Spin qubits in semiconductor quantum dots - The state of the art in Delft

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The high control reached in the manipulation of a single electron spin in a semiconductor environment is encouraging for future application of this natural two-level system in quantum computation. Nanofabricated quantum bits permit large-scale integration but usually suffer from short ***coherence times*** due to interactions with their solid-state environment. In fact the semiconductor environment implies that the electron is intimately in contact with phonons, charge fluctuations and nuclear spins and those interactions are responsible for the relaxation and dephasing process of the electron spin. The outstanding challenge is to engineer the environment so that it minimally affects the qubit, but still allows qubit control and scalability.

Early experiments were possible with III-V semiconductor materials because they allow great control on device structure. However, neither Ga, As or Al exist as nuclear spin free stable isotopes. For this reason, the hosted electron spin qubits interact with tens of thousands of nuclear spins via the hyperfine interaction and the ***quantum coherence*** is considerably quenched (T_2^*≈10ns). To overcome this limitation we are now investigating Si/SiGe quantum dots where hyperfine interaction is weak being roughly proportional to the fraction of nuclear spins and having naturally composed Si crystals only a small (4.7%) fraction of ½ spin carrying isotopes. In our experiments, the spin is driven by resonant microwave electric fields in a transverse magnetic field gradient from a local micromagnet and we observed a ***coherence time of the order of 1 μs***, almost two orders of magnitude longer than the intrinsic timescales in GaAs quantum dots. The slow dephasing and fast Rabi frequency of 1.4 MHz yield an average single qubit gate fidelity measured to be 99.1+-0.2% via randomized benchmarking. This is above the threshold required for quantum error correction using surface codes. These advances strongly improve the prospects for quantum information processing based on quantum dots.

The other time scale to take into account in the characterization of the qubit is the electron spin lifetime T_1 (**relaxation time**). At magnetic fields of the order of Tesla, spin relaxation in GaAs dots was found to be dominated by the spin-orbit interaction in combination with piezo-electric phonons. Recently we demonstrated a high anisotropy of the spin-orbit effect in GaAs, along different in-plane crystallographic directions since we observed a strong variation of T_1 (by more than an order of magnitude) when rotating a 3 Tesla field, reaching about 80 ms for the magic angle. We infer from the data that in our device the sign of the Rashba and Dresselhaus constants are opposite.

Finally, the need for the **scalability** of such quantum processors calls for coherent coupling between spatially separated qubits. One proposal for getting a long-distance coupling between spin qubits is based on entangling the spin state with a superconducting microwave resonator. Recent experimental attempts to achieve hybrid spin-photon states (**strong-coupling** regime) using this scheme have been unsuccessful due to the insufficient interaction strength. Recently we took a new approach in the design of the superconducting resonators using a thin film of NbTiN with high kinetic inductance, in order to fabricate a resonator which develops 10 times higher vacuum fluctuation voltages, compared with the standard coplanar waveguide resonators.

References

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