

SPINTRONICS

Taming spin currents

Versatile room-temperature control of spin currents without a net charge flow paves the way for new methods to transfer and process information.

Igor Žutić and Hanan Dery

Taking advantage of the fact that electrons, photons and some elementary excitations have an intrinsic angular momentum (spin) offers a fascinating opportunity to study materials properties. Introducing a net imbalance between spins pointing in different directions (say, 'up' and 'down') is one way to probe phenomena including spin-orbit and hyperfine coupling, pairing of unconventional superconductors, and the quantum Hall effect¹. This spin imbalance also naturally lends itself to a wide range of applications, from commercially available computer hard drives and magnetic random access memories, to more forward-looking spin transistors, magneto-logic gates, spin-lasers and even spin-based quantum computing¹⁻³. An elegant realization of such an imbalance is offered by spin currents, which flow without any charge transfer. These currents can circumvent the constraints of conventional electronics and enable low-power and high-bandwidth information transfer.

So there are several good reasons for the quest to tame these spin currents effectively. Two related breakthroughs, in different materials systems, are now

reported in *Nature Materials*. Ando *et al.*⁴ report surprising results for a robust spin imbalance in low-resistance ferromagnetic metal/semiconductor junctions. Using a similar technique to generate and detect spin currents, Kurebayashi *et al.*⁵ reveal an intriguing way to enhance spin currents in ferromagnetic insulators.

How can spin currents be generated? Traditional approaches include optical orientation using circularly polarized light^{1,6} and electrical spin injection from magnetic contacts^{1,2,7} (Fig. 1a,b). But by using the well-established phenomenon of ferromagnetic resonance⁸, Ando *et al.*⁴ and Kurebayashi *et al.*⁵ chose spin pumping as an elegant alternative way to generate spin currents^{4,5,9}. To understand the spin pumping mechanism, we can view the preferred orientation of spins and their associated magnetic moments in ferromagnetic materials as a macroscopic spin or a compass needle carrying angular momentum characterized by a corresponding net magnetization \mathbf{M} (Fig. 1c). On applying a static magnetic field not aligned with \mathbf{M} , the resulting torque forces \mathbf{M} to precess with a frequency proportional to the magnetic field. Eventually, just like the compass

needle, damping effects will align \mathbf{M} with the magnetic field. By adding a small oscillating magnetic field (for example using microwaves^{4,5}), the damping effects can be cancelled, leading to a resonant condition with a constant-angle precession of \mathbf{M} . Effectively, this excited ferromagnet is a spin pump that transfers angular momentum between the ferromagnetic (F) and non-magnetic material (N). The transfer is mediated by magnons — low-energy quantized spin-waves — which through the conservation of angular momentum are responsible for spin flips of electrons reflected at the F/N interface (Fig. 1c). The flow of spin-up and spin-down electrons in opposite directions leads to the spin current, free of charge transfer.

With the generation of spin currents in hand, how do we detect them? It is important to realize that the spin and orbital motion are not independent. They are coupled because the electron spin interacts with a relativistic magnetic field (this field is generated by moving charges that the electron sees in its rest frame). Although the average speed of electrons (as contributing to the charge current) is modest, individually they can move at relativistic speeds while they are

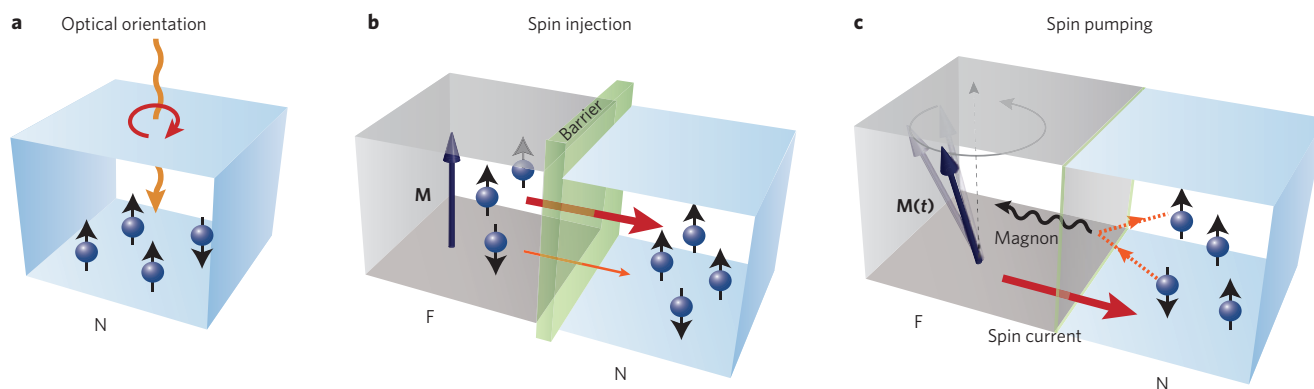


Figure 1 | Generating spin imbalance. **a**, In the presence of spin-orbit coupling, circularly polarized photons (wavy line) transfer angular momentum to electrons, preferentially aligning their spins (straight arrows). This process is particularly effective when the non-magnetic (N) region is a direct-bandgap semiconductor. **b**, With applied bias, the difference between the number of spin-up and spin-down electrons in the ferromagnetic (F) region is transferred across the spin-selective barrier to the N region. **c**, The precession of magnetization (\mathbf{M}) perturbs the magnetic order in the F region and leads to propagation of magnons (wavy line), which carry angular momentum along the precession axis. Electrons flip their spins if they emit or absorb a magnon. The excess magnons, which carry the missing angular momentum of the perturbed magnet, are absorbed at the F/N interface and transfer the angular momentum into the N region (realized by preferential spin flips). This pumping of spin current is more efficient if reflected electrons easily reach the interfacial region (for example for low-resistance contacts).

scattered through the crystal that produces the spin–orbit coupling¹⁰. The authors^{4,5} take advantage of this coupling for detection of spin currents using the inverse spin Hall effect^{4,5,11,12}, as depicted in Fig. 2. The spin–orbit coupling leads to asymmetry in scattering: opposite spins moving in opposite directions are deflected towards the same edge of the N region. As a result, the spin current yields a charge imbalance measured by a voltage.

For spin currents the spin–orbit coupling is both friend and foe. On the one hand, it is often the main culprit in a loss of spin imbalance by providing an effective mechanism for spin relaxation^{1,10}, limiting the length scale for spin information transfer. Indeed, the spin–orbit coupling in a ferromagnet usually makes its lattice an efficient sink for the angular momentum carried by magnons. On the other hand, as revealed by Kurebayashi *et al.*⁵, a slight change in the applied magnetic field increases the number of magnons and the lattice has a change of heart: it acts as a source, not a sink, of angular momentum back into the spin system. By using a ferromagnetic insulator yttrium iron garnet (YIG) as a source of spin current¹³, and non-magnetic platinum as the detector (Fig. 2), Kurebayashi *et al.* demonstrated an intriguing enhancement of spin currents across the YIG/Pt interface⁵. Furthermore, the large spin–orbit coupling

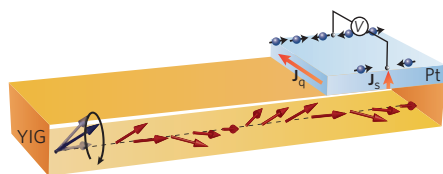


Figure 2 | Detection of spin currents generated by magnons. The flow of angular momentum into the platinum layer is detected by measuring a charge imbalance voltage arising from spin-dependent deflections. This spin-to-charge current conversion ($J_s \rightarrow J_q$, until the charge imbalance is established) represents the inverse spin Hall effect. The angular momentum transfer is mediated by magnons represented by the red precessing arrows along the YIG layer. By adjusting the resonance condition between the applied static magnetic field and the microwave frequency, Kurebayashi *et al.*⁵ have demonstrated that the amplitude of the readout voltage increases. This increase comes from a three-magnon process (initial magnon splits into two) in which an additional angular momentum from the YIG lattice flows to the magnetic subsystem and leads to enhanced J_s across the YIG/Pt interface. Using similar generation and detection techniques, Ando *et al.* have demonstrated robust spin pumping across low-resistance NiFe/GaAs contacts⁴.

in platinum provided another advantage: better conversion of spin current into the measured voltage.

By focusing on NiFe/GaAs ferromagnetic metal/semiconductor junctions, Ando and colleagues⁴ tackled the important challenge of generating robust spin currents in a semiconductor. Seemingly this should be a simple task for spin injection (Fig. 1b). But because of the much larger resistance of semiconductors, the analysis of spin injection developed for all-metallic systems⁷ implies that a large spin-dependent barrier resistance is required, or the injection current would not be spin-polarized (the so-called impedance mismatch problem)^{1,2}. Unfortunately, the higher resistance of such barriers also leads to smaller spin and charge currents, diminishing the prospect of having large signals in semiconductors. The study of spin pumping across NiFe/GaAs junctions⁴ has accomplished two feats at once: first, in contrast to conventional spin injection, spin pumping works better for low-resistance ohmic contacts (Fig. 1c); and second, bias voltage across these junctions provides a versatile and dynamically tunable spin injector (through modification of the interfacial band structure with bias).

With several fundamental phenomena elucidated by Ando *et al.*⁴ and Kurebayashi *et al.*⁵, what are the possible next steps? The implementation of spin pumping is not limited to ferromagnetic resonance, one could forgo the application of external magnetic fields and instead rely on spin-transfer torque^{1,2}. Passing a large spin current across the F region also results in magnetization precession, while promising that the area of the spin-pump circuit could be scaled down. Convincing the lattice to be a spin source should also be possible in other systems, including those with weaker spin–orbit coupling, offering a magnifying glass to study spin currents. One desirable path would be to combine this effect with the advantages of spin-transfer torque and apply it to silicon, known for its weak spin–orbit coupling, allowing a macroscopic transfer of spin information¹⁴. Figure 3 illustrates a possible implementation in which the spin pumping could enable information transfer density to be orders of magnitude greater than in the currently available interconnects¹⁵. Moreover, electrically tunable spin contacts could be the missing link to realize electrically pumped spin lasers at room temperature. Such lasers have been theoretically shown to yield better dynamical properties than their conventional (spin-unpolarized) counterparts¹⁶. With spin currents effectively tamed, exciting new twists are emerging in this story. □

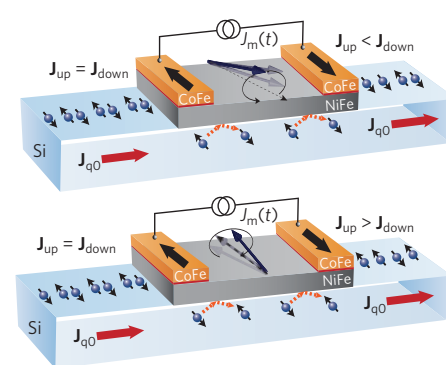


Figure 3 | Information transfer by spin pumping. The precessing magnetization (indicated by the large central arrows) in the soft magnetic layer (NiFe) is controlled by a spin-transfer torque oscillator using the modulated current $J_m(t)$ from the magnetically hard CoFe layers (magnetization pinned in the plane). Owing to spin pumping, the constant charge current J_{q0} in the Si wire becomes spin-polarized ($J_{up} < J_{down}$ or $J_{up} > J_{down}$ top and bottom panels, respectively) and the encoded information (1 or 0) depends on the direction of magnetization in the NiFe layer. Detrimental dynamical cross-talk between the adjacent wires is eliminated because the charge current in each wire is constant. The density of such wires can be extremely high and, together with the high modulation frequency produced by spin-transfer torque, the information bandwidth can exceed¹⁵ 1,000 terabits $s^{-1} cm^{-2}$. For comparison, in modern complementary metal-oxide-semiconductor circuits the cross-talk between transmission lines limits the bandwidth to ~ 3.5 terabits $s^{-1} cm^{-2}$.

Igor Žutić is in the Department of Physics, University at Buffalo, the State University of New York, Buffalo, New York 14260, USA. Hanan Dery is in the Department of Electrical and Computer Engineering, University at Rochester, Rochester, New York 14267, USA. e-mail: zigor@buffalo.edu; hdery@ece.rochester.edu

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