The Total Energy Distribution of Field Emission Electrons from Graphene-like Structures.

Georgy Fursey, Nikolay Egorov, Ildar Zakirov, Yulai Yumaguzin

Abstract—In our previous study it has been found that the half-width of the total energy distribution of the field emission electrons (TED), emitted from carbon nanoclusters, is significantly broadened as compared with that of metals. The value of the TED broadening increases with the growth of the electric field. It has been shown that the maximum of the energy distribution shifts with increasing electric field in the region of lower energies.

Index Terms— field emission, carbon nanoclusters, graphene-like structure, energy distribution, low-threshold electron emission, size quantization, resonance tunneling

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1 Introduction

In our previous studies of carbon nanoclusters by direct experiments [1], [2], [3], [4], [5] (see also chapter 8.6 [6] and 8.13 [7]) it has been found that the excitation of the field emission (FE) occurs in the fields of 2-3 orders of magnitude less than in the cases of metals and semiconductors. In the same studies it has been also shown by the methods of FE and Scanning Electron Microscopy (SEM) that the mechanism of the low-threshold (LT) emission cannot be explained by the amplification of the field on micro-roughness of the surface [3], [4].

In the papers [3], [4], [8] the mechanism of LT emission was proposed, based on the idea of the size quantization resulting in the resonance tunneling of the electrons from the solid state into the vacuum.

The present study of the distribution of field emission electrons in total energy (TED) was undertaken in order to obtain the additional information on the mechanism of the LT electron emission in the strong electric field.

The important experimental data that would permit to elucidate the mechanism of the LT field emission become the results on the energy range from which the tunneling of the electrons into the vacuum occurs.

The studies of the TED were carried out by the methods of dispersion analysis (p. 91 in [9]) and of retarding potential [10], [11], [12] (p. 85 in [9]). The method of the dispersion analysis is the best in the characteristics, but is limited by the geometry of the experiment and by the values of the field. In order to increase the range of the applied electric fields, we applied the method of the retarding potential.

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2 Experiment

The layout of the experimental setups used for the methods of the dispersion analysis and of the retarding potential are presented in Figs. 1a and 1b, consequently.

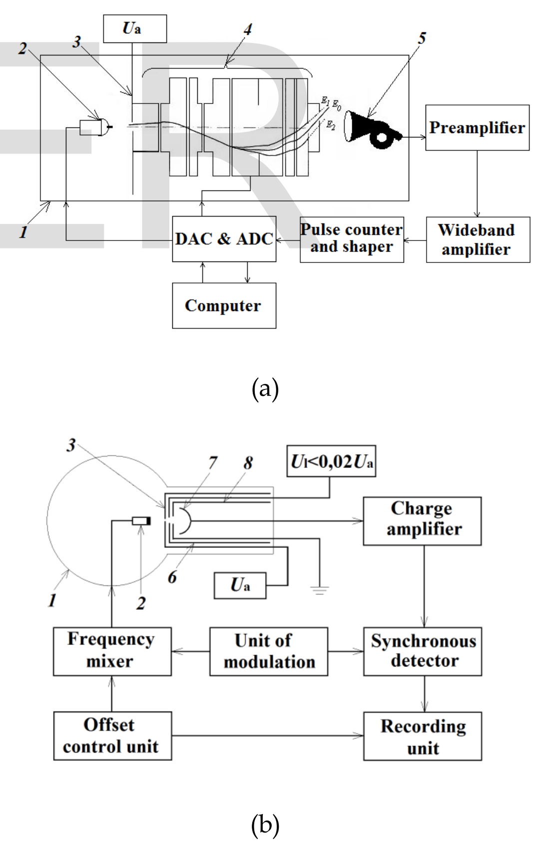

Fig. 1. Schematic diagrams of the experimental sets for dispersion analyzer (a) and retarding potential methods (b). (1- high vacuum experimental apparatus, 2- cathode, 3- fluorescent screen (anode), 4- dispersion energy analyzer, 5- secondary electron multiplier, 6- electron lens, 7- hemispherical collector, 8- protective cylinder).

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As a subject of study we used the samples of graphene-like multi-layered structures obtained by the method of the explosive synthesis [13]. The sample was the separated cluster (flakes) fixed on the holder of the cathode with the help of the special conducting binder (Fig.2).

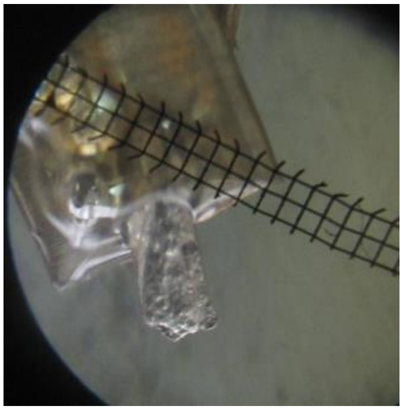
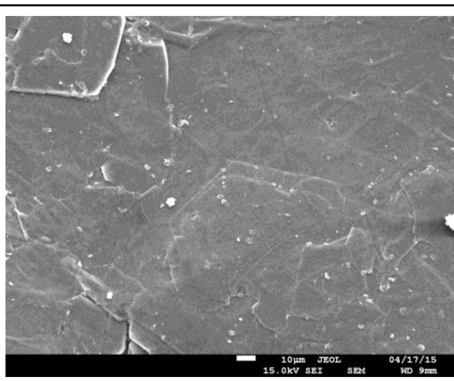


Fig. 2. Cathode surface photo in optical microscope.

The design of the cathode provided the heating of the sample by a tungsten wire filament. The temperature was varied in the range from 300° K to 1200° K.

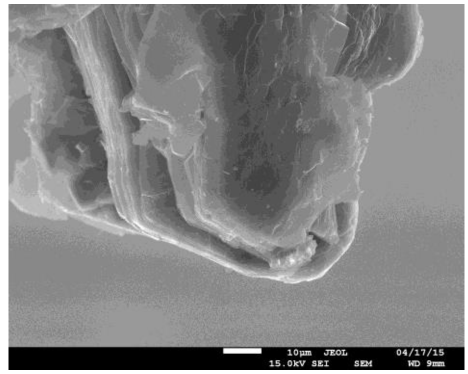
When measuring the current-voltage characteristics, the FE currents were in the limits of 10^{-9} - 10^{-5}A. The vacuum in the system was kept at pressures of 10^{-7} – 10^{-6} Pa.

The electron-microscopic image of the surface of the graphene-like structure is shown in Fig. 3a, b, c. As one can see the surface is sufficiently smooth and practically doesn't contain the micro-grooves. On the surface of the sample one can observe the separate flat fragments of the graphene.

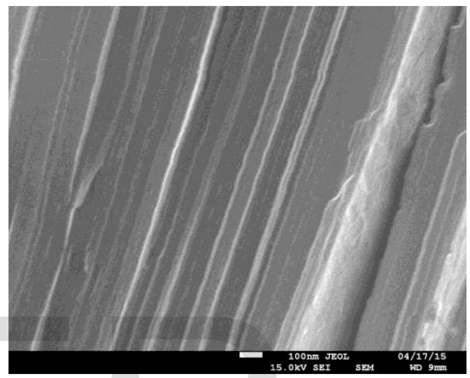


(a)

Fig. 3. Graphene-like structure (flake) surface photo in SEM (a).



(b)



(c)

Fig. 3. Graphene-like structure (flake) surface photo in SEM: local element of flake (b), cross section of flake (c).

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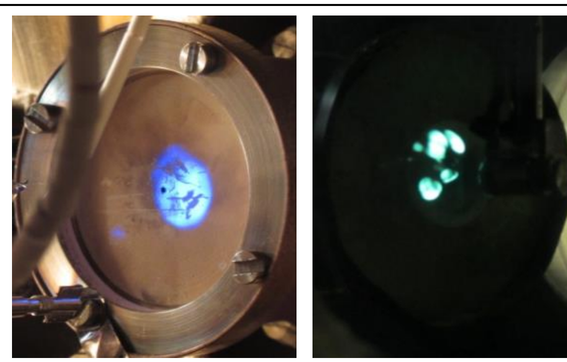
3 RESULTS

1. The emission image of the cathode surface was observed on the luminescence screen Fig. 4a, b that gave the opportunity to record the TED from the different regions of the emitting surface.



(a) (b)

Fig. 4. Field emission pictures in the experimental sets for retarding potential methods (a) and dispersion analyzer (b).

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2. The current-voltage characteristics (Fig. 5) obtained in the given experiment reasonably correlate with the data published in the paper [4]. In the Fowler-Nordheim coordinates the current-voltage characteristics have mostly the linear behavior (part II). In the range of high currents the slow current growth takes place (part I). Such a character of the current variation is similar to that early observed on the semiconductors [1] (see also chapter 5 in [6], [7]). The data obtained confirm the low-threshold character of the excitation of the field emission from the graphene-like structures. The values of the fields at which the field emission is initiated, do not exceed 10^5 V/cm.

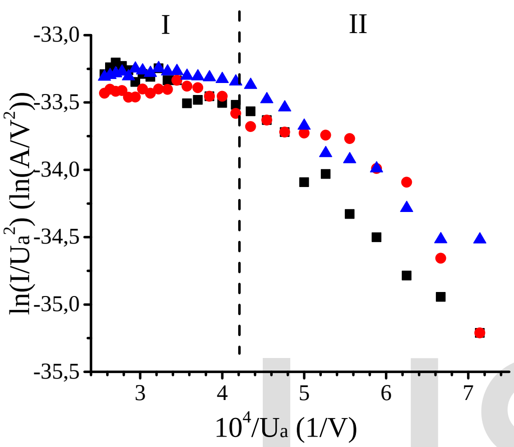


Fig. 5. The current-voltage characteristics in the Fowler-Nordheim coordinates.

3. The TED curves of the field emission electrons are shown in Fig. 6 a, b. The curves 1-5 were obtained for our graphene-like structure at gradual increasing of the anode voltage, and the curve 6 is the reference one, obtained for tungsten. The zero energy is assumed to be the energy of the free electron in a vacuum.

The characteristic features of the TED found in our experiments are the following:

a) A maximum of the distribution is shifted in respect to the Fermi level of the metal (Fig.6, curve 6) towards the lower energies (Fig 6, curves 1-5).

b) It has been found that the TED curves for graphene-like structures had the significantly larger half-width (ΔE = 0.5 – 3 eV) as compared with the values ($\Delta E \approx 0.3$ eV) typical for metals. For the studied samples the half-width of the TED increases with anode voltage and, hence, with emission current (Fig. 6).

c) It has been noticed that the maximum of the TED shifts to the region of low energies as the anode voltage Ua increases.

d) The observation of the second maximum. The maxima are separated from each other on the distance of 0.7 – 1.7 eV.

The study of the local parts of the emitting surface with the help of probing and field-emission microscopy have shown that the shape of the TED curve depends on the local position of the probing region of the emitting surface (Fig. 7a, b).

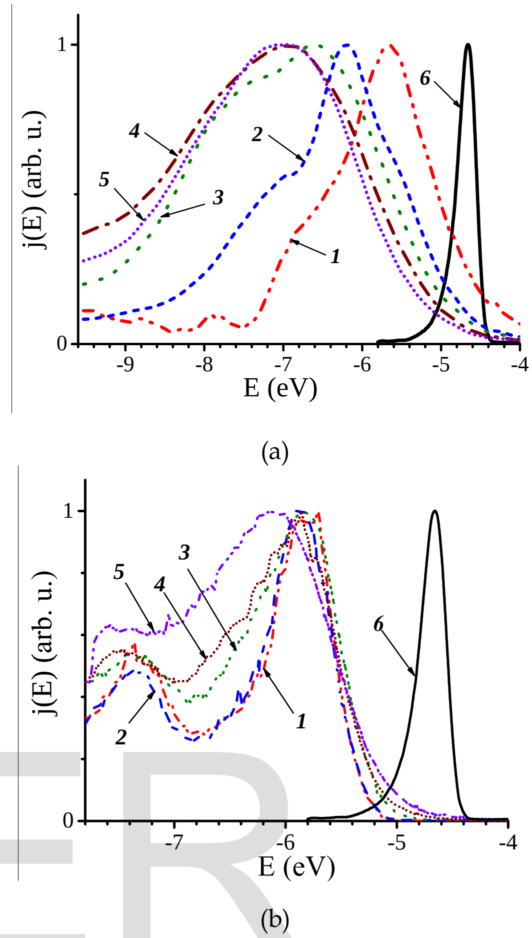
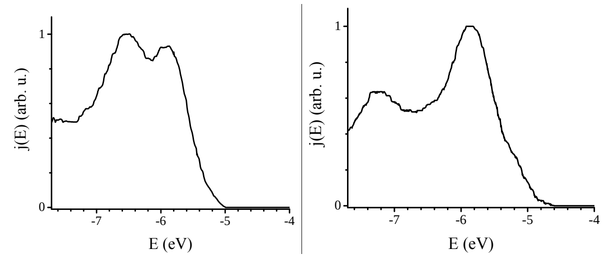


Fig. 6. TED curves of the field emission electrons by dispersion analyzer (a) and retarding potential (b) methods.



(a) (b)

Fig. 7. TED curves of the field emission electrons for various local areas (a, b) graphene-like structure emitting surface

4 Conclusion

The behavior of the TED shows that the field emission electrons are emitted from the region located essentially lower than the Fermi level (the similar results were previously obtained in the study of the diamond-like films [14]).

We suggest that in this region under strong electric fields the deep energy states are formed, from which the tunneling of electrons into vacuum takes place. On our opinion, the

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mechanism of the electron release from graphene-like structures is connected with the effect of the size quantization and resonance tunneling [3], [4], [8].

The detection of the two maxima in the energy spectrum means that in the near-surface region of graphene–like structures, there are, at least, two discrete domains of the energy states, from which the resonance tunneling emerges. The increase of the half-width of the energy distribution could be attributed to the action of the electric field on the spectrum of the electron energy states in the specimen.

It has been also found that the character of the electron energy distribution is different for the various regions of the emitting surface

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