From Deterministic Positioning to Universal Control: Spin Pumping and Trion Coherence in Pyramidal Quantum Dots

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Deterministically positioned pyramidal InGaAs quantum dots (QDs) grown in (111)B GaAs pyramidal recesses (Fig. 1(a)) offer a compelling route to scalable solid-state quantum hardware, combining site control with excellent optical quality and compatibility with on-chip photonics [1]. A central challenge for quantum networks and processor architectures is to realize emitters that can be both reproducibly integrated in arrays and operated as high-fidelity spin–photon interfaces with coherent, ultrafast control. Here we present two recent advances that jointly address this challenge in pyramidal QDs, linking spin preparation with universal optical control in the same platform.

In a longitudinal (Faraday) magnetic field, heavy-hole mixing in a positively charged pyramidal QD yields a four-level double-Λ system with near-circular polarization optical selection rules (Fig. 1(b)). Using resonant excitation together with weak above-band randomization, we demonstrate robust hole-spin pumping and initialization (Fig. 1(c)) via the optical transitions of the double-Λ manifold, achieving high-fidelity preparation across a broad range of driving conditions [2].

Building on the same level structure and exploiting background-free detection on an undriven branch, we implement picosecond resonant control of the trion-hole transition. We observe pulse-area-dependent Rabi rotations, Ramsey interference to quantify the optical coherence of the trion-based qubit, and full SU(2) control by jointly tuning pulse areas and relative phase, providing access to the complete Bloch sphere (Fig. 1(d)) [3]. Together, these results establish pyramidal QDs as a scalable quantum-dot platform that supports deterministic positioning alongside high-quality spin initialization and coherent optical control. These are key ingredients for integrated quantum photonics and quantum-network oriented device architectures and lay the groundwork towards establishing spins in this type of quantum emitter as a viable qubit platform.

References

[1] G. Juska et al. Nat. Phot. 7, 527 (2011).
[2] R. A. Barcan et al. Phys. Rev. B 112, L121301 (2025)
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Figures

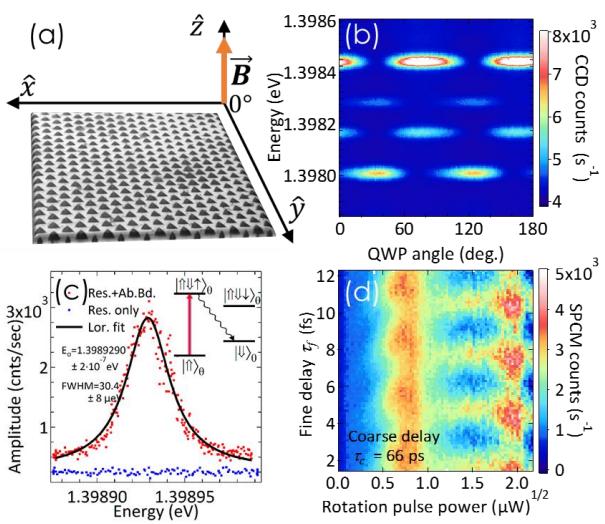

Figure 1: (a) Rendered pyramidal QD sample and B-field orientation. (b) Circular polarization emission from double-Λ system. (c) Spin pumping and high-fidelity initialization. (d) Complete coherent control of the trion to hole-ground-state transition.