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A Compact Setup Based on a Gas Diode for Studying of Cathodoluminescence

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Abstract—A compact setup for investigating the cathodoluminescence was created on the basis of a gas diode, a compact GIN-55-01 pulse–periodic generator, and an industrial spectrometer. Under the excitation by a beam of runaway electrons with a pulse duration (full width at half maximum) of ~100 ps, the cathodoluminescence spectra of natural and synthetic diamonds, calcite, cesium iodide, zinc selenide, zirconium dioxide, sapphire, gallium oxide (III), cadmium sulfide, zinc sulfide, calcium fluoride, and other crystals were recorded. The prospects of using gas diodes, which were developed at the Institute of High Current Electronics (Siberian Branch, Russian Academy of Sciences), and pulsers, which were created by the FID-Tekhnologiya Company (St. Petersburg), were shown when studying the properties of pulsed cathodoluminescence.

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INTRODUCTION

Much attention has been paid to studies of the cathodoluminescence in various materials [1–4]. The luminescence spectra that are initiated by an electron beam make it possible to reveal various properties of crystals, in particular, the presence of various impurities in them. The use of electron beams of nanosecond duration allowed the luminescence intensity and the sensitivity of the instrumentation in the identification of impurities in excited substances to be increased [4, 5].

It was shown in [6, 7] that when studying cathodoluminescence, one can use runaway-electron beams of subnanosecond duration, which are generated in diodes that are filled with air at atmospheric pressure. At an FWHM duration of the beam current pulse of ~100 ps, the emission spectra of synthetic ruby, spodumene, and natural diamond were recorded.

The application of SLEP-150 accelerators with gas diodes and a PD025 photodiode by the Photek Company (LNS20 cathode) allowed recording not only the emission spectra of various crystals but also the time characteristics of the luminescence in natural and synthetic diamonds, calcite, spodumene, garnet, and polymethyl methacrylate with a resolution of up to 100 ps [8–13]. However, RADAN [14], NORA [15], and SLEP [16] pulsers were used in [5–13]. They operate at comparatively low pulse repetition frequencies and are not produced commercially. Furthermore, these pulsers operate at voltages of hundreds of kilovolts, thus complicating the protection against X-rays. Moreover, the NORA pulser has a high level of electromagnetic interference.

The objective of this study was (i) the creation and testing of a small-sized setup for investigating the emission spectra of various substances, which is based on industrially produced compact voltage pulse generators that operate at low-level electromagnetic noise with a high pulse repetition rate; (ii) testing of standard spectrometers with a quartz optical fiber; and (iii) the development of a gas diode that provides the maximum beam current pulse amplitudes.

THE EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

Figure 1 shows a block diagram of the developed experimental setup that includes a GIN-55-01 voltage pulse generator (FID-Tekhnologiya, St. Petersburg), a spectrometer with an optical fiber, and a specially designed gas diode.

As was determined in our studies [18, 19], to obtain the maximum currents of a runaway-electron beam behind the anode foil of a gas diode, which is an ultrashort avalanche electron beam (UAEB) with a subnanosecond voltage pulse rise time, it is necessary to use conical insulators that cover the lateral walls of the gas diode (*2* in Fig. 1). Tubular cathodes should be used to attain the maximum UAEB current densities [19]. In addition, the connection between the trans-

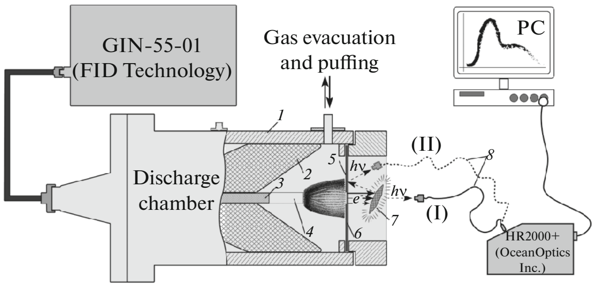

Fig. 1. A schematic diagram of the experimental setup: (*1*) metal case of the discharge chamber; (*2*) caprolon insulator; (*3*) potential input; (*4*) tubular electrode (cathode); (*5*) diaphragm; (*6*) foil (anode); (*7*) crystal; and (*8*) optical fiber. I and II are the ways of placing the optical fibers for detecting the luminescence directly behind the crystal and in foil-anode-reflected rays.

mission line and gas diode must be smooth with a minimum change in the characteristic impedance, which was provided by the shape of the above-mentioned insulator.

The GIN-55-01 generator formed voltage pulses with an amplitude of 15–55 kV in the incident wave, which was transmitted through a 2.5-m-long cable with a characteristic impedance of 75 Ω, a pulse duration (FWHM) of ≈1 ns, and a pulse rise time of ≈0.7 ns. The cable was connected to a specially developed gas diode. The pulse repetition frequency could be varied from 1 to 100 Hz with a step of 1 Hz.

Figure 2 shows the design of the discharge chamber with side windows that allowed recording of the UAEB current using a current collector. When the collector was replaced by a shunt that was manufactured using film resistors (chip resistors) [20], the current through the gas diode could be measured.

The screening of the gas-diode side walls by the insulator was incomplete (see Fig. 2), thus resulting in a decrease in the UAEB current pulse amplitude by ≈20%. However, the presence of windows made it possible to observe and photograph the forms of discharges under different conditions.

Two types of cathodes that were made of stainless steel and aluminum were tested. First-type cathode had the form of a 6-mm-diameter tube with a 100-μm-thick wall and a 30-μm rounding radius. The second-type cathode was cone shaped with a vertex angle of 30° and a 30-μm rounding radius. A grid with a transparency of 64%, which reinforced an aluminum foil with a thickness of 10 μm from the side, which was at a lower pressure, served as the anode.

It was determined in [18] that due to changes in atmospheric-air pressure and humidity, the UAEB current pulse parameters behind the anode foil of the gas diode may considerably change upon changes in the weather and season. Therefore, the gas diode was filled with nitrogen with an impurity content of at most 0.0001%. In some experiments on the investigation of the UAEB current pulse parameters, atmospheric air was also used to fill the gas diode.

The cathodoluminescence spectra were recorded using a commercially available HR2000+ spectrometer (OceanOptics Inc., United States) with a 1-m-long quartz optical fiber, which allowed optical radiation to be registered in a wavelength range of 200–1100 nm. Transparent samples with plane–parallel sides were installed in parallel to the anode foil at a minimum distance from it, while the receiving part of the fiber was positioned behind the sample (way I in Fig. 1). Nontransparent samples were installed behind the foil at an angle to it of at most 30°; the crystal-sample luminescence was registered with a fiber in rays that were reflected by the aluminum foil (way II).

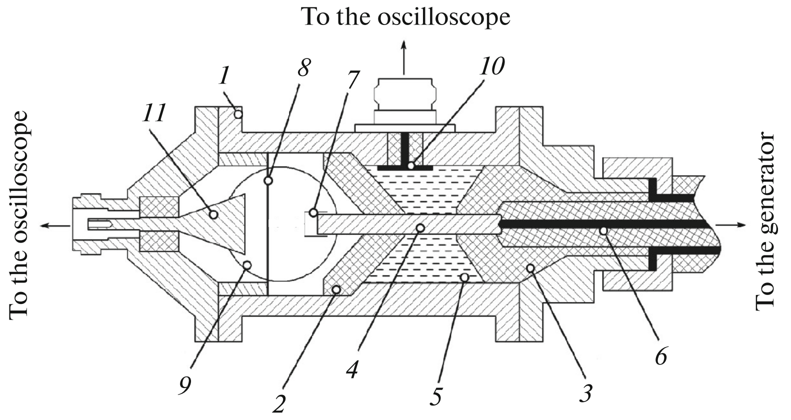

Fig. 2. The design of the discharge chamber: (*1*) metal case; (*2*) caprolon insulator; (*3*) insulator; (*4*) inner conductor of the coaxial line; (*5*) transformer oil; (*6*) high-voltage cable from the generator; (*7*) tubular electrode (cathode); (*8*) grid and aluminum-foil anode; (*9*) side window of the chamber; (*10*) voltage divider; and (*11*) collector.

When measuring the luminescence spectra, samples were irradiated with an electron beam in a pulse–periodic mode at a frequency of 60 Hz. The number of pulses that were required to obtain one spectrogram ranged from 10^2 to 10^4.

Electric signals from the capacitive divider, collector, and shunt were registered using a DSO-X6004A real-time oscilloscope (Keysight Technologies, United States) with a passband of 6 GHz (20 samples/ns) and using RG58-A/U high-frequency cables (Antenna Network Lab Inc., United States) with a length of 1.5 m. N-type Suhner 11 N-50-3-28/133 NE (HUBER+SUHNER, Switzerland) and SMA-type Radiall R125.075.000 (Radiall, France) connectors were used to connect the cables. Signals were attenuated using 142-NM attenuators (Barth Electronics, United States) that allowed voltage pulses with a duration of up to 50 ps to be recorded without considerable distortion.

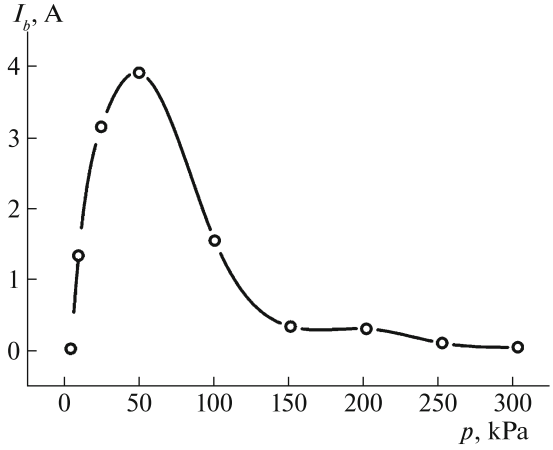

Fig. 3. The dependence of the amplitude value of the UAEB-current pulse on the nitrogen pressure p in the gas diode. The interelectrode distance is 5 mm.

THE RESULTS OF STUDIES OF THE BEAM CURRENT PARAMETERS

Before the spectral studies, measurements of the UAEB current pulse parameters as functions of the nitrogen pressure, pulse repetition frequency, the cathode material and shape, and the amplitude of the generator-formed voltage pulse were performed. The maximum beam current pulse amplitudes behind the 10-μm-thick Al foil were obtained at a maximum generator voltage of 55 kV in an incident wave. The amplitude and density of the UAEB current were higher when using the tubular cathode; this coincides with the results of the previous investigations [21]. Aluminum was found to be the optimal material. When the stainless steel cathode was used, the UAEB current pulse amplitude decreased because of the relatively small amplitude and duration of the voltage pulse from this generator. Therefore, the main experiments were carried out with a tubular aluminum cathode. The dependence of the UAEB current pulse amplitude on the nitrogen pressure is shown in Fig. 3.

This dependence was obtained at a pulse-repetition frequency of 1 Hz and an interelectrode gap of 5 mm, using a newly manufactured aluminum cathode. Each point in Fig. 3 results from averaging over 32 pulses. The maximum UAEB current pulse amplitude was registered at a nitrogen pressure of 50 kPa. Figure 4 shows the dependences of the beam current pulse amplitude and duration on the pulse repetition frequency *f* and the nitrogen pressure.

The aluminum cathode that was used in these experiments operated with more than 10^5 pulses. This number of pulses resulted in a decrease in the beam-current amplitude, did not appreciably change during the further operation. This fact is associated with partial polishing of the cathode. Under these conditions, the FWHM duration of beam current pulses was $\approx$110 ps. The tests that were performed showed that the maximum effect on the crystal is observed at a pulse repetition frequency of 60 Hz (Fig. 4).

The energy spectrum of runaway electrons of the beam, which was generated in the gas diode, was determined from the curves of attenuation in Al foils using a technique that was described in detail in [22]. Figure 5a shows the energy distribution of electrons that is typical for these conditions, while the experimental and calculated attenuation curves are shown in Fig. 5b.

The maximum electron energy approximately corresponds to the largest voltage drop across the gas diode in the operating mode ($f = 60$ Hz). The maximum in the energy distribution of electrons under these conditions was observed for a voltage of $\approx$60 kV, which corresponds to the energy distributions of electrons that were obtained in [22–24].

Waveforms of voltage across the gas diode, the current through the discharge gap, and the UAEB current behind the Al-foil anode under identical conditions were similar for nitrogen and air pressures of 50–100 kPa. Changes in the gas kind, its pressure, and the interelectrode gap mainly influenced the pulse amplitude.

Typical waveforms from the capacitive voltage divider U_{div}, the current shunt I_{sh}, and the collector I_b are shown in Fig. 6.

The recorded waveforms are typical of this UAEB generation mode for a gas diode filled with both nitrogen and atmospheric air. The UAEB current pulse duration in atmospheric-pressure air is also ~100 ps. Pulses from the voltage divider and current pulses were synchronized according to the capacitive current of the "cold" diode I_{dis} (the current in the absence of dense plasma in the gap) [20]. A similar procedure was performed when synchronizing current pulses through the gap and the UAEB current from the collector, for

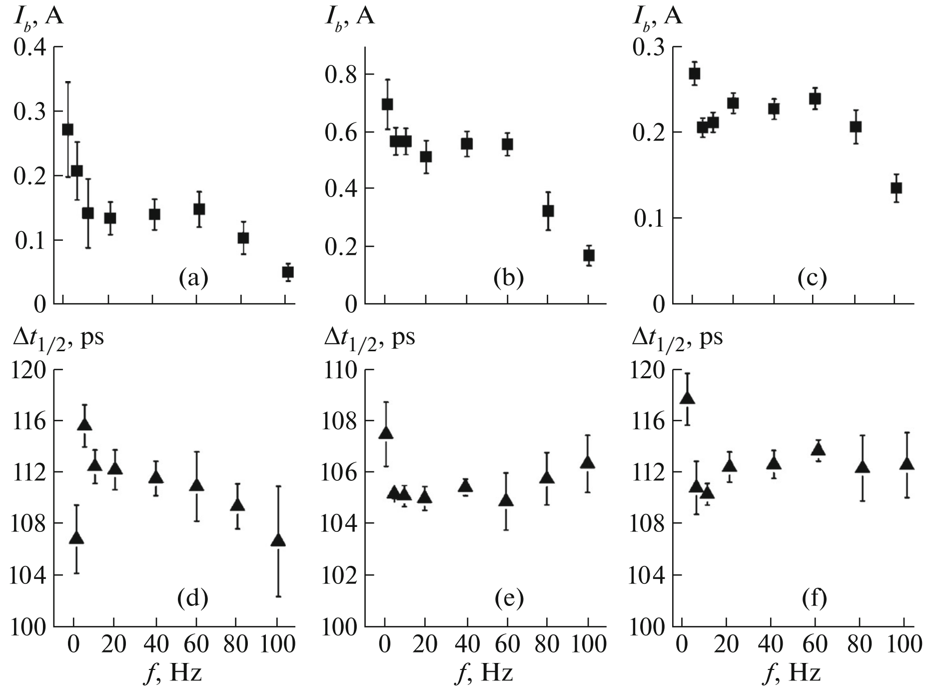

Fig. 4. The dependences of the (a–c) amplitude and (d–f) FWHM duration of UAEB-current pulses on the pulse-repetition frequency f at nitrogen pressures of (a, d) 25, (b, e) 50, and (c, f) 100 kPa. The voltage amplitude in the incident wave is 55 kV; the interelectrode distance is 5 mm. Each point results from averaging over 2560 pulses.

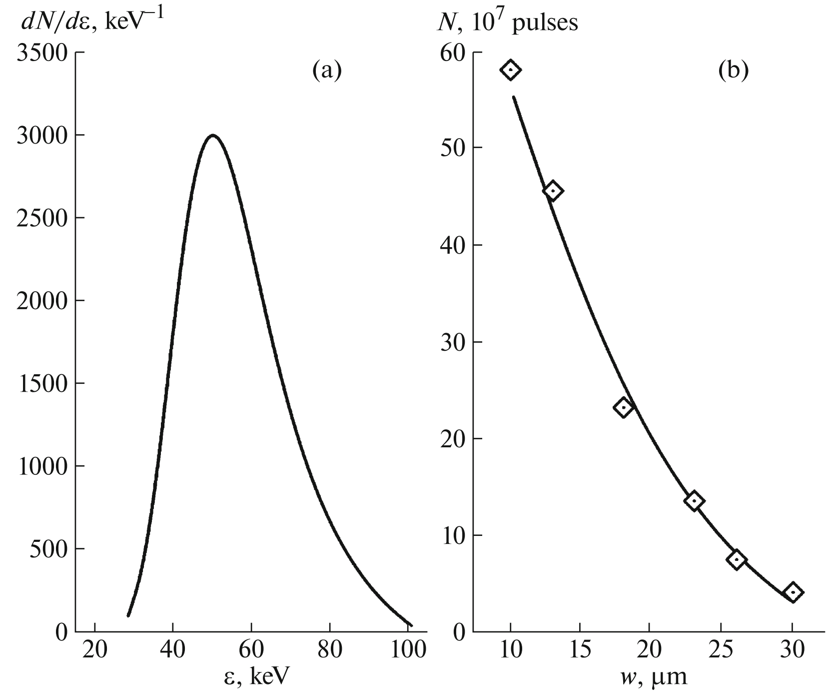

Fig. 5. (a) The energy distribution of electrons in the beam; (b) the experimental (dots) and calculated (solid line) attenuation curves for the electron beam behind the aluminum foil of different thicknesses w. The interelectrode distance is 5 mm; the voltage amplitude in the incident wave is 55 kV, $f = 1$ Hz, the nitrogen pressure is 50 kPa, the cathode is an aluminum tube.

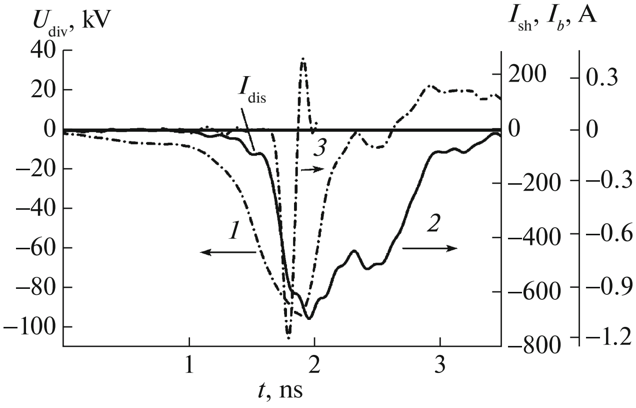

Fig. 6. Oscillograms of pulses from the (*1*) voltage divider U_{div}, (*2*) current shunt I_{sh}, and (*3*) current collector I_b. I_{dis} is the capacitive current of the "cold diode" (displacement current). The interelectrode distance is 5 mm, the air pressure is 100 kPa, and the cathode is an aluminum tube.

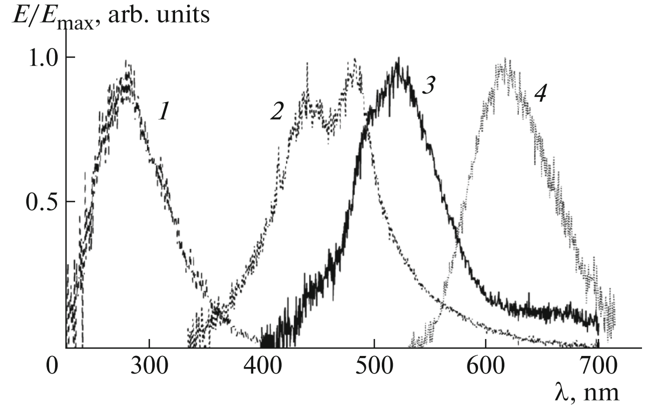

Fig. 7. The spectral distribution of the emission energy of crystals under the impact of a runaway-electron beam: (*1*) CaF_2; (*2*) natural diamond; (*3*) ZnS; and (*4*) $CaCO_3$. The spectral data are given with allowance for the spectral sensitivity of the instrument.

which the latter was recorded behind both the foil and grid anodes [20, 24]. In the second case, the collector registered not only the UAEB current but also the capacitive current of the "cold" diode, as well as the dynamic capacitive current. This technique was described in detail in [20, 24, 25].

THE CATHODOLUMINESCENCE SPECTRA

This setup was used to record the cathodoluminescence spectra of 16 transparent and nontransparent samples, including powder samples that were fixed in a grid with a small mesh. Small transparent samples were placed close to the foil that was positioned behind the grid anode.

Nontransparent samples were placed at a distance of 3–4 mm from the foil at an angle to it. In this case, the electron beam excited air in the gap between the foil and sample. The optical fiber for detecting the luminescence from samples was then placed as shown in Fig. 1 (way II). The cathodoluminescence intensities in CaF_2, natural diamond, ZnS, and $CaCO_3$ crystals are maximized under excitation by an electron beam with a pulse FWHM duration of ≈100 ps. Examples of the measured luminescence spectra are shown in Fig. 7.

The emission of the second positive nitrogen system that was excited upon the electron-beam passage through air was not registered under these conditions because of the comparatively low beam intensity.

This setup was characterized by a low electromagnetic-noise level, thus allowing a computer and other sensitive instruments to be installed close to it. We note that the developed gas diode can operate with generators produced by the FID-Tekhnologiya Company, which provide a shorter voltage-pulse rise time and a large amplitude. This, in turn, makes it possible to improve the UAEB parameters and extend the number of problems that can be solved within the framework of studying the cathodoluminescence of various substances.

CONCLUSIONS

A small-sized setup designed on the basis of a gas diode, a compact pulse-periodic GIN-55-01 generator, and a commercial HR2000+ spectrometer, which is intended for investigations of the cathodoluminescence in various substances, has been developed. The parameters of the runaway electron beam current pulses behind the anode foil were studied. Data on the influence of the pulse repetition frequency and the nitrogen pressure on the beam current pulse amplitude and duration were obtained. The energy distribution of beam electrons was reconstructed for a nitrogen pressure of 50 kPa. The cathodoluminescence spectra in natural and synthetic diamond, calcite, cesium iodide, zinc selenide, zirconium dioxide, sapphire, gallium oxide (III), cadmium sulfide, zinc sulfide, calcium fluoride, and other crystals were recorded. The crystals were excited by an electron beam with a pulse FWHM duration of ~100 ps. It was shown that the gas diodes that were developed at the Institute of High-Current Electronics (Siberian Branch, Russian Academy of Sciences) and voltage pulse generators manufactured by the FID Teknologiya Company are promising for creating compact installations for studying pulse cathodoluminescence.

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REFERENCES

1. *Lyuminestsentnyi analiz* (Fluorimetric Analysis), Konstantinova-Shlezinger, M.A., Ed., Moscow: Fizmatgiz, 1961.
2. Marfunin, A.S., *Spektroskopiya, lyuminestsentsiya i radiatsionnye tsentry v mineralakh* (Spectroscopy, Luminescence, and Radiation Centers in Minerals), Moscow: Nedra, 1975.
3. *Luminescence — An Outlook on the Phenomena and their Applications*, Thirumalai, J., Ed., Rijeka: InTech, 2016.
4. Solomonov, V.I., Mikhailov, S.G., *Impul'snaya katodolyuminestsentsiya i ee primenenie dlya analiza kondensirovannykh veshchestv* (Impulse Cathodoluminescence and its Applications to Condensed Matter Analysis), Yekaterinburg: Ural. Otd. Ross. Akad. Nauk, 2003.
5. Mikhailov, S.G., Osipov, V.V., and Solomonov, V.I., *Prib. Tekh. Eksp.*, 2001, no. 3, p. 164.
6. Lipatov, E.I., Tarasenko, V.F., Orlovskii, V.M., Alekseev, S.B., and Rybka, D.V., *Pis'ma Zh. Tekh. Fiz.*, 2005, vol. 31, no. 6, p. 29.
7. Lipatov, E.I., Tarasenko, V.F., Orlovskii, V.M., and Alekseev, S.B., *Quantum Electron.*, 2005, vol. 35, no. 8, p. 745.
8. Baksht, E.Kh., Burachenko, A.G., and Tarasenko, V.F., *Pis'ma Zh. Tekh. Fiz.*, 2010, vol. 36, no. 12, p. 102.
9. Baksht, E.Kh., Burachenko, A.G., Solomonov, V.I., and Tarasenko, V.F., *Izv. Vyssh. Uchebn. Zaved., Fiz.*, 2011, vol. 54, no. 6, p. 17.
10. Tarasenko, V.F., Solomonov, V.I., Polisadova, E.F., Burachenko, A.G., and Baksht, E.Kh., *Tech. Phys.*, 2012, vol. 57, no. 5, p. 720.
11. Lipatov, E.I., Lisitsyn, V.M., Oleshko, V.I., Polisadova, E.F., Tarasenko, V.F., and Baksht, E.H., in *Cathodoluminescence*, Croatia: InTech, 2012, p. 31.
12. Baksht, E.Kh., Burachenko, A.G., Beloplotov, D.V., and Tarasenko, V.F., *Izv. Vyssh. Uchebn. Zaved., Fiz.*, 2016, vol. 59, no. 4, p. 15.
13. Tarasenko, V.F., Baksht, E.Kh., Burachenko, A.G., Beloplotov, D.V., and Kozyrev, A.V., *Dokl. Akad. Nauk.*, 2016, vol. 471, no. 2, p. 150.
14. Yalandin, M.I. and Shpak, V.G., *Instrum. Exp. Tech.*, 2001, vol. 44, no. 3, p. 285.
15. Mesyats, G.A., *Impul'snaya energetika i elektronika* (Pulse Power Generation and Electronics), Moscow: Nauka, 2004.
16. Kostyrya, I.D., Tarasenko, V.F., and Shitts, D.V., *Prib. Tekh. Eksp.*, 2008, no. 4, p. 159.
17. Efanov, V.M., Efanov, M.V., Komashko, A.V., Kirilenko, A.V., Yarin, P.M., and Zazoulin, S.V., in *Ultra-Wideband, Short Pulse Electromagnetics 9,* Sabath, F., Giri, D.V., Rachidi-Haeri, F., and Kaelin, A., Eds., New York: Springer-Verlag, 2010, part 5, p. 301.
18. Kostyrya, I.D., Baksht, E.Kh., and Tarasenko, V.F., *Instrum. Exp. Tech.*, 2010, vol. 53, no. 4, p. 545.
19. Kostyrya, I.D., Rybka, D.V., and Tarasenko, V.F., *Instrum. Exp. Tech.*, 2012, vol. 55, no. 1, p. 72.
20. Shao Tao, Tarasenko, V.F., Zhang Cheng, Burachenko, A.G., Rybka, D.V., Kostyrya, I.D., Lomaev, M.I., Baksht, E.Kh., and Yan Ping, *Rev. Sci. Instrum.*, 2013, vol. 84, p. 053506. doi 10.1063/1.4807154
21. Tarasenko, V.F., Skakun, V.S., Kostyrya, I.D., Alekseev, S.B., and Orlovskii, V.M., *Laser Part. Beams*, 2004, vol. 22, no. 1, p. 75. doi 10.1017/S0263034604221152
22. Kozyrev, A.V., Kozhevnikov, V.Yu., Vorobyev, M.S., Baksht, E.Kh., Burachenko, A.G., Koval, N.N., and Tarasenko, V.F., *Laser Part. Beams*, 2015, vol. 33, no. 2, p. 183. doi 10.1017/S0263034615000324
23. Baksht, E.H., Burachenko, A.G., Kozhevnikov, V.Yu., Kozyrev, A.V., Kostyrya, I.D., and Tarasenko, V.F., *J. Phys. D: Appl. Phys.*, 2010, vol. 43, p. 305201. doi 10.1088/0022-3727/43/30/305201
24. Burachenko, A.G. and Tarasenko, V.F., *Tech. Phys. Lett.*, 2010, vol. 36, no. 12, p. 1158.
25. Tarasenko, V.F. and Rybka, D.V., *High Voltage*, 2016, vol. 1, no. 1, p. 43.

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