# Topological photonics – 4D-laser technology for nanoelectronics on new physical principles to create the element base of next generation

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**Abstract.** In the paper we consider femtonanophotonics of the topological controlled low-dimensional dynamic structures in thin films induced by laser radiation on the surface of solids, using the achievements of quantum technologies and nonlinear dynamics for different regimes of electroconductivity.
We completed several laser procedures for obtaining nanostructures and thin films with controllable topology. They occur under the development of different nonlinear processes in the system (thermodiffusion, gas-dynamic evaporation in pore-like structures with bubbles, ablation products, ballistic movement of the particles in liquid). A simple 2-steps mechanism for enhancement of quantum behavior (e.g. in electroconductivity) exists for different conditions.
First, when inelastic length $l_{inelastic} > a_{cluster}$ (size of cluster) we have no incoherent electron-phonon (e-ph) scattering, and coherent process occurs with scale ℓcoh.
Second, when de Broglie length $\lambda_{dB} \equiv \ell_{coh} > \Lambda$ ($\Lambda$ – spatial period of the nanoparticle distribution) the coherent tunneling without loss occurs, and a long-range order with interference of the states takes place in the medium due to lattice structure in system.
Under such conditions, the electroconductivity enhancement can result in paradoxical phenomenon when electroconductivity in granulated structure may be higher than in monolith sample due to many surface/boundary units – like topological states in topological insulator.

## 1. Introduction

In the paper we consider femtonanophotonics of the topological controlled low-dimensional dynamic structures in thin films induced by laser radiation on the surface of solids, using the achievements of quantum technologies and nonlinear dynamics for different regimes of electroconductivity.

Currently, in practical aspect, all modern microelectronics is faced with problems of both technical and fundamental nature for technoprocesses.

In the first case, we are talking about the scaling limits, when with an increase in the density of the transistor arrangement, the heat release in the nanometer process increases and uncertainties arise due to quantum processes associated, for example, with tunnel currents [1]. In addition, the high cost of processes with a size of units of nanometers (see [2, 3]) and the requirements for the stability and reliability of their operation modes in the real conditions of the moving board location (vibrations, temperature variation and jumps, aggressive environment, oxidation, radiation etc.) determine the required practical scale of tens or even hundreds of nanometers (see, for example, [4]).

In the second case, in the fundamental aspect, the key drawback of the traditional von Neumann architecture is the fact that the commands for processing data and the data itself are stored together in memory, but the data processing operations and the execution of the actual calculations have a high speed in comparison with conversion to the memory [5]. In addition, there are natural fundamental limitations when the size of the designed element cannot be less than the lattice scale of the material (for silicon, for example, it is 0.5 nm).

An intermediate solution to these problems may be the transition to a neuromorphic architecture of a photon processor, when information is stored and processed simultaneously using photons of light [6]. This new hardware level is completely integrated into existing electronic circuits and functionally we are talking about hybrid systems «electrophysics+optics» [7].

A more global solution to the problem is the use of quantum technologies, including quantum infocommunication systems and quantum cryptography based on the achievements of quantum information advantages, and as the ultimate goal in future – the development of a quantum computer [8].

Taking into account the creation of an appropriate element base in nanoelectronic field by the achievements of modern laser experiments – femtonanophotonics [9], it is possible to control the spatio-temporal characteristics of such elements in the required direction to solve the problem of changing their functional properties in necessary directions. These, in fact, the 4D-technologies are the tool that should allow you to develop elements of logical systems on new physical principles. There are a number of directions for implementing these plans (see, for example, [10]).

In presented paper, we discuss one of the possible implementations along this problem – using nanophotonics approaches of low-dimensional topological thin-film structures, being, probably, a way for "Digital sovereignty" of Russia by unique kind hybrid systems and devices (electrophysics+optics).

Indeed, as demonstrated e.g. in our work [11], the electrical resistivity R of nanostructured samples can vary depending on the topology of structures deposited by laser methods on a solid substrate (for example, gold-Au nanoclusters) by more than 4 orders of magnitude when the nanocluster sizes change from 50 nm to 5 nm (Figure 1). In this case, everything is determined by the fractal dimension D of the obtained nanocluster structures (respectively, from, $D = 1.39$ to $D = 1.93$ by our calculation). Moreover, fairly uniform histograms of the size distribution of nanoclusters can be obtained quite easily, for example, at a scale of 10 nm±0.25 nm (see Figure 1 on the right).

Naturally, for such different topological structures, the optical transmission spectra of the substrates also change, and the Au-plasmon resonances shift/change in the region of 580 nm – Figure 2 (for monolithic Au-samples, the absorption wavelength of the plasmon resonance is 520 nm). At the same time, the maximum optical transmission is observed for $D = 1.93$ But the problems arise for such a granular structure (vs form, size and distribution, manylayers vs thickness) that not so easy to have one-way correspondence between topology and optical spectra – like in photonic crystals with varied parameters.

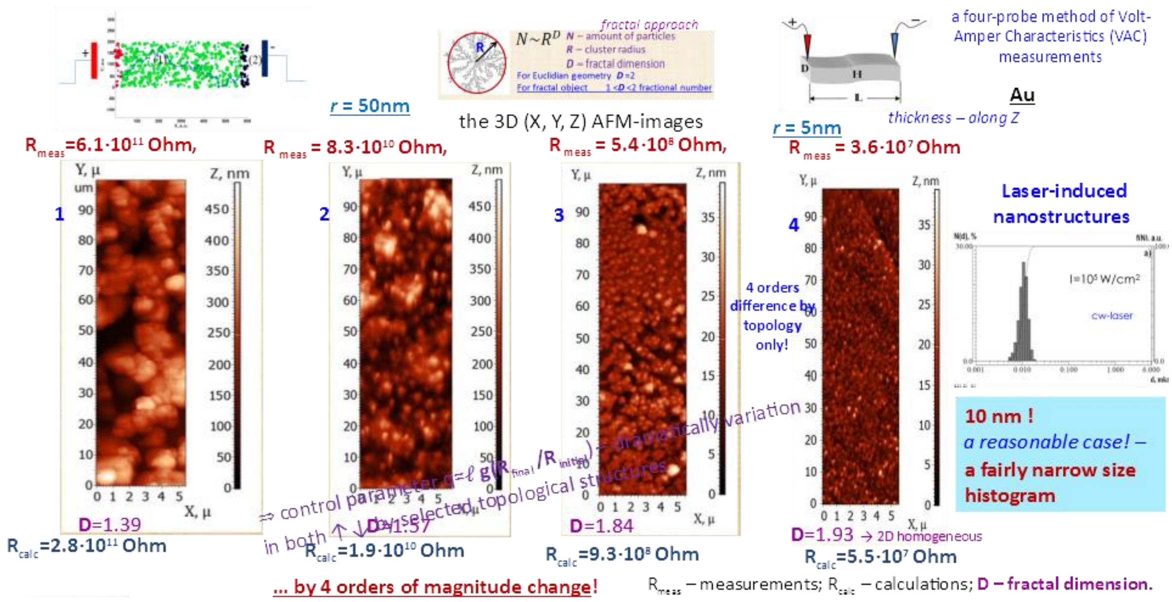



**Figure. 1.** Our measurements: electroresistance $R_{meas}$ vs nanoparticle size (r) and topology (D) – over a wide range of the values. Here: $R_{calc}$ – calculation result by adjustable fractal dimension. The narrow histogram over the size distribution of the nanoparticles is shown on the right.

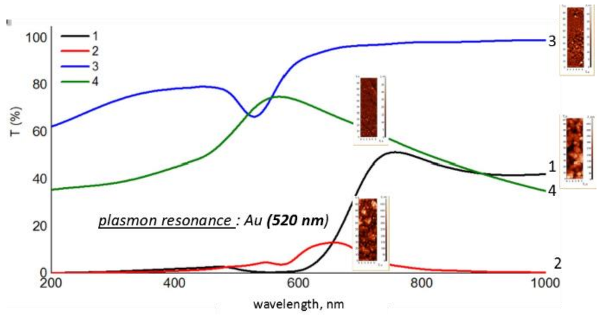



**Figure. 2.** The nanocluster structure should be correlated with the transmission spectra (vs structure: more conductivity in shell like system – wide optical spectra). Key parameters: sharpness (width and depth), and therefore a shift of spectra light propagation like it occurs through photonic structure.

The material of the paper is organized by following way. In next division 2 we discuss the 4D-Laser technology fabrication of new nanostructures and materials/cluster materials on solid surface, and consider the physical picture for several functional properties. In division 3 we analyze dendrite/fractal structures. In conclusion, we enumerate the summary collection over our different experiments on the topology peculiarities of the granulated metallic film deposited on dielectric substrates in frame of the topology photonics, and discuss as well the several perspective directions in the field.

## 2. The 4D-Laser technology fabrication of new nanostructures and materials/cluster materials on solid surface. Physical picture for several functional properties

Nanostructures and thin films with controllable cluster topology vs time depend on the laser pulses duration. In general, the interaction effects of solid targets with laser pulses of different durations for obtaining various nanocluster structures can be viewed as the possibility of synthesizing the 4D-objects, when the result depends not only on the stationary topological/geometric parameters of the system, but also on the dynamic interactions in the system leading to different final stable structures.

This is due to the fact that for different durations of laser pulses the specific mechanisms of nanostructuring are activated (i.e. Thermodiffusion, Gas-dynamic evaporation in pore-like structures with bubbles, Ablation products, Ballistic movement of the particles in liquid). Therefore, time plays the role of a control parameter responsible for phase transitions, as well as the spatial parameters do when nanoparticles (NPs) of various dimensions arise – from quantum dots (0D) to 3D nanostructures. In addition, for short laser pulses we have non-equilibrium/transient phase transitions over the steady-state pressure-temperature (PT) phase-diagram according to the laser trajectory of heating. Although the conventionality of this consideration is obvious (the equilibrium phase diagram cannot be used for non-stationary processes), but it allows to discuss the current trends and clarifying the basic physical picture.

Necessary conditions for quantum correlations are under expression for de Broglie lengths $\lambda_{dB}$= $h(mK_BT)^{-1/3}$ >> R~ $(V/N)^{1/3}$, where $K_B$ – Boltzman constant, m – charged particle mass, T – temperature, h – Plank constant, R – an average distance/ interaction spatial scale between NPs, V – volume, N – number of NPs. For typical monolith semiconductors relation between effective electronic mass $m_{eff}$ in solid and free electon mass $m_0$ is: $m_{eff}/m_0$~0.1, $K_BT$=0.025eV (for the room temperature), and $\lambda_{dB}$ =25nm (in contrast with metal, where $\lambda_{dB}$ < 1nm). But for certain materials this value of $m_{eff}/m_0$ is less in 10 times, e.g. for InSb $m_{eff}$ =0.013 $m_0$ (~$10^{-32}$kg) – see e.g. [4]. Therefore, we can talk about macroscopic quantum objects, especially for granulated structures when a spatial dispersion plays a principal role: $m_{eff} = \hbar^2 * \left[\frac{d^2\varepsilon}{dk^2}\right]^{-1}$, ε (k) – dispersive curve for the structure.

The formation of topological nanocluster structures in multilayer thin films on a solid surface in a controlled manner was realized in our experiment by laser methods according to a two-stage scheme (see, for example, [11]) – Figure 3.

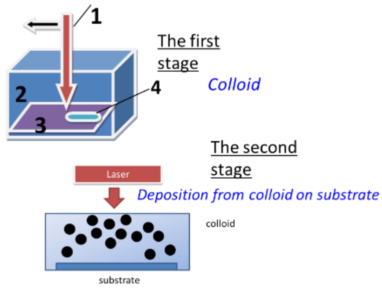
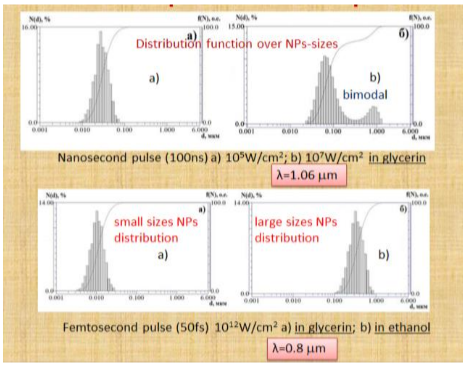



**Figure. 3.** Two-stage scheme for obtaining nanostructures on the surface of a solid surface (the explanation is given in the text).

First, the synthesis of nanoparticles/nanoclusters was carried out during laser ablation (1) of a target (3) from different materials placed in certain liquids (2) to obtain a colloidal system. In this case, laser radiation with different pulse durations was used – with a repetition rate of 20-100 kHz from msec to fsec – with an average power of $10^6$-$10^7$ W/cm$^2$.

Second, the deposition of nanostructures from colloid on the surface of a solid substrate under the action of continuous laser radiation of different power (up to 10W) when a certain strategy (4) of scanning a laser beam in a colloidal system took place.

This makes it possible to obtain histograms for the size distribution of nanoparticles with the required distributions, including bimodal and trimodal (see Figure 4).

I) 

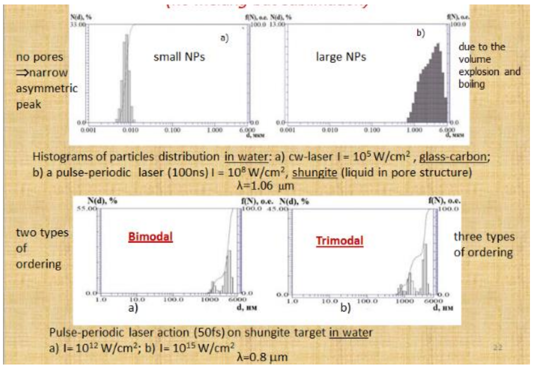

II) 


**Figure. 4.** Histograms of the controlled size distribution of Cu-nanoparticles (I) and carbon-nanoparticles (II) in the colloid for different conditions (they are shown directly in the Figures).

The fundamental features of the nanoclusters under consideration (see Table 1) are determined by the following factors [12].

(1) Physical meaning – is determined by not only the number of atoms N in cluster but number of electronic states, i.e. (N·valence) – valent electrons resulting in an effective nanocluster size.

(2) The ratio of the number of atoms on the surface layer (of the volume $\Delta V$ with the surface thickness $\delta$) – $N_\delta$ to the number of atoms in the volume V – $N_v$ is comparable $N_\delta/N_V \sim 1$. Thus, new physics arises due to individual interaction of both surface and bulk particles.

(3) The Core – Shell model, and therefore the magic numbers of particles can be applied to the nanocluster object under some conditions.

**Table 1.** Number N of nanoparticles in clusters (the size d) for different substance

| Substance | C | Fe | Ag | W | Au |
|---|---|---|---|---|---|
| Density, g/cm$^3$ | 3.5 | 7.9 | 10.5 | 19.4 | 19.3 |
| M $_{\text{atom unity mass}}$ | 12 | 55.8 | 108 | 184 | 197 |
| N (d =100 nm) | 9.1*10$^7$ | 4.25*10$^7$ | 2.9*10$^7$ | 3.1*10$^7$ | 2.9*10$^7$ |
| N (d =20 nm) | 7.3*10$^5$ | 3.4*10$^5$ | 2.3*10$^5$ | 2.5*10$^5$ | 2.3*10$^5$ |
| N (d =10 nm) | 9.1*10$^4$ | 4.25*10$^4$ | 2.9*10$^4$ | 3.1*10$^4$ | 2.9*10$^4$ |
| N (d =5 nm) | 1.1*10$^4$ | 5.3*10$^3$ | 3.6*10$^3$ | 3.9*10$^3$ | 3.6*10$^3$ |
| N (d =2 nm) | 7.3*10$^2$ | 3.4*10$^2$ | 2.3*10$^2$ | 2.5*10$^2$ | 2.3*10$^2$ |
| N (d =1 nm) | 91 | 42 | 29 | 31 | 29 |

If we are talking about the peculiarities of solid state physics, the goal is to change the functional properties of the units. The physical properties of nanocluster systems are very sensitive to the form, size and distance between their composing elements, and the fact is very well known for any material in general, but to change these parameters and to carry out the stable conditions for ordinary solid state object we need both to put the object under extremal high pressure ($\gtrsim 10^6$ atm) and to work in low (liquid He) temperature range ($\lesssim$30K) [13].In contrast, nanocluster structures can be easily modified in necessary direction and also by controlled way in femto- nanophotonics experiments [9]. The variation of the enumerated above topology parameters can result in new type of correlation states for charged particles with coupled states. Moreover, the electronic energetic bands of the materials can dramatically vary in the case, resulting in new physical behavior of the system.

We completed several laser procedures for obtaining nanostructures and thin films with controllable topology. They occur under the development of different nonlinear processes in the system (thermodiffusion, gas-dynamic evaporation in pore-like structures with bubbles, ablation products, ballistic movement of the particles in liquid). All these processes can be analyzed in accordance with different nonlinear hydrodynamic regimes. We discuss both some possible nonlinear mechanisms being responsible for a high electroconductivity and the features of obtaining a hopping conductivity in such inhomogeneous the thin film surface structures (with the thickness of up to 100 nm) when the charged particles are propagating along their boundary surface.

A simple 2-steps mechanism for enhancement of quantum behavior (e.g. in electroconductivity) exists for different conditions.

First, when inelastic length $l_{inelastic} > a_{cluster}$ (where $a_{cluster}$ – the cluster size) we have not incoherent electron-phonon (*e-ph*) scattering, and coherent process occurs with spatial scale $\ell_{coh}$.

Second, when de Broglie length $\lambda_{dB} \equiv \ell_{coh} > \Lambda$ ( $\Lambda$ – spatial period of the nanoparticle distribution) the coherent tunneling without loss occurs, and a long-range order with interference of the states takes place in the medium due to lattice/grid structure in the system.

Under such conditions, the electroconductivity enhancement can result in paradoxical phenomenon when electroconductivity in granulated structure may be higher than in monolith sample due to many surface/boundary units – like topological states in topological insulator [1, 4].

Moreover, in terms of basic aspects we can discuss a steady state random ergodic processes in cluster dynamic systems under conditions of dimensional quantization. The problems arise in two aspects.

First, a breaking of ergodic state due to several key-factors being specific: initial state principal item, coupling processes, dimensional quantization.

Second, optimal topology states can be induced with paradoxes in probability theory and statistics when a simple presentation for ergodic dynamic stochastic process does not work: final probability distribution due to averaging over time t does not equivalent to averaging over statistical spatial ensemble.

In the case, continuous spectrum for development of the unit in time and dissipation can result in strange attractor. In fact, it is possible to carry out the key parameter modelling for hopping phenomena by selected cluster energy in a quantum evolution system, and we have non-ergodicity behavior in electroconductivity in granular nanostructure due to the enhancement contribution effect for several states (cf. [14]) being the new phase states.

Let's consider the 1D-structures and functional characteristics of different types for the case. The principal modeling results are presented in Figures. 5,6 (cf. [15]).

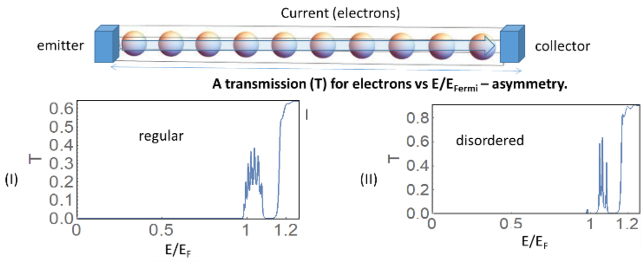



**Figure 5.** Electroconductivity in a quasi 1D-case. Electric quantum tunneling through 10 nanoclusters (Kronig-Penney 1D-model), i.e. nanocluster array (nanocluster superlattice) in both ordered (I) and disordered cases (II).Transmittance of a quasi 1D-structure consisted of nanoclusters as a function of the electron energy E (by ratio $E/E_F$, were $E_F$ – Fermy energy) for the regular (left) and disordered (right) structure. The numerical values: $N_e$ =40, $r_s$ =2.1, $m_{eff}$ =1.4, $m_0$ =0.708MeV, $E_F \approx$ 6eV $\hbar/\tau=10^{-3}E_F$ , $\ell\approx$20nm (distance between two clusters). Here $r_s$ – $Wigner\text{-}Seitz\ parameter \left(\sim \frac{1}{N_e^{\frac{1}{3}}}\right)$, $r_s = 2.1$.

Quantum-mechanical tunneling of electrons can occur both (1) into the nanocluster and (2) from the nanocluster into a neighbored nanoclusters. Resonant tunneling refers to tunneling in which the electron transmission coefficient through a structure is sharply peaked about certain energies. For electrons with an energy corresponding approximately to the virtual resonant energy level of the quantum well, the transmission coefficient is close to unity. That is why an electron with this resonant energy can cross the potential barrier without being reflected. This resonant phenomenon is similar to that taking place in the optical Fabry-Perot resonator and/or in the microwave capacitive-coupled transmission-line resonators, i.e. like Klein passing without reflection (see e.g. [16]).

The e-transmission spectrum of superlattice is splitted into a number of spectral bands (like Fano-resonance/interference).For calculation, we used transfer matrix approach with the Morse potential $V(r) = D_e\left(1 - e^{-a(r-r_0)}\right)^2$, where $D_e$ – a depth of the potential well; $a = \omega_0\sqrt{m_e/2D_e}$ – the width of the potential well; $\omega_0$ – a frequency of harmonic oscillator; $r_0$ – a local minimum position (for equilibrium state) [1].

As soon as the voltage at the microcontacts of the quantum well structure (see Figure 5) is out to corresponding energy of one of its resonant states, the tunneling current increases (region 1).

With a positive bias applied to the right contact relative to the left, the Fermi energy on the left is pulled through the resonant level $E_F$. As the Fermi energy passes through the resonant energy, a large current flows occur due to the increased transmission from left to right. It leads to significant increase of current (region 2). With higher bias, the current ceases to flow, when $E_F$ falls below the conduction-band edge. The result is a marked decrease of the current with increasing voltage, giving rise to a region of negative differential resistance or significant current suppression (region 3 – in accordance to the plateau in Figure 5). At larger bias the current increases again as particles acquire enough kinetic energy (region 4). Electrical current J is defined as: $J = eS\int_0^{p_f}\frac{\hbar k_z}{m^*}T(k_z)\frac{2\pi\,(p_F^2-\hbar^2k_Z^2)}{(2\pi\hbar)^3}\hbar dk_z$, where S – the cross-section area of the structure, $p_F$ – Fermi momentum, $T(k_z)$ – transfer matrix for transmission coefficient.

A special case of 1D-structure is a creation of Long Linear Carbon Chain (LLCC) being a new carbyne phase for carbon [17].

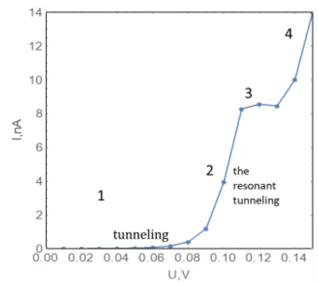



**Figure 6.** Voltage-current characteristic (VAC) of a quasi 1D-structure consisting of nanoclusters (the explanations are given in the text).

As an example we introduce one of our experimental results for Volt-Ampere Characteristics (VAC) for complex Au/Ag with carbon, resulting in a LLCC (see [18]), that presented in Figure 7.

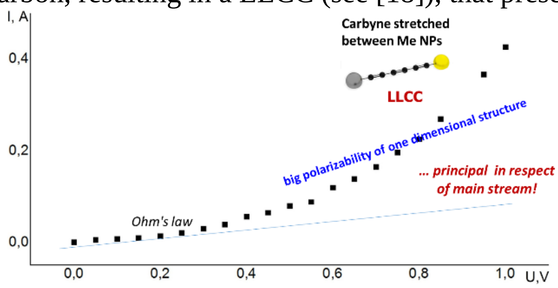



**Figure. 7.** VAC of the Au/Ag-Carbone linear structure (i.e. Au/Ag-carbyne structure) thin films with thickness 30nm on glass substrate. The enhancement of electroconductivity in comparison with the linear Ohm's dependence can explain by a big polarizability of linear dimensional 1D-structure – LLCC.

This result is principal because demonstrates the possible trend with comparison with the behavior like tendency to superconductivity in the 1D-electron stripe-stretch structure of cuprates O+Cu (they discuss high temperature superconductivity up to 600ºC (!)) – cf. [19, 20].

All these data result in new states in the topology photonics and optoelectronics.

In tact, for nanostructures (granulated size 10-100 nm) the thermodynamic, kinetic/transport and structure properties depend on the composite size particles due to their chemical nature, morphology of the particles, interphase surface and some interaction dimension effects like in heterogeneous systems. And we can speak about a real phase transition (vs thermodynamic parameters) but in this case not vs temperature T (like in condensed matter) and also both not vs external fields (e.g. vs magnetic field H in Liquid Crystal) and vs laser pulse duration (the temperature phase transition trajectory in fs-time domain) but now with a principal new behavior, i.e vs particle size – the nanostructure topology.

Physical reason for last case is that the inhomogeneous structure results in self-overcome of the energetic barriers for equilibrium states; in non-equilibrium systems the velocity dependence of the process in inhomogeneous structure is determined by kinetic parameters of the unit.

Finally, in general for clearance, the laser ablation (used by us) diagram in both time and space domains is shown in Figure 8 [21, 22].

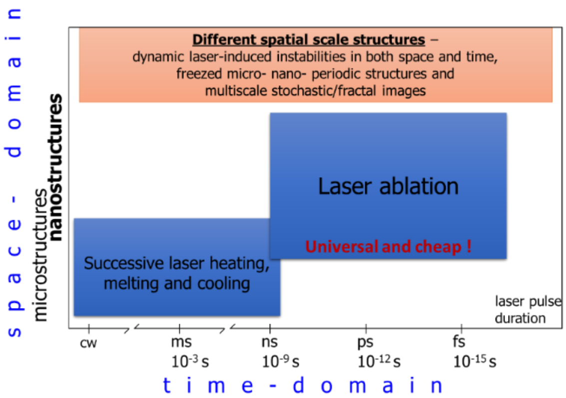



**Figure. 8.** Laser landscape – the 4D-technologies map [21,22].

## 3. Dendrite/fractal structures – prototypes of future topological elements

The model DLA – Diffuse Limited Aggregation of deposition and the formation of complex dendrites/fractal structures on surface, is based on the procedure with the algorithm consists of the several steps [23]:

1) on a square two-dimensional lattice, a germ structure is specified;
2) far from the cluster (from the nucleus), a new particle is generated in the nucleation region;
3) a new particle wanders randomly, taking into account the viscosity of the medium;
4) if a particle comes to a busy cell, then it sticks with a given probability;
5) if the particle moves far enough away from the cluster, it is destroyed;
6) repeat, starting from step 3, until the particle sticks with a given probability, after which a new particle is launched.

In the computer simulation we used both the initial concentration of the aggregation centers varied (center and lower boundary — (a), (b); and the probability of sticking of particles within the two-dimensional von Neumann neighborhood of order 1 (c) – Figure 9.

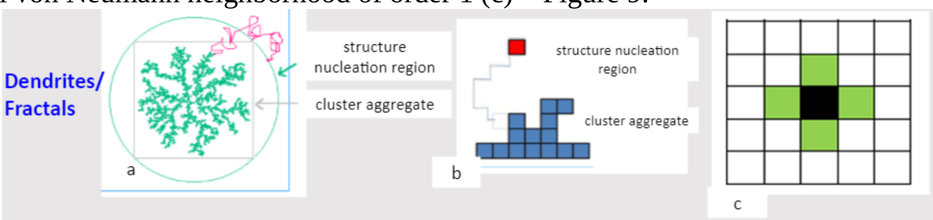



**Figure. 9.** Island model – DLA-scheme (Diffuse Limited Aggregation): (a) – formation from the center of the computational domain; (b) – formation from the lower boundary of the computational domain; (c) – von Neumann neighborhood.

The results of both calculation and experiments are presented in Figures 10, 11.

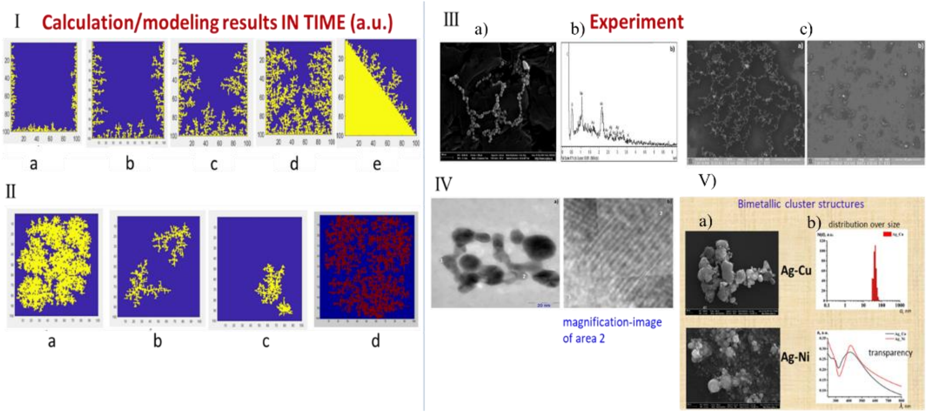



**Figure 10.** Development of Dendrite/Fractal structures.

I. Aggregation centers (top view) – the line on both the side and bottom boundaries for different islands of the computational domain: p = 0.1, sc = 0.1; (b) p = 0.1, sc = 0.5; (c) p = 0.5, sc = 1; (d) p = 0.8, sc = 1; (e) p = 0.5, sc = 1, where the controlling parameters are: sc – particle sticking probability (vs diffusion) ; p – viscosity.
II. The Model films (below view): 5 islands: p = 1, sc = 0.1 (a); 2 islands: p = 0.1, sc = 1 (b); 2 islands: p = 0.1, sc = 0.1 (c); 5 islands: p = 0.5, sc = 1 (d).
III. REM-images of deposited Au-Ag cluster on the carbon surface (a) and X-ray spectra of the elements (b). REM-images of Au-Ag cluster deposited on the quartz surface with various concentration of nanoparticles in water (c): 1:10 (left); 1:20 (right).
IV. TEM-image of deposited Au-Ag cluster (area 1), lattice constants $d_1$=2,05±0,07A; $d_2$=2,07±0,07A (area 2). The interplanar values d(002) for both Au, and Ag.
V. Bimetallic cluster structure: (a) – structure, (b) – the particle size histogram (up) and transperancy spectrum (down).

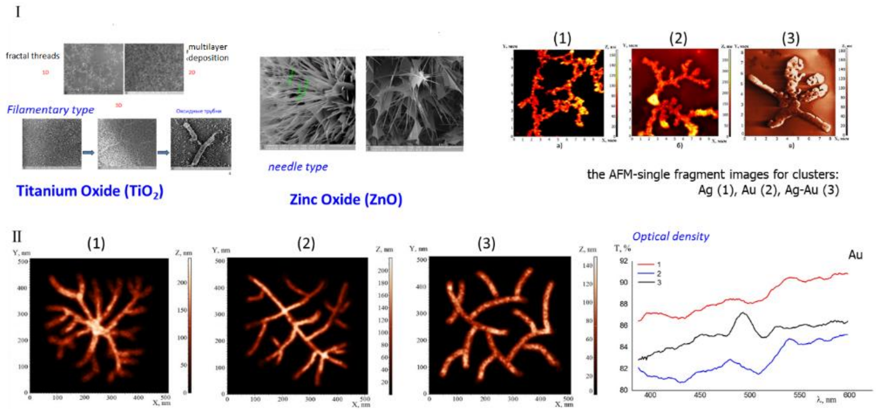



**Figure 11.** (I) Obtained different Fractal structures in Experiment (up platform). (II) Morphological variety of the deposited cluster and consequent optical density (down platform). Explanations are directly given in the Figures.

In progress, such complex structures may establish a new mechanism of the charge transport in thin films based on coherent migration of the deformation of the nanoclusters potential, which carries with it an electron. We define a defect in the form of a potential deformation, similarly to a defection (cf. e.g. [24], and see also [1,4,10]), as a quasiparticle being a distortion.

**Conclusion**

Let's enumerate the summary collections over our different experiments on the topology peculiarities of the granulated metallic film deposited on dielectric substrates – in frame of the topology photonics (cf. [7,25]).

First, in electroconductivity:
- the tunneling delocalized effect depends on the size of NPs, distance between them and shape of tunnel barriers and also vs variation of the thickness of the films, transition from amorphous to crystalline structure;
- the thermally activated hopping regime of the electron transport between localized centers;
- the topology enhancement electroconductivity tendency for cluster like for topological insulator with coupling electron states.

Second, in optical characteristics:
- the broadening of energetic electronic levels occurs;
- optical metasurfaces characteristics arise;
- strong optical response occurs;
- density of e-state (on Fermi-surface) can be varied by controlling way.

Third, the symmetry breaking process (Majorana states for quasi-particles, the quantum Hall partial size effect, Landau-levels, Tamm-states …) may be developed.

The principal problem on the subject is how to determine specific numerical values of the topology control parameters of a nanocluster system relying on these general relations for the achievement of the desired final result in the experiment. This requires a detailed research (in both theory and experiment) of the influence of nanocluster topological parameters on the functional properties of the substances used.

Nevertheless, the discussed phenomena give us an opportunity to establish the basis of new physical principles to create the functional elements for topological photonics in hybrid set-up (optics + electrophysics) being controlled by quantum coupled states and nonlinear dynamic processes. In progress, we can discuss the tendency and trends to superconductivity by adjustable both the element composition and the topology structure (cf. [26,27]).

Finally, we enumerate the list of perspectives-accents hybrid circuits (electrophysics + optics) [21].

**A.** Nanoelectronics and Materials: 2D materials, such as transition metal dichalcogenides (for example, $MoS_2$), black phosphorus (in some sense similar to graphene), topological insulators, and others.

Key parameters.

(1)Transport properties: topological insulators, low scattering and high mobility of current carriers.

(2)Power dissipation and scaling.

Directions.

(a) Neuromorphic computing, i.e. parallel analog computing, such as neural networks.

(b) Spintronics.

**B.** Nanophotonics: terahertz modes, nanoplasmonics and metamaterials.

**C.** Nanoenergy: nanostructured systems for improved light collection.

**D.** Nanomedicine: nanomaterials for the development of cell/molecular biology and tissue engineering.

In conclusion, let's enumerate the few points of modern advantages and activities in this several selected directions:

(1) A squeezed quantum microcomb on a chip, [28].
The quantum computing market is projected to reach $65 billion by 2030, a hot topic for investors and scientists alike because of its potential to solve incomprehensibly complex problems.
(2) Single-electron spin resonance in a nanoelectronic device using a global field by [29].
(3) Preparation and Readout of Multielectron High-Spin States in a Gate-Defined GaAs/AlGaAs Quantum Dot [30].
(4) Quantum proton entanglement on a nanocrystalline silicon surface [31].
(5) Layer Hall effect in a 2D topological axion antiferromagnet. [32].
(6) A post-quantum chip with hardware Trojans [33].

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