
Supplementary information

**Chiral-spin rotation of non-collinear
antiferromagnet by spin–orbit torque**

In the format provided by the
authors and unedited

Chiral-spin rotation of non-collinear antiferromagnet by spin-orbit torque

Yutaro Takeuchi^{1,2}, Yuta Yamane^{1,3}, Ju-Young Yoon¹, Ryuichi Itoh¹, Butsurin Jinnai², Shun Kanai^{1,4,5,6}, Jun'ichi Ieda^{1,7}, Shunsuke Fukami^{1,2,4,6,8} and Hideo Ohno^{1,2,4,6,8}

¹Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan,

²WPI-Advanced Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577,

³Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, 6-3 Aramaki Aza Aoba, Aoba-ku, Sendai 980-0845, Japan,

⁴Center for Spintronics Research Network, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577

⁵Division for the Establishment of Frontier Sciences, Tohoku University, Sendai 980-8577, Japan,

⁶Center for Science and Innovation in Spintronics, Tohoku University, Sendai 980-8577, Japan

⁷Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan,

⁸Center for Innovative Integrated Electronic Systems, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai 980-0845, Japan

SUPPLEMENTARY INFORMATION

Contents:

S1. Evaluation of temperature rise due to Joule heating

S2. R_H - H curves at elevated temperatures

S3. Switching by electric current along the [0001] direction of Mn_3Sn

S4. Threshold current in heterostructures with different cap layers

S5. DC current dependence of switching field

S6. Calculation of dynamics of chiral-spin structure under spin-orbit torque

S7. R - I curves under perpendicular magnetic field

S8. Measurement and analysis of anomalous Hall resistance fluctuation

S9. Model of anomalous Hall resistance fluctuation in multi-domain formed chiral-spin structure

S10. Determination of Mn_3Sn thickness and current density

S1. Evaluation of temperature rise due to Joule heating

In addition to the generation of SOT exerted on the magnetic moments in Mn_3Sn layer, the in-plane current can also cause Joule heating and raise the temperature in the prepared devices. Here we evaluate the temperature rise due to the Joule heating by comparing the dependencies of the channel resistance R_{ch} on temperature and DC current. For the former measurement, we put the Hall device on a stage of probe station with an electric heating system and measure R_{ch} of the Hall device using the two-probe method. The substrate temperature T during the resistance measurement was monitored by K-type thermocouple sensor. Figure S1a shows T dependence of R_{ch} in a $\text{W}(3) / \text{Ta}(1) / \text{Mn}_3\text{Sn}(9.9) / \text{Pt}(4)$ heterostructure with $W_{\text{ch}} = 10 \mu\text{m}$. The resistance of the prepared device increases from 262.0Ω at 22°C to 271.2Ω at 100°C . The slope of $0.125 \pm 0.013 \Omega/^\circ\text{C}$ and the intercept of $258.25 \pm 0.90 \Omega$ are obtained by linear fitting of R_{ch} vs T . We then measure DC current I_{DC} dependence of R_{ch} , which is summarized in Figure S1b. The device temperature during the current application is then evaluated by linear fitting of Figure S1a. In our SOT experiments, the Hall resistance of the prepared device is measured with pulse current density J_{HM} ($\parallel [11\bar{2}0]$) below 5 MA cm^{-2} for $t_{\text{Mn}_3\text{Sn}} < 10 \text{ nm}$ (Fig. 2e and Fig.5b). The temperature rise is therefore determined as less than $11 \pm 8^\circ\text{C}$.

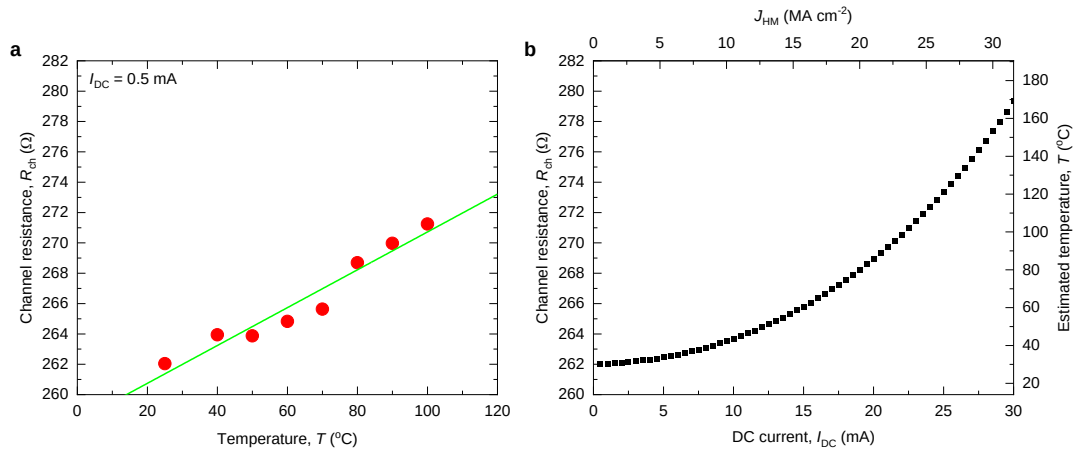


Figure S1 Temperature rise due to Joule heating in W/Ta/Mn₃Sn/Pt heterostructure. **a**, Temperature T dependence of channel resistance R_{ch} in $\text{W}(3) / \text{Ta}(1) / \text{Mn}_3\text{Sn}(9.9) / \text{Pt}(4)$. Solid line is the fitted curve by linear approximation. **b**, DC current I_{DC} dependence of R_{ch} . The right axis shows the estimated temperature T evaluated by linear fitting of R_{ch} vs T .

S2. R_{H} - H curves at elevated temperatures

To confirm that the chiral-spin ordering in Mn_3Sn is retained under Joule heating, we then measure R_{H} - H curves in the prepared device at higher temperatures up to 100°C . Figure S2 shows R_{H} - H curves of $\text{W}(3) / \text{Ta}(1)$

/Mn₃Sn(9.9)/Pt(4) stack at various temperatures. Clear hysteresis curves of R_H - H are observed in the temperature range of 22 – 80 °C. As shown in the previous section, the temperature rise in our experiment is determined as less than 20 °C. Hence, the chiral-spin ordering in Mn₃Sn is sustained throughout our SOT experiments.

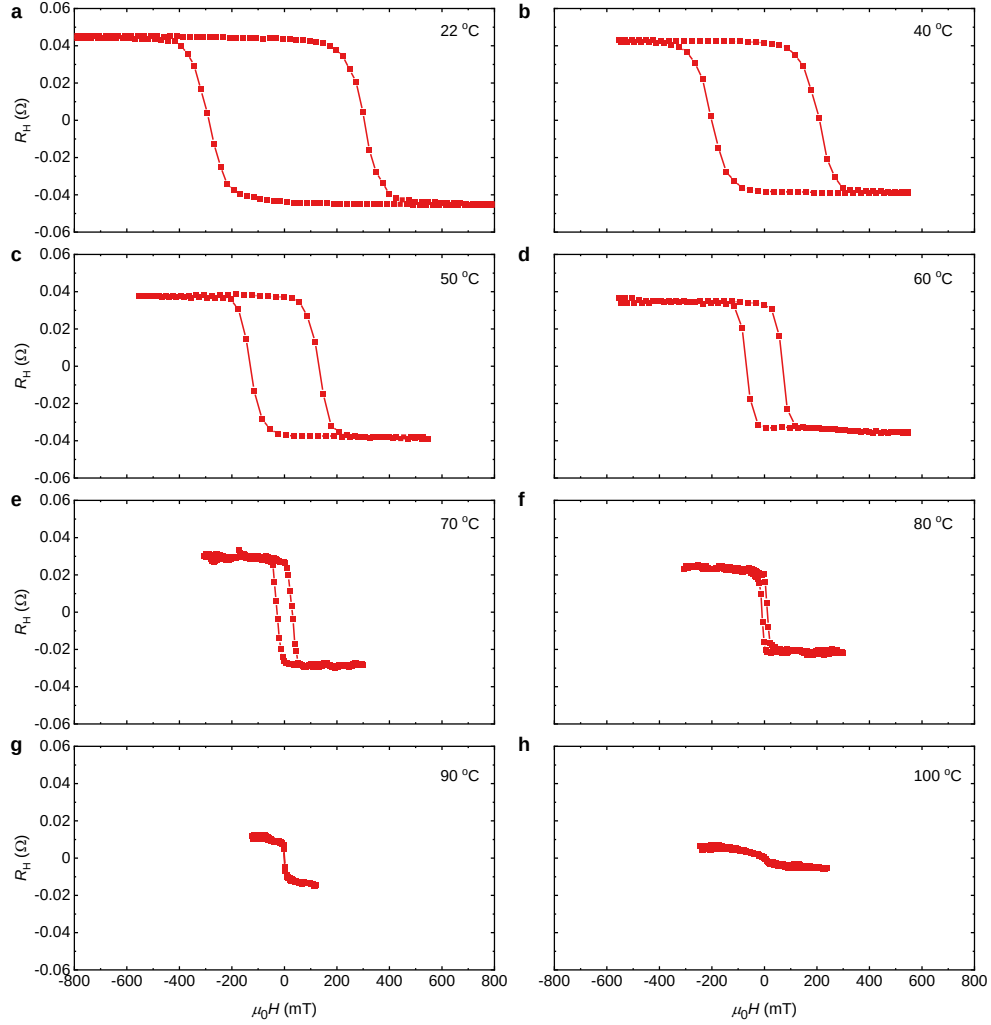


Figure S2 R_H - H curves at high temperatures. a-h, Hall resistance R_H as a function of out-of-plane magnetic field H at various temperatures. The in-plane current along the [0001] direction of Mn₃Sn is applied to detect Hall voltage.

S3. Switching by electric current along the [0001] direction of Mn₃Sn

As we discussed in the main text, a current-induced bipolar switching was observed in poly-crystalline Mn₃Sn film under an in-plane magnetic field ¹. According to Ref. 1, the observed bipolar switching is explained by a

switching of Mn_3Sn domains whose $[0001]$ axis is aligned parallel to the current I . To examine this scenario, we measure $R_{\text{H}}-I$ curves of our $(1\bar{1}00)$ -oriented epitaxial- Mn_3Sn sample with the configuration of $I \parallel [0001]$ under various in-plane magnetic fields H_{001} , which is applied along the current direction.

Figure S3a shows $R_{\text{H}}-H$ curve of the measured $\text{W}(3) / \text{Ta}(1) / \text{Mn}_3\text{Sn}(8.3) / \text{Pt}(4)$ stack. The $R_{\text{H}}-I$ curves with various in-plane magnetic fields are summarized in Figure S3b. The measurement is performed after initializing the chiral spin structures by a large negative magnetic field. The bipolar switching is observed under finite magnetic fields and the polarity of the $R_{\text{H}}-I$ hysteresis changes with the sign of the in-plane magnetic field as in the SOT-induced switching of ferromagnet, in consistent with the previous report¹.

However, we also find an inconsistency with the scenario discussed in Ref. 1. Firstly, the switching amplitude of the Hall resistance under the current application [Fig. S3b] is much smaller than the case for field-driven switching [Fig. S3a] although an epitaxial film is used unlike the previous work. In addition, numerical calculation following this scenario indicates that switching of the chiral-spin structure necessitates a large current density of the order of 10^4 MA cm^{-2} , whereas the switching is observed with the current density of 10 MA cm^{-2} . These inconsistencies imply an existence of some unknown mechanism relating to the observed bipolar switching.

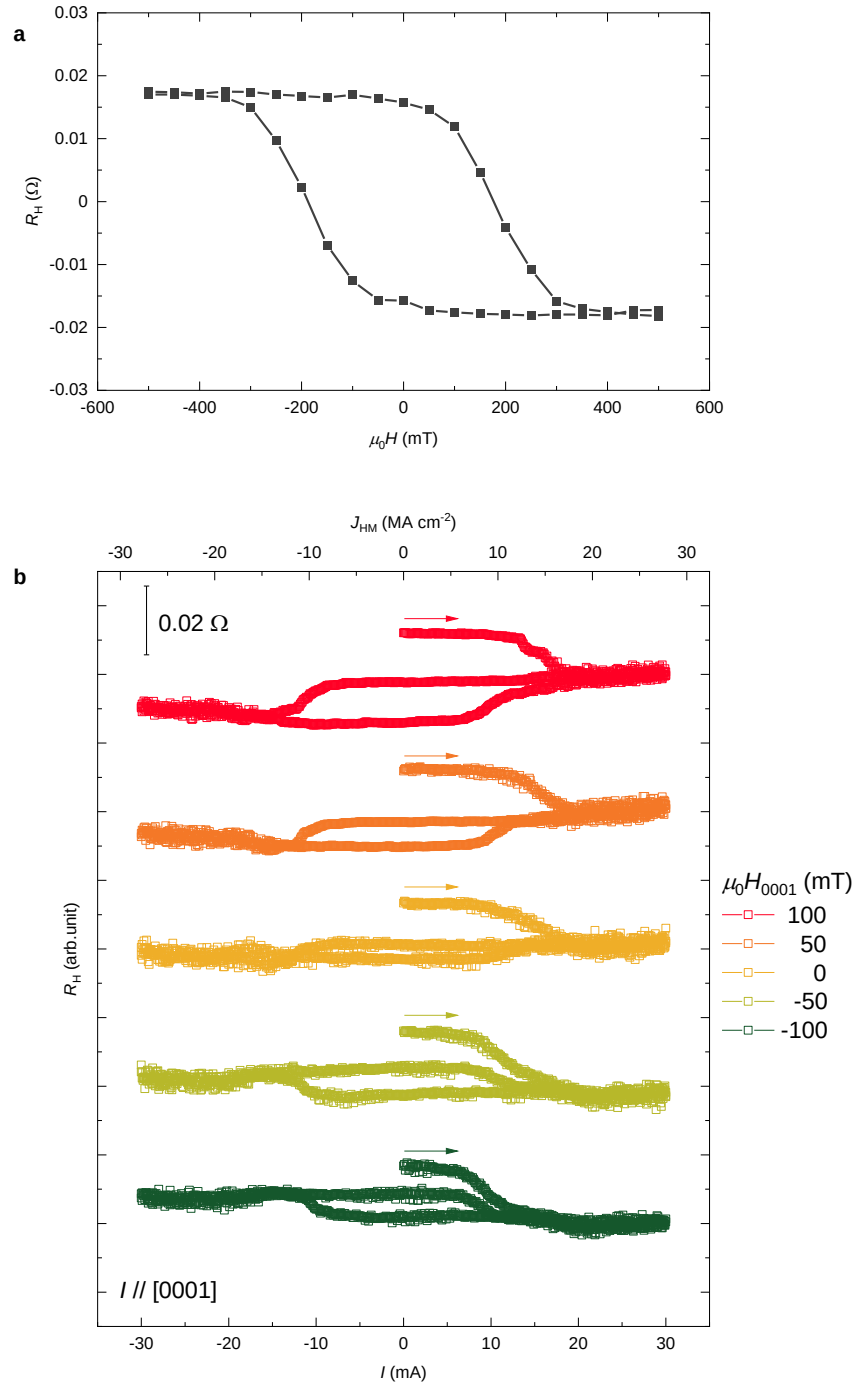


Figure S3 Deterministic switching by electric current of $I \parallel [0001]$ in the epitaxial Mn_3Sn film. **a**, R_H - H curve of W(3) / Ta(1) / Mn_3Sn (8.3) / Pt(4). **b**, In-plane magnetic field dependence H_{0001} of R_H - I curves. Both the pulse current I and magnetic field H_{0001} are applied along the [0001] direction of Mn_3Sn .

The obtained results in the main body and Supplementary Information S9 together with Ref. S6 (Ref. 32 in the main body) can be summarized in Table S1.

Table 1 Difference between the present work and Ref. S6 (Ref. 32 in the main body)

	Ref. 32	This work (Fig. 2e)	This work (Fig. S3b)
Crystal structure	Poly crystal	Single crystal	Single crystal
Current direction to crystallographic axis	Various	$I \parallel [11\bar{2}0]$	$I \parallel [0001]$
External field	Required	Not required	Required
Observed behaviour	Bipolar switching	Transition to intermediate level	Bipolar switching
Explanation	Chiral-spin reversal in crystal grains with $I \parallel [0001]$	Chiral-spin rotation	Chiral-spin reversal
Threshold current density	$\sim 10 \text{ MA cm}^{-2}$	$\sim 1 \text{ MA cm}^{-2}$	$\sim 10 \text{ MA cm}^{-2}$

S4. Threshold current in heterostructures with different cap layers

In order to evaluate the SOT contribution to the current induced change in the Hall resistance, we measure the threshold current for W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / MgO(1.3) / Ru(1) stacks, which is expected to exhibit smaller SOT efficiency compared with W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / Pt(4) heterostructures. Figure S4a is the R_{H} - I curve for the former heterostructure with $t_{\text{Mn3Sn}} = 12.0 \text{ nm}$ and similar behaviour is observed for the other t_{Mn3Sn} . Figure S4b and c, respectively, show the threshold current I_{C} and the threshold current density J_{C} as functions of t_{Mn3Sn} . J_{C} for W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / MgO(1.3) / Ru(1) stacks is 2~3 times larger than that for W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / Pt(4). This result can be attributed to relatively small SOT efficiency of the former. In other words, the result shown in the main body evidences that the SOTs generated by W/Ta underlayer and Pt cap layer dominantly cause the change in R_{H} .

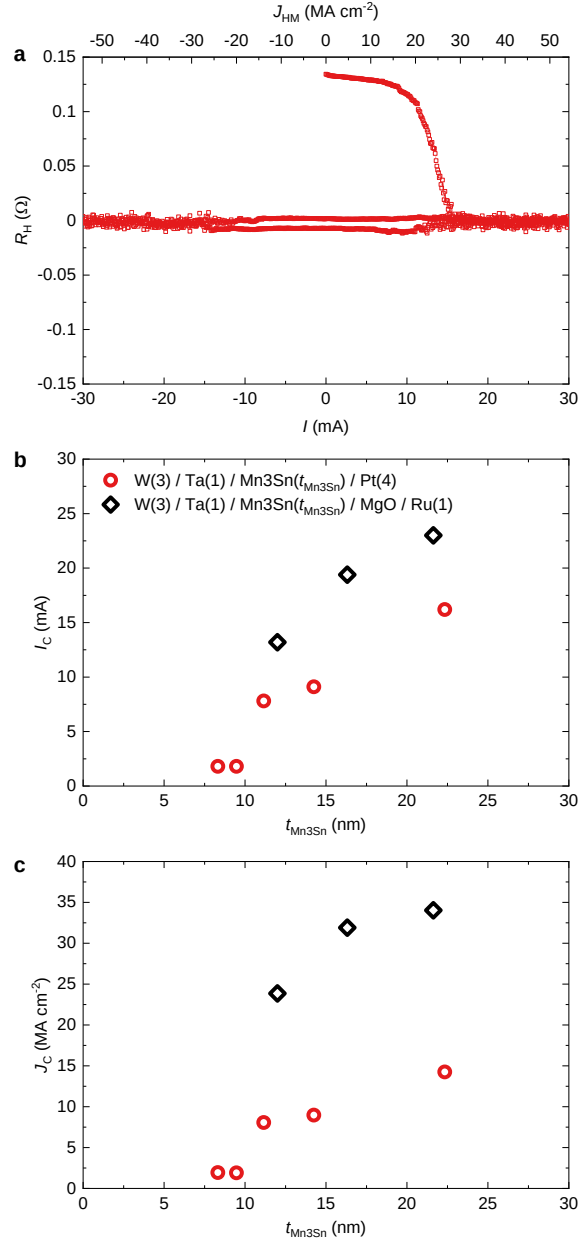


Figure S4 Current induced Hall resistance change in W / Ta / Mn₃Sn / MgO / Ru. **a**, R_H - I curve of W(3) / Ta(1) / Mn₃Sn(12.0) / MgO(1.3) / Ru(1) for the case of $I \parallel [11\bar{2}0]$. For the initializing of chiral-spin structure, the out of plane magnetic field of -1.0 T is applied before measuring R_H - I curve. **b**, **c**, Mn₃Sn thickness dependence of threshold current I_C and threshold current density J_C respectively. Red (black) symbol represents threshold for the heterostructure capped by Pt (MgO / Ru).

S5. DC current dependence of switching field

We measure DC current I_{DC} dependence of the switching field H_C in Mn₃Sn / heavy metal heterostructure in order to further examine the effect of current on the chiral spin structures. Figure S5 a-d shows R_H - H curves with various applied DC currents. H_C decreases as I_{DC} increases. H_C versus I_{DC} for W(3) / Ta(1) / Mn₃Sn(8.3) / Pt(4)

and W(3) / Ta(1) / Mn₃Sn(12.0) / MgO(1.3) / Ru(1) are summarized in Figure S5e and f, respectively. The virtually linear relationship between H_C and I_{DC} indicates that the SOT takes on a dominant role in the decrease of H_C by electric current ² (If the Joule heating plays a major role, the dependence should be deviated from the linear relation). H_C/J_{HM} of 0.047 ± 0.002 T MA⁻¹ cm² and 0.010 ± 0.001 T MA⁻¹ cm are obtained for W(3) / Ta(1) / Mn₃Sn(8.3) / Pt(4) and W(3) / Ta(1) / Mn₃Sn(12.0) / MgO(1.3) / Ru(1), respectively, through the linear fitting of H_C versus I_{DC} . We also note that the obtained H_C/J_{HM} is in good agreement with H_C/J_C shown in Fig. 5c of the main text, evidencing that H_C/J_C is a good index to evaluate the efficiency of current to manipulate the chiral spin structures.

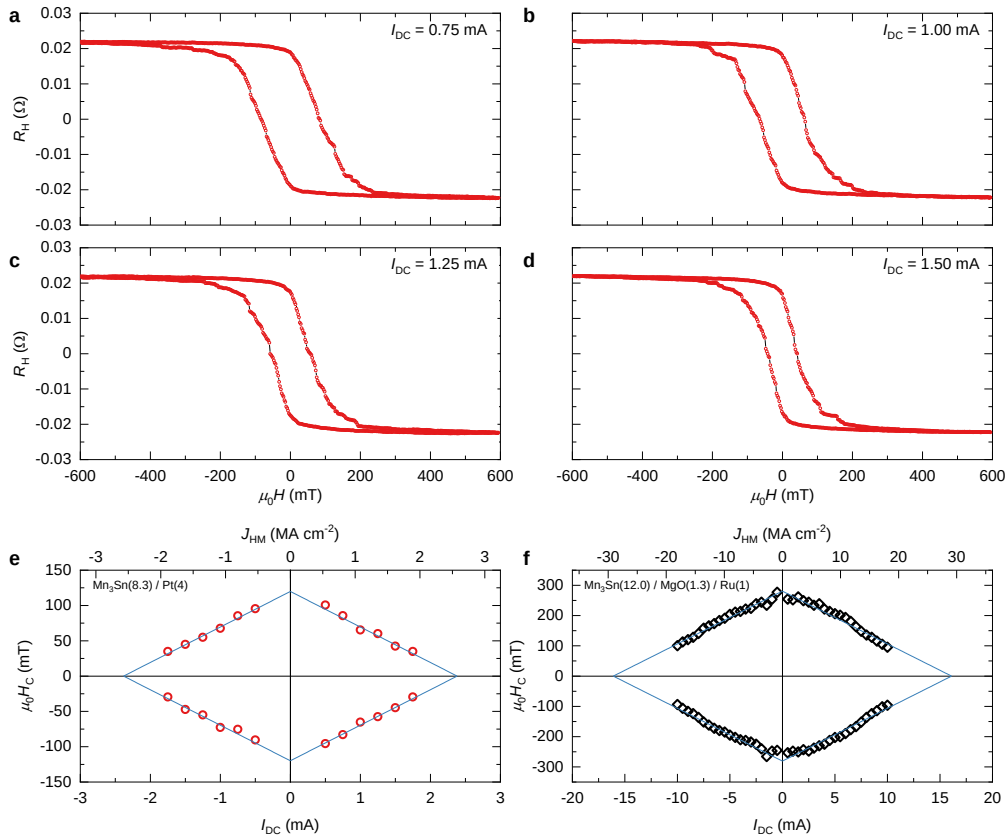


Figure S5 DC current dependence of switching field in Mn₃Sn / Heavy metal. **a-d**, R_H - H curves of W(3) / Ta(1) / Mn₃Sn(8.3) / Pt(4) under various DC currents. **e, f**, Switching field H_C as a function of DC current I_{DC} respectively for W(3) / Ta(1) / Mn₃Sn(8.3) / Pt(4) and W(3) / Ta(1) / Mn₃Sn(12.0) / MgO(1.3) / Ru(1). The DC current I_{DC} is applied along the $[11\bar{2}0]$ direction of Mn₃Sn.

S6. Calculation of dynamics of chiral-spin structure under spin-orbit torque

We model Mn_3Sn by an antiferromagnet (AFM) composed of three equivalent magnetic sublattices (A , B and C) with constant saturation magnetization M_S . As the spatial variation of the magnetic moment within each sublattice can be assumed to be negligible in our experimental situation, we perform a coarse graining for each sublattice so that the AFM is described by three classical vectors $\mathbf{m}_{A,B,C}$ ³, representing the direction of the three sublattice magnetizations. We adopt the magnetic energy density given by

$$u = J_0 \sum_{\langle\mu\nu\rangle} \mathbf{m}_\mu \cdot \mathbf{m}_\nu + D \mathbf{e}_z \sum_{\langle\mu\nu\rangle} \mathbf{m}_\mu \times \mathbf{m}_\nu - K \sum_{\mu=A,B,C} (\mathbf{m}_\mu \cdot \mathbf{e}_{K,\mu})^2 \quad (\text{S1})$$

where $\langle\mu\nu\rangle$ indicates the sum over the pairs $(\mu\nu) = (A, B)$, (B, C) and (C, A) . The first two terms in Eq. (S1) are the antiferromagnetic exchange and Dzyaloshinskii-Moriya interactions, respectively, with J_0 and D being positive constants. The third term describes the uniaxial anisotropies for the three sublattices, with the common constant K and the easy axes $\mathbf{e}_{K,A} = (-\mathbf{e}_x + \sqrt{3}\mathbf{e}_y)/2$, $\mathbf{e}_{K,B} = -(\mathbf{e}_x + \sqrt{3}\mathbf{e}_y)/2$ and $\mathbf{e}_{K,C} = -\mathbf{e}_x$. The Cartesian coordinates are set as the x and z axes coincide with $[11\bar{2}0]$ and $[0001]$, respectively.

The dynamics of $\mathbf{m}_\mu$ ($\mu = A, B, C$) are given by the coupled Landau-Lifshitz-Gilbert equations

$$\frac{\partial \mathbf{m}_\mu}{\partial t} = -\gamma \mathbf{m}_\mu \times \mathbf{H}_\mu + \alpha \mathbf{m}_\mu \times \frac{\partial \mathbf{m}_\mu}{\partial t} - \frac{\gamma \hbar \theta_{SH} I}{2eM_S d} \mathbf{m}_\mu \times (\mathbf{m}_\mu \times \mathbf{s}) \quad (\text{S2})$$

where γ and α are the gyromagnetic ratio and the Gilbert damping constant, respectively, which are assumed to be sublattice independent, and $\mathbf{H}_\mu = -(M_S)^{-1} \delta u / \delta \mathbf{m}_\mu$ are the effective magnetic fields for the sublattice μ . The last term in Eq. (S2) is the spin-orbit torque (SOT), with e the elementary electric charge, θ_{SH} the effective spin Hall angle of the adjacent heavy metal, d is the thickness of the Mn_3Sn film and the vector $\mathbf{s}$ ($|\mathbf{s}| = 1$) represents the polarization of the spin current injected into Mn_3Sn . For the simulation of Eq. (S2) with (S1), we employ $J_0 = 10^8 \text{ J m}^{-3}$, $D = 10^7 \text{ J m}^{-3}$, $K = 1.6 \times 10^6 \text{ J m}^{-3}$, $M_S = 1.26 \text{ T}$, $\alpha = 0.01$, $\theta_{SH} = 0.15$ and $d = 10 \text{ nm}$, to be consistent with our experiment. The weak ferromagnetic moment $\mathbf{m} \equiv (\mathbf{m}_A + \mathbf{m}_B + \mathbf{m}_C)/3 \cong 0.0046$ is observed in the x - y (kagome) plane in equilibrium, exhibiting a six-fold anisotropy within the same plane.

There is a one-to-one correspondence between the chiral spin structure and the direction of $\mathbf{m}$ in the kagome plane, and thus a rotation of the former is accompanied by that of the latter. In Fig. S6 displayed is the temporal evolution of $\mathbf{m}$ in the presence of current pulses. Figure S6a,b presents the results for the $[11\bar{2}0]$ component of $\mathbf{m}$, for $\mathbf{s} \parallel [0001]$ and $\mathbf{s} \parallel [11\bar{2}0]$, respectively. In both cases the current pulses are applied from $t = 8$ to 32 ns . Figure S6a is the same as Fig. 3a in the main text. Figure S6b shows that the chiral spin structure does not rotate when

the spin polarization $\mathbf{s}$ lies in the kagome plane, even with as high current density as 250 MA cm^{-2} . With the same current density, the SOT with $\mathbf{s} \parallel [11\bar{2}0]$ also does not drive the chiral-spin rotation (not shown). This observation is consistent with the previous theoretical prediction^{4,5}. Figure S6c and d are the corresponding results for the $[0001]$ component, where the same color scheme as in Fig. S6a and b for different current densities are adopted. It is seen in Fig. S6c that the increase of $m_{[0001]}$ during the rotational motion remains negligibly small compared to the in-plane component.

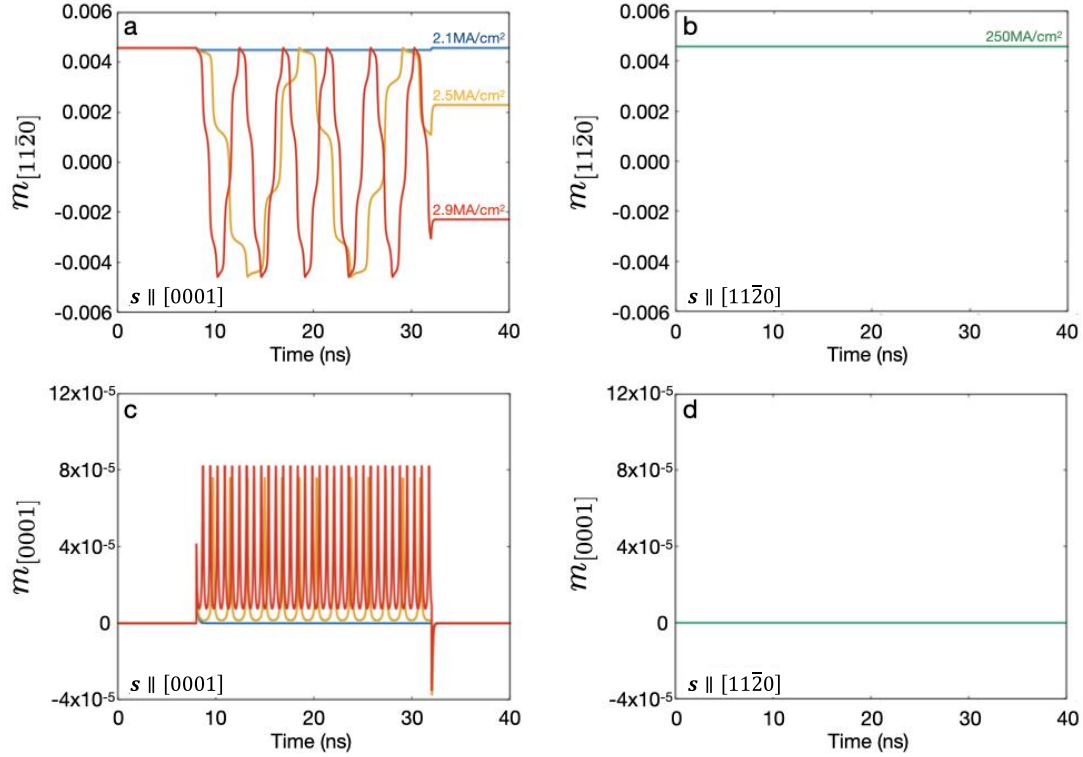


Figure S6 Numerical calculation of trajectory of chiral-spin structure under SOT. a-d, temporal evolution of Mn_3Sn weak ferromagnetic moment $\mathbf{m}$. The electric current pulses are applied from time $t = 8$ to 32 ns . a,b, $m_{[11\bar{2}0]}$ vs t for $\mathbf{s} \parallel [0001]$ and $\mathbf{s} \parallel [11\bar{2}0]$, respectively. c,d, $m_{[0001]}$ vs t for $\mathbf{s} \parallel [0001]$ and $\mathbf{s} \parallel [11\bar{2}0]$, respectively.

Within our macroscopic three-spin model, the frequency f of the persistent rotation can approximately be estimated as (see, e.g., Eq. (15) of reference 3)

$$f = \frac{\gamma \hbar \theta_{SH}}{4\pi e M_S d \alpha} J \quad (\text{S3})$$

Note that we have assumed in deriving Eq. (S3) that the SOT (i.e. the electric current density J) is large enough that the effective six-fold magnetic anisotropy has little influence on f . We compare in Fig. S7 the analytical estimation with numerical results for f . One sees a very good agreement between the two calculations for $J \gg$

$J_c \cong 2.41 \text{ MAcm}^{-2}$. This result indicates that in our experiment the chiral spin structure rotates with frequency of the order of GHz.

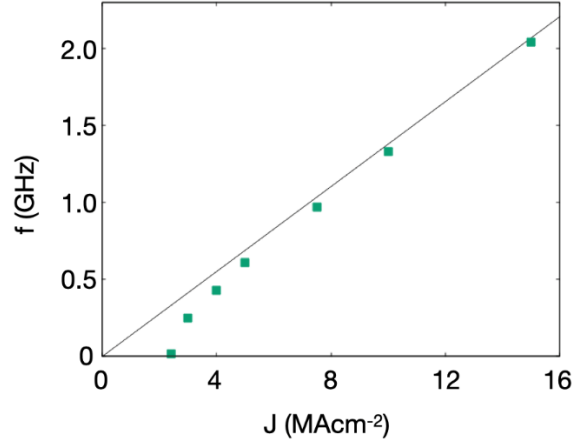


Figure S7 J -dependence of frequency f of chiral-spin rotation under SOT. The solid line plots Eq. (S3) while the square symbols are obtained by numerically solving Eq. (S2).

S7. R - I curves under perpendicular magnetic field

For further understanding of the unconventional response of Hall resistance to electric current, we measure R_H - I curves under various magnetic fields. Figure S8a shows the out-of-plane magnetic field dependence of R_H - I curve in Mn_3Sn / Pt heterostructure. For $|\mu_0 H| < 75 \text{ mT}$, the average value of R_H and its fluctuation in the higher I regime is significantly dependent on H . The average value of R_H in the high current range is shifted to the high (low) level of R_H by the negative (positive) magnetic field. The change of R_H can be attributed to the lift of degeneracy for the possible six chiral-spin structures [see Fig. S10a-f of Supplementary information 9] due to the out-of-plane magnetic field ⁶, and hence agrees with the inferred scenario that the current-induced change in the Hall resistance reflects the rotation of chiral spin structure of Mn_3Sn layer with multiple domains.

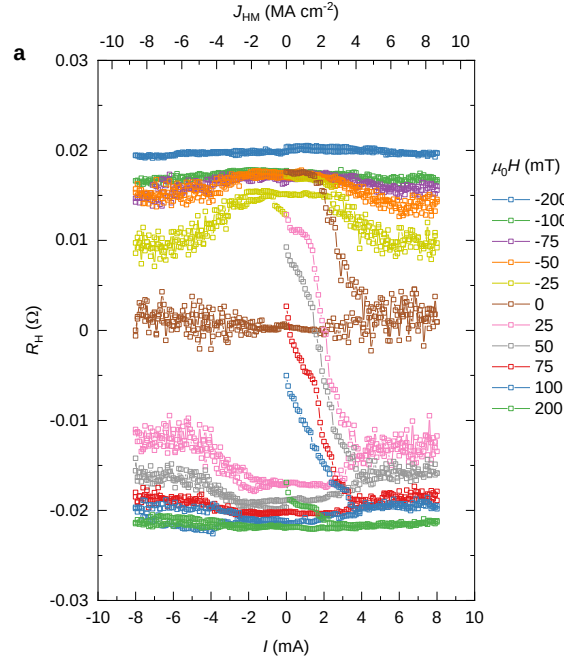


Figure S8 Magnetic field dependence of R_H - I curves in Mn_3Sn / Heavy metal. **a**, R_H - I curves of $\text{W}(3) / \text{Ta}(1) / \text{Mn}_3\text{Sn}(8.3) / \text{Pt}(4)$ under out-of-plane magnetic field H . For the initializing of Mn_3Sn , the out-of-plane magnetic field of -1.0 T is applied before the measurement of R_H - I curve. The pulse current I is applied along the $[11\bar{2}0]$ direction of Mn_3Sn .

S8. Measurement and analysis of anomalous Hall resistance fluctuation

In Fig. 4a-g of the main text, we display the Hall resistance as a function of current pulse number and the sample-size dependence of the Hall resistance fluctuation for $t_{\text{Mn}_3\text{Sn}} = 9.4$ nm. Here we show the method we used to evaluate the anomalous Hall resistance fluctuation from R_H vs pulse number. The R_H measurement is performed 2,000 times repeatedly, requiring an hour of experimental time in total. The pulse current is applied before every R_H measurement. Figure S9a and b show raw data of the pulse number dependence of R_H for the high and low pulse currents, respectively. To remove the long-term change in the base level of R_H , we utilise the method of the simple moving average (SMA) for R_H vs pulse number. The black solid lines in Fig. S9a and b represent the SMA signals $\langle R_H \rangle$ with filter length of 250 samples. By subtracting $\langle R_H \rangle$ from R_H , the fluctuation of R_H due to the chiral-spin rotation plus measurement error can be obtained. Figure S9c and d show the pulse number dependence of $(R_H - \langle R_H \rangle)$ for the high and low pulse currents, respectively. In Fig. 4a-f of the main text, $(R_H - \langle R_H \rangle)$ is normalized by the zero-field anomalous Hall resistance R_{AHE} to exclude device-to-device deviation of R_{AHE} .

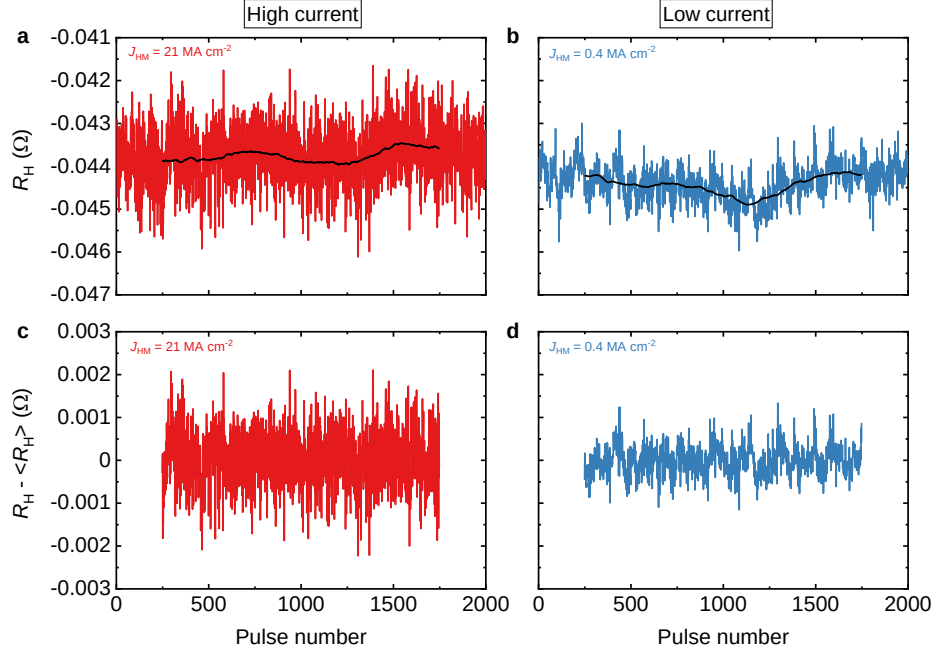


Figure S9 Measurement and simple moving average of R_H vs pulse number. **a,b**, R_H vs pulse number of Hall device with $t_{\text{Mn}_3\text{Sn}} = 9.4 \text{ nm}$ and $W_{\text{ch}} = 3 \text{ }\mu\text{m}$ for high and low current, respectively. Black line represents signal of SMA $\langle R_H \rangle$. **c,d**, $R_H - \langle R_H \rangle$ vs pulse number for high and low current, respectively. Current density J_{HM} of 21 (0.4) MA cm^{-2} is applied for the case of high (low) current.

S9. Model of anomalous Hall resistance fluctuation in multi-domain formed chiral-spin structure

We evaluate the average domain size in Mn_3Sn from the sample-size dependence of the fluctuation in R_H using Eq. (2) of the main text. Equation (2) is derived from a model considering the rotation of the chiral-spin structure in multiple domains⁶. Mn_3Sn has a magnetic anisotropy of six-fold symmetry, and the six chiral spin states shown in Fig. S10a-f are allowed and degenerate in the ground states. Figure S10 (a,b), (c,d) and (e,f) correspond to the high, middle and low levels of anomalous Hall resistance, respectively. For the case of multi-domain structure, the standard deviation of $(R_H - \langle R_H \rangle)/R_{\text{AHE}}$ can be evaluated by

$$\sigma_{\text{rotation}} = \sqrt{\frac{2}{3N_{\text{domain}}}} \quad (\text{S3})$$

assuming that each of the six states is found in the multi-domain structures with equal probability 1/6. Here N_{domain} represents the number of domains in Mn_3Sn . If the area of the Hall cross ($S = W_{\text{ch}} \times W_{\text{probe}}$) is larger than the average

area of domain (S_{domain}), the number of domains is estimated by $N_{\text{domain}} \approx S/S_{\text{domain}}$. Therefore, Eq. (S3) leads to the following expression:

$$\sigma_{\text{rotation}} \sim \sqrt{\frac{2}{3(S/S_{\text{domain}})}}. \quad (\text{S4})$$

Eq. (S4) is the same as Eq. (2) of the main text.

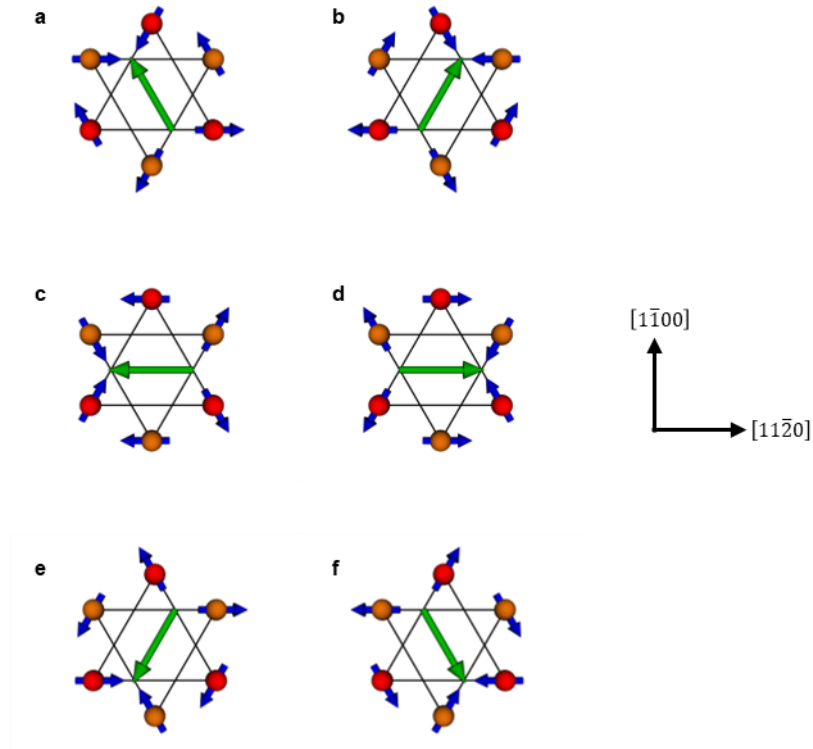


Figure S10 Stable chiral-spin structures in Mn_3Sn . a-f, the six stable states of the chiral-spin structure. The red and yellow spheres represent Mn atoms at $z = 0$ and $1/2$, respectively. Blue arrows denote local magnetic moments of Mn atoms. Green arrows represent weak ferromagnet of Mn_3Sn . (a,b), (c,d) and (e,f) are the configurations respectively for high, middle and low levels of anomalous Hall resistance in the sample with $\text{Mn}_3\text{Sn}(1\bar{1}00)$ grown in the film plane.

S10. Determination of Mn_3Sn thickness and current density

We prepared the heterostructures by magnetron and bias sputtering as described in Methods. The stacks for the Hall devices consist of MgO(110) substrate / W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / Pt(4). Accordingly, following a parallel resistance model, the total channel conductance G of the Hall devices is given by

$$G = G_{\text{W/Ta}} + \frac{t_{\text{Mn3Sn}}}{\rho_{\text{Mn3Sn}}} \frac{W_{\text{ch}}}{L_{\text{ch}}} + \frac{t_{\text{Pt}}}{\rho_{\text{Pt}}} \frac{W_{\text{ch}}}{L_{\text{ch}}}, \quad (\text{S5})$$

where $G_{\text{W/Ta}}$ is the channel conductance of W(3) / Ta(1) layers, $\rho_{\text{Mn3Sn(Pt)}}$ the resistivities of Mn₃Sn (Pt) layers and t_{Pt} the thickness of Pt. $G_{\text{W/Ta}} = 1.35$ mS, $\rho_{\text{Mn3Sn}} = 330$ $\mu\Omega\text{cm}$ and $\rho_{\text{Pt}} = 42.9$ $\mu\Omega\text{cm}$ are obtained from sheet resistance measurement of blanket films with various thicknesses. Eq. (S5) leads to the following expression:

$$t_{\text{Mn3Sn}} = \left\{ (G - G_{\text{W/Ta}}) \frac{L_{\text{ch}}}{W_{\text{ch}}} - \frac{t_{\text{Pt}}}{\rho_{\text{Pt}}} \right\} \rho_{\text{Mn3Sn}}. \quad (\text{S6})$$

Hence, t_{Mn3Sn} can be determined by the measurement of G of the Hall device with Eq. (S6). All t_{Mn3Sn} in this study are evaluated using this method. In addition, J_{HM} can be derived from Eq. (S5) for a given total current. For stacks of W(3) / Ta(1) / Mn₃Sn(t_{Mn3Sn}) / MgO(1.3) / Ru(1), we use Ru resistivity ρ_{Ru} of 36.2 $\mu\Omega\text{cm}$ to evaluate the conductance of MgO(1.3) / Ru(1) capping layer.

Supplementary references

- ¹Tsai, H. *et al.* Electrical manipulation of a topological antiferromagnetic state. *Nature* **580**, 608–613 (2020).
- ² Pai, C.-F., Ou, Y., Vilela-Leão, L. H., Ralph, D. C. & Buhrman, R. A., Dependence of the efficiency of spin Hall torque on the transparency of Pt/ferromagnetic layer interfaces. *Phys. Rev. B* **92**, 064426 (2015).
- ³ E. M. Lifshitz and L. P. Pitaevskii, *Statistical Physics, Course of Theoretical Physics* (Pergamon, Oxford, 1980), Vol. **9**, Pt. 2.
- ⁴ Fujita, H. Field-free, spin-current control of magnetization in non-collinear chiral antiferromagnets. *Phys. Status Solidi - Rapid Res. Lett.* **11**, 1600360 (2017).
- ⁵ Yamane, Y., Gomonay, O. & Sinova, J. Dynamics of noncollinear antiferromagnetic textures driven by spin current injection. *Phys. Rev. B* **100**, 54415 (2019).
- ⁶ Liu, J. & Balents, L. Anomalous Hall Effect and Topological Defects in Antiferromagnetic Weyl Semimetals: Mn₃Sn/Ge. *Phys. Rev. Lett.* **119**, 087202 (2017).