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SEMICONDUCTOR SPINTRONICS

Spins go their own way

A semiconductor device that integrates electron spin injection, transport, modulation and detection in a single structure provides an important step in versatility for both fundamental research and practical spintronic applications.

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Spintronics is the science of exploiting electronic spin for new applications in metals, semiconductors and other materials. Although initial spintronic devices (also known as magnetoelectronic devices) were based on intrinsically magnetic materials, the last decade has seen tremendous progress in our ability to generate, transport and control spin currents in non-magnetic materials. But for semiconductor spintronics to realize its full potential, an effective means to convert electrical signals into spin signals and back again is crucial, so that spintronics can be integrated with conventional electronics. To this end, on page 197 of this issue, Lou and colleagues demonstrate a semiconductor device that not only makes such integration possible, but also enables the spin currents to be injected, transported and detected by all electrical meansin a single device structure[1].

For several years now, it has been possible to polarize and measure the spin-state of electrons in non-magnetic semiconductors by exploiting the optical selection rules of III–V semiconductors, such as gallium arsenide. These selection rules dictate that when a III–V semiconductor is illuminated with circularly polarized light, spin-polarized electrons with a preferred spin direction are excited, enabling the generation of a spin-polarized current. Conversely, these rules also mean that when a spin-polarized electron–hole pair recombines, it will generate circularly polarized light, enabling detection by optical techniques. But although such techniques provide an excellent means of studying fundamental spin dynamics in the laboratory, they are not very suitable as a means for realizing practical spintronic devices, let alone for integrating these devices in a complex spintronic system. For this an 'all-electrical' interfacing scheme is required.

This necessitates the use of ferromagnetic contacts, because in ferromagnets there is an intrinsic unbalance between spins aligned parallel or antiparallel to their magnetization direction. They can therefore be used as electrical spin injectors and detectors. Electrical spin injection from a ferromagnet into a semiconductor was first demonstrated in devices known as spin light-emitting diodes (spin-LEDs)[2–4]. One of the key challenges that had to be overcome in the development of the spin-LED arose from the nature of the contact between a ferromagnet (see Fig. 1a) and a semiconductor. When a ferromagnetic metal is brought into contact with a non-magnetic metal, the carriers it injects into the non-magnetic metal will be spin polarized, typically by a few percent. But when a ferromagnetic metal (or indeed any metal) is brought into contact with a semiconductor, it forms a potential barrier, known as a Schottky barrier. This barrier only allows those carriers with energies greater than the barrier to pass over it. Moreover, not only does having sufficient energy enable these carriers to pass over the barrier, it enables them to pass back and forth between the semiconductor and the metal regardless of their spin direction. This severely limits the spin-selectivity of the contact, and is a manifestation of the so-called 'conductivity mismatch' problem[5].

The solution to this problem is to change the nature of the barrier so that carriers are forced to tunnel quantum-mechanically through it, rather than go over it. This is done by growing a thin oxide layer between the ferromagnetic contact and the semiconductor, which restores the spin-selectivity of the junction, and enables the injection of spin-polarized currents into the semiconductor. But this comes at a cost. In order to drive enough current through the oxide, a considerable bias voltage

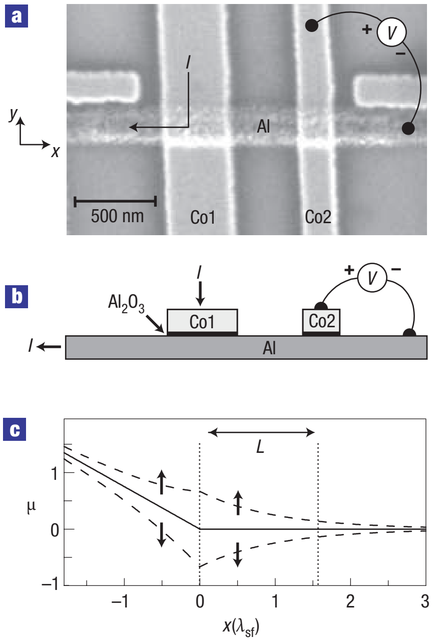

Figure 1 Spin injection and detection with a non-local device geometry. **a**,**b**, Scanning electron microscope image (**a**) and cross-sectional schematic (**b**) of an all-metal device used for non-local spin injection and detection. This device consists of two cobalt contacts (Co1 and Co2) whose magnetization can be independently controlled, deposited over an aluminium strip (Al) and separated by thin oxide layer to form two ferromagnetic tunnel junctions. When a spin-polarized current is injected from Co1 into the aluminium strip, it causes an accumulation of spins underneath the contact, which diffuse outwards. If the two cobalt contacts are close enough, spins diffusing from Co1 will accumulate underneath Co2, generating a voltage, V, across the junction between Co2 and the strip. **c**, The electrochemical potentials (μ) of spin-up and spin-down electrons as a function of distance (in spin-relaxation lengths) from the injector contact. L is the distance between the contacts. The solid line indicates the situation when the current injected from Co1 is unpolarized, in which case there will be no voltage drop across the junction at Co2. The upper and lower dashed line denote the situation for the injection of a spin-polarized current, in which case the voltage across the Co2 junction will depend on the magnetization of the contact (Figures reprinted with permission from ref. 10).

must be applied across the junction. This is not a problem for spin injection, but it is for spin detection. The point is that when an accumulation of spin-polarized carriers develops in a semiconductor, it is usually small. Despite the oxide between the metal and the semiconductor, a smaller Schottky-like barrier will still exist in the semiconductor that hinders the tunnelling of the lowest energy carriers. In an important technological breakthrough reported in previous work[6,7], Lou *et al.* showed that this can be addressed by heavily doping the semiconductor in the region of the junction. This reduces the thickness of the Schottky barrier and increases the number of carriers that can tunnel through it, even under the small voltages that develop as a result of spin accumulation, making it possible to measure such accumulation.

Despite the success in achieving both injection and detection of spins in a semiconductor, other challenges to the development of integrated spintronic systems arise. The archetypal device geometry for demonstrating spin detection is that of a (two-terminal) spin-valve, in which the flow of a spin-polarized current is manifest by a difference in resistance of the device when the relative magnetization direction of its two ferromagnetic contacts are aligned parallel and antiparallel[8]. But because both spin and charge flow in the same region of such a structure, it is often difficult to discern the small signals that arise from a spin current, and those that arise from non-spin-related effects, such as Hall voltages. Consequently, making conclusive interpretations of the results of previous experiments has been problematic.

The solution to this problem was first demonstrated in a 1988 by an elegant and pioneering experiment by Johnson and Silsbee[9]. Their idea was to separate the paths of the charge and the spin currents, by using extra device contacts to perform the functions of spin injection and spin detection, in a so-called 'non-local' device geometry. Figure 1 illustrates a similar approach constructed for an all-metal device by Jedema *et al.* (ref. 10).

When a signal is observed in this so-called non-local geometry it can be due to spin transport only. But despite this and the solutions to the many other challenges faced in the construction of a single integrated spintronic system, it is only the present study by Lou *et al.*[1] that definitively demonstrates such a system in a semiconductor.

In addition to providing an integrated platform for the development of future spintronic devices, Lou *et al.* also use their system to investigate the so-called Hanle effect. When a magnetic field is applied perpendicular to the direction of the injected spins, the spins will undergo Larmor precession around it. Depending on the magnitude of the field, and 'time of flight' for the electrons to go from injector to detector, this modulates the spin signal measured at the detector contact. Not only does this provide further evidence for the practical efficacy of their approach, but illustrates the potential of the authors' platform for fundamental studies of behaviour of spins in semiconductors.

The next challenge will be to optimise the authors' approach to other semiconducting materials and operating conditions. From their experiments they calculate that the spin relaxation length in their system can exceed 10 μm, which is long compared with metals. However, if such a system is to find practical use in spintronics, the operating temperature will need to be increased substantially above the 70 K demonstrated in the present work. Whether this will even be possible is still open to question. But with the pace of progress as it is, it is a question that may be answered soon.

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SUPERCONDUCTIVITY

Are we there yet?

It's more than twenty years since our journey towards a theory of high-temperature superconductivity began, but we've yet to reach our destination. The road ahead is winding, but there are new data and ideas to guide us.

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Many outside the field — and indeed many within it — have lost interest in high-temperature superconductivity. After twenty years of painstaking effort, people are still debating the very mechanism of superconductivity. What is the nature of the 'glue' binding the electrons in pairs, such that they can travel macroscopic distances without resistance? One main group believes that lattice vibrations, or phonons, are responsible, whereas another believes just as firmly that magnetic excitations, or magnons, provide this glue. And to complicate matters, both sides use the presence of 'kinks' in photoemission data as evidence for electron–boson coupling — the contention being over which boson mode: phonon or magnon.

That there is no accepted solution reflects the depth and complexity of the problem, but, as illustrated by papers in this issue, there are many ways forward. Baptiste Vignolle and co-workers[1] present inelastic neutron scattering data that support the model of magnetically mediated superconductivity, and thus counter some recent claims to the contrary. There are also two creative theoretical papers. Krzysztof Byczuk *et al.*[2] undermine the relevance of the kinks by showing that they can arise as a consequence of electron–electron interactions; in other words, kinks may have nothing to do with superconductivity. And in an effort to tip the balance, Dennis Newns and