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Optimization of the field cathode high voltage training based on field projector data

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The paper describes a technique for training multi-tip field cathodes with high voltage, which makes it possible to optimize the emission current on the basis of field projector data. The paper presents an algorithm for obtaining and analyzing experimental data, which allows for controlled training of the cathode surface, and also presents the results of the analysis of experimental data obtained for a promising nanocomposite structure of carbon nanotubes in polystyrene.

Keywords: Field emission, test of the cold field emission mode, nanocomposite with carbon nanotubes, computerized field emission projector.

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The surface optimization of the field emitter to obtain maximum magnitude and stability of emission currents is one of the first tasks in the development of modern vacuum nanoelectronics. The main parameters that need to be improved when solving this problem are the uniformity of the distribution of emission sites over the cathode surface with a decrease in the effect of their mutual screening, the uniformity of the distribution of sites by heights, shape and work function of the surface, an increase in the aspect ratio of the sites in combination with an increase in thermal stability due to selection of materials and optimization of heat removal, improvement of adhesion of sites to the surface of the substrate, etc. Methods for influencing the surface of the already created emission structure in order to optimize the above parameters are also different. This can be exposure to high temperatures to clean the surface from adsorbates, controlled ion bombardment to clean the surface and destroy the highest and most unstable sites, laser processing to align the sites in height, coating the sites with additional materials that reduce the work function and increase thermal stability, including deposition of nanoparticles that increase the aspect ratio and, accordingly, the current output. The most accessible and widespread is the the emitter exposure to high voltages, which, in particular, are applied to obtain the emission current.

A high voltage can cause the removal of the highest and weakly attached emission sites from the cathode surface due to pulling ponderomotive forces. The same forces can clean the cathode surface from adsorbates and microparticles. The appearance of the emission current can cause the heating of individual, highest sites and their self-destruction due to the thermal explosion of their peaks. The emission current can also lead to ionization of particles of the residual atmosphere in the interelectrode gap and the appearance of ion bombardment, which can also both purify and destroy high emission sites. The first measurements of the emission current for a fresh emitter that has not yet been exposed to high fields, as a rule, lead to a change in its surface under the action of sudden vacuum discharges, which are accompanied by the destruction of unstable emission sites, as well as the activation of new sites (the so-called cathode training).

An example of the high voltage action on the cathode surface is the results of studies carried out with arrays of carbon nanotubes (CNTs) [1–5].

In [1] arrays of multi-walled CNTs grown by the CVD (chemical vapor deposition) method with a catalyst on a metal substrate were studied. Using the scanning electron microscopy (SEM) method, we estimated the statistics of the CNTs distribution by heights before and after treatment with direct emission current. With the treatment current level increasing, the maximum height in the distribution of CNTs decreased. A theory of the thermal balance of CNTs is developed, where either a thermal explosion of the CNT tip or a melt of contact between the CNT and the substrate leads to the destruction of the emission site. It is shown theoretically that as the CNT height increases, the critical current density for the contact melt decreases, and, starting from a certain height above the contact melt, the explosion of the CNT tip prevails.

In [2] „planarization“ of the cathode surface from vertically oriented CNTs by controlled vacuum discharge (the so-called μEDM — micro-electro-discharge machining method) was also studied. The treatment increased the uniformity of CNT heights by several times.

The use of a field projector with a luminescent coating on a transparent anode (the IMLS method — integral measurement system with luminescent screen) makes it possible to obtain information on the distribution of emission sites and observe their change (in fact, individual destruction) as a result of surface training.

Thus, with the help of IMLS the process of training the emitters in the form of fibers woven from carbon nanotubes was studied, while a significant increase in the emission area and the field enhancement factor was observed [3].

Similarly, the change in the array of CNTs grown by the MOCVD (metalorganic chemical vapor deposition) method on porous aluminum was studied [4]. The ratio of the number of flickering emission sites (which give fluctuations in the emission current with the characteristics of flicker noise), the number of stable sites, the number of destroyed sites, and the number of activated sites was obtained. Long-term exposure to high voltage (current $\sim 250\,\mu$A for 2 h) increased the number of emission sites by almost 2 times. At the same time, the total emission current fell exponentially during the entire time test, so that it decreased by almost 1.5 times (at a residual atmosphere pressure of 10^{-6} mbar). The increase in the pressure of the residual gas in the chamber leads to the increase in the effect of ion bombardment and even greater drop in current up to the complete destruction of the sites. It is shown in the paper that the combination of high voltage supply methods with registration of current-voltage characteristics (IVC) and IMLS makes it possible to optimize the surface of a multi-pointed field cathode.

In the paper [5], using IMLS the influence of high currents on a regular array of islands with CNTs obtained by screen printing was studied (a suspension of ZnO nanoparticles with an average diameter of 30 nm, mixed with in solution of cellulose in terpineol was used). Treatment with high emission currents led to increase in the uniformity of the distribution pattern of emission sites due to the destruction of individual protruding CNTs, which shielded the rest of the CNTs in their islands. At the same time, the total current level dropped and the IVC became lower, however, the limiting voltage, achievable without the occurrence of vacuum discharges, increased.

Dekker's experiments [6] showed that CNT behaves like a nanowire with a limiting current density of 10^9 A/cm^2, which is higher than CNT at room temperature is destroyed. Based on the results of similar studies, which related to the study of single-tip tungsten and molybdenum emitters, a field emission test (the so-called Forbes test) [7] was created. The test allows you to determine the maximum allowable voltages from the experimental IVC of the field cathode. If the voltages registered in the experiment exceed the limit values, this means that the experiment has gone beyond the scope of field emission.

The purpose of this paper is to describe the algorithm for optimizing the surface of multi-tip field cathode by applying a high voltage. The main idea of optimization is to determine the relationship between the increase in emitter stability due to the destruction of high sites and the decrease in the total emission current as a result of the same process.

To illustrate the expected optimization effect, a field emitter model was created from several emission sites with parameters close to the parameters of single-walled CNTs

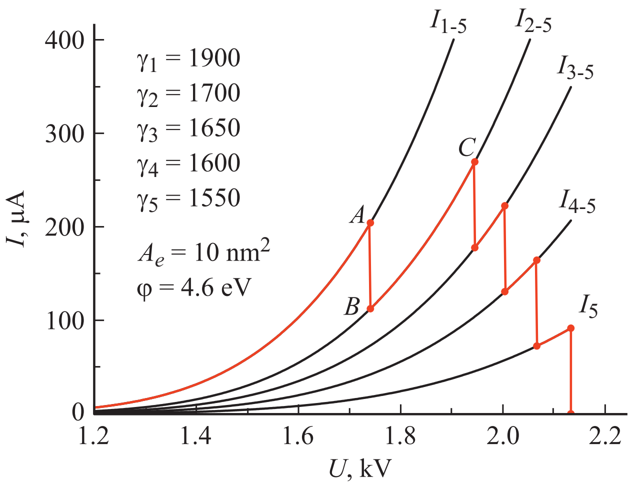

Figure 1. IVC of a model emitter consisting of five emission sites: with voltage increasing the sites are destroyed one by one and the current level decreases sharply. Monotone curves with indices $I_{i\text{-}5}$ correspond to the total IVCs of the corresponding subgroups of emission sites.

of real multi-tip cathodes [8]. Fig. 1 shows the calculated IVC.

The emission area of each site was set equal to $A_e = 10\,\text{nm}^2$, the work function was $\varphi = 4.6\,\text{eV}$, the field enhancement factors were taken equal to $\gamma = 1550$, 1600, 1650, 1700, 1900. To calculate the emission current density of each site, the Fowler–Nordheim formula was used in the Elinson–Shrednik approximation [9]:

$$J = (a_{\text{FN}}/1.1)\varphi^{-1}F_R^2 f^2 \exp(1.03\eta)\exp(-0.95\eta/f). \quad (1)$$

Here J — current density [A/m^2], φ — work function of emitter surface [eV], F — electric field on the surface, $f = F/F_R$ — dimensionless field associated with the potential barrier removal field $F_R = \varphi^2 c_S^{-2}$, where $c_S^2 = 1.44 \cdot 10^{-9}\,\text{eV}^2 \cdot \text{m/V}$ — Schottky constant,

$$\eta(\varphi) = b_{\text{FN}}\varphi^{3/2}/F_R = b_{\text{FN}}c_S^2\varphi^{-1/2},$$

$$a_{\text{FN}}{=}1.54 \cdot 10^{-6}\text{A}\cdot\text{ev}\cdot\text{V}^{-2},$$

$$b_{\text{FN}}{=}6.83\cdot 10^9\text{eV}^{-3/2}\cdot\text{V/m}$$

— the first and second Fowler–Nordheim constants.

In the case of plane-parallel electrodes, when the inter-electrode distance is much greater than the height of the emission site, the field F is related to the applied voltage by the formula

$$F = \gamma U/d_{A-C}, \quad (2)$$

where the interelectrode distance is $d_{AC} = 300\,\mu$m.

The total current I was obtained by multiplying the current density by the emission area:

$$I = JA_e. \quad (3)$$

The limit current density was obtained from Forbes research data [7]: $J_{\max} = 9.2 \cdot 10^8\,\mathrm{A/cm^2}$ (corresponds to the field $f = 0.75$).

It can be seen that as the voltage level increases, the current reaches such a level that the first, highest site (point A) is destroyed. As a result, the total current loses its contribution, and the IVC changes its shape to the IVC of emitter consisting of four sites (point B). Then the second site is destroyed, and the IVC changes again (point C), and so on. It can be seen from the resulting graph that the destruction of the highest sites leads to an increase in the available voltage range and, accordingly, to an increase in the maximum current. However, starting from some emission site (point C), this growth stops and the total current begins to drop, associated with a decrease in the total current output of the emitter. The analysis shows that for the such peak existence in the „fir-like " IVC, it is necessary that initially, when the sites are destroyed, the increase in the total current with increase in voltage is observed. Such increasing is possible if the current drop due to the combustion of one site (the difference in currents at points A and B) turns out to be less than the increase in current with voltage increasing from the threshold voltage of this site to the threshold voltage of the next one (the difference in currents at points C and B). This is possible only if the difference between the field enhancement factors of the sites (neighbors in the distribution) is sufficiently large.

To check the presence of such optimum in the experiment, we used data from study of field cathode based on a nanocomposite „single-wall CNTs in polystyrene". The study was conducted on a computerized installation for multichannel data collection and online processing [8]. The installation is equipped with a field projector, a high-voltage fast scanning system, and a program that makes it possible to obtain data on the location and magnitude of the current load of individual microscopic emission sites based on the glow patterns observed on the luminophore. The current load is obtained by distributing the macroscopic recorded current over the sites according to their local brightness. The corresponding field enhancement factor is found by numerically solving the Fowler–Nordheim equation (1) with the following general parameters: interelectrode distance $d_{AC} = 370\,\mu\mathrm{m}$, CNT work function $\varphi = 4.6\,\mathrm{eV}$, emission area $A_e = 10\,\mathrm{nm}^2$. The emission area was given as the average estimate $A_e = A_{eff}/N$, where $A_{eff} = 7577\,\mathrm{nm}^2$ — the effective emission area obtained by plotting a trend line to the IVC in the Fowler–Nordheim coordinates [9], $N = 767$ — the number of emission sites registered with the field projector. Besides, according to the SEM data, the radius of curvature of the CNT tops of the prototype is 2–4 nm, which is in good agreement with the emission area A_e.

Fig. 2 shows the obtained experimental data: the distribution histogram of the sites according to the field enhancement factor γ, as well as the pattern of the field projector glow.

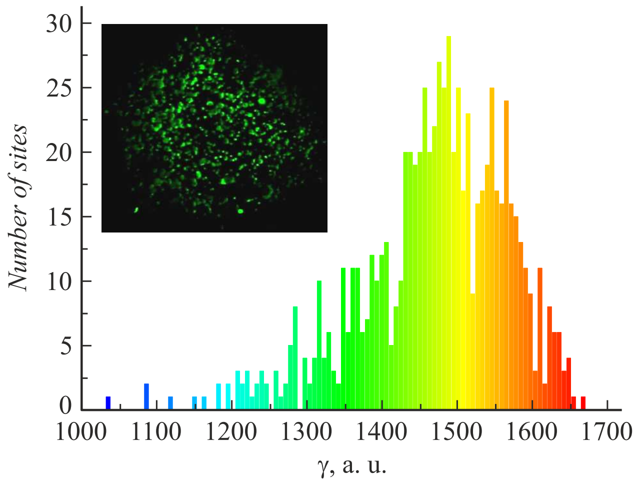

Figure 2. Histogram of values of the field enhancement factor of individual emission sites of the field cathode, obtained by processing the glow patterns online. The insert shows a photograph of the instantaneous glow pattern.

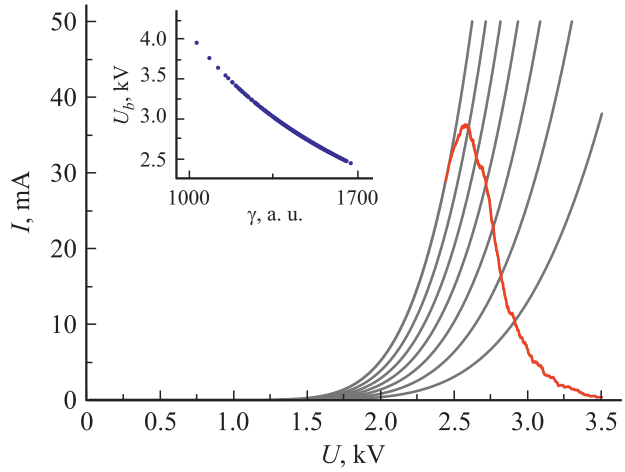

Figure 3. Behavior of the emission current level with voltage level increasing under the condition of successive destruction of emission sites. The monotonic curves represent the total IVCs of the respective subgroups plotted after every 100 destroyed sites. The insert shows the site destruction voltage vs. its field enhancement factor.

Note that the distribution of emission sites according to the field enhancement factor can in principle be obtained not only with the help of a field projector, but also with the help of other methods, for example, SAFEM (scanning anode field emission microscope) [10].

Site destruction voltages U_b corresponding to the limiting current density $J_{\max}$ were calculated from the above obtained experimental data by numerically solving the Fowler–NordGame equation (1): $U_b = 2.44{-}3.96\,\mathrm{kV}$, i. e. at 2.44 kV, the destruction of the first, highest emission site is expected, and at 3.96 kV, none of the registered sites should remain.

Fig. 3 shows the result of the analysis of the process of sites destruction by high voltage effect on the IVC shape. Monotonic curves — IVC of the sum of the lowest sites with difference of 100 sites. The broken IVC is the result of successive destruction of emission sites (the insert shows the destruction voltage of each site vs. its field enhancement factor). The graph shows a clear maximum at $U = 2.58$ kV. This is the voltage to which it makes sense to train the cathode. In this case, ~ 80 of the highest and most unstable emission sites self-destruct, and the current reaches the maximum possible value of 36.4 mA. Exceeding this voltage should lead to the emitter degradation and the loss of its total current load.

The above calculations do not take into account the possibility of the emission area change of individual emission sites with voltage increasing, as well as this area dependence on the field enhancement factor. These dependencies are quite complex and are the subject of further study.

Also note that with voltage increasing the formation of new emission sites is possible (as a result of a thermal explosion on the cathode surface, or the effect of tip self-sharpening, or a change in the mutual screening condition when a high emission site is destroyed, etc.). However, as a rule, new emission sites do not exceed in field amplification factor those that were destroyed by high voltage before they appeared, so that the trend of the dependences plotted above is retained.

In conclusion, note that the method of controlled training of the cathode can be applied not only to the cathode exposure to high voltage, but also to other types of technological processing of its surface.

Conflict of interest

The authors declare that they have no conflict of interest.

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