All-electrical switching of a topological non-collinear antiferromagnet at room temperature

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ABSTRACT

Non-collinear antiferromagnetic Weyl semimetals, combining the advantages of a zero stray field and ultrafast spin dynamics, as well as a large anomalous Hall effect and the chiral anomaly of Weyl fermions, have attracted extensive interest. However, the all-electrical control of such systems at room temperature, a crucial step toward practical application, has not been reported. Here, using a small writing current density of around $5 \times 10^6$ A·cm$^{-2}$, we realize the all-electrical current-induced deterministic switching of the non-collinear antiferromagnet Mn$_3$Sn, with a strong readout signal at room temperature in the Si/SiO$_2$/Mn$_3$Sn/AlO$_x$ structure, and without external magnetic field or injected spin current. Our simulations reveal that the switching originates from the current-induced intrinsic non-collinear spin-orbit torques in Mn$_3$Sn itself. Our findings pave the way for the development of topological antiferromagnetic spintronics.

Keywords: spintronics, non-collinear antiferromagnetic Weyl semimetals, all-electrical switching, spin-orbit torques

INTRODUCTION

Antiferromagnets have recently attracted tremendous interest as candidates for next-generation spintronics devices, as they have the prospect of offering higher storage density and faster data processing than their ferromagnetic counterparts [1,2]. However, the weak readout signals of conventional collinear antiferromagnets driven by electrical approaches greatly restrict their practical applications [3,4]. Alternatively, large magnetotransport signatures, such as the intrinsic anomalous Hall effect in topological antiferromagnets, could provide a solution to this issue [5,6]. In particular, the non-collinear antiferromagnetic Weyl semimetal Mn$_3$Sn has recently fascinated the condensed matter physics and information technology communities because of its non-trivial band topology [7,8] and unusual magnetic responses [9–11].

Mn$_3$Sn hosts an ABAB stacking sequence of the (0001) kagome lattice of Mn (Fig. 1a), with a 120° non-collinear antiferromagnetic ordering of the Mn magnetic moments below the Néel temperature of $T_N \approx 430$ K [9]. This antiferromagnetic state on the kagome bilayers can be viewed as a ferroic ordering of a cluster magnetic octupole (Fig. 1b), which macroscopically breaks the time-reversal symmetry and results in a large anomalous Hall effect [9,12]. With the assistance of an auxiliary magnetic field, the deterministic switching of the magnetic octupole in Mn$_3$Sn has been achieved by spin-orbit torques from a heavy-metal layer [13,14]. However, as a critical step toward practical application, the field-free manipulation of Mn$_3$Sn, driven by electrical currents at room temperature, has not been reported. Here, we demonstrate the all-electrical switching of topological antiferromagnetic states in heavy-metal-layer-free Mn$_3$Sn devices.

RESULTS

Experiments were performed on sputter-deposited Mn$_3$Sn (50 nm)/AlO$_x$ (2 nm) thin films, and on the reference samples with heavy metals consisting of Ru (3 nm)/Mn$_3$Sn (50 nm)/AlO$_x$ (2 nm) and Ru
(3 nm)/Mn₃Sn (50 nm)/Pt (8 nm)/AlOₓ (2 nm). All samples were deposited on thermally oxidized Si substrate. Unless otherwise stated, all the measurements were performed on the Mn₃Sn (50 nm)/AlOₓ (2 nm) materials or devices without heavy metals. We first characterize the structure, transport properties and magnetic properties of Mn₃Sn. The X-ray diffraction peaks of (010) and (020) at 18° and 36° confirm the hexagonal D0₁₉ Mn₃Sn structure, and no additional peaks coming from plausible impurity phases were observed [15,16] (see the details in Supplementary Section S1 and more related analysis in Supplementary Sections S2–S4). The microstructure of our film and the chemical composition of Mn₃₋₀.₆Sn₀.₄ were measured by cross-sectional high-resolution transmission electron microscopy (HR-TEM) and energy-dispersive X-ray spectroscopy (EDX) [17,18] (Supplementary Fig. S3), respectively. The magnetotransport phenomena observed in our thin films (Fig. 1c and Supplementary Fig. S4) are consistent with previous measurements [13], where the angular dependence of the in-plane longitudinal magnetococonductivity (Δσ = σ − σ∥) and planar Hall conductivity σ⁺HIE can be well fitted by the theoretical equations for the chiral anomaly (Equations S6 and S7 in Supplementary Section S6). (d) Optical micrograph of our fabricated Hall device and measurement scheme. (e) Anomalous Hall resistivity (top) and magnetic circular dichroism (MCD) signal (bottom) versus μ₀Hz for the 50-nm-thick Mn₃Sn device at room temperature. Both of them exhibit clear hysteresis loops with a coercive field μ₀Hc of ~0.75 T. (f) Temperature dependence of Δρ∥ and μ₀Hc derived from the hysteresis loops of the 50-nm-thick Mn₃Sn device, suggesting a Néel temperature Tᵣ ≈ 430 K (Supplementary Fig. S7).

Figure 1. Crystal and magnetic structures, and the magnetotransport and magnetic properties of the Mn₃Sn device. (a) Mn₃Sn crystal structure. The large red and blue spheres (small gray and black spheres) represent the Mn (Sn) atoms at the z = 0 and 1/2 planes, respectively. (b) Magnetic structure of Mn₃Sn. The magnetic moments of Mn (green and pink arrows in different layers) are arranged along the kagome planes and form a spin structure with inverse triangular texture. The six adjacent moments between layers (light blue hexagon) constitute ferroic ordering of a cluster magnetic octupole (large orange arrow). (c) Angular dependence of the in-plane longitudinal magnetococonductivity Δσ (top) and planar Hall conductivity σ⁺HIE (bottom) of the 50-nm-thick Mn₃Sn device at room temperature and 1.8 T. The red and cyan solid lines for Δσ and σ⁺HIE are the fitting results using the theoretical equations for the chiral anomaly (Equations S6 and S7 in Supplementary Section S6). (d) Optical micrograph of our fabricated Hall device and measurement scheme. (e) Anomalous Hall resistivity (top) and magnetic circular dichroism (MCD) signal (bottom) versus μ₀Hz for the 50-nm-thick Mn₃Sn device at room temperature. Both of them exhibit clear hysteresis loops with a coercive field μ₀Hc of ~0.75 T. (f) Temperature dependence of Δρ∥ and μ₀Hc derived from the hysteresis loops of the 50-nm-thick Mn₃Sn device, suggesting a Néel temperature Tᵣ ≈ 430 K (Supplementary Fig. S7).
resistivity (Fig. 1e (top)). Moreover, the $M - \mu_0 H_Z$ curves were measured at different temperatures ($T$) using a vibrating sample magnetometer and the extracted magnetization of $\sim 8$ emu/cc at 300 K and 5 mT (Supplementary Fig. S5f), which is comparable with previous reported values [13,15,20,21]. The longitudinal resistivity and Hall resistivity as a function of temperature under zero magnetic field are illustrated in Supplementary Fig. S6. Both the $M - T$ and $\rho_{H}$ - $T$ curves show a rapid decrease at $\sim 250$ K, which corresponds to the transition to spiral phase [22–24]. The Néel temperature $T_N$, corresponding to the disappearance of $\Delta \rho_{H}^0$ and $\mu_0 H_C$ of the anomalous Hall hysteresis loops, is found to be $\sim 430$ K (Fig. 1f and Supplementary Fig. S7), which is close to that of single crystal Mn$_3$Sn [9]. The results confirm that our thin films have physical properties similar to those of previous reports.

We then examined the possible current-induced topological non-collinear antiferromagnetic state switching. For the reference samples, the current-induced deterministic switching can only be observed under an auxiliary magnetic field for Ru/Mn$_3$Sn/Pt devices (Supplementary Fig. S8), which is consistent with previous works [13,14]. Interestingly, different current-induced switching behaviors were observed in our heavy-metal-layer-free devices. Figure 2a presents the $\rho_{H} - \mu_0 H_Z$ curve of a 50-nm-thick Mn$_3$Sn device. Under zero magnetic field, a 50-ms writing current pulse $I_{\text{write}}$ followed by a DC reading current of $I_{\text{read}} = 0.1$ mA is applied along the $x$ direction. Surprisingly, as shown by the black curve in Fig. 2b, the electrical current flowing through the device leads to a clear negative (positive) jump in $\rho_{H}$ at a positive (negative) threshold writing current, implying a reversing of the $z$ component of the octupole. The magnitude of the Hall resistivity jump $\Delta \rho_{H}^0$ is $\sim 58\%$ of $\Delta \rho_{H}^0$ in the field-swept measurements (Fig. 2a). Figure 2b also shows the $\rho_{H} - I_{\text{write}}$ loops in an in-plane magnetic field $\mu_0 H_x$ of $\pm 0.2$ T and $\pm 0.4$ T. With the increase of positive (negative) applied magnetic field, the gradual shift of $\rho_{H} - I_{\text{write}}$ loops toward a negative (positive) $I_{\text{write}}$, together with the reduction of $\Delta \rho_{H}^0$, is observed, which is clearer in the field dependence of the threshold current in Fig. 2c. The current-induced magnetization switching disappears for a sufficiently large bias field, e.g. 1 T $> \mu_0 H_Z$, probably because the magnetic octupoles are aligned to the external field direction.

Compared with the Mn$_3$Sn/(heavy-) metal reference devices (Supplementary Fig. S8), here, the writing current is fully injected into the Mn$_3$Sn layer without passing through a highly conductive metal layer. In addition, the strong inversion asymmetry along the $x(y)$ direction was confirmed by our non-linear Hall measurements [25,26]. As a

Figure 2. Zero-field current-induced switching of the antiferromagnetic states in the Mn$_3$Sn device. (a) Anomalous Hall resistivity $\rho_{H}$ dependence on $\mu_0 H_Z$ for the Mn$_3$Sn device at room temperature. (b) $\rho_{H}$ versus $J_{\text{write}}$ at $\mu_0 H_x = 0$, $\pm 0.2$ T, $\pm 0.4$ T for the Mn$_3$Sn device at room temperature. (c) The critical current density $J_c$ as a function of temperature under zero magnetic field, a 50-ms writing current pulse $I_{\text{write}}$ followed by a DC reading current of $I_{\text{read}} = 0.1$ mA after each writing current pulse. (e and f) $\rho_{H}$ versus $\mu_0 H_Z$ and $J_{\text{write}}$ loops for the Mn$_3$Sn device at room temperature. The minimum $\mu_0 H_Z^{\text{min}}$ and $J_{\text{write}}^{\text{min}}$ determine the magnitude of the field- and current-driven Hall resistivity switching.
CoFe/Ru/CoFe/Pt [31], Co2MnGa/Ti [37] and SrRuO3/SrIrO3 devices at room temperature. The yellow shaded region highlights the scaling materials, including ferromagnets (Co/Pt [31], CoFeB/Ta [32], CoFeB/W [33], CoPt/CuPt [34], CoFe/Ru/CoFe/Pt [35], Fe3GeTe2/WTe2 [36], Co2MnGa/Ti [37] and SrRuO3/SrIrO3 [38]), ferrimagnets (CoGd/Pt [39]), collinear antiferromagnets (PtMn/Pt [40] and Fe3O4/Pt [41]) and Mn3Sn/Pt [13], at various temperatures. The red star indicates our Mn3Sn device, which is less than half that of the great potential of Mn3Sn in neuromorphic computing [21,27,29,30].

Our experiments confirm that the deterministic switching of the Mn3Sn devices is due to the current-induced torque exerted on the non-collinear antiferromagnetic spin texture. This reproducible bipolar switching can act as an antiferromagnetic memory. The alternating current pulses $|J_{\text{write}}| J_c$ along opposite directions switch the antiferromagnetic state back and forth reproducibly (Fig. 2d), indicating its reliable controllability. Remarkably, our Mn3Sn device can provide multilevel signals by varying the magnitude of $\mu_0 H_L$ or $J_{\text{write}}$. With a fixed maximum positive magnetic field (Fig. 2e) or writing current (Fig. 2f), the change of $\Delta \rho$ increases with the increasing magnitude of $\mu_0 H_L$ or $J_{\text{min}}$ (Fig. 2g).

To compare the efficiency of the readout signal driven by an electrical current with that of other heavy-metal/magnet bilayer structures, we defined the readout efficiency as $\xi = |\Delta \rho| / J_c$. In the case of our Mn3Sn device, $\xi \sim 2.4 \times 10^{-13} \text{ cm}^2 / \text{A}$. This is close to readout efficiencies of ferromagnetic materials such as Co2MnGa and CoFeB [31–38] but one to three orders of magnitude larger than those of ferrimagnets, collinear antiferromagnets and Mn3Sn/Pt devices [13,39–41]. Interestingly, a scaling law of $\xi$ with the magnetization $M$ is observed for collinear antiferromagnets, ferrimagnets and ferromagnets, as indicated by the shaded region in Fig. 3. This is because the anomalous Hall resistance is proportional to the magnetization, whereas the critical switching current is insensitive to the magnetization in the case of the current-induced magnetization switching dominated by the spin Hall effect in heavy-metal/magnet bilayer systems [42]. The large $\xi$ for Mn3Sn is due to the strong anomalous Hall effect originating from the non-zero Berry curvature in momentum space [7,8]. The readout efficiency obtained in our pure Mn3Sn is one order of magnitude higher than that in ref. [13], probably because our Mn3Sn devices have higher inversion asymmetry and do not have a heavy-metal layer. We can thus achieve a strong readout anomalous Hall signal driven by a small writing current of $5 \times 10^6 \text{ A cm}^{-2}$ in our Mn3Sn device.
**DISCUSSION**

Now we illustrate the possible mechanisms of intrinsic non-collinear spin-orbit torques that induce the deterministic all-electrical switching in our Mn₃Sn device. We argue that the current-induced switching requires an inversion asymmetry in our polycrystal device, for the following reasons.

In our Mn₃Sn polycrystal, the measured non-zero anomalous Hall signal implies that the different configurations in our samples are not compensated. To understand this, we note that any crystal grain in the polycrystalline Mn₃Sn can be decomposed into the z–x, x–y and y–z configurations, according to the direction of kagome plane (Fig. 4a). The octupole rotates only in the kagome plane, so the out-of-plane magnetic field $H_z$ can only switch configurations z–x and y–z. Considering the weak tunneling between the kagome layers, $I_x$ is not expected to be able to switch configuration y–z effectively, i.e. the in-plane current $I_x$ can only switch configurations z–x and x–y. The anomalous Hall signal depends on the z component of the octupole, so $V_{AHE}$ can be used to read out only configurations z–x and y–z. This infers that the Hall response of the $\mu_0 H_z$-hysteresis is around 2 to 2.3 times (considering that the octupole may relax at positions within ±30 degrees from the full polarization) that of the $J_{vortex}$-hysteresis, close to the data in Fig. 2a and b. According to the above discussion, only configuration z–x in Fig. 4a can be switched by the current and is measurable by the anomalous Hall effect.

More importantly, the z–x configuration of single-crystal Mn₃Sn requires an inversion asymmetry to be deterministically switched. Because the octupole is a pseudo vector, which is invariant under inversion, it does not reverse as the current changes sign, if there is inversion symmetry (see also the symmetry and microscopic analysis in Supplementary Sections S13 and S14). The occurrence of the inversion asymmetry in polycrystalline Mn₃Sn was confirmed by our non-linear Hall measurements. The inversion asymmetry can induce Rashba-like spin-orbit coupling, which can convert the injected electric current into spin currents or spin accumulations. The spin accumulations, when not aligned with the local Mn moments, can induce intrinsic non-collinear spin-orbit torques to rotate the Mn moments. The octupole is defined by the Mn moments in the Mn₃Sn magnetic structure with inverse triangular spin structure (Supplementary Sections S15). Thus, in this sense, it is switchable by the current, and its z component leads to a measurable anomalous Hall signal.

To verify our speculations regarding the microscopic mechanism behind the observed switching, we performed numerical simulations for the octupole polarization. For a given electrical current $I_x$, the simulation starts with an initial magnetic structure of the Mn moments $m_{ia}$, which behave as local Zeeman fields on the electrons described by an s–d model. Using the linear-response theory, the local spin accumulations induced by the current in the presence of the Rashba spin-orbit coupling are calculated. The effective magnetic field of the spin accumulations is then converted into magnetic torques $T_{ia}$ in the Landau-Lifshitz-Gilbert equation to generate a new magnetic structure. The above steps are iterated until the magnetic structure converges to yield the octupole moment for the given injected current (see details in Methods Section simulating current-induced switching of the non-collinear antiferromagnet).

Figure 4b shows the simulated octuple angle $\varphi$ as a function of time at different current intensities, which demonstrates that the current must be sufficiently strong to drive a switching. Its insets also show the microscopic dynamics in terms of the calculated torques being exerted on the Mn moments at different stages of a successful switching for $I_x$, well above the critical value. The non-collinear antiferromagnetic structure tends to be maintained during the switching, and the rotation of the Mn moments (collectively as octupole) is determined by the sum of the nutation tendencies of the sublattice moments driven by the torques.

Figure 4c–e shows that a larger Rashba spin-orbit coupling $\lambda_R$ leads to an enhanced spin accumulation, faster switching and a smaller critical current. Figure 4f shows that increasing/decreasing the magnetic-structure parameters $K/(J_m, D)$ leads to a failed/faster switching, where $J_m$ and $D$ stabilize the inverse 120° triangular structure, whereas $K$ introduces a small deviation to exert torques that relax the octupole to one of the six stable positions ($\varphi = \pi/6 +$ integer times of $\pi/3$). In other words, the switching requires the torques from the current-induced spin accumulations to overcome the stable-position-favored torques due to the magnetic structure, which favors the six stable positions. Figure 4g shows that the hysteresis loop can be shifted by the $x$-direction magnetic field of ±0.0012 T (the theoretical values are usually magnitudes smaller than those in the experiments [9,13], probably because the external magnetic field is screened in the realistic polycrystals). More importantly, the simulations confirm that, without external magnetic fields and heavy metals, the all-electrical switching of the non-collinear antiferromagnet can be achieved, owing to the intrinsic non-collinear spin-orbit torques from the current-induced local spin accumulations in Mn₃Sn itself.
Figure 4. Numerically simulated switching of the Mn$_3$Sn octupole. The spin-orbit coupling converts the current $I_x$ (experimental $J_{\text{write}}$) into spin accumulations, which exert intrinsic non-collinear spin-orbit torques to rotate the Mn moments and octupole. (a) The kagome lattices in polycrystal can be decomposed into three configurations, $z-x$, $x-y$ and $y-z$. $I_x$ can switch configurations $z-x$ and $x-y$ and $V_{\text{HEL}}$ can read out configurations $z-x$ and $y-z$, so the simulation focuses on configuration $z-x$. (b) Simulated octupole angle $\phi$ versus time, driven by a $I_x$ pulse with duration of 2–30 ns (pink shadowed region), for $I_x$ below (29 mA), at (30 mA), and well above (180 mA) the critical current. For $I_x = 180$ mA, the insets show the dynamics of the torques (blue arrows) being exerted on the Mn moments (green arrows), at three stages (hollow circles), as $\phi$ starts from $\pi/6$ (an easy axis), then is switched to $\pi$ (normal to $I_x$) after turning on $I_x$, and finally relaxes to $7\pi/6$ (another easy axis) after turning off $I_x$. (c) Simulated $x$- and $z$-direction spin accumulations on Mn 2 (denoted in panel (a)) as a function of $\phi$, for different Rashba spin-orbit coupling $\lambda_R$ (Equation 2 in Methods of Supplementary). (d) The same as the 30 mA case in panel (b), but also for $\lambda_R$ below and above the critical value. (e) Simulated hysteresis loops of the Hall response $V_{\text{HEL}}$ driven by $I_x$, for different $\lambda_R$. (f) The same as the 30 mA case in panel (b). Combinations of the magnetic-structure parameters $K/J_m, D$ (Equation 1 in Methods of Supplementary) below (solid curves) and above (dashed curves) the critical combination are also considered. (g) The same as the $\lambda_R = 0.2t$ case in panel (e). The presence of the $x$-axis magnetic field $H_x$ is also considered. More simulation results by changing $\lambda_R$, $K/J_m, D$, and initial states can be found in Supplementary Section S16.

CONCLUSIONS

Our findings promise potential applications of Mn$_3$Sn in information technologies. Specifically, the all-electrical control of the binary and multilevel states with large Mn$_3$Sn readout signals could act as the building block for magnetic random-access memory and artificial synapses, respectively. Furthermore, in-memory computing may also be achieved by utilizing the all-electrical control of topological non-collinear antiferromagnets.

METHODS

Sample and device fabrication

The samples used for the current-induced switching measurements, which consist of Mn$_3$Sn (50)/AlO$_x$ (2) (the thicknesses shown in parentheses are in nanometers), were grown on thermally oxidized Si substrates. The top AlO$_x$ layer was used as the capping layer. For comparison, reference samples consisting of Ru (3)/Mn$_3$Sn (50)/AlO$_x$ (2) and Ru (3)/Mn$_3$Sn (50)/Pt (8)/AlO$_x$ (2) were also deposited on Si/SiO$_2$. The Mn$_3$Sn, Ru and Pt layers were deposited at room temperature using a DC magnetron sputtering system with a base pressure of $\sim 5 \times 10^{-9}$ Torr (at rates of $\sim 0.05$, 0.01 and 0.02 nm/s, power of 30 W and Ar gas pressure of 0.8 mTorr). Next, the AlO$_x$ layers were grown using an radio frequency (RF) magnetron sputtering system with a power of 80 W and Ar gas pressure of 2 mTorr. The Mn$_3$Sn (50)/AlO$_x$ (2), Ru (3)/Mn$_3$Sn (50)/AlO$_x$ (2) and Ru (3)/Mn$_3$Sn (50)/Pt (8)/AlO$_x$ (2) samples were then annealed...
at 450°C for 1 hour using a vacuum annealing furnace (F800-35, East Changing Technologies, China) at a base pressure of $5 \times 10^{-7}$ Torr. The samples were patterned into Hall bar devices with a current channel width of 10 μm using standard photolithography and Ar-ion etching. For more methods of measurement and simulation, see the Methods section in the supplementary materials.

SUPPLEMENTARY DATA

Supplementary data are available at NSR online.

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