

Coupling effects on electron-phonon scattering in double quantum dots

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In this work we study the electron-phonon interaction in GaAs/AlGaAs double-dot systems for cylindrical and spherical geometries with finite confinement, coupled by a tunnelling barrier and an external dc electric field. The eigenenergies and envelope wave functions are numerically obtained for different values of the external bias. We study the effects of field and the dots-shape on the relaxation rates of electronic transitions between double-dot states by electron-acoustic phonon and electron-optical phonon interaction. We found the piezoelectric interaction to be small compared with the deformation potential one, and the spherical more convenient than the cylindrical geometry to reduce the electron-phonon decay rates.

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1 Introduction Double quantum dots have been proposed as good candidates to the implementation of nano-devices both for optoelectronics and quantum computation [1, 2]. Tunability of states and long coherence times are the main advantages of such systems [3, 4]. Such properties have aroused great expectation and interest about studying and controlling the decoherence processes in this kind of structure. There is an agreement that electron-phonon interactions are the main decoherence channels, since embedded in or grown on host materials, the interaction between the confined carriers and the lattice nucleus is inevitable. Former works on electron-phonon interaction have been done for GaAs double quantum dots with harmonic infinite confinement potential [4, 5], and for finite confinement in rectangular dots [6]. In this work we study spherical and cylindrical dots with a finite step potential confinement. In the first place, eigenenergies and envelope wave functions are found. Having into account such transition energies, electron-optical phonon interactions are discussed. After that, decay rates of electronic transitions by electron-acoustic phonon are calculated. Finally we analyse and conclude the effects of the bias field and the dot-shape on those rates.

2 Energy states and coupling between dots The systems we focus on are pairs of quantum dots close enough to be electronically coupled, which is equivalent to having their individual states hybridized. They are modelled as islands of GaAs embedded in an Al_{0.4}Ga_{0.6}As matrix. Parameters are as in reference [6]. The confinement potential is modelled as a finite potential step. We consider spherical and cylindrical geometries. For cylindrical dots there are two options; stacked or lateral coupling. These two configurations are expected to have different behaviour since in the latter one, the axial symmetry is broken. We found the energy levels by solving numerically the modified Schrödinger equation in the one-band effective mass approximation. The ground state in spherical dots as well as in cylindrical dots has like-*S* symmetry. The first excited state in cylindrical dots has double-maxima symmetry along the axial direction while for spherical dots it has like-*P* symmetry being triply degenerate. The other level we

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consider is the second excited one in cylindrical dots which is doubly degenerate about the axial direction. We focus on the first five states of the coupled systems (in the spherical case, states 3 and 4 are degenerate). DC bias electric field is used as coupling parameter to tune the high delocalization regime. A volume ratio of 4.3 between the dots and an inter dot distance of 13.5 nm were used for the calculations. Figure 1 shows the transition energies for the three considered geometries. Minima mean strong coupling between dots and highest delocalization.

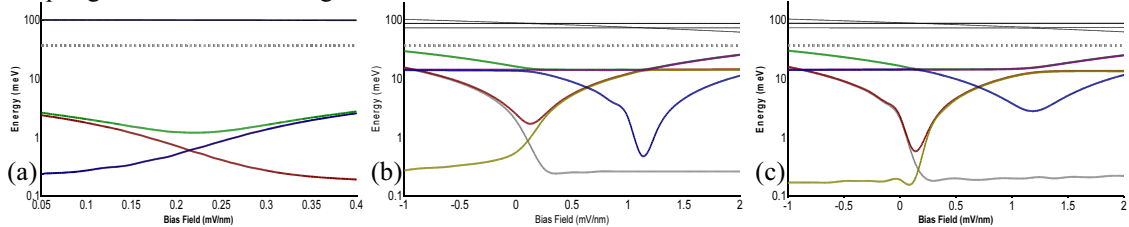


Fig. 1 Transition energies for (a) spherical dots, (b) cylindrical lateral dots, (c) cylindrical vertical dots. In all cases transitions from the fifth level (black upper lines) are too close to be resolved at the plot scale. The dotted line is the optical phonon energy.

3 Interaction with optical phonons As shown in Fig. 1, the transition energies do not include values close to the longitudinal optical phonon. It has been discussed [7, 8] that the polar coupling in 0D structures is relevant, but the experimental evidences show that the interaction between two states is appreciable only close to the crossing region between the lower state with phonon and the upper one without phonon [9, 10].

In the cases of cylindrical geometry there is a transition (2-1) whose characteristic energy is close to twice the optical phonon energy. That nearness eventually could favour the polar coupling by a second order interaction as is mentioned in [10]; nevertheless in that reference, the coupling exists through a third intermediate state which is close to the lower one with one phonon. That state is the π_+ from the splitting by the magnetic field. In our case, we do not have any state with such a position at the spectrum to be able to mediate a second order transition with two phonons emission. Even at the case of having some suitable intermediate state, with a dimensionless coupling constant $\alpha \sim 0.15$ as it is frequent in III-V quantum dots, the quadratic coupling is more than six times smaller that the linear one [11].

4 Interaction with acoustic phonons Using the Fermi golden rule approximation, we calculate the decay rates for transitions induced by acoustic phonons. Interaction by deformation and piezoelectric potential are considered using in both cases a Fröhlich Hamiltonian.

4.1 Deformation potential interaction Figure 2 shows the decay rates for deformation potential interaction. Only transition with energies less than 20 meV were considered. In the spherical, because of the degeneracy and sharing of symmetry of states 3 and 4, rates from or to them are equal (e.g. $\Gamma_{5-4} = \Gamma_{5-3}$, $\Gamma_{4-2} = \Gamma_{3-2}$).

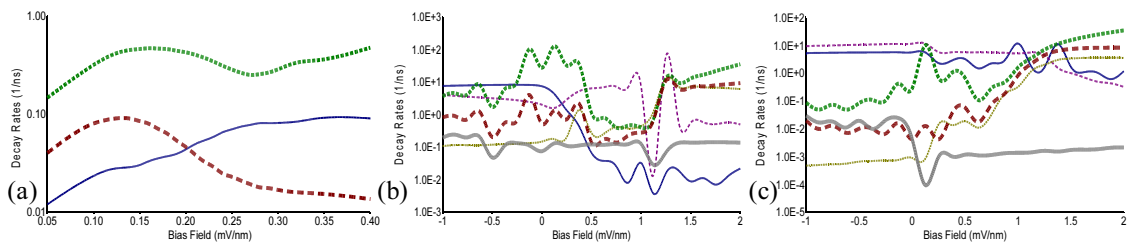


Fig. 2 Decay rates for electron-acoustic phonon interaction by deformation potential in: (a) spherical double dots, (b) cylindrical lateral double dots, (c) cylindrical vertical double dots. Transitions: 5-4 (Gray bold solid), 5-3 (Red bold dashed), 5-2 (Green bold dotted), 4-3 (Brown fine dotted), 4-2 (Violet fine dashed), 3-2 (Blue fine solid).

4.2 Piezoelectric interaction Figure 3 shows the decay rates for piezoelectric. Same considerations as in Section 4.1 were used.

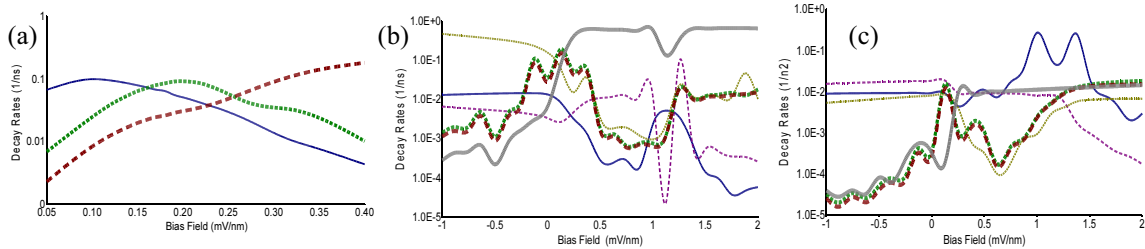


Fig. 3 As plotted in Fig. 2 but considering transitions by piezoelectric potential.

5 Analysis and conclusions Figures 2 and 3 allow us to compare the orders of magnitude of the deformation and piezoelectric potential interactions. It is clear that the rates associated to the piezoelectric potential are at least one order of magnitude less than the rates related to deformation potential. That is in agreement with the reported in [4, 12] and though there is a discrepancy with reported in [13], the trend for high tunnelling is fulfilled.

The curves-shape is basically complicated but some characteristics are clear to interpret. At the points where there is maximum delocalization (~ 0.22 mV/nm for spherical dots, 0.125 and 1.2 mV/nm for cylindrical dots, see Fig. 1), the curves present their main features. Most of the crossings between rates happen at those points, because this is where the symmetries of the wave functions change. The strongest oscillations are found also at those points where the double-dot character influences the interaction. Oscillatory behaviour has been also predicted for multiple dot-system with infinite confinement in [5, 14]. In general, the decay rates are larger for laterally coupled cylindrical dots, for stacked coupled cylindrical dots and finally are smallest for spherical dots. Then this shows a relationship between the symmetry of the system and the magnitude of the coupling. As the more symmetrical the system is, the electron-acoustic phonon interaction is smaller. Similar behaviour has been reported for elliptical dots compared with spherical ones in single dots [15].

Summarizing, deformation potential contribution to relaxation by electron-acoustic phonon was found to be larger than the piezoelectric one. Delocalization and changes of the symmetries of the wave functions at anticrossing points produce strong variations of the interaction magnitude. Finally, increasing of the scattering rates with the loss of geometry of the system was observed.

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