require the robust, continual development of both scientific understanding and engineering skill within this new and fascinating arena.

References and Notes

1. M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge Univ. Press, Cambridge, 2000).
2. N. D. Mermin, *Quantum Computer Science* (Cambridge Univ. Press, Cambridge, 2007).
3. P. W. Shor, *Phys. Rev. A* **52**, R2493 (1995).
4. A. Steane, *Proc. R. Soc. London Ser. A* **452**, 2551 (1996).
5. E. Knill, R. Laflamme, *Phys. Rev. A* **55**, 900 (1997).
6. D. Gottesman, thesis, California Institute of Technology (1997).
7. S. Lloyd, *Science* **273**, 1073 (1996).
8. See, for example, J. I. Cirac, P. Zoller, Goals and opportunities in quantum simulations. *Nat. Phys.* **8**, 264 (2012) and other articles in this special issue.
9. H. J. Kimble, *Nature* **453**, 1023 (2008).
10. Direct quantum spin simulations, such as aimed at by the machine constructed by D-Wave Systems Inc., are outside the scope of this article.
11. M. H. Devoret, J. M. Martinis, *Quant. Inf. Proc.* **3**, 381 (2004).
12. R. J. Schoelkopf, S. M. Girvin, *Nature* **451**, 664 (2008).
13. J. Clarke, F. K. Wilhelm, *Nature* **453**, 1031 (2008).
14. J. Q. You, F. Nori, *Phys. Today* **58**, 42 (2005).
15. D. P. DiVincenzo, *Fortschr. Phys.* **48**, 771 (2000).
16. C. Sayrin *et al.*, *Nature* **477**, 73 (2011).
17. K. Geerlings *et al.*, http://arxiv.org/abs/1211.0491 (2012).
18. R. Vijay *et al.*, *Nature* **490**, 77 (2012).
19. K. W. Murch *et al.*, *Phys. Rev. Lett.* **109**, 183602 (2012).
20. S. Diehl *et al.*, *Nat. Phys.* **4**, 878 (2008).
21. J. T. Barreiro *et al.*, *Nature* **470**, 486 (2011).
22. P. Schindler *et al.*, *Science* **332**, 1059 (2011).
23. M. D. Reed *et al.*, *Nature* **482**, 382 (2012).
24. D. Ristè, C. C. Bultink, K. W. Lehnert, L. DiCarlo, *Phys. Rev. Lett.* **109**, 240502 (2013).
25. P. Campagne-Ibarq *et al.*, http://arxiv.org/abs/1301.6095 (2013).
26. J. Preskill, http://arxiv.org/abs/quant-ph/9712048 (1997).
27. M. H. Devoret, in *Quantum Fluctuations*, S. Reynaud, E. Giacobino, J. Zinn-Justin, Eds. (Elsevier Science, Amsterdam, 1997).
28. V. Bouchiat, D. Vion, P. Joyez, D. Esteve, M. H. Devoret, *Phys. Scr.* **1998**, 165 (1998).
29. Y. Nakamura, Yu. A. Pashkin, J. S. Tsai, *Nature* **398**, 786 (1999).
30. J. E. Mooij *et al.*, *Science* **285**, 1036 (1999).
31. C. H. van der Wal *et al.*, *Science* **290**, 773 (2000).
32. J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo, J. E. Lukens, *Nature* **406**, 43 (2000).
33. I. Chiorescu, Y. Nakamura, C. J. Harmans, J. E. Mooij, *Science* **299**, 1869 (2003).
34. J. M. Martinis, S. Nam, J. Aumentado, C. Urbina, *Phys. Rev. Lett.* **89**, 117901 (2002).
35. J. Martinis, *Quant. Inf. Proc.* **8**, 81 (2009).
36. A. Cottet *et al.*, *Physica C* **367**, 197 (2002).
37. D. Vion *et al.*, *Science* **296**, 886 (2002).
38. J. Koch *et al.*, *Phys. Rev. A* **76**, 042319 (2007).
39. A. A. Houck *et al.*, *Phys. Rev. Lett.* **101**, 080502 (2008).
40. V. E. Manucharyan, J. Koch, L. I. Glazman, M. H. Devoret, *Science* **326**, 113 (2009).
41. M. Steffen *et al.*, *Phys. Rev. Lett.* **105**, 100502 (2010).
42. S. E. Nigg *et al.*, *Phys. Rev. Lett.* **108**, 240502 (2012).
43. H. Paik *et al.*, *Phys. Rev. Lett.* **107**, 240501 (2011).
44. A. Wallraff *et al.*, *Nature* **431**, 162 (2004).
45. A. Megrant *et al.*, *Appl. Phys. Lett.* **100**, 113510 (2012).
46. J. Bylander *et al.*, *Nat. Phys.* **7**, 565 (2011).
47. Z. Kim *et al.*, *Phys. Rev. Lett.* **106**, 120501 (2011).
48. A. Palacios-Laloy *et al.*, *Nat. Phys.* **6**, 442 (2010).
49. R. Vijay, D. H. Slichter, I. Siddiqi, *Phys. Rev. Lett.* **106**, 110502 (2011).
50. L. M. Duan, B. B. Blinov, D. L. Moehring, C. Monroe, *Quantum Inf. Comput.* **4**, 165 (2004).
51. M. Hatridge *et al.*, *Science* **339**, 178 (2013).
52. D. Bintley *et al.*, *Proc. SPIE* **8452**, 845208 (2012).
53. J. Zmuidzinas, *Annu. Rev. Condens. Matter Phys.* **3**, 169 (2012).
54. J. Jones, NMR Quantum Computation (nmr.physics.ox.ac.uk/pdfs/lhnmrqc.pdf).
55. M. P. da Silva, O. Landon-Cardinal, D. Poulin, *Phys. Rev. Lett.* **107**, 210404 (2011).
56. S. Bravyi, A. Yu. Kitaev, *Quantum Computers Comput.* **2**, 43 (2001).
57. M. H. Freedman, D. A. Meyer, *Found. Comput. Math.* **1**, 325 (2001).
58. A. G. Fowler, M. Mariantoni, J. M. Martinis, A. N. Cleland, *Phys. Rev. A* **86**, 032324 (2012).
59. S. Haroche, J. M. Raimond, *Exploring the Quantum: Atoms, Cavities, and Photons* (Oxford Univ. Press, Oxford, 2006).
60. C. Eichler *et al.*, *Phys. Rev. Lett.* **106**, 220503 (2011).
61. M. Mariantoni *et al.*, *Nat. Phys.* **7**, 287 (2011).
62. Z. Leghtas *et al.*, http://arxiv.org/abs/1207.0679.
63. Y. Nakamura, Y. A. Pashkin, T. Yamamoto, J. S. Tsai, *Phys. Rev. Lett.* **88**, 047901 (2002).
64. A. Sears *et al.*, *Phys. Rev. B* **86**, 180504 (2012).
65. C. Rigetti *et al.*, *Phys. Rev. B* **86**, 100506 (2012).
66. M. Reagor *et al.*, http://arxiv.org/abs/1302.4408 (2013).
67. S. Kuhr *et al.*, *Appl. Phys. Lett.* **90**, 164101 (2007).
68. A. Wallraff *et al.*, *Phys. Rev. Lett.* **95**, 060501 (2005).
69. E. Magesan *et al.*, *Phys. Rev. Lett.* **109**, 080505 (2012).
70. E. Lucero *et al.*, *Phys. Rev. Lett.* **100**, 247001 (2008).
71. J. M. Chow *et al.*, *Phys. Rev. Lett.* **109**, 060501 (2012).

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REVIEW

Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors

David D. Awschalom,[1]* Lee C. Bassett,[1] Andrew S. Dzurak,[2] Evelyn L. Hu,[3] Jason R. Petta[4]

The past decade has seen remarkable progress in isolating and controlling quantum coherence using charges and spins in semiconductors. Quantum control has been established at room temperature, and electron spin coherence times now exceed several seconds, a nine–order-of-magnitude increase in coherence compared with the first semiconductor qubits. These coherence times rival those traditionally found only in atomic systems, ushering in a new era of ultracoherent spintronics. We review recent advances in quantum measurements, coherent control, and the generation of entangled states and describe some of the challenges that remain for processing quantum information with spins in semiconductors.

In a marriage of quantum physics, information theory, and nanoscale engineering, quantum information science endeavors to build machines that can use the power of quantum mechanics for practical purposes. Such machines have great potential, including cryptography guaranteed by the laws of physics, quantum-enhanced sensing and imaging technology, and quantum computers able to crack problems inaccessible to even the most powerful classical computers of the foreseeable future.

The complexity of building quantum machines is a fantastic challenge, and recent years have seen a vast array of proposals for quantum information processing in diverse systems. Although specific requirements vary considerably, there are a few generalized prerequisites for quantum computers (*1*). The target quantum system must be controllable, in the sense that it can be initialized, manipulated, and read out to achieve a computation; it must be correctable, such that unavoidable errors can be detected and compensated; and it must be scalable, such that a linear increase in the effective size of the system—corresponding to an exponential increase in computing power—does not require an exponential increase of resources. The first two requirements require some degree of isolation of the quantum system from its environment, to keep quantum information from "leaking away" (decohering) at a rate faster than the computation is achieved. Because no system is entirely free of decoherence, the goal of most approaches is to balance the need for isolation with the ability to accurately and quickly control the system, ideally in architectures with potential for scaling to larger systems once the fundamentals are established.

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Nature's own atoms and ions, isolated in vacuum, served as the first quantum information test beds, with many groundbreaking experiments in atomic and optical physics demonstrating exquisite control of individual quantum systems. Inspired by this success, solid-state physicists have recently developed a wide array of "designer atoms" based on semiconductor nanostructures whose quantum states can also be coherently controlled (*2*). The spins of individual electrons and nuclei, in particular, offer a promising combination of environmental isolation and controllability, with wide flexibility in terms of materials and design. Furthermore, solid-state technologies offer the promise of large-scale integration using fabrication processes developed by the semiconductor industry (*3*). Approaches are markedly varied, employing different materials, temperatures, device structures, and both electrical and optical measurements. We focus on several key advances of the past few years in controlling quantum coherence and entanglement in several semiconductor architectures, and outline the major challenges and goals ahead.

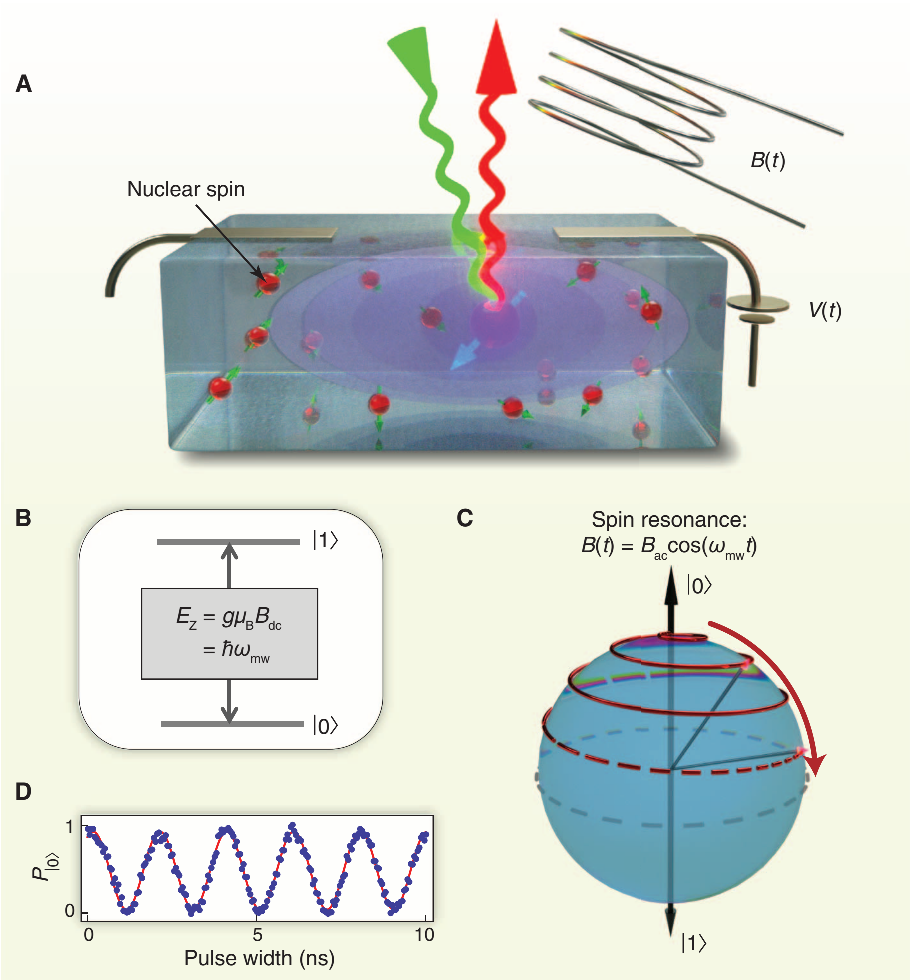

Fig. 1. (**A**) Single electron spins (blue arrow) can be confined in solid-state systems and manipulated with various "control knobs," including gate voltages [$V(t)$], microwave magnetic fields [$B(t)$], and light (green and red wiggly arrows). Quantum coherence is lost (fading purple cloud) through interactions with the local environment of, for example, nuclear spins (green arrows), phonons, or leaky mirrors in a cavity. Recent advances in materials science have made it possible to achieve electron spin coherence times up to several seconds (*15*), rivaling those traditionally found only in atomic systems. (**B**) A single electron spin placed in a dc magnetic field, B_{dc}, forms a quantum bit with states $|0\rangle$ and $|1\rangle$ corresponding to parallel and antiparallel spin alignment to the field, split by the Zeeman energy E_Z. (**C**) The application of an oscillating magnetic field $B(t)$ perpendicular to B_{dc} and resonant with the Zeeman energy causes the qubit to oscillate between states $|0\rangle$ and $|1\rangle$ at the Rabi frequency (changing the qubit amplitude, θ), while the phase ϕ accumulates due to precession in B_{dc}. (**D**) Rabi nutations of a single electronic spin in diamond, measured optically, showing the probability to measure the state $|0\rangle$ as a function of the width of an ac magnetic field pulse. Conventional electron spin resonance has focused on the dynamics of large ensembles of $\gtrsim 10^{15}$ spins; it has recently become possible to coherently control single-spin dynamics. [Originally published in (*60*) and adapted with permission]

Spin Qubits for Computation

The spin carried by a single electron is a prototypical quantum bit, or qubit (Fig. 1A). In an external magnetic field, B_{dc}, the spin's energy levels are quantized into states where the magnetic moment points either parallel or antiparallel to the magnetic field. These two states are separated by the Zeeman energy, $E_Z = g\mu_B B_{dc}$, where g is the Landé g factor and μ_B is the Bohr magneton (Fig. 1B). By identifying one spin orientation as "0" and the other as "1," spins can serve as the logical elements for Boolean computation. Even as classical bits, spins offer advantages over today's charge-based microprocessors and form the basis for emerging technologies termed spintronics. The more ambitious goal of building a spin-based quantum computer requires not only manipulation of the spin eigenstates $|0\rangle$ and $|1\rangle$ but also coherent superpositions of the form $|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$, where both the amplitude, θ, and the phase, ϕ, must be controlled with high precision. Most challengingly, quantum computing requires the creation and coherent control of nonclassical correlations—i.e., entanglement—between distinct qubits in the device and preservation of these fragile many-body states on time scales long enough to perform calculations. At the few-qubit level, both of these goals have been met in recent years.

As qubits, spins in semiconductors have distinct technical advantages. Host-dependent band structure and spin-orbit interactions imprint critical characteristics on spins in different materials, providing widely tunable qubit properties. Particularly in materials where spin-orbit coupling is weak, spins are relatively insensitive to many sources of decoherence in solid-state systems, including electrical noise and thermal vibrations of the semiconductor lattice. Furthermore, experimental methods for coherent control of single-spin qubit states are now established (Fig. 1C), building on decades of research in magnetic resonance. Figure 2 shows examples of four types of spin qubits featured in current research. Despite vastly different methods for production and individual advantages and challenges of the different systems, coherent quantum control of individual qubits has been demonstrated in all cases, and in several systems entangled multiqubit devices have been realized in recent years.

Following a proposal based on spins in quantum dots (*4*), the first semiconductor qubits were based on group III/V materials (*5*), taking advantage of the well-developed growth of ultrapure GaAs/AlGaAs heterostructures. Heterostructures provide the means to confine electrons and/or holes into reduced dimensions, to the ultimate limit of a zero-dimensional "box"—a quantum dot (QD)—containing a single spin. QDs can be formed either through top-down approaches in which nanofabricated surface electrodes deplete charges from a buried two-dimensional electron gas (Fig. 2A) or through bottom-up growth techniques in which small islands of a III/V alloy, typically InAs, self-assemble on a GaAs surface (Fig. 2B).

The small magnetic moment of the electron renders it highly insensitive to the local environment, leading to long spin coherence times. At the same time, however, rapid spin control using conventional electron spin resonance requires large ac magnetic field amplitudes that are difficult to produce in cryogenic environments. Qubit selectivity is also exacerbated in nanoscale devices (Fig. 2A), where each spin needs to be individually controlled without disturbing its nearest neighbors only ≈50 nm away. Two approaches have been developed to circumvent these challenges. The first is to use quantum interference of two-electron spin states for rapid quantum control. By rapidly tuning through an avoided crossing in the energy-level diagram, two electrons in a correlated (e.g., singlet) state can be "split" and then recombined after a free evolution time, enabling nanosecond spin rotations without the application of an electron spin resonance field (*6*). Another approach to single-spin control harnesses the strong spin-orbit interactions intrinsic to materials such as InAs and InSb. With such "spin-orbit qubits," it is possible to perform spin rotations using electric rather than magnetic fields, which are easier to generate and localize in a device (*7*).

Self-assembled QDs in III/V materials confine both electrons and holes and can therefore support optical transitions between a ground-state spin qubit configuration (e.g., a single electron or hole) and optically excited "excitons" with additional bound electron-hole pairs. Strong spin-orbit interactions give rise to optical transitions with strict spin- and polarization-dependent selection rules, and relatively large optical dipole moments (compared with atoms) make these transitions highly efficient. These key features enable coherent optical control of the QD spin state using ultrafast (picosecond-scale) pulses of light (*8*, *9*) and the generation of entanglement between the qubit spin state and a single photon emitted by the QD (*10*, *11*). Such light-matter coupling is the key to building distributed networks of qubit nodes with coherent information transfer mediated by photons.

Only a few years ago, the intrinsic "spin bath" of host nuclear spins in III/V materials was the primary impediment to achieving long spin coherence times in these systems. This problem has been practically solved through the use of dynamical decoupling protocols that can extend the useful coherence time by orders of magnitude (*12*–*14*). Still, it helps to remove as many potential noise sources as possible. Group IV semiconductors can be isotopically purified to provide a nearly spin-free environment consisting only of spin-zero nuclei such as ^{12}C and ^{28}Si, and weaker spin-orbit coupling than in III/V materials reduce susceptibility to electrical and thermal noise. With recent reports of electron-spin coherence times measured in seconds (*15*) and nuclear spin coherence times of minutes (*16*) for neutral donor atoms in ^{28}Si, for example, these materials are poised to have a major role in coming years.

Silicon, the dominant material used for conventional microprocessor chips, was identified early on as a prime candidate for quantum information processing through several proposals to use the electron and/or nuclear spins of individual donor atoms, particularly phosphorus, as spin qubits (*17*, *18*). The first such single-atom qubit in silicon (Fig. 2C) used the spin of a phosphorus donor electron implanted into a silicon chip as the qubit (*19*). An adjacent metal-oxide-semiconductor–based single-electron transistor implements a spin-to-charge conversion protocol for initialization and readout (*20*) similar to that developed for III/V quantum dots (*21*), and coherent control is achieved through electron spin resonance using an integrated microwave transmission line. Fabricated using a silicon substrate with the natural 4.7% isotopic fraction of ^{29}Si, the spin coherence time of the device in (*19*) was limited by the nuclear spin bath to $T_2 \approx 200$ μs, but it is anticipated that similar devices constructed from isotopically enriched ^{28}Si substrates will open a path to the exceptional coherence times (≈1 s) that have been measured for bulk ^{28}Si:P ensembles (*15*). The device depicted in Fig. 2C has also been used to demonstrate a nuclear spin qubit (*22*) based on the ^{31}P dopant nucleus. These nuclear spins could serve as long-lived quantum memories (*18*) in future quantum processors.

In some ways, dopant-based qubits in silicon represent a powerful combination of both top-down and bottom-up fabrication approaches, because a natural and highly reproducible qubit (a single atom) is controllably placed within a nanofabricated electronic device. At the same

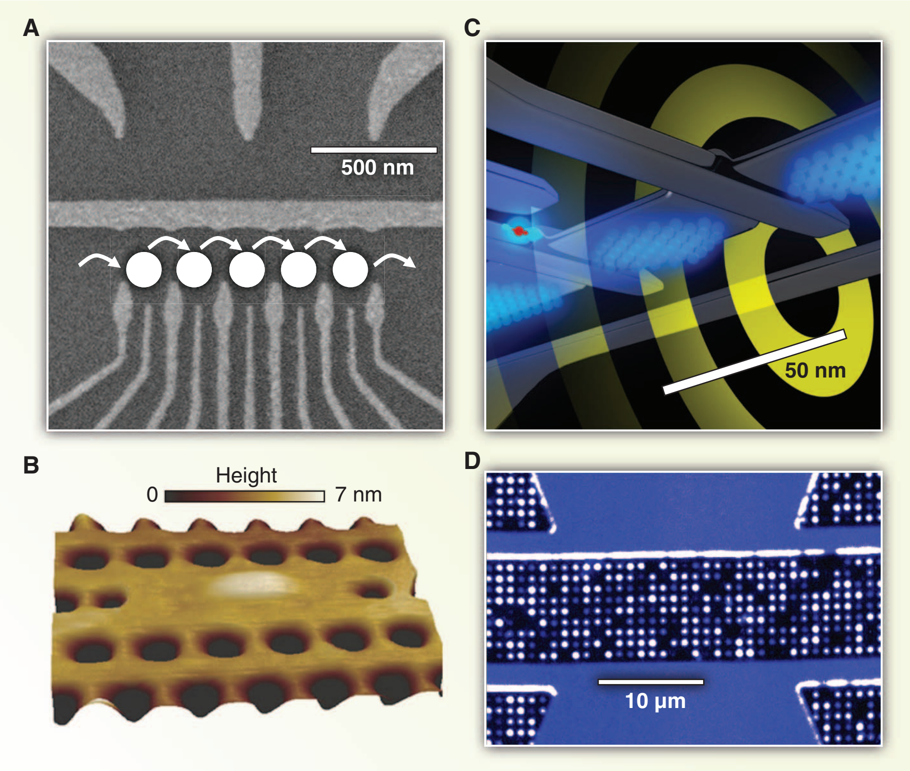

Fig. 2. Semiconductor qubit architectures. (**A**) Scanning electron microscope image of a gate-defined quintuple QD in a GaAs/AlGaAs heterostructure. Each QD is designed to contain one or two electron spins. (**B**) Atomic force microscope image of a single self-assembled InAs QD strongly coupled to a GaAs photonic crystal cavity, which is used to confine photons to small regions of space. Originally published in (*46*) and adapted with permission. (**C**) Schematic of a spin qubit device based on a single phosphorus dopant atom (red) implanted in silicon (*19*). The qubit electron spin is initialized and measured electronically through spin-dependent tunnel coupling to a nanofabricated single-electron transistor (gray) and manipulated using pulsed ac magnetic fields (yellow concentric circles) delivered by an integrated microwave transmission line. Image credit: W. Algar-Chuklin. (**D**) Confocal microscope image showing an array of implanted nitrogen vacancy centers in diamond aligned to a microwave transmission line. [Adapted with permission from (*61*); copyright (2010) American Chemical Society]

time, artificial atoms formed using gate electrodes in analogy with QDs in III/V heterostructures have also met with success (*18*). Coherent oscillations between two-electron singlet and triplet states of a double QD defined in a Si/SiGe heterostructure were demonstrated in 2012 (*23*), in direct analogy with experiments in III/V QDs (*21*). The measured dephasing time $T_2^* \approx 360$ ns was more than an order of magnitude longer than in GaAs thanks to the much weaker hyperfine coupling in natural silicon, and further improvements are expected for devices using isotopically enriched ^{28}Si.

Another group IV material with great promise for quantum information technology is diamond. With its large 5.5 eV band gap, diamond supports a plethora of optically active point defects, many of which are paramagnetic and could therefore serve as spin qubits. The most intensely studied of these is the nitrogen-vacancy (NV) center, consisting of a substitutional nitrogen atom adjacent to a vacancy in the diamond crystal. In its negatively charged ground state, the NV center is an electron spin triplet, and a special set of optical transitions facilitate the initialization and measurement of its spin state simply through optical excitation and fluorescence detection, respectively (*24*). Diamond's unique properties, particularly weak spin-orbit interactions, an extremely high Debye temperature (limiting spin-lattice relaxation), and the large band gap that energetically isolates interband electronic states, endow NV center spins with remarkable coherence properties that persist up to room temperature. Furthermore, isotopic purification of spin-free ^{12}C diamond leads to ultralong coherence times, up to several milliseconds at room temperature (*25*). With on-chip microwave-frequency waveguides enabling quantum control operations on subnanosecond time scales (*26*), more than one million coherent operations can be performed within the NV center's spin coherence time.

A key feature of NV center spin qubits is access not only to the electronic spin state but also to the individual nuclear spins of the intrinsic nitrogen atom and proximal ^{13}C nuclei (*27*). This makes each NV center a small "quantum register" consisting of several individually addressable nuclear spin qubits with exceptional coherence properties that can be initialized (*28*), measured nondestructively in a single shot (*29*), and even entangled (*30*) through their interactions with the electron spin. These nuclear spins could act as operational qubits in their own right, with the electron spins serving as ancillary qubits for initialization and readout, or as integrated quantum memory nodes associated with each electronic spin qubit. A room-temperature quantum memory consisting of a single ^{13}C nucleus weakly coupled to an NV center has been demonstrated with coherence exceeding 1 s (*31*). At temperatures $\lesssim$10 K, coherent optical transitions enable nondestructive single-shot spin measurements (*32*), coherent control (*33*), and spin-photon entanglement (*34*), with promise for integrating distributed NV center nodes within a large-scale optical network.

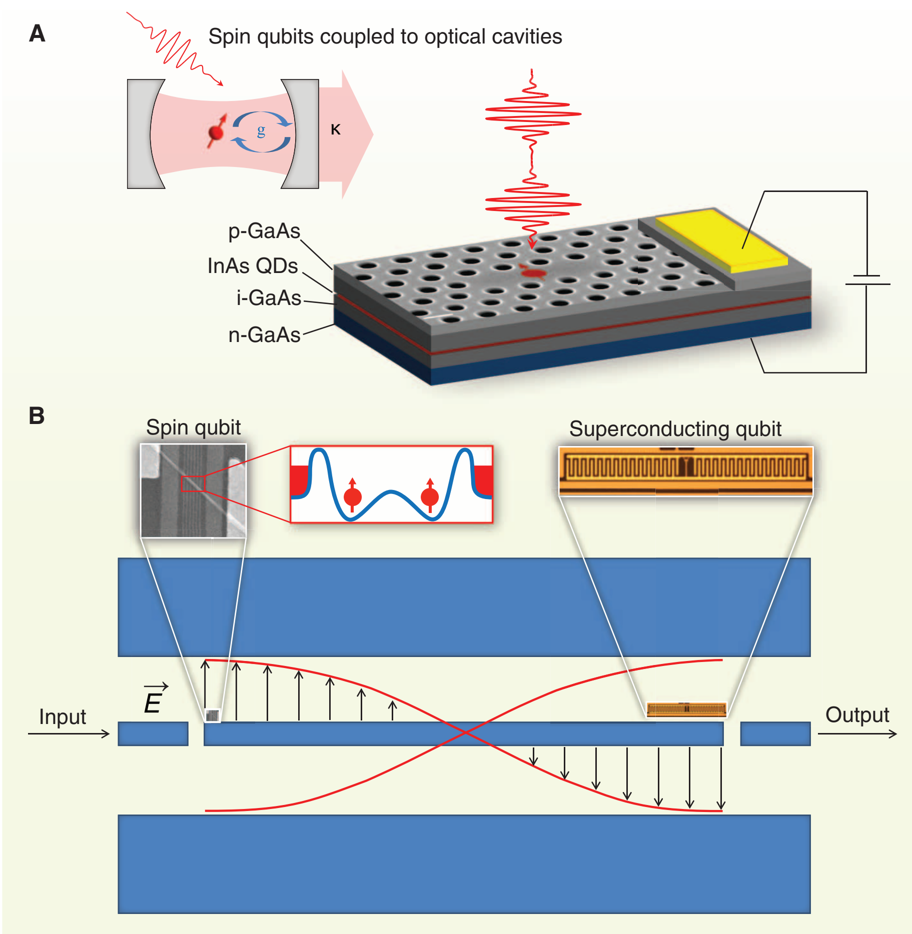

Fig. 3. (**A**) Cavity quantum electrodynamics with optical photons. (Upper left) Schematic of a single spin embedded within an optical cavity. If the qubit-cavity coupling strength, *g*, dominates over both qubit decoherence and the loss rate of photons from the cavity, κ, the system is in the strong coupling regime. (Lower right) Schematic of a photonic crystal cavity integrated with a diode structure used to realize coherent optical control of a cavity-coupled QD spin (*48*). [Image courtesy of D. Gammon, U.S. Naval Research Laboratory] (**B**) Superconducting qubits and spin qubits have quantum transitions in the microelectron volt range, closely matching the energy of microwave photons. This cartoon depicts a circuit quantum electrodynamics architecture that is used to couple a spin qubit to a superconducting qubit via a microwave cavity.

Scalable Architectures

With high-fidelity control of individual spin qubits now routine in many semiconductor systems, solid-state devices are poised to reach their full potential for integration and scalability. Nevertheless, a pressing challenge is the development of a robust two-qubit gate that can be scaled up to link many computational nodes into a larger network. One approach is to fabricate multiple qubits close enough together to use "direct" interactions such as magnetic dipole-dipole or electrostatic coupling to generate an entangling gate—for example, to implement a "surface code" computation using nearest-neighbor interactions only (*35*, *36*). This has been achieved both for pairs of lithographic quantum dot qubits in GaAs (*37*) and for NV center spins (*38*), although in both cases the gate time is rather long, limiting the entanglement fidelity. Furthermore, for applications in quantum communication and distributed quantum computing, it is desirable to be able to implement two-qubit gates between spins that are spatially separated beyond the reach of nearest-neighbor interactions. Such long-range coupling requires a "quantum bus" to transmit quantum information between local nodes. Although ideas exist for using nanomechanical resonators (*39*), "chains" of fixed spins (*40*), or electrons themselves carried by travelling QDs (*41*, *42*) as such a bus, an obvious choice of "flying qubit" to transmit information is the photon.

Photons are an excellent means of linking physical nodes within a network (*43*). They are capable of rapid propagation, low dissipation, and low signal loss via integrated waveguides or fibers leading to or from the outside world. Furthermore, high-quality solid-state optical cavities mediate the coupling strength between spin qubits and photons (*44*), providing tools for photon-based selective readout and state preparation. When a qubit is optimally matched to an optical cavity—in the "strong coupling" regime (Fig. 3A)—the coherent interaction between the qubit and the cavity modes dominates over other, dissipative processes, such as the loss of photons from the cavity or the emission of qubit excitations to competing states. Notably, progress in the design and fabrication of dielectric optical cavities over the past decade has allowed the achievement of strong coupling between microcavities and semiconductor QDs (*45*, *46*). Strongly coupled systems produce entangled qubit-cavity states, such that the resulting photons carry the signature of the quantum state of the qubit, allowing long-distance propagation of that physical state information throughout the network. Although tremendous progress has been made in controlling purely photonic behavior with high-*Q* cavities and optically active QDs (*47*), it has remained a challenge to study cavity-coupled spin qubits. Promisingly, a photonic crystal cavity device integrated with a diode structure (Fig. 3A), necessary to tune the charge state of embedded QDs, has enabled coherent optical control of cavity-coupled spin qubits (*48*).

For "emerging" materials like diamond, where new fabrication techniques are required, cavity coupling to NV centers and other optical qubits still has much room for progress (*49*). Even without well-developed optical cavities, however, photons can still mediate coherent information transfer between distant qubits. A protocol has recently been developed to generate heralded entanglement between two NV center electron spins in separate cryostats 3 m apart (*50*). Using the dc Stark effect to tune the NV center optical transitions (*51*), a pair of indistinguishable photons is prepared, each entangled with their source NV center spins. By performing joint quantum measurements on the photons, the spin-photon entanglement is "swapped" to generate an entangled state of the two spins. Given the ability to initialize, measure, and entangle nuclear spin quantum registers local to each NV center (*28*–*30*), this protocol could enable long-distance quantum teleportation of spin states, quantum repeaters, and extended quantum networks.

Although optically active qubits such as self-assembled QDs and NV centers lend themselves naturally to photonic coupling, electronic qubits can also couple to photons, particularly those in the microwave regime. In fact, typical spin resonance frequencies of electronic spins in moderate magnetic fields are in the gigahertz range, closely matched to existing microwave resonator designs and even superconducting qubit architectures (*52*). A first step toward implementing "circuit quantum electrodynamics" with spin qubits was the recent demonstration of coupling between an InAs spin-orbit qubit and a superconducting resonator (*53*). Superconducting resonators have been effectively used to couple superconducting qubits that are separated by nearly a centimeter (*54*) and could similarly link semiconductor spins either to each other or to superconducting qubits (Fig. 3B).

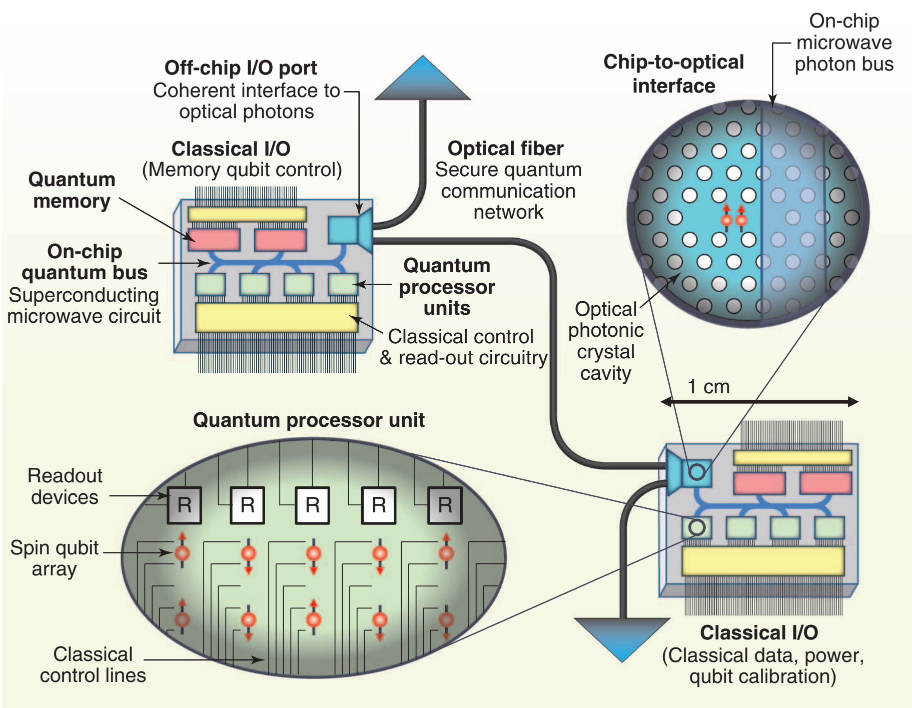

Fig. 4. A future integrated quantum device architecture might consist of quantum processor units comprising arrays of single-spin qubits, locally coupled on-chip using either photonic or microwave cavities. Photonic crystal cavities could be used to interface electron spins with optical photons, allowing long-distance transfer of quantum information via an optical fiber. Quantum memory might be located remotely from the processor units as depicted here or integrated with the processor qubits by using the nuclear spins of individual atoms. Classical circuitry provides qubit readout and calibration.

Outlook

It is tempting to view the wide array of systems under development as a race to find the "optimal" qubit, but this is likely to be the wrong perspective. Each implementation has relative strengths and weaknesses for different applications, and it could well serve to use each to its advantage. Modern computers comprise many types of logical implementations, including transistor logic, data transfer busses, and a large variety of memory nodes optimized either for fast access or long-term storage. A similar hybrid future could be in store for quantum computers, as envisaged in Fig. 4. Computational qubits will be chosen that are fast and easily coupled together, whereas memory nodes should be long lived but each need to be coupled to only one computational node. This might mean that the memory is not physically separated but is instead intrinsic to each computational node, being, for example, the nuclear spin of an NV center in diamond (*55*) or a phosphorus donor in silicon (*22*). Although optical interconnects are likely to serve as ports to transfer quantum information to and from the outside world, on-chip communication could be accomplished through either optical waveguides or superconducting microwave circuitry.

Although many challenges remain on the road to constructing a "useful" quantum computer, the pace of discovery seems to be accelerating, and spins in semiconductors are poised to play a major role. Several materials systems and architectures have already come to fruition, but others waiting in the wings might prove to be even better for some applications. For example, the remarkable properties of the diamond NV center motivates the search for other impurity-based spin systems with similar properties, possibly in more versatile host materials (*56*). Indeed, optically addressable defect spins with room-temperature coherence have recently been discovered in silicon carbide (*57*), which boasts well-developed techniques for heteroepitaxy and fabrication of complex structures. These and other material systems, such as rare-earth ions in crystals (*58*) and II/VI semiconductors (*59*), are likely to be a major focus in coming years.

The breadth of research in solid-state quantum information science is largely what makes the field so exciting. Advances achieved in one system are often directly applicable to many others, and solving the challenges that arise leads to breakthroughs that carry over to other fields of science and engineering. Clearly, the synergies between solid state and atomic physics are accelerating discoveries and demonstrations in both fields. Besides the potential we already recognize for quantum machines, our quest for greater control over quantum systems will surely lead to new materials and applications we have yet to imagine, just as the pioneers of classical computing could not have predicted exactly how the digital revolution has shaped our information age.

References and Notes

1. T. D. Ladd *et al.*, *Nature* **464**, 45 (2010).
2. R. Hanson, D. D. Awschalom, *Nature* **453**, 1043 (2008).
3. G. E. Moore, *Electronics* **38**, 114 (1965).
4. D. Loss, D. P. DiVincenzo, *Phys. Rev. A* **57**, 120 (1998).
5. R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, L. M. K. Vandersypen, *Rev. Mod. Phys.* **79**, 1217 (2007).
6. J. R. Petta, H. Lu, A. C. Gossard, *Science* **327**, 669 (2010).
7. S. Nadj-Perge, S. M. Frolov, E. P. A. M. Bakkers, L. P. Kouwenhoven, *Nature* **468**, 1084 (2010).
8. J. Berezovsky, M. H. Mikkelsen, N. G. Stoltz, L. A. Coldren, D. D. Awschalom, *Science* **320**, 349 (2008).
9. D. Press, T. D. Ladd, B. Zhang, Y. Yamamoto, *Nature* **456**, 218 (2008).
10. W. B. Gao, P. Fallahi, E. Togan, J. Miguel-Sanchez, A. Imamoglu, *Nature* **491**, 426 (2012).
11. K. De Greve *et al.*, *Nature* **491**, 421 (2012).
12. G. de Lange, Z. H. Wang, D. Ristè, V. V. Dobrovitski, R. Hanson, *Science* **330**, 60 (2010).
13. C. A. Ryan, J. S. Hodges, D. G. Cory, *Phys. Rev. Lett.* **105**, 200402 (2010).
14. H. Bluhm *et al.*, *Nat. Phys.* **7**, 109 (2011).
15. A. M. Tyryshkin *et al.*, *Nat. Mater.* **11**, 143 (2011).
16. M. Steger *et al.*, *Science* **336**, 1280 (2012).
17. B. E. Kane, *Nature* **393**, 133 (1998).
18. J. J. L. Morton, D. R. McCamey, M. A. Eriksson, S. A. Lyon, *Nature* **479**, 345 (2011).
19. J. J. Pla *et al.*, *Nature* **489**, 541 (2012).
20. A. Morello *et al.*, *Nature* **467**, 687 (2010).
21. J. R. Petta *et al.*, *Science* **309**, 2180 (2005).
22. J. J. Pla *et al.*, http://arxiv.org/abs/1302.0047.
23. B. M. Maune *et al.*, *Nature* **481**, 344 (2012).
24. F. Jelezko, T. Gaebel, I. Popa, A. Gruber, J. Wrachtrup, *Phys. Rev. Lett.* **92**, 076401 (2004).
25. G. Balasubramanian *et al.*, *Nat. Mater.* **8**, 383 (2009).
26. G. D. Fuchs, V. V. Dobrovitski, D. M. Toyli, F. J. Heremans, D. D. Awschalom, *Science* **326**, 1520 (2009).
27. L. Childress *et al.*, *Science* **314**, 281 (2006).
28. M. V. G. Dutt *et al.*, *Science* **316**, 1312 (2007).
29. P. Neumann *et al.*, *Science* **329**, 542 (2010).
30. W. Pfaff *et al.*, *Nat. Phys.* **9**, 29 (2013).
31. P. C. Maurer *et al.*, *Science* **336**, 1283 (2012).
32. L. Robledo *et al.*, *Nature* **477**, 574 (2011).
33. B. B. Buckley, G. D. Fuchs, L. C. Bassett, D. D. Awschalom, *Science* **330**, 1212 (2010).
34. E. Togan *et al.*, *Nature* **466**, 730 (2010).
35. L. Trifunovic *et al.*, *Phys. Rev. X* **2**, 011006 (2012).
36. R. Raussendorf, J. Harrington, *Phys. Rev. Lett.* **98**, 190504 (2007).
37. M. D. Shulman *et al.*, *Science* **336**, 202 (2012).
38. F. Dolde *et al.*, http://arxiv.org/abs/1212.2804 (2012).
39. P. Rabl *et al.*, *Nat. Phys.* **6**, 602 (2010).
40. S. Bose, *Contemp. Phys.* **48**, 13 (2007).
41. R. P. G. McNeil *et al.*, *Nature* **477**, 439 (2011).
42. S. Hermelin *et al.*, *Nature* **477**, 435 (2011).
43. H. J. Kimble, *Nature* **453**, 1023 (2008).
44. K. J. Vahala, *Nature* **424**, 839 (2003).
45. J. P. Reithmaier *et al.*, *Nature* **432**, 197 (2004).
46. K. Hennessy *et al.*, *Nature* **445**, 896 (2007).
47. I. Fushman *et al.*, *Science* **320**, 769 (2008).
48. S. G. Carter *et al.*, http://arxiv.org/abs/1211.4540 (2012).
49. I. Aharonovich, A. D. Greentree, S. Prawer, *Nat. Photonics* **5**, 397 (2011).
50. H. Bernien *et al.*, http://arxiv.org/abs/1212.6136 (2012).
51. L. C. Bassett, F. J. Heremans, C. G. Yale, B. B. Buckley, D. D. Awschalom, *Phys. Rev. Lett.* **107**, 266403 (2011).
52. A. Wallraff *et al.*, *Nature* **431**, 162 (2004).
53. K. D. Petersson *et al.*, *Nature* **490**, 380 (2012).
54. L. DiCarlo *et al.*, *Nature* **467**, 574 (2010).
55. G. D. Fuchs, G. Burkard, P. V. Klimov, D. D. Awschalom, *Nat. Phys.* **7**, 789 (2011).
56. J. R. Weber *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 8513 (2010).
57. W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, D. D. Awschalom, *Nature* **479**, 84 (2011).
58. R. Kolesov *et al.*, http://arxiv.org/abs/1301.5215 (2013).
59. T. D. Ladd, K. Sanaka, Y. Yamamoto, A. Pawlis, K. Lischka, *Phys. Status Solidi B* **247**, 1543 (2010).
60. G. D. Fuchs *et al.*, *Nat. Phys.* **6**, 668 (2010).
61. D. M. Toyli, C. D. Weis, G. D. Fuchs, T. Schenkel, D. D. Awschalom, *Nano Lett.* **10**, 3168 (2010).

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REVIEW

Topological Quantum Computation—From Basic Concepts to First Experiments

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Quantum computation requires controlled engineering of quantum states to perform tasks that go beyond those possible with classical computers. Topological quantum computation aims to achieve this goal by using non-Abelian quantum phases of matter. Such phases allow for quantum information to be stored and manipulated in a nonlocal manner, which protects it from imperfections in the implemented protocols and from interactions with the environment. Recently, substantial progress in this field has been made on both theoretical and experimental fronts. We review the basic concepts of non-Abelian phases and their topologically protected use in quantum information processing tasks. We discuss different possible realizations of these concepts in experimentally available solid-state systems, including systems hosting Majorana fermions, their recently proposed fractional counterparts, and non-Abelian quantum Hall states.

The principal obstacles on the road to quantum computing are noise and decoherence. By noise, we mean imperfections in the execution of the operations on the qubits (quantum bits). Decoherence arises when the quantum system that encodes the qubits becomes entangled with its environment, which is a bigger, uncontrolled system. There are two approaches to tackling these barriers. One is based on complete isolation of the computer from its environment, careful elimination of noise, and protocols for quantum correction of unavoidable errors. Enormous progress has been achieved in this direction in the past few years. The other approach, which is at the root of topological quantum computation, is very different. It uses a non-Abelian state of matter (*1–10*) to encode and manipulate quantum information in a nonlocal manner. This nonlocality endows the information with immunity to the effects of noise and decoherence (*2–6*).

Non-Abelian States of Matter

Several properties define a non-Abelian state of matter (*1*, *2*, *6–10*). It is a quantum system whose

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