MERIT　Internship Report

Ramsey interferometry for the noise coupling to the electron spin qubit

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Abstract

Noise coupling to the electron spin qubit in SiGe quantum dot has been measured by Ramsey interferometry. Combining several methods, noise spectrum over 9 magnitudes in frequency is has been extracted. The spectrum shows that noise is dominated by nuclear spins, even though, interestingly, the spectrum shape does not match the theoretical prediction based on the diffusion model.

Background

Recently, the limit of Moore's law has been predicted and quantum computer has been attracting much attention as a new technology for information processing. Quantum computing utilizes state superposition and entanglement, which are unique to quantum mechanics, and it is expected to boost up the information processing speed. The basic unit where information is encoded is called qubit and it requires a quantum two-level system. Electron spins in semiconductor quantum dot offer two energy levels of spin-up state and spin-down state and have been widely studied as the promising candidate for quantum computing.

Because coherence of qubit should be preserved during quantum computing, the coherence time of qubit is crucial. Typically, coherence time of electron spin qubit in Si/SiGe quantum dot is 2 μs for natural silicon [1] and 20 μs for isotopically enriched silicon [2]. These times are limited by surrounding noise which affects qubit, and therefore, the study of the noise source is important for improvements of the performance. In this work, we investigate the frequency spectrum of noise which is coupling to the qubit by measuring the accumulated phase that the noise induces on the qubit.

Methods

Our electron spin qubit is hosted in a natural-silicon device. Figure 1a shows the vertical structure of the device. By applying positive voltage to the top gate, two-dimensional electron gas (2DEG) is induced on the interface of Si/SiGe heterostructure. Then, by applying negative voltage to fine gates, the gas is partially depleted and quantum dots having an electron spin are formed. The micromagnet locating on the top of the device induces the inhomogeneous magnetic field and slanting magnetic field. By oscillating the electron spatially with microwave (MW), we can realize Electron Spin Resonance (ESR) and can manipulate the qubit state [3].

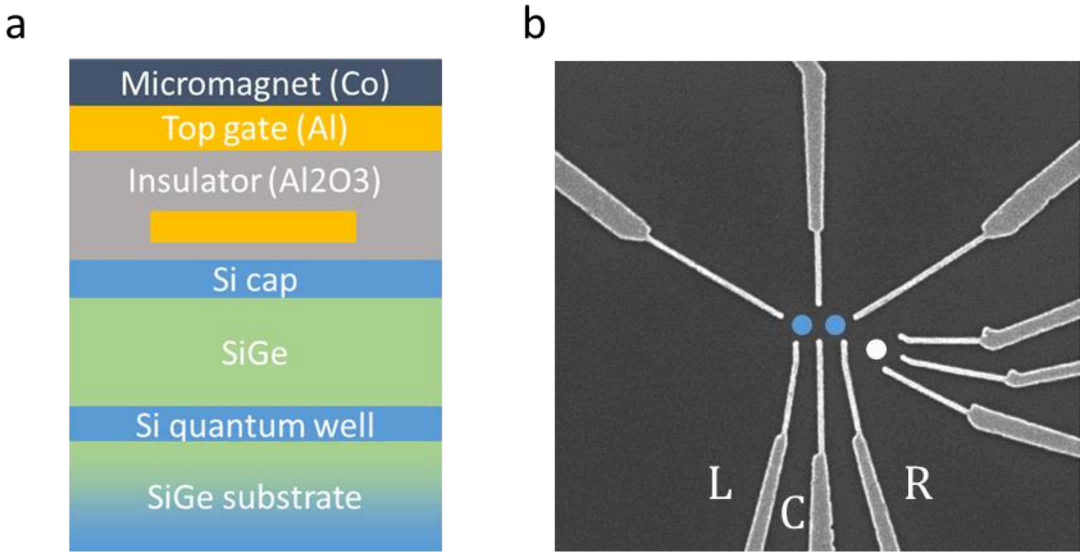

Fig. 1 The structure of the device. **a** Vertical structure of the device. 2DEG is induced on the interface of Si quantum well and SiGe buffer layer. **b** Top view of the fine gates of the device. 2DEG is partially depleted by applying negative voltage to the fine gates to form DQD shown as blue circles. The number of electrons in DQD and its spin state is readout via SET shown as the white circle.

The detail structure of fine gates is shown in Fig. 1b. Double quantum dot (DQD) is formed in the center region and MW is applied to C gate. The proximity SET works as a charge sensor and is used for readout of the state of the qubit.

The phase of the qubit is measured by Ramsey interference experiment (Fig. 2). First, the qubit whose state is spin-down is rotated by $\pi/2$ and initialized to the direction orthogonal to the external magnetic field, where the phase is accumulated for the evolution time t. Next, the qubit is rotated by $\pi/2$ again. Because the acquired phase is reflected on the spin-up probability of the qubit, we can measure the phase by readout the state of the qubit.

The low-frequency noise can be extracted by applying Fourier transform to the time variation of the resonance frequency estimated from the t dependence of the spin-up probability. Assuming single-shot measurement takes 1 ms and we repeat it 10 times for 100 values of evolution time t, the highest frequency that can be obtained in this way is 10^0 Hz. Alternatively, high-frequency-noise can be extracted by applying decoupling pulses to construct a virtual filter[4]. In this case, the minimal frequency is limited by the relaxation time of the qubit and the error of decoupling pulse, and it is typically 10^4 Hz. Therefore, there is a problem that it is difficult to obtain the noise in the middle-frequency region. Here, we have solved this problem by calculating the correlation between single-shot measurement outcomes for fixed t [5] and obtaining the spectrum of the noise.

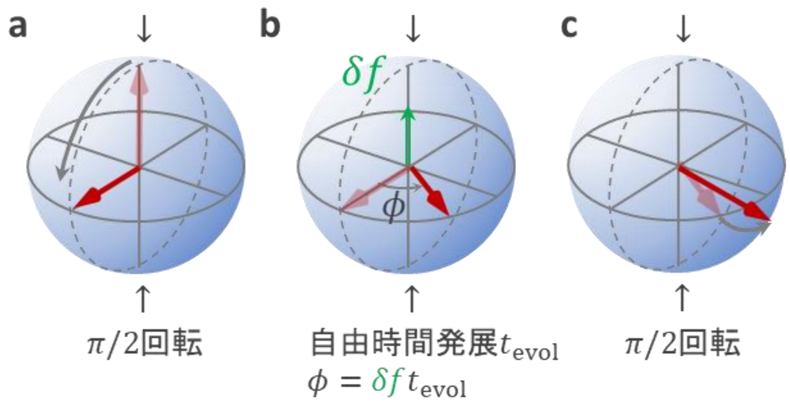

Fig. 2 Schematic pictures of transition of the spin state on the Bloch sphere of a Ramsey interferometry measurement. Bloch sphere is a representation method of for a state of a qubit with a unit sphere. When the state of the qubit is on either of the poles, it means that the state is either spin-up or spin-down. It is possible to estimate the shift of the resonance frequency (δf). **a** Spin is initialized to the orthogonal direction to the external magnetic field. **b** A phase is accumulated on the qubit. **c** The phase component is transferred to the spin-up probability of the qubit by applying $\pi/2$ pulse.

Results and discussion

First, we have confirmed that DQD is formed in the device (Fig. 3) and the electron spins can be rotated by ESR . Figure 4 shows the observed chevron patterns. The Rabi frequency is around 2 MHz, leading to 125 ns time required for a $\pi/2$ rotation. This is shorter than the coherence time of the qubit, indicating that the Ramsey interferometry measurement is possible.

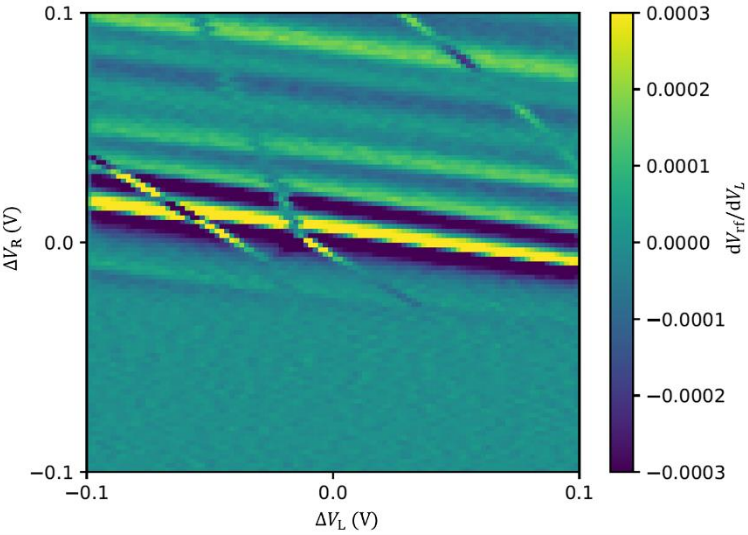

Fig. 3 The stability diagram. There are two charge transition lines, indicating that double quantum dot is formed.

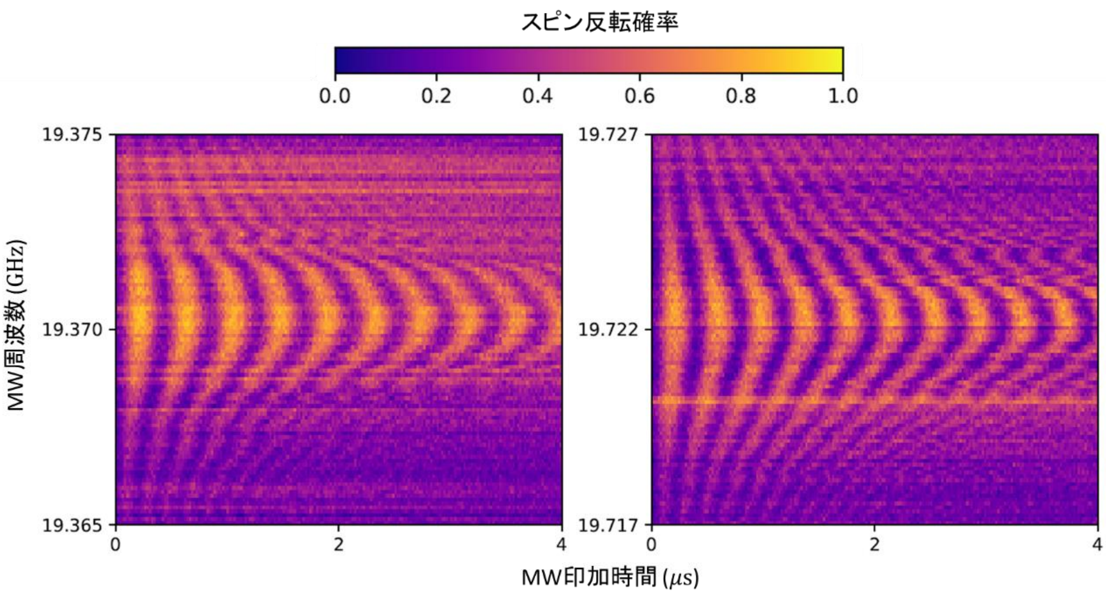

Fig. 4 The Chevron patterns. The left (right) pattern is obtained by using the spin qubit in the left (right) quantum dot. The spin flip probability depends on the MW duration. We can prepare an arbitrary state by changing the MW duration.

Next, we measure the frequency property of the noise coupling to the qubits (Fig. 5). By combining the above three methods (Fourier transform for the time variance of the resonance frequency, [4], [5]), we successfully obtained the noise spectrum over 9 magnitudes in frequency. Obtaining the noise spectrum in such a large range without significant gaps is an achievement that have heen reached for the first time in the field of single-electron spin qubits in Si, to the best of our knowledge. Both of qubits follows f^{-1} in the region $f < 10^{-1}$ Hz and follows $f^{-1.4}$ in the region $10^{-1} < f < 10^3$ Hz. There are two candidates for the dominant noise source: magnetic noise and charge noise. Magnetic noise is generated by fluctuation sof nuclear spins in the device and charge noise is generated by charge/discharge of impurities on the device. The fact that the noise spectra obtained in this way for two devices (in the same wafer) were very similar suggests that the noise origin is in nuclei, since charge noise is usually strongly dependent. On the other hand, the diffusion model constructed for GaAs predicts [6] constant spectral density of nuclear spin induced noise at low frequency. In contrast to this prediction, our results show low-frequency noise with f^{-1} shape, casting doubt on the validity of the diffusion model description in Si.

In the region around 10^3 Hz, which we have obtained for the first time in Si, one can observe that the noise does not follow the $f^{-1.4}$ dependence. This fact indicates that there might be a cut-off of nuclear spin noise in this region. In other words, it suggests that there is a limit for the strength of the interaction among nuclear spins. In the region $f > 10^5$ Hz, the noise resembles white noise but further study would be needed to confirm it.

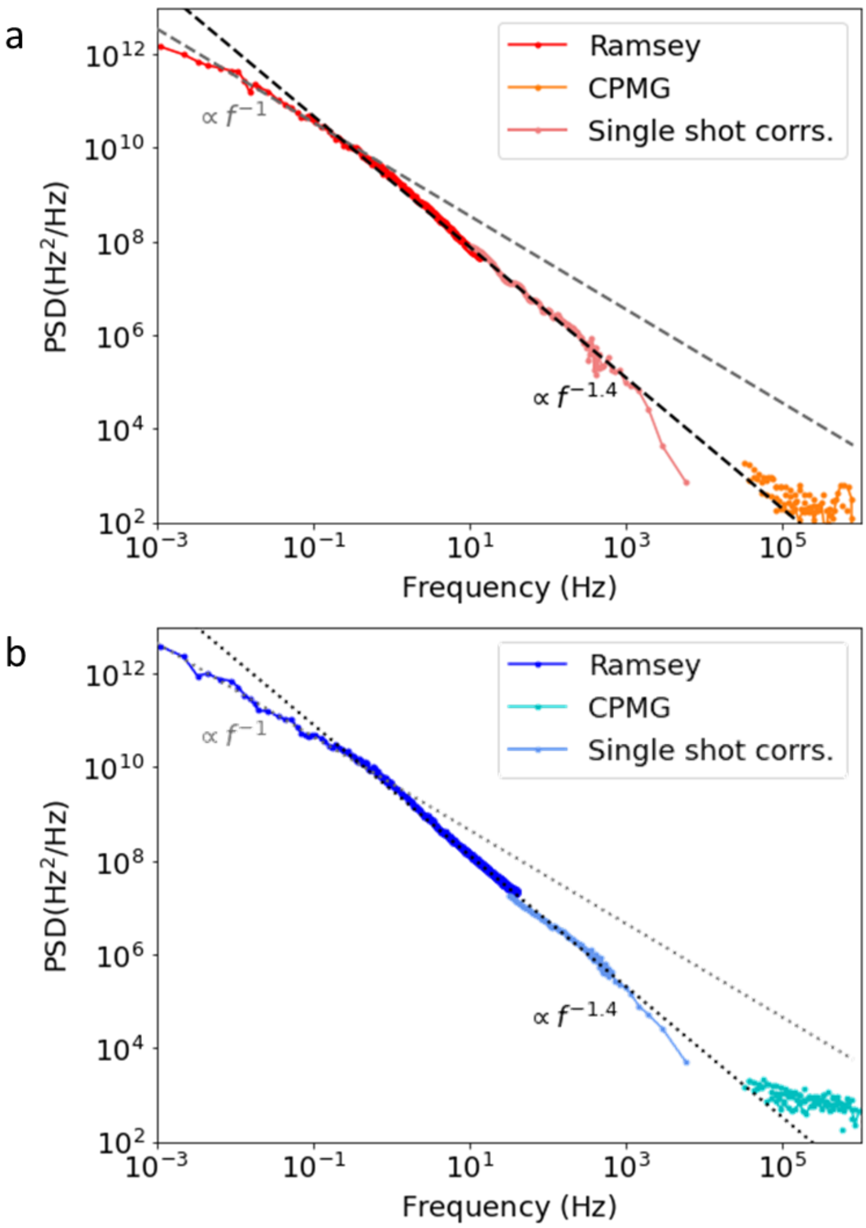

Fig. 5 The spectra of the noise coupling to the qubits. **a** (**b**) is obtained using the qubit in the left (right) QD. Ramsey shows the date obtained by Fourier transform, CPMG shows the data obtained by [4], and Single shot corrs. shows the data obtained by [5].

Conclusion

We have obtained the noise spectrum over 9 magnitudes in frequency for the first time with a single-electron spin qubit in Si. The noise is dominated by nuclear-spin noise for $f < 10^3$ Hz, but its spectral density does not follow the prediction from the diffusion model. Furthermore, we have observed the cut-off in the regime around 10^3 Hz, implying the limit of the strength of the interaction among nuclear spins. These results call for further theoretical research towards the possible models describing dynamics of nuclear noise in Si.

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