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Long-term reproducibility of emission characteristics of high-current diamond-graphite sources of electrons with field emission under non-stationary vacuum operating conditions

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The results of a study of the long-term reproducibility of the emission characteristics of electron sources with field emission density of up to 1000 A/cm^2 of based on composite nanocarbon films are presented. It was found that high-current field emission is accompanied by the sputtering of residual gas ions from atoms of the cathode material and its sedimentation on the anode. The results can be used to predict the durability of high-current diamond-graphite cathodes with field emission when operating in unsteady temperature-vacuum conditions.

Keywords: diamond-graphite nanocomposite, high-current field emission, reproducibility of field emission parameters, service life of cathode with field emission.

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Electro-vacuum devices of the microwave, sub- and terahertz (THz) ranges are widely used in both ground-based and aerospace radio engineering devices. Along with increasing the operating frequency, power and ensuring instantaneous availability of navigation and space communication systems, tasks are being set to increase their reliability and service life by tens and hundreds of thousands of hours [1]. The development of the THz-band is carried out with the help of solid-state or vacuum emission electronics devices. However, limitations on the realized power associated with a set of physical effects, the instrument manifestations of which are known as „terahertz pit“, allow for the implementation of powerful THz devices to give preference to vacuum emission electronics devices. The implementation of miniature analogues of TWL (traveling wave lamps) and RWL (reverse wave lamps) becomes relevant.

As practice shows, the reliability and durability, as well as the stability of the characteristics of electro-vacuum devices (EVDs) are largely determined by the emission reliability and durability of cathodes. Currently, thermionic metal-porous cathodes (MPCs) with various additives designed to reduce the temperature coefficient of the electron output have been used in most EVDs produced in the world, including the microwave wavelength range. One of the main requirements for EVDs, especially from the side of miniature traveling wave lamps of the millimeter and terahertz ranges, is an increase in the density of the sampled current, which is achieved by increasing the operating temperature. However, this leads to an increase in the evaporation rate of the active substance that is part of the MPC, and, taking into account its limited amount, with small dimensions of the EVDs, to a decrease in service life.

Currently, in the production of microwave and sub-terahertz EVDs, the possibility of using, in addition to MPC, electron sources, the functioning of which is based on the phenomenon of field emission of electrons, which, unlike thermocathodes, have ultra-high speed [2], is being considered. One of the most promising materials for creating this type of device is nanocarbon film structures [3–5]. It is shown that when choosing the synthesis modes of diamond graphite nanocomposites in a nonequilibrium microwave plasma of low-pressure ethanol vapors, a decrease in the threshold of field electron emission from 15−17 to 4−6 V/μm and an increase in the density of the autoemission current in pulses of microsecond duration over 100 can be obtained,A/cm^2 [6].

The purpose of this work is to study the long-term stability of the emission characteristics of field electron sources based on composite nanocarbon film coatings with an autoemission current density of at least 100 A/cm^2 in non-stationary temperature and vacuum operating conditions.

Diamond graphite film structures with a thickness of about 0.1 μm deposited on polycore plates in a microwave plasma of ethanol vapors according to the procedure described in [6] were used as auto-emission cathodes. The emitting part of the cathodes were the ends of the diamond graphite film, at a distance of $7 \cdot 10^{-3}$ m from which a metal contact with the applied cathode potential was sprayed. The measuring device provided equal distance of the cathode end points relative to the molybdenum anode with a diameter of $5.5 \cdot 10^{-3}$ m. The interelectrode gap

was $4 \cdot 10^{-5}$ m. The measurements were carried out in a vacuum chamber at a pressure of $P = (3-4) \cdot 10^{-5}$ Pa using a DC power supply. The measuring part of the installation, in addition to the power supply, included a recording multichannel oscilloscope, a high-voltage voltage divider, as well as a measuring resistance of PEV-100 with a nominal value of $5.017 \cdot 10^3$ Ω for monitoring voltage and field current changes.

Determination of the elemental composition of the surfaces of planar-end-end auto-emission structures after electrical tests was carried out using the MIRA 2 LMU auto-emission scanning microscope manufactured by Tescan, equipped with the Oxford INCA Energy 350 system. The Oxford INCA Energy 350 X-ray energy dispersive microanalysis system with the PentaFET-x3 detector has a resolution of K_αMn no worse than 133 eV and a detector crystal area of 30 mm^2, which allowed quantitative analysis of chemical elements from boron to uranium.

After the general decontamination of the measuring device, which was carried out during heating by built-in heaters and pressure in the vacuum chamber $1.6 \cdot 10^{-5}$ Pa, the anode was decontaminated by an auto-emission current of the cathode about $8 \cdot 10^{-3}$ A. The process was accompanied by a glow, the intensity of which increased with an increase in the electric field strength and the magnitude of the auto-emission current (Fig. 1). Tests for long-term reproducibility of cathode characteristics were carried out with cyclic vacuum changes in the range from $9 \cdot 10^{-6}$ Pa with a high-vacuum pump running to 0.1 Pa by the end of the test period. Simulated conditions with an emergency shutdown of the supply voltage and pumping means, which consisted of the following. After testing the autocathode at a given voltage for a certain period of time (from 0.5 to 3 h in different cycles), the volt-ampere characteristics (VAC) were measured and the power supply was switched off. After cooling of the measuring device, the pumping means were switched off, as a result of which the pressure in the chamber increased to 0.1 Pa. Further, the test cycle with pumping, voltage rise, exposure at the applied voltage and VAC measurements was repeated.

Fig. 2 shows the changes in the emission current (curve I) and voltage (curve II) of a power supply with an unstable output voltage during eight test cycles with a total duration of over 13.5 h. During this duration, the time of disconnecting the power supply and pumping means was not included. It can be seen that the field current, as expected according to Fowler and Nordheim [7], is very sensitive to voltage instability of the power supply. With a fixed field strength of about 50 V/μm and a cyclic change in the vacuum operating conditions of the autocathode, the field current varied from $6 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ A, what constitutes about 25% with an average current collector density of $1.3 \cdot 10^3$ A/cm^2.

Fig. 3 shows the VAC of the autocathode obtained at the beginning of the tests and after the completion of eight cycles. It can be seen that, despite the unfavorable factors associated with periodic disconnection of the supply

Figure 1. The glow of the cathode end at a field current density of 1450 A /cm^2.

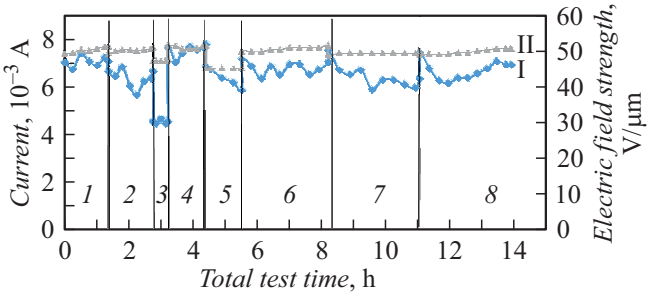

Figure 2. Changes in field current (I) and field strength (II) in the interelectrode gap during eight long-term test cycles (*1–8* — test cycles).

voltage and deterioration of the vacuum, the field emission capacity of the cathode during the tests had good reproducibility. This is evidenced, in particular, by the linear dependences of currents on the electric field strength, constructed in Fowler–Nordheim coordinates for modes providing ultra-high current density of field emission.

In order to clarify the nature of the glow after dismantling the vacuum measuring device, studies of the anode surface were carried out. The study of the elemental composition of its surface showed the presence of a carbon phase.

In the study [6] it is shown that diamond graphite film composites used in tests as field electron sources are graphite matrices with diamond nanocrystallites immersed in them. Therefore, most likely, the graphite component of the matrix is sprayed. This may be evidenced by the high reproducibility of the VAC after various test cycles, which, under the assumption of auto-emission not only from diamond nanocrystallites, but also from graphite micro-steps, could undergo significant transformations. The predominant

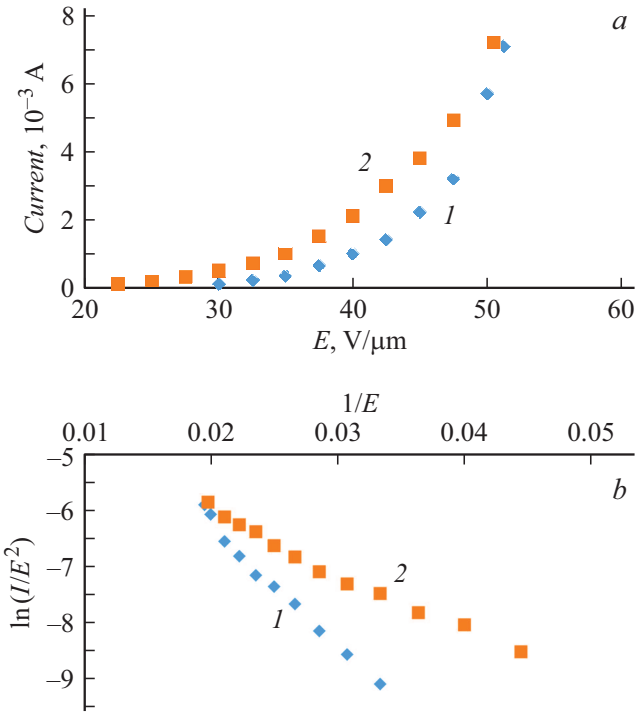

Figure 3. Cathode VAC obtained before (*1*) and after eight test cycles (*2*). *a* — in linear coordinates; *b* — in Fowler–Nordheim coordinates.

sputtering of the graphite phase, which is surrounded by diamond nanocrystallites, is due to the lower thermal conductivity of graphite and, as a consequence, higher heating temperature and the coefficient of atomization by ions of the residual atmosphere of the device. The atomized carbon atoms are ionized in a strong electric field, forming during recombination in the flow of electrons emitted by the autocathode, glowing vacuum-plasma cathode flares [8].

The results obtained indicate a sufficiently high long-term reproducibility of the emission characteristics of field electron sources based on diamond-graphite film structures. They can be used to predict the service life of autocathodes during operation in specified power current modes with the possible occurrence of non-stationary temperature and vacuum conditions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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