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FIELD EMITTERS MADE OF THE CONTACTED YTTERBIUM AND CARBON NANOLAYERS

The operation of field emitters of a new type prepared from contacted nanolayers of ytterbium and carbon has been investigated. The performed calculations and experiments allowed to optimize the emission characteristics of the emitters. The calculations took into account the existence of a transition zone between the layers of Yb and C. Emission characteristics of the cathodes including up to 40 pairs of layers of carbon and ytterbium with optimum thicknesses of 5 and 2 nm respectively were measured. The created multilayered emitters provide the average emission current density over the surface of the emitter up to 10 - 20 A/cm^2 and show promise for use in miniature electronic devices.

FIELD EMITTER, CONTACT POTENTIAL DIFFERENCE, YTTERBIUM, CARBON, CALCULATION, EXPERIMENT.

1. Introduction

One of the intractable problems of any field emitter is the need to obtain fields of the order or even more than $2 \cdot 10^7$ V/cm near their surface at moderate voltages. Earlier we have demonstrated the possibility of using the fields near the nanocontacts of materials with different work functions $e\varphi$ [1, 2] for this purpose. Field emitters prepared from contacted layers of materials with greatly different work functions were developed. When first such cathodes were fabricated, thermal evaporation was used to create thin layers of contacting materials. This technology allows to make the emitters consisting of no more than three or four pairs of layers with different work functions. It is obvious that to obtain intensive field emission we are bound to have a system with a large number of pairs of layers and to collect current from such a layered cathode. In this paper, we report the results on the development and investigation of multilayer cathodes including up to 40 pairs of layers with varying work functions.

2. Numerical computations

We present here the calculation data obtained for the structure prepared from ytterbium (Yb, $e\varphi$ = 3.1 eV) and carbon (C, $e\varphi$ = 4.7 eV) layers.

Calculations necessary to optimize the layered field emitters and determine their emission characteristics have been carried out using the Comsol software. Electric fields, electron trajectories, current density distributions over the surface of the field emitter and emitter currents were found. The calculations took into account the existence of a transition zone between the layers of Yb and C, where the mixture of these materials exists [3]. The current to the anode was determined by the Fowler-Nordheim equation (see for example Ref. [4]).

Emission of the layered cathode is conditioned by the fields that exist due to the difference in work functions of contacted materials, as well as by the 'external' field associated with the supply of voltage U_a between

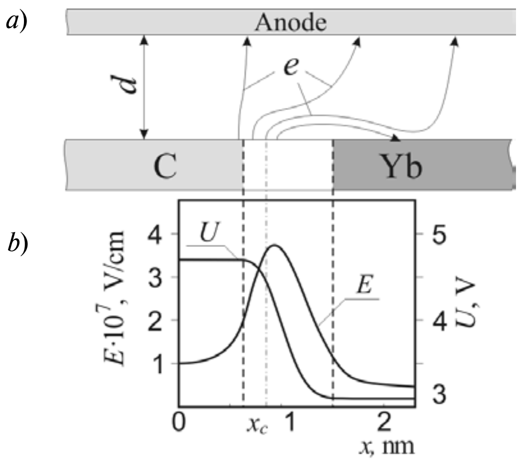

Fig. 1. Schematic representation of the problem statement: a region of the diode system (*a*) and the distributions of potential *U* and electric field *E* near the contact between the Yb and C layers (*b*). Trajectories of the electrons *e* are shown; *d* is a distance, x_c is a position of the critical point

the cathode and the anode. The distribution of the potential *U*(*x*) in the transition zone due to the difference in the work functions of contacted materials was described by the function:

$$U(x) = 3.1 + 1.6 \cdot \cos\left(\frac{\pi}{2} \cdot \left(\frac{x}{l}\right)^{A1}\right)^{A2},$$

where *l* is a width of the transition zone.

The shape of this distribution can be varied by changing the coefficients *A*1 and *A*2. The coefficients were chosen so as to ensure the best possible agreement between the calculation and the experimental results on the emission characteristics of the layered cathode.

Fig. 1, *a* schematically shows the contact region of adjacent Yb and C layers. The vertical dashed lines indicate the boundaries of the transition zone between the layers. Fig. 1, *b* demonstrates typical distributions (used in the calculations) of the potential *U* and the total electric field *E* in the contact area defined at U_a = 6 kV and the given value $\Delta e\varphi$ = 1.6 eV of the work function difference for these layers in the diode with a gap of 1 mm between the cathode and the anode. Typical electron trajectories (*e*) are shown in Fig. 1, *a* as well.

As follows from the calculation results of electron trajectories, electrons emitted by the cathode region $x \le x_c$ reach the anode at a fixed voltage U_a, whereas those from the region $x > x_c$ return to the cathode at the same voltage.

The performed calculations revealed that the anode current of the layered cathodes depends on the thickness of the contacted layers. Typical calculated dependencies of the anode current I_a upon the thickness values of the ytterbium (d_{Yb}) and the carbon (d_C) layers are shown in Fig. 2.

According to the information in literature (see for example Ref. [3, 5]), the width of the transition zone is typically about 0.6 – 0.8 nm. Therefore, we can probably take d_C = 1 – 2 nm as the optimal thickness of a carbon layer, as it is only a little more than the transition zone dimension. Thickness d_{Yb} of the ytterbium layers should be much more, and may be taken, for example, as about 5 nm.

Two current-voltage characteristics of the cathodes including 20 pairs of Yb-C layers are shown in Fig. 3. The former was obtained for

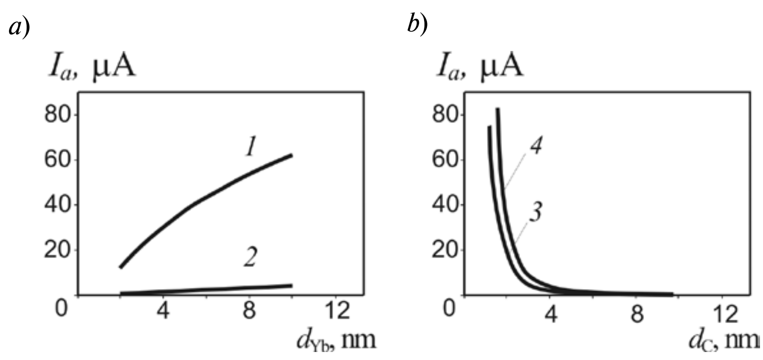

Fig. 2. Plots of the anode currents versus thicknesses of Yb (*a*) and C (*b*) layers at two values of the C (*a*) and Yb (*b*) layer thickness $d_{C,Yb}$, nm: 2 (*1*), 5 (*2*), 3 (*3*) and 5 (*4*). In the calculations, we put U_a = 6 kV

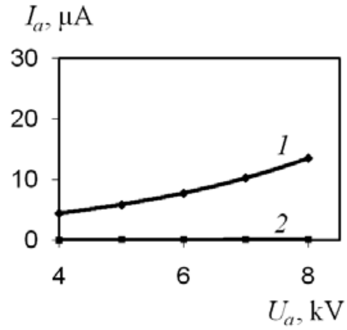

Fig. 3. Calculated current-voltage characteristics for the emitter with 20 pairs of layers structure with d_{Yb} = 5 nm, d_C = 2nm (*1*) and d_{Yb} = 2nm, d_C = 5nm (*2*)

optimal thickness values d_{Yb} = 5 nm and d_C = 2 nm, the latter was calculated for the cathode with different thickness values of the Yb and C layers: d_{Yb} = 2 nm and d_C = 5 nm. It can be seen that the deviation from the optimal dimensions leads to a significant drop of current.

3. Experimental investigation

Layered cathodes were made using magnetron sputtering. The carbon and ytterbium layers were sequentially deposited on a single crystal substrate of gallium arsenide. Two–three cathode systems, differing in the number *N* of pairs of layers (ytterbium-carbon) and/or in layer thicknesses, were located on a surface of a single substrate. After the procedure of the layers application was completed, cleavage of the single crystal and of the bottom part of the layered cathodes was accomplished. Thus, an atomically smooth emitting surface of the cathode was formed. The cathode surface morphology was examined with a scanning electron microscope Supra 45 WDXC.

The triode system for the investigation of the layered cathodes emission characteristics is shown schematically in Fig. 4. Measurements of the field emission currents were carried out in pulsed mode (2 μs, 200 Hz).

Fig. 4 shows the cathode system with three layered structures as an object. A pulse of negative voltage was supplied to the cathode system (*C*) through a metallization layer (*M*) (200 nm of titanium). Flows of electrons from all three layered structures penetrating the grid (*G*) to the corresponding collector *1*, *2* or *3* were

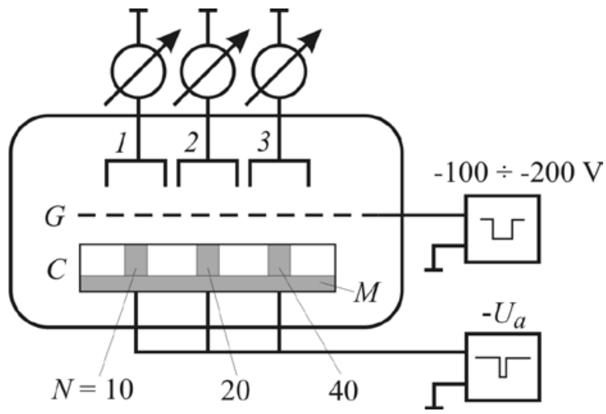

Fig. 4. The triode system scheme to measure the emission characteristics of a sandwich-layered cathode: *G* is a grid; *C* is a cathode system: *1*–*3* are collectors; *N* is the quantity of pairs of layers in the layered structures; *M* is a metallization layer to apply a voltage to the cathode system; power supply units (on the right) and measuring equipment (at the top) are shown as well

detected simultaneously. A negative voltage of 100 – 200 V to earth was applied to the grid in order to reduce the flow of secondary electrons from the collectors.

Typical current-voltage characteristics of the cathodes with different quantities (*N*) of pairs of layers are shown in Fig. 5. As expected, the field emission current was built up with the *N* value. The dashed line in Fig. 5 demonstrates the calculated current-voltage characteristic of the cathode including 40 pairs of layers. Emission currents from the cathode with 40 pairs of layers reached 50 – 100 μA. At higher

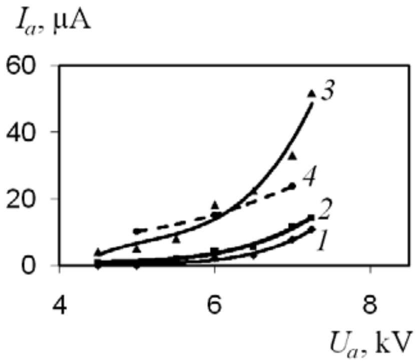

Fig. 5. The experimental (*1*–*3*) and the calculated (*4*) current-voltage characteristics of layered systems with the different quantities of layers *N*: 10 (*1*), 20 (*2*), 40 (*3*, *4*)

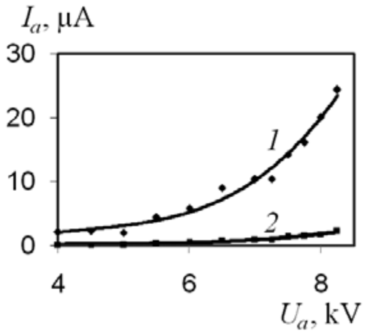

Fig. 6. The experimental current-voltage characteristics of emitter with 20pairs of layers structure with d_{Yb} = 5 nm d_C = 2nm (*1*) and d_{Yb} = 2nm, d_C = 5nm (*2*)

currents, destruction of the cathodes occurred. The emission current densities averaged over the surface of the layered cathode reached values of ~(1 – 2)·10 A/cm^2.

To test the validity of the calculation results on the optimal layer thicknesses in the layered structure, we measured emission characteristics of two cathodes with the same quantity (N = 20) of pairs of layers but with significantly different layer thicknesses (see Fig. 6).

The curve *1* was obtained for the cathode with optimal (according to our calculations) thicknesses of the ytterbium layers d_{Yb} = 5 nm and the carbon ones d_C = 2 nm. The curve *2* was derived for the cathode with non-optimal layer thicknesses of ytterbium and carbon, respectively equal to 2 and 5 nm. The obtained data revealed that the currents from optimized layered structure were substantially higher than those from the structure with non-optimal layer thicknesses. Thus, these measurements prove the correctness of the conducted optimization.

4. Summary

We have investigated the operation of field emitters of a new type made of contacted nanolayers of ytterbium and carbon. The most important results of this study are the following:

The technology of multilayer cathodes production from the contacted layers of materials with different work functions was developed;

The calculation technique for multilayer structures and their optimization was worked out;

An experimental method to investigate multilayer structures was developed and achievable emission characteristics of multilayer cathodes were obtained;

The emission characteristics of the cathodes including 10, 20 and 40 pairs of layers of carbon and ytterbium were determined. The possibility of obtaining emission current densities (averaged over the cathode surface) up to 10 – 20 A/cm^2 was demonstrated.

The investigated cold cathodes showed considerable promise as a means of producing miniature vacuum devices with high emission current densities.

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Соминский Г.Г., Сезонов В.Е., Задиранов Ю.М. ПОЛЕВЫЕ ЭМИТТЕРЫ, ИЗГОТОВЛЕННЫЕ ИЗ ПРИВЕДЕННЫХ В КОНТАКТ НАНОСЛОЕВ ИТТЕРБИЯ И УГЛЕРОДА.

Изучена работа полевых эмиттеров нового типа, изготовленных из нанослоев иттербия и углерода, которые были приведены в контакт. Проведены расчеты, позволяющие оптимизировать характеристики такого слоистого катода. В расчетах было учтено наличие переходной области между слоями Yb и C. Определены эмиссионные характеристики катодов, включающих до 40 пар слоев с оптимальной толщиной слоев Yb и C 5 и 2 нм соответственно. Показана возможность получения плотностей тока полевой эмиссии до 10 – 20 А/см^2.

ПОЛЕВОЙ ЭМИТТЕР, ПОЛЕ КОНТАКТНОЙ РАЗНОСТИ ПОТЕНЦИАЛОВ, ИТТЕРБИЙ, УГЛЕРОД, РАСЧЕТ, ЭКСПЕРИМЕНТ.

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