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EMISSION CHARACTERISTICS OF CARBON NANOTUBE-BASED CATHODS

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Abstract. There have been studied the Current-Voltage Characteristics (CVC) of a field emission cathode on the basis of carbon nanotubes (CNT). It is shown that the origin of a deviation of these characteristics from the classical Fowler-Nordheim dependence, observed at low voltages and currents, is caused by a statistical spread of geometrical parameters of individual nanotubes. The interconnection between the magnitude of the relative dispersion of the electrical field amplification factor γ and the shape of CVC has been established assuming the normal distribution of that. This interconnection is used for processing the CVC measured by various authors. The results obtained imply a considerable statistical spread of the amplification factor $\Delta\gamma/\gamma$ = 0,1 – 0,3.

1. INTRODUCTION

High emission properties of CNT are caused by their good electron conductivity and a specific geometry, resulting in a drastic amplification of the electrical field strength in a vicinity of the nanotube cup [1-3]. These features of CNT along with their high mechanical and chemical stability make CNT-based field emission cathodes beyond comparison with materials used usually in electron displays and others electron field emission vacuum devices. Wide application of such devices is still hindered by a relatively high production cost of CNT, which will be surely lowered as a result of intense efforts of technologists and developers.

Another problem, the solution of which determines a wide development of CNT-based emission cathodes, concerns to a spatial homogeneity of the emission characteristics of a cathode. One of possible reasons for disrupting the homogeneity is a statistical spread of parameters of CNT, which is reflected on the relevant spread of their emission characteristics. Thus a spread in longitudinal and transverse sizes of CNT is followed by the relevant spread in the aspect ratio, which in its turn is reflected on the electrical field strength amplification factor in a vicinity of the CNT cup. Besides of that, single walled CNT have a spread in their chirality [3], which results in a diversity of the conductivity and the work function of individual CNT. Therefore one can expect that the statistical spread in parameters of CNT should cause a deviation of the CVC of a CNT-based emitter from the classical Fowler-Nordheim dependence [4] even in the case when the CVC of an individual CNT do obey to this dependence. Such deviations have been observed in many experiments. Thereby the main part of the CVC is usually described quite well by the Fowler-Nordheim dependence, while the most notable deviations relate to a range of a relatively low voltage, where the excess in the emission current can reach orders of magnitude. In this work a quantitative description of CVC of CNT-based electron emitters with taking into account the statistical spread of their parameter is given. This permits one to establish an interconnec-

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tion between the parameters, characterizing this spread, and the shape of CVC. The interconnection obtained is used for processing the available experimental data and determining the degree of homogeneity of CNT-based emission cathodes.

2. THEORY

Let the main parameter determining the emission characteristics of an individual CNT is the electrical field strength amplification factor $\gamma = E/E_o$. This parameter is defined as the ratio of the real magnitude of the electrical field strength E near the frontal (faced to the anode) surface of a CNT to the volumetrically averaged value $E_0 = U/D$ (U is the voltage applied and D is the inter-electrode gap, which is supposed to exceed considerably the length of an individual nanotube l). Analyze the influence of the statistical spread of this parameter on the emission characteristics of a cathode consisted of a large number of individual nanotubes. The CVC of an individual nanotube is assumed to obey the known Fowler-Nordheim relationship:

$$J_i = C_1 E^2 \exp(-C_2/E), \qquad (1)$$

where J is the electron emission current density, C_1 and C_2 are the parameters depending on the geometry and electron properties of an emitter.

Since the parameter γ is characterized by a statistical spread, the magnitude of the electrical field strength E near the frontal surface of various nanotubes also have a spread, resulting in a distinction between the CVC of a cathode consisted of a large number of nanotubes and relation (1). Determine the character of this distinction using a simple model, assuming the normal distribution of the parameter γ

$$P(\gamma) = \frac{1}{\Delta\gamma\sqrt{\pi}} \exp\left[-\frac{(\gamma-\gamma_0)^2}{\Delta\gamma^2}\right]. \qquad (2)$$

Here $P(\gamma)$ is the probability density of the given value γ, γ_o is the mean magnitude of this parameter, $\Delta\gamma$ is the dispersion.

Neglecting the mutual influence of neighboring CNT on their emission characteristics, represent the emission current density as a result of the statistical averaging of the CVC of an individual CNT (1) with taking into account the distribution (2):

$$J = \int_0^\infty P(\gamma) J_i d\gamma =$$

$$\int_0^\infty \frac{C_1 E_0^2 \gamma^2}{\Delta\gamma\sqrt{\pi}} \exp\left[-\frac{C_2}{\gamma E_0} - \frac{(\gamma-\gamma_0)^2}{\Delta\gamma^2}\right] d\gamma. \qquad (3)$$

This integral can be quite easily calculated analytically under conditions

$$\Delta\gamma << \gamma_o; \quad C_2/E_o\gamma_o >> 1. \qquad (4)$$

Indeed, in this case, firstly, the lower integration limit can be extended down to $-\infty$, secondly, the smooth pre-exponential dependence in the integrand can be neglected in comparison against the sharply changing exponential function, and thirdly the first item under exponent can be represented in the form of the obvious expansion:

$$\frac{C_2}{\gamma E_0} \approx \frac{C_2}{\gamma_0 E_0}\left(1 - \frac{\gamma-\gamma_0}{\gamma_0}\right). \qquad (5)$$

These simplifications allow to calculate analytically the expression (3), which results in the following approximate equation for the CVC of an emission cathode:

$$J = C_1 E_0^2 \gamma_0^2 \exp\left[-\frac{C_2}{\gamma_0 E_0} + \frac{C_2^2 \Delta\gamma^2}{4\gamma_0^4 E_0^2}\right]. \qquad (6)$$

The equation obtained contains two factors, the first of which corresponds to the classical Fowler-Nordheim expression (1) and prevails at relatively high fields

$$E_0 >> \frac{C_2}{4\gamma_0}\frac{\Delta\gamma^2}{\gamma_0^2}, \qquad (7)$$

while the second one becomes notable in the low field region, obeying to the opposite condition.

Eq. (6) expressed in standard Fowler-Nordheim variables has the following form:

$$\ln\frac{J}{E_0^2} = \ln(C_1\gamma_0^2) - \frac{C_2}{\gamma_0 E_0} + \frac{C_2^2\Delta\gamma^2}{4\gamma_0^4 E_0^2}. \qquad (8)$$

As is seen, the right part of this expression contains quadratic dependence on the inverse electrical field $1/E_o$ along with the standard linear one.

3. RESULTS AND DISCUSSION

The dependence obtained (8) can be used for processing CVC of CNT-based field emission cathodes with the aim of determination of the degree of homogeneity of their emission characteristics. A typical CVC of such a kind is shown on Fig. 1 in Fowler-Nordheim variables [5]. As is seen, in the range of relatively high fields this dependence presents a practically straight line, which corresponds to the Fowler-Nordheim expression (1). In a low field re-

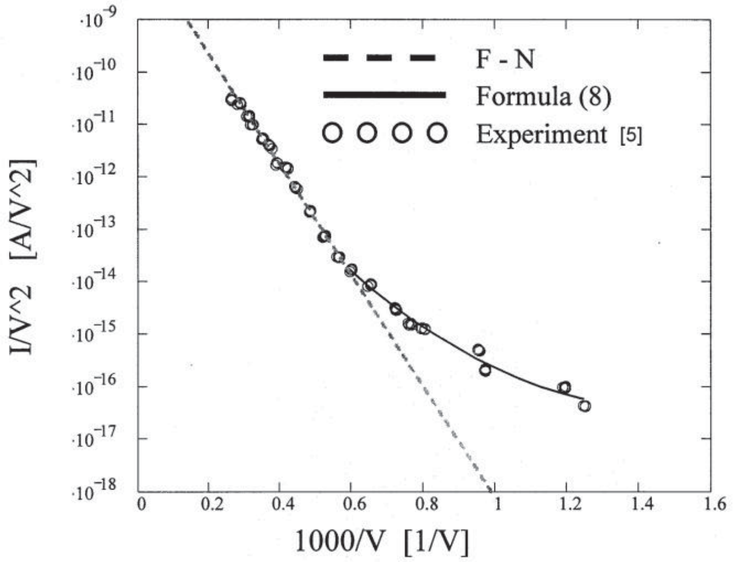

Fig.1. Current-voltage characteristics of the CNT-based cathode measured by the authors [5] (dots) and calculated on the basis of approximate relation (8) with $\Delta\gamma/\gamma = 0.24$. The broken line corresponds to the Fowler-Nordheim dependence (1).

gion a considerable deviation takes place, which is caused by a statistical spread of CNT parameters. The experimental CVC shown on Fig.1 is described quite well by the expression (8) with $\Delta\gamma/\gamma = 0.24$.

The procedure of fitting experimental and calculation dependencies was the following. Firstly the coefficient C_2/γ was determined through processing the linear part of CVC. Then non-linear part of CVC was approximated by the quadratic dependence on $1/E$, and parameter $\Delta\gamma/\gamma$ was determined through fitting this approximation with experimental dependence. Comparison of experimental and calculation dependence, which is also shown on Fig.1, gives an indication about the degree of accuracy of approximation (5) used.

Table 1 shows the results of processing several experimental CVC of CNT-based field emission cathodes, measured by various authors. As is seen, the relative spread of the parameter $\Delta\gamma$ determined on the basis of various measurements ranges within $\Delta\gamma/\gamma = 0.1 - 0.3$. Having regard to a sharp exponential dependence of the emission current on this parameter, one should conclude that the degree of the surface non-homogeneity of CNT-based cathodes

Table 1. The relative spread of the amplification factor of CNT $\Delta\gamma/\gamma$, determined by processing the experimental CVC of CNT-based field emission cathodes.

The type of CNT	Diameter of CNT, nm	Density of emitters, см$^{-2}$	Cathode-anode gap, mm	$\Delta\gamma/\gamma$	Voltage range, kV	Current range, μA	Ref.
SW*	5	10^5	5 - 20	0.24	5 - 15	$10^{-4} - 10^2$	[5]
SW	1 - 2	10^5	0.006	0.16	0.01 – 0.02	$10^{-4} - 10^2$	[6]
		10^5	0,002	0.105	0.02 – 0.07	0,1 - 5	[7]
SW	1,2		0,25	0.103	0.2-0.4	$10^{-6} - 1$	[8]
MW	25		0,25	0.13	0.4-0.7	$10^{-6} - 0{,}1$	[8]
MW	20		1	0.18	0.02 – 0.04	0.1 - 5	[9]

* SW – single walled nanotubes; MW – multi-walled nanotubes

used is rather high. On the other hand, the interconnection between the CVC of a cathode and the degree of its surface non-homogeneity, established in this work, can be used to control the quality of a CNT layer grown, which is not necessary designed for field emission targets.

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