Single electron spin dephasing in the InAs(P)/InP quantum dot studied by the Hanle effect

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Quantum dots' (QDs) spins are promising qubit candidates for quantum information processing due to the possible long relaxation time resulting from strong spatial confinement. However, the spin of a localized electron is under the influence of the nuclear spin fluctuations, affecting practical applications [1]. Short spin dephasing time limits the time available to perform qubit control operations and reduces the entanglement fidelity [2]. While optical methods enable effective spin initialization and control, understanding dephasing mechanisms of the single spin remains essential. We performed the Hanle effect measurement on single QDs emitting in the telecom spectral range, and to the best of our knowledge, this is the first report of this method being applied specifically to individual QDs in this highly application relevant spectral range. Compared to other methods of spin decoherence investigation, the Hanle effect provides a way to probe spin dephasing in both an ensemble and single quantum dot without the need for time-resolved measurements.

In this work, we performed studies on single InAs(P)/InP QDs emitting in the 3rd telecommunication window. The structure was grown via the molecular beam epitaxy, assisted by the ripening process resulting in the low spatial density of the QDs ($\sim 2 \times 10^{9}\ cm^{-2}$). A distributed Bragg reflector beneath the QDs increases the photon extraction efficiency to 6.8% for the planar sample and even to 13.3% for QDs in cylindrical mesas, for the numerical aperture $NA = 0.4$ of the microscope objective [3]. These QDs are good candidates for emitters in single photon sources, as they were proven to have low probability of multi-photon emission events ($g^{(2)}(0) < 0.01$) [4]. Such a material system can be used for optically driven spintronics compatible with telecom infrastructure.

We identified the excitonic complexes originating from the same QD using power, polarization and magnetic field (in the Voigt configuration) dependent photoluminescence measurements. Further studies focused on the trion with a 4.8 meV binding energy. Under circularly polarized quasiresonant excitation, we observed a degree of circular polarization $\mathrm{DOCP} = -36\%$. The unusual negative circular polarization suggests the trion to be negatively charged [5, 6]. The excitation-emission energy difference ($\Delta E = 37$ meV) suggests phonon-assisted excitation into the higher energy state (the energy of longitudinal optical phonon in the InP substrate $E_{\mathrm{LO}} = 43$ meV). Using Hanle effect measurements and previously reported electron g-factors ($g_e = 0.25$) [7] we estimated the optically oriented residual electron spin dephasing time as $T_2^* = 1.6$ ns. The result suggests that the primary dephasing mechanism is the interaction with the frozen fluctuation of the nuclear spin [8]. At low magnetic fields, where the external magnetic field is weaker than the Overhauser field, dephasing is dominated by the hyperfine interaction [9]. Despite the large nuclear spin of indium $I = 9/2$ and its hyperfine constant $A_{\mathrm{In}} = 56$ μeV [6], observed spin dephasing times are comparable to those reported for GaAs QDs [8, 10]. This suggests that the influence of indium is probably partially compensated by a larger volume of telecom QDs [8]. Additionally, the obtained T_2^* value being close to the radiative recombination lifetime for these structures, enables the realization of an efficient spin-photon interface – essential among others for multiphoton entanglement generation, a fundamental component of photonic quantum repeaters.

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