【Grant-in-Aid for Scientific Research (S)】

Exploring spin coherence engineering in group IV semiconductor quantum structures

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Project Information	Project Number : 23H05455 Keywords : spin qubit, semiconductor quantum dot, silicon, germanium	Project Period (FY) : 2023-2027

Purpose and Background of the Research

●Outline of the Research (figure 1)

Quantum computers use the unique properties of quantum states to perform calculations. They are expected to have much more powerful computing capabilities than supercomputers. To develop quantum computers using materials like silicon and germanium, it is crucial to understand the fundamental concept of spin. This understanding is necessary also for mixed compositions of these materials, known as mixed crystals. By investigating these crystals, we aim to explore the potential of significantly prolonging the spin coherence time, during which spins can retain quantum information. Additionally, we strive to establish the principles of controlling spin coherence, ultimately paving the way for spin coherence engineering as a scientific discipline.

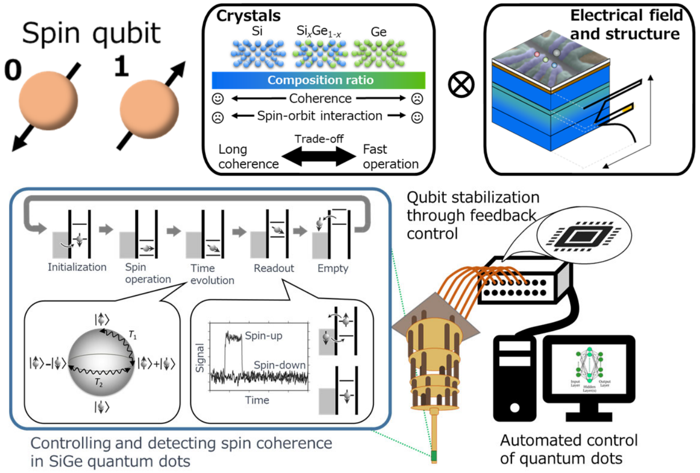

Figure 1. Overall research concept

●Purpose and Background

Semiconductor quantum dots are nano-scale quantum structures (with a diameter of about 100 nanometers, which is 1/1000th the width of a hair) that contain electrons with spin. Spin qubits in quantum dots exhibit relatively good coherence and can be integrated using mature semiconductor fabrication techniques, making them promising candidates for large-scale integration of qubits. Our own research has focused on proof-of-principle demonstrations including achieving high-precision spin manipulation with error rates below 0.1% and realizing quantum error correction. On the other hand, in germanium-based systems, the “spin-orbit interaction” (corresponding to the coupling between spin and electric fields) is stronger, leading to the potential for high-speed manipulation using alternating electric fields. While faster manipulation than for silicon has indeed been achieved, it has been observed that the coherence deteriorates due to the strong spin-orbit interaction.

To address this trade-off (as shown in Figure 1), it has become clear that understanding the fundamental physics of spin coherence and optimizing semiconductor materials and structures are essential.

The objective of this research is to elucidate the underlying physics of spin coherence in quantum structures and establish control principles. We have focused on the possibility of unique physical phenomena in quantum structures and adopted our own approach. Specifically, we apply our developed dynamic measurement techniques to silicon, germanium, and their mixed compositions in quantum dot systems. This allows us to investigate the control of spin-orbit interaction, understand its impact on spin relaxation, and quantitatively evaluate spin coherence. Additionally, we develop novel techniques such as state stabilization through feedback control and automation and acceleration of voltage adjustments using information science methodologies to acquire systematic data. Through these efforts, we aim to derive the physics of spin coherence in semiconductor quantum structures.

Expected Research Achievements

In this research, we focus on the spin-orbit interaction and electrical noise that affect spin coherence in nanostructures. We create quantum dots using silicon, germanium, and their mixed compositions and combine them with charge distribution control using electric fields. Through this approach, we aim to control material-dependent properties and the asymmetry of quantum structures, striving to achieve spin qubits that exhibit both long coherence lifetimes and high-speed control.

●Research objectives (Figure 2):

① Understanding and controlling the spin-orbit interaction in Group IV semiconductor quantum structures

② Development and measurement of spin coherence in silicon-germanium mixed quantum dots

③ Automated and high-speed voltage tuning techniques for spin qubits

④ Development of spin qubit stabilization using feedback control

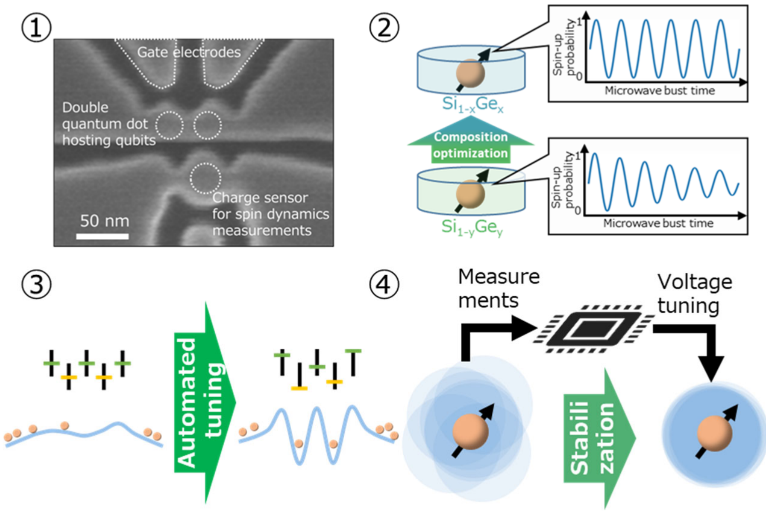

Figure 2. Research objectives

Homepage Address, etc.	http://www.quantum.ee.e.titech.ac.jp/