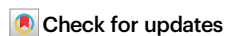


All-electrical magnetisation switching via tilting spin propagation and polarization in MnTe spin source

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Crystallographic symmetry fundamentally governs the generation, propagation, and polarization of spin currents, which are the core processes in spin-orbit torque technology, yet harnessing this principle to realize field-free switching remains a critical challenge. Here, we propose a general symmetry-engineering strategy that tailors spin currents via tilting crystal axis. In epitaxial tilted MnTe (0001) thin films, all-electrical magnetization switching due to strong out-of-plane spin polarization was successfully observed, where spin propagation was reoriented. Remarkably, this approach yields an exceptionally high y-polarized spin-orbit torque efficiency ($\xi_y = 0.58$), together with a significant z-polarized component ($\xi_z = 0.07$). Our work proves crystal symmetry engineering as a powerful and versatile pathway for designing spin-source materials, opening new avenues for integrating high in-plane symmetry crystals into practical, energy-efficient spintronic devices.

The efficient control of magnetization via spin-orbit torque (SOT) is central to the development of next-generation non-volatile magnetic memory and logic technologies, offering compelling advantages in speed, endurance, and scalability^{1–5}. At its core, SOT-driven switching relies on the transfer of angular momentum from a spin current to a perpendicular magnetic moment. Deterministic switching requires a spin component aligned anti-parallel to this moment. However, a fundamental symmetry constraint limits conventional SOT systems: charge-to-spin conversion in polycrystalline materials or single crystal materials with very high symmetry, such as heavy metals Pt, W, and Ta, produces spin currents with polarization transverse to both the charge current and the film normal⁶. This geometry yields spins that either cannot couple efficiently to a perpendicular magnet or drive it symmetrically into competing states, necessitating an external magnetic field to break the degeneracy and define the final magnetization orientation⁷. However, this requirement for an additional external

magnetic field complicates device design and impedes practical integration.

To achieve field-free operation, significant research has focused on generating a symmetry-breaking effective magnetic field or unconventional spin polarization. Strategies include engineering structural asymmetries^{8,9}, establishing exchange bias^{10,11}, creating compositional gradients¹², or employing materials with low crystal symmetry^{13–15} or specific magnetic order^{16–19}. The effectiveness of some of these approaches relies on symmetry breaking to activate unconventional components of the spin conductivity tensor. While successful, they often involve complex heterostructure engineering and typically achieve limited efficiency in generating the crucial z-spin component. A promising alternative pathway would be to coherently manipulate the propagation and polarization direction of inherently large conventional spin currents to transform them into the desired out-of-plane component, which is a

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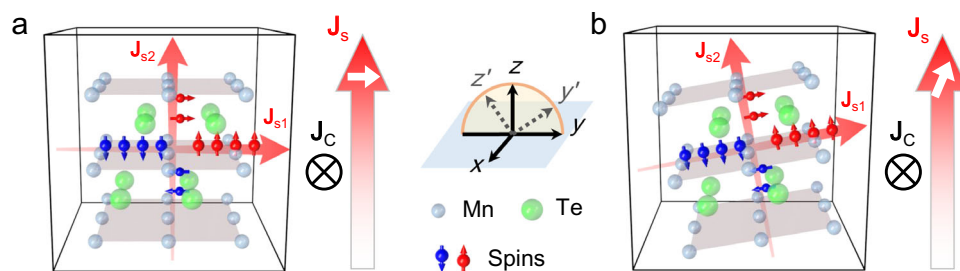


Fig. 1 | Schematic of spin propagation and polarization in MnTe. **a** Spin current projected onto the in-plane and out-of-plane directions in normal MnTe, illustrating the propagation and polarization directions. The red and blue spheres with arrows represent spin-up and spin-down electrons, respectively. The light-blue and green spheres denote Mn and Te atoms, respectively. The large and small arrows on the right indicate the net spin propagation and polarization directions in the

system. **b** Schematic showing the modified propagation and polarization of the spin current projected onto the y' - and z' -directions when the crystal axis of MnTe, originally along z , is tilted by an angle towards the $-y$ direction to a new z' -direction. J_c , J_s , J_{s1} , and J_{s2} represent charge current, net spin current, and spin currents with propagation along the y (y') and z (z') directions, respectively.

strategy that could unlock substantially higher overall SOT efficiency.

This is achieved by introducing controlled tilting of the crystal axes as a general symmetry-engineering strategy. For this purpose, intentionally tilted hexagonal MnTe (0001) is utilized as a model spin source system while the interfacial strain in this system, engineered through the epitaxial lattice mismatch and Volmer-Weber growth mode, tilts the [0001] crystal axis^{20,21}. This structural manipulation simultaneously reorients spin propagation and induces a substantial out-of-plane spin polarization, effectively converting conventional spin currents into a form that carries the necessary z -component for field-free switching. Consequently, efficient and deterministic switching of perpendicular magnetization is experimentally demonstrated in the absence of an external magnetic field. This work establishes crystal-axis tilting as a novel and powerful materials-design paradigm for generating unconventional spin polarizations, highlighting its significant potential to enable high-density, energy-efficient spintronic devices.

Results and discussion

MnTe has a hexagonal crystal structure (NiAs-type, space group $P6_3/mmc$)²², where Te atoms form a hexagonal close-packed (hcp) sublattice, and Mn atoms occupy all the octahedral interstitial sites, forming a corrugated honeycomb layer within the ab -plane (Fig. 1a). Below its Néel temperature ($T_N \approx 307$ K²³), MnTe exhibits A-type antiferromagnetic order characterized by ferromagnetically coupled moments within each Mn honeycomb layer, with adjacent layers aligned antiferromagnetically along the c -axis²⁴. Recently, MnTe has been proposed to host the g -wave altermagnetism^{25,26}. However, despite the nonrelativistic spin-split band structure, the g -wave spin distribution prevents the nonrelativistic spin current generation²⁷. Although single-domain altermagnetic MnTe may, in principle, host spin-orbit coupling-enabled spin current responses with both T-odd and T-even components, the net magnetism-related T-odd contribution is expected to be strongly suppressed in our films because MnTe generally forms multiple antiferromagnetic domains²⁸. The T-odd contributions from symmetry-related domains tend to compensate each other, whereas the T-even contributions add up to give the same symmetry-allowed tensor structure as that of the nonmagnetic phase, as detailed in Supplementary Note 1. Therefore, in the following discussion, MnTe is treated as a non-magnetic spin source material. As shown in Supplementary Note 2, the validity of this treatment is further supported by the consistent switching behaviors observed in MnTe-based SOT devices below and above the Néel temperature.

As illustrated in Fig. 1a for MnTe, when a charge current is applied collinear to the [11 $\bar{2}$ 0] crystal axis (the $-x$ direction), it is converted into a spin current via spin Hall effect^{29,30}. In a well oriented (0001) film, the

in-plane component of this spin current (denoted as J_{s1} with the spin conductivity σ_1) propagates along the $\pm y$ direction with spin polarization oriented along $\pm z$, while the out-of-plane component (denoted as J_{s2} with the spin conductivity σ_2) propagates along $\pm z$ with polarization along $\pm y$. In this case, the net spin current (J_s) injected into the top magnetic layer propagates along $+z$ and is polarized along $+y$.

Figure 1b shows the case where the MnTe (0001) crystal axis is tilted away from the film normal (the z -direction) towards the z' -direction, which can be conceptualized as rotated MnTe (0001) around the x axis. In this case, J_{s1} and J_{s2} propagate along the z' - and y' -directions with the mixed spin polarization, as illustrated in Fig. 1b. A simple symmetry analysis shows that the net spin current by summing J_{s1} and J_{s2} hosts the spin conductivity with both y -polarized component $\sigma^y = -\sigma_1 \sin^2 \theta_T + \sigma_2 \cos^2 \theta_T$ and z -polarized component $\sigma^z = (\sigma_1 + \sigma_2) \cos \theta_T \sin \theta_T$, where θ_T is the tilted angle of the growth direction. Since MnTe is a hexagonal crystal and thus no symmetry will enforce $\sigma_1 + \sigma_2 = 0$, nonzero σ^z will be expected as long as $\theta_T \neq 0$ or 90° (see Supplementary Note 3).

To validate this model, MnTe (20 nm)/Pt (1.5 nm)/Co (0.4 nm)/Pt (2 nm) multilayer films were fabricated on MgO (111) and CaF₂ (111) substrates, with the Pt/Co/Pt structure growing in a polycrystalline form. The MnTe (0001) film epitaxially grown on MgO (111) spontaneously develops a tilt angle relative to the normal direction of the thin film. In contrast, the MnTe grown on CaF₂ (111) with less lattice mismatch exhibits a (0001) crystal plane parallel to the film plane, thereby serving as a control sample where symmetry remains unbroken. Schematic diagrams of the stacking structure of two multilayer films and their corresponding field-free switching results are shown in Fig. 2a, c, where R_{xy} denotes the Hall resistance. A pronounced field-free switching loop is observed in the MgO (111)/MnTe (0001)/Pt/Co/Pt with a tilted MnTe (0001) crystal axis, while the CaF₂ (111)/MnTe (0001)/Pt/Co/Pt system, which lacks the crystallographic tilt, shows no field-free switching, confirming that the crystallographic tilt is a prerequisite for this effect.

The angular relationship between MnTe [0001] and the substrate normal direction was confirmed through pole figure measurements in X-ray diffraction (XRD), as shown in Fig. 2b, d. Pole figure analysis reveals that the MnTe (0001) plane on the MgO (111) substrate exhibits a tilting angle of $\theta_T \approx 5^\circ$ relative to the film plane, with the tilting direction aligned toward the MnTe [1100] crystal axis. The epitaxial relationship in MgO/MnTe heterostructure and the relative orientation between the MgO [111] crystal axis (the substrate surface normal direction is within $\pm 0.5^\circ$ of the $\langle 111 \rangle$ direction) and MnTe [0001] crystal axis were further verified by XRD and high-angle annular dark-field transmission electron microscopy (HAADF-STEM) image. Specifically, the epitaxial relationship is MnTe (0001) // MgO (111) and MnTe [11 $\bar{2}$ 0] // MgO [110]. In the MgO/MnTe system, the lattice spacing

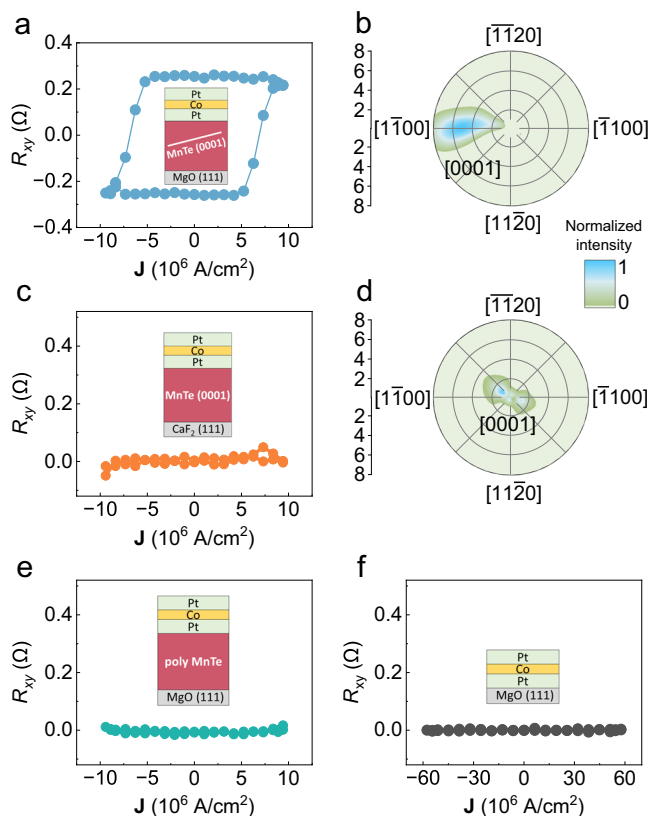


Fig. 2 | Field-free switching in Pt/Co/Pt trilayers under several configurations. **a** Field-free switching results and corresponding device stack schematic of MgO (111)/MnTe (0001)/Pt/Co/Pt. **b** Pole figure of MnTe (0001) on MgO (111) substrate. **c** Field-free switching results and corresponding device stack schematic of CaF₂ (111)/MnTe (0001)/Pt/Co/Pt. **d** Pole figure of MnTe (0001) on CaF₂ (111) substrate. **e**, **f** Field-free switching results and device stack schematics of MgO (111)/poly-MnTe/Pt/Co/Pt (**e**) and MgO (111)/Pt/Co/Pt (**f**).

mismatch between the film and the substrate causes MnTe to relieve the interfacial strain by tilting during epitaxial growth³¹, as detailed in Supplementary Fig. S2. In contrast, due to the small lattice mismatch between MnTe and CaF₂, the MnTe (0001) peak is centered in the pole figure for the film grown on CaF₂ (111) substrate, indicating a negligible tilt angle. A direct correlation can be established between the presence of crystallographic tilt, as determined from the pole figures, and the successful observations of the field-free switching.

To further substantiate our claim, two types of control samples were fabricated: polycrystalline MnTe/Pt/Co/Pt multilayers and Pt/Co/Pt trilayers without MnTe. Their schematic cross-sections and corresponding field-free switching results are shown in Fig. 2e and f, respectively. Neither sample showed field-free switching, thereby ruling out any contribution from the MgO (111) substrate or the intrinsic properties of the Pt/Co/Pt stack itself. Furthermore, possible factors such as wedge-shaped film growth^{32,33}, deviation of the easy magnetic axis from the film normal³⁴, and interfacial exchange bias^{9,10} may also induce field-free switching. These scenarios are discussed separately in Supplementary Notes 5–7. The results show that these factors are not present in our MgO (111)/MnTe (0001)/Pt/Co/Pt system. Therefore, the field-free switching is conclusively attributed to the generation of unconventional spin polarizations induced by the tilting of the MnTe [0001] crystal axis.

It is necessary to further investigate the angular dependence of field-free switching in the MgO (111)/MnTe (0001)/Pt/Co/Pt system. The schematic and optical images of Hall bar device structures for angular measurement of field-free switching are shown in Fig. 3a and b.

These devices are patterned at various in-plane orientations relative to the crystal axis, while the angle between the charge current direction and the MnTe [1120] crystal axis is defined as α (Fig. 3c). Since the MnTe [0001] crystal axis is tilted toward the [1100] direction, $\alpha = 0^\circ$ and 90° correspond to the current being perpendicular and parallel to the tilt direction of the crystal axis, respectively. The field-free switching and the field-induced anomalous Hall Effect (AHE) loop measurement for devices with different current directions are shown in Fig. 3d–f. When $\alpha = 0^\circ$, the Hall resistance exhibits the largest amplitude variation and a counterclockwise hysteresis loop with respect to the current, consistent with the configuration in Fig. 3g, where the applied current breaks the mirror symmetry. The current-induced change in R_{xy} is approximately 0.50Ω , whereas the change in R_{xy} from the magnetic-field-induced AHE loop is approximately 1.66Ω , indicating partial switching with a switching ratio of about 30%. As α increases, the change in Hall resistance gradually decreases. When $\alpha = 90^\circ$ (Fig. 3e), the Hall resistance remains nearly constant with the current, indicating the suppression of field-free switching. The occurrence of this phenomenon is attributed to the applied current along the tilting of the crystal axis, which fails to break the symmetry. Consequently, no net z -polarized spin current propagates toward the MnTe/ferromagnetic layer interface, corresponding to the configuration in Fig. 3h. As α increases beyond 90° , the switching hysteresis loop reappears. The change in Hall resistance reaches a maximum again at $\alpha = 180^\circ$, where the switching curve exhibits a clockwise hysteresis with respect to the current (Fig. 3f). This reversal in loop direction indicates an inversion of the spin current polarity due to the reversed charge current direction³⁵. In Fig. 3d–f, the changes in R_{xy} from the field-induced AHE loops are approximately equal under different angles of current, whereas the current-induced field-free switching behavior differs. The switching ratio is defined as the ratio of the current-induced R_{xy} difference at zero current to the field-induced R_{xy} difference at zero magnetic field. Its dependence on the angle of current α is shown in Fig. 3i. The maximum switching ratio, approximately $\pm 30\%$, occurs near $\alpha = 0^\circ$ and 180° . The angular dependence exhibits unidirectional symmetry, which corresponds exactly to the unidirectional anisotropy arising from the tilted crystal axis. The reproducibility of this angular dependence of the switching ratio was further validated using additional independent devices, as presented in Supplementary Note 10.

To quantify the spin current generated by the crystal axis tilt in MnTe, the shift in the AHE hysteresis loop under various auxiliary magnetic fields was employed. Here, the auxiliary field ($\mathbf{H}_x$) is defined as an external magnetic field always applied parallel to the current direction⁷. Figure 4a shows the AHE loop shift for the device with $\alpha = 0^\circ$ at $\mathbf{H}_x = 0$. Under a large current of ± 11 mA, the AHE loop of the MnTe/Pt/Co/Pt stack exhibits a certain horizontal shift along the field axis, as shown in the inset of Fig. 4a. We quantify this shift via an effective magnetic field $\Delta\mathbf{H}_z$, defined as $\Delta\mathbf{H}_z = \mathbf{H}_{\text{center}}(I^+) - \mathbf{H}_{\text{center}}(I^-)$, where $\mathbf{H}_{\text{center}}(I^\pm) = \frac{\mathbf{H}_t^+(I^\pm) - \mathbf{H}_t^-(I^\pm)}{2}$ represents the center position of AHE loop for positive and negative currents³⁶. For the device with $\alpha = 0^\circ$ and $\mathbf{H}_x = 0$, $\Delta\mathbf{H}_z$ is 6.3 Oe at ± 11 mA, confirming the presence of a net z -polarized spin current along the film's normal direction in this system. By varying the magnitude of the auxiliary field, the value of the effective field $\Delta\mathbf{H}_z$ can be considerably modulated. Figure 4b shows the variation of $\Delta\mathbf{H}_z$ with current density as $\mathbf{H}_x$ is swept from -200 Oe to 200 Oe. The current density is calculated using a current shunt model³⁷, where $I_{\text{MnTe}} = \frac{R_{\text{Pt/Co/Pt}}}{R_{\text{Pt/Co/Pt}} + R_{\text{MnTe}}} \times I_{\text{Total}}$, and the current density is defined as the current per unit cross-sectional area in the MnTe layer. For each auxiliary magnetic field $\mathbf{H}_x$, $\Delta\mathbf{H}_z$ increases linearly with the current density over the range of 1.9×10^6 A/cm² to 3.4×10^6 A/cm².

The slope of the linear relationship, defined as $\chi = \frac{\Delta\mathbf{H}_z}{J_{\text{MnTe}}}$, exhibits a strong dependence on the auxiliary field $\mathbf{H}_x$. As shown in Fig. 4c, the

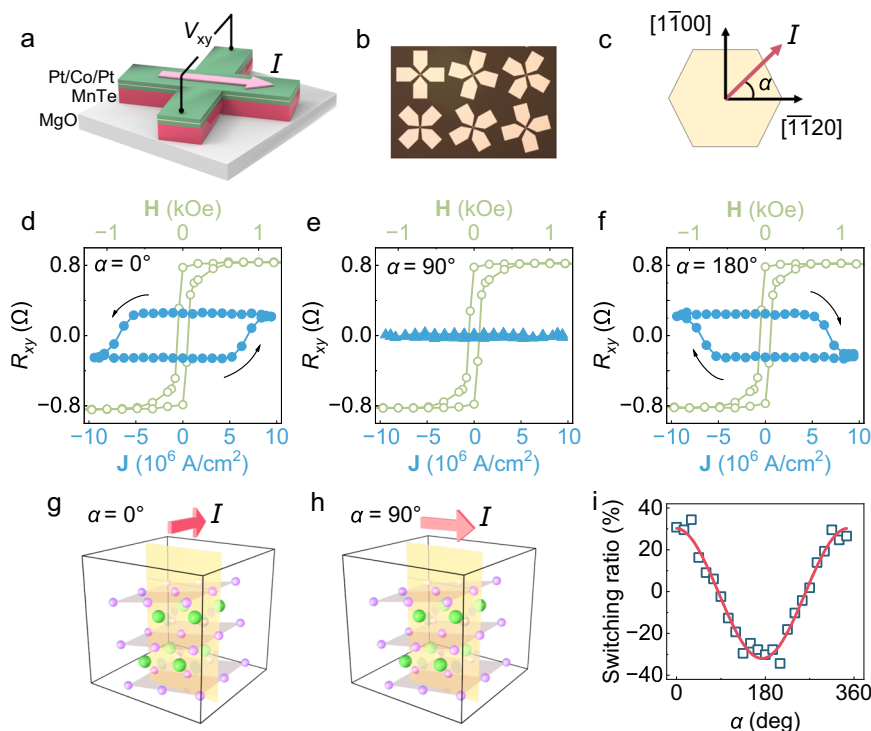


Fig. 3 | Current direction dependence of field-free switching in MgO/MnTe/Pt/Co/Pt. **a, b** Schematic diagram and optical image of the measurement devices. **c** Definition of the direction of current. **d–f** Field-free switching behavior and the

field-induced AHE loop under different angles of current (0° , 90° , 180°). **g, h** The schematic diagrams of current at $\alpha = 0^\circ$ and 90° , where the current I breaks and does not break symmetry, respectively. **i** Switching ratio as a function of α .

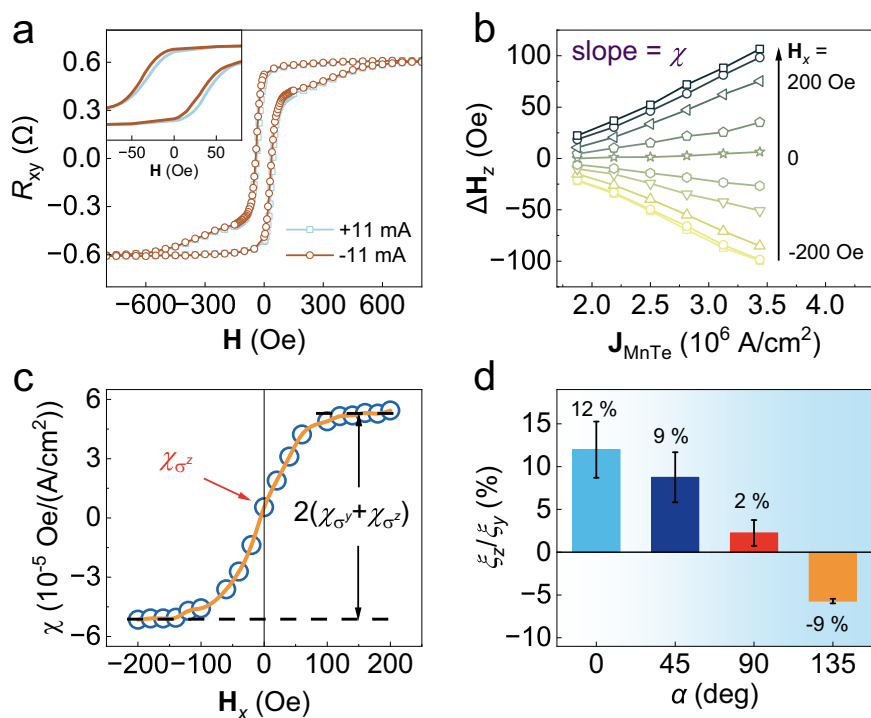


Fig. 4 | Quantification of SOT efficiency from AHE loop shifts. **a** Measurement of AHE loop shifts at zero auxiliary field under ± 11 mA currents. The inset provides a magnified view of the AHE curve near zero magnetic field, revealing the shift in detail. **b** Effective field ΔH_z as a function of current density in MnTe when the

auxiliary magnetic field H_x is changed from -200 Oe to 200 Oe. **c** Dependence of χ on the auxiliary magnetic field. **d**. Ratio of z-polarized to y-polarized SOT efficiency as a function of the direction of current. Error bars, SD ($n = 5$).

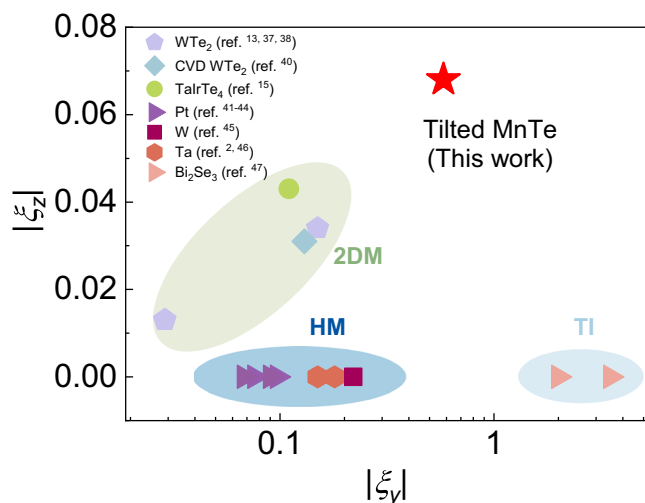


Fig. 5 | Comparison of z-polarized and y-polarized SOT efficiencies across low-symmetry 2D materials (2DM), heavy metals (HM), and topological insulators (TI). Each color represents a distinct material system, and the ξ_y and ξ_z values along with the corresponding measurement methodologies are summarized in Supplementary Note 9.

magnitude of χ exhibits a monotonic increase with $\mathbf{H}_x$, eventually saturating at a value χ_s for both positive and negative fields. Crucially, at zero external field ($\mathbf{H}_x = 0$), χ shows a finite value $\chi_{\sigma^z} = 0.54 \times 10^{-5} \text{Oe}/(\text{A}/\text{cm}^2)$, which is attributed entirely to the z-polarized spin current. At high auxiliary magnetic field, χ is jointly contributed by the y-polarized and z-polarized SOTs, i.e., $2\chi_s = 2(\chi_{\sigma^z} + \chi_{\sigma^y})$, from which the $\chi_{\sigma^y} = 4.5 \times 10^{-5} \text{Oe}/(\text{A}/\text{cm}^2)$ can be calculated.

The effective SOT efficiency is a function of χ :⁷

$$\xi_i = \frac{4e\mu_0\mathbf{M}_s t}{\pi\hbar} \chi_{\sigma^i}, \quad (1)$$

where $i = z$ or y . Here e , μ_0 , $\mathbf{M}_s$, t and $\hbar$ represent the electron charge, vacuum permeability, saturation magnetization of the magnetic layer Co, thickness of Co layer, and reduced Planck's constant, respectively. As mentioned earlier, the thickness of Co layer is 0.4 nm, and the saturation magnetization is measured to be 1070 emu/cm³ (see Supplementary Fig. S7). Using Eq. (1), when $\alpha = 0^\circ$, the z-polarized and y-polarized SOT efficiencies are calculated as $\xi_z = 0.07$ and $\xi_y = 0.58$, respectively, yielding a ratio ξ_z/ξ_y of approximately 12 %. The variation of this ratio with current direction is summarized in Fig. 4d. As the α increases from 0° to 135° , ξ_z/ξ_y gradually decreases from 12 % to -9 %. This trend aligns perfectly with the unidirectional anisotropy observed in the difference in Hall resistance ΔR_{xy} (Fig. 3i), providing conclusive evidence that the switching is driven by the z-polarized spin current generated via the crystal axis tilt.

For a quantitative analysis of the SOT efficiencies, it is essential to compare the findings of this study to the broader landscape of spin-source materials. As summarized in Fig. 5, the z- and y-polarized SOT efficiencies of tilted MnTe are systematically compared with those of low-symmetry 2D materials (2DM), heavy metals (HM), and topological insulators (TI). Here, the contribution from the Pt layers to ξ_y is omitted, with further details provided in Supplementary Note 11. This comparison serves two purposes: first, to compare the performance of the proposed symmetry-engineering strategy against established alternative approaches for generating out-of-plane spin currents; and second, to highlight the unique advantages enabled by decoupling high SOT efficiency from inherent low in-plane symmetry.

The results clearly validate the core principle of our strategy. In comparison with low-symmetry 2D materials (such as WTe₂^{13,38-40} and TaIrTe₄¹⁵), which rely on their intrinsic crystal structure to break symmetry, the tilted MnTe demonstrates superior values for both ξ_y (0.58) and ξ_z (0.07). This difference arises from the distinct mechanisms of z-spin generation in the two cases. In low-symmetry 2D materials, the values of the spin conductivity tensor for the z-polarization (σ^z) at the k_+ and k_- wave vectors in the Brillouin zone are no longer equal, and their mutual cancellation yields only a weak net σ^z . In contrast, σ^y is generally large because it originates from the sum of σ^y at the k_+ and k_- points. This fact is exploited in our work on MnTe: by tilting the crystal axis, the intrinsically large σ^y is linearly recombined along the film normal direction, thereby generating a σ^z component. Given that MnTe's relatively large lattice constant ratio $c/a \approx 1.6$, substantial z-spin generation is achieved, with performance comparable to or even surpassing that of low-symmetry systems.

Furthermore, when compared with traditional polycrystalline heavy metals (e.g., Pt⁴¹⁻⁴⁴, W⁴⁵, Ta^{2,46}), a significant advantage in ξ_y is observed in MnTe. This highlights a key strength of this approach, which lies in the fact that the magnitude of the conventional in-plane spin current is not sacrificed to obtain the out-of-plane component. Instead, the inherently large spin Hall efficiency of materials such as MnTe is leveraged, and a portion of the spin Hall conductivity (SHC) is generated along the out-of-plane direction via the linear combination of SHC components along the tilted crystal axes, an effect enabled by the crystal geometry. The exceptionally high ξ_y provides a significant performance margin, which is advantageous for overcoming reversal barriers in a wider variety of device geometries, thereby enhancing practical integration potential and device reliability. The combination of remarkably high y-polarized efficiency alongside a functionally significant z-polarized component distinguishes the crystal-axis-tilting paradigm, thereby establishing it as a versatile and powerful materials-design strategy for next-generation, field-free spintronics devices.

While other superior spin source materials like TIs have been reported to exhibit in-plane SOT efficiencies exceeding 1⁴⁷, MnTe offers a distinct advantage through its finite out-of-plane SOT efficiency, which is sufficient for field-free switching. At the same time, it is worth noting that, due to the semiconducting nature of MnTe and its relatively high resistivity, a given SHC can generate a larger spin current, which is one of the key reasons for the relatively large SOT efficiency observed in MnTe. In the present case, the estimated spin Hall conductivities are $\sigma^z = 3 \times 10^3 (2e/\hbar) (\Omega^{-1}\text{m}^{-1})$ and $\sigma^y = 25 \times 10^3 (2e/\hbar) (\Omega^{-1}\text{m}^{-1})$. Therefore, while MnTe exhibits exceptionally large SOT efficiency, its SHC remains on the same order as - or even lower - than that of conventional heavy metals when its high resistivity is taken into account. It is worth noting that the resistivity of MnTe is not a fixed limitation, but rather a tunable parameter. Through gating or doping, this parameter can be leveraged to simultaneously engineer both the SOT efficiency and the SHC, opening new avenues for future functional material design⁴⁸.

Our work demonstrates a novel and effective mechanism for achieving field-free switching not through conventional in-plane symmetry breaking, but by geometrically tilting the propagation direction of a conventional, high-efficiency spin current. This strategy of controlled crystal axis tilting establishes a general paradigm for transforming conventional spin currents - typically limited to in-plane polarization - into a form that carries the necessary out-of-plane spin component for deterministic switching of perpendicular magnetization. The key distinction lies in actively tilting the spin propagation vector, thereby accessing unconventional components of the spin conductivity tensor from materials that may possess high in-plane lattice symmetry. A significant advantage of this approach is that it does not require low in-plane symmetry of the spin source material, a prerequisite for many conventional field-free switching schemes^{13,15,37-39}. The effect instead relies on the inherent anisotropy

between in-plane and out-of-plane spin conductivities, which is naturally present in many hexagonal systems. This work does not distinguish between the contributions of spin current and orbital current due to their identical symmetry. However, it should be noted that distinguishing and harnessing the orbital contribution remains an important direction for future research.

The compatibility of this tilt-engineering method with MgO (111) substrates facilitates its integration into existing semiconductor process flows. Looking ahead, this approach could be extended using techniques such as chemical templating on amorphous substrates⁴⁹, paving the way for scalable device fabrication. It is important to note, however, that this mechanism relies on the presence of a significant intrinsic spin current with a well-defined polarization axis relative to the crystal lattice, which is then coherently reoriented by the tilt. As detailed in Supplementary Note 3, this method takes advantage of the in-plane/out-of-plane anisotropy of the material and is particularly effective for non-cubic crystal systems (e.g., hexagonal or tetragonal). In contrast, for materials with highly symmetric in-plane/out-of-plane isotropic structures (such as cubic systems), field-free switching cannot be induced even if the crystal axis is tilted. Future work should therefore focus on exploring a broader range of material systems with suitable crystal structures, in which the proposed tilt-engineering strategy can be applied to harness their potentially large conventional spin currents for efficient field-free switching, thereby opening new avenues for material discovery and functional device design.

In conclusion, we have introduced and demonstrated a general symmetry-engineering strategy for field-free SOT switching based on the tilting of spin current propagation. By epitaxially growing a tilted MnTe (0001) layer on MgO (111) substrate, we coherently reorient the generated spin current. This geometric manipulation effectively converts a portion of the conventional, high-magnitude in-plane spin current into a crucial out-of-plane spin polarization, enabling deterministic switching in an adjacent Pt/Co/Pt heterostructure without any external magnetic field. The unidirectional switching anisotropy is directly correlated with crystal axis tilting. The system exhibits an outstandingly high y -polarized SOT efficiency ($\xi_y = 0.58$), which serves as the powerful source current, alongside a significant generated z -polarized component ($\xi_z = 0.07$). This work establishes crystal axis tilting as a powerful and versatile materials-design paradigm, highlighting a promising pathway towards developing high-performance, energy-efficient spintronic devices by ingeniously harnessing conventional spin currents.

Methods

Sample preparation and characterization

The MnTe/Pt/Co/Pt sample was fabricated by ultra-high-vacuum magnetron sputtering, with MgO (111) and CaF₂ (111) as substrates. MnTe was deposited at 550 °C, followed by post-deposition annealing for 20 min before cooling down to room temperature. Subsequently, the Pt/Co/Pt trilayer was deposited at ambient temperature to form a polycrystalline structure. All layers were deposited at an Ar pressure of 0.4 Pa, with sputtering powers of 10 W for MnTe and Pt, and 6 W for Co. The structure of the thin film was characterized by XRD and HAADF-STEM, and the magnetic properties were measured using a superconducting quantum interference device (SQUID).

Device fabrication and transport measurement

The sample was fabricated into a Hall-bar device using micro-nano fabrication techniques, with adjacent devices oriented differently relative to the crystal axis. The width of the current channel of a switching device is 8 μm . The combination of the Keithley 6221 AC/DC Current Source and 2182A Nanovoltmeter forms a powerful, integrated solution, enabling easy implementation of AHE measurements with an in-plane auxiliary magnetic field. For field-free switching

measurements, the sample was positioned away from the magnet to ensure the absence of external magnetic field interference.

Data availability

The datasets generated and/or analyzed in the current study are provided in the Source Data file. Source data are provided with this paper.

References

1. Miron, I. M. et al. Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature* **476**, 189–193 (2011).
2. Liu, L. et al. Spin-torque switching with the giant spin Hall effect of tantalum. *Science* **336**, 555–558 (2012).
3. Yang, H. et al. Two-dimensional materials prospects for non-volatile spintronic memories. *Nature* **606**, 663–673 (2022).
4. Dieny, B. et al. Opportunities and challenges for spintronics in the microelectronics industry. *Nat. Electron.* **3**, 446–459 (2020).
5. Qiu, X. et al. Spin-orbit-torque engineering via oxygen manipulation. *Nat. Nanotechnol.* **10**, 333–338 (2015).
6. Zhang, Y. et al. Different types of spin currents in the comprehensive materials database of nonmagnetic spin Hall effect. *npj Comput. Mater.* **7**, 167 (2021).
7. Pai, C. F., Mann, M., Tan, A. J. & Beach, G. S. D. Determination of spin torque efficiencies in heterostructures with perpendicular magnetic anisotropy. *Phys. Rev. B* **93**, 144409 (2016).
8. Yu, G. et al. Switching of perpendicular magnetization by spin-orbit torques in the absence of external magnetic fields. *Nat. Nanotechnol.* **9**, 548–554 (2014).
9. Akyol, M. et al. Current-induced spin-orbit torque switching of perpendicularly magnetized Hf[CoFeB]/MgO and Hf[CoFeB]/TaO_x structures. *Appl. Phys. Lett.* **106**, 162409 (2015).
10. Oh, Y. W. et al. Field-free switching of perpendicular magnetization through spin-orbit torque in antiferromagnet/ferromagnet/oxide structures. *Nat. Nanotechnol.* **11**, 878–884 (2016).
11. Fukami, S., Zhang, C., DuttaGupta, S., Kurenkov, A. & Ohno, H. Magnetization switching by spin-orbit torque in an antiferromagnet-ferromagnet bilayer system. *Nat. Mater.* **15**, 535–541 (2016).
12. Cao, Y. et al. Deterministic magnetization switching using lateral spin-orbit torque. *Adv. Mater.* **32**, 1907929 (2020).
13. MacNeill, D. et al. Control of spin-orbit torques through crystal symmetry in WTe₂/ferromagnet bilayers. *Nat. Phys.* **13**, 300–305 (2017).
14. Shi, S. et al. All-electric magnetization switching and Dzyaloshinskii-Moriya interaction in WTe₂/ferromagnet heterostructures. *Nat. Nanotechnol.* **14**, 945–949 (2019).
15. Liu, Y. et al. Field-free switching of perpendicular magnetization at room temperature using out-of-plane spins from TaIrTe₄. *Nat. Electron.* **6**, 732–738 (2023).
16. Hu, S. et al. Efficient perpendicular magnetization switching by a magnetic spin Hall effect in a noncollinear antiferromagnet. *Nat. Commun.* **13**, 4447 (2022).
17. Cao, C. et al. Anomalous spin current anisotropy in a noncollinear antiferromagnet. *Nat. Commun.* **14**, 5873 (2023).
18. Hu, S. et al. Frontiers in all electrical control of magnetization by spin-orbit torque. *J. Phys.: Condens. Matter* **36**, 253001 (2024).
19. Zhou, Z. et al. Manipulation of the altermagnetic order in CrSb via crystal symmetry. *Nature* **638**, 645–650 (2025).
20. Vashaei, Z. et al. Structural variation of cubic and hexagonal Mg_xZn_{1-x}O layers grown on MgO (111) / c-sapphire. *J. Appl. Phys.* **98**, 054911 (2005).
21. Ahn, J. et al. Identification of an actual strain-induced effect on fast ion conduction in a thin-film electrolyte. *Nano Lett* **18**, 2794–2801 (2018).

22. Mori, S., Hatayama, S., Shuang, Y., Ando, D. & Sutou, Y. Reversible displacive transformation in MnTe polymorphic semiconductor. *Nat. commun.* **11**, 85 (2020).
23. Kriegner, D. et al. Multiple-stable anisotropic magnetoresistance memory in antiferromagnetic MnTe. *Nat. commun.* **7**, 11623 (2016).
24. Kriegner, D. et al. Magnetic anisotropy in antiferromagnetic hexagonal MnTe. *Phys. Rev. B* **96**, 214418 (2017).
25. Krempaský, J. et al. Altermagnetic lifting of Kramers spin degeneracy. *Nature* **626**, 517–522 (2024).
26. Lee, S. et al. Broken Kramers degeneracy in altermagnetic MnTe. *Phys. Rev. Lett.* **132**, 036702 (2024).
27. González-Hernández, R. et al. Efficient electrical spin splitter based on nonrelativistic collinear antiferromagnetism. *Phys. Rev. Lett.* **126**, 127701 (2021).
28. Amin, O. J. et al. Nanoscale imaging and control of altermagnetism in MnTe. *Nature* **636**, 348–353 (2024).
29. Hirsch, J. E. Spin hall effect. *Phys. Rev. Lett.* **83**, 1834 (1999).
30. Sinova, J. et al. Spin hall effects. *Rev. Mod. Phys.* **87**, 1213–1260 (2015).
31. Woo, S. Y. et al. Tilted epitaxy on (211)-oriented substrates. *Appl. Phys. Lett.* **102**, 132103 (2013).
32. Bai, R. et al. Uniform and robust field-free spin-orbit torque switching via complementary double-wedge structure. *Nano Lett.* **25**, 16725–16732 (2025).
33. Wu, B. et al. Shape anisotropy induced field-free switching and enhancement of dampinglike field in Pt/Co/PtMn heterostructures with a wedged ultrathin antiferromagnetic PtMn layer. *Phys. Rev. B* **108**, 054417 (2023).
34. Liang, Y. et al. Field-free spin-orbit switching of perpendicular magnetization enabled by dislocation-induced in-plane symmetry breaking. *Nat. Commun.* **14**, 5458 (2023).
35. Zhao, Y. et al. Field-free perpendicular magnetization switching through topological surface state in type-II Dirac semimetal Pt₃Sn. *Adv. Mater.* **37**, 2418663 (2025).
36. Baek, S. C. et al. Spin currents and spin-orbit torques in ferromagnetic trilayers. *Nat. Mater.* **17**, 509–513 (2018).
37. Zhang, M. et al. Electrical manipulation of field-free magnetization switching driven by spin-orbit torque in amorphous gradient-Mn₃Sn. *Adv. Sci.* **12**, 2417621 (2025).
38. Wang, F. et al. Field-free switching of perpendicular magnetization by two-dimensional PtTe₂/WTe₂ van der Waals heterostructures with high spin Hall conductivity. *Nat. Mater.* **23**, 768–774 (2024).
39. Wang, X. et al. Room temperature field-free switching of CoFeB/MgO heterostructure based on large-scale few-layer WTe₂. *Cell Rep. Phys. Sci.* **4**, 101468 (2023).
40. Shi, S. et al. Observation of the out-of-plane polarized spin current from CVD grown WTe₂. *Adv. Quantum Technol.* **4**, 2100038 (2021).
41. Liu, L. et al. Spin-torque ferromagnetic resonance induced by the spin Hall effect. *Phys. Rev. Lett.* **106**, 036601 (2011).
42. Jiang, D. et al. Substrate-induced spin-torque-like signal in spin-torque ferromagnetic resonance measurement. *Phys. Rev. Appl.* **21**, 024021 (2024).
43. Karimeddini, S., Mittelstaedt, J. A., Buhrman, R. A. & Ralph, D. C. Transverse and longitudinal spin-torque ferromagnetic resonance for improved measurement of spin-orbit torque. *Phys. Rev. Appl.* **14**, 024024 (2020).
44. Peterson, T. A., McFadden, A. P., Palmstrøm, C. J. & Crowell, P. A. Influence of the magnetic proximity effect on spin-orbit torque efficiencies in ferromagnet/platinum bilayers. *Phys. Rev. B* **97**, 020403 (2018).
45. Okada, A. et al. Spin-pumping-free determination of spin-orbit torque efficiency from spin-torque ferromagnetic resonance. *Phys. Rev. Appl.* **12**, 014040 (2019).
46. Kato, Y. et al. Improvement of write efficiency in voltage-controlled spintronic memory by development of a Ta-B spin hall electrode. *Phys. Rev. Appl.* **10**, 044011 (2018).
47. Mellnik, A. R. et al. Spin-transfer torque generated by a topological insulator. *Nature* **511**, 449–451 (2014).
48. Khang, N. H. D. et al. A conductive topological insulator with large spin Hall effect for ultralow power spin-orbit torque switching. *Nat. Mater.* **17**, 808–813 (2018).
49. Garg, C. et al. Ferrimagnetic Heusler tunnel junctions with fast spin-transfer torque switching enabled by low magnetization. *Nat. Nanotechnol.* **20**, 360–365 (2025).

Author contributions

Y.D. and Y.G. contributed equally to this work. S.W. supervised the project. Y.D. and M.Y. designed the experiments, analyzed the data, and wrote the paper. Y.D. and Y.G. performed the sample growth, device fabrication, XRD characterization, and transport measurement. Y.J. and T.M. contributed to the discussion on the mechanism. Y.Z. performed FIB sample preparation. B.L. and D.S. Song performed HAADF-STEM characterization and analysis. X.Q. and D.F. Shao jointly contributed to the interpretation of the mechanism and the editing of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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