Spintronics

The term "spintronics" usually refers to the branch of physics concerned with the manipulation, storage, and transfer of information by means of electron spins in addition to or in place of the electron charge as in conventional electronics. Introduced in 1996, spintronics (the word coined by S. Wolf) was originally the name for a Defense Advanced Research Projects Agency (DARPA) program managed by Wolf. In conventional electronics, only the charge of the electrons is of consequence for device operation, but using the electron's other fundamental property, its spin, has opened up the new field of spintronics. Major advances in electron spin transport started in 1979–1980 with the discovery of large low-temperature magnetoresistance in metallic superlattices. Later demonstrations of the "giant" effect at room temperature evolved toward application in practical devices.

Spintronics promises the possibility of integrating memory and logic into a single device. In certain cases, switching times approaching a picosecond are possible, which can greatly increase the efficiency of optical devices such as light-emitting diodes (LEDs) and lasers. The control of spin is central as well to efforts to create entirely new ways of computing, such as quantum computing, or analog computing that uses the phases of signals for computations.

Spin is a fundamental quantum-mechanical property. It is the intrinsic angular momentum of an elementary particle, such as the 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. Then, in 1988, it was demonstrated that currents flowing from a ferromagnet into an ordinary metal retain their spin alignment for distances longer than interatomic spaces, so that spin and its associated magnetic moment can be transported just as charge. This means that magnetization as well can be transferred from one place to another.

Giant magnetoresistive effect. The first practical application of this phenomenon is in the giant magnetoresistive effect (GMR). The GMR is observed in thin-film materials composed of alternate ferromagnetic and nonmagnetic layers (**Fig. 1**). The resistance of the material is lowest when the magnetic moments in 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 additional resistance. But when the magnetic fields are oriented in the same direction, the spin-aligned currents pass through easily.

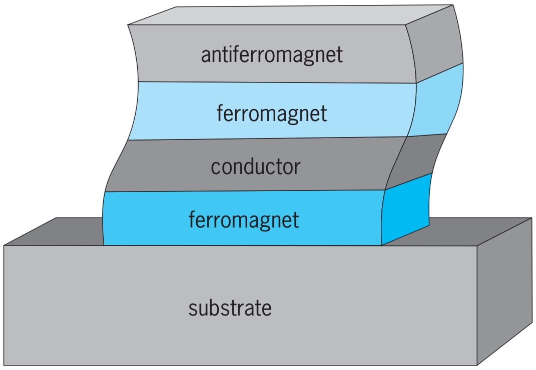

Fig. 1. Simple trilayer GMR structure.

Current GMR materials operate at room temperature and exhibit 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 magnetic orientation of one of the two layers, disrupting their relative orientation and thus changing the resistivity. The first GMR-based magnetic field sensor was created in 1994, and high-performance disk drives utilizing GMR-based read heads to detect magnetic fields were realized in 1997 and now are ubiquitous. These read heads are responsible for the very rapid growth in magnetic storage densities that has occurred in the last decade.

Spin-dependent tunneling device. A spin-dependent tunneling device (SDT) is similar to a GMR cell but replaces the metal between the two ferromagnetic layers with a very thin insulator through which a current can tunnel preferentially when the two magnetic orientations are aligned. The difference in resistance between the spin-aligned and nonaligned cases is much greater than for GMR devices and large enough that the low-resistance state can encode, say, a "1" and the high-resistance state, a "0." Recently, an SDT device was used in the first commercial magnetoresistive random access memory (MRAM), a fast RAM that is nonvolatile, meaning it does not require power to retain information.

Spin momentum transfer effect. Significant developments ensure that MRAM will be able to scale down to 60 nm and below. The most notable of these was the discovery of the spin momentum transfer effect (SMT), predicted theoretically in 1996, in which the angular momentum carried by a spin-polarized current can exert a torque on the magnetization of a magnetic film that is magnetized in any nonparallel direction. This effect, also known as spin torque, was experimentally observed in 2000.

SMT-MRAM. Conventional MRAM utilizes current-generated magnetic fields to rotate the magnetization in the free layer. In spite of advances in the switching methodology to make the switching robust to disturbances, increase the yield, and lower the switching current by magnetic cladding of the word and bit lines, SMT potentially offers orders-of-magnitude lower switching currents and concomitantly much lower energy per bit to write. Apparently SMT switching can significantly improve the performance of MRAM and make it a truly universal memory. Key areas of research to be addressed in the near future include using MRAM in embedded memory and for multibit memory (stacked memory).

Projected performance of MRAM, SMT-MRAM, and more conventional semiconductor memories

	Standard MRAM, 90 nm[*]	DRAM, 90 nm	SRAM, 90 nm	SMT MRAM, 90 nm[*]	FLASH, 90 nm[†]	FLASH, 32 nm[†]	SMT MRAM, 32 nm[*]
Cell size, μm^2 (cell density)	0.25 (256 Mbit/cm^2)	0.25 (256 Mbit/cm^2)	1–1.3[‡] (64 Mbit/cm^2)[‡]	0.12 (512 Mbit/cm^2)	0.1 (512 Mbit/cm^2)	0.02 (2.5 Gbit/cm^2)	0.01 (5 Gbit/cm^2)
Read time	10 ns	10 ns	1.1 ns	10 ns	10–50 ns	10–50 ns	1 ns
Program time	5–20 ns	10 ns	1.1 ns	10 ns	0.1–100 ms[‡]	0.1–100 ms[‡]	1 ns
Program energy/bit	120 pJ	5 pJ, needs refresh[‡]	5 pJ	0.4 pJ	30–120 nJ[‡]	10 nJ[‡]	0.02 pJ
Endurance	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$ read, $>10^{6}$ write[‡]	$>10^{15}$ read, $>10^{6}$ write[‡]	$>10^{15}$
Nonvolatility	Yes	No[‡]	No[‡]	Yes	Yes	Yes	Yes

[*] MRAM values are projected.
[†] These values are from the ITRS roadmap.
[‡] Technological shortfall for this memory device.

A summary of the projected performance of MRAM and SMT-MRAM is presented in the **table**, in which the performance of the more conventional semiconductor memories is included. SMT-MRAM has the potential to dominate this aspect of memory technology, particularly because of its nonvolatility and very low power. Even at the 90-nm node, SMT-MRAM competes favorably with flash memory in density and has advantages over flash in speed, energy, and endurance.

Domain-wall "racetrack" memory. Spin momentum transfer can also provide a pathway to other novel memories as solid-state replacements for magnetic hard drives. This type of memory involves storing information by the presence or absence of a domain wall or boundary between oppositely magnetized regions of a ferromagnetic film. The domain walls form a linear array in a U-shaped magnetic film confined to a trench or channel in a silicon chip that is similar to the trench used to form the storage capacitor in a dynamic random access memory (DRAM; **Fig. 2**).

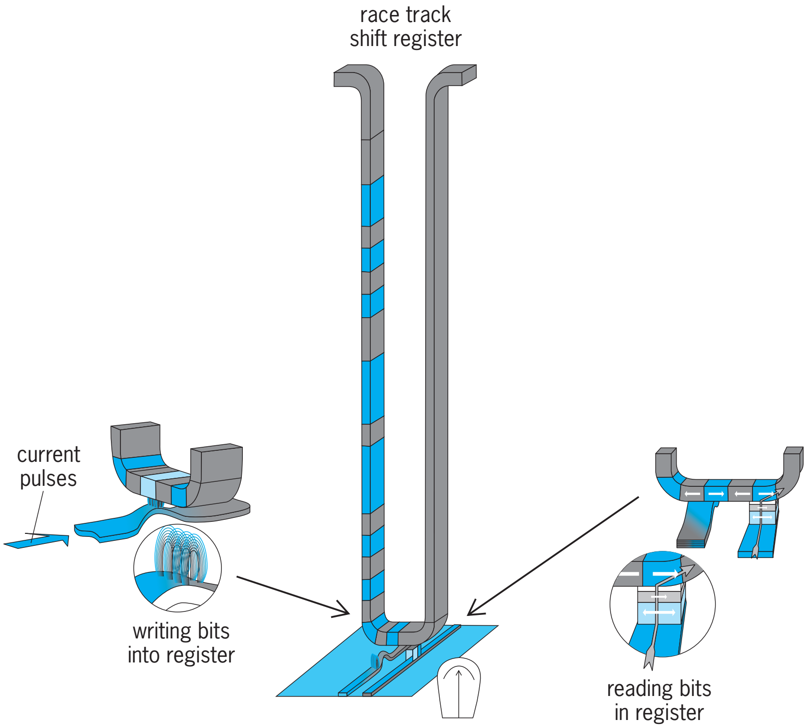

Fig. 2. Domain-wall "racetrack" memory device concept. To write bits into the racetrack shift register, current pulses move domain walls in nearby wire, and fringing fields from domain walls write bits. Magnetic tunneling junction (MTJ) sensor reads bit pattern in register.

Oscillators. Another important property of spin momentum transfer is the generation of radio-frequency and microwave radiation by the conversion of the momentum of the spin-polarized current into coherent (that is, having a well-defined phase) spin waves in a magnetic host subject to a magnetic field. These spin waves radiate significant power in the frequency range from a few to tens of gigahertz. Theoretical predictions indicate a much larger bandwidth than has been experimentally observed to date. A frequency-agile nanoscale source of electromagnetic radiation in the frequency range from tens to potentially hundreds of gigahertz is attractive for a host of applications. For example, these oscillators can provide tunable sources for phased-array transceivers, sources for chip-to-chip and on-chip clocks, and local oscillators for handheld wideband radios.

Sensing devices. GMR-based sensing devices have also been developed, including analog magnetic field sensors, differential magnetic field sensors (gradiometers), digital magnetic field sensors, digital signal isolators, and isolated bus transceivers. The cost and power are extremely low, making these devices highly competitive. The performance of the isolators, in particular, can be much better than their optical counterparts at lower cost. These devices are sold in large numbers.

Spin-polarized field-effect transistors. While fast nonvolatile memories could be very important to increasing computer capabilities, a key bottleneck is moving information between memories and logic circuits. Ideally, if individual devices could both process and store information, transfer delays could 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). 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 source and drain contacts are made from ferromagnetic materials, the electrons emitted from each contact have a preferential spin. Thus the current can be controlled either by applying a bias voltage as in a conventional FET, or by changing the orientation of the spins as they move from the source to the drain by rotation or by electric-field-controlled scattering.

There is, however, a serious difficulty that 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. This means that there are far more mobile electrons in the ferromagnet than in the semiconductors, so only a few of the spin-aligned electrons are able to enter the semiconductor. For a large transfer of spin-aligned electrons, the conductivity of the ferromagnets and the semiconductors must be closely matched, or there must be a tunneling contact between the ferromagnet and the semiconductor to match the conductivities. One way to achieve this match is to utilize ferromagnetic semiconductors as the source and the drain.

The first ferromagnetic semiconductors with Curie temperatures (T_C) above 50 K (−223°C or −370°F), 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 still had to be cooled to cryogenic temperatures to exhibit ferromagnetism. Subsequent research has shown that other types of semiconductors can exhibit ferromagnetism at much higher temperatures. In 1998 ferromagnetic behavior of GaMnAs was reported with a Curie temperature of about 110 K (−163°C or −262°F), which was subsequently raised to nearly 200 K (−73°C or −100°F). In 2000 room-temperature ferromagnetism in $TiCoO_2$ was discovered in Japan. There have also been reports, not widely reproduced, of ferromagnetism in many other semiconductors near or above room temperature. One of the key features of some of these materials is that they exhibit carrier-mediated ferromagnetism, in which the ferromagnetism is caused by the interaction of the magnetic ions with the carriers—electrons or holes. The Curie temperature and other magnetic properties can be modified by changing the carrier concentration with electric fields (gates) or with optical excitation. This ability to gate the magnetism by changing carrier concentration presents a new paradigm for novel devices in which carrier concentration and spin polarization are controlled concurrently. These discoveries appear to bring practical spin FETs within reach.

Spin resonant tunneling diodes. The addition of spin sensitivity can potentially produce devices that switch faster than any transistor. One such extremely fast switch is a spin resonant tunneling diode (RTD). This consists of a quantum well sandwiched between two insulating barriers. Current can flow only when the applied voltage reaches a precise value that allows a quantum-mechanically resonant state to exist within the quantum well. Such switches can turn on and off within 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 effective barrier height is different for spin-up and spin-down electrons in a modest magnetic field because of Zeeman splitting, generating two resonant voltages, one for each spin state. This allows the spin of the electron to be uniquely determined by measuring the tunneling probabilities. By using ferromagnetic contacts and thus varying 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, and thus potentially creating an ultrafast logic device. Estimates show that, when scaled, the device could be 100 times better than CMOS in power, with the same speed (or be 10 times better in power and 10 times better in speed).

Quantum computing. 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 spin-$^1/_2$ particles can be used as an implementation of a qubit (quantum bit, 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-dependent transport. Quantum computers execute a series of simple unitary operations (gates) on one or two 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 quick solutions to hard problems possible. For some very special problems, such as factorization of large prime numbers or exhaustive database searches, quantum-computing algorithms have been developed that show a very significant speed-up in computation time and a reduction in complexity. For certain calculations that find global properties of functions such as factoring and discrete logarithms, the speed-up for a quantum processor is dramatic. For these operations, a 30-logical-qubit quantum processor can perform the same calculation in the same time as a 10^9-bit classical computer.

Scientists are searching for quantum-mechanical two-state systems with long dephasing times, which would provide the ability to carry out computations before stored information is lost. It must be possible to readily farbricate and scale these quantum systems if they are to perform quantum algorithms. One very viable candidate for quantum information is electron spins in coupled quantum dots. However, other two-level systems have been proposed for implementing qubits, and include nuclear magnetic resonance (NMR), which involves nuclear spins in special molecules; excited states of ions in traps;

cavity quantum electrodynamic systems; Josephson junctions; and SQUIDs (superconducting quantum interference devices). The potential uses of quantum qubit systems range from quantum key distribution, quantum encryption, and quantum dense coding to quantum teleportation and ultraprecise clock synchronization.

For background information *see* COMPUTER STORAGE TECHNOLOGY; DOMAIN (ELECTRICITY AND MAGNETISM); FERROMAGNETISM; MAGNETIC RECORDING; MAGNETISM; MAGNETIZATION; MAGNETORESISTANCE; QUANTIZED ELECTRONIC STRUCTURE (QUEST); QUANTUM COMPUTATION; SEMICONDUCTOR MEMORIES; SPIN (QUANTUM MECHANICS); TRANSISTOR; ZEEMAN EFFECT in the McGraw-Hill Encyclopedia of Science & Technology.

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