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ELECTRICAL PROPERTIES OF QUANTUM NANOWIRES

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In the present work we suggest equations for the description of electrical conductivity of semiconductor quantum nanowires. By use of these equations we explain such features of their current-voltage characteristics as existence of areas with negative differential resistance as well as oscillating behavior of the curves. We take into account scale-invariant, hierarchically self-similar, fractal structure of nanostructures. We consider that quantum nanowires form fractal clusters at their interaction. Electrical potential of these structures can be described as a fractal measure. Theoretical results are confirmed by specific experimental results on study of electrical properties of nanocluster semiconductors.

Keywords: nanostructure, morphology, fractal dimension, current-voltage characteristics, semiconductor.

Introduction

Investigation of structure and physical (including electrical) properties of nanoclusters semiconductors is one of the urgent problems of modern electronics. Unique physical properties of these materials make it possible to use them in different nanoelectronic devices such as nanosensors, solar cells, batteries, etc. [1-3].

Surface structure of nanocluster films is characterized by hierarchically self-similar and scale-invariant structure. This fact has been confirmed by experimental photographs obtained by use of modern methods of microscopy such as atomic force, scanning tunneling, electron microscopy [4-7]. Growth of films at non-linear and non-equilibrium conditions in open systems leads to formation on their surfaces of quantum-sized structures such as quantum nanowires, dots, wells with different arrangement. Type of nanostructures on a film surface significantly determines its electrical and optical properties.

Regularities of electrical conductivity of semiconductor nanowires have been described in many experimental and theoretical papers developing the theory proposed by Landauer for the description of quantum conductivity [8-10]. The theory is based on the description of tunnel contacts between two quasi-one-dimensional structures. However, universal approaches for explanation of processes related to this problem have not yet been completely established.

Recent studies have shown that current-voltage characteristics of semiconductor nanowires are generally non-monotonic functions and have a number of characteristic features such as oscillating behavior of curves of the current-voltage characteristics, hysteresis loops, existence of areas with negative differential resistance [11-15]. These features are inherent in current-voltage characteristics of semiconductor nanowires both at low (about several kelvins) and at room temperatures. Such behavior of the curves is typical for semiconductor nanowires with different chemical composition [16-18].

Electrical conductivity of semiconductor nanostructures depends on method used for growth of the film, and, therefore, on its porosity, types of nanostructures grown on the film surface and their mutual arrangement. Nowadays, there is no complete theory which is fully explaining the above-mentioned features of electrical conductivity of nanocluster semiconductor films (hysteresis loops on current-voltage characteristics, their oscillating behavior, amplitude and location of oscillations, areas of current-voltage characteristics with negative differential resistance, etc.) depending on their nanoscale structure.

Earlier in our papers, we have explained some electrical properties of nanowires based on the idea of fractal structure of nanocluster semiconductor films [4-7]. Because of non-linear fluctuation properties, nanowires are self-similarly deformed and, interacting, form fractal clusters. A quantum nanowire has an irregular structure, so, for its description we must take into account not only value of external potential between electrodes, but also value of potential providing by internal non-uniform distribution of electrons. Values of this potential can be represented as non-linear fractal measures. As usual, nanoclusters have fractal geometrical structure.

So, such structures are characterized by multi-barrier tunneling effects leading to formation of areas with negative differential resistance and hysteresis loops in current-voltage characteristics of nanostructures [6, 18].

Aim of the present work is to describe by use of our equations some regularities of electrical conductivity of semiconductor thin films containing quantum nanowires.

1. Electrical conductivity of quantum nanowires

Electrical properties of quantum nanowires can be described by use of the approach suggested in our previous works [6, 18]. According to this approach, a separate nanostructure (quantum nanowire) can be considered as a resistor with ideal contacts, to which external voltage U is applied.

Quantum nanowires containing in semiconductor films can form fractal nanoclusters because of self-organization. These nanoclusters have different sizes and chaotically oriented to each other. Inside a cluster, an electron moves under action of so-called scattering potential $V(U)$ characterizing metastable statements. The cluster potential is an additive value and because of this it can be considered as a nonlinear fractal measure.

Considering that resistance R is also a fractal measure, the system of equations describing current I inside a nanowire, potential V of a fractal cluster and its electrical resistance can be described as

$$I(U) = \frac{V(U)}{R(U)}, \tag{1}$$

$$V(U) = V_0\left(\left|1 - \left|\frac{V(U)}{U}\right|\right|\right)^{-\gamma}, \tag{2}$$

$$R(U) = R_\lambda\left(\left|1 - \left|\frac{U}{I(U)R(U) - V_0}\right|\right|\right)^{-\gamma}, \tag{3}$$

where $\gamma = D - d$ is scaling factor, D is fractal dimension of space where a single nanowire with topological dimension $d = 1$ is placed in, R_λ is resistance of a regular (non-fractal) wire, λ is the de Broglie wavelength.

Structure of nanoscale clusters formed in a film substantially determines regularities of electrical conductivity of the considered film. Singularities of surface structure of a nanostructured semiconductor film can be taken into account by corresponding choice of parameter γ. Due to the fact that properties of nanowires change as current passes through them, we accept difference between value of current and relation $V_0/R(U)$ in Eq. (3) as a determining variable.

2. Results and discussion

Current-voltage characteristic of a quantum nanowire obtained by numerical analysis of equations (1)-(3) is presented in Figure 1. As an estimated value, we can accept that $V_0 = E_g$, where E_g is value of silicon band gap measured in eV, because this value also characterizes the breakdown of energy values at the boundary of structures (Brillouin zones). According to physical meaning, $V_0 = E_g$ is maximal value of negative potential localizing an electron in a fractal cluster. We have used external voltage U as a determining variable. For the correct choice of numerical value of parameter $\gamma = D - d$ we have taken into account that generally value of topological dimension d isn't equal to maximal integer part of fractal dimension D. A quantum nanowire can be considered as a structure $d = 1$ and $1 < D < 2$. So, for our calculations we have accepted value of γ as $0 < \gamma < 1$.

As can be seen from the Figure 1, the current-voltage characteristic is a non-monotonic function, characterizing by oscillating behavior and contains areas with negative differential resistance. Oscillations of the curves related with nanocluster stricter of the films. Amplitude of oscillations is described by value of scaling factor γ by the following way: increase of the amplitude of oscillations corresponds to increase of γ. Figure 1 demonstrates that the current-voltage characteristic contains areas with negative differential resistance. It can be explained by fractality of geometry of formations consisting of quantum nanowires leading to multi-barrier tunneling effects.

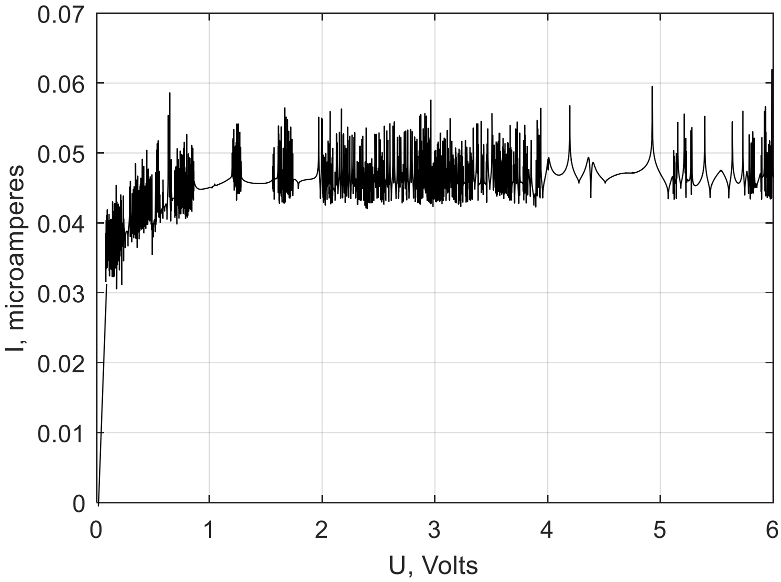

Fig. 1. Current-voltage characteristic of quantum nanowire.
$V_0 = 1.12$ V, $\gamma = 0.03$.

Figure 1 also demonstrates that oscillations on curves of the current-voltage characteristic are clustered. This effect is confirmed by experimental studies described in [10, 13] and can be explained by quantization of conductivity in semiconductor thin films.

Clustering of oscillations is related to quantization of film conductivity presented in Figure 2. Dependence of resistance on external voltage presented in this figure has been obtained by use of Eqs. (1)-(3). Scaling factor used for modeling of this dependence is relatively small because of small difference between values of fractal and topological dimensions. Quantization of conductivity corresponds with statements of the ballistic theory of electrical conductivity. According to these statements electrical resistance of a system depends on quantum effects in this system. It's necessary to notice that singularities of quantum effects observed in nanostructured semiconductor films are substantially determined by types of quantum-size structures contained in these films (quantum dots, quantum wells, quantum nanowires) and their relative position.

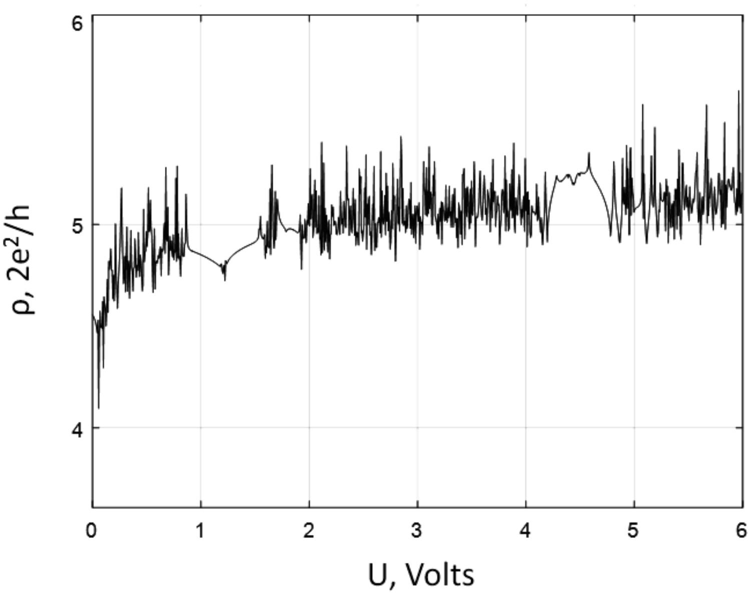

Fig. 2. Dependence of conductivity of quantum nanowire on external voltage.
$V_0 = 1.12$ V, $\gamma = 0.03$.

As an example, quantizing process of conductivity of an electron gas in a film AlGaAs / GaAs is schematically shown in Figure 3 [19]. The abscissa axis is the voltage in volts, the ordinate axis is conductivity in units of measurements of quantum conductivity $2e^2/h$. Here e is elementary charge, h is the Planck constant. Such dependence is typical for semiconductor film with different nanocluster structure and chemical composition.

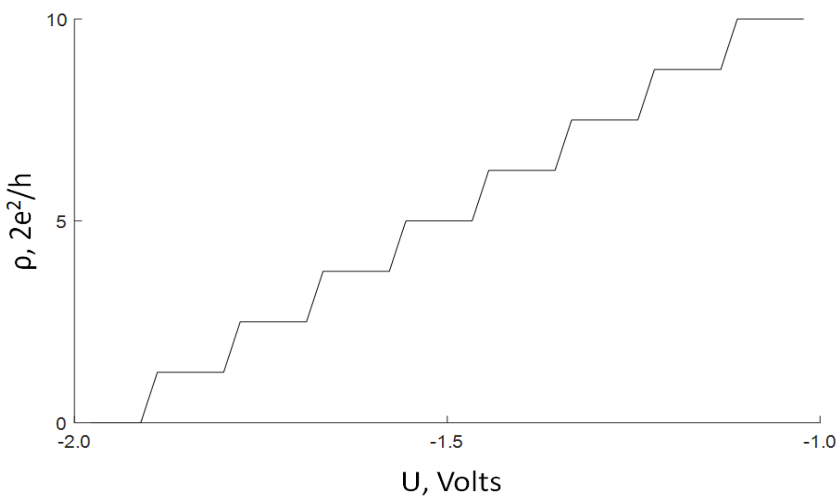

Fig. 3. Quantization of electron gas conductivity in semiconductors

Quantization of conductivity has been observed in a big amount of experimental research works. This effect is typical not only for semiconductor thin films, but also for metals and carbon nanotubes with different configurations [11-15]. Stepwise nature of the dependence of conductivity on external voltage is observed not only at low temperatures about several kelvins, but at room temperatures also.

Thus, it can be noted that formulas (1)-(3) correctly describe the basic regularities of electrical conductivity of quantum nanowires.

Conclusion

In this paper we have presented a new approach for the description of regularities of electrical conductivity of semiconductor films containing quantum-sized structures. We have taken into account scale invariant, hierarchically self-similar fractal structure of these films. By use of the equations suggested in the present paper we have described such features of current-voltage characteristics of nanostructured semiconductor films as their oscillating behavior, clustering of the oscillations because of quantum effects in the considered systems, existence of areas with negative differential resistance related with multi-barrier tunneling effects. Theoretical results obtained in this paper qualitatively agree with corresponding experimental data [8-15] on study of electrical properties of nanostructured semiconductors.

Results of the present work can be used for development of nanoelectronic devices and improvement of their parameters.

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