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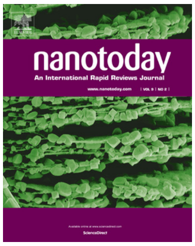

NEWS AND OPINIONS

Switching nano-magnets with the spin—orbit interaction

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Summary In this opinions piece we give an introduction to the topic of spin—orbit torques, reviewing the most important experiments and providing an outlook for the future.

How does a magnet respond to electricity? And, specifically, how does the magnetisation vector of a ferromagnet respond? There are good reasons for physicists and engineers to ask this question, as we try to think of energy efficient, scalable and fast ways in which to switch the nanoscale magnets that promise to provide next generation memory devices.

An initial attempt to answer our question may involve the torque the magnetisation experiences under the current generated magnetic field — the Oersted field. However, in certain thin magnetic films, stronger current induced torques, may also act. The best known example of a current induced torque is the spin transfer torque which occurs when electricity is passed through a magnetic structure with non-uniform magnetisation [1].

The magnetic tunnel junction, consisting of two nanoscale magnets separated by a tunnel barrier, provides the archetypal device in which to observe the spin transfer torque. Pass electricity between the magnets and the electrons get their spins polarised by the 'fixed' magnetic layer and pass angular momentum into the 'free' magnetic layer, forcing the 'free' layer to switch. The spin transfer torque is effective at switching as it has a dominant component that acts to oppose the torque from magnetic damping — it is an anti-damping torque. This elegant physics is now commercially used in the spin transfer torque magnetic random access memory (STT-MRAM), where it is central to the scaling of memory density. However, we will discuss here a different type of current induced torque, the spin — orbit torque which occurs in samples with uniform magnetisation — i.e. just a 'free' layer. And while the spin—orbit torque may be of importance for domain wall propagation in thin films [2], we will restrict our discussion to its role in the context of magnetisation switching.

A simplified mechanism of the spin—orbit torque is that, due to the spin—orbit coupled properties of a material, the current leads to a spin polarisation of the charge carriers, causing a torque to be applied to the magnetisation. In order for a current to lead to a spin polarisation of the carriers, via the 'so-called' inverse spin galvanic effect [3,4], the material must appear different to charge carriers propagating in opposite directions — i.e. it lacks inversion symmetry. There are two ways to achieve this, either the unit cell of a non-centrosymmetric crystal breaks the symmetry (Fig. 1a),

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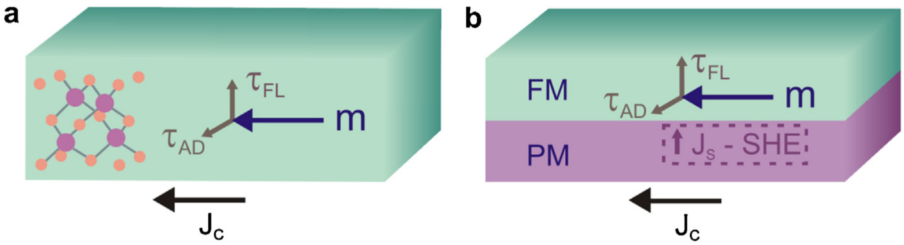

Figure 1 (a) Field like (τ_{FL}) and anti-damping (τ_{AD}) spin—orbit torque is generated by a current (J_c) in a ferromagnetic (FM) film with bulk inversion asymmetry due to, for example, the zinc—blende crystal structure in (Ga,Mn)As. (b) Spin—orbit torques are also present for thin ferromagnetic (FM) layers which have structural inversion asymmetry, due to being coupled to a paramagnetic (PM) conductor. In this system the spin orbit torque must also compete with a spin-transfer torque due to a spin-current (J_s) created by the spin-Hall effect (SHE).

known as bulk inversion asymmetry, or the structure breaks the symmetry by consisting of, for example, a bilayer film with dissimilar materials (Fig. 1b).

Following its earlier theoretical prediction [5,6], the first experimental demonstration of the spin—orbit torque was in (Ga,Mn)As, a ferromagnetic semiconductor based on the zinc—blende structure and consequently having bulk inversion asymmetry [7]. Current induced switching between the magnetic easy axes was shown for a microscale disc and the torque responsible was seen to be field-like [8]. This behaviour was subsequently theoretically modelled [9] and experimentally confirmed by others [10,11].

As its name suggests, the field-like torque acts as if an external magnetic field were applied, the effect being to change the equilibrium position of the magnetisation. With a field-like torque, as with an externally applied magnetic field, it is possible to perform magnetic switching but the current induced field needs to compete with the magnetic anisotropy field. The anti-damping torque must just compete with the damping torque intrinsic to the material for magnetic switching to occur and in a low damping magnetic material this is an easier prospect than competing with the magnetic anisotropy. Also, a constant anti-damping torque, differently from a field-like torque, is able to continuously drive precession of the magnetisation [1].

In our research group we used a microwave current to drive ferromagnetic resonance in (Ga,Mn)As via the spin—orbit torque [11]. By analysing the electrically detected ferromagnetic resonance data, it was possible to observe an anti-damping spin—orbit torque in addition to the previously measured field-like torque [12]. Theory developed by colleagues in Prague and in Mainz, showed the anti-damping spin—orbit torque can be explained by the Berry curvature in a similar way to another important spintronic effect, the intrinsic spin-Hall effect [13]. The anti-damping torque results from the carrier spins precessing around the vector sum of the exchange field and the current induced spin—orbit field. The origin of the intrinsic spin-Hall effect, occurring in a non-magnetic conductor, is similar except the carrier spin precession occurs around the current induced spin—orbit field alone. These studies in (Ga,Mn)As show generally that the spin—orbit torque in a ferromagnet can have an intrinsic anti-damping component as well as a field-like component.

In addition to the spin—orbit torques observed at low temperature in (Ga,Mn)As, spin—orbit torques have also been observed at room temperature multilayer thin films with structural inversion asymmetry [14]. In a trilayer of AlO_x/Co/Pt, where the Co film was only 0.6 nm thickness, a field-like torque attributed to the symmetry breaking of the interfaces was observed. In subsequent work by the same authors it was shown that an anti-damping contribution to current induced torque could lead to switching of a prototypical memory element [15]. A thorough analysis of the symmetries of the spin—orbit torques in these and similar layers showed comparable magnitude of anti-damping and field like torques, as well as a significant contribution from spin—orbit torques with high-order angle dependencies [16].

The interpretation of the current induced torque in metal thin films as a spin—orbit torque is at present debated. The spin—orbit torque is not the only possible current induced torque in ferromagnet/paramagnet bilayers, the spin-Hall effect is also known to contribute and experiments with relatively thick bilayers (e.g. Pt(6 nm)/NiFe(4 nm)) are well explained by the spin-Hall effect + spin transfer torque [17]. Differently from the inverse spin galvanic effect which causes a net spin accumulation of spins under electrical current injection, the spin-Hall effect causes a redistribution of the spins within the paramagnetic conductor. In this way the spin-Hall effect can drive an electron spin current into the ferromagnetic layer, applying a torque to the ferromagnet by the transfer of angular momentum as in the conventional spin transfer torque.

The most recent experiments on thin bilayer films have attempted to resolve the contribution from spin-Hall and spin—orbit torques by systematically studying current induced torques in multilayers with different metal layer thicknesses [18—20]. In these studies the ratio of field-like and anti-damping components of the torque are seen to change in magnitude and sign as the film thickness is reduced. These experiments, together with the higher order terms in the current-induced torque [16], indicate deviations from existing models of the spin-Hall effect generated spin transfer torque and Rashba spin—orbit torque.

In conclusion, the spin orbit interaction plays an important role in electrically applying torques to uniformly magnetised magnetic systems. The situation is more complex than in the case of the spin transfer torque and the role of a variety of spin—orbit effects (e.g. anisotropic damping, anisotropic spin relaxation, Dzyaloshinskii—Moriya interaction, the Berry curvature etc.) need to be considered to explain the existing data.

Finally, the electrical control that spin—orbit torques allow over classical magnetic bits may soon make this quantum technology widespread in a variety of memory applications.

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