Methods for measuring the local emission characteristics of CNT based multi-tip emitters

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Abstract. The work is aimed at obtaining microscopic emission characteristics of individual emission sites of a multi-tip field cathode or large-area emitter (LAFE) based on processing the current-voltage characteristics and emission glow patterns. Processing was carried out on a hardware-software complex for the study of field emission characteristics in real time. The calculation of the microscopic characteristics of the local emission sites — the field enhancement factor and emission area — was carried out by several different algorithms. A comparison of the results showed that the algorithms gave close values of the characteristics, which increases the reliability of the estimates made.

1. Introduction

Field emission electron sources with high total electron current and high macroscopic current densities are being actively developed for use in portable X-ray tubes [1, 2], sources for medical 3D tomography [3, 4], perspective terahertz frequency devices [5], etc.

The need for sources with high emission currents (at low threshold voltages) stimulates the development of technologies for creating emitters [6-9]. Obviously, it is possible to develop high currents by using emitters consisting of many emission tips [10]. Emitters with huge amount of emitting tips and emission area are called large area field emitters (LAFE).

Currently, there are two problems that impede the development of high current LAFE technologies. First problem relates to theoretical researches. The efforts of many theorists are aimed to the formation of a field emission model taking into account the curvature of the tip apex and, accordingly, the influence on the shape of the current voltage characteristic (IVC). The first is the solution of the Schrödinger equation for a wave function that takes into account the atomic structure. These are the so-called first principle calculations, for example, [11]. The second is the inclusion of curvature in the Gamow integral, as a correction to the expression of the Coulomb forces of the charge image [12]. The third way is to solve the electrostatic problem for a curved surface. However, the calculations of emission currents in this case are carried out without changing the structure of the basic field emission formula [13]. Combinations of these approaches are also possible.

In addition, there is the second problem. It lies in the weaknesses of the LAFE fundamental experimental research methods, which could provide a connection between the theoretical LAFE models and the measured current-voltage characteristics. To study LAFE, new research methods should be applied that take into account the complex multi-parameter behavior of the object, the dynamics of the emission process, as well as the phenomena accompanying field emission [14].
The most promising method for analyzing the properties of microscopic emission sites seems to be the observation of the emission glow pattern on a flat luminescent screen, as a kind of field emission projector without a significant magnification of image. Such observations are carried out in many field emission experiments [15-17]. However, computer processing of luminous patterns to determine the parameters of individual microscopic emission site is still poorly developed. The first studies devoted to real time computer processing of emission glow patterns were carried out in the ref. [18, 19]. In addition, there was an attempt to observe the brightness fluctuations of individual emission sites in real time [20]. However, as follows from the ref. [21] and the recently published work [22], a software algorithm for tracking all emission sites on the cathode surface has not yet been implemented.

Within the framework of the created and constantly evolving multichannel system for collecting and processing in real time the emission parameters of LAFE [23-28], a technique for analyzing the glow patterns was also developed. The first reports about capture of the glow pattern and its real time processing by LabVIEW tools was carried out as far back as 2015 [24]. Subsequently, the technique turned into a rather advanced tool, which allows not only to obtain individual brightness parameters of the set of emission sites on the cathode surface online, but also in combination with the registration of fast IVCs of the cathode, to obtain local characteristics of individual site (locIVC) [25]. The aim of this study was to develop approaches to obtaining and processing the IVC of individual emission sites, as well as comparing macroscopic IVCs and the scatter of parameters of local IVC.

2. Experimental
The developed real-time complex, the elements of which are reflected in Refs [26-28], uses three main research approaches: multichannel data collection, online data processing, and multiple high-voltage sample scanning in different power modes. Multichannel collection and online processing are performed in the LabVIEW software environment using a special program (Figure 1).

![Figure 1](image-url)

Figure 1. Flowchart for the process of collecting multichannel field emission data, vacuum chamber diagram: (1) high-voltage vacuum cathode input, (2) anode system with phosphor ITO glass, (3.1) frontside USB microscope, (3.2) side USB microscope, (4) vacuum flanges to the time-of-flight mass spectrometer, neutral volatile products, (5) ion source, (6) path and grouping of ion packs, (7) microchannel amplifier, (8) pumping

At the same time, electrical signals (IVC), the total vacuum level in the measuring chamber, the temperature of electrodes, the glow patterns of the sample, and partial pressures (using a time-of-flight mass spectrometer, neutral volatile products, (5) ion source, (6) path and grouping of ion packs, (7) microchannel amplifier, (8) pumping

At the same time, electrical signals (IVC), the total vacuum level in the measuring chamber, the temperature of electrodes, the glow patterns of the sample, and partial pressures (using a time-of-flight mass spectrometer) are recorded. Two modes are used for scanning: fast (with the frequency of the supply network) and slow (the duration is set by the experimenter). This approach, combined with a computer recording of temporary implementations, allows to collect a large amount of the experimental data and analyze statistics, as well as study the dynamics of the process.
The general concept of our developed methodology includes the principle of modularity (Figure 2). Each of the new techniques, both hardware and software, can be integrated into the measurement process. Software online processing allows inclusion of new modules - methods for processing IVC and other signals, as well as inter-module interaction and data transfer between them. Figure 1 shows an idealized diagram of this approach. One can compare it with the concept of the Basic and Complete methods for studying modern field emitters presented in a recent work [14].

Figure 2. The modular principle of collecting and processing field emission data

As a model field cathode, the SWCNT / PS nanocomposite field cathode based on single-walled carbon nanotubes randomly distributed in a polymer matrix (polystyrene) was used. This type of field cathodes is characterized by increased stability of the emission sites to the pulling forces of the electric field, as well as sufficiently low threshold voltages (~ 1 kV) and high emission currents (up to 30 mA from the surface of 1 cm²).

3. Estimation of the local emission characteristics

3.1. Effective estimation using total IVC

The main measuring module of the stand is the module for measuring the IVC in the "fast" scanning mode with high voltage (1 IVC during 20 ms). This measurement is accompanied by online processing, which plots the measured IVC in the Fowler-Nordheim semi-logarithmic coordinates (FN-plot) and performs linear regression analysis of the most rectilinear fragment of this dependence. As a result of the analysis, the slope $S_{fit}$ and the intercept $\ln(R_{fit})$ of the approximating trend line are obtained. Then, effective microscopic cathode parameters are obtained: field enhancement factor $\gamma_{eff}$ and emission area $A_{eff}$ using the modified field emission equation in the Elinson-Schrednik approximation [28]:

$$\alpha_{eff} = -B_\phi / S_{fit}$$  \hspace{1cm} (1)

$$A_{eff} = R_{fit}^{2}(S_{fit})^2 / (A_\phi B_\phi^2)$$  \hspace{1cm} (2)

$$\gamma_{eff} = d_{sep}\alpha_{eff}$$  \hspace{1cm} (3)

where $A_\phi$ and $B_\phi$ are coefficients which depend on the work function of the cathode $\phi$ (we assume in the calculations $\phi = 4.6$ eV), $d_{sep}$ is the interelectrode distance (in the experiments $d_{sep} = 350$ μm).

The exact values of the coefficients for the modified Elinson-Schrednik equation in SI units are:

$$A_\phi = (1,541433873 \cdot 10^{-6}/1,109650605) \varphi^{-1} \exp(10,170626392/\sqrt{\varphi})$$  \hspace{1cm} (4)

$$B_\phi = 6,489345176 \cdot 10^9 \varphi^{3/2}.$$  \hspace{1cm} (5)
Knowing the emission area of each emission site $A_I$ (for nanotubes it can be estimated as the hemisphere area at the top of the nanotube), we can estimate the number of emission sites as $N = A_{eff}/A_I$. On the other hand, knowing the number of emission sites one can estimate the emission area of each of them as:

$$A_{eff-1} = A_{eff}/N$$  \hspace{1cm} (6)

Figure 3 (a) shows the experimental FN-plot and its trend line. Note the smoothness of the experimental dependence, which is characteristic of the “fast” scanning mode. The obtained parameter values were: $\gamma_{eff} = 1634$ and $A_{eff} = 11640 \text{ nm}^2$.

The result of registering emission sites by a computerized field projector is shown in inset Figure 3 (b). Their number was $N = 1140$, whence $A_{eff-1} = 10.21 \text{ nm}^2$.

**Figure 3.** Experimental FN-plot of the nanocomposite field cathode SWCNT / PS (a) and experimental local FN-plot for one of the emission sites (b) (the inset shows the luminescence of the field projector, squares indicate the tracking zones for individual emission sites).

**3.2. Estimation using local IVCs**

Another measuring module of the experimental setup is a module for registering the glow patterns of a field emission projector. A program specially developed in the LabVIEW performs an online analysis of recorded glow patterns [25]. As a result, in a few minutes of cathode operation in a stable mode, all emission sites (of the order of several hundreds) are detected and tracking of the emission activity of each site begins. The distribution of the total emission current $I$ (also online) among the emission sites in accordance with their brightness makes it possible to trace the change in the local current level $I_{loc}$ of each site with a change in the level of voltage $U$ applied to the cathode.

A smooth change in voltage allows one to get a family of locIVC. An analysis of these characteristics by the same linear regression method as described above for macroscopic IVC allows one to obtain effective parameters of specific emission sites: the field enhancement factor $\gamma_{eff-loc}$ and the emission area $A_{eff-loc}$. Unlike the averaged parameters $\gamma_{eff}$ and $A_{eff-1}$, these characteristics are quite individual.

Figure 3 (b) shows one of the experimental local FN-plot. The values $\gamma_{eff-loc} = 1695$ and $A_{eff-loc} = 10.31 \text{ nm}^2$ obtained from this curve are in good agreement with the values found above $\gamma_{eff}$ and $A_{eff-1}$.

The difference in the field enhancement factor is due to the fact that the selected emission site is one of the brightest, that is, it has a higher current efficiency compared to other sites and, accordingly, a larger $\gamma_{eff-loc}$ value, while $\gamma_{eff}$ value is a kind of averaged value over to the entire cathode.

Figure 4 (a) presents a diagram of the dependence of $A_{eff-loc}$ on $\gamma_{eff-loc}$ for all emission sites that have a local FN-plot available for analysis (the remaining sites are so prone to adsorption-desorption processes on the cathode surface that their local IVC is too broken under given experimental conditions). Note that the local field enhancement factor is a fairly stable value when changing the voltage range used to sample the full local FN plot from experimental data.
On the other hand, the local emission area changes quite strongly with a change in the sampling range, which ideally requires repeated experimentation with averaging of the results. However, even for sufficiently smooth curves, such as the macroscopic FN-plot shown in Figure 3 (a), this effect of the instability of the emission area to the choice of the range is also observed.

![Diagram](https://via.placeholder.com/150)

**Figure 4.** Diagram of the values of \( A_{\text{eff-loc}} \) and \( \gamma_{\text{eff-loc}} \) obtained for "adequate" emission sites (a). A histogram of local field enhancement coefficients obtained by finding the optimal emission activity of the sites at a fixed level of applied voltage and a relatively stable level of emission current (b).

### 3.3. Estimation using maxima of the local emission currents

The third approach to estimating the parameters of emission sites is an intermediate version of the calculation. In this approach, information is collected on the maximum emissivity of the site (maximum local currents), shown by the sites for several minutes of tracking in the mode of a relatively stable level of emission current. Based on these data, a histogram of the local field enhancement factors \( \gamma_{\text{eff-max}} \) is constructed. To find them, a numerical solution of the field emission equation is used for the known \( I, U, \phi \), as well as the emission area of one site \( A_{\text{eff-1}} \), which is taken from previous calculations on eq. (6).

The result of the third approach to assessing the microscopic emission parameters of the cathode is shown in Figure 4 (b). The histogram shows the \( \gamma_{\text{eff-max}} \) value (denoted as \( \gamma_{\text{site}} \)), corresponding to one emission site, the characteristic of which was presented in Figure 3 (b). The coefficient value obtained in this way was \( \gamma_{\text{site}} = 1709 \), which is quite close to the estimate \( \beta_{\text{eff-loc}} = 1695 \) obtained using the locIVC-FN analysis. The average value of the field enhancement calculated by the third method was \( \beta_{\text{mean}} = 1637 \).

### 4. Conclusion

We have developed a new methodology for LAFE studying.

We have demonstrated not only the principle and the possibility of obtaining information about local emission sites based on the redistribution of the total emission current, but also proposed several methods for such processing.

This method includes:
- detection of the distribution of local field enhancement factor coefficients based on the value of the effective emission area of the value per one emission site. This method allows building the emission profile of the cathode at a given stable level of emission current, obtaining histograms of the distribution of FEF over time.
- visualize the distribution of FEF in the form of a three-dimensional distribution over the surface of the cathode.
- plot the current-voltage characteristics of each emission site. Based on processing it in the FN-plot coordinates (in this paper, using the modified Elinson-Shrednik formula), we obtain effective values - not only FEF, but also the emission area of individual sites.
The obtained parameters showed reasonable and self-consistent values. This allows us to eliminate the problems associated with the interpretation of the obtained field enhancement factor values and the number of actually emitting sites.

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