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NONLINEAR CURRENT OSCILLATIONS IN A JOSEPHSON JUNCTION WITH FRACTAL RADIOISOTOPE COMPOSITES

We present a new form of the Josephson junction with dielectric layer containing radioisotopic inclusions. The presence of additional generators of ionization in a semiconducting material (due to α – particles emitted by radioisotope inclusions) causes the essentially nonequilibrium dispersive characteristics of composite materials. Nonlinear current oscillations in such nonequilibrium Josephson junctions are investigated. It is worth noting that a Josephson junction with fractal layer acquires additional characteristics. Taking into account that the medium is a fractal one, the generalization of the oscillation equation by means of fractional integro-differential operators can be an adequate model of a tunnel junction in this case. An analysis of general modes of linear and nonlinear oscillations in a nonequilibrium fractal Josephson junction is carried out. Such electronic elements can be used for chaotic communication.

1. INTRODUCTION

In recent years, the composite materials, i. e. materials with a complicated (fractal) structure, find expanding applications in many fields of physics and technology (for example, as protective coatings).

From our viewpoint, the fractal radioisotopic composite materials such as dielectric materials with fractal inclusions including conductive α-radioactive elements [1,2] can be used with greater efficiency as perspective composite materials. The main peculiarities of such new materials are related with

- Appearance of nonlinear properties of fractal layers,
- Formation of nonequilibrium states of the electron system as a result of the action of radioisotopic inclusions,
- Appearance of a nonstationary track structure in such materials,
- Appearance of the additional irreversibility and the memory of fractal materials.

Partly, these properties of fractal radioisotopic media have been already studied in our works. The fractal media possess the property that their macroscopic properties (the coefficients of heat conduction, electrical conduction, diffusion, etc.) and dielectric properties depend on their fractal characteristics (for example, on the fractal dimension of a material or its porosity). The artificial fractal media with radioactive inclusions are characterized by nonequilibrium, irreversibility (and, in this connection, by the general and universal property of “forgetting” or “information loss” [3]), appearance of the states with power distribution functions and with a decay of correlations [4], and nonstationarity of dispersive properties.

The radioisotopic inclusions are sources of additional ionization of a material by α-particles. The presence of permanent sources of ionizing radiation in the system, sinks of particles as a result of the recombination of excess charges, and emission currents from a composite material leads to the possibility of the appearance of quasistationary states of electrons with power asymptotics in the region of energies that exceed significantly the Fermi energy [4].

In the present work, we will consider a Josephson junction with a fractal layer consisting of such composite material with inclusions of α-radioactive elements and will study the influence of all the main peculiarities of fractal radioisotopic materials on the properties of junctions. The fractal radioisotopic composite materials, due to their unique combination of fractal, nonequilibrium, chaotic, and nonlinear properties, can be efficiently used in the systems with chaotic communication [5]. We will demonstrate the possibilities to use the properties of new junctions undergoing the action of external signals in the realization of a chaotic communication.

2. ON NONLINEAR AND NONEQUILIBRIUM DISPERSIVE PROPERTIES OF THE FRACTAL LAYER OF A CONTACT

The radioactive inclusions form the conductive component of a dielectric matrix. If the metallic component has conductance σ_m, then the structure-dependent contribution $\delta\sigma_{eff}$ to the effective conductance σ_{eff} of the two-component infinite medium on the percolation threshold depends only on the parameter $\xi = \dfrac{\sigma_D}{\sigma_m}$, where σ_D is the effective conductance of the semiconductor matrix, and is described by the power law [6]

$$\delta\sigma_{eff} = \sigma_m \xi^u, \tag{1}$$

where u is the critical index ($u = 0.5$ in the two-dimensional case). The conductance σ with the effective contributions of the linear conductance σ_{eff} and the nonlinear one $\alpha_e E^2$ (derived in [6]) reads

$$\sigma = \sigma_{eff} + \alpha_e E^2, \tag{2}$$

where E is the mean electric field and the nonlinear conductance α_{eff} is described by the power dependence on the quantity $\alpha_{eff} \approx \alpha_D \xi^{-w}$ (for a thin layer, $w = 5$).

The presence of radioactive inclusions in the insulating layer, besides the above-mentioned nonequilibrium additions, makes the conductance of a junction to be nonstationary as a result of irradiation of the junction with fragments emitted due to the decay of radioactive inclusions.

3. NONLINEAR OSCILLATIONS IN A FRACTAL JOSEPHSON JUNCTION AND THE PROCESSES OF REGULARIZATION

As known, a system consisting of two weakly interacting superconductors, to a potential difference $U(t)$ is supplied, is phenomenologically described by the difference of phases of the wave functions in the superconductors according to the relation

$$\frac{\partial \varphi}{\partial t} = \frac{2e}{h} U(t) \tag{3}$$

and is defined by the presence of the oscillating superconducting component I_s in the total current in the system I, which is defined by the connection between the superconductors $I_s = I_c \sin(\varphi(t))$.

We take into account the fact that the junction has capacitance C and supplement the above-presented relations by the equation for currents in the circuit which follows from the fact that the sum of the superconduction current, conduction current and displacement current is the total current in the circuit. This leads to a single equation for the phase in a junction which coincides with the equation for a fractal Josephson junction [2], but with nonstationary impedance $Z_n(t)$:

$$\frac{\hbar C}{2e}\frac{\partial^2 \varphi}{\partial t^2} + \frac{\hbar}{2e}\frac{1}{z_n(t)}(\xi^{1/2} + \alpha_D \xi^{-3/2} \alpha_e U(t)^2)\frac{\partial \varphi}{\partial t} + I_c \sin(\varphi(t)) = I(t). \tag{4}$$

In a wide range of parameters, this equation has chaotic solutions and it is very difficult to analytically perform the qualitative analysis of oscillations, because the dynamical systems diagnostics and restoring of its form are reduced to the necessity of solutions ill-posed problem [7].

4. CONTROL OVER NONLINEAR OSCILLATIONS IN A FRACTAL JOSEPHSON JUNCTION AND THE CHAOTIC COMMUNICATION

The parameter ξ defines the properties of a composite material and is constant in the course of time. However, this parameter (the ratio of the conductances of a matrix and inclusions) can be easily made controllable, for example, in the presence of an external magnetic field $H(t)$, if the admixtures are magnetic substances [9]. In this case, $\xi = \dfrac{\sigma_D}{\sigma_m(H)} = \xi(H)$, and a variation of the magnetic field with time will change the modes of oscillations $\xi = \xi(t)$ in a junction.

In Fig. 1, we present the oscillations for various values of the parameter ξ.

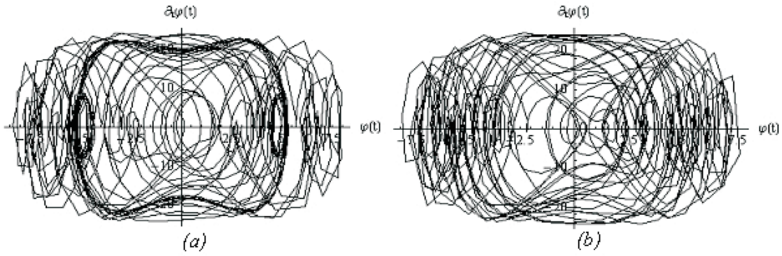

Fig. 1. Phase trajectories of oscillations of the potential on the fractal Josephson junction for ξ = 0.1 (a) and ξ = 0.09 (b).

We now show how the control over the modes of oscillations in a Josephson junction can be realized. Let the magnetic field be changed with time by the law presented in Fig. 2.

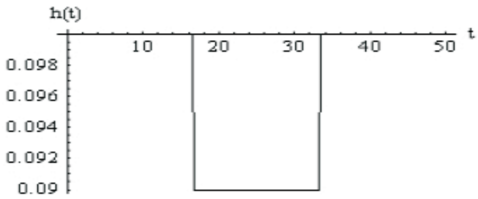

Fig. 2. Temporal dependence of the controlling parameter $\xi(t)$.

Then a realization of the current through the junction will have the form given in Fig. 3.

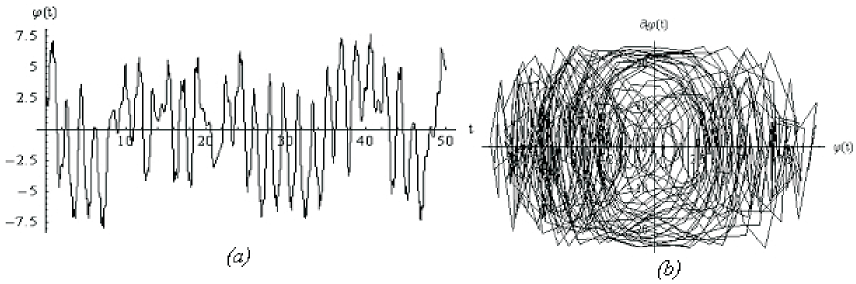

Fig. 3. Temporal dependence of the current in a junction (a) and the phase plane (b).

The magnetic field may change completely the behavior of parameter ξ in the junction due to the phase reversal (so called π-junction [9]).
A slow variation of the statistical characteristics of a realization of the current through (or the potential across) a Josephson fractal junction can be for chaotic communication.

The informational binary signal modulates the statistical characteristics of chaotic oscillations of a Josephson junction. A chaotic realization appears which can be transmitted and received as an electromagnetic signal. In this case, we are faced with the problem of reconstruction of an informational signal by the chaotic realization.

5. MODEL OF NONSTATIONARY PROPERTIES OF A LAYER OF COMPOSITE MATERIALS WITH RADIOISOTOPIC INCLUSIONS

Consider the nonstationary properties of a composite layer which are conditioned by the permanent change of the internal conducting structure at the expense of permanent appearance of new tracks from products of the decay of radioisotopic inclusions. The main peculiarities of properties of the layer with radioisotopic inclusions are the appearance of resonance phenomena and the irregular sequence of peaks of the complex-valued resistance.

We will consider that the tracks of ?-particles are the regions possessing the inductance and the dielectric regions between tracks possess the capacitance. Such an approach allows us to qualitatively represent the nonstationary behavior of the conductance of the semiconductor layer caused by a change of its internal structure due to the permanent appearance of new tracks from products of the decay of radioisotopic inclusions by a change of the number of links in the equivalent radiotechnical scheme which models this structure and is presented in Fig. 4.

The scheme is an LC–chain of the ladder type, whose impedance is defined by the recurrence relations [10]

$$z_n + 1 = z_1 + \frac{z_n z_2}{z_n + z_2}, \quad n = 1, 2, ..., \infty, \tag{5}$$

where z_1 and z_2 are the complex-valued resistances of the elements of the chain. For any ratios between z_1 and z_2, there exists always a fixed point z^* determined from the equation

$$z^* = \frac{z_1}{2} \pm \sqrt{\frac{z_1^2}{4} + z_1 z_2}. \tag{6}$$

If the fixed point z^* is stable, the impedance of the infinite ladder-type chain exists and is the limit $\lim\limits_{n \to \infty} z_n = z^*$. Otherwise, the limit $\lim\limits_{n \to \infty} z_n$

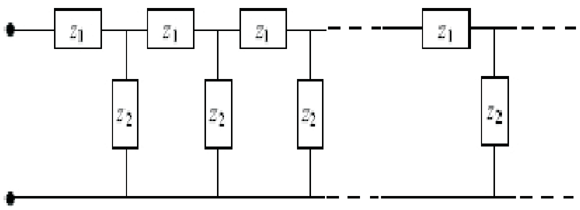

Fig. 4. Equivalent radiotechnical scheme of the nonstationary structure of the layer of a composite material: z_1 – inductive component of the impedance; z_2 – capacitive component of the impedance.

In accordance with the results of work [10], if the ratio of the chain impedances $z_p = {}^{z1}/_{z2}$ satisfies the inequality

$$0 \leq z_p \leq 4, \tag{7}$$

the fixed point is unstable. For this point, the dependence of the ladder chain impedance (see Fig. 4) on the number of elements has the form presented in Fig. 5.

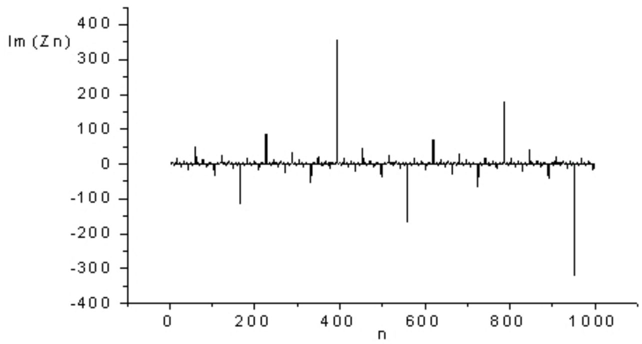

Fig. 5. Impedance of the layer of a composite material with the nonstationary structure of its conductance versus the number of links (the number of the tracks of charged particles in the layer).

It is seen from Fig. 5 that the impedance changes chaotically with time and in a very wide scope. The use of such an element with strongly nonstationary impedance in an oscillatory contour must cause complex oscillations possessing both regular and chaotic components. In this case, we are faced with the important problem (of a sufficiently general character) of the separation of the regular component with small amplitude against the background of the chaotic component with regular great amplitude. One of the methods to solve such problems consists in the application of the methods of regularization [7] and adaptive processing of data [5].

6. CONCLUSION

Thus, a Josephson junction with a fractal layer possesses nonlinear and nonstationary properties allowing efficient control over the mode of oscillations with the help of a slow variation of the ratio of the conductances of components of a composite material. Basing on the high sensitivity of the mode of oscillations of a Josephson junction to the variation of its parameters, we propose to use it in realizations of chaotic communication.

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