Evaluation of numerical characteristics of the current load distribution on the surface of multi-tip field emitters

S V Filippov\(^1\), E O Popov\(^1\), A G Kolosko\(^1\) and R N Vinnichek\(^1\)

\(^1\)A.F. Ioffe Physico-Technical Institute of Russian Academy of Sciences, ul. Polytekhnicheskaya 26, St.-Petersburg, 194021, Russian Federation

Abstract. The uniformity of the emission sites distribution over the surface of the multi-tip field emitter is one of the main factors affecting its electrical characteristics. Increase of the uniformity leads to increase of the thermal stability and allowable current limit. The paper describes an experimental setup and a method for monitoring uniformity of the emission sites based on analysis of a field emission site images registered on the phosphor screen of a computerized field-emission projector. The analysis includes estimation of the statistical distributions of the sites by radius, by angle and by intensity, as well as the distribution of the current load over the emitter surface. The technique was tested with the perspective nanocomposite cathode MWCNT / polystyrene.

1. Introduction

Field emitters based on nanostructured materials are very promising for the development of vacuum nanoelectronics [1]. Unlike thermal cathodes, they do not require heating and cooling devices, they are based on the inertia-free mechanism of the electron tunneling and allow the formation of a large area cathodes. The introduction of a field emission electronics in modern nanotechnology has a number of fundamental challenges. The main drawback of these quantum structures is the thermal instability of an individual emission sites on their surface. These sites withstand an excessive current load in the course of the field emission experiment and explode in unpredictable way with appearance a vacuum discharge in the interelectrode gap. These processes don't allow to obtain high emission currents and require ultrahigh vacuum conditions, purity and homogeneity of the emitter surface. Therefore, search of the optimal distribution of the current load on the emission sites is one of the main technological problems in creating the nanostructured field cathodes [1-3].

One of the main tools for analyzing the uniformity and purity of the surface of field emitters is the registration of a "glow pattern" with emission site images [4, 5]. For this purpose, a parallel cathode-anode system is used, where the anode is glass with a transparent conductive coating (usually ITO) and a phosphor layer (usually phosphorus-based). The glowing spots observed on the surface of the phosphor layer show the electron beams from the corresponding emission centers located on the surface of the cathode and give information about the dimensions, emissivity and mutual arrangement of these sites.

Using this technique, technological optimization of the process of creating a field cathode is often carried out. For example, in [6] the concentration of the nanotube solution in the PMMA polymer was optimized, as well as the number of layers of the solution applied to the plastic substrate using the spraying method (PMMA solution to the MWCNT-dispersed solution).
It was shown in [7] that nanocomposites based on vertically aligned multiwalled carbon nanotubes with a polymer (PMMA) have enhanced emission properties, including increased brightness and uniformity of the "glow patterns". The effect was due to a decrease in the mutual screening of emission centers. The coating of nanotubes with strontium titanate molecules (emitter PMMA-STO-CNT) also improved the efficiency of field emission.

In [8] improved emission and more uniform "glow patterns" were observed when nickel atoms were added to the nanotube array. To create emitter, the electrophoresis method (EPD) was applied.

In [9] the "glow pattern" was used to characterize the emissivity of a transparent coating of nanotubes. A coating thickness of ~ 100 nm was obtained by the rapid evaporation of a solution placed on a glass substrate or flexible plastic. "Glow patterns" were obtained by shooting through the sample.

Curiously enough, a quantitative analysis of the emission site images on the "glow pattern" is performed infrequently.

In [10] an attempt was made to estimate the emission area of individual emission sites on the surface of emitter from an array of carbon nanotubes using digitizing "glow patterns" and computer simulation (MWCNT film was synthesized by microwave plasma enhanced CVD system).

In [11] a nanocomposite with multiwalled carbon nanotubes and organic binder was applied to the ITO coating by screen printing in the form of an array of round points. Analysis of the "glow patterns" at different voltage levels gives a histogram of the nanocenter distribution in terms of the threshold voltage level. After sample annealing, the distribution was substantially narrowed, so that emission sites with low threshold voltages were disappeared.

In [12] the emission properties of nanotubes grown by CVD (using ferrocene as single source precursor) on a porous aluminum membrane were studied. Emission sites were divided into three groups: stable, flickering and dying out. This allowed estimating the degree of stability of the cathode emitting surface.

2. Experimental

To register the emission characteristics, we used a multichannel computerized setup [13]. It consists of a plane-parallel diode system with field emission projector equipped with a long-focus USB microscope. The developed method for estimating the distribution of the current load is based on synchronous recording of the applied to the sample voltage level, of the emission current and the "glow pattern" of the field emission projector. Software processing of registered data was performed using the LabView 2016 directly during the experiment.

In this work, we considered a model emitter based on the promising nanocomposite MWCNT / polystyrene (MWCNT by Samsung, according to the SEM length of tubes is ~ 10 μm and diameter is ~ 19 nm) and numerically estimated the quality of its emission surface.

3. Results and discussion

Figure 1a, b shows the SEM image of the model emitter and its I-V characteristic and the time dependence of the current in the stability regime (~ 400 μA).

Figure 2 shows stages of the process of recording the maxima of the standard "glow pattern" obtained at the emission current 100 μA. To separate the brightness peaks that correspond to the emission centers, from the digital noise of the video camera, we used a smoothing of the glow pattern (the linear filter IMAQ Convolute VI). Search for the maximum brightness on the filtered picture was made using a sliding window (3x3 pixels). The resulting coordinates were displayed in a black and white "maximum / not maximum" picture, which was then subjected to automatic analysis (IMAG Particle Analysis VI tool) with finding the geometric centers of white areas and rectangular zones circumscribing them.

Note that our processing cannot be carried out for high emission current levels because of phosphor screen illumination at which emission centers cannot be distinguished. Moreover, at high currents the vacuum breakdown is expected (in our case the threshold current is 1 mA).
Figure 1. SEM image of the model nanocomposite emitter MWCNT / polystyrene (a) and I-V characteristic of the model emitter (b). The inset shows the current versus time in the mode of stable emitter operation.

Figure 2. The "glow patterns" processing with emission site images at stable current level 400 µA.
Figure 3. Time dependence of number of the distinct emission sites on the total black and white pattern collected over investigation time (a) and dependence of number of the distinct emission sites on the black and white "glow pattern" on the brightness level $Y_0$ (b).

Since the adsorption-desorption processes cause the change of "glow pattern" over time, the addition of black-and-white fluctuation patterns (the IMAQ Add VI tool) in stable emission current mode was performed before finding geometric centers. Accumulation was carried out until reaching the horizontal level of the time dependence of the total number of registered sites (figure 3a).

The brightness level $Y_0$ below which the maxima were not searched, was determined from the brightness level $Y$ of the number of isolated spots in the black-and-white "glow pattern" (obtained from the instantaneous "glow pattern" by the IMAQ Threshold VI tool). Beginning with a certain value of $Y_0 = 80$, the number of spots with brightness $Y > Y_0$ begins to grow rapidly due to the appearance of noise fluctuations in brightness on the picture (see figure 3b), furthermore below 80 in the halo area non-existent sites appear.

The brightness of each of the registered emission sites was considered to be the maximum brightness in the region of the corresponding rectangular zone (inside this district the maximum position and brightness fluctuation). The current load on the emission sites was calculated from the current level $I$ with the condition that the brightness of the sites on the "glow pattern" is proportional to the local current (total sum of the site currents equal total emission current $I$). Figure 4a shows the time dependence of the current load of one emission site found using this technique.

Figure 4. Time dependence of the current level of a certain rectangle (one emission site) at total current level $I = 400 \, \mu A$ (a) and distribution of the emission sites on current loading levels (b). In the inset: flat diagram of the current distribution over the surface.
The maximum current load at each of the emission site was calculated in the same way as the current one, but instead of the current level of brightness, the maximum level was taken over a certain period of time (several minutes of operation of the emitter in stable mode), and instead of the current level, the average current was taken (~ 400 μA).

The calculated parameters of each emission site in the "glow pattern" were subjected to statistical processing. Figures 5a, b and 6a show the distribution of emission sites over brightness, the distance to the emitter site, and the angle relative to the center, and comparison of them with the ideal distributions. Ideal distribution corresponds to some ideal emitter which have the same number of the emission sites distributed on the emitter surface uniformly and the same average brightness. It is expected that ideal emitter have an optimum current load distribution and optimum heat dissipation. So numerical comparison of distributions presents the goodness of the investigated emitter.

Figure 5. The histogram of the distance of the centers to the emitter center (a) and the histogram of the spread along the angle (b). Triangle represent an ideal distribution. Horizontal rectangle represent an ideal distribution.

Figure 6. Histogram of the spread in brightness level (a) and an “ideal” emitter – emitter with uniform distribution of emission sites (b). The mean value on brightness distribution corresponding to ideal emitter.

For the distance distribution to the emitter center, a Pearson correlation coefficient was calculated: \( \rho_{xy} = 3\% \) (maximal correlation between experimental and ideal histograms is 100%).

For the distribution of sites along the rotation angle around the center of the emitter, the coefficient of variation was used: \( cv_A = 36\% \). It describes the deviation of the distribution from the mean angle \( 2\pi/N \) (maximal correlation between experimental and ideal histograms is 0%).
For the brightness distribution, the coefficient of variation was also taken, but the deviation was considered from the level of average brightness $Y_{ср}$: $cv_Y = 33\%$.

All three estimates of the distribution of emission sites can be applied to the technological optimization of the manufacturing process of a multitip emitter. Moreover, each of the estimates has its own priority in different methods a field cathode manufacturing.

For example, the distance distribution from the emitter center is important for methods using radially symmetric systems as a spin coating and spraying techniques.

The distribution of the sites over rotation angles plays an important role in methods where the slope of the substrate or the uneven distribution of temperature over it can create angular unevenness of the emission surface as CVD or arc discharge methods.

The distribution of brightness is important for estimating the uniformity of sites over height which can be determined by the unevenness of the profile of the original substrate or by the presence of protrusions on the emitter surface.

To estimate the thermal stability of the sample, we calculated the current load distribution on its surface by virtual separation of the emitter surface into segments of equal area and plot corresponding histogram (figure 6b). The corresponding coefficient of variation was calculated: $cv_D = 72\%$ (deviation was considered from the level of average current loading).

The total distribution of the emission sites on current loading levels is presented in figure 4b with the flat diagram of the current load distribution over the emitter surface in the insert. Red spots on the diagram point to the regions where the emitter overheating with vacuum breakdown at high emission currents is expected.

4. Conclusion

We developed the method for the numerical evaluation of the emission current distribution on the surface of multi-tip field emitters. The model sample based on a nanocomposite "carbon nanotubes / polystyrene" was investigated.

The numerical evaluation of the spatial uniformity of the emission sites distribution is produced. We plot histograms of the site distributions by angle, distance, brightness and density of the current load and derive the coefficients $\rho_{XY}$, $cv_A$, $cv_Y$ and $cv_D$ which present the conformity of the experimental emission site distribution to the ideal one. The flat diagram of the current load distribution over the emitter surface revealed most unstable regions of the cathode.

The method allows to carry out a numerical comparison of the field emitters quality and optimize their technological processing.

References

[1] Milne W I, Teo K B K and Amaratunga G A J 2004 J. Mater. Chem. 14 933-943
[2] Parmee R J, Collins C M, Milne W I and Cole M T 2015 Nano Convergence 2:1 1-27
[3] Zhu W, Baumann P K and Bower C A 2001 Vacuum Microelectronics (New York: John Wiley & Sons) pp 247-288
[4] De Heer W A, Bonard J-M, Fauth K and Ugarte D 1997 Adv. Materials 9:1 87-89
[5] Lin P-H et al. 2015 Nanoscale Research Letters 10:297 1-6
[6] Jung H, An S Y, Jang D M, Kim J M, Park J Y and Kim D 2012 Carbon 50 987-993
[7] Pandey A et al. 2013 ACS Nano 7:1 117–125
[8] Xiao X, Ye Y, Zheng L and Guo T 2012 J. Semicond. 33:5 053004-1-6
[9] Kuznetzov A A et al. 2010 Carbon 48 41–46.
[10] Patra R, Singh A, Vankar V D and Ghosh S 2016 Adv. Mater. Lett. 7:10 771-776
[11] Liu W, Zeng F, Xin L, Zhu C and He Y 2008 J. Vac. Sci. Technol. B 26:1 32-35
[12] Lysenkov D et al. 2005 J. Vac. Sci. Technol. B 23:2 809 - 813
[13] Popov E O, Kolosko A G, Filippov S V, Romanov P A and Fedichkin I L 2016 Nanomaterials and Nanostructures - XXI 7:1 14-26