

Investigation of Electrical Conductivity in a Quantum Dot Crystal

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Recently proposed applications of self-assembled quantum dot arrays as far-infrared photodetectors, thermoelectric elements, and photovoltaic cells require detail knowledge of the electrical conductivity in such structures [1]. Theoretical models used so far for the electrical conductivity in quantum dot arrays are very rough and based on either effective medium approximation for a given volume fraction of the dot material or on the assumption of small wave function barrier penetration, which preserves discrete energy levels in the dots.

The above mentioned approaches became particularly poor for highly regimented three-dimensional (3D) arrays of quantum dots, which have recently been synthesized [2]. The coupling among quantum dots and long-range regimentation lead to the splitting of the quantized carrier energy levels of the single dots and formation of the series of three-dimensional mini-bands. For this reason we refer to the 3D regimented quantum dot superlattice as a quantum dot crystal (QDC).

Here we theoretically investigate the electrical conductivity tensor \mathbf{s} of QDCs. Our model is based on the envelope function approximation and uses a specific type of coordinate-separable confining potential. The conductivity tensor includes contributions from all mini-bands

$$\mathbf{s} = \sum_n \mathbf{s}^{(n)}.$$

The tensor components are mostly determined by the energy dispersion of mini-bands, the position of the Fermi level, and the carrier distribution. Temperature and position of the quasi Fermi levels determine the contribution of every mini-band.

In the low electric field limit, component of the conductivity tensor are given as

$$s_{ij}^{(n)} = \frac{e^2 \tau_0}{4\pi^3 k_B T} \int_{QBZ} v_i^{(n)}(\mathbf{k}) v_j^{(n)}(\mathbf{k}) \frac{\exp\left[\frac{E^{(n)}(\mathbf{k}) - E_F}{k_B T}\right]}{\left\{\exp\left[\frac{E^{(n)}(\mathbf{k}) - E_F}{k_B T}\right] + 1\right\}^2} d\mathbf{k}$$

where e is the electron charge, τ_0 is the relaxation time, E_F is the Fermi energy, k_B is Boltzmann's constant, and T is the temperature.

The carrier dispersion $E(\mathbf{k})$ in QDC is calculated using original approach developed by us [3]. We show that by changing the size of quantum dots, inter-dot

distances, barrier height and regimentation, one can control the electronic band structure of this artificial crystal and modify the carrier group velocity, which is proportional to the dispersion gradient

$$v_i^{(n)}(\mathbf{k}) = \frac{1}{\hbar} \frac{\partial E^{(n)}(\mathbf{k})}{\partial k_i}.$$

Since the components of the velocity vector depend only on the one corresponding direction in the \mathbf{k} -space, the conductivity tensor is diagonal not only in the QDC of cubical symmetry. Moreover, in the case of tetragonal symmetry the following holds $\sigma_{xx} = \sigma_{yy}$.

The calculated electrical conductivity in QDC as a function of the inverse temperature is presented in Figure 1. The Fermi energy shift and change of the carrier distribution function with the temperature determine the main features of this dependence. The higher the temperature the more mini-bands are involved into the conduction process. This is responsible for the observed maximum below the room temperature. We have also observed the onset of non-Ohmic behavior at lower electric fields than in corresponding bulk materials.

The obtained theoretical curve for the electrical conductivity in QDC is in excellent agreement with available experimental data. Strong dependence of the electrical conductivity on the parameters of quantum dot crystal creates an opportunity for re-engineering of optical, electronic, and thermal properties of this nanostructure through modification of its electronic states.

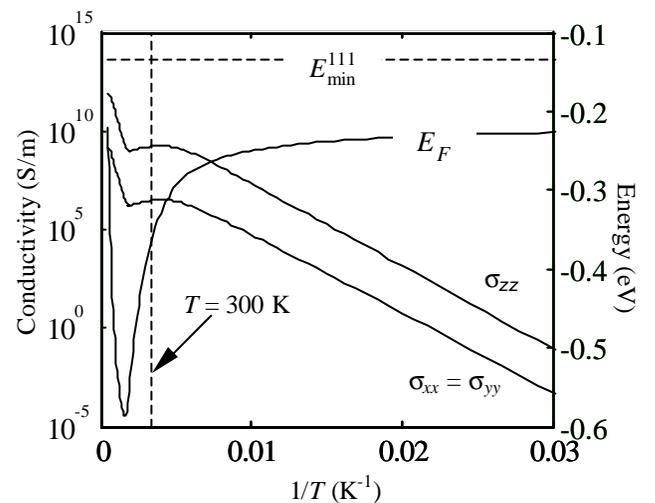


Figure 1 Electrical conductivity (left axis) and Fermi energy (right axis) as the functions of the inverse temperature calculated for InAs/GaAs QDC with the following parameters: cuboid dots size $L_x = L_y = 11$ nm, $L_z = 10$ nm; interdot distance $H_x = H_y = H_z = 5$ nm. The donor doping concentration is $N_D = 10^{16}$ cm $^{-3}$ with the energy levels at $E_D = -0.3$ eV. Relaxation time is $\tau_0 = 10^{-12}$ sec. E_{\min}^{111} denotes the edge of the lowest mini-band for electrons.

[1]. K.L. Wang and A. Balandin, *Quantum Dots: Properties and Applications*, in *Optics of Nanostructured Materials*, ed. by V. Markel and T. George, (J. Wiley & Sons, New York, 2000) p. 515.

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[3]. O.L. Lazarenkova and A. Balandin, *J. Appl. Phys.*, to appear in **89** (11), June 1, 2001.

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