Tunneling-related electron spin relaxation in quantum-dot molecules

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We study theoretically the process of spin relaxation during phonon-assisted tunneling of an electron in self-assembled InAs/GaAs quantum-dot molecules formed by vertically stacked dots [1]. We find that the spin-flip tunneling rate may be as high as 1% of the spin-conserving one. The process is active at a considerable rate even without the magnetic field and scales with the latter differently than the relaxation in a Zeeman doublet.

Investigation of spin dynamics in semiconductor nanostructures is motivated by both still not fully explored physics of spin relaxation and decoherence as well as the potential role of such structures in spintronics and quantum information processing. While various types of structures can be utilized for these purposes, self-aseembled quantum dots (QDs) come with the possibility of optical control as they are optically active. Recently, much attention is focused on tunnel-coupled structures like QD molecules, as the coupling may be exploited in promising protocols developed for quantum-information processing.

While there is a considerable amount of theoretical works on spin relaxation of carriers in single QDs, the field of coupled QDs is far less explored. Regarding phonon-assisted tunneling in QD molecules, although the physics of the orbital transition has been widely recognized, studies of spin behavior during tunneling are scarce.

Here, we focus on the phonon-assisted tunneling of electrons between coupled QDs and calculate the rate of such a transition affected by a spin flip as compared to the spin-conserving one. Employing a multi-band theoretical $\boldsymbol{k}\cdot\boldsymbol{p}$ framework, we calculate electron states as well as their coupling to phonons and the resultant rates of dissipative transitions. By selectively enabling the spin-mixing terms in both kinetic-energy and carrier-phonon interaction Hamiltonians, we quantify the impact of various mechanisms of spin relaxation. Those, via the effective conduction band description, can be associated with known perturbative interaction terms. We find that up to $B \simeq 15\,\mathrm{T}$ the main contribution comes from the opposite-spin admixtures to the electron ground state caused by the Dresselhaus spin-orbit interaction, in agreement with our previous perturbative estimation [2]. At higher field, another source of admixtures becomes dominant, which is the structural shear strain, known to dominate in the Zeeman-doublet relaxation [3]. Furthermore, we check the impact of typical details of structure morphology, and find that the misalignment of QDs may elevate the zero-field relaxation rate by an order of magnitude.

Finally, we also find that at nonzero temperatures the process in question strongly enhances spin relaxation in Zeeman doublets in each of the QDs via virtual repetitive tunneling affected by spin flips. In fact, we deal not only with a mere enhancement, but with a channel of spin relaxation without the magnetic field that may set the limit for spin lifetime of stationary carriers confined in tunnel-coupled structures utilized currently in spintronics and quantum information protocols.

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