Control of spin–orbit torques through crystal symmetry in WTe$_2$/ferromagnet bilayers

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Recent discoveries regarding current-induced spin–orbit torques produced by heavy-metal/ferromagnet and topological-insulator/ferromagnet bilayers provide the potential for dramatically improved efficiency in the manipulation of magnetic devices. However, in experiments performed to date, spin–orbit torques have an important limitation—the component of torque that can compensate magnetic damping is required by symmetry to lie within the device plane. This means that spin–orbit torques can drive the most current-efficient type of magnetic reversal (antidamping switching) only for magnetic devices with in-plane anisotropy, not the devices with perpendicular magnetic anisotropy that are needed for high-density applications. Here we show experimentally that this state of affairs is not fundamental, but rather one can change the allowed symmetries of spin–orbit torques in spin-source/ferromagnet bilayer devices by using a spin-source material with low crystalline symmetry. We use WTe$_2$, a transition-metal dichalcogenide whose surface crystal structure has only one mirror plane and no two-fold rotational invariance. Consistent with these symmetries, we generate an out-of-plane antidamping torque when current is applied along a low-symmetry axis of WTe$_2$/Permalloy bilayers, but not when current is applied along a high-symmetry axis. Controlling spin–orbit torques by crystal symmetries in multilayer samples provides a new strategy for optimizing future magnetic technologies.

Current-induced torques generated by materials with strong spin–orbit (S–O) interactions are a promising approach for energy-efficient manipulation of nonvolatile magnetic memory and logic technologies$. However, S–O torques observed to date are limited by their symmetry so that they cannot efficiently switch the nanoscale magnets with perpendicular magnetic anisotropy (PMA) that are required for high-density applications$. S–O torques generated either in conventional heavy-metal/ferromagnet thin-film bilayers$^{11-13}$ or in topological-insulator/ferromagnet bilayers$^{14,15}$ are restricted by symmetry to have a particular form$^{16}$: an ‘antidamping-like’ component oriented in the sample plane that is even upon reversal of the magnetization direction, $\mathbf{m}$, plus an ‘effective-field’ component that is odd in $\mathbf{m}$. The fact that the antidamping torque lies in-plane means that the most efficient mechanism of S–O-torque-driven magnetic reversal for small devices (antidamping switching)$^{17,18}$ is available only for magnetic samples with in-plane magnetic anisotropy$^{9,9}$, and not PMA samples (see Supplementary Information). S–O torques can also arise from broken crystalline inversion symmetry, even within single layers of ferromagnets$^{19-22}$ or antiferromagnets$^{23}$, but the antidamping torques that have been measured to date are still limited to lie in the sample plane$^{21,24,25}$. Here we demonstrate that the allowed symmetries of S–O torques in spin-source/ferromagnet bilayer samples can be changed by using a spin-source material with reduced crystalline symmetry. We generate an out-of-plane antidamping S–O torque when current is applied along a low-symmetry axis of the bilayer. This previously unobserved form of S–O torque is quenched when current is applied along a high-symmetry axis.

As our low-symmetry spin-source material, we use the semi-metal WTe$_2$, a layered orthorhombic transition-metal dichalcogenide (TMD) with strong S–O coupling$^{26-29}$. TMD materials are attractive for use as sources of S–O torque because they can be prepared as monocrystalline thin films with atomically flat surfaces down to the single-layer level. They provide a broad palette of crystal symmetries, S–O coupling strengths, and electrical conductivities$^{30,31}$. Other research groups have recently demonstrated the generation of S–O torques in devices made with the TMD MoS$_2$, and the Onsager reciprocal process (voltage generation from spin pumping) in MoS$_2$/Al/Cr heterostructures$^{32}$. Compared to MoS$_2$, the crystal structure of WTe$_2$ has lower symmetry, with the space group $Pnm\overline{2}$, for bulk WTe$_2$ crystals$^{34}$. In a WTe$_2$/ferromagnet bilayer sample, the screw-axis and glide-plane symmetries of this space group are broken at the interface, so that WTe$_2$/ferromagnet bilayers have only one symmetry, a mirror symmetry relative to the $bc$ plane (depicted in Fig. 1a). There is no mirror symmetry in the $ac$ plane, and therefore no $180^\circ$ rotational symmetry about the $c$-axis (perpendicular to the sample plane).

We fabricate our devices by mechanically exfoliating an artificially grown crystal of WTe$_2$ onto a high-resistivity oxidized Si wafer, transferring to a high-vacuum sputter system without exposure to air, and sputter depositing 6 nm of Permalloy (Py = Ni$_{80}$Fe$_{20}$) with a 1 nm protective Al cap (see Methods). The Py magnetic moment is in-plane for all devices studied. The coated WTe$_2$ flakes are patterned into bars by electron-beam lithography and Ar ion milling (Fig. 1b,c), and electrical connection is made by Ti/Pt contact pads. After completion of the device fabrication, we determine the crystallographic axes of each WTe$_2$ flake relative to the bar using polarized Raman spectroscopy (Methods and Supplementary Information). We study only devices in which the active region has minimal surface roughness ($<$300 pm) and no monolayer steps in the WTe$_2$ as measured by atomic force microscopy. We have measured a total of 15 devices with bars oriented at a variety of alignments to the WTe$_2$ crystal axes and with WTe$_2$ thicknesses ranging from 1.8 nm to 15.0 nm (Supplementary Table 1).

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To measure the S–O torques produced by our WTe2/Py bilayers, we use the technique of spin-torque ferromagnetic resonance (ST-FMR)23, performed at room temperature. In ST-FMR, an in-plane alternating current is applied through the bilayer at a frequency characteristic of ferromagnetic resonance (here, 5–12 GHz). The torques generated by the current excite the magnetic moment away from equilibrium and cause it to precess, creating a time-dependent change in the resistance of the bilayer due to the anisotropic magnetoresistance (AMR) in the ferromagnet. This change in the resistance mixes with the alternating current to create a d.c. voltage, \( V_{\text{mix}} \), across the bar. The circuit used to measure \( V_{\text{mix}} \) is depicted in Fig. 1c. By sweeping an applied in-plane magnetic field, we tune the ferromagnetic resonance through the applied frequency, giving rise to a resonance feature in \( V_{\text{mix}} \) (Fig. 1d,e). The in-plane (\( \tau_\parallel \)) and out-of-plane (\( \tau_\perp \)) torque amplitudes defined in Fig. 1b contribute to the symmetric and antisymmetric parts of the \( V_{\text{mix}} \) lineshape, respectively. This allows determination of the torque components by fitting \( V_{\text{mix}} \) as a function of applied magnetic field to a sum of symmetric and antisymmetric Lorentzians (Supplementary Information). The amplitudes of the Lorentzians are related to the two components of torque by:

\[
V_S = \frac{I_{\text{d}}}{2} \left( \frac{dR}{d\phi} \right) \frac{1}{\alpha_G \gamma (2B_0 + \mu_0 M_{\text{eff}}) \tau_\parallel}
\]

\[
V_A = \frac{I_{\text{d}}}{2} \left( \frac{dR}{d\phi} \right) \frac{\sqrt{1 + \mu_0 M_{\text{eff}} / B_0}}{\alpha_G \gamma (2B_0 + \mu_0 M_{\text{eff}}) \tau_\perp}
\]

where \( R \) is the device resistance, \( \phi \) is the angular orientation of the magnetization relative to the direction of applied current in the sample, \( dR/d\phi \) is due to the AMR in the Py, \( \mu_0 M_{\text{eff}} \) is the out-of-plane demagnetization field, \( B_0 \) is the resonance field, \( I_{\text{d}} \) is the microwave current in the bilayer, \( \alpha_G \) is the Gilbert damping coefficient and \( \gamma \) is the gyromagnetic ratio. In our devices, \( \mu_0 M_{\text{eff}} = 0.7 \, \text{T} \) and \( \alpha_G = 0.011 \), as determined by the ST-FMR resonance frequency and linewidth, respectively, and \( R(\phi) \) is measured directly by rotating the magnetic field using a projected-field apparatus.

During a ST-FMR measurement, the applied magnetic field fixes the average angle of the magnetization at a given value, \( \phi \). The strengths of the current-induced torques for different angles of the magnetization are related to the symmetries of the device. For example, in a Pt/Py structure, the two-fold rotational symmetry requires that the S–O torque changes sign when the magnetization is rotated in-plane by 180°, correspondingly changing the sign of \( V_{\text{mix}} \) but maintaining the same magnitude. This is illustrated in Fig. 1d, where we plot ST-FMR traces for a Pt(6 nm)/Py(6 nm) bilayer at \( \phi = 40° \) and 220°, showing nearly identical lineshapes after multiplying the \( \phi = 220° \) trace by \(-1\).

Figure 1e shows the results of the same experiment carried out on a WTe2/Py bilayer with the current applied along the low-symmetry crystal axis of WTe2, parallel to the \( a \)-axis (device 1). In this case, we find that \( V_{\text{mix}} (40°) \) and \(- V_{\text{mix}} (220°) \) differ significantly in both amplitude and shape, indicating that the current-induced torques in the two cases differ in both magnitude and direction. This observation is incompatible with two-fold rotational symmetry, indicating that the current-induced torques are affected by the reduced symmetry of the WTe2 surface.

To analyse this result in more detail, we consider the full angular dependence of the ST-FMR signal as an external magnetic field is used to rotate the direction of the magnetization within the
The unusual angular dependence we measure for the antisymmetric ST-FMR signal with current applied along the a-axis can be fitted well by the simple addition of a term proportional to \( \sin(2\phi) \): \[ V_A(\phi) = A \cos(\phi) \sin(2\phi) + B \sin(2\phi) \] (3)

where \( A \) and \( B \) are constants independent of the field angle (see the solid line in Fig. 2b bottom panel). To quantitatively translate the measured angular dependence of \( V_A \) and \( V_S \) to torques, we can use equations (1) and (2) to remove the contribution from the sample plane. In a simple heavy-metal/ferromagnet bilayer with no broken lateral symmetries, the current-induced torque amplitudes (due to the spin Hall effect, the Rashba–Edelstein effect, or the Oersted field) have a \( \cos(2\phi) \) dependence. The AMR in Permalloy has an angular dependence that scales as \( \cos^2 \phi \), which enters \( V_{\text{mix}} \) as \( dR/d\phi \propto \sin(2\phi) \). The product of these two contributions then yields the same angular dependence for the symmetric and antisymmetric ST-FMR components: \( V_S = S \cos \phi \sin 2\phi \) and \( V_A = A \cos(\phi) \sin(2\phi) \). Our Pt/Py control samples are well described by this behaviour (Fig. 2a; the parameter \( \phi_0 \) accounts for any misalignment between the sample and the magnet, and is typically \( \sim 5^\circ \)).

For our WTe\(_2\)/Permalloy samples with current along the a-axis, the symmetric component of the ST-FMR signal also has this form (Fig. 2b top panel). The non-zero symmetric component indicates that S–O torques are present in the WTe\(_2\)/Permalloy bilayer, since the symmetric component corresponds to an in-plane torque and cannot be generated by an Oersted field. However, the more striking result is that the angular dependence of the antisymmetric component is very different from \( \cos(\phi) \sin(2\phi) \) (Fig. 2b bottom panel). The variations in the absolute values of signal amplitudes reflect the broken symmetries of the WTe\(_2\) surface: the absence of mirror symmetry in the ac plane (corresponding to \( \phi \rightarrow 180^\circ - \phi \), since \( \bm{m} \) is a pseudovector) and the absence of two-fold rotational symmetry about the c-axis (\( \phi \rightarrow 180^\circ + \phi \)). This result indicates the existence of a source of out-of-plane torque not previously observed in any S–O torque experiment.

The unusual angular dependence we measure for the antisymmetric ST-FMR signal with current applied along the a-axis can be fitted well by the simple addition of a term proportional to \( \sin(2\phi) \): \[ V_A(\phi) = A \cos(\phi) \sin(2\phi) + B \sin(2\phi) \] (3)
angular dependence of the AMR. The fits in Fig. 2b then correspond to angular dependencies for the in-plane and perpendicular torque amplitudes of the form

\[ \tau_1(\phi) = \tau_s \cos(\phi) \]  
\[ \tau_2(\phi) = \tau_a \cos(\phi) + \tau_b \]

where \( \tau_s, \tau_a, \) and \( \tau_b \) are independent of \( \phi \). The terms proportional to \( \cos(\phi) \) are the usual terms observed previously, and in the Pt/Pt control samples. The new term \( (\tau_b) \) corresponds to an out-of-plane torque that is independent of the in-plane magnetization orientation; that is, it is even in \( \mathbf{m} \) and, therefore, an antidiamping-like torque. It is consistent with predictions\(^{23} \) that broken lateral mirror symmetry can allow an out-of-plane torque of the form \( \tau_{AD} \propto \mathbf{m} \times (\mathbf{m} \times \mathbf{c}) \). That an out-of-plane antidiamping-like torque with the form of \( \tau_b \) could exist has also been discussed in an analysis of the allowed symmetries for S-O torques in GaMnAs/Fe samples\(^{24} \), but this torque has not previously been identified in experiment.

In commonly studied bilayer systems with any broken in-plane symmetries, a linear-in-current out-of-plane torque that is independent of the in-plane magnetization cannot exist by symmetry. For example, the presence of a two-fold rotation disallows \( \tau_b \). In samples with two-fold rotational symmetry, rotating the sample by 180° is equivalent to changing the sign of an in-plane current without changing the sign of \( \tau_b \), which violates the linear-in-current requirement. However, WTe\(_2\)/Py bilayers do not have two-fold rotational symmetry. The only symmetry in our WTe\(_2\)/Py bilayers is the bc plane mirror, \( \sigma_r(bc) \). The effect of \( \sigma_r(bc) \) on a WTe\(_2\)/Py bilayer with current flowing along the a-axis is illustrated in Fig. 2c. Both the out-of-plane torque (a pseudovector) and the current change sign under \( \sigma_r(bc) \), \( \tau_0 \rightarrow -\tau_0 \) and \( I \rightarrow -I \), which is the expected behaviour for a current-generated S-O torque: the sign of torque must change with the sign of the current. A torque with the symmetry of \( \tau_0 \) is therefore allowed for WTe\(_2\)/Py bilayers with current along the a-axis.

We observe that \( \tau_b \) goes to zero when the current is applied parallel to the b-axis of WTe\(_2\). Figure 3a shows the antisymmetric ST-FMR component \( V_A \) (red circles) as a function of \( \phi \) for device 2, in which the current is applied along the b-axis. The angular fit to equation (3) yields a value of \( B \) equal to 0 within experimental uncertainty. This result is again consistent with the symmetries of the WTe\(_2\) surface layer. When the mirror symmetry operation \( \sigma_r(bc) \) is applied in this case (Fig. 3b), the out-of-plane torque is inverted but the current is not, and therefore an out-of-plane component of torque that is independent of the in-plane magnetization angle is forbidden by symmetry. Higher-order angular terms [namely \( \tau_0 \propto \cos(m\phi) \) with \( m \) odd or \( \tau_0 \propto \sin(m\phi) \) with \( m \) even] are symmetry-allowed for current along the b-axis, and can be included in fits of \( V_A \) versus \( \phi \) to improve the quantitative agreement (Supplementary Information). We also continue to observe a non-zero symmetric ST-FMR signal when the current is aligned with the b-axis, which has the same functional form as the symmetric ST-FMR signal in the devices with current along the a-axis (Supplementary Information).

We further investigated the symmetry dependence of \( \tau_0 \) by studying devices with different angles, \( \phi_{d}, \) between the a-axis of the WTe\(_2\) and the applied current direction. We fabricated 15 devices with different \( \phi_{d} \) and performed full angle-dependent ST-FMR measurements on each to extract \( A, B \) and \( S \) (Supplementary Table 1). Figure 4a shows the ratio of \( \tau_b/\tau_s \) at a given frequency \( (f = 9\text{ GHz}) \) as a function of \( \phi_{d} \) for these different devices. We consistently see that the ratio of \( \tau_b/\tau_s \) is large when current is aligned with the a-axis, and is gradually quenched as the projection of the current along the b-axis grows. This provides strong additional evidence that the observed magnetization-independent out-of-plane torque is correlated with the symmetries present in the WTe\(_2\) crystal. The dependence of the measured torques on WTe\(_2\) thickness provides insight into the mechanism of torque generation. If the torques arise through bulk mechanisms, clear thickness dependences should be expected; however, if the torques are generated by interface effects they should not depend on WTe\(_2\) thickness. Figure 4b shows the dependence of the torque ratios \( \tau_b/\tau_s \) and \( \tau_s/\tau_A \) on WTe\(_2\) thickness for devices that have current along the a-axis. (The individual dependences of \( \tau_s, \tau_b, \) and \( \tau_A \) on WTe\(_2\) thickness and on the angle of the current relative to the a-axis are plotted in the Supplementary Information.) Neither \( \tau_b/\tau_s \) nor \( \tau_s/\tau_A \) show any significant dependence on WTe\(_2\) thickness. This requires \( \tau_s, \tau_b, \) and \( \tau_A \) to either all have the same thickness dependence or have no definite thickness dependence. However, a bulk contribution to \( \tau_b \) is forbidden by the screw symmetry of the WTe\(_2\) crystal structure. The bulk WTe\(_2\) structure is mapped onto itself if it is rotated by 180° about an axis normal to the layers (c-axis) and translated by half a unit cell along both the c- and a-axis (in the c direction, half a unit cell is one layer spacing). A bulk contribution to \( \tau_b \) would be left unaltered by this operation, while the direction of an in-plane charge current is reversed. This implies that there can be no net bulk contribution to \( \tau_b \) that is linear in the applied in-plane current (see also Supplementary Information). We have verified the surface origin of \( \tau_b \) experimentally using a sample containing a single-layer step; the strength of \( \tau_b \) is suppressed because contributions from two surfaces with opposite symmetry largely cancel (Supplementary Information). The symmetry constraints on \( \tau_b \), together with the lack of dependence on WTe\(_2\) thickness for \( \tau_b/\tau_A \) and \( \tau_s/\tau_A \), suggest

![Figure 3](image-url)
that all three torque components arise from interfacial effects in the WTe$_2$/Py bilayer.

The strength of the individual components of torque can be determined quantitatively from equations (1) and (2), using independently measured values of the resistance as a function of magnetization angle (dR/df) and the transmitted and reflected microwave power ($S_{||}$ and $S_{\perp}$) to determine $I_B$ (Supplementary Information). We will express these strengths as torque conductivities ($\sigma_{a}$, $\sigma_{a\perp}$, $\sigma_{\parallel}$; torques per unit area per unit electric field) because the electric field applied across the device can be determined accurately, while the division of current density flowing in the different layers has larger uncertainties. We find for current along the $a$-axis that $\sigma_{a} = (8 \pm 2) \times 10^{5}$ (h/2e) (Om)$^{-1}$, $\sigma_{a\perp} = (9 \pm 3) \times 10^{5}$ (h/2e) (Om)$^{-1}$, and $\sigma_{\parallel} = (3.6 \pm 0.8) \times 10^{5}$ (h/2e) (Om)$^{-1}$, where the uncertainties give the standard deviation across our devices. The spin-torque conductivities can also be related to a common figure of merit, the spin-torque ratios, according to, for example, $\theta_{h} = (2e/h)\rho\sigma_{a\perp}$, where $\rho$ is the resistivity of the WTe$_2$ layer. This assumes that the torque is due to current density flowing in the WTe$_2$ layer, which may not be the case for an interface mechanism (see Supplementary Information). Using the value of $\rho$ for a thick WTe$_2$ sample (Methods) we find $\theta_{h} \approx 0.013$, or about 1/6th of the value for the in-plane antidiamping torque generated by Pt/Py samples.

We find it interesting that although a broken lateral mirror symmetry should also allow additional terms for the in-plane S–O torque when current is applied along the $a$-axis—for example an effective-field torque of the form $\propto \hat{m} \times \hat{c}$ (ref. 35)—we detect no such contributions. A term $\propto \hat{m} \times \hat{c}$ would add a $\phi$-independent contribution to equation (4), $\tau_{\parallel} \rightarrow \tau_{\parallel} \cos(\phi) + \tau_{\perp}$, that would cause the absolute values of the amplitudes for the symmetric part of the ST-FMR resonance (Fig. 2c) to be asymmetric under the operations $\phi \rightarrow 180^\circ - \phi$ and $\phi \rightarrow 180^\circ + \phi$. We can set a limit for our devices that $|\tau_{\parallel}| \leq 0.05\tau_{\perp}$. Our results are therefore opposite to those of a report about S–O torques in ‘wedge’ samples (35) which claimed that the breaking of lateral mirror symmetry by the wedge structure generated an effective-field torque $\propto \hat{m} \times \hat{c}$, but no out-of-plane antidiamping torque. We question whether the extremely small thickness gradient in ref. 35 (a difference in average thickness of $<0.5$ pm, or 0.002 of an atom, between the two sides of a 20-µm-wide sample) actually provides a meaningful breaking of structural mirror symmetry.

We note one additional consequence of strong S–O coupling at the WTe$_2$/Py interface—the magnetic anisotropy easy axis of the Py is determined by the crystal lattice of the WTe$_2$. The magnetic anisotropy can be determined from our ST-FMR data via the $\phi$ dependence of the magnetic resonance frequency and by direct AMR measurements (Supplementary Information). Regardless of the orientation of the sample channel with respect to the WTe$_2$ crystal lattice, we find that the magnetic easy axis is always parallel to the $b$-axis of WTe$_2$. The effective anisotropy field in different devices ranges from 4.9 to 17.3 mT for 6 nm of Py (Supplementary Table 1).

In summary, we have demonstrated that it is possible to generate an out-of-plane antidiamping-like S–O torque in spin-source/ferromagnet bilayers by using a spin-source material whose surface crystal structure has a broken lateral mirror symmetry. This is important, as it provides a strategy for achieving efficient manipulation of magnetic devices with perpendicular magnetic anisotropy. Compared to in-plane-magnetized devices, PMA devices are of interest because they can be scaled to smaller sizes and higher density while maintaining thermal stability. PMA devices can be switched much more efficiently using an out-of-plane antidiamping torque, $\tau_{AD}$, compared to an effective-field torque, $\tau_{FE}$, since the effective-field torque required for switching in the macrospin limit is $|\tau_{FE}| \approx \gamma H_{anis}$, where $H_{anis}$ is the anisotropy field, while the antidiamping torque required is much smaller: $|\tau_{AD} / |\tau_{FE}| \approx \gamma \beta H_{anis} / \delta_{c} \approx 0.01$ (ref. 18). Previously, because S–O torques could generate an antidiamping-like component only in the sample plane, they have been incapable of switching PMA devices by this efficient antidiamping process—an in-plane antidiamping torque switches PMA devices through a mechanism involving domain nucleation and domain-wall propagation (37–41) that becomes inefficient at small size scales. Our results therefore suggest a strategy, based on control of broken crystal symmetry in materials with strong S–O coupling, that has the potential to enable efficient antidiamping switching of PMA memory and logic devices at a size scale of tens of nanometres.

**Note added in proof:** One of our reviewers suggested that second-harmonic Hall measurements as a function of the angle of an in-plane applied magnetic field can provide an independent method to measure an out-of-plane antidiamping torque. We find that this method gives results consistent with our ST-FMR measurements (Supplementary Information).

**Methods**

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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**Figure 4** | Dependence of the spin–orbit torques on the angle of applied current and the thickness of WTe$_2$. a, Ratio of the out-of-plane antidiamping torque $\tau_a$ to the out-of-plane effective-field torque $\tau_{\parallel}$ as a function of the angle between the $a$-axis and the applied current. b, Torque ratios as a function of the thickness of the WTe$_2$ layer for current applied along the $a$-axis. Here $\tau_a$ is the in-plane current-induced torque. The error bars in a and b represent estimated standard deviations calculated via error propagation from the least-squares fitting procedure used to determine $\tau_a$, $\tau_b$ and $\tau_c$.

| $\phi_{\perp}$ (°) | $f = 9$ GHz | $t (nm)$ |
|-----------------|--------------|----------|
| 0  | 0.0  | 0.1  |
| 2  | 0.3  | 0.4  |
| 4  | 0.5  | 0.6  |
| 6  | 0.7  | 0.8  |

| $|B/ A|$ | $\tau_{||}/\tau_{\parallel}$ |
|--------|-----------------|
| 0.0  | 0.1  |
| 0.2  | 0.3  |
| 0.4  | 0.5  |

| $|B/ A|$ | $\tau_{\perp}/\tau_{\parallel}$ |
|--------|-----------------|
| 0.0  | 0.1  |
| 0.2  | 0.3  |
| 0.4  | 0.5  |

Table 1: Torque ratios as a function of the thickness of WTe$_2$.
References

1. Brataas, A., Kent, A. D. & Ohno, H. Current-induced torques in magnetic materials. Nat. Mater. 11, 372–381 (2012).
2. Zhang, C., Fukami, S., Sato, H., Matsukura, F. & Ohno, H. Spin–orbit torque induced magnetization switching in nano-scale Ta/CoFeB/MgO. Appl. Phys. Lett. 107, 012401 (2015).
3. Ando, K. et al. Electric manipulation of spin relaxation using the spin Hall effect. Phys. Rev. Lett. 101, 036601 (2008).
4. Pi, U. H. et al. Tilting of the spin orientation induced by Rashba effect in ferromagnetic metal layer. Appl. Phys. Lett. 97, 162507 (2010).
5. Miron, I. M. et al. Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer. Nat. Mater. 9, 230–234 (2010).
6. Liu, L., Moriyama, T., Ralph, D. C. & Buhrman, R. A. Spin-torque ferromagnetic resonance induced by the spin Hall effect. Phys. Rev. Lett. 106, 036601 (2011).
7. Miron, I. M. et al. Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. Nature 476, 189–193 (2011).
8. Liu, L. et al. Spin-torque switching with giant spin Hall effect of tantalum. Science 336, 555–558 (2012).
9. Pai, C. et al. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. Appl. Phys. Lett. 101, 122404 (2012).
10. Kim, J. et al. Layer thickness dependence of the current-induced effective field vector in Ta[CoFeB]/MgO. Nat. Mater. 12, 240–245 (2013).
11. Haazen, P. J. et al. Domain wall depinning governed by the spin Hall effect. Nat. Mater. 12, 299–303 (2013).
12. Emori, S., Bauer, U., Ahn, S.-M., Martinez, E. & Beach, G. S. D. Current-driven dynamics of chiral ferromagnetic domain walls. Nat. Mater. 12, 611–616 (2013).
13. Ryu, K.-S., Thomas, L., Yang, S.-H. & Parkin, S. S. P. Chiral spin torque at magnetic domain walls. Nat. Nanotech. 8, 527–533 (2013).
14. Mellnik, A. R. et al. Spin-transfer torque generated by a topological insulator. Nature 511, 449–451 (2014).
15. Fan, Y. et al. Magnetization switching through giant spin–orbit torque in a magnetically doped topological insulator heterostructure. Nat. Mater. 13, 699–704 (2014).
16. Garello, K. et al. Symmetry and magnitude of spin–orbit torques in ferromagnetic heterostructures. Nat. Nanotech. 8, 587–593 (2013).
17. Slonczewski, J. C. Current-driven excitation of magnetic multilayers. J. Magn. Magn. Mater. 159, L1–L7 (1996).
18. Sun, J. Z. Spin–current interaction with a monodomain magnetic body: a model study. Phys. Rev. B 62, 570–578 (2000).
19. Chernynshov, A. et al. Evidence for reversible control of magnetization in a ferromagnetic material by means of spin–orbit magnetic field. Nat. Phys. 5, 656–659 (2009).
20. Endo, M., Matsukura, F. & Ohno, H. Current induced effective magnetic field and magnetization reversal in uniaxial anisotropy (Ga,Mn)As. Appl. Phys. Lett. 97, 222501 (2010).
21. Fang, D. et al. Spin–orbit-driven ferromagnetic resonance. Nat. Nanotech. 6, 413–417 (2011).
22. Kurebayashi, H. et al. An antidamping spin–orbit torque originating from the Berry curvature. Nat. Nanotech. 9, 211–217 (2014).
23. Wadley, P. et al. Electrical switching of an antiferromagnet. Science 351, 587–590 (2016).
24. Skinner, T. D. et al. Complementary spin–Hall and inverse spin–galvanic effect torques in a ferromagnet/semiconductor bilayer. Nat. Commun. 6, 6730 (2015).
25. Ahn, S.-M., Emori, S., Bauer, U., Martinez, E. & Beach, G. S. D. Electric manipulation of spin relaxation using the spin Hall effect. Phys. Rev. B 89, 024418 (2014).
26. Yu, G. et al. Magnetization switching through spin–Hall-effect-induced chiral domain wall propagation. Phys. Rev. B 89, 104421 (2014).
27. Garello, K. et al. Ultrafast magnetization switching by spin–orbit torques. Appl. Phys. Lett. 105, 212402 (2014).
28. Rhodes, D. et al. Role of spin–orbit coupling and evolution of the electronic structure of WTe$_2$ under an external magnetic field. Phys. Rev. Lett. 92, 125512 (2005).
29. Wang, L. et al. Tuning magnetotransport in a compensated semimetal at the atomic scale. Nat. Commun. 6, 8892 (2015).
30. Wilson, J. A. & Yoffe, A. D. The transition metal dichalcogenides discussion and interpretation of the observed optical, electrical and structural properties. Adv. Phys. 18, 193–335 (1969).
31. Huang, Q. H. et al. Electronics and Electronotronics of two-dimensional transition metal dichalcogenides. Nat. Nanotech. 7, 699–712 (2012).
32. Zhang, W. et al. Research update: spin transfer toreres in permallyo on monolayer MoS$_2$ monolayer with spin pumping. Preprint at http://arxiv.org/abs/1510.03451 (2015).
33. Brown, B. E. The crystal structures of WTe$_2$ and high-temperature MoTe$_2$. Acta Crystallogr. 20, 268–274 (1966).
34. Garello, K. et al. Ultrafast magnetization switching by spin–orbit torques. Appl. Phys. Lett. 105, 212402 (2014).
35. Mikuszeit, N. et al. Spin–orbit torque driven chiral magnetization reversal in ultrathin nanostuctures. Phys. Rev. B 92, 144424 (2015).
36. Rojas-Sanchez, J.-C. et al. Perpendicular magnetization reversal in Pt/[Co/Ni]$_2$/Al multilayers via the spin Hall effect of Pt. Appl. Phys. Lett. 108, 082406 (2016).

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Author contributions

D.M., G.M.S., M.H.D.G. and D.C.R. conceived the idea for the experiment. D.M. performed the sample fabrication. G.M.S. made the measurements. D.M. and G.M.S. performed the analysis with help from M.H.D.G., R.A.B., J.P. and D.C.R. D.M., G.M.S., M.H.D.G. and D.C.R. wrote the manuscript and all authors contributed to the final version.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.C.R.

Competing financial interests

The authors declare no competing financial interests.
Methods

Device fabrication. Our device fabrication starts with high-quality artificially grown crystals of WTe₂ (HQ Graphene) which we exfoliate onto a high-resistivity silicon wafer with 1 μm of thermal oxide. The exfoliation is performed in flowing dry nitrogen in the load-lock chamber of our sputtering system, so that the exfoliated samples can be transferred into the sputter system with minimal exposure to air. We have also carried out measurements on samples exfoliated in vacuum with similar results. The exfoliation results in the deposition of single-crystal flakes of WTe₂ up to 40 μm in lateral extent and with a distribution of thicknesses. To minimize damage to the WTe₂ flakes, we use grazing-angle magnetron sputtering to deposit 6 nm of Permalloy (Py=Ni₂₈Fe₇₂) onto the WTe₂. The Py deposition rates are kept below 0.2 Å s⁻¹ and are performed in an ambient Ar background pressure of 4 mtorr while the substrate rotates at 3 rotations per minute. We then deposit a protective aluminium oxide cap in situ onto the WTe₂/Py bilayer by sputter deposition of 1 nm aluminium, which is subsequently oxidized in a dry N₂/O₂ mixture.

After deposition of the ferromagnet and aluminium oxide cap, we use optical contrast and atomic force microscopy to select WTe₂ flakes for further study. Flakes are chosen to ensure an active region with homogeneous thickness (that is, no monolayer steps or tape residue) and minimal roughness (typically <300 pm r.m.s.). An atomic force microscopy image of a typical WTe₂/Py bilayer prior to patterning is shown in the Supplementary Information.

The WTe₂/Py bilayers are patterned into bars of width 3–4 μm. The bars are defined via Ar ion milling, using either a hard mask (silicon or aluminium oxide) or an e-beam-exposed PMMA/HSQ bilayer. After etching, another step of e-beam lithography is used to make electrical contact to the bars with Ti/Pt contact pads, which have a ground-signal-ground geometry compatible with microwave probes (Fig. 1c). The active region between the contacts is 3–6 μm long. For hard-mask devices, an additional reactive-ion etching (RIE) or wet etch step is used prior to the Ti/Pt deposition to remove the mask in the contact region.

The Py resistivity in our devices is (100±10) μΩ cm. The WTe₂ bulk resistivity value is (380±10) μΩ cm with the current flowing along the a-axis, and is likely higher in thinner flakes 25. The resistivity of WTe₂ is anisotropic, and we find the resistivity with current flowing along the a-axis to be 1.4–2 times larger than the resistivity for current flowing along the b-axis.

Measurements. For ST-FMR measurements a microwave current at a fixed frequency (ranging from 5 to 12 GHz) is applied to the WTe₂/Py bilayer through a bias T (Fig. 1c). The amplitude of the microwave current is modulated at kilohertz frequencies, which allows a lock-in measurement of the d.c. mixing voltage (V_mix) at the inductive side of the bias T. In-plane magnetic fields are applied using a projected-field electromagnet which can be rotated 360° about the vertical axis. Magnetic fields are swept from 0.24 T to 0 T to drive the Py through its resonance condition. The transmission and reflection coefficients for the RF cabling and devices, respectively, are determined by calibrated vector network analyser measurements in the relevant frequency range (5–12 GHz). Measurements of the AMR in the Py are made in a constant 0.08 T field using a Wheatstone bridge and a lock-in amplifier.

Determination of the WTe₂ crystal axes. The crystal axes of WTe₂ are determined by polarized Raman measurements using a Renishaw inVia confocal Raman microscope with a linearly polarized 488 nm wavelength excitation and the excitation electric field in the sample plane. Previous calculations and measurements have shown that the 165.7 cm⁻¹ (P6) and 211.3 cm⁻¹ (P7) Raman peaks of WTe₂ are sensitive to the alignment of the electric field and the crystal axes 41. We measure the intensity of the P6 and P7 Raman peaks as a function of angle by rotating the sample from 0° to 180° in steps of 10° or 20° (keeping the electric field in the sample plane). The angle for which the ratio of peak intensities, P6/P7, is maximized identifies the a-axis, allowing determination of the angle between the a-axis and current direction, ϕA (Supplementary Information).

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

References
42. Kong, W.-D. et al. Raman scattering investigation of large positive magnetoresistance material WTe₂. *Appl. Phys. Lett.* **106**, 081906 (2015).