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Tilted spin current generated by an antiferromagnet

Measurements reveal that the antiferromagnet ruthenium dioxide (RuO_2) can generate an electric-field-induced spin current with a component of spin polarization perpendicular to the sample plane. This verifies theoretical predictions and provides a strategy for the future development of highly energy-efficient magnetic storage devices.

The question

One of the primary goals in the field of spintronics is to develop an efficient, reliable means by which an applied electric field can control the magnetization orientation in ferromagnetic devices. One of the most promising mechanisms is spin–orbit torque, whereby an applied electric field within a heavy metal or topological insulator layer is used to produce a spin current, which carries an angular momentum that exerts a torque on an adjacent magnetic layer[1]. However, for reasons of symmetry, the spin–orbit torque produced by most materials points strictly within the sample plane and is not capable of efficiently switching the magnetization direction of layers with perpendicular magnetic anisotropy. This switching is required to enable the production of very dense magnetic memory technologies[2]. Our research is part of an effort to understand mechanisms by which an electric field might generate spin torques with an arbitrary direction and, in particular, a strong component perpendicular to the plane of a layered magnetic sample.

The observation

Previous studies have predicted that RuO_2 — a collinear antiferromagnet — is capable of producing electrically generated spin currents through a previously unrecognized mechanism, with a polarization direction for the spin current approximately parallel to the orientation of the spin order of the antiferromagnet (that is, the Néel vector)[3]. If the Néel vector is tilted relative to the sample plane, the polarization of the generated spin current (and the associated torque that is exerted by this spin current) would have a strong component perpendicular to the sample plane (Fig. 1a). This mechanism is of interest because it arises from magnetic exchange interactions and crystal fields, instead of the spin–orbit interactions, which had previously been the focus of spintronics research. Additionally, for a single-domain RuO_2 sample the torque obtained with this mechanism is predicted to be stronger than that obtained using conventional spin–orbit-torque approaches.

Our Cornell group tested this prediction by making devices consisting of a RuO_2 layer integrated with a magnetic Permalloy layer. We applied in-plane electric fields and used electrical techniques to measure the deflection of the magnetization of the Permalloy resulting from the electrically generated torques. We measured these torques as a function of the angle of the applied electric field for two different crystalline orientations of RuO_2, thereby changing the orientation of the Néel vector (Fig. 1b–d). These measurements confirmed that RuO_2 generates a spin current with a well-defined tilted spin orientation approximately parallel to the Néel vector. The out-of-plane component of the spin torque generated by this effect is among the strongest measured so far from any low-symmetry spin-source material.

The implications

For a single-domain sample of RuO_2, the antiferromagnetic spin-torque mechanism is predicted to be able to generate out-of-plane torques much stronger than those produced by the conventional spin–orbit mechanism. However, the domain structure of the RuO_2 has not been controlled in our present experimental work, and the resulting torques are likely to be diminished by partial cancellation between oppositely oriented domains. A challenging next step is to characterize and control this domain structure, and to see if the strength of the torque can be increased further.

More research is also required to definitively distinguish the antiferromagnetic spin-torque mechanism from the conventional spin–orbit-torque mechanism. A spin–orbit mechanism is not expected to produce a spin polarization aligned with the Néel vector, nor the temperature dependence observed in our experiment, but the magnitudes of the torques measured so far are still in the range that could be explained by a spin–orbit mechanism.

The long-term goal of this research is to make spin-splitter-based non-volatile magnetic memory elements that are more energy efficient than other non-volatile memory devices, and perhaps even more efficient than volatile memory devices such as silicon-based static random-access memory (SRAM). To achieve this, it will be necessary to control the RuO_2 domain structure and fabricate high-quality magnetic tunnel junctions on RuO_2 layers.

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EXPERT OPINION

"This is a ground-breaking experiment. It supports a theoretical prediction that collinear magnets with vanishing net magnetization can generate strong spin currents of non-relativistic origin, and that these spin currents can be efficiently used in spintronic charge–spin conversion devices. This experiment is extremely timely, following immediately after the publication of the theoretical prediction of the effect." **Tomas Jungwirth, Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic.**

FIGURE

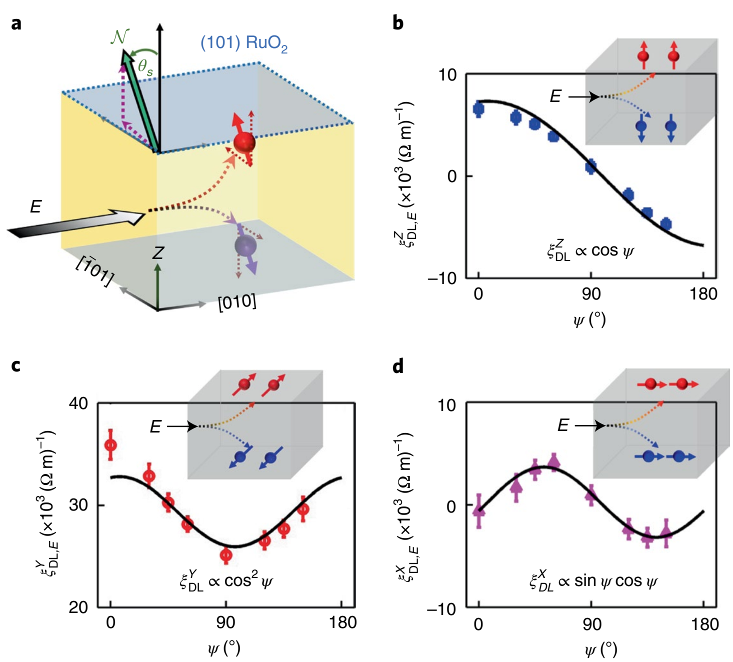

Fig. 1 | Generating a tilted spin current. a, An illustration of the generation of a vertically flowing spin current with a tilted spin polarization in RuO_2. When the Néel vector (N) is tilted an angle θ_s away from the out-of-plane direction, the antiferromagnetic spin-torque mechanism[3] allows an applied electric field (E) to generate a spin current polarized approximately parallel to N. **b**–**d**, The orientation of the spin polarization is determined by measuring the vector components of the damping-like spin-torque efficiency per unit applied electric field in the Z, Y and X directions, $\xi^{Z,Y,X}_{DL,E}$, as a function of the angle (ψ) of the electric field. The solid black lines represent a fit to the theoretical prediction and the error bars are the standard deviations. The insets illustrate the components of spin current associated with each case. © 2022, Bose, A. et al., corrected publication 2022

BEHIND THE PAPER

Like many scientific advances, this one was partly accidental. We were not originally aiming to study the effect of antiferromagnetism on the generation of spin currents. Instead, this work was part of a larger study investigating spin torques generated by the conducting rutile materials iridium oxide (IrO_2) and RuO_2. We were exploring the possibility that the Dirac nodal lines present in the band structures of both materials and the symmetry breaking generated by epitaxial growth might produce strong spin-torques. Initially, we were quite surprised by the striking differences between IrO_2 (ref. [4]) and RuO_2, but demonstrations[5] of antiferromagnetism in RuO_2 and the predictions of Rafael González-Hernández and collaborators[3] pointed the way to an explanation. **A.B.**

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FROM THE EDITOR

"This work experimentally confirms a new mechanism for generating spin-polarized currents with collinear antiferromagnets. The mechanism leads to spin currents with a tilted spin orientation that closely aligns to the Néel vector. By controlling the crystal orientation of the antiferromagnetic films (and with this the Néel vector), spin-polarized currents with a strong out-of-plane component can be achieved that have the necessary symmetry to efficiently manipulate magnetic memory devices with perpendicular magnetic anisotropy." **Katharina Zeissler, Associate Editor, *Nature Electronics*.**