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Control fidelities in isotopically natural and enriched silicon quantum dot qubits

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Abstract

We investigate spin qubit performance in silicon quantum dots with different concentrations of ^{29}Si isotope. They have different values of ensemble phase coherence times and qubit control fidelities.

1. Introduction

Single electron spins in quantum dots are a promising candidate for solid-state quantum bits (qubits), especially for potential scalability offered by semiconductor integration technologies. However, coherence and control fidelity of a spin qubit is still limited by slowly fluctuating noise characterized by the ensemble phase coherence time, T_2^*. In early developed GaAs devices, T_2^* was no longer than 10 ns, due to surrounding million nuclear spins [2]. In silicon, where only 5% of the atoms carry nuclear spins naturally, magnetic fluctuation is suppressed to yield longer $T_2^* \sim 1$ μs [3]. Further coherence enhancement has been demonstrated by isotopic purification with $T_2^* \sim 30-120$ μs [4].

Here, we report measurement and comparison of the coherence times and control fidelities of isotopically natural and enriched Si/SiGe quantum-dot based spin qubits. From Ramsey interferometry, we obtain $T_2^* \sim 2$ μs for the ^{nat}Si/SiGe qubit [5] and ~ 20 μs for the ^{28}Si/SiGe qubit [6]. The randomized benchmarking results reveal that the averaged single-qubit control fidelities in the ^{nat}Si/SiGe qubit are likely to be limited by the dephasing, whereas in the enriched ^{28}Si/SiGe qubit, those are limited by the residual control pulse errors rather than the decoherence.

2. Results

We define electron spin qubits in Si/SiGe quantum dot devices and apply voltage pulses to initialize, manipulate and read out the qubit state. We incorporate a micro-magnet on top of the quantum dot to induce an inhomogeneous local magnetic field whose parallel and perpendicular components are both slanting (Fig. 1). These slanting components enable fast electrical spin rotations [7], and electrical tuning of the qubit frequency, respectively. Aside from improving qubit controllability, the extrinsic field mediates dephasing in the presence of the fluctuating electrical field or charge noise.

To first prove the enhanced spin controllability, we drive electric dipole spin resonance by applying microwave pulses to the gate electrode. Figure 2 shows the resulting Rabi oscillation with a frequency of 3.9 MHz. The rotation frequency can be raised by the microwave amplitude up to approximately 30 MHz. Similar results are obtained with ^{nat}Si/SiGe qubits.

We then investigate the phase coherence time from the Ramsey interference effect (Fig. 3 (a)). We measure T_2^* to be ~ 2 μs for the ^{nat}Si/SiGe qubit (Fig. 3(b)) and ~20 μs for the ^{28}Si/SiGe qubit (Fig. 3(c)). These are 2 or 3 orders of magnitude larger than those in similar GaAs spin qubits [2, 8].

To show the overall qubit performance improvement, we quantify single-qubit control fidelities (F_C) based on randomized benchmarking protocols (Figs. 4(a) and 4(b)). For the ^{nat}Si/SiGe qubit, we obtain $F_C = 99.6$ %. In the ^{28}Si/SiGe qubit, we obtain $F_C = 99.93$ %, which corresponds to roughly one order of magnitude reduction of the control errors owing to the enhanced T_2^*.

We further evaluate the fidelity of each single-qubit operation individually through the interleaved benchmarking. In ^{nat}Si/SiGe qubit, we find the fidelities for $\pi/2$ rotations are higher than those for π rotations, consistent with the dephasing limited operation. For the ^{28}Si/SiGe qubit, in contrast, we find that the fidelities for $\pi/2$ rotations are strongly sign dependent. We therefore believe that the gate errors are caused mainly by systematic pulse errors rather than dephasing and that they may be further improved by control microwave engineering and composite pulses.

3. Conclusions

In summary, we have characterized and compared the performance of isotopically natural and enriched Si/SiGe spin qubits. Isotopic enrichment enhances the coherence time and enables an unprecedented qubit control fidelity, which is well above the threshold for fault-tolerant quantum computing [9] and rivals those in state-of-the-art superconducting qubits. Further improvement may be possible by engineering the microwave control techniques because the control fidelity is limited by the systematic pulse errors.

Acknowledgements

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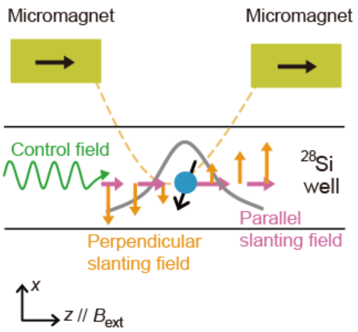


Figure 1. Schematic of the quantum dot device and micromagnet.

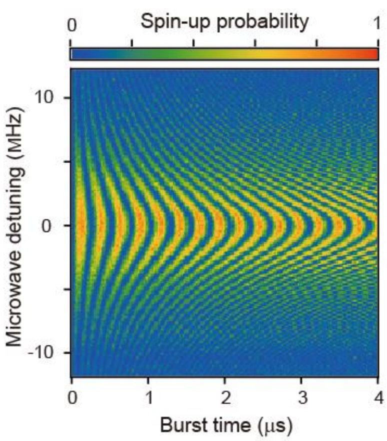


Figure 2. Rabi oscillation of the ^{28}Si/SiGe spin qubit.

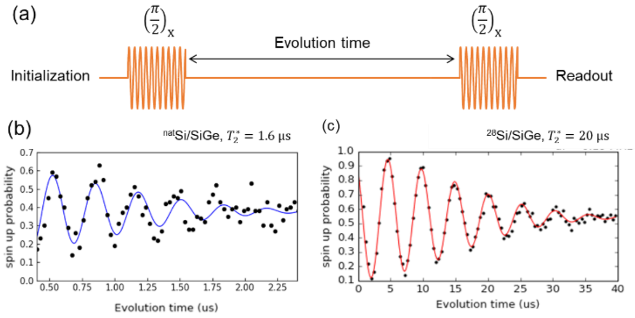
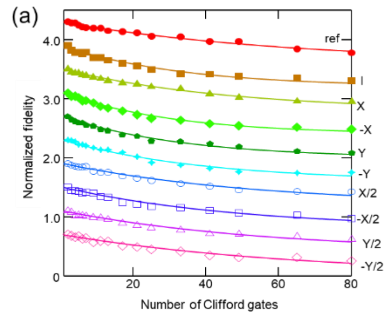
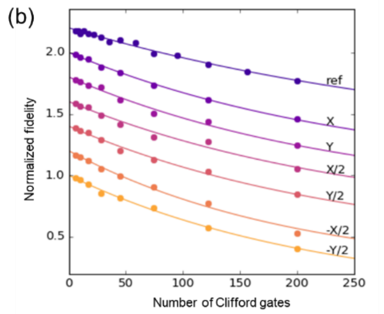


Figure 3. Ramsey measurement. (a) schematic of the Ramsey pulse sequence. (b) measurement result of the ^{nat}Si/SiGe qubit. The blue solid line shows a fitting with a Gaussian decay function. (c) measurement result of the ^{28}Si/SiGe qubit. The red solid line shows a fitting with a Gaussian decay function.



Gate	Fidelity (%)
Ref	99.59 ± 0.029
I	99.35
X	99.65
-X	99.26
Y	99.36
-Y	99.53
X/2	99.77
-X/2	99.70
Y/2	99.80
-Y/2	99.89



Gate	Fidelity (%)
Ref	99.926 ± 0.002
I	
X	99.94
-X	
Y	99.94
-Y	
X/2	99.95
-X/2	99.89
Y/2	99.94
-Y/2	99.91

Figure 4. Randomized benchmarking. (a) fidelities measured with the ^{nat}Si/SiGe qubit. (b) fidelities measured with the ^{28}Si/SiGe qubit.