Putting a new spin on quantum-dot qubits

Researchers have shown that the electron spins of interest for quantum computation can be electrically controlled by spin–orbit coupling.

Realizing the potential of quantum computing requires finding viable ways to store and manipulate representations of the binary bits, 0 and 1. The many two-level quantum systems being explored for such qubits include not only the up and down spins of trapped atoms or ions and the polarized states of photons, but also the quantum states of superconducting Josephson junctions and electron spins trapped in quantum dots. A quantum dot is a nanostructure that confines a conduction-band electron in three spatial dimensions.

Quantum-dot qubits take advantage of the extensive experience gained over decades of engineering and manufacturing semiconductor devices. They were proposed[1] in 1998 by Daniel Loss (now at the University of Basel, Switzerland) and David DiVincenzo (RWTH Aachen University). A central challenge is to manipulate the electron spin in a time that's short compared with the time for it to lose coherence, and to do it in a spatially selective way—so that each qubit can be addressed individually. Resonant magnetic fields can flip the spins,[2] but the magnetic fields involved are not very selective spatially. Plus, the time to reverse the spin is too slow except at high field strengths. The experiments also require high frequencies and very low temperatures. "You put all of this together and it makes for a very hard experiment," remarks Jason Petta of Princeton University.

A more desirable approach is to control the spins with just electric fields.[3] Although they can't directly affect an electron's magnetic moment, electric fields can impact it indirectly through the coupling between the electron's orbital motion and its spin. Electrical control of single spins via such spin–orbit coupling was demonstrated three years ago in gallium arsenide quantum dots by Lieven Vandersypen and colleagues at the Delft University of Technology in the Netherlands, but the manipulation times were too slow (about 110 ns for a spin flip) to allow quick and precise control.[4]

By turning to indium arsenide, whose spin–orbit coupling is known to be stronger than that in GaAs,[5] Leo Kouwenhoven and his collaborators at Delft and at the Eindhoven University of Technology have now demonstrated electrical control with spin-flip times of about 8 ns.[6] The experiment was done with quantum dots formed in a one-dimensional wire just 50 to 80 nm in diameter. Using a nanowire may enable experimenters to vary slightly the properties as a function of length. It should also facilitate the interfacing of the InAs with other materials. A more exotic possibility is that InAs nanowires might be used to create the Majorana particles that are of interest for topological quantum computing (see the box on page 20).

David Awschalom of the University of California, Santa Barbara (UCSB) describes the new experiment as "a beautiful demonstration of how coherent quantum states can be electrically manipulated via spin–orbit interactions." He hopes that beyond its applicability to quantum computing, the work will lead to new fundamental studies of quantum spin transport.

A parallel approach to implementing quantum-dot qubits is to couple the

The expanding search for Majorana particles

The reports in this issue about half-quantum vortices in strontium ruthenate (page 17) and about spin–orbit coupling in a nanowire (page 19) both involve a system in which theorists have proposed that one might find an elusive Majorana particle. A system of Majorana particles might be a good candidate for a topological quantum computer.

Before his mysterious disappearance in 1938, the young Italian theorist Ettore Majorana had modified Dirac's equations for spin-½ particles such as electrons and holes. In Majorana's modification, the creation and annihilation operators for particles are self conjugate and the resulting Majorana particles are their own antiparticles. To date, no one has identified a physical realization of those exotic objects, although neutrinos are leading candidates.[1] Others include supersymmetric partners of known bosons and constituents of dark matter.

Recently the search has broadened to include a number of solid-state systems. Some theorists have predicted that Majorana particles might emerge as composite particles, or quasiparticles, in interacting systems. Majoranas constitute a subset of the broader category of non-abelian particles that lie at the heart of topological computational schemes. As its name implies, topological computing expects to encode information not in individual particles but in the collective degrees of freedom of the particles, which depend on their physical arrangement on a surface. The hope is that such a scheme will be largely immune to perturbations from the local environment. Local interactions might distort the collective quantum state, much as one might stretch or skew a sheet of rubber, but the state's coherence should not be lost. (See Physics Today, October 2005, page 21.)

Non-abelian particles do not obey the conventional statistics that define fermions and bosons. When one interchanges identical bosons, the wavefunction is unchanged. For fermions, it reverses sign. For abelian particles known as anyons, the exchange produces a phase that can assume any value. For non-abelian particles, however, the exchange takes the entire ground state into another of a set of *n* degenerate ground states, or a superposition of them. Imagine then representing a system of non-abelian particles by an *n*-dimensional vector whose components are the amplitudes for being in a given degenerate ground state. Moving from one state of the system to another (by exchanging two particles, for example) is equivalent to a matrix multiplication. In a non-abelian system, those matrices don't commute. That's precisely the property required for topological computing. If the matrices did commute, the logical operations would be too simple and they would not lend themselves to quantum computing.

The fractional quantum Hall (FQH) state, which has been a strong focus of the topological computation effort, manifests collective interactions whose excitations are composite fermions with fractional charges. However, only the FQH state with filling factor of 5/2 is expected to be a non-abelian system. (See the article by Sankar Das Sarma, Michael Freedman, and Chetan Nayak in Physics Today, July 2006, page 32.)

A decade ago, Nicholas Read and Dmitry Green of Yale University recognized that the wavefunctions for a non-abelian state such as the 5/2 FQH system are formally equivalent to those describing some forms of *p*-wave superconductor, in which electrons are paired in a spin-triplet state.[2] The non-abelian equivalency does not hold for all *p*-wave superconductors, only for chiral superconductors, in which all the electrons orbit each other either clockwise or counterclockwise. That picture of orbiting electrons is reminiscent of the cyclotron motion of electrons about magnetic field lines in the FQH state.

Majorana particles do not lurk in the bulk of the chiral *p*-wave superconductor but rather in the vortices that form when magnetic field lines penetrate the sample. In a quantum computer, the vortices would presumably form the qubits of information. Researchers are exploring whether a strontium ruthenate superconductor might be home to Majorana particles.[3] The observation of half-quantum vortices, reported on page 17, is necessary but not sufficient to establish the existence of a chiral *p*-wave.

Another formula for getting Majorana particles is to sandwich a semiconductor whose conduction electrons manifest strong spin–orbit coupling between a ferromagnetic insulator and a conventional superconductor.[4] The latter induces superconductivity in the semiconductor through the proximity effect. The interplay of spin–orbit coupling and magnetic field ensure that any induced superconductivity is *p*-wave and chiral.[5,6] A simplification of that arrangement[7,8] involves the indium arsenide nanowires described on page 19.

Yet another variant of these proposals for a heterostructure, which chronologically preceded them, is to interface conventional superconductors with topological insulators.[4] The latter are solids in which there is no charge conduction in the bulk but only on the surface. (See the article by Xiao-Liang Qi and Shou-Cheng Zhang in Physics Today, January 2010, page 33.)

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spins on neighboring dots, thereby forming two-electron spin states. The qubit then consists of a double quantum dot, whose quantum state—singlet or triplet—can be rapidly controlled by voltage pulses[7] (see Physics Today, March 2006, page 16). Last year Princeton's Petta, along with Hong Lu and Art Gossard of UCSB, introduced a technique that enables control of a spin state as fast as 1.5 ns.[8] In addition, Amir Yacoby and his collaborators at Harvard University and at the Weizmann Institute of Science in Rehovot, Israel, have demonstrated techniques to extend the decoherence times for double quantum-dot qubits[9] to values as long as 200 μs. Charles Marcus and his colleagues at Harvard and at UCSB reported similar results.[10]

Nanowire qubits

The device built by Kouwenhoven and his team is shown in figure 1a. The electrostatic potentials on five electric gates below the nanowire define two quantum dots, as shown in figures 1b and 1c. One dot is the qubit; the other is used for reading out the state of the qubit. The qubit operation scheme is depicted schematically in figure 1c. To initialize the information, the potentials are adjusted so that electrons can flow from one quantum dot to the next, but they do so one at a time and only if consecutive electrons have opposite spins.

Thanks to the Pauli exclusion principle, current stops when the spins of electrons on the two dots are parallel. During manipulation of the quantum information, the potential of the qubit is reduced, and the charge blockade prevents electrons from escaping. To read out the final state of the qubit, electrons are again allowed to flow. The presence or absence of current signals tells experimenters whether the qubit spin ended up antiparallel or parallel to the readout spin.

To understand the spin–orbit coupling used to manipulate the qubit spin, consider an electron moving in the electric field of the positively charged nuclei in the semiconductor. In its rest frame, the electron experiences not only an electric field from those charges but also a magnetic field, which interacts with the electron's magnetic moment, or spin. The experimenters exploit that coupling by applying a 13-GHz microwave field to electrode 4 to move the electron slightly back and forth with a frequency on resonance with the spin-precession frequency.

To demonstrate that spin–orbit coupling allows coherent spin control, Kouwenhoven and his collaborators measured the current through the coupled quantum dots as a function of the burst time for the oscillating field. The current varies cyclically as the spin changes its orientation, resulting in the so-called Rabi oscillations seen in figure 2. The experimenters could resolve at least five cycles before decoherence excessively damped the signal. Each half cycle represents a spin flip. The shortest cycle, corresponding to a frequency of 60 MHz, was obtained at the highest microwave power.

One disappointment of the InAs nanowire qubit is the short spin decoherence time. Decoherence most likely results from the interaction of the electron spins with the magnetic field of the randomly oriented nuclear spins. Fluctuating nuclear spins produce a shift in the precession frequency and in the resonance condition of the electron spin. Because measurements of Rabi oscillations are averaged in time over a million single-spin measurements, the qubit rotates by a slightly different angle each measurement, thereby causing the apparent decoherence—that is, the washing out of the Rabi oscillations.

To partially reverse its effect, researchers have borrowed the spin-echo technique from nuclear magnetic resonance: First they allow the spins to evolve freely for a period of time T. They then apply a pulse of just the right duration to flip the spins and wait another time period of T before reading out the qubit. The effect of the field on the flipped spins in the second period acts to cancel the decoherence that occurred during the first.

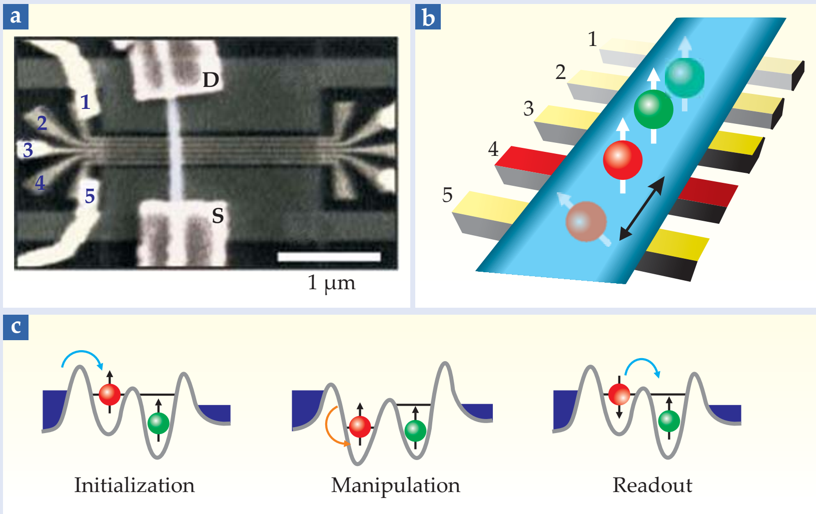

Figure 1. Nanowire qubits. (a) This scanning electron microscope image shows the nanowire coupled to source (S) and drain (D) electrodes and lying atop five narrow electrical gates. **(b)** Voltages applied to the gates define two quantum dots: a qubit (red) and a readout dot (green). A microwave pulse oscillates the qubit (dark and lighter red) and controls its spin via spin–orbit coupling. **(c)** During initialization, electrons hop between adjacent dots (blue arrow) only until the two spins are parallel. During manipulation of its spin (yellow arrow), the qubit is isolated by a potential barrier. During readout, the current flows only when the two spins are antiparallel. (Adapted from ref. 6.)

By repeated application of the spin-echo technique to the InAs nanowire qubits, the Delft–Eindhoven collaborators were able to extend the decoherence time to nearly 200 ns. That is still orders of magnitude below the 270 μs times measured in GaAs singlet–triplet qubits using multiple-pulse spin echo techniques.[9] The long time measured in GaAs has been shown to result from the slow dynamics of the nuclear bath and is in quantitative agreement with theoretical predictions.[11] It's not known if the same effect exists in InAs. Kouwenhoven suspects that InAs's shorter decoherence time is related to the larger nuclear spin of indium compared with gallium or arsenic.

Flexibility of nanowires

One reason for interest in the recent Delft–Eindhoven work is the possibility of combining different semiconductor materials in the same nanowire. Kouwenhoven points out this should be

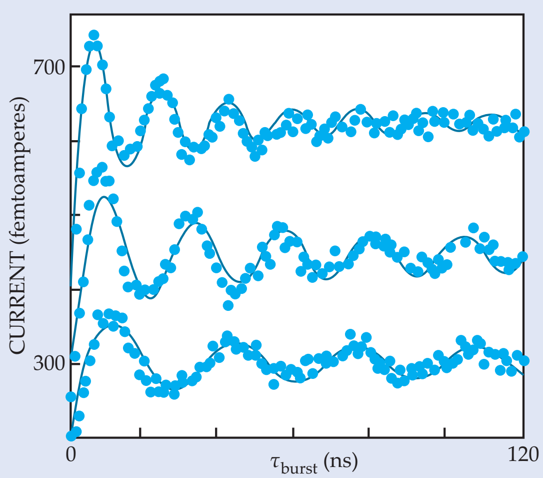

Figure 2. Oscillations of the qubit spin plotted as a function of the duration of the microwave burst, τ_{burst}, for three different values of microwave power, offset for clarity. Top curve corresponds to the highest power. Each cycle represents the rotation of the qubit spin through 360°. A spin flip takes about 8 ns. (Adapted from ref. 6.)

much easier in nanowires because you don't have the same strain due to lattice mismatch that arises on a 2D surface. For example, one might mate InAs with nuclear-spin-free silicon so that qubits can still be manipulated using the strong spin–orbit coupling of InAs while being stored in silicon, where they survive far longer. Another possibility is to create an optoelectronic device to convert the spin state to a photon for long-distance transportation of quantum information.

Experimenters might also be able to tailor the composition of the nanowire as a function of its length: By causing each qubit to experience a slightly different Zeeman splitting (via a difference in gyromagnetic ratios between adjacent dots), they could address each one more precisely.

Sankar Das Sarma of the University of Maryland is especially excited about InAs nanowires as a possible new approach to topological computation (see the box). The basic element of a topological computer is a non-abelian quasiparticle that does not obey the same symmetry rules as fermions or bosons under exchange of identical particles (see the article by Das Sarma, Michael Freedman, and Chetan Nayak in PHYSICS TODAY, July 2006, page 32). Das Sarma is among those who have proposed that a non-abelian particle known as a Majorana fermion might arise from spin–orbit coupling in a semiconductor, if that semiconductor is placed in a magnetic field in the proximity of a conventional superconductor.

It's certainly too early to pick a winner in the competition for the elements of a quantum computer. Perhaps a combination of approaches will be the best answer to the challenges of quantum computation.

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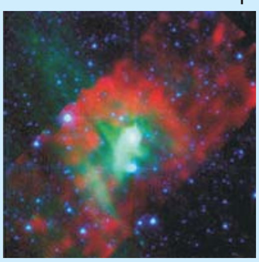
physics update

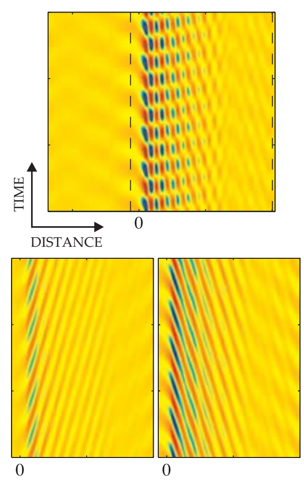
These items, with supplementary material, first appeared at http://www.physicstoday.org.

A standard candle slowly burns down. Cepheid stars are remarkable beacons. Each pulses with a regular frequency related to its intrinsic brightness. An astronomer can therefore determine the distance to a Cepheid by comparing its observed and intrinsic luminosities. Cepheids, in turn, calibrate other classes of



luminosity-signaling standard candles that can be viewed from farther away. Iterating the process yields a cosmic distance ladder that enables distance estimation across the cosmos. Astronomers had long thought the behavior of Cepheids was unchanging, but Pauline Barmby of the University of Western Ontario and colleagues now report that of 29 Cepheids that the team studied, about one-fourth are losing mass. As they do so, they shroud themselves with dust that could introduce errors in distance estimations. The figure, from an earlier, related study, shows an IR image obtained with the *Spitzer Space Telescope* of one such star, Delta Cephei. The red region is a shock created as the star plows through interstellar gas and dust. The detailed form of the shock reveals that it was shaped by a stellar wind emanating from Delta Cephei that's a million times stronger than that from our Sun. So, is a lower rung on the cosmic distance ladder rotten, making the ladder itself unreliable? To the contrary, argued team member Massimo Marengo in January at the American Astronomical Society meeting in Seattle. Even with its uncertainties, the Cepheid rung is strong and observations based on the Cepheids remain trustworthy. Furthermore, now that astronomers are gaining a deeper understanding of those stars, they will be able to better determine their brightness and construct an even sturdier ladder. (M. Marengo et al., *Astrophys. J.* **725**, 2392, 2010; P. Barmby et al., *Astron. J.* **141**, 42, 2011.) —SKB

Tabletop measurements of Hawking radiation. Stephen Hawking proposed in 1974 that black holes evaporate. In essence, vacuum fluctuations near a black hole's horizon produce particle–antiparticle pairs. One of each pair falls into the hole while the other escapes. Since the escaping particle has energy, the black hole must lose energy. A blackbody temperature inversely proportional to the black hole's mass can be assigned to the process, yet the temperature is so low—on the order of 100 nK for a solar mass—that the radiation is difficult to observe directly. But William Unruh (University of British Columbia) demonstrated an analogy between the behaviors of waves near the black hole and sound waves in moving fluids. Now, physicists Silke Weinfurtner, Matthew Penrice, and Unruh and engineers Edmund Tedford and Gregory Lawrence at UBC have used another analogous system, surface waves, to study the Hawking process. They put a streamlined object shaped like an airplane wing into a channel of flowing water to create a region of high-velocity flow. Long-wavelength surface waves created downstream could propagate upstream toward that region but were blocked by the obstacle and converted into short-wavelength waves. The figure shows the converted waves (bottom) and the interference between them and the incoming wave (top). The obstacle behaves like a so-called white hole, which, as a time-reversed black hole, lets no radiation in but does let radiation escape. The conversion is the analogue of stimulated emission, and the team's measurements of the amplitudes of the converted waves matched the expected thermal distribution. Moreover, despite the system's nonlinearities, turbulence, and viscosity, and along with prior numerical work by various groups, the new results demonstrate the generic nature of Hawking radiation. (S. Weinfurtner et al., *Phys. Rev. Lett.* **106**, 021302, 2011.)



—RJF