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MAGNETIC DEVICES

Picosecond switching in a ferromagnet

An ultrashort pulse of electric current can be used to switch the magnetization of a micrometre-scale magnetic element via spin–orbit torques.

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Spin–orbit torques (SOTs) were discovered around a decade ago and have become a convenient tool for electrically manipulating the magnetization of magnetic heterostructures[1]. SOTs can, for example, switch the magnetization of a material between different stable states[2], displace magnetic domain walls[3] and generate coherent magnetic oscillations[4]. Such current-induced magnetic torques arise in magnetic systems with broken inversion symmetry and a strong spin–orbit coupling (Fig. 1a). Unlike conventional spin-transfer torque (STT) schemes, where a spin current can be obtained by passing a charge current through a magnetic conductor (a magnetic polarizer), the spin current in the SOT scheme originates from relativistic spin–orbit interactions in the bulk or at the interfaces of materials[1]. In this scheme, the charge and spin currents travel orthogonally, and a polarizing layer is thus not required, offering great flexibility in device design and material system.

A range of SOT-operated devices has been explored for application in memory and logic technologies, including magnetic random-access memory (MRAM)[5]. An MRAM device can store data in the magnetization of the free layer of a magnetic tunnel junction, which can be switched by SOTs[6] (Fig. 1b). Fast and efficient magnetization switching via SOTs is a desired property for such devices. However, while the principles of STT switching are well understood, the fundamental limits of SOT-induced switching speed remain unclear. In particular, fast SOT-induced magnetization switching in a ferromagnet using current pulses of 180 ps has been reported, limited only by the instruments used[6,7]. The high damping, large perpendicular anisotropy and small incubation delays in ultrathin ferromagnets should, in principle, though allow for faster switching in the lower picosecond range. And while terahertz operation has been reported for antiferromagnets[8], such ultrafast switching has not yet been achieved in a conventional ferromagnet.

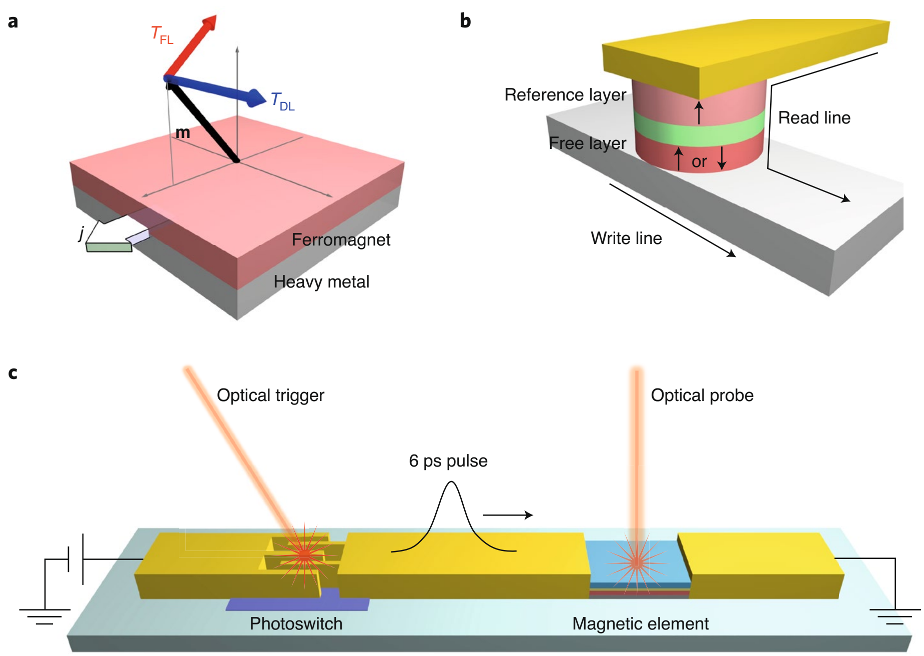

Fig. 1 | Picosecond SOT switching of a ferromagnet. a, Current-induced SOTs consist of damping-like (T_{DL}) and field-like torque (T_{FL}) components. SOTs are observed, among other systems, in magnetic heterostructures consisting of non-magnetic heavy metals and ferromagnets. *j*, electric current density; **m**, magnetization direction. **b**, A magnetic tunnel junction device with two ferromagnetic layers that are separated by an oxide tunnel barrier. The resistance of the device is maximum when the magnetization of the two ferromagnetic layers is in an antiparallel configuration, and minimum when it is parallel. The magnetization of the free layer is controlled by SOTs, when current flows through the 'write' line. The state of the device is probed by measuring the resistance along the 'read' line. Magnetic tunnel junctions are the building blocks of MRAMs. **c**, A simplified schematic of the circuit that was developed to generate picosecond-long intense current pulses to switch the magnetic element via SOTs.

Writing in *Nature Electronics*, Jon Gorchon and colleagues now report SOT-based magnetization switching in a nanometre-thick cobalt layer using a single electrical pulse of just 6 ps (ref. [9]). The researchers also investigate the magnetization dynamics using 3.7 ps pulses with sub-switching-threshold amplitudes, and show that the interplay of SOTs and heat-induced ultrafast changes in the magnetic properties play a critical role in the reversal mechanism. The 30-fold improvement in switching speed, with respect to the state of the art, which takes the switching close to the terahertz regime, in a common spintronic material, highlights the significant potential of SOT devices in ultrafast spintronics.

Gorchon and colleagues — who are based at institutes in France, Peru and the US — used a multilayer stack composed of platinum–cobalt–copper–tantalum, where the cobalt layer exhibits strong perpendicular magnetic anisotropy: an essential feature for long-term data retention and thermal stability in memory applications. This stack design is optimized for strong SOT generation due to the combined SOTs from the tantalum/cobalt and cobalt/platinum interfaces (the copper layer is transparent to the incoming spin current from the tantalum layer). To probe and switch the magnetic state of the cobalt layer at ultrashort timescales, the researchers fabricated a circuit based on a photoconductive switch (also known as an Auston switch), which is connected to the magnetic stack with lateral dimensions of $5 \times 4\ \mu m^2$ (Fig. 1c). In such a set-up, the photoswitch can be triggered by a femtosecond laser pulse, generating a-few-picosecond-long intense electrical pulses that traverse the magnetic element. A second laser beam that is focused on the magnetic structure can then be applied to probe the magnetization state using the magneto-optic Kerr effect (during or subsequent to the pulse injection). Using this approach, it was possible to reversibly switch the magnetization of the cobalt layer between the up and down states in the presence of an in-plane field, which is required to break the rotational symmetry of SOTs[2].

The study — experimentally and through simulations — of the magnetization dynamics driven by SOTs suggests that the switching occurs via the coherent rotation of the magnetization. This effect is due to the combined action of SOTs, as well as heat-induced effects reminiscent of ultrafast demagnetization, commonly observed in the optical pump–probe experiments with ultrashort laser pulses[10]. Previous studies have suggested that the switching occurs by domain nucleation and propagation in devices with lateral size larger than the domain wall width (typically a few nanometres)[11]. Therefore, it has been generally assumed that the limiting factor for fast SOT-induced switching is the size of the device, due to the finite domain wall velocities. The work of Gorchon and colleagues, which is based on a large device ($20\ \mu m^2$), challenges this assumption and calls for a better understanding of SOT-based switching on ultrashort timescales.

The work also opens up many possibilities for further experimental and theoretical research. In particular, the device scheme and measurement method are readily applicable to other SOT systems, including topological insulators, transition metal dichalcogenides and antiferromagnets; an adapted fabrication protocol would though be required, as well as impedance matching for efficient transmission of the electrical pulses. Furthermore, the study of the effect of parameters such as device size, pulse amplitude, pulse width, in-plane field, ferromagnetic material and SOT source, on SOT-induced ultrafast switching may offer additional insights on the unexpected switching behaviour, and provide useful input for potential applications. A more comprehensive physical model is also required in order to explore the effect of ultrafast demagnetization and thermal diffusion on the switching process. The large parameter space available, together with the wide range of relevant materials, create a fertile ground for additional breakthroughs. ❐

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Competing interests

The author declares no competing interests.