PbTe island film hopping electrical conductivity model

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Abstract. The paper discusses experimental and modeled characteristics of the electrical conductivity of PbTe island films. The volt-ampere characteristics were measured using a four-contact circuit. The hopping conductivity was modeled as the Miller-Abraham network. Using the proposed approach, calculations were made for a network of 100 particles with a variation in the parameter value corresponding to the temperature.

1. Introduction
Island and granular metal films have a number of unique properties. In particular, in these metal films, the dielectric character of conductivity was observed, i.e. it was found that the electrical conductivity of the films increases with increasing temperature. [1, 2]

In the case of deposition of semiconductor films for materials with a high dielectric constant, this dependence can be even more pronounced. One of the materials demonstrating the quantum effects in conductivity in the formation of cluster structures is PbTe [3].

2. Results of the experiment
The initial heteroepitaxial structures of PbTe were grown by the method of molecular beam epitaxy in the laboratory of ETH (Zurich). The features of the process of depositing lead telluride layers and the parameters of the investigated films are described in detail in [4].

To investigate the current-voltage characteristic, a four-contact circuit was used, the two end contacts were made in the form of clamping areas, and two internal contacts were the needles of an atomic force microscope, which made it possible to measure at distances up to 100 μm between the needles. The resulting value is obtained by averaging 10 measurements in one position, the total measurement time at one point is 1 minute. Within the framework of the studies carried out, longitudinal and transverse measurements were made with respect to the modification area, the pressure contacts in both cases were located 1 cm apart along the laser modification region. The current-voltage characteristics of the initial and modified PbTe films are shown in Figure 1.
Figure 1. Volt-ampere characteristics of the initial and modified PbTe films as measured in the longitudinal direction.

3. Mathematical model
The structure of island PbTe films can be modeled as a disordered system of particles aggregated into clusters. In such structures, transport of charge carriers is due to tunneling of electrons. Thus, hopping conductivity between particles in disordered systems can be modeled as a network of random resistors, called the Miller-Abraham network. [5]

The conductivity of the network $G_{ij}$ was calculated as

$$G_{ij} = \frac{e^2}{k_BT} \exp\left(-\frac{E_{ij}}{k_BT} - \frac{2r_{ij}}{a} \frac{1}{\tau_0}\right),$$

$E_{ij}$ - the energy difference between the particles i and j, $1/\tau_0$ has the order of the phonon frequency, $r_{ij}$ - distance between i and j, $a$ - Bohr radius, $k_b$ – Boltzman constant, $e$ – elementary electric charge $T$ – temperature of the system [6].

4. Results of the modeling
Using the proposed approach, calculations were made for a network of 100 particles with a variation in the parameter value corresponding to the temperature. Conductivity between two particles was represented in exponential form in the dependence of distance and energy. A random resistor network was visualized (Figure 2), energy and average conductivity were found for all particles (Figure 3).
The Figure 2 shows the networks for two different realizations of one electron hope. Comparing Figure 2 (a) and Figure 2 (b), it can be noted that there are obvious changes in conductivity around the areas from which electrons leave and begin to jump, as well as between particles that are relatively far from the considered. When an electron jumps from particle i to an unoccupied particle j, the sign of the Coulomb interaction of energy between the particle i (j) and other particles is reversed, which can significantly affect the conductivity between the sections.

To estimate the effect of temperature on the conductivity, conductivity calculations were performed with a variation in the value of the parameter corresponding to the temperature and the parameter corresponding to the dielectric constant (Figures 3, 4). The temperature parameter varied from 1 to 2 rel. units, the dielectric constant was from 1 to 1.2 rel. units.

Figure 3. The average conductivity for all particles at a) T = 1 rel. units b) T = 1.5 c) T = 1.8 rel. units d) T = 2 rel. units.
Figure 4. Dependence of the average relative conductivity on temperature.

It was also found that the Coulomb interaction plays an important role in the calculation of hopping conductivity between particles, and also that the total energy of all the transitions realizations for one electron hope can correspond to the Gaussian distribution [6] From the calculations it was found that with increasing temperature the intensity of the jumps increases, so the conductivity also increases.

5. Conclusion
The character of the obtained model dependences corresponds to the theoretical and experimental data [1], which allows us to apply the approach to study the electrical conductivity of PbTe island films in the first approximation.

Acknowledgments
The reported study was also supported by the Ministry of Education and Science of the Russian Federation (state project no.16.1123.2017/4.6), RFBR grant 16-42-330461 r_a, President grant for young scientist MK-2842.2017.2.

References
[1] Antipov A A, Arakelian S M etc 2016 Electric conductivity of nanocluster PbTe structures with controlled topology: Manifestation of macroscopic quantum effects Bulletin of the Russian Academy of Sciences: Physics 80(7) 818-27
[2] Kavokin A, Kutrovskaya S etc 2017 The crossover between tunnel and hopping conductivity in granulated films of noble metals Superlattices and Microstructures 111 335-39
[3] Antipov A A, Araklian S M etc 2014 Electrical properties of metal cluster structures formed on the surface of dielectrics Technical Physics Letters 40(6) 529-32
[4] Antipov A A, Arakelyan S M etc 2011 CW laser-induced formation of a nanoparticle ensemble with a bimodal size distribution on PbTe films Quantum Electronics 41(8) 735-37
[5] Pochtennyi A E 2016 Hopping conductivity at constant current in intrinsic and impurity organic semiconductors: monography (Minsk: BSTU) p 171
[6] Amirhossein B O, Uttandaraman S and P Mertiny 2014 Tunneling Conductivity and Piezoresistivity of Composites Containing Randomly Dispersed Conductive Nano-Platelets Materials 7 2501-21