Verification of the quantum dimension effects in electrical conductivity with different topology of laser-induced thin-film structures

S Arakelian, A Kucherik, S Kutrovskaya, A Osipov, A Istratov, I Skryabin
Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky Street, Vladimir 600000, Russia

E-mail: kucherik@vlsu.ru

Abstract A clear physical model for the quantum states verification in nanocluster structures with jump/tunneling electroconductivity are under study in both theory and experiment. The accent is made on consideration of low-dimensional structures when the structural phase transitions occur and the tendency to high enhancement electroconductivity obtained. The results give us an opportunity to establish a basis for new physical principles to create the functional elements for the optoelectronics and photonics in hybrid set-up (optics + electrophysics) by the nanocluster technology approach.

1. Introduction
We focus our attention on the fact that physical properties of nanocluster/granular systems are very sensitive to the form, size and distance between their composing elements. The phenomena are 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 at low (liquid He) temperature range (\( \lesssim 30 K \)) [1]. In contrast, the nanocluster structures can be easily modified both in necessary direction and by controlled way in femto-nanophotonics experiments.

In our experiment we use the method of laser-assisted deposition metal particles from colloidal system [2]. For the deposition, we have used ytterbium fiber laser (\( \lambda = 1.06 \mu \)) with a pulse duration of 100 ns, pulse repetition rate of 20 kHz, and a pulse energy up to 1mJ. The diameter of the laser beam in the focal plane was 50 microns. Nanoparticle array formation on the substrate surface was performed by the scanning laser beam along the same direction.

The Volt-Amper characteristics (VAC) of the thin film were measured using a four-probe scheme. The electrical transport properties in analogy with tunnel and quantum correlated states are considered; namely the tunneling/thermal activation effects observed.

2. Features of the electrical conductivity in granular films: experiments and preliminary discussion

2.1. Noble metal structures
The experimental results for the thin films of gold, are shown in
Figs. 1, 2. Presented data are by averaging over 10 measurements; the film thickness (over Z-axis) was about 50 nm; nanoparticle size – about several nm.

We can see the jumps (Fig. 1) on the obtained I(U) dependences for different thickness. Moreover, we have a six orders difference in values of R (Fig. 2) by topology variation only (different fractal dimension D: from D=1.39 to D=1.93 measured by a special procedure [3]. The tendency is, to decrease R when the nanostructure sample becomes more homogeneous as a 2D-structure.

Figure 1. (a) Experimental data for voltage-current characteristics (VAC) of the deposited layer for clustered Au-films with different thickness h;
(b) The dependences for R vs h; more detailed picture for initial part is shown in insertion, and can be presented as an analogue of the Kondo effect R(T) but in our case in version R(h).

To recognize a namely mechanism of conductivity for the cases, we carried out different experimental conditions by changing the topology of the film structure so as to realize the most optimal conditions for a given type of conductivity.

Figure 2. Experimental and theoretical (by fractal approach) comparison of values for electroresistance R for Au-nanostructure: a) Rmeas=5.4\times10^8 Ohm, D=1.39, Rcalc=9.3\times10^8 Ohm; b) Rmeas = 3.6\times10^7 Ohm, D=1.57, Rcalc=5.5\times10^7 Ohm; c) Rmeas = 5.4\times10^6 Ohm, D=1.84, Rcalc=9.3\times10^6 Ohm; d) Rmeas = 3.6\times10^2 Ohm, D=1.93, Rcalc=5.5\times10^2 Ohm, where Rmeas – measurements; Rcalc – calculations; D – fractal dimension.
2.2. Bimetallic structures

To observe such effects is reasonable to use the bimetallic gold and silver nanostructurised films, in which the dielectric barrier (silver oxide) will be formed between the metal (Au and Ag) particles. For bimetallic cluster conductivity of films, deposited on the glass surface, a nonmonotonic dependence of the electroresistance of the film thickness from the amount of deposited materials is obtained (Fig. 3). In fact, we observed a competition between opening of new channels and area of the grains: for the (Fig. 3a)-case than more thickness weaker resistance in contrast with the (Fig. 3b)-case than more thickness more resistance.

First view of last obtained dependences can be explain by mechanism like Wannier-Stark ladder in super-lattices when e-conductivity has two contributions (cf. [4]): metallic conductivity for delocalized states and jump/tunneling mechanism for localized states (insulator).

At the same time the thermal activation effect impacts also on current value in the formed island films structure (Fig. 4). The activation energy measured by the slope of presented Arrenius like curves gives the value in 0.98 – 1.1 eV range.

2.3. The Volt-Amper measurements for PbTe-semiconductor; tunnel effect recognition

The observed VAC for different experimental conditions is shown in Fig. 5. Quantum tunnel conductivity was detected for specific conditions of the experiment (see Fig. 5a,b). We present the results of detecting the tunnel conductivity for different morphology of NPs on the substrate. Moreover, the occurrence of jump conductivity is universal—there have been shown free types of the electrical resistance measurements, the fact depending only on the topology of the conducting layer (fixed for a given sample). So, the implementation of the electrons transition from the bound state to a free state can be taken into account in the frames of shell model clusters.
2.4. Fabrication of the carbon linear structure

The stabilizing of long linear carbon chains [5] (carbyne chains) has been achieved by standard technique of laser ablation in different liquids in the presence of noble/gold nanoparticles which leads to the consolidation of the ends of linear chains on the surface of gold particles and prevents them from instabilities/destruction, i.e. twisting further in tangles. In addition, the symmetry environment of isotropic liquid from any side assisted as well to the LLLC stabilization [6].

Because of the linear carbon system has been stretched/ fixed by noble metal atoms like linear system between two metallic contacts (we may practically have a large dipole moment that should result in high electroconductivity in created elements. In fact, the dependence presented in Fig. 6 strongly support the idea.

Figure 6. The VAC for Au-carbyne thin films with thickness 30nm: the enhancement of electroconductivity in comparison with linear Ohm’s dependence due to 1D-structure.

Conclusion

We studied the cluster structures taking into account in both theory and experiment the correlations in nanoparticle-ensemble with the topological quantum states. The problem of high temperature superconductivity (due to topological surface structures with localized states resulting in coupled states on new dimensional principles) may be considered.

Future activity in the field should be focused on the more detailed comparison of obtained experimental results in dramatic increase of electroconductivity in induced (by controlling way) nanocluster systems and concrete mechanism of its development in different conditions. The results should give us the directions for possible applications of the phenomena in photonic devices of new generation.
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