Scientists achieve key elements for fault-tolerant quantum computation in silicon spin qubits

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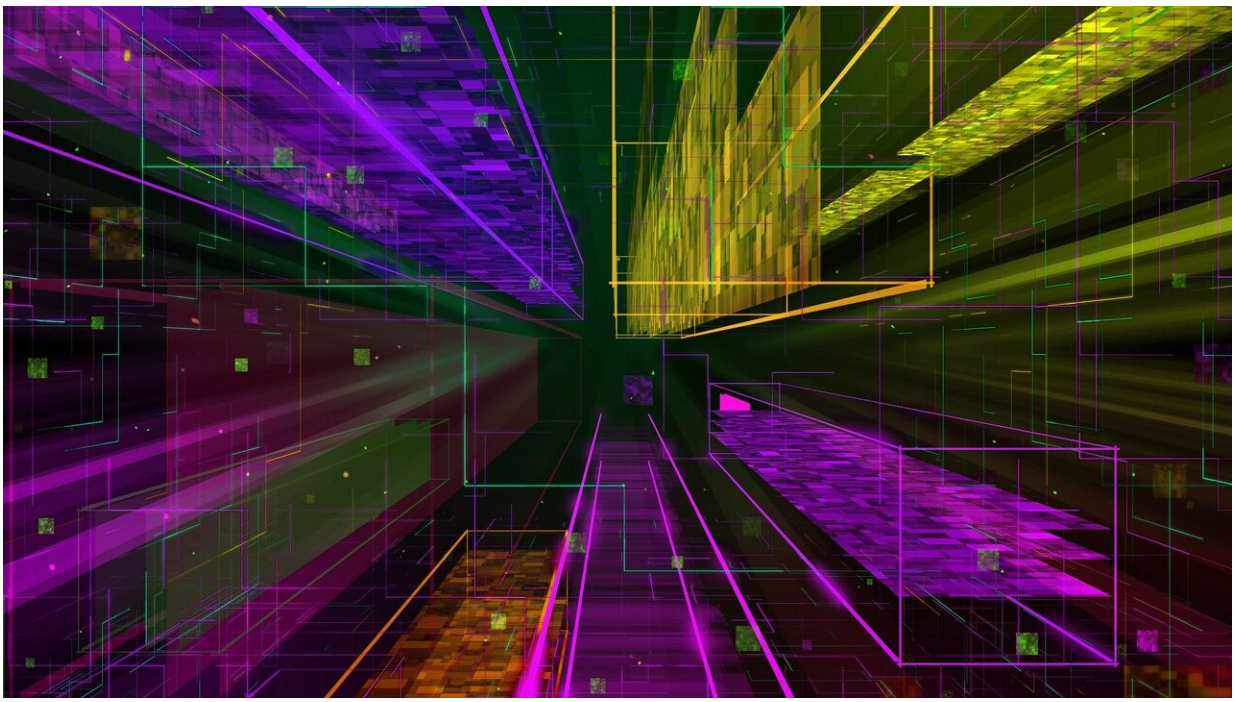

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Researchers from RIKEN and QuTech—a collaboration between TU Delft and the Netherlands Organisation for Applied Scientific Research (TNO)— have achieved a key milestone toward the development of a fault-tolerant quantum computer. They were able to demonstrate a two-

qubit gate fidelity of 99.5 percent—higher than the 99 percent considered to be the threshold for building fault-tolerant computers—using electron spin qubits in silicon, which are promising for large-scale quantum computers as the nanofabrication technology for building them already exists. This study was published in *Nature*.

The world is currently in a race to develop large-scale quantum computers that could vastly outperform classical computers in certain areas. However, these efforts have been hindered by a number of factors, including in particular the problem of decoherence, or noise generated in the qubits. This problem becomes more serious with the number of qubits, hampering scaling up. In order to achieve a large-scale computer that could be used for useful applications, it is believed that a two-qubit gate fidelity of at least 99 percent to implement the surface code for error correction is required. This has been achieved in certain types of computers, using qubits based on superconducting circuits, trapped ions, and nitrogen-vacancy centers in diamond, but these are hard to scale up to the millions of qubits required to implement practical quantum computation with an error correction.

To address these problems, the group decided to experiment with a quantum dot structure that was nanofabricated on a strained silicon/silicon germanium quantum well substrate, using a controlled-NOT (CNOT) gate. In previous experiments, the gate fidelity was limited due to slow gate speed. To improve the gate speed, they carefully designed the device and tuned it by applying different voltages to the gate electrodes. This combined an established fast single-spin rotation technique using micromagnets with large two-qubit coupling. The result was a gate speed that was 10 times better than previous attempts. Interestingly, although it had been thought that increasing gate speed would always lead to better fidelity, they found that there was a limit beyond which increasing the speed actually made the fidelity worse.

In the course of the experiments, they discovered that a property called the Rabi frequency—a marker of how the qubits change states in response to an oscillating field—is key to the performance of the system, and they found a range of frequencies for which the single-qubit gate fidelity was 99.8 percent and the two-qubit gate fidelity was 99.5 percent, clearing the required threshold.

Through this, they demonstrated that they could achieve universal operations, meaning that all the basic operations that constitute quantum operations, consisting of a single qubit operation and a two-qubit operation, could be performed at gate fidelities above the error correction threshold.

To test the capability of the new system, the researchers implemented a two-qubit Deutsch-Jozsa algorithm and the Grover search algorithm. Both algorithms output correct results with a high fidelity of 96%-97%, demonstrating that silicon quantum computers can perform quantum calculations with high accuracy.

Akito Noiri, the first author of the study, says, "We are very happy to have achieved a high-fidelity universal quantum gate set, one of the key challenges for silicon quantum computers."

Seigo Tarucha, leader of the research groups, said, "The presented result makes spin qubits, for the first time, competitive against superconducting circuits and ion traps in terms of universal quantum control performance. This study demonstrates that silicon quantum computers are promising candidates, along with superconductivity and ion traps, for research and development toward the realization of large-scale quantum computers.

More information: Akito Noiri, Fast universal quantum gate above the fault-tolerance threshold in silicon, *Nature* (2022). DOI:

10.1038/s41586-021-04182-y.
www.nature.com/articles/s41586-021-04182-y

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