

A Thesis for the Degree of Ph.D. in Science

Electron paramagnetic resonance of
photoexcited triplet states of
oxygen-vacancy centers in silicon

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Abstract

Spin-based quantum computation is one of the most ambitious applications of spintronic where the electron and/or nuclear spins are employed as quantum bits (qubits). In the scheme of semiconductor silicon-based quantum computing, electron spins and nuclear spins of phosphorus donors and nuclear spins of ^{29}Si have attracted much attention as candidates for qubits. However, neither physical processes to transfer quantum information into and out of a particular spin qubit nor methods to exchange information between spin qubits have been established.

The present thesis shows that the presence of photoexcited triplet electron spins of oxygen-vacancy centers (SL1 centers) in silicon establishes a novel way to induce spin flip-flops of the triplet spins with phosphorus electron spins even in the absence of electromagnetic excitation field. Moreover, SL1 center is shown to be an excellent center to transfer quantum information into and out of ^{29}Si nuclear spin qubits.

The thesis is composed of six chapters. Chapter 1 is an introduction which includes the motivation and the detail description of the spin systems utilized in this work. Chapter 2 provides the basic principles of magnetic resonance techniques employed in this work.

Chapter 3 shows the spin dependent recombination processes via phosphorus donor states and SL1 triplet states in silicon detected by the change in the photoconductivity of samples. This corresponds to electrically detected magnetic resonance (EDMR) of electron and nuclear spin states of phosphorus and SL1, i. e., electrical readout of spin qubit states in silicon. Furthermore electrical detection of cross relaxation (EDCR), flip-flops between phosphorus bound electron spins and SL1 triplet spins, is shown. When the Zeeman splittings of the dipolar coupled phosphorus electron and photoexcited triplet electron spins are made equal by appropriate tuning of the external magnetic field, they undergo flip-flop transitions which change the overall recombination of the photoexcited carriers and thus changing the photoconductivity of the sample.

Chapter 4 investigates the lifetime of the photoexcited triplet SL1 centers and their interaction with the nearest-neighbor ^{29}Si nuclear spins using pulsed electron paramagnetic spin resonance (pEPR). While the population rates of the three triplet levels are almost equal, the decay rate from each triplet level to the ground singlet state is found to be different leading to $\approx 100\%$ spin polarization in about 1.5 ms after creation of the photoexcited states by the laser pulse. The electron spin echo envelop modulation

reveals the hyperfine coupling of the triplet electron spins with the nearest-neighbor nuclear spins of ^{29}Si ($I=1/2$).

Chapter 5 describes a proof-of-concept operation of ^{29}Si nuclear spin quantum memory in silicon. The coupling between the highly polarized triplet electron spins and ^{29}Si nuclear spins facilitate the transfer and storage of the coherent state of the triplet electron spins in the nuclear spin degrees of freedom using a series of resonant microwave and radio frequency pulses in the pulse electron nuclear double resonance (pENDOR). We found nuclear storage time of nearly 5 ms which is close to the previously reported T_{2n} of 5.6 ms for ^{29}Si .

Finally summary and outlook are provided in Chapter 6.