Towards Scalable Silicon Quantum Computing: A Donor-cluster Architecture for Logical Qubits and Chemical Simulation

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Abstract— Semiconductor quantum dot spin qubits are promising for quantum computing due to their long coherence times, high-fidelity control, and compatibility with semiconductor technology. However, scaling up spin-based systems and implementing quantum error correction remain key challenges. Here, we propose a scalable architecture using arrays of phosphorus-donor clusters in silicon. Each cluster contains multiple donors sharing one electron, enabling individually addressable nuclear spins via hyperfine variation, with tunable inter-cluster exchange providing local all-to-all connectivity. The design predicts $> 99\%$ fidelity for the intra-cluster two-qubit gate and the inter-cluster five-qubit gate, and supports bias-tailored quantum error correction [1]. On a silicon-based donor-cluster processor, we report a four-qubit error detection circuit with stabilizers to detect arbitrary single-qubit errors, and recover the encoded Bell-state entanglement information on the basis of the detected errors [2]. We demonstrate the fault-tolerant logical state preparation, high-fidelity Clifford gates, and measurement-induced logical T-gates using the $[[4, 2, 2]]$ code. Using these logical qubits, we perform a variational quantum eigensolver computation of the water-molecule ground state, achieving an energy deviation of 22.7 mHa from theory [3]. This cluster-array architecture offers a hardware-efficient pathway toward scalable, fault-tolerant spin-based quantum computing in silicon.

REFERENCES

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