

Embracing the quantum limit in silicon computing

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Quantum computers hold the promise of massive performance enhancements across a range of applications, from cryptography and databases to revolutionary scientific simulation tools. Such computers would make use of the same quantum mechanical phenomena that pose limitations on the continued shrinking of conventional information processing devices. Many of the key requirements for quantum computing differ markedly from those of conventional computers. However, silicon, which plays a central part in conventional information processing, has many properties that make it a superb platform around which to build a quantum computer.

Technological progress has often faced seemingly fundamental barriers. When viewed from a new perspective, these barriers can be transformed into opportunities for innovation. So it is with the quantum mechanical limitations that silicon-based electronics have been charging towards over the past few decades. The silicon-processing length scale has shrunk tenfold every 15 years since 1971 and now stands at 22 nm. At such dimensions, there is a discrete, countable number of donors (10–100) in the transistor channel, and the electrical characteristics of individual dopant atoms can be observed in commercial field-effect transistors, albeit at low temperatures¹. Furthermore, quantum effects such as the onset of quantum tunnelling of electrons through potential barriers limit the ability to confine charges to a densely packed array.

One way to address the quantum limit is to turn these properties into advantages: that is, to build a device whose function relies precisely on coherent quantum behaviour, including effects such as tunnelling, and to use the states of individual atoms, either natural or artificial, to store information. Such a device would be able to process quantum information² (a richer form of information than the ones and zeroes of classical bits) and would thus be capable of fundamentally outperforming conventional computers at solving certain classes of problem³ (Fig. 1). In conventional electronics, charge is used to represent information; however, it is difficult to maintain coherent superpositions of charge states for long periods of time⁴; so, using charge to store information is a challenging approach for quantum computation. By contrast, the spin of an electron can exist in coherent states for periods of as long as seconds⁵. This is many orders of magnitude longer than the few nanoseconds that it takes to manipulate a spin, in principle allowing quantum information to be perpetually maintained through quantum error-correction codes⁶.

Silicon is a particularly attractive material for hosting spin quantum bits (qubits) for several reasons. Silicon has low spin–orbit coupling, and silicon's nuclear-spin-bearing isotope has a low natural abundance (only 5% of natural silicon is ²⁹Si, which can be removed by isotopic enrichment⁷). Both of these properties contribute to long spin coherence times. Furthermore, the advanced state of silicon electronics offers a common platform for spin qubits alongside sophisticated classical integrated circuits.

Spin qubits can be realized in silicon using naturally confined

donor-bound spins or lithographically defined silicon-based quantum dots (Box 1 and Fig. 2). In this Review, we evaluate how such approaches perform with respect to key metrics, which are as applicable to quantum computers as they are to conventional ones: robustness against information loss, speed and fidelity of control operations and measurement, and interconversion between different storage media. Finally, we assess the challenges that lie ahead for silicon-based spin qubits in terms of materials, as well as the nanofabrication requirements that must be met to construct a quantum computer in silicon.

Spin coherence and mechanisms for decoherence

The corruption of the state of the electron spin is characterized by two timescales: T_1 describes spin relaxation from the spin-up to the spin-down state (or the loss of classical information stored in the spin), whereas T_2 is the coherence time, which characterizes spin decoherence (or the loss of the phase information that is necessary to store quantum information) (Fig. 3). Silicon was one of the first semiconductors to be highly purified and grown in large crystals, which led to it being used to explore and develop new electron spin-resonance (ESR) methods.

For electrons bound to donors in silicon, T_1 becomes very long (minutes to hours⁸) at low temperatures. Above a few kelvin, T_1 is limited by thermal excitation to the valley–orbit excited state of the donor, whereas it is controlled by phonon scattering at lower temperatures. For donors, T_2 can be considerably shorter than T_1 , and measuring T_2 necessitated the development of electron spin-echo techniques. In the first microwave electron spin-echo experiment, in 1958, Gordon and Bowers measured the decay of the spin echo from electrons bound to lithium and phosphorus donors in silicon⁹: a T_2 of 0.5 ms was found for a crystal of isotopically enriched ²⁸Si:P. This T_2 was longer than that observed in natural Si, thus demonstrating that ²⁹Si contributes to the electron spin decoherence, and was probably the longest coherence time measured for an electron spin in a condensed matter system for almost half a century.

As interest grew in identifying electron spin systems with long coherence times for applications in quantum information processing, understanding the limits of electron spin coherence took on a new importance. Studies of bulk silicon doped with donors have established that interactions among the donor electron spins and between the electrons and residual ²⁹Si nuclear moments were responsible for the T_2

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BOX 1

Confining electron spins in silicon

Spin qubits can be realized in silicon in two ways: in donor-bound spins in silicon or in silicon-based quantum dots.

Donors

Semiconductors provide a natural mechanism for trapping single spins: using electrons bound to individual donor atoms at low temperature. Phosphorus donors have been the most-studied dopant atom in silicon⁸, especially for quantum information applications^{12,70}. Other donors, including arsenic (ref. 37), antimony (ref. 35), bismuth (refs 52, 75) and lithium (ref. 76), may have different advantages. To incorporate donor-based spins into nanoscale devices, it is necessary to position electrostatic gates with respect to the donor and to position many donors with respect to each other (the precision that is required depends on the precise architecture that is sought^{25,70,77–79}).

Donor atoms can be positioned in silicon by using ion implantation, even at the level of individual donors^{80,81}, although the precision with which this can be achieved is limited to approximately 10 nm owing to straggling. Transport measurements — in which electrons tunnel through individual implanted donor atoms in metal–oxide–semiconductor field-effect transistor (MOSFET)-like devices⁸² or in fin field-effect transistors (FinFETs)⁸³ — can be performed. Recently, it was shown that donors can be tunnel-coupled directly to silicon single-electron transistors, an architecture that allows measurement with a large signal-to-noise ratio⁴². Moreover, donors can be positioned with extremely high precision by using a lithographic technique based on the removal of a hydrogen resist by a scanning tunnelling microscopy tip^{67,84}. Lines of donors for use as leads and gates can also be fabricated in this way, allowing the precise alignment of a cluster of a few donors⁷⁴ or a single donor.

Quantum dots

Alternatively, spins can be confined in ‘artificial atoms’, by using lithographically defined quantum dots^{71,85}. In contrast to donors, quantum dots are extremely tunable^{86,87}, but they have only recently been developed in silicon because of materials challenges that ranged from the relatively large effective mass of electrons in silicon to the substantial mismatch in the lattice constants of various group IV semiconductors. These challenges have been overcome, and quantum dots have been formed in Si/SiGe heterostructures using Schottky gates^{88,89}, as well as in structures that closely resemble silicon MOS transistors^{65,90,91}, in patterned regions of ultra-high dopant density^{74,92} and in gated nanowires^{93,94}. In each case, individual charge occupation has been demonstrated^{94–96}.

An early concern about silicon-based quantum-dot spin qubits involved the conduction band in silicon, which, in its unstrained bulk form, has six equivalent minima (valleys). Early experiments on two-dimensionally confined systems showed that, although it was relatively easy to move four of the valley states to a high energy, the quantum states arising from the two z-valleys, perpendicular to the two-dimensional layer, were nearly degenerate unless very large magnetic fields were applied^{97,98}. Valley degeneracy could be a useful property of qubits⁹⁹; however, in current experimental systems, it is thought that this degeneracy of the z-valley states is lifted by coupling between them¹⁰⁰, as demonstrated by recent observations of spin blockade in silicon-based quantum dots^{45,46,101}.

value measured by Gordon and Bowers. Spectral diffusion of electron spins resulting from their interaction with nuclear magnetic moments has been observed in many systems, but recent theoretical developments using cluster expansion techniques have shown excellent agreement with electron spin-coherence measurements in silicon^{10,11}. By reducing the ²⁹Si concentration to 50 p.p.m. and the donor density to $1 \times 10^{14} \text{ cm}^{-3}$, as well as by using techniques to suppress the effects of dipolar interactions among the donors^{5,12}, coherence times of about 10 s have been observed at 1.8 K. This T_2 is still two orders of magnitude lower than T_1 at this temperature, and efforts to further reduce the effects of nuclear moments and interactions among the donor electron spins are under way.

Donor-bound electrons near the surface of the silicon can have significantly shorter spin-coherence times than those in the bulk: Schenkel and colleagues¹³ found a T_2 of 2.1 ms for donors with a distribution that peaked at a depth of 150 nm from the silicon surface, and this decreased to about 0.75 ms for donors that were 50 nm below the surface. In each case, T_1 was about 15 ms at 5.2 K, which was comparable to that of bulk antimony donors. The origin of this additional decoherence is under investigation: it is possible that it arises from interactions with spins at the silicon surface or from defects remaining as a result of the ion implantation of the dopant atoms. Charge noise associated with the surface could also couple to the donor spins by Stark shifting the electron spin-resonance frequency.

Although the coherence of electrons that are tightly bound to donors extends to seconds, the situation is different for free electrons in silicon. High-mobility two-dimensional electron systems in Si/SiGe heterostructures show both a T_1 and a T_2 in the microsecond range at 4.2 K, with a T_2 of about 3 μs being the longest directly measured coherence time¹⁴. These results are comparable to those obtained at higher temperatures from coherent spin transport experiments in bulk silicon¹⁵. A T_1 of about 1 ms for free electrons in a Si/SiGe two-dimensional electron gas has been inferred from high-field electrically detected magnetic resonance experiments¹⁶, but this has not been confirmed by direct pulsed measurements.

In pulsed-ESR measurements of a two-dimensional electron system, it has been found that T_2 can exceed T_1 (in general, T_2 is limited to $2T_1$ and only reaches this length when the dominant process is relaxation). Values of T_1 and T_2 in the microsecond range can be understood as arising from the spin–orbit interaction in the form of a Rashba effective magnetic field^{14,17}. Lower-mobility two-dimensional electrons in silicon metal–oxide–semiconductor (MOS) structures have a T_1 and T_2 that are about an order of magnitude less than in high-mobility Si/SiGe heterostructures¹⁸.

For quantum dots, T_1 times of many milliseconds and even seconds have been reported for both MOS¹⁹ and Si/SiGe-based^{20,21} systems, although little is known about the coherence of these spins. At present, several research groups are making an intense effort to determine the dephasing time, T_2^* , in electron double-dot experiments in silicon. Such measurements build on techniques used to determine T_2^* for GaAs quantum dots²². There has been one pulsed-ESR measurement of isolated electrons localized at a MOS interface by disorder potentials (so-called natural quantum dots); this gave a lower bound for T_2 of about 30 μs at 350 mK (ref. 18), with this short T_2 being attributed to exchange coupling between electrons in the shallow quantum dots.

Long coherence times are advantageous for quantum information processing. However, some form of error correction, analogous to refreshing dynamic random access memory (DRAM) bits in classical computing, will always be essential. A key figure of merit for fault-tolerant quantum computation therefore becomes the ratio of the coherence time to the duration of a qubit control operation.

Control of electron spins in silicon

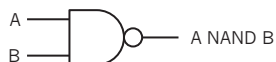
One of the advantages of encoding quantum information in electron spins is the ability to manipulate spin by using established ESR techniques²³, in which resonant microwave fields drive spins between eigenstates, typically on timescales of 1–100 ns (Fig. 4a). By applying

a Classical information processing

Bit
0 or 1

Boolean logic
NOT AND (NAND)

A	B	A NAND B
0	0	1
0	1	1
1	0	1
1	1	0

**b Quantum information processing**

Qubit
 $\psi = \alpha|0\rangle + \beta|1\rangle$

Quantum logic
Controlled NOT (CNOT)

Before	After
Control Target⟩	Control Target'⟩
00⟩	00⟩
01⟩	01⟩
10⟩	11⟩
11⟩	10⟩

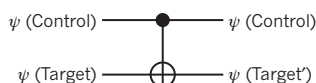


Figure 1 | Classical versus quantum information. The classical binary digit (bit) exists in one of two states, known as 0 and 1 (a). Quantum mechanics, by contrast, allows a two-state system to exist in a superposition of the two states, with a defined phase between the two (b). The most basic unit of quantum information (the quantum bit, or qubit) is therefore written as a combination of the states $|0\rangle$ and $|1\rangle$ defined by the complex numbers α and β . In both types of information processing (classical and quantum), there is a universal set of logic operations from which any algorithm can be composed. As is the case for conventional logic gates (such as NAND), the action of quantum logic operations (such as CNOT) can be understood from truth tables (centre), which show how output states depend on inputs. Importantly, quantum logic gates can act on superpositions of input states (bottom).

an appropriate sequence of pulses with a precise duration and phase, arbitrary single- or multiple-qubit operations can be performed. ESR techniques can also be used to implement dynamical decoupling schemes, which can be used to combat the effects of random environment variations, thus extending coherence times²⁴.

The spins in silicon provide well-defined, reproducible qubits, especially in the case of donors. However, as a result of this uniformity, globally applying ESR pulses to a large ensemble of qubits manipulates all of them in the same way. Some quantum computing architectures can function using only such 'global control' methods²⁵, but it is generally advantageous to be able to selectively address individual spins. There are two leading approaches to achieving this selectivity (Fig. 4b). In the first, the oscillating magnetic fields that are used to drive spin resonance are

spatially restricted, which can be achieved, for example, by fabricating local resonators that are located close to each individual qubit. This is technically demanding for a.c. magnetic fields; however, a quantum dot can be driven using an a.c. electric field, by placing the dot in a magnetic field gradient (for example, provided by a nearby micromagnet), as was recently demonstrated on a III–V quantum dot²⁶.

To selectively manipulate tightly packed donor-based or quantum-dot-based qubits within a global a.c. magnetic field, it is possible to spatially distort the wavefunction of the electron, modifying its spin-resonance frequency and bringing it in or out of resonance with the applied field. Spatial distortion of the donor wavefunction can be achieved by applying electric fields (Stark shifting)²⁷ or by straining the lattice²⁸; the latter case allows tuning of the hyperfine interaction strength by nearly 1%.

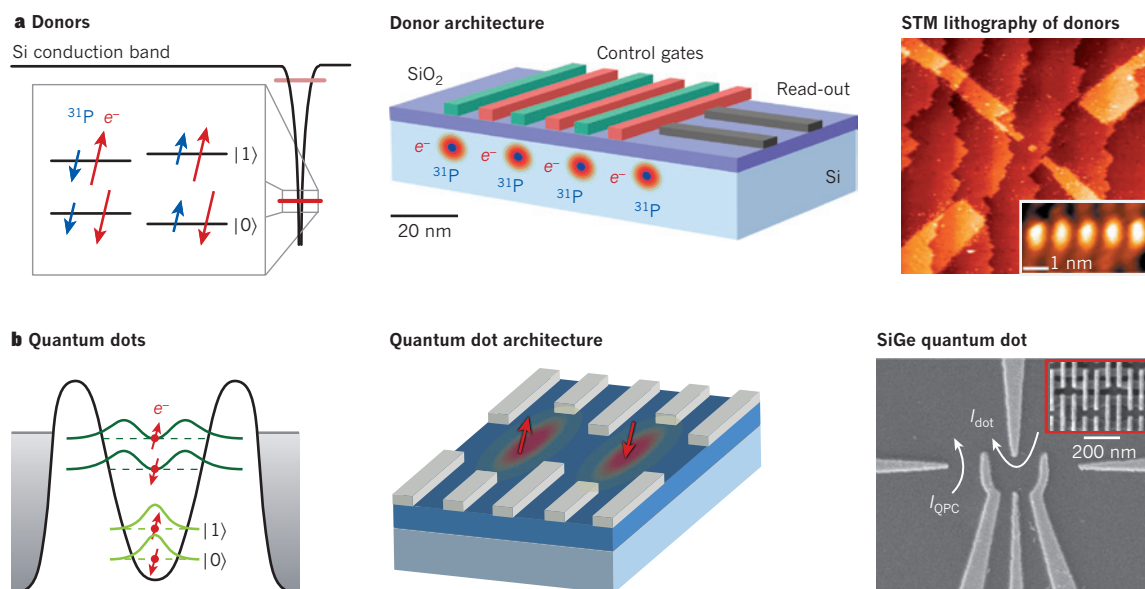


Figure 2 | Fundamental building blocks of silicon-based qubits. Electrons are localized using either donors (for example, phosphorus) (a) or artificial quantum dots (b) (see also Box 1). Left, The electron spin eigenstates (red), which are energetically separated by a Zeeman interaction with an external magnetic field, can be used to encode the $|0\rangle$ and $|1\rangle$ states of a quantum bit. Donor electron spins have an additional hyperfine interaction with the ^{31}P nuclear spin (blue), which can be exploited for both storing information in the nuclear spin and for read-out. Quantum-dot electrons have several bound orbital states (green). Centre, Quantum computing architectures usually incorporate buried arrays of donors or quantum dots with control gates on the surface of the silicon. Right, Scanning probe techniques, such as scanning tunnelling microscopy (STM), can be used to fabricate arrays of

donors with atomic precision (top, inset), as well as the electrical leads and gates with which to control and address them (top, main image). Quantum dots are usually fabricated using SiGe or metal–oxide–semiconductor (MOS) structures, in which a buried two-dimensional electron gas is constricted to form a dot containing a single electron. The quantum dot can be measured using the current flowing through the dot (I_{dot}) and/or flowing through a nearby quantum point contact (I_{QPC}). A typical surface-gate-defined quantum dot (bottom) is shown on the same scale as the gate layers that are used in conventional 22-nm static random access memory (SRAM) chips (inset)⁷³. The image on the right of panel a is reproduced, with permission, from ref. 74. The inset within this image is reproduced, with permission, from ref. 67.

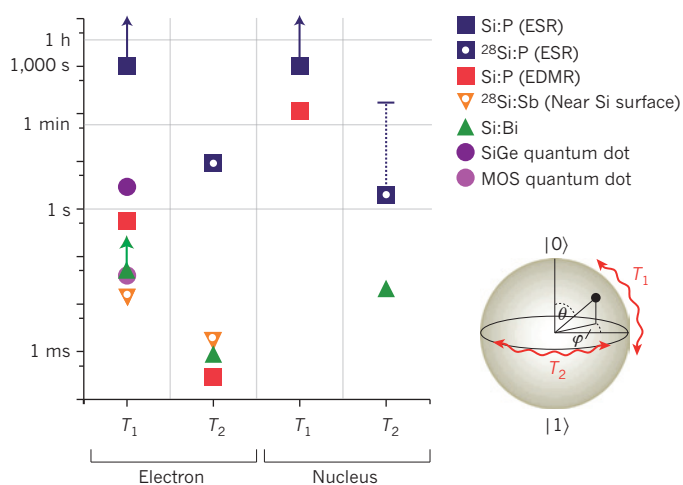


Figure 3 | Information lifetimes for various spins in silicon. A qubit can be represented as a point on the surface of a sphere (bottom right). Corruption of the qubit state can be separated into two timescales: T_1 describes the randomization of θ , whereas T_2 describes the randomization of ϕ . This figure summarizes the measurements that have been made for the T_1 and T_2 of the electron spin of donors in silicon and of silicon-based quantum dots. In the case of donor-bound electron spins, the relaxation times of the donor's nuclear spin can also be extracted. Unless otherwise indicated, natural silicon (with $\sim 5\%$ ^{29}Si) was used. The arrows indicate that these times become even longer at lower temperatures; the dashed line indicates unpublished results. From the top to bottom of the graph, electron T_1 data are taken from refs 8, 21, 41, 52 and 75, 19, and 13; electron T_2 data from refs 5, 13, 52 and 33; nuclear T_1 data from refs 8 and 57; and nuclear T_2 data from M. Thewalt (measured by optically detected magnetic resonance; personal communication) and ref. 51, and ref. 52. EDMR, electrically detected magnetic resonance.

Read-out and measurement methods

In addition to the ability to control qubits, it is necessary to be able to determine their state after implementing an algorithm. An entire class of quantum information processing (using cluster states) can be implemented by global manipulation, if individual donors can be selectively read out. Superficially, read-out seems a simple problem: many thousands of spin-resonance experiments are undertaken every day using read-out by magnetic induction, and single spins can be measured in a similar way²⁹. The difficulty arises in that the magnetic signal from a single spin is extremely small, requiring a long time for a single measurement. To overcome this challenge, alternative techniques have been developed. These are based on converting the information from the spin to another property that is more readily measurable, such as current (charge) or light.

Electrically and optically detected magnetic resonance

One class of measurement methods uses the spin of an electron to control its ability to move: the spin information is mapped onto a current through a process of spin-dependent scattering, tunnelling or recombination. Spin-dependent recombination was first demonstrated nearly 50 years ago³⁰, when the photoconductivity of silicon was modified by incoherently manipulating the spin of an ensemble of phosphorus donor electrons. More recently, this technique has been used to investigate ensembles of fewer than 100 donors³¹ and extended to allow read-out after coherent spin manipulation³², resulting in phase coherence times of $\sim 100\ \mu\text{s}$ (ref. 33). These times are shorter than those that can be measured by standard ESR methods because the free charge carriers (which form a fundamental part of these spin-dependent recombination methods) also induce spin relaxation. In addition, the recombination rate is generally fixed, resulting in either long read-out times or short state lifetimes, although it might be possible to control the recombination rate by varying the wavefunction overlap between the donor and probe spins using externally applied electric fields³⁴.

To overcome the limitations associated with photoexcited carriers, gated structures such as MOS field-effect transistors (MOSFETs) could be used to provide greater control over the conduction electrons used for read-out. The donors in such devices have been studied using spin-dependent scattering processes^{35,36}. Indeed, the current that passes through a MOSFET can be controlled according to the state of the donor spins in the channel, providing a glimpse of the power of incorporating quantum systems into conventional electronics. At present, the spin-dependent effect on MOSFET conductivity is weak: changes of up to 0.03–0.3% were observed using high magnetic fields (3.4 T)³⁷. Nevertheless, with sufficient signal averaging, it is possible to detect the signature of a single spin (of an unknown defect) in a MOSFET³⁸.

Another promising measurement avenue is the use of high-precision optical spectroscopy to selectively photoexcite donors in specific spin states, along the lines of optically detected magnetic resonance³⁹. The photoexcitation of donors can then be detected by an optical pump-probe approach, by measuring the change in photoconductivity as above or by inducing scattering between quantum Hall edge states. Although the methods described in this section can be scaled to the single-spin level, a range of single-spin read-out schemes have no parallel for measuring ensembles and have only recently become experimentally accessible.

Single-shot read-out of electron spins

Single-shot read-out of single spins relies on a version of spin-to-charge conversion in which the spin controls the tunnelling of an individual electron, which can be measured with an integrated charge sensor^{22,40} (Fig. 5). An electron is loaded in a quantum dot²¹ or, equivalently, a donor⁴¹ and occupies either a spin-up or spin-down state, and these states are Zeeman split by an applied magnetic field. A gate voltage is used to tune the quantum dot or donor so that the spin states straddle the Fermi level of a nearby charge reservoir. If the higher-energy spin state is occupied, the electron will tunnel off the donor or out of the quantum dot, and the resultant change in the charge state of the donor or quantum dot will be detected as a current transient. Shortly afterwards, an electron of opposite spin will tunnel into the lower-energy spin state, and the detectable current signature will disappear.

This method has recently been demonstrated in silicon for single electrons confined either to a single donor⁴² or in a quantum dot²¹. Using this and similar methods, T_1 was measured for single spins in both silicon-based quantum dots and donors in silicon, and times up to and exceeding 1 s were recorded^{19–21,42}. T_1 has been observed to increase extremely rapidly with decreasing strength of the magnetic field, which is in agreement with theory⁴³.

Spin blockade and singlet–triplet qubits

In low but non-zero magnetic fields, in which T_1 is longest, the Zeeman splitting that is used for single-shot read-out of electron spins is relatively small, leading to lower-fidelity measurements than in stronger magnetic fields. For this reason, it is interesting to consider encoding a qubit using two-electron spin-singlet and spin-triplet states^{22,44}. The read-out mechanism in this approach relies on the energy splitting between the singlet and triplet states for two electrons in a single quantum dot (or on a single donor) to prevent tunnelling. This effect, known as Pauli spin blockade, has been observed in both silicon-based quantum dots^{45,46} and donors in silicon⁴⁷.

Hybrid qubits in silicon

Current technologies transfer information between different physical representations to take advantage of their relative strengths: for example, moving information from magnetic domains of hard disks to charge in SRAM cells to light pulses in optical fibres. Similarly, one of the advantages of electron spin qubits is the flexibility they provide through their interactions with other quantum degrees of freedom, such

as nuclear spin, charge and photons, all of which can be used to improve coherence lifetimes, processing or read-out⁴⁸.

Because their magnetic moment is weaker than that of electron spins, nuclear spins typically have longer relaxation times (both T_1 and T_2)⁴⁹; therefore, the nuclear spin of a donor provides a potentially long-lived memory element in which the electron spin state may be stored⁵⁰. Through a combination of resonant microwave and radio frequency pulses, the state of a P donor's electron spin may be

coherently swapped with that of the ^{31}P nuclear spin in 'read' and 'write' operations, with fidelities of more than 97% (ref. 51). By comparing the loss of coherence after a write-then-read operation, nuclear T_2 times of up to several seconds have been measured for ^{31}P . These times are comparable to the best times achieved for electron spins, but they should be more robust in proximity to interfaces and in the presence of residual ^{29}Si . Similar operations could be performed using other group V donors. Indeed, the large nuclear spin of ^{209}Bi

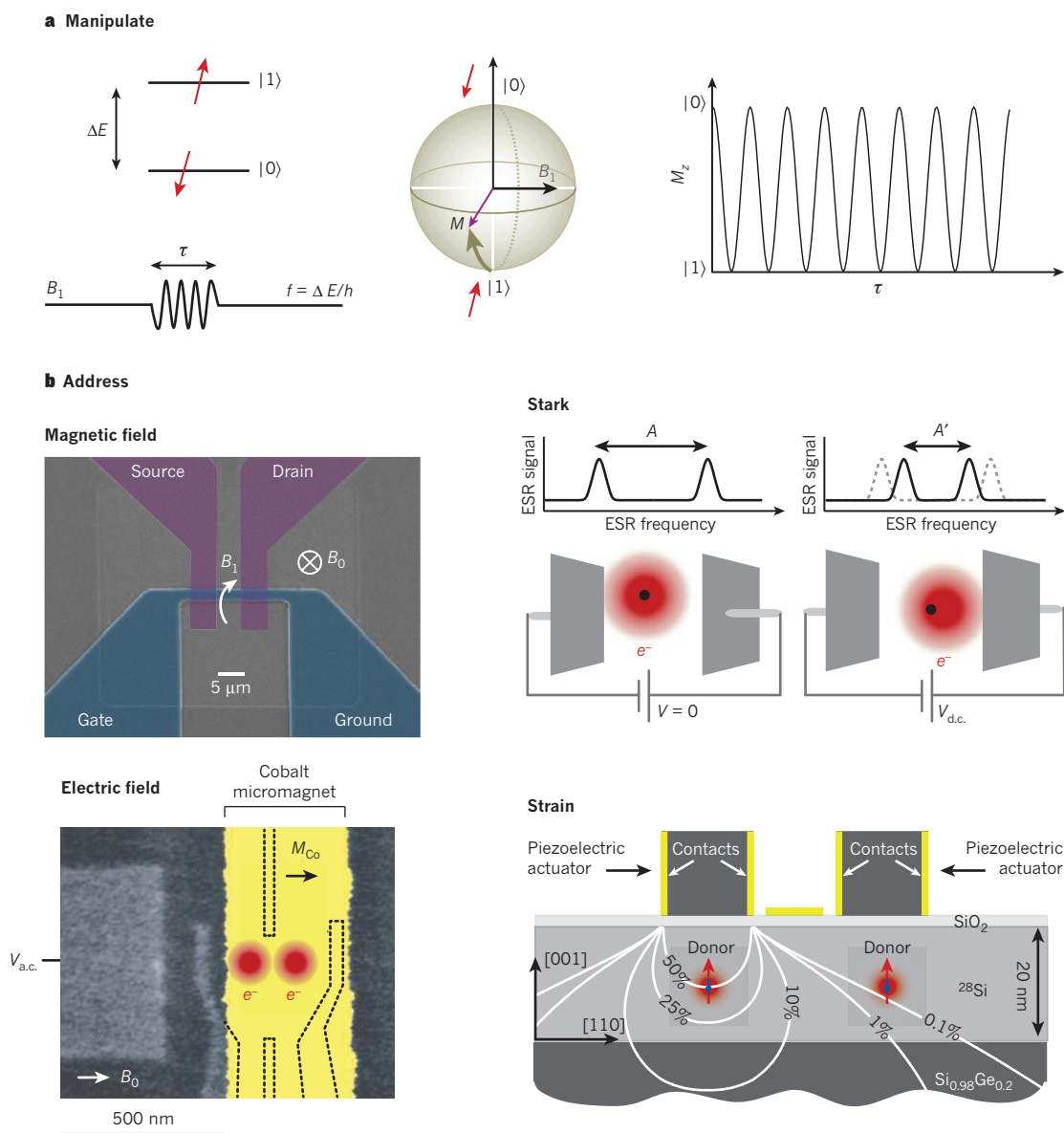


Figure 4 | Controlling and manipulating spins. **a**, Spins (whose eigenstates are separated in energy by ΔE) can be coherently manipulated using resonant microwave pulses of frequency, $f = \Delta E/h$, (where h is Planck's constant). A pulse of a given magnetic field strength, B_1 , and duration, τ , will drive a spin from the $|0\rangle$ to the $|1\rangle$ state, whereas a pulse of half this duration will leave the spin in an equal superposition of the two states. The evolution of the spin magnetization, M , under an applied pulse can be understood as a rotation around the Bloch sphere (green trajectory) perpendicular to the direction of B_1 . This can be measured as coherent oscillations in the z component of the magnetization as the duration of the pulse is increased. **b**, These control pulses can be locally applied using microwave transmission lines located near each qubit, driving the spin directly with an a.c. magnetic field, B_1 , perpendicular to the static field B_0 (top left). The blue structure functions as a gate that induces a two-dimensional electron gas, as well as a microwave transmission line. The current flowing through the source and the drain

contacts is measured to perform electrically detected magnetic resonance of P donors under the gate. Alternatively, the spin of a quantum dot can be driven indirectly using an a.c. voltage, $V_{a.c.}$ (bottom left), which modulates the position of the spin within a magnetic field gradient created by a cobalt micromagnet (with magnetization M_{Co}). Spin manipulation pulses can also be applied globally, and the resonance of individual spins can be modified so that they can be selectively manipulated. This can be achieved by locally applying a d.c. voltage, $V_{d.c.}$, and exploiting the Stark effect (top right) or by using strain fields (bottom right). This modifies the wavefunction of the donor electron, changing the hyperfine interaction with the nuclear spin and thus the electron spin-resonance frequency. Strain is applied using piezoelectric actuators, which strain a ^{28}Si epitaxial layer on SiGe . The image at the top left of panel **b** is adapted, with permission, from ref. 36. The image at the bottom right of panel **b** is reproduced, with permission, from ref. 28. The image at the bottom left of panel **b** is reproduced, with permission, from ref. 26.

($I = 9/2$, where I is the total angular momentum of the nucleus) provides a large Hilbert space in which several spin qubits could be stored⁵². Although the weak magnetic moment of the nuclear spin also makes it challenging to initialize qubits, nuclear spins can be polarized through coupling to an electron spin (for example, ^{31}P in Si), by using optically driven dynamic nuclear polarization^{53,54} or spin-resonance pulse sequences⁵⁵.

In addition to advantages for quantum memory, nuclear spins provide a route to achieving quantum non-demolition measurement, which is an ideal quantum measurement that does not itself perturb the system beyond the inevitable collapse of the wavefunction that is brought about by discovering its state. In the scheme proposed by Sarovar and colleagues⁵⁶, a quantum non-demolition measurement of a nuclear spin is made by measuring the resonance frequency of a coupled electron that is shifted by the state of the nuclear spin as a result of the hyperfine coupling. The electron spin is measured using one of the methods described above, each of which is destructive to the state of the electron but largely preserves the state of a coupled nuclear spin⁵⁷ (Fig. 5c).

Of the various approaches for quantum computing using solid-state devices, researchers have made particularly strong progress in coupling multiple qubits together by using qubits based on superconducting circuits, generating up to three-qubit entangled states^{58,59}. However, such qubits remain limited in their applicability by short coherence times, which are typically a few microseconds to

tens of microseconds. One important application of spins in silicon could be as memory elements operating in the microwave regime: superconducting qubits can exchange their state with a microwave photon in a superconducting coplanar waveguide cavity, and the state of this photon can be stored, in turn, within a spin ensemble^{60–63}.

For long-distance transmission of quantum information, a similar state transfer would need to be performed with photons in the optical regime, allowing seamless quantum computation and communication. Unfortunately, the poor optical properties of silicon make this challenging. Optical emission from excitons bound to phosphorus donors in silicon can be used to measure the state of both the electron spin and the nuclear spin⁵⁴; however, the measurement efficiency is low, prohibiting even single-spin measurements let alone qubit state transfer. Other defects in silicon, such as erbium, result in luminescence from an inner-shell transition and may be better suited to such applications. If such a state transfer is successful, single optical photons could be routed on-chip using silica-on-silicon waveguides, which have been used to perform quantum logic operations, albeit non-deterministically⁶⁴.

Materials and nanofabrication

Great progress has recently been made in the development of spin-based quantum devices in silicon, but there are a number of challenges to be met before these structures become practical, scalable systems. The most pressing issues revolve around materials: limiting the

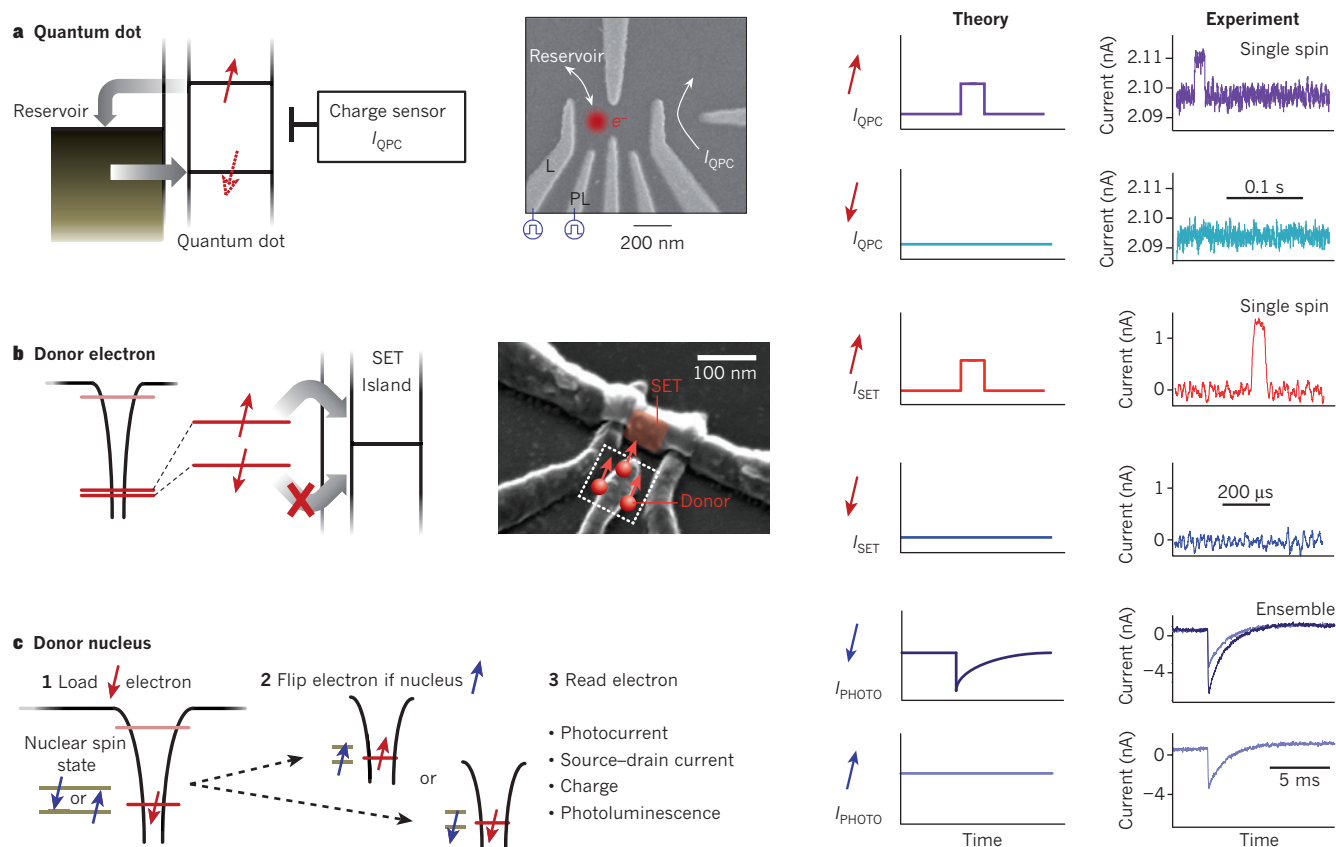


Figure 5 | Spin read-out of quantum dots and donors. Three read-out schemes, each using spin-controlled electron current are shown, including a schematic of how the spin-current conversion is performed (left), a scanning electron microscopy image of the device (centre) and data showing spin measurement (right). **a**, The current through a charge sensing quantum point contact (I_{QPC}), can be used to monitor the occupancy of a quantum dot. Selectively biasing the quantum dot (with a voltage pulse on the gates labelled L and PL) results in electron tunnelling of the dot to a nearby reservoir only if it is in the spin-up state. The signal from the charge sensor changes only if the electron moves. Experimental data are taken from ref. 21.

b, Alternatively, an electron may be induced to tunnel from a donor onto the island of a nearby single electron transistor (SET), modifying its current. Experimental data are taken from ref. 42. The image in the centre of panel **b** is reproduced, with permission, from ref. 42. **c**, The state of the donor nuclear spin can also be measured as a result of its hyperfine coupling to the electron. For example, a charge-trap mechanism can be used; this results in a reduction in photocurrent only if the electron is spin down. By using the hyperfine interaction to selectively rotate the electron based on the spin of the nucleus, the current reflects the nuclear state. Experimental data are taken from ref. 57.

impact of impurities in the devices, controlling defect formation, and fabricating sufficiently small and reproducible devices. The easiest problem to solve is probably the requirement for isotopically enriched ^{28}Si . Processing ^{28}Si at the level needed for the Avogadro Project⁷, or for multi-second T_2 times, is challenging, but a donor-electron spin coherence of 60 ms has been obtained with commercially grown epitaxial layers of ^{28}Si on natural Si at a moderate cost¹².

Patterning the gates that control the electrons and their spins at a sufficiently small length scale is often a significant hurdle in device research. The size of quantum-dot-based devices is much less than 1 μm , and donor-based devices are even smaller. It is tempting to look at what the semiconductor industry can produce (Fig. 2b, inset) and to declare victory — the industry already fabricates copious quantities of devices that are smaller than those in research laboratories. However, this ignores the fact that modern silicon devices are designed and optimized for operation at room temperature, whereas silicon-based quantum structures operate at millikelvin temperatures and require control over individual electrons. Defects that are of little concern in room temperature devices become problematic at a low temperature and low electron density. For example, charges that are trapped in an insulating layer on the silicon can lead to localization of electrons in unintentional (and unwanted) parasitic quantum dots. In addition, various high-energy processing techniques, including ion implantation and plasma-based processes, are ubiquitous in modern integrated-circuit fabrication and can lead to trapped charges in the gate oxide and other dielectric layers. Nordberg and colleagues have investigated how various processing steps affect the performance of devices that are intended to manipulate one or a few electrons at millikelvin temperatures⁶⁵. Through a combination of judicious choices of processing techniques and annealing, they have demonstrated working quantum devices, with few parasitic quantum dots.

Using heterostructures of Si and SiGe is one possible solution to meeting some of the challenges of defects. Instead of the electrons inhabiting an interface between crystalline silicon and an amorphous oxide, the electrons are held at the interface between two crystalline semiconductors. Electrons with very high mobility (indicative of a low density of defects and trapped charges) have been observed in these structures⁶⁶, which is a promising development; however, using these heterostructures is a step farther away from standard silicon processing. For example, maintaining the quality of the heterostructure interface imposes severe restrictions on the subsequent processes that can be used to define the devices.

Issues of defects, trapped charges and extra spins can ultimately be traced back to a modern silicon integrated circuit being made of many layers of different materials. An alternative approach is to use only crystalline silicon. At a low temperature, silicon becomes an insulator, except where it is degenerately doped. Simmons and co-workers have demonstrated how to control the incorporation of phosphorus at the atomic scale, allowing degenerate doping of local regions of the silicon with true atomic-scale resolution⁶⁷.

The successful development of processes for the fabrication of quantum devices in large numbers will open the door to the scaling of quantum processors. Questions of device uniformity, reproducibility and appropriate architecture will become important. For example, many designs require multiple classical control gates for each qubit, even though triple quantum-dot structures can be defined with only two top gates⁶⁸. As noted earlier, mobile electrons in silicon lose their spin coherence much more rapidly than tightly bound spins; however, if the spins are to be localized, a high level of device reproducibility will be required to keep the number of control lines manageable⁶⁹.

Future directions

The approaches based on donor atoms and quantum dots each have their own advantages in terms of coherence times, control and read-out methods, and it is possible that both approaches could be combined in a

future quantum processor. Indeed, this has already been shown to some extent in the single-shot measurement of a donor electron spin, by using controlled tunnelling onto a single-electron transistor (SET) quantum dot⁴². In both cases, it is clear that the single-qubit properties are excellent; they are sufficient for fault-tolerant quantum computing and are far ahead of other solid-state rival systems in many cases. A key goal of future work in silicon-based quantum computing is therefore to identify the best way in which to couple multiple, spatially separated qubits.

Spins on neighbouring qubits can interact through dipolar or exchange coupling. The exchange coupling between donors or quantum dots could be tuned using intermediate gates^{70,71}, although in the case of donors this would require ultra-precise positioning of the donors with respect to each other and the control gates. Dipolar coupling is typically a less attractive option than exchange coupling because of its weaker strength (leading to a slower gate); however, the long coherence times in silicon may allow it to be used. Interactions can be 'always on' (and still allow universal quantum computing) or turned on or off by moving the qubit into a nuclear-spin degree of freedom that shows much weaker dipole coupling⁵¹. An alternative route would be to dispense with the through-space coupling of spins and use the portable nature of the electron to move the spin qubit between different quantum dot or donor sites^{25,72}. These different coupling methods must be assessed with respect to gate speed and fidelity, in addition to how well they lend themselves to scaling up based on the opportunities provided by silicon-based nanofabrication.

Silicon has been the material of choice for hosting the remarkable developments in information processing of the past 50 years, and it shows every promise of surviving the transition from the classical computer to the quantum computer. ■

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