Features of evaluating properties of field emitters using effective parameters

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Abstract

The paper considers the features of evaluating the effective parameters of nanostructured field cathodes – the area of the field emission S_{eff} and the field gain β_{eff}. A variety of approaches to parameter estimates is shown. The dependence of these estimates on the magnitude of the applied electric voltage is shown by the example of a three-dimensional model of a carbon nanotube. The possibility of the experimentally estimation of individual emission sites using a computerized field projector is considered. A method for analyzing the current-voltage characteristics in Fowler-Nordheim coordinates (IVC-FN) with an interval estimate of the effective parameters is proposed.

The motivations and methods

Multi-tip field emitters have rather big prospects in the field of MEMS creation. They differ from thermal cathodes in low inertia and energy efficiency (do not require heating). Based on this type of the free electron sources, scientists create prototypes of microscopic gas sensors [1], mass spectrometers [2], light sources [3], microfluidic system utilizing optical detection with fluorescent dyes [4] e.t.s. The most promising today are large area field emitters (LAFEs) with plenty of an individual emission sites on the surface. They are created by various methods: lithography, controlled growth of conductive and semiconducting nanostructures, deposition of different kinds nanocomposites on metal surfaces e.t.s.

The object of this study was a LAFE made of Si in the form of regular arrays of microscopic cones. Fig. 1 demonstrates SEM images of the sample.

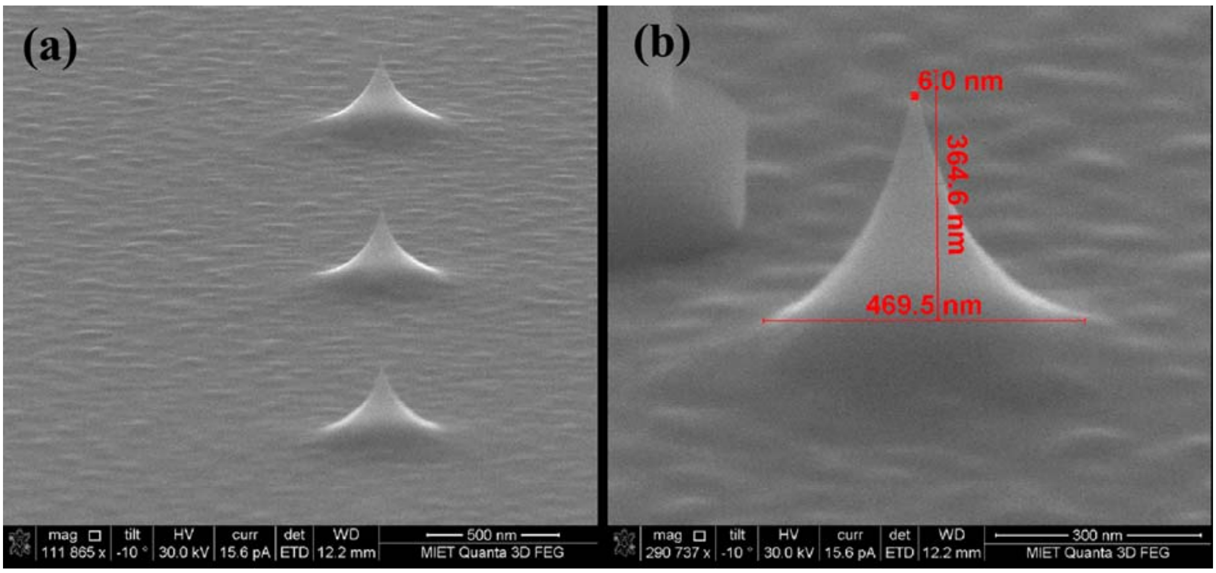

Fig. 1. SEM images of the sample.

To evaluate the LAFEs used in MEMS, the effective parameters calculated by current-voltage characteristics (IVC) analysis based on the simplified law of field emission are usually used [5, 6]. Such parameters as the effective emission area (Seff) and the effective field enhancement factor (βeff), found for a given work function of the cathode, allow to evaluate the quality of the field cathode and compare various cathodes with each other.

However, a number of features may make such an assessment inadequate.

Firstly, it is the bending of a macroscopic IVC under the influence of various factors. This is: elastic or irreversible changes in the shape of the emission sites; strong heating of these sites by the Joule heat, which leads to the appearance of a thermionic contribution in the total emission current; presence on the cathode surface of the emission sites groups that differ greatly in parameters e.t.s. But the most common effect is the influence of the adsorption-desorption processes on the emitter surface. Applying a regression analysis to such influenced IVC becomes inadequate. However, individual sections of the IVC may represent the emissivity of the cathode in the corresponding voltage range. In this paper, we proposed a method for estimating the effective cathode parameters based on dividing the IVC into multiple intervals and plotting diagrams of the corresponding effective parameters. A similar approach was used by us earlier to assess the compliance of various parts of an experimental IVC with classical field emission (so-called Forbes Test) [7].

Secondly, IVC is affected by the spread of the emission sites in form. In the case of carbon nanotubes (CNTs), this is usually a variation in the local field enhancement factor (βloc). Replacing this manifold of microscopic effective parameters with one effective parameter βeff may also be inadequate, at least in view of the loss of variance information. In this paper, we presented a methodology for assessing this manifold based on analysis of glow patterns of the computerized field emission projector (CFEP). A detailed review of the technique for processing glow patterns and the device of our field projector can be found in [8].

Thirdly, each emission site is a separate emission system with a nonlinear dependence of the emission area on the applied voltage. In [9], we presented a variety of formulations of the notion "emission area", and also showed their dependence on the level of applied voltage by the modeling a carbon nanotube in the HCP form (hemisphere on the post). In this paper, we presented the results of modeling cone-shaped emission sites and their model effective parameters (βmod and Smod).

To register the IVC we had applied the fast high-voltage scanning mode with half-sinusoidal voltage pulses [10]. This significantly improved the experimental IVCs. However, in this case there is a strong dependence of the IVC-FN shape on the pulse amplitude and non-trivial relationship to IVCs registered in the slow scanning mode.

Macroscopic IVC-FN analysis with effective parameters estimation

Fig. 3a shows an experimental IVC-FN of the investigated LAFE with interelectrode distance 200 μm. The tail of the IVC-FN was limited by current value close to the noise level that was determined by the condition: length of the IVC-FN must be maximum, but residue of the trend line mast be smaller than 0,0005. Top of the curve corresponded to stable current level I_m = 370 μA (amplitude of the pulses in the fast high-voltage scanning mode). It is noteworthy that the trend line is secant for the bended IVC-FN, so there is a strong dependence on the voltage diapason taken into account. The variety of the voltage ranges of the experimental IVC-FN generates plenty of values S_{eff} and β_{eff} (Fig. 3b).

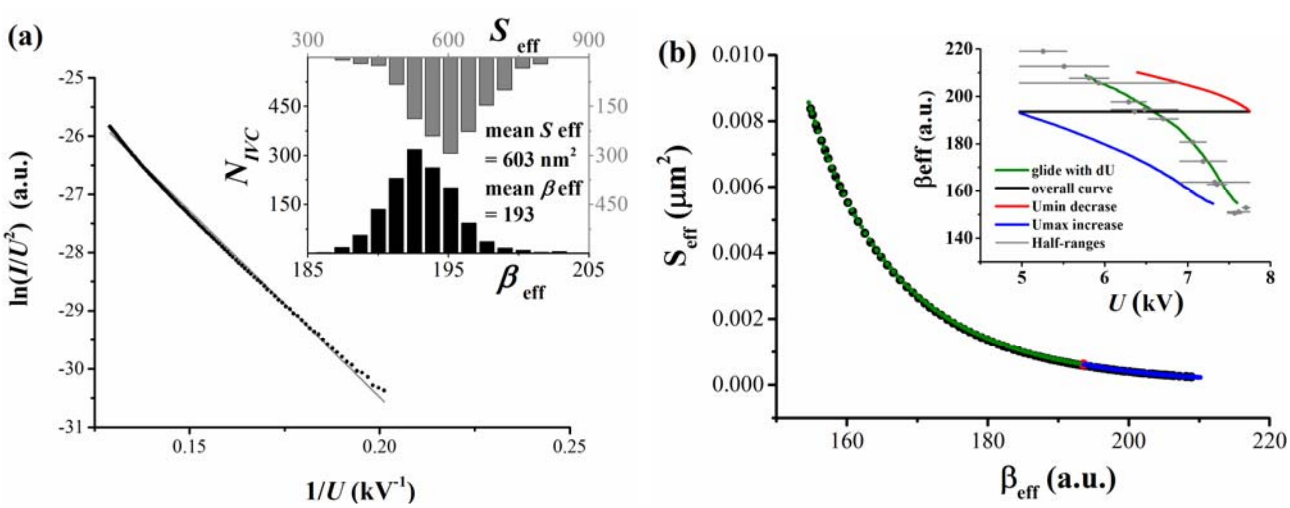

Fig. 2. Macroscopic IVC analysis: a – experimental IVC-FN (black dots), its trend line (gray line) and statistics of the effective parameters for 1500 IVC loops in the insert (time interval – 30 s); b – dependence of the effective parameters β_{eff} and S_{eff} from each other and dependence of the β_{eff} on the voltage range in insert (ends of horisontal lines – diapasons of voltage and thier level – corresponding β_{eff} value).

Microscopic emission sites analysis with effective parameters estimation

Fig. 3 demonstrates histogram of the local effective field enhancement factors $\beta_{eff\text{-}site}$ of the emission sites calculated from glow patterns using computerized field emission projector. The local field emission area was set as $S_{eff\text{-}loc} = S_{eff} / N_{sites}$ = 10 nm^2. It is worth noting that the distribution center is usually larger than overall

β_{eff}.

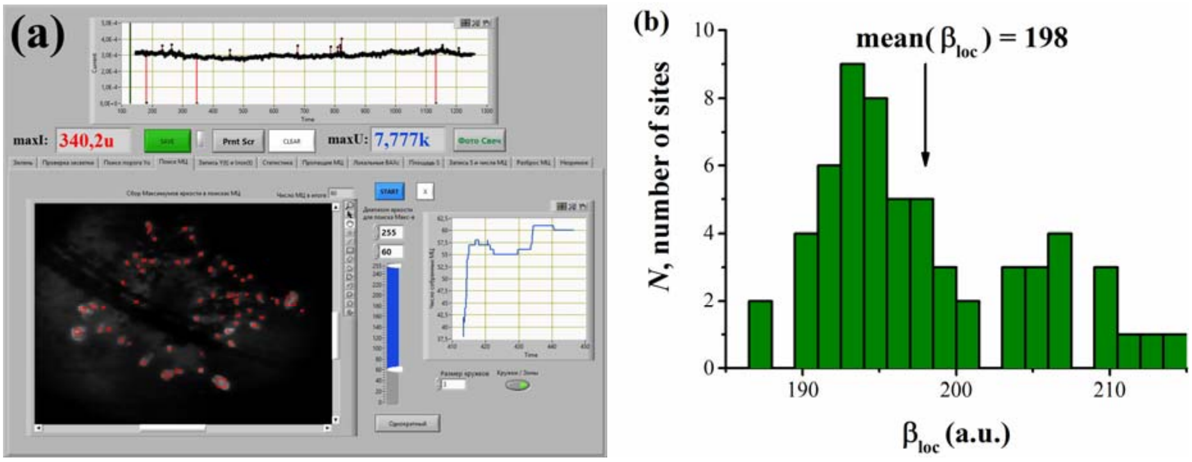

Fig. 3. Collection of the statistics about local field enhancement factor of the emission sites on the cathode surface: a – interface of the program which processed the glow images; b – histogram of the local effective field enhancement factors βloc.

Theoretic emission sites analysis with effective parameters estimation

Fig. 4a shows the electric field distribution (field enhancement factor which is not depend on the voltage) on the top of the model emitter with cone form. Model was performed in the COMSOL Multiphisics program. Each of the surface segments emitted the electrons by the classical field emission law (an exponential-type approximation of the Elinson–Shrednik equation [9]) with uniform field over the its surface. So total IVC was found as summary of the IVCs of the segments. The effective field emission area (Smod) and corresponding effective field enhancement factor (βmod) were calculated for different applied voltages *U* using small range of the total IVC (100 V around *U*). Fig. 4b shows these dependences. Values of βmod have not good coincidence with β_{eff} or β_{loc} because of model has a cone form instead of hyperbolic profile.

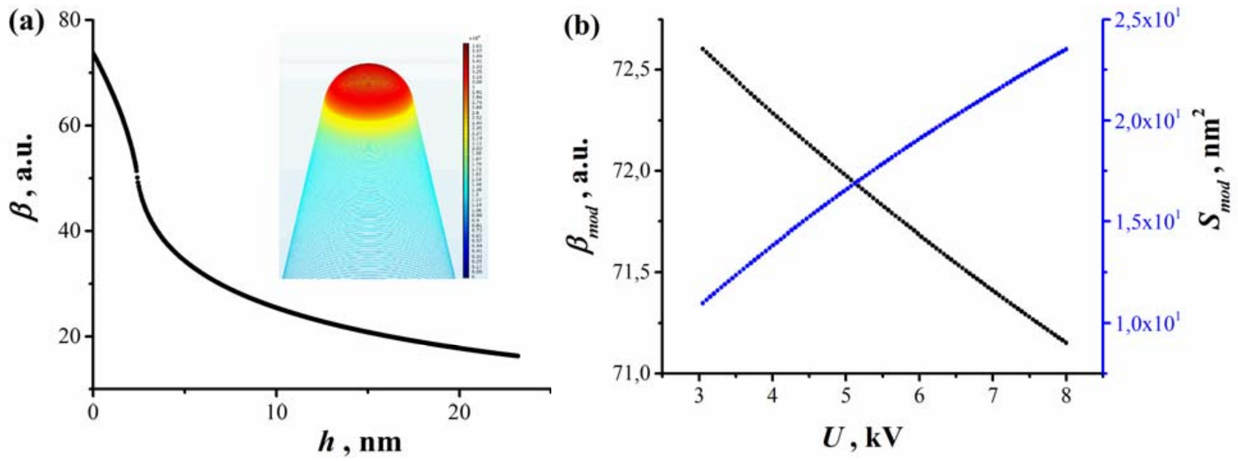

Fig. 4. Modeling of the cone shaped field emitter: a – distribution of the electric field on the cone top and COMSOL printscreen in the insert; b – dependences of the effective field emission areas on applied voltage and total IVC of the model cone in the insert.

Summary

We investigated the dependences on the applied voltage of the effective emission parameters of the LAFE based on silicon microscopic cones. Influence of the macroscopic IVC bending was considered. Distribution of the emission activity on the microscopic emission sites was investigated by CFEP. Theoretic dependences of the effective parameters on the applied voltage for one emission site having cone form was investigated using COMSOL calculations.

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