Real-time implementation of the “orthodoxy test” for conformity of current–voltage characteristics with classical field electron emission theory

Anatoly G. Kolosko, Sergey V. Filippov, Pavel A. Romanov, Eugeni O. Popov, and Richard G. Forbes

Citation: *Journal of Vacuum Science & Technology B* **34**, 041802 (2016); doi: 10.1116/1.4946834

View online: <http://dx.doi.org/10.1116/1.4946834>

View Table of Contents: <http://scitation.aip.org/content/avs/journal/jvstb/34/4?ver=pdfcov>

Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

Articles you may be interested in

[Outstanding field emission properties of wet-processed titanium dioxide coated carbon nanotube based field emission devices](#)

Appl. Phys. Lett. **106**, 073501 (2015); 10.1063/1.4909552

[Breakdown voltage reduction by field emission in multi-walled carbon nanotubes based ionization gas sensor](#)

Appl. Phys. Lett. **104**, 123105 (2014); 10.1063/1.4869758

[Stable electron emission from BCN/carbon nanotube field emitter\(s\)](#)

J. Vac. Sci. Technol. B **27**, 744 (2009); 10.1116/1.3093893

[La B 6 tip-modified multiwalled carbon nanotube as high quality field emission electron source](#)

Appl. Phys. Lett. **89**, 203112 (2006); 10.1063/1.2388862

[Transistor characteristics of thermal chemical vapor deposition carbon nanotubes field emission triode](#)

J. Vac. Sci. Technol. B **23**, 868 (2005); 10.1116/1.1864062

PFEIFFER VACUUM

VACUUM SOLUTIONS FROM A SINGLE SOURCE

Pfeiffer Vacuum stands for innovative and custom vacuum solutions worldwide, technological perfection, competent advice and reliable service.

Real-time implementation of the “orthodoxy test” for conformity of current–voltage characteristics with classical field electron emission theory

Anatoly G. Kolosko

A. F. Ioffe Physico-Technical Institute, ul. Polytechnicheskaya 26, St. Petersburg 194021, Russia
and The Bonch-Bruевич St. Petersburg State University of Telecommunications, pr. Bolshhevikov 22,
St. Petersburg 193232, Russia

Sergey V. Filippov and Pavel A. Romanov

A. F. Ioffe Physico-Technical Institute, ul. Polytechnicheskaya 26, St. Petersburg 194021, Russia

Eugeni O. Popov^{a)}

A. F. Ioffe Physico-Technical Institute, ul. Polytechnicheskaya 26, St. Petersburg 194021, Russia
and Peter the Great St. Petersburg Polytechnical University, ul. Polytechnicheskaya 29,
St. Petersburg 195251, Russia

Richard G. Forbes^{b)}

Advanced Technology Institute and Department of Electrical and Electronic Engineering,
University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

(Received 18 December 2015; accepted 4 April 2016; published 15 April 2016)

An experimental apparatus and a LabView-based software suite were developed to conduct real-time research on field electron emission. The authors observed and analyzed the current–voltage characteristics of emitters based on carbon nanotube/polystyrene nanocomposites. A simple quantitative test was used to compare such characteristics with the classical field electron emission theory. © 2016 American Vacuum Society. [<http://dx.doi.org/10.1116/1.4946834>]

I. BACKGROUND

A. General introduction

Large-area (multitip) field electron emitter arrays (LAFEs) have many uses as large-area electron sources.^{1–4} The quality and performance of LAFE depend on the nature, structure, and properties of the emitting materials. There is ongoing research to develop better emitting materials and characterize operating behavior. The most common characterization technique involves measuring LAFE current–voltage $I_m(V_m)$ characteristics (IVCs) in a parallel-plate configuration with the LAFE coated onto the cathode plate. Then, the IVCs can be sampled and recorded, and analyzed using Fowler–Nordheim (FN) plots.

An important characterization parameter is a physical *characteristic macroscopic field enhancement factor* (FEF) denoted in this paper by γ_C . This is often defined using the formula

$$\gamma_C = F_C/F_M \approx F_C d_{\text{sep}}/V_p. \quad (1)$$

Here, the *characteristic barrier field* F_C is a local surface field at one of the strongly emitting sites (usually thought of as the apex field for a relevant individual emitter). The *macroscopic field* F_M is the field between the plates that would exist in the absence of the emitting protrusions, and is given by V_p/d_{sep} , where V_p is the voltage between the plates, and d_{sep} is the separation of their inner surfaces.

In recent literature, the typical FN plot has been a plot of $\ln\{J_m/F_A^2\}$ against $1/F_A$, where F_A is the *apparent macroscopic field*, given by $F_A = V_m/d_{\text{sep}}$. J_m is the *macroscopic*

current density given by $J_m = I_m/A_m$, where A_m is the LAFE’s *macroscopic area* or “footprint.” From this plot, the slope can be characterized by what is called the *apparent* FEF β^{app} , by using the formula

$$\beta^{\text{app}} = -b\phi^{3/2}/S^{\text{fit}}, \quad (2)$$

where b is the second FN constant ($\approx 6.831 \text{ eV}^{-3/2} \text{ V nm}^{-1}$), ϕ is the local work-function, and S^{fit} is the slope of the straight line fitted to the FN plot.

The slope characterization parameter β^{app} is **not** always equal to the characteristic macroscopic FEF γ_C . Rather, the relationship between these parameters should be expressed as

$$\gamma_C = \sigma_t \beta^{\text{app}}, \quad (3)$$

where σ_t is an appropriate *slope correction factor*.

An emission situation (including the electrical operating or measurement circuit) can be described as *formally well-behaved* if there are no complicating effects. Such effects could be due to field-dependent changes in emitter geometry or to series or parallel resistance in the electrical circuit. It is assumed that the only parameters in the FN-type equation that vary significantly with the measured voltage are the voltage itself (and/or exactly proportional field values) and the barrier-form correction factor.⁵ In particular, if emission is formally well-behaved, then $V_m = V_p$ and $F_A = F_M$.

For a formally well-behaved emission situation, the value of σ_t depends on the form (i.e., shape) assumed for the tunneling barrier. The so-called *elementary* data-analysis method, often used in recent literature, assumes that the barrier is exactly triangular (ET). The resulting FEF estimate γ_C^{elem} is found by taking $\sigma_t = 1$, which yields

^{a)}Electronic mail: e.popov@mail.ioffe.ru

^{b)}Electronic mail: r.forbes@surrey.ac.uk

$$\gamma_C^{\text{elem}} = \beta^{\text{app}} = -b\phi^{3/2}/S^{\text{fit}}. \quad (4)$$

In contrast, so-called *orthodox* methods assume that the tunneling barrier is a Schottky–Nordheim (SN) barrier, which results in a FEF estimate γ_C^{orth} of

$$\gamma_C^{\text{orth}} = s_t \beta^{\text{app}} \approx 0.95 \beta^{\text{app}} = -0.95b\phi^{3/2}/S^{\text{fit}}, \quad (5)$$

where s_t is the appropriate value (called the *fitting value*) of a special mathematical function s sometimes called the *slope correction function for the SN barrier*. The approximation $s_t \approx 0.95$ is usually considered adequate for technological purposes. The discrepancy of 5% between γ_C^{orth} and γ_C^{elem} is insignificant for most technological purposes, although it does mean that there is no scientific justification for giving values of γ_C^{elem} to a precision involving more than two significant figures.

When the emission situation is formally well-behaved, then estimates of formal emission area can also be made, using either the elementary method or an orthodox method. However, in this case, the elementary and orthodox estimates typically differ by a large factor.⁵ Thus, it is important to choose the correct form for the tunneling barrier when calculating formal-area values.

Fowler and Nordheim⁶ believed that barrier rounding by image forces would not be a significant effect, and calculations by Nordheim supported this view.⁷ However, studies conducted by Burgess *et al.*⁸ and Murphy and Good⁹ in the 1950s detected mistakes in Nordheim’s mathematics and showed that the assumption about barrier rounding was not physically justified. Since then, most theoreticians working in field electron emission have assumed that the SN barrier should be a better model than the ET barrier, certainly in the metal-type FN theory normally used in FN-plot analysis. The situation where the emission is formally well behaved *and* it is adequate to assume that emission takes place through an SN barrier has been called the *orthodox emission situation*.

B. “Orthodoxy test”

In reality, practical emission situations are often **not** formally well-behaved, and are referred to as *nonorthodox*. There are various possible reasons for the occurrence of non-orthodox emission situations, the most common being the presence of series resistance in the conduction path from the high-voltage generator to the emitting regions at emitter apices.

When the emission situation is nonorthodox, application of either formula (3) or formula (4) leads to spurious results, which usually take the form of spuriously large FEF estimates. These spuriously large FEF values, when reported in the literature, are misleading for technologists attempting to assess the relative merits of different emitter materials, particularly for those with limited field emission experience.

In a previous work,¹⁰ a test has been developed for detecting nonorthodox behavior. This test uses the parameter *scaled barrier field* f defined by

$$f = F_C/F_R = c^2\phi^{-2}F_C, \quad (6)$$

where F_R is the *reference field* at which the top of a SN barrier of zero-field height equal to the local work-function gets pulled below the Fermi level; for $\phi = 4.5$ eV, $F_R = 14.1$ V/nm. The condition $f = 1$ corresponds to the situation where, as the field increases at 0 K, Fermi level electrons begin to escape over the top of the barrier, rather than through it.

The orthodoxy test is currently set up as an easy-to-use spreadsheet that can be downloaded from the Royal Society of London website. The experimenter can manually enter FN-plot data from the emitters into this spreadsheet, in order to find the range of f -values that corresponds to the measured voltage range (or to the range of deduced apparent macroscopic fields), and a form of engineering triage test is then applied to this extracted range (see below).

The formula used in the spreadsheet, in the case of plots made using common logarithms, is

$$f^{\text{extr}} = \frac{-s_t \eta}{(\ln 10) \times S_{10}^{\text{fit}} \times (X^{-1})^{\text{expt}}}. \quad (7)$$

Here, X is the measured independent variable (normally V_m or F_A) that appears in the form X^{-1} on the horizontal axis of a FN plot; S_{10}^{fit} is the slope of the FN plot made against $1/X$, using common logarithms; and η is the dimensionless scaling parameter in the exponent of scaled forms of FN-type equations based on the SN barrier, with η given by

$$\eta = bc^2\phi^{-1/2} \approx 9.8362 (\phi/\text{eV})^{-1/2}, \quad (8)$$

where c is the Schottky constant.¹¹ For $\phi = 4.50$ eV, $\eta \approx 4.637$; in this case, $s_t \eta \approx 4.405$ and $s_t \eta / \ln 10 = 1.913$. η -values for other ϕ -values are shown in Table 2 of Ref. 3.

The outcome of this procedure is a range of extracted f -values $f_2 < f^{\text{extr}} < f_1$. For the orthodoxy test, this range is compared with a set of four defined f -values $\{f_{\text{lb}} < f_{\text{low}} < f_{\text{up}} < f_{\text{ub}}\}$. For $\phi = 4.50$ eV, the set is $\{0.10, 0.15, 0.45, 0.75\}$; sets for other work-function values can be deduced from Table 2 in Ref. 3.

The orthodoxy-test criteria are: (1) if the extracted range $f_2|f_1$ lies totally within the range $f_{\text{low}}|f_{\text{up}}$, then the emission is deemed orthodox, and extracted FEF values can be considered reliable (this is a “green result”); (2) if $f_2 < f_{\text{lb}}$, or $f_1 > f_{\text{ub}}$, or both, then the emission is deemed clearly nonorthodox, and the extracted FEF values are almost certainly spurious (this is a “red result”); if the range $f_2|f_1$ lies inside the range $f_{\text{lb}}|f_{\text{ub}}$, but part of the range $f_2|f_1$ lies outside the range $f_{\text{low}}|f_{\text{up}}$, then the test is not decisive and further investigation is required, but it is possible or probable that the extracted FEF values may be unreliable (this is an “orange result”).

II. PRACTICAL DETAILS

A. Computerized data processing

In recent years, the A. F. Ioffe Institute field electron emission group in St. Petersburg has developed a relevant experimental apparatus and a LabView-based software suite

for real-time control and analysis of emitter behavior.¹² IVC analysis results include calculated values for the apparent macroscopic FEF β^{app} and estimation of the number of emission sites. The suite can also construct slope-intercept diagrams based on large sets of FN plots. The system also records real-time variations in partial pressures of volatile substances present in the vacuum volume. For continuity with this previous work, the symbol “ U ” will be used in Secs. II–III to denote the measured voltage, denoted in Sec. IA, by “ V_m .”

Two power supply modes are available: a “fast” mode, in which the IVC is recorded within 20 ms, and a “slow” mode, in which IVC is recorded within a time interval greater than 5 s (set by the experimenter). In the fast mode, a voltage pulse with a time profile (i.e., “shape”) is applied to the emitter, as shown in Fig. 1(a). The shape of the resulting current pulse also is shown in Fig. 1(a). The results of such a scan are digitized and stored, to allow detailed analysis. The corresponding complete current–voltage characteristic (IVC), which runs from low values $\{I_{\min}, U_{\min}\}$ to high values $\{I_{\max}, U_{\max}\}$ is shown as a direct plot in Fig. 1(b) and as an $I(U)$ –form FN plot in Fig. 1(c).

The fast-mode pulses can be repeated regularly in order to obtain samples related to time-dependent changes in the emitter. Some of our experiments are deliberately run under “industrial vacuum conditions” of the type that LAFE-type devices might be expected to encounter in practice. In such conditions, the dynamics of surface adsorption, diffusion, and desorption processes (and conceivably emitter erosion) might be expected to affect emission characteristics.

This paper reports on a recent addition to the software suite, which has been an option to apply the orthodoxy test described above, in real time, to the FN plot derived from a single pulse. To do this, we combined Eqs. (7) and (8) into the customized formula

$$f_n = \frac{-9.34}{(U_n^{-1})^{\text{expt}} \times (\ln 10) \times S_{10}^{\text{fit}} \times (\phi/\text{eV})^{1/2}}. \quad (9)$$

We then used this formula to extract the values f_2 and f_1 that correspond to a chosen range in the current–voltage characteristics stretching from the low values $\{I_2, U_2\}$ to the high values $\{I_1, U_1\}$, applied the orthodoxy test, and arranged for results to be reported to the suite’s display screen. The value of S_{10}^{fit} is determined by linear regression on the data points in the chosen range. The display includes a qualitative indicator of test results, as shown in Fig. 2.

The software suite also contains options for two types of special analysis of IVC shown on Fig. 1(a). To calculate the slope (S_{10}^{fit}), different intervals of the plot in the FN coordinates are taken [Fig. 1(c)], either from $U_{\min}$ to $U_{\max}$ or backward from $U_{\max}$ to $U_{\min}$ (actual threshold levels). Thus, we consider two types of dependences that are conditionally referred to as “low-voltage range” type (“LVR”) or “high-voltage range” type (“HVR”). For LVR-type, U_1 is varied from $U_{\min}$ to $U_{\max}$ while U_2 is kept constant at $U_{\min}$. For HVR-type, U_2 is varied from $U_{\max}$ to $U_{\min}$ while keeping U_1 constant at $U_{\max}$. Thus, a S_{10}^{fit} value was obtained for each

FIG. 1. (Color online) Current–voltage dependences obtained in fast power supply mode: (a) time profiles of voltage and current pulses; (b) corresponding direct IVC; and (c) IVC in FN coordinates. On the vertical axis of (c), the units of I/U^2 are A/V^2 .

small change in current. Some investigations of type LVR are discussed in Sec. III.

In spite of the fact that a single pulse to current and voltage is processed this way (one time realization of current and voltage), an unlimited number of such dependences can be observed. Our method is principally focused on repeatability of IVC characteristics. For this purpose, dependences were calculated approximately once a second (shown in Figs. 3–5). Accordingly, these dependences were obtained in a slow mode of scanning by high voltage right after scanning pulses stopped.

Fig. 2. (Color online) Interface of the Labview-based software that shows the outputs of the orthodoxy test.

B. Preparation of samples

Two types of nanocomposite emitters were studied: single-walled carbon nanotubes embedded in polystyrene (SWCNT/PS emitters) and multiwalled carbon nanotubes embedded in polystyrene (MWCNT/PS). Field electron emitters of these types yield good emission currents¹³ and are potential candidates for use as electron sources in various applications, including medical and industrial x-ray devices, and cold cathodes for microwave electronics and for ionization gauges. Our emitters were prepared using suspensions of polystyrene and carbon nanotubes (CNTs). Three stages were involved: (1) formulation of a solution of polystyrene in orthoxylene; (2) creation of a suspension of CNTs in orthoxylene by treatment in an ultrasonic bath; (3) mixing the liquids, and then many hours of treatment to increase the uniformity of the CNT distribution. After this, the suspension was applied by spin-coating onto a polished stainless steel substrate (diameter 10 mm). The concentration of CNTs in the polystyrene matrix of the nanocomposite was 10% by weight.

The single-walled CNTs had lengths up to 10 μm and diameters of $\sim 2\text{ nm}$ (OCSiAl production). The multiwalled carbon nanotubes were up to 10 μm in length, with diameters of $\sim 19\text{ nm}$ (Samsung production). Other details related to depositing an emitter film on a substrate, and experimental details of IVC measurement, were performed as described by Kolosko *et al.*¹⁴

Fig. 3. (Color online) Calculated dependences for a fast scan on the nanocomposite SWCNT/PS emitter: parameters f_1 and f_2 on the current range, for an LVR-type scan. The emission-current pulse amplitude was 1 mA. On the vertical axis of (b), the units of I/U^2 are A/V^2 .

Fig. 4. (Color online) Calculated dependences for a fast scan on the nanocomposite MWCNT/PS emitter: parameters f_1 and f_2 on the current range, for an LVR-type scan. The emission-current pulse amplitude was 1 mA.

Fig. 5. (Color online) Calculated dependences for a high-pulse-current fast scan on a MWCNT/PS nanocomposite emitter. (a) Dependences of the parameters f_1 and f_2 on the current range, for an LVR-type scan. (b) FN plot for complete current range. The emission-current pulse amplitude was 10 mA. On the vertical axis of (b), the units of I/U^2 are A/V^2 .

III. RESULTS AND DISCUSSION

The orthodoxy test is relatively new, so the test’s overall reliability, as well as the best way to apply it to achieve reliable results, is still under investigation. Preliminary experiments showed that changes in the voltage (and emission-current) ranges, U_2 to U_1 (and hence I_2 to I_1), involved in making the FN plot, may affect the value of the fitted slope S_{10}^{fit} . This in turn influences the extracted values f_1 and f_2 , and would also influence the extracted apparent FEF value β^{app} . In this section, we first report some experiments made to explore and illustrate this effect, and then compare results obtained from fast and slow scans.

A. Fast scans on SWCNT-based samples

The first sample used was a SWCNT/PS emitter. The sample area A_M was 0.78 cm^2 , the plate separation d_{sep} was $300 \mu\text{m}$, and the sample work function was assumed to be 4.5 eV . The amplitude (maximum value) of the scanning voltage pulses was set at $\sim 1.7 \text{ kV}$. The amplitude (maximum value) of corresponding emission current pulses was $\sim 1 \text{ mA}$,

and thus, the current data range $I_{min}|I_{max}$ was taken as about $1 \mu\text{A}|1 \text{ mA}$.

Results corresponding to an analysis of type LVR, as described in Sec. II, are shown in Fig. 3. In the analysis, U_2 and I_2 were held constant at U_{min} and I_{min} , respectively, so the only reason for U_1 -dependent (or I_1 -dependent) changes in f_2 is a change in fitted slope as U_1 increases. A change in fitted slope could, in principle, be because the “true physical FN plot” is not actually a straight line (hence, sampling a small part of it at one end may be expected to give a different result from samples taken over a wider range in voltage). Alternatively, and more likely, a change in fitted slope may arise from “noise” in the data points. In this case, we would expect the slope value (and hence the derived f_2 -value) to stabilize as U_1 and I_1 increase. In Fig. 1, f_2 shows an initial small increase and then stabilizes. Figure 1(c) clearly shows noise in the data points near I_{min} , making the observed behavior of f_2 compatible with the “data-point-noise” explanation presented above.

In orthodox theory, the parameter f functions as a scaled voltage as well as a scaled barrier field.¹⁰ Thus, if the emission situation is orthodox, one expects a plot of I_1 vs f_1 to have the same general shape as the plot of I vs U shown in Fig. 1(b). As the upper “ f_1 ” curve in Fig. 3(a) is a plot of f_1 against I_1 , it ought to have the same shape as the curve in Fig. 1(b), when this curve is reflected about a line at 45% to the horizontal axis. This appears to be the case. For all values of I_1 , the range $f_2|f_1$ is within the “green” range of values $0.15|0.45$. Hence, one concludes that the emission situation is orthodox.

B. Fast scans on MWCNT-based samples

Figure 4 shows results relating to a LVR-type analysis on data taken from a MWCNT/PS sample. As before, the sample area A_M was 0.78 cm^2 , the plate separation d_{sep} was $300 \mu\text{m}$, and the sample work function was assumed to be 4.5 eV . Other conditions were as described for the SWCNT/PS emitter above. The related FN plot is shown in Fig. 1(c).

In general, the behaviors of the parameters f_1 and f_2 are the same as before, and they do not exceed the “orthodoxy” limits $0.15|0.45$. This indicates good consistency of emission characteristics with orthodox classical FN theory for both single- and multiwalled emitters. However, the values of the parameters f_1 and f_2 in Fig. 4 are less than in Fig. 3. This is related to a higher FN plot slope in this case, related to the fact that the characteristic FEF for the MWCNT/PS sample ($\gamma_C = 850$) is less than that for the SWCNT/PS sample ($\gamma_C = 1300$), because of a difference in nanotube radius.

C. Fast scans at higher current levels

Scans taken on a MWCNT/PS sample using a sufficiently high pulse-amplitude of emission current (I_{max} about 10 mA) showed significant differences in behavior, as compared with the lower-current regimes discussed above. Figure 5(a) shows that, instead of stabilizing, the value of f_2 falls steadily as U_1 and I_1 increase. This indicates that the magnitude

$|S_{10}^{\text{fit}}|$ of the slope fitted by regression over the relevant low-voltage range is steadily increasing.

Figure 5(b) shows that, in the midpart of the range, the magnitude of the *local slope* (i.e., the tangent to the FN plot) is actually decreasing slightly as U_1 and I_1 increase. Hence, the observed effect [and also the observed shape of the f_1 -plot in Fig. 5(a)] is mainly attributed to the effect (on the regression analysis) of the data-point noise visible at the low-current end of this plot. The absolute values of the parameters f_1 and f_2 lie in the “orthodox emission” range 0.15|0.45. In general, SWCNT/PS- and MWCNT/PS-type emitters meet this compliance criterion when operating at high emission currents (i.e., up to 10 mA) and high current densities (up to 13 mA/cm², i.e., 130 A/m²).

D. Slow regime of power supply

To ensure the correct application of the test, we compared the different modes of high-voltage power supply. The shape of the scanning voltage in the slow mode is shown in Fig. 6(a). The selected amplitude of the voltage was approximately the same as for the fast mode ($I_{\text{max}} \sim 1$ mA). It is interesting that the dependences of f_1 and f_2 are similar to those that were obtained for emitters operating in fast mode at large emission currents ($I_{\text{max}} \sim 10$ mA). However, in slow mode parameters f_1 and f_2 have more complicated dependences even at small emission currents, and data no longer meet the orthodoxy criteria at the low end of the currency range [Fig. 6(b)], or processed currents are too large.

IV. SUMMARY AND CONCLUSIONS

A recently devised orthodoxy test was implemented as part of a software suite for real-time analysis of field electron emitter behavior. The technique was used to investigate the behavior of two forms of nanocomposite emitter (SWCNT/PS and MWCNT/PS emitters).

The original test (as reported in Ref. 10) allowed only a single pair of f -values to be extracted from the experimental data, with these values corresponding to the high and low ends of the experimental data range. In our software implementation, the context of the test was extended to be applied to a low-voltage range selected from a given set of stored FN-plot data, and/or to a high-voltage range selected from the data. Further, the software can present results for the f -values corresponding to the range limits, as the high end of the low-voltage range is extended to higher values, or as the low end of the high-voltage range is extended to lower values. Our thinking has been that these capabilities will prove useful in investigating: (1) the effects of data noise and any other artifacts; and (2) FN plots from emitters where only a portion of the data-range conforms to orthodox classical FN theory.

This paper has reported some preliminary investigations of effects occurring in the low-voltage-range type of analysis. In all cases, for the nanocomposite emitters chosen, the derived f -values have been within the range expected if the emitters conform to orthodox classical FN theory. This is a useful result in itself and appears to indicate that these

Fig. 6. (Color online) Dependences of parameter f on I_{max} and I_{min} , and corresponding FN plot for emission current range 1.4 mA in DC (slow) mode (PS-MWCNT, Samsung): (a) time profiles of voltage and current pulses; (b) dependences of the parameters f_1 and f_2 on the current range, for an LVR-type scan; (c) FN plot for complete current range. On the vertical axis of (c), the units of I/U^2 are A/V².

emitters are reasonably good conductors. However, we also observed that noise in the data at the low-current end of the FN plot can influence the shapes of the curves that show how the extracted values of f_1 and f_2 depend on the chosen upper point of the low-voltage range. This investigation is ongoing, but a provisional conclusion is that, when extracting f -values, a “sufficiently large” range of values of the FN-plot should be used, and possibly that any low-current data points that are obviously “particularly noisy” should be

excluded. The issue of how best to define sufficiently large is part of the ongoing investigation.

ACKNOWLEDGMENT

S. Filippov thanks the (Russian) Foundation for giving assistance to Small Innovative Enterprises in Science and Technology (No. 0015113) for partially supporting this project.

¹N. V. Egorov and E. P. Sheshin, *Field Emission: Principles and Instruments* (Intellekt, Dolgoprudnyi, 2011), p. 704 (in Russian).

²*Vacuum Microelectronics*, edited by W. Zhu (Wiley, New York, 2001), p. 396.

³A. Evtukh, H. L. Hartnagel, O. Yilmazoglu, H. Mimura, and D. Pavlidis, *Vacuum Nanoelectronic Devices: Novel Electron Sources and Applications* (Wiley, Chichester, 2015), p. 472.

⁴M. T. Cole, M. Mann, K. B. K. Teo, and W. I. Milne, “Engineered carbon nanotube field emission devices,” in *Emerging Nanotechnologies for Manufacturing*, edited by W. Ahmed and J. M. Jackson (Elsevier, Amsterdam, 2015), Chap. 5, pp. 125–186.

⁵R. G. Forbes, *Int. Vac. Nanoelectron. Conf.* **2015**, 70.

⁶R. H. Fowler and L. Nordheim, *Proc. R. Soc. London, A* **119**, 173 (1928).

⁷L. W. Nordheim, *Proc. R. Soc. London, A* **121**, 626 (1928).

⁸R. E. Burgess, H. Kroemer, and J. M. Houston, *Phys. Rev.* **90**, 515 (1953).

⁹E. L. Murphy and R. H. Good, *Phys. Rev.* **102**, 1464 (1956).

¹⁰R. G. Forbes, *Proc. R. Soc., A* **469**, 20130271 (2013).

¹¹R. G. Forbes and J. H. B. Deane, *Proc. R. Soc. London, A* **467**, 2927 (2011). For constants, see electronic supplementary material.

¹²E. O. Popov, A. G. Kolosko, M. V. Ershov, and S. V. Filippov, *Int. Vac. Nanoelectron. Conf.* **2012**, 1.

¹³D. Leberl, B. Hensel, H. Kapitza, H. Zeininger, and S. F. Tedde, *J. Vac. Sci. Technol., B* **31**, 052204 (2013).

¹⁴A. G. Kolosko, M. V. Ershov, S. V. Filippov, and E. O. Popov, *Tech. Phys. Lett.* **39**, 484 (2013).