High-efficiency magnetism modulation of a single Co$_3$Sn$_2$S$_2$ layer directly by current

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Flexible manipulation of local magnetic configurations on the sub-micro scale has long been a pursuit in the field of magnetism science owing to its potential applications in future spintronic devices. This goal can be achieved by using current-induced spin torque to drive the magnetic domain walls$^{1-5}$. However, the current density threshold of $10^6$-$10^8$
A/cm² in metallic systems induced by intrinsic and extrinsic pinning effects increases the energy consumption of the device and limits its application³,⁵–¹². The marriage between magnetism and topology opens a door for efficient magnetism manipulation, but to date, complex structures (such as multilayer film structures) are still required¹³–¹⁶. Here, we report a unique process of magnetism modulation in the recently discovered magnetic Weyl semimetal Co₃Sn₂S₂¹⁷–¹⁹ through current-assisted domain wall depinning. Non-adiabatic spin-transfer torques, which are induced by current and significantly modulated by the linear dispersion of Weyl fermions, impose on the local magnetic moments inside the domain walls, leading to a greatly improved efficiency of domain wall motion in magnetic Weyl semimetals compared with conventional metals. By analysing the changes of hysteresis loops under different DC currents, a low current threshold of 1.5×10⁵ A/cm² and two orders of magnitude improvement of depinning efficiency are obtained in this single material layer. The high efficiency to drive domain walls by current suggests that magnetic Weyl semimetal is a hopeful material system for realizing low-energy consumption spintronic devices.

The interaction between current and magnetic domain walls (DWs) is of fundamental interest in spintronics. Using this interaction in new technologies can enable a variety of applications in memory and logic devices, such as racetrack memory⁴,⁵, to show unprecedented results. Although a lower current threshold to drive the DW motion can be achieved at the cost of lower DW velocity or smaller depinning field in semiconductors²⁰,²¹, an efficient approach to overcome the magnetic DW pinning effect in metallic systems that usually has high DW
velocity is under tight demand for practical applications. The recently discovered magnetic
Weyl semimetal (MWSM) Co$_3$Sn$_2$S$_2$ combines topology, magnetism, and metallicity in a single
material, providing a promising platform to study current-controlled magnetism manipulation.

In theory, a vanishing intrinsic current threshold for depinning a DW and a high current-
induced DW velocity in MWSMs have been proposed$^{22,23}$, but relevant experiments are still
lacking. Here, we report that in synthesized Co$_3$Sn$_2$S$_2$ flakes (35-165 nm), a low current density
on the order of $10^5$-$10^6$ A/cm$^2$ can reduce the coercive field $H_c$ of Co$_3$Sn$_2$S$_2$ from as high as 20
kOe down to zero. A current threshold $J_c$ can be observed in all measured samples and at all
temperatures, with a value as low as $1.5\times10^5$ A/cm$^2$. The threshold current can be further tuned
by the contact electrode geometry. The magnetism reversal process in our samples is verified
to be dominated by DW depinning. A current-assisted DW depinning model is applied to
elucidate the high-efficiency magnetism modulation of the single Co$_3$Sn$_2$S$_2$ flake, and other
known magnetic interactions, such as local thermal activation and spin-orbit torque (SOT), are
carefully examined and excluded. To evaluate the depinning efficiency, we calculate $\mu_0H_c/J_c$ at
different temperatures, and the values are two orders of magnitude larger than the highest value
reported so far. Our experimental findings demonstrate the low current density threshold and
high efficiency of current-assisted DW depinning in MWSMs and propose MWSM as a
promising candidate for next-generation magnetic functional devices.

Co$_3$Sn$_2$S$_2$ is a ferromagnetic Weyl semimetal with a quasi-two-dimensional crystal structure
consisting of stacked kagome lattices of cobalt atoms (Fig. 1a) and three pairs of Weyl points
$\sim$50 meV above the Fermi level in the first Brillouin zone$^{18}$. In our work, high-quality single-
crystalline $\text{Co}_3\text{Sn}_2\text{S}_2$ nanoflakes were directly grown on substrates (sapphire or SiO$_2$) via a modified chemical vapor transport method (Fig. 1b and Supplementary Fig. S1), and then the standard Hall-bar devices were defined by electron beam lithography followed by an ion milling process (see Fig. 1b and Methods). From the electrical transport measurements, the $\text{Co}_3\text{Sn}_2\text{S}_2$ nanoflake shows ferromagnetism with a Curie temperature of about 175 K (Fig. 1c), a large anomalous Hall angle up to 25.0% at 117 K, and a strong easy-axis effective anisotropy field $H_{\text{keff}}$ larger than 100 kOe (Supplementary Fig. S2), which are consistent with those of reported bulk $\text{Co}_3\text{Sn}_2\text{S}_2$ single crystals$^{17,24,25}$, indicating the high quality of our $\text{Co}_3\text{Sn}_2\text{S}_2$ nanoflakes.

We measured the anomalous Hall resistance, $R_{xy}$, hysteresis loops of the $\text{Co}_3\text{Sn}_2\text{S}_2$ Hall devices under different DC currents. For the 35 nm thick sample (as shown in Fig. 1b), a clear current modulation pattern of the hysteresis loop is observed (Fig. 1d and Fig. 1e). When the applied DC current is lower than a threshold current, the hysteresis loop and coercive field remain unchanged. When the current exceeds the threshold, the coercivity begins to drop rapidly and eventually reaches zero as the current increases. For all test temperatures from 5 K to 150 K (more data are presented in Supplementary Fig. S3), we have observed clear current thresholds $I_c = 2.1-4.4$ mA. Eight samples from three different growth batches are tested, and all samples show the same current modulation behaviour. These devices have a thickness of 35-165 nm, a width of 4-6 $\mu$m, and a length of 10-40 $\mu$m, and they are grown and fabricated on sapphire or SiO$_2$ substrates, indicating the robustness of this phenomenon. At 5 K, the coercive field does not decrease to zero (Fig. 1d) because we limited the maximum applied
current to 5.4 mA to protect the device for subsequent measurements. In another device, we can see that a coercive field up to 20 kOe is zeroed by the current (Supplementary Fig. S4).

**Fig. 1 Current modulation of the magnetism reversal process.**

**a,** Crystal structure of Co₃Sn₂S₂ with a space group of R-3m (no. 166). The cobalt atoms form a quasi-2D kagome lattice. **b,** Optical images of the as-grown Co₃Sn₂S₂ nanoflakes on a sapphire substrate and a fabricated 35 nm thick Hall-bar device (sample 1). **c,** The temperature dependence of the longitudinal ($R_{xx}$) and transverse ($R_{xy}$) resistance under 0.1 kOe field cooling along the $c$-axis. A Curie temperature of $T_c \approx 175$ K is obtained. **d,** When the applied DC current exceeds the current threshold, the coercive field $H_c$ begins to decrease. With a limited current range (to protect the device for subsequent measurements), $H_c$ decreases from 4 kOe to zero at 150 K, and from 23 kOe to 11 kOe at 5 K. **e,** The hysteresis loops of $R_{xy}$ under different DC currents measured at 150 K. Each loop is measured twice to ensure repeatability.
To unravel the mechanism of the current lowering $H_c$, we first investigated the magnetization reversal nature of our Co$_3$Sn$_2$S$_2$ sample. At 150 K, the coercive field $H_c$ is about 4 kOe, much smaller than $H_{keff}$, which implies that the reversal process is dominated by DW motion rather than coherent rotation$^{26,27}$. Fig. 2a shows the hysteresis loop evolution as a function of the field angle in the $xz$-plane. First, $H_c$ monotonically increases with $\theta$, following a good $1/\cos\theta$ behaviour (as shown in Fig. 2b), in agreement with the case of DW depinning$^{28,29}$. Second, all hysteresis loops are rectangle-shaped, which clarifies the mechanism of the reversal process, that is, the mobile DWs suddenly appear at $H_c$ and then continue to move until the magnetization of the whole sample is reversed$^{27}$ (Fig. 2c). These mobile DWs can be generated by nucleation or depinning. We find that (1) the good linear correlation between $H_c$ and $T$ is consistent with Arrhenius’s law for DW depinning$^{30,31}$ (Supplementary Fig. S5), and (2) the current-assisted DW depinning model naturally fits the experimentally observed coercivity reduction and the current threshold, while it is difficult to imagine modulating the nucleation process by current injection with a threshold. Therefore, we conclude that DW depinning is the dominant magnetization reversal mechanism in Co$_3$Sn$_2$S$_2$.

We further confirmed that the DC current-assisted magnetization reversal in the single Co$_3$Sn$_2$S$_2$ layer is significantly different from the expected results of known magnetic interactions. The Oersted field is much smaller$^{32}$ than $H_c$ and should cause asymmetric $H_c^{+}$ and $H_c^{-}$, which is incompatible with the experimental observation. The average temperature rises $\Delta T_{\text{avg}}$ under the threshold current at different measurement temperatures can be extracted from the changes of the Hall resistance (Fig. 3a). The temperature rise is too small to reach the Curie
temperature (Fig. 3b), and the hysteresis loop maintains the good rectangle shape and exhibits an obvious current threshold, thereby eliminating the possibility of magnetic reversal caused by the overall Joule heating. A large contact resistance will also generate severe Joule heating in a small area. If the contact area contains pinning sites, the local temperature increase ΔT_{loc}

Fig. 2 DW depinning in Co$_3$Sn$_2$S$_2$. a, Field angle dependence of $R_{xy}(H)$ at 150 K. The sample lies in the $xy$-plane. The magnetic field $H$ is applied in the $xz$-plane, and $\theta$ is the angle between $H$ and the $z$-axis. The loops are vertically shifted for clarity. Each loop is measured twice. b, $\theta$ dependence of the coercive field $H_c$. The filled blue triangles are the experimental data points extracted from a, with error bars (both horizontal and vertical) smaller than the data points. The red dashed line represents the fitting of $H_c(0)/\cos \theta$, which is the predicted value when the magnetization reversal is dominated by DW depinning. $H_c(0)$ is measured when the external magnetic field is applied along the $z$-axis. c, Illustration of the magnetization reversal process in Co$_3$Sn$_2$S$_2$. Small reversed domains exist at the pinning sites. The force exerted by the magnetic field (blue arrows) or current (red arrow) will depin the DWs. Magnetization is completely reversed after the depinned DW (grey solid line) propagates through the whole sample. The direction of the current-induced force is opposite to the driving current (see text below and Fig. 4a,b).
will increase the probability of depinning; at the same time, a large $\Delta T_{\text{loc}}$ may cause a decrease of the perpendicular magnetism anisotropy (PMA) energy $^{30}$. Both of these two effects could lead to DW depinning under a smaller magnetic field, thereby reducing $H_c$. The local temperature rise $\Delta T_{\text{loc}}$ is difficult to measure directly, but it should be proportional to $\Delta T_{\text{avg}}$. If the PMA is responsible, $\Delta T_{\text{avg}}$ should follow a linear fit as $T_c - T$ with a scale factor (as shown in Fig. 3b), which does not match the nonlinear temperature increase measured at different temperatures. More importantly, as shown in Fig. 3d, we found two strong pieces of evidence against the thermal activation in another device: (1) asymmetric threshold currents of $I_{c^+} \approx 1.2$ mA and $I_{c^-} \approx -6.8$ mA, while Joule heating is always symmetric for $I^+$ and $I^-$; (2) an abnormal increase of $H_c$ near $I = -1.2$ mA with the increase of current (marked by the black arrow in Fig. 3d), while Joule heating always tends to decrease $H_c$. Taking these factors into account, we ruled out the possibility of local thermal activation.

At last, a damping-like SOT may also reduce the coercivity under the macrospin model $^{33-35}$, but this does not conform to our experimental results either. Theoretically, SOT may originate from the spin Hall effect or spin-orbit coupling in non-centrosymmetric systems $^{36-39}$. The former requires a heavy metal layer, which is not present in our experiments. The latter is also ruled out because that (1) the thicknesses of all our samples are much larger than the characteristic length of the interface effect $\sim 1$ nm $^{36,40-42}$; (2) the phenomena observed in the samples prepared on the sapphire and SiO$_2$ substrates are consistent; (3) Co$_3$Sn$_2$S$_2$ has a centrosymmetric crystalline structure. Besides, the large magnetic anisotropy of $>100$ kOe is hard to tune by SOT. Experimentally, when $H$ is parallel to the $x$-axis, we did not observe the
Fig. 3 Confirming the current-assisted DW depinning process. a,b, The average temperature rise in sample 1 under different measurement temperatures. The red squares and blue triangles represent the data at positive and negative threshold currents, respectively. a, Changes of $R_{xy}$ measured under different currents and temperatures. b, Average temperature rises $\Delta T_{\text{avg}}$ at the threshold currents under different measurement temperatures $T$. The vertical grey line represents the Curie temperature, and the green dashed line is the $\Delta T$ required for loss of PMA. $\Delta T_{\text{avg}}$ is extracted by comparing current-induced $R_{xy}$ rise in a and the $R_{xy}(T)$ values. c, The evolution of $H_c$ with the applied current in the simple case where two pinning sites with

![Diagram of current-assisted DW depinning process with graphs and data points.]
different pinning strengths are located under source and drain electrodes, respectively. The depinning field \( H_d \) of these pinning sites are coloured blue and yellow, respectively, and the smallest \( H_d \) determines the coercive field (solid line). When the current reaches the value marked by the green arrow, where \( H_{d,1}=H_{d,2} \), the decisive pinning site changes (also shown in d).

\[ H_d \]

The evolution of \( H_c \) and hysteresis loop of sample 2 (40 \( \mu \text{m} \times 6 \mu\text{m} \times 92 \text{ nm} \)) under different DC currents, showing the features including the abnormal increase of \( H_c \) with the current in a narrow current range, asymmetric current thresholds \( I_{c,+} \neq I_{c,-} \), and multi-domain. The wide vertical grey lines separate different regions of single-domain, multi-domain, and zero coercivity. The representative hysteresis loops are shown at the top.

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typical current switching behaviour in the SOT model\(^{33,35,37} \) (Supplementary Fig. S6). The characteristics of the multi-domain feature and the asymmetry of \( I_{c} \) shown in Fig. 3d further exclude the possibility of SOT modulated magnetic reversal. As a result, we unambiguously attribute the magnetism modulation observed in a single \( \text{Co}_3\text{Sn}_2\text{S}_2 \) layer to efficient current-assisted DW depinning in MWSMs.

Recall the magnetization reversal process in \( \text{Co}_3\text{Sn}_2\text{S}_2 \). There are small domains with reversed magnetization near the imperfections of the sample, where DWs are pinned in the local potential wells, as illustrated in Fig. 2c. Each pinning site has a depinning field \( H_d \). The lowest depinning field determines the coercive field, that is, \( H_c=H_{d,\text{min}} \). It can be seen that if the applied DC current reduces \( H_d \), then \( H_c \) will also decrease. The current changes \( H_d \) by inducing spin-transfer torques (STTs) on the local magnetic moments inside the DWs\(^{3,43} \), expressed as...
where $T$ is the current-induced spin torque, $j_s$ is the spin current, and $\mathbf{M}(r)$ is the direction of the local magnetic moment. The two terms on the right side of the equation correspond to adiabatic and non-adiabatic STT, respectively, where the dimensionless parameter $\beta$ represents the strength of the non-adiabatic term. In conventional metals, $\beta$ is much smaller than unity, therefore the applied current must first overcome a large current threshold before driving the DW due to the intrinsic pinning effect of the dominant adiabatic STT. On the contrary, in MWSMs, the Weyl Hamiltonian with linear dispersion relationship significantly modifies the form of STT. An analytical model with Weyl-type spin-orbit coupling is used to capture the physics, where a one-to-one correspondence between the axial current and the non-equilibrium spin polarization leads to a large non-adiabatic STT and ensures that the adiabatic STT does not appear in the lowest order of the axial magnetic field (see detailed derivation in Supplementary Information). Numerical calculations indicate that the results in more realistic cases are almost the same\textsuperscript{22,23}. Since DWs driven by the non-adiabatic STT are less affected by the intrinsic pinning effect, we can expect the efficiency of current-driven DW motion in MWSMs will be higher than that of conventional metals. This also explains why similar current modulation behaviour has never been observed in other single materials before.

The force induced by STT is an odd function of current, so its effect on $H_d$ depends on the direction of the current. For a specific pinning site, DW depinning is enhanced (suppressed) when the current induced force is along (against) the propagation direction of the DW. In Fig. 3c, we illustrate how the DC current will affect the DW depinning process of two distinct
pinning sites with opposite DW propagation directions. The yellow and blue lines respectively represent the $H_0$ of the two sites, which have slightly different pinning strengths and current thresholds. Then, the coercive field $H_c$ is represented by the solid lines, which is determined by the minimum $H_0$ values at different applied currents. We found that this simple model captured the two main abnormal features we observed experimentally in Fig. 3d. First, the decisive pinning site changes at $H_{d,1} = H_{d,2}$ (marked by the green arrows in Fig. 3c and Fig. 3d), resulting in asymmetric threshold currents of $I_{c+} \approx 1.2$ mA and $I_{c-} \approx -6.8$ mA, which is consistent with the conclusion of multiple pinning sites. Second, $H_c$ increases abnormally with the current at $-I_{c+}$ (symmetric to $+I_{c+}$), as expected in this current-assisted DW depinning picture. To clarify the origin of the pinning sites for different DW propagation directions, we defined multiple electrodes on sample 3 (Fig. 4a). As shown in Fig. 4b, when current is injected through paths 1-2 and 1-3, the positive current threshold ($I_{c+}$) remains almost unchanged, while the negative current threshold ($I_{c-}$) shows a significant difference, which indicates that the locations of the modulated pinning sites are under source and drain electrodes. Since the propagation directions of the DWs to reverse the whole magnetization at the two sides are opposite, the direction of the modulation current used must also be opposite. Besides, this experiment helps to confirm that the direction of the current-induced force is along with the electron flow (as shown in Fig. 2c), and also suggests that the current threshold can be further optimized through electrode design. The multi-domain features observed experimentally (Fig. 3d) are naturally consistent with the current-assisted DW depinning picture, which is less relevant to this topic, so we discuss it in the Supplementary Information.
We calculated the current density threshold $J_c = I_c/A$, where $A$ is the cross-sectional area of the channel. The local current density should be smaller than the obtained $J_c$ at the threshold because the contact area between the electrode and Co$_3$Sn$_2$S$_2$ is larger than the sample cross-

**Fig. 4 High efficiency of current-assisted DW depinning.** a, Schematic diagram of sample 3 (25 $\mu$m×5.5 $\mu$m×165 nm), with one large electrode at one side and two small electrodes on the other side. Electrodes 2 and 3 are triangular and rectangular shaped, respectively. b, Evolution of $H_c$ with DC current amplitude under different current paths in sample 3. When current is applied through electrodes 1-2 or 1-3, the change of $H_c$ is basically the same under positive currents but shows evident difference under negative currents. c, The characteristic parameter $\mu_0 H_c/J_c$ of DW depinning efficiency in Co$_3$Sn$_2$S$_2$ (stars) and other metallic material systems (Ref. 6–12) at different measurement temperatures. FI indicates ferrimagnet. The half-filled data points indicate that a multilayer structure is required, usually with heavy metal or metal oxide layers. The efficiency in Co$_3$Sn$_2$S$_2$ shows two orders of magnitude improvement of current-assisted DW depinning.
section (except for the small electrodes 2 and 3 of sample 3 for the control experiments, and these data are not included in the subsequent evaluation). The best obtained value of $J_c$ is as low as $1.5 \times 10^5$ A/cm$^2$ at 150 K. At the same time, we calculated $\mu_0 H_c/J_c$ to evaluate the depinning efficiency. Compared with the previously reported material systems, the efficiency is improved by two orders of magnitude (Fig. 4c)$^6$-$^{12}$. If a stable DW can be prepared in a Co$_3$Sn$_2$S$_2$ nanowire, the depinning efficiency can be further improved, and a quantitative relationship between DW velocity and current density can be obtained. Moreover, from the instantaneous magnetization reversal process, we have reason to believe that Co$_3$Sn$_2$S$_2$ has a large DW velocity, which meets another basic requirement in the design of racetrack memory. Related experiments are being carried out in our laboratory.

In conclusion, we found that DC current can significantly reduce the coercivity and modulate the magnetization reversal process of Co$_3$Sn$_2$S$_2$ nanoflakes. This reduction is attributed to current-assisted DW depinning. The low current threshold and high depinning efficiency coincide with earlier theoretical predictions, which appears to be unique in magnetic Weyl semimetals. This work provides a new approach of flexible magnetism manipulation and makes Co$_3$Sn$_2$S$_2$ a promising candidate for DW storage and logic devices$^{44,45}$ operated above liquid nitrogen temperature. In addition, with the development of more magnetic Weyl semimetals with higher Curie temperatures$^{46-48}$, it is expected similar phenomena to occur at room temperature, thus providing a potential platform for highly efficient non-violate DW spintronic devices.
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