# Challenges for semiconductor spintronics

High-volume information-processing and communications devices are at present based on semiconductor devices, whereas information-storage devices rely on multilayers of magnetic metals and insulators. Switching within information-processing devices is performed by the controlled motion of small pools of charge, whereas in the magnetic storage devices information storage and retrieval is performed by reorienting magnetic domains (although charge motion is often used for the final stage of readout). Semiconductor spintronics offers a possible direction towards the development of hybrid devices that could perform all three of these operations, logic, communications and storage, within the same materials technology. By taking advantage of spin coherence it also may sidestep some limitations on information manipulation previously thought to be fundamental. This article focuses on advances towards these goals in the past decade, during which experimental progress has been extraordinary.

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Semiconductor information-processing devices are among the most sophisticated, complex high-performance structures. As the construction cost of a new fabrication line approaches $3.5 billion, and 25% of its tools are obsolete and need replacement every three years, it is reasonable to question the appeal of alternate methods of information processing. Is it even realistic to imagine that an entirely distinct method of performing logical operations might be competitive? Metallic spintronic devices, such as hard disk read heads and magnetic random access memory (MRAM) are one of the most successful technologies of the past decade, with scaling trends outdoing even CMOS — can semiconductor analogues provide enough new functionality to warrant interest? Electro-optic modulators are also a successful room-temperature technology. What is the advantage of replacing these devices with magnetic analogues? Quantum computing seems to be progressing rapidly with atoms and superconductors — why use spins in semiconductors?

Metallic spintronic devices[1], originating from the discovery of giant magnetoresistance (GMR)[2,3] in 1988 and the subsequent development of the spin valve[4], can be understood by assuming that any current of spins is carried by two 'types' of carriers, spin-up and spin-down. The two-channel picture of spin transport proposed by Mott[5] explains the behaviour of magnetoresistive devices[6–10], including GMR and tunnelling magnetoresistance[11] (TMR), as well as spin injection into metals[12]. This theoretical treatment does not treat spin 'coherence', in which a persistent component of the spin can be maintained transverse to an applied magnetic field or magnetization. Even though respectable spin-coherence times had been measured via electron spin resonance[13] in materials used for spin transport, and although spin coherence was verified in several of the situations above (such as spin injection) it was not central to the phenomena probed, which we refer to as 'non-coherent spintronic devices'. A second generation of metallic spintronic phenomena requires a recognition of the importance of 'spin coherence', in which spin orientations transverse to the magnetization of magnetic domains, to internal effective magnetic fields, or to the orientations of other spin populations, are important in the overall dynamics or material properties of a system. Examples of coherent spintronic properties include current-induced precession of the magnetization of magnetic materials[14,15] and the spin Hall effect in aluminium[16]. These phenomena would be used in 'coherent spintronic devices'. By any measure the progress in metallic spintronics has been exceptionally rapid, with revolutionary commercial devices available within ten years from the discovery of fundamental physical effects. More common timelines from discovery to the marketplace are 20–30 years.

Semiconductor spintronic device physics is progressing along a similar path to metallic spintronics and has achieved remarkable success in the past decade. A timeline of selected key experimental demonstrations since 1994 is shown in Fig. 1. Measurements of exceptionally long room-temperature spin-coherence times in non-magnetic semiconductors (three orders of magnitude longer than in non-magnetic metals)[17,18] preceded the convincing demonstration of high-efficiency semiconductor spin-injection from a spin-polarized material[19–25] and of coherent spin transport in non-magnetic semiconductors[26]. Initial theories of electronic spin transport, within the two-channel model, emphasized the importance of drift for the motion of spin-density packets in semiconductors relative to metals[27–31], and have more recently tackled the fundamentals of diffusive spin transport in magnetic fields[32]. The optical accessibility of spin in semiconductors, which permitted early studies of spin dynamics[33], has eased the observation of coherent phenomena in spin transport, including spin precession in an internal crystal magnetic field (without any applied magnetic field)[34], electrically driven motion of domain walls[35], and the spin Hall effect[36–39] (before it was discovered in metals)[40–44]. Rapid progress towards room-temperature effects has been seen over the past couple of years, suggesting that room-temperature devices based on semiconductor spintronics may

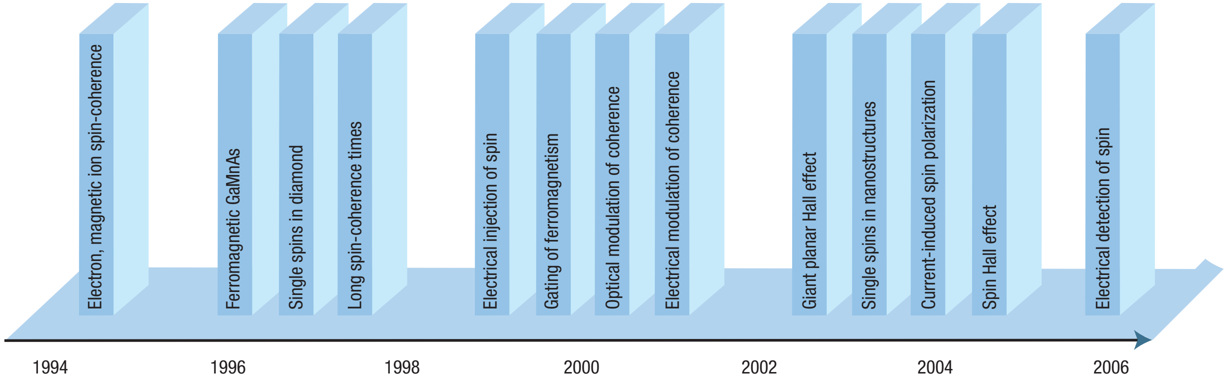

**Figure 1** Timeline of key experimental discoveries since 1994 in semiconductor spintronics. The pace of progress continues to increase, and with the recent demonstration of electrical detection of spin, all essential elements for a semiconductor spintronic technology have been demonstrated under some experimental conditions.

be soon possible. Here we are not treating the highly successful area of spins in semiconductors for solid-state quantum computation — for a review see ref. 45. Our focus here is on ensembles of spins, especially for near-room-temperature operation.

In addition to manipulating spin dynamics within non-magnetic materials, semiconductor spintronics offers materials possibilities very unlikely in metal systems. Electrical control of the Curie temperature[46] or coercive field[47] of ferromagnetic semiconductors has been demonstrated. These phenomena require depleting the carrier concentration within the materials by a substantial fraction, a requirement that would be exceptionally challenging for ferromagnetic metals (with carrier concentrations three or four orders of magnitude higher). The highly coupled spin-orbit character of the magnetic dopants present in these systems provide additional possibilities for coherent spin manipulation[48], using electric fields instead of magnetic ones to manipulate the spin degree of freedom. Figure 2 shows a metallic spintronic MRAM device from Freescale, and the demonstration of domain-wall motion due to current in the magnetic semiconductor GaMnAs. This effect might eventually permit the development of an MRAM technology based on magnetic semiconductors.

## POTENTIAL ADVANTAGES OF SEMICONDUCTOR SPINTRONICS

### LOGIC

Charge-based switching devices differentiate between a ‘0’ and a ‘1’ by the location of a small quantity of charge. For example, a field-effect transistor is ‘on’ if the channel is charged and thus metallic, and is ‘off’ if the channel is not charged, and thus insulating. This switching device can be imagined as two wells separated by a barrier of adjustable height. This barrier must be high enough so that a charge placed in one well will stay there, but must be lowered to move the charge from one well to another. In separate analyses several authors have found a minimum switching energy to move from one configuration to another, $E_{\text{bit}} = kT\ln2 \sim 23$ meV (ref. 49). This limit is fundamental for charge-based switching devices that are, once the charge is placed in one of the wells, allowed to reach thermal equilibrium. However, current and projected semiconductor logic devices are still far from this limit, for the minimum switching energy is derived assuming adiabatic (slow) charge motion, and the desired switching speed of semiconductor logic devices is fast and continues to increase. The projected gate-switching energy in 2018 for low-standby-power CMOS and a 10 nm gate width is 15 eV, which is three orders of magnitude larger than the theoretical minimum[50].

Information encoded in the electron spin orientation, rather than the position of a pool of charge, is not subject to the above limitations on switching energies. A pool of spin-polarized electrons will maintain its spin orientation without the presence of any barrier between spin-up and spin-down states for times exceeding 10 ns at room temperature in common semiconductor materials. Changing the information from a ‘1’ to a ‘0’ would consist of applying a small magnetic field, which as described below can be a real magnetic field or an ‘effective’ field, to coherently rotate the spin by 180°. Thus none of the operations involving electron spin need to raise or lower a barrier to charge motion. If the operations are done coherently the minimum switching energy derived for charge-based information processing does not apply. Even when the motion of charge (such as in an electrical gate contact) is used to manipulate spin, the switching energy of a fast spin-based device can be much closer to the fundamental limit than a charge-based device[51]. Semiconductor spintronic devices thus would avoid the above thermodynamic limitation of a minimum switching energy by remaining out of equilibrium for long periods of time (of the order of the spin coherence times).

Coherent semiconductor spintronic devices, by virtue of the exceptionally long room-temperature spin-coherence times discovered in ordinary semiconductor materials[17,18], could in principle perform multiple independent operations before the carriers reach thermal equilibrium. Interference of spin packets is one example, whereby two packets with spin polarizations oriented at 90° to each other generate a new packet with spins oriented at 45° to the two original packets (interference in a ring structure has been demonstrated[52]). Routing of spins via the spin Hall effect may be possible, as the sign of the spin Hall conductivity depends on the mobility[53], and thus could be tuned either by an applied ordinary voltage or an applied spin-bias[54].

Speed is another essential concern for next-generation information-processing devices. In charge-based devices the speed is limited by the capacitance of the device and the drive current. As the semiconductor spintronic device is a coherent one, the speed limitations are given by typical precession frequencies of electron spins, and range from GHz to THz. For example, in order to coherently rotate a spin by 180° at a THz rate, an energy splitting of the order of 3 meV must be generated between the up and down spins. This energy splitting is an order of magnitude lower than the thermal energy at room temperature. This is both a benefit and a danger for semiconductor spintronics. Local thermal equilibrium cannot be relied on to keep the information ‘safe’, even during a logical operation. Thus the system must be sufficiently isolated from the environment (stray magnetic fields in particular) to perform its operation robustly.

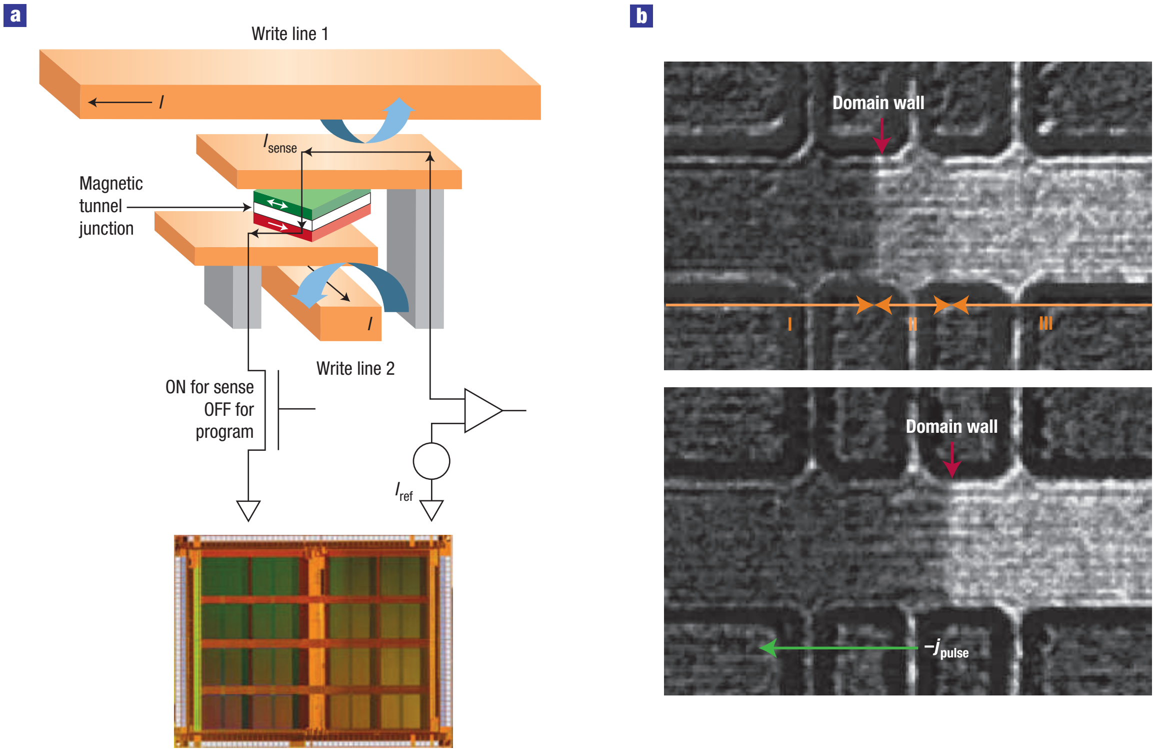

**Figure 2** Electrical reorientation of magnetic domains in metals and semiconductors. **a**, Schematic diagram of MRAM produced by Freescale. (Figures from http://www.freescale.com/files/memory/doc/white_paper/MRAMWP.pdf). $I_{sense}$ is the sensing current. $I_{ref}$ the reference current. The white arrows represent the free and fixed magnetization orientations. **b**, A domain wall in GaMnAs is electrically controlled at low temperatures using current pulses. The domain wall image in the initial position (top panel) and final position (bottom panel) are imaged using MOKE. Three regions (I, II, III) having different GaMnAs thicknesses were made to pattern coercivity and to confine the domain wall in region II. $J_{pulse}$ is the current that moves the domain wall from one side of II to the other. This experimental demonstration (from ref. 35) sets the stage for similar device developments in semiconductor spintronics.

### STORAGE

Non-volatile storage and logic have traditionally been performed by independent technologies. The dominant technological implementation of non-volatile storage is through the magnetic orientation of media, such as on the platters in hard disks. MRAM, which uses magnetism to store information without moving parts, has become available commercially this summer from Freescale. However MRAM, like other magnetic non-volatile storage, relies on magnetic metals and insulators — not semiconductors. If the fundamental physical phenomena underlying MRAM can be demonstrated at room temperature in semiconductors it may be possible to integrate non-volatile storage directly into logical processors. Spin transfer torque, the current-induced reorientation of the magnetization of a magnet[55,56] that is central to second-generation MRAM, has been demonstrated in the magnetic semiconductor GaMnAs, albeit at low temperature (Fig. 2). Even more promising is the possibility of integrated magnetic transistor devices, which blend non-volatility or reprogrammability with the central transistor property of gain. These magnetic transistor devices, such as the unipolar spin transistor[57] or the magnetic bipolar transistor[58], have yet to be demonstrated.

Long-lived polarizations are also possible within the nuclear system. Substantial effective nuclear magnetic fields (>1 T) can be generated via the Overhauser effect[59,60] and persist for many minutes with only a small applied magnetic field (0.15 T), although at low temperature. These could be used for optoelectronic coupling, or for reprogrammable logic, and have been demonstrated both in ring interference[52] and in all-optical NMR[61].

### COMMUNICATIONS

Isolation of one optical component of a communications system from the other optical components is achieved through one-way transmission of light. This ‘non-reciprocal’ transmission requires a magnetic component, otherwise the time-reversal invariance of the apparatus will guarantee that the transmission properties for light travelling in one direction will be the same as the properties for light travelling in the other direction. Thus magneto-optical elements (Faraday rotators) play a key role in the laser systems central to current communications. Although the magnetic orientation of such an element can be changed with an applied magnetic field, the material properties themselves are inflexible. Metals and insulators cannot be sufficiently changed by applied electric fields to provide markedly different magnetic properties. Magnetic semiconductors, however, can have their Curie temperatures significantly changed[46] as well as their magnetic easy axes by an electric field[47]. Electrically gatable Faraday rotators would provide a seamless coupling between linear optics and electrical signals, potentially with less optical loss than typical for electro-optic modulators working via the quantum-confined Stark effect. High-speed optical switches based on spin have also been suggested and demonstrated at room temperature; here, the very fast spin lifetimes in some materials, or the tunable nature of the spin lifetime with electric fields, provides advantages over charge-based switches. Spin-based lasing may provide ways to efficiently modulate high-power semiconductor lasers, as the carrier density in an active region would not need to be changed, the intensity of the emitted coherent light could be modulated by controlling the degree of spin polarization of the current injected into the active region.

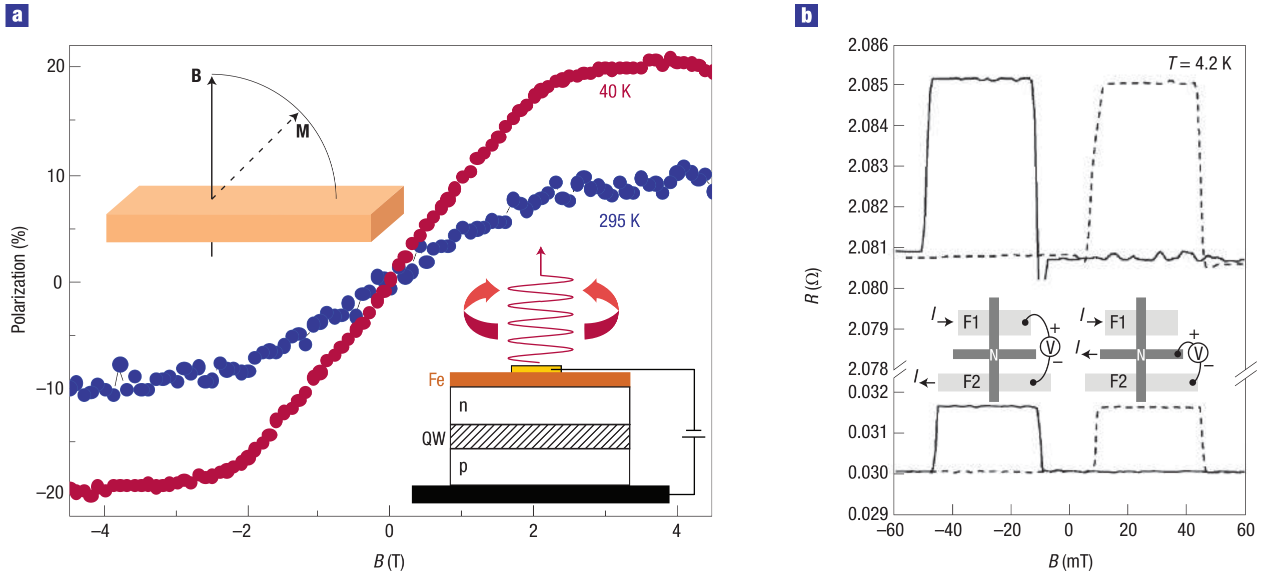

**Figure 3** Spin transport through non-magnetic semiconductors and metals. **a**, Electroluminescence polarization in an Fe/Al$_{0.1}$Ga$_{0.9}$As spin-LED. A schematic of the device is shown in the lower inset. Spin-polarized electrons injected from Fe recombine with holes in the quantum well (QW). The magnetic field (*B*) rotates the magnetization (*M*) of the Fe film out of the plane (upper inset). Reprinted with permission from ref. 23. Copyright (2005) by the American Physical Society. **b**, Spin-valve effect (top curve, and left cartoon) and non-local electrical detection of spin injection (bottom curve, and right cartoon) in a lateral metallic spin-valve device[75]. *R* is resistance. In the ordinary spin-valve measurement, the current *I* flows from ferromagnetic contact F1 through the normal metal N to ferromagnetic contact F2, and the voltage is measured between F1 and F2. In the non-local measurement, the current flows from F1 into the normal metal N, and the voltage is measured between the detection contact F2 and a reference contact on the normal metal. Reprinted with permission from ref. 75. Copyright (2003) by the American Physical Society.

### QUANTUM COMPUTATION

Spin-based solid-state approaches for quantum computation provide the potential for fixing isolated quantum degrees of freedom in space, by embedding quantum dots or ions within a solid matrix, and then addressing those degrees of freedom with small electrical contacts. Progress in understanding the coupling between spin degrees of freedom and electrical fields[48,62–64], principally through the spin-orbit interaction but also through nanomagnetic fabrication[65], avoid some of the problems with producing highly localized a.c. magnetic fields. Extremely long room-temperature spin-coherence times, such as 350 μs for nitrogen vacancy centres in diamond[66], and short gate times[67], provide ratios of coherence times to gate times that exceed $10^3$. Through the coupling of the spin degree of freedom of an electron to optical fields there is a clear method of coupling photons into and out of a spin-based quantum computer[68], and those photons can have wavelengths compatible with current communications.

### MULTIFUNCTIONALITY

As mobile phones and other gadgets become smaller and more powerful, one could consider whether all the elements of modern information manipulation (logic, storage and communication) could be combined and performed on a single chip. Some of the applications of spintronics described above are in the area of low-power electronics, so such a multifunctional chip might make possible complex but inexpensive submicrometre remote sensors.

## CHALLENGES AND ADVANCES IN SEMICONDUCTOR SPINTRONICS

### LOGIC

Improving or optimizing a spintronic device requires attention to very different problems than for charge-based devices. Optimization of charge transport usually means efficient transfer of charge current from one region to another, or conductivities that are very sensitive to gate voltages. Thus in some regions large doping densities, and in other regions large electric fields, are useful for shuttling the charges efficiently around a chip. Designers of spin devices have to worry about the loss of spin polarization or spin coherence, wherein a carrier that is spin polarized in one direction effectively turns into another 'charge'. Two of the accelerants for spin decoherence are large doping densities for semiconductors and large electric fields[33,69,70]. Both for large doping densities and large electric fields a spin-polarized carrier will experience a large, randomly oriented, internal effective magnetic field.

These accelerants are now significant barriers towards achieving nearly 100% efficient spin injection from a ferromagnetic metal into a semiconductor and similarly efficient spin detection. The initial challenge for spin injection, however, was quite different, and was traced to the substantial difference in conductivity between most ferromagnets and semiconductors[71]. This difference made it difficult for the ferromagnet to drive a large enough chemical potential difference between spin-up and spin-down in the semiconductor. Inserting a spin-dependent interface resistance from a Schottky barrier or tunnel barrier resolves this problem[72–74], and the effect of spin-density drift in the semiconductor also helps[29,30]. Spin injection from a ferromagnetic metal into a semiconductor has been demonstrated experimentally with this approach using the spin-dependent resistances of Schottky barriers[21,23], and oxide insulators[22]. The room-temperature efficiency of spin injection now exceeds 70% (ref. 24), and further progress is expected as materials and interface physics improves. Engineering the device doping and field profile region will therefore be required in the design of optimally performing semiconductor spintronic chips. Shown in Fig. 3 are results for optically detected spin injection into a semiconductor through a Schottky barrier (reported in ref. 23) and for electrically detected spin injection into a metal[75]. A successful

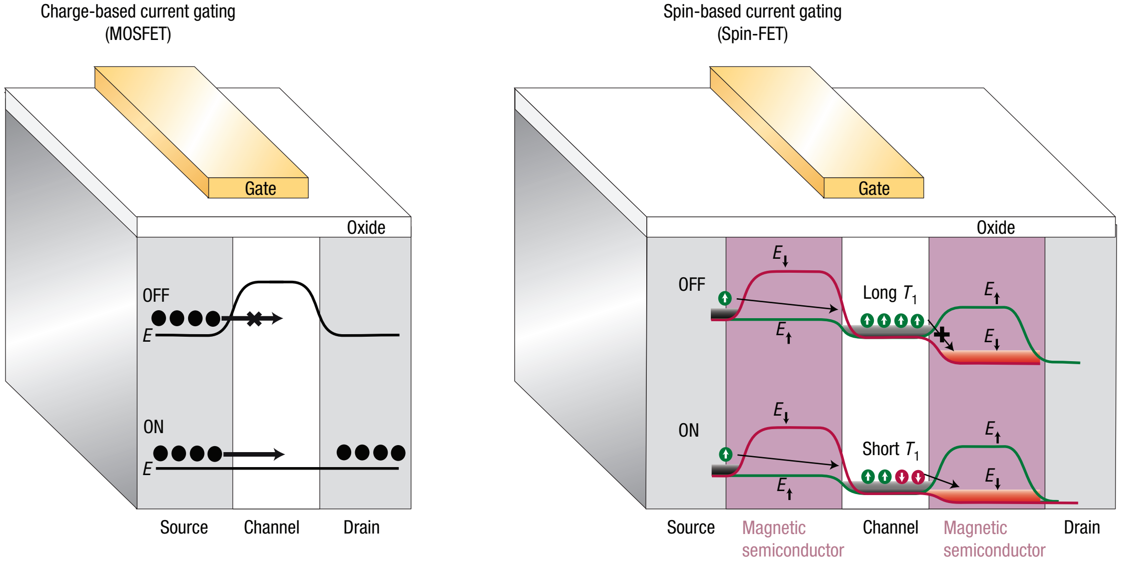

**Figure 4** Schematic structure of a MOSFET (left) and a spin-FET (right). MOSFETs work by raising and lowering a barrier to turn the current on or off. A magnetic semiconductor spin lifetime FET uses static spin-dependent barriers and changes the spin character of the electrons in the channel to turn the current on or off. Reused with permission from ref. 51. Copyright 2006, American institute of Physics.

non-local electrically detected spin-injection experiment sensitive to precession has also been performed for a semiconductor[76].

Spin injection and detection can be considered the 'input' and 'read-out' stages of a logic device within which the spin is manipulated by external or internal magnetic fields or by spin-selective scattering. It has been demonstrated that the internal effective magnetic fields in semiconductors with spin-orbit interactions can be used to reorient spins and also to drive magnetic resonance[34]. These effective internal magnetic fields can be manipulated with applied external electric fields[77,78], which implies new gating mechanisms for spin-based transistors[79]. Furthermore the separation of spins can be achieved through the recently demonstrated spin Hall effect, first seen in semiconductors[40–42,44], later in metals[16], and most recently at room temperature[43]. Control of the spin Hall effect via control of the material mobility may be used to change spin currents in magnitude or even direction[54], using a controllable spin Hall effect to route spins for logic. Finally, it might be possible to do away with magnetic materials entirely due to the achievement of spontaneous spin polarization at room temperature in a non-magnetic semiconductor[80,81].

## STORAGE

Many of the ferromagnetic semiconductor materials have extremely high carrier-doping levels, and controlling the interfaces of these materials is a great challenge. If novel storage devices based on ferromagnetic semiconductors are to be attempted, then achieving ferromagnetism in lower-doped semiconductor materials will be highly desirable. There are some indications that this might occur naturally at the edges of ferromagnetic materials, as the carriers are depleted from the region but magnetism remains[82].

Only very recently has there been a report of a p–n diode made with a ferromagnetic material[83,84] — previous attempts led to poor diodes because the doping level in the intrinsic, or depletion, region was too high to support a significant voltage. Another recent achievement was the demonstration of exchange biasing in magnetic semiconductors[85]. A central element of metallic MRAM, exchange biasing will be a key element of semiconductor spintronics storage technology.

## COMMUNICATIONS

Optics and ferromagnetism has turned out to be a dirty partnership so far in GaMnAs. The optical lifetimes are so short, unlike for non-magnetic semiconductors, that it was some time before they could be measured[86]. As the desired magneto-optical devices typically require substantial Faraday rotation without significant optical losses, magnetic semiconductors have not been successful at dislodging magnetic insulators from this niche. Experiments on CdMnTe and CdMnHgTe optical isolators, however, suggest competitive values to yttrium iron garnet for the optical rotation relative to optical loss[87,88] in a material that can be monolithically integrated on a semiconductor substrate. A semiconductor waveguide with an integrated ferromagnetic metal clad has also shown good performance as an optical isolator[89].

As the materials become cleaner and more controlled the magneto-optical properties should improve further. It has been discovered that much cleaner GaMnAs could be achieved through very long low-temperature post-growth annealing. At the same time the optical properties of very lightly doped GaMnAs seem quite good, even though the material itself is not doped sufficiently to become ferromagnetic. New discoveries of ferromagnetic semiconductors suggest there should be materials with better optical properties, such as ZnCrTe. Whether this material is a carrier-mediated ferromagnet or not is not clear yet, although it is dopable and the magnetism has a large influence on the optical properties.

## QUANTUM COMPUTING

The achievement of large-scale quantum-information processing in any physical system will be a tremendous success. Recent experimental advances in semiconductor spintronic quantum computing include the demonstration of long $T_1$ and $T_2$ times in semiconductor quantum dots (albeit at low temperatures[45]), the demonstration of coherent single-spin manipulation in diamond, and numerous examples of gate operations performed on ensembles of spins[90–92], but expected to be extended to single-spin manipulation in quantum dots or embedded ions in the near future.

## SURPRISES AND (VERY) OPEN QUESTIONS

### *Do we need magnetic materials for a functional semiconductor spintronic technology?*

Current-induced spin polarization and the spin Hall effect have both been demonstrated at room temperature[43]. If the current-induced spin polarization can be made large enough this effect could replace spin injection from a ferromagnetic metal as the central method of injecting spins into non-magnetic semiconductors at room temperature. Similarly a spin-Hall-effect detector could replace the need for a ferromagnetic detector contact to electrically measure spin polarization at room temperature. Manipulation of the spins could be done using internal effective magnetic fields[34,93] or perhaps using the spin Hall effect to directly drive resonance[94].

### *Are there interesting semiconductor spintronic devices that do not require large $T_2$ times?*

Although much of the initial interest in semiconductor spintronics was due to the exceptionally long spin-coherence times seen in ordinary semiconductor material, theoretical work indicating that $T_1$ times can be tuned by orders of magnitude at room temperature[70] seems to provide a pathway to a new switching mechanism for a spin-field-effect transistor[95,96]. Comparisons of the scaling properties of this approach to CMOS indicate that spin-based field-effect transistors could compete with end-of-roadmap CMOS for low-standby-power devices[51]. Elegant approaches to balancing precessional transport in lateral devices might permit efficient spin manipulation of ensembles, but in the diffusive regime[97] rather than the ballistic regime[79].

An example of such a spin transistor device is shown in Fig. 4, and compared with a MOSFET. A MOSFET works by controlling the height of a barrier to electron flow, with the barrier height and width largely determined by the desired on–off current ratio and leakage current. The spin-based FET has static spin-dependent barriers (generated by a magnetic insulator or magnetic semiconductor), and works by controlling the spin lifetime in the base[95]. Application of an electric field generates an effective magnetic field[98] (a 'Rashba field'[99]), which decoheres the spins. As the spin orientation of the source–channel barrier and channel–drain barrier are opposite to each other, current only flows if the spin lifetime in the channel is short. For the spin-FET the inputs and outputs are incoherent, but the transistor mechanism is spintronic. It has been argued that the spin lifetime FET device shown in Fig. 4 has superior power-dissipation properties to end-of-roadmap CMOS[51]. The requirements for spin lifetimes in the absence of a gate field and for spin-injection efficiency, however, are very high for this device. Multi-lead devices with coherent inputs and outputs might provide even better performance.

### *What is the connection between spin-coherence times and optical coherence?*

Remarkable measurements of the lasing threshold dependence of a semiconductor microcavity on the $T_2$ time of a spin in a quantum dot inside that cavity suggest that semiconductor spin-coherence could be closely tied to optical coherence in microcavity geometries[100]. This might provide efficient ways of transmitting information from single photons to single spins, or be used to generate a hybrid device for quantum-information processing with both optical and spin components.

### *What might exotic materials provide for semiconductor spintronics?*

Individual defect centres in diamond have been coherently manipulated to demonstrate magnetic resonance[90–92] at room temperature. Rapid advances in controlling the electrical and optical properties of this system may lead to future diamond-based technologies. Other wide-bandgap materials such as oxide semiconductors also seem promising for room-temperature spintronic devices.

### *More physics or more engineering?*

Perhaps the mechanism for driving the next new technology based on semiconductor spintronics is already known, and among the wide variety of interesting device physics effects produced from the past decade of intensive research. It may now be time for circuit designers and systems engineers to take a closer look at these demonstrated mechanisms to see how a semiconductor spintronics architecture should be assembled. Even if that is not yet possible, systems and circuit engineers may greatly help the field of semiconductor spintronics by identifying those areas that most need progress in order to achieve a commercially viable technology.

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## Competing Interests

The authors declare that they have no competing interests.