Optics and Spectroscopy, 2024, Vol. 132, No. 11

10

Modeling of electron emitters based on carbon nanotubes

© I.A. Rozhleys, G.V. Tertyshnikova, D.G. Sannikov

Ulyanovsk State University,
Ulyanovsk, Russia

e-mail: sannikov-dg@yandex.ru

Received May 03, 2024
Revised July 26, 2024
Accepted November 30, 2024

A simplified (two-dimensional) model of an electron emitter based on a carbon nanotube is proposed. The model is implemented using the finite element method with COMSOL Multiphysics. It is found by modeling that the falling Fowler-Nordheim dependences are obtained when the electron emission period decreases inversely proportional to the cube of the voltage applied to the anode. Using graphs in Fowler-Nordheim coordinates the effective values of the electron work function and the electric field gain coefficient are found, and the results are compared with known experimental data. The reasons for the deviation of the obtained results from the experimental and Fowler-Nordheim theory predictions are discussed.

Keywords: carbon nanotube, field emission, Fowler-Nordheim model.

DOI: 10.61011/EOS.2024.11.60311.6506-24

Auto-electron emission in the Fowler-Nordheim (FN) [1] model is described as sub-barrier tunneling of conduction electrons in an external electric field [2]. The FN theory provides a good description of the experimental dependences for traditional tip-shaped metallic emitters, provided that the radius of curvature of the tip is more than 100 nm. For small emitters it is necessary to take into account peculiarities in the density of states, the character of resistive heating of the emitter, the influence of dimensional quantization, thermoelectric effects, and so on. Auto-electron emission is widely used in the development of flat-screen monitors, miniature X-ray tubes and vacuum tubes, light-emitting devices, terahertz amplifiers, and high-frequency vacuum switches [3]. Among the difficulties in developing field emitters — the problems of creating sufficiently large field emission currents, cathode durability, and technology complexity. The electric field distribution in the vicinity of the nanotube-emitter is determined by the ratio of the interelectrode distance to the radius of the spherical end of the carbon nanotube (CNT). The field in the vicinity of the CNT end can exceed the volume average value hundreds of times, estimated as the ratio of the voltage drop to the value of the interelectrode gap. As a result, the emission properties of CNTs are manifested at lower values of applied voltage compared to traditional autoemission cathodes based on macroscopic metal tips. At values of the emitter radius less than 10 nm (comparable to the width of the potential barrier, as well as to the de Broglie wavelength in the emitter volume), the current densities on FN significantly exceed the calculated current densities (taking into account the specific three-dimensional form of the potential barrier and the effect of dimensional quantization) [4].

Currently, technologies have been developed to create field emission sources based on CNTs. The best samples of CNT cathodes provide field emission current densities up to 8.5 A/cm^2. The most suitable technology for the creation of CNT emitters, providing the specified currents in high-voltage microwave devices, is the so-called „sandwich“-technology [5]. CNT field emitters can be fabricated by bonding a CNT film to a graphite rod. After thermal annealing in vacuum, the CNT emitters exhibit improved autoemission properties due to increased crystallinity and reduced defects in CNTs, and good stability and repeatability of autoemission [5,6].

Typical current-voltage characteristic curves of a single emitter based on a multi-walled CNT (before and after heat treatment) were measured in the experimental study [7]. Field emission from CNTs of different lengths (from a few nanometers to tens of nanometers) is considered in [8,9]. The emission current was calculated on the basis of the quantum mechanical description, and the linear dependence of the current envelopes on the field strength was established.

In this paper, we propose a simplified model of electron emitters based on multi-walled CNTs. We analyze the dependence of the electron emission period on the electric potential difference applied to the CNT emitter and anode, providing a decreasing linear dependence of the emission current in FN coordinates. The obtained effective values of electron work function and electric field enhancement factor are compared with the known experimental data.

Fig. 1 shows a schematic of the CNT-based autoemission cathode. For the analysis we use the finite element method and consider the system in 2D geometry.

To calculate the emission current in the circuit, we selected experimental parameters from the study by Zhao and colleagues [7]. The authors used the classical FN

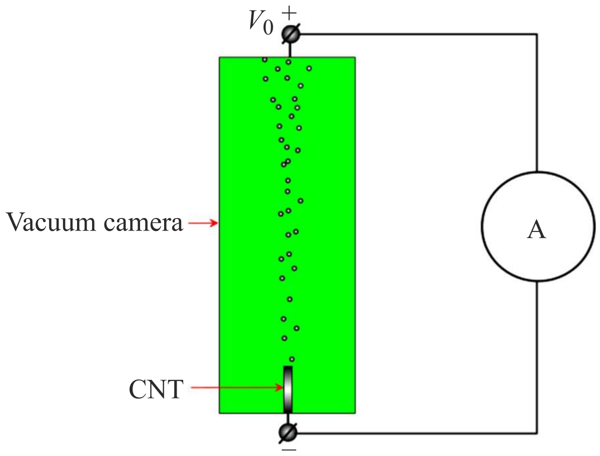

Figure 1. Geometry of the problem. A single CNT emitter (cathode) is located vertically in the vacuum chamber (dimensions are notional).

formula [10,11]:

$$\log(I/V_0^2) = \log\frac{\beta^2 c_0 A}{\varphi^{1/2}} + \frac{c_1}{\varphi^{1/2}} - \frac{c_2\varphi^{3/2}}{\beta V_0}, \qquad (1)$$

where log is the natural logarithm, I is the anode current [A], V_0 is the bias voltage [V], constants $c_0 = 1.5 \cdot 10^{-6}\,[\mathrm{eV}^{1/2}]$, $c_1 = 1.5 \cdot 10^{-6}\,[\mathrm{eV}^{1/2}]$, $c_2 = 6.44 \cdot 10^7\,[\mathrm{V\,cm\,(eV)}^{-3/2}]$, $\beta = E/V_0$ is the field enhancement factor $[\mathrm{cm}^{-1}]$, E is the electric field strength [V/cm], φ is the electron work function [eV]. It should be noted that the FN relation is approximate and corresponds to the one-dimensional case (1) when the emitting surface has the form of an infinite plane perpendicular to the direction of the external electric field. Usually in the theory of FN it is assumed that all conduction electrons in the emitter have the same energy corresponding to the Fermi level of the material, which is equivalent to the assumption that the temperature of the conductor is negligibly small compared to the Fermi energy (or work function). In case this assumption is violated, the electrons capable of emission have different energies, and there is also a temperature dependence of the emission current, accounted for by an appropriate correction to the expression FN [3]. A multi-walled CNT with the parameters indicated in the caption to Fig. 2 was chosen as a model CNT.

Fig. 2 shows the dependences of the emission current on the bias voltage in FN coordinates for CNTs placed in a vacuum chamber with different interelectrode distances d_0 $(d_0 = d_2 - d_1)$. The statistical analysis of the electron emission process has shown that the incident, close to linear FN dependences are obtained when the period of electron emission T_{em} decreases inversely proportional to the cube of the voltage applied to the anode V_0, i.e.

$$T_{\mathrm{em}} = \frac{c_3}{V_0^3}, \qquad (2)$$

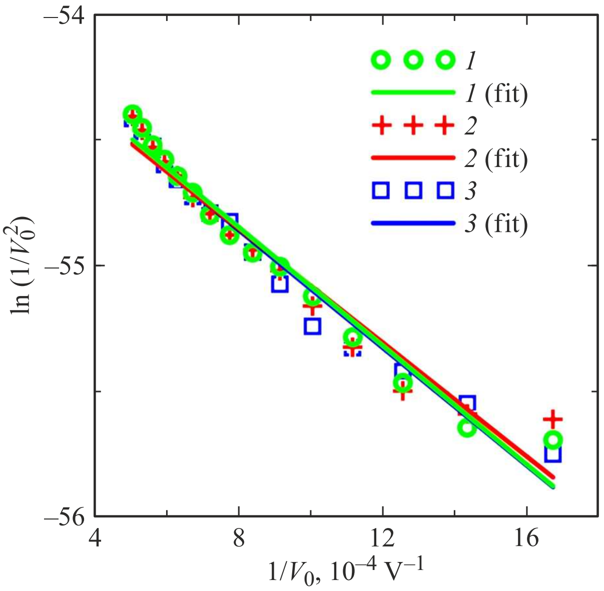

Figure 2. The plots in FN coordinates for the CNT emitter (emitting surface area $A_{\mathrm{em}} = 3.2 \cdot 10^{-17}\,\mathrm{m}^2$ [7]). The chamber height $d_2 = 50, 100, 200\,\mu$m (the corresponding icons and approximating straight lines have indices *1, 2* and *3*); CNT length $d_1 = 0.5\,\mu$m. The voltage V_0 varies in the range of 500 to 2000 V. The total emission time $t_{\mathrm{em}} = 40$ ps. The electron emission period T_{em} varies according to the law (2).

Comparison of the calculated CNT parameters (№ 2) and those experimentally obtained in [7]. The value of the constant $c_3 = 6.(7) \cdot 10^7\,[\mathrm{V}^3\,\mathrm{s}]$

Parameter	β, cm^{-1}	φ, eV
This study	$1.56 \cdot 10^5$	6.72
Zhao et al. (2006) [7]	$1.09 \cdot 10^5$	5.1

where the constant c_3 is found empirically. In general, the graphs in Fig. 2 can be approximated by incident linear dependencies in the range of applied voltage variation. The slopes of the straight lines make it possible, using the relation (1), to determine the effective value of the output work for the emitting material and the field enhancement factor (see the table).

The table shows that the data we have obtained are in good agreement with those given in [7]. Note that to obtain the FN plots, we varied the anodic voltage values in the range of 500 to 2000 V, whereas in [7] it was varied in the range of 300−600 V. The difference in the results may also be due to the fact that in [7] the CNT was tilted a few degrees from the axis of the supporting structure, as well as the inaccuracy of the coefficients in formula (1), which may change with the inevitable heating of the emitting surface.

Fig. 3 shows instantaneous snapshots of electron trajectories at different moments of time. It can be seen that the vast majority of electrons in the modeled beam

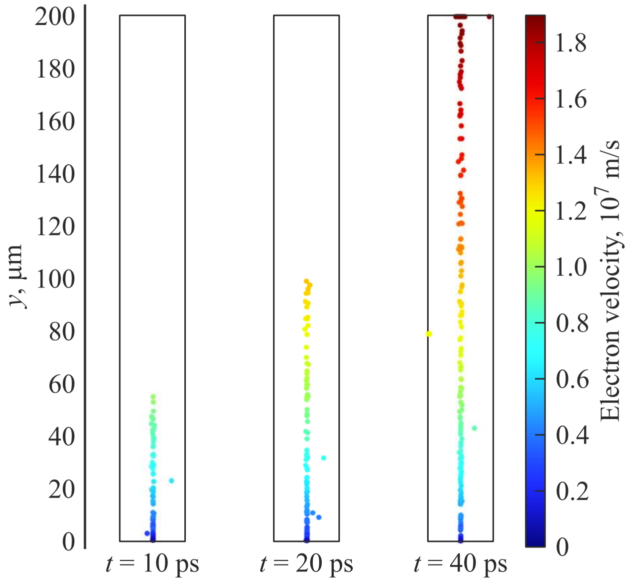

Figure 3. The autoemission pattern of CNTs in a vacuum chamber at different time instants. The chamber height is $d_2 = 200\,\mu$m; the voltage is $V_0 = 1000$ V. Other parameters are the same, as in Fig. 2.

move almost vertically, and only a small fraction of them deviate from the symmetry axis of the system. For the selected voltage, the current at the anode does not appear immediately, but after the time $t_{\text{em}}/2 = 20$ ps. This circumstance was taken into account in finding the FN-characteristics. Note that in this study we did not take into account the appearance of the thermionic emission component associated with the heating of a single CNT, which can occur when the field emission current [12] flows through the CNT.

Conclusion

In this paper, the process of auto-electron emission from the end face of a multi-walled single carbon nanotube placed in a vacuum chamber has been numerically investigated. For the electron emission period T, an empirical relationship of the form $T = \text{const} \cdot V_0^{-3}$ has been established, enabling the derivation of descending F-N (Fowler-Nordheim) dependencies. The values of electron work function and electric field enhancement factor determined using the obtained dependence of emission current on the applied electric voltage are close to those obtained in [7].

Acknowledgments

The authors thank S.G. Moiseyev for helpful discussions.

Funding

The research was supported by the Russian Science Foundation (grant № 23-19-00880).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] R.H. Fowler, L.W. Nordheim. Proc. R. Soc. A, **119** (781), 173 (1928). DOI: 10.1098/rspa.1928.0091
[2] A.V. Eletskii. Physics-Uspekhi, **45** (4), 369 (2002). DOI: 10.1070/PU2002V045N04ABEH001033.
[3] A.V. Eletskii. Uspekhi Fiz. Nauk, **180** (9), 897 (2010). DOI: 10.3367/UFNr.0180.201009a.0897.
[4] V.I. Kleshch, P.A. Zestanakis, J.P. Xanthakis. Appl. Surf. Sci., **623**, 156990 (2023). DOI: 10.1016/J.APSUSC.2023.156990
[5] G.G. Sominsky, T.A. Tumareva. Izvestiya vuzov. (in Russian) PND, **23** (2), 74 (2015). DOI: 10.18500/0869-6632-2015-23-2-74-93
[6] Y. Sun, D.H. Shin, K.N. Yun, Y.M. Hwang, Y. Song, G. Leti, S.G. Jeon, J. Il Kim, Y. Saito, C.J. Lee. AIP Adv., **4** (7), 77110 (2014).
[7] G. Zhao, J. Zhang, Q. Zhang, H. Zhang, O. Zhou, L.C. Qin, J. Tang. Appl. Phys. Lett., **89**, 193113 (2006). DOI: 10.1063/1.2387961/332084
[8] N.R. Sadykov, S.E. Zholnirov, I.A. Pilipenko. Tech. Phys., **66**, 1032 (2021). DOI: 10.1134/S1063784221070148.
[9] N.R. Sadykov, R.S. Khrabrov, I.A. Pilipenko. Pisma v ZhTF (in Russian) **48** (16), 34 (2022). DOI: 10.21883/PJTF.2022.16.53205.19216
[10] J.P. Sun, Z.X. Zhang, S.M. Hou, G.M. Zhang, Z.N. Gu, X.Y. Zhao, W.M. Liu, Z.Q. Xue. Appl. Phys. A Mater. Sci. Process., **75** (4), 479 (2002). DOI: 10.1007/s003390201403
[11] V.T. Binh, N. Garcia, S.T. Purcell. In: *Adv. Imaging Electron Phys.* (Elsevier, 1996), p. 63–153. DOI: 10.1016/s1076-5670(08)70156-3
[12] S.V. Bulyarskiy, A.A. Dudin, A.V. Lakalin, A.P. Orlov, A.A. Pavlov, R.M. Ryazanov, A.A. Shamanaev. Tech. Phys., **63**, 894–899 (2018). DOI: 10.1134/S1063784218060099.

Translated by J.Savelyeva