Electronics in a spin

Michael L. Roukes

Electrons can be shuttled around according to their 'spin', as well as their charge. Do this efficiently in a semiconductor and the future of electronics starts to look very different.

Essentially all semiconductor technology is based on electronic devices, such as transistors, that operate by internally shuttling small packets of electronic charge. In the past decade, however, devices have been developed that exploit the electron's 'spin' rather than its charge[1]. As a consequence of quantum mechanics, all electrons have spin, which gives them a magnetic moment — much as if they were tiny bar magnets. Many advances have been made in this new field of spin electronics, known also as spintronics, but scientists have not yet reached the same exquisite control over the flow of spin in microscale devices as they have over the flow of charge in conventional electronic devices.

On page 770 of this issue, Malajovich *et al.*[2] report an important advance in semiconductor spintronics. They show that it is feasible to transfer spins coherently (in a spin-aligned state), and with high efficiency, across interfaces between different semiconductor materials. This achievement is a milestone in the quest to build devices that exploit electron spin.

One of the most compelling and intriguing applications of semiconductor spintronics is quantum computation. Quantum computers could be enormously powerful, in part because binary digits or 'bits' in classical computers have just two available states (0 or 1), whereas quantum bits or 'qubits' have many more, which are all possible complex mixtures of 0 and 1. Robust examples of these elemental qubits have, so far, been demonstrated only in the form of ultracold atoms or ions. Such qubits are typically shrouded deep within a forest of specialized equipment that maintains them in an ultra-high vacuum, where they are nurtured and interrogated by a vast and intricate assemblage of precision laser instrumentation. But practical quantum computers will ultimately require arrays, comprising many qubits, all operating cooperatively and coherently. Scaling up the existing technology to allow the trapping of many ultracold atoms and ions at the requisite level of complexity is clearly impractical. The success of microelectronics, however, raises high expectations that electron or nuclear spins within semiconductor devices may provide the key to such scalability. But spins in semiconductors must possess several attributes before they can be harnessed to build usable qubits.

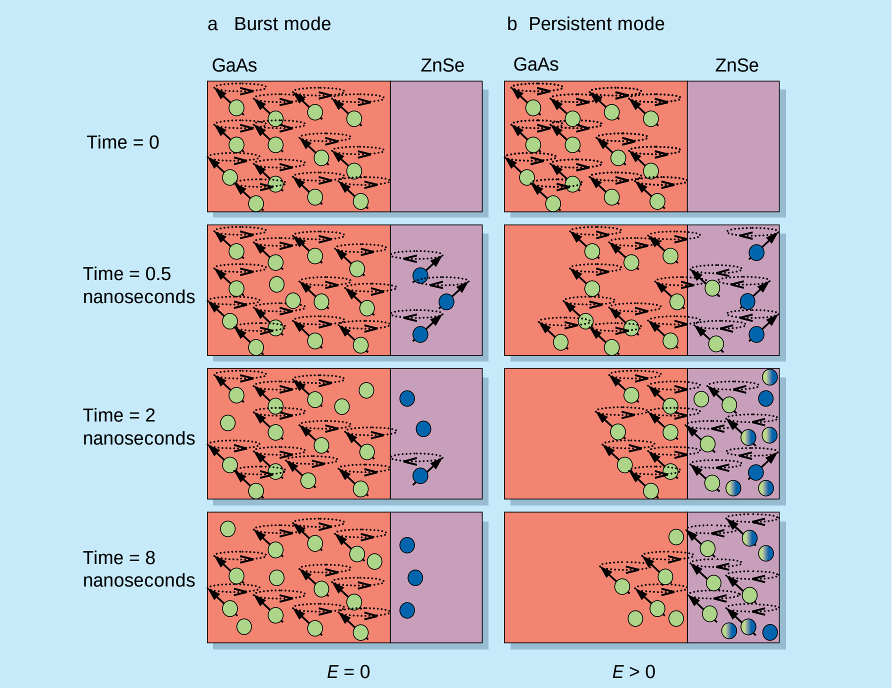

Figure 1 **Electron spin transfer across an interface between two different semiconductors (gallium arsenide, GaAs, and zinc selenide, ZnSe) in a magnetic field.** a, **Burst mode. When no external electrical field is applied ($E = 0$), only a short, fast burst of spins (circles) crosses the interface. Most of the spins remain trapped within the GaAs spin reservoir. Once spins cross into ZnSe they actually precess in the opposite direction and decay at a rate characteristic of ZnSe spins (blue).** b, **Persistent mode. When an electrical field ($E > 0$) is used to drag spins from the GaAs reservoir into the ZnSe layer, spins that have just arrived into ZnSe carry with them information about the spin precession in the reservoir (green). Spins that have been in ZnSe for a while (green/blue) have lost that information, and spins that crossed in the initial burst (blue) never had it, so these two spin species do not contribute to the net spin. Meanwhile, the continuous supply of fresh spins from GaAs results in a spin current, which is not characteristic of ZnSe, but evolves in the fashion of GaAs spins.**

Work in spintronics has emerged from research into spin behaviour in metallic devices. Metal-based spintronics is already being used in state-of-the art computer hard drives and other magnetic devices. But spintronics is now becoming increasingly centred on semiconductor materials and processing techniques. Innovations in the mainstream semiconductor electronics industry have advanced these both to the point that a truly remarkable degree of material purity and technical precision can be attained. These innovations provide an opportunity to assemble new devices and materials in ways that are compatible with existing electronics methodology. In addition to potential applications in quantum information systems, spintronics may also lead in the near future to the development of semiconductor devices capable of performing high-speed logic and memory operations, similar to that achieved by conventional charge-based electronics, but at a fraction of the power.

At a fundamental level, nuclear and electronic spins are responsible for a material's magnetism. So the ability to sense and control magnetic properties is clearly at the heart of spintronic device operation. There are three long-standing prerequisites for success in semiconductor spintronics, which involve three fundamental aspects of spintronic device operation. First, all spintronic devices rely on spin-polarized carriers: electrons that are predominantly in a spin-aligned state, being nearly all 'spin-up' or 'spin-down'. Robust spin polarization arises naturally in ferromagnetic materials, which can serve as a stable source of spin-polarized carriers under ordinary conditions. Second, the mobile spins need to be transferred efficiently across interfaces between different semiconductor materials. Because such interfaces are ubiquitous in complex electronic devices, this transfer must proceed without appreciable loss of spin polarization. Third, once the spins are transferred into the heart of a device, where the switching or memory function actually occurs, their polarization must be preserved long enough for the desired operation to be carried out.

Progress towards satisfying these prerequisites has been made just within the past few years. Semiconductors that are not normally magnetic, such as gallium arsenide, have been turned into ferromagnetic materials by adding magnetic dopants[3–5]. Some of these new materials remain ferromagnetic even at relatively high temperatures. Crucially, their compatibility with conventional non-magnetic semiconductors enables optimal interfaces to be constructed in all-semiconductor spintronic devices. This allows spin-polarized electrons to be transferred efficiently between the respective material layers. This has clearly been demonstrated by the recent success of spintronics-based light-emitting diodes, which use electrical spin injection to emit circularly polarized light[6–8]. Optical techniques have been used to excite spins in doped semiconductors. In a magnetic field these spins continuously precess (rotate) about the field. The important point is that this precession has been observed to persist coherently for surprisingly long periods of time[9].

These are promising starts, yet not all of the pieces are in place. For example, efficient electrical injection (transfer) of spins across interfaces has, so far, only been demonstrated in structures involving semi-magnetic materials[6,8], which provide spin-polarized electrons solely when subjected to very high magnetic fields, that is, at levels available only in the laboratory from superconducting magnets. By contrast, when electrons from a ferromagnetic superconductor, which have intrinsic spin polarization even in the absence of an external field, are electrically injected from a ferromagnetic semiconductor across an interface into another non-magnetic semiconductor, the results to date are much less pronounced. Although the demonstration under these conditions is an important achievement in itself, the efficiency attained so far is only a few per cent[7].

Malajovich and co-workers[2] have now shown that spin-transfer efficiency can be increased by up to a factor of 40 by using electric fields to 'drag' spins across a semiconductor interface. The authors first use a laser pulse at the right frequency to create a long-lived reservoir of spin-polarized carriers, here in gallium arsenide, and then, in two separate experiments, show that both externally applied and built-in electric fields can be highly effective at transferring spins from this reservoir to another semiconductor, here zinc selenide (Fig. 1). In the latter case, internal built-in electric fields are created by the explicit inclusion of electrical dopants of different polarities in the semiconductor layers. In this way, a 'natural' potential arises at the interface between the differently doped semiconductors; this forms the basis for semiconductor diodes.

Electrons in solids have different spin properties to those in a vacuum. The electron's magnetic properties (and therefore its spin) are quantified in terms of a 'g-factor', which characterizes the electron's energy in a magnetic field. One of the intriguing aspects of the new work is that, under the best spin-transfer conditions, the entire population of transferred spins (within the collecting layer) is found to behave, overall, with the character of their original environment — in this case the original semiconductor reservoir.

This occurs because of a newly identified, persistent mode of spin transfer, which makes the reservoir act, in effect, as a spin 'battery'. This means that, under special conditions, a spin reservoir can be made to continuously source a spin-polarized current across the interface until the reservoir itself is depleted.

This is demonstrated by Malajovich *et al.*[2] using a sensitive technique that allows them to interrogate the identity (effective g-factor) of the ensemble of transferred spins. They find that the effective g-factor for the population of transferred spins can be continuously metamorphosed from a value characteristic of the spin reservoir to that of the collecting semiconductor. The precise behaviour depends on the strength of the effective electric field. This unexpected phenomenon may provide the basis for what the authors call multifunctional spintronic devices, in which the character of the spin currents can be controlled by both electric and magnetic fields. This prospect injects an intriguing new 'spin' into the emerging technology of semiconductor spintronics. ■

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Plant microbiology

Quieting the raucous crowd

Jared R. Leadbetter

Many bacteria communicate by using dedicated signalling molecules. Signal-degrading enzymes from other bacteria interrupt the conversation, and can protect tobacco and potato plants from infection.

Most of us have had occasion to reach into a refrigerator crisper drawer to sponge out the remnants of a wilted, slimy head of lettuce. One of the major culprits of this horror is *Erwinia*, a bacterium that also causes economically important wilts and soft-rots of crops. On page 813 of this issue, Dong and colleagues[1] introduce a promising new way of controlling *Erwinia* infections — an approach that might also have implications for treating some human diseases.

The past 30 years have seen the discovery that *Erwinia* and many other bacteria can not only sense, but also respond to, increases in their population density. When crowded, they dramatically change their physiology. This process, called quorum sensing, is often associated with the bacteria shifting from a free-living lifestyle to becoming dependent on a particular host[2]. Many of these bacteria produce, monitor and respond to the accumulation of soluble signalling molecules — quorum-sensing signals. Molecules in one class of these signals have a specific chemical structure described as an acyl-homoserine lactone (AHL; Fig. 1). In the case of *Erwinia*, AHLs activate the expression of diverse 'virulence factors' such as slime, and enzymes that solubilize polysaccharides[3,4] to provide the bacteria with nutrients.

Dong *et al.*[1] took advantage of *Erwinia*'s quorum-sensing signals to develop a new way of controlling quorum-regulated processes. They call their technique 'quorum quenching'. Instead of trying to target bacterial growth or viability directly, the authors focused on ways to degrade the AHL signals as they are produced, with the aim of reducing or eliminating the expression of quorum-regulated virulence factors. To do this, Dong *et al.* constructed transgenic tobacco and potato plants expressing the bacterial gene *aiiA*. This gene encodes an enzyme that renders AHLs biologically inactive. Remarkably, the transgenic plants became resistant to *Erwinia* infection, even when unrealistically high numbers of *Erwinia* cells were introduced into wounded tissues. In rare cases where there were localized signs of disease, the transgenic plants managed to fight off the infection over time. By comparison, control plants succumbed to an uncontrol-