Hybrid Acousto-Optic Driving of Rabi Oscillations of Electron Spin in a Quantum Dot

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Performing coherent Rabi rotations is a necessary step toward complete control of a qubit. For a quantum bit based on spin states, it can be achieved with microwaves [1]. However, such control with macroscopically long waves causes problems when considering the miniaturization of integrated circuits. While for an electron confined in a semiconductor quantum dot (QD), state control has been achieved with optical pulses [2], such methods are unavailable for many other promising solid-state systems (like NV centers or superconducting qubits). A promising solution is to use acoustic waves that couple to all mentioned systems and allow chip miniaturization.

In this contribution, we propose a hybrid (acousto-optic) approach to controlling the spin state of an electron in a QD. We theoretically show Rabi oscillations for the Zeeman-split ground state of a QD-confined electron modulated using the acoustic field. The acoustic field amplitude sets the rotation axis, while spin rotations are controlled by pulsed off-resonant optical coupling to the trion state. Thus, we take advantage of orders of magnitude shorter lengths of acoustic fields compared to microwaves and rotate the spin with two nanoscale-compatible fields.

Although direct coupling between spin states and deformations is negligible in such systems, our hybrid control leads to controllable Rabi oscillations with a frequency that depends on the amplitudes of both acoustic and optical fields. The ground state doublet and the trion level form a configuration known as a Λ-system [3]. In our model, the acoustic field modulates the trion level, to which both spin states are coupled via optical pulses. This leads to the second-order coupling between the spin states.

To better understand the evolution of the system, we compare direct numerical calculations with the results of approximate analytical derivation. To this end, we model the system using a Hamiltonian in the dipole and rotating wave approximation. We derive an effective Hamiltonian of the ground state doublet by eliminating the trion level in the quasi-degenerate perturbation theory [4]. This effective description allows us to predict the evolution of the spin qubit. Importantly, due to the specific form of effective coupling, we find a way of varying the spin-rotation axis. Lastly, we study the destructive processes accompanying the evolution of the system. For this, we use the Lindblad master equation and show that trion recombination has negligible effects for short optical pulses.

We anticipate our work to be a starting point for designing and creating a controllable qubit and its extension to a two-qubit gate defined on tunnel-coupled QDs.

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