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UV RADIATION SOURCES

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Point-like pulse-periodic UV radiation source with a short pulse duration

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***Abstract.* The radiation of discharge plasma was investigated in the nanosecond breakdown of short interelectrode gaps in a nonuniform electric field. Voltage pulses with an incident wave amplitude of ~10 kV, a FWHM duration of ~1 ns, and a rise time of ~200 ps were used. X-ray radiation from the discharge gap was recorded for an interelectrode gap of 0.5 mm, which confirms the generation of runaway electrons in the discharge formation. In the pulse-periodic air breakdown of a 0.5-mm wide gap at atmospheric pressure, the lines of electrode materials and the continuum were shown to make the main contribution to the plasma emission; the highest radiation intensity fell on the 200 – 300 nm region, which accounted for ~40 % of the total emission energy.**

Keywords: *point UV radiation source, pulse-periodic regime, spectral composition of radiation.*

1. Introduction

At present the sources of UV and VUV spontaneous radiation are vigorously investigated and enjoy wide use in different areas of science and technology [1 – 3]. However, the devices developed to date and manufactured by the industry do not satisfy all requirements. For instance, to calibrate spectral instruments and optical elements requires point UV and VUV radiation sources with a radiating volume of ~1 mm^3 and a relatively high pulsed output power (above 1 W). Also of practical interest are the sources with a nanosecond pulse duration operating in a pulse-periodic regime.

To make pulsed sources with a small emitting surface area, advantage is most often taken of barrier-discharge excilamps. [4]. In these sources, use is made of the radiation of one or several diffusive microdischarges. In the case of an elevated-pressure barrier discharge, its homogeneity is achieved by placing dielectric barriers at one or both electrodes; however, their use increases the dimensions of discharge plasma region and limits the discharge current. The latter leads to a lowering in pulsed radiation power. Furthermore, the optimal dimensions of the interelectrode gaps in barrier discharge excilamps are equal to 5 – 8 mm and depend on the gas mixture composition.

The implementation of UV and VUV radiation sources with excitation by a runaway electron ionised diffuse discharge (REP DD) has been reported in the literature [5 – 7]. For low pulse repetition rates these sources are capable of delivering low and high (~1 MW [5]) pulsed output powers in the VUV spectral domain. However, to produce a REP DD use is commonly made of voltage pulses with an amplitude above 100 kV and of interelectrode gaps of 1 cm and wider.

The authors of Ref. [8] demonstrated the feasibility of employing the REP DD regime for the development of miniature sources operating at a pulse repetition rate up to 1 kHz. The radiation pulse duration of the 2$^+$ system of nitrogen in the air at atmospheric pressure was equal to ~3 ns for a 2-mm wide interelectrode gap. The diffusive discharge between two electrodes with a small radius of curvature in the air at atmospheric pressure was produced due to enhancement of the electric field at the electrodes and subnanosecond-long voltage pulses with an amplitude of ~14 kV.

The aim of our work is to study the radiative characteristics of a nanosecond high-voltage discharge with electrodes of small radius of curvature and to make a point short-pulse UV radiation source with a radiating plasma volume of less than 1 mm^3 operating in a pulse-periodic regime. The impetus to the commencement of this work was lent by the data of spectral investigations [8]. It was discovered (see Fig. 5 in Ref. [5]) that narrowing the interelectrode gap gave rise to a new band in the 200 – 300-nm wavelength domain, which was lower in intensity than the nitrogen 2$^+$ system emission.

2. Experimental

In our experiments use was made of an FPG-10 generator with a voltage pulse amplitude up to 12.5 kV in the transmission line. In comparison with the generator employed in Ref. [8], this generator version afforded, in the case of operation with a matched load, a longer half-amplitude voltage pulse duration for a rise time of ~0.2 ns at a 0.1 – 0.9 level (Fig. 1a). The generator was connected to the discharge gap via a 50-Ω cable of length 1.3 m. To measure the voltage across the discharge gap and the discharge current (Fig. 1b), a part of the cable connected to the generator was replaced with a 50-Ω transmission line with two built-in capacitive voltage dividers. The discharge was formed in the atmospheric pressure air between the two electrodes terminating in cusps with small radii of curvature. They were made of stainless steel, aluminium, copper, titanium, tantalum, and tungsten. Stainless steel electrodes were standard medical needles with an outer diam-

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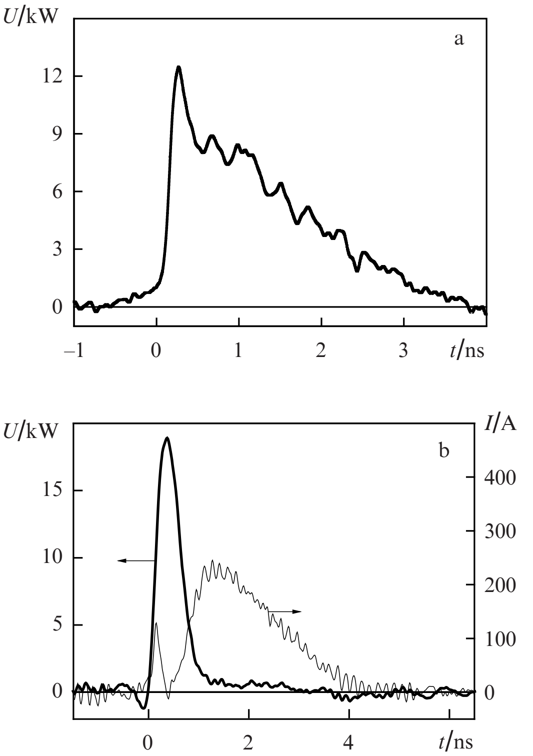

Figure 1. Oscilloscope trace of the incident voltage wave from the FPG-10 generator (a) and the recovered voltage pulses across the discharge gap and the current through the discharge gap for an interelectrode gap $d = 0.5$ mm (b).

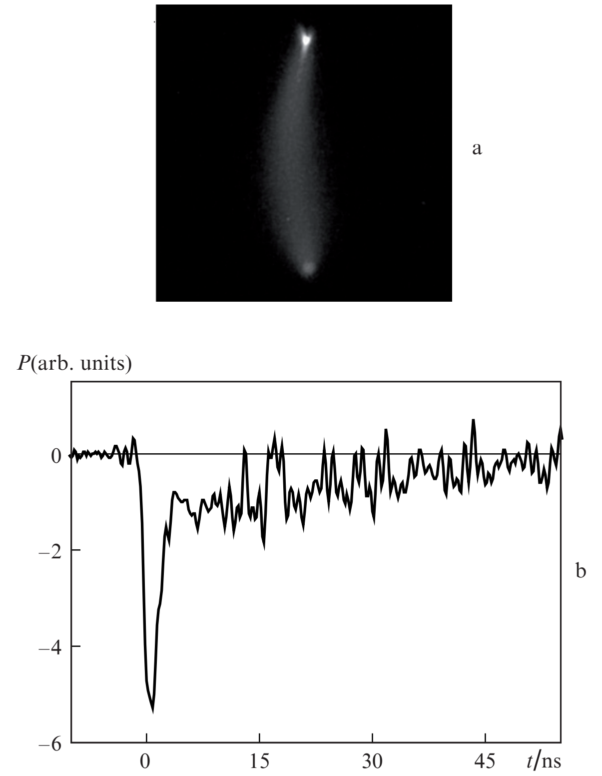

Figure 2. Integral discharge photograph taken in one pulse (a) and oscilloscope trace of a radiation pulse (b) for $d = 2$ mm.

eter of 0.5 mm and the other electrodes were made of foils of these materials. Our investigations were carried out with gaps of 0.5, 1, and 2 mm and a pulse repetition rate ranging from 370 to 1050 Hz.

The temporal shape of radiation pulses was recorded with a fast-response Photek PD025 Low Noise S20 photodiode located at a distance of 2 cm from the radiation source. This distance is sufficiently long to treat as a point source a source with characteristic dimensions of 2 mm and smaller [9]. In this case, the energy of radiation into a solid angle of 4π is easily estimated [10]. The discharge emission spectra were recorded with StellarNet-Inc. EPP2000C-25 (195–850 nm operating range) and Ocean Optics BV HR4000 (200–300 nm) spectrometers with known spectral responsivities. The discharge was photographed using a Sony A100 digital camera and an HSFC-PRO CCD camera. A DPO70604 (6 GHz, 25×10^9 samplings s^{-1}) digital oscilloscope was employed to record electric signals. To record the X-ray discharge radiation, advantage was taken of a large-block polystyrene-based scintillation detector with a Philips XP 2020 photomultiplier [11] as well as of Kodak RAR 2497 film accommodated in a light- and soft-X-ray-tight envelope, which had a window covered with 15-μm thick beryllium foil (its long-wavelength transmission edge corresponded to an X-ray photon energy of ~0.7 keV).

3. Experimental results and their discussion

Our experiments yielded the following results. A diffusive discharged was produced for an interelectrode gap of 2 mm (Fig. 2a), which turned into a spark gap when the interelectrode gap was made narrower (Fig. 3a), the diffusive discharge phase always being present early in the discharge formation in this case. This is clearly seen from comparison of Figs 3c and 3d, which show discharge photographs taken at different point in time with the help of the CCD camera. The diffusive discharge phase supposedly corresponds to the REP DD.

Figures 2b and 3b show the oscilloscope traces of radiation pulses for interelectrode gaps of width $d=2$ and 0.5 mm, respectively. The half-amplitude radiation pulse duration was equal to ~3 ns for a gap of 2 mm and to about 70 ns for a gap of 0.5 mm. Such a long pulse duration in the case of a 0.5-mm gap (in comparison with the duration of excitation pulses delivered by the FPG-10 generator) is attributable to the fact that the voltage pulses were partly reflected from the load (the discharge gap) and then from the generator to arrive at the discharge gap again. In this case, the reflection from the load was significantly stronger than for a 2-mm gap, when the load resistance was close to the wave resistance of the transmission line (the cable).

The pulses of current through the discharge gap and of the voltage across the discharge gap, which were reconstructed from the oscilloscope traces of incident and reflected voltage waves (with the inclusion of the reactance of the load circuit) are given in Fig. 1b. These pulses correspond to the point in time when the excitation pulse from the FPG-10 generator arrives at the gap (prior to the arrival of reflections) and therefore to the first nanoseconds of discharge, i.e. to the diffusive phase (this follows from analysis of the photographs taken with the help of the CCD camera). The first current pulse in Fig. 1b is the capacitive current in the load circuit.

In the course of experiments we discovered that weak X-ray radiation emanated from the 0.5-mm wide discharge

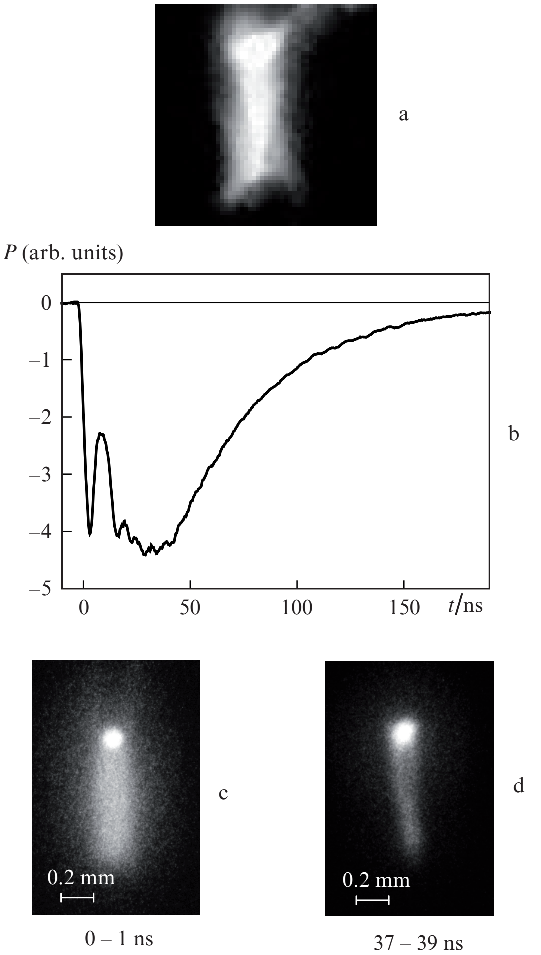

Figure 3. Integral discharge photograph taken in one pulse (a), oscilloscope trace of a radiation pulse (b), and discharge photographs (c, d) taken for $d = 0.5$ mm in one pulse at different points in time.

gap. It was recorded using a scintillation detector as well as from an imprint on a photographic film opposite the window covered with a beryllium filter. The generation of X-ray radiation in the discharge gap is attributable to the bremsstrahlung of runaway electrons, which are produced at the initial stage of discharge formation and furnish the conditions for the diffusive discharge.

Also investigated was the spectral composition of discharge radiation for interelectrode gaps of 2, 1, and 0.5 mm. For a 2-mm gap, in the emission spectrum of diffusive discharge, like in Refs [7, 8, 12], we observed primarily the bands of the second positive nitrogen system (Fig. 4a). In passing from the 2-mm gap to a 0.5-mm gap there changed the discharge spectrum: together with the 2^+ nitrogen band emission we observed the emergence of continuum emission and additional spectral lines (Fig. 4b). In this case, the radiation power of the second positive nitrogen system was hardly changed, while the broadband and metal line radiation powers became substantially higher. The energy of radiation in the 200–300 nm range accounted for ~40% of the energy of radiation in the entire spectral range investigated (200–850 nm). Figure 5 depicts the emission spectrum of a Fe arc discharge along with the emission spectrum of the spark discharge (d = 0.5 mm) recorded with a high resolution. The majority of lines in the spark spectrum and the iron spectrum are seen to coincide (for clearness, a portion of the spectrum is magnified). This is indication that the lines observed in the spark spectrum correspond to the lines of electrode material vapour, iron in the case in question. For an interelectrode gap d = 1 mm, a smaller amount of energy was concentrated in the continuum and the Fe spectral lines in comparison with the case of $d = 0.5$ mm, i.e., this case is intermediate in going over from $d = 2$ mm to $d = 0.5$ mm.

With the use of electrodes made of other materials, the most interesting results were obtained employing copper, niobium, and tungsten electrodes. These spectra are given in

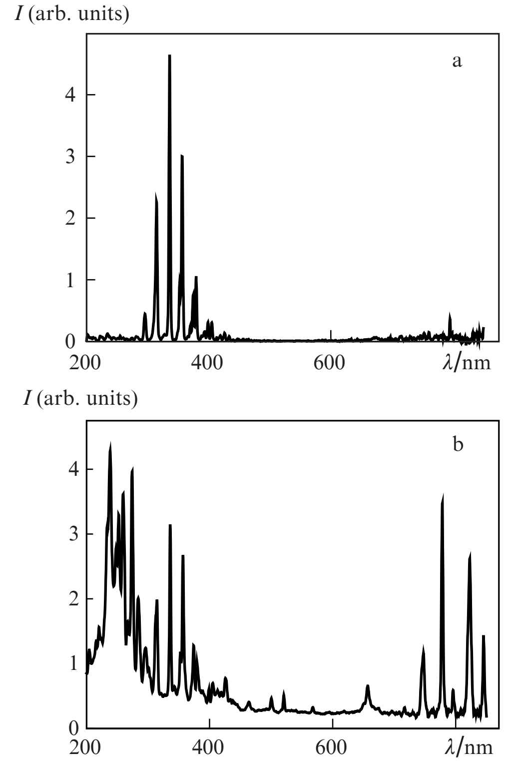

Figure 4. Discharge emission spectra for an interelectrode gap d = 2 mm (a) and $d = 0.5$ mm (b); the electrodes were made of stainless steel.

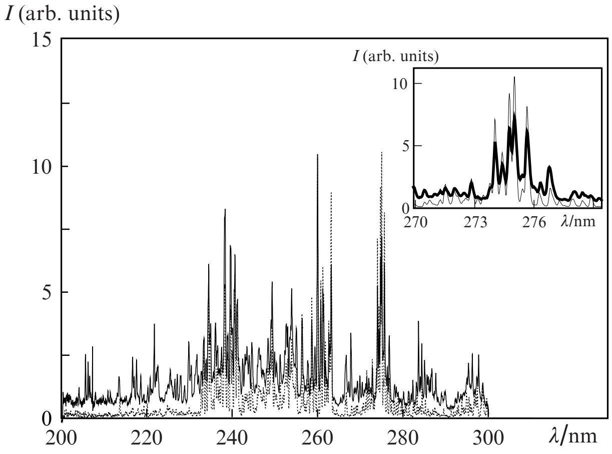

Figure 5. Emission spectrum of discharge with stainless steel electrodes, which was recorded with a high resolution in the 200–300 nm spectral range. The dotted curve (the thin curve in the inset) stands for the arc spectrum of Fe, $d = 0.5$ mm.

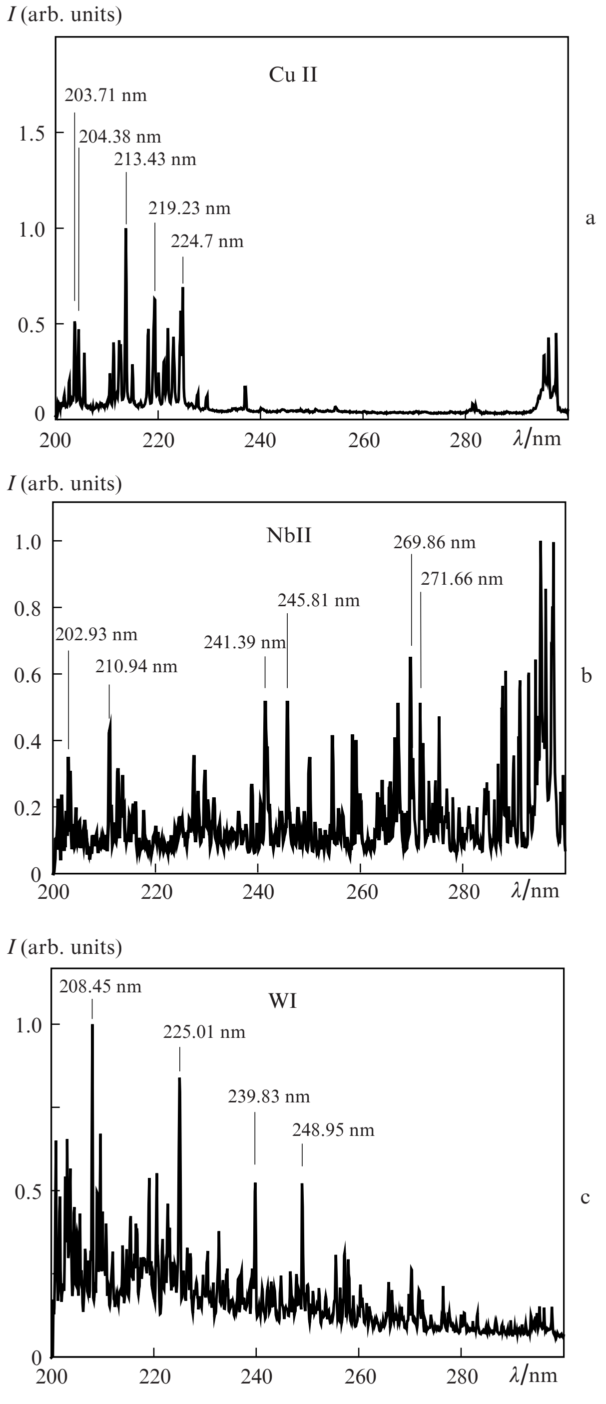

Figure 6. Emission spectra of discharge with electrodes made of copper (a), niobium (b), and tungsten (c), which were recorded with a high resolution in the 200–300 nm spectral range for $d = 0.5$ mm.

Fig. 6. One can see that the emission of discharges with electrodes made of these materials contains the lines of neutral atoms as well as of their ions.

4. Conclusions

Therefore, we have investigated the emission of discharge plasma in the breakdown of narrow interelectrode gaps (0.5, 1, and 2 mm) in a nonuniform electric field. It was discovered that the breakdown of an atmospheric-pressure air gap $d =$ 0.5 mm with a strongly nonuniform electric field is accompanied with the production of runaway electrons in the initial stage of discharge. This manifests itself in the emission of X-ray radiation from the discharge gap and the consequential preionisation of the discharge gap by the runaway electrons and the X-rays, as well as in the existence of diffusive discharge stage. As shown in our work, in the breakdown by voltage pulses with an amplitude of ~10 kV at a repetition frequency of 1 kHz under these conditions (0.5 mm) the main contribution to the plasma emission is made by continuum emission and the lines of electrode material, about ~40% of the total radiation energy being concentrated in the 200–300 nm range. We plan to use these discharge regimes for producing point UV radiation sources with the emission spectrum varied in different parts by employing various electrode materials.

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