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SIMULATION OF THE ELECTRON-OPTICAL SYSTEM WITH A FIELD EMITTER FOR A SHORT-WAVE DIAGNOSTIC GYROTRON

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The operational capability of multi-tip silicon emitters with protective metal fullerene coatings in a three-electrode electron-optical system (EOS) with magnetic confinement has been studied. This EOS is intended for electron-stream generation in the diagnostic shortwave gyrotron. Three-dimensional calculations were performed using the Comsol software package. The feasibility of attainment of currents beyond 20 – 30 mA required for the diagnostic gyratron operation was shown. In the course of the calculations, the ratio of the currents falling on the control electrode and on the collector was determined. In the absence of a magnetic field, the control electrode's current was 0.5% of the cathode's one. No control electrode's current existed when the values of the magnetic field induction in the region between the cathode and the control electrode were beyond 0.07 T.

Keywords: multi-tip field emitter, electron gun, magnetic tracking, electron beam

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МОДЕЛИРОВАНИЕ ЭЛЕКТРОННО-ОПТИЧЕСКОЙ СИСТЕМЫ С ПОЛЕВЫМ ЭМИТТЕРОМ ДЛЯ КОРОТКОВОЛНОВОГО ДИАГНОСТИЧЕСКОГО ГИРОТРОНА

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Изучена возможность работы многоострийных кремниевых эмиттеров с защитными металлфуллереновыми покрытиями в трехэлектродной электронно-оптической системе (ЭОС) с магнитным удержанием. Данная ЭОС предназначена для формирования электронного потока в коротковолновом диагностическом гиротроне. Были проведены трехмерные расчеты с использованием программного пакета Comsol. Показана возможность получения токов свыше 20 – 30 мА, необходимых для работы диагностического гиротрона. В ходе расчетов было определено соотношение токов, попадающих на управляющий электрод и на коллектор. В отсутствие магнитного поля ток управляющего электрода составлял 0,5% от тока катода. При значениях индукции магнитного поля в области между катодом и управляющим электродом свыше 0,07 Тл, ток управляющего электрода отсутствовал.

Ключевые слова: многоострийный полевой эмиттер, электронная пушка, магнитное сопровождение, электронный пучок

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Introduction

Miniature electronic microwave devices operating in the short-wave (millimeter and submillimeter) range, with diverse applications in different fields, particularly, in physics, medicine and biology, have been attracting increasing attention. For example, these devices are used for high-density plasma diagnostics, nuclear magnetic resonance spectroscopy and dynamic nuclear polarization. While hot cathodes are fairly popular in systems for generating electron streams in vacuum microwave devices, this type of cathodes may cause some serious problems in operation of small-sized devices.

The sizes of the device's components change as the cathode is heated, negatively affecting the output characteristics. Furthermore, startup and shutdown of microwave devices have to be inertia-free for some applications, which is problematic with hot cathodes. For these reasons, replacing hot cathodes with field emitters, which do not need to be heated and are in fact virtually inertia-free, seems to be an attractive option. Despite these obvious advantages, field emitters are rarely used in microwave devices. Cold emitters have short lifetimes under intense ion bombardment; it is also difficult to achieve the required high emission currents with these emitters, which is why they are unsuitable for miniature high-voltage devices operating in low vacuum. Emission currents of more than 20–30 mA at current densities over 100 mA/cm are necessary for stable operation of even relatively low-power (tens of watts) diagnostic gyrotrons.

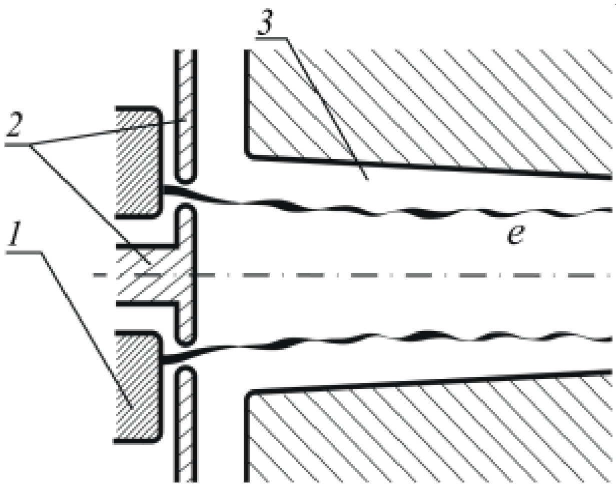

Fig. 1. Schematic view of the cross-section of the developed electron gun with a ring field emitter [10]: cathode system *1* with a field emitter at the end face, control electrode *2* with ring-shaped aperture, channel *3* for transport of electron beam (*e*)

Efforts are currently underway to integrate "distributed" field emitters capable of providing the necessary field emission currents into high-voltage devices [2–6]. One of the most successful attempts to create microwave devices involved Spindt cathodes [6–8]. However, the few demonstration experiments with these cathodes were short-term and were carried out either in low-voltage (below 4 kV) traveling wave tubes of the centimeter range (fairly long-wave) [6, 7], or in extremely high-voltage (above 40 kV) X-ray sources [8]. In other words, the devices in these experiments either had low sputtering yields for the ions bombarding the cathode or small ionization cross-sections of residual gas molecules (and accordingly small fluxes of ions incident on the cathode). Another study considered a field emitter based on carbon nanotubes, integrated into a gyrotron with a magnetic injection electron gun [9]. The operation of such a cathode was tested at a frequency of 0.2 THz but the output power obtained did not exceed even 0.5 W. Such a low value was most likely because the cathode had an abnormally large uneven surface, which the components of the gyrotron and the configuration of the emitter were ill-suited for.

More recently, a model of a triode electron-optical system (EOS) with a field emitter for a diagnostic gyrotron was developed as a joint effort between the High-Voltage and Microwave Electronics Laboratory at Peter the Great St. Petersburg Polytechnic University and the Institute of Applied Physics RAS (Nizhny Novgorod) [10]. The proposed gyrotron operates in the millimeter wavelength range at voltages of the order of 15–20 kV. Fig. 1 shows a schematic of EOS comprising cathode system *1* with a field emitter on the end face, control electrode *2* with a ring-shaped aperture, and channel *3* for electron beam transport. Multitip emitters developed and

Table

Simulation parameter values

Object	Parameter	Value
Triode system	Distance between control electrode and cathode	2 mm
	Aperture width in control electrode	2 mm
Cathode	Mean diameter	14 mm
	Emitting strip width	0.65 mm
	Tip height, distance between tips	30 μm
	Tip radius	10–40 nm
	Tip work function	5.3 eV
	Coating work function	5.3 eV
Solenoid	Coil diameter:	
	external	480 mm
	internal	130 mm
	Solenoid coil thickness	190 mm
	Coil wire diameter	2 mm

studied at the Laboratory [11–13] are intended to be used as electron sources in this EOS. These emitters are made of silicon [14] with special two-layer metal fullerene coating.

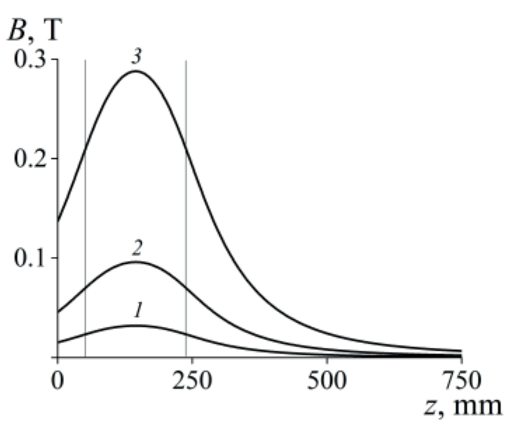

Fig. 2. Magnetic field distribution along the axis of the device at different currents I_s in the solenoid coil. I_s values, A: 1 (curve *1*), 3 (*2*), 9 (*3*). Vertical lines indicate the boundaries of the solenoid.

Multitip silicon cathodes with a two-layer metal fullerene coating that had an emitting surface area of about 0.2–0.3 cm^2 were considered in [12]. Coating the surface of the silicon emitter with a molybdenum layer 5–15 nm thick increased the conductivity and strength of the tips. Two or three monolayers of fullerene C_{60} molecules were deposited over the metal layer to protect the emitter against destructive ion bombardment [15].

The emission characteristics were measured in continuous mode with the currents from the cathode never exceeding 1.0–1.5 mA to minimize the heating of the collector, caused by intense electron bombardment of its surface. Measurements at high currents were carried out only in pulse mode (1–2 μs, 50–500 Hz). Extremely high (up to 100–110 mA) total emission currents were also obtained in this mode at emission current densities above 0.4 A/cm^2 [16].Conversely, obtaining high currents in continuous mode is preferable for many applications.

This can be achieved if heating induced by electron bombardment of EOS electrodes is minimized as much as possible. Overheating of

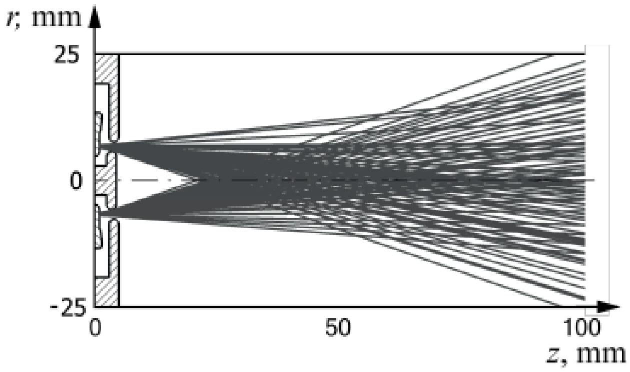

Fig. 3. Typical trajectories of electron current in the EOS in the absence of a magnetic field. The calculation was carried out for a cathode with R = 15 nm, at a voltage U = 15 kV

the large-sized EOS collector can be avoided by forced water cooling. However, water cooling proves difficult for a miniature control electrode. It is therefore extremely important to ensure that the greater part of the electron beam is transmitted through the aperture of this electrode.

In this study, we have considered solving this problem in the system generating the electron beam by introducing a confining magnetic field into the device, preventing the electrons from accumulating on the control electrode.

Calculation procedure

The calculations were performed for a triode system (see Fig. 1). The main calculated parameters and their values are given in Table.

The magnetic field was generated using a solenoid whose axis coincided with the axis of rotation of the EOS. The calculations were performed in a wide range of magnetic field values (from 0 to 0.3 T). The magnetic field of the solenoid in the region of generation and transport of the electron beam was calculated by standard methods with COMSOL software, using fixed dimensions of the solenoid (see Table). The magnetic field was regulated by changing the current I_s in the solenoid coil. The distribution of the magnetic field along the axis of the device at different currents I_s in the solenoid coil is shown in Fig. 2. The z coordinate in Fig. 2 was counted from the cathode.

Optimal dimensions and surface morphology were chosen for the cathode in the calculations. The calculated parameters of the ring cathode are also given in Table. The height h of the tips and the distance L between them were assumed to be equal. The radius R of each tip (taking into account the coating thickness) ranged from 10 to 40 nm. The work function of the tips $e\varphi$ was taken equal to the work function of the fullerene coating in the calculations. Negative voltage $1 \le U \le 20$ kV relative to the grounded control electrode and collector was applied to the cathode.

The currents from the cathode, the currents to the control electrode I_g and the currents to the collector I_c were calculated by the procedure given in [18]. The collector current was determined by subtracting the current in the control electrode from the total current I_Σ in the emitter. All calculations were carried out in a three-dimensional model using the COMSOL Multiphysics software package.

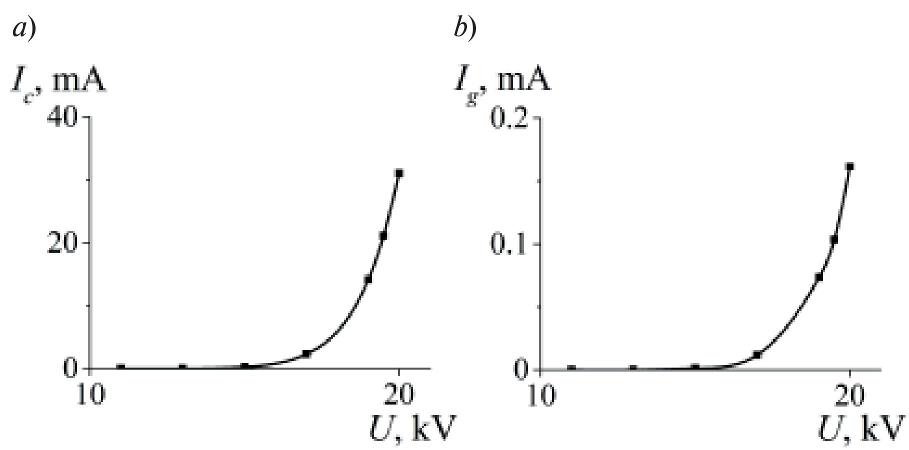

Fig. 4. Typical dependences of emission current on applied voltage: *a* corresponds to the collector current, *b* to the control electrode current. The calculation was carried out for a cathode with R = 15 nm, I_s = 0

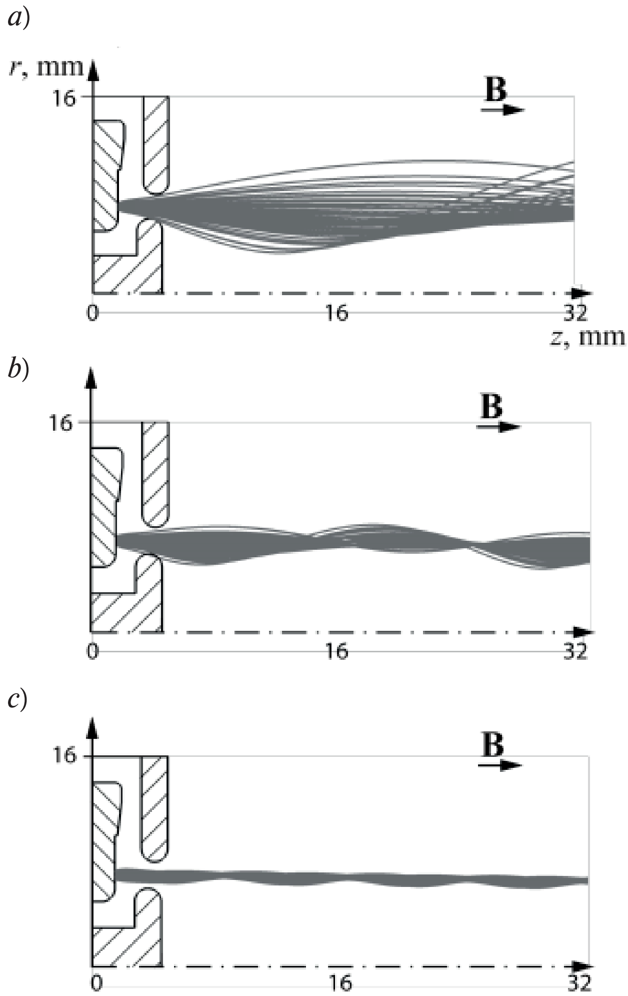

Fig. 5. Typical trajectories of electrons in the EOS for different solenoid currents I_s, A: 1 (*a*), 3 (*b*), 9 (*c*). The axis of rotation of the EOS coincides with the axis *z*

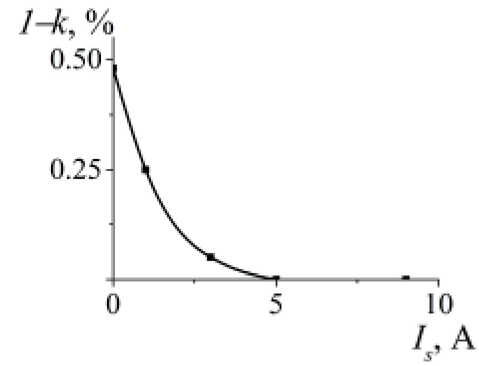

Fig. 6. Ratio of emission current of the electrons incident on the control electrode to total current of the cathode as a function of the current in the solenoid

Calculation results and discussion

The coefficient *k* of electron transmission through the control electrode, numerically equal to the ratio of the electron current through the aperture in the control electrode (current to the collector), to the electron current leaving the emitter is an important parameter affecting the operation of the EOS.

Only a small part (0.5%) of the emitted electrons reached the control electrode of the EOS in the absence of a magnetic field. The larger part of the electrons (99.5%) passed through the aperture and reached the collector. Fig. 3 shows typical electron trajectories in the triode EOS with a multitip field emitter, calculated in the absence of a magnetic field, with fixed values of R = 15 nm and U = 15 kV.

The electron stream started to accumulate on the walls of the electron transport channel (collector) with a diameter of 50 mm at a distance as small as 100 mm from the end face of the cathode. Fig. 4 shows the current-voltage curves for the collector and the control electrode.

It follows from the calculations that the coefficient of transmission through the control electrode tends to unity even in the absence of a magnetic field generated by the electron beam, and aperture intercepts no more than about 0.5% of the total current in the cathode. However, since this current was deposited on a small area of the control electrode, parts of the control electrode surface may start heating at high voltages. For example, for R = 15 nm with U = 20 kV (Fig. 4), the collector current was 31.5 mA, which is enough for the diagnostic gyrotron to operate. The current in the control electrode was equal to 0.15 mA. This relatively small current was deposited on an area of approximately 0.2 cm^2. The specific power released in this area reached about 15 W/cm^2. Noticeable heating of the collector was observed with increased pressure in the vacuum chamber for these approximate specific powers in the experiments in [13].

The magnetic field affected the changes in the trajectories of the electrons and the decrease in the current intercepted by the control electrode. According to the calculations, all electrons that left the emitter passed through the aperture when the magnetic flux density in the cathode was equal to or greater than 0.07 T. The electrons passing through the aperture accumulated on the inner surface of the beam transport channel (on the collector) at a distance (over 500 mm) from the cathode. Fig. 5 shows electron paths at different values of the solenoid current. Fig. 6 illustrates the change in the ratio of the current in the control electrode to the total current in the cathode with increasing solenoid current.

Conclusion

We have considered the potential of integrating multitip silicon emitters with protective metal fullerene coatings into a three-electrode electron-optical system (EOS) with magnetic confinement. Our major findings are as follows.

We have determined the effect of magnetic field on electron motion in a three-electrode gun, confirming that interception of electrons by the control electrode with an aperture can be prevented.

We have established that emission currents necessary for operation of the diagnostic gyrotron can be obtained in the triode system.

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