by Stuart A. Wolf, Daryl Treger, and Almadena Chtchelkanova

Electronics with a Twist

In conventional electronics, only the charge of the electrons matters. But using an electron's other fundamental property—its spin—is starting to open up a new field, dubbed "spintronics." Begun only in 1988 and rapidly evolving toward practical devices over the past two years, spintronics promises the possibilities of integrating memory and logic into a single device, allowing switching times faster than 1 ps, and greatly increasing the efficiency of optical devices such as light-emitting diodes (LEDs) and lasers. The control of spin is also central to efforts to create entirely new ways of computing, such as quantum computing, or analog computing that uses the phase of signals for computations (Figure 1).

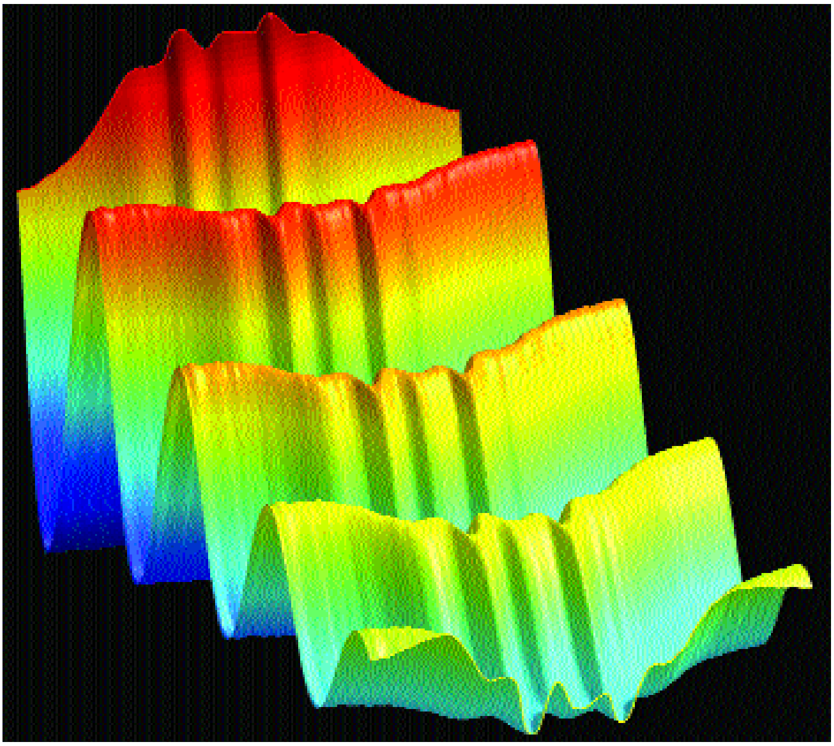

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Figure 1. Measurements of optically excited coherent electron spins precessing in GaAs as a function of time and magnetic field suggest new opportunities for quantum spintronics using both electronic and nuclear spins in solid-state materials.

The basics

Spin is a fundamental quantum mechanical property. It is the intrinsic angular momentum of an elementary particle, such as an electron. Of course, any charged object possessing spin also possesses an intrinsic magnetic moment. It has been known for decades that in ferromagnetism, the spins of electrons are preferentially aligned in one direction. But only in 1988 was it recognized that in the currents flowing from a ferromagnet into an ordinary metal the electrons retain their spin alignment, so that spin and its associated magnetic field can be transported just as charge can be. This means that magnetization can be conveyed from one spot to another.

The first practical application of this phenomenon was in the giant magnetoresistive (GMR) effect, which is observed in artificial thin-film materials composed of alternate layers of ferromagnetic and nonmagnetic materials (*1*). The resistance of the material is lowest when the magnetic moments in the ferromagnetic layers are aligned in the same direction and highest when they are antialigned. This is because the spin-aligned currents from one layer are scattered strongly when they encounter a layer that is magnetically aligned in the opposite direction, creating resistance. But when the magnetic fields are oriented in the same direction, the spin-aligned currents pass through easily.

Current GMR materials operate at room temperature and show significant changes in resistivity when subjected to relatively small external magnetic fields. Thus, they can be used as magnetic field sensors. The imposed magnetic field changes the magnetization of one of the two layers, disrupting the alignment and increasing resistivity. The first GMR-based sensor for magnetic fields was created in 1994, and GMR-based read heads to detect magnetic fields in high-performance disk drives were realized in 1997.

Several groups are trying to develop a device similar to a GMR cell as a basis for a nonvolatile memory, one that does not require power to store information. The new device, termed a tunneling magnet resistance device, or TMR, replaces the metal between the two ferromagnetic layers with a very thin insulator through which a current can tunnel, but only when the magnetic orientations on the two sides of the insulator are aligned. The difference in resistance between the spin-aligned and nonaligned cases is about 40%, greater than for GMR devices and enough for the low resistance state to encode, say, a 1 and the high resistance state a 0 (2).

The difficulty in developing this device, however, is the very thin insulator (10–15 Å thick), which must be uniform over large areas. A Defense Advanced Research Projects Agency (DARPA) project called Spintronics (for spin transport electronics) is funding efforts by Motorola (Figure 2), IBM, and Honeywell to develop advanced prototypes of this memory device, starting with a 1-megabit chip that is being developed by Honeywell.

Spin and memory

Although fast nonvolatile memories could greatly increase the capabilities of computers, a key bottleneck is moving information between memories and logic circuits. Ideally, if individual devices could both process and store information, transfer delays would be eliminated, at least for data in immediate use. A spin-based device that could accomplish this dual task is a spin-polarized field-effect transistor (spin-FET), first proposed in 1990. In a conventional FET, when a bias voltage is applied, a conducting channel is created between the source and the drain regions, allowing the transistor to act as a switch. If the source and drain contacts are made of ferromagnetic materials, then the electrons coming from each contact have a preferential spin. This means that the current can be controlled by applying the bias voltage, as in a conventional FET, or by changing the orientation of the magnetic field in one of the ferromagnetic contacts. Because this orientation remains the same even with the power switched off, each spin-FET will have a built-in nonvolatile memory of its last state.

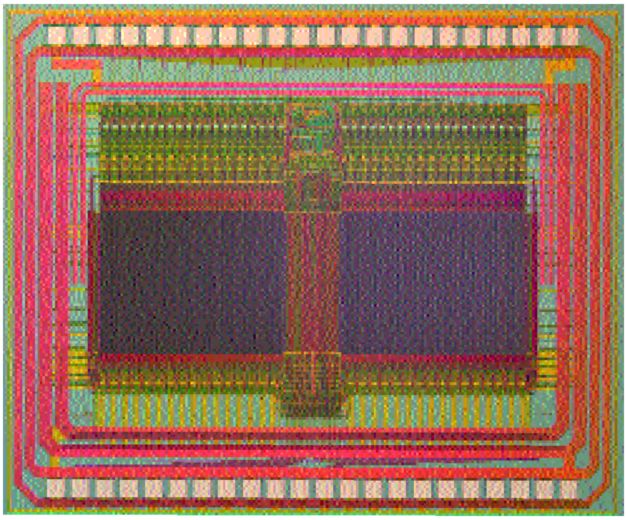
Motorola, Inc.

Figure 2. This 256-kb, nonvolatile, magnetoresistive random access memory chip is based on a memory cell defined by a single transistor and a single magnetic tunnel junction with read and write cycles of <50 ns.

A serious difficulty, however, has so far prevented the development of practical spin-FETs. The conductivity of ferromagnetic materials, generally metals, is much higher than that of the semiconductors that make up the rest of the FET. Thus, there are far more mobile electrons in the ferromagnet than in the semiconductors, so when the spin-aligned electrons try to squeeze into the semiconductor, only a few of them make it. For a large transfer of spin-aligned electrons, the conductivity of the ferromagnets and the semiconductors must be closely matched. To achieve this match, the ferromagnetic contacts must be semiconductors.

The first ferromagnetic semiconductors, developed in 1996, were diluted magnetic semiconductors—alloys in which some atoms are randomly replaced by magnetic atoms, such as manganese. However, these early materials had to be cooled to below 60 K to exhibit ferromagnetism. More recent research has shown that other types of semiconductors exhibit ferromagnetism—and at much higher temperatures. In 1998, the ferromagnetic behavior of GaMnAs at a critical temperature, T_c , of around 110 K was reported, and in 2000, above-room-temperature ferromagnetism in $TiCoO_2$ was discovered in Japan (*3,4*). This latest discovery brings practical spin-FETs within reach.

The addition of spin sensitivity could be use to produce devices that can switch faster than any transistor. One such extremely fast switch is a resonant tunneling diode (RTD), which consists of a quantum well sandwiched between two insulating barriers. Current flows only when the applied voltage reaches a precise value that allows a quantum mechanically resonant state to exist in the quantum well. Such switches can turn on and off in less than 1 ps. However, conventional RTDs cannot substitute for transistors because they lack a third terminal that allows an input signal to alter the switch's functioning.

A spin-RTD, in contrast, can act like a transistor. In such a device, the barriers are of unequal thickness, generating two resonant voltages, one for each spin state. By using ferromagnetic contacts to vary the spin states of electrons in the current, the RTD can be switched between two states with different resonant voltage, allowing the third input to affect the current flowing across the RTD. This design could be used to create an ultrafast logic device (*5*).

Polarized electrons

When electrons and holes combine in an LED, light is generated. But if the electrons are spin-polarized, the emitted light is circularly polarized as well. This makes spin-LEDs a good way to detect and measure the degree of spin polarization in currents in spintronics devices: the greater the degree of circular polarization in the emitted light, the greater the amount of spin polarization of the electron current. For example, spin injection efficiencies greater than 50% were measured for diluted magnetic semiconductors (*6*).

Spin-LEDs could also greatly increase the efficiency of LED light production. For one thing, circularly polarized light is often desired as the end product, but in conventional LEDs this is achieved with polarizing filters, which throw away part of the light produced. With spin-LEDs, the polarization can be produced intrinsically in the light, avoiding filtering. Furthermore, in certain LEDs based on polymers, light is emitted only when holes and electrons having opposite spins combine, reducing overall efficacy. By polarizing the electrons' spins, spin-LEDs can increase the efficiency of light production.

Just as electron spins can affect the polarization of light, so polarized light can be used to control spin, a phenomenon that might lead to alternatives to digital computing (*7*). When electrons are exposed to circularly polarized light while in an external magnetic field, the electrons' spins line up parallel to each other, but perpendicular to the direction of the external field. The direction of their spins, the resulting intrinsic magnetic field, precesses around in a circle at constant frequency. Left to itself, this coherent state will readily break up because of small irregularities in the field. But repeated pulses from an ultrafast laser maintain and amplify the spin-coherent state, just as repeated pushes on a swing amplify its oscillation.

One can measure electron-spin coherence by detemining the angle of rotation of a linearly polarized probe beam. The polarization of the probe beam as it passes through the semiconductor rotates by an angle proportional to the net magnetization of the system. Hence systems of light pulses can create, alter, and detect spin polarization states.

Researchers have shown theoretically that such coherent spin states could be used in new forms of analog computing, in which the values of variables are encoded as differences in the phase or direction of the rotating magnetic fields. This might be more useful for some applications than current techniques that encode data as digital numbers. For example, human and other mammalian brains appear to use such phase relations as a fundamental way of encoding data. This enables them to harness the work of hundreds of millions of neurons in performing tasks such as image recognition far more efficiently than any digital computer.

Another avenue for using the spins of elementary particles comes from the rapidly developing field of quantum computing. The states of spin of electrons or other 1/2-spin particles can be used as an implementation of a qubit (quantum bit , which is the unit of quantum information). Information can be encoded using the polarization of the spin, manipulation (computation) can be done using external magnetic fields or laser pulses, and readout can be done by measuring spin-polarized current. Quantum computers execute a series of simple unitary operations (gates) on 1 or 2 qubits at a time. The computation on a quantum computer is a sequence of unitary transformations of an initial state of a set of qubits. After the computation is performed, the qubits can be measured, and the outcome of the measurement is the result of the quantum computation.

Quantum effects such as interference and entanglement are used as computational resources and make fast solutions to hard problems possible. For some special but important problems, such as factorization of large prime numbers or database search, quantum computing algorithms have been developed that show a significantly shorter computation time and reduced complexity. For certain calculations that find global properties of functions like factoring and discrete logarithms, the speed-up for a quantum processor is dramatic. For these operations, a 30-qubit quantum processor can perform the same calculation in the same time as a 1-gigabit classical computer.

The main goal of a new DARPA program, the Quantum Information, Science and Technology Program, is the “qubit” quest—a search for quantum mechanical two-state systems with long dephasing times that allow them to carry out computations before stored information is lost. These quantum systems must be readily fabricated and scaled to perform quantum algorithms. Many candidates for implementing qubits have been proposed to date—coupled quantum dots, nuclear magnetic resonance, ion traps, cavity quantum electrodynamic systems, Josephson junctions, and superconducting quantum interference devices (SQUIDs). The uses of the quantum qubit systems range from quantum key distribution, quantum encryption, and quantum dense coding, to quantum teleportation and ultraprecise clock synchronization. This exciting new perspective for using the spin degree of freedom as a qubit is another illustration that the spin is the missing link between classical and quantum systems.

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