QUANTUM COMPUTING with semiconductor spins

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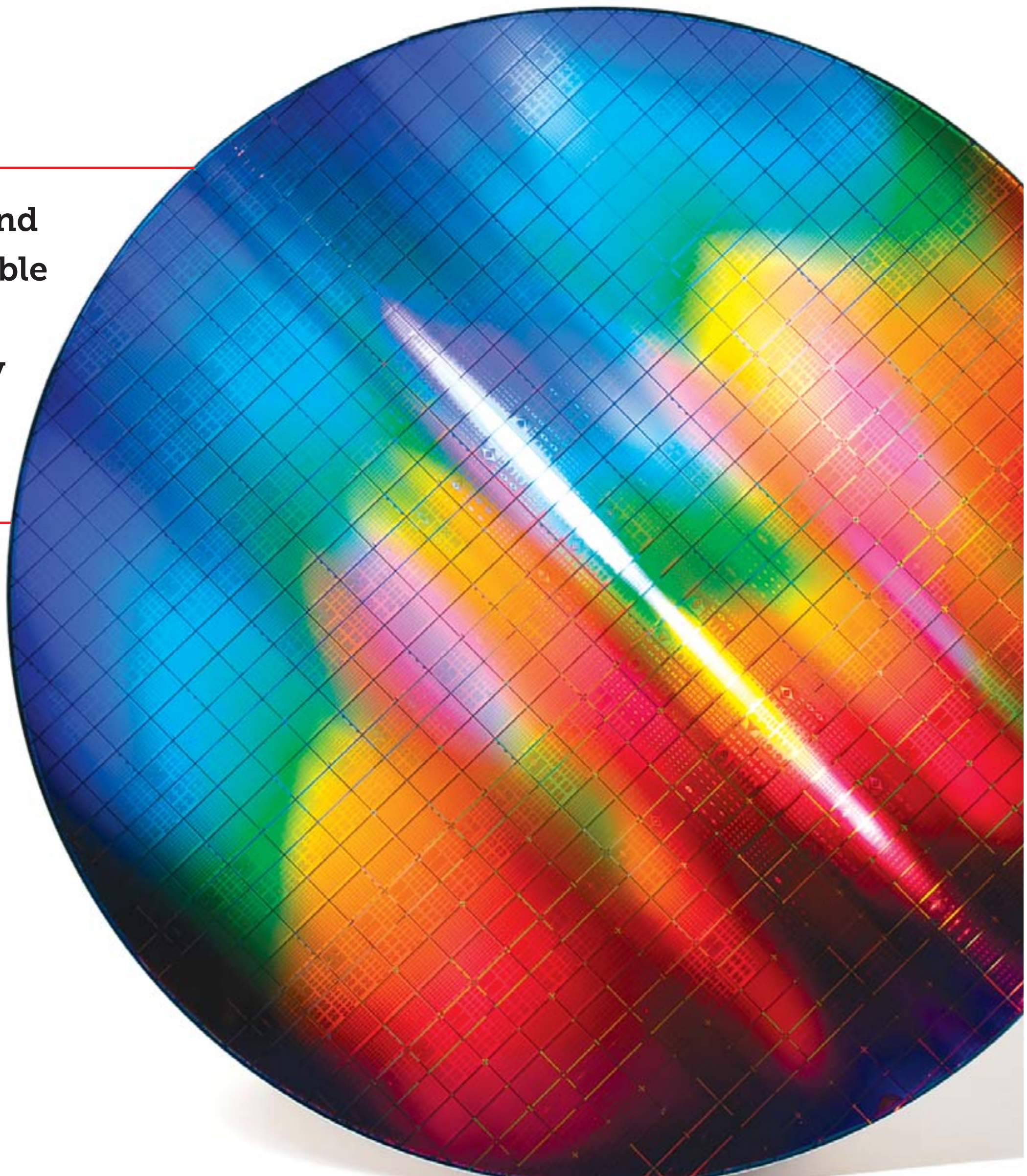
Arrays of electrically and magnetically controllable electron-spin qubits can be lithographically fabricated on silicon wafers.



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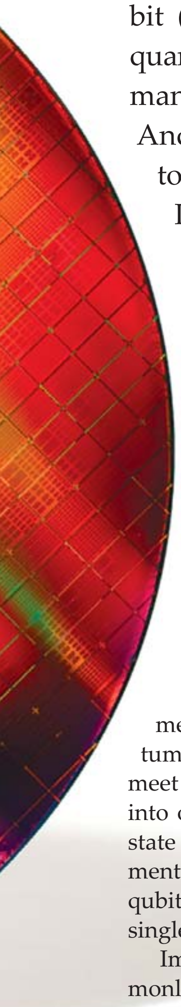


Open any textbook on quantum mechanics, and the two-state system of choice is likely to be a spin-½ particle, such as an electron. The corresponding states, spin up and spin down, form the prototypical quantum bit (qubit), and rotations of the spin state constitute the simplest quantum logic gates. Because of their negative charge, electrons can be manipulated with voltages applied to nanoscale electrodes, or gates. And the application of appropriate voltages can confine the electrons to small islands called quantum dots (see the article by Marc Kastner, Physics Today, January 1993, page 24).

Twenty years ago Daniel Loss and David DiVincenzo proposed that the spin of a single electron in a semiconductor quantum dot could form not just a model but also a real, physical qubit.[1] Their theoretical work predated by four years the first experiments to successfully trap a single electron in a gate-defined quantum dot, and it predated by several more years the first coherent manipulation of a single spin in a semiconductor. Semiconductor spin qubits now come in four distinct flavors, each of which was proposed by theory that set a target for experiments to pursue. Those experiments always brought surprises, and the interplay between theory and experiment makes semiconductor spin qubits a particularly vibrant field of study.

In this article we describe the experimental development and the current state of the art of semiconductor quantum-dot spin qubits. Functional and scalable qubits must meet well-defined criteria.[2] First, reliably initializing each qubit into one of its two levels must be possible. Second, the final state of each qubit must be knowable by a projective measurement that gives the correct answer with high probability. Third, qubit manipulation must be implementable using high-quality single- and two-qubit gates.

Imagine the spin state as a vector pointing on a sphere, commonly known as the Bloch sphere. Single-qubit gates correspond to rotations of the state vector that are independent of the state of any other qubit in the system. In the case of two-qubit gates, rotation of one qubit depends on the state of the other. And when the second qubit itself starts off in a superposition of states, the two qubits become entangled with each other. The recent satisfaction of all those requirements with quantum dots led to the demonstration of the first—and at two qubits the smallest possible—quantum semiconductor processor.

That single-electron spins in a semiconductor chip can act as qubits is remarkable. Unlike atoms or photons in a vacuum, an electron in a semiconductor resides in a noisy, solid-state environment. Engineering that environment so that it doesn't rapidly degrade or decohere the spin-qubit states has been a key challenge for our field.

Errors are unavoidable and necessitate quantum error-correction techniques (see Physics Today, February 2005, page 19). To be effective, the techniques require that initialization, readout, and single- and two-qubit operations have error rates below 1%. Furthermore, quantum error correction involves an overhead in the number of qubits that can easily reach 1000 physical error-prone qubits to encode one protected error-free qubit. Therefore, a future quantum computer capable of solving relevant problems beyond the reach of a supercomputer will likely contain millions of physical qubits. (See the article by David Weiss and Mark Saffman, Physics Today, July 2017, page 44.)

Semiconductor quantum dots have a tiny footprint that offers the prospect of integrating millions of qubits, akin to classical integrated circuits. The corresponding electron density in quantum-dot devices, however, is far smaller than in classical transistors, with each single electron in a qubit typically spread over a region roughly 20 nm × 20 nm in size. For such a device to work as intended, the materials and nanofabricated structures must have very little disorder, to ensure that electrons are easy to position and control. Pulling off that achievement entails uniform patterning of the gate electrodes but also having low densities of trapped charges in the substrate, in the dielectrics, and at the interfaces.

Because of the need for ultrahigh quality, the path to a large-scale quantum computer of any type is a marathon, not a

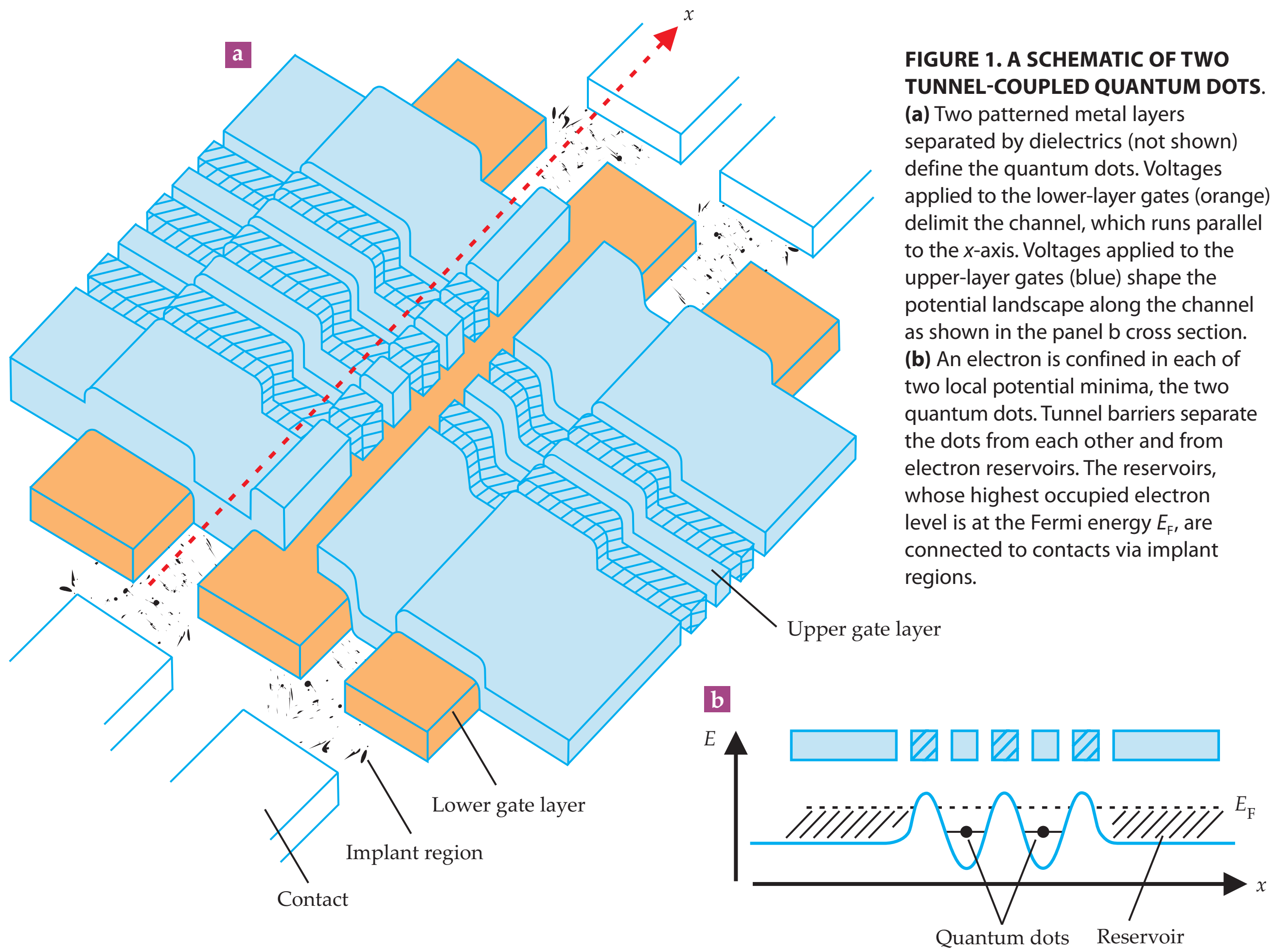


FIGURE 1. A SCHEMATIC OF TWO TUNNEL-COUPLED QUANTUM DOTS. **(a)** Two patterned metal layers separated by dielectrics (not shown) define the quantum dots. Voltages applied to the lower-layer gates (orange) delimit the channel, which runs parallel to the *x*-axis. Voltages applied to the upper-layer gates (blue) shape the potential landscape along the channel as shown in the panel b cross section. **(b)** An electron is confined in each of two local potential minima, the two quantum dots. Tunnel barriers separate the dots from each other and from electron reservoirs. The reservoirs, whose highest occupied electron level is at the Fermi energy E_F, are connected to contacts via implant regions.

sprint. And research today is motivated by a vision that will take years to bring to fruition. In the case of semiconductor spin qubits, that vision relies on long coherence times and on recent advances in gate fidelity—a common metric to express the quality of quantum gates—fueled by a move to silicon-based devices.

Intriguingly, spin qubits in semiconductors could also be integrated with classical integrated-circuit technology, including processing, memory, and the distribution of signals. Integration on chip is natural, because quantum-dot qubits use gate electrodes just as field-effect transistors do. Integration could also occur at the system level, with clusters of chips communicating with one another.

From transistor to qubit

The field-effect transistor is a good starting point for understanding a quantum dot. In a transistor, the flow of electrons between two contacts (source and drain) is switched on or off via the voltage on a metal gate electrode placed above the space between the contacts (the channel). A positive gate voltage attracts electrons to the channel and produces a conducting path from source to drain. A negative gate voltage, by contrast, empties the channel such that no source–drain current can flow. If one were to replace the gate electrode with three independently biased electrodes, the electronic potential landscape between the contacts could be shaped to create a potential-energy minimum separated from the contact regions by potential barriers.

At low temperature, typically below 4 K, the thermal energy is lower than the energy needed to add or remove electrons from the potential well. Thus the well is occupied by a discrete number of electrons. When the electrons are confined tightly enough that orbital motion is frozen out quantum mechanically, the device is known as a quantum dot.

Arrays of tunnel-coupled quantum dots can be formed with additional gate electrodes, as shown in figure 1. The voltages on the blue gate electrodes control the depth of the potential minima and thereby the number of electrons on each quantum dot. The voltages on the hatched blue gates control the tunnel barriers between adjacent dots and between the dots and the reservoirs. Nowadays, quantum dots are routinely tuned to the limit in which just a single electron resides on each dot. Researchers can verify the tuning by monitoring the current through an auxiliary nearby quantum dot that acts as an electrometer.

Spin qubits

When one electron resides in each quantum dot in the presence of a magnetic field, each electron spin becomes an appealing qubit. Indeed, that simple configuration, with one electron in one dot, was proposed by Loss and DiVincenzo in 1998. In subsequent years, alternative spin qubits have made their debut.

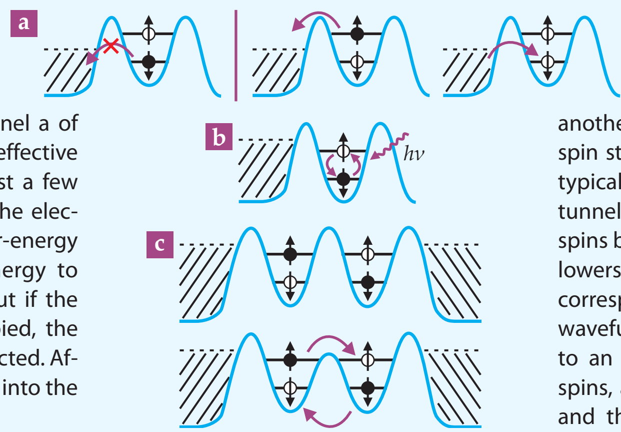
HOW TO INITIALIZE, MANIPULATE, AND READ OUT A SPIN QUBIT

Reading out the spin state of an electron on a quantum dot involves making a so-called spin-to-charge conversion,[16] whereby the electron is allowed to tunnel from one location to another in a way that depends on its spin state—or more specifically, on whether the qubit is up or down. A nearby charge sensor is sensitive to the dots' electron occupation; the current through the sensor thus indirectly reveals the spin state.

In one scenario, the Pauli exclusion principle provides the spin dependence: Two electrons can reside on the same dot only when they are in a spin-singlet state. For a spin-triplet state, each electron is forced to reside on its own dot. In another scenario, a qubit's two spin states are aligned above and below the reservoir's Fermi level—the highest occupied energy level (see panel a of the figure). That protocol is usually effective for any qubit separated by at least a few times the thermal energy. When the electron in the dot occupies the lower-energy spin, it doesn't have enough energy to leave and no tunneling occurs. But if the higher-energy spin state is occupied, the electron can tunnel out and is detected. Afterwards, another electron tunnels into the dot from the reservoir.

Initialization is commonly the result of readout, after which an electron with a known spin resides in the dot. Alternatively, initialization can be achieved by allowing the electron spin qubit to thermalize to its ground state.

Resonant control of spin qubits uses magnetic or electric excitation at radio or microwave frequencies. Magnetic excitation can coherently drive spin transitions directly when the excitation is resonant with the energy difference between spin-up and spin-down states (see panel b in the figure).[17] The excitation's amplitude controls the rotation frequency of the spin vector around the Bloch sphere, its phase controls the rotation axis, and its duration controls the rotation angle.



Resonant electrical excitation, by contrast, can drive single-spin transitions because of spin–orbit coupling.[18] The excitation causes the electron to oscillate back and forth in a quantum dot, and the electron experiences an oscillating effective magnetic field that rotates the electron's spin. Alternatively, in the presence of a suitably engineered magnetic field gradient at the dot location, an electrically driven electron experiences a real, oscillating magnetic field, again allowing for coherent spin rotations. In the case of the quantum-dot hybrid qubit (three electrons in two dots), resonant electric fields alone drive transitions between the qubit states.[5]

Gate-voltage pulses provide another method to controllably manipulate spin states. The basic idea is to abruptly—typically within nanoseconds—turn on the tunnel coupling between two neighboring spins by applying a gate-voltage pulse that lowers the tunneling barrier between their corresponding dots, so that the electron wavefunctions overlap. The overlap leads to an exchange interaction between the spins, as suggested in the figure's panel c, and the two spin states are periodically exchanged.

For instance, a qubit can comprise two collective states of two or three spins that reside in either two or three quantum dots. Those flavors are known as singlet–triplet qubits[3] (two electrons, one each in two dots), exchange-only qubits[4] (three electrons in three dots), and quantum-dot hybrid qubits (three electrons in two dots).[5] The trade-offs between them are many and still under investigation. Ultimately, the various qubit types are initialized, manipulated, and read out using the same physical principles, but their robustness to specific noise sources varies, as does their ease of operation.

The first wave of successful spin-qubit experiments started in the early 2000s and used quantum dots defined by gate electrodes over a gallium arsenide/aluminum gallium arsenide two-dimensional electron gas. That heterostructure technology had been the workhorse of mesoscopic physics for more than a decade and provided a platform in which spin qubits were easy to control. Initial work largely met the important requirements for individual qubits—namely, that they could be initialized, manipulated, and read out.

As outlined in the box above, qubits can be implemented using nanosecond gate-voltage pulses and resonant microwave excitation of gate electrodes or current-carrying wires. Single-shot readout is performed indirectly, by inducing spin-dependent tunneling of an electron while detecting the position of the electron in real time. The groups of Leo Kouwenhoven and one of us (Vandersypen) at Delft University of Technology (TU Delft), Charles Marcus at Harvard University, and Seigo Tarucha at the University of Tokyo were the main players to carry out those early experimental demonstrations. The GaAs work culminated in the creation of entangled states of singlet–triplet qubits by Amir Yacoby and coworkers at Harvard. They reached a fidelity—the extent to which the actual state resembles a two-qubit entangled state—of 72% and later improved it[6] to greater than 90%.

Relaxation and decoherence

Spin qubits in GaAs benefit from remarkably long energy relaxation times T_1, the time it takes a qubit to change from a high-energy state to the ground state. For single-spin qubits, T_1 can exceed 1 second at low temperature (100 mK or lower) in a 1 T field. That's three orders of magnitude longer than the longest T_1 in superconducting qubits.

By comparison, T_2^*, the time it takes the qubit phase to randomize, is just tens of nanoseconds in GaAs dots.[3] The phase of the electron's spin is randomized through hyperfine coupling to the roughly 1 million nuclear spins of atoms in the

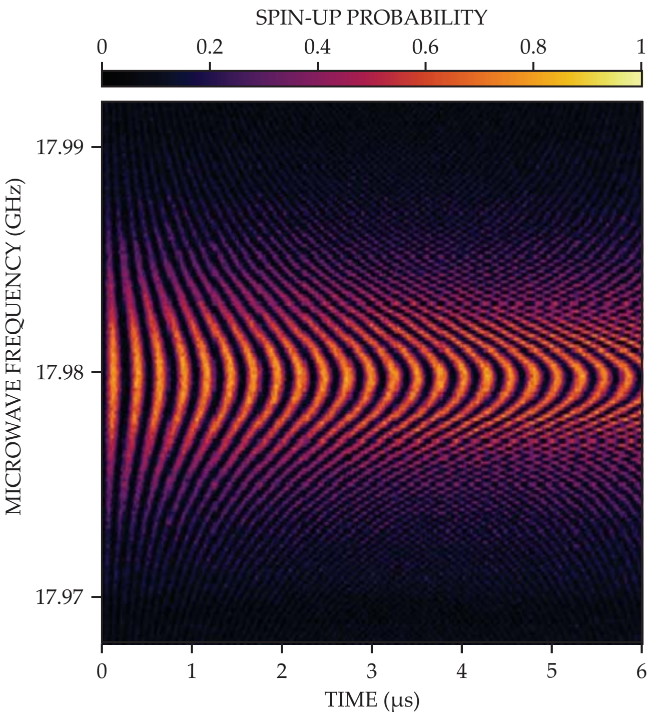


FIGURE 2. DRIVEN EVOLUTION OF A SINGLE QUBIT. When an applied microwave pulse is close to resonance with the spin qubit—that is, with the energy difference between its up and down states (17.98 GHz here)—the qubit undergoes driven rotations, or Rabi oscillation, and the probability of finding it spin-up oscillates as a function of the pulse duration. (Adapted from ref. 10.)

quantum dot, with which the electron wavefunction overlaps. The interaction is impossible to avoid because every Ga and As isotope carries a nuclear spin of $3/2$.

Moreover, despite the low temperatures and strong magnetic fields used with typical spin-qubit measurements, the nuclear spins point in nearly random orientations. The result is a statistically fluctuating and slowly varying collective effect on the electron spin known as the random nuclear or Overhauser field. Although the randomness of the nuclear field can be significantly reduced for singlet–triplet qubits by using sophisticated pulse schemes,[6] the random nuclear field has significantly slowed the progress of GaAs-based spin qubits.

Enter silicon

As early as 1998, it was clear that silicon would be preferable to GaAs as a host material for spin qubits. Fewer than 5% of naturally occurring Si atoms carry a nuclear spin, and those nuclear spins can be largely eliminated by using isotopically enriched ^{28}Si. Although Si is the cornerstone of today's semiconductor technology, it has taken many years of materials development and nanofabrication advances to make Si quantum dots suitable for spin-qubit experiments.

Two main quantum-dot platforms have emerged. In the first, pioneered by one of us (Eriksson) and colleagues at the University of Wisconsin–Madison, electrons are confined in Si quantum wells by silicon germanium barriers above and below the well.[7] In the second, developed by Andrew Dzurak and colleagues at the University of New South Wales (UNSW) in Sydney, electrons are confined against a Si-SiO_2 interface—as in n-doped metal oxide semiconductor technology.[8] In both cases, gate electrodes on the surface are used to accumulate electrons in quantum dots and to form tunnel barriers between the dots.

The randomization time T_2^* is significantly longer in Si than in GaAs, with T_2^* reaching 1 μs in natural Si and up to 100 μs in purified ^{28}Si. That's an improvement over GaAs by four orders of magnitude,[9] and it translates directly to single-spin gate

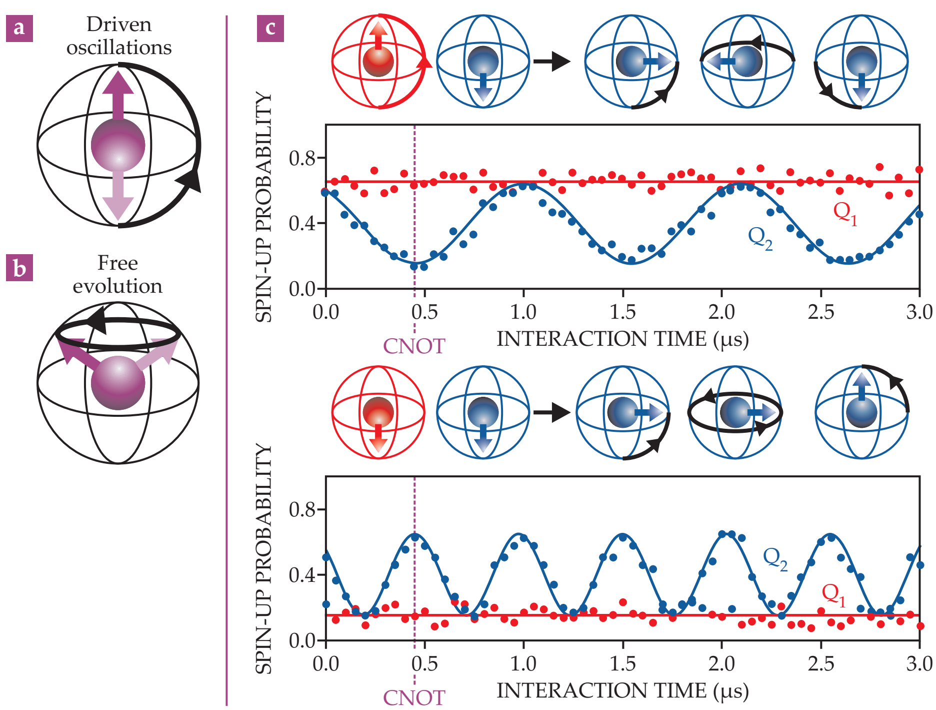


FIGURE 3. A TWO-QUBIT LOGIC GATE. (a) In a Bloch sphere diagram, a qubit rotates along a line of longitude during a resonant microwave pulse (see figure 2). **(b)** In the absence of a microwave pulse, a state precesses along a latitude line around the vertical axis of the Bloch sphere. **(c)** A controlled NOT (CNOT) gate is an operation that flips a target qubit (Q2, blue) based on the state of the control qubit (Q1, red). With Q2 initialized spin down, the plots show the time evolution of the spin-up probability of both qubits when Q1 is spin up (top) or spin down (bottom). In each case, two single-qubit $\pi/2$ rotations are applied, separated by free evolution, during which the two qubits interact. For an interaction of 0.5 μs, the sequence flips Q2 if Q1 is down but not if Q1 is up. (Adapted from ref. 11, M. Veldhorst et al.)

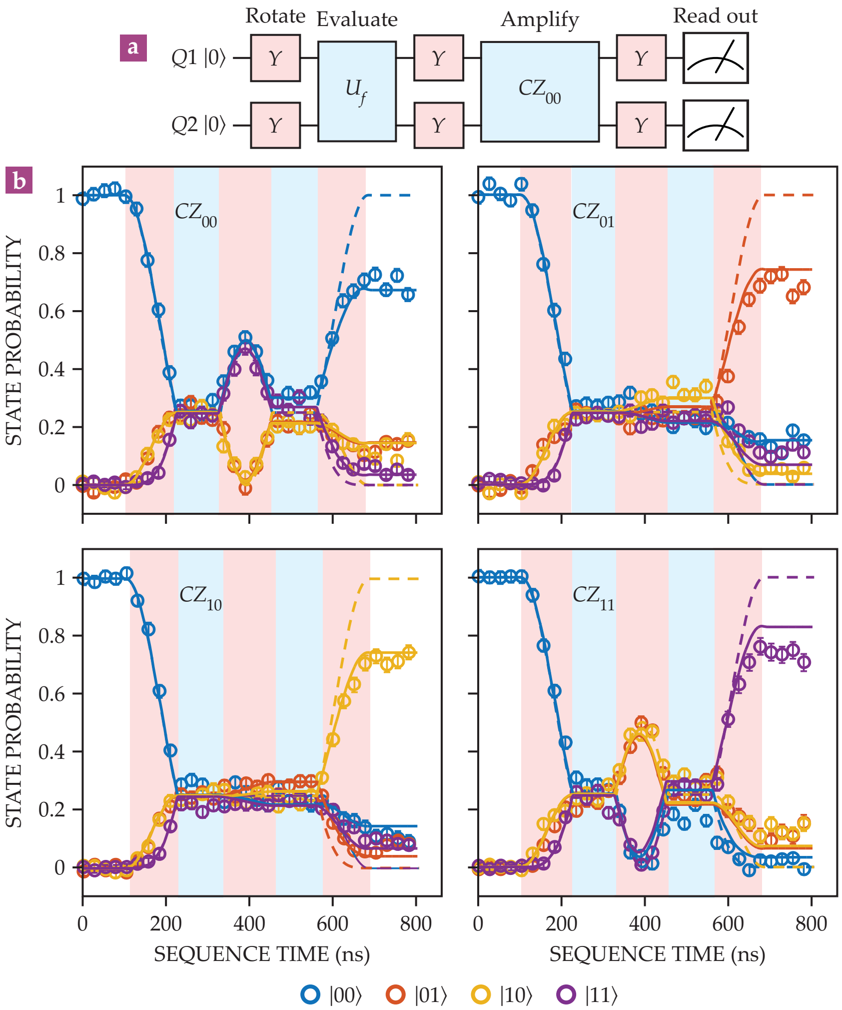


FIGURE 4. A TWO-QUBIT CIRCUIT THAT IMPLEMENTS A QUANTUM SEARCH ALGORITHM. (a) A sequence of operations acts on qubits Q1 and Q2: rotation (Y), interaction (U_f), and amplification (CZ). A detector reads out the final state probabilities of each qubit. **(b)** The two-spin probabilities of the qubit states' populations are plotted as a function of time; the background colors (white, pink, and blue) correspond to the colors of operations in the circuit. After the first rotation around the y-axis, the qubits are in a superposition $(|00\rangle + |01\rangle + |10\rangle + |11\rangle)/2$, with each term having equal weight. In each panel, U_f is a different interaction (CZ_{ij}) that picks out one particular two-qubit state; that state then gets amplified in subsequent steps due to quantum interference. Dashed and solid lines show, respectively, the ideal populations and the results of a model that includes decoherence. (Adapted from ref. 11, T. F. Watson et al.)

fidelities[10] of greater than 99.9% (see figure 2). Furthermore, given that the nuclear-spin bath evolves slowly on the time scale of the electron-spin dynamics, it is possible to extend the coherence times to tens of milliseconds[9] using dynamic decoupling techniques, extensions of the Hahn spin-echo concept.

Even longer electron-spin coherence times are obtained for electrons bound to phosphorus-31 dopants in ^{28}Si-enriched material. The positively charged ^{31}P donor provides the confining potential for the electron. The system is convenient because it avoids the need for bandgap engineering, though actual devices do contain gate electrodes to manipulate the confining potential in time. The group of Andrea Morello at UNSW has shown that individual ^{31}P nuclear spins can provide a nuclear-spin qubit with an exceedingly long T_2^* of 0.6 s.

Quantum-dot and donor qubits in ^{28}Si behave in many respects like isolated electrons trapped in a vacuum, and they allow for extremely high single-qubit control fidelity. In contrast to quantum-dot lithography, ion implantation produces an uncertainty that makes it challenging to position multiple donors with respect to each other. The group of Michelle Simmons, also at UNSW, has shown that scanning tunneling microscope lithography can position atoms with much higher precision than is possible through implantation.

With isotopically enriched ^{28}Si now available on wafer scales and at moderate costs, and with several methods available to confine electron spins in electronic devices, the prospects for practical Si spin qubits have risen sharply.

Putting it all together

Building on the long-lived coherence in Si quantum-dot spin qubits, several groups have now demonstrated high-fidelity control of two single-spin qubits.[11] In 2015 the Dzurak group got a two-qubit gate working with single-qubit control and independent readout of the two spins. The two-qubit gate relied on the interaction between neighboring spins, as outlined in the box. That interaction, in combination with single-qubit rotations, enables a controlled-NOT (CNOT) gate, as illustrated in figure 3. Two years later two teams—a collaboration of our own groups at TU Delft and at the University of Wisconsin–Madison and, independently, the group of Jason Petta at Princeton University—demonstrated entanglement of two single-spin qubits in a Si/SiGe double quantum dot.

To further illustrate the recent progress of Si spin qubits, figure 4 shows the implementation of a simple quantum algorithm on two Si spin qubits. We and our colleagues at TU Delft and the University of Wisconsin–Madison successfully programmed all four instances of Grover's search algorithm for two qubits.[11] The algorithm is designed to invert a function $f(x)$ and identify the unique n-bit input value x_0 for which $f(x_0) = 1$. For all other input values, $f(x) = 0$. Without further knowledge of f, there is no more efficient method using a classical computer than exhaustively searching through the space of input values, evaluating $f(x)$ using one input value after another until hitting the input value x_0.

The quantum case behaves very differently. Figure 4 illustrates how the occupation probabilities of the four basis states $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$ evolve throughout the steps of the quantum algorithm for each of the four possible functions f. Starting off with qubits Q1 and Q2 both in the $|00\rangle$ ground state, the first step is to prepare an equal superposition of the four basis states via simultaneous 90-degree rotations of each qubit from about 100 ns to 200 ns in the circuit. Next, a unitary transformation U_f is executed that corresponds to calling the function f from about 200 ns to 350 ns.

Because the qubits are in superposition, the function is evaluated for all four of its input values (00, 01, 10, and 11) in a quantum superposition as well. The function call is implemented with a two-qubit gate, which flips the phase of the $|x_0\rangle$ component in the superposition. At that point in the circuit, all probabilities remain ¼, as shown in figure 4. Subsequent single-qubit and two-qubit operations, identical for the four cases, boost the amplitude of the term $|x_0\rangle$ using quantum interference at the expense of the other terms.

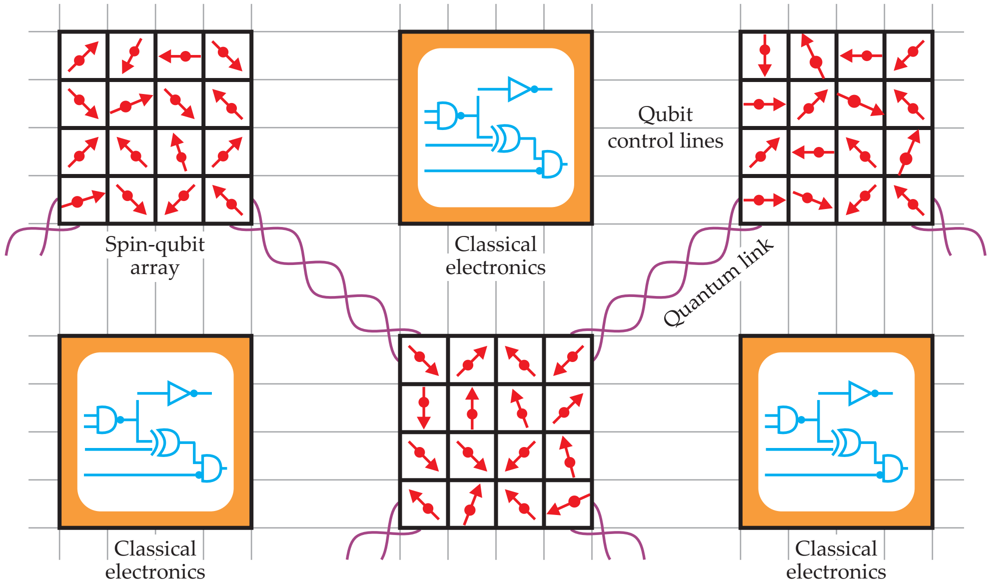


FIGURE 5. A VISION OF FUTURE SILICON QUANTUM ELECTRONICS, containing dense local registers of quantum dots interconnected with quantum links. Classical electronics between the spin-qubit arrays distribute signals on the chip.

Networked qubit registers

The two-qubit experiment can be scaled up to a few dozen qubits in linear arrays of quantum dots. Researchers, most notably at CNRS Grenoble, have already gone beyond 1D arrays and reported the first demonstrations of small 2D arrays of quantum dots. But limits exist to the number of tunnel-coupled quantum dots that can be realistically integrated monolithically. To scale up further, it is likely that on-chip quantum links will be required to connect distant quantum registers with each other, forming networks of interconnected multiqubit registers.

Many proposals exist for making such links, and their realization is an active area of research. One heavily pursued approach uses microwave photons stored in on-chip superconducting resonators to indirectly mediate the coupling between distant spins on the chip. Adopting that tack, three groups made a major breakthrough in their recent observation of so-called strong coupling of a single microwave photon and an electron spin qubit (see reference 12 and PHYSICS TODAY, April 2018, page 17). A second promising approach is to apply periodic gate voltages to induce a traveling-wave potential that shuttles electrons through channels across the chip. Initial results on quantum-dot arrays indicate that spin coherence can be preserved during such shuttling.[13]

Challenges in scaling up

Low fabrication yield still slows progress in many labs, and working devices are not all identical. Researchers must compensate for disorder in the form of charged defects and impurities in the semiconductor by tweaking the gate voltages. That's time-consuming, and low-frequency charge noise makes frequent retuning necessary. Furthermore, high-frequency charge noise limits the two-qubit gate fidelity. Nevertheless, the first experiments achieved two-qubit gate fidelities of 92–98% under suboptimal conditions, and 99% fidelity seems within reach.[14]

Recent experiments have shown encouraging improvements in charge noise. And yield, qubit uniformity, and charge noise are expected to benefit from industrial efforts to fabricate quantum-dot arrays using commercial methods. The work is ongoing at the CEA's Leti Institute, an electronics information technology laboratory in Grenoble, France; at Imec, headquartered in Belgium, using electron-beam lithography; and at Intel Corp using all-optical lithography (see page 38).

Another challenge comes from the nature of Si, whose conduction band has six degenerate minima, or valleys, in the bulk. The degeneracy is problematic for spin-qubit operation because the Pauli exclusion principle, which normally forbids two electrons with the same spin to occupy the orbital ground state, gets circumvented and the two-qubit gate fails.

Confined structures such as quantum dots lift that sixfold degeneracy. But the so-called valley splitting—the energy gap to the first excited valley state—depends strongly on atomic-scale details that are locked in during growth and that can vary across a sample. In some of the Si/SiGe quantum dots measured to date, the valley splitting is too small to be useful. In contrast, a metal-oxide semiconductor quantum dot can have large valley splitting because of the hard confinement from the silicon oxide layer. The flip side is that this same oxide interface is a source of disorder that is larger than the disorder at the epitaxial interface of Si/SiGe quantum wells.

Scaling challenges can also arise at higher levels in the system—from the control electronics to the quantum-computer architecture and software layers. For example, every quantum dot (and superconducting qubit) made today requires that at least one wire be connected off-chip, which presents a wiring bottleneck for going beyond a few thousand qubits. To overcome the bottleneck, we envision two solutions that work in tandem: crossbar addressing schemes, like those used in displays and memory chips, and on-chip classical multiplexing circuits to distribute signals.[15]

A vision of qubit registers

Imagine a large-scale Si chip consisting of local 2D quantum-dot arrays addressed using crossbars and classical multiplexing electronics that are connected by quantum links.[15] Figure 5 depicts what such a network of quantum and classical electronics might look like.

Si spin qubits are particularly well suited to realize that vision. First, the quantum dots, quantum links, and classical on-chip electronics can all be integrated using the same process steps. Those parts, moreover, can leverage today's transistor technology. Second, with a typical spacing of 100 nm, quantum dots are extremely compact: 1000 dots can fit inside an area of 10 μm^2. Third, Si spin-qubit coherence times are extremely long and can accommodate sequential operations on the qubits, which may be needed using crossbar addressing schemes. Fourth, Si spin qubits are resilient to temperature and suffer only modest degradation of charge noise and spin-relaxation times between 20 mK and 1 K.

Those are significant assets for scaling up Si spin qubits into a truly integrated circuit of quantum and classical components on a single chip. Scientific and technological challenges remain, but the prospect is very real that Si spin qubits may be scaled up to the many millions of qubits that will likely be needed to solve real-world problems beyond the reach of any classical machine. For example, a large-scale quantum computer will be capable of efficiently computing the properties of materials and molecules, with possible applications ranging from energy harvesting and storage to the design of drugs and catalysts.

We thank our many colleagues at TU Delft, the University of Wisconsin–Madison, and around the world for numerous collaborations and productive discussions.

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