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Influence of local phonon modes in wideband matrix on tunnel current-voltage characteristics for semiconductor quantum dots

Vladimir Krevchik[1], Michael Semenov[1], Roman Zaitsev[1], Dmitry Filatov[2], Paul Krevchik[1], Anastas Bukharaev[3], Askar Aringazin[4], Vladimir Kalinin[1]

[1]Department of Physics, Penza State University, Penza, Russia
[2]Physico-Technical Research Institute, Nizhny Novgorod State University of N. I. Lobachevsky, Nizhny Novgrod, Russia
[3]Laboratory of Physics and Chemistry of the Surface, Kazan Volga Federal University, Kazan, Russia
[4]Institute for Basic Research, Eurasian National University of L. Gumilev, Astana, Kazakhstan

Email address

physics@pnzgu.ru (V. D. Krevchik), filatov@phys.unn.ru (D. O. Filatov), a_bukharaev@kfti.knc.ru (A. A. Bukharaev)

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Abstract

One-dimensional dissipative quantum tunneling model has been proposed to interpret the experimental current-voltage characteristics of tunnel contact between atomic force microscope (AFM) probe and surface of InAs/GaAs(001) quantum dots studied in the tunneling AFM experiment on measuring local density of states. Within the framework of our approach of dilute instanton-antiinstanton gas, we made exact analytical calculation of tunneling probability rate for one charged particle weakly interacting with two local phonon modes in the wide-band matrix, which characterizes medium. The obtained theoretical result is in a good agreement with the experimental current-voltage characteristics. Namely, number, position, and heights of the observed peaks in the current-voltage characteristics of quantum dot devices based on a single-electron tunnel effect can be explained by the calculated effect of the wide-band matrix on the tunneling probability rate. This discovery enable possibility to set control over current-voltage characteristics of the semiconductor tunnel nanoelectronic devices.

Keywords

Quantum Tunneling with Dissipation, Quantum Dots, Tunnel Current-Voltage Characteristics

1. Introduction

Scanning probe microscopy techniques, including scanning tunneling microscopy (STM) and atomic - force microscopy (AFM) are widely used for studying the morphology, atomic structure and the energy spectrum of quantum semiconductor structures. STM method on the cross cleavage in ultrahigh vacuum (UHV) has been used to measure the local density of states (LPS) in quantum wells [1].

This work has been initiated by the experiment, conducted in the Kazan Physical-Technical Institute, named by E.K. Zavoysky and in Kazan Scientific Center, Russian Academy of Sciences, by measuring the tunneling current-voltage characteristic of semiconductor quantum dots (QD) InAs / GaAs (001), where several randomly spaced peaks have been found.

It should be noted that the features of the observed tunneling current-voltage characteristic is usually interpreted in terms of resonant tunneling model [2, 3]. The assumption that tunneling mechanism, involving two promoter phonon modes of wide-band matrix, is possible in the regime of weak dissipation, has been theoretically justified in this paper.

This non-resonant mechanism for tunneling transfer, which is specific for metal quantum dots (QD), can take place in doped QD under conditions when the concentration of charge carriers can be changed in a rather wide range by an external electric field.

The aims of this work are:

- Experimental study of tunneling current-voltage characteristics, obtained by imaging of the local density of states in quantum dots InAs / GaAs (001), using tunneling atomic force microscopy (AFM);
- Theoretical study of the oscillating mode for dissipative 1D - tunneling transfer based on two local phonon modes for wide-band matrix in an external electric field at finite temperature.
- The qualitative comparison of the theoretical dependence of the probability of 1D - tunneling from the external electric field with the experimental CVC for the AFM probe contact to the surface of QDs.

2. Experiment

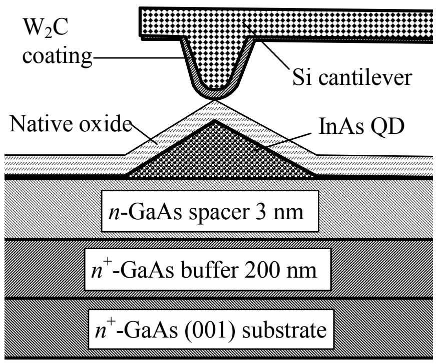
Samples for studies of spatial and energy distribution of LPS in the InAs-QDs by the tunneling AFM method were grown on substrates of n + - GaAs (001) doped with Sn, by MOC – hydride epitaxy (MOCVD) at atmospheric pressure by Ph.D. B.N. Zvonkov at the Research Institute of Physics and Technology (NIFTI) in Nizhny Novgorod State University (UNN), named by N.I. Lobachevsky.

The scheme of the investigated samples is shown in Fig. 1a. Buffer layers of n-GaAs of 200 nm thickness, doped by Si (donor concentration ND ~ 10^{18} cm-3) have been grown at a temperature of 650 C; spacer layers of undoped n-GaAs (ND ~ 1015 cm-3) with a thickness of 3 nm,have been grown on their surfaces, that is necessary for the formation of the triangular potential barrier between QD and n +-GaAs buffer layer [4]. InAs - QDs have been formed by the Stranski-Krastanov mechanism at 530 C. The nominal thickness of the deposited layer of InAs was 1,5 nm.

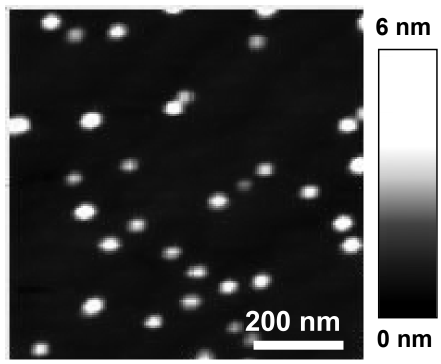
Experiment on visualization of the spatial distribution of LPS in QD InAs / GaAs (001) with usage of the tunneling AFM method was performed in Kazan Physical-Technical Institute, named by. E.K.Zavoysky, and in Kazan Scientific Center, Russian Academy of Sciences. The experiment was conducted at room temperature under UHV conditions using a scanning probe microscope (SPM) Omicron UHV AFM / STM VT composed of complex UHV Omicron MultiProbe P. Basic pressure in SPM chamber was ~ 10-10 Torr.

Sample surface coated with natural oxides, formed during the transfer from the growth installation in the UHV chamber for SPM studies, has been scanned by p +-Si AFM tip coated with W2C in contact mode (Fig. 1a); voltage Vg has been applied between the n +-GaAs substrate and the AFM cantilever tip. Spatial distribution of current between the AFM tip and the sample I_t , as function of the AFM tip coordinate to the sample surface in a plane x, y (current image) at a constant value of Vg = const, has been experimentally recorded. CVC for contact of AFM probe to the surface of QD have been obtained by measuring of the current series for QD images at different values of Vg. The methods of cultivation and tunneling spectroscopy for QD have been described more detailed in [5].

Fig. 1b shows the AFM image of the sample surface. The surface QD had a height h = 5 ÷ 6 nm. It should be noted that the lateral size of QD in Fig. 1b is significantly higher than expected for a QD, with shape as four-sided pyramid, faceted by planes (101) for these values h of h (10 ÷ 12 nm), due to the effect of convolution, because to the finite size of the curvature radius of the tip, used for AFM probes with $R_p \approx 35$ nm.



a



b

Fig. 1. *Scheme for measurement of current image for surface- QD InAs / GaAs (001) (a); AFM image of the surface QD InAs / GaAs (001) (b).*

Peaks, associated with the tunneling of electrons from filled states below the Fermi level in the coating material on the AFM probe of W2C to dimensionally quantized levels in QD [5, 6], have been detected on the tunneling spectra of QD. Under interpretation of tunneling spectra of QD, it should be noted, that the experiments have been performed at room temperature, therefore, in these conditions, processes of electron tunneling with absorption or emission of phonons are possible. At the same time, it is known that GaAs has two kinds of optical phonons: cross (TA) with the energy $\hbar\Omega \approx 34$ meV and longitudinal (LO) with $\hbar\Omega \approx 38$ meV. This fact determines the expediency for consideration of two local phonon modes in wide-band matrix in the weak dissipation limit.

3. Calculating of the 1D - Dissipative Tunneling Probability with Account of Two Local Phonon Modes in Wide-Band Matrix

Statement of the problem is similar to that, which has been used earlier by the authors under consideration of the 1D - dissipative tunneling models with a double-oscillator potential in an external electric field (Fig. 2) at finite temperature and of the standard dissipative tunneling Hamiltonian taking into account the two phonon modes for wide-band matrix [7]. Calculations are performed in the system of units in which $\hbar = m = 1$.

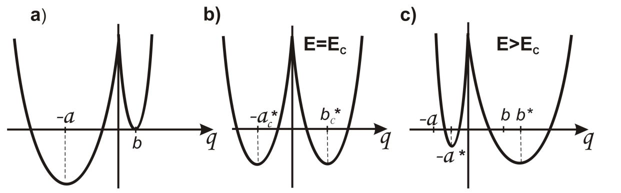


Fig. 2. The electric field influence on the asymmetric double-well oscillator potential. Fig. 2 (b) shows the case of a symmetric potential at a certain value of the electric field strength.

It can be shown that the 1D - quasiclassical action in the instanton with account of the wide-band matrix influence takes the form:

$$S_B = 2\omega_0^2 \left(q_0 + q_1\right) q_0 \tau_0 - \frac{2\omega_0^2 \left(q_0 + q_1\right)^2 \tau_0^2}{\beta} - \frac{4\omega_0^4 \left(q_0 + q_1\right)^2}{\beta} \sum_{n=1}^{\infty} \frac{\sin^2 \nu_n \tau_0}{\nu_n^2 \left(\nu_n^2 + \omega_0^2 + \zeta_n\right)}, \quad (1)$$

where q1 and q0 - parameters of the renormalized two-oscillator potential in the electric field: $q_1 = b = b^* + \frac{|e|E}{\omega_0^2}$, $q_0 = a = a^* - \frac{|e|E}{\omega_0^2}$. Applied external electric field along the tunneling coordinate changes symmetry of 1D - oscillator potential as shown in Fig. 2.

Pre-exponential factor is determined by the contribution of trajectories closely spaced from the instanton, while the tunneling probability per unit time can be written as $\Gamma = B\exp\left(-S_B\right)$ [7]. Expression for the probability of 1D - dissipative tunneling up to the pre-exponential factor is given in [8].

An analytical formula, obtained in [8], for the probability of 1D - dissipative tunneling with account of the influence of two local phonon modes of dielectric matrix, allows to investigate features of the $\Gamma(E)$ - dependence, which is important for comparison with the experimental tunnel CVC.

Qualitative comparison of the theoretical curve for the 1D - dissipative tunneling probability dependence on an external electric field (with the influence of two local phonon modes) and experimental CVC CT InAS / GaAs (001) is shown in Fig. 3.

Fig. 3 shows that the characteristic peaks spectrum are not equidistant on the experimental CVC and the corresponding peaks in the theoretical dependence of the 1D - dissipative tunneling probability on the applied electric field have better quality match than it was in the case of the model, which takes into account the influence of only one local phonon mode for wide-band matrix [6].

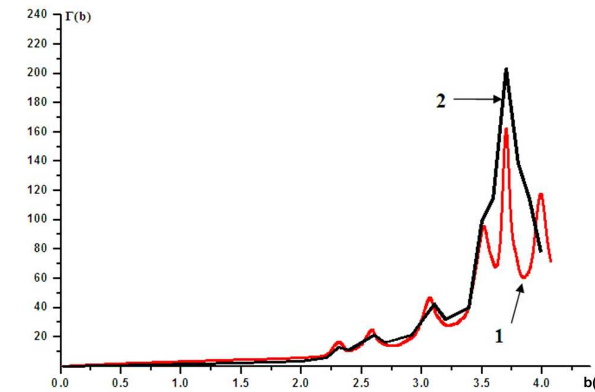


Fig. 3. Comparison of the theoretical curve (1) for the dissipative tunneling probability (in oscillating mode) in the model taking into account the influence of two local modes for environment, with the experimental curve (2)

4. Conclusion

Theory of quantum tunneling with dissipation, which previously has been applied to describe systems with Josephson junctions and low-temperature kinetics of the individual chemical reactions that occur by a tunneling mechanism, now is developed to the case of tunneling transport for quantum dots in external electric field in the combined AFM / STM. In addition to the pioneering work of Professor. Sethna, a number of works, developing this theory, by famous authors, including works by prof. Leggett, Larkin et al. have been included in the cited monographs [2, 3]. The book [3] has also a comparison with the available experimental data in the framework of 1d - dissipative tunneling theory with account of the local promoting phonon mode influence in the heat - bath or wide-band matrix. It is not possible to obtain good qualitative agreement with the experimental current-voltage characteristics data, in the framework of the above model. The advantage of this article is the fact that the inclusion in the model of 1d- dissipative tunneling effect of two promoting local phonon modes of wide-band matrix has yielded convincing qualitative agreement between theory and experiment.

In this paper the probability of the 1D - dissipative tunneling in a double-well oscillator potential model taking into account the influence of the two promoter local phonon modes for wide-band matrix under external electric field at a finite temperature, has been calculated. Dissipative tunneling mode in the limit of weak dissipation is likely to be typical for degenerate semiconductors along with a common mechanism of resonant tunneling.

Oscillating mode for the dissipative tunneling transfer of nonresonant nature theoretically allowed to reveal good qualitative agreement with experimental data. In the experimental study of the tunneling spectrum of QD it has been considered that at room temperature, processes of electron tunneling with absorption and emission of phonons are possible. It should be noted that earlier [5, 6] under the interpretation of tunneling spectra for QD InAs / GaAs (001), this fact has not taken into account.

Thus, along with the regime of resonant tunneling [1, 2], as previously assumed, it should be considered the contribution of dissipative oscillatory regime (in the limit of "weak" damping), which can appear in the tunneling current-voltage characteristic for semiconductor QDs placed in wide-band matrix. The authors are grateful to BN Zvonkov for the samples growing and to PA Borodin for experiments fulfillment.

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