Role of Nuclear Quadrupole Coupling on Decoherence and Relaxation of Central Spins in Quantum Dots

N. A. Sinitsyn, A. Saxena, D. L. Smith (T-Division, Los Alamos); Yan Li, Scott Crooker (NHMFL- Los Alamos)

Introduction

Spin decoherence and finite spin lifetimes are currently the major factors that limit our ability to control electron and hole spin states in quantum dots. A single "central" (i.e., electron or hole) spin in a dot interacts via hyperfine coupling with a large number (10^4–10^6) of nuclear spins. The net effect of this coupling to the nuclear spin bath can be characterized by an effective Overhauser magnetic field $\mathbf{B_n}$ that acts upon the central spin. Within a quantum dot ensemble, each central spin precesses around a different $\mathbf{B_n}$. If $\mathbf{B_n}$ is time independent, such precession alone cannot lead to complete relaxation of the central spin polarization. This is evidenced from the observation of spin echoes that can be used to cancel the dephasing of central spins in an ensemble of dots with different constant $\mathbf{B_n}$. However, stochastic *dynamics* of the Overhauser field $\mathbf{B_n}$ induces irreversible relaxation and decoherence of the central spin.

It was suggested that, at microsecond time scales, the dynamics of $\mathbf{B_n}$ is dominated by hyperfine-mediated nuclear co-flips, which originate from unequal strengths of the hyperfine couplings of the central spin to different nuclear spins inside the same dot. Numerics showed that such co-flips generally lead only to a logarithmically slow central spin relaxation. In contrast, recent experimental studies with hole-doped InGaAs quantum dots reported [1] a nearly ideal Lorentzian shape of the spin noise power spectrum, indicating exponential relaxation of central hole spins rather than a power-law or logarithmic relaxation.

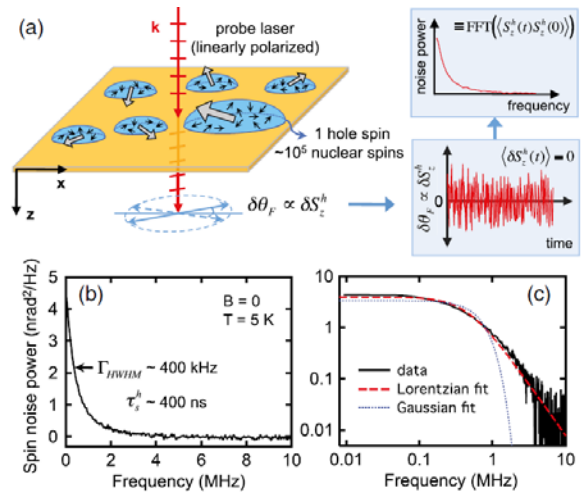

Figure 1. Experimental spin noise data showing exponential spin relaxation of hole central spins in InGaAs quantum dots, in contrast to theoretical expectation. From [1].

Results and Discussion

Here we show that quadrupolar couplings (QC) of nuclear spins to the strain-induced electric field gradients inside typical semiconductor quantum dots can induce relatively fast dynamics of $\mathbf{B_n}$, and consequently accelerated relaxation of electron and hole spins in weak external fields. Our model directly applies to InGaAs self-assembled quantum dot systems, which are among the most popular platforms for spin memories and qubits; however, the model applies generally to all dots composed of quadrupolar-active nuclei. We model such a nuclear spin bath by introducing static fields acting on nuclear spins due to QC, in addition to the hyperfine couplings to the central spin. We numerically compute the dynamics of our model by applying a time-dependent mean field algorithm that allows us to study the relaxation of a central spin coupled to an unpolarized spin bath containing up to 10000 nuclear spins.

We show [2] that when the quadrupolar coupling strength is comparable to or larger than the hyperfine coupling strength between nuclei and the central spin, the relaxation rate of the central spin is strongly enhanced and can be exponential. We demonstrate a good agreement with recent experiments on spin relaxation in hole-doped (In,Ga)As self-assembled quantum dots. This work was supported by the Los Alamos LDRD program.

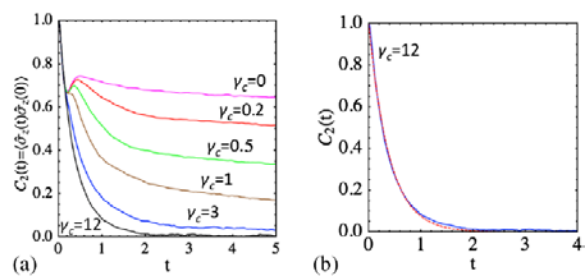

Figure 2. Results of a numerical model of central spin relaxation in the presence of increasing quadrupolar hyperfine coupling \gamma_c. With increasing \gamma_c, relaxation of the central spin evolves from inverse-log to a much faster exponential relaxation. From [2].

[1] Yan Li *et al.*, Phys. Rev.Lett. **108**, 186603 (2012).
[2] N. A. Sinitsyn *et al.*, Phys. Rev. Lett. **109**, 166605 (2012).