PHYSICAL ELECTRONICS

Original article
DOI: https://doi.org/10.18721/JPM.18109

FORMATION OF AN ELECTRON BEAM BY AN ELECTRON-OPTICAL SYSTEM USING A COMPOSITE FIELD EMITTER MADE OF THERMALLY EXPANDED GRAPHITE AND A MIXTURE OF THERMALLY EXPANDED GRAPHITE WITH DIAMOND GRANULES

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Abstract. In the paper, the characteristics of electron flows formed by an electron-optical system with composite field emitters, made from thermally expanded graphite or a mixture of such graphite with diamond granules have been studied. These cathodes were developed at the Saint Petersburg Polytechnic University and the Central Research Institute of Materials. A distinguishing feature of these cathodes is their improved geometry. The maximum achievable emission currents, as well as the longitudinal and transverse components of the velocity of emitted electrons in the electron flow, were determined. The measurements were carried out in pulsed and continuous operations. Experiments showed that these types of cathodes provided emission currents up to 30 mA and operated stably under technical vacuum conditions.

Keywords: field emission, composite cathodes, thermally expanded graphite, electron-optical system, electron beam

Funding: The reported study was funded by Russian Science Foundation (Grant No. 23-29-00224).

Citation: Taradaev E. P., Sominskii G. G., Taradaev S. P., Gordeev S. G., Formation of an electron beam by an electron-optical system using a composite field emitter made of thermally expanded graphite and a mixture of thermally expanded graphite with diamond granules, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (1) (2025) 103–110. DOI: https://doi.org/10.18721/JPM.18109

Научная статья
УДК 537.533
DOI: https://doi.org/10.18721/JPM.18109

ФОРМИРОВАНИЕ ПОТОКА ЭЛЕКТРОНОВ ЭЛЕКТРОННО-ОПТИЧЕСКОЙ СИСТЕМОЙ С КОМПОЗИТНЫМ ПОЛЕВЫМ ЭМИТТЕРОМ ИЗ ТЕРМОРАСШИРЕННОГО ГРАФИТА И ИЗ СМЕСИ ТЕРМОРАСШИРЕННОГО ГРАФИТА С ГРАНУЛАМИ АЛМАЗА

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Аннотация. В работе изучены характеристики электронных потоков, формируемых электронно-оптической системой с композитными полевыми катодами, изготовленными из терморасширенного графита или из смеси такого графита с алмазными гранулами. Отличительной особенностью катодов, разработанных в Санкт-Петербургском политехническом университете и АО «ЦНИИМ», является их усовершенствованная геометрия. Были определены максимально достижимые токи эмиссии, а также продольная и поперечная составляющие скорости эмитированных электронов в электронном потоке. Измерения проводились в двух режимах: импульсном и непрерывном. Проведенные эксперименты показали, что катоды данного типа обеспечивают токи эмиссии до 30 мА и устойчиво работают в условиях технического вакуума.

Ключевые слова: полевая эмиссия, композитные катоды, терморасширенный графит, электронно-оптическая система, электронный пучок

Финансирование: Работа выполнена при финансовой поддержке гранта Российского научного фонда № 00224-29-23.

Ссылка для цитирования: Тарадаев Е. П., Соминский Г. Г., Тарадаев С. П., Гордеев С. К. Формирование потока электронов электронно-оптической системой с композитным полевым эмиттером из терморасширенного графита и из смеси терморасширенного графита с гранулами алмаза // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 1. С. 103–110. DOI: https://doi.org/10.18721/JPM.18109

Introduction

Interest towards development and improvement of gyrotrons in the terahertz and subterahertz ranges has been steadily growing over the recent years [1, 2]. Such high-frequency devices can be used, for example, for diagnostic purposes in medicine and biology [3], for compositional analysis of molecular gases, for detection of explosives and other prohibited substances, as well as in many other applications [4].

Terahertz and subterahertz gyrotrons are small in size, which makes it difficult to incorporate traditional hot cathodes into their architecture, since such cathodes require heating. Moreover, hot cathodes cannot provide inertia-free switching of devices, which is necessary in many cases. For these reasons, it is tempting to replace hot cathodes with cold field emitters, which do not require heating and are practically inertia-free [5, 6].

Multi-tip silicon field emitters with bilayer metal-fullerene protective coating [7], as well as multi-layer emitters composed of multiple layer pairs made of materials with different work functions, brought into contact [8] were previously developed and studied at the High-Voltage and Microwave Electronics Laboratory at Peter the Great St. Petersburg Polytechnic University. Emitters of this type are suitable for generating annular and sheet-like electron beams (see, for example, [9]). They are capable of generating emission currents necessary for a number of applications [10]. However, despite their obvious advantages, such emitters are highly complex to manufacture, complicating their widespread use.

We subsequently collaborated with scientists from the Central Research Institute of Materials named after D.I. Mendeleev to develop composite field emitters based on thermally expanded graphite (TEG) and its mixture with diamond granules (TEG+gD) [11]. These field emitters were made by a simpler manufacturing technology. Thanks to their porous structure, composite cathodes had a well-developed emission surface with a large number of protrusions enhancing the electric field [12, 13].

Further modification of TEG emitters consisted of improving their geometry.

The goal of this study is to analyze the characteristics of electron beams generated by an electron-optical system with cathodes made of TEG and its mixture with diamond granules (TEG+gD), as well as to evaluate the influence of geometric improvements in cathodes on their emission properties.

Measurement procedure and equipment

We considered composite cathodes consisting only of thermally expanded graphite (TEG) particles as well as cathodes consisting of a mixture of TEG with diamond granules (TEG+gD).

The characteristic size of the diamond granules was 20 μm; the content of these granules in the composite was 30 wt%.

To fabricate composite cathodes, TEG particles or TEG+gD particles were mixed into a blend with homogeneous volume and then pressed under high pressure (40–200 MPa) in customized molds with the required cathode sizes.

Cathodes with a triangular protrusion at the base of the emitting structure were formed, characterized by increased strength compared to the previously studied sheet-like and annular emitters [11]. Fig. 1 shows the cross-section of this type of cathode with the main geometric dimensions.

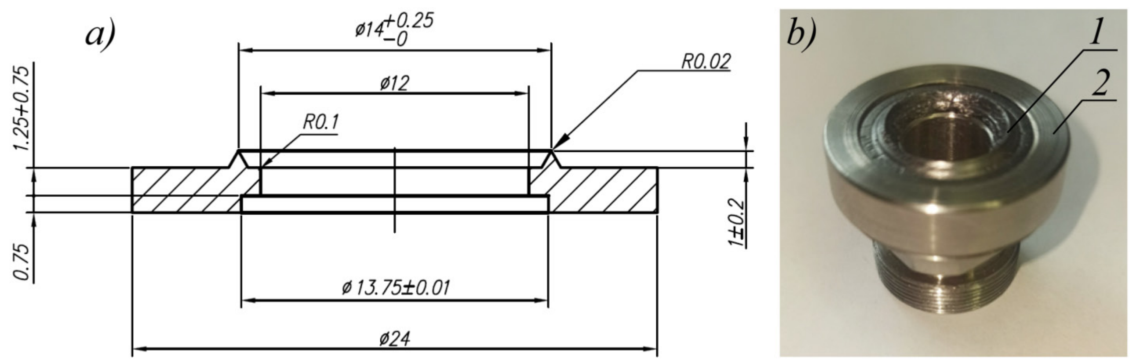

Fig. 1. Drawing of cathode with the new geometry (*a*)
and photograph of this cathode (*1*) mounted in the holder (*2*) (*b*)

Fig. 2 shows the electron-optical system (EOS) with a composite emitter used to generate and study the electron beam. The system included electron gun *1*, channel *2* for electron beam transport and solenoid (*3*). The figure also shows the analyzer incorporated into the system.

To generate an electron beam, a negative (relative to the grounded control electrode) voltage U was applied to the cathode. The electrons that passed through the annular aperture in the control electrode of the gun entered the transport channel, which also served as an electron collector.

The measurements were carried out in two modes: pulsed, with a pulse duration of 1 μs and a repetition frequency of 50–100 Hz, and continuous. To avoid excessive heating of the electrodes in continuous operation, the current from the cathode was limited to 5–10 mA. The operation of cathodes at high currents was studied in pulsed mode.

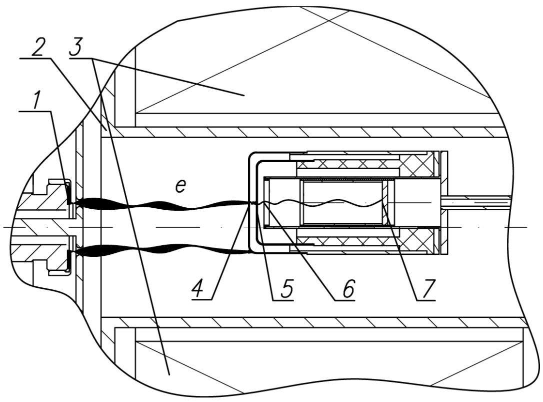

Fig. 2. Schematic of electron-optical system with analyzer installed (*4*–*7*):
electron gun *1*; channel *2* for electron beam transport (*e* is the electron beam); solenoid *3*; entrance aperture *4*; retarding and shielding grids *5* and *6*, respectively; analyzer collector *7*

The electron beam propagated in a magnetic field generated by the solenoid. The solenoid was 200 mm long, with internal and external diameters of 120 and 450 mm, respectively. The magnetic field increased from a minimum value of B_c at the cathode to a maximum value of B_{max} at the center of the solenoid. The B_{max} value did not exceed 0.1 T. The magnetization reversal coefficient $k = B_{max}/B_c$ was adjusted by changing the position of the solenoid relative to the cathode; the value of k did not exceed 8 in all experiments.

The analyzer with a movable entrance aperture located in the transport channel was used to measure the velocity distribution of electrons emitted by the cathode in the beam generated by the EOS (see Fig. 2). The analyzer could move in radial and azimuthal directions. The diameter of the entrance aperture was 300 μm. The electron velocity distribution was measured by the retarding field method [9].

The measurements were carried out under low vacuum conditions at pressures of the order of 10^{-7} Torr. The following quantities were measured: the emission currents of the cathode (I), the control electrode and the collector, as well as the longitudinal ($V_{||}$) and transverse ($V_{\perp}$) (relative to the magnetic field lines) velocity components of the emitted electrons.

Results and discussion

Fig. 3 shows typical measured current–voltage characteristics $I(U)$ and variations in the emission current of cathodes during their operation.

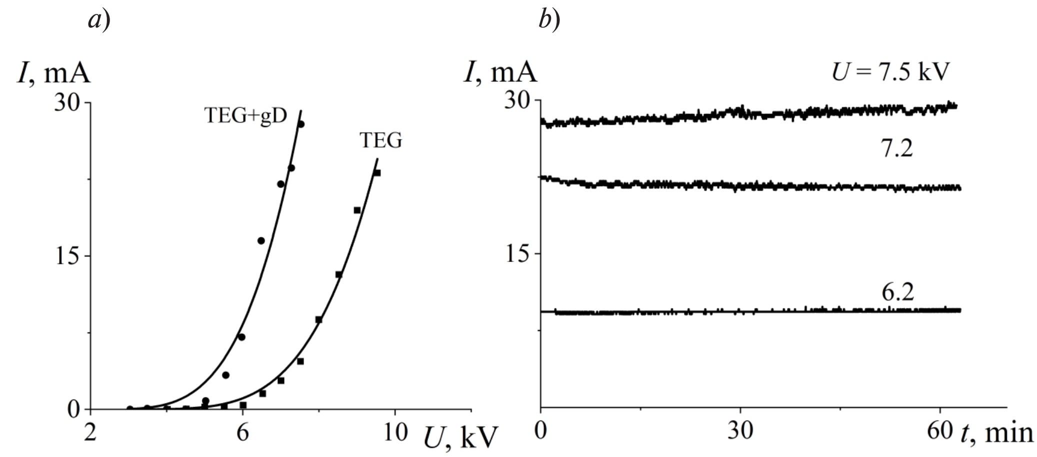

Fig. 3. Typical experimental data obtained from measurements: current–voltage characteristics of composite field emitters based on TEG and TEG+gD (*a*), time dependences of emission current in TEG+gD cathode at different negative voltages *U* (*b*)

Fig. 4,*a* shows the electron distribution in the beam cross-section, measured during the movement of the analyzer. Fig. 4,*b* shows the spectra of transverse velocity components of electrons, measured in different regions along the wall cross-section of the beam. Analyzing the data obtained, we concluded that annular emitters made of TEG and TEG+gD can provide emission currents up to 30 mA from an area of 0.04–0.05 cm^2, providing stable current outputs in low vacuum under intense ion bombardment. The shape of the transverse velocity distribution remained almost unchanged throughout the studied range of electron beam currents.

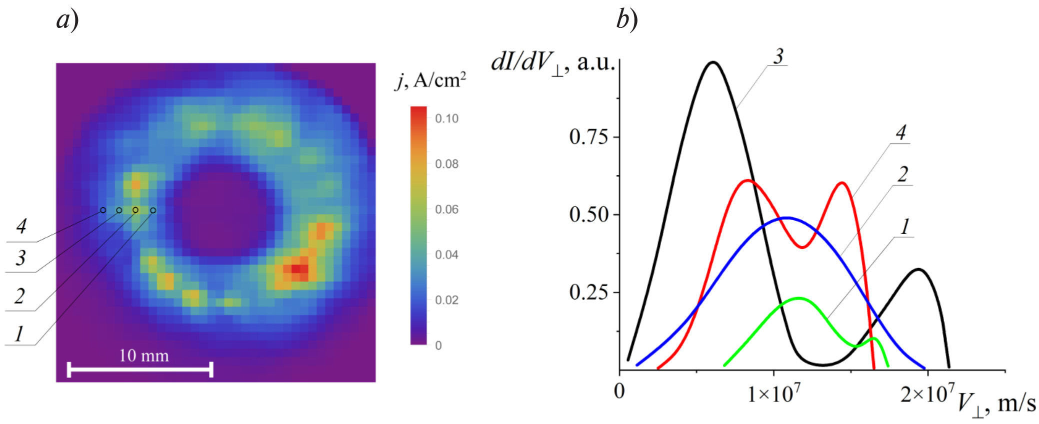

Fig. 4. Typical experimental results: current density distribution in electron beam cross-section (*a*), spectra of transverse velocity components of emitted electrons measured in different regions along the wall cross-section of the beam (*b*)

The spread in transverse velocity components for the entire electron beam, defined as the relative standard deviation from the mean transverse velocity of electrons, did not exceed about 50%.

The cathodes produced stable emission under low vacuum conditions at a pressure of 10^{-7} Torr throughout the entire measurement process. However, a drawback of the cathodes is inhomogeneity of the generated beam in the azimuthal and radial directions.

Conclusion

The experimental results presented in this paper allow us to conclude that the geometrically modified composite cathodes considered, both based on thermally expanded graphite and mixtures of such graphite with diamond granules, show promise for applications in short-wave gyrotrons of the terahertz and subterahertz ranges. These cathodes with a triangular protrusion on the surface are rather durable and easy to manufacture, which reduces their production costs.

In the future, it is planned to continue research on electron-optical systems with composite cathodes, focusing on new approaches to improving their current characteristics and increasing the uniformity of the electron beams they generate.

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Received 31.10.2024. Approved after reviewing 11.11.2024. Accepted 11.11.2024.

Статья поступила в редакцию 31.10.2024. Одобрена после рецензирования 11.11.2024. Принята 11.11.2024.