# Spin Qubit Operation with Fidelities Above the Fault-Tolerant Threshold

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# Abstract

Spin qubits in silicon are a promising platform for quantum computation due to their potential for large-scale fabrication leveraging existing semiconductor technologies. Scalable quantum computation requires fault-tolerant quantum computing, which in turn demands qubit operation fidelities exceeding the 99% threshold. Here we demonstrate high-fidelity control of spin qubits in isotopically enriched silicon devices exceeding this fault-tolerance threshold.

We achieve a two-qubit controlled-NOT (CNOT) gate fidelity of 99.5% in an exchange-always-on two-qubit system [1]. We find the CNOT gate fidelity being limited by a coherent controlled-phase error and develop a systematic method to measure and calibrate this error. The improvement in gate fidelity is verified with randomized benchmarking (RB) and gate-set tomography (GST) experiments. The calibration method also allows us to implement a virtual controlled-phase (CZ) gate in the exchange-always-on system. We then realize a single-qubit gate fidelity of >99.99% in a five-qubit device using pulse shaping technique [2]. The smooth shaped pulse removes unwanted higher harmonic frequencies and randomization in signal phase. We further demonstrate high-fidelity simultaneous single-qubit operation maintaining >99.99% fidelity up to three qubits, and a 99.9% fidelity when operating the whole device. Simulations taking into account the noise measured from the device indicates this fidelity can be improved further by optimizing the driving gradient field.

These results demonstrate the ability of spin qubits to meet the requirements for fault-tolerant quantum computing. Furthermore, the ability to perform simultaneous operations on multiple qubits while maintaining high fidelity enhances the scalability of future spin qubit devices. These achievements pave the way for implementing fault-tolerant quantum computing with spin qubit devices.

[1] Wu et. al., npj Quantum Inf 10, 8 (2024).

[2] Wu et. al., In submission. (2025)