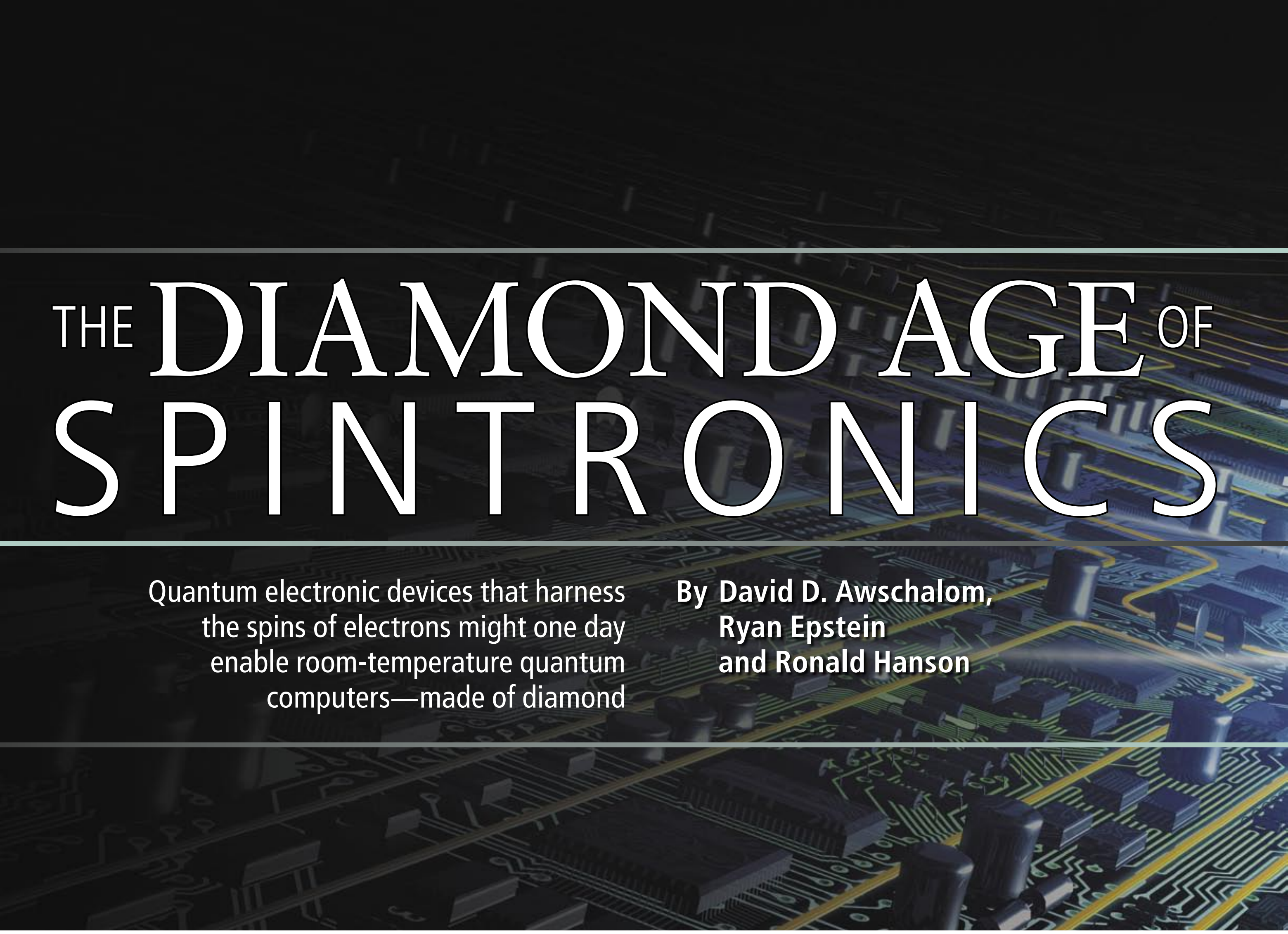


THE DIAMOND AGE OF SPINTRONICS

Quantum electronic devices that harness the spins of electrons might one day enable room-temperature quantum computers—made of diamond

By David D. Awschalom, Ryan Epstein and Ronald Hanson

KEY CONCEPTS

- Electrons carry both charge and spin, but only spintronic devices exploit the two properties simultaneously to achieve innovative capabilities.
- Spintronics brings us disk-drive read heads and nonvolatile memory chips today and perhaps instant-on computers with reconfigurable chips tomorrow.
- Synthetic semiconducting diamond may be the new silicon for a future era of quantum spintronic technology that manipulates single spins, enabling quantum computers and other quantum information devices.

—The Editors

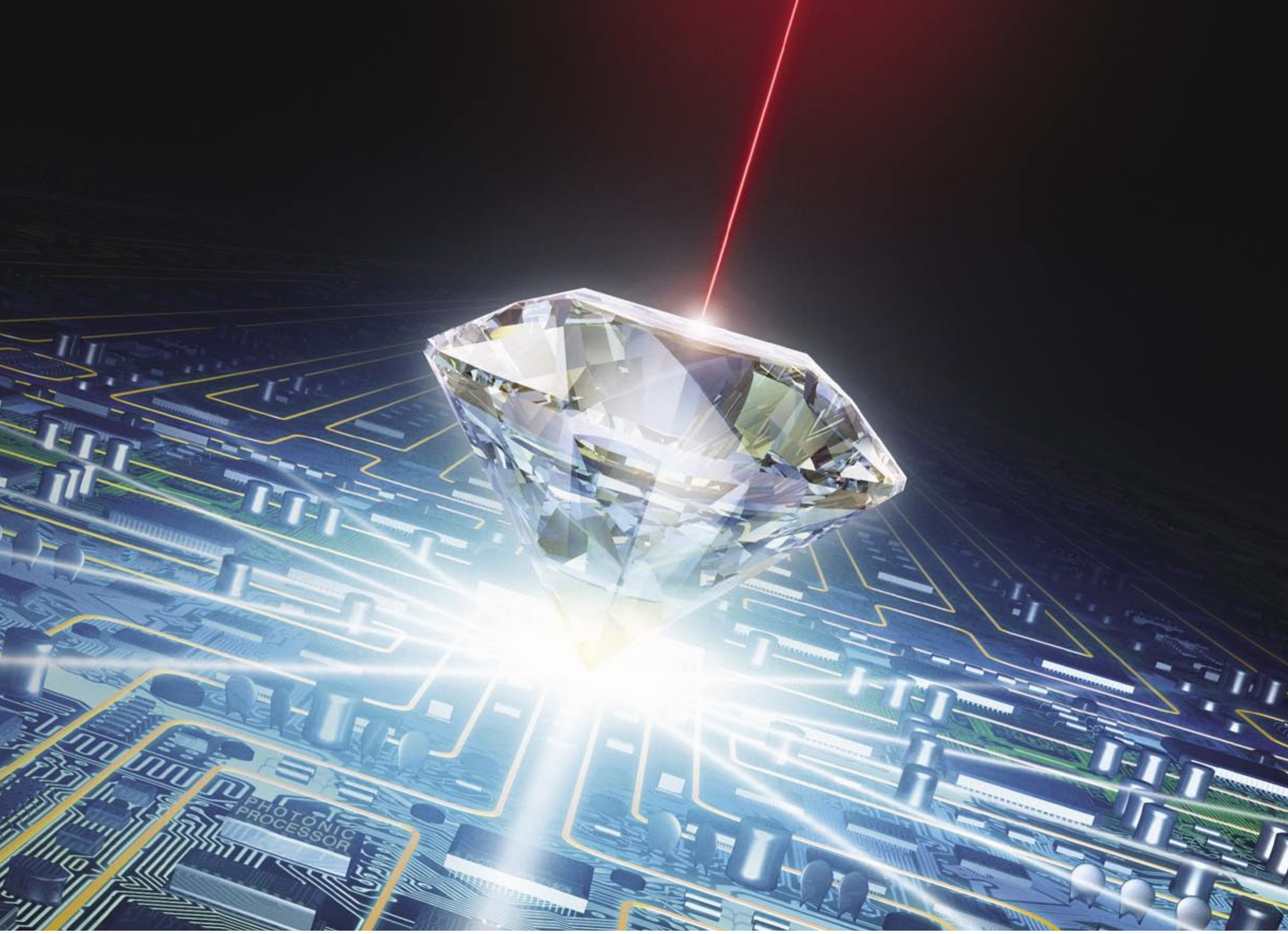
Diamond has a track record of extremes, including ultrahardness, higher thermal conductivity than any other solid material and transparency to ultraviolet light. In addition, diamond has recently become much more attractive for solid-state electronics, with the development of techniques to grow high-purity, single-crystal synthetic diamonds and insert suitable impurities into them (doping). Pure diamond is an electrical insulator, but doped, it can become a semiconductor with exceptional properties. It could be used for detecting ultraviolet light, ultraviolet light-emitting diodes and optics, and high-power microwave electronics. But the application that has many researchers excited is quantum spintronics, which could lead to a practical quantum computer—capable of feats believed impossible for regular computers—and ultrasecure communication.

Spintronics is an advanced form of electronics that harnesses not just the electrical charge of electrons (as in conventional electronics) but also a property called spin that makes electrons act like tiny bar magnets. Your computer probably already contains the first and most rudimentary commercial application of spintronics: since 1998 hard-drive read heads have used a spintronic effect called giant magnetoresistance to detect the microscopic magnetic domains on a disk that represent the 1s and 0s of the data it contains.

Another spintronic device, one that you may find in new computers in the next few years, is magnetoresistive random-access memory (MRAM). As with a hard drive, MRAM stores information as magnetization and therefore is nonvolatile, meaning that the data are not lost when the device's power is turned off. The readout is done electrically, just like any other charge-based memories [see "Spintronics," by David D. Awschalom, Michael E. Flatté and Nitin Samarth; SCIENTIFIC AMERICAN, June 2002]. Freescale Semiconductor, a spin-off of Motorola, began selling the first MRAM in 2006.

Nonvolatile memory chips could lead to computers that will not need to reload programs laboriously from a hard drive every time they are switched on. Instead a computer would be ready within a fraction of a second to proceed from

KENN BROWN



where it left off (much like handhelds today) because all the necessary programming and data would remain ready and waiting in the chip.

More advanced spintronic technologies that are in the early research stages—such as spin transistors, which would make use of spin in controlling current flow—could enable computer chips with logic circuitry capable of being reconfigured on the fly.

Quantum Electronics

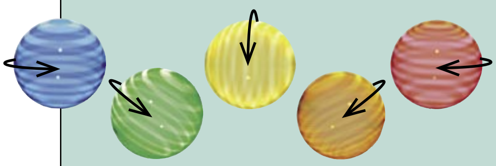
Devices such as read heads and MRAM chips represent one class of spintronics, in which the spins of large numbers of electrons are aligned the same way, as with a collection of toy tops all spinning clockwise on the floor. These so-called spin-polarized electrons typically flow through some part of the device, forming a spin-polarized current, or spin current, that is highly analogous to a polarized beam of light. Researchers have made many exciting advances in this area in the past few years, including discovery of ways to generate and manipulate spin polarization in semiconductors without relying on a magnetic material or relatively bulky wiring to generate a magnetic field. In particular, our group and others have observed a potentially very useful phenomenon called the spin Hall effect [see "Spin Control for the Masses," on page 88].

Much further from store shelves is the second class—quantum spintronics—which involves the manipulation of individual electrons to exploit the quantum properties of spin. Quantum spintronics could provide a practical way to carry out quantum information processing, which replaces the definite 0s and 1s of ordinary computing with quantum bits, or qubits, capable of being 0 and 1 simultaneously, a condition called a quantum superposition [see "Rules for a Complex Quantum World," by Michael A. Nielsen; Scientific American, November 2002].

Quantum computers, if they can be built, would exploit superpositions of qubits to perform a kind of parallel processing that would be extremely effective for certain tasks, such as searching databases and factoring large numbers. Efficient number factoring looms large because it would render obsolete cryptographic

[THE BASICS]

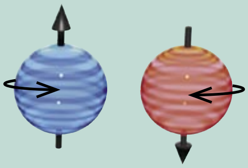
SPIN AND ITS USES



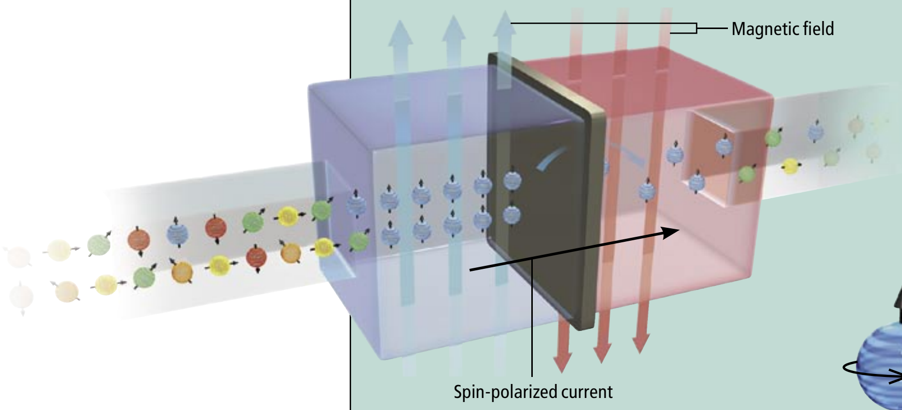
WHAT IS SPIN?

In addition to their mass and electric charge, electrons have an intrinsic quantity of angular momentum called spin, almost as if they were tiny spinning balls.

Scientists represent spin with a vector. For a sphere spinning "west to east," the vector points "north," or "up." It points "down" for the opposite spin.



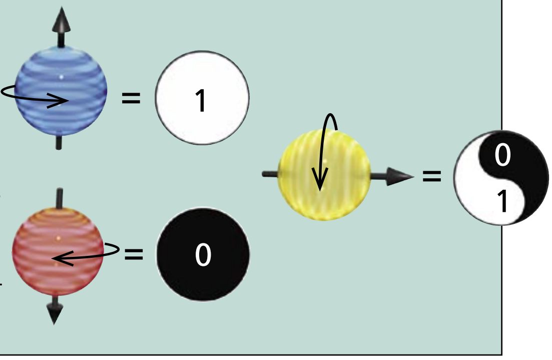
Magnetic tunnel junction



TWO KINDS OF SPINTRONICS

The first class of spintronic devices uses spin-polarized electric currents, in which the electrons have their spins aligned. The earliest of these devices, such as magnetic tunnel junctions (*left*), rely on magnetic fields to polarize the electrons and are already commercially available.

The second class controls individual electrons, using them to represent quantum bits (qubits) and to carry out quantum information processing. If spin "up" is a 1 and spin "down" a 0, a tilted electron spin is a quantum superposition of 0 and 1. These devices all remain highly experimental and include the diamond-based spintronics.



codes that are widely used, including for secure communication over the Internet. Anyone with a large enough working quantum computer (say, an intelligence or law enforcement agency or a corporation) would be able to decode countless formerly secret messages at will.

Perhaps the greatest impact of a future quantum computer will lie in its unique capability to simulate, or model, other quantum systems, a task that current computers are hopelessly bad at. For example, quantum simulations will be required to understand the behavior of matter at the nanometer scale and could therefore bring huge advances in physics, chemistry, materials science and biology.

This exciting prospect has led to a worldwide race to find the most suitable system for storing and processing quantum information. The most advanced quantum information-processing units to date are arguably spins of ions trapped in electromagnetic fields. But these systems have the disadvantages of requiring an ultrahigh vacuum and complex trapping architectures to hold the individual particles in place and isolated from disturbances. Developing chips with large numbers of such traps on them is a major challenge. In contrast, solid-state qubits, which reside directly in a solid substrate, could allow developers to build on decades of experience fabricating semiconductor chips.

Yet many questions have loomed large for researchers hoping to implement solid-state quantum computing: Can spins in solids be individually addressed and controlled? Can scientists come up with suitable interactions to implement quantum logic gates reliably? Can spins in solids maintain quantum information long enough to perform a useful number of operations on that information? In the past few years, all these questions have been answered positively. Surprising-

ILLUSTRATIONS BY JEAN-FRANCOIS PODEVIN

ly, one of the most promising host materials for spins turned out to be diamond.

Glitter of Diamonds

The diamond we use in our experiments looks very different from the sparkling gemstones found in jewelry. Recent advances in materials science make it possible to synthesize thin films of diamond—typically a few hundred nanometers thick over areas as large as many square centimeters—by chemical vapor deposition. In this process, a gas made up of carbon-containing molecules (often methane) and hydrogen is broken down into individual atoms (for example, by high-power microwave radiation), allowing the carbon atoms to deposit on a silicon substrate. The diamond that forms can be extremely pure but often consists of many small crystals, or grains, with grain sizes ranging from nanometers to microns depending on the conditions in the chamber. The best device performance usually comes from using single-crystal diamond, in which diamond's characteristic tetrahedral lattice of carbon atoms is uninterrupted by the disorderly grain boundaries, which degrade the quality of the material for both optics and electronics. The ability to engineer diamond into many forms will likely have a profound effect on electronics, both conventional and quantum.

A key property of diamond for quantum elec-

ENABLED BY SPINTRONICS

Very high densities of data storage on disk drives.

Nonvolatile memory chips.

"Instant-on" computers.

Chips that both store and process data.

Chips operating at higher speeds and consuming less power than conventional ones.

Chips with logic gates that can be reconfigured on the fly.

Quantum cryptography and quantum computing at room temperature.

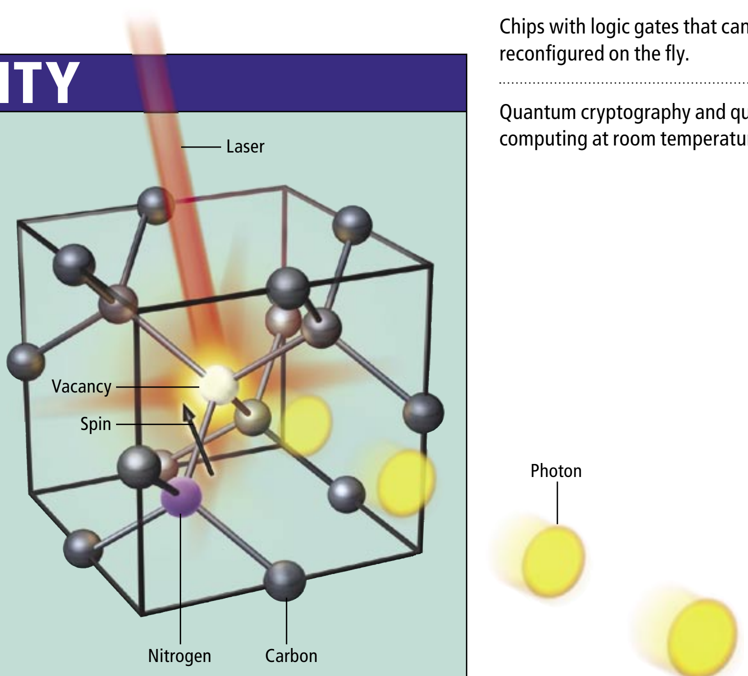
[DIAMOND SPINTRONICS]

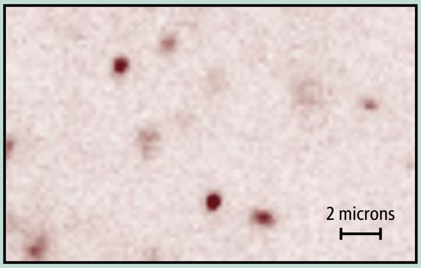
A MAGICAL IMPURITY

As with semiconductors in conventional electronics, the key to making diamond functional for quantum spintronics is doping it with an impurity, in this case a so-called nitrogen-vacancy (N-V) center.

At an N-V center, two adjacent sites in diamond's tetrahedral lattice of carbon atoms are altered. One has a nitrogen atom instead of a carbon, and the other has an empty space. Electrons orbit in the vacancy and around the adjacent four atoms and carry a spin that quantum applications can exploit.

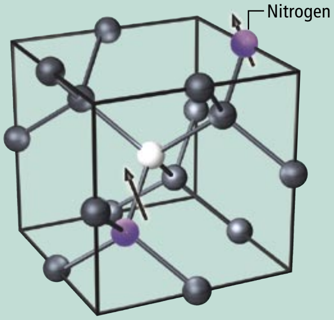
For example, a laser can repeatedly excite an electron at the N-V center, which each time emits a single photon in a specific quantum state when it decays back to its unexcited state. Researchers have used diamond in this way to demonstrate quantum cryptography prototypes, which rely on a steady supply of single photons.





N-V centers in diamond show up as bright spots (*red*) when pumped by a laser. Centers whose spin is in state 1 are much brighter than centers whose spin is in state 0. Radio-frequency waves tuned to a precise frequency change the N-V centers back and forth between 0 and 1, passing through transitional states that are quantum superpositions of the two.

Inserting a second nitrogen atom near the N-V center provides a system of two coupled qubits that enables logic processing. The frequency required to flip the N-V center's qubit is now slightly lower or higher, depending on the state of the second nitrogen. Applying waves at the higher frequency can therefore flip the N-V qubit only if the other qubit is 1. That operation is known as a controlled NOT logic gate, which enables arbitrary quantum computations.



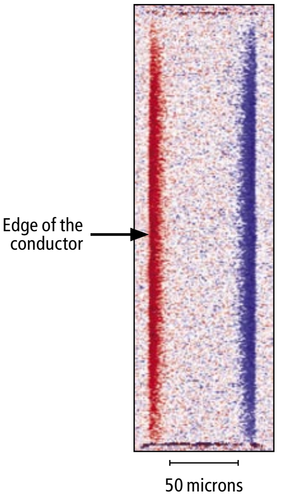
ILLUSTRATIONS BY JEAN-FRANCOIS PODEVIN; DATA BY DAVID D. AWSCHALOM

[SPIN CURRENTS]

SPIN CONTROL FOR THE MASSES

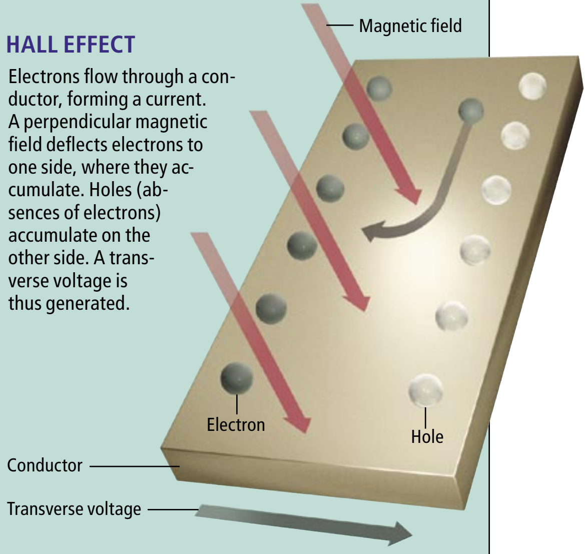
By Yuichiro K. Kato

SPIN HALL EFFECT EXPERIMENTALLY OBSERVED



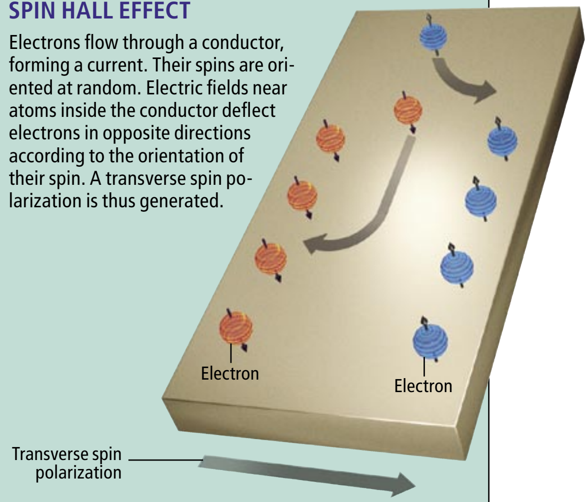
MEASUREMENT made in 2005 detected electrons with opposite spin polarizations (*red, blue*) accumulating at the edges of a conductor that had a current passing through it lengthwise.

HALL EFFECT



Electrons flow through a conductor, forming a current. A perpendicular magnetic field deflects electrons to one side, where they accumulate. Holes (absences of electrons) accumulate on the other side. A transverse voltage is thus generated.

SPIN HALL EFFECT



Electrons flow through a conductor, forming a current. Their spins are oriented at random. Electric fields near atoms inside the conductor deflect electrons in opposite directions according to the orientation of their spin. A transverse spin polarization is thus generated.

Spintronic devices exploit spin, a property of electrons that makes them like tiny bar magnets. There are two classes of such devices—those that manipulate the spins of single electrons [*see main text*] and those that control large groups of spin-polarized electrons flowing en masse in semiconductors (spin currents). Along with working toward single-electron devices, researchers are making exciting discoveries in controlling spin currents.

I was fortunate enough to play a role in these advances while I was a graduate student working in David D. Awschalom's group at the University of California, Santa Barbara, from 2000 to 2005. In particular, we found new ways to generate and manipulate spin polarization. We also observed for the first time a phenomenon called the spin Hall effect, which may provide a way to sort and route electrons based on the direction of their spins.

Because spins behave like tiny magnets, people control them by applying magnetic fields. Producing magnetic fields usually requires magnetic materials or external magnets, however. Instead, using electrical fields might enable smaller, faster spintronic devices that are simpler to fabricate because electric fields are easier to confine to small regions and easier to produce with high frequencies (which enable faster operations). Unfortunately, spins, like all magnets, do not respond to electric fields under normal circumstances.

A relativistic effect comes to the rescue: electrons that move perpendicular to an electric field "see" a weak magnetic field mixed in with the electric one. The magnetic field influences the electron's spin. This interaction is called spin-orbit coupling because physicists first studied it in relation to electrons "orbiting" in the electric field of atomic nuclei.

The Santa Barbara group initially studied this effect in gallium arsenide, a semiconductor commonly used in electronics. We saw that when we moved packets of spin-polarized electrons through this material, the spins rotated as if they were in a magnetic field. The phantom magnetic field could also align the spins of unpolarized electrons.

Spin-orbit coupling also gives rise to the spin Hall effect, which was predicted in 1971 by Michel D'yakonov and Vladimir Perel of the Ioffe Institute in Leningrad. It is named by analogy with the Hall effect (discovered in 1879 by Edwin Hall), in which opposite charges build up on each side of a material that carries a current in a magnetic field (*top right*). In the spin Hall effect, a small spin polarization accumulates on the edges of a material carrying an electric current (*bottom right*), but without requiring a magnetic field. This effect would be another nonmagnetic way to generate spin polarization and to direct electrons according to their spin orientation.

In late 2004 Robert C. Myers (another graduate student), Arthur C. Gossard, Awschalom and I reported seeing the expected spin polarization at the edges of a slab of gallium arsenide chilled to 30 kelvins. A few months later a group led by Jörg Wunderlich at Hitachi Laboratory in Cambridge, England, published observations of the spin Hall effect involving holes (absences of electrons). About a year ago the Awschalom group went on to demonstrate the spin Hall effect at room temperature in the semiconductor zinc selenide.

Taken together, these discoveries offer exciting possibilities for developing spin-based semiconductor technology.

Yuichiro K. Kato is associate professor in the Institute of Engineering Innovation at the University of Tokyo.

ILLUSTRATIONS BY JEAN-FRANCOIS PODEVIN; DATA BY DAVID D. AWSCHALOM

tronics is the large amount of energy needed to dislodge an electron so that it can flow through the material. Physicists visualize the states that electrons can have in a solid as bands of different energy forming a ladder of unevenly spaced rungs. For semiconductors, the two important bands are the valence band, which is the highest band containing electrons, and the empty conduction band just above it, in which electrons can flow freely. The size of the energy gap, or band gap, between these two bands in diamond is 5.5 electron volts, about twice as much energy as present in a visible-light photon and five times as large as the band gap in silicon.

Generally electrons in a semiconductor cannot have an energy that lies in the gap, but impurity atoms added to the material can introduce discrete states in the gap, like additional thin rungs to the ladder. Diamond's gap is big enough that two of these states can differ by an energy as large as that of a visible-light photon. Thus, optical-wavelength light can excite an electron at an impurity atom from one discrete state to another without knocking it all the way to the conduction band. When the electron falls back into its lower energy state, it emits a photon with a frequency corresponding to the energy-level difference—the process commonly known as fluorescence. Under continuous illumination, the optical excitation and relaxation process repeats over and over, and an impurity can emit millions of photons per second. In 1997 a group led by Jörg Wrachtrup, who was then at the University of Technology in Chemnitz, Germany, detected individual impurities in diamond fluorescing in this way, igniting a wave of research in the optical detection of single impurities.

The particular impurity that Wrachtrup's group detected in those first experiments consisted of a nitrogen atom in place of one carbon atom and an adjacent void where another carbon usually would be, which is known as a nitrogen-vacancy (N-V) center. The N-V center in diamond has a number of remarkable properties that make it the favorite subject of research for many groups around the world. Interestingly, the void plays a crucial role: the N-V center is quite different from a single nitrogen atom without a neighboring vacancy. The electrons in the N-V center move in orbits that span the vacancy and its three neighboring carbons and spend only a little time near the nitrogen. Because of these molecularlike orbits, it is convenient to think of the N-V center as being a single impurity rather than a somewhat odd composite of a nitrogen atom and a vacancy.

Single impurities, such as an N-V center, emit one photon at a time—a vital property for the burgeoning field of quantum cryptography [see "Best-Kept Secrets," by Gary Stix; Scientific American, January 2005]. Quantum cryptography systems transmit information in the form of single photons carrying one qubit apiece. The laws of physics guarantee that an eavesdropper cannot intercept the photons without disturbing the qubits in ways that the intended recipient can detect. In 2002 Philippe Grangier and his coworkers at the Institute of Optics in Orsay, France, demonstrated the first quantum cryptography prototype system based on a pulsed source of single photons. This breakthrough relied on having an extremely stable and reliable single-photon source—an N-V center in diamond.

The N-V center electrons also carry a spin state, one which can be polarized conveniently with optical-wavelength light. And whereas other spin systems in the solid state typically must be cooled to very low temperatures to be polarized, the N-V center spin naturally goes into a specific spin state under optical illumination even at room temperature. Furthermore, experimenters soon discovered that one of the spin states fluoresces much more brightly than the others. Thus, fluorescence intensity can be used for spin-state readout—bright for state "1," dim for state "0."

Diamonds Are Forever

During the past few years, our group at the University of California, Santa Barbara, has developed a single-photon imaging technique to observe such individual spins and their orientation in the diamond lattice and to manipulate them. We have thereby studied how single spins interact with their environment—in this case the diamond that surrounds them—a topic of fundamental importance in developing quantum applications. The interactions of the N-V centers with nearby atoms have allowed us to observe so-called dark spins in diamond—impurity nitrogens without an associated vacancy that are invisible to optical detection on their own.

Crucially, as observed in these measurements, spins in diamond are extremely stable against environmental disturbances. Indeed, one of the most exciting aspects of the N-V center is that it exhibits quantum behavior even at room temperature. Quantum phenomena tend to be washed out by thermal excitations, and many solid-state quantum effects require extremely cold temperatures, making them hard to study and

DIAMOND'S MANY FACETS

The name "diamond" derives from the ancient Greek word *adamas*, meaning "invincible."

Diamond is the hardest known naturally occurring substance. The hardest known substance overall is aggregated diamond nanorods, which are 1.11 times as hard as diamond by one measure.

Diamond conducts heat better than any other solid material.

Diamond has a high refractive index (2.4, compared with about 1.5 for glass).

Pure diamond is an electrical insulator (blocking all current flow), but when doped with impurities it can become semiconducting.

Because the energy gap between bound electrons and conduction electrons is large in semiconducting diamond, it is transparent to ultraviolet light and so could be used for ultraviolet detectors and light-emitting diodes. High-power electronics is another application.

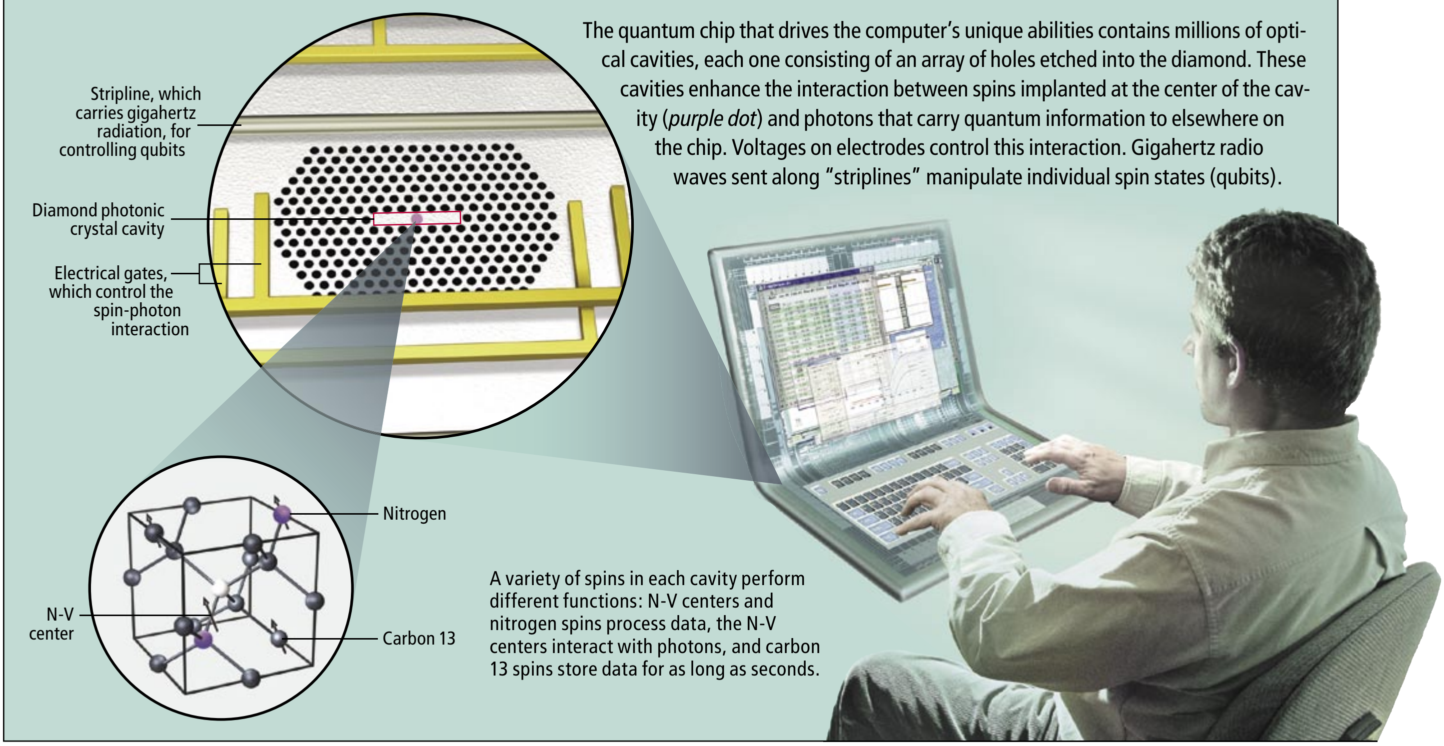
By allowing impurities to be excited without becoming ionized, the large energy gap is one of the keys to the quantum spintronics applications.

Quantum spin states of impurities in diamond can retain their quantum character for usefully long times (about a millisecond), even at room temperature.

[QUANTUM FUTURE]

DIAMOND MICROPROCESSOR

In the future, people wishing to carry out certain specialized tasks may use quantum computers based on diamond spintronics.



The quantum chip that drives the computer's unique abilities contains millions of optical cavities, each one consisting of an array of holes etched into the diamond. These cavities enhance the interaction between spins implanted at the center of the cavity (*purple dot*) and photons that carry quantum information to elsewhere on the chip. Voltages on electrodes control this interaction. Gigahertz radio waves sent along "striplines" manipulate individual spin states (qubits).

A variety of spins in each cavity perform different functions: N-V centers and nitrogen spins process data, the N-V centers interact with photons, and carbon 13 spins store data for as long as seconds.

even harder to turn into practical technology.

In this regard, spins in solid materials typically suffer from two problems. The first is an interaction called spin-orbit coupling, which involves the electron's spin and its orbital motion. The second is magnetic interactions with other spins, such as the spins of the nuclei that make up the lattice. In diamond, both these effects are very weak. For example, the nuclei of carbon 12, which makes up 99 percent of natural carbon, have zero spin and thus no effect on the spin of an N-V center. Because it is so immune to outside disturbances of this kind, the quantum state of the N-V center spin can be used to encode quantum information even at room temperature.

Of course, "immune" is a relative term. The quantum information stored in an N-V center spin state is lost after about one millisecond in high-purity diamond at room temperature. This loss is equivalent to a bit being flipped in a regular computer. As with such errors in ordinary computers, mistakes in qubits can be corrected provided the error rate is low enough. A rule of thumb for quantum error correction is that at most one in 10,000 operations may fail; any more than that and the procedure becomes a losing battle, with the extra data and operations needed to perform the correction themselves introducing too many new errors.

How does the N-V center in diamond measure up against the one-in-10,000 criterion? Radio-frequency radiation guided to the N-V center through on-chip waveguides can deliberately change the N-V center spin within 10 nanoseconds. About 100,000 such operations can occur in the millisecond-long lifetime of the spin's quantum state, and thus the error rate will be very roughly one failure in 100,000 operations. This rate is well below the threshold and is better than any other system of solid-state qubits to date.

Quantum cryptography requires only a sequence of individual qubits, but for quantum computation the qubits must interact to produce new qubits, a process that is analogous to how logic gates process pairs of input bits to produce an output in ordinary computers. For example, an AND gate produces an output of 1 if both inputs are 1 and produces 0 otherwise. Quantum logic gates must do similar operations and must also accept quantum superpositions of bits as inputs and produce superpositions as outputs. The next step toward quantum information processing with impurity spins is controlling the coupling between two spins to perform quantum logic.

➥ MORE TO EXPLORE

A Hall of Spin. Vanessa Sih, Yuichiro Kato and David D. Awschalom in *Physics World,* Vol. 18, pages 33–37; 2005.

Two Groups Observe the Spin Hall Effect in Semiconductors. Charles Day in *Physics Today,* Vol. 58, No. 2, pages 17–19; February 2005.

Challenges for Semiconductor Spintronics. David D. Awschalom and Michael E. Flatté in *Nature Physics,* Vol. 3, pages 153–159; 2007.

Spins in Few-Electron Quantum Dots. R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha and L.M.K. Vandersypen in *Reviews of Modern Physics* (in press).

ILLUSTRATION/PHOTOILLUSTRATION BY JEAN-FRANCOIS PODEVIN

Our group and Wrachtrup's have studied an interaction that could carry out quantum logic by using two spins that are near each other in the diamond lattice. Specifically, we have measured how the spin on an N-V center interacts with another spin on a nearby nitrogen impurity (with no vacancy). The interaction is largely magnetic dipole coupling, essentially the same as the force that makes two macroscopic bar magnets align with north poles facing south poles.

The interaction works as follows. The 0 and 1 states of an N-V center have somewhat different energies. The energy difference, or splitting, between the 0 and the 1 is much smaller than the energy of an optical photon, and instead gigahertz radio waves will drive the spins back and forth between 0 and 1 and superpositions thereof. When the N-V center is close to another nitrogen atom, the splitting of its 0 and 1 states depends on the other nitrogen's spin state. This dependence makes possible a controlled NOT (CNOT) gate, in which one qubit is inverted if and only if the other qubit is a 1. The gate would work by using radio waves tuned to the frequency that will flip the N-V center provided the nitrogen spin is a 1. If the nitrogen spin is a 0, the N-V center's energy splitting will be different and the radio waves will not affect it.

The CNOT gate is quite special: we can compose any arbitrary quantum operation on any number of qubits by combining CNOT gates acting on pairs of qubits and rotations of individual qubits (which can also be carried out by applying radio waves to spins; individual spins could be addressed by bringing the radiation to them along special circuits called striplines). Demonstrations of a CNOT gate and qubit rotation are therefore major research goals.

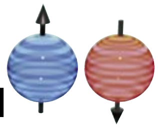
Longer distance interactions between N-V spins in diamond may be possible by using photons as mediators. On-chip optical devices such as waveguides made of the same diamond substrate could route the photons. Integrating the N-V centers in structures called optical cavities, in which light forms standing waves, would enhance the strength of the interaction between the spins and the photons. At Santa Barbara, in a collaboration with Evelyn Hu and her students, we recently demonstrated proof-of-concept photonic crystal cavities. Each "optical cavity" consists of a region of diamond with a honeycomb of holes etched into it. The holes work to confine and amplify light at the center of the structure [see "Photonic Crystals: Semiconductors of Light," by Eli Yablonovitch; Scientific American, December 2001]. Thus far, however, this work is very preliminary: the N-V centers, which are randomly distributed in the diamond instead of being precisely positioned in the cavities, are bystanders in our studies.

Placing Impurities

Many of the experiments on N-V centers to date have been carried out using synthetic diamonds like those used for our optical cavities: the N-V centers were formed naturally but in random locations during the diamond growth process. Now researchers at the Australian National University, the University of Bochum in Germany and Lawrence Berkeley National Laboratory are making great progress in placing individual impurities at specific locations. They use advanced ion implantation techniques to insert single ions of nitrogen with submicron accuracy. Then they heat the diamond to 850 degrees Celsius, which causes the vacancies in the diamond to migrate. When a vacancy meets a nitrogen atom it stays next to it, forming an N-V center.

N-V centers seem a promising technology for processing quantum information, but what about storage for times longer than the millisecond-long decay time of their electronic spin states? Researchers in Mikhail Lukin's group at Harvard University have explored an approach that makes use of the spins of carbon nuclei. Because the nucleus of the most common isotope of carbon, carbon 12, has zero spin in total, the group used carbon 13 atoms, whose nuclei have the spin of their one extra neutron. The scientists transferred the information encoded in a single N-V center spin to a single nuclear spin of carbon 13 and retrieved it 20 milliseconds later. The nuclear spin showed no sign of decay, indicating that the quantum state could survive for seconds. Thus, nuclear spins appear to be a propitious route to qubit storage. The Harvard researchers have also proposed a design for constructing a quantum repeater based on this work. Quantum repeaters are a basic element needed for quantum communication (transmitting qubits over longer distances).

It is an exciting time for quantum information research, with many different computation architectures vying for supremacy. Considering the rapid rise and successes of diamond-based spin research over the past few years and with companies such as Hewlett-Packard getting into the game, the prospect of room-temperature quantum information processors is sounding less like science fiction. The diamond age of quantum electronics could be just around the corner. ■



[THE AUTHORS]

David D. Awschalom, Ryan Epstein and **Ronald Hanson** are associated with the Center for Spintronics and Quantum Computation at the University of California, Santa Barbara. Awschalom is director of the center and professor of physics and of electrical and computer engineering at Santa Barbara. His research group is primarily concerned with investigating electron-spin dynamics in a variety of semiconductor systems. Epstein obtained his Ph.D. in Awschalom's group, studying nitrogen-vacancy centers in diamond. He is now doing postdoctoral research on trapped ions at the National Institute of Standards and Technology in Boulder, Colo. Hanson was a postdoctoral researcher in the group and has just become assistant professor of physics at the Kavli Nanoscience Institute in Delft, the Netherlands. For his Ph.D., he studied single-electron spins in gallium arsenide quantum dots at the Delft University of Technology.