Chapter 1

Introduction - Engineering strong light-matter coupling for quantum technologies

1.1 Motivation

The question that motivates the research described in this thesis is: Can the spin of localized electrons bound to impurities in a semiconductor serve to store a pulse of light? Realizing this would be a small step in a much larger (global) effort that strives to develop a new generation of faster, more energy efficient electronics that relies not only on conventional electron charge transport, but also uses light as well as the electron’s spin as information carriers. This field, which is still taking shape, is commonly referred to by labels such as ‘optoelectronics’ or ‘spintronics’. Manipulating light-matter interaction in this way is also important for quantum information science. The desire to use light as information carrier stems in one part from the fact that it moves at the ultimate speed. Optical fiber technology is nowadays widespread because it facilitates high-speed data transmission. To achieve high speed in electronic components such as integrated circuits, these devices have to be reduced in size (to reduce the distance traveled by the electrons). Current technology has rapidly approached the limit where the size of components is only tens of atoms. Besides that one atom would be a fundamental size barrier, at the current lengthscale there are other significant drawbacks, such as heating of the components due to resistivity in the circuit. This highlights another aspect of light, that it moves freely through space or along properly designed guiding structures. Energy consumption can thus be reduced by
developing an equivalent of electronic circuits based on light. However the last point relates to a major difficulty for using light in circuit-like components: it is more difficult to control than electrons, especially at small scale. Electronic currents can be switched (notably in a three-terminal transistor configuration) and electronic energy can be stored in memory elements. For light such active components are still being developed.

A final interesting prospect is that photons can mediate coherent interaction between material systems, while traveling over long distances. This makes optical circuit technology promising for quantum information applications: Quantum mechanics is at the heart of how all modern computers work, through CMOS technology. Quantum computers however aim to use quantum mechanical properties (such as state coherence) of the units on which computation is actually performed, the bits of information. With electron spins as a prime candidate of a material system that shows a high degree of coherence, even inside a crystal where the environment is very crowded with other (quasi)particles, it is desirable to create an interface between the two. Such an interface should allow to transfer the state of photons to the quantum state of electron spins and vice versa.

1.2 Why quantum technology?

The last point of the previous section is particularly interesting from a scientific point of view. Because the fundamentals of quantum physics still pose many open questions [1], it is therefore of current importance to keep extending the number of experimental testing grounds. The prospect of applications is however another matter. The use of scientific discovery can often not be envisioned at the moment when the discovery is done. For example, the first demonstration of a Maser proposed that it be used as a low noise amplifier and that it ”may be useful in a restricted range of applications”. Specifically, the authors suggest that it could serve to amplify microwave signals from outer space. The subsequent discovery of the Laser was first thought to be mainly useful for atomic spectroscopy. These scientists could not possibly have foreseen that laser beams would soon be used for precision cutting in industry and for surgical techniques,
1.2 Why quantum technology?

and that they would connect people around the world by enabling fiber optic communications technology. The present quest for realizing quantum technologies could well be at a comparable stage. There is a general sense that it is important, but no guarantee that the applications we think of now are the ones that will have most impact. Not being able to look into the future we have to motivate ourselves with the main candidates we have now: quantum communication (mainly the aspect of cryptography) and quantum computation. The physical requirements for both applications concern to a large extent the same challenges, and we will further examine here the quantum computer to see what quantum technology is and what the challenges are.

Quantum computers aim to use quantum mechanical properties of the units on which computation is actually performed, the bits of information. To understand what the requirements for this are we look at the heart of the theory: The discovery of wave-particle duality led to a theoretical framework where the state of every physical entity is properly described by a wave function. The wave function contains probabilistic information of all properties of the system, it evolves according to the equations of motion in a deterministic way. But, curiously, measurement outcomes are given by the square of the wave function. The consequence of this is that the wave function can be multiplied by a complex phase factor without altering the measurement outcome. In the case of two systems (x and y) that have (hypothetically) never interacted the wave function of the combined system is $\psi_x \psi_y$, resulting in multiplication of probabilities in the classical sense. But when systems have a history of interaction there wave function will be $\psi_{xy}$ which is generally not separable as a product of single system wave functions. When this is the case measurements on x influence measurements on y (and vice versa) in a way that has no counterpart in classical physics. The interaction in the past leads to this entanglement. Studies of entanglement have a history that goes back to the Einstein-Podolsky-Rosen paradox and the Bell inequalities, and is still central in current fundamental research (for a review see [2]).

Entanglement can be stronger or weaker depending on the interaction that caused it. For entangled systems the phase factor becomes important
and deterministic evolution of systems x and y with retention of their relative phase (i.e. coherent evolution) preserves the entanglement. In the context of quantum computing the systems x and y can be considered qubits and the inclusion of phase enables them to carry more information than classical bits. Proposals for quantum computing using qubits involve preparation of the states of the qubits, planning of the sequence of subsequent interaction between qubits (the interaction is the computation step) and readout of the final state of the qubits. After the interaction steps take place as planned the final state yields the result of the computation.

However, if system x subsequently has interaction with a system z they in turn become entangled and the triplet of particles (x,y,z) are now entangled together. When the interaction with z happened unknowingly (because during an experiment e.g. it is a particle in the environment that is not tracked and measured) it interrupts the deterministic, coherent evolution of the entangled pair (x,y) for the observer who is only tracking x and y. There cannot be a deterministic equation of motion for x and y that takes such interaction events (that can be described as scattering processes) with z into account, hence they must be added in the form of probabilistic decoherence (for elastic scattering) and decay (for inelastic scattering) processes. For quantum computation to be successful the computation should finish before decoherence and decay disturb the system.

Based on the foregoing discussion we can establish that in a quantum computer the objective is to keep the system isolated from the environment (at least as long as it takes to compute) and to make interactions within the system deterministic. Spins and photons are considered to in principle be able to fulfill the former, the latter requires the designed spin-photon coupling to be 'strong' which basically means that a photon should not miss its destination.

1.3 This thesis: Coherent coupling between photons and bound electron spins in GaAs

In this thesis we work with an ensemble of electron spins bound to Si donors in GaAs with the aim to use this material to store and retrieve a pulse of light. To this end we focus on measurement of electromagnetically
induced transparency (EIT) in the system. This effect is an important precursor to many methods in quantum communication [3, 4, 5] and also, but to a lesser extent, quantum computing [6].

We demonstrate EIT, but show that the interaction of the electron spin with the nuclear spins poses a severe difficulty for proceeding beyond this. These nuclear spins are in fact untracked particles in the environment of the system that we wish to control, in the sense it was discussed in the previous section. However the nuclear spins form a special type of environment which moves slowly compared to the dynamics of the electron. In contrast to a Markovian environment which is the same at every instant, the nuclear spin environment can be changed. In the main chapters of this thesis we develop and test a method that can prepare the nuclear spins in a state of reduced fluctuations, in order to extend the electron spin dephasing time. In the experiments we find partial confirmation of our method and point out several issues that can be improved on the experimental method.

The thesis is built up as follows: Chapter 2 is a technical introduction to the donor-bound electron system in GaAs, to electromagnetically induced transparency, and dynamic nuclear spin polarization. These are topics that are fundamental to the research described in this thesis. In Chapter 3 presents how electromagnetically induced transparency can be used to measure nuclear spin polarization. Optically-induced dynamic nuclear spin polarization (DNP) is demonstrated and its dynamics is characterized. Chapter 4 introduces the proposal for a technique to reduce nuclear spin fluctuations through DNP. It is shown that when the DNP is induced by two lasers that are on a two-photon resonance condition, this can have a stabilizing effect on the nuclear spins. Chapter 5 presents measurements that test the model and proposed control technique of Chapter 4. In Chapter 6, more details of the DNP process are studied, in particular the dependence on photon ennergy of the light that induces it. Chapter 7 shows spectroscopy measurements of the system in a magnetic field in order to resolve the level structure of the donor-bound exciton. Chapter 8 describes the methods used to do the experiments described in the earlier chapters, in particular the sample preparation, microscope
design and spectroscopy technique. Finally, conclusions from the various chapters are grouped and presented in Chapter 9.

References


