of Al I with $\lambda = 396.15$ nm and (2^+)

nitrogen system with $\lambda = 380.1$ nm as well as waveform of the discharge current at the nitrogen pressure of 200 Torr are presented in figure 5. The waveform of the discharge current consists from some short spikes (about 40 ns) due to multiple reflections of the voltage pulse. It is caused by an impedance mismatch. Full duration of the discharge current is about 1.5 μ s. Duration of one spike on the base is about 35 ns. Radiation of (2^+) nitrogen system with $\lambda = 380.1$ nm is registered during first spike (the diffuse stage of the discharge). Duration of the Al I radiation with $\lambda = 396.15$ nm is about 3 μ s and exceeds the one of the discharge current. Likely, such character of the waveform of the Al I radiation is determined by a recombination afterglow.

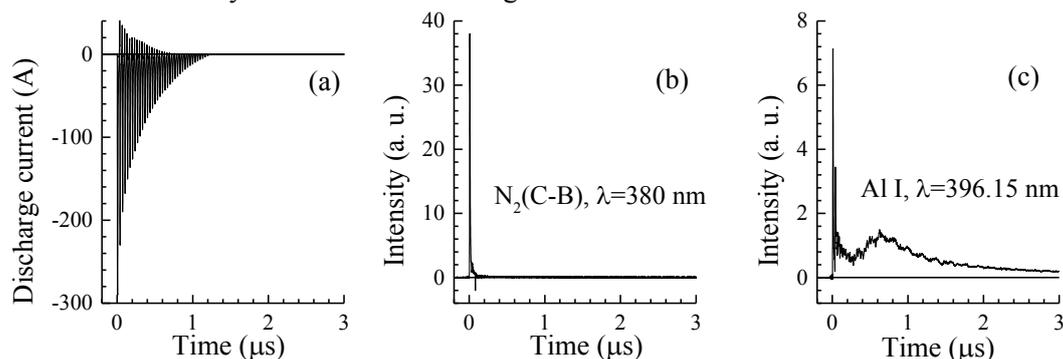


Figure 5. Waveforms of discharge current (a), radiation intensity of $N_2(C-B)$ with $\lambda = 380$ nm (b) and radiation intensity of Al I with $\lambda = 396.15$ nm. Interelectrode distance is 2 mm. Nitrogen pressure is 200 Torr.

3.3. Copper

When the cathode was made of a copper green jets were observed. Like in case of the aluminum cathode, the green jets are observed on whole cathode surface at gas pressure of 30 and 50 Torr. At pressure above 100 Torr the green jets are observed near the cathode tip only. In emission spectrum of the discharge plasma radiation Cu I lines with $\lambda = 324.8, 327.3, 510.6, 515.3, 521.8, 522$ nm were registered. It is necessary to note that radiation intensity of Cu I with $\lambda = 510.6$ and 578.2 nm (laser lines) was a far fewer as compared with the one of Cu I with $\lambda = 324.8, 327.3, 515.3, 521.8, 522$ nm. Dependence of the radiation intensity of Cu I on gas pressure is similar to the one of Al I.

In air and nitrogen a glow of discharge plasma had an interest feature. Orange jets from discharge channel flowing along the anode surface were observed (figure 6a). However, the orange jets were not

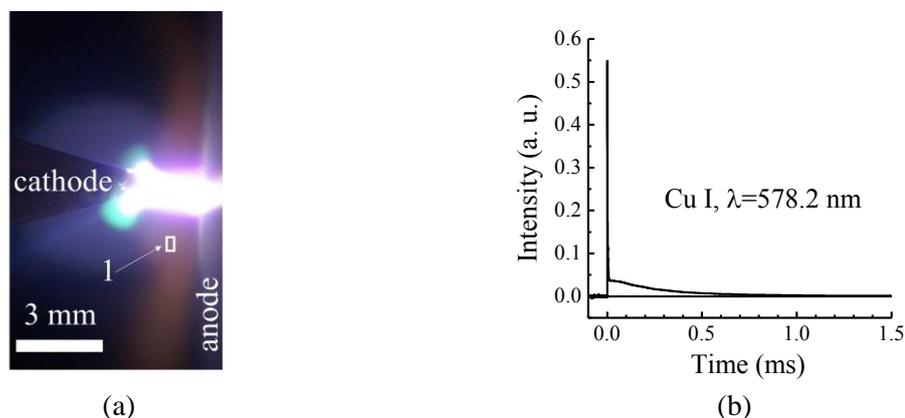


Figure 6. Image of the discharge plasma glow in nitrogen at pressure of 200 Torr (a) (exposure time is 1 s, pulse repetition rate is 60 Hz, cathode made of a copper) and waveform of radiation intensity of Cu I with $\lambda = 578.2$ nm from region 1 (b). Interelectrode distance is 2 mm. observed in argon and/or when the cathode was made of aluminum or stainless steel.

In the paper [10] it is noted that there is the resonance energy transfer from metastable $A^3\Pi_u^+$ level of nitrogen molecule (spontaneous lifetime is 13 s) to $3d^{10}4d$ level of Cu I in plasma. Moreover, high-energy vibrational levels of $X^1\Sigma_g^+$ state of nitrogen molecule can transmit energy to $3d^{10}4p$ level of Cu I. It leads to increasing of the luminescence duration of the Cu I with $\lambda = 578.2$ nm up to 1.5 ms (figure 5b).

Discharge plasma products sputter in radial direction at the discharge constriction. Copper atoms contained in the ones provide the orange glow of the jets. Thereby the sputtering of the discharge plasma products is visualized. Material deposition on the inner side surface of the discharge chamber in region that stood in the way of the orange jets was found. Deposited material consists from homogeneous particles with thickness about 0.5 μm and length about 3–5 μm .

4. Conclusion

We studies experimentally the spectral and amplitude-temporal characteristics of optical radiation of the nanosecond pulse-periodic discharge in air, nitrogen and argon at pressure range of 30–760 Torr. It was found that in diffuse discharge jets of different colour are formed on the cathode surface due to explosive emission. It was shown, that on the one hand, pressure increasing leads to increasing intensity of the metal vapour formation due to constrictions of the diffuse discharge but in other hand, the one leads to reduction of the injection distance of the metal vapour. Colour of jets depends on the cathode material. Intense lines of the atoms and ions of iron, copper and aluminum, including the multiple charged ion Al VI with $\lambda = 360.39$ and 361.65 nm, were registered. It was found that due to the resonance energy transfer from metastable $A^3\Pi_u^+$ level of nitrogen molecule to $3d^{10}4d$ level of Cu the luminescence duration of Cu I with $\lambda = 578.2$ nm reaches about 1.5 ms. During constriction of the diffuse discharge the sputtering of material occurs in the direction perpendicular to the longitudinal axis of the discharge gap.

Acknowledgments

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