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SPINTRONICS

Anatomy of spin-orbit torques

The use of time-resolved X-ray microscopy allows a direct visualization of the magnetization switching for nanomagnets under the effect of spin-orbit torques.

Within the field of spintronics, standardised techniques to probe magnetic moments are usually of electrical and/or magneto-optical nature, the latter exploiting visible light. A drawback of these approaches is that they cannot achieve the temporal and spatial resolutions needed to detect fast transients of magnetic dynamics at the nanoscale. This limitation has held back our progress in understanding precise mechanisms of current-induced magnetisation reversal in nanomagnets – a key technology in the quest for smaller memory devices with lower power consumption. Now, writing in *Nature Nanotechnology* [1], Baumgartner *et al.* use state-of-the-art time-resolved x-ray microscopy techniques to visualize the time-evolution of the magnetisation switching for a single nanomagnet under electrical current pulses, and unveil the detailed mechanism and robustness of the switching events.

A spintronic memory device is typically composed of a collection of small magnetic cells and the writing of a bit is performed by reversing the magnetisation of a single cell. In conventional hard disk drives, the torque required to rotate the magnetic moments is generated by a magnetic field from an electrical coil. However, this classical magnetic field is more and more energy inefficient upon progressively reducing the size of the magnetic cells. It was reported that electrical currents flowing inside the cells can flip the magnetic moments much more efficiently by exerting so-called current-induced torques [2]. The efficiency of this mechanism scales with size as the torques produced by this mechanism are proportional to the electric current density, opposed to the ones generated by classical magnetic fields being proportional to the total current. Memory devices based on such torques – such as spin-transfer-torque magnetic random-access memories (MRAMs) [3] – require few pJ to switch a magnetic cell [4].

Yet, there is ample room to improve the efficiency of magnetic switching – in fact, the magnetic energy required to safely retain data for ten years in a typical MRAM cell (100 nm × 100 nm × 10 nm volume) is less than 1 fJ [5]. The reduction of the writing current will not only improve the power consumption of future MRAMs but also enhance their density by shrinking the size of transistors to drive currents in the magnetic cells. It is envisaged that writing currents below 20 μA will enable multi-gigabit MRAMs [6]. However, to help advancing in this technological challenge, a clear and detailed understanding of the current-induced magnetisation switching processes is of pivotal importance.

Using scanning transmission x-ray microscopy, Baumgartner *et al.* successfully establish a complete picture of the magnetic switching driven by a particular kind of current-induced torques – the spin-orbit torques [7]. The technique used by the researchers produces stroboscopic snapshots of a perpendicularly-magnetised, 5-nm-thick Co disc – similarly to x-ray images we take in a hospital, but much faster (every 100 ps) and with a much higher spatial resolution (25 nm). The researchers confirm that the reversal process driven by spin-orbit torques is gradual and deterministic, with no significant time-delay in switching after the instance of the pulse injections. This lack of any incubation time is a unique characteristic of the spin-orbit-torque-induced switching [8], distinct from the conventional spin-transfer-torque-induced switching where thermal fluctuations cause random incubation times of the order of few ns – a relevant aspect for the operation speed of spin-transfer torque MRAMs.

The images acquired by the researchers exhibit a characteristic geometrical feature that is reproducible and universal for various amplitudes and durations of the pulse current. Given that the Co disc has 500 nm in diameter and contains a macroscopic number of atomic magnetic moments, one could expect that the thermal fluctuations result in random nucleation of small domains anywhere in the sample. This stochastic switching scenario has been excluded by the current observations – the magnetisation switching process always begins at specific corners of the samples (see figure). After the nucleation, the magnetic domain with inverted magnetisation propagates at an oblique angle with respect to the electrical current before sweeping across the entire disc. The nucleation point alternates between the four quadrants with respect to the direction of the current, controlled by the signs of the current and the external magnetic field.

These features can be concisely explained by a simple phenomenological model that takes into account two components of the spin-orbit torque, namely damping-like and field-like torques, along with the external magnetic field and the Dzyaloshinskii–Moriya interaction intrinsic to the Co nanostructure. Although the damping-like torque is well-known to be a crucial element during spin-orbit-torque-induced switching, the existence and role of the field-like component had been rather subtle and unclear. Baumgartner *et al.* have demonstrated that the concerted effect of the field-like spin-orbit torque, the external magnetic field and the Dzyaloshinskii–Moriya interaction determines the nucleation and the propagation of the inverted domains. Fine-tuning of these three fields by thin-film growth technology will potentially offer a precise control of the switching and its efficiency.

The authors also report on more than 10 trillion consecutive switching events in a single sample, with each event completed at a speed of approximately 1 ns. This appears to be sufficiently robust and fast for non-volatile magnetic memory applications, reassuring the position of spin-orbit torques as a leading contender for the future generation of magnetisation switching technology.

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Figure 1: The geometry of the magnetic switching
The nucleation point of the magnetisation reversal is determined by an interplay between the field-like spin-orbit torque, external magnetic field and the Dzyaloshinskii–Moriya interaction, acting as an effective field (represented by red, green and blue thin arrows, respectively). The nucleation occurs at a point where the three vectors add up to make a maximum length. The field-like torque flips the sign when the direction of the electric current (thick red arrow) is reversed which, combined with the sign of the magnetic field, results in a symmetric alternation of the nucleation point among the four quadrants. The field-like torque is indispensable for deciding the nucleation point uniquely.