explicitly account for the contributions of native wild pollinators, which may be responsible for as much as 50% of the needed pollination services (*15*). Within their native range, some amount of pollination by western honey bees is natural, although the historic density of wild colonies is largely unknown. Safe densities of managed honey bees will vary from natural and protected habitats, where wild native pollinators are most abundant and beekeeping is mainly done for honey production, to agricultural and managed landscapes, which are less important for the conservation of the most threatened pollinator species.

Management practices must also address the periods when no or insufficient mass-flowering crops are in bloom because managed honey bees are likely to compete most intensively with wild native pollinators during these times. In the United States, honey bee hives are moved around to track the bloom of various crops, from California almond groves in early spring to Washington apples in the late summer. Similar approaches might be needed across Europe and other places to match pollinator supply to pollination demand but must address the risk of spreading diseases. Policies to limit the number of honey bees in specific periods might also be needed, such as early honey removal and keeping the individual hives smaller. If implemented wisely, such strategies will come with no extra cost to farmers but may increase the price of honey.

Fulfilling the need for sufficient and effective pollination of the world's crops without jeopardizing biodiversity will also require an ambitious research agenda. The past decade has seen an explosion in research tackling the decline in managed honey bees, specifically focused on the potential loss of pollination services. This research has been heavily supported by the private sector and governments, particularly in Europe and the United States, which have invested millions to reverse the loss of managed honey bees. Comparatively little research has been undertaken to understand wild native pollinator declines, including the potential negative role of managed honey bees. The European project STEP (Status and Trends in European Pollinators; www.step-project.net), which aimed to document the nature and extent of pollinator declines and brought together 21 universities and institutions from 16 countries, exemplifies the type of research initiative needed to elucidate the drivers of pollinator declines.

Concern about honey bees has been an engine for shining light on the decline of pollinators and has likely been important in raising awareness of pollinator declines at large (*4*, *5*). Thus, a more nuanced understanding of the role of domesticated honey bees must not be misconstrued as a general lack of importance of conservation attention on wild native pollinators. Half of all European bees are threatened with extinction (*1*), and the conservation of wild native pollinators is among the most important conservation challenges in many parts of the world. We therefore see a need for a conservation strategy that explicitly focuses on the main drivers of the current declines in wild native pollinators, not on agricultural yield.

As a first step, crop pollination by managed honey bees should not be considered an ecosystem service because those pollination services are delivered by an agricultural animal and not by the local ecosystems. Further, managed honey bee hives should not be placed in protected areas, where they are likely to do the biggest damage to wild pollinators. In other areas of conservation importance, beekeeping may require impact assessments that consider potential spillover after the bloom of adjacent mass flowering crops. Honey bees may be necessary for crop pollination, but beekeeping is an agrarian activity that should not be confused with wildlife conservation. ■

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QUANTUM INFORMATION

# Toward a silicon-based quantum computer

A controlled NOT gate for two quantum bits is demonstrated with a strained-silicon device

*By* **Lars R. Schreiber** *and* **Hendrik Bluhm**

Quantum computing could enable exponential speedups for certain classes of problems by exploiting superposition and entanglement in the manipulation of quantum bits (qubits). The leading quantum systems that can be used include trapped ions, superconducting qubits, and spins in semiconductors. The latter are considered particularly promising for scaling to very large numbers of qubits. On page 439 of this issue, Zajac *et al.* (*1*) demonstrate a quantum operation involving two qubits in silicon (Si), which is a major step for the field of semiconductor qubits. Together with easier-to-achieve manipulation of single qubits, these operations represent the basic steps of any quantum algorithm.

> ***"…creating systems that cannot be simulated with today's supercomputers will take about 50 qubits."***

The coupling between the two qubits is achieved through the so-called exchange interaction, which results from coupling of the two electrons through a tunnel barrier. This barrier can be controlled by changing the voltage on the central gate. The authors further use microwave excitation to implement the desired operation. In an external magnetic field, spins that are not aligned with the field precess around it like an

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asymmetrically suspended top. If an excitation (a microwave signal applied to one of the gates, which translates to a magnetic microwave field in the inhomogeneous stray field of a micromagnet) has the same frequency as the precession, it is possible to rotate the spin direction, for example, from parallel to antiparallel with the field.

This technique, commonly used to control individual qubits, enables two-qubit operation via the dependence of the precession rate of one spin on the state of the other because of the exchange interaction. Whether single-qubit or two-qubit operation is executed can be selected by the choice of tunnel coupling and microwave frequency. For the two-qubit operation, they are set such that if the so-called control spin is aligned with the external field, the other so-called target spin is on resonance with the microwave signal (and off resonance if anti-aligned). Whether the target spin is inverted depends on the state of the control spin, so this system functions as a controlled NOT (CNOT) gate.

Zajac *et al.* used a device consisting of a layer of Si that was strained by being grown between two layers of SiGe (Si/SiGe), which confine electrons to the Si layer. Additional lateral confinement was provided by electrostatic gates fabricated on top of the structure, which were arranged such that two electrons can be captured (see the figure). The spin of each of those electrons encoded one qubit. Similar qubits have been realized in GaAs/AlGaAs heterostructures, but in that material system, the interaction with unavoidable nuclear spins is a major complication that impedes highly accurate qubit operation (*2*). Only 4.7% of the nuclei carry spin in Si with a natural composition, and that fraction can be further reduced with isotopic purification. This approach has recently led to record-setting coherence times over which quantum states could be preserved (*3*). However, the controlled confinement of single electrons in Si has been a major challenge because of disorder in the material. Petta and coworkers (*4*) made important progress on sample quality and design, culminating in an array of nine quantum dots, which could in principle host nine qubits.

A key figure of merit for any qubit is the gate fidelity, which specifies how accurately it can be manipulated. Values in excess of the 99.9% thought to be needed for quantum error corrections have now been shown for Si-based spin qubits in Si/SiGe (*5*) and in Si metal-oxide-semiconductor (MOS) structures, in which the electrons are confined at a Si/$SiO_2$ interface (*6*). Two-qubit operations required for quantum algorithms have already been demonstrated in Si MOS (*7*) but were not characterized as thoroughly as is now done by Zajac *et al.* Moreover, in parallel with the Vandersypen group (*8*), they have now demonstrated a two-qubit operation in Si/SiGe.

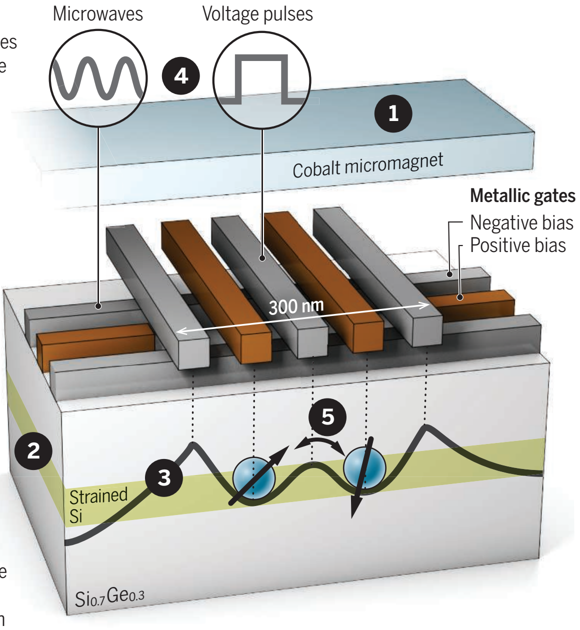
As a measure of the accuracy of the operation, the authors use a standard method (state tomography) to determine how well they can produce entangled states. The resulting fidelity (i.e., similarity with the desired state) of 78% is still far from the required 99.9%. Part of the reason is likely measurement uncertainties that can be reduced by using technically more involved, but well-established, techniques to determine the qubit state. Furthermore, it is likely that charge, and possibly nuclear spin noise, plays a role, given that the authors used a sample with natural isotopic composition. Understanding and substantially reducing these sources of errors, e.g., by optimized pulse sequences, are the next challenges to overcome. In GaAs, for example, optimized pulse sequences pushed the single-qubit gate fidelity near the predicted values (*9*). The ultimate limit will likely depend on charge noise, which is currently poorly understood and characterized.

In the near future, the results of Zajac *et al.* should be readily applicable to their nine-qubit array. For comparison, creating systems that cannot be simulated with today's supercomputers will take about 50 qubits. The most promising applications, such as solving quantum chemistry problems or the factorization of large numbers, are expected to require a redundant encoding of information to enable quantum error correction, which increases the number of qubits required to some millions. Thus, scalable quantum computing architectures with a fabrication yield as achieved in industrial silicon foundries are necessary.

It is encouraging that today's microprocessors have a comparable complexity. Nevertheless, the remaining challenges are substantial. For the quantum layer, long-range coupling of qubits at least a few micrometers apart will likely be required to make space for wiring or on-chip classical control electronics operating at cryogenic temperatures (*10*). Possible approaches include microwave cavities (*11*, *12*) and shuttling around electrons while preserving the quantum state of their spins. None of these have achieved the required fidelity yet. Finally, the creation of sufficiently powerful control systems will mark a whole new era of quantum computing research. ■

## Manipulating electron spins

A schematic of the two-electron–trap sample used by Zajac *et al.* is shown. Negatively biased electrostatic gates (gray) form tunnel barriers, whereas positively biased gates (brown) accumulate electron reservoirs or exactly two electrons in the double-dot potential. Each electron spin qubit can be separately set in quantum superposition state, or the two qubits can be entangled with the microwave and voltage pulses.



**1** Stray field from micromagnet couples electron spins to the electric field.

**2** Strain in Si layer vertically confines electrons.

**3** Potential created by metal gates laterally confines electrons.

**4** Spin alignment of the electrons is controlled with microwaves and voltage pulses.

**5** Tunnel coupling through the barrier between the two electrons (blue) causes an exchange interaction between the two spins, which drives entanglement.

GRAPHIC: V. ALTOUNIAN/*SCIENCE*

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