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COLD FIELD EMITTERS FOR ELECTRON DEVICES OPERATING IN TECHNICAL VACUUM

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ХОЛОДНЫЕ ПОЛЕВЫЕ ЭМИТТЕРЫ ДЛЯ ЭЛЕКТРОННЫХ УСТРОЙСТВ, РАБОТАЮЩИХ В ТЕХНИЧЕСКОМ ВАКУУМЕ

The paper describes the field emitters of a new type: multi-tip cathodes with special protective coatings and layered cathodes prepared from the nano-layers of the materials with different work function values. The article presents data on the technology of emitter creation and their operation at technical vacuum conditions.

FIELD EMITTER, HIGH EMISSION CURRENTS, HIGH DURABILITY IN TECHNICAL VACUUM, EXPERIMENT, NUMERICAL COMPUTATION.

В статье описаны эмиттеры нового типа: многоострийные катоды со специальными защитными покрытиями и слоистые катоды, изготовленные из нанослоев материалов с разной работой выхода. Приведены данные о технологии изготовления эмиттеров и об их работе в условиях технического вакуума.

ПОЛЕВОЙ ЭМИТТЕР, БОЛЬШИЕ ЭМИССИОННЫЕ ТОКИ, ВЫСОКАЯ ДОЛГОВЕЧНОСТЬ В ТЕХНИЧЕСКОМ ВАКУУМЕ, ЭКСПЕРИМЕНТ, ЧИСЛЕННЫЙ РАСЧЕТ.

I. Introduction

Interest to the cold field emitters has increased significantly during the last years in connection with the appearance and development of comparatively low-power microwave electron devices operating in the range of terahertz waves. Such devices may be used to implement different types of diagnostics, in particular for some types of medical diagnostic and diagnostic of dense plasma. The miniature cold field emitters are very attractive for such devices. Difficulties in achieving high durability at technical vacuum conditions and obtaining high enough currents prevent the application of field emitters in high voltage microwave electron devices. The authors searched for the methods to create the durable and high current field emitters for microwave devices operating in technical vacuum. Two prospective cathode systems can be proposed for such application. They are multi-tip cathodes with special protective coatings and nano-layered cathodes prepared from materials with greatly different work function values developed by the authors from St. Petersburg State Polytechnic University (SPbSPU) [1, 2].

II. Tip Field Emitters with Fullerene Coatings

Multi-tip silicon systems that we are investigating now provide in pulse regime (1 – 2 μs, 100 – 200 Hz) currents about 100 mA from the square of approximately 1 cm^2. Production of such systems is organized in Institute of Crystallography RAS (Moscow). But the cathodes of this type usually have low conductivity and provide such a high level of emission only at heightened temperatures, when their conductivity is increased due to the heating. Cathodes of this type are insufficiently steady and usually are destroyed in static regime at significantly lower currents under the action of ponderomotive forces. In addition, silicon cathodes are easily damaged in the presence of an intense ion bombardment. So, one needs to find the ways to increase their conductivity and strength to the action of the ponderomotive forces and ion bombardment to solve the problem of the practical use of silicon cathodes.

The previously performed investigations [3 – 7] of single-tip tungsten field emitters showed that fullerene coatings can be used to protect them from the destructive action of ion bombardment. Fullerene coatings have high work function ($e\varphi \sim 5{,}0 - 5{,}4$ eV). However, creation of a structure including a large amount of roughly equal in size protrusions on the surface of emitters allowed emitters with fullerene coatings to operate at moderate voltages. Additional reduction of the operating voltages was achieved as the result of activating the fullerene coating by a flow of slow (40 eV) potassium ions.

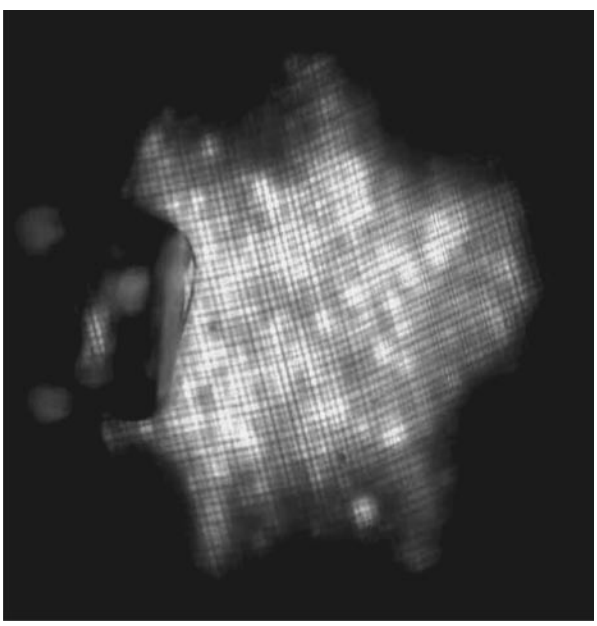

Fig. 1. The image of a single-tip tungsten emitter with activated fullerene coating obtained in the field emitter microscope at residual gas pressure about 10^{-7} Torr

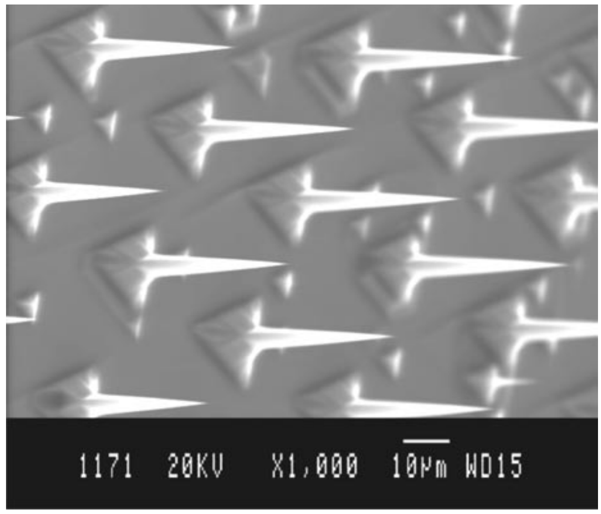

Fig. 2. Multi-tip silicon system

Tungsten tip emitter with activated fullerene coating stably operates at technical vacuum conditions. Fig. 1 demonstrates typical image of a single-tip tungsten emitter obtained in the field emitter microscope at residual gas pressure of about 10^{-7} Torr. The revealed mechanism of fullerene coating self-reproduction in the presence of intensive ion bombardment explains the stable operation of such emitters at technical vacuum conditions [3, 4].

It was important to understand the possibility to use the fullerene coating for shielding silicon tip field emitters from the destructive action of the ion bombardment. We have investigated the functioning of multi-tip silicon system which is demonstrated in Fig. 2. Our measurements showed that application of a thin (two – three monolayer) activated fullerene coating on the surface of the silicon multi-tip field emitter allowed to increase significantly the stability of its operation in a static regime at low (less than 1 – 2 μA) currents, but not prevented its destruction at higher currents. Significantly better results were obtained for the cathodes with more complex evaporated two-layer coating comprising a metal (molybdenum) layer (with thickness of several tens of nm) and a thin (several monolayers) layer of activated fullerene molecules. Cathodes with such coverage allowed to obtain the field emission current

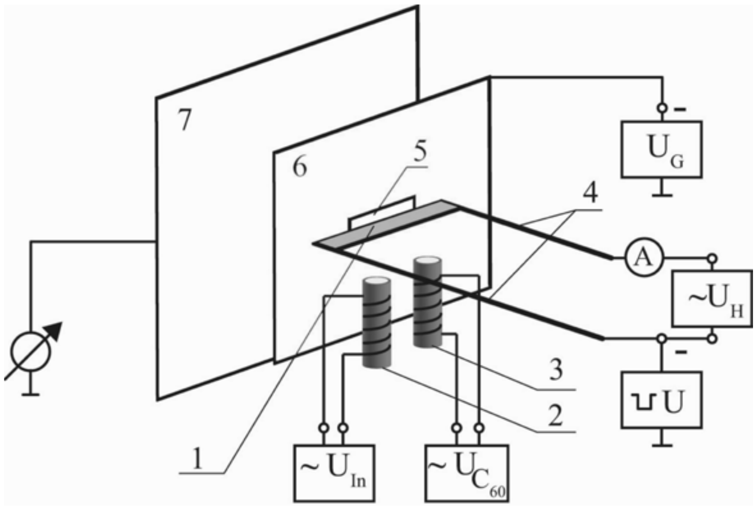

Fig. 3. Triode type system used for the investigation of the layered emitters

density approximately up to 0,1 – 0,5 A/cm^2 without heating. The experiments showed that these cathodes can operate in static regime for a long time at residual gas pressure of the order of 10^{-7} Torr.

III. Nano-Layered Cathodes of New Type

A. Experimental Investigation

Creation and investigation of the layered emitters were performed in a triode type system (Fig. 3). The layers of indium ($e\varphi \sim 3{,}6 - 3{,}8$ eV) and fullerenes ($e\varphi \sim 5{,}0 - 5{,}4$ eV) were deposited alternately from the heated sources *2* and *3* onto the side surface of tungsten substrate – foil *1* (10 μm × 2 mm × 25 mm). Electrons from the frontal surface of the layered cathode reach the collector *7* through the transparent (75 %) grid in the slot *5* (4 × 10 mm) of the anode *6*. Thicknesses of In and C_{60} layers were determined by the measurements of so-called evaporation curves [4, 5]. The thickness of In and C_{60} layers was varied approximately from 1 to 10 nm. Measurements of cathodes emission characteristics were performed in pulse regime (1 – 2 μs, 100 – 200 Hz) in technical vacuum (~ 10^{-7} Torr).

Performed measurements showed that the emission current I increased with the rise of quantity N of pairs In – C_{60} layers. Typical current-voltage characteristics of the cathodes that differ in the quantity N of pairs are shown in Fig. 4. The fields produced by the voltage U near the front of the cathode system can secure only small currents from the substrate S. The currents of cathodes $C1$, $C2$ and $C3$ increased with the quantity N of the pairs of layers. This demonstrates the existence of field emission from the nano-contacts of materials with different work functions.

B. Numerical Computation

Numerical computations were performed using the Comsol program. These computations were aimed at determining the regularities and mechanisms of field emission of layered systems prepared of materials with different

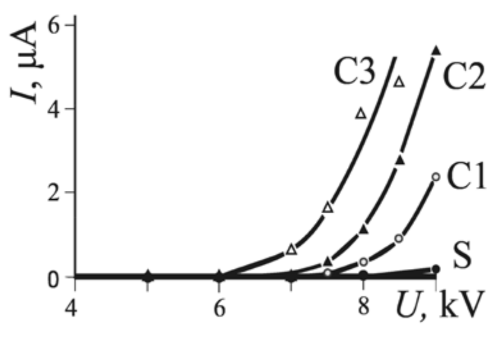

Fig. 4. Typical current-voltage characteristics of cathodes that differ in the quantity N of pairs of layers with different work function values. Cathodes $C1$, $C2$ and $C3$ include correspondingly 1, 2 and 3 pairs of layers. S is the current-voltage characteristic of the W substrate

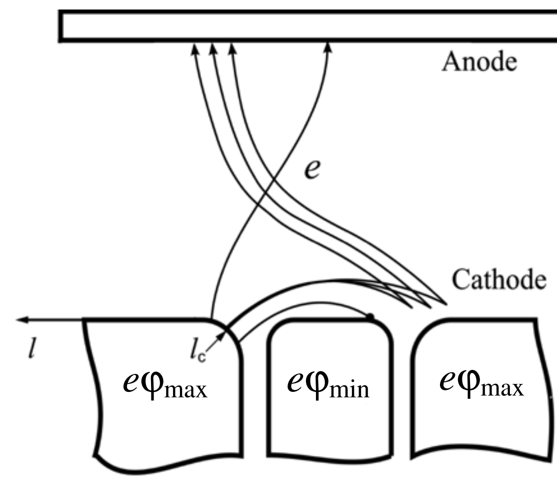

Fig. 5. Typical trajectories of electrons (e) emitted from the material with higher work function ($e\varphi_{max}$) of a layered cathode system.
Here l_c is a critical value of coordinate l that divides the electrons into two main groups: the electrons arriving at the anode, and the electrons returning to the cathode; $e\varphi_{min}$ is the work function of the layer with minimal work function

work functions. Electric field distributions between the layered cathode and flat anode were calculated taking into account not only the «external» field but the fields produced by the contacts of materials with different work functions. These data were used for the calculation of electron trajectories and emission currents.

Typical trajectories of electrons (e) emitted from the material with higher work function ($e\varphi_{max}$) are shown in Fig. 5. Here l_c is a critical value of coordinate l that divides the electrons into two main groups: the electrons arriving at the anode, and the electrons returning to the cathode. The layer with minimal work function is named $e\varphi_{min}$.

The typical distributions of the emission current density $j(l)$ computed at different values of the fullerene layer thickness d_{C60} and at fixed thickness of In layers $d_{In} = 5$ nm are shown in Fig. 6. The calculations were performed with voltage $U = 10$ kV for the cathode containing 10 pairs of layers on the substrate of the thickness $d_s = 10$ μm.

The calculations indicated that the current density j is maximal at $l = l_c$. The value of j increased with the decrease of C_{60} layers thick-

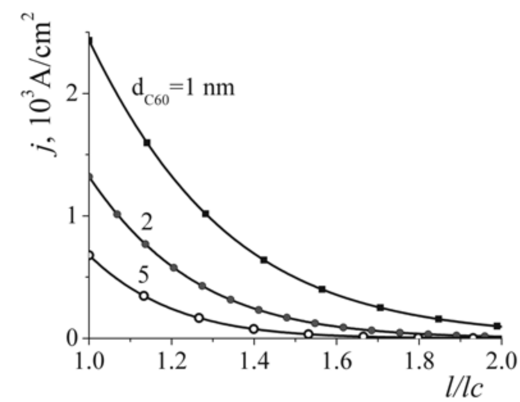

Fig. 6. Dependencies of current density j versus l/l_c measured at voltage $U = 10$ kV, thickness of substrate $d_s = 10$ μm, $d_{In} = 5$ nm, $\Delta e\varphi = 1.2$ eV, $e\varphi_{max} = 5.0$ eV

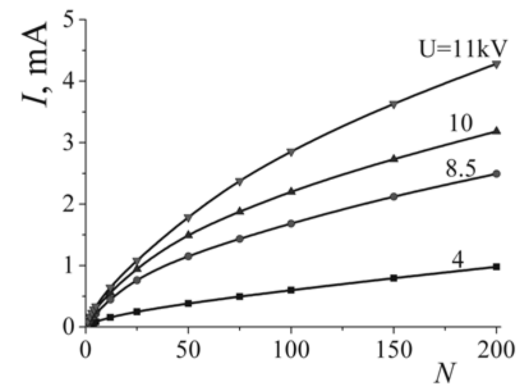

Fig. 7. Dependencies of current I versus quantity N of pairs of layers measured at different values of voltage U; $d_s = 10$ μm, $d_{In} = 5$ nm, $d_{C60} = 1$ nm; $\Delta e\varphi = 1.5$ eV, $e\varphi_{max} = 5.3$ eV

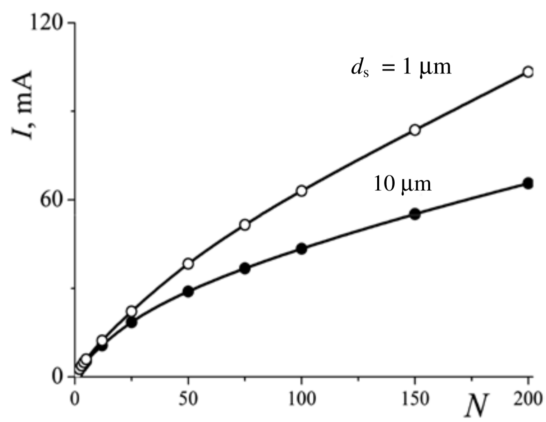

Fig. 8. Dependencies of current I versus quantity N of pairs of layers measured at two values of d_s:1 and 10 μm; $U = 11$ kV, $d_{In} = 5$ nm, $d_{C60} = 1$ nm; $\Delta e\varphi = 1.8$ eV, $e\varphi_{max} = 5.3$ eV

ness d_{C60} (see Fig. 6) and with the growth of In layers thickness d_{In}. The value of j increased also with the diminution of the substrate thickness d_s.

The total current of the layered cathode is obtained by integrating emission current density from the area with coordinates $l > l_c$, from which electrons enter the anode. This current is increased with the rise of work function difference $\Delta e\varphi$ for neighboring layers, and also with the rise of voltage U and quantity N of the pairs of layers. Besides, the current is increased with the decrease of the substrate thickness d_s. Fig. 6 – 8 demonstrate the typical changes of emission current at different values of these parameters.

According to calculations, the maximal current about 100 mA can be obtained from the cathode containing 200 pairs of layers on the thin substrate (d_s = 1 μm) at voltage U = 11 kV and at the difference in the work function of neighboring layers $\Delta e\varphi$ = 1.8 eV when optimal thicknesses of the layers d_{In} = 3 – 5 nm and d_{C60} = 1 nm are set.

IV. Conclusion

The main results of the work are the following:

operation of multi-tip silicon field emitters with special two-layer coatings were investigated at technical vacuum conditions, and emission current density up to 0.1 – 0.5 A/cm^2 was derived;

the possibility of field emission from nanocontacts of materials with different work function values was demonstrated in the experiments and computations. The main regularities and mechanisms of such emission were determined;

influence of the layers and substrate thicknesses, quantity of the layers, work function difference and voltage value on the emission current was determined. The possibility to obtain currents of field emission of about 50 – 100 mA from investigated systems was demonstrated.

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