Meet the spin doctors . . .

A small band of researchers is plotting a revolution in electronics — one that exploits the spins of electrons, rather than their charges. Philip Ball profiles the emerging field of spintronics.

The last time electronics was reinvented was in 1948, when Ralph Bown, research director of Bell Laboratories in New Jersey, announced “the electrical equivalent of a vacuum tube amplifier”. “We have called it the transistor,” he told the press.

At the time, not even the transistor’s inventors, Bell Labs researchers John Bardeen, Walter Brattain and William Shockley realized just how revolutionary their semiconductor device would be. It changed the conceptual landscape of electronics. No longer would electronic engineers think in terms of electrons travelling along metal wires or through a vacuum. Instead, they were able to construct gates and interfaces with which to manipulate the ‘charge carriers’ in semiconductors — electrons and positively charged ‘holes’.

The latest reinvention of electronics may herald a similar conceptual revolution. Some call the field magnetoelectronics. But it is the catchier tag of ‘spintronics’ that best illustrates the new discipline’s departure from conventional electronics. Rather than using electrical fields to manipulate a flow of electrons using their charge as a handle, spintronics marshalls electrons through their spin.

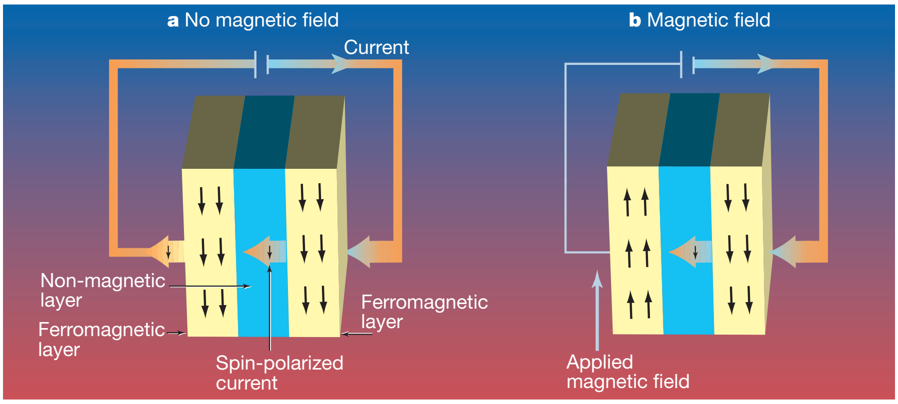
Metaphorical marvel

The spin of an electron is a quantum-mechanical metaphor that arises from Paul Dirac’s relativistic wave equation, derived in the late 1920s. Spin is a characteristic as fundamental as charge, but has no analogue in the macroscopic world. An electron does not spin like a top, but it can nevertheless be described by a quantum number characteristic of its intrinsic angular momentum. And because the spin of an electron imparts a magnetic moment, electrons can be manipulated by magnetic fields.

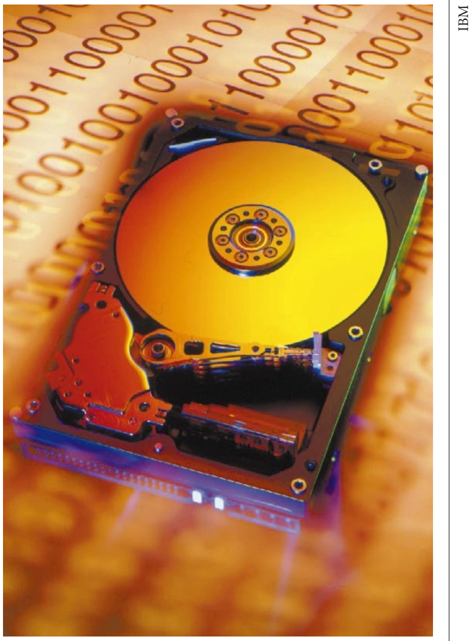
It is still too early to say whether spintronics will sound the death knell for conventional microelectronics, just as silicon devices did for the vacuum tube. But in principle, it could move electronics from a technology grounded in classical physics to one that fully exploits the quantum nature of electrons — perhaps preparing the way for ultrapowerful quantum computers.

Yet even if this young field produces nothing more spectacular than a handful of useful devices, it should have a powerful impact on information technology. Companies including IBM and Motorola are investing heavily. The US Defense Advanced Research Projects Agency (DARPA), the high-tech research arm of the Pentagon, plans to spend “well over US$100 million” on the field over the next few years, according to Stuart Wolf, who oversees the agency’s spintronics projects.

Indeed, magnetoelectronic devices are already in commercial use, as read-out heads for computer hard drives. The market for these devices, which were introduced by IBM in 1997, is now worth around $1 billion per year. The read-out heads exploit an effect called giant magnetoresistance (GMR), which occurs in multilayer ‘heterostructures’ composed of alternating thin films of a ferromagnetic metal, for example cobalt or iron, and a non-magnetic metal such as copper. The electrical resistance of these structures can be altered profoundly by a magnetic field.



A spin valve in action. a, **With no magnetic field, the spin-polarized current can flow.** b, **When a magnetic field is applied, the spin-polarized current cannot pass through both ferromagnetic layers.**



Well read: spintronics has dramatically increased data storage densities in hard drives.

IBM

Like all spintronics devices, GMR multilayer structures rely on spin-polarized transport: a flow of current in which electrons are in a spin-aligned state, either spin ‘up’ or ‘down’. This arises naturally in ferromagnets. When such a material is magnetized, the spins of its constituent atoms all align in one direction. Electrons passing through a thin film of the magnetized ferromagnet acquire this same spin bias, creating a partially spin-polarized current.

In GMR hard-drive read-out heads, a current of this type is created when electrons pass through the first magnetic layer. Whether this current passes through the next ferromagnetic layer depends on whether the spins of its electrons are aligned with those of the atoms of the layer. Only if this is so can the current pass freely. In GMR multilayers, the magnetization — and therefore the orientation of the atomic spins — in successive ferromagnetic layers alternates. So the passage of a spin-polarized current is hindered. (Because the spin polarization conferred on a current is only partial in ferromagnetic metals, a small amount current still flows.) But if an external magnetic field is applied, which aligns the spins of all the ferromagnetic layers, the barrier to spin-polarized transport is removed and the resistance drops.

The result is an electronic device that is very sensitive to external magnetic fields. Hard-drive read-out heads based on this principle can register smaller magnetized domains than the previous generation of devices, which used a much more modest magnetoresistive effect in permalloy, an alloy of iron, nickel and molybdenum. Already, this has allowed storage densities of commercial hard drives to be increased by a factor of three. Given recent laboratory findings, Stuart Parkin of IBM's Almaden Research Center in San Jose, whose group pioneered work on GMR read-out heads, has no doubt that it will be possible to improve storage densities a further several-fold.

Memorable events

In the early 1990s, Parkin's group proposed that, for fully spin-polarized currents, a mere three-layer device of this sort can act as a 'spin valve'. These devices comprise a film of non-magnetic metal sandwiched between two films of ferromagnetic material. A spin-polarized current will pass when the magnetization is aligned in the two ferromagnetic layers, but will be totally blocked if the magnetization of just one of them is flipped, for example by a nearby electromagnetic induction loop (see diagram). This is, in essence, the GMR effect taken to its extreme.

Once flipped, the magnetic film in a spin valve retains its direction of magnetization until it is switched once again. This means that the device can act as a memory element. Switching is fast and easy but, unlike the switching in transistors, the device retains its switched configuration when the power is turned off. This means that spintronics could furnish computers with 'non-volatile' magnetic random-access memories (MRAMs), which are not wiped clean by a power failure. They would be particularly valuable on board satellites, where a temporary loss of power can be catastrophic.

Prototype MRAMs consisting of arrays of electrically connected spin valves have been developed by Honeywell, IBM and Motorola. In terms of storage capacity, Honeywell has led the way: for military use, it is producing MRAMs in the megabit range. These are too expensive for consumer applications, but IBM has achieved affordable MRAMs of about 1 kilobit capacity with access times of less than 3 nanoseconds — comparable to those of conventional semiconductor RAMs. These devices all use a subtly different and stronger magnetoresistive effect that depends on 'spin-dependent electron tunnelling'. This is a quantum-mechanical property of electrons that allows them to travel across an interface between two materials even when, according to classical physics, they do not have sufficient energy to do so.

In theory, similar spintronic devices might be used not just for information storage, but also as logic gates — the building blocks from which the circuitry of a microchip is constructed. Not only are spintronic logic gates potentially very fast, but they could also be reconfigured by applying magnetic fields. A prototype device of this type was reported in February by Russell Cowburn and Mark Welland of the University of Cambridge[1]. "But no one has demonstrated that you can reliably write and reconfigure a processing function in such a circuit," cautions Parkin. He believes this may prove very difficult to achieve.


Ohno: pioneering semiconductor spintronics.

Semiconductor sandwiches

Another obstacle for spintronics is that electronics companies are geared up to working with semiconductors, not metals. So one important goal is to make devices using semiconductors that are compatible with existing chip technology. The problem is that the conventional semiconductors used in integrated circuits — primarily gallium arsenide (GaAs) and silicon — are not magnetic. At least, they never used to be. Now, however, several research groups are exploring ways of turning these semiconductors into ferromagnetic materials.

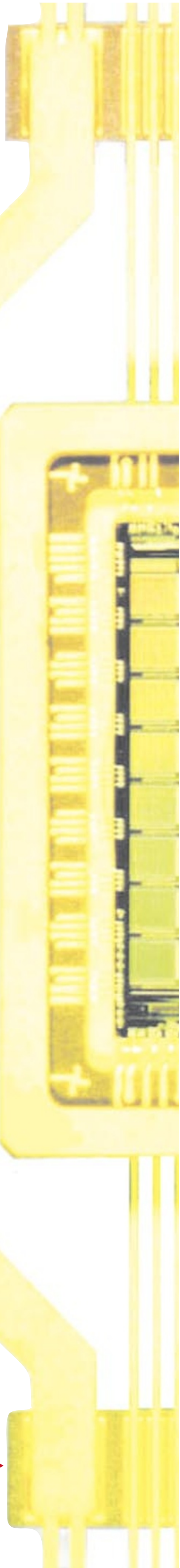
Hideo Ohno of Tohoku University in Japan is one of the pioneers. In 1996, his team showed that ferromagnetic atoms such as manganese can be introduced into GaAs chips fabricated by molecular-beam epitaxy (MBE) — a technique that deposits materials one atomic layer at a time. The solubility of manganese in GaAs is normally very low, but MBE can create a material in which up to 7 per cent of the gallium atoms are substituted for manganese[2]. This alloy behaves as a ferromagnet at temperatures up to 110 K.

Spintronics will offer completely new kinds of functionality in microelectronics.

Using this doped material, Ohno and his colleagues have made a three-layer device based entirely on GaAs, in which the non-magnetic layer consists of aluminium gallium arsenide. Earlier this month, they reported observing a magnetoresistive effect[3]. But "it's not giant, yet", says Ohno — the device does not behave as a fully switchable spin valve.

The biggest problem in building such devices is sustaining spin-polarized transport across the interfaces between different materials. Interfaces between semiconductors and ferromagnetic metals, where a double layer of charge carriers forms, are especially problematic. This 'Schottky barrier' lets current flow in only one direction and can scatter charge carriers moving across the interface, which leads to loss of spin polarization. Last year, however, a team led by Mark Johnson of the US Naval Research Laboratory in Washington DC claimed to have injected a spin-polarized current from a nickel–iron alloy into a semiconductor[4]. But the reported efficiency was low, which would make spin valves based on such composite structures extremely leaky.

Injecting spin across the interface between two semiconductors — one magnetic and one non-magnetic — should be easier, because there is no Schottky barrier. And late last year, two groups succeeded in transporting a spin-polarized current across such a junction. Laurens Molenkamp and colleagues at the University of Würzburg in Germany used ▶


HONEYWELL

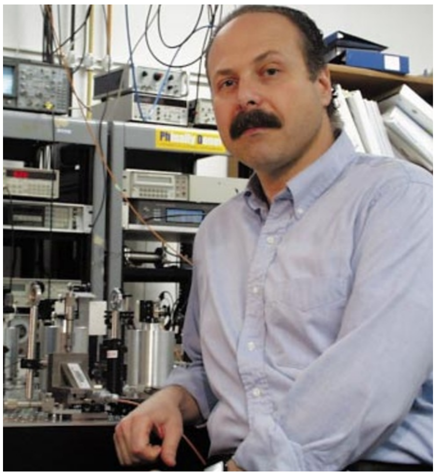
Magnetic memory: Honeywell uses spintronics in its RAM chip.

the magnetic semiconductor zinc selenide doped with beryllium and manganese as the spin-aligning ferromagnetic layer[5]; Ohno, working with David Awschalom's team at the University of California, Santa Barbara, used manganese-doped GaAs[6]. In both cases, the researchers passed their spin-polarized current into a GaAs-based light-emitting diode with an efficiency of about 90 per cent. Their success was confirmed by the fact that the emitted light was circularly polarized — a direct consequence of the spin polarization of the current.

These results imply that fully switchable all-semiconductor spin valves should be feasible, and Awschalom cautiously predicts that such devices will be demonstrated within the next few years. He also believes that a semiconductor spin transistor, which would amplify a current rather than merely switching it on and off, will be developed on a similar timescale.

Beyond MRAMs and spin transistors, there is an even more ambitious vision for spintronics: fully exploiting the quantum-mechanical nature of spin. Interest in this possibility has been stimulated by the idea of quantum computing. This offers the prospect of massively powerful information processing by manipulating quantum objects in a 'superposition' of states. Using the language of classical physics, a spin is either up or down, but quantum mechanics means that it can also be held in a superposition that is simultaneously up and down. This makes spin an ideal candidate for the quantum bits (qubits) of quantum computing. Whereas the binary-encoded bits of classical computing have two available states, 1 and 0, qubits have more — greatly expanding computing power.

But processing information with many qubits requires that they are all maintained in a 'coherent' superposition — an interweaving in which none of the qubits is allowed to collapse into its up or down state. This is the hard part, because any interactions of the qubits with their environment tends to induce this 'decoherence', losing information.



Awschalom: a "genuine quantum electronics" would exploit electrons' wave-like properties.

However, recent studies have raised hopes that it might be possible to sustain spin coherence among charge carriers in solid-state circuits. This is not the same as simply imposing spin polarization on a current, just as polarized light is not the same as a laser beam. Coherent spin carriers are not simply aligned but are coupled in a collective quantum state, described by a single wavefunction.

Extending the range

In 1997, Awschalom's team reported that electron spins could survive in a coherent state for more than 100 nanoseconds[7]. Then last year Awschalom and his colleague James Kikkawa managed to transport a coherent 'spin packet' of electrons over a distance comparable to the size of a typical electronic device[8]. They used a laser pulse to excite a spin packet in a sample of GaAs, and dragged it along using an electric field.

Awschalom's team has also succeeded in trapping coherent spin packets in semiconductor 'quantum dots' — crystals of cadmium selenide between 2 and 8 nanometres across[9]. This shows that qubits could be temporarily stored in a quantum computer without becoming scrambled.

Awschalom believes that creating coherent spin packets using light and probing for their existence optically, as his team has done, will become increasingly important. It will allow spintronics to interact with the field of optoelectronics, important in telecommunications. Information is generally transmitted over long distances as a series of light pulses in optical fibres. But at present, the signals must be converted back to electronic form for processing and storage, and this is an inefficient process. "The bottleneck is the photon-to-electron conversion," Awschalom explains. He believes this conversion can be achieved more efficiently in optically controlled spintronic devices.

> Spin is an ideal candidate for the quantum bits of quantum computing.

For quantum computing, meanwhile, many of the theoretical proposals invoke the manipulation of the spins of atomic nuclei, rather than those of electrons. This can be done using nuclear magnetic resonance, which usually relies on flipping nuclear spins using pulses of radio waves. However, Awschalom and Kikkawa have shown that it can also be achieved using light: by pulsing an optical beam at an appropriate resonant frequency, they were able to flip nuclear spins in GaAs[10]. The light pulses create packets of spin-coherent electrons, whose magnetic fields then influence the nuclear spins.

While practical quantum computers remain a distant prospect, spin coherence could be applied in simpler spintronic devices. Awschalom foresees a "genuine quantum electronics". Rather than treating electrons like tiny billiard balls, this would exploit their wave-like properties. In a coherent spin packet, the electron waves are all in phase. This might offer a new switching mechanism, using destructive interference effects to 'cancel out' two out-of-phase coherent spin packets. Awschalom predicts that this will offer "completely news kinds of functionality" in microelectronic and optoelectronic devices. For example, a team led by Sasha Hallstein of the Max Planck Institute for Solid State Physics in Stuttgart has already used electron spin coherence to construct an ultrafast optical switch[11].

With GMR read-out heads now in widespread use and MRAM devices soon to reach the market, spintronics is already starting to make its presence felt. Whether the microelectronics industry will embrace the vision of quantum electronics remains to be seen. But Wolf at DARPA is confident that the future is bright. "Spin hopefully will provide a host of new devices for very-high-speed, low-power electronics and optoelectronics," he says. ■

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