Supplementary Materials for

Setting of the magnetic structure of chiral kagome antiferromagnets by a seeded spin-orbit torque

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Supplementary Text
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References
Electrical switching measurement

The electrical switching experiments were performed in a PPMS (Quantum Design, Inc.) and probe station (Lakeshore cryotronics) system. Two distinct switching protocols were used in these investigations. In protocol I (Fig. S1 A), first a write pulse of variable pulse length [switching scheme 1, 2 and 3 in Fig. S2] was used. After a specific delay period (0.5 s), the resultant magnetic orientations were probed by measuring the transverse voltage in the Hall bar with a 1 mA d.c. read current. In switching protocol II (Fig. S1 B), a single current pulse is used for both writing and simultaneous reading [switching scheme 4 in Fig. S2]. The schematic diagram of four different switching schemes, namely (1) 'ns-write and dc-read' (2) 'µs-write and dc-read' (3) 'ms-write and dc-read', and (4) 'simultaneous read and write', are summarized in Fig. S2.

For scheme 1 ('ns-write and dc-read'), scheme 2 ('µs-write and dc-read'), and scheme 3 ('ms-write and dc-read'), the writing pulses were applied with PSPL10300 (ns pulse with 750 ps rise/fall time), Keithley 4200 (µs pulse with 20 ns rise/fall time), and Keithley 2635B (ms pulse) pulse generators, respectively. The Hall resistance $R_{xy}$ measurements were performed by the Keithley 2635B. For scheme 4, 'simultaneous read and write', a set of Keithley 6221 and 2182a nanovoltmeter, which was trigger-linked, was used. In this scheme, the Hall resistance $R_{xy}$ was measured during the writing current pulse. The diagrams of these measurement sequences are shown in Fig. S1.

![Fig. S1. Current induced Switching protocol.](image)

(A) Switching protocol I, where writing pulses of different pulse length (5 ns - 100 ms) were used and $R_{xy}$ was measured after a specific delay with a dc current of 1 mA. For (A), internal and external switching relay circuits were used for
switching between writing and reading. Note that open and closed circles indicate open and closed relays, respectively. (B) Switching protocol II, where the same current pulses were used for writing and reading. Blue arrows denote the points where the reading data was taken.

Figure S2. Schematics of different switching. (A) (inset) a microscopic image of a Hall Bar that was used for the switching experiments. (A)-(C) Schematics for ns, µs, and ms writing pulse, respectively and delayed reading with dc current (1 mA). (D) Schematics for 'simultaneous read and write’ measurement. During experiments current was applied along ‘x’ and the magnetic field was applied along different direction as mentioned in the text.
I. Structural analysis and magnetic properties of Mn$_3$Sn thin film

The texture of the polycrystalline Mn$_3$Sn film was studied by X-ray diffraction using a Bruker D8 Discover four circle diffractometer operated with monochromatized Cu-K-\(\alpha_1\) radiation and a six-circle diffractometer using focused Ga-K-\(\alpha\) radiation from a Ga-jet x-ray source.

Fig. S3 a shows the 20-0 scan on a logarithmic intensity scale in the range between 20° = 20° and 80° collected with the Bruker D8 Discover using a two-dimensional pixel detector operated in one-dimensional scan mode. The measurement was carried out on a 100 nm thick Mn$_3$Sn thin film. Within this angular interval, all reflections could be observed with exception of the (0002) reflection near 20 = 40° which is too weak, while in other studies it has been detected (29, 47). Already on a qualitative basis this suggests that our film is highly textured with a preferential orientation of the (11\(\bar{2}\)0) crystal face parallel to the film surface. Moreover, in our case the (11\(\bar{2}\)0) reflection is about three times as strong as compared to the (20\(\bar{2}\)1) reflection. The latter should be the strongest one in the ideal case of a polycrystal with a completely random orientation of the crystallites, which is observed in the XRD patterns of Refs (29, 47). The inset shows the reciprocal space map (RSM) in the vicinity of the (20\(\bar{2}\)1) reflection. In the RSM data which were collected using a six-circle diffractometer and a Ga-jet X-ray source under grazing incidence (incidence angle \(\mu = 1°\)) of the primary beam, three diffraction rings are observed which are identified as reflections belonging to TaN (10\(\bar{1}\)1) and to the Mn$_3$Sn (0002) and (20\(\bar{2}\)1) reflection. The intensity ratio between the latter is equal to about 1:5. In order to evaluate the presence of a texture in the deposited film we have quantitatively analyzed the reflection intensities by integrating the peaks and deriving an effective multiplicity as shortly outlined as follows:

The integrated intensity \([I(hkil)]\) of a polycrystalline (powder) sample at the Bragg angle \(\theta\) is given by (49)

\[
I(hkil) \propto \frac{|F(hkil)|^2 \times H \times V_x}{\sin^2(\theta) \times \cos(\theta) \times \mu \times v_{uc}^2}
\]

where \(|F(hkil)|\), \(V_x\), \(v_{uc}\) and \(\mu\) represent the structure factor magnitude, the volume of the crystal, the volume of the unit cell (uc) and the linear absorption coefficient, respectively. Importantly, the factor \(H\) represents the multiplicity (i.e. the statistical weight) of the crystal faces in a polycrystalline sample. For instance, in space group (SGR) P6$_3$/mmc the multiplicity of the basis-pinacoid \(\{0001\}\) is equal to 2, while for the hexagonal prism \(\{10\bar{1}0\}\) it is equal to 6.
Fig. S3. Crystallographic characterizations of Mn$_3$Sn. (A) 20-0 scan for the Mn$_3$Sn film on Al$_2$O$_3$ (1̅102). Narrow weak reflections originate from the Mn$_3$Sn film and are indexed. The inset shows a reciprocal space map in the vicinity of the (20̅21) reflection. (B) Plot of $H_{hkil}^{\text{eff}}$ derived for all nine reflections (hkil) shown in Fig. S3 (A). The size of the circles approximately represents $H_{hkil}^{\text{eff}}$ normalized to 1.0 for the (11̅20) reflection. Circles are located according to the position of the corresponding crystal faces in a stereographic projection using Wulff's net.

We have used the above equation and calculated values for $|F(hkil)|^2$ to derive the effective H-values ($H_{hkil}^{\text{eff}}$) from the integrated intensities for each reflection (hkil). The factors $\mu$, $V_x$ and $v_{uc}$ cancel out as we evaluate normalized and relative values for $H_{hkil}^{\text{eff}}$. In an ideal polycrystalline sample (powder) $H_{hkil}^{\text{eff}}$ should be equal to 1 for all reflections.

Fig. S3 (B) shows the result, where $H_{hkil}^{\text{eff}}$ is roughly represented by the area of the circles. We use a stereographic projection along the c-axis of the crystal lattice to represent the position of the crystal faces. The reflection indices and $H_{hkil}^{\text{eff}}$ for all reflections are indicated next to the circles. The most important result is the strong preference of the (1120) reflection while the (10̅11) reflection also has an appreciable weight. $H_{hkil}^{\text{eff}}$ for first and second order reflections deviate by up to 40% which we attribute to both the statistical error resulting from the very weak reflections and to the fact that we are using $|F(hkil)|$ values calculated on the basis of the perfect structure, which is likely not absolutely correct, especially with regard to the presence of disorder. We emphasize however, that a scatter of $H_{hkil}^{\text{eff}}$ in the range of 40% is very small as compared to the overall dynamics of $H_{hkil}^{\text{eff}}$ throughout the data set. We find small and extremely small values for most reflections [e.g. (2020), (0002), (2021), (2242)] which are two orders of magnitude lower than expected for a random orientation of the crystallites. This demonstrates that the sample surface is characterized by a majority ($\approx$ 50%) of crystallites preferentially oriented with their (1120) crystal faces parallel to the sample surface.

Fig. S4 A displays a scanning-TEM micrograph of 30 nm Mn$_3$Sn film (viewed along [1120] direction) which illustrates that the film is highly ordered locally, although it’s textured
globally as found from the XRD analysis. The surface roughness of the film is increased from 2 nm to 4 nm with the increase of film thickness from 30 nm to 100 nm. A typical AFM image for 30 nm Mn$_3$Sn thin films is shown in Fig. S4 B.

![AFM image](image_url)

**Fig. S4. STEM and AFM characterization of Mn$_3$Sn.** (A) Cross-section scanning-TEM (STEM) micrograph of 30 nm Mn$_3$Sn film which is grown on Al$_2$O$_3$ (11̅02) substrate, viewed along the [1120] of Mn$_3$Sn (B) Atomic force micrograph of the Mn$_3$Sn (30 nm) / W (8 nm) bilayer film over 5×5 µm$^2$ scan area.

To Probe the small moment which lies in the kagome plane of Mn$_3$Sn, magnetization measurements were carried out as a function of applied out-of-plane magnetic field ($H_z \parallel [1120]$) at $T = 300$ K. A typical variation of magnetization as a function of $H_z$ is shown in Fig. S5 (A) for Mn$_3$Sn (80 nm) / W (8 nm) sample where magnetic signal is mostly dominated by a diamagnetic contribution known to originate from the diamagnetic Al$_2$O$_3$ substrate. The film, on the other hand, exhibits a very weak magnetic signal. The background diamagnetic moment of the substrate has been subtracted from the raw data and the corrected magnetic data (film contribution) is shown in Fig. S5 (B). The spontaneous magnetization is found to be very small (25 emu/cm$^3$) as expected for the non-collinear AFM Mn$_3$Sn thin film (50, 51). The magnetization is almost independent of the film thickness. Further, field cooled ($H_{FC} = 10$ mT) magnetization measurements have been carried out as function of temperature in the out-of-plane geometry to confirm the inverse triangular structure. It can be seen from Fig. S5 (C) that the magnetization goes through a transition around $T = 260$ K which manifests the transition from a triangular to a helical structure for the Mn$_3$Sn film. These results are consistent with previous reports (29, 34).
Fig. S5. Magnetic measurements on Mn₃Sn. (A) Magnetic moment as a function of $H_z$ at room temperature (both substrate and thin-film contribution.) (B) Magnetization ($M$) as a function of $H_z$ after substrate contribution is subtracted. (C) Temperature dependent evolution of $M$ in field cooled condition ($H_z = 10$ mT).

II. Model tight-binding calculations

The purpose of this section is to show that the net magnetic moment $\mathbf{m}$ of a kagome triangle allows to determine the shape of the resistivity tensor, even though it is not the order parameter. For the purpose of generality, we do not restrict our calculations to Mn₃Sn but model a generic kagome magnet that exhibits a phase with a negative vector spin chirality and is AB stacked. Since Mn₃Sn $d$ bands dominate near the Fermi level, we consider 5 $d$ orbitals for each of the three lattice sites giving us 30 bands in total. The electronic Hamiltonian reads

$$H = \sum_{ij\alpha\beta} t_{ij}^{\alpha\beta} a_{i\alpha\sigma}^\dagger a_{j\beta\sigma} + \lambda \sum_{i\alpha\beta\sigma} a_{i\alpha\sigma}^\dagger S a_{i\beta\sigma} + m \sum_{i\alpha\sigma} a_{i\alpha\sigma}^\dagger \left( \mathbf{m}_i \cdot \mathbf{\sigma} \right) a_{i\alpha\sigma}.$$  

The first term comprises the hopping terms, accounting for the electrons’ kinetic energy. An electron with orbital $\alpha$ and spin $\sigma$ is annihilated at site $i$ (operator $a_{i\alpha\sigma}^\dagger$) and is created with orbital $\beta$ at site $j$ with the same spin (operator $a_{j\beta\sigma}$). This process is quantified by the hopping amplitude $t_{ij}^{\alpha\beta}$. Note, that not all hopping amplitudes are independent of each other.

In fact, for $d$ electrons there exist exactly 3 Slater-Koster parameters to quantify all the hopping amplitudes via a linear combination of directional cosines. We have chosen these Slater-Koster parameters as $V_\pi = -V_\sigma = -V_\delta = 1$ eV. The second term in the electronic Hamiltonian characterizes the spin-orbit coupling with amplitude $\lambda = 0.2$ eV and the interaction matrix...
\[
S = i \begin{pmatrix}
0 & \sigma_y & -\sigma_x & 2\sigma_z & 0 \\
-\sigma_y & 0 & \sigma_z & -\sigma_x & -\sqrt{3}\sigma_x \\
\sigma_x & -\sigma_z & 0 & -\sigma_y & \sqrt{3}\sigma_y \\
-2\sigma_z & \sigma_x & \sigma_y & 0 & 0 \\
0 & \sqrt{3}\sigma_x & -\sqrt{3}\sigma_y & 0 & 0
\end{pmatrix},
\]

where \( \sigma_x, \sigma_y \) and \( \sigma_z \) are the Pauli matrices. The SOC term is an onsite term that mixes different orbitals according to \( S \). The third term is the interaction of the electron spin (\( \sigma \) vector of Pauli matrices) with the magnetic texture (\( m_i \) unit vectors). This is also an onsite term but it mixes different spin directions. The strength of this coupling is \( m = 0.2 \text{ eV} \).

We diagonalize the Hamiltonian to determine the band structure \( E_n \) and the eigenvectors \( |n\rangle \), both dependent on the reciprocal vector \( k \). We calculate the Berry curvature tensor for band \( n \)

\[
\Omega_{n,ij} = -2 \text{ Im} \sum_{m \neq n} \frac{\langle n| \partial_{k_i} H |m \rangle}{(E_n - E_m)^2} \frac{\langle m| \partial_{k_j} H |n \rangle}{(E_n - E_m)^2}.
\]

From the Berry curvature, we can calculate the intrinsic contribution to the Hall conductivity as the integral over all occupied states (energy below the Fermi energy \( E_F \))

\[
\sigma_{ij} = -\frac{e^2}{h} \frac{1}{(2\pi)^2} \sum_n \int_{E_n(k) \leq E_F} \Omega_{n,ij}(k) \, dk.
\]

First, we simulate the six different equilibrium magnetic phases (\( \varphi = 30^\circ, 90^\circ, 150^\circ, 210^\circ, 270^\circ, 330^\circ \)) that we have discussed in the paper. Our numerical results (three exemplary phases in Fig. S6) reveal that the conductivity tensor can be decomposed as

\[
\rho^{-1} = \sigma = \begin{pmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{pmatrix} = \sigma_0 \begin{pmatrix}
0 & \sin \varphi & -\cos \varphi \\
-\sin \varphi & 0 & 0 \\
\cos \varphi & 0 & 0
\end{pmatrix}.
\]

This means, that the plane of Hall transport is perpendicular to the net magnetization, similar to the situation in a ferromagnet.
Fig. S6. Hall conductance for different magnetic configurations of Mn₃Sn. The kagome plane is the yz plane. The corresponding yz tensor element is always zero. The other two elements change according to the tensor representation above. The considered configurations in (A)-(C) correspond to $\varphi = 30^\circ, 90^\circ, 150^\circ$ considered in the main text.

However, the mechanism behind it is very different. The net moment is way too small to explain the measured signal. The origin is a set of broken symmetries by the arrangement of magnetic moments. This effect remains, even if we artificially fix the moments at angles 120° with respect to each other, so that the net magnetization is exactly zero. As is shown in Figure S7, this only changes the Hall conductivity very slightly. This means, the net moment is not the order parameter but under the experimental conditions, it still allows to determine the shape of the resistivity tensor. In the experiment, we measure the xy element which is why we observe the maximum signal for the field-switching mechanism that involves switching between the $\varphi = 90^\circ$ and $\varphi = 270^\circ$ configurations where the sine has its extrema. For the other four configurations, that are relevant for the SOT switching, the sine is only $\pm 0.5$.

Fig. S7. Hall conductance with and without net magnetic moment. (A,B) show stable magnetic configurations in Mn₃Sn without and with easy-axis anisotropy taken into account
[dashed lines in (B); effect exaggerated]. The configuration in (A) has no net moment, \( m = 0 \). In (C) the Hall conductivity is shown for both configurations. The difference is only marginal.

III. Theoretical simulation of current induced switching

We have carried out theoretical simulation of current induced switching as discussed in the previous publication (29). When a current is applied along \( x \), the SHE in W injects a spin current with a polarization \( s \parallel \pm y \) into the Mn$_3$Sn layer, \( i.e., \) along \( \varphi = 0^\circ \) or \( \varphi = 180^\circ \), depending on the sign of the current. If the current density is sufficiently large, the injected spin current orients all the magnetic configurations along these two unstable configurations (cf. energy maxima in Fig. 1C in the main text). Using atomistic simulations this change in the magnetic state can be calculated, as illustrated in Fig. S8 (A, B). The absence of the bias field \( (H_x) \) leads to a perfect alignment of \( m \) along the two directions characterized by \( \varphi = 0^\circ, 180^\circ \), once the applied current is larger than the critical current. These configurations correspond to two energy maxima shown in Fig. 1C. For this reason, once the current is turned off, domains in the configuration \( \varphi = 0^\circ \) will relax either to \( \varphi = 30^\circ \) or \( \varphi = 330^\circ \) (two equally close energy minima). The probability for both relaxation processes is equal and since the two configurations are characterized by \( m_z = +0.5m \) and \( m_z = -0.5m \), respectively, the measured \( xy \) Hall resistivity cancels. The same argument holds for the domains that are in a \( \varphi = 180^\circ \) state. These relax either to \( \varphi = 150^\circ \) or \( \varphi = 210^\circ \).

In the presence of \( H_x \), the metastable states never reach exactly the injected spin orientations \( \varphi = 0^\circ \) and \( \varphi = 180^\circ \) but approach close to these values depending on the current density. The direction (sign with respect to \( z \)) of \( \mathbf{H} \times \mathbf{s} \) determines whether \( \varphi \) is slightly smaller or larger than these saturation values. When the current is turned off, the system then relaxes to the nearest energy minimum depending on the sign of \( \mathbf{H} \times \mathbf{s} \). This means that by reversing the current direction (and therefore \( s \)), the magnetic configurations are switched from either \( \varphi = 330^\circ \) to \( 30^\circ \) or from \( \varphi = 210^\circ \) to \( 150^\circ \) and vice-versa (depending on the \( H_x \) direction), thereby changing the sign of the Hall voltage. For both metastable states, this corresponds to a switching between configurations with a projected net moment of \( m_x = \pm 0.5 \vert m \vert \). Therefore, the theoretically highest possible Hall signal is half as large as that in the field-switching experiment, \( i.e., \) \( \sim \pm 25 \text{ m}\Omega \) for the present study.
**Fig. S8. Theoretical simulation of electrical switching.** (A)-(B) Theoretical description of current-induced SOT switching in the presence of a bias field $H_x = 0$ T and 0.1 T.

**IV. Determination of device temperature from current induced switching using Protocol II**

Current induced switching experiment is shown in Fig. S9 A using Protocol II in the absence of bias field ($H_x=0$). The non-linear behavior of $R_{xy}$ reflects that a finite $R_{xx}$ contribution to $R_{xy}$ due to a small mismatch in the voltage contacts and this helps to calibrate the device temperature. Taking the $R_{xy}$ value at $J_x = 0$ for zero field at different measurement temperature (inset of Fig. S9 A), the device temperature is found to be 435 K when switching occurs. The dependence of $J_c$ on the pulse length and as a function of temperature, is summarized in Fig. S9 B (from Protocol II).

**Fig. S9. Device temperature from protocol II and pulse width dependent critical current variation.** (A) $R_{xy}$ as a function of $J_x$ with $H_x = 0$ T using Switching protocol II. In inset $R_{xy}$ value at $J_x = 0$ is plotted against measurement temperature to calibrate the device temperature (B) Dependence of $J_c$ on current pulse length and measurement temperature.
V. Magneto-transport properties of Mn$_3$Sn thin films

Fig. S10 A shows the zero-field longitudinal resistivity ($\rho_{xx}$) as a function of temperature over the temperature range from 5K to 400K for the 30 nm Mn$_3$Sn thin film. It exhibits a metallic transport behavior as expected with residual resistivity ratio (RRR) $\sim$ 1.75 which demonstrates a high quality of thin film. $\rho_{xx}$ is 180±10 $\mu$Ω cm at room temperature for the different thicknesses of Mn$_3$Sn. We have also measured the longitudinal resistance ($R_{xx}$) of the device during the writing pulse application. Lower inset of Fig. S10 A shows that the resistance of the device is increasing more than 12 $\Omega$ for a write pulse of magnitude ±9V. By comparing this change in $R_{xx}$ with temperature dependent $R_{xx}$ measurements (upper inset of Fig. S10 A) we conclude that the temperature of the device is beyond 400 K for a voltage close to ±9V. Variable temperature Hall measurements were carried out to investigate the change in Hall signal when the temperature of the system is increased. A few representative $R'_{xy}$ vs $H_z$ plots at different temperatures for the Mn$_3$Sn (30 nm) / W (8 nm) bi-layer are shown in Fig. S10 B. It can be seen that $R'_{xy}$ for $H = 0$ exhibits a large change from 50 to -50 m$\Omega$ at $T = 300$ K. The change in the zero field Hall resistance ($R'_{xy}$ at $H_z = 0$) and coercivity ($H_c$) are plotted against temperature as depicted in Fig. S10 C.

![Fig. S10. Longitudinal resistivity and anomalous Hall measurements.](image)

(A) Variation of $\rho_{xx}$ as a function of temperature at $H_z = 0$ T. Upper inset shows actual resistance of the device as a function of temperature. Lower inset shows the change of device resistance during writing pulse sweep. (B) $H_z$ dependence of $R'_{xy}$ at different temperatures. (C) Temperature dependence of $\Delta R'_{xy}$ which is extracted by measuring anomalous Hall hysteresis at different temperatures.

VI. Thermal randomization in Mn$_3$Sn in absence of spin current

The anomalous Hall and current induced switching of single layer 40 nm Mn$_3$Sn is shown in Fig. S11 A and B. Although there is no spin current source, $R'_{xy}$ rapidly decreases at a critical current. This clearly show that there is no role of spin orbit torque for the setting of magnetic states or chiral spin rotation (30) rather the magnetic states sets by thermally.
Fig. S11. Anomalous Hall resistance and electrical switching of Mn₃Sn without W. (A) $R'_{xy}$ as a function of $H_z$ at room temperature for 40 nm single layer Mn₃Sn. (B) Current-induced switching with $H_x = 0.0$ T for the same sample.

VII. Current-induced switching of different thicknesses of Mn₃Sn/W bi-layers

Here, we show the current-induced switching of the other prepared thicknesses of Mn₃Sn ($d_{AF} = 40, 60, 80$ and $100$ nm) with a fixed thickness of 8 nm of W. The change in Hall resistance ($\Delta R'_{xy}$) during the magnetic-field-induced switching is shown in Fig. S12-15 A for the 40 to 100 nm Mn₃Sn thin films. The corresponding electrical switching, based on the type-I protocol, with $H_x = \pm 0.1$ T, is displayed in Fig. S12-15 B. It is evident that the threshold current density is the same for all thicknesses and percentage of switching is $\sim 40\%$ for all films except 100 nm film.

Fig. S12. Anomalous Hall resistance and electrical switching of 30 nm Mn₃Sn. (A) $R'_{xy}$ as a function of $H_z$ at room temperature. (B) Current-induced switching with $H_x = \pm 0.1$T.
Fig. S13. Anomalous Hall resistance and electrical switching of 60 nm Mn₃Sn. (A) $R'_{xy}$ as a function of $H_z$ at room temperature. (B) Current-induced switching with $H_x = \pm 0.1$T.

Fig. S14. Anomalous Hall resistance and electrical switching of 80 nm Mn₃Sn. (A) $R'_{xy}$ as a function of $H_z$ at room temperature. (B) Current-induced switching with $H_x = \pm 0.1$ T.

Fig. S15. Anomalous Hall resistance and electrical switching of 100 nm Mn₃Sn/W/TaN. (A) $R'_{xy}$ as a function of $H_z$ at 300 K. (B) Current-induced switching with $H_x = \pm 0.1$T.
VIII. Numerical modeling of the Joule heating and cooling during current pulse application

Here we present the details of the finite element method for the Joule heating and cooling simulations that were used to estimate the variation of the device temperature during the current-induced switching. The ‘Joule heating’ and the ‘heat transfer’ modules of the COMSOL multi-physics software were used for this study. First, a rectangular writing pulse (with amplitude $V_0$ and pulse length, $\tau_L$) were applied on the Hall bar device (Fig. S16). The time ($t$) dependent evolution of the temperature ($T$) during and after application of the writing pulse was estimated by numerically solving the transient heat-diffusion equation:

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \frac{J^2}{\sigma}$$

where $\rho$ is the density, $C_p$ is the specific heat capacity, $T$ is the temperature, $\kappa$ is the thermal heat conductivity, $J$ is the applied current density and $\sigma$ is electrical conductivity of the device. Since all our measurements were carried out in vacuum condition, convective cooling processes were not included in our simulation. The Hall bar of our experiment is comprised of a stack sequence Al$_2$O$_3$ (substrate) / Mn$_3$Sn (30 nm) / W (8 nm) / TaN (3 nm). Here, in COMSOL, this Hall bar is modeled as a single layer metallic film whose effective electrical conductivity ($\sigma$) and thermal conductivity ($\kappa$) were estimated from the $\sigma$ and $\kappa$ of Mn$_3$Sn and W. Since these devices consist mainly of the Mn$_3$Sn layer, other materials properties were approximated for Mn$_3$Sn only.

Fig. S16 A shows a representative temperature profile of a device during the application of a writing pulse as obtained from the simulation. The color plot (Fig. S16 A and C) shows that the device heats up significantly compared to its surrounding. For a better estimation, the time dependent variation of the temperature of the device, as obtained from a point in the center of the Hall bar, is shown in Fig. S16 B for the application of a square-shaped writing pulse ($\tau_L \sim 100$ ns) of different magnitudes ($V_0$). Two important observations can be made from these data as explained in the main section: (1) Depending on the magnitude of the writing pulse, the device temperature can increase significantly even for a 100 ns pulse. (2) The system cools down relatively fast if the applied writing pulse is switched off on a sub-ns time scale. In particular, the temperature drop is approximately 30% of the maximum temperature after 20 ns ($\frac{\Delta T_{100 \text{ ns}} - \Delta T_{120 \text{ ns}}}{\Delta T_{100 \text{ ns}}} \times 100\% \approx 30\%$).
Fig. S16. Joule heating and cooling simulations using COMSOL. (A) Geometry of the sample used for the simulation. (B) Variation of the device temperature under the application of a 100 ns pulse with different applied voltages. (C) Closer look of the device during current pulse application.

IX. Estimation of $\Delta R'_{xy}$ and $J_c$ during $H_x$ dependent switching experiments

In Fig. 5, B and C of the main text (for Mn$_3$Sn), $\Delta R'_{xy}$ and $J_c$ were estimated in four different conditions. $\Delta R'_{xy}$ are defined as $\Delta R'_{xy} = [R'_{xy} \text{ (after switch)} - R'_{xy} \text{ (before switch)}]$

(1) Black points (+$H_x$ and -$J_x$) in Fig. 5, A and C: Estimated when $H_x$ is positive and the current sweep is from zero to the negative direction as shown here in Fig. S17, A. The value of $\Delta R'_{xy}$ is positive in this case.

(2) Red points (+$H_x$ and +$J_x$) in Fig. 5, B and C: Estimated when $H_x$ is positive and the current sweep is from zero to the positive direction as shown here in Fig. S17, B. The value of $\Delta R'_{xy}$ is negative in this case.

(3) Purple points (-$H_x$ and -$J_x$) in Fig. 5, B and C: Estimated when $H_x$ is negative and the current sweep is from zero to the negative direction as shown in here in Fig. S17, C. The value of $\Delta R'_{xy}$ is negative in this case.

(4) Blue points (-$H_x$ and +$J_x$) in Fig. 5, B and C: Estimated when $H_x$ is negative and the current sweep is from zero to the positive direction as shown in here in Fig. S17, D. The value of $\Delta R'_{xy}$ is positive in this case.
Fig. S17. Estimation of $\Delta R_{xy}$ and $J_c$ from electrical switching. Four different cases, (A) positive $H_x$ and negative $J_x$ (B) positive $H_x$ and positive $J_x$ (C) negative $H_x$ and negative $J_x$ (D) negative $H_x$ and positive $J_x$.

X. Switching mechanism comparison with standard FM switching in a CoFeB film

Here we compare the switching mechanism of Mn$_3$Sn with the standard switching mechanism of a perpendicular magnetic anisotropic (PMA) ferromagnet Ta (5 nm) / CoFeB (1 nm) / MgO (2 nm) / Ta (3 nm). Results of current-induced switching (protocol-I) at different $H_x$ for the PMA ferromagnet are summarized in Fig. S18. In the case of CoFeB, $J_c$ shows a strong dependence on $H_x$ (Fig. S18 B). It decreases monotonically with increasing $H_x$. However, in case of Mn$_3$Sn, $J_c$ does not show any dependence on the applied $H_x$ (Fig. 5B, main text). This is because the field only serves as a bias and becomes only relevant when the critical current is reached and the system is in a switchable state. Also, in the case of the normal PMA sample $\Delta R'_{xy}$ is almost independent of the applied $H_x$ (Fig. S18 C). This is because the switching happens always between two distinct magnetic states. Intriguingly, $\Delta R'_{xy}$ in Mn$_3$Sn exhibits a strong non-monotonic dependence on the applied magnetic field as is evident from Fig. 5C in the main text.
Fig. S18. Electrical switching of PMA CoFeB film. (A) Current-induced switching using different $H_x$. (B, C) $H_x$ dependence of $J_c$ and $\Delta R_{xy}'$.

XI. Combination of field and current induced switching

In the main manuscript, we have discussed two distinct switching mechanisms: A field switching mechanism, when the field $H_z$ is oriented along $\varphi=\pm 90^\circ$, and a SSOT switching, for which a field perpendicular to the kagome plane ($H_x$) provides a bias $\Delta \varphi$ during the switching. Next, we explore the combination of both effects. We apply a field of $\pm 100$ mT at an angle $\psi$ with respect to $x$ and within the $xz$ plane (Fig. S19 A). A very interesting finding is that there are now 4 distinct $R_{xy}'$ states whose magnitudes are highly sensitive to $\psi$ as shown in Fig. S19 B. At $\psi = 0^\circ$, $R_{xy}' = \pm 20$ m$\Omega$ is measured; the same value as discussed earlier for $H$ oriented along $\pm x$. Once $H$ is tilted away from $x$, we observe that there are two branches for $R_{xy}'$ corresponding to $\pm H$, shown in Fig. S19 B as blue and red. For each $\psi$ along each branch, the sample can be switched hysteretically by current, between two distinct $R_{xy}'$ states, whose difference decreases with increasing $\psi$. The average values of these states are shifted either upwards (blue) and downwards (red) from zero, as $\psi$ is varied away from zero. $R_{xy}'$ can also be switched from the red to the blue hysteresis curve when the field is reversed but only if the critical current is exceeded. In particular, for $\psi = 90^\circ$, the maximum values of $R_{xy}'$ in each of the branches approaches those values obtained in pure magnetic field switching i.e. $\pm 50$ m$\Omega$ (see Fig. S10 B). However, here a field of just 100 mT is required as compared to 1T needed for pure field switching. The difference is caused by the heating provided by the current. Note that for $\psi = 90^\circ$ the SOT provided by the current has no effect on the switching and, therefore, cannot provide a seeding layer. Still, it heats up the sample and the magnetic field ($H_z$ along $\varphi = \pm 90^\circ$) provides the bias throughout the whole Mn$_3$Sn layer. In short, the field-switching mechanism is also strongly affected by current-induced heating in a favorable way. Finally, Fig. S19 C shows how the 4 states can be accessed for $\psi = 10^\circ$ by
applying current pulses in the presence of \( H = \pm 0.1 \text{ T} \). We conclude that there are 4 distinct \( R'_{xy} \) states that can be accessed by a current-induced switching mechanism that is strongly influenced by relatively small magnetic fields. These 4 states do not correspond to four individual magnetic phases but to different ratios of the six energetically preferred states presented in Fig. 1C in the main manuscript.

![Figure S19](image)

**Fig. S19. Combination of field and current induced switching.** (A) Schematic of measurement protocol. (B) \( R'_{xy} \) as a function of \( \varphi \) in the \( xz \) plane. (C) Switching from positive \( H (+0.1 \text{ T}) \) hysteretic loop to negative \( H (-0.1 \text{ T}) \) hysteretic loop for \( \varphi = 10^\circ \).

**XII. Fast Magnetization reversal with nanosecond current pulse in presence of a bias**

SSOT mediated switching can only take place if the device relaxes from the ordering temperature in presence of SOT provided by a critical spin current density \( (S^*) \). Switching experiments using nanosecond current pulses (with fall time ~ 750 ps) lead to very small switching efficiency \( (\xi) \) since the spin current source turnoff abruptly even before the system relaxes below \( T^* \). Therefore to overcome this situation, switching experiments were carried out using nanosecond current pulses ranging from 100 ns to 10 ns in presence of a bias (Fig. S20). It is to be noted that the role of the bias is to provide critical spin current density when the system \( (S^*) \) when the system cools below \( T^* \). We note that the magnitude of the bias...
voltage (2V) is below the critical current density necessary to switch the device.

Fig. S20. Electrical switching with ns pulse in presence of dc bias. (A) - (F), Switching experiments using nanosecond current pulses ranging from 100 ns to 10 ns in presence of a bias (2V).
REFERENCES AND NOTES

1. A. Brataas, A. D. Kent, H. Ohno, Current-induced torques in magnetic materials. *Nat. Mater.* **11**, 372–381 (2012).

2. A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, P. Gambardella, Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems. *Rev. Mod. Phys.* **91**, 035004 (2019).

3. I. M. Miron, K. Garello, G. Gaudin, P.J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, P. Gambardella, Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature* **476**, 189–193 (2011).

4. K. Ando, S. Takahashi, K. Harii, K. Sasage, J. Ieda, S. Maekawa, E. Saitoh, Electric manipulation of spin relaxation using the spin Hall effect. *Phys. Rev. Lett.* **101**, 036601 (2008).

5. A. Chernyshov, M. Overby, X. Liu, J.K. Furdyna, Y. Lyanda-Geller, L.P. Rokhinson, Evidence for reversible control of magnetization in a ferromagnetic material by means of spin–orbit magnetic field. *Nat. Phys.* **5**, 656–659 (2009).

6. L. Liu, T. Moriyama, D. C. Ralph, R. A. Buhrman, Spin-torque ferromagnetic resonance induced by the spin Hall effect. *Phys. Rev. Lett.* **106**, 036601 (2011).

7. I. Mihai Miron, G. Gaudin, S. Auffret, B. Rodmacq, A. Schuhl, S. Pizzini, J. Vogel, P. Gambardella, Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer. *Nat. Mater.* **9**, 230–234 (2010).

8. J. Yu, D. Bang, R. Mishra, R. Ramaswamy, J. H. Oh, H. J. Park, Y. Jeong, P. van Thach, D. K. Lee, G. Go, S. W. Lee, Y. Wang, S. Shi, X. Qiu, H. Awano, K. J. Lee, H. Yang, Long spin coherence length and bulk-like spin–Orbit torque in ferrimagnetic multilayers. *Nat. Mater.* **18**, 29–34 (2019).

9. T. Jungwirth, X. Marti, P. Wadley, J. Wunderlich, Antiferromagnetic spintronics. *Nat. Nanotechnol.* **11**, 231–241 (2016).
10. V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, Y. Tserkovnyak, Antiferromagnetic spintronics. Rev. Mod. Phys. 90, 015005 (2018).

11. P. Wadley, B. Howells, J. Železný, C. Andrews, V. Hills, R. P. Campion, V. Novák, K. Olejník, F. Maccherozzi, S. S. Dhesi, S. Y. Martin, T. Wagner, J. Wunderlich, F. Freimuth, Y. Mokrousov, J. Kuneš, J. S. Chauhan, M. J. Grzybowski, A. W. Rushforth, K. W. Edmonds, B. L. Gallagher, T. Jungwirth, Electrical switching of an antiferromagnet. Science 351, 587–590 (2016).

12. J. Železný, H. Gao, K. Výborný, J. Zemen, J. Mašek, A. Manchon, J. Wunderlich, J. Sinova, T. Jungwirth, Relativistic néel-order fields induced by electrical current in antiferromagnets. Phys. Rev. Lett. 113, 157201 (2014).

13. L. Šmejkal, J. Železný, J. Sinova, T. Jungwirth, Electric control of dirac quasiparticles by spin-orbit torque in an antiferromagnet. Phys. Rev. Lett. 118, 106402 (2017).

14. Y. Cheng, S. Yu, M. Zhu, J. Hwang, F. Yang, Electrical r in α−Fe2O3 epitaxial films. Phys. Rev. Lett. 124, 027202 (2020).

15. X. Z. Chen, R. Zarzuela, J. Zhang, C. Song, X. F. Zhou, G. Y. Shi, F. Li, H. A. Zhou, W. J. Jiang, F. Pan, Y. Tserkovnyak, Antidamping-torque-induced switching in biaxial antiferromagnetic insulators. Phys. Rev. Lett. 120, 207204 (2018).

16. M. Dunz, T. Matalla-Wagner, M. Meinert, Spin-orbit torque induced electrical switching of antiferromagnetic MnN. Phys. Rev. Research 2, 013347 (2020).

17. S. Y. Bodnar, L. Šmejkal, I. Turek, T. Jungwirth, O. Gomonay, J. Sinova, A. A. Sapozhnik, H.J. Elmers, M. Kläui, M. Jourdan, Writing and reading antiferromagnetic Mn2Au by Néel spin-orbit torques and large anisotropic magnetoresistance. Nat. Commun. 9, 348 (2018).

18. T. Hajiri, S. Ishino, K. Matsuura, H. Asano, Electrical current switching of the noncollinear antiferromagnet Mn3GaN. Appl. Phys. Lett. 115, 052403 (2019).
19. T. Hajiri, K. Matsuura, K. Sonoda, E. Tanaka, K. Ueda, H. Asano, Spin-orbit-torque switching of noncollinear antiferromagnetic antiperovskite manganese NitrideMn3GaN. *Phys. Rev. Appl.* **16**, 024003 (2021).

20. S.-H. Yang, R. Naaman, Y. Paltiel, S. S. P. Parkin, Chiral spintronics. *Nat. Rev. Phys.* **3**, 328–343 (2021).

21. M. Meinert, D. Graulich, T. Matalla-Wagner, Electrical switching of antiferromagnetic Mn$_2$Au and the role of thermal activation. *Phys. Rev. Appl.* **9**, 064040 (2018).

22. C. C. Chiang, S. Y. Huang, D. Qu, P. H. Wu, C. L. Chien, Absence of evidence of electrical switching of the antiferromagnetic néel vector. *Phys. Rev. Lett.* **123**, 227203 (2019).

23. W. Zhang, W. Han, S.H. Yang, Y. Sun, Y. Zhang, B. Yan, S. S. P. Parkin, Giant facet-dependent spin-orbit torque and spin Hall conductivity in the triangular antiferromagnet IrMn$_3$. *Sci. Adv.* **2**, e1600759 (2016).

24. A. K. Nayak, J. E. Fischer, Y. Sun, B. Yan, J. Karel, A. C. Komarek, C. Shekhar, N. Kumar, W. Schnelle, J. Kübler, C. Felser, S. S. P. Parkin, Large anomalous Hall effect driven by a nonvanishing Berry curvature in the noncollinear antiferromagnet Mn$_3$Ge. *Sci. Adv.* **2**, e1501870 (2016).

25. S. Nakatsuji, N. Kiyohara, T. Higo, Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature. *Nature* **527**, 212–215 (2015).

26. H. Yang, Y. Sun, Y. Zhang, W.J. Shi, S. S. P. Parkin, B. Yan, Topological weyl semimetals in the chiral antiferromagnetic materials Mn$_3$Ge and Mn$_3$Sn. *New J. Phys.* **19**, 015008 (2017).

27. T. Higo, H. Man, D. B. Gopman, L. Wu, T. Koretsune, O. M. J. van ‘t Erve, Y. P. Kabanov, D. Rees, Y. Li, M.T. Suzuki, S. Patankar, M. Ikhlas, C. L. Chien, R. Arita, R. D. Shull, J. Orenstein, S. Nakatsuji, Large magneto-optical Kerr effect and imaging of magnetic octupole domains in an antiferromagnetic metal. *Nat. Photonics* **12**, 73–78 (2018).

28. A. L. Balk, N. H. Sung, S. M. Thomas, P. F. S. Rosa, R. D. McDonald, J. D. Thompson, E. D. Bauer, F. Ronning, S. A. Crooker, Comparing the anomalous Hall effect and the magneto-optical
Kerr effect through antiferromagnetic phase transitions in Mn$_3$Sn. *Appl. Phys. Lett.* **114**, 032401 (2019).

29. H. Tsai, T. Higo, K. Kondou, T. Nomoto, A. Sakai, A. Kobayashi, T. Nakano, K. Yakushiji, R. Arita, S. Miwa, Y. Otani, S. Nakatsuji, Electrical manipulation of a topological antiferromagnetic state. *Nature* **580**, 608–613 (2020).

30. Y. Takeuchi, Y. Yamane, J. Y. Yoon, R. Itoh, B. Jinnai, S. Kanai, J. Ieda, S. Fukami, H. Ohno, Chiral-spin rotation of non-collinear antiferromagnet by spin–orbit torque. *Nat. Mater.* **20**, 1364–1370 (2021).

31. P. K. Muduli, T. Higo, T. Nishikawa, D. Qu, H. Isshiki, K. Kondou, D. Nishio-Hamane, S. Nakatsuji, Y.C. Otani, Evaluation of spin diffusion length and spin Hall angle of the antiferromagnetic Weyl semimetal Mn$_3$Sn. *Phys. Rev. B* **99**, 184425 (2019).

32. J. Liu, L. Balents, Anomalous Hall effect and topological defects in antiferromagnetic weyl semimetals: Mn$_3$Sn/Ge. *Phys. Rev. Lett.* **119**, 087202 (2017).

33. S. Tomiyoshi, Y. Yamaguchi, Magnetic structure and weak ferromagnetism of Mn$_3$Sn studied by polarized neutron diffraction. *J. Physical Soc. Japan* **51**, 2478–2486 (1982).

34. N. Sung, F. Ronning, J. Thompson, E. Bauer, Magnetic phase dependence of the anomalous Hall effect in Mn$_3$Sn single crystals. *Appl. Phys. Lett.* **112**, 132406 (2018).

35. P. J. Brown, V. Nunez, F. Tasset, J. B. Forsyth, P. Radhakrishna, Determination of the magnetic structure of Mn$_3$Sn using generalized neutron polarization analysis. *J. Phys. Condens. Matter* **2**, 9409–9422 (1990).

36. T. Nagamiya, S. Tomiyoshi, Y. Yamaguchi, Triangular spin configuration and weak ferromagnetism of Mn$_3$Sn and Mn$_3$Ge. *Solid State Commun.* **42**, 385–388 (1982).

37. N. Roschewsky, C.-H. Lambert, S. Salahuddin, Spin-orbit torque switching of ultralarge-thickness ferrimagnetic GdFeCo. *Phys. Rev. B* **96**, 064406 (2017).
38. E. Grimaldi, V. Krizakova, G. Sala, F. Yasin, S. Couet, G. Sankar Kar, K. Garelo, P. Gambardella, Single-shot dynamics of spin–orbit torque and spin transfer torque switching in three-terminal magnetic tunnel junctions. *Nat. Nanotechnol.* **15**, 111–117 (2020).

39. W. Zhu, L. Seve, R. Sears, B. Sinkovic, S. S. P. Parkin, Field cooling induced changes in the antiferromagnetic structure of nio films. *Phys. Rev. Lett.* **86**, 5389–5392 (2001).

40. J. M. Taylor, E. Lesne, A. Markou, F. K. Dejene, B. Ernst, A. Kalache, K. G. Rana, N. Kumar, P. Werner, C. Felser, S. S. P. Parkin, Epitaxial growth, structural characterization, and exchange bias of noncollinear antiferromagnetic Mn$_3$Ir thin films. *Phys. Rev. Mater.* **3**, 074409 (2019).

41. M. Finazzi, M. Savoini, A. R. Khorsand, A. Tsukamoto, A. Itoh, L. Duò, A. Kirilyuk, T. Rasing, M. Ezawa, Laser-induced magnetic nanostructures with tunable topological properties. *Phys. Rev. Lett.* **110**, 177205 (2013).

42. W. Koshibae, N. Nagaosa, Creation of skyrmions and antiskyrmions by local heating. *Nat. Commun.* **5**, 5148 (2014).

43. S.-G. Je, P. Vallobra, T. Srivastava, J. C. Rojas-Sánchez, T. H. Pham, M. Hehn, G. Malinowski, C. Baraduc, S. Auffret, G. Gaudin, S. Mangin, H. Béa, O. Boulle, Creation of magnetic skyrmion bubble lattices by ultrafast laser in ultrathin films. *Nano Lett.* **18**, 7362–7371 (2018).

44. A. Nordrum, The fight for the future of the disk drive. *IEEE Spectr.* **56**, 44–47 (2019).

45. C. Hahn, G. Wolf, B. Kardasz, S. Watts, M. Pinarbasi, A. D. Kent, Time-resolved studies of the spin-transfer reversal mechanism in perpendicularly magnetized magnetic tunnel junctions. *Phys. Rev. B* **94**, 214432 (2016).

46. H. Tomita, K. Konishi, T. Nozaki, H. Kubota, A. Fukushima, K. Yakushiji, S. Yuasa, Y. Nakatani, T. Shinjo, M. Shiraishi, Y. Suzuki, Single-shot measurements of spin-transfer switching in CoFeB/MgO/CoFeB magnetic tunnel junctions. *Appl. Phys. Express* **1**, 061303 (2008).

47. T. Higo, D. Qu, Y. Li, C. L. Chien, Y. Otani, S. Nakatsuji, Anomalous Hall effect in thin films of the Weyl antiferromagnet Mn$_3$Sn. *Appl. Phys. Lett.* **113**, 202402 (2018).
48. J. C. Slonczewski, Current-driven excitation of magnetic multilayers. *J. Magn. Magn. Mater.* **159**, L1–L7 (1996).

49. W. H. Zachariasen, *Theory of X-Ray Diffraction in Crystals* (Dover Publications Inc., 1994).

50. J. M. Taylor, A. Markou, E. Lesne, P. K. Sivakumar, C. Luo, F. Radu, P. Werner, C. Felser, S. S. P. Parkin, Anomalous and topological Hall effects in epitaxial thin films of the noncollinear antiferromagnet Mn$_3$Sn. *Phys. Rev. B* **101**, 094404 (2020).

51. Y. You, X. Chen, X. Zhou, Y. Gu, R. Zhang, F. Pan, C. Song, Anomalous Hall effect–like behavior with in-plane magnetic field in noncollinear antiferromagnetic Mn$_3$Sn films. *Adv. Electron. Mater.* **5**, 1800818 (2019).