Electromagnetically induced transparency with localized impurity electron spins in a semiconductor

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Academic summary

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This PhD thesis contributes to a research field that aims to understand and extend the limits of how well quantum states of matter and electromagnetic fields can be prepared, controlled and detected. On the one hand, this field is driven by fundamental questions that are not yet fully answered: can we better understand the transition between quantum physics and classical physics that is observed in the behavior of several material systems, and what are the limits for obtaining purely quantum mechanical behavior for suitably designed systems? On the other hand, this field is driven by proposed applications from quantum information science. These proposals consider that the state of a bit of information (which classically can only be in the state 0 or 1) can behave quantum-mechanically (such that the bit can be in a quantum state that is 0 and 1 at the same time). The performance of quantum information processing can be dramatically superior to classical information processing, but it is currently still a scientific challenge to realize quantum information systems that are large and stable enough for actual application in society. Just as for the fundamental questions, progress here requires better understanding of how a material system can have pure quantum mechanical behavior that is only weakly and slowly disturbed by noise from its environment.

The research presented in this PhD thesis investigated questions with relevance for this field with laser control of the quantum state of electron spins in a semiconductor. It thereby addressed the challenge of realizing quantum information systems with semiconductor technology, for which it is anticipated that it is (relative to other material systems) well suited for scaling small units to large-scale systems. The focus was on the spin of donor electrons, which occur as localized singe-electron systems at donor atoms (intentionally added impurities) in the semiconductor gallium arsenide (GaAs). The rational for working with this

material system is that it has good optical properties that are well understood, and that the material can be grown as very pure and high quality crystals.

Central to this PhD research was the question whether Electromagnetically Induced Transparency (EIT) could be realized with the spin of donor-impurity electrons in GaAs. This effect, EIT, had already been realized and widely studied with laser control of atomic vapors, but was not yet widely explored with atom-like systems in a solid-state material. EIT is the phenomenon that (near-) resonant laser driving of an electronic transition of a medium does not behave as an optically absorbing resonance, but allows the laser field to propagate as in a transparent medium because a second laser field also influences the medium. In particular, it can occur when the two lasers each drive a transition from one of two spin states to the same excited state. The electronic system is then trapped in a controllable quantum superposition of the two spin states, and the system's driven dynamics does not give transitions to the excited state because the two paths in parallel interfere destructively. EIT forms the basis of many quantum-optical control schemes that use long-lived spin states that must be coupled to optical signal fields.

After an introductory chapter, *Chapter 2* presents an approach to, and successful demonstration of EIT with an ensemble of donor-bound electron spins in GaAs. It used optical transitions from the Zeeman-split electron spin states of the donors to an excited state where an additional electron-hole pair is localized around the donor impurity (donor-bound exciton). The quality of the spectral signature of EIT could be used to derive that the electron spin dephasing time was about 2 ns. The behavior of the spectral EIT signature also indicated that the electron spin coherence was limited by the coupling of the electron spin to the spins of many surrounding nuclei in the GaAs lattice (hyperfine interaction).

Next, in *Chapter 3*, we report a further investigation of the optical transitions between the donor ground state and the donor-bound-exciton states. Our approach to EIT also yields a method for high-resolution optical spectroscopy of these transitions in a transmission experiment. The results do not only contribute to ongoing research into the fundamental properties of donor-bound excitons, but are also relevant for optimizing EIT control with this material system. We compare our results to existing theory, and conclude that existing models do not yet fully describe our observations. At the same time, our results do establish what the suitable optical transitions are for EIT, and how nearby transitions to other levels of the donor-bound-exciton system can possibly influence the behavior of EIT.

Chapter 4 of this thesis described results of exploring how driving EIT with donor electrons in GaAs can influence and probe the interactions between each donor electron spin and the ensemble of nuclear spins in its direct surroundings (hyperfine interaction). We observe how EIT can both drive and probe dynamic nuclear polarization (DNP). DNP can occur when one drives the electron spin polarization out of thermal equilibrium (as we can do with the EIT laser control scheme), while relaxation of the electron spin polarization to its equilibrium value causes polarization of the nuclear spins (the hyperfine interaction gives electron-nuclear-spin flip-flop as relaxation processes). Since nuclear spin polarization influences the energy splitting between the electron spin states, it should also influence the spectral signature of EIT. We indeed observe that EIT can be used for influencing and monitoring the build-up and decay of DNP. This observation is of value as a first step towards laser control of the nuclear spins into a state that gives less dephasing for the electron spin coherence.

In *Chapters 5 and 6* we report on the design, development and testing of dedicated instrumentation that was required for the research of the previous chapters. We did all experiments in a helium-bath cryostat with applied magnetic fields up to 9 Tesla in the measurement volume. For sending well-defined laser beams to GaAs samples we developed an approach with a polarization-maintaining optical fiber and a compact confocal microscope in the measurement volume, with a piezo-motor driven focussing mechanism. Initial work used detection signals from photodiodes inside the cryogenic measurement volume. At later stages this instrumentation was developed further to one where a pair of multi-mode fibers was aligned to collect light after transmission through GaAs (or emitted by GaAs) for more advanced light detection and signal analysis outside the cryostat. This set-up allows for recording an EIT spectrum much faster, and will be useful for future quantum-optical and DNP experiments with our GaAs material system.