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Macroscopic effects of dissipative tunneling in semiconductive InAs/GaAs quantum dots

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Abstract. Temperature effects of 1D-dissipative tunneling for the two-well oscillator potential model within the strong dissipation limit for the case of semiconductor QDs of InAs, were analyzed using a combined atomic force and scanning tunneling microscope. The effect of thermal control for the amplitude of single peaks on the field dependence of the one-dimensional dissipative tunneling probability in the model under consideration was theoretically revealed. A qualitative comparison of the calculated field dependences of the 1D-dissipative tunneling probability at a finite temperature within a strong coupling limit (with allowance for the influence of two local phonon modes) with experimental tunnel CVC was obtained. A fairly convincing agreement of theoretical and experimental curves was demonstrated. It is shown that in addition to temperature and external electric field, another important controlling parameter of dissipative tunneling is the type of thermostat matrix in which QDs have been synthesized, taking into account the number of local phonon modes involved in the tunneling process.

1. Introduction

Quantum tunneling is important for research involving electron transport through molecular filaments, structures with quantum dots or quantum wells, and low-temperature chemical reactions [1-15]. Many of the mentioned systems are considered from the standpoint of the instanton approach. When the tunneling constant is calculated from the instanton approximation, all the listed phenomena appear similar to one another in some sense. In chemical reactions, the rate constant assumes an exponential evolution for the transport probability, whereas in electronic devices the rate constant determines the tunnel current. In the work of Yu. N. Ovchinnikov [9], it was shown that the conductivity of granular metal films is related to the tunneling processes between neighboring granules, and also that the interaction with the thermostat, which provides a real transition to the states localized in the "adjacent" cluster, is rather small. Thus, the characteristics of the tunneling current in the systems under study can be considered in the limit of comparatively "weak" dissipation, but sufficient to ensure the "decay" of the double-well oscillator potential used in the proposed model. In addition, an appreciable contribution to the tunneling current can be provided by the tunneling probability estimated to within a pre-exponential factor. In investigations of quasi-zero-dimensional systems with semiconductor single-QDs, the strong dissipation approximation is justified by accounting for the influence of two local phonon modes on the tunneling probability. We observed a series of sharp resonant features in the tunneling differential conductance of InAs quantum dots. We found that dissipative quantum tunneling has a strong influence on the operation of nanodevices. Because of such tunneling, the current-voltage characteristics of a tunnel contact between an atomic force microscope tip and a surface of InAs/GaAs quantum dots include many interesting peaks. We found that the number, position, and heights of these peaks are associated with the phonon modes involved. Our experimental data are well described with an exactly solvable model where one charged particle is weakly interacting with two promoting phonon modes associated with the external medium. We conclude that the characteristics of tunnel nanoelectronic devices can thus be controlled by a proper choice of phonons in the materials, which are involved.

2. 1-D dissipative tunneling in the limit of strong dissipation

Several non-equidistant peaks on the tunnel CVCs (current-voltage characteristics) for semiconductor quantum dots (QDs) of InAs/GaAs (001) were observed and interpreted by us earlier in the framework of the 1D-dissipative tunneling model with allowance for one local phonon mode [4]. In this case, the proposed theoretical model allowed us to identify only two single peaks, one of which turned out to be unstable, which did not fully correspond to the available experimental data. It should be noted that the features of the observed tunneling CVCs are usually interpreted within the framework of the resonance tunneling model. In this paper, we assert and theoretically justify that a tunneling transport mechanism involving two local phonon modes of the surrounding matrix is possible in the strong-dissipation regime. It is known that two types of optical phonons exist in GaAs: transverse phonons (TO) with energies $\hbar\Omega \approx 34$ MeV and longitudinal phonons (LO) with energies $\hbar\Omega \approx 38$ MeV. This explains why the two local phonon modes should be considered for a surrounding matrix in the weak dissipation limit. Since the highest values of the electron-phonon interaction constants in GaAs are observed for TO and LO phonons, only these modes are usually taken into account. Other modes are neglected because the values of the electron-phonon interaction constants for them are much less.

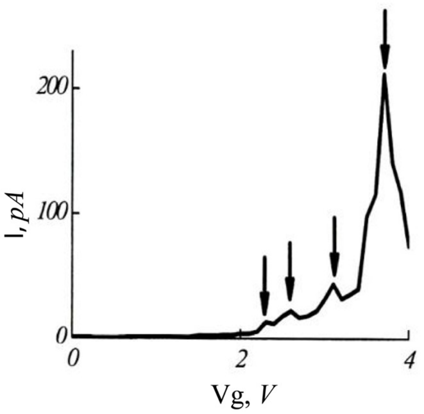

Figure 1. CVC of the AFM probe contact to the QD - surface at the point corresponding to the QD-top.

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The peaks (see figure 1) associated with tunneling of electrons from the filled electron states below the Fermi level in the AFM coating material of the W_2C probe to the QDs dimensional-quantized levels (figure 2) were found in the QD tunneling spectra [4].

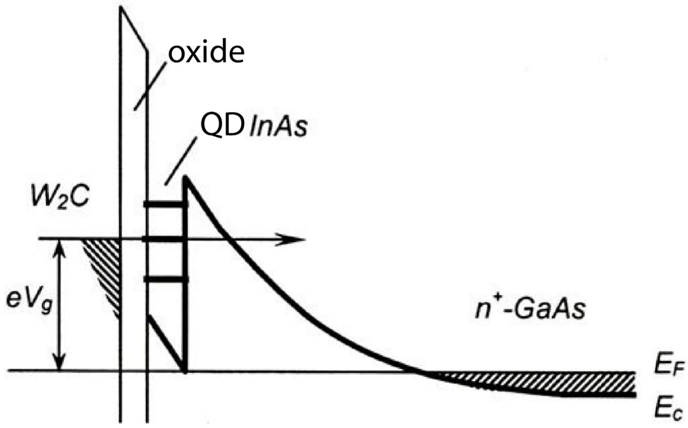

Figure 2. Zone diagram of a metallized AFM probe with a QD surface

When interpreting the QDs tunneling spectra, one should take into account that the experiments were carried out at room temperature. Therefore, under these conditions, dissipative electron tunneling with absorption or emission of phonons is possible. Previously, when interpreting the tunnel spectra of InAs/GaAs (001) QDs, this factor was not taken into account. This nonresonant mechanism of tunneling transport, characteristic for metallic QDs, can occur in doped QDs when the concentration of charge carriers can be varied within fairly wide limits by means of an external electric field.

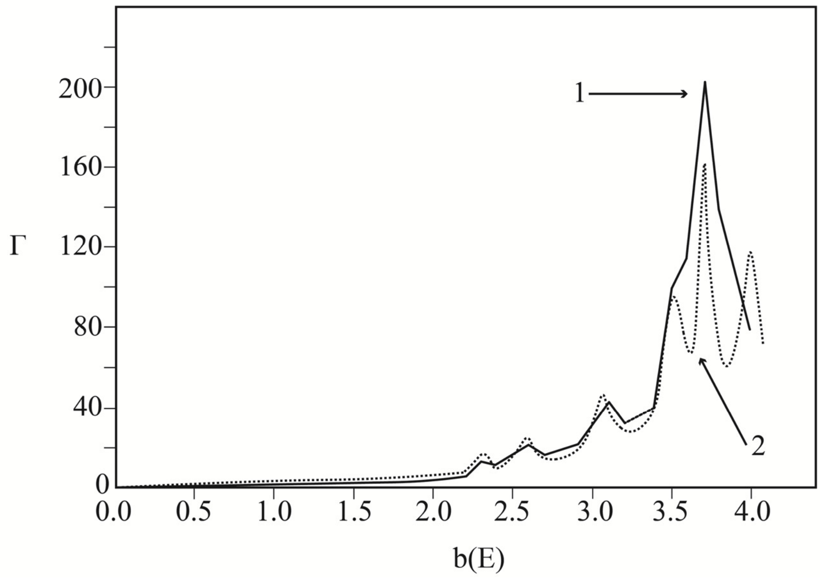

Figure 3. Comparison of the theoretical curve (line 2) for the tunnel probability $\Gamma = B\ exp\ (-S)$ in the 1D dissipative tunneling model taking into account the influence of two local modes of the heat-bath with the experimental current-voltage characteristics (CVCs curves) for semiconductor quantum dots of InAS / GaAs (line 1) [4]. b(E) is the dimensionless asymmetry parameter of the double-well oscillatory potential, which is weakly nonlinearly dependent on the strength of the external electric field.

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A qualitative comparison of the model curve for the 1D-dissipative tunneling probability $\Gamma = B\exp(-S)$ (see [4]) with allowance for the influence of two local phonon modes of the heat-bath with the experimental *I-V* characteristics for semiconductor QDs of InAs / GaAs is presented in figure 3. Here the characteristic non-equidistant peaks in the experimental CVCs (for semiconductor quantum dots of InAs/GaAs) match the corresponding peaks in the theoretical dependence of the 1D-dissipative tunneling probability (with allowance for influence of two local phonon modes of the heat-bath) on the strength of the applied electric field. This match is qualitatively much better than that observed in the model, which accounts for the impact of only one local phonon mode. The temperature dependence of the amplitude of single peaks in the investigated curves has also been theoretically analyzed.

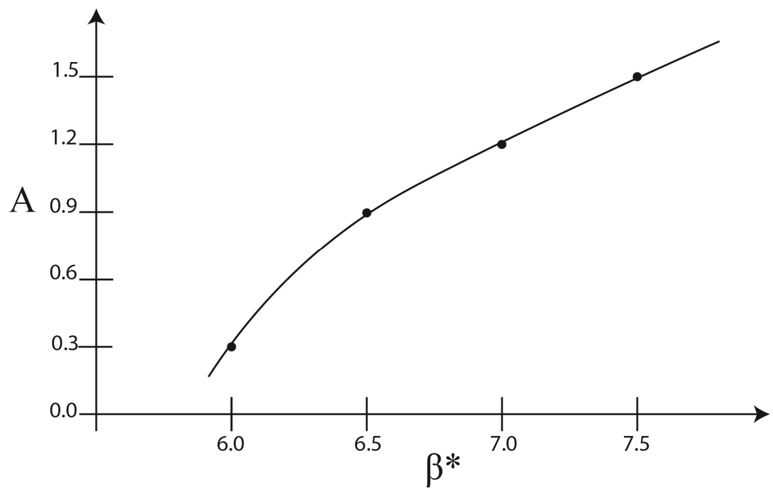

Figure 4. Dependence of the amplitude *A* of a single peak in the field dependence of the 1D-dissipative tunneling probability on the dimensionless reciprocal temperature parameter $\beta^{*}=\hbar\omega/kT$.

It is shown (see figure 4) that these amplitudes grow slightly nonlinearly with decreasing temperature. Theoretical calculations have shown that both oscillating and non-oscillating tunneling transfer regimes are possible in the dependence of the 1D-dissipative tunneling probability on the strength of the external electric field at a finite temperature and fixed parameters of the surrounding matrix (see figures 3 and 5).

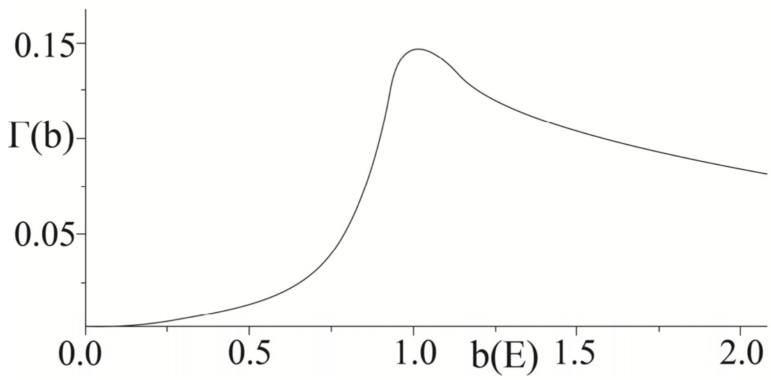

Figure 5. Theoretical curve for the 1D-dissipative tunneling probability in the non-oscillating transport regime

The oscillating regime is due to the energy exchange of a tunneling electron with two phonons. This can cause the formation of states with different lifetimes. Their interference, along with the "tuning" of the starting energy level under them in an external electric field, can produce the corresponding oscillations of the tunneling probability field dependence. As the interaction constant with the contact medium increases (with an increase in its "viscosity"), this interference turns out to be suppressed, and a non-oscillating regime of dissipative tunneling is realized (see figure 5).

3. Conclusion

Thus, the performed analysis demonstrated the qualitative agreement of the calculated curves for the tunneling probability with some experimental CVCs in the schemes for studying the controlled conductivity characteristics of individual InAs/GaAs semiconductor quantum dots. Although a number of features on the experimental tunnel CVCs were previously interpreted by other authors [14] as conservative (resonance) tunneling effects, a qualitative comparison of the obtained theoretical field dependences with the experimental CVCs allowed us to conclude that dissipative tunneling effects are realized in individual cases. We also found that the characteristic non-equidistant peaks in the experimental *I–V* characteristics (for semiconductor InAs/GaAs quantum dots) match the corresponding peaks in the theoretical dependence of the 1D dissipative tunneling probability on the applied electric field intensity (accounting for the influence of two local phonon modes of the heat bath). This match is much better than what was observed in the model, which accounts for the influence of only one local phonon mode. The oscillating and non-oscillating regimes of 1D - dissipative tunnel transfer were identified theoretically by taking into account the influence of two local phonon modes, while a qualitative correspondence with the experimental tunneling current-voltage characteristics for semiconductor InAs/GaAs quantum dots was observed only in the case of the oscillating regime of one-dimensional dissipative tunneling.

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References

[1] Caldeira A O and Leggett A J Quantum tunneling in a dissipative system 1983 *Annals of Physics* **149** 374
[2] Larkin A I and Ovchinnikov Yu N Decay of the supercurrent in tunnel junctions 1983 *Physical Review B* **28** 6281
[3] Leggett A J *et al* 2005 *Transfer Processes in Low-dimensional systems* (Tokyo: UT Research Press)
[4] Kusmartsev F V *et al* 2016 *JETP Letters* **104** 392
[5] Leggett A J (ed) 2011 *Controllable dissipative tunneling. Tunnel transport in low-dimensional systems, in Russian* (Moscow: Fizmatlit)
[6] Krevchik V D, Ovchinnikov A A, Semenov M B, Aringazin A K, Dahnovsky Yu and Yamamoto K Two-dimensional tunnel correlations with dissipation 2003 *Physical Review B* **68** 155426
[7] Zhukovskii V C *et al* Study of the tunneling controllability in such structures as “quantum dot - quantum well” or "quantum molecule" 2006 *Moscow University Physics Bulletin* **3** 24
[8] Zhukovskii V C *et al* 2007 *Moscow University Physics Bulletin* **2** 10
[9] Ovchinnikov Yu N Conductivity of granulated metallic films 2007 *JETP* **131** 286
[10] Ullien D, Cohen H and Porath D The effect of the number of parallel DNA molecules on electric charge transport through “standing DNA” 2007 *Nanotechnology* **18** 424015
[11] Louis A A and Sethna J P Atomic tunneling from a Scanning-Tunneling or Atomic-Force Microscope tip: Dissipative quantum effects from phonons 1995 *Physical Review Letters* **74**

1363
[12] Yanagi H and Ohno T Nanofabrication of gold particles in glass films by AFM – assisted local reduction 1999 *Langmuir* **15** 4773
[13] Bychkov A M and Stace T M 0.4 and 0.7 conductance anomalies in quantum point contacts 2007 *Nanotechnology* **18** 185403
[14] Antonov D A, Vugalter G A, Gorshkov O N, Kasatkin A P, Filatov D O and Shenina M E 2007 Resonant tunneling of electrons through nanoclusters formed in stabilized zirconi dioxide by ion implantation method, *in Russian, Vestnik of Lobachevsky state university of Nizhny Novgorod* **3** 55
[15] Zhukovskii V C *et al* 2009 Controllable dissipative tunneling in an external electric field *Moscow University Physics Bulletin* **64** 27