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New Thermal Field Electron Emission Energy Conversion Method

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New thermal field electron emission energy conversion method for vacuum electron-optical systems (EOS) with a nanostructured surface electron sources is offered and developed. Physical and numerical modeling of an electron emission and transport processes for different EOS is carried out. It is shown that at the specific configuration of electrostatic and magnetic fields in the EOS offered method permits to realize energy conversion processes with high efficiency.

Keywords: Energy conversion, Thermal field electron emission, Nanostructures.

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1. INTRODUCTION

Achievements of last decades in area of micro-and nanotechnology promoted revival of scientific interest to a problem of direct transformation of thermal and light energy to electric energy. As a result of development of nanotechnology methods researchers had new possibilities for use in the workings out of the fundamental physical phenomena which remained earlier not claimed. In particular, reproduced formations of quasi 1D and 2D nanostructures (NS) have allowed to raise essentially efficiency of thermoelectric materials and devices [1, 2] and also to start working out of "solid-state" thermionic energy converters [3].

As is known, electron emission from a surface can be achieved via two mechanisms: tunneling and thermionics. Converting thermal energy to electrical power using these mechanisms is achieved by generation of an electron current from the emitter to the collector, and production of a voltage potential between electrodes due to the potential energy difference between the electrodes.

At present the thermionic energy conversion method is developed in a sufficient measure.

Let us note that thermionic method permits implementation of energy conversion with the efficiency $\eta \sim 20\ \%$ and the energy effectiveness (ε) before $\sim 10^2 W/cm^2$.

However, the possibility of the thermal field emission phenomenon application in energy conversion devices (ECD) not studied.

In the present work the possibility of using thermal field emission (TFE) phenomenon from the NS cathode surface for energy conversion purposes is investigated.

As a result of spent before researches of the thermal field emission from the NS surfaces it has been established [4-6], that the basic laws of electron emission process from the NS surface essentially differ from the known classical representations [7] describing process of (TFE) from a homogeneous substance surface.

In [6], in particular, it has been shown, that in rather low macroscopical electrostatic fields (F_e) (less ~ 50 V/μm), some NS (ZrO_2/W and ZrO_2/Mo) at temperatures of substance NS ≈ 1900 K possess an abnormally high reduced brightness (to ~ 10^6 A/(cm^2 sr V)) and high stability of thermal field emission properties. The found out (in specified above physical conditions) phenomenon of sharp increase NS emission ability has been named by "abnormal thermal field emission" (ATFE). The basic conclusions offered in [5] ATFE mechanism phenomenological model consists in the following.

1. In the ATFE conditions an emitted in vacuum electron flux, is formed from electrons which are injected in a dielectric film as on the thermionic mechanism (TE) over Schottky barrier, and on the TFE mechanism. The basic physical factor, which defines features (or anomalies) process of ATFE from the surface of low-dimensional NS, is formation in the forbidden zone of a thin dielectric film of a high density of bounded space charge which results from ionization of the localized states.

2. With other things being equal, ATFE emission properties essentially depend on a thickness (τ) of the dielectric films on a substrate. In particular, at enough small thickness of the dielectric film ($\tau < 100$ nm) electron transport in the film in strong electric field is carried out mainly on a ballistic mechanism. As consequence, average kinetic energy of an electron on the interface: the film-vacuum, can make from units to tens electron-volt. Owing to listed above factors, in the ATFE conditions the power density of electron flux can reach values of an order ~ 10^6 W/cm^2.

From the above-stated follows, that from the thermodynamics point of view of the processes proceeding in EOS with an electron source on the basis of the NS of a kind: the conductor - a thin dielectric nanofilm, in EOS takes place effective transformation thermal and radiation (infra-red range) energies to electric energy.

The approached theoretical analysis of the energy balance equation for thermal and emission processes, including of an electron transport processes, has shown *apriori*, that EOS with ATFE an electron source allows to carrying out highly effective conversion of thermal and radiation (infra-red) energies to electric energy.

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2. PHYSICAL AND NUMERICAL MODELING OF THE ECD WITH ATFE CATHODE

As appears from the Introduction to realize the offered method of power conversion it is necessary to develop ECD which would allow to effectively transform absorbed by ATFE cathode thermal energy or energy of radiation (in infra-red range) to energy of an electric current. It means that in a limiting (ideal) case in such ECD all emitted from ATFE cathode surface a high-intensity electron flux should reach collector surfaces. In other words, one of the conditions of high ECD efficiency is the condition $(I_c/I_e) \to 1$, where I_c - an electron current, reached collector ECD, I_e – ATFE current.

A first possible prototype of the ECD which physical principle of action is based on the ATFE phenomenon is shown on Fig. 1.

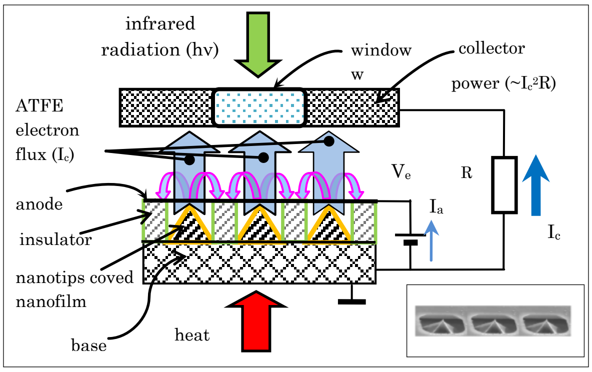


Fig. 1 – Possible prototype of the ECD which physical principle of action is based on the ATFE phenomenon; on an insert to the figure an electronic microphotography of the ordered nanotips ensemble fragment is shown

Using possibilities of the CPO software [8], the executed numerical calculations of the electron transport processes showed that realization ECD according to the diagram, given in Fig. 1, is unpromising, since Ic/Ie << 1.

The next version EOS of the ECD, for which was executed the numerical simulation of the electron transport processes under the ATFE conditions for the electron emission from the surface of a quasi 1D NS (or the "point" ATFE emitter), is shown on Fig. 2.

As appears from the done calculations (Ic/Ie) ≈ 0.04. Since it is impossible to recognize the received result satisfactory, we had been offered and investigated other approach to design (to synthesize) of EOS for ECD.

As the analysis showed the main disadvantage of the EOS, given on figs. 1, 2, consists in the limitation of electron flux to the collector by the action of the electron flux SC field. In order to remove the problem indicated it was proposed "to divide" the processes of extraction and subsequent transport of the extracted electron flux.

For this purpose was developed the electron-optical system, in which the process of the electron extraction was achieved under the action of strong electrostatic field on the nanostructured surface of the ATFE cathode, and the process of the electron transport occurred under the Lorentz force action. The basic idea of this approach consists in that it is essential to reduce electron SC density in the course of carrying over of the flux from the cathode to collector surface of the EOS. Realization of such approach is shown on Fig. 3.

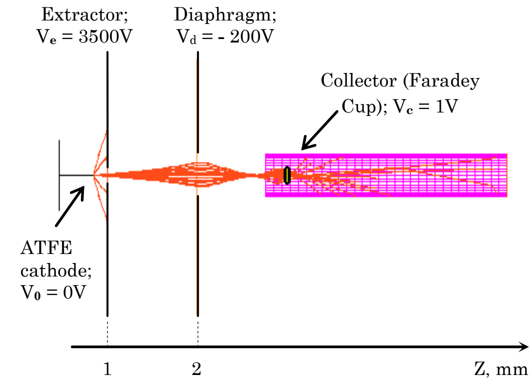


Fig. 2 – Electrodes configuration of the EOS and results of electron trajectories numerical modeling for ECD with a "point" ATFE cathode; total current = – 5.349E + 00 mA; Faraday cup current = – 0.195 mA; average cathode brightness, = – 3.088E + 04 A/ster.cm², beam brightness = – 1.792E + 05 A/V.ster.cm²

Thus, in the specified conditions (see Fig. 3) it appears possible to reach values (I_c/I_e), close to ~ 1. As can be seen in the course of electron transport in the area of superposition electrostatic and homogeneous magnetic fields electron moves on a helicoidal trajectory with a cyclotron frequency.

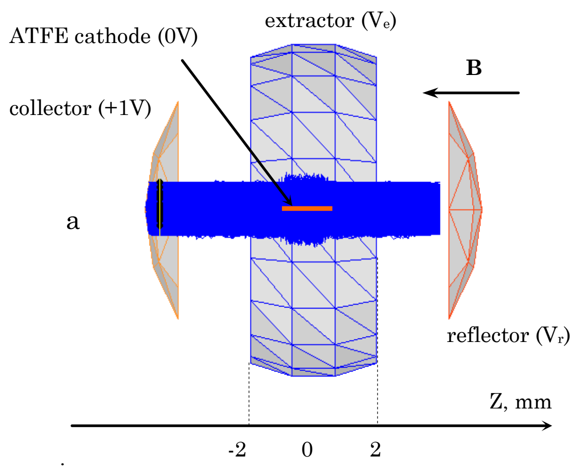
3. MODELING OF THE INFRA-RED RADIATION ABSORPTION PROCESSES IN THE NANOSTRUCTURED CATHODES OF THE ECD WITH ATFE CATHODE

As appears from the data of Introduction, activation and excitation of ATFE process can take place as well as a result of ionization deep (≈ 1eV) localized states in the forbidden zone of a dielectric nanofilm.

In this connection in the given work a question on efficiency of infra-red radiation absorption processes in nanofilms are investigated also.

We employed the boundary integral equation method for the theoretical description of the relief and phase diffraction structures [9, 10]. The program computes the energy and polarization for an arbitrary number of layers of different profile types, if the profiles of the layers and the inclusions are strictly separated. The integral equations are discretized with a collocation method.

The code developed and tested is found to be accurate and efficient for solving various in-plane and off-plane diffraction problems including high-conductive gratings, surfaces with edges, real groove profiles, and gratings with non-function and closed boundary profiles. The high rate of convergence, the high accuracy, and the short computation time of the suggested solver were demonstrated for various samples. The quadratic time dependence on the main accuracy parameter (number of collocation points) has been realized.



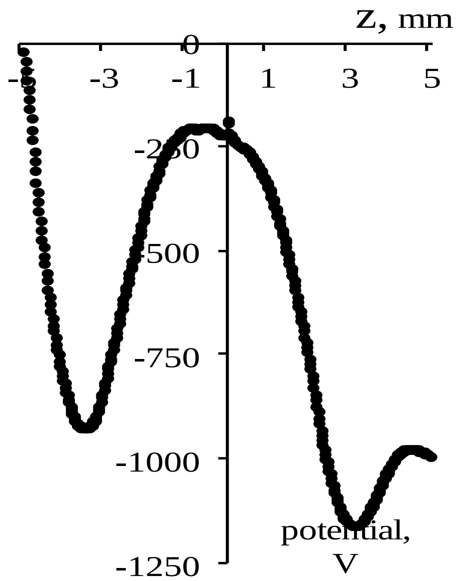


Fig. 3 – Electrodes configuration for EOS of ECD and results of computer modeling (a) of an electronic trajectories (V_e = 3500 B; V_r = – 1000 B; the potential of an electron source in the form of the cylinder in length 8 microns and diameter 0.2 microns, located on z axis is equal 0V; an induction of a homogeneous magnetic field B_z = 0.2 Тл, $B_x = B_y = 0$); potential distribution of the self-co-ordinated electrostatic field (b). (Information on the iteration: total current = – 8.129 A; average cathode brightness = – 3.471E + 05 A/ster.cm²; beam brightness = – 3.323E + 09 A/V.ster.cm²; total time for ray tracing is 322 mins 19 secs)

Results of absorption modeling of the infra-red radiation (1.37 μm) in thin ZrO_2 films on a tungsten substrate are presented on Fig. 4.

4. DISCUSSION AND CONCLUSION

As a result of the executed researches it is shown, that ATFE phenomenon can be used as a physical basis

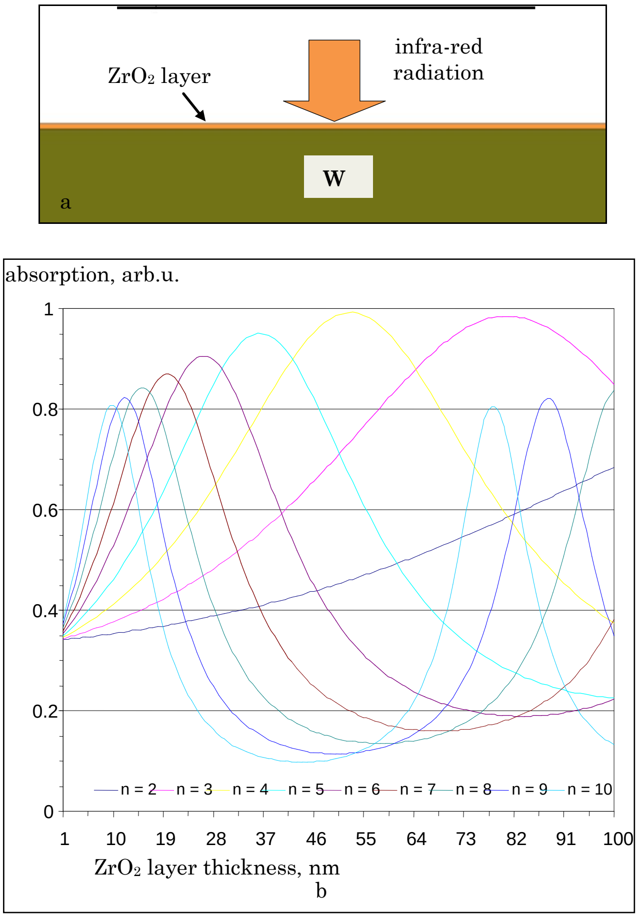


Fig. 4 – [9]. Geometry of the 1D ZrO_2/W NS radiation process (a) and a dependence of an absorption of the 1D ZrO_2/W NS on layer thickness for different values of the ZrO_2 layer refractive index n (b).

for working out of a highly effective new method of conversion of thermal and infra-red radiation energies to electric energy. For creation on the basis of this method of operating ECDs, it is necessary to carry out additional researches, namely, to find the decision of a problem of synthesis of an optimum EOS electrode configuration. As have shown preliminary experiments (in which it has been realized EOS with ATFE cathode on the basis of ZrO_2/W NHS) energy efficiency (ε) such ECD reaches values ε ~ 10^4 W/cm². It is necessary to notice, that reached level of ε values for experimental prototype ECD more than on two order of size exceeds efficiency of modern thermionic converters. According to the spent calculations and estimations, the efficiency (η) for such ECD depends on physical conditions of the ATFE process and can make from ~ 55 % to ~ 80 %. Criterion of the task decision in view of ECD optimization is achievement of the greatest possible perveance values for EOS and also ε and η for ECD.

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