A new twist for spin torques in antiferromagnets

Spintronics

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Standfirst: A large non-adiabatic spin-transfer torque in an antiferromagnetically-coupled ferrimagnet can provide fast and efficient control of spin textures – and challenge current understanding of such effects.

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Spintronic devices use the spin of electrons for data storage and processing. Such devices are usually based on ferromagnets, due to the natural spin polarization of their conduction electrons. However, recently it has been shown that spin current can be injected into antiferromagnetic materials – where neighbouring spins are aligned antiparallel to each other – in order to manipulate their ordering parameter, the Néel vector (Fig. 1a); a result that has opened up the field of antiferromagnetic spintronics[1,2]. Like ferromagnets, antiferromagnets can offer energy-efficient, non-volatile switching of their magnetization. However, antiferromagnetic materials have additional advantages such as improved robustness against external magnetic fields and enhanced intrinsic magnetization dynamics (typically three orders of magnitude higher than in ferromagnetic materials).

Readout of the ordering parameter in antiferromagnets is, however, difficult using traditional methods. One approach to overcome this is to use a ferrimagnet – a material in which two ferromagnetic sublattices are coupled antiferromagnetically. Such materials have, in particular, a specific temperature at which the magnetic moments of the two sublattices compensate each other, resulting in a system that behaves like an antiferromagnetic material. By operating around this compensation temperature, the antiferromagnetic properties of this state can be accessed and, based on a tiny but finite magnetic moment, its ordering parameter can be probed using traditional methods.

Writing in *Nature Electronics*, Teruo Ono and colleagues now show that the antiferromagnetic ordering parameter in a ferrimagnetic gadolinium–iron–cobalt (GdCoFe) alloy can be manipulated efficiently using spin-transfer torques induced by a charge current through the material[3]. The researchers – who are based institutes in Japan, Korea and the US – find that the non-adiabatic component of the spin-transfer torque is significantly larger than the Gilbert damping parameter: a result that is in contrast to non-adiabatic spin-transfer torque in ferromagnets, and challenges current understanding of this type of torque. Notably, the non-adiabatic spin-transfer torque can also provide fast and efficient manipulation of spin textures, such as switching the magnetization (or Néel-vector) of the material or moving magnetic domain walls (the transition region between two areas of different homogeneous magnetic ordering).

Spin-transfer torque is a transport mechanism that can be induced, for example, by a spin-polarized charge current (simply termed, a spin current) flowing through a device – a process that results in the transfer of angular momentum from one region to another. As a result, the transfer of angular momentum from a the conduction electrons to the localized magnetic moment induces a torque on the local magnetization. This transfer process is called adiabatic when the spin direction of the spin current follows the local magnetization direction adiabatically which is the case for most

ferromagnetic materials. However, initial experiments on adiabatic torque were not in agreement with theoretical predictions. Hence, the non-adiabatic spin-transfer torque was introduced as an empirical term to explain the mismatch between theory and experiments – and was quickly termed the 'spin-torque fudge factor', as the theoretical interpretation has still not reached a consensus about its dominant underlying mechanism.

Currently, the most intuitive interpretation of the non-adiabatic torque is based on a 'mistracking' of the spin current direction with reference to the local magnetization when an electron spin traverses a spin texture e.g. a domain wall (Fig. 1b). This mismatch between the direction of the spin current and the local magnetization leads to a field-like torque on the local magnetization. The field-like torque acts similarly as the torque induced by a magnetic field with the same direction as the spin-current polarization. Following from this simplistic description, the non-adiabatic contribution to the torque becomes sizable when the local magnetization changes quickly, for example, when there are large gradients in the magnetic texture relative to the velocity of the spin current. Antiferromagnetic ordering lies at the extreme limit of this scale because the magnetic moment varies on the atomic scale. Hence, if the mistracking interpretation is valid, it could be observed in materials within an atomically alternating magnetic moment, such as a sharp domain wall in a simple antiferromagnetic ordering.

This relatively simple, but often criticised and re-evaluated, interpretation of the underlying microscopic mechanism of the non-adiabatic spin-transfer torque has now been re-examined by Ono and colleagues. The researchers study, in particular, current-assisted magnetic domain wall motion in a sputtered GdCoFe alloy system, where the Gd and CoFe atoms form the antiferromagnetically-coupled sublattices. This material has a compensation temperature of around 240 K, where it behaves as an antiferromagnet. By studying the effect of the torques in detail, a large non-adiabatic torque was found.

The work of Ono and colleagues also highlights new opportunities to better understand the non-adiabatic spin-transfer torque. To start, experimental approaches are now required to do the same detailed analysis on systems that are intrinsic antiferromagnets, where probing the order parameter on an atomic length scale and with high time resolution are difficult. The antiferromagnetic regime allows, in particular, the time domain to be pushed towards the terahertz regime: for instance, by adding ultrafast (femtosecond scale), optically-induced spin-current effects, which intrinsically allow a larger detection bandwidth and manipulation of the order parameter[4]. Moreover, when combined with plasmonics, both temporal and spatial resolution could be enhanced. From a theoretical point of view, many complicated processes still need to be taken into account, such as the different scattering mechanisms combined with electric band structure calculations, both of which are challenging for the disordered sputter-deposited materials used by Ono and colleagues.

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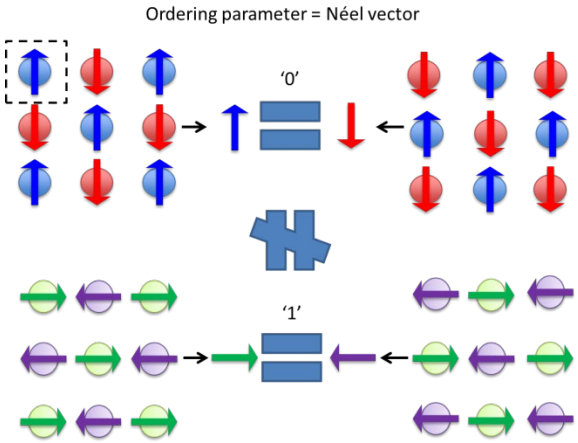
Figure 1. Magnetic ordering and spin-transfer torque in a ferrimagnet. a, Four different orderings of a 3x3 site antiferromagnet, where the Néel vector is defined as the orientation of the top left magnetic moment (arrow) of every arrangement. The top and bottom arrangements cannot be easily distinguished between them using traditional methods. However, the difference between the top and bottom arrangements (a 90-degree rotation) can be detected and is usually used to define a '0' or '1' in logic applications.



b, Spin mistracking in a ferrimagnetic domain wall. In the case of adiabatic torque (left panel) the spin-polarized conduction electrons (green arrows) follow the domain wall profile (as given by the Neel vector $\vec{N}$) very well. This results in the adiabatic torque (bottom-left panel). If the domain wall is narrower, spin-polarized conduction electrons cannot track the spins of the domain wall (DW) profile (right panel). In this case, non-adiabatic torque is applied on the spins of the ferromagnetic domain wall and it is perpendicular to adiabatic torque.