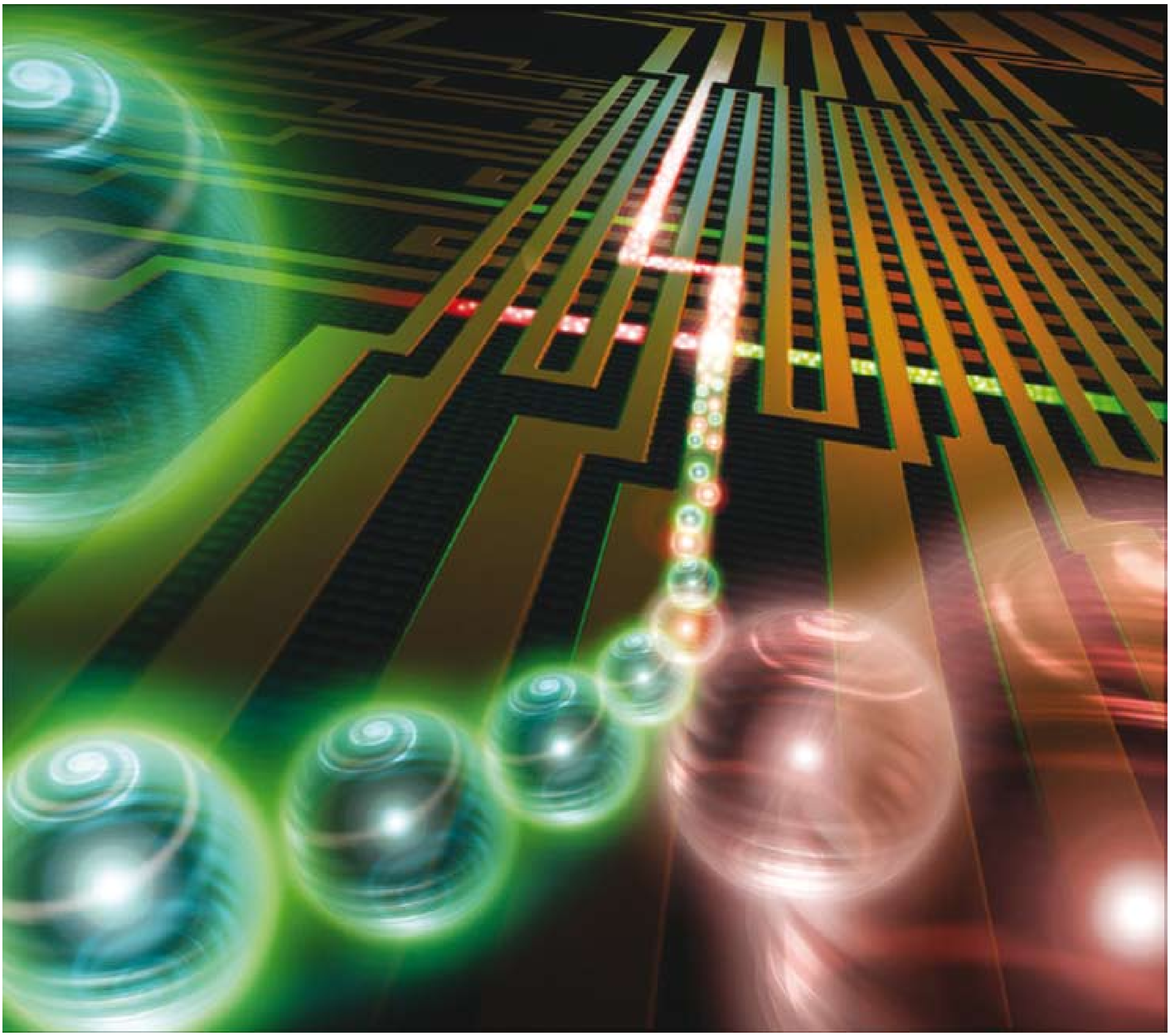
The spin doctors

Researchers around the world are looking to develop advanced computers based on electrons' spin, rather than just their charge. Matthew Chalmers examines how close the promised devices are to becoming reality

DAVID AWSCHALOM



It's a promise perpetuated in popular magazines, academic papers and grant proposals: hyper-functional magnetoelectronic computing devices that harness the spin of electrons. By allowing bits of information to be stored and processed natively in the same material, rather than in the separate memory and processor components of today's computers, 'spintronics' could revolutionise information technology.

Since the invention of the transistor in 1947, microelectronics has transformed our way of life by shunting electronic charge around transistors etched in ever smaller wafers of semiconductor, namely silicon. But were such components also able to process the intrinsic angular momentum – spin – of electrons, they would permit devices with far greater speed and functionality and which emit much less heat. Spintronics may be the only way to continue the miniaturisation trend of semiconductor electronics, which in the past four decades has seen the density of transistors on silicon chips double every two years (the latest processors pack around one billion in a few square centimetres). And to take that step into semiconductor spintronics, new materials are key.

Predicted in the late 1920s by Paul Dirac, spin is a quantum mechanical property of particles that, in conjunction with the Pauli exclusion principle, is partly responsible for the structure of the periodic table, dictating how many electrons occupy each shell. An electron has two possible spin states – plus or minus a half in units of Planck's constant divided by 2pi, but often simply called 'up' and 'down' – which causes it to line up like tiny bar magnet with or against the direction of an external magnetic field.

Because quantum mechanics permits an electron to be in a superposition of two spin states, of which there are an infinite combination, spintronics offers a route to a quantum computer with the ability to solve problems intractable with conventional microelectronics. Even a simple device that reads and writes information in terms of the angle of a single particle's spin could lead to an enormous increase in storage density and computing power. 'I'd say this is the major justification for working in semiconductor spintronics,' says Kees de Groot of the University of Southampton, UK.

Processing problems

Spintronic data storage devices based on magnetic metals are already big business. They lie in the hard-disk units of almost all computers, and originate from the Nobel-prize winning discovery of giant magnetoresistance (GMR) made independently in 1988 by physicists Albert Fert and Peter Grünberg (see box). But the full promise of spintronics – storing and processing information together – cannot be realised with metals. Instead, researchers need to perfect the art of spin manipulation in more functional materials such as semiconductors.

A major goal of spintronics is to develop reliable transistors – the workhorses of logic – that switch or amplify a signal depending on its spin. Designs for spin transistors have been around since 1990, but a potential commercial device seems far away. Despite huge progress in semiconductor spintronics in the past 15 years, researchers are only now beginning to find efficient ways to inject, transport and detect spin-polarised electrons in silicon.

Semiconductors, especially silicon, are better at preserving the spin of electrons than metals because they have fewer scattering mechanisms – for example due to weaker 'spin-orbit' coupling (the interaction between an electron's spin and its motion through the electromagnetic field of the nucleus, which shifts atomic energy levels). Moreover, in semiconductors such spin-orbit effects can be tuned via band-gap engineering, altering conduction and valence bands and the chemical potential, which allows the spins to be manipulated. In 1999 David Awschalom's group at the University of California in Santa Barbara, US, maintained record spin coherence over a distance of 100 micrometres in a chunk of the semiconductor gallium arsenide, for example, and last year Ian Appelbaum, now at the University of Maryland, US, and co-workers managed to transport spin-polarised electrons in silicon over a distance of several millimetres.

Getting a useful spin current into a semiconductor in the first place is a different matter (see box p48). One well trodden approach is to inject spin by shining circularly polarised light on a semiconductor and transferring the angular momentum of the photons to electrons (and detecting it via the reverse optical process). This works well in gallium arsenide, but not in silicon due to the material's

In short

- **Computing devices based on electron spin promise to be far faster and more powerful that current devices, which process information using electron charge alone**
- **Today's computer hard drives already exploit spintronic effects**
- **New semiconductor materials are needed before spintronic data processing becomes a practical reality**

Storage solutions

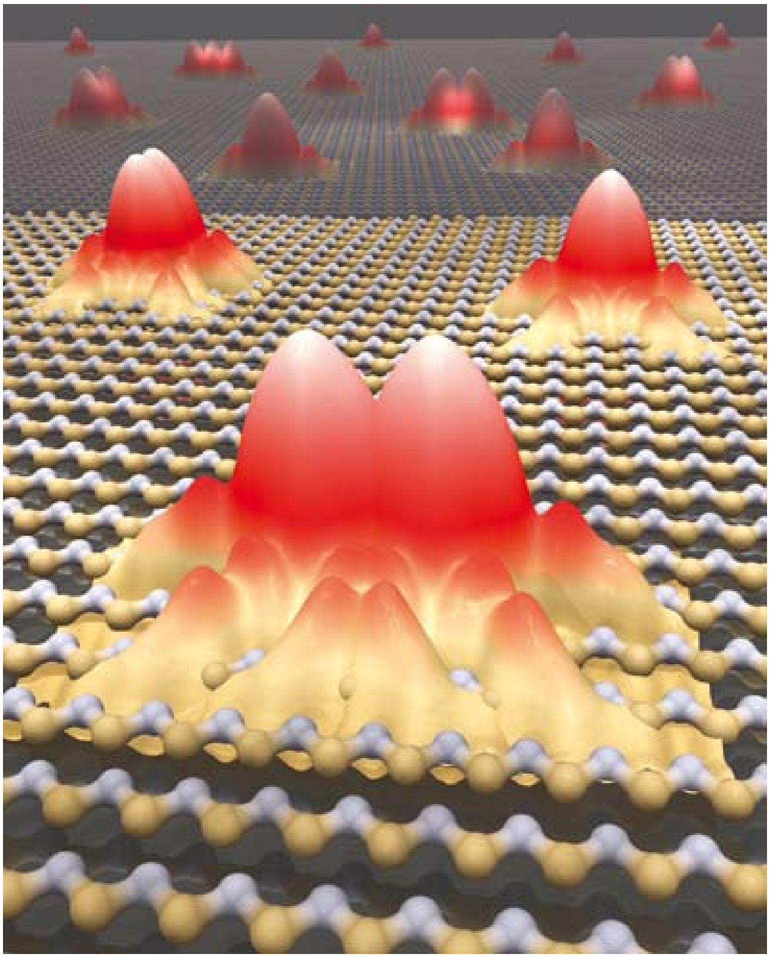
The Nobel prize winning discovery of giant magnetoresistance (GMR) in 1988 kick-started the spintronics revolution, becoming a commercial success for data storage within an astonishing 10 years. If you allow spin-polarised electrons (those in the same spin state) to diffuse through a thin film of alternating ferromagnetic and nonmagnetic metal layers, their motion will be restricted because the magnetisation of adjacent ferromagnetic layers naturally lines up in opposite directions. Switch those layers to being parallel using an external magnetic field, however, and they line up to reduce the resistance – by at least 70 per cent in today's devices. This 'spin-valve' behaviour has allowed the magnetic read heads of hard disks to be over a thousand times more sensitive to magnetic changes, allowing vast quantities of information to be stored in the magnetic regions on the disk surface.

A similar effect called tunnel magnetoresistance (TMR) promises non-volatile memory that stores information permanently without requiring electrical power, allowing computers to switch on instantly. Magnetic random access memory (MRAM) exploits quantum tunnelling across ferromagnetic-insulating layers. If the magnetic moments of neighbouring ferromagnetic layers are parallel (controlled by passing an electric current through an input line) electrons are able to tunnel between them, generating a low resistance which represents a '1'; the antiparallel state, in which the exclusion principle reduces the chances of electron tunnelling, is taken to represent a '0'. Room temperature TMR was first demonstrated in 1995, and in 2006 Freescale Semiconductor announced a commercial 1MB MRAM chip, while Motorola has demonstrated a 4MB MRAM chip.

A third type of metallic spintronic device was demonstrated in 2008 by Stuart Parkin and colleagues at IBM Almaden. Called 'racetrack' memory, it uses spin currents to directly manipulate the magnetic state of nanoscale domain walls within magnetic nanowires via a phenomenon called spin-torque switching, promising ultra dense solid-state memory with similar costs to magnetic disk storage.

Stuart Parkin also studies MRAM

IBM


DRS A. YAZDANI & D.J. HORNBAKER / SCIENCE PHOTO LIBRARY

Scanning tunnelling micrograph showing ferromagnetic interactions (red and yellow) in a gallium arsenide semiconductor doped with manganese

‘Semiconductor spintronics requires a breakthrough in basic materials’

weaker spin-orbit coupling and its indirect band structure. In any case, nobody wants cumbersome optical elements around when etching chips at the nanoscale.

One alternative is to inject spin polarised electrons from magnets. In 1999, Awschalom’s group, in collaboration with researchers at Tohoku University in Japan, injected spin from the ferromagnetic semiconductor GaMnAs into GaAs without using magnetic fields, while Laurens Molenkamp and colleagues at Würzburg University, Germany, employed the dilute magnetic semiconductor BeMnZnSe to inject spin into GaAs with a reported efficiency of 90 per cent, although at low temperatures and with the aid of an external magnetic field.

Dilute magnetic semiconductors (DMS), made ferromagnetic by doping the semiconductor with transition metal atoms, produce an army of spin-aligned electrons ready for injection across an interface into a pure semiconductor. The challenge is to find materials that can achieve this at room temperature without too much doping (which makes band engineering difficult) or the help of an external magnetic field. Efficient injection also requires atomically flat interfaces between the DMS and semiconductor in order to reduce chemical mixing between the materials, which disrupts the spin-states of passing electrons.

Effective injection

Despite promising theoretical predictions for high ‘Curie’ temperatures (above which materials lose their ferromagnetism) in DMS materials and a decade spent trying to realise them, the current record – nearly 200K in GaMnAs by researchers at the University of Nottingham, UK, and the Czech Academy of Sciences – still isn’t sufficient for device applications. Many researchers are working on alternative approaches. ‘Currently, metallic tunnel junctions are the only promising route towards room temperature spin injection,’ says Georg Schmidt at the University of Würzburg in Germany.

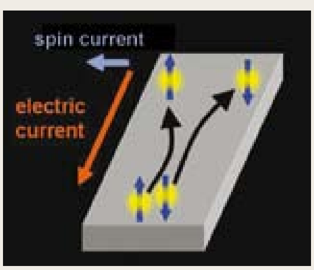
Metallic tunnel junctions (MTJs), which underpin TMR in metallic spintronics (see box p47), allow electrons to tunnel with their spins intact from a magnetic metal into a nonmagnetic semiconductor. In 2001 Klaus Ploog and co-workers at the Paul Drude Institute in Berlin, Germany, demonstrated spin injection from a layer of iron into gallium arsenide at room temperature via an MTJ. Unfortunately, engineering sufficiently thin and abrupt interfaces between ferromagnetic metals and silicon is much more difficult.

In May 2007, Appelbaum’s group made a breakthrough in silicon spintronics. They injected spin-polarised electrons through a thin film of $Co_{84}Fe_{16}$ into silicon and transported them for a distance of about 10µm at a temperature of 85K. To overcome the resistance mismatch between the two materials, the team used a voltage drop to make the electrons energetic or ‘hot’ – effectively firing them across the

Avoiding injections

In 2004, David Awschalom’s group unearthed a phenomenon called the spin Hall effect which allows spin polarisation to be achieved directly in semiconductors by electrical means, without the use of magnetic fields and circumventing the problems with spin injection. ‘The spin Hall effect could further revolutionise spintronics by allowing efficient detection of spins,’ says Ramamoorthy Ramesh of the University of California at Berkeley, US.

Like the classical Hall effect, in which a voltage develops at right angles to both a current



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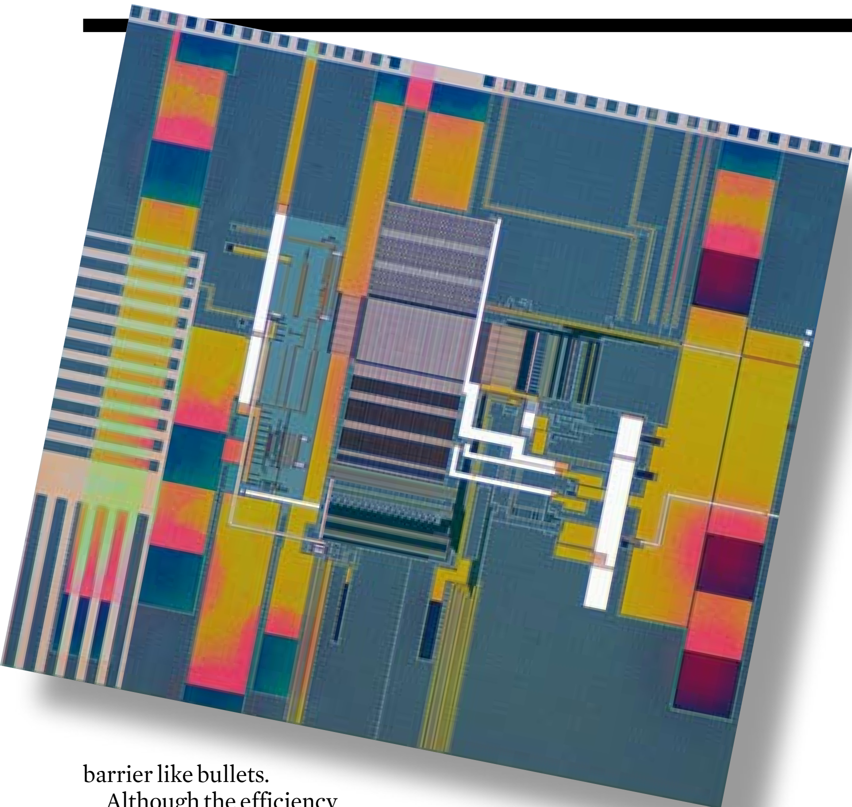
Spins separated

flowing through a material and a transverse external magnetic field, the spin Hall effect harnesses the spin-orbit coupling of electrons to cause ‘spin up’ and ‘spin down’ electrons to accumulate at opposite edges of a conducting channel – effectively separating the spin of electrons from their charge and making devices more compatible with existing semiconductor manufacturing techniques. Awschalom’s team observed the effect in GaAs at 20K, but it has since been detected at room temperature in thin surface layers of ZnSe. A hot area now, say some researchers, is the quantum spin Hall effect recently observed in the semiconductor HgTe by scientists at Würzberg University, Germany, which is an intrinsic property of some materials and may be more robust to material defects.



IBM

Could MRAM be the memory of the future?

barrier like bullets.

Although the efficiency of Appelbaum's silicon spin injection was only 2 per cent (his team subsequently has achieved a polarisation of 37 per cent), the researchers used a magnetic field to make the electron spins precess as they travel. They also detected the spin-polarisation electrically using a $Ni_{80}Fe_{20}$ film attached to the other side of the silicon which, like the CoFe injection layer, acted as a spin filter.

Such control is essential for a spintronic transistor and thus for the low-power, reprogrammable logic that may eventually overthrow the fixed-function logical units possible by pushing just electric charge around. Researchers have had some success in programming a metallic MRAM element (see box p47) to carry out basic logical operations.

The organic movement

Carbon-based materials such as nanotubes, diamond and graphene (sheets of carbon just a single atom thick), which can behave as semiconductors and insulators, display even weaker spin-orbit interactions than silicon, due to carbon's lower atomic number and wider band gaps. That should allow electron spins to be preserved for longer and at higher temperatures, although graphene so far has performed worse than expected and some researchers question whether spin transport is really being observed in organic semiconductors.

Researchers at the University of California in Riverside, US, have used multiwalled nanotube channels to demonstrate GMR effects of 6 per cent at temperatures up to 14K, and many groups are trying to fabricate sheets of graphene to further understand spin transport and manipulation in organic materials. In 2006 a team at the National Institute of Standards and Technology in the US sandwiched a layer of octanethiol between cobalt and nickel contacts which acted as a molecular spin valve, allowing only electrons in one spin state to pass through the insulating carbon layer.

'Molecular spintronics has only taken off in the last few years,' says Walther Schwarzacher of the University of Bristol in the UK, who is using scanning tunnelling microscopy to investigate spin transport and GMR effects in simple alkane chains such as pentane. 'In terms of components, people don't yet have a totally clear idea of what spintronics will do, so there are a lot of different approaches.'

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David Awschalom says 'quantum engineers' are needed to exploit spintronics know-how

Two decades since the discovery of GMR and virtually all the world's data is stored and accessed depending on which direction the intrinsic angular momentum of electrons points. Yet the hurdles facing researchers building the spintronics revolution are numerous. 'In semiconductor spintronics a breakthrough in basic materials is required,' says Shinji Yuasa at AIST in Japan. Harnessing the potential of organic spintronics in particular requires intensive numerical simulations to work out how different molecules bond to the metal contacts and how their shape and vibrational modes affect spin transport.

Despite being tantalisingly close to demonstrating transistor-like behaviour in the lab, most researchers see a commercial spin transistor as a long way off. 'This is research,' says Appelbaum, who declines to put a date on when such a device may exist. Kees de Groot reckons a quantum computer probably is still 20 years away.

It's time, thinks Awschalom, for a new breed of 'quantum engineer' to take a closer look at the spintronic phenomena already unearthed in university labs. 'You can't simply replace "charge" for "spin" in today's technology and think things will be better,' he points out. 'The real impact of this field is to make a discontinuous change in technology – a totally different way at looking at systems architecture.' Other than dropping the power consumption of existing electronic devices, Awschalom says it's not even obvious that a spin transistor alone would launch a spintronic revolution. 'We can now approach industry with robust, controllable quantum effects at room temperature,' he says. 'It's a pretty interesting time for us.'

Matthew Chalmers is a freelance science writer based in Bristol, UK

Further reading

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