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Characteristics of High-Current Pulse Discharge in Air with Ectonic Mechanism of Copper Vapor Injection into a Discharge Gap

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Abstract—The characteristics of bipolar high-current nanosecond discharge in the air between the copper electrodes is described. With an inter-electrode gap of 1–2 mm and the air pressure of 0.05–3.0 atm the conditions for obtaining a homogeneous volume discharge in the inhomogeneous electric field, associated with the generation of a beam of a runaway electron and concomitant X-ray radiation, are realized. It is shown that this discharge is a simple point source of radiation in the spectral range of 200–230 nm on the transitions of singly charged copper ions. The results of the optimization of the UV-emitter depending on the pump conditions and parameters of the discharge medium are provided. It is found that under the influence of a discharge, a deposition of thin nanostructured membranes made of electrodes erosion products and products of dissociation of air molecules is possible.

Keywords: bipolar nanosecond discharge, copper, air, emission and transmission spectrum, nanostructures

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INTRODUCTION

At present, the most efficient and powerful gas discharge ultraviolet lamps are exiplex lamps on electron-oscillation transitions of monohalogenides of inert gases (XeCl, XeBr, KrF, KrCl and other similar molecules) with pumping of different types of barrier discharge [1, 2]. Equally effective exiplex lamps for the visible portion of the spectrum are emitters on mercury monohalogenides with a working medium based on salts of mercury dihalogenides [3]. They are extensively used in photochemistry, photobiology, micronanoelectronics, medicine, ecology and a number of other fields of science and engineering [4, 5]. These lamps emit a single band up to 10 nm or several such bands, which exceed a spectral range of radiation of 120–355 nm only partially. The radiation of the exiplex gas discharge lamps does not exceed the window in a spectral interval of 210–220 nm.

A number of spectroscopic applications require the point sources of a relatively intense UV-radiation with a plasma level of 1–5 mm^3, which can be realized technically due to a barrier discharge [6]. Therefore, the development of the point UF-lamp on the copper vapors is of high priority, which exceeds spectral interval of 200–230 nm. Air at $p = 1$ atm can be the major gas for this lamp, which is essential for the development of the windowless point lamps with a cheap working medium free from pollution of the working window with the products of the electrode evaporation. In plasma of nanosecond discharges in air, one of the main accumulators of energy are nitrogen molecules in a metastable state. The energy from these states is efficiently transferred by the copper atoms [7]. The stepwise excitation and ionization of metastable or quasi-metastable copper atoms ensure the formation of copper ions in the excited states.

Study of the pulse discharges between metal electrodes in the air at their ignition from the generators of high voltage pulses with nanosecond duration showed that on their bases the selective point ultraviolet (UV) lamps filled with the vapors of the electrode material can be elaborated [8]. These discharges in the air of the atmospheric pressure at small electrode gaps ($d = 1$–2 mm) are spatially homogeneous even at a strongly inhomogeneous distribution of the electric field intensity in the inter-electrode gap. They can ignite in a strongly overvoltage gas gaps and can be accompanied by generation of the beam of runaway electrons and concomitant X-ray radiation [9]. The runaway electrons and concomitant X-ray radiation perform the automatic role of pre-ionization, which is important when using these discharges as ultra-violet emitters. The characteristics of similar emitters is more thoroughly studied using the monopolar pulses of high voltage with duration of 1–5 ns [10].

Because the radiation spectra of these discharges in the UV-range of the wave lengths are determined by the spectral lines of atoms and ions of the electrodes' materials, the study of optical features of plasma of these emitters is of interest, together with pumping by

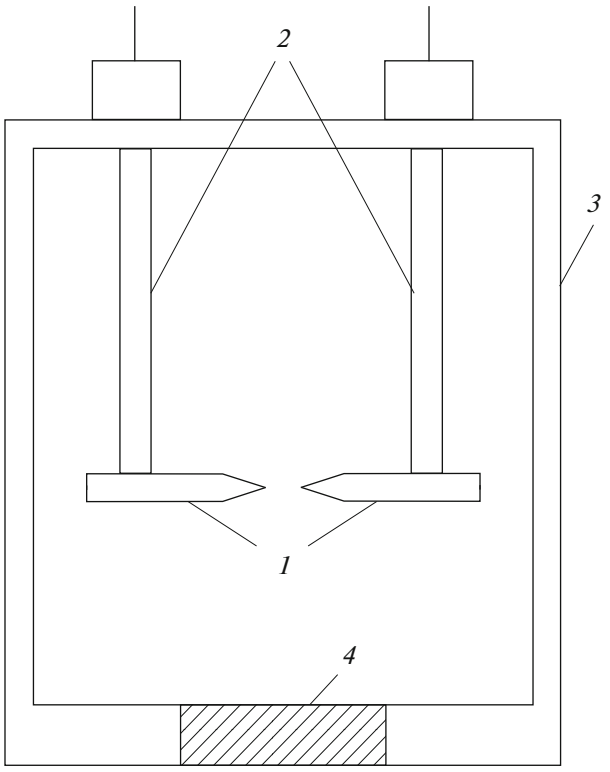

Fig. 1. Scheme of discharge chamber: *1* is copper electrodes; *2* is the high voltage in-let holders for copper electrodes; *3* is a vacuum chamber made of dielectric; *4* is the window from quartz KU.

the pulses of current and voltage of the order of 50–100 ns. The use of bipolar pulses of high voltage makes this device more compact, which allows using the electrode material more uniformly at its destruction in strong electric fields due to the ectonic mechanism of injection of metal vapors into the discharge plasma of the air [11]. Ectons imply the occurrence of short-term avalanches of electrons, when the conditions for their emission are ensured by the electrons themselves. The term "ecton" has its root in the initial letters of the English expression "explosive center". The appearance of the ecton in high voltage discharges is generally connected with the autoelectronic emission from the cathode microprotrusions. The current density in similar discharges reaches 10^7–10^9 A/cm^2, which causes the microprotrusions' explosions at the cathode surface. The time of the emission of electrons reaches 10 ns; further, the emission decays in itself, since the explosive center cools by itself due to a high heat transfer of the metal cathode. The latter processes are accompanied by the drop of the current density and decrease in the mass injection of the electrode material [12, 13].

This article presents the results of the study of spatial, electric and optical characteristic of bipolar high-current discharge with copper electrodes in air.

EXPERIMENTAL

Figure 1 shows the construction of the system of electrodes between which was ignited a nanosecond discharge in the air. The electrodes were placed into a hermetic dielectric chamber 3 L in volume. Most experiments were performed in a windowless regime of the work of UF-emitter (with the quartz output window being absent). The pressure of air was 1 atm. Prior to the letting-to-air into the chamber, the latter could be pumped out up to a residual air pressure of 5–10 Pa. The pressure in the chamber varied in the range of 0.05–3.0 atm.

To decrease the effect of the electromagnetic pick-ups on the system of registration of characteristics of the discharge, the cell with the electrode system was installed into the screen from the metal wirecloth. The cylinder copper electrodes were 5 mm in diameter, and the radius of rounding of the working flank of the electrodes was 3 mm.

For the discharge ignition the electrodes were supplied with bipolar pulses of high voltage of a total duration of 50–100 ns and the amplitude of ±(20–40) kV. Simultaneously, between the electrodes' tips the uniform discharge was ignited with the pulse amplitude of the current of 50–170 A [14]. The plasma volume was up to 5–10 mm^3. With the interelectrode gap being 1 mm, the discharge gap was heavily overvoltaged. In such a mode of ignition of the discharge, the favorable conditions were created for the formation of the electrons' beam of high energy. The electrons were continually accelerating and leaving the discharge gap [3]. As shown in the direct measurements of the intensity of the runaway electrons' beam, which passed through the thin metal film anode in a nanosecond high current discharge in nitrogen at a discharge voltage of 30–35 kV and the distance between the electrodes of 2–20 mm, the beam of runaway electrons can be formed only at a nitrogen pressure less than 100 torr [15]. Therefore, under conditions of our experiment with the air pressure of p = 1–3 atm the main factor to ensure the formation of a relatively uniform nanosecond discharge is the effect of the system of a preliminary ionization, whose role in this case belongs to the UV-HUV and the X-ray radiation of the discharge plasma.

The voltage pulses at a discharge gap and the discharge current were measured using a wide-band capacity divider, Rogowski coil and a 6-LOR 04 wide-band oscillography. The time resolution of this system of registration was 2–3 ns. The study of the spatial characteristics of the discharge was performed using a digital photocamera. The repetition rate of the pulses varied in the range of f = 35–1000 Hz. To register the spectra of radiation of plasma we used a MDR-2 monochromator, an FEU-106 photo multiplier cell, amplifier of the constant current and electronic potentiometer. The discharge radiation of plasma was analyzed in the spectral region of 200–650 nm. The system of registration of plasma radiation was cali-

brated according to the radiation of deuterium lamp in the spectral range of 200–400 nm and band-lamp in the range of 400–650 nm.

The measurement of the total relative power of the UF-radiation of the discharge in the spectral range of 200–280 nm was done using a TKA-PKM ultraviolet meter of the power of the radiation.

CHARACTERISTICS OF BIPOLAR HIGH CURRENT DISCHARGE

The article presents the results of the study of spatial, electric and optical characteristics of a high current nanosecond discharge on copper and air vapors under condition of explosions of micropoints at the electrodes' surfaces and the ectons' formation, as well as at a strong overvoltage of the discharge gap in the air at pressures of 1–3 atm.

The microimages of the discharges at different frequencies of voltage pulse repetition in air of the atmospheric pressure are shown in Fig. 2. At small frequencies of repetition of the pump pulses $f = 35$–150 Hz, the discharge had a diffusion form, and a diameter of a spherical plasmaformation in the discharge gap was about the value of the interelectrode distance (Fig. 1a). With an increase in the frequency of repetition of the voltage pulses up to 400–1000 Hz, the diameter of the plasmaformation increased 3- to 4-fold times and embraces new sections of surface of the spherical part of the electrodes (Fig. 1b). This behavior of the discharge can be attributed to the residual phenomena in plasma, when the density of the charged particles has no time for relaxing to its initial value at the interpulse period.

The diffusion form of the discharge under study at the atmospheric pressure of the air is supported by the results of the study of the spatial characteristics of the transverse nanosecond discharge without a special system of preionization. It was ignited from a modulator with the amplitude of the voltage pulses less than 35 kV in nitrogen at $p = 30$—760 torr. Photographing this discharge with a simultaneous examining its spatial characteristics, using a CCD camera, showed that the diffusion form of similar discharges remains unchanged through the entire duration of the voltage pulse and at different frequencies of its repetition [15].

Because of the inconsistent coming-out of the high voltage modulator and the discharge and the presence of the reflected pulses from the discharge gap with plasma, the voltage pulse consisted of separate pulse spikes with duration of about 5–10 ns. The duration of the main part of the voltage pulse train reached 50–100 ns. The amplitude of the bipolar voltage pulse spikes had positive and negative components of up to 30 kV (Fig. 3). The current pulses of the nanosecond discharge were a succession of short bipolar pulse spikes of current with the amplitude of positive and negative ejections of 120–150 A. The overall length of

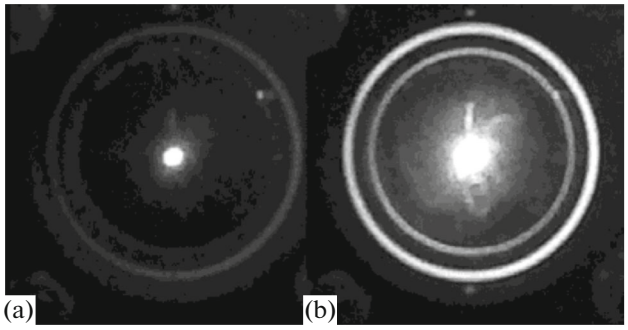

Fig. 2. Microimages of the discharge in air of atmospheric pressure at a distance of $d = 1$ mm between the electrodes and the frequency of repetition of voltage pulses of 40 (a) and 400 (b) Hz.

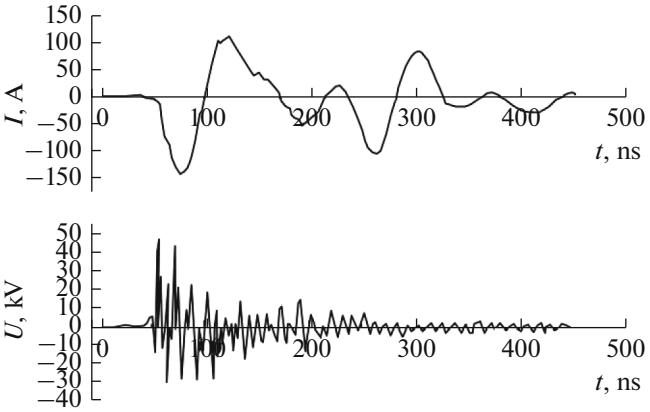

Fig. 3. Pulses of current and voltage of bipolar nanosecond discharge at the air pressure of $p = 101.325$ kPa ($d = 1$ mm).

succession of the pulse spikes of current with the amplitude droppiing in time reached 150–200 ns (Fig. 3). By means of a graphic multiplication of oscillogram of the pulses of current and voltage, we obtained a distribution in time of the pulse energy contribution into the plasma of bipolar nanosecond discharge. The maximum pulse power of the discharge was detected at the initial stage of the breakdown of the discharge gap and it reached 4 MW.

Time integration of the pulse power allowed us to determine the electric energy that was supplied into plasma of the charge under study during the time of a single succession of pulses of voltage and current. For the conditions of ignition of bipolar nanosecond discharge at an air pressure of 1 atm and other conditions presented under Fig. 2, this value of energy maximally reached E = 105 mJ [14].

Figure 4 shows the dependences of the average power of the UV-radiation of the discharge plasma (in arb. units) in a spectral range of 200–280 nm on the frequency of the voltage (current) pulse repetition and the value of the charge intensity of the working capacity of the high voltage modulator.

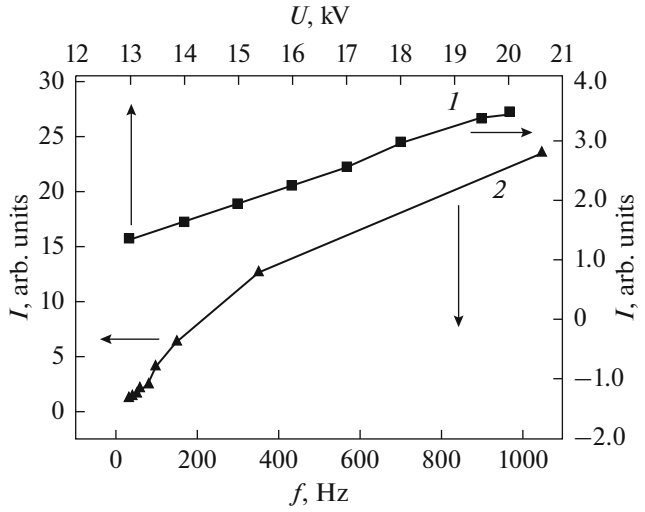

Fig. 4. Dependences of relative intensity of the UV-radiation of plasma of bipolar nanosecond discharge in the spectral range of 200–280 nm on the frequency of the current pulses repetition at the charge voltage of the working capacitor of high voltage modulator U_{ch} = 13 kV and the magnitude of the charge voltage of the working capacitor of high voltage modulator (*2*) (at f = 35 Hz).

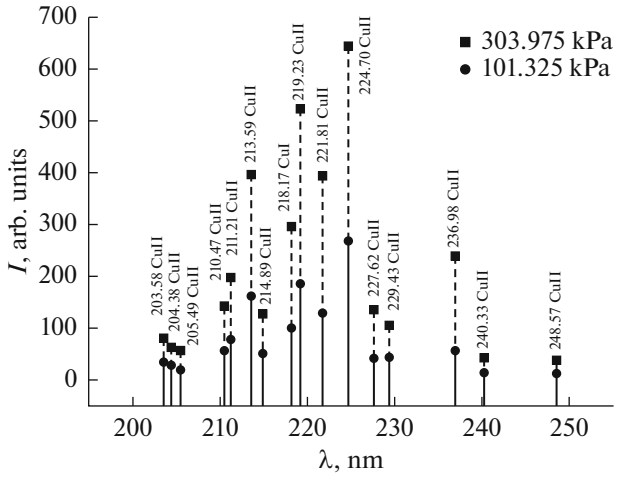

Fig. 5. The section of radiation spectrum of plasma with the most intense spectral lines of radiation of atoms and ions of copper at the air pressure of 101.325 kPa and 303.975 kPa (U_{ch} = 13 kV, d = 1 mm, and f = 40 Hz).

As can be seen in Fig. 4, the dependence of the power of the UV-radiation of the discharge on the frequency was nonlinear, its maximum increase was registered in the range of frequencies of 40–50 Hz. With an increase in the frequency of the voltage pulse repetition from 50 to 1000 Hz the average power of the UV-radiation of the discharge increased by about an order of magnitude. Meanwhile, the growth in the charge voltage of the working capacitor from 13 to 20 kV (at f = 35 Hz) increased the UV-radiation power by about two times. The obtained results show that to increase the average power of the UV-radiation of the discharge the most promising is the increase in the frequency of the voltage pulse repetition.

The study of the spectral characteristics of the discharge radiation showed that about 90% of its power of plasma radiation in the spectral range of 200–1000 nm is focused in the spectral range of 200—230 nm.

Figure 5 shows the section of plasma radiation spectrum (λ = 200–230 nm) of nanosecond discharge in the air between the copper electrodes. The spectrum was aligned with the sensitivity of the photomultiplier and monochromator in this spectral range of the wave lengths. An increase in air pressure of 1–3 atm caused all spectral lines in the range of the wave lengths of 200–230 nm to increase in intensity.

The same as for a less powerful unipolar nanosecond discharge between the copper electrodes [8], the spectral lines of the copper ions were the main in the radiation spectrum. The obtained spectrum of the UV-radiation also well correlated with the radiation spectrum of the unipolar nanosecond discharge with a beam of runaway electrons (at the length of pulses of voltage 1–5 ns between the copper electrodes and d = 0.5 mm) [10].

The results of identification of the radiation spectrum are shown in Table 1.

Because, in the present experiment, the main mechanism was ectonic (the micropoints' explosion at the surface of the electrodes) for the copper vapor that enters plasma, with the density of electrons in plasma reaching 10^{16}–10^{17} cm^{-3} [11], the mechanism of formation of excited copper ions can be determined by the processes of excitation of copper ions in the major state of electrons, as well as by the processes of the electron-ion recombination. The efficient cross-sec-

Table 1. The results of identification of the most intensive spectral lines in radiation spectrum of bipolar nanosecond discharge in air (p = 1 atm, d = 1 mm and f = 100 Hz)

λ, nm	Object	I, arb. units	E_n, eV	E_v, eV	Transition
203.1	Cu II	15	8.23	14.34	$4p\ ^3P^0$-$4d\ ^3P$
203.5	Cu II	30	2.98	9.06	$4s\ ^3D$-$4p\ ^3D^0$
203.7	Cu II	30	2.83	8.92	$4s\ ^3D$-$4p\ ^1F^0$
204.3	Cu II	60	2.72	8.78	$4s\ ^3D$-$4p\ ^3D^0$
205.4	Cu II	50	2.83	8.86	$4s\ ^3D$-$4p\ ^3D^0$
212.6	Cu II	50	2.83	8.66	$4s\ ^3D$-$4p\ ^3F^0$
213.5	Cu II	75	2.72	8.52	$4s\ ^3D$-$4p\ ^3F^0$
224.1	Cu I	2	11.83	17.36	$4d\ ^4D$-15^0
224.7	Cu II	75	2.72	8.32	$4s\ ^3D$-$4p\ ^3P^0$

tions of these processes, e.g., for the ions of indium, zinc and cadmium, are fairly large and reach 10^{-16} cm^2 [16, 17].

CONCLUSIONS

It was found that the nanosecond discharge in air of atmospheric pressure between the copper electrodes at a strong overvoltage of the discharge gap is a selective source of radiations of copper ions in a spectral range of 200—300 nm; the maximum pulse energy contribution of 4 MW into plasma was reached, and the energy contributed into the discharge during a single pulse is about 0.1 J; the most probable mechanisms of excitation of the UV-radiation of the copper ions are the ectonic mechanism of erosion of the surface of copper electrodes with an electron impact, as well as the formation of Cu^{+}* ions in the processes of electron-ion recombination of double-charge copper ions and electrons.

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