Analysis of microscopic emission sites regularity of nanocomposite field cathodes

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The paper presents an analysis of the emission activity of microscopic sites on the surface of a field emission cathode based on nanocomposite with nanotubes in a polymer matrix. The correlation of the total brightness of the registered sites with the total emission current is estimated. The definitions of two types of regularity are introduced and the corresponding distributions of emission sites were obtained. The contribution of sites with increased regularity to the total current is calculated.

1. Introduction
Field emission was discovered in the early years of 20th century. It is used in the development of a number of experienced energy-saving devices, such as high-speed displays, X-ray tubes, klystrons, traveling wave tubes, terahertz amplifiers, etc. The improvement of the prototypes of these devices requires high currents and stability of the field emitter [1].

Multi-tip nanocomposite structures demonstrate the highest currents, but their application in a vacuum (more than 10⁻⁵ Torr) leads to unpredictable stochastic processes on their surface associated with the adsorption of particles from residual atmosphere [2]. Even in the stable current mode, these processes lead to fluctuations appear of the noise type.

The presented work is aimed at an experimental study of fluctuations in the current characteristics of a nanocomposite field cathode using a computerized field emission projector and the multichannel recording of current-voltage characteristics (IVC).

2. Experiment
Experimental setup with multichannel IVC registration and analysis of the luminescence patterns of the field emission projector was described in [3]. As a phosphor screen the glass with ITO coating, coated with a phosphor layer (SVETOSOSTAV K49), was used. The luminescence patterns were registered using a long-focus USB microscope. Current and voltage detection is performed using voltage dividers and multichannel data acquisition system based on the National Instruments data acquisition board.

The experiments were carried out under the conditions of a technical vacuum (10⁻⁷ Torr). For the recording and processing of experimental data, we used programs written on the LabView 2016. The methodology for finding positions of the emission sites on the cathode surface and the calculation of the local currents flowing through them was presented in [4, 5].
Sample was based on the multi-walled carbon nanotubes / polystyrene nanocomposite (CNT of the "Taunit-M" brand). Participation of the polystyrene binder in the emitter structure leads to an increased adhesion of nanotubes to the metal substrate, and reduces their mutual influence [6]. The brightest images of emission sites on the luminescence pattern of such cathodes are usually associated with macroscopic protrusions on the emitter surface [7].

3. Correlation and regularity

Online processing of the luminescence patterns allowed obtaining temporal dependences of the brightness of each emission site (~ 450 emission sites) synchronous with the time dependence of the total emission current. The brightness of each site $Y_i$ was measured in byte-levels from 0 to 255.

To estimate the relationship between the emission current level $I$ and the brightness of the emission sites $Y_i$ we performed a correlation analysis of these quantities using the

$$r_{Y_{\text{sum}}-I} = \frac{\sum(Y_{\text{sum}}I)}{\sqrt{\sum(Y_{\text{sum}})^2 \sum(I)^2}}$$

where $\hat{I}$ is the normalized total emission current, $\hat{Y}_{\text{sum}}$ is the normalized total brightness of the emission sites.

The correlation analysis was carried out for three types of the field emission experiments:

1) at a constant level of applied voltage and stable current level ($r_{Y_{\text{sum}}-I}$ was equal to 72%),

2) at the involuntarily increasing current level in the unstable field emission mode ($r_{Y_{\text{sum}}-I}$ was equal to 93%),

3) At a linearly increasing voltage level and, correspondingly, an increasing current level ($r_{Y_{\text{sum}}-I}$ was equal to 99.5%).

Fig. 1 shows the corresponding time dependences, as well as the dependence of the total emission current on the total brightness and the histogram of ratio $C = \hat{I} / \hat{Y}_{\text{sum}}$.

The highest level of correlation corresponds to the controlled increase in the emission current. The correlation for the experiment at involuntary increase in current is a little behind. Correlation of the emission current and brightness level of the sites in the stable mode of operation of the field emitter (at a constant level of voltage and current) also showed fairly high values. That allows one to associate the brightness of individual emission sites with their local current.

Note that the proportionality coefficient of the brightness and the current levels, which was found from the histogram in the stable mode of the cathode operation ($C = 3.4 \cdot 10^{-9}$), differs by an order of magnitude from the similar coefficients found from the histogram and trend line for experiments with a varying current level ($C \sim 1.4 \cdot 10^{-8}$). That indicates a possible relationship between the brightness of the phosphor screen reaction on electron fluxes during a long-term observation (our experiment at a stable current level was performed an order of magnitude longer). In addition, during the experiment, new emission sites appear on the cathode surface, which were not registered earlier at the beginning of the experiment and therefore were not taken into account in the calculation of the current load on the microscopic emission sites.

The complexity and diversity of the brightness fluctuations of the emission sites observed in the luminescence pattern of a field emission projector raises questions about the mechanism of generation of the total emission current. The first question to answer in this paper – is the main current level determined by result of the work of the most stable sites or the main contribution to emission given by unstable sites? In the first case, the system will resemble a shower jet at a high pressure (strong shower), and in the second - a jet at a low pressure (weak shower), which is formed by separate drops, flowing out of the shower chaotically. The second question: how is the brightness of the emission sites related to the stability of their operation? Since the brightest sites have an increased current load, the Joule heating of them must increase the probability of particle desorption from their surface and,
consequently, reduce the brightness fluctuation. On the other hand, the increased field strength in the region of their tips can lead to an increased ion bombardment and, accordingly, to an increase in the intensity of the fluctuations.

Figure 1. Time dependences of voltage, current and emission sites summary brightness levels for three types of experiment: constant current level (a), involuntary current rise with constant voltage level (b) and current decrease with controlled voltage decrease (c). Corresponding dependences of the summary brightness on the total current (d, e, f) and diagrams of the current-to-brightness ratio are presented in the inserts.
Long-term observation of the emission sites and recording the brightness level $Y_i$ of each site (experiment #1 in the experimental trio considered above) allowed to analyze the fluctuations in the overall FEP image. For this purpose, we introduced two different mutually complementary concepts of the regularity. The first regularity of the "on / off" type is associated with the "filling factor" of the brightness time dependence of the emission site:

$$ \text{Reg 1} = \frac{t(Y > Y_0)}{t_{\text{total}}} $$

where $t(Y > Y_0)$ is the total time of the site when it was in state with a brightness level higher than a given threshold value $Y_0$, and $t_{\text{total}}$ is the time of the whole experiment. In presented experiment the threshold brightness was chosen to be 100, since the detection and accumulation of sites was carried out with this threshold.

The second – "dispersion" regularity is connected with spread of the site's brightness values relative to its average within the range between the minimum and maximum values:

$$ \text{Reg 2} = 1 - \frac{2S}{(Y_{\text{max}} - Y_{\text{min}})} $$

where $S$ is the standard deviation of the brightness over time, $Y_{\text{max}}$ and $Y_{\text{min}}$ are the maximum and minimum values of the site brightness during the experiment. This regularity reflects the fluctuations of even the brightest, non-switching sites.

Fig. 2 presents dependences of the regularity level of the following functions:

- the distribution function of the sites by values of (1-Reg)
  $$ F_{N-\text{Reg}}(\text{Reg}_0) = N(\text{Reg} > \text{Reg}_0), $$

- the average maximum (maximum for all the experiment time) brightness of the sites within a given range of regularity
  $$ \langle \text{max}Y \rangle(\text{Reg}_0) = \left[ \sum_{\text{Reg} \in [\text{Reg}_0]} \text{max}_i(Y) \right] / N_0. $$

- the distribution function of the total brightness averaged over the experiment by values of (1-Reg)
  $$ F_{N-\text{Ysum}}(\text{Reg}_0) = \sum_{\text{Reg}>\text{Reg}_0} Y, $$

- the distribution function of the correlation of the total brightness level with the total current level by values of (1-Reg)
  $$ F_{\text{CorrYI}}(\text{Reg}_0) = r(\sum_{\text{Reg}>\text{Reg}_0} Y, I). $$

Graphs were plotted for two methods for estimating the regularity: for Reg 1 and for Reg 2.

The distribution of emission sites with respect to the regularity level $\text{Reg}_0$ for both types of regularity has the character of a normal distribution, as evidenced by the corresponding cumulative distribution functions in Fig. 2a, c (black lines).
Figure 2. Dependences on the regularity level of: cumulative distribution function of the emission sites $F_{N-Reg}$ and maximum brightness of the corresponding site for all experiment $\langle maxY \rangle$ (a, c), cumulative distribution function of the summary brightness $F_{N-Ysum}$ and correlation function of the total brightness with the total current $F_{CorrYI}$ (b, d). There are two type of regularity $Reg 1$ – "on/off" type (a, b) and $Reg 2$ – "dispersion" type (c, d).

The maximum brightness of the sites in Fig. 2a, c (green lines) shows a smooth growth simultaneously with regularity increasing $Reg 1$ ("on / off" type), which is explained by the interrelation of the average level of the site brightness with the value of its maximum brightness. For the second regularity $Reg 2$ ("dispersion" type), such relationship is not observed. Moreover, for regularities more than 0.5 the brightness begins to fall almost exponentially. That is, the brightest sites at their average level show the strongest dispersion noise. Perhaps it is because they have an increased field enhancement factor and attract more ions from the interelectrode gap, which increases the frequency of fluctuations in their work function.

The integral estimation of the current contribution (Fig. 2b, d red lines) showed that when estimating the regularity of $Reg 1$, the main part of the emission current (90%) gives sites with a regularity more than 0.43, while in the $Reg 2$ estimation the same part is provided by sites with regularity more than 0.5. That is, the least stable tips give about 10% of the total current, which excludes the "weak shower" model.

On the other hand, sites with increased regularity ($> 0.8$) provide 73% of the current of the cathode for the estimation of $Reg 1$ and only 5% for $Reg 2$. The difference in the forms of the considered graphs Fig. 2b and Fig. 2d is related to the principal difference in the form of their derivatives: the almost exponential growth of the local current load in $Reg 1$ and the near-normal character distribution in $Reg 2$ with a peak around value 0.65.
Correlation of the total brightness with the total emission current shows continuous growth with decreasing threshold regularity for both Reg 2 and Reg 1 up to the level of 0.5. Sites with a regularity level less than 0.5 give a negative contribution to the correlation, reducing it by about 1/8 part.

4. Conclusion
The fluctuations of the local emission currents recorded with a computerized field emission projector on the surface of a nanocomposite field cathode in a technical vacuum were analyzed. Results of the analysis allowed to estimate stability of the emission surface of the nanocomposite cathode.

Analysis of the correlation of the emission current with the total brightness of the microscopic sites showed high values for three different types of stability of macroscopic emission signals (constant / falling voltage and dependent / independent current growth).

Two complementary types of emission sites regularity were introduced: "on / off" type and "dispersion" type. Analysis of the dependencies of various distribution functions on the regularity level showed that the brightest sites exhibit the strongest dispersion noise, which can be explained by the increased ion bombardment of their vertices. The main part of the emission current falls on the sites with a regularity more than 0.5, which indicates a low role of unstable tips in the emission process. The increased current load is carried by tips with a high "on / off" type stability, which cannot be said for "dispersion" type stability. The latter is characterized by a peak value of the current load in the third quarter of the range (> 0.65).

It is worth to note that, despite the lack of bright results and the overall complexity of interpreting the results of the analysis, the work is part of a wider range of studies. Based on the study of fluctuations in the brightness dependences of individual sites over time, it is possible to determine the coefficients of the fundamental stochastic processes of adsorption / desorption occurring on the surface of a multi-tip cathode. Coefficients can be used in the computer model that we are developing, which selects the keys to reproduce quite complex effects observed in the current-voltage characteristics of real field cathodes.

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