Limiting currents of matrix field emission cathodes based on carbon nanotubes

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Abstract. The limiting emission currents of matrix field cathodes based on carbon nanotubes are investigated for their dependence on the cathode working area, as well as the features of the Fowler-Nordheim curves in cyclic measurements of the I-V characteristics under cyclic measurements of CVC. The migration of the thermal overload region of emitters with a temperature of more than 1500 K (with emission in the visible spectral range) on the surface of a matrix cathode is set, as well as two types of divergence of the Fowler-Nordheim curves under cyclic measurements of CVC.

1. Introduction

One of the most noticeable trends in recent years is the advancement of vacuum field emission electronics in the regions of short millimeter waves and the terahertz range [1]. These are, in the first place, devices of microwave electronics – triodes, klystrons, magnetrons, traveling wave tubes for space communication systems, radar, IR observations (visualization and identification), and moreover, for diagnostic purposes - sensing dangerous goods (explosives, drugs), among other uses. The key problem of vacuum microwave electronics is that of the high-current field emission cathodes.

A promising material for creating high-current field emission cathodes are carbon nanotubes (CNTs) [2, 3]. The prospects for the use of CNTs are due to a unique combination of their electrical, chemical, optical, thermal and mechanical properties. Important properties of CNTs are namely their high electrical conductivity and unusually high emissivity due to their quasi-one-dimensional structure with a high aspect ratio. Further advantages of CNTs are a high coefficient of amplification of the electric field by an individual emitter, unattainable in any of the known types of emitters - up to 30,000 rel. units, the record low threshold strength of the emission field for all known types of emitters - at a threshold electron emission current of 1 mA / cm² - 0.2 V / μm, record high thermal conductivity of the individual emitter (higher than that of diamond emitters) - 3000 W / (mK). Other advantages of field emission cathodes on the basis of CNTs are resistance to all types of radiation, up to complete destruction of the material, stable operation over a wide temperature range from -130 °C to +300 °C,
lack of inertia and low power consumption. However, to date, commercial devices based on CNT field-emission cathodes are not available on the world market.

It is possible to distinguish three characteristic parameters that determine the possibility of using CNT field-emission cathodes for instruments and devices of field emission microwave electronics: a - field emission current density \( J_{FE} \); b - operating voltage \( U_{FE} \); c - stability of emission parameters and durability of CNT field-emission cathodes. In this article, we consider issues related to the problem of obtaining high current density of field emission of CNT field-emission cathodes.

For a number of significant applications in the field of microwave electronics (triodes, klystrons, traveling wave tubes) are needed \( J_{FE} \geq 1 \text{ A/cm}^2 \) from the working area of the cathode \( S_W \geq 1 \text{ cm}^2 \). The theoretical limit for field-emission cathodes based on nanosized carbon materials reaches \( J_{FE} = 10^9 \text{ A/cm}^2 \) [4]. For the matrix of point emitters, even with allowance of space-charge effects, are theoretically achievable \( J_{FE} = 10^7 \text{ A/cm}^2 \) [5]. In addition, it was shown in [6] that the screening effect of the space charge in the case of a nanoscale emitter is insignificant up to the limiting emission current densities. However, to date, in practice, even under laboratory conditions, the limit of the emission current density for CNT field-emission cathodes from the cathode working area \( S_W \geq 1 \text{ cm}^2 \) is not more than \( 1 \text{ A/cm}^2 \).

In this work, we have studied the limiting emission current as a function of the working area of the matrix CNT field emission cathodes, as well as the characteristics of the Fowler-Nordheim curves with multiple cyclic passes to the region of limiting currents when measuring the current-voltage.

2. Experiment

CNT field emission cathodes were produced by CVD synthesis technology with the catalytic pyrolysis of the hydrocarbon mixtures of ferrocene \((C_5H_5)Fe\) with xylene \((C_8H_10)\) \((0,15 \div 0,5 \text{ cm}^3/\text{min})\) in the presence of the localized and pre-structured catalyst on the substrate. The content of ferrocene in this “feeding solution” was 0,1% wt %. A flow rate of carrier gas \((\text{Ar}, \text{N}_2)\) \(100 \text{ cm}^3/\text{min}\). As a substrate for subsequent CNTs growth, \(n\)-type silicon wafers with high doping level KES-0, 01 (100) was used. The localized catalyst is a metallic layer of \(\text{Al} \text{Ni}\) with a thickness of 10 nm and 1 nm, respectively. To prevent interaction of Al with Si the Si-substrate was coated with molybdenum film with a thickness of 200 nm. The topology of the test structure is obtained by lift-off photolithography. Immediately prior to the CNT synthesis, the substrate was subjected to mechanical cleaning and washing in alcohol (ethanol or isopropanol). The topology is a set of simple elements \(2 \times 2 \mu \text{m}^2\) dots with 100 \(\mu \text{m}\) and 5 \(\mu \text{m}\) spacing. The active area of test topology was 1,2 \(\times 3 \text{ mm}\). High reproducibility in combination with low synthesis temperature \((650 ^\circ \text{C})\) yielded the cathodes with an emitter diameter 5 – 10 nm, high adhesion to the substrate and a minimum height nonuniformity of nanotubes.

As it is shown in our patent [7], the use of volatile catalyst Fe from \((C_5H_5)Fe\) source in combination with the multilayer localized catalyst \(\text{Mo} \text{Al} \text{Ni}\), play the role of the activator of metal-organic compound dissociation, which insures the obtaining of the few-wall \((2 – 6 \text{ walls})\) CNTs with narrow diameter distribution of low defect density, high adhesion to the substrate and minimum micro- and macro nonuniformity of CNTs height.

Study of the geometric features of the experimental samples of CNT FECs were carried out using a scanning \((\text{JEOL 6510})\) and transmission \((\text{JEOL 100CX})\) electron microscopes. The FE properties of the experimental samples of CNT cathodes were investigated with the field emission scanning microscope \((\text{FESM})\) for spatially resolved measurements (University of Wuppertal, Germany) at a pressure of \(10^{-6}\) with Torr residual gases, and also using a diode-type cell with a fixed spacer (BSUIR, Belarus). The migration processes of the emission region along the cathode surface have been investigated in real time using a field emission scanning microscope \((\text{FESM})\) and a built-in video camera.
3. Results and discussion

3.1 The relationship of the emission current density and the working area of the cathode

Figure 1 (a) shows a micrograph (scanning electron microscopy, SEM) of a single, separately standing element of a CNT field-emission cathodes matrix with a geometric size of 2 μm, distanced from the others by 100 μm. The internal structure of an element consisting of carbon nanotubes 5 – 10 nm in diameter is shown in Figure 1 (b) (transmission electron microscopy, TEM). Figure 1 (c) shows the current-voltage characteristic of a single element of the CNT field-emission cathodes matrix measured in DC mode using a field emission scanning microscope and an anode of 30 μm in diameter. Since the distance between the unit elements is 100 μm, the working area of the emission is determined by the size of a single, separately standing element of the CNT field-emission cathodes matrix. The maximum achievable value of the emission current is obtained for a single element $I_{FE} = 2.8 \times 10^{-5}$ A, as illustrated in Figure 1 (c). The dashed line in Figure 1 (a) denotes an area of $5 \times 5$ μm, corresponding to a single element in the matrix structure with a pitch of 5 μm, excluding the screening of the field by adjacent elements (excluding the near-field effect).

The matrix structure of CNT PEC of densely packed single elements with a 5 μm step is shown in Figure 2 (a, b) (SEM). Packing density of unit cells in the cathode matrix is $4 \times 10^6$ cm$^{-2}$. Taking into account the emission current value of $2.8 \cdot 10^5$ measured at the unit cell and the unit packing density of $4 \cdot 10^6$ / cm$^2$, the estimated expected (potential) density of the field emission current of such a matrix CNT field-emission cathodes $J_{FE} = 2.8 \cdot 10^5 A \times 4 \cdot 10^6 / cm^2 = 110$ A/cm$^2$.

Figure 1. Micrograph (a) scanning, (b) transmission electron microscopy, and (c) current-voltage characteristics of a single element of the matrix CNT cathode distanced from others.

Figure 2. Microphotographs (a, b) of scanning electron microscopy and (c) current-voltage characteristics of matrix CNT cathode.

Figure 2 (c) shows the actual CVC of a matrix cathode with a unit element pitch of 5 μm, measured in DC mode from the working area of the emission $S_w = 1.7 \cdot 10^4$ cm$^2$, corresponding to an anode diameter of 150 μm. The anode-cathode distance is 50 μm, the topology of the sample corresponds to Figure 2 (a, b). As follows from Figure 2 (c), the maximum value of the measured emission current is
The graph of the $J_{FE}$ with $S_W$ dependence of a matrix cathode with a step of unit elements of 5 μm is shown in Figure 3 (curve 1). As follows from the graph, the dependence of $J_{FE}$ on $S_W$ is linear. The maximum value of $J_{FE}$ = 110 A/cm² was received from the working area of the cathode $S_W$ = 2.5·10⁻² cm². With an increase in $S_W$, the values for $J_{FE}$ fall sharply and with $S_W$ = 1.7·10⁻⁴ cm² we obtain $J_{FE}$ = 1.9 A/cm² (Figure 3, curve 1). Consider the possible causes of the fall of $J_{FE}$ with increasing $S_W$.

**3.2 Analysis of the relationship between the emission current density and the cathode working area**

One possible reason for the observed patterns of the dependence of $J_{FE}$ on $S_W$ is the statistical spread of the structural parameters of individual emitters over the area of the matrix cathode, associated with the imperfection of the technology of CVD synthesis of CNT. In the case of matrices with a significant number of tip emitters, to achieve limiting $J_{FE}$, ideal uniformity (unification) of the structure along the height and diameter of the individual emitters is required, as well as sufficient distance between them and the magnitude of the interelectrode gap. In practice, the ideal unification of the structure of CNTs in the processes of self-organization (growth) is technologically difficult to achieve in all known growth technologies, such as CVD, arc discharge, laser ablation, etc. In all mechanisms of synthesis, it is impossible to avoid heterogeneity in diameter, height of carbon nanotubes, and the distance between them.

The emission current density $J_{FE}$ of field-emission cathodes is described by the modified Fowler-Nordheim expression [8-10]:

$$J_{FE} = \frac{A \beta^2 E_{FE}^2}{\varphi} \exp\left[\frac{-B \varphi^{3/2}}{\beta E_{FE}}\right] \text{A/cm}^2,$$

where $E_{FE}$ – the intensity of an external electric field (V/cm), defined as $E_{FE} = U_{FE}/d$, where $U_{FE}$ – operating voltage, $d$ – interelectrode gap, $\varphi$ – the work function of the emitter material (eV), $\beta$ – a field amplification factor, $A = 154$ and $B = 6830$ – constant values. For multi-walled carbon CNTs $\varphi = 5$ eV [11, 12].

The most significant variable in the Fowler-Nordheim equation is the value of the field amplification factor $\beta$, which determines the degree of transformation of an external macroscopic field into a local nanoscopic field at the end of a nanotube, leading to electron emission. Experimentally $\beta$ can be determined from the slope of the Fowler-Nordheim graph, which is a graph of the function $\ln(I/E^2)$ = $f(1/E)$ and for the case of field emission has the form of a straight line. In this case $\beta$ is calculated as:

![Figure 3. Experimental dependence of the current density on the working area of the CNT FEC.](image-url)
\[
\beta = \frac{C\phi^2}{\ln \alpha},
\]

where \(\tan \alpha = \frac{d(\ln(f/E^2))/d(1/E)}{d(1/E)}\) – the tangent of the inclination angle of the Fowler-Nordheim curve, \(\varphi\) – the work function of the emitter material and \(C\) is the intersection point of the Fowler-Nordheim graph with the ordinate axis.

In the paper [10], the idea of a hybrid field amplification scheme was proposed, according to which the field amplification effect has two components: field amplification factor \(\beta\) (internal factor) and external factor \(\gamma\), defined by electrostatic screening, connected with the close arrangement of individual CNTs relative to each other (near-field effect). Internal factor \(\beta\) is determined by one separately located free-standing CNT without neighbors. It is determined by the geometry of the CNT and can be calculated as \(\beta = l/r\) [13], where \(l\) – length of CNT, \(r\) – curvature radius of the tip of CNT. External factor \(\gamma\) can be determined by calculation using numerical methods.

In practice, the decisive influence on the current density of the emission in the array is exerted by an external factor \(\gamma\) [14]. In paper [15] it is shown that field-emission cathodes should provide optimal emission efficiency in the case that the length of CNT \(l\) is at least 10 times greater than the diameter, and the distance \(h\) between two neighboring CNTs is at least \(2l\). This means that the array must be sufficiently sparse. On the other hand, a significant decrease in the density of the array can lead to a decrease in the current density due to a decrease in the number of emitting CNTs per unit area. Therefore, in order to obtain high efficiency of field-emission cathodes, it is important to choose the optimal ratio of length, diameter and density of CNTs in the array.

In accordance with the Fowler-Nordheim formula [8] considered above, as well as its generalization, the Murphy-Hood formula [16], the values \(E_{FE}\) and \(J_{FE}\) are related by an exponential relationship. Depending on the region of the curve \(J_{FE}/E_{FE}\) increment of \(E_{FE}\) at 10 \% may lead to an increase of \(J_{FE}\) of an individual emitter in 5 – 10 times. At the same time, the value of the statistical variation in height and diameter of individual emitters proportionally changes the required value of the electric field strength \(E_{FE}\), since the height determines the interelectrode gap between the emitter and the anode, and the emitter diameter is the internal field amplification factor \(\beta\) on the individual emitter. Thus, a statistical spread of 10\% in height and diameter of individual emitters can lead to a spread of field emission currents from individual emitters by 5 – 10 times. In turn, a change in the distance between the individual tip emitters also contributes to the spread of the value of \(J_{FE}\), since it changes the value of the external field amplification factor \(\gamma\), associated with the screening of the field with a sufficient approach of the emitters (near-field effect).

The statistical spread of the geometric parameters of neighboring tip emitters (individual carbon nanotubes) can be defined as the microinhomogeneity of the structure. At the same time, with an increase in the working area of the cathode \(S_W\) the heterogeneity of the CNTs parameters at different parts of the cathode matrix also begins to play a role, determined by the heterogeneity of the growth conditions of CNT on the extended synthesis zone in the CVD reactor. Such heterogeneity can be defined as macroinhomogeneity. Starting from a certain micro surface area, the microinhomogeneities of the structure are averaged and with an increase in the working area of the cathode matrix, it is macroinhomogeneities that can make the main contribution to limiting the value of \(J_{FE}\) measured in practice.

In CVD synthesis processes, one of the key parameters that determine the diameter and growth rate (height) and density of carbon nanotubes are the geometric dimensions and topology of metal catalyst clusters [17]. As a consequence, one of the ways to unify the geometric parameters of CNTs can be use of nanolithography technology to specify the shape, size, and exact localization of metal-catalyst clusters on a substrate. Such work was carried out within the framework of the project CANVAD of the 5th European Framework Program [18, 19]. The topology of clusters was formed using electron-beam lithography. The cathode matrix obtained from the CVD process was an almost perfect structure with a distance of 10 \(\mu m\) (with an accuracy of 1\%) of CNT field-emission cathodes with a height of 5 \(\mu m\) (with an accuracy of 4\%) and a diameter of 50 \(\mu m\) (with an accuracy of 6\%) [18,
19]. At these cathodes, when measured in the DC mode from cathode working areas $S_W = 2.2 \cdot 10^{-7}$ cm$^2$ and $S_W = 3 \cdot 10^{-3}$ cm$^2$ calculated emission current density was obtained, respectively, $J_{FE} = 400$ A/cm$^2$ and $J_{FE} = 1$ A/cm$^2$. If we denote on the graph in the coordinates $J_{FE}/S_W$ position of the obtained measurement results, then we observe the same pattern associated with a sharp fall $J_{FE}$ with increasing $S_W$ (Figure 3, curve 2).

Thus, even with the use of nanolithography technology, it is impossible to avoid a characteristic drop-dependence of $J_{FE}$ on $S_W$. It is interesting to note that in the article [18], a summary graph of the distribution of the measurement results of CNT field-emission cathodes is presented on the basis of an analysis of 14 publications by different authors. The same characteristic feature of the graph is observed: a drop in the values $J_{FE}$ with increasing of values $S_W$. In particular, when $S_W$ corresponds to $10^{-4}$ cm$^2$ they report receiving $J_{FE} = 6$ A/cm$^2$ [20], however when $S_W$ is $10^{-1}$ cm$^2$ the maximum achievable is only $J_{FE} = 10^{-3}$ A/cm$^2$ [21], which correlates with the results obtained by us (Figure 3, curves 1 and 2).

### 3.3 Interrelation of the emission current density and heterogeneity of the CNT field-emission cathodes structure

Let us consider possible mechanisms of $J_{FE}$ restriction of CNT field emission due to the statistical spread of geometric parameters. Almost all the advantages of carbon nanotubes for field-emission cathodes applications listed at the beginning of this article (see Introduction) refer to single-wall CNTs of small diameter (nanometer units) with metallic conductivity type. However, as a rule, real individual emitters are multi-walled carbon nanotubes, which are characterized by low electrical conductivity, a significant defectiveness of graphene walls and the problem of mechanical, electrical and thermal contact with the substrate [22]. These problems can lead to strong heating of emitters during the passage of field emission currents (Joule heat), especially on structural defects and in the area of poor contact with the substrate. In addition, as the voltage increases due to the statistical spread of the structural parameters, individual emitters on the working area of the cathode matrix are loaded non-uniformly. The temperature of the more emitters (with a larger height and smaller diameter) is rising. The exceeding by $I_{FE}$ of some critical limit leads to thermal destruction of the overloaded individual emitters and transfer of the load to neighboring emitters. At the same time, from our point of view, several variants of the development of events are possible. If the loaded emitters have shielded neighboring emitters (due to the microinhomogeneities of the cathode structure), then after their destruction, these neighboring emitters are activated, and the effective emission region retains its localization. Otherwise, the emission migrates to other regions of the emitter matrix, determined by the macro-inhomogeneities of the cathode structure.

In the article [23], in which the distribution of emitted electrons by energy was studied, it was established that multi-walled CNTs in the emission process could be heated up to 2000 K without significant loss of emission properties. However, the authors have worked in the field of low density field emission currents. In the case of high $J_{FE}$, it may be possible that the temperature rises above 2000 K, since the destruction of the emitter carbon material recorded by us at the emission limit currents can correspond to a temperature of 4500 K. High temperatures make it possible to record the localization of the loaded emission regions by the characteristic glow of heated emitters in the visible spectral range, starting from temperatures above 1500 K [23]. We investigated these processes in real time using a field emission scanning microscope (FESM) and a built-in video camera.

Figure 4 (a, b) shows microphotographs of the emission region of CNT field-emission cathodes for different values of the operating voltage obtained with the built-in video camera. When the working voltage is changed, the area of intense glow also changes its shape. The luminescence region can be defined as the area of effective emission, and the area occupied by it is the effective emission area. Obviously, the effective emission area can be very different from the working area of the cathode $S_W$.

Figure 4 (c) shows the Fowler-Nordheim dependence for a sample of CNT PEC for multiple passes (rise and fall) of the operating voltage. A characteristic feature of these Fowler-Nordheim curves is the presence of saturation of the emission current, known as the effect of emitter current saturation [18].
Saturation occurs at the emission currents $I_{FE} \approx 10^6 - 10^5$ A (in our case, this corresponds to current densities of $J_{FE} = 5 - 50$ mA/cm$^2$) and correlates in time with the appearance of the luminescence effect in the emission area. The saturation effect was recorded by us on all types of samples studied when $J_{FE} > 5 - 50$ mA/cm$^2$ was exceeded and was considered in detail in our work [24]. Another observed feature of the Fowler-Nordheim curves is the splitting of the curves with multiple cyclic passes to the area of the maximum emission currents (Figure 4 (c)).

An example of the behavior of another type of sample, with a high macroinhomogeneity of the structure of the matrix cathode, is shown in Figure 5. Microphotographs, as depicted in Figures 5 (a-d), show effective emission regions, determined by the characteristic luminescence of overloaded emitters. As the voltage rises, migration of the luminescence area over the cathode working area is observed due to the high macroinhomogeneity of the cathode structure. The features of the behavior of a sample of the first type, in Figure 4 (a-c) can be attributed to the case of fairly homogeneous samples of CNT field-emission cathodes with a low macroinhomogeneity of the structure. For a sample of the second type, such as that depicted in Figure 5 (a-e), we can assume a sufficiently high macroinhomogeneity of the cathode structure.

3.4 Features of the Fowler-Nordheim dependencies in cyclic CVC measurements

The difference in the character of the heterogeneity of the structure is reflected in the Fowler-Nordheim curves. Depending on the type of prevailing inhomogeneity, there is a different character of the divergence of the Fowler-Nordheim curves for multiple passes of the CVC measurements. In the case of sufficiently homogeneous samples of CNT field-emission cathodes with a low macroinhomogeneity of the structure, the tangent of the curve slope to the coordinate axes is observed to change, as in Figure 4 (c), in the other case, the tangent of the slope angle remains unchanged, as in Figure 5 (e). Let us try to find an explanation for these features.

As follows from formulas (1) and (2), the tangent of the slope angle $\alpha$ in the Fowler-Nordheim coordinates is proportional to the ratio of the work function of the material $\varphi$ and the field amplification factor $\beta$ ($\tan \alpha = \varphi / \beta$). The work function depends on the sorption-desorption processes of the residual gases at the end face of the emitter, as well as the temperature of the emitter [25]. The field amplification factor $\beta$ is determined mainly by the geometric parameters (the apex ratio) of the emitter. The measurements were carried out using field emission scanning microscope (University of Wuppertal, Germany) at a residual gas pressure of $10^{-9}$ Torr, which minimizes the role of sorption-desorption processes of residual gases at the end face of the emitter at multiple passes. A more significant contribution can be made by the work function of the material $\varphi$, which is essentially temperature dependent. With the onset of the transition to the thermal overload of the emitter after the inflection point (the beginning of the process of saturation of the emission current due to the drop in the large potential on the emitter, the heating by Joule heat, the appearance of intense luminescence in the emission region), the most effective individual emitters (carbon nanotubes with a high aspect ratio) are destroyed. However, this reduces the work function of the output $\varphi$, which compensates for the decrease in the amplification factor $\beta$, and the tangent of the slope of the curve of $\tan \alpha$ remains unchanged. When the operating voltage returns backward, the work function of the output $\varphi$ restores its value, however, the amplification factor $\beta$ is significantly reduced due to the destruction of active emitters during the high-temperature heating period, which leads to a change in the tangent of the slope angle $\tan \alpha$ below the inflection point and explains the characteristic form of the Fowler-Nordheim curves diverging downwards, shown in Figure 4 (c).

In the other case, in the presence of high macroinhomogeneity, with repeated passes and returns to the region of low stresses (and, correspondingly, temperatures), the slope tangent $\tan \alpha$ remains unchanged. Taking into account the stability of the work function $\varphi$ in the low-temperature region (self-heating of the emitter being negligible), it can be concluded that the field amplification factor $\beta$ remains practically unchanged. This can correspond to the case when the effective emission region shifts (migrates) over the cathode working area with the inclusion of new cathode regions with the same...
microstructure of the emitters and the field amplification factor \( \beta \), respectively, after each passage, yet with an increased interelectrode gap. On micrographs, we see the shift of the luminescence region (the area of effective emission) to new regions of the working area of the cathode matrix, displayed in Figure 5 (a-d). It can be assumed that the migration of effective emission regions allows maintaining the stability of the field amplification factor \( \beta \) for multiple passes in the case of high macroinhomogeneity of the structure of the matrix cathode, in Figure 5 (e). The areas of effective emission change their localization, yet the total size of the effective emission area can remain constant.

**Figure 4.** Microphotographs of the working area of the emission at different values of the field emission current (a-b) and the Fowler-Nordheim dependence (c) for a sample of CNT field-emission cathodes with low macroheterogeneity of the cathode structure.

**Figure 5.** Microphotographs of the working area of the emission at different values of the field emission current (a-d) and the Fowler-Nordheim dependence (e) for a sample of CNT field-emission cathodes with high macroheterogeneity of the cathode structure.

Thus, the characteristic feature of the divergence of the Fowler-Nordheim curves found by us at multiple passes of CVC-measurements can be explained by migration of the effective emission region along the cathode working surface, recorded by the characteristic luminescence of an overloaded current region. As in the cases of migration and fixed emission areas, a common feature is a significant difference between the effective emission area and the cathode working area \( S_W \), which can be considered as one of the main reasons for limiting the practical values of the density of the autoemission current of CNT field-emission cathodes. It is the micro- and macroinhomogeneities, in the first place, that determine the characteristic features of the field electron emission processes and the limits of the emission current densities achievable in practice on the matrix of the pointed CNTs field-emission cathodes. At the same time, intense luminescence in the region of effective emission before current disruption testifies to the thermal character of irreversible degradation and destruction of emitters, as can be seen from the strong stratification of the Fowler-Nordheim curves after the rise to the region of limiting currents.

**4. Conclusions**

The limiting emission currents of matrix field cathodes based on carbon nanotubes are investigated depending on the cathode working area, as well as the features of the Fowler-Nordheim curves in cyclic measurements of CVC. The migration of the thermal overload region of emitters with a
temperature of more than 1500 K (with emission in the visible spectral range) on the surface of a matrix cathode is determined.

It was found that the measurement of current-voltage characteristics in the mode of multiple passes to limit the emission currents has several options of emission development processes. In the first case, when returning to the low-current region, the value of the field amplification factor $\beta$ drops, which can be associated with the destruction of the most efficient emitters in the field of effective emission as a result of thermal overload. In another case, the field amplification factor $\beta$ retains its value, which may be due to the migration of the effective emission area on the surface of the matrix cathode.

Thus, it is possible to single out the key problem of obtaining a high limiting current density from matrix cathodes based on carbon nanotubes. The problem is related to the micro- and macroinhomogeneities of the cathode structure, which are the reason for limiting the area of effective emission in comparison with the cathode working area. In order to solve this problem, it is required to search for a synthesis technology that is unified by geometric parameters (height, diameter, distancing) of defect-free CNTs over a large area of the substrate surface (more than 1 cm$^2$) with low micro- and macroinhomogeneity of the structure, both. To solve this problem would open the way to getting high emission current densities for matrix field emission cathodes based on carbon nanotubes with a density of emission current of up to several thousand amperes per cm$^2$ and to the creation, on the basis of CNT field-emission cathodes of a new generation of instruments and devices of high-current field emission microwave electronics.

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