SPINTRONICS

Solar spin devices see the light

Semiconductor devices that convert light of arbitrary polarization into a flow of electron spin have now been demonstrated using an approach that is applicable to any semiconductor material.

Ron Jansen

The generation and control of spin current — the flow of spin angular momentum — is the basis of spintronics, an information technology in which digital data is represented by the spin orientation of electrons[1–3]. Spintronic devices built from ferromagnetic and non-magnetic metals have already transformed magnetic data storage technology. Semiconductors are also attractive materials for next-generation spintronic devices because their (spin) properties can be manipulated by doping, gate electric fields and quantum effects in reduced dimensions. Moreover, semiconductors can also couple to light. Writing in *Nature Communications*, Bernhard Endres and colleagues now demonstrate semiconductor devices (a spin solar cell and a spin photodiode) that convert light into a spin current[4]. Significantly, the approach places no restrictions on the semiconductor material itself, and does not require the use of circularly polarized light: mainstream semiconductors such as silicon and sunlight will do just fine.

It was established decades ago that electrons with a preferred orientation of the spin can be created in certain semiconductors by illumination through a process known as optical orientation[5]. For circularly polarized light, the non-zero angular momentum can be transferred to the carriers, resulting in a higher density of electrons with spin pointing in a given direction, and a smaller density with spin pointing in the opposite direction. The carriers are said to be spin polarized. Unfortunately, optical orientation requires circularly polarized light and materials with the appropriate electronic structure. The process works well for III–V semiconductors such as gallium arsenide, but not for Si and Ge, the technologically important semiconductors that are at the heart of modern-day electronics.

How can the restrictions on the material and light be overcome? One possibility is to use thermally induced spin-flows, using the energy of the light to create a thermal gradient that drives a spin current. Based on the demonstration[6] that a heat flow across a ferromagnetic tunnel contact on a semiconductor is accompanied by a spin current, it was proposed[6] that light can induce a spin polarization in any semiconductor and without the need for circularly polarized light. Indeed, this was recently observed for Ge with CoFe/MgO tunnel contacts in which the ferromagnetic CoFe electrode was illuminated with a laser to induce a heat flow, and thereby a spin current, across the contact[7].

The approach now demonstrated by Endres and colleagues[4] is not thermal. Rather, it is based on junctions[8,9] between a p- and an n-type semiconductor, of which one of them is a ferromagnet (p-type GaMnAs with a large hole concentration). The other semiconductor is n-type GaAs with a smaller carrier concentration, such that most of the carrier depletion and internal electric field is on the GaAs side of the boundary. In the configuration of the spin solar cell (Fig. 1a), there are no external electrical connections and the depletion region is chosen to be narrow enough for electrons to tunnel through. The light excites electrons and holes mainly in the non-magnetic GaAs. Separation of electrons and holes by the internal electric field near the boundary creates a photocurrent that is not spin polarized, because for non-polarized light, the photoexcited carriers have no preferred spin orientation. However, because no leads are connected to the device, the build-up of charge (the photovoltage) drives a restoring current in the opposite direction, consisting of electrons that tunnel from the n-type region into the ferromagnetic region. Because the probability of tunnelling is higher for spins aligned with

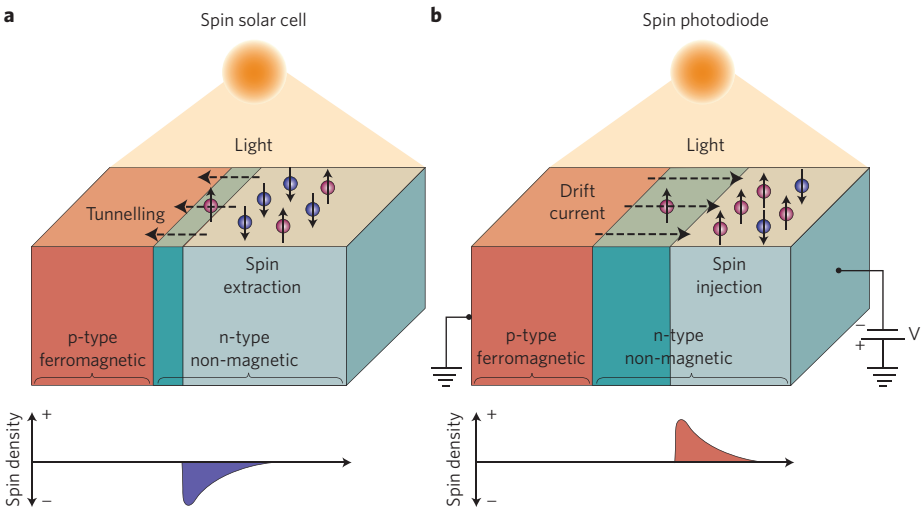

Figure 1 | Semiconductor devices that convert light of arbitrary polarization into a spin current. **a**, In the spin solar cell, the boundary between the non-magnetic n-type semiconductor and the p-type ferromagnetic region consists of a narrow, heavily doped barrier region (darker shaded central region), through which photoexcited electrons created in the n-type region can tunnel. The probability to tunnel into the ferromagnet is largest for electrons with spin pointing up (red), leaving behind electrons with the opposite spin polarization (spin extraction; blue). **b**, In the spin photodiode, the boundary region is moderately doped and thus wider, so that tunnelling is suppressed. However, under a large reverse bias voltage, spin-polarized photoelectrons created on the ferromagnetic side can drift in the electric field into the n-type region (spin injection), creating a positive spin-polarization.

the spins in the ferromagnet (red spins in Fig. 1), they are extracted from the n-type region at a higher rate, leaving behind more electrons with opposite spin (blue spins in Fig. 1). A spin polarization of the electrons in the n-type GaAs region under illumination is exactly what Endres and colleagues observed[4].

In the second configuration, the spin photodiode (Fig. 1b), there are the following differences: the doping density in the n-type region near the boundary is smaller, the depletion region is wider and tunnelling is suppressed. Furthermore, a large reverse bias is applied across the junction. Photoexcited electrons created on the ferromagnetic side, with spin pointing predominantly in the positive direction (red spins; Fig. 1), are then driven into the n-type region by the strong electric field (spin injection). As Endres and colleagues observed in their experiments[4], the electrons accumulating in the n-type region have a positive spin polarization, which is opposite to that observed in the spin solar cell.

Although it had already been reported that linearly polarized light can create a spin polarization in GaAs in proximity to a boundary with a ferromagnet[10], no specific mechanism for this effect was identified and thermal spin currents were neither considered nor excluded. The latest work by Endres and colleagues[4] demonstrates the basic principle of their approach and the detailed mechanism, and their control experiments exclude thermal effects. The next natural step is to replace the GaMnAs ferromagnetic semiconductor with a metallic ferromagnet that remains polarized well above room temperature. And, although we may expect the approach to work for any semiconductor, this needs to be explicitly shown by replacing the n-type GaAs with silicon or germanium. Furthermore, an examination of the speed of the spin-current generation would also be of interest.

So what can we do with the spin current? Injection of a spin current into a ferromagnetic material exerts a torque on its magnetization, and induces a controlled dynamic motion or even a reversal of the magnetization direction. This spin injection is used to control the magnetic state of ferromagnetic elements in non-volatile magnetic memory devices and microwave oscillators[1]. Injection of a spin current is the prevalent method of creating a spin polarization in a non-magnetic material[2,3]. This is essential for constructing devices such as spin transistors and for building spin-based logic circuits. Ideally, spin currents are created without an accompanying charge current and the associated energy dissipation.

The generation of spin currents by light opens the door to the integration of electronics and optics. Although the connection between spintronics and optics has been achieved for III–V semiconductors, the new approach to convert light of arbitrary polarization into spin current allows this connection to be established for the broader family of mainstream semiconductors. Together with the recent advances in silicon- and germanium-based optics[11], these results hint at a bright future for spin optics in group IV semiconductors. The developments in this area of research definitely deserve the close attention of scientists and engineers alike. ❐

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PHOTOCATALYSIS

A source of energetic electrons

Photoexcited diamond can inject highly energetic electrons in solution and promote the catalysis of a broad range of chemical reactions.

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Solvated electrons (electrons trapped in water, liquid ammonia, alcohols, amines and other polar liquids) are one of the simplest but most important reactive species in chemistry and biology[1]. Although they are mostly produced by means of highly energetic radiation that ionizes the molecular species present in a solvent, growing importance is now attributed to alternative synthesis methods based on the injection of free electrons from solid semiconducting catalysts in the surrounding liquid[2].

Figure 1 shows the conduction (CB) and valence (VB) bands, as well as the effective bandgap (E_g), of a broad variety of semiconductors[3]. The energy barrier between the minimum of the CB and the energy level of electrons in vacuum (E_{VAC}) is called the electron affinity.

Electrons can be excited from the VB to the CB by thermal excitation, by electrical pumping (in a semiconductor diode or transistor device) or by absorption of light radiation higher than E_g. The subsequent injection of these electrons in the surrounding environment is a complex phenomenon that depends on the alignment of the CB with the reduction energy levels of the molecules in liquid (the energy levels of N_2, CO_2 and water are shown in Fig. 1, right axis). Importantly, these electrons can participate only in those reduction reactions having an energy level lower than the CB minimum. Therefore, the effectiveness of a semiconductor material as a catalyst depends on the position of the CB (that is, on its electron affinity), as well as on its resistance to chemical degradation in the reactant solution. A widely used material for water reduction (or water splitting) is TiO_2, which has strong catalytic activity, high chemical stability and a long lifetime of electron–hole pairs[4]. As shown in Fig. 1, its electron affinity is about 4.2 eV and its CB minimum lies above the reduction energy level of water, $E(H^+/H_2O)$. However, TiO_2 cannot catalyse reactions