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Fundamental electrical noises and nondestructive testing of electronic devices

Boris I. Yakubovich, *Saint Petersburg Institute of Nuclear Physics, National Research Center Kurchatov Institute, Russia, Gatchina*

Борис И. Якубович

Abstract. Aim. *The research of potential wide applications of electrical noises in nondestructive testing of electronic devices and theoretic justification of their use for such purposes. To that effect, fundamental electrical noises are examined and the types of those that in principle can be used for nondestructive testing are analyzed.* **Methods.** *The article contains theoretical research finding regarding fluctuation processes behind several types of electrical noise and degradation processes in electronic devices. The connection between the spectral properties of the fluctuations with the characteristics of the degradation processes in electronic devices is analyzed. On this basis, conclusions are made regarding the opportunities of using electrical noises for non-destructive testing of electronic devices. Electrical fluctuation phenomena caused by capture and emission of charge carriers by traps created by structural defects in the solid body structure. The processes of capture and emission of charge carriers by traps are a fundamental cause of the following fundamental types of electrical noise: excess, generation-recombination and burst. Various types of noise significantly differ in terms of the parameters and statistical properties of fluctuation processes. That is the reason for the analysis of electrical fluctuations caused by traps in order to provide a sufficiently general description of such fluctuation phenomena. The work resulted in a rigorous description of the electrical fluctuations caused by traps. A general expression for the fluctuation spectrum was calculated. In special cases, from it we can pass to the spectrums of excess, generation-recombination and bursts noises. The findings regarding the electric fluctuations causes by traps can be used for identification of spectral properties of fluctuations in solid materials and solid-state electronic devices. A rigorous quantitative analysis was made of the degradation processes that occur in solid-state electronic devices in order to establish associations between the spectral characteristics of noises caused by capture and emission of charge carriers by structural defects with the degree of materials defectiveness in order to be able to better exploit the noises in the evaluation of the quality and dependability of electronic devices. It was established that the noise spectral density is associated with the degree and rate of the structure's degradation. Thus, noises in electronic devices contain information on the degree and rate of degradation. The following practical conclusions were made. The noise spectral density is associated with the number of defects in the device at the baseline, as well as the rate of defect formation and, consequently, the ageing rate of the electronic device. Therefore, noise contains information on the quality of the manufactured device and its characteristics change rate. Accordingly, the noise spectrum can be used in evaluation of an electronic device's deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation.* **Conclusions.** *The paper substantiates the potential wide applications of electrical noises in non-destructive testing of electronic devices, shows the feasibility of using fundamental types of electrical noises for the above purposes. The rigorous substantiation of the use of electrical noises for nondestructive testing of electronic devices, feasibility of evaluation of the devices' defects caused by various factors, use of common frequently prevailing types of noise, high sensitivity of fluctuation spectroscopy highlight the efficiency of electrical noise in nondestructive testing of electronic devices.*

Keywords: *noise, fluctuations, nondestructive testing, dependability, solid bodies, semiconductors, electronic devices.*

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Introduction

Electrical noises can be used in nondestructive testing of electronic devices. That is suggested by many experimental findings. A correlation between the noise characteristics and duration of no-failure operation has been found. Such correlation has been identified in many electronic devices manufactured with the use of various types of solid materials. An overview of the research in that area is given in [1, 2]. The presence of such correlation is attributed to the fact that the origins of a number of noise processes are due to the structural defects of solid materials [2-5]. An increased concentration of defects in a device's structural materials can indicate its potential undependability. There are also reasons to believe that low-frequency electrical noise may be due to degradation processes occurring in electronic devices [6-8]. The potential for using electrical noises for evaluation of defects in solid materials in devices and characterize degradation-related changes in electronic devices makes the noise spectroscopy a sufficiently universal method of nondestructive testing of electronics. The high sensitivity of fluctuation spectroscopy indicates the efficiency of such method.

Given the above, a wider application of noise spectroscopy in nondestructive testing of electronic devices and more rigorous substantiation of the applicability of electrical noises for those purposes are advisable. To that effect, let us examine the fundamental electrical noises, as those can be observed in a wide range of various objects, and analyze those types that in principle can be used in nondestructive testing. Among those are the low-frequency excess, generation-recombination and bursts noises. Low-frequency excess noise is a noise of which the spectral density changes according to the law $S(f)=1/f^{\alpha}$, where α is close to 1. The most significant theoretical model that explains this type of noise associates its origins with the capture and emission of charge carriers by traps created by structural defects in the solid body structure [3, 5]. The generation-recombination noise is caused by generation-recombination processes in semiconductors that in most cases go through centers of generation-recombination formed by structural defects [5, 9, 10]. The burst noise has the form of a random staircase signal and the most convincing explanation of its origins makes reference to the processes of capture and emission of charge carriers by traps under low frequencies of this process [5, 11]. Further, let us analyze the excess, generation-recombination and burst noises, provide a rigorous quantitative description of the underlying fluctuation processes and clarify the connections between the noise spectrums and the degradation processes in electronic devices for the purpose of exploring the potential for using fundamental electrical noises of those types in nondestructive testing of electronic devices.

Electrical noises

Electrical fluctuation phenomena caused by capture and emission of charge carriers by traps created by structural defects in the solid body structure. The processes of capture and emission of charge carriers by traps is the primary cause of excess, generation-recombination and burst noises. The nature of the noise caused by traps is largely defined by the type of the traps, their concentration, statistical properties of the processes of capture and emission of carriers by traps. The difference primarily in those indicators causes the different types of electrical noise that have the same source, i.e. the stochastic processes of capture and emission of charge carriers by traps. In the given situation, the fluctuations that are due to the total cause of capture and emission of carriers by traps under different additional conditions cause different types of electrical noise. In this context it appears to be advisable to analyze in a fairly general manner the electric fluctuations caused by capture and emission of charge carriers by traps formed by structural defects. Let us analyze the fluctuations with no restrictions on the relations between the parameters of the fluctuation process under the generally defined distributions of times between consecutive events of the fluctuation process. As in electronics semiconductor materials prevail, let us consider electrical fluctuations in semiconductors.

We are examining electrical fluctuations in semiconductors caused by capture and emission of charge carriers by traps formed by structural defects. Transition of free carriers into bound state in traps causes conductivity fluctuations and, consequently, electrical noise in semiconductors. Let us calculate the spectrum of fluctuations in the number of free carriers in a semiconductor caused by traps. Let us analyze the fluctuations generally. The concentrations of free carriers and traps are in random relations. The probability of change of the number of free carriers in a semiconductor is statistically related with the numbers of free carriers, captured carriers and empty traps at the current moment in time. As the number of free carriers in the absence of captures and the number of traps in the sample are fixed, at any moment in time the number of free carriers completely defines the number of captured carriers and empty traps. Let us analyze the fluctuation process, for which the probability of change of the number of free carriers is statistically related with the number of free carriers at the current moment in time and the statistical relation is defined in general. The fluctuations under consideration that are caused by a stochastic process of change of the number N of free carriers have the form of a random sequence of rectangular pulses, of which the amplitude δN is defined by formula $\delta N=N-\langle N\rangle$, while the duration of the next pulse equals to the period of time between consecutive events of change of the number of free carriers in the sample (caused by capture and emission of carriers by traps). Under the above statistical relations of the considered fluctuation process the duration of the pulse is statistically related with its amplitude, while the amplitude of the pulse is statistically related with the amplitude of the previous pulse. Let us calculate the spectrum of fluctuations in the number of free carriers in a semiconductor, assuming the fluctuation process is stationary. To that effect, let us calculate the above described random sequence of pulses. The fluctuation of the number of free carriers in a semiconductor can be written as follows:

$$\delta N=\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right),\qquad(1)$$

where n is the number of pulses in the sequence with the duration T, $x(t)$ is the function that describes the pulse form, δNj is the amplitude, θ_j is the pulse duration. The Fourier transformation is as follows

$$F(f)=\int_{-\infty}^{\infty}\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right)e^{-2\pi ift}dt=$$

$$=\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right),\qquad(2)$$

Where

$$F_0\left(f,\theta_j\right)=\int_{-\infty}^{\infty}x\left(t,\theta_j\right)e^{-2\pi ift}dt.\qquad(3)$$

Consequently,

$$\left|F\left(f\right)\right|^2=\sum_{j=1}^{n}\delta N_j^2\left|F_0\left(f,\theta_j\right)\right|^2+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-1}\sum_{i=1}^{n-j}\delta N_j^2\delta N_{j+i}e^{2\pi if\left(\theta_j+...+\theta_{j+i-1}\right)}\cdot F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+i}\right).\qquad(4)$$

Let us calculate the assembly average $\left\langle\left|F\left(f\right)\right|^2\right\rangle$ by using the independence of a number of parameters in the considered sequence of pulses

$$\left\langle\left|F\left(f\right)\right|^2\right\rangle=\sum_{j=1}^{n}\left\langle\delta N_j^2\left|F_0\left(f,\theta_j\right)\right|^2\right\rangle+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-1}\left\langle\delta N_j\delta N_{j+1}e^{2\pi if\theta_j}\cdot F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+1}\right)\right\rangle+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-2}\sum_{i=2}^{n-j}\left\langle\delta N_j e^{2\pi if\theta_j}F_0\left(f,\theta_j\right)\right\rangle\cdot$$

$$\cdot\left\langle\delta N_{j+i}F_0^*\left(f,\theta_{j+i}\right)\right\rangle\left\langle e^{2\pi if\theta_{j+1}}\right\rangle...\left\langle e^{2\pi if\theta_{j+i-1}}\right\rangle.\qquad(5)$$

Let us calculate the spectrum density of fluctuation of the number of free carriers

$$S_N\left(f\right)=\lim_{T\to\infty}\frac{\left\langle\left|F\left(f\right)\right|^2\right\rangle}{T}.\qquad(6)$$

Given the stationary nature of the stochastic process under consideration we deduce the spectral density of fluctuations as follows:

$$S_N\left(f\right)=v\left\{\left\langle\delta N^2\left|F_0\left(f,\theta\right)\right|^2\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{2\pi if\theta}F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+1}\right)\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta NF_0^*\left(f,\theta\right)\right\rangle\left\langle\delta Ne^{2\pi if\theta}F_0\left(f,\theta\right)\right\rangle\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\},\qquad(7)$$

where $v=\lim_{T\to\infty}n/T$ is the average number of captures and emissions of carriers by traps per time unit. Obviously, $v=1/\langle\theta\rangle$. Let us calculate the Fourier transformation of a single pulse, given that the pulse is rectangular

$$F_0\left(f,\theta\right)=\int_0^{\theta}x\left(t\right)e^{-2\pi ift}dt=\frac{e^{-\pi if\theta}\sin\pi f\theta}{\pi f}.\qquad(8)$$

As a result, the spectrum of fluctuations of the number of free carriers in semiconductors under random proportion of concentrations of traps and free carriers is as follows

$$S_N\left(f\right)=\frac{1}{\pi^2f^2\left\langle\theta\right\rangle}\left\{\left\langle\delta N^2\sin^2\pi f\theta\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{\pi if\left(\theta_j+\theta_{j+1}\right)}\sin\pi f\theta_j\sin\pi f\theta_{j+1}\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta Ne^{\pi if\theta}\sin\pi f\theta\right\rangle^2\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\}.\qquad(9)$$

Out of the formula (9) we directly proceed to the expression for the fluctuations spectrum of the current that flows in the semiconductor under constant voltage applied to the sample. As the current is proportional to the number of free carriers in the sample, the spectrum of normalized current fluctuations in the semiconductor is as follows:

$$\frac{S\left(f\right)}{I^2}=\frac{1}{\left\langle N\right\rangle^2\pi^2f^2\left\langle\theta\right\rangle}\left\{\left\langle\delta N^2\sin^2\pi f\theta\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{\pi if\left(\theta_j+\theta_{j+1}\right)}\sin\pi f\theta_j\sin\pi f\theta_{j+1}\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta Ne^{\pi if\theta}\sin\pi f\theta\right\rangle^2\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\}.\qquad(10)$$

Thus, we have examined the electrical fluctuations in semiconductors caused by stochastic processes of capture and emission of charge carriers by structural defects. The calculated general formula of the fluctuation spectrum can be used in the description of excess, generation-recombination and bursts noises. By defining the relations between the fluctuation process parameters and time distributions characteristic of a particular type of noise, we can deduce the formula of this noise's spectrum out of the general formula (10). In specific situations, by analyzing electrical fluctuations in solid bodies and solid-state electronic devices we can identify the spectral characteristics of the fluctuations by using the general formula (10) and defining the characteristics of the solid material and the parameters of the fluctuation process. The findings regarding the electrical fluctuations caused by capture and emission of charge carriers by structural defects can be used for identifying the spectral properties of fluctuations in solid bodies and solid-state electronic devices, as well as establishing the relations between the spectral properties and the characteristics of solid materials.

Degradation processes

Let us analyze the degradation processes that occur in solid materials and solid-state electronic devices. The relevance of such research is due to the following. There is a group of electrical noises, of which the origins are due to structural defects of solid materials. The spectral properties of such noises depend on the degree of structural defect. A rigorous quantitative analysis would allow establishing associations between the spectral characteristics of noises with the degree of materials defectiveness and thus would allow using the noises in the evaluation of the quality and dependability of electronic devices.

Let us examine a degradation processes that occurs in a solid material. The result of this process is the increased number of structural defects. The number of defects increases with time. Broadly speaking, events of appearance and destruction of defects are possible. In other words, structural degradations are a stochastic process of defect number change. Such stochastic process can only assume non-negative values, process changes can occur at any moment in time t. At any moment it can either increase by 1 or decrease by 1 or remain unchanged. A stochastic process of this type is described with a system of Kolmogorov differential equations [12]:

$$\frac{dp_0(t)}{dt}=u_1(t)p_1(t)-w_0(t)p_0(t)$$

$$\frac{dp_1(t)}{dt}=w_0(t)p_0(t)+u_2(t)p_2(t)-\left(w_1(t)+u_1(t)\right)p_1(t)$$

...

$$\frac{dp_i(t)}{dt}=w_{i-1}(t)p_{i-1}(t)+u_{i+1}(t)p_{i+1}(t)-\left(w_i(t)+u_i(t)\right)p_i(t),\quad(11)$$

where $i = 1, 2, 3,\ldots$, $p_i(t)$ is the probability of the number i of structural defects at the moment of time t, $w_i(t)$ is the rate of occurrence of the events causing the increase of the number of defects, $u_i(t)$ is the rate of occurrence of the events causing the decrease of the number of defects. Let us find the average number of defects $N_d(t)$ at the moment of time t. Let us do that as follows. Let us multiply the left and right parts of the i^{th} equation of the system (11) by the value i:

$$\frac{dp_1(t)}{dt}=w_0(t)p_0(t)+u_2(t)p_2(t)-\left(w_1(t)+u_1(t)\right)p_1(t)$$

...

$$i\frac{dp_i(t)}{dt}=iw_{i-1}(t)p_{i-1}(t)+iu_{i+1}(t)p_{i+1}(t)-i\left(w_i(t)+u_i(t)\right)p_i(t).\quad(12)$$

Let us combine the left and right parts of the resulting equations:

$$\sum_{i=1}^{\infty}i\frac{dp_i(t)}{dt}=\sum_{i=1}^{\infty}\begin{bmatrix}iw_{i-1}(t)p_{i-1}(t)+iu_{i+1}(t)p_{i+1}(t)-\\-i\left(w_i(t)+u_i(t)\right)p_i(t)\end{bmatrix}.\quad(13)$$

Let us transform the left part of the equation:

$$\sum_{i=1}^{\infty}i\frac{dp_i(t)}{dt}=\frac{d}{dt}\sum_{i=1}^{\infty}ip_i(t)=\frac{d}{dt}N_d(t).\quad(14)$$

Let us have regard for the formulas:

$$\sum_{i=1}^{\infty}iw_{i-1}(t)p_{i-1}(t)=\sum_{i=1}^{\infty}(i+1)w_i(t)p_i(t),\quad(15)$$

$$\sum_{i=1}^{\infty}iu_{i+1}(t)p_{i+1}(t)=\sum_{i=1}^{\infty}(i-1)u_i(t)p_i(t).\quad(16)$$

As the result we obtain:

$$\frac{dN_d(t)}{dt}=\sum_{i=1}^{\infty}\left(w_i(t)-u_i(t)\right)p(t).\quad(17)$$

Real degradation processes occurring in solid bodies are normally characterized by the formula $w_i(t)=w(t)$ which means that the defect rate depends on the time and not the number of defects at the current moment. As under realistic defect concentrations the defects do not influence each other, the formula $u_i(t)=iu(t)$ is fulfilled, where $u(t)$ is the rate of occurrence for one defect, while the value $u(t)$ is usually quite small. Given that:

$$\sum_{i=1}^{\infty}w_i(t)p_i(t)=w(t)\sum_{i=1}^{\infty}p_i(t)=w(t),\quad(18)$$

$$\sum_{i=1}^{\infty}u_i(t)p_i(t)=u(t)\sum_{i=1}^{\infty}ip_i(t)=u(t)N_d(t).\quad(19)$$

Finally, we deduce the formula for $N_d(t)$:

$$\frac{dN_d(t)}{dt}=w(t)-u(t)N_d(t).\quad(20)$$

Its solution under the initial condition $N_d(0)$ is as follows:

$$N_d(t)=e^{-\int_0^t u(\theta)d\theta}\left[\int_0^t w(x)e^{\int_0^x u(\theta)d\theta}dx+N_d(0)\right].\quad(21)$$

As the spectral density of the noises caused by structural defects is directly linked with the number of defects [1-3, 5], then using the formula (21) we can make the following conclusions. The spectral density of noise depends on the number of defects and, therefore, is linked to the degree of structural degradation. The spectral density of noise depends on the defect rate and, therefore, on the structural degradation rate. Thus, the noises in solid-state electronic devices contain information on the degree and rate of degradation. Below are the practical conclusions. The noise spectral density is associated with the number of defects in the device at the baseline, and, therefore, characterizes the quality of the manufactured device. Additionally, the spectral density of noise depends on the defect rate and, therefore, on the ageing rate of the electronic device. Thus, the spectral density of noise is linked with the device's operational characteristics change rate. Accordingly, the noise spectrum can be used in evaluation of an electronic device's deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation.

Conclusion

The paper analyzed the electric fluctuations in solid materials and solid-state electronic devices caused by defects. A quantitative description of fluctuation was provided. A general expression for the fluctuation spectrum was calculated. The findings can be used in the description of excess, generation-recombination and bursts noises. The noises of those types are fundamental and largely define the appearance of the spectrum and intensity of noise in many electronic devices. Those noises are largely associated with the defects of solid materials and can be widely used for nondestructive quality testing of solid-state electronics. The findings set forth in the article enable a simple identification of the spectral properties of and intensity of noises caused by defects in various electronic devices.

Degradation processes that occur in solid-state electronic devices were analyzed. The quantitative characteristics of the degradation processes were identified. The connection between the electrical noises caused by defects and both the degree and rate of degradation processes in electronic devices were shown. It was established that the noise spectrum contains information on electronic devices' deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation. The paper substantiates the potential wide applications of electrical noises in nondestructive testing of electronic devices, shows the feasibility of using fundamental types of electrical noises for the above purposes. The rigorous substantiation of the use of electrical noises for nondestructive testing of electronic devices, feasibility of evaluation of the devices' defects caused by various factors, use of common frequently prevailing types of noise, high sensitivity of fluctuation spectroscopy highlight the efficiency of electrical noise in nondestructive testing of electronic devices.

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About the authors

Boris I. Yakubovich, Candidate of Physics and Mathematics, Senior Researcher, Saint Petersburg Institute of Nuclear Physics, National Research Center Kurchatov Institute, Orlova roshcha, 188300 Gatchina, Leningrad Oblast, Russia, tel.: 81371 4 64 92, e-mail: yakubovich_bi@pnpi.nrcki.ru

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