Nuclear Spin Control in GaAs Quantum Dots via Nuclear Quadrupole Resonance

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THE HYPERFINE INTERACTION AND QUANTUM MEMORY IN QDs

- Quantum dots (QDs) are an attractive system for **quantum information storage and processing in a network**.
- Qubits are realized using an **optically active electron spin** confined in all directions to length scales of 10 nm, whose energy levels are **Zeeman-split** using a constant magnetic field**,** interacting with $10^4 - 10^6$ **nuclei** within the QD[1].
- The electron can be driven with electromagnetic radiation, and its state can be read out using **spin selective optical transitions**.
- Electrons in QDs can exhibit coherence times of the order of 100 μs [2], while nuclei can achieve coherence times of the order of 100 ms [3].

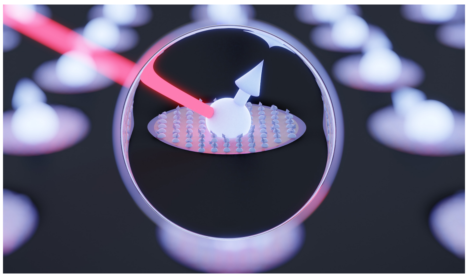

Fig. 1: Illustration of a QD, with an optically driven (red beam) electron spin in light blue in the center, surrounded by "smaller" nuclear spins

- The central electron is coupled to neighboring nuclei via the hyperfine interaction, which can be used to **transfer electron spin states** to this nuclear register [4,5] with significantly **longer coherence times**, effectively realizing quantum memory.
- Protocols to implement and protect such a memory requires **accurate and efficient control of the nuclear spin register**.

NUCLEAR QUADRUPOLE RESONANCE

- Nuclear spins are traditionally controlled via **nuclear magnetic resonance** (NMR). However, NMR is constrained by the requirement of driving large currents in proximal coils, which causes unwanted heating in cryogenic environments, thus limiting **scalability**.
- Our goal is to develop a new way of inducing nuclear spin transitions in GaAs QDs using nuclear quadrupole resonance (NQR), a method based on the **quadrupolar coupling between the spin-3/2 nuclei and an oscillating electric field gradient** (EFG).

$$\hat{H} = \hbar\omega_L \hat{I}_{\vec{u}} + \frac{eQ}{2I(2I-1)}\hat{\vec{I}} \cdot V(t) \cdot \hat{\vec{I}}$$

$$\begin{cases} \Omega_1 \approx \dfrac{\sqrt{3}eQ}{12\hbar}|V_{xx}\sin(2\theta)| \\ \Omega_2 \approx \dfrac{\sqrt{3}eQ}{24\hbar}|V_{xx}|(\cos(2\theta)+3) \end{cases}$$

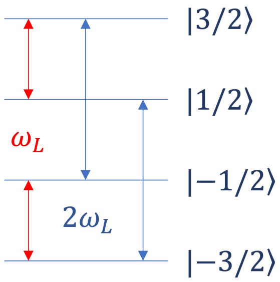

Fig. 2: Nuclear spin energy level diagram

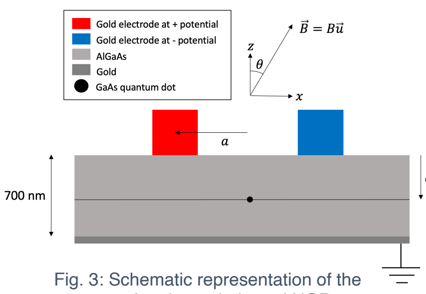

Fig. 3: Schematic representation of the setup for electrode-based NQR

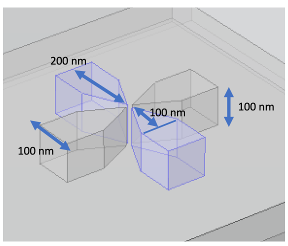

Fig. 4: Typical electrode geometry (from a COMSOL simulation)

ELECTRIC FIELD GRADIENTS AND RESONANT DRIVING

- Electrodes forming a **quadrupole** with sinusoidally oscillating electric potentials close to the **transition frequencies** of the nuclei, related to the Larmor frequency ω_L.
- Toy model solved analytically using the **quasistatic approximation**, and more realistic model using COMSOL which accounts for the **polarizability** of the medium.
- Experiments will need to make use of **resonant LC circuits**, with a matching inductor L. To this end, we've also modeled and simulated the capacitance C between electrodes.

$$V_{xx}(a,d) = c_1 \frac{(a-c_2)^2}{\left((a-c_2)^2 + (d-c_3)^2\right)^{\frac{5}{2}}}$$

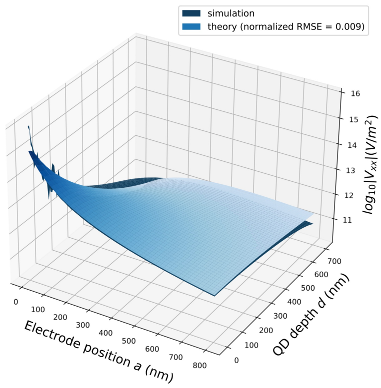

Fig. 5: Largest component of EFG per electrode voltage

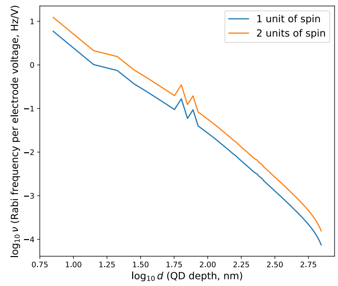

Fig. 6: Maximum Rabi frequency per electrode voltage

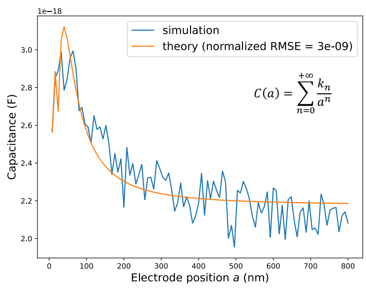

Fig. 7: Electrode capacitance

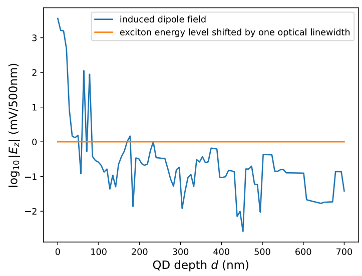

Fig. 8: Induced dipole fields in the sample per electrode voltage

CONCLUSIONS & FUTURE WORK

- AC quadrupole electrodes etched onto an AlGaAs sample can be used to **drive QD nuclear spin transitions locally.**
- Main challenges in NQR: obtaining sufficiently **high Rabi frequencies** and avoiding unwanted **dipole fields** in the material for realistic dimensions and applied voltages.
- **Resonant circuit driving** can help reduce generator voltage drastically, but this still requires very high voltages on the electrodes relative to the relevant breakdown voltages (air: 0.3 V, high vacuum: 10 – 100 V).
- One could also implement NQR using **strain waves** which generate time-dependent EFGs. This will be addressed in future work.

REFERENCES

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