Spin Noise of Electrons and Holes in Self-Assembled InGaAs Quantum Dots

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The dynamical properties of electron and hole spins in semiconductor quantum dots (QDs) are actively investigated for potential applications in spintronics and quantum information processing. Optical pump-probe studies have proven essential in this regard, directly revealing the g-factors and coherence decays of spins in QD ensembles and in single QDs. In principle, these important properties are also accessible via alternative measurement approaches based on "spin noise" spectroscopy, in which the intrinsic fluctuation spectra of the spins -- if measurable -- also reveal this dynamical information, in accord with the fluctuation-dissipation theorem. In general, spin noise signals scale favorably as the number of measured spins decreases (falling only as $\sqrt{N}$), suggesting their use as viable probes of few-spin systems. Indeed, single electron spin detection using ultra-sensitive cantilevers exploited spin noise, and nuclear spin noise imaging of nm-scale specimens has been demonstrated. Using optical probes, electron spin noise spectra were recently measured in alkali vapors, bulk GaAs, and quantum wells. However, spin noise spectroscopy of fully quantum-confined electrons and holes in QDs has not yet been achieved, due in part to the very small magnitude of their noise signatures which are typically much less than the background noise density from electronic and photon shot noise. Considerable signal-averaging and efficient use of the available data stream are therefore essential aspects of these experiments.

Here we demonstrate spin noise spectroscopy to be a powerful probe of the dynamical properties of spins localized in semiconductor QD ensembles. Spin fluctuation spectra from 0-1 GHz are measured continuously in real time (no dead time), using an optical Faraday rotation magnetometer coupled to a fast FPGA-based digital spectrum analyzer. The data exhibit sub-nanorad/root-Hz sensitivity over the entire spectral range, revealing the tiny spin noise signatures from both quantum-confined electrons and holes. The evolution of these noise peaks with magnetic field directly reveals their g-factors and dephasing rates, and clearly exposes a marked, energy-dependent anisotropy of the in-plane hole g-factor which -- in contrast to electron g-factors -- has been predicted to be a sensitive probe of QD confinement potentials.

Fig. 1(a) shows the experiment. (In,Ga)As/GaAs QDs are grown by molecular beam epitaxy on (100) GaAs and then annealed. All structures contain 20 layers of QDs separated by 60 nm GaAs barriers, with $10^{10}$ QDs/cm$^2$ per layer. The QDs are nominally undoped. The samples are mounted on the cold finger of an optical cryostat. Random spin fluctuations in the QDs, $\delta S_z(t)$, impart Faraday rotation fluctuations $\delta \theta(t)$ on a narrowband probe laser that is focused to a 3.5 $\mu$m spot on the sample. Balanced photodiodes detect $\delta \theta(t)$, and the amplified output voltage $\delta V(t)$ is sent to a 1 GHz real-time digital spectrum analyzer implemented in the parallel configurable logic of a field-programmable gate array (FPGA). This FPGA-based approach to spectral analysis and averaging maximizes the data collection efficiency and therefore the noise sensitivity. In comparison, traditional spectrum analyzers employing "swept" local oscillators ignore most of the available signal -- e.g., measuring a 0-1 GHz spectrum with 1–MHz resolution effectively discards ~99.9% of the relevant data stream at any given time. Improved throughput is achieved by digitizing and averaging fast-Fourier transforms (FFTs) of the data stream so that all frequencies are averaged simultaneously. However, the finite interface bandwidth between typical plug-in digitizers and host computers -- and the substantial computational demands on the host processor(s) -- can impose significant limitations. Using standard digitizers to realize 1–GHz bandwidth, typically <5% of the available signal is actually used, with a corresponding reduction in experimental sensitivity.

Figure 1. a) Experimental schematic. Spin fluctuations impart Faraday rotation fluctuations on the probe laser. $V(t)$ is digitized at 2 GS/s, and its power spectrum from 0-1 GHz is computed and averaged continuously on a FPGA. (b) A raw power spectrum showing hole spin noise in (In,Ga)As QDs after 600 s averaging (1.2 TB of processed data).