Research summary

An array of four germanium qubits

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A four-qubit quantum processor based on germanium hole spin quantum dots is presented. Universal quantum logic is demonstrated on qubits that are positioned in a two-by-two grid, revealing that spin qubits can be coupled in two dimensions.

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Competing interests
The authors declare no competing interests.

The mission

Quantum computers promise to solve problems that are intractable on classical computers. Advances in their capabilities rely largely on the quantum bits (qubits) that make up their fundamental units of information. One particularly attractive platform is spin qubits, which store information in the spin of the charge carriers in semiconductor quantum dots[1]. These qubits have inherent similarities to classical transistors, which can be integrated by the billions into silicon chips[2]. This system therefore has good prospects for using the vast knowledge in the advanced semiconductor manufacturing industry to scale up to the size needed for practical applications. Many of the architectures proposed for such scaling require the qubits to be interconnected along two dimensions. However, all of the demonstrations so far have been restricted to two-qubit systems.

The solution

We have overcome the issues of coupling spin qubits in two dimensions, and operate a fully connected four-qubit quantum processor in a two-by-two layout (Fig. 1). We use strained planar germanium heterostructures with confined valence-band holes as a host for the qubits. Early quantum-dot research focused on the group III–V semiconductor gallium arsenide owing to its low degree of disorder, which can be used to generate reproducible and well-controlled quantum dots. However, the nuclear spins in group III–V materials weaken the quantum coherence. Moving to the group IV semiconductor silicon, which can be purified to contain vanishingly small amounts of nuclear spins, drastically improves coherence[3]. Furthermore, silicon's compatibility with semiconductor manufacturing makes it much easier to integrate quantum and classical technology.

Germanium has the same advantages as silicon[4], and the holes in its valence band can be confined with very low disorder[5]. Its strong potential is validated by the fact that many road maps for classical electronics include strained germanium as the dominant p-channel material[6]. For quantum applications, the strong spin-orbit coupling associated with the hole states enables fast and all-electric control without the need for striplines or micromagnets[7–9]. Furthermore, the low effective mass and high material quality of planar germanium allow the formation of well-defined quantum dots, with a high degree of control over the physical properties[10]. Thus, planar germanium has all the properties needed for the design of two-dimensional qubit grids.

We exploit these properties to define a two-by-two grid of spin qubits and control their individual couplings with dedicated gate electrodes. Single-qubit logic is implemented all-electrically and multi-qubit gates can be realized using the exchange interaction that arises as a result of tunnel coupling between the qubits[1]. The high degree of control in the platform enables rapid manipulation of the different quantum-dot couplings, resulting in a highly connected system and fast qubit operation. Our four-qubit quantum circuit shows that spin qubits can be coupled in two dimensions, and that semiconductor qubits can go beyond two-qubit logic.

Future directions

This work is an important step in using semiconductor technology to scale up quantum systems. The ability to couple multiple spin qubits in two dimensions, without the need for microscopic elements, paves the way for dense grids. Given that semiconductor technology has been shown to be highly scalable, this approach constitutes a very promising route towards practical quantum applications.

Although the qubit fidelities in our work compete with the best in other semiconductor platforms, further advancements are needed for practical applications. In particular, the length of time that information can be stored in the qubit (known as the dephasing time) could potentially be increased by using purified isotopes of germanium to grow the quantum well. This would eliminate the magnetic noise that acts on the qubit state as a result of fluctuations of the germanium nuclear spins. Furthermore, although spin-orbit coupling enables a fast and local driving mechanism, it can also increase spin dephasing. Fortunately, theoretical works predict the existence of 'sweet spots' in the electric potential, in which dephasing can be brought to a minimum.

Further research should explore these strategies to enhance qubit coherence. Moreover, the exact implementation of the quantum gates can be tailored for the germanium system to improve their performance. Over the past three years, the number of coupled germanium qubits has increased at an unprecedented rate, owing to the beneficial properties of the system. Research efforts should therefore also focus on continuing this trend and increasing the system size further. Together, these efforts will lead to bigger, better and faster quantum processors in the solid state.

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EXPERT OPINION

The report of single and multi-qubit operations of four qubits in a Ge/SiGe quantum-dot device is at the forefront of the current state of the art of spin-qubit research in terms of qubit number. The performance also looks quite competitive compared with other recent results. The material platform used was essentially unexplored a few years ago and carries considerable promise to move ahead over other semiconductor-based approaches. The remarkably rapid progress reflected by this and earlier work underscores this potential.”
Hendrik Bluhm, JARA Institute for Quantum Information, RWTH Aachen University and Forschungszentrum Jülich, Aachen, Germany.

FIGURE

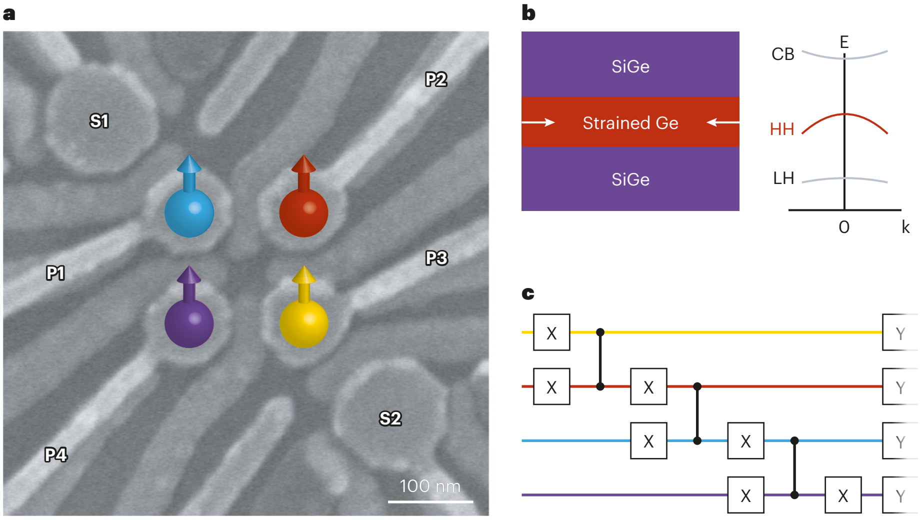

Figure 1 | A four-qubit germanium quantum processor. a, Scanning electron microscope image of the device. The qubits (coloured shapes) underneath the four plunger gates (P1–P4) can be measured using the sensors S1 and S2. **b**, The qubits are defined on heavy holes (HH) that have been confined in a quantum well made of strained germanium. The heterostructure growth is compatible with a semiconductor foundry line, and the spin-orbit coupling enables local and all-electrical qubit control, allowing for a small qubit footprint. **c**, Using the exchange interaction between neighbouring quantum dots, multi-qubit interactions are established, resulting in a highly connected circuit and enabling a coherent four-qubit algorithm. X and Y are one-qubit gates, the black connecting lines represent two-qubit gates and the fading indicates that only half of the algorithm is shown. Coloured lines represent qubits of the same colour as in part a. CB, conduction band; E, energy; LH, light hole; k, wavevector; Figure part a is Figure 1a of full paper.

BEHIND THE PAPER

Germanium is an exciting quantum material and provides a compelling platform for many research directions in condensed-matter physics. We initially aimed to study hybrid superconductor–germanium devices, and demonstrated gate-tunable supercurrents in this platform. We were sceptical about the potential of germanium spin qubits, owing to the strong spin-orbit coupling present in this material. However, the unprecedented pace at which planar germanium has developed over the past few years really changed our minds, and the potentially detrimental spin-orbit coupling was turned into a key asset by providing local qubit control.
The demonstration of four-qubit logic in germanium defines the state-of-the-art for the field of quantum dots and highlights the crucial role of materials science for quantum computation.

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