Fully Field-Free Spin-Orbit Torque Switching Induced by Spin Splitting Effect in Altermagnetic RuO_2

Zhuoyi Li[1], Zhe Zhang[1], Xianyang Lu[1], Yongbing Xu[1, 2]*,

[1]*National Key Laboratory of Spintronics, Nanjing University, Suzhou 215163, China, ybxu@*nju.edu.cn
[2]*York-Nanjing International Center for Spintronics, School of Physics, Engineering and Technology, University of York, York YO10 5DD, UK*

Altermagnetism, a newly identified class of magnetism blending characteristics of both ferromagnetism and antiferromagnetism, is emerging as a compelling frontier in spintronics. This work report a groundbreaking discovery of robust, 100% field-free spin-orbit torque (SOT) switching in a RuO_2 (101)/Co/Pt/Co/Pt/Ta structure. The spin currents, induced by the in-plane charge current, are found to flow along the [100] axis with the spin polarization direction aligned parallel to the Néel vector. These z-polarized spins generate an out-of-plane anti-damping torque, enabling deterministic switching of the Co/Pt layer without the necessity of an external magnetic field. This study highlights the potential of RuO_2 as a powerful spin current generator, opening new avenues for advancing spin-torque switching technologies and other cutting-edge spintronic devices.

***Index Terms*— Altermagnetism; SOT Effect; Spin Current.**

A novel class of magnetism, which exhibits characteristics of both ferromagnetism and antiferromagnetism, has recently been identified. This new phenomenon, predicted to occur in over 200 materials, has been termed "altermagnetism"[1,2]. Materials such as ruthenium dioxide (RuO2) could exhibit this dual nature, combining the stable, fast spin-flipping properties of antiferromagnets with the distinct spin states of ferromagnets. Unlike conventional magnetic materials where electron spins align with the atomic orientation in the crystal lattice, in altermagnets, spin arrows can rotate independently of the atoms. Previously considered a paramagnet, RuO_2 has been shown to exhibit itinerant antiferromagnetism, with a Néel temperature above 300 K and the Néel vector aligned along the [001] axis [3]. Recent theoretical work has suggested that the collinear antiferromagnet RuO_2 might generate strong electric-field-induced spin currents with spin orientation roughly aligned along the Néel vector. RuO_2 crystallizes in the rutile structure with the P42/mnm space group, where ruthenium atoms are situated in the centers of stretched oxygen octahedrons [4]. This octahedral crystal field results in an anisotropic electronic structure and elliptical Fermi surfaces at kz = 04. The 90° rotation of Ru atoms in opposite magnetic sublattices, surrounded by directionally distinct oxygen octahedrons, leads to anisotropic spin band splitting in momentum space, making RuO_2 an efficient spin splitter [5]. In this work, we propose a RuO_2 (101)/Co/Pt/Co/Pt/Ta structure for efficient and robust field-free SOT switching with perpendicular magnetization. The z-polarized spins from the (101)-oriented RuO_2 layer are found to generate an out-of-plane anti-damping torque, enabling deterministic switching of the Co/Pt layer without the necessity of an external magnetic field. And it has been observed to have a clear dependence on the direction of J_C. The sample demonstrates an optimal switching ratio nearly 100% at an applied in-plane field H_x = 0 Oe, when JC flows along the $[01\bar{0}]$ axis. Notably, the ASSE dominates the spin current, especially when the applied current aligns with the [010] direction (θ = 90°). In this configuration, the spin polarization component σ_z creates a substantial field-like effective field. This interplay highlights the crucial role of σ_z in enhancing spin-torque efficiency, thereby elucidating the mechanics of spin flow modulation within this crystalline context.

I. Sample Preparations

All the samples were grown on Al_2O_3 $(1\bar{1}02)$ substrates using a magnetron sputtering system. The layer sequence RuO_2 (15 nm)/Co (0.5 nm)/Pt (1 nm)/Co (0.5 nm)/Pt (1 nm)/Ta (2 nm) was deposited from bottom to top, as shown in Fig. 1a. The (101)-oriented RuO_2 generates spin current with out-of-plane spin polarization. The spin current (J_S) flowing along the [100] axis, induced by the charge current (J_C) along the $[0\,\bar{1}\,0]$ axis.The spin polarization direction (σ) for J_S is approximately aligned parallel to the Néel vector ([001] axis). High-quality RuO_2 (101) films were grown on single-crystal Al_2O_3 $(1\bar{1}02)$ substrates by introducing O_2 gas into an Ar base gas during film growth in our magnetron sputtering system. To achieve defect-free, high-quality RuO_2 epitaxial films that can exhibit excellent ASSE, we optimized the growth conditions of the films and identified the optimal oxygen flow rate and growth temperature. During the film growth process, a 50 standard cubic centimeter per minute (sccm) Ar gas flow was introduced, while the O_2 flow rate was controlled at 10 sccm. A pure ruthenium target was used, with the Radio Frequency (RF) power set at 50 W. The substrate temperature was fixed at 500 ℃ during deposition. More details on the optimization process are presented in Supplementary Information. As shown in Fig. 1c, the clear and sharp RHEED pattern for the 15 nm RuO_2 (101) film indicates that the film exhibits good crystallinity with a flat, well-ordered surface. XRD measurements of a 50 nm RuO_2 film, shown in Fig. 1d, reveal clear and sharp RuO_2 (101) and RuO_2 (202) peaks, confirming the good (101) orientation of our RuO_2 films. Raman spectroscopy analysis, shown in Fig. 1e, indicates three Raman active modes for the RuO_2 (101) film: E_g, A_{1g} and B_{2g} modes. High-resolution cross-sectional scanning transmission electron microscopy (HRTEM) was conducted on the RuO_2 (101)/Co/Pt/Co/Pt structure, as shown in Fig. 1f. The

results demonstrate the high-quality layered growth of the multilayer thin film structure.

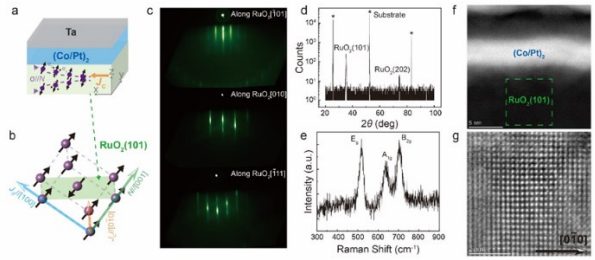

Fig. 1. a, Schematic representation of our sample. The spin polarization direction (σ) for the spin current (J_S) is aligned parallel to the Néel vector ([001] axis). **b,** The schematic illustrates J_S flowing along the [100] axis induced by the charge current (J_C) along the [$0\bar{1}0$] axis. The RuO_2 (101) crystal plane is highlighted by the green shading. **c,** Reflection high-energy electron diffraction (RHEED) patterns of a 15 nm RuO_2 (101) film grown on the Al_2O_3 ($1\bar{1}02$) substrate. **d,** θ-2θ scan x-ray diffraction (XRD) spectrum of a 50 nm thick RuO_2 (101) film grown on the Al_2O_3 ($1\bar{1}02$) substrate. Peaks from the substrate are marked with *. **e,** Raman spectra of a 50 nm thick RuO_2 (101) film grown on the Al_2O_3 ($1\bar{1}02$) substrate, showing three active modes: E_g, A_{1g} and B_{2g} modes. **f,** High-resolution HAADF image of the cross-section of RuO_2 (101)/$(Co/Pt)_2$/Ta and **g,** RuO_2 (101) film.

II. Results and Discussions

We investigate the current induced field-free SOT switching behavior. Fig. 2a and Fig. 2b present schematic diagrams illustrating the generation of spin current via ASSE in the (101)-oriented RuO_2 film, along with the Hall device used for the experiments. Fig. 2c compares the anomalous Hall effect (AHE) measurement curves at different θ, all of which exhibit good perpendicular magnetic anisotropy (PMA) with coercive fields around 300 Oe. To achieve SOT switching, we swept a pulsed direct current and measured the Hall resistance change of the Hall bar. Fig. 2d-f display the current-induced SOT magnetization switching loops in RuO_2/Co/Pt/Co/Pt at different in-plane external fields (H_{ext}) from + 400 Oe to - 400 Oe at θ values of 90°, 45°, and 0°, respectively, with H_{ext} aligned parallel to the direction of the applied current (I_{pulse}). In conventional structures [6,7], no switching loop occurs at zero magnetic field, necessitating H_{ext} to break the rotational symmetry of the spin torque. Remarkably, at θ = 90°, where the current flows along the x-axis ([010] crystal direction), SOT switching has been achieved without H_{ext}, with a switching ratio approaching 100% ($R_{SOT}/R_{AHE} = 1$, where R_{SOT} and R_{AHE} denote the Hall resistance responses to SOT and magnetic field variations, respectively), as shown in Fig. 2d. Similarly, in Fig. 2e, field-free SOT switching is observed at θ = 45°, with a switching ratio of approximately 85%, while no magnetization switching occurs at θ = 0° (Fig. 2f).

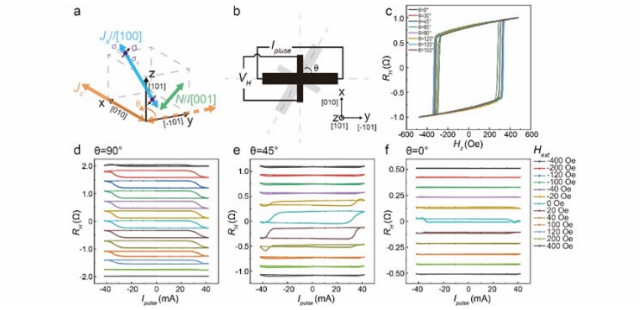

Fig. 2. a, Schematic diagram illustrating the generation of spin current via ASSE in the (101)-oriented RuO_2 film. **b,** The Hall device used for the experiments. θ represents the angle between the current direction and the y-axis. **c,** Anomalous Hall effect (AHE) loops for diffenent values of θ. **d-f,** Corresponding current-induced magnetization switching behaviors observed in Co/Pt multilayers at θ = 90°, 45° and 0°.

III. Conclusion

We have demonstrated the full 100% SOT switching in the RuO_2 (101)/Co/Pt/Co/Pt/Ta structure where any possible pinning effects in the Co/Pt/Co/Pt multi-layers are eliminated due to the reduced formation of AFM domains associated with the high-quality growth of the single crystal RuO_2 (101) layer achieved by a well-controlled magnetron sputtering growth process. Our research further reveals that (101)-oriented RuO_2 films effectively generate spin currents with an out-of-plane spin polarization component σ_z, driven by the altermagnetic spin splitting effect (ASSE). The controllability of spin polarization and the high efficiency of out-of-plane spin current generation position RuO_2 as a standout candidate for next-generation spintronic devices.

References

[1] Šmejkal, L., Sinova, J. & Jungwirth, T. Emerging Research Landscape of Altermagnetism. *Phys. Rev. X* **12** (2022).

[2] Šmejkal, L., Sinova, J. & Jungwirth, T. Beyond Conventional Ferromagnetism and Antiferromagnetism: A Phase with Nonrelativistic Spin and Crystal Rotation Symmetry. *Phys. Rev. X* **12** (2022)..

[3] Berlijn, T. et al. Itinerant Antiferromagnetism in RuO2. Phys. Rev. Lett. 118, 077201 (2017).

[4] .Mattheiss, L. F. Electronic structure of RuO2, OsO2, and IrO2. *Phys. Rev. B* **13**, 2433 (1976).

[5] Bai, H. *et al.* Observation of Spin Splitting Torque in a Collinear Antiferromagnet RuO2. *Phys. Rev. Lett.* **128**, 197202 (2022)

[6] Kong, W. J. *et al.* Spin-orbit torque switching in a T-type magnetic configuration with current orthogonal to easy axes. *Nat. Commun.* **10**, 233 (2019)..

[7] Liu, L., Lee, O. J., Gudmundsen, T. J., Ralph, D. C. & Buhrman, R. A. Current-induced switching of perpendicularly magnetized magnetic layers using spin torque from the spin Hall effect. *Phys. Rev. Lett.* **109**, 096602 (2012).