

Spintronics

A new class of device based on the quantum of electron spin, rather than on charge, may yield the next generation of microelectronics

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The last half of the 20th century, it has been argued with considerable justification, could be called the microelectronics era. During that 50-year period, the world witnessed a revolution based on a digital logic of electrons. From the earliest transistor to the remarkably powerful microprocessor in your desktop computer, most electronic devices have employed circuits that express data as binary digits, or bits—ones and zeroes represented by the existence or absence of electric charge. Furthermore, the communication between microelectronic devices occurs by the binary flow of electric charges. The technologies that emerged from this simple logic have created a multi-trillion dollar per year global industry whose products are ubiquitous. Indeed, the relentless growth of microelectronics is often popularly summarized in Moore's Law, which holds that microprocessors will double in power every 18 months as electronic devices shrink and more logic is packed into every chip.

Yet even Moore's Law will run out of momentum one day as the size of individual bits approaches the dimension of atoms—this has been called the end of the silicon road map. For this reason and also to enhance the multifunctionality of devices (for example,

carrying out processing and data storage on the same chip), investigators have been eager to exploit another property of the electron—a characteristic known as spin. Spin is a purely quantum phenomenon roughly akin to the spinning of a child's top or the directional behavior of a compass needle. The top could spin in the clockwise or counterclockwise direction; electrons have spin of a sort in which their compass needles can point either "up" or "down" in relation to a magnetic field. Spin therefore lends itself elegantly to a new kind of binary logic of ones and zeros. The movement of spin, like the flow of charge, can also carry information among devices. One advantage of spin over charge is that spin can be easily manipulated by externally applied magnetic fields, a property already in use in magnetic storage technology. Another more subtle (but potentially significant) property of spin is its long coherence, or relaxation, time—once created it tends to stay that way for a long time, unlike charge states, which are easily destroyed by scattering or collision with defects, impurities or other charges.

These characteristics open the possibility of developing devices that could be much smaller, consume less electricity and be more powerful for certain types of computations than is possible with electron-charge-based systems. Those of us in the spintronics (short for spin electronics) community hope that by understanding the behavior of electron spin in materials we can learn something fundamentally new about solid state physics that will lead to a new generation of electronic devices based on the flow of spin in addition to

the flow of charge. In fact, the spintronics dream is a seamless integration of electronic, optoelectronic and magneto-electronic multifunctionality on a single device that can perform much more than is possible with today's microelectronic devices.

The Logic Of Spin

Spin relaxation (how spins are created and disappear) and spin transport (how spins move in metals and semiconductors) are fundamentally important not only as basic physics questions but also because of their demonstrated value as phenomena in electronic technology. One device already in use is the giant magnetoresistive, or GMR, sandwich structure, which consists of alternating ferromagnetic (that is, permanently magnetized) and nonmagnetic metal layers. Depending on the relative orientation of the magnetizations in the magnetic layers, the electrical resistance through the layers changes from small (parallel magnetizations) to large (antiparallel magnetizations). Investigators discovered that they could use this change in resistance (called magnetoresistance, and "giant" because of the large magnitude of the effect in this case) to construct exquisitely sensitive detectors of changing magnetic fields, such as those marking the data on a computer hard-disk platter. These disk drive read/write heads have been wildly successful, permitting the storage of tens of gigabytes of data on notebook computer hard drives, and have created a billion-dollar per year industry. Groups have also been working to develop nonvolatile memory elements from these materials, possibly a route to instant-on computers.

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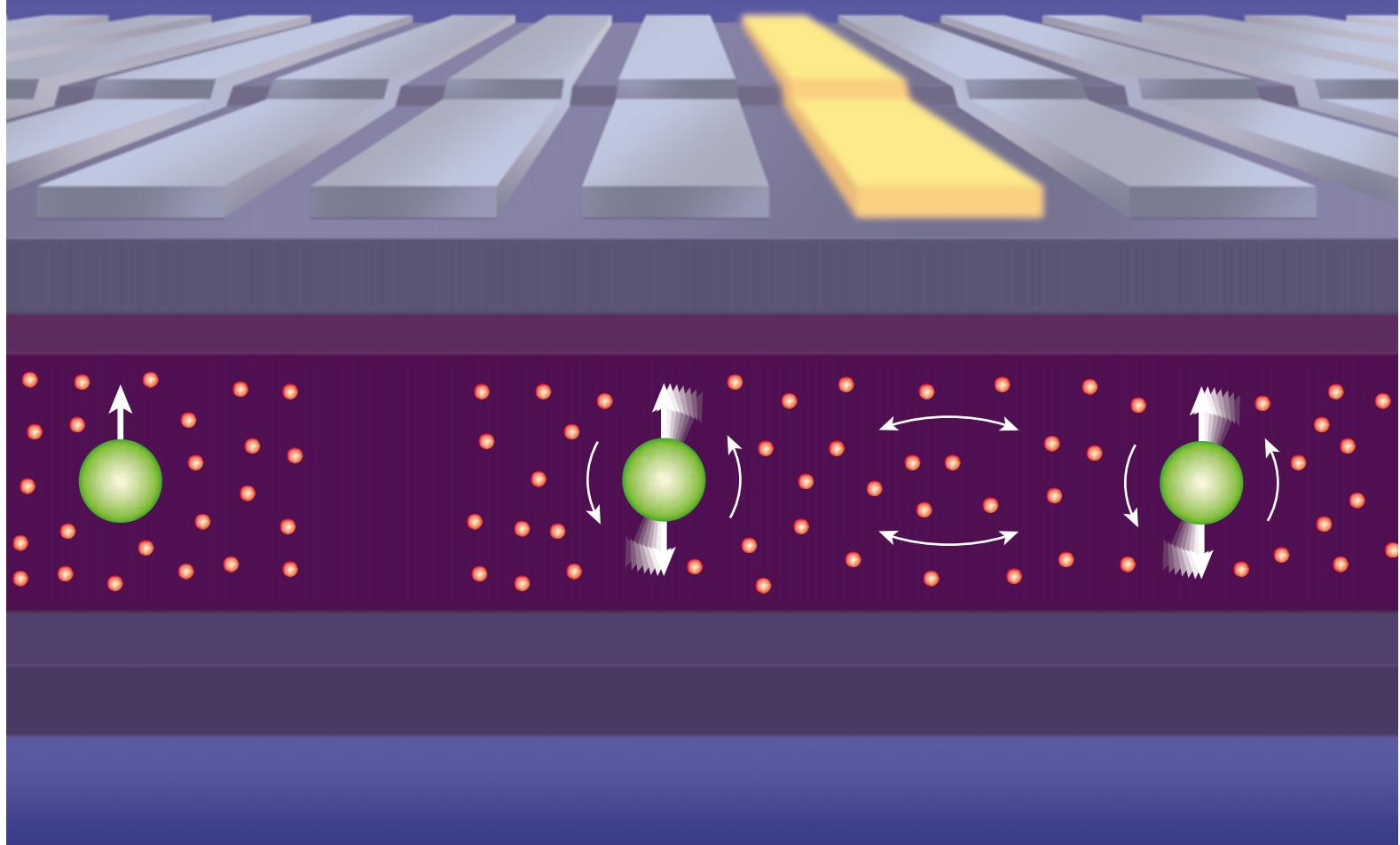


Figure 1. Physicists and engineers are creating an entirely new generation of microelectronic devices that operate on a quantum mechanical property of electrons called “spin” rather than on the electron’s electrical charge. These investigators are racing to use spin effects to create transistors and other circuit elements, including quantum computers, in a field known as spintronics. Shown here is an artist’s depiction of a proposal by Bruce Kane, now at the University of Maryland, for a quantum computer based on the nuclear spin of phosphorus atoms. The quantum properties of superposition and entanglement may someday permit quantum computers to perform certain types of computations much more quickly using less power than is possible with conventional charge-based devices. For an explanation of how a quantum computer might work, see Figure 7.

Researchers and developers of spintronic devices currently take two different approaches. In the first, they seek to perfect the existing GMR-based technology either by developing new materials with larger populations of oriented spins (called spin polarization) or by making improvements in existing devices to provide better spin filtering. The second effort, which is more radical, focuses on finding novel ways both to generate and to utilize spin-polarized currents—that is, to actively control spin dynamics. The intent is to thoroughly investigate spin transport in semiconductors and search for ways in which semiconductors can

function as spin polarizers and spin valves. This is crucial because, unlike semiconductor transistors, existing metal-based devices do not amplify signals (although they are successful switches or valves). If spintronic devices could be made from semiconductors, however, then in principle they would provide amplification and serve, in general, as multi-functional devices. Perhaps even more importantly, semiconductor-based devices could much more easily be integrated with traditional semiconductor technology.

Although semiconductors offer clear advantages for use in novel spintronic

applications, many basic questions pertaining to combining semiconductors with other materials to produce viable spintronic technology remain unanswered. For example, it is far from well understood whether or how placing a semiconductor in contact with another material would impede spin transport across the interface. In the past, our strategy for understanding spin transport in hybrid semiconductor structures was to borrow knowledge obtained from studies of more traditional magnetic materials. More recently, however, investigators have begun direct investigation of spin transport

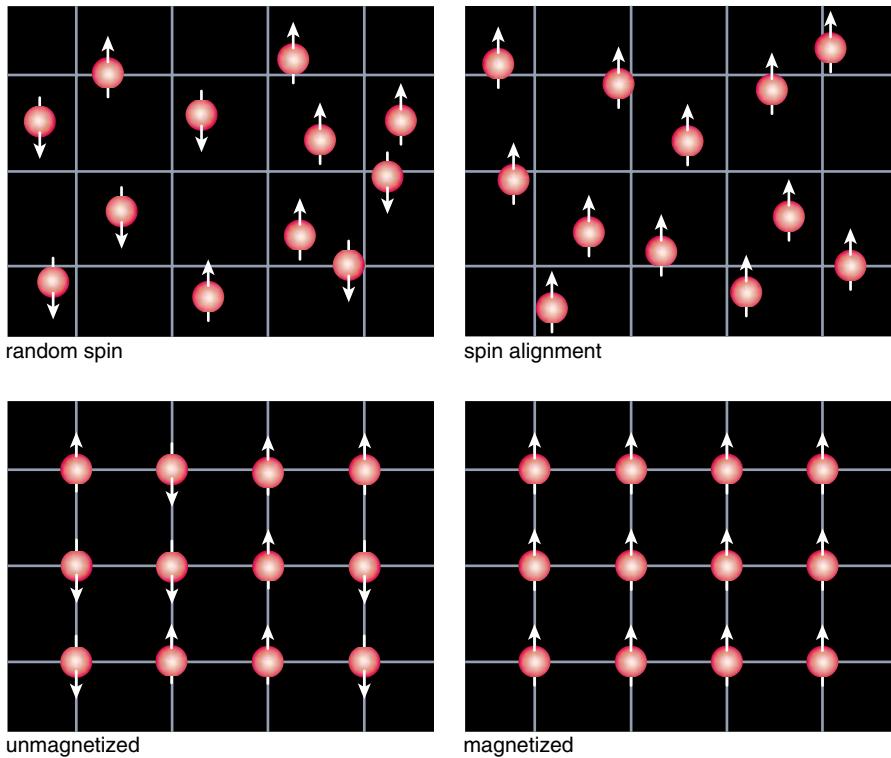


Figure 2. Spins can arrange themselves in a variety of ways that are important for spintronic devices. They can be completely random, with their spins pointing in every possible direction and located throughout a material in no particular order (*upper left*). Or these randomly located spins can all point in the same direction, called *spin alignment* (*upper right*). In solid state materials, the spins might be located in an orderly fashion on a crystal lattice (*lower left*) forming a nonmagnetic material. Or the spins may be on a lattice and be aligned as in a magnetic material (*lower right*).

across interfaces in all-semiconductor devices. In such a scenario a combination of optical manipulation (for example, shining circularly polarized light on a material to create net spin polarization) and material inhomogeneities (by suitable doping as in a recently discovered class of gallium-manganese-arsenide ferromagnetic materials) can be employed to tailor spin transport properties.

In addition to the near-term studies of various spin transistors and spin transport properties of semiconductors, a long-term and ambitious subfield of spintronics is the application of electron and nuclear spins to quantum information processing and quantum computation. The late Richard Feynman and others have pointed out that quantum mechanics may provide great advantages over classical physics in computation. However, the real boom started after Peter Shor of Bell Labs devised a quantum algorithm that would factor very large numbers into primes, an immensely difficult task for conventional computers and the basis for modern encryption. It turns out that

spin devices may be well suited to such tasks, since spin is an intrinsically quantum property.

Spintronic Devices

The first scheme for a spintronic device based on the metal-oxide-semiconductor technology familiar to microelectronics designers was the field effect spin transistor proposed in 1989 by Supriyo Datta and Biswajit Das of Purdue University. In a conventional field effect transistor, electric charge is introduced via a source electrode and collected at a drain electrode. A third electrode, the gate, generates an electric field that changes the size of the channel through which the source-drain current can flow, akin to stepping on a garden hose. This results in a very small electric field being able to control large currents.

In the Datta-Das device, a structure made from indium-aluminum-arsenide and indium-gallium-arsenide provides a channel for two-dimensional electron transport between two ferromagnetic electrodes. One electrode acts as an emitter, the other a collector

(similar, in effect, to the source and drain, respectively, in a field effect transistor). The emitter emits electrons with their spins oriented along the direction of the electrode's magnetization, while the collector (with the same electrode magnetization) acts as a spin filter and accepts electrons with the same spin only. In the absence of any changes to the spins during transport, every emitted electron enters the collector. In this device, the gate electrode produces a field that forces the electron spins to precess, just like the precession of a spinning top under the force of gravity. The electron current is modulated by the degree of precession in electron spin introduced by the gate field: An electron passes through the collector if its spin is parallel, and does not if it is antiparallel, to the magnetization. The Datta-Das effect should be most visible for narrow band-gap semiconductors such as InGaAs, which have relatively large spin-orbit interactions (that is, a magnetic field introduced by the gate current has a relatively large effect on electron spin). Despite several years of effort, however, the effect has yet to be convincingly demonstrated experimentally.

Another interesting concept is the all-metal spin transistor developed by Mark Johnson at the Naval Research Laboratory. Its trilayer structure consists of a nonmagnetic metallic layer sandwiched between two ferromagnets. The all-metal transistor has the same design philosophy as do giant magnetoresistive devices: The current flowing through the structure is modified by the relative orientation of the magnetic layers, which in turn can be controlled by an applied magnetic field. In this scheme, a battery is connected to the control circuit (emitter-base), while the direction of the current in the working circuit (base-collector) is effectively switched by changing the magnetization of the collector. The current is drained from the base in order to allow for the working current to flow under the "reverse" base-collector bias (antiparallel magnetizations). Neither current nor voltage is amplified, but the device acts as a switch or spin valve to sense changes in an external magnetic field. A potentially significant feature of the Johnson transistor is that, being all metallic, it can in principle be made extremely small using nanolithographic techniques (perhaps as small as tens of nanometers). An im-

portant disadvantage of Johnson's transistor is that, being all-metallic, it will be difficult to integrate this spin transistor device into existing semiconductor microelectronic circuitry.

As noted previously, a critical disadvantage of metal-based spintronic devices is that they do not amplify signals. There is no obvious metallic analog of the traditional semiconductor transistor in which draining one electron from the base allows tens of electrons to pass from the emitter into the collector (by reducing the electrostatic barrier generated by electrons trapped in the base). Motivated by the possibility of having both spin polarization and amplification, my group has recently studied a prototype device, the spin-polarized p-n junction. (In the p, or positive, region the electrons are the minority carriers, holes the majority; in the n, or negative, region the roles are reversed.) In our scheme we illuminate the surface of the p-type region of a gallium arsenide p-n junction with circularly polarized light to optically orient the minority electrons. By performing a realistic device-modeling calculation we have discovered that the spin can be effectively transferred from the p side into the n side, via what we call spin pumping through the minority channel. In effect, the spin gets amplified going from the p to the n region through the depletion layer.

One possible application of our proposed spin-polarized p-n junction is something we call the spin-polarized solar cell. As in ordinary solar cells, light illuminates the depletion layer of a semiconductor (such as gallium arsenide), generating electron-hole pairs. The huge built-in electric field in the layer (typically 10^4 volts per centimeter) swiftly sweeps electrons into the n region and holes into the p region. If a wire connects the edges of the junction, a current flows. If the light is circularly polarized (from filtered solar photons, for instance), the generated electrons are spin polarized. (Holes in III-V semiconductors—for example, gallium arsenide, indium arsenide and others—which are most useful for opto-spin-electronic purposes, lose their spin very quickly, so that their polarization can be neglected.) As the spin-polarized electrons created in the depletion layer pump the spin into the n region, the resulting current is spin polarized. Hence, photons of light are converted into oriented spins.

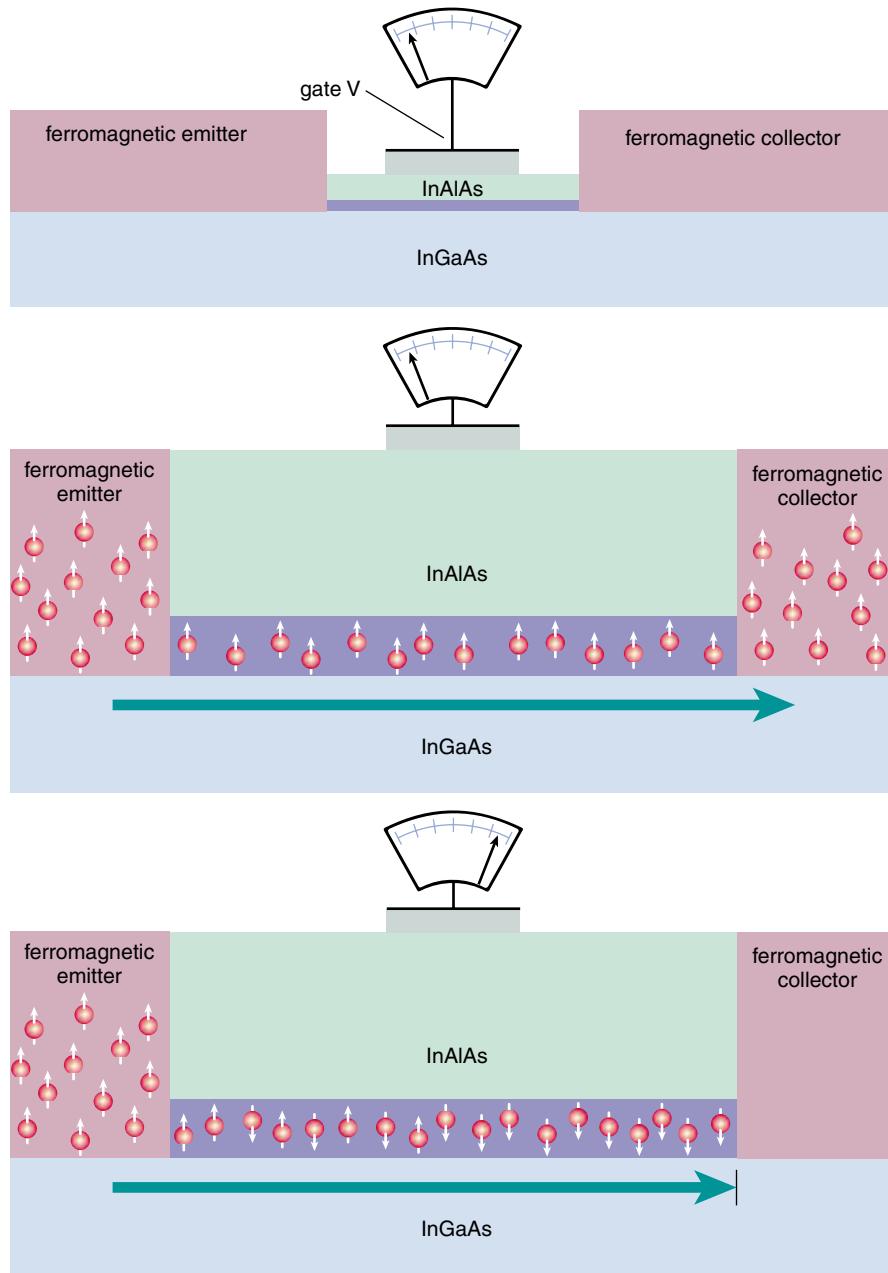


Figure 3. Datta-Das spin transistor was the first spintronic device to be proposed for fabrication in a metal-oxide-semiconductor geometry familiar in conventional microelectronics. An electrode made of a ferromagnetic material (purple) emits spin-aligned electrons (red spheres), which pass through a narrow channel (blue) controlled by the gate electrode (gold) and are collected by another ferromagnetic electrode (top). With the gate voltage off, the aligned spins pass through the channel and are collected at the other side (middle). With the gate voltage on, the field produces magnetic interaction that causes the spins to precess, like spinning tops in a gravity field. If the spins are not aligned with the direction of magnetization of the collector, no current can pass. In this way, the emitter-collector current is modulated by the gate electrode. As yet, no convincingly successful application of this proposal has been demonstrated.

Most recently, Igor Žutić, Jaroslav Fabian and I have proposed a new kind of magnetic field effect transistor. Electrodes of an external circuit are placed perpendicular to the p-n junction. The current is determined by the amount of available electrons in the region of the

junction around the electrodes. If the depletion layer is wider than the electrodes, no (or very small) electric current flows. As the width decreases, more and more electrons come into contact with the electrodes and the current rapidly increases. Traditionally,

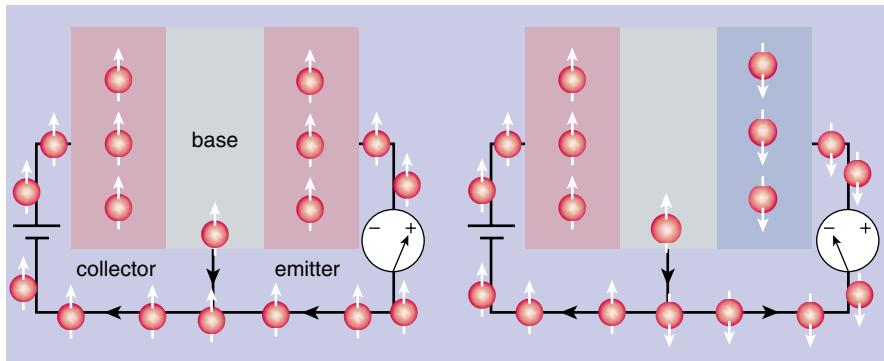


Figure 4. In the spin transistor invented by Mark Johnson, two ferromagnetic electrodes—the emitter and collector—sandwich a nonmagnetic layer—the base. When the ferromagnets are aligned, current flows from emitter to collector (left). But when the ferromagnets have different directions of magnetization, the current flows out of the base to emitter and collector (right). Although it can act as a spin valve, this structure shares the disadvantage of all-metal spintronic devices in that it cannot be an amplifier.

field effect transistors operate with an applied electric field (voltage) along the junction, as the width of the depletion layer is sensitive to the voltage. We propose to use instead a magnetic field. If the n or p region (or both) is doped with magnetic impurities, an external magnetic field produces a physical effect equivalent to applying an external voltage and could effectively tailor the width of the junction. (At the same time, this affects spin-up and spin-down electrons differently: A spin-polarized current results as well). Such a

device could find use in magnetic sensor technology such as magnetic read heads or magnetic memory cells.

Go with the Flow

If spintronic devices are ever to be practical, we need to understand how spins move through materials and how to create large quantities of aligned spins. Thirty years ago, pioneering experiments on spin transport were performed by Paul Tedrow and Robert Meservy of MIT on ferromagnet/superconductor sandwiches to demonstrate that current across the interface

is spin-polarized. Today, the range of materials we can study has significantly increased, including novel ferromagnetic semiconductors, high-temperature superconductors and carbon nanotubes. But several questions—such as the role of the interface separating different materials and how to create and measure spin polarization—still remain open and are of fundamental importance to novel spintronic applications.

As devices decrease in size, the scattering from interfaces plays a dominant role. In these hybrid structures the presence of magnetically active interfaces can lead to spin-dependent transmission (spin filtering) and strongly influence operation of spintronic devices by modifying the degree of spin polarization. One way to test these ideas is by directly injecting spins from a ferromagnet, where the spins start out in alignment, into a nonmagnetic semiconductor. Understanding this kind of spin injection is also required for hybrid semiconductor devices, such as the Datta-Das spin transistor discussed in the previous section. But this situation is very complicated, and a complete picture of transport across the ferromagnetic-semiconductor interface is not yet available. In its absence, researchers have been studying a simpler case of normal metal - semiconductor contacts.

Unfortunately, experiments on spin injection into a semiconductor indicate that the obtained spin polarization is substantially smaller than in the ferromagnetic spin injector, spelling trouble for spintronic devices. In this case, where spins diffuse across the interface, there is a large mismatch in conductivities, and this presents a basic obstacle to achieving higher semiconductor spin polarization with injection. An interesting solution has been proposed to circumvent this limitation. By inserting tunnel contacts—a special kind of express lane for carriers—investigators found that they could eliminate the conductivity mismatch. Moreover, to reduce significant material differences between ferromagnets and semiconductors, one can use a magnetic semiconductor as the injector. While it was shown that this approach could lead to a high degree of spin polarization in a nonmagnetic semiconductor, it only worked at low temperature. For successful spintronic applications, future efforts will have to concentrate on

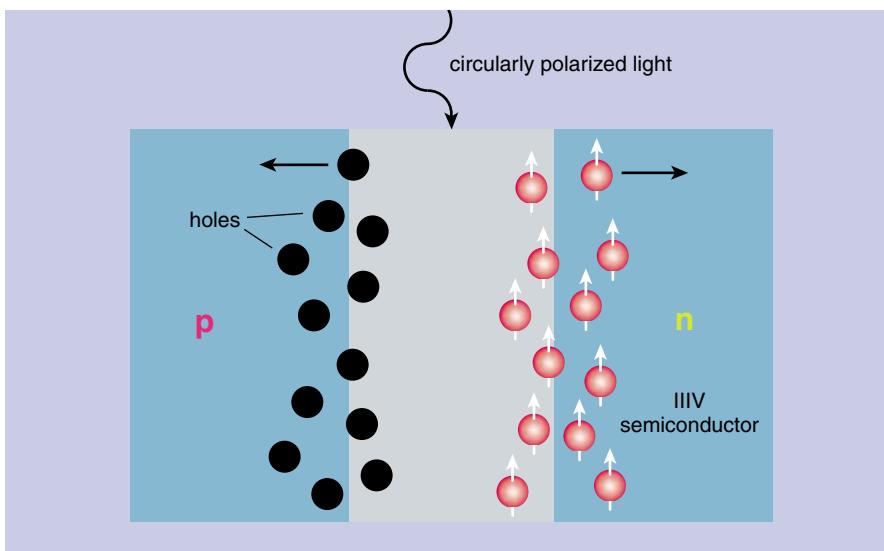


Figure 5. Spintronic solar cells have been proposed by the author and his colleagues. Sunlight passes through a filter to produce circularly polarized light, which is absorbed in the region between p-type and n-type semiconductors. This creates spin-polarized electron-hole pairs in this so-called “depletion” layer, but if a semiconductor of the III-V variety is used (gallium arsenide, for example), the polarization is only retained by the electrons. The inherent electric field at the layer boundaries sweeps the holes to the p side and the electrons to the n side. Just as with a conventional solar cell, a wire connected from the p electrode to the n electrode will now have a current flowing in it, but in this case the current is spin polarized.

fabricating ferromagnetic semiconductors in which ferromagnetism will persist at higher temperatures.

The issues involving spin injection in semiconductors, as well as efforts to fabricate hybrid structures, point toward a need to develop methods to study fundamental aspects of spin-polarized transport in semiconductors. We recently suggested studying hybrid semiconductor-superconductor structures for understanding spin transmission properties, where the presence of the superconducting region can serve as a tool to investigate interfacial transparency and spin-polarization. In addition to charge transport, which can be used to infer the degree of spin-polarization, one could also consider pure spin transport. Igor Žutić and I have been able to calculate this in a hybrid semiconductor structure with our model of the interface. We choose a geometry where semi-infinite semiconductor and superconductor regions are separated by an interface at which particles can experience potential and spin-flip scattering. In this approach we need to identify the appropriate scattering processes and their corresponding magnitudes. We find that although spin conductance shows high sensitivity to spin polarization, there remains an experimental challenge to directly measure the spin current, rather than the usual charge current.

Computing with Spins

One of the most ambitious spintronic devices is the spin-based quantum computer in solid-state structures. The use of electron (or nuclear) spin for these purposes is a manifestly obvious idea. The particles that physicists call “fermions” have two states of spin and so can assume either “up” or “down” states, making them natural and intrinsic binary units called quantum bits, or *qubits*. A qubit, as opposed to a classical binary computing bit, however, is not restricted to representing just 0 or 1. Because of the quantum property of *superposition*, it may represent arbitrary combinations of both values—that is, an infinite number of possibilities between 0 and 1. To perform a computation, some initial state is imposed on the spins, and this state is allowed to evolve in time through a process of *entanglement*. (Quantum entanglement means that the spins of particles polarized together remain correlated, even though they may become spatially sep-

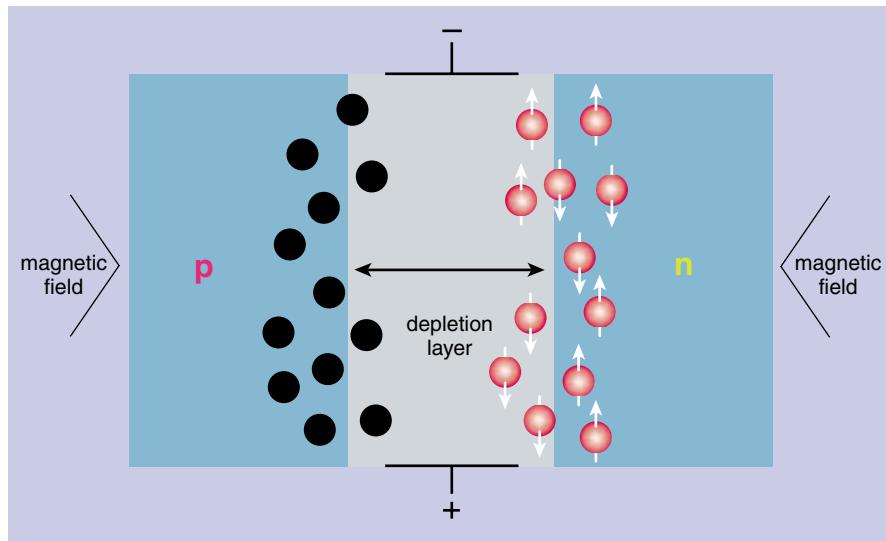


Figure 6. In the magnetic field effect transistor proposed by the author and his colleagues, an external current flows vertically through the structure shown. Normally, semiconductors are “doped” with impurity atoms to create the p-type and n-type materials, but if these impurities are magnetic atoms, then a magnetic field applied in the direction shown can alter the thickness of the middle depletion layer. As the size of this channel is increased and decreased, the current flowing in the external circuit is increased and decreased, respectively. Thus a small magnetic field can exert a large effect on an electric current. This is analogous to a conventional field effect transistor where an electric field controls the thickness of the depletion layer and hence the current.

arated.) These properties give a quantum computer the ability to, in effect, operate in parallel—making many computations simultaneously.

Quantum computation requires that the quantum states remain coherent, or undisturbed by interactions with the outside world, for a long time, and the states need to be controlled precisely. Because of the requirement of very long coherence time for a quantum computer, both nuclear spin and electron spin have been proposed as qubits, since spins inherently have long coherence times because they are immune to the long-range electrostatic Coulomb interactions between charges. I will review only a few of the representative schemes proposed during the past several years and discuss some recent work with my colleagues on electron spin based quantum computation.

One such scheme uses the spin of a single electron trapped in an isolated structure called a quantum dot as its qubit. Local magnetic fields are used to manipulate single spins, while inter-dot interaction is used to couple neighboring qubits and introduce two-qubit entanglement. A single trapped electron in a quantum dot implies an extremely low carrier density, which means very low coupling with the outside world. Thus the electron spins should remain

coherent much longer than even their already long coherence times in the bulk. However, to trap a single electron in a gated quantum dot is a difficult task experimentally. In addition, to apply a local magnetic field on one quantum dot without affecting other neighboring dots and trapped spins may also be impossible in practice.

We recently showed that in principle it is possible (albeit with great difficulties) to overcome both of these problems. Regarding the difficulty of trapping single electrons in an array of quantum dots, Xuedong Hu and I carried out a multi-electron calculation and showed that, subject to certain conditions, an odd number of electrons trapped in a quantum dot could effectively work as a qubit. The problem of the local magnetic field may be solved by the method of quantum error correction. The lack of a purely local magnetic field that acts on just a single qubit is essentially a problem of an inhomogeneous magnetic field that the other qubits feel. Such a field may come from magnetic impurities or unwanted currents away from the structure. We have done a detailed analysis and found that there is an error proportional to the field inhomogeneity. Using realistic estimates for such an inhomogeneous magnetic field on

nanometer scale quantum dots showed that the error introduced by the field can actually be corrected (with great difficulty).

One of the most influential schemes is the nuclear spin based quantum computer proposed by Bruce Kane, now at the University of Maryland. Here silicon donor nuclei serve as qubits, while donor electrons together with external gates provide single-qubit (using an external magnetic field) and two-qubit operations (using electron-nuclear and electron-electron spin interactions). The donor electrons are essentially shuttles between different nuclear qubits and are controlled by

external gate voltages. In addition, the final measurement is also supplied by the donor electrons by converting spin information into charge information. A significant advantage of silicon is that its most abundant isotope is spinless, thus providing a “quiet” environment for donor nuclear spin qubits. In general, nuclear spins have very long coherence times because they do not strongly couple with their environment and are thus good candidates for qubits. However, this isolation from the environment also brings with it the baggage that individual nuclear spins are difficult to control. This is why donor electrons play a crucial role in

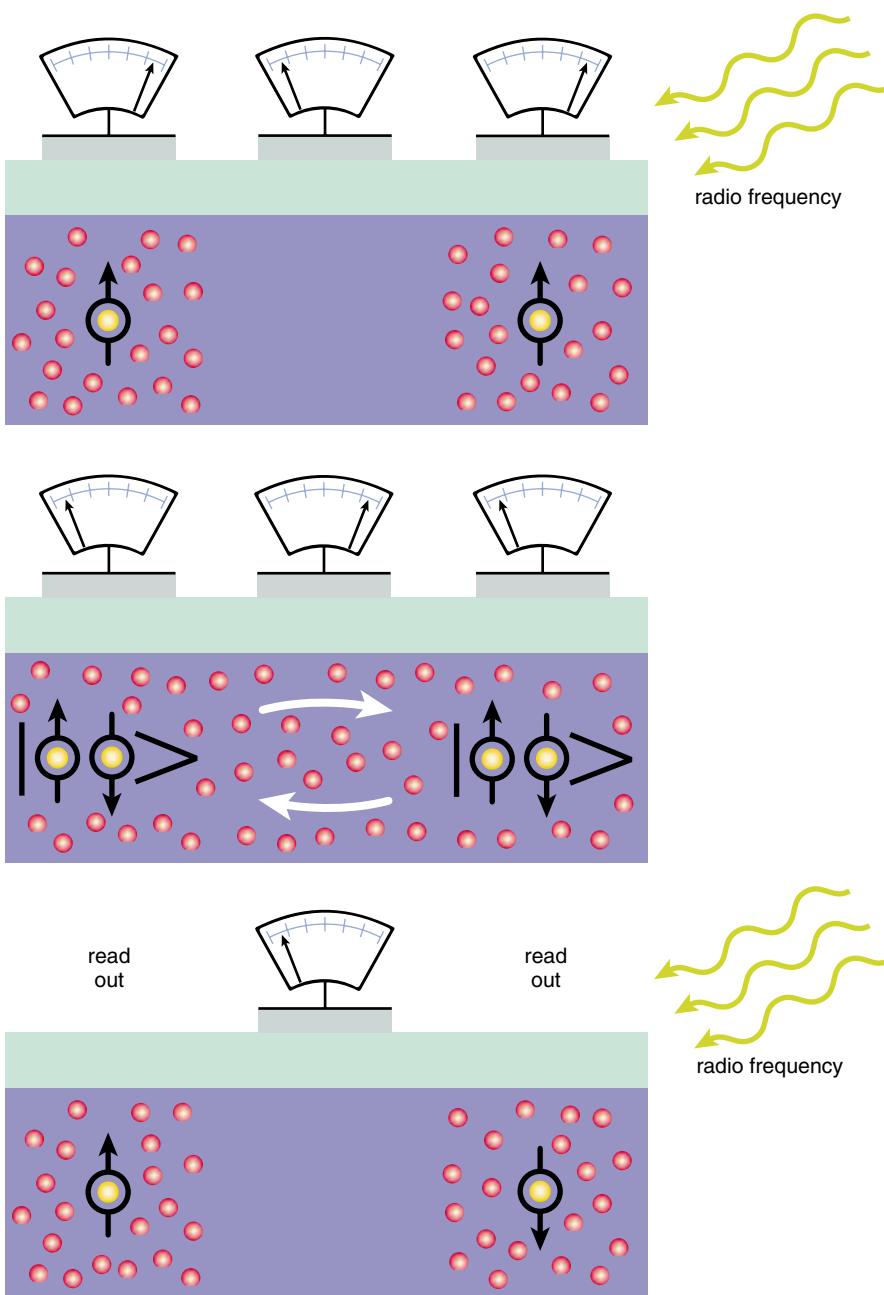
the silicon computer scheme. Another potential advantage of a quantum computer based on silicon is the prospect of using the vast resources available from the semiconductor chip industry.

In addition to all the operational problems discussed above, there is still the very hard question of how to reliably measure single electron spins (the readout in quantum computers). Not only must one be able to measure single spin states, but one has to be able to do it reasonably fast (nanoseconds to microseconds) so that the spin state does not decay before readout. Existing spin-measurement techniques can at best measure 500 to 1,000 electron spins, and extensive experimental exploration is needed to solve this problem.

Future prospects

Much remains to be understood about the behavior of electron spins in materials for technological applications, but much has been accomplished. A number of novel spin-based microelectronic devices have been proposed, and the giant magnetoresistive sandwich structure is a proven commercial success, being a part of every computer coming off the production line. In addition, spintronic-based nonvolatile memory elements may very well become available in the near future. But before we can move forward into broad application of spin-based multifunctional and novel technologies, we face the funda-

Figure 7. Quantum computing may be possible one day with spintronic devices. In an implementation proposed by Bruce Kane, phosphorus atoms doped into a silicon substrate act as the quantum computing elements. The diagram shows one part of a larger array of phosphorus atoms in a hypothetical quantum computer. Each phosphorus nucleus embedded in the substrate has its own nuclear spin and each donates an electron, which in turn have their own spin. The state of the nuclear spins can be read and written by the outer electrodes, called “A gates,” and the nuclear spins can be allowed to interact via the electrons, which are controlled with the center, or “J gates.” In a typical series of steps, the nuclear spins would be set with a pulse of a radio frequency magnetic field (top panel). Next, the electrons (red spheres) would be activated with the J gates to move between the phosphorus atoms (black circles with arrows), creating a quantum mechanical “entangled” state (middle panel). Finally, the gates are used again to read out the final quantum state of the array of phosphorus atoms via the spin state of the electrons (bottom panel).



mental challenges of creating and measuring spin, understanding better the transport of spin at interfaces, particularly at ferromagnetic/semiconductor interfaces, and clarifying the types of errors in spin-based computational systems. Tackling these will require that we develop new experimental tools and broaden considerably our theoretical understanding of quantum spin, learning in the process how to actively control and manipulate spins in ultrasmall structures. If we can do this, the payoff will be an entirely new world of spin technology with new capabilities and opportunities. In particular, the tantalizing possibility of building a spintronics quantum computer will keep researchers busy for quite some time.

Acknowledgment

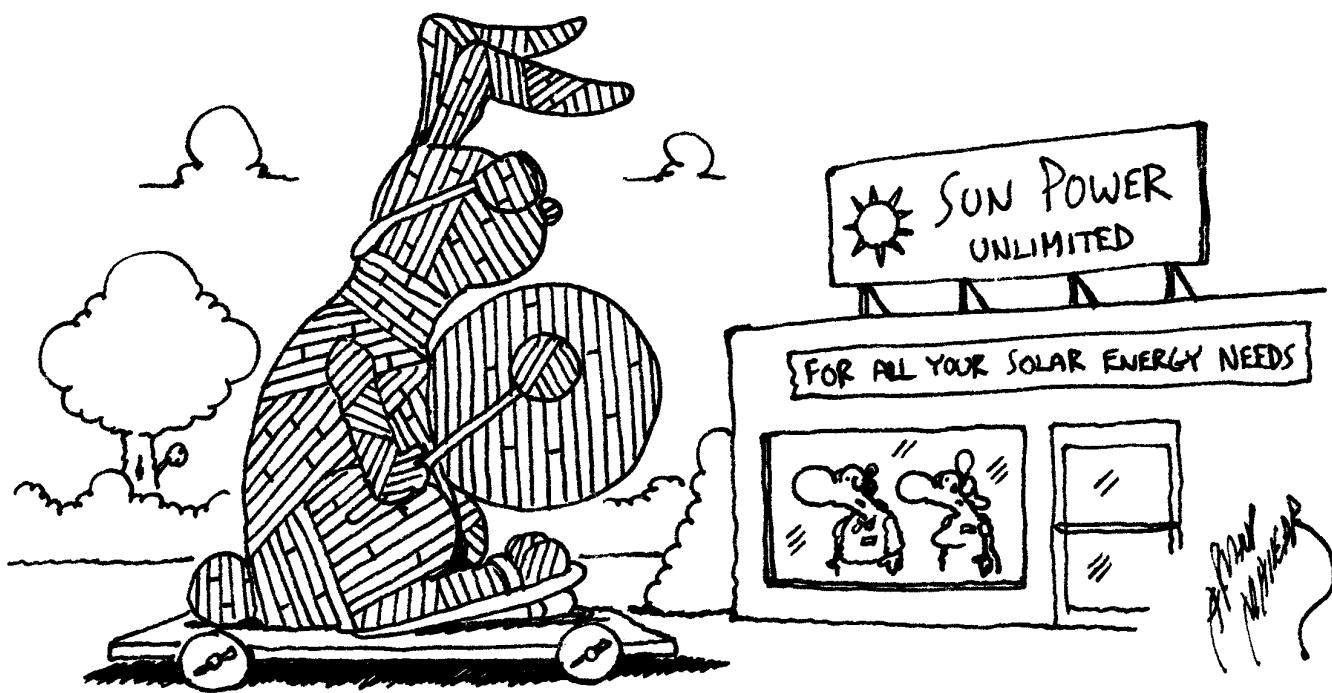
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"IT CAME WITH A NOTE FROM SOME BATTERY COMPANY."