

Devices that exploit the spin of the electron promise to revolutionize microelectronics once polarized electrons can be injected efficiently into semiconductors at room temperature

# Spintronics

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LATER this year physicists will be celebrating the centenary of Paul Dirac's birth. One of the most influential scientists of the 20th century, Dirac combined quantum mechanics and special relativity to explain the strange magnetic or "spin" properties of the electron. What Dirac could not have foreseen, however, is how the spin of the electron could change the field of microelectronics.

Indeed, the spin of the electron has attracted renewed interest recently because it promises a wide variety of new devices that combine logic, storage and sensor applications. Moreover, these "spintronic" devices might lead to quantum computers and quantum communication based on electronic solid-state devices, thus changing the perspective of information technology in the 21st century.

Since the 1970s conventional electronic microprocessors have operated by shuttling packets of electronic charge along ever-smaller semiconductor channels. Although this trend will continue for the next few years, experts predict that silicon technology is beginning to approach fundamental limits. By 2008, for example, the width of the "gate electrodes" in a silicon microprocessor will be just 45 nanometres across, which will place severe demands on the materials and manufacturing techniques used in the semiconductor industry. Indeed, the cost of implementing a new production line for such devices is predicted to reach \$33bn.

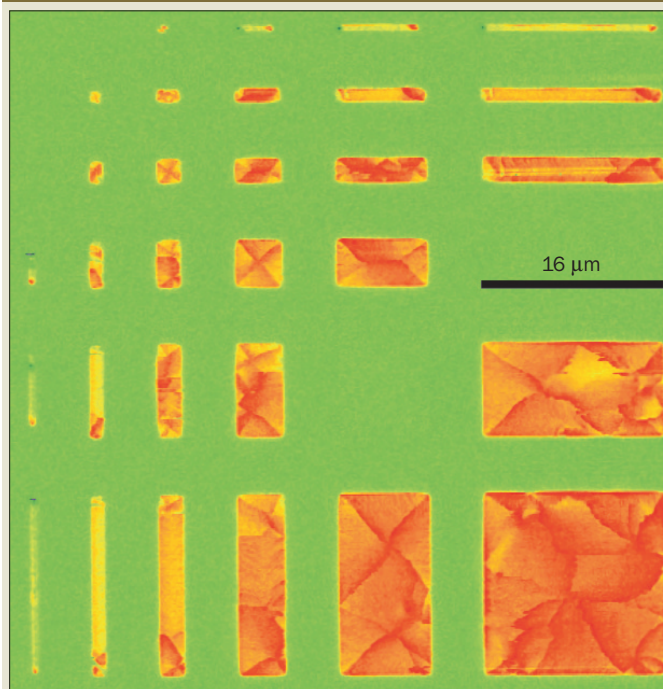
Although successors to silicon technology have been discussed, most of them rely on a complete set of new materials, new handling and processing techniques, and altered circuit design, among other developments. These new technologies include single-electron transistors and molecular-electronic devices based on organic materials or carbon nanotubes (see *Physics World* June 2000 pp31–36).

But the ability to exploit the spin degree of freedom in semiconductors promises new logic devices with enhanced functionality, higher speeds and reduced power consumption. Crucially, these devices could be fabricated with many of the tools already used in the electronics industry, thereby speeding up their development. The challenge for manufacturers is to combine the technology in the semiconductor industry with the completely different techniques used in the magnetic-recording industry to produce devices on the nanometre scale.

## Metals make their mark

The use of the electron's spin or magnetic moment, rather than its charge, is a recent advance in electronics and has been dubbed magnetoelectronics, spin electronics or spintronics. Indeed, the orientation of the spin of the electron is

## 1 Magnetic moment



Magnetic domains in a patterned permalloy film just 20 nm thick. All the magnetic moments point in the same direction in structures measuring less than 500 nm in one dimension. Magnetic domains start to form as the area increases. The microstructures were fabricated and imaged using magnetic force microscopy by Guido Meier at Hamburg University.

already exploited by the latest generation of magnetic sensors, in particular by the "read heads" of hard-disk drives.

All magnetic-recording media, including computer disks, have a recording surface that contains a magnetic layer divided into small magnetic domains (see figure 1). The magnetic moments of these domains represent the "0" and "1" states of digital information, and – in the case of hard disks – they are read by a sensitive thin-film device that consists of alternating layers of magnetic and non-magnetic materials.

The storage capacity of magnetic materials has increased dramatically in recent years following the discovery that the electrical resistance of these metallic multilayer devices changes significantly in a magnetic field. Known as giant magnetoresistance (GMR), this effect was discovered independently by Albert Fert at the Université Paris Sud and Peter Grünberg at the Forschungszentrum Jülich in Germany in 1988 (see *Physics World* November 1994 pp34–38).

GMR is caused by spin-up and spin-down electrons encountering different resistances as they pass through a magnetic multilayer. Electrons with their spins aligned in the same direction as the magnetic moment of a ferromagnetic layer encounter less resistance than those with their spins pointing in the opposite direction.

Pioneering experiments in 1985 by Robert Silsbee of Cornell University and Mark Johnson, now at the Naval Research Laboratory in Washington DC, showed that it was possible to “inject” spin from a ferromagnet into a non-magnetic metal. But preserving the spin of the electrons as they pass through the metallic layers is crucial for GMR devices. This is only possible if the thickness of the metallic layers is smaller than the “spin-scattering length” – the distance over which the spin of an electron flips. Thin-film deposition techniques, which allow layers of metal just a few nanometres thick to be grown on top of each other with exquisite precision, have transformed GMR into a billion-dollar business within a decade of its discovery.

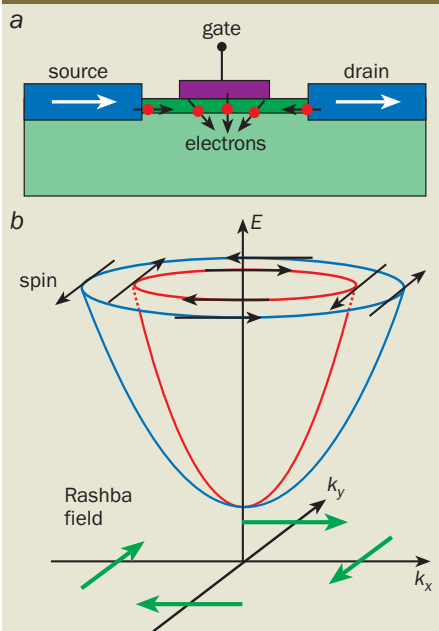
Similar rapid development is expected from devices that are made from two ferromagnetic layers separated by an insulating metal-oxide layer just 1 nanometre thick. The ease with which electrons can tunnel through the insulating barrier depends on the relative magnetization of the two magnetic layers, and on the fact that the electrons preserve their spin as they pass through the barrier. Dubbed tunnelling magnetoresistance (TMR), this effect gives rise to a more pronounced resistance change in small applied fields than is found in GMR devices.

In 1995 Jagadeesh Moodera and colleagues at the Massachusetts Institute of Technology demonstrated TMR at room temperatures in devices with very thin oxide layers. Less than a decade on, Motorola, IBM and Infineon are manufacturing a fast magnetic-storage device that incorporates dense arrays of TMR elements. Known as magnetic random access memory, these devices are due to be launched onto the mass market in 2004.

### Spin in semiconductors

In spite of the advances in the magnetic-recording industry, semiconductor manufacturers are still ignoring spin. Experts predict a wealth of new opportunities if both “spin up” and “spin down” electrons can be exploited in semiconductor devices. Logic and storage capabilities could be combined to produce a single multifunctional computational device that could replace several conventional electronic components. Meanwhile, new types of sensors and microprocessors could be possible because the spin in semiconductors can be manipulated and controlled. Many researchers believe

## 2 Spin transistors



(a) The spin-FET conceived by Datta and Das is based on a semiconductor heterostructure. Electrons (red) injected from the source flow along the indium-arsenide channel (green) and are detected at the drain. The gate voltage produces an electric field in the growth direction of the heterostructure, which leads to a magnetic field known as the Rashba field. Since this field is perpendicular to both the electric field and the transport direction, the spin of the injected electron can precess. The gate voltage on the transistor controls the Rashba field, thereby modulating the current. (b) The energy of the electrons as a function of momentum,  $k$ . The Rashba field (green) splits the electrons in the conduction band into two sub-bands that are distinguished by the orientation of their spins. For a given field direction, the two spin-states have slightly different momenta.

that such devices would compute more rapidly, consume less energy and provide a more efficient way of transmitting and storing information.

One of the most exciting potential applications of spintronics, however, utilizes the truly quantum-mechanical nature of spin. According to quantum mechanics, the electron’s spin is a superposition of spin up and spin down states, and its wavefunction is described by both an amplitude and a phase. In the same way that laser radiation is completely coherent in space and time, the amplitude and the phase of an electron’s spin may be completely correlated. If this “spin coherence” can be preserved in a semiconductor, it could be exploited in quantum communication and computation. Indeed, the spintronics bug has bitten scores of physicists and has sparked numerous research efforts across the world.

Before spin can become big business, however, researchers need to fulfil three fundamental requirements in semiconductors. First, they must ensure that the spin-scattering length is larger than the device so that the spin orientation is not destroyed. Second, they must be able to inject or impose spin information on the current flowing between the source and drain electrodes. Finally, they must devise a way to control the orientation of the spin externally.

### How spintronics works

Shortly after the discovery of GMR, Supriyo Datta and Biswajit Das of Purdue University in the US proposed a new type of field effect transistor (FET) that exploits the spin of the electrons travelling through a semiconductor without being scattered. When a voltage is applied to the gate electrode of a FET, the resulting electric field creates a conducting channel between the source and the drain electrodes. Datta and Das suggested that the field could also be used to control the orientation of the spin so that it modulates the current. The beauty of their idea is that the “spin-FET” can be fabricated using the standard equipment in microelectronics to produce new logic and sensor applications. Little wonder that their concept has become a paradigm of semiconductor spintronics and has stimulated a worldwide research effort.

To understand how an electric field can control spin, we have to look at the effect of relativity on the spin of the electron as formulated in the Dirac equation. In simple terms, an electron has an intrinsic magnetic dipole moment and behaves like a miniature bar magnet that is aligned along its axis of angular momentum. The electron can have spin of either  $+\hbar/2$  or  $-\hbar/2$ , where  $\hbar$  is the Planck constant divided by  $2\pi$ . As it orbits around the nucleus, the electron produces a magnetic field that modifies its own magnetic moment – an interaction known as “spin-orbit coupling”. In the rest frame of the

electron, however, the electric field of the nucleus appears to be a magnetic field – this is a purely relativistic effect. As a result, the spin of the electron actually precesses as it orbits the nucleus.

Similar effects are felt by electrons moving through the electric field inside certain types of semiconductor crystals. A pioneer of this topic is the theorist Emmanuel Rashba, now at the State University of New York at Buffalo. In the early 1960s he devised a quantity that describes how the electric field transforms into a magnetic field (known as the Rashba field) and thereby affects the spin-state of the electron. This so-called Rashba parameter depends on various properties of the semiconductor that are related to the spin-orbit interaction of the valence electrons. Following this approach, physicists have recognized that in semiconductors with strong spin-orbit coupling – such as indium arsenide and indium gallium arsenide – electric fields can control spins more effectively than those with weaker coupling, like gallium arsenide.

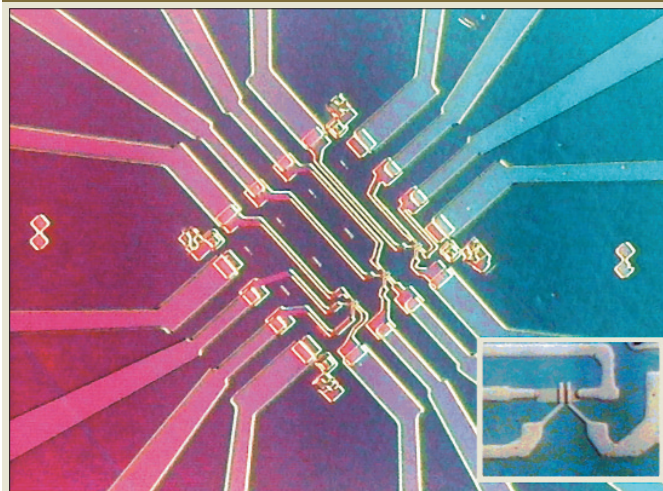
Rashba's ideas underlie the spin-FET conceived by Datta and Das, and continue to be developed by both theorists and experimentalists. The Purdue team originally proposed building the device from a semiconductor heterostructure in which the electrons can flow freely through an undoped “high-mobility” region. The important ingredient in the device was a layer containing indium gallium arsenide in which the electrons could flow (figure 2a).

Ulrich Merkt's group at Hamburg University has taken a different approach and developed a device that is very similar to a metal-oxide-semiconductor field effect transistor (MOSFET) – a key component in large-scale integrated circuits based on silicon. Merkt and colleagues replace the silicon with an indium-arsenide crystal to create a device that is somewhat different in design to the Datta and Das spin-FET but a convincing alternative nevertheless (figure 3).

In an indium-arsenide MOSFET, the Rashba parameter,  $\alpha$ , is particularly large and can be controlled efficiently by applying a voltage to the gate electrode (see Matsuyama *et al.* in further reading). The resulting Rashba field splits the electrons in the conduction band into two sub-bands that are distinguished by the orientation of their spins (figure 2b). For a given direction in space, there are two spins-states that have slightly different momenta. Like the original spin-FET conceived by Datta and Das, the Hamburg device exploits this difference in momentum,  $\Delta k$ .

An electron injected from the source electrode into the conduction channel can be described by a superposition of two spin-states with slightly different momenta. As the two spin-states move coherently through the semiconductor, they acquire a relative phase shift  $\theta = \Delta k L = 2m^* \alpha L / \hbar^2$ , where  $m^*$  is the effective mass of the electron and  $L$  is the length of the device. As a result, the spin of the injected electron precesses as it moves through the conduction channel and can point in a completely different direction by the time it reaches the drain. The final orientation of the electron can be controlled via the Rashba parameter and the gate voltage. If the source and drain electrodes are made from a ferromagnetic material, then the magnetoresistance of the spin-FET can be altered without an external magnetic field. This suggests that spin-FETs could have new features. For example, a spin-FET could be used as a building block for a fast reprogrammable logic device that remembers its last state if the power is switched off. Moreover, spin-FETs could elim-

### 3 Testing time for spintronics



Spins are injected into an indium-arsenide crystal and then detected by this test chip, which was fabricated by Christopher Schierholz at Hamburg University using photo- and electron-beam lithography. Electron transport is studied by means of superconducting leads, which are hardly affected by noise at low temperature. The inset shows the ferromagnetic source and drain measuring 1  $\mu\text{m}$  across separated by a semiconductor channel just 150 nm in length. The gate electrode that completes this MOSFET has been omitted.

inate the time delay that currently exists between data being read out from a magnetic-storage medium and then processed in a semiconductor device.

#### Long-distance transport

For semiconductor spintronics to work, the electrons must first be polarized so that all their spins point in the same direction. It is also important that the spin polarization is largely preserved as the electrons propagate through the semiconductor. Wolfgang Rühle's group at the University of Marburg in Germany and David Awschalom and co-workers from the University of California at Santa Barbara have recently made great advances in this particular direction. Their results show that electron spins can be transported for over 100 micrometres in gallium arsenide, much further than the length of the semiconductor channel envisaged for future spintronics devices. In addition, Awschalom and co-workers reported that a “packet” of electrons remains coherent over the same distance. The successful spin transport was detected using sophisticated optical techniques – for example the amount of circularly polarized light produced by the recombination of spin-polarized electrons with holes gives a measure of the spin orientation.

Curiously, intense research at Santa Barbara and elsewhere suggests that the number of defects in bulk semiconductors, such as gallium arsenide and gallium nitride, has little effect on spin orientation. Spin can also be transported successfully across the interface between two different semiconductors. Last year Irina Malajovich at Santa Barbara and co-workers at Pennsylvania State University observed that a spin-polarized current can flow uninterrupted from a layer of gallium arsenide to a layer of zinc selenide (see Malajovich *et al.* in further reading). Both the amplitude and the phase of the spin current can be controlled, even on femtosecond timescales ( $10^{-15}$  s). The ability to control the phase of the electron spin with a stack of semiconductor interfaces offers intriguing possibilities for future applications in quantum computation.

This is technologically feasible because molecular beam epitaxy can routinely produce semiconductor layers just one atom thick.

### Spin injection

Unlike multilayer devices made from metals or metal-oxides, semiconductors can transport electron-spin information over macroscopic distances, and from one device to another.

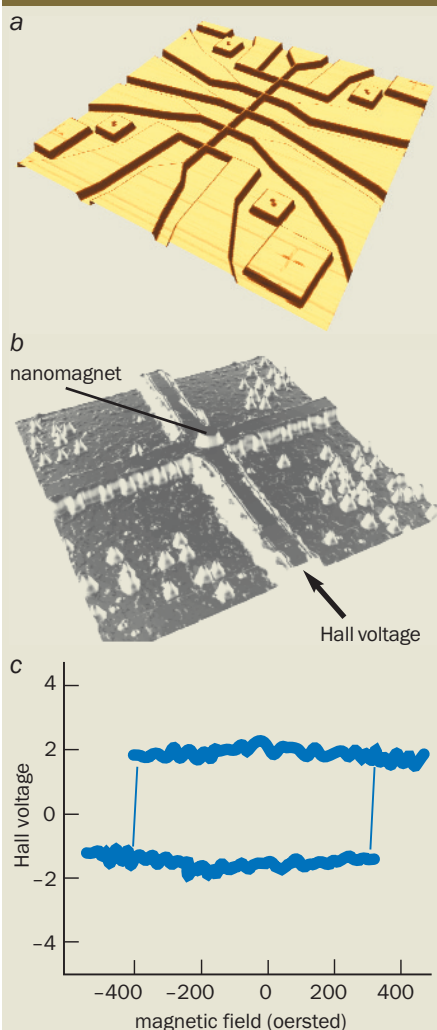
Engineers envisage a wealth of spin-based optoelectronic devices, including light-emitting diodes (LEDs) that generate polarized light intrinsically. Such LEDs would eliminate the need for the polarizing filters that are currently inserted into conventional devices and reduce their brilliance. The crucial issue now is to find a material that can inject a spin-polarized current efficiently into a semiconductor at room temperature. To get round this problem, most research groups have created short bursts of spin-polarized electrons by illuminating the surface of the semiconductor with pulses of circularly polarized light. But the ultimate goal is to inject spins electrically.

To date, two different approaches have been taken to solve the problem. The first involves growing additional spin-aligning layers of a magnetic semiconductor on top of the existing material using molecular beam epitaxy. Hideo Ohno and colleagues at Tohoku University in Japan, Laurens Molenkamp's group at Würzburg University in Germany, Michael Oestreich of Hanover University together with Rühle of Marburg, and Berend Jonker of the US Naval Research Laboratory and co-workers have made important developments following this route in recent years. They have shown that the concept works well at low temperatures, achieving injection efficiencies as high as 90%. However, the efficiency of this technique drops dramatically above 4 K for fundamental reasons related to the spin-aligning characteristics of magnetic semiconductors.

The second approach involves injecting spin-polarized electrons from a ferromagnetic metal like cobalt, nickel or iron, but this has proved difficult because layers containing randomly oriented spins form between the metal and the semiconductor. Last year, however, Klaus Ploog's group at the Paul Drude Institute in Berlin showed that it was possible to inject spins from iron into gallium arsenide. The key to the success was the careful growth of the ferromagnetic layers onto the semiconductor material. Using optical techniques to measure the amount of spin in the semiconductor, the Berlin group reported a spin-injection efficiency of 2% at room temperature.

Ploog and co-workers believe that the spins were able to

## 4 Remnant field



(a) A Hall sensor fabricated from a nanostructured two-dimensional electron system. (b) The enlarged view shows a nickel nanomagnet, which produces a stray field that induces a Hall voltage. (c) The Hall voltage as a function of magnetic field produced by a nanomagnet some 90 nm in diameter and 160 nm high. In future spintronic devices, the local magnetic field may be used to split electron states into up and down states.

quantum-mechanically tunnel through the so-called Schottky barrier that had formed between the iron and the gallium arsenide. Yet the spin-injection efficiency remained far below the bulk spin polarization of the iron film, which is about 40%. Several microscopic effects might explain the shortage of spin in the semiconductor, including “spin-flip” scattering at the metal–semiconductor interface or spin dephasing in the semiconductor heterostructure. Spin transfer between a metallic ferromagnet and a semiconductor therefore remains a challenge.

However, a recent spin-injection experiment using a scanning-probe technique may provide new insights into the problem. Vincent LaBella and colleagues at the University of Arkansas in the US have scanned the surface of gallium arsenide with a sharp tip consisting of a wire made from a single crystal of nickel. By injecting a 100% spin-polarized current into the material, the Arkansas team was able to correlate the spin-injection efficiency with surface features on the semiconductor. They found that while 92% of the electrons injected into flat terraces kept the same polarization, the situation changed dramatically near sharp steps. Most of the electrons flipped their spins within a few nanometres of a step edge, thereby disrupting the flow of spin.

The electrons injected from the metallic ferromagnet into the semiconductor in the Berlin experiment are sometimes called “hot” electrons because they have more energy than electrons in the conduction band of the semiconductor. One idea that has not yet been explored as fully is the injection of electrons that have the same energy as the most energetic electrons in the conduction band, i.e. injection at the Fermi energy. This might be achieved if there was an Ohmic contact – one with negligible resistance – between the ferromagnet and the semiconductor. Another good reason to use indium arsenide, rather than gallium arsenide, is that it does not form a Schottky barrier when it is in contact with a metallic ferromagnet.

Recently Can-Ming Hu at Hamburg in collaboration with Junsaku Nitta and co-workers at NTT in Japan, and independently Guido Meier and colleagues at Hamburg have built devices that can both inject and detect spins electrically, and that incorporate a submicron semiconductor channel. Since the indium-arsenide channel was only 150 nanometres long, electron scattering was significantly reduced at low temperatures. This allowed spins to be transported from the source to the drain, both of which were made of the magnetic material permalloy. Both groups have reported that the spin-injection efficiency of their devices is low, of the order of a few per cent.

Experts have argued that these ferromagnet–semiconductor hybrid structures may also suffer from parasitic magnetoresistance phenomena. Unlike the metallic or oxide interlayers in GMR and TMR devices, semiconductor channels are very sensitive to magnetic fields. Indeed, the stray field due to a single ferromagnetic nanostructure is often sufficient to deflect electrons and create additional resistance. Andrey Geim and colleagues at Manchester University in the UK, our group and others have studied stray fields in detail (figure 4). The results have shown the importance of the shape of the ferromagnetic domains in the source and the drain. Indeed micromagnetic simulations and magnetic imaging have been crucial for understanding all-electrical spin-injection experiments.

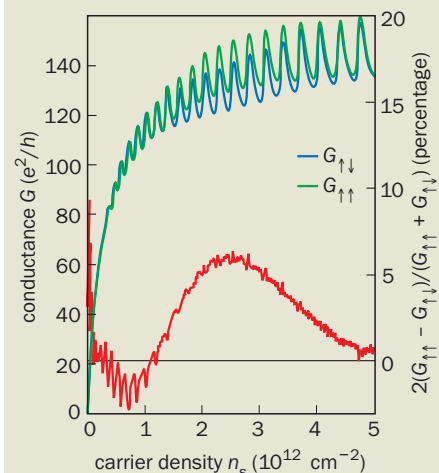
### Spintronics: the future

In spite of the current difficulties with ferromagnet–semiconductor hybrid structures, one of the beauties of these devices is that the spin can be controlled in many different ways. Experiments have already shown that electron spins can be manipulated optically, as well as with magnetic and electric fields. And there are hints that spin amplification might be possible in semiconductors. Moreover, spin can even be controlled at the nanometre level using nanomagnets, which produce very localized magnetic fields (figure 4). Even the phase of a coherent spin current can be adjusted at the interface between two dissimilar semiconductors.

In the case of electric-field control, our group has recently developed a theory to explain electron transport in a realistic spin-MOSFET in which spins are injected and detected electrically. Our model takes into account the material characteristics, spin-dependent transmission across the ferromagnet–semiconductor interface, and the dependence of the density of charge carriers and the Rashba field on the gate voltage. It predicts that the magnetoresistance of the MOSFET changes with voltage in a similar way to the spin-FET devised by Datta and Das (see figure 5 and Matsuyama in further reading).

Various groups have shown that a spin transistor comprising a semiconductor sandwiched between a gate, a source and a drain made from conventional metallic ferromagnets works in principle, but progress has been hampered because the spin-injection efficiency is low. One way round this problem might be to use semiconductors that are ferromagnetic at room temperature. However, several research groups are taking a different approach and are investigating the growth of so-called Heusler alloys. These materials are made of metals that are only partially aligned in their pure state but have all their spins aligned at room temperature in alloy form. In principle, we can boost magnetoresistance effects to 100% if we fabricate sources and drains from these materials.

### 5 Spin transistor in action



Theoretical behaviour of a spin-MOSFET made from indium arsenide and a partially polarized ferromagnetic source and drain. Our model predicts the conductance (the inverse of resistance) as a function of the carrier density in the semiconductor channel, which is in turn related to the applied voltage. The green and blue curves show the conductance for a device in which the source and drain are magnetized in the same and in opposite directions, respectively. The coherent spin wavefunction is reflected at interfaces within the device and leads to a characteristic interference pattern. The red curve shows the difference between the green and blue curves divided by the average conductance. This is the accepted way of defining the magnetoresistance of a device. Intriguingly, the conductance can be negative for certain values of gate voltage – behaviour that is new and peculiar to semiconductor spintronics devices.

in a superposition of different quantum states, it can be used as a quantum bit or “qubit” in quantum computation and communication. The implementation of realistic qubits is an ambitious and long-term research goal that will go on fascinating solid-state physicists long after Dirac’s 100th anniversary.

### Further reading

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