A THESIS FOR THE DEGREE OF PH.D. IN SCIENCE

Magnetic resonance of bismuth donors in silicon detected by spin dependent recombination

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Abstract

Realization of quantum information processing devices including quantum computers is one of the most highlighted projects physicists are pursuing today. When realized, quantum computers will be composed of multiple elements such as processors, memories, communication lines, etc. just like today's computers. While superconducting qubits are excellent candidates as quantum processors, hydrogenic donors in silicon are considered very promising as quantum memory qubits. Among them, bismuth (Bi) donors in silicon are important since they demonstrate long coherence (quantum memory) time and, in the low enough magnetic field needed by the superconducting qubits to operate, the energy separation between $|0\rangle$ and $|1\rangle$ states is compatible with that of superconducting qubits making them connectible to each other.

The present thesis shows the successful manipulation and the electrical detection of Bi donor spins in silicon at arbitrarily chosen magnetic fields, establishing a novel way to readout electron and nuclear spins of Bi in the zero-field limit. Moreover, the hyperfine clock transitions of Bi that are extremely robust against external electric field noise are identified experimentally for future applications to quantum memories.

The present thesis is composed of six chapters. Chapter 1 introduces the motivation of the research. Chapter 2 describes the basics of spin systems utilized in this work. Chapter 3 summarizes the experimental techniques including sample preparations and measurements. Chapter 4 describes the low-field (6-110 mT) magnetic resonance spectroscopy of Bi in silicon. It is performed by monitoring the change in photoconductivity of the sample induced by the spin dependent recombination. Spectra at various resonance frequencies show signal intensity distributions drastically different from those observed by the conventional electron paramagnetic resonance spectroscopy. A theoretical model considering the recombination rates for the forty possible combinations of spin states of a pair of a Bi donor and a paramagnetic recombination center is shown to describe the experimental observation well. Moreover, excellent tunability of the Bi excitation energy for the future coupling with superconducting qubits at low fields is demonstrated. Chapter 5 presents comparison of Bi spectra in ^{28}Si and ^{nat}Si crystals. The hyperfine clock transition, at which the linewidth is significantly narrowed, is observed. The experimental results are modeled quantitatively by the effect of hyperfine and Zeeman interactions in the context of molecular orbital theory for the pair of a Bi donor and a spin dependent recombination center. Chapter 6 provides summary and outlook.