DOI: 10.17277/amt.2018.04.pp.031-037

Fluctuations of the Field Emission Current of Carbon Fibers

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Abstract

Fluctuation current is a factor that limits the functionality of virtually all electronic devices. Excess noise can be caused by parameter fluctuations, in nonlinear elements. Flicker noise has a spectrum of pink noise, so sometimes these two are considered synonymous. The *I–T* (*current–time*) characteristics of field emission current display trains of pulses with characteristics distribution, which appears to change unpredictably from one train to another. Sometimes a train will exhibit a totally random noise. The analysis of the behavior of the power spectrum and autocorrelation individual pulses indicates that the observed noise is due to diversity of processes, such as adsorption, flip-flop. For the first time, carbon fibers represent a field of electron emission source that can work in the pressure range found in commercially made tubes. The studies on carbon fibers have shown that they have the ability to become powerful sources of electrons for some technological and microscopy applications. Carbon tips also have found other applications. Carbon fibers have a diameter of 6 to 10 μm; they are thinner than a human hair.

Keywords

Fluctuations; auto emission; carbon fiber; flicker noise; instability of the field emission current.

Introduction

In studying the current-field fluctuations of field emission, there has been purely scientific interest [1, 2], as well as practical interest [3] in the development of field electron cathodes. The exponential dependence of the auto emission current on the opacity of the potential barrier, through which the electrons tunnel causes a strong dependence of the current fluctuations on the processes. This processes occurring on the surface of the cathode and in its near-surface regions gives a high sensitivity of the noise measurement method for surface investigation. Spectral characteristics, especially low-frequency fluctuations, carry information about the temporal and static parameters of electronic and adsorption-migration processes on the surface of auto-cathodes.

1. Flicker noise

The results of work on the field-emission fluctuations both in the low-frequency range and in the high-frequency range [4, 5] indicate that the types of the fluctuation process predominant on the surface of the autocathodes is a flicker noise with a characteristic dependence of the noise intensity W on the frequency f in the form

$$W \approx 1/f \,. \qquad (1)$$

However, there have been reports that in a number of cases, the field emission current of carbon materials fluctuations are purely physical in nature and are manifested in the form of pulsed current surges. Therefore, an attempt was made to reveal the nature of fluctuation processes observed in the selection of the field emission current from polyacrylonitrile carbon fibers.

In the course of the experiment, about 10^4 implementation was analyzed. The measurements showed that the registered implementations for the field-emission current fluctuations could be divided into five types according to the simplest configuration (Fig. 1).

The remaining forms of the fluctuations can be represented as the result of superimposing these

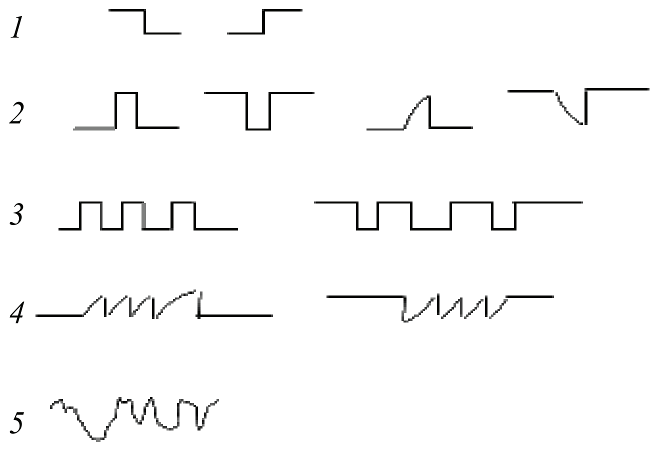

Fig. 1. Types of configurations of field-emission current fluctuations:
1 – jump-like current transfer to another level; *2* – impulse measurement of the current value; *3* – pulse generation with a constant amplitude and a relatively fast front; *4* – pulse generation with a relatively slow front; *5* – noise-like signal

configurations with different amplitude and time characteristics on each other. Fluctuations have a pronounced impulse character. In the current range 1–10 mA, the pulsed fluctuation forms are often resolved, and even at t = 100 s, individual pulses were detected on the realizations. When the current was increased to 1–10 μA, the $\sigma / \bar{I}$ value decreased, where σ is standard deviation, I is average value of the cathode. Disassembly of the values I, σ from realization to implementation became significantly smaller, and with increasing t_p, a noise-like signal was formed more often than in the case of low currents.

An increase in the current to 50 μA further reduced the relative magnitude of the fluctuations. When the autocathode current I_k = 10 μA, the value σ/I was 3–7, and when I_k = 50 μA it was of the order of 2–4, i.e. increasing current from 1 nA to 50 μA reduced the relative magnitude of fluctuations and reduced their amplitude dependence on time. With increasing current collection, the current stability of the investigated autocathodes in the LF and HF regions substantially increased. The analysis of the instantaneous fluctuations at t_p = 100 s showed a good approximation to the normal distribution. Measurement of the spectrum in the frequency band 10^{-2}–10^{-6} Hz showed that the geophysical spectrum of the process was close to 1/f.

The observations of pulsed lasing of type *3* (Fig. 1) generated by a single emission center showed that as the current increases, the average noise spectrum shifts to a higher frequency region, i.e. the average number of pulsed current switching per unit time increased with the increasing current. The truncation of the maximum interval between pulsed switching by three orders of magnitude with the increasing current from 1 nA to 10 μA confirms the observed phenomenon. At the same time, the projector showed that the number of emission centers in terms of the field emission pattern with the increasing current from 1 nA to 10 μA practically did not change. This allows us to conclude that with the increasing current the rate of fluctuation processes on the cathode surface increases. The increase in the process speed for the measurements of σ is analogous to the effect of increasing t_{mid}, which should lead to a decrease in the σ dependence on time if t_{mid} remains unchanged. Thus, the observed decrease in scatter is the result of a shift in the fluctuations of the emission regions and centers in the region of shorter times due to an increase in the rate of fluctuation processes on the cathode surface. An increase in the current from 1 nA to 10 μA also leads to an increase in the rate of pulse switching of emission centers with frontal times from 1 ms for currents of 1–10 nA and tens of nanoseconds and less for a current of 10 μA. The extremely short values of the fronts are not smoothed out.

Based on the results obtained, a model of the process in which the total current flowing through the cathode is represented as the sum of the currents of the independently fluctuating emission center is proposed. That fluctuation of field emission current causes the probability distribution of the field emission current probability to be close to normal. The increase in current increases the rate of fluctuation processes on the surface of the emission centers, which shifts the fluctuations of the field emission current into the region of shorter times, leading to a decrease in the amplitude dependence of the fluctuations on time.

2. Fluctuations in the current of field emission of carbon fibers

The control of the level of fluctuations in the process of controlling the background allows one to judge from the peculiarities of the spectra behavior about the physical nature of processes on the surface of the autocathodes, the speed and nature of its rearrangement.

For unformed cathodes, the fluctuation spectra are physically incorrect according to this technique, since with the first inclusions of such autocathodes their surface changes rapidly, i.e. the process of selection is essentially non-stationary. When these cathodes are formed, the surface becomes more stable and the level of fluctuations in the emission current becomes much

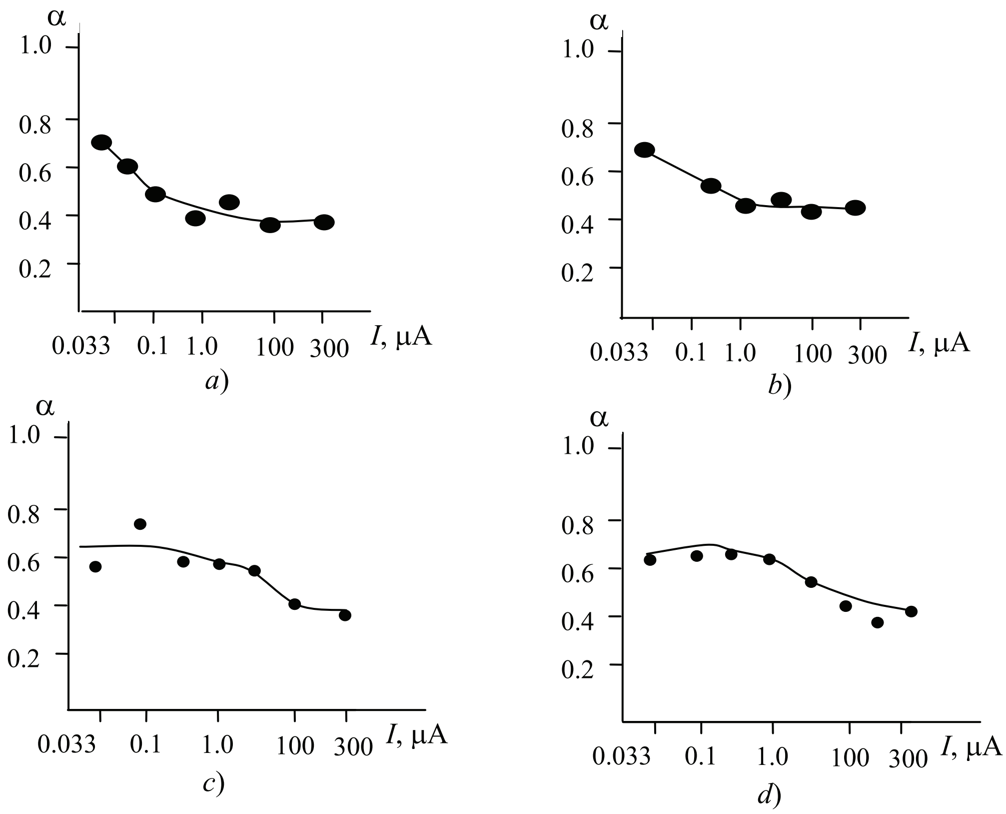

Fig. 2. Experimental dependence of the value of α on the average emission current for the dispersion estimates:
a, *b*, *c* – polyacrylonitrile fiber after linear molding with a duration of 80.60.30 min, respectively;
d – a bundle of polyacrylonitrile fibers after 2 hours of molding

lower. As shown by experiments, the successively taken spectra of instability of molded cathodes practically do not differ from each other.

The analysis of the fluctuations in the entire band reception measured currents with a minimum of 20 nA current to cathodes of carbon materials of different structures, namely, a single fiber type febrile HMB-RK with the annealing temperature 2000 °C, bundles of fibers of type BMH-4 an overall diameter of 100 microns. The anode-cathode distance was set visually at a level of 2 mm for cathodes of the same fibers and 0.2–0.5 mm for cathodes from the remaining materials. It was found that all the obtained spectra obey to the law $1/f_{gr}^{\infty}$. This law is similar to the frequency dependence of the spectral density of some low-frequency noise [4, 6].

Interesting physical results can be obtained by constructing the dependence of the exponent α on the average current. By knowing the dependence of the current level of instability on one of the frequencies, one can fully describe the spectra in the considered frequency range and the measurement times, without resorting to rather cumbersome graphs.

Thus, the information is double-compressed; in the first stage, when estimating the dispersion of a signal from 125 current values, one dispersion value is obtained, and in the second stage, from the frequency dependence of the dispersion estimates, we obtain, for example, its maximum value and exponent. Figure 2 presents the results of a similar processing of spectra for auto cathodes from different carbon fibers.

The inter-electric effect was detected in the analysis of noise by the method of the spectral density of the field emission current [7] for carbon fibers.

3. Mechanisms of instability of field emission current

When constructing models of noise processes accompanied by emission of cathode fieldwork, it is necessary to emphasize the role and conditions of physical phenomena, leading to fluctuations in the emission current. Such phenomena include electronic processes in the volume and on the surface of the cathode material (conduction fluctuations) of adsorption-mitral processes (fluctuations in the electronic work), as well as the destruction of the radiating surface by ponderomotive forces and ion bombardment (fluctuations of the form factor and the area of the radiating surface). Conductivity fluctuations in the cathode material are too small to cause any noticeable changes in the emission current. The resistance of a single fibril fiber used as cathodes does not exceed units of a kilo, as well as other materials, even less. At a current of 1 mA, the voltage drop on the fibril fiber (from the holder to the radiating surface) does not exceed 1 V, and its fluctuations are much smaller (at least 3 orders of magnitude). Consequently, the current-induced fluctuations of the "cathode-anode" current cannot lead to the observed current stability.

The presence of residual adsorbed gas atoms on the surface of the cathodes results in a change in function in comparison with the atomically clean surface. At the same time, carbon oxides, unlike metals are volatile. Consequently, the fluctuations in the work function must be less than, for example, the metal AEC. To obtain numerical estimates of this mechanism, a quasistatic model of explosive noise can be used. It is assumed that the emission current is equal to the sum of the currents of N weakly interacting centers, with which the current decreases exponentially with time. It is assumed that the "inclusion" moments are arbitrary points, and the relaxation time is distributed over a wide range of values for a specific surface of the law $g(\tau)$. It is shown that if the initial values for all existing emission centers are equal, regardless of the relative dispersion of the fluctuations, a simple expression is obtained

$$\sigma^2 = \frac{1}{2N}, \tag{2}$$

where N is the number of emitting centers.

The spectral power density of the fluctuations varies with frequency as $1/f$. The physical nature of the fluctuations, according to this model, is as follows. On the surface under the AEC adatoms, the film has a high technical vacuum, which, under the action of mechanical stresses, can be moved by an electric field and thereby cause oscillations in the function of work. The most probable value of the work function in this case is in the range 4–5 eV, that is, its fluctuations are no more than 10–15 %.

Close estimates of the number of emitting centers are given by another model of the explosive noise [7].

We denote the fluctuation in the work function of the output φ_0 as $\chi(\varphi)$, i.e.

$$\chi(\varphi) = \frac{\varphi}{\varphi_0} - 1. \tag{3}$$

Then the Fowler-Nordheim equation for graphite (φ = 4.7 eV) can be written in the following simplified form

$$I = \frac{A}{(1+x)} 10^{-B(1+x)^{3/2}}, \quad I_0 = A \cdot 10^{-B}, \tag{4}$$

where I_0 is the average current, $A = 3.28 \cdot 10^{-7} S\beta^2 U^2$, $B = 3.02 \cdot 10^8/\beta U$, S is the emission area in cm^2, β is the form factor (cm^{-1}), and U is the voltage in volts. Fluctuation of the current can be written in the form

$$\sigma(I) = \frac{I}{I_0} - 1 = (1-x)10^{-(3/2)Bx} - 1, \tag{5}$$

$$\sigma(I) = -x\left(1 + \frac{3}{2} B \ln 10\right) \tag{6}$$

for polyacrylonitrile carbon fiber after 80 min. Forming $\beta = 9.2 \cdot 10^4$ cm^{-1}, i.e. $B = 3.33 \cdot 10^3 / U$.

If U = 1 kV, $\sigma(I) = -13\chi$, and I_0 = 60 μA; U = = 630 V, $\sigma(I) = -19\chi$, and I_0 = 30 nA. Thus, the adsorption instability of the current caused by fluctuations in the work function is weakly dependent on the average current. If it changes by more than three orders of magnitude, the fluctuation level changes by a factor of 1.5, decreasing monotonically with increasing current.

The physical conditions in which there is a current volatility associated with the destruction of the emitting microprotrusions is as follows: 1) the ponderomotive loads on these micro-points are close to critical; 2) intensive ion bombardment accelerates the degradation of the cathode surface. The fact of participation in the release of more microprotrusions at the same time (N jokes) makes it easy to calculate that the current from each of them is the same and equal

$$I = \frac{I_0}{N}, \tag{7}$$

where I_0 is the total current of the cathode.

After the microprojection is turned on, its gradual destruction by ions and field begins, that is, the current from it should decrease with time. The death of microscopic can occur either because of its gradual shrinkage, or after the separation from the microcrystallite of the cathode it is formed. Then this leads to the formation and incorporation of a new microscopic into the work. Such an instability mechanism is associated with fluctuations in the microstructure surface, so you can enter the short name "microstructural instability" for it. With some approximation, this mechanism can be used for exchange, the same quantitative models as for the work of the fluctuation function.

The actual current fluctuations caused by changes in the work function and microprotrusion degradation naturally differ from the model, so the value of the coefficient a (α_φ and α_β, respectively) for each of these mechanisms will differ from each other. Thus, the change in the physical conditions on the surface accompanying the change in the average current from the cathode must be accompanied by a transition from one to the other of the values of α. This is clearly illustrated by the dependencies shown in Figure 3 (*1 – 2*) referring to the same material-fibril fiber, the values $\alpha = 0.38$ for them are identical at high currents, as well as $\alpha = 0.7$ at low currents. Thus, the clear physical meaning of the graphs in Fig. 3 has been revealed. They show some kind of physical mechanism that causes the instability problem at different current levels. In this transition region, the regions of predominance of each of the two mechanisms of instability are quantified.

As it is also shown on the graphs in Fig. 3, the threshold molding current is determined, at which the distribution completes the cathode skeleton structure and the microstructure regime becomes the fluctuation, i.e., the current threshold value corresponds to low-current boundary microstructural fluctuations. For example, it is possible to determine the threshold current for the formation of individual fibers and beams, such as 1 and 30 mA, respectively. Due to the increase in the rate of current rise during molding from 0.75 to 2 mA/min the threshold current from 1 to 10 mA increases. This increase in the threshold current of reduction during molding is natural because the degree of destruction of the radiating surface is determined not only by the time of the selected emission current.

Although this method measures not only the spectral density *S*, but the actual dispersion of the current, it is easy to obtain that *S* also depends on the frequency according to the law $1/f^{\infty}$:

$$S(f) = \frac{d}{df}\sigma^2 \approx \frac{d}{df}\left(\frac{1}{f^a}\right) \approx \frac{1}{f^{(a+1)}}. \quad (8)$$

That is $a = \alpha + 1$. The values of *a* made up 1.4–1.8 for the materials considered. From the analysis of the model used, it is possible to obtain another important physical inference in a wide range of currents (more than two orders of magnitude) when the voltage increases, the current increases in proportion to the number of emitting microprotrusions. As already mentioned,

$$\sigma^2 = \frac{1}{2N}, \text{ i. e. } N = \frac{1}{2a^2}. \quad (9)$$

Measurements of instability directly confirm that with more "soft" molding modes, the number of emitting microprotrusions increases (Fig. 3). Summarizing the above results, it can be concluded that the formation of autocathodes from fibril fibers results in the release of a large number of microprotrusions of the skeletal structure made of fibers; emitting area with the most "soft" molding is reduced to $8 \cdot 10^{-12}$ cm, and the number of workers reaches microprotrusions of 800 pieces, i.e. an area of one order of 100 A. Such dimensions may be characteristic for microprotrusions consisting of one fibril. The decrease in the coefficient γ for casting shows that it promotes the release of a microprojection having a more uniform distribution of the emission parameters. The study of the emission-current spectra of the instability can be summarized as follows. The instability has a frequency dependence of the widespread type $1/f^{\infty}$ caused by two main causes – for small currents this oscillation of the work function is weakly dependent on the average current value.

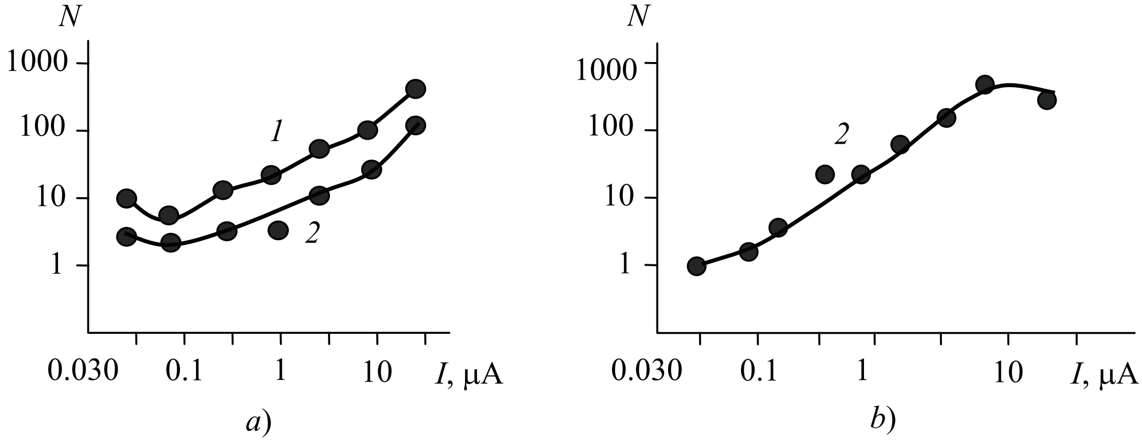

Fig. 3. Dependence of the emissivity of the emitting centers on the average current:
a – fibril fiber: *1* – after molding 80 min; *2* – after forming 30 min; *b* – bundle of fibers

At high currents, these are fluctuations in the microstructure of the emitting surface, caused by ponderomotive loads and ion bombardment. This process is characterized by a rapid decrease in instability with increasing current for AEC from the studied carbon materials. Quantitatively, the regions of predominance of each current growth are associated with an almost proportional increase in the number of emission centers. It has been experimentally proved that in the process of forming an increase in the number of microprotrusions close to the emission parameters and a decrease in the current instability level occur.

4. Methods for reducing the fluctuation of the emission current

Stability of field emission current, in particular, fluctuations in the emission current, is one of the main problems in the practical use of autocathodes. This problem is common for auto cathodes from any materials, rather than how many auto-cathodes of carbon materials.

Stability of field emission current, all other things being equal, depends on the vacuum conditions. Thus, it is shown that at a pressure of the residual gases about 10^{14} mm Hg. the lifetime of even a tungsten tip is practically unlimited [8]. Under ordinary vacuum conditions $p \approx 10^{6}–10^{7}$ mm Hg, autoemitters adsorb residual gases and are bombarded by positive ions, which increases the change in the work function of the electrons. The simplest way to reduce the fluctuations of the field emission current is to heat the autocathode [9]; thermal desorption of molecules of residual gases. Such heating can be carried out both in the regime of constant heating [10] and in the regime of pulsed heating [11].

The opposite method is deep cooling (at least to the temperature of liquid nitrogen). However, this method leads to significant complications in the design of the device and its operation, which makes sense only for expensive and unique devices.

For some types, more stability of the electron beam and a smaller value of current fluctuations can be obtained if the anode surface, which is bombarded with electrons by the material, for example, by zirconium, titanium, thorium, barium [12]. Prior to the operation of the electron gun with the autocathode, they are evacuated to an ultrahigh vacuum 10^{-8}–10^{-9} mm Hg. After that, the anode is heated to a temperature of 1070 K for continuous evacuation.

At the same time, the molecules of the residual gas adsorbed on the anode surface evaporate, the anode surface is degassed, and the getter is activated.

After degassing, a very small number of molecules are desorbed from the surface of the anode under the action of electron bombardment from the autocathode since these molecules are bound by the getter. Moreover, the molecules of the residual gas are strongly absorbed by the activated getter. Thus, the auto-cathode is protected from ion bombardment and a stable electron beam is obtained.

For example, for large devices, such as electron microscopes, one of the options for reducing the parasitic desorption of molecules of residual gases is the use of a differential pumping system [13], in which the autocathode is located in a chamber with ultrahigh vacuum and the object of the action of the electron beam is at a relatively low vacuum (10^{-6}–10^{-5} mm Hg). These chambers are separated by a sufficiently small aperture with a holes (≈ 0.5 mm), sufficient to pass the electron beam and maintain the desired pressure difference.

Another method of reducing the ion bombardment of the working surface of the autocathode involves creating submicron gaps of the anode-cathode [14] to reduce the operating voltage to ≈10 V, i.e. to lower ionization potential of residual gas molecules. However, in the case of autocathodes made of carbon materials, this method (for all its attractiveness) is associated with significant technological difficulties not overcome by now.

The next large group of methods for reducing the fluctuations of field emission current is the use of various electronic circuits.

A simple and sometimes used method is the continuous heating of the cathode, however, for sufficiently effective desorption of the residual gases, sufficiently large temperatures are required, which significantly reduces the dignity of the cathode. If heating is necessary, pulse heating is more appropriate [15]. The period of the pulses is determined by the degree of vacuum in the device and the operating conditions, but is usually made up to ≈ 10 s. The pulse width depends on the heating temperature. Temperature fluctuations lie in the range of 420–1270 K. Temperature less than 420 K does not very well clean the surface of the cathode. The most promising of this kind of mode can be for devices of raster type, where the time of the backstroke of the beam coincides with the time of cleaning the cathode.

Results

The *I–T* characteristics of carbon fibers were taken for subject and independent measurements with the power unit (Fig. 4). It can be seen that some of its

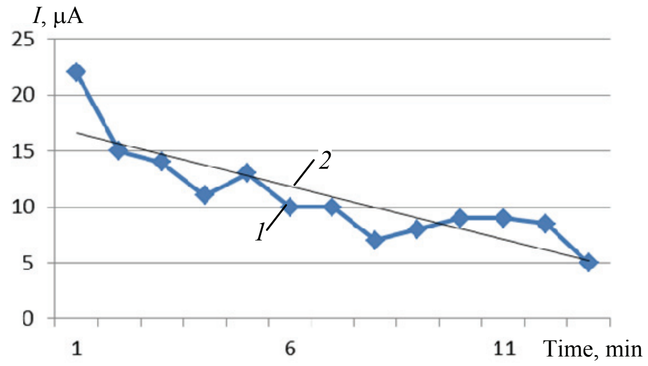

Fig. 4. ***I–t* characteristics of carbon fibers:**
1 – *I* & *T*; *2* – linear *I* & *T*

graph is low and after a while, the current rises. *F–N* are built on the basis of average current values, as current tends to increase/decrease for a long time of this experiment. In Fig. 4, a variety of *I–t* characteristics of the electron emission field from carbon fiber is shown.

A striking observation is that fluctuations occur in phases of current with a characteristic distribution that appears on the form for changing one phase to another. Somewhere a certain current pulse will be displayed in 25 to 65 minutes, despite the fact that the situation may vary depending on the state of the sample.

Conclusion

Flicker noise was caused by fluctuations in radio communication parameters; one can observe when a voltage is applied to an element, or by passing a current through it. Flicker noise appears most noticeably at low frequencies. The original exploratory work was carried out on fibers that were heat treated only at 500 °C. These results were very promising; however, since their origin was unknown, further work was carried out on clearly defined fibers. However, it is worth noting that pink noise is an exclusively mathematical model, and flicker noise is a real hindrance, therefore it is impossible to identify these two concepts. If it is necessary to set the relaxation time, the characteristic of quasistationary τ is the process of measuring the statistical averaging of their noise characteristics was enough to spend a certain time much more than τ. Fluctuation current sometimes flows just as straight as, but it always flows as shown in Fig. 4.

References

1. Aldert Van Der Ziel Noise: Sources, Characterization, Measurement. Englewood Cliffs (New Jersey): Prentice-Hall, 1970.

2. Bahtizin R.Z., Goc S. S. Vzryvnoj shum v avtojemissiionnyh priborah [Explosive noise in autoemission instruments]. *Radiotehnika i jelektronika*. 1981, Vol. XXYI, Issue 11, pp.2390-237. (Rus)

3. Carev B.M. *Raschet i konstruirovanie jelektronnyh lamp* [Calculation and design of electron tubes]. M.; Jenergija, 1967. (Rus)

4. Makuha V.I., Romanov A.D., Tishin E.A. Fliker-shum avtojelektronnogo toka katoda iz grafita [Flicker-noise of field-current cathode from graphite]. *Fizicheskie processy v priborah jelektronnyj tehniki*. M.; MFTI, 1980, pp. 19-20. (Rus)

5. Romanov A.D, Makukha V.I., Tishin E.A. Noise of the field-current current of the Siberian Crustacean cathode from graphite. *Proceedings of the reports of the XVIII All-Union Conference on Emission Electronics*. M.; Science, 1981, p.215. (Rus)

6. Kogan Sh. M. Nizkochastotnyj tokovyj shum so spektral'noj plotnost'ju v tverdyh telah [Low-frequency current noise with spectral density in solids]. *Uspehi fizicheskih nauk*, 1989, Vol. 145, Is. 2, pp. 285-328. (Rus)

7. Romanov A.D., Kirillov V.P., Tishin E.A. Vzryvnoj shum avtojemissiionnogo toka [Explosive noise of field emission current]. *Trudy MFTI; Ser. Radiotehnika i jelektronika*, 1975, Is. 10, pp.139-141. (Rus)

8. Swan D. J., Smith K. C. A. Lifetime and noise characteri of tungsten field emitters. *Proc. of the 6th Annual Scanning Electron Microscope Symposium*. 1973, pp.41.

9. Yamamoto S., Hosoki S., Fukuhara M. Stability of carbon field emission current. *Surf. Sci*. 1979, Vol. 86, pp. 734-742.

10. Osipov N.I. Avtojemissionnye katody iz uglerodnyh volokon [Autoemission cathodes form carbon fibers]. *Tezisy dokladov XII Vsesojuznoj konferencii po jelektronnoj mikroskopii*. M.; Nauka, 1982, pp. 57. (Rus)

11. Swan D.J. *Investigation relating to the applications of the field emissions cathodes*. Downing college, Cambridge, 1971.

12. Patent 4337422 USA Cl. 315/383. *Field emission electron gun*. Sakitani.

13. Patent 3881125 USA. *Separable-chamber electron beam tube including means for puncturing*. Baker T.A., Balsiger M.M., Considine K.N., Litsjo N.E.

14. Djuzhev N.A., Mahov V. I. Raschet ionnoj bombardirovki avtokatoda [Calculation of the ion bombardment of the autocathode]. *Tezisy dokladov XX Vsesojuznoj konferencii po jemissionnoj jelektronike*, Kiev,1987, Vol.1, p.231. (Rus)

15. Patent 3786268 USA. *Electron gun device of field emission type*. Nomura S.