

## **Nanocluster fractal electrical conductivity in thin films on a solid surface: dimensional models of different configurations and demonstration of results in a laser experiment**

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**Abstract:** Models for the formation of nanocluster fractal structures of various configurations are considered within the framework of a number of approaches in the aspect of controlling their electrophysical characteristics, and the results of some experiments in this direction by laser experiment are presented. Emphasis is placed on the discussion and analysis of the following issues: physical principles and models for the electrical conductivity in topological nanostructures; local fields in nanoscale and their contribution to the gain coefficient for electrical conductivity in aspect of parameters of the medium and the geometry factors for roughness; experimental technique; current-voltage characteristics and mechanisms of electrical conduction for topological nanostructures under different conditions. At the same time, occurrence of conduction electropaths, and also the algorithms and models considered for calculating of electrical conductivity for nanostructures of different configuration are analyzed, experimental results and their interpretation are presented, and the role of photoconductivity were studied in such nanostructures. The results obtained can be useful in the development of certain elements and systems of nanotopological electrophysics and nanophotonics based on new physical principles.

**Keywords:** nanoclusters; fractal configurations; topological electrical conductivity; dimensional effects; modeling and experiments with different mechanisms of electrical conductivity in various conditions.

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## **Нанокластерная фрактальная электропроводимость в тонких пленках на твердой поверхности: размерные модели разных конфигураций и демонстрация результатов в лазерном эксперименте**

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**Аннотация:** Рассмотрены модели формирования нанокластерных фрактальных структур разной конфигурации в рамках ряда подходов в аспекте управления их электрофизическими характеристиками и приведены результаты некоторых экспериментов по данному направлению в лазерных схемах. Акценты сделаны на обсуждении и анализе следующих вопросов: физические принципы и модели для электропроводимости топологических наноструктур; локальные поля на наномасштабах и их роль в зависимости от параметров среды и геометрии шероховатости в коэффициентах усиления для электропроводимости; методика эксперимента; вольт-амперные характеристики топологических наноструктур и механизмы электропроводности в разных условиях эксперимента. При этом исследованы возникающие дорожки электропроводимости, рассмотрены алгоритмы и модели для расчета электропроводимости, проанализированы наноструктуры разной конфигурации, приведены

демонстрационные экспериментальные результаты и дана их интерпретация, оценена роль фотопроводимости в подобных наноструктурах. Полученные результаты могут быть полезны при разработке различных элементов и систем топологической наноэлектрофизики и нанофотоники на новых физических принципах.

**Ключевые слова:** нанокластеры; фрактальные конфигурации; топологическая электропроводимость; размерные эффекты; модели и эксперименты с разными механизмами электропроводимости в определенных условиях.

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## 1. Introduction

Electrophysics of thin-film systems with nanoclusters (nanodots) with different controlled topology on the surface of a solid body, obtained in a laser experiment, has a number of fundamental features [1]. Such nanostructured surface configurations, related in terms of electrophysics for inhomogeneous media to granular/island objects [2], are controlled by different methods of laser deposition of almost any substance and/or alloy with different concentrations of defects in nanocomposites onto a solid surface, in particular, using the process of laser ablation of a material in a liquid [1, 3]. Thus, the possibility of synthesizing structures with arbitrary elemental/chemical compositions appears.

The fundamental physical fact here is that this process occurs under normal external conditions, but nevertheless, extreme conditions are realized in local areas even when exposed to relatively low-power laser radiation. This leads to a number of effects; secondly, a special allotropic form of carbon, carbene [1, 4, 5] with 1D carbon chains, is realized. The production of such long 1D chains – Long Liner Carbon Chain (LLCC) – has now become a routine process in a certain procedure of laser ablation of carbon materials in association with noble metals [6–10].

When considering the possibility of a cardinal change in a given way in the electrical characteristics of such systems, determined by an increase in electrical conductivity due to surface conductivity with cluster boundaries, topological nanocluster structures of the fractal type are of greater interest, both in fundamental and applied aspects, since the electrical conductivity can vary by many orders of magnitude [7, 10, 11]. In this case, the electrical conductivity is defined here as the specific conductivity, depending on the dimension  $D$  of the object (from 1 to 3), in units of  $\sigma_D$  [ $\text{Ohm}^{-1}\text{cm}^{2-D}$ ]. The control parameter is the characteristics of the topological structures, the change of which plays a role similar to the change in temperature during ordinary phase transitions with a certain order parameter.

In this aspect, the search for new materials with the required functional characteristics is similar to inducing the corresponding topological configurations on a solid surface in a laser experiment.

In similar size-quantized semiconductor-type systems, the distance between the  $\delta\varepsilon$  energy levels in a cluster is determined by the density of states at the Fermi level in a  $g_F$  bulk sample and the average volume of one  $a^3$  cluster according to the relation [12]:  $\delta\varepsilon = (g_F a^3)^{-1}$ , where  $\delta\varepsilon \approx 10\text{K} \sim 10^{-3}\text{ eV}$  at  $a = 5\text{ nm}$ .

In this regard, there is a simple physical analogy with such a key problem as the achievement of high-temperature superconductivity ( $\sim 300\text{ K}$ , which is  $\approx 0.03\text{ eV}$  in energy units), for which, in the general case, the necessary condition for this, in fact, directed delocalization is, firstly, a decrease in the scattering of charge carriers – electrons on phonons, and secondly, a certain small energy band gap near the Fermi level (in the presence of a sharp Fermi surface), leading to electron pairing (Cooper pairs) with a virtual exchange of phonons with energy, exceeding the energy of thermal fluctuations [13]. An important feature of precisely neutral nanoclusters is their charge neutrality; therefore, the mechanism of such pairing has the nature of van der Waals attraction.

In this case, the band gap itself (the lower boundary of the conduction band) also depends on the number of nanolayers on the substrate, and it will decrease with their growth, tending to a normal metal in the limit.

Although the detailed nature of high-temperature superconductivity is not yet completely clear [14], the definition of the relevant physical principles for identifying trends and regularities for increasing electrical conductivity in topological nanocluster structures with a selectable inhomogeneous configuration on the dielectric surface of a solid (systems with “voids” – cf. [10, 11, 15]), can be considered as an analogy with the electrophysics of topological insulators [2, 16, 17].

The physics of such processes is determined by electron interference (the Aronov–Altshuler effect

[13, 18, 19]), which can also be preserved at room temperature. This leads to a quantum correction in units of the conductance quantum (conductance  $\sim e^2/h$ , where  $e$  is the charge of an electron with the reciprocal dimension to the resistance  $\sim (1/4110 \text{ Ohm})$ . The electrical conductivity itself depends on the dimension of the system, but when this correction becomes positive, then a superconducting state can arise [12, 13].

The presence of “voids” in the topological nanostructure can be considered in terms of the analogy of the insulator-metal/superconductor transition [17]. In this case, the role of quantum tunneling effects between delocalized states both between clusters and within one cluster increases in surface nanoclusters. They can be weakened by the Coulomb blockade effect, but this does not occur for a 5 nm cluster at high temperatures  $\sim 300 \text{ K}$  under conditions when the surface electrical conductivity increases inversely with the thickness of the surface layer (the nanoobject is located on a solid surface like a film) [2].

Thus, such a set of nanoclusters on a solid surface can lead to a significant increase in the electrical conductivity characteristics, but in contrast to the hopping conductivity of charge carriers between localized states, tunneling is about their transition between delocalized states [2, 13, 18, 19]. This is determined, on the one hand, by the size of an isolated conducting cluster and the density of states at the Fermi level in it, and, on the other hand, by the interaction between the clusters themselves [2, 12]. It is this latter factor that distinguishes such a nanocluster structure from a bulky bulk sample in terms of the value of the critical temperature of superconductivity, which depends on the particular topology and energy barriers that arise.

For the electrical resistance of fractal structures, of greatest interest are fractal objects, which with a controlled configuration [1] can be obtained, for example, by laser deposition of nanoparticles from colloidal systems onto a solid substrate [10, 20]. Such systems can easily arise in a controlled and universal procedure for laser ablation of various materials in liquids [3]. In this case, depending on the topological structure, for example, for a semiconductor nanocluster system, here it becomes possible to control the band gap with its modified boundaries to implement direct and indirect electron transitions from the valence band to the conduction band [2, 19]. In the second case of indirect transitions, the process proceeds with the participation/exchange of phonons. This makes it possible to realize paired states of electrons under certain conditions.

On the other hand, the very presence of “voids” (pores) with a certain distribution function can serve as an analogue of doping in the presence of such vacancies. Similar effects in a polydisperse medium are characteristic of a non-ideal surface and are considered with different roughness models. They affect the value of the work of the electron quantum yield and its depth for such nanostructured heterogeneous media with the manifestation of size effects [10, 18].

It is important to emphasize that, in such fractal-type nanocluster structures, the attainment of the superconducting state does not necessarily lead to a drop in the electrical resistance to zero along the entire length of the sample [2, 12]. This is due to the effect of tunneling through “voids” between clusters, if the main resistance in the current channels is determined precisely by the transition of charge carriers through these “voids”. In a sense, here we can talk about analogies with the Josephson effect in superconductivity through a contact, when the application of an external constant electric field of voltage  $U$  to such a tunnel contact already passes with the presence of dissipation [2, 13, 18, 19]. In this case, the voltage drop  $\Delta U = RI + U$  (where  $R$  is the resistance,  $I$  is the current flowing in the circuit) has the usual form for alloys. The peculiarity of a tunnel junction with a superconductor (in the presence of  $R$  in the circuit) is associated with the value of  $I$  determined by the phase difference on both sides of the contact  $\phi_{12}$ :  $I \sim \sin \phi_{12}$ .

In such cluster-fractal structures, one can draw an analogy with the usual current propagation, for example, along a wire with a large length and a small cross section, when the current trajectories look like winding lines in the gaps between clusters in the form of Brownian motion in the fractal structure [2, 21].

On the other hand, they can lead to complex helicoidal structures, in particular, in graphene layers, and twisted configurations, which significantly affect their electrophysical characteristics [22]. Moreover, such twisting can effectively lead to states similar to the states of electrons with opposite spins, forming Cooper pairs (correlations in the momentum space with a probability of zero momentum sum and with symmetry with respect to time reversal) [12, 13]. But everything here is determined by the specific configuration of the resulting topological nanostructure.

Of fundamental importance is the fact that, by changing its configuration in a controlled way even at the stage of its creation, one can, in particular, radically change the electronic states of the sample substance and the shape of its Fermi surface, and

therefore influence the electrical resistance of the resulting sample [8, 10, 11].

Another feature of such topological fractal structures in the aspect of considering the tendency to the superconducting state is that we are talking here about granular inhomogeneous objects, where a second-order phase transition to the state of weak superconductors can be realized. For them, it is a mandatory criterion to study the influence and role of an external magnetic field and the depth of its penetration into the medium when a superconducting state appears, but in this topological case this requirement does not play a special role [13, 18, 19]. Moreover, the process of formation of such structures can occur under conditions of negative surface tension in the dynamics of the formed nanoclusters (conditions of a local isobaric state – cf. [23]), but with the fixation of usually unstable similar objects and their further existence under normal conditions. This is typical, as mentioned above, for the process of laser ablation of a graphite target in a liquid, for example, during the formation of micronanodiamonds. Therefore, the requirement of minimum energy for the final stable state of the system is fulfilled [14, 18].

However, for such nanostructured objects and their compositions, there is a real physical problem when using the numerical values of the material macroscopic parameters of a massive medium for such micro-nanoscale systems. But in the case of clarification of the ongoing trends, such an approximation is apparently still possible and / or it is necessary to renormalize the parameters used, for example, the value of resistivity  $\rho$  should be considered as a certain calibration coefficient. In particular, in [10, 11], jumps in electrical resistance by a factor of  $10^4$  were observed in the experiment for a certain topology of fractal objects in thin surface layers on solid samples. They are probably not reduced to obvious short-circuit currents, since, firstly, they are smoothly and reversibly regulated depending on the topology and its dimensions in accordance with the model estimates, and secondly, in the experiment they demonstrate a clear dependence on a specific value topological dimension.

Obviously, for the problem of real and possible achievement with a trend towards the required superconducting state, it is necessary to use correct measured material parameters for samples with the selected appropriate elemental composition and realized topology.

The fractal structures under consideration were modeled by us within the framework of different approaches, taking into account the achievements of

laser methods, and the results obtained are presented in the corresponding sections of this article.

Section 1 considers the physical principles and models for the electrical conductivity of topological structures. Section 2 discusses local fields and gains for electrical conductivity under different conditions. Section 3 deals with the experimental technique. Section 4 presents the current-voltage characteristics (CVCs) and discusses the mechanisms of electrical conductivity, as well as demonstration experimental results and their interpretation; in addition, issues with the representation of the role of photoconductivity are considered and calculations are performed for the temperature field.

In the Conclusion, the main conclusions on the work are presented in the aspect of their consideration for topical problems of modern topological nanoelectrophysics and nanophotonics for thin-film systems.

## **2. Materials and methods: physical principles and models for the electrical conductivity of topological structures**

When forming a nanocluster of electrical conductivity, i.e., a platform within which the current is most likely to flow [2, 24, 25], it is necessary to select an electrical conductivity track in it, along which the electric current can flow, taking into account the topological structure of the simulated film. This makes it possible to estimate the current-voltage characteristics of such a fractal structure based on the standard Ohm's law.

In this case, 2 types of configurations of the synthesized topology are possible, firstly, a network of closely spaced nanoclusters/islands connected to each other by conducting "bridges", and, secondly, a system of nanoclusters/islands isolated by large distances from each other, which can be characterized by a dielectric type of conductivity [2, 18, 26–29].

In the first case, we are talking about a continuous path of current flow. Therefore, such a 2D area can be classified as a nanofilm with a percolation type of electrical conductivity. In the second case, there are no continuous paths of current flow, and the mechanism of electrical conductivity, when it occurs, should have a jump-like character.

According to the physical picture, one of the factors affecting the current-voltage characteristics of nanostructures with object sizes of  $\sim 10\text{--}100$  nm is the total electrical resistance  $R$  of a microcontact formed in an inhomogeneous structure with a characteristic



length of the resistor section determined by the mean free path of an electron [2, 21]:

$$R = \frac{16\rho^\infty\lambda^\infty}{\pi d^2} \left( 1 + \frac{L}{d} + \frac{d}{\lambda^\infty} \right), \quad (1)$$

where  $d$  is contact diameter,  $\lambda$  is the mean free path of electrons in a bulk material,  $\rho$  is the electrical resistivity of the contacting particles of the material,  $L$  is the length of the microcontact.

Then the electric current in this system of contacting nanoparticles will flow only through the contact surfaces - areas with an area tending to zero.

We mean the formation of a plurality of longitudinal channels for the flow of current, which significantly complicates the transverse propagation of the current (there is no integral/homogeneous cross section for a section of the conductor circuit). In this case, to estimate the total electrical resistance of the microcontact, it is necessary to modify the expression for the standard Ohm's law for the circuit section, from which relation (1) is also derived.

In such nanocluster fractal structures with a given topology in thin-film flat solid-state samples, the calculation of the electrical resistance  $R$  of a circuit section (current path) with a fractal relief (here we are talking about static structural inhomogeneities, in contrast to dynamic – temperature ones) can be performed according to the following model relation [21]:

$$R = A\rho \frac{l_n(L_0/l_n)^D}{S_n(S_0/S_n)^{2-D_1}}, \quad (2)$$

where  $\rho$  is the resistivity of the bulk material,  $A$  is a normalization coefficient that takes into account the scale of the inhomogeneity,  $L_0$  is the length of the observed curve along the line from the initial to the final points of the microcontacts when measuring the current on the conducting surface,  $l_n$  is the length of the set of coatings (the distance between neighboring clusters),  $S_n$  is the area of the minimum coverage element,  $S_0$  is the area of the ellipse into which the averaged relief of the transverse cut is inscribed,  $D$  is the fractal dimension of the observed averaged relief along the longitudinal direction (it is calculated by the method presented, for example, in [1]),  $D_1$  is the fractal dimension of the boundary of the transverse cut of the conducting area on the surface of the substrate.

The principal control parameters in this model (2) are nanoclusters with fractal dimensions  $D$  and  $D_1$ , which can be obtained in the experiment, and their fractal parameters, which are calculated according to

a certain procedure (in particular, as in a percolation effective medium within the framework of the cellular automaton model [29–31] using images of real nanocluster structures obtained with an atomic force microscope for the nanocluster system under study [21]. In this case, sufficient measurement accuracy ( $D$ ,  $D_1$ ) to the second decimal place is provided, for example, at a length  $L_0 = 100 \mu\text{m}$  with a resolution of 1000 measured points (determines the value of  $l_n$ ).

Therefore, when measuring the electrical resistance in nanostructures, it is necessary to take into account the change in the resistance value depending on the topology of the surface nanolayer obtained in the process of laser deposition [21, 30, 31]. We will return to this in 2.4 of this paper.

Nevertheless, the classical method for estimating the CVC based on Ohm's law, with regard to the methods of fractal geometry, can be applied to nanocluster structures; we will use it with certain restrictions.

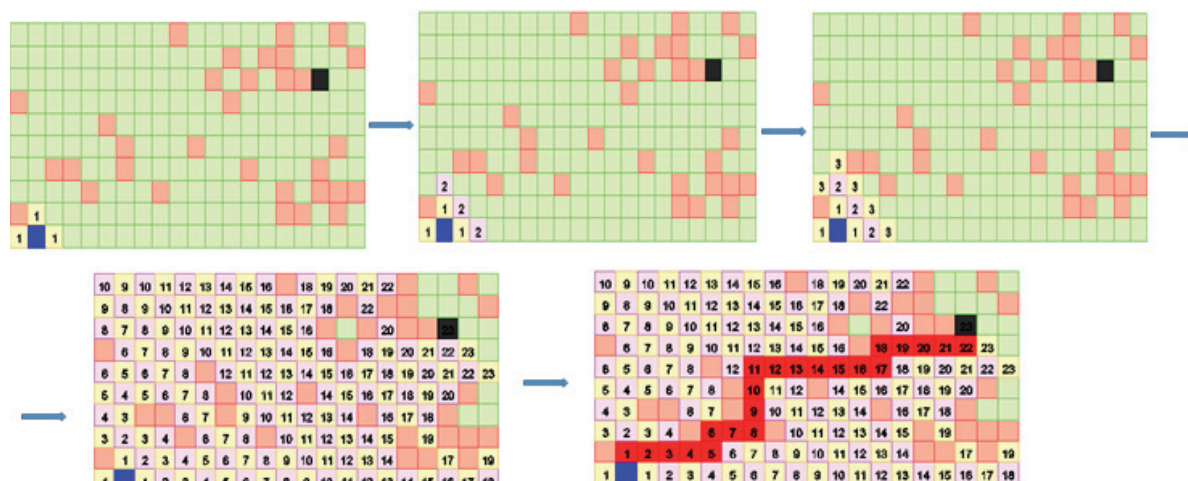
Below, we will model such nanocluster structures both in terms of configuration and electrical parameters, presenting a number of results with samples of different nanocluster configurations. Examples of pictures of some real synthesized structures in the obtained samples are shown below.

## 2.1. Conduction paths

Figure 1 shows a diagram of the Lie algorithm we use [2, 32–34], which consists of two stages: current propagation along the conduction path and restoration of its path.

The current propagation is characterized by the fact that, starting from the starting cell, neighboring cells with such an initial cell and located within the Neumann neighborhood are marked with a number one greater than the original one. Path restoration is implemented when, starting from the finish cell, the path is built as a selection of neighboring cells with a label one less than the current one. Thus, the length of the path will correspond to the number of cells of the computational area of which it consists.

The model of the cluster structure being constructed is built within the framework of the DLA (Diffusion Limited Aggregation) approximation with a change in the probability of consolidation of elements forming a cluster (according to the physical process, for example, deposition on a solid surface from a colloid – we are talking about the probabilistic degree of sticking of objects to each other, which is associated with intensity of diffusion in time, in our case in the interval of probabilities  $s[1; 0.01]$  for three



**Fig. 1.** Construction of a conduction path according to the Lee algorithm [33]. Sequential numbers mark the order of propagation from the original cell 1. The final cell formed in this case is labeled 23 here

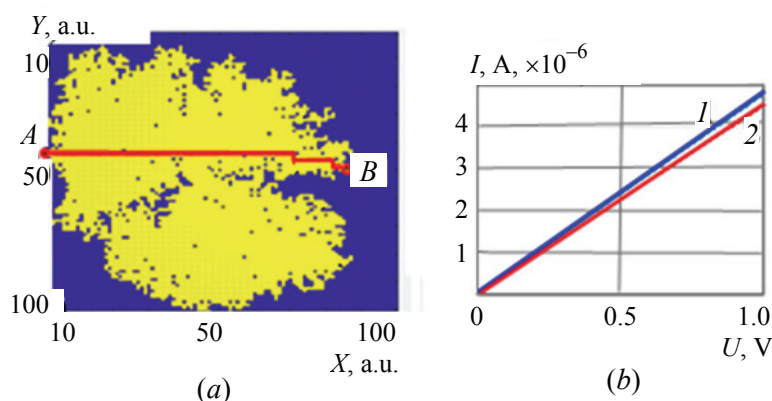
randomly located initial germ particles (granules) with a final surface density with a chosen value of  $5.17 \cdot 10^8 \text{ cm}^{-2}$ , and with a distinguished conduction path (AB) length of 90 rel. un., determined by the Lee algorithm. This path is fixed by the location of the microcontacts in the experimental current measurement circuit.

Figure 2 shows the corresponding CVC at a granule size of 10 nm and an electrical resistivity parameter using the example of a  $\rho_{\text{PbTe}}$  semiconductor film  $\rho_{\text{PbTe}} = 2.32 \cdot 10^7 \text{ (Ohm}\cdot\text{m)}$  [35], with which we performed the experiment.

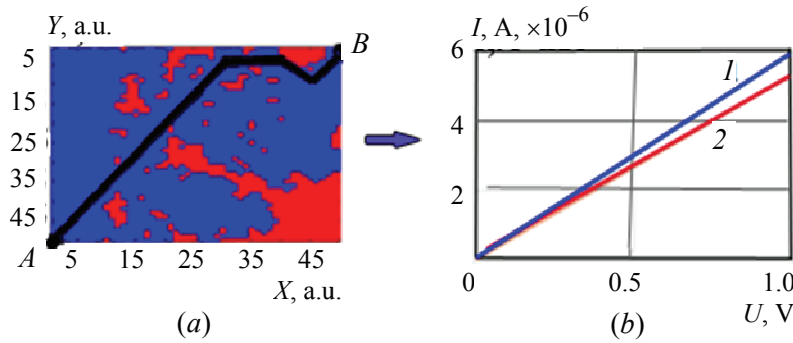
The specified values allow us to estimate the resistance of the conduction path as  $0.208 \cdot 10^6 \text{ Ohm}$ . The difference between the calculated resistance value and the simulated one is  $\sim 5.5 \%$ . The difference between the estimated CVCs on the basis of the average resistance value from the experimental data and the CVCmodel dependences is about  $5.8 \%$ .

The obtained errors testify to the adequacy of the applied approximation for CVC description.

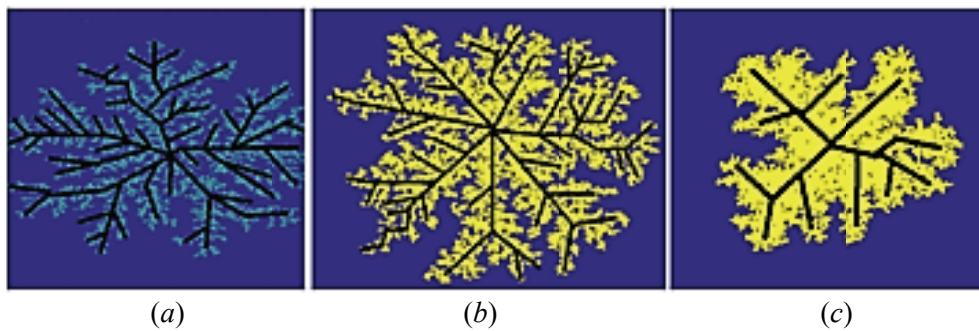
Figure 3 shows the calculated CVC at a nanocluster size of 20 nm for a model of a well-formed semiconductor nanocluster/island PbTe film in the directional percolation model approximation at a probability  $s = 0.5$  with a surface density of  $5.38 \cdot 10^8 \text{ cm}^{-2}$  on the computational domain with an area of  $50 \times 50$  rel. units (Fig. 3a) with a dedicated conduction path in accordance with the Lee algorithm with a length of 85 rel. units. The comparison was made with an experiment for which the resistivity was  $2.1 \cdot 10^7 \text{ Ohm}\cdot\text{m}$ . For the model structure, the calculated resistance was  $0.17 \cdot 10^6 \text{ Ohm}$ . The difference between the calculated resistance value and the experimentally measured one gives a value of  $10 \%$ . A similar difference was observed between the CVC values.



**Fig. 2.** Model of a PbTe film with a dedicated conduction path (a), CVC of the film for the AB path at a granule size of 10 nm (b): 1 – model dependence; 2 – dependence based on the experimentally estimated average resistance, calculated in the Ohm's law approximation



**Fig. 3.** Model of a nanocluster/island PbTe film in the directional percolation approximation (a), its CVC was determined at a grain size of 20 nm: 1 – model dependence; 2 – dependence based on the experimentally estimated average resistance calculated in the Ohm's law approximation (b)



**Fig. 4.** Nanocluster film skeleton at  $s = 1$  (a);  $s = 0.1$  (b);  $s = 0.01$  (c)

Figure 4 shows the obtained models of nanoclusters for different sticking probabilities  $s$ , in which the skeleton of a fractal configuration was previously selected. It tends to complicate its structure with increasing value of  $s$ , and behaves in the same way as the fractal itself that contains it.

## 2.2. Algorithms for calculating electrical conductivity

For nanofilms with a dielectric type of electrical conductivity, with a sparse structure of nanoclusters/islands, we have developed an essentially quantum model of electrical conductivity [30, 36, 37], which implements the CVC estimate taking into account the tunneling effect [30] and charge/electron jumps between islands [37] (they are shown below in Fig. 5).

Then the CVC of the nanofilm is estimated in terms of the sum of the strengths of the currents flowing through the nanoclusters/islands both within them and between them, calculated in accordance with Ohm's law [38]. The resistance of the conduction path in the system of nanoclusters/islands was calculated using the standard formula, taking into account the fact that the length of a possible current path should be the shortest distance between the points of voltage application by microcontacts.

The search for such a distance is carried out according to Dijkstra's algorithm [31].

To determine the direction of such an electrical conduction path between the islands, we used the hopping conductivity approximation, which was implemented as a process of carrier transfer taking into account localized states at a given temperature (it determines the efficiency of electrical conductivity by the thermal activation mechanism). Localized states were understood as states represented by wave functions given in a limited region of space and exponentially decreasing with distance  $r$  outside it:

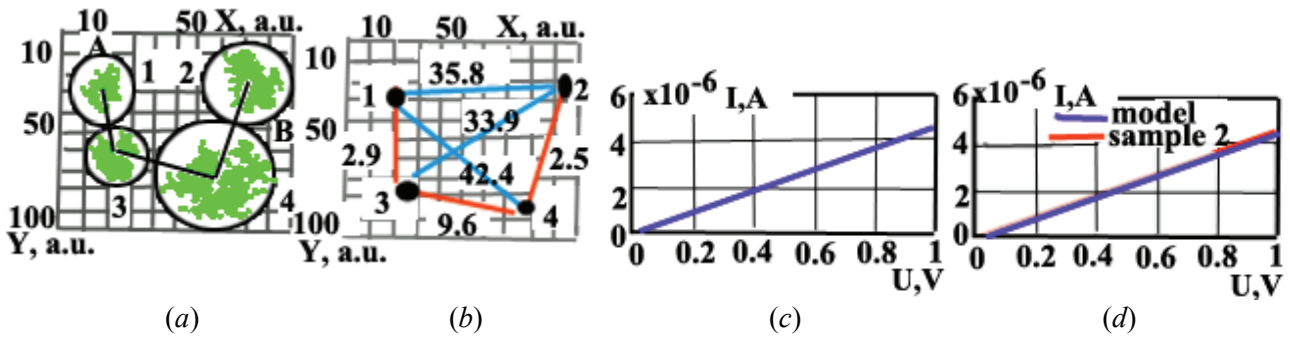
$$\Psi(r) \sim \exp(-r/a_b), \quad (3)$$

where  $a_b$  is the localization radius, i.e. the size of the cluster.

Thus, hopping conductivity is realized in this model as carrier transfer along localized centers [2].

Such hopping conductivity can be described within the framework of the Miller–Abrahams approach [2, 13, 39], when, based on the localized wave functions of an electron, it becomes possible to estimate the probability of its transition between two neighboring localization centers. Further, by calculating the resulting current, one can estimate the resistance of the electronic junction and reduce the problem to calculating the electrical conductivity of an equivalent network of random resistances.





**Fig. 5.** Model of an island PbTe nanofilm of 4 isolated islands and its I-V characteristic at  $T = 300$  K:

*a* – DLA model of the structure with selected minimum coverage circles, *A* and *B* the voltage application points;  
*b* – electron hopping graph; *c* – corresponding CVC; *d* – comparison of the CVC for the sample calculated according to Ohm's law with the simulation results

The resistance connected between a pair of nodes of such a Miller–Abrahams grid [39] has the form:

$$R_{ij} = R_{ij}^0 \exp\left(\frac{2r_{ij}}{a} + \frac{\varepsilon_{ij}}{k_B T}\right), \quad (4)$$

where  $R_{ij}^0$  is the proportionality factor,  $r_{ij}$  is the distance between  $i$  and  $j$  grid nodes,  $a$  is electron or cluster localization radius,  $\varepsilon_{ij}$  is the electron/cluster energy difference at  $i$  and  $j$  nodes,  $k_B$  is Boltzmann's constant,  $T$  is temperature.

The length of the electrical conduction path between nanoclusters/islands  $L_h$  was determined by the Dijkstra algorithm [31, 34] as the shortest distance with the minimum weight.

In this case, the resistance  $R_h$  for the one-electron case is calculated as [40]:

$$R_h = \sum_{i=1}^n R_{ij}, \quad R_{ij} = R_{03} \exp\left(\frac{2w_{ij}}{a} + \frac{\varphi}{k_B T}\right), \quad (5)$$

where  $n$  is the number of edges that make up the conduction path,  $R_{ij}$  is the resistance of the edges included in the conduction path  $L_h$ ;  $R_{03}$  is a constant depending on the radius and character of the distribution of island localization centers,  $w_{ij}$  is the statistical weight of the edge entering the conduction path,  $a$  is the electron localization radius – (hereinafter, for definiteness, we will talk about the electron),  $\varphi$  is the activation energy of conduction.

In this case, for a random distribution of localization centers,  $R_{03}$  has the form:

$$R_{03} = L \frac{\pi \hbar a}{16 q^2} \exp\left(\frac{2}{a N^{1/3}}\right), \quad (6)$$

where  $N$  is the concentration of localization centers,  $q$  is the electron charge,  $\hbar$  is the reduced Planck constant,  $L$  is the scale factor.

Figure 5 shows a model image of a PbTe film with a surface density of nanoclusters characteristic of the real sample 2 we are studying below. For clusters, the circles of the minimum coverage are selected (Fig. 5a), and the corresponding graph (Fig. 5b) of electron hops is constructed, with voltage applied to the points of microcontacts *A* and *B*, taking into account the maximum value of the jump, equal to the localization radius for PbTe with  $a = 50$  nm.

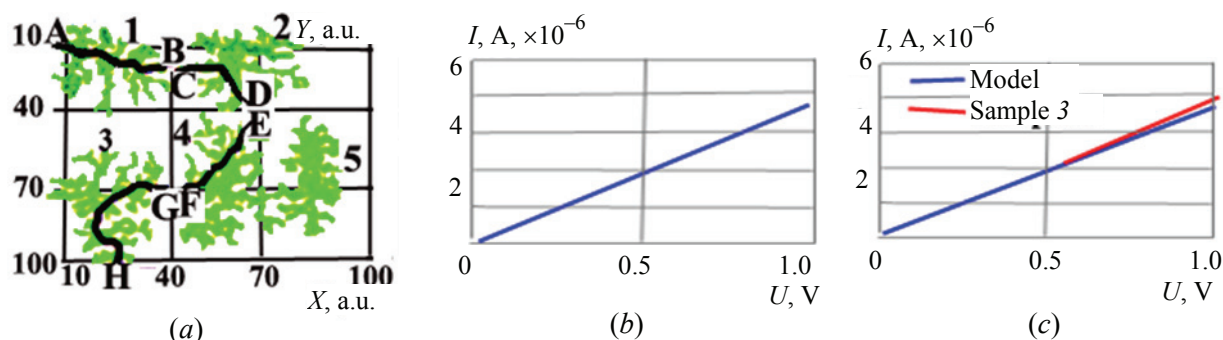
Thus, the total length of the conduction path over islands was 140 rel. units in the model. In absolute terms, taking into account the cell size of the computational region of 10 nm, its digital value is 1400 nm (Fig. 5a). This value corresponds to the resistance  $R_h$ ; inside the nanocluster itself, we denote the resistance by  $R_c$ .

The graph in Fig. 5b shows the shortest distance between islands 1 and 2, the value of which was 15.9 nm. At  $T = 300$  K PbTe parameters:  $\rho = 2.23$  Ohm·m,  $\varphi = 0.31$  eV,  $a = 50$  nm,  $N = 0.15 \cdot 10^{16}$  cm $^{-3}$ ,  $R_h = 0.021 \cdot 10^6$  Ohm, and  $R_c = 0.19 \cdot 10^6$  Ohm. The total resistance is  $R = 0.21 \cdot 10^6$  Ohm.

The magnitude of the calculation error was estimated by the difference  $d$  between the calculated ( $R_m$ ) and average measured ( $R_e$ ) resistances:  $d(R_{me}) = |R_m - R_e|$ . It was 3.8 %.

Figure 5c shows the calculated CVC, taking into account the calculated resistance for the voltage range [0; 1] V at  $s = 1$ . Figure 5d compares the CVC calculated according to Ohm's law for sample 2, taking into account the experimentally measured resistance values, with the calculated current strength





**Fig. 6.** Model of a PbTe island film of 5 isolated islands and its CVC at  $T = 328$  K: DLA model of the structure with the selected shortest distance between the given points A–B (a); CVC (b); the difference between the calculated and measured resistance  $d(R_{me})$  for comparing the CVC characteristics for sample 3 calculated according to Ohm's law with the simulation results (c)

From this figure, we can conclude that the results of experimental measurements and calculations are in satisfactory agreement – their difference does not exceed 10 %.

At  $T \sim 300$  K and parameters corresponding to the cluster structure of PbTe, but for another sample 3 we have:  $R_h = 0.016 \cdot 10^6$  Ohm, and  $R_c = 0.196 \cdot 10^6$  Ohm. Then the total resistance is  $R = 0.212 \cdot 10^6$  Ohm. The results are shown in Fig. 6. Estimating the difference between the results of the experimental measurement of the average resistance and the model calculation for the resistance, we can conclude that it does not exceed 6 %, which also indicates a satisfactory degree of agreement between the simulation results and experimental measurements.

Thus, we can conclude that the use of the electrical conductivity model based on the formation of a conductivity cluster, taking into account tunneling and the hopping mechanism between cluster islands, makes it possible to describe the experimentally observed phenomena for island/nanocluster nanofilms of various elemental compositions (we considered this approach and used it for different substances: Au, Ag and their complexes, PbTe, etc.) [1, 26].

### 2.3. Local fields and amplification factors for electrical conductivity

In a dense ensemble of nanoparticles on the surface of a semiconductor with a static permittivity  $\epsilon_S$  (for PbTe  $\epsilon_S \sim 400$  at  $T = 296$  K [41]), the local electrostatic field  $E_i$  in such a cluster system, due to inhomogeneities and collective effects, can greatly exceed the external applied field  $E_e$  due to the localization of the electric field at the sharp boundaries of the tips of inhomogeneities. This is the basis in optics, for example, of the effect of a sharp increase in the intensity of Raman scattering of light

by molecules on a surface (Surface Enhanced Raman Scattering – SERS) for surface rough metal media (see, for example, [1, 2, 18, 19]). The physics of this phenomenon is associated with the occurrence of localized surface plasmon resonances for certain wavelengths, depending on the surface material. However, geometric factors are of fundamental importance – the size of such local protrusions with their boundary conditions, as well as the density of these objects. But in electrophysics, everything is more complicated due to the ongoing averaging of parameters along the streamline, in particular, with a statistical spread of roughness heights and a finite size of the tip of the measuring microcontact/needle.

When considering this effect, an ensemble of nanoclusters on the surface of a semiconductor will be modeled by cylindrical nanoprotusions that allow an analytical solution, with a static permittivity  $\epsilon_S$ , a height of  $2b$ , and a diameter of  $2a$ .

If the condition on these key parameters  $b \ll a$  is satisfied, then it is unfavorable in terms of strengthening the local field, since such a structure is practically flat.

Within the framework of this model, it is considered that the protrusions are randomly distributed over the surface with a density of  $n$  [ $\text{cm}^{-2}$ ], and they are under the influence of an external lateral electrostatic field  $E_e$ .

It is physically clear that the field amplification factor  $G$  at an isolated inhomogeneity tip can be estimated as  $G \sim b/a$  [42]. However, the local field inside the selected nanoprotusion is formed as the sum of the nanocluster field violating the cylindrical symmetry (we call the effect of such a defect by the term depolarization effect)  $E_L$ , and the field  $E_\beta$ , acting on the selected nanoprotusion from the surrounding objects:

$$E_i = E_e - E_L + E_\beta, \quad (7)$$

where  $E_L = \frac{4\pi Ld}{V}$ ,  $L$  is the depolarization factor of the shape of a cylindrical nanocluster,  $d$  is the dipole moment,  $V = 2\pi a^2 b$  is its volume,  $E_\beta = \frac{4\pi\beta d}{V}$ ,  $\beta$  is the acting field factor [43]. In this approximation, we do not take into account the difference in the parameters of the medium in terms of scale for a monolithic sample and a micronanostructured one.

Given that

$$\frac{d}{V} = \frac{(\varepsilon_S - 1)E_i}{4\pi}, \quad (8)$$

we obtain an amplification of the local field inside the nanocluster [42, 44]:

$$E_i = \frac{E_e}{[1 - (\varepsilon_S - 1)(\beta - L)]} = GE_e, \quad (9)$$

where  $G = 1/[1 - (\varepsilon_S - 1)(\beta - L)]$  is field enhancement coefficient inside the nanoprotusion (if  $\beta > 1$ ).

To estimate  $\beta$ , we calculate the field created inside a selected cylindrical nanoprotusion (with radius vector  $r$ ) by the dipoles surrounding it. The dipole  $d$ , with radius-vector  $r$ , creates a field in the center of the base of the selected cylinder  $E_d = d/r^3$ . Summing over all dipoles, except for the selected one, we have for the total field of dipoles in the center of the selected quasi-planar nanocluster:

$$E_d = n \int_0^{2\pi} \int_0^\infty d\varphi \int_a^\infty r \left( \frac{d}{r^3} \right) dr = \frac{d2\pi n}{a}. \quad (10)$$

From the equality  $4\pi\beta d/V = E_d$  we find the estimate of the factor of the acting electrostatic field  $\beta = \pi nab$ .

The depolarization factor of the cylinder in the case of an electrostatic field is determined numerically [43]. It shows that the depolarization factor of the cylinder practically coincides with the depolarization factor of the ellipsoid with the same aspect ratio for its axes  $b/a$ .

So, for an ellipsoid, under the condition  $a \gg b$  depolarization can be represented as:

$$L = \left( \frac{b}{2a} \right) \arctg \left( \frac{a}{b} \right) < \left( \frac{b}{a} \right) \left( \frac{\pi}{4} \right) \quad (11)$$

and the acting field factor, using the relation  $n = 1/(\pi a^2)$ , has the form:

$$\beta = \pi nab = \frac{b}{a} > \left( \frac{b}{a} \right). \quad (12)$$

Comparing the obtained expressions for  $L$  and  $\beta$ , respectively (11) and (12), we can conclude that in the electrostatic case under consideration, a situation is possible when  $\beta > L$ . If there is a wide spread in the aspect ratio of nanoclusters in their ensemble, the presence of a subensemble with  $\beta \sim L$  is possible. Then from (9) it follows that in the case under consideration with  $\varepsilon_S \gg 1$ , it is possible, in principle, to increase by orders of magnitude ( $G \gg 1$ ) the electrostatic field  $E_i$  inside the nanocluster compared to the external field  $E_e$ , since the denominator in relation (9) can become close to zero for  $\beta \gtrsim L$ , and a condition arises in the denominator for the expression for  $G$  when  $(\varepsilon_S - 1)(\beta - L) \leq 1$ .

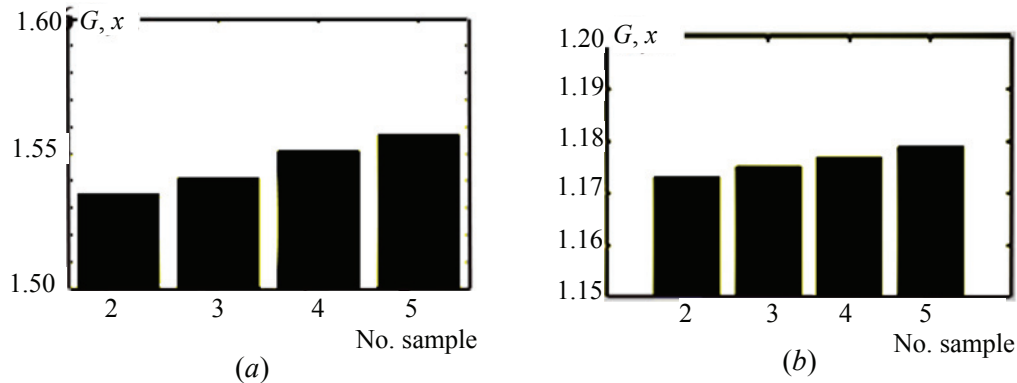
However, the very value of the density  $n$  and the shape of the inhomogeneity tip are also important [42]. In particular, for large  $n$ , the field can be screened from neighboring nanoclusters with different parameters.

We make such an estimate of the amplification factor  $G$  in the above approximation depending on the density of nanoclusters on the sample surface ( $n$ ). We define the dependence of the nanoprotusion radius on the density of nanoclusters as  $a(n) = 1/\sqrt{\pi n}$ . Then, taking into account relations (9) and (11), the dependence of the gain on the density of nanoclusters will have the form:

$$G(n) = \frac{1}{1 - (\varepsilon_S - 1) \left( \frac{b}{a(n)} - \frac{b}{a(n)} \arctg \left( \frac{a(n)}{b} \right) \right)}. \quad (13)$$

Then for the values of  $n$  and the value of  $\varepsilon_S \sim 400$  at  $T = 295$  K for the parameter  $b = 100$  nm in the approximation of cylindrical nanoprotusions, the calculated field enhancement does not exceed 1.56, i.e. 50 % of the average value for the longitudinal direction (Fig. 7a) and a value of 1.179 or 17 % of the average value for the transverse direction (Fig. 7b). The modeling error turned out to be about 3.8 % for the longitudinal direction and 1.6 % for the transverse one. Such error values testify to the satisfactory adequacy of the proposed model.

Thus, within the framework of the model used, we see that the amplification factor  $G$  for a semiconductor material (in our case, this is PbTe) is significantly inferior to its values, for example, for noble metals (it is  $\sim 1000$  for them). But what



**Fig. 7.** Calculated value of the field strength gain according to the model of the system of nanoprotusions for samples 2–5 with different surface topology: *a* – longitudinal direction; *b* – transverse direction

is important for us now is mainly methodological approaches for carrying out calculations. For SERS-activation of semiconductor materials, complex amplification mechanisms are implemented, which are determined by various defects and vacancies in them, as well as by the composition of the studied molecules. This requires modification of the parameters, in particular, in relation (13), with a significant decrease in the value of its denominator. However, such an assessment of these factors is beyond the scope of this paper. But, on the other hand, our estimates indicate the possible conditions for using the approaches of macroscopic electrodynamics of monolithic samples for the considered nanostructured objects, in our case, for PbTe. This is important in practice when analyzing certain problems of nanoelectronics and nanophotonics.

#### 2.4. Experimental methodology

To study the electrical conductivity of nanocluster/island nanofilms, their electrical resistance is analyzed. At present, there are many methods for measuring the resistivity of metal and semiconductor island nanomaterials and structures [44–46].

The main characteristics of the most popular and convenient methods for determining the resistivity of nanostructures are summarized in Table 1. Analyzing the above table, we can conclude that the four-probe method is most suitable for measuring the nanocluster/island nanofilms obtained by us.

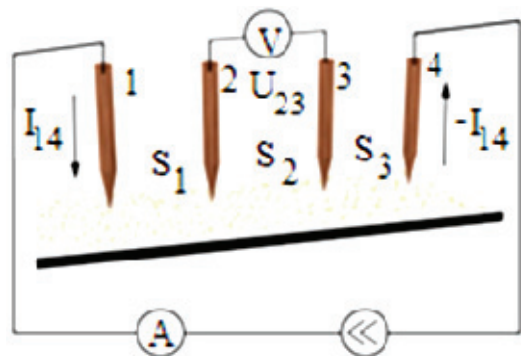
Experimental studies of the electrophysical properties of the nanocluster/island nanofilms obtained by us were realized through the measurement of their CVC. In this case, the analysis was carried out using a four-probe circuit with a linear arrangement of contacts (Fig. 8) [45–47]: two extreme contacts 1 and 4 provided a direct current supply  $I$  using a stabilized power source and were located at the same distance from each other,

$S_1 + S_2 + S_3 = (6 \pm 0.01)$  mm. The inner probes, 2 and 3, were conducting needles of an atomic force microscope with a radius of curvature of 100 nm. The pressing force of the probe was about 1 N.

The required current was set on the source, and the corresponding voltage was taken from the voltmeter. To carry out temperature measurements, the entire circuit was assembled in a vacuum thermal chamber with the possibility of reaching a pressure of  $10^{-3}$  Torr and heating the sample to 100 °C.

**Table 1.** Characteristics of methods for measuring the resistivity of semiconductor structures

Method	Error, %	Locality	Range $\rho$ , Ohm·cm
Four-probe	1–5	10–50 $\mu$ m	$10^{-4} - 5 \cdot 10^3$
Spreading resistance	5–20	10 $\mu$ m	$10^{-3} - 5 \cdot 10^2$
Contactless	10–20	1 mm	$5 - 10^2$



**Fig. 8.** Schematic representation of a 4-probe circuit

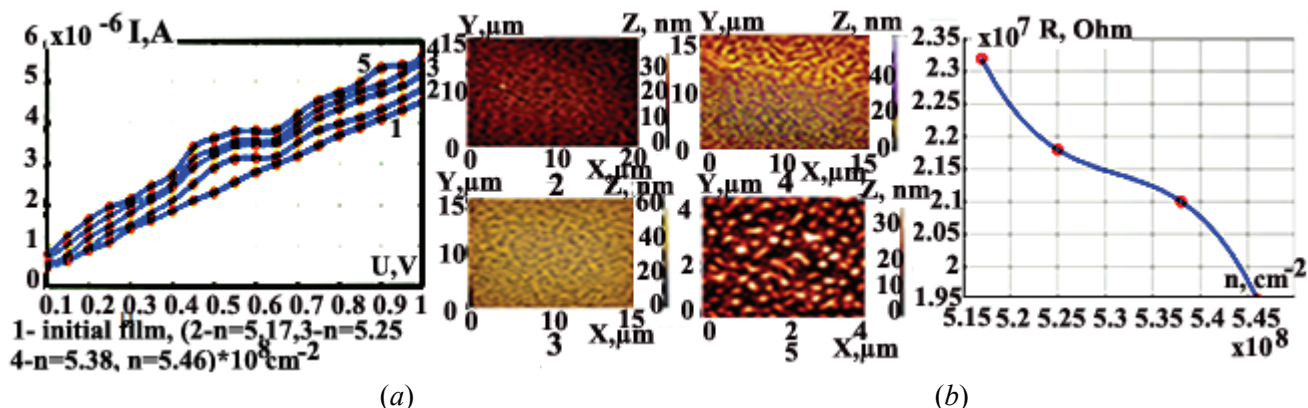


Fig. 9. *a* – CVCs (shown on the left)  $I(U)$  for the original ( $I$ ) and nanommodified (2–5) nanocluster/island PbTe thin films (their AFM images, which were obtained using NT-MDT NTEGRA, are shown on the right) – the surface density of nanoobjects is indicated directly by the curves; *b* – experimental dependence of electrical resistance on the surface density of used nanoobjects [51]

### 3. Results and Discussion

#### 3.1. Current-voltage characteristics and conduction mechanisms

The current-voltage characteristics of the original and nanommodified PbTe films are shown in Fig. 9. The CVC measurement in the experiment was carried out at room temperature ( $23 \pm 2$ ) °C. The voltage varied from 0.1 to 1 V. The resistance value in the studied range was about 107 Ohm. To average the result, 8–10 points on the sample surface were used [48, 49]. The resulting dependence was approximated by cubic splines for 100 points implemented in the MATLAB environment [50]. The current strength was about  $10^{-6}$  A. The current strength measurement error was 0.5% of its average value. CVC measurements were made in the longitudinal and transverse directions, which made it possible to show the dependence of the current on the topology of the sample under study (Fig. 9) [51].

It is clear from Fig. 9a (straight line  $I$ ), that in the absence of an ensemble of nanodots/nanoclusters on the film surface, its CVC has a linear character, in accordance with Ohm's law, with the dependence of the current density  $J$  on the external applied field  $E_e$  [49]:

$$J(E_e) = \sigma E_e, \quad (14)$$

where  $\sigma$  is electrical conductivity.

Analyzing Fig. 9a, we can conclude that the nanomodification of the surface leads to the appearance of characteristic features of the CVC for PbTe: an increase in its slope and the appearance of a pronounced local maximum. However, the dependence of CVC on average demonstrates a linear character in the voltage intervals (0.1–0.4) V and (0.65–1) V, and for the average voltage values in the

interval (0.4–0.65) V, a resonant current surge was observed. The magnitude of this surge was about 50 % of the average value for the longitudinal direction: the maximum value of the CVC surge is  $0.5 \cdot 10^{-6}$  A. In the case of the transverse direction, the maximum value of such a surge was about 16 % –  $0.15 \cdot 10^{-6}$  A. This can be caused by a higher density of cluster nanogranules in the longitudinal direction compared to the transverse one, which amounted to an average ratio of their densities of about 5.5 (Fig. 9b).

In this aspect, 1D structures are a typical example of an increase in electrical conductivity due to the dominant polarizability along one preferred direction. An illustrative example of such an effect is demonstrated by our experiments with a 1D carbon structure (LLCC) [4, 5, 8, 10, 11].

This demonstration curve for the CVCs obtained experimentally [10, 11] for an LLCC system in combination with Au–C–Au atoms is shown in Fig. 10 for a thin film 30 nm thick. An increase in electrical conductivity compared to the usual Ohm's law occurs due to the high polarizability of the 1D LLCC structure along the preferred direction [10, 11].

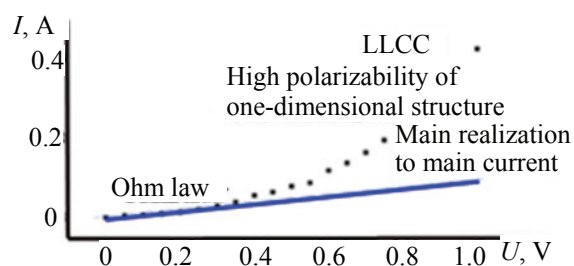


Fig. 10. Current-voltage characteristics for carbyne in the Au–C–Au system in a thin film on a solid surface with a thickness of 30 nm [10, 11]



In addition, the appearance of a resonant burst, as well as an increase in the CVC slope, can be considered as a result of the participation of weakly and strongly bound electrons in the surface electrical conductivity, which are initially at the size quantization levels in nanoclusters, taking into account the enhancement of the local field [50]. Thus, we assume that electrons are in a potential well (the standard quantum model of a cluster) [19] with a width of  $2a$  and a depth of  $P$ , and occupy energy levels of size quantization. In this case, the uppermost

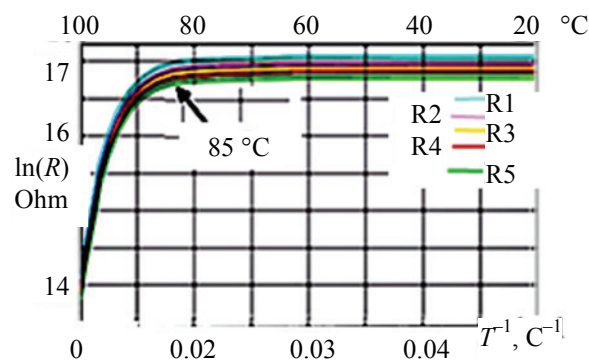
level ( $N$ th) of the filled levels has the  $\varepsilon_N = \frac{N^2 \pi^2 \hbar^2}{8m^* a^2}$ ,

energy, where  $m^*$  is the effective electron mass,  $\hbar$  is the constant Planck, and is separated from the top of the potential well by the energy distance  $\Delta_N = P - \varepsilon_N \gg k_B T$ ,  $T$  is the temperature,  $k_B$  is the Boltzmann constant. Under these conditions, a spontaneous transition of bound electrons to a free state (to the conduction band) at ordinary temperature is unlikely. However, due to the cluster structure, the presence of a local field  $E_i$ , even without an external applied field  $E_e$ , reduces the effective energy barrier depth for an electron by  $eE_i 2a$ . In this case, thermal ejection of an electron from the upper energy level from the well becomes possible [51].

Comparing the CVC for different films – a continuous PbTe film (the initial one in Fig. 9 and a nanocluster/island thin PbTe film, samples 2–5 in Fig. 9), we can conclude that the electrical conductive properties of the island structure have their own significant features. Therefore, the use of semiconductor nanostructured thin-film cluster structures in certain cases for a number of tasks is more preferable than solid films.

To elucidate the mechanism of electrical conductivity, the electrical resistance of the films was studied as a function of temperature in the range from 20 to 100 °C [51, 52]. Figure 11 shows the dependences of the natural logarithm of the resistance  $R$  on the reciprocal temperature  $1/T$ . Curves R1 – R5 correspond to films with different density of nanoclusters/dots on the surface (according to the data for samples 1–5 in Fig. 9).

As can be seen from Fig. 11, in the range from 20 to 85 °C, the electrical conductivity has a tunneling character – it does not depend on temperature. At temperatures above 85 °C, the behavior of electrical conductivity changes, which is caused by the manifestation of the thermal activation effect; the character of electrical conductivity becomes predominantly hopping [10, 51, 52].



**Fig. 11.** Temperature dependence of the natural logarithm of the resistance  $\ln(R)$  of films obtained under various deposition modes (see Fig. 9) with the same activation energy for all samples, equal to 0.3 eV [51, 52]

To estimate the experimental dependence of resistance  $R$  on temperature  $T$ , the relation [2, 13] is applicable:

$$R \approx R_0 + R_1 \exp\left(\frac{\varphi}{k_B T}\right), \quad (14)$$

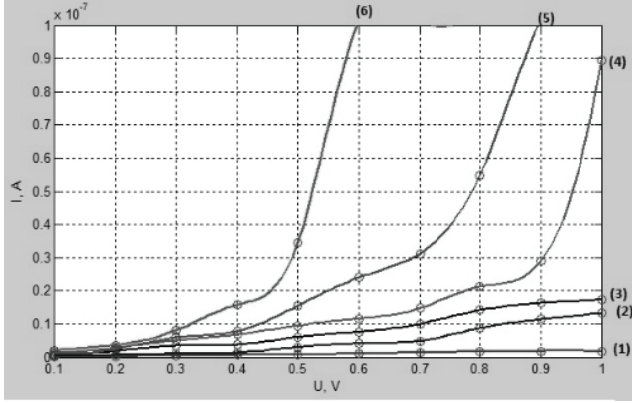
where  $k_B$  is Boltzmann constant,  $\varphi$  is the activation energy.

The first term in (14),  $R_0$  is due to the temperature-independent tunneling effect, and the second one –  $R_1$  is determined by thermally activated electron jumps. The thermal activation energy of hops between islands turns out to be significantly lower than the electron work function for this material in a bulk/monolithic sample, which is due to the effect of the granular structure on the substrate [2]. This allows us to speak about the possibility of creating effective elements of nanoelectronics and nanophotonics by analogy with quantum cascade devices [12].

### 3.2. The role of photoconductivity

For the electrophysics of thin films with a fractal structure, it is necessary to take into account the role of photoelectric conductivity, which depends on the spectral characteristics of the external radiation surrounding the sample. We simulated this process for the case of sample illumination with green laser radiation. In this case, the tunnel photocurrent naturally increases depending on the degree of illumination [2].

To evaluate the obtained dependencies, we used the apparatus of mathematical modeling in the MATLAB environment. The current-voltage characteristics were modeled in the Schottky



**Fig. 12.** Current-voltage characteristics of the tunnel current at different degrees of illumination:

$I$  – dark current, and also at different values of  $\gamma$  (%):  
2 – 5 %; 3 – 25 %; 4 – 50 %; 5 – 75 %; 6 – 100 %

photodiode approximation as the sum of the dark current  $I_d$  of the photocurrent  $I_{ph}$  [2, 13, 32]:

$$I = I_d + I_{ph}. \quad (15)$$

The dark current was estimated as:

$$I_d = I_0 \exp(qU/Nkt) - 1, \quad (16)$$

where  $I_0 = RA^* T \exp(-\phi/kT)$ ,  $q$  is the electron charge,  $\phi$  is the potential barrier,  $U$  is voltage,  $k_B$  is Boltzmann constant,  $T$  is temperature,  $A^*$  is Richardson constant,  $S$  is contact area,  $R$  is the electron reflection coefficient,  $N$  is the structure ideality coefficient. The sample temperature was assumed to be 293 K, the contact area was  $10^{-16} \pi \text{ (m}^2\text{)}$ , i.e. its radius was assumed to be 10 nm. The photocurrent was estimated as [53]:

$$I_{ph} = (qF\mu\tau/d^2)\gamma, \quad (17)$$

where  $F = (2qU/m_e)^{1/2}$  is the velocity of free electrons,  $\mu = (F U)/d$  is mobility,  $d$  is the distance from the nanofilm to the probe (1 nm),  $m_e$  is the electron mass,  $\tau$  is the lifetime ( $10^{-10}$  s),  $\gamma$  is the degree of illumination: it was a fitting factor and was estimated as  $\gamma = I_{100}/I_\gamma$ , where  $I_{100}$  is the measured current at 100 % illumination,  $I_\gamma$  is the measured current at illumination in  $\gamma$  %.

Figure 12 shows the model CVCs of the tunnel current in the case of different illumination intensity for the voltage range from 0.1 to 1 V, which we built in MATLAB using spline approximation.

For the proposed model, it was possible to achieve an error of the order of  $10^{-2}$ , which indicates a satisfactory degree of adequacy and allows, in a first approximation, to estimate the photoelectric properties of the structures obtained. This is of particular interest for various applications.

### 3.3. Temperature field calculation

Next, we briefly dwell on the calculation of the temperature field  $T$  that arises when scanning a laser beam of size  $a$  during the deposition of nanoclusters from a colloid on a solid surface under conditions of a moving laser source of intensity  $I$  over the sample surface using the following relationship [2, 18, 19]:

$$T(x, y, z, t) = \int \int_{-\infty}^{\infty} AI(x', y') W(x, y, z, x', y', v) dx' dy', \quad (18)$$

where the following parameters are indicated:

$$W(x, y, z, x', y', v) = \frac{1}{2\pi KR} \exp\left(-\frac{j}{2a}(x - x' + R)\right),$$

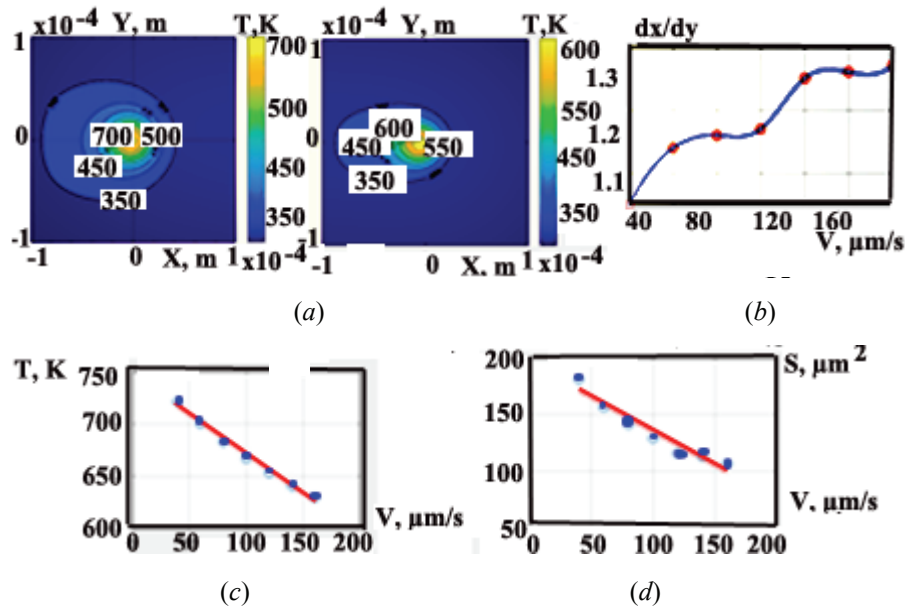
$$R = \sqrt{x^2 + y^2 + z^2},$$

coefficient  $A$  is the absorbance of the material,  $K$  is the thermal conductivity ( $\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$ ),  $j = K/\rho c_p$  is the thermal diffusivity ( $\text{m}^2 \cdot \text{s}^{-1}$ ) of the material,  $v$  is the scanning speed of the laser beam ( $\text{m} \cdot \text{s}^{-1}$ ),  $\rho$  is the density ( $\text{kg} \cdot \text{m}^{-3}$ ) of the sample substance,  $c_p$  is the specific heat capacity. Expression (18) was calculated using the fast Fourier transform (FFT) [54].

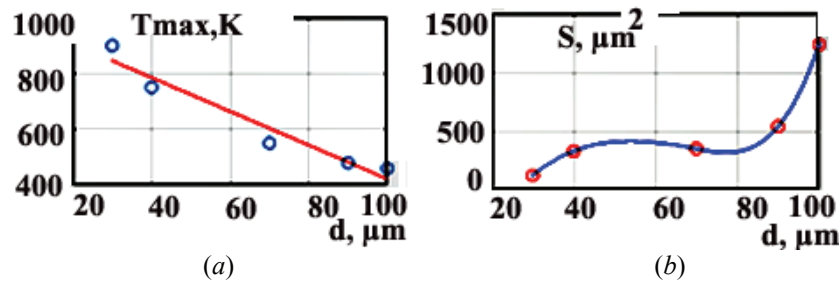
These calculations of the temperature field distribution on the surface of a target (sample in the form of a plate) made of lead telluride [49, 55] were carried out for the following parameters:  $A = 0.01$ ,  $K = 2.3 \text{ W} \cdot (\text{m} \cdot \text{K})^{-1}$ ,  $\rho = 8200 \text{ kg} \cdot \text{m}^{-3}$ ,  $c_p = 151 \text{ J} \cdot (\text{kg} \cdot \text{K})^{-1}$  on a model square calculation area with a size of 400  $\mu\text{m}$ .

For example, the results of calculations for the case of laser exposure with a power of  $P = 8 \text{ W}$  at beam diameters  $d_{\text{beam}} = 30 \mu\text{m}$  and  $d_{\text{beam}} = 100 \mu\text{m}$  at a scanning speed  $v_{\text{sc}} = 80 \mu\text{m} \cdot \text{s}^{-1}$  of the laser beam over the surface are shown in Fig. 13. The laser beam was applied to the center of the computational area. The initial temperature of the sample plate was 300 K.

Figure 13 shows that in the case of a laser spot diameter on the sample surface of 30  $\mu\text{m}$ , the maximum temperature at the center of the spot is  $(776 \pm 0.2) \text{ K}$ , which is much lower than the melting point of lead telluride (1190 K). With an increase in the beam diameter, the temperature field expands significantly with a simultaneous significant decrease in temperature to  $(420 \pm 0.2) \text{ K}$  at the center of the laser spot. The temperature distribution is asymmetric on the plane and is elongated in the direction of the laser beam: the target material in front of the moving source ( $x > 0$ ) is heated weakly.



**Fig. 13.** *a* – Effect of the laser beam velocity at its scanning of the sample surface on the temperature field at the laser power  $P = 7$  W,  $d_{\text{beam}} = 50$   $\mu\text{m}$ : temperature field in the case of a velocity of 40  $\mu\text{m}\cdot\text{s}^{-1}$  (left) and 160  $\mu\text{m}\cdot\text{s}^{-1}$  (right);  
*b* – the dependence of the eccentricity of the temperature area on the velocity in the approximation by splines;  
*c* – dependence of the maximum heating temperature on the velocity;  
*d* – dependence of the area of the heated region on the velocity



**Fig. 14.** Influence of the laser beam parameters on the realized surface temperature area: *a* – dependence of the maximum temperature  $T_{\text{max}}$  on the laser beam diameter  $d$ ; *b* – dependence on the beam diameter for the area of heating regions with the same temperature 350 K

The characteristic heating region (Fig. 13) has a value on the order of the laser beam cross-sectional area on the sample surface. Its shape differs from round and is elongated in the direction of movement of the radiation source. The temperature of the heating region decays slightly, and the length of the elongated part of the heating region does not exceed a quarter of the length of the heating region.

In the case of an increase in  $d_{\text{beam}}$  at fixed power  $P = 7$  W,  $v_{\text{sc}} = 80$   $\mu\text{m}\cdot\text{s}^{-1}$ , the following modes are realized: the maximum temperature  $T_{\text{max}}$  decreases in accordance with the following approximation:  $T_{\text{max}}(d_{\text{beam}}) = -0.0061d_{\text{beam}} + 1.0279$  (Fig. 14a), and the heated area  $S$  increases significantly (Fig. 14b).

#### 4. Conclusion

The thin-film solid-surface nanocluster structures of various configurations with cardinally controlled electrophysical characteristics considered in this article indicate the possibility of developing and creating nanoelectronics and photonics elements and systems with specified/required functional characteristics based on new physical principles.

Although we discussed only electrophysics, such a transformation of properties also applies to other characteristics, in particular, to optical ones (see, for example, the review in [1]). To date, a number of priority areas have already been formulated in this area. Among them are the following.

First, the presence of lateral fractal-type segments of different structures can, firstly, link various 1D current transport trajectories into a single ensemble [29] and increase (by analogy with a conventional conductor) the effective cross section in the form of such a bundle of trajectories (compare with [56]). Secondly, to lead to strong local electric fields at the "tips" of nanoclusters with sharp boundaries with the implementation of the effects of hopping conductivity and/or phenomena with a Coulomb gap, and/or with the thermally activated nature of electrical conductivity [28, 52, 57]. Third, they can be considered as a model of a medium by analogy with quasicrystals and structures with superlattices with translational symmetry [58].

Second, consideration of the formation of closed 2D structures of various configurations with edge channels on a percolation grid makes it possible to implement various controlled modes of electrical conductivity with different mechanisms in synthesized fractal cluster systems with a controlled electrical resistance over a wide range [28, 53].

Third, the quantum analysis of electrophysics for such objects, taking into account quantum fluctuations within the framework of the ideology of quantum phase transitions, makes it possible to substantiate the controlled obtaining in an experiment under normal conditions of exotic effects considered until now [59, 60] in electrical conductivity, which are realized under extreme conditions [10, 11, 15, 50]. First of all, this concerns one-dimensional 1D systems and their transformation in 2D and 3D structures of complex configuration for carbon materials both in carbon objects pure in elemental composition and in their various compositions, in particular, with noble metals [61–66].

A unique basis for successes and achievements in this field has already been created thanks to the solution of the problems of synthesizing a large class of carbon compounds with outstanding results even on an industrial scale [67–73].

All this can be very important for various topologically modified structures with superconducting phase states in carbon-containing compositions with different configurations and elements. This should determine the corresponding trends and trends in the increase in electrical conductivity, and will make it possible to predict the manifestation of such fundamental properties, on the basis of which the discussed real prototypes of hybrid topological electrophysical objects can be created on the basis of new physical principles [66]. Fundamental success here can be predicted for the future, taking into

account modern technological capabilities for the synthesis of carbon-containing systems of various dimensions (from 0D to 3D) and their complexes. Progress in this area is very dynamic, especially in terms of developing technology and equipment for the industrial production of nanostructured carbon materials of various compositions in complex systems for various purposes [67–73]. Of great importance here are studies in conglomerates with scandium, which, as shown in a recent paper [74].

The considered technologies using laser ablation are universal, they do not require expensive vacuum equipment used in epitaxial electronics, and constitute a promising area of printed electronics with controlled functional characteristics of synthesized objects, including nanotopological electrophysics and optics/photonics. It is precisely the controlled configuration of similar samples with surface topology of different dimensions and controlled elemental composition [41] that makes it possible to determine the physical principles and tendencies towards achieving superconducting states in micronanosystems for possible use in various CVC devices and new generation systems, including nanoelectronics and nanophotonics [10, 11, 75–103].

## 5. Additional materials (Appendix) Models of controlled synthesis of fractal structures

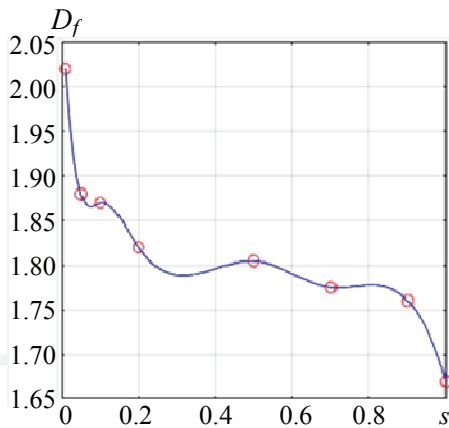
Without dwelling on the model images of the formed clusters and their structure (cf. Fig. 9) in dynamics, we only note once again that the process depends on the sticking probability parameter  $s$  of clusters to each other, which makes it possible to take into account the intensity of the thermal diffusion coefficient in the simulated system. Its value significantly affects the shape of nanoclusters/islands of a nanofilm: at low values, clusters with high degrees of filling are generated, and at large values, with low degrees of filling. The degree of branching of the structure (value and number of branches), expressed by the values of the fractal dimension characterizing the inhomogeneity, is proportional to the sticking probability (see Fig. A.1 below).

Thus, the number of main branches  $N_{bm}$  of a single cluster can be estimated depending on the fractal dimension  $D_f$  based on the relation:

$$N_{bm}(D_f) = \left\lfloor \frac{2}{D_f - 1} + 1 \right\rfloor + 1, \quad (\text{A.1})$$

where two vertical lines  $\lfloor \cdot \rfloor$  mean taking the whole part of the number.





**Fig. A.1.** Dependence of the fractal dimension ( $D_f$ ) on the sticking probability value ( $s$ ) taking into account the cubic spline approximation of the MATLAB programming

The performed computational experiments and their statistical processing have shown that the DLA model of aggregation with limited diffusion [50] makes it possible to obtain fractal clusters with dimensions ranging from 1.67 to  $(2.02 \pm 0.03)$  by varying the sticking probability  $s$  in the range of values  $[1; 0.01]$  (Fig. A.1).

In turn, the temperature dependence for the fractal dimension is determined by the relation:

$$D_f(T) \approx A_0 T^\alpha, \quad (\text{A.2})$$

where  $A_0$  and  $\alpha$  are proportionality coefficients within a certain calculation procedure [1, 55].

The anisotropy of the experimentally obtained fractal nanocluster configurations in the model used by us for the computational domain can be specified by determining non-equiprobable single random displacements of a particle during its diffusion wandering. This method of taking into account the anisotropy makes it possible to set the direction of diffusion of nanoparticles into the region of laser

heating as an increased probability of random displacements.

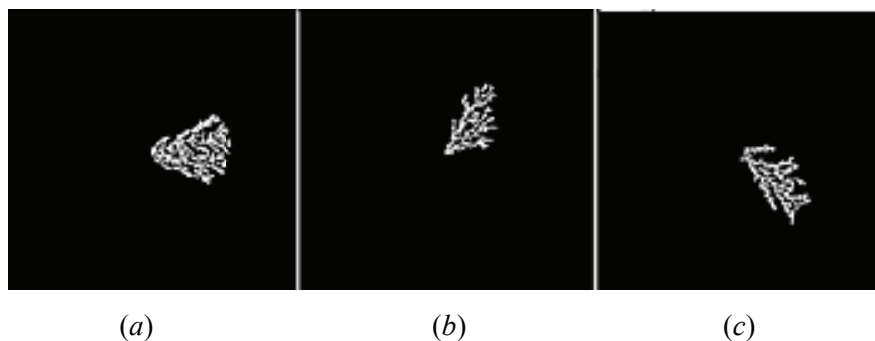
Specific values of  $D_f$  should be substituted into the ratio (A.2) for electrical resistance.

Thus, Fig. A.2 shows the results of the calculation within the framework of the DLA scheme, presented in Section 2, in the case of non-equiprobable displacements from a single initial nucleus located, for example, in the center of the computational domain.

Figure A.2 shows that the growth of the cluster is realized in directions with maximum probabilities of single displacements. In this case, the area of influence of laser radiation is located to the right of the center for the model from Fig. A2a, at the top on the right diagonal for the model from Fig. A2b, at the bottom on the left diagonal for the model from Fig. A2c.

The anisotropy of the computational domain can also be specified through the definition of the temperature field. Then, having a temperature distribution in the case of a flat substrate in the form of a system of isothermal regions, it becomes possible to estimate the sticking probability for a wandering particle when it enters one or another isothermal region.

We determine the temperature field directly for the PbTe sample. Since the length of thermal diffusion along the normal to the surface during the passage of the laser beam ( $\sim 1$  mm) was estimated to be much larger than the absorption length of laser radiation ( $\sim 10$   $\mu\text{m}$ ), the heat source was considered to be surface [18, 67]. In addition, the radiation source had a sufficiently high speed of movement, so the heat losses can be neglected and the flat case can be considered without taking into account heat fluxes. Also, since the thickness of the heated layer is much less than the thickness of the epitaxial film, the influence of the substrate can be neglected.



**Fig. A.2.** Model images of clusters at  $s=1$  in the case of different non-equiprobable displacements:  
 a – the probabilities of displacement up and down are the same in value 0.25, to the left 0.05, to the right 0.45;  
 b – up 0.45, down 0.05, left 0.05, right 0.45; c – up 0.03, down 0.22, left 0.05, right 0.45

Thus, our model has the following assumptions [68]:

(1) a plane case on a square computational domain is considered;

(2) heat losses and the effect of the substrate on the temperature field are not taken into account;

(3) boundary conditions are given by I-type conditions: a constant temperature is maintained at the boundaries;

(4) the quasi-stationary case is considered.

In this approximation, we considered the models of fractal nanocluster systems in Section 2, for which we analyzed the electrophysical characteristics for thin films on a solid surface in this article. At the same time, carbon-containing compositions synthesized of various types and their configurations of various dimensions, especially low-dimensional ones, exhibiting quantum properties, as well as demonstrating modes of nonlinear dynamics in localized structures with the implementation of topological phase transitions of various nature, are of particular fundamental importance both in fundamental and applied aspects.

In general, it should be emphasized that a large volume of scientific, scientific, technical and technological and industrial publications in this area determines the unique possibilities for obtaining and controlling the functional characteristics of various similar structures and hybrid systems based on them using powerful methods of mathematical and computer modeling, situational predictive modeling with prediction of obtaining the required characteristics and results in various applications, both technical and biomedical ones [104–162].

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## 8. Conflict of interest

The authors declare no conflict of interest.

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