Single spins in self-assembled quantum dots

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A solid-state system that mimics the properties of a few-level atom is an attractive proposition for various applications involving single photons. The solid-state environment "traps" the emitters enabling them to be probed and manipulated one by one. One example is a nano-structured semiconductor such as a quantum dot. Notably, quantum dots can be self-assembled in the growth, the best example being InAs quantum dots in a GaAs host.

Quantum dots in GaAs have many attractive features. First, the semiconductor host leads to a reduced radiative lifetime of just 1 ns resulting in an increased flux of single photons. In fact a single quantum dot is a robust, high-brightness, narrow-linewidth source of single photons, properties probably not shared by any other emitter. Secondly, the environment of a single quantum dot can be tailored relatively easily using a semiconductor heterostructure and post-growth processing techniques. This facilitates control over the photonic modes with which the quantum dot interacts. It also allows single charges to be trapped inside a quantum dot via electrical techniques.

A single electron or hole trapped inside a quantum dot has a spin and can be used as a spin qubit [1]. The single spin benefits from the strong optical transition: the spin can be initialized, manipulated and subsequently read-out optically. A notable point is that the manipulation, a spin rotation for instance, can be carried out on sub-nanosecond timescales by exploiting the large optical dipole.

The complex physics lies in the decoherence (T_2 processes) and dephasing (T_2^* processes) of the optical qubits and spin qubits. In the best case (high quality material at low temperature with weak resonant optical excitation), the optical qubit decoheres simply by radiative recombination, but the origin of the dephasing is subject to debate. The electron spin qubit dephases rather rapidly with T_2^* times of just a few nano-seconds: this dephasing arises from the hyperfine interaction of the single electron spin with the 100,000 nuclear spins. This is a complex central spin problem. The electron spin Hahn-echo T_2 times are much larger than the T_2^* times, typically in the micro-second regime.

A number of approaches can be pursued to prolong the dephasing times. One is to reduce the noise in the nuclear spin ensemble. Another is to switch from an electron spin to a hole spin. The contact part of the hyperfine interaction is strongly suppressed for a hole spin; the dipole-dipole part of the hyperfine interaction remains but in the case of a pure heavy hole state, the noise can be strongly suppressed with an in-plane magnetic field. Presented here are the results of experiments facilitated by the detection of resonance fluorescence from single spins in single quantum dots. The main results are: (i) determination of the charge noise and spin noise spectra [2], (ii) demonstration that nuclear spin noise (and not charge noise) is the main contributor to exciton dephasing [2], (iii) active reduction of charge noise with feedback [3], and (iv) close-to-ideal hole spin coherence but with charge noise-induced spin dephasing [4]. Prospects for engineering spin coherence and for enhancing the spin-photon interaction with a micro-cavity will be discussed.

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