Ultra-efficient magnetism modulation in a Weyl ferromagnet by current-assisted domain wall motion

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Flexible and efficient manipulation of magnetic configurations can be challenging. In the design of practical devices, achieving high effective magnetic field with low working current is under tight demand. Here, we report a unique method for efficient magnetism modulation by direct current injection in magnetic Weyl semimetal Co3Sn2S2. We demonstrate that the modulation process stems from current-assisted domain wall motion. Through two independent methods, we reveal that the spin-transfer torque efficiency of Co3Sn2S2 reaches as high as 2.4-5.6 kOe MA−1 cm2, and the threshold current density for driving the magnetic domain walls is as low as < 5.1×105 A/cm2 without an external field, and < 1.5×105 A/cm2 with a moderate external field. Our findings manifest a new and powerful approach for sub-micron magnetism manipulation, and also open the door towards a new paradigm of spintronics that combines magnetism, topology, and metallicity for low-energy consumption memory and computing.
The interaction between current and magnetic domain wall (DW) is of fundamental interest in spintronics and has inspired a variety of applications in memory and logic devices, such as racetrack memory, to show unprecedented results. When a spin-polarized current passes through a non-uniform magnetic texture such as a magnetic DW, spin-transfer torques (STTs) are applied to the local magnetization, so that the magnetic configuration can be directly controlled without the need to use the multilayer film structure required in the spin-orbit torque (SOT) approach. But the STT approach also has its own problems. First, the use of STT to push DWs in metallic systems requires a current density threshold of 10^6-10^8 A/cm^2 due to the intrinsic and extrinsic pinning effects, which increases the energy consumption of the device and limits its application. Although a lower threshold current density can be realized at the cost of a lower DW velocity or a smaller depinning field in a semiconductor, an efficient approach that overcomes the magnetic DW pinning to achieve higher DW velocities in metallic systems is under tight demand for practical applications. Second, few attempts have been made to modulate the magnetic properties such as the coercive field in a single material layer utilizing STT, while SOT can be used in some cases when (local) inversion symmetry is broken.

The recently discovered magnetic Weyl semimetal Co₃Sn₂S₂ combines topology, magnetism, and metallicity in a single material, making it a promising platform for studying current-controlled magnetism manipulation. Theoretically, the linear dispersion of Weyl fermions significantly alters the form of STT, leading to a large non-adiabatic torque and ensuring that the adiabatic torque vanishes at the lowest order of the axial magnetic field (see Supplementary Note 1 for details). Since the non-adiabatic STT-driven DWs are less affected by the intrinsic pinning effect, a lower intrinsic current threshold and a higher DW motion efficiency are anticipated in Co₃Sn₂S₂, but relevant experiments are still lacking.

We report that in the synthesized Co₃Sn₂S₂ flakes (35-165 nm thick, grown on sapphire or SiO₂ substrates), a low current density on the order of 10^5-10^7 A/cm^2 can reduce the coercive field \( H_C \) of Co₃Sn₂S₂ from as high as 20 kOe down to smaller than 0.1 kOe. The threshold current to reduce \( H_C \) as well as the symmetry of the +/– current can be further tuned by the geometry of the contact electrode. We reasonably deduce that the magnetism modulation behavior mainly comes from the current-assisted DW motion, specifically, through STT. To evaluate the STT efficiency, we fabricated Co₃Sn₂S₂ nanowire devices and measured their DW velocities in the parameter space of current, magnetic field, and temperature. We find a giant STT effective field of 2.4-5.6 kOe MA⁻¹ cm² at 150 K, which is even larger at lower temperatures, consistent with the results obtained by the reduction of coercive field in Hall devices. Also, very low current-induced DW motion thresholds of < 5.1×10^5 A/cm² (without external field) and < 1.5×10^5 A/cm² (with modest external field) in Co₃Sn₂S₂ are obtained. These findings demonstrate the high efficiency of the current-assisted DW motion and thus magnetism modulation in Co₃Sn₂S₂. Similar characteristics of other room-temperature magnetic Weyl semimetals are thus of great interest for broader applications.

**Magnetism modulation with ultra-high efficiency in Co₃Sn₂S₂**

Co₃Sn₂S₂ is a ferromagnetic Weyl semimetal with a quasi-2D crystal structure consisting of stacked kagome lattices of cobalt atoms (Fig. 1a) and three pairs of Weyl points that are ~50 meV above the Fermi level in the first Brillouin zone. In our work, high-quality single-
crystalline Co₃Sn₂S₂ nanoflakes were directly grown on substrates (sapphire or SiO₂) via a modified chemical vapor transport method and then fabricated into standard Hall-bar devices (Fig. 1b, see details in Fig. S1 and Methods). From the electrical transport measurements, the Co₃Sn₂S₂ nanoflake shows ferromagnetism with a Curie temperature of about 175 K (Fig. 1c) and a large anomalous Hall angle up to 25.0%, consistent with those of reported bulk Co₃Sn₂S₂ single crystals.²⁶,²⁷,³⁰

The magnetization of Co₃Sn₂S₂ lies perpendicular to the sample plane. Due to the kagome lattice structure and the quasi-2D electronic and magnetic characteristics, Co₃Sn₂S₂ exhibits a relatively small saturation magnetization $M_S$ of 29.3-48.8 emu/cm³ as an itinerant ferromagnet, but an extremely large out-of-plane anisotropy field $H_K$ of 80-118 kOe at 150-170 K (the temperature range of this paper’s main focus), which is much larger than the coercive field $H_c$ of no larger than 4 kOe in this temperature range.³¹ The corresponding magnetic anisotropy constant $K$ in this temperature range is $(1.17-2.88) \times 10^6$ erg/cm³ (full description of electrical and magnetic properties in Supplementary Note 3). In both SOT and STT cases, small magnetization will result in high current-induced torque efficiency, which is expected to be inversely proportional to the free layer magnetization. For example, in the flow (i.e. linear) region, the current-induced DW velocity is $v_{DW} \propto P J / M_S$ ($P$, the spin polarization of the current; $J$, the current density), regardless of whether adiabatic or non-adiabatic STT is considered. Meanwhile, the field-driven DW velocity is $v_{DW} \propto \Delta = (A/K)^{1/2}$ ($\Delta$, magnetic DW width constant; $A$, exchange stiffness). In other words, the large magnetic anisotropy will not only form thinner DWs, allowing downscaling of spintronic devices, but also reduce the perturbation from external fields, improve device stability, and further increase the current-induced effective field.³²-³⁴

To explore the significant current-induced effects in Co₃Sn₂S₂, we measured the anomalous Hall resistance, $R_{yx}$, hysteresis loops of the Hall devices under different DC currents. Surprisingly, in this simple device structure containing only one material – Co₃Sn₂S₂ and Cr/Au contacts, a clear current modulation pattern of the hysteresis loop is observed (Fig. 1d and Fig. 1e from device 1). When the applied DC current is lower than the threshold current, the hysteresis loop and coercive field remain roughly unaffected – they only change slowly following the temperature rise caused by Joule heating. But when the current exceeds the threshold, the coercivity begins to drop rapidly, and eventually reaches a remarkably small value as the current increases. The change of $H_c$ in this region deviates significantly from the change caused by pure thermal effect (Fig. 1d). The current threshold behaviors are observed at all measured temperatures from 5 K to 150 K (more data is provided in Supplementary Fig. S3). Eight samples from three different growth batches are tested, and all samples show the same current modulation behavior. These devices have a thickness of 35-165 nm, a width of 4-6 μm, and a length of 10-40 μm, and they are grown and fabricated on sapphire or SiO₂ substrates, demonstrating the robustness of this phenomenon. At 5 K, the coercive field does not decrease to the lowest value (Fig. 1d) because we limit the maximum applied current to 5.4 mA to protect the device for subsequent measurements. In another device, $H_c$ up to 20 kOe is tuned to < 0.1 kOe by current (Supplementary Fig. S4). Noticeably, if we define the efficiency of the current-induced magnetism modulation effect as the slope $\Delta H_c / \Delta I$ in the region above the threshold (thermal effect contribution is subtracted, see detailed discussion of thermal effect in Supplementary Note 5), it reaches 3.1 kOe MA⁻¹ cm² (150 K) - 10.4 kOe MA⁻¹ cm² (50 K).
For comparison, the effective field generated by SOT in BiSb/MnGa $\theta_{SH} \approx 52$ is 2.3 kOe MA$^{-1}$ cm$^2$, while the reported STT efficiency of driving magnetic DWs is 0.4 kOe MA$^{-1}$ cm$^2$ in (Ga,Mn)(As,P) and only 0.2-8.0 Oe MA$^{-1}$ cm$^2$ in Co-Pt-based systems$^{12,35,36}$.

**Current-assisted domain wall motion model**

The giant efficiency of current-induced $H_C$ reduction is unusual. To unravel the underlying mechanism, we first investigated the magnetization reversal nature of the Co$_3$Sn$_2$S$_2$ samples. Figure 2a shows the hysteresis loop evolution as a function of the field angle in the $xz$-plane. $H_C$ increases monotonically with $\theta$ and follows the standard $1/\cos \theta$ behavior (Fig. 2b), indicating that the magnetization reversal process in Co$_3$Sn$_2$S$_2$ is dominated by DW motion rather than coherent rotation$^{37,38}$. The multi-domain nature of the switching is also evidenced by the fact that $H_C \ll H_K$ (Fig. S2d). As a result, any macro-spin model fails. Meantime, all hysteresis loops are rectangle-shaped, clarifying that the mobile DWs suddenly appear at $H_C$ (nucleation) and then continue to move (propagation) until the magnetization of the whole sample is reversed.

Next, devices with asymmetric contact electrodes (devices 2 and 3) were fabricated to explore how current affects the DW nucleation and propagation. Figure 2c shows the representative hysteresis loops of device 2 under different currents, and Fig. 2d plots the variation of $H_C$ with the current. In this device, several characteristic features imply that the DW nucleation process is greatly modified by DC current injection, therefore the magnetic hysteresis loops and $H_C$ are modulated. First, under the small current when $H_C$ begins to decrease, the hysteresis loop remains rectangular (–7.6 mA in Fig. 2c) and shrinks with the current, indicating that the coercive field $H_C$ is still determined by the nucleation field $H_n$. Under larger currents, the hysteresis loop becomes irregular, and the sample enters a multi-domain state (–11.1 mA and 4.6 mA in Fig. 2c). In this region, $H_n$ is the field when the total magnetization starts to drop, while DW propagation determines the field that fully reverses the sample. As shown in Fig. 2c, both the nucleation and propagation fields are reduced by large currents. Second, an abnormal increase of $H_C$ with the increase of the current absolute value occurs between –(0.9-1.7) mA. Marked by the red dashed line in Fig. 2d, starting at the same magnitude of the positive current threshold $|I_{C,1}^+| = |I_{C,1}^-| = 0.9$ mA, $H_C$ decreases with $|I_{C,1}^+|$, but increases with $|I_{C,1}^-|$, which shows that $\Delta |H_C| = \Delta |H_n|$ is an odd function of current. This symmetry is different from the common current effects in perpendicularly magnetized samples (details in Supplementary Note 6), including Joule heating (even function of current, regardless of homogenous or nonhomogeneous cases), SOT (even function of current when the external field is out-of-plane) and Oersted field (odd function of the field)$^{39,40}$. There must be some other responsible effects, which we will attribute to the current-assisted DW motion that altered the DW nucleation process discussed later in this paper. Third, the appearance of another platform of $H_C$ and a larger negative current threshold $I_{C,2}^- \approx$ –6.2 mA (the blue dashed line in Fig. 2d) indicates that multiple nucleation sites are involved, otherwise this non-monotonic change on the negative current side will not occur.

To further study the contributive nucleation location of DW and clarify its STT origin, we designed a device (device 3) with two drain electrodes of different shapes and contact areas (Fig. 2e). When current is injected through paths 1-2 or 1-3, the path with the smaller electrode
2 shows an evidently smaller positive current threshold than that of electrode 3, while the negative current thresholds of the two paths are almost the same (Fig. 2f). This signifies that the effective nucleation of DW is close to the source or drain electrodes – the negative current only contributes to the DW nucleation near electrode 1, while the positive current only contributes to the DW nucleation near electrode 2 or 3. The local and unidirectional nature of this interaction further suggests the STT origin of this phenomenon. Besides, the unidirectionality confirms that the direction of the current-induced force on magnetic DWs is along the electron flow direction (consistent with the DW velocity measurement results discussed later), and demonstrates that the current modulation behavior can be artificially controlled by the design of the electrode geometry.

Now we can use the current-assisted DW motion model to describe all the observed magnetism modulation phenomena (Fig. 2g). As mentioned earlier, under a moderate current, the coercive field $H_C$ of the sample is determined by the nucleation field $H_n$. Note that there can be multiple nucleation sites, and $H_C$ equals the lowest nucleation field, that is, $H_C = H_{n, \text{min}}$. From the above experiments, the current will affect the DW nucleation process near the source and drain electrodes. We assume that the injected current applies STT on the DW. Since the force induced by STT is an odd function of current, its influence on $H_n$ depends on the current direction. Since the magnetization easy-axis is out-of-plane and perpendicular to the current, the magnetization direction will not affect $H_n$. For a specific nucleation location, $H_n$ decreases (increases) when the current induced force is along (against) the DW propagation direction. Figure 2g illustrates how the DC current affects the DW nucleation process at two different locations with opposite DW propagation directions. The blue and red lines represent the $H_n$ at the two locations, whose nucleation fields and current thresholds are slightly different. Then, the coercive field $H_C$ is represented by the solid lines, which is determined by the minimum $H_n$ values under different applied currents. We found that this simple model captured the two main abnormal features we observed experimentally in Fig. 2d. First, the decisive nucleation position is switched at $H_{n,1} = H_{n,2}$ (marked by the purple arrows in Fig. 2d and Fig. 2g), resulting in asymmetric threshold currents of $I_{\text{T,1}}^+ \approx 1.2 \, \text{mA}$ and $I_{\text{DC,2}}^- \approx -6.2 \, \text{mA}$. Second, $H_C$ increases abnormally with the current at $I_{\text{C,3}}^+$ (symmetric to $I_{\text{C,1}}^+$), as expected in this current-assisted DW motion picture. This model is further verified by the control experiments illustrated in Fig. 3c-h, and a detailed discussion of the effect of current on nucleation can be found in the Supplementary Information Note 6 and 8.

**Domain wall velocity measurement revealing giant STT efficiency**

Despite the above model qualitatively explains the magnetism modulation phenomenon, it lacks a quantitative measurement of DW dynamics. To better assign the current-assisted DW motion model and understand its ultra-high efficiency, we managed to measure the field and current dependent DW velocity in Co$_3$Sn$_2$S$_2$ through the time-of-flight method$^{41,42}$. The measurement scheme is depicted in Fig. 3a. We fabricated a 1 μm wide and 62 nm thick Co$_3$Sn$_2$S$_2$ nanowire with three pairs of Hall bars in the middle, two Au heaters on both sides, and source/drain electrodes (device 4). The sample magnetization is first saturated by a negative field larger than $H_C$. Next, the field is changed to positive $H_z < H_C$, and a DC current $I_{\text{DC}}$ is applied in the nanowire. At this time, the sample is magnetized in the $-z$-direction. The magnetic DW is then prepared by injecting a current pulse into the heater (the left one in the schematic). Under the mutual effect of current, field and heating, a DW is generated near the
heater and propagates in the opposite direction of $I_{DC}$ (from left to right in the schematic). The motion of the DW is monitored by an oscilloscope recording the Hall voltage change (thus the change of $R_{yx}$) on two Hall bars separated by 15 μm, so that the DW velocity can be obtained as a function of $H_z$ or $I_{DC}$. The typical waveforms of the heater pulse and $R_{yx}$ changes are shown in Fig. 3b. Clearly, the DW propagates across Hall bar 2 and 3 subsequently (along with the direction of the electron flow), resulting in a $2R_0$ change in $R_{yx}$, where $R_0$ is the saturated anomalous Hall resistance. We also used a lock-in amplifier to monitor the $R_{yx}$ at Hall bar 1 to ensure the magnetization direction and saturation of the nanowire before and after the current pulse.

Before the DW dynamics measurement, we utilized the nanowire device to cross-check the role of Joule heating and current-assisted DW motion by STT in the magnetism modulation process (Fig. 3c-h). A tiny 1 μA AC current is used to track the Hall resistance $R_{yx}$, while the effects of Joule heating and STT are separated by the DC current injection into the heater and Co$_3$Sn$_2$S$_2$ nanowire, respectively. Figures 3c-d show the $R_{yx}$ hysteresis loops as a function of the heater current $I_{heater}$ from the configuration that current is only applied on the heater. When $I_{heater}$ is large enough, the temperature near the heater will rise, lowering the energy barrier for DW nucleation, so $H_C$ will decrease. Because it is a pure thermal effect, negative $I_{heater}$ also has the same effect (not shown in the figure). In addition, $I_{heater}$ will not increase $H_C$. Figures 3e-f show the results when both the heater and the nanowire run current. $I_{heater}$ is now fixed at 15 mA to release the magnetic DW near the heater and let it propagate from left to right during the magnetic reversal process. The resulting hysteresis loops as a function of the current in the nanowire $I_{sd}$ (positive direction defined from right to left) are shown in Fig. 3f. Contrary to the heater-only case (Fig. 3d), $+/- I_{sd}$ show opposite modulation behavior to $H_C$. Positive $I_{sd}$ exerts a force on the DW away from the heater to help its nucleation and propagation process, thus reducing $H_C$, and vice versa. In the intermediate current region between −0.2 mA and 0 mA, the modulation efficiency $\Delta H_C/\Delta J$ reaches 2.2 kOe MA$^{-1}$ cm$^2$, very close to the value obtained in device 1. In Fig. 3g-h, when only $I_{sd}$ is applied, the hysteresis loop remains unchanged in the same $I_{sd}$ range as in Fig. 3e-f, indicating that $I_{sd}$ does not bring severe heating effect. The comparison of the three cases in Fig. 3c-h illustrates that STT plays an important role in the magnetism modulation process by affecting DW nucleation, thus resulting in the ultra-high efficiency, while Joule heating ensures that the dominated nucleation process occurs near the source/drain electrodes, so DW propagates unidirectionally during the magnetization reversal process and $H_n$ can be effectively modulated.

We finally perform DW velocity measurements to give an unambiguous result of STT efficiency. Figure 3i shows the contour plot of the DW velocity $v_{DW}$ as a function of $H_z$ and $J$, where three “iso-speed” lines with an interval of 1 m/s are displayed by the black dashed lines. Interestingly, $v_{DW}$ shows an excellent linear dependence on the field and current density covering our whole measurement range, which can be expressed as $v_{DW} = \eta J + \mu H_z$, where $\eta$ and $\mu$ are the current- and field-dependent domain wall mobility, respectively. The linear relationship can be seen more clearly in Fig. 3j,k, where the dependence of $v_{DW}$ on $J$ and $H_z$ is measured at various temperatures, showing that the magnetic DW enters the linear flow region under a small current density of $\sim 10^5$ A/cm$^2$ and magnetic field of $\sim 0.1$ kOe $^{32}$. The linear relationship demonstrates the field-like effect of STT on DW dynamics, so the effective field of STT can be obtained as $\eta/\mu$, reaching 2.4 kOe MA$^{-1}$ cm$^2$ at 150 K in device 4, and 5.6 kOe
MA$^{-1}$ cm$^2$ in another device (device 5, Supplementary Fig. S9). Note that the magnetism modulation efficiencies observed in devices 1-3 at the same temperature are 3.3-3.8 kOe MA$^{-1}$ cm$^2$, which is within the STT efficiency range obtained by DW dynamics measurements. A full comparison between these two efficiencies obtained from different devices is depicted in Fig. 4. Their values and the temperature-dependences are well matched (see Supplementary Note 8), which strengthens the current-assisted DW motion model and provides direct evidence of the ultra-high STT efficiency in Co$_3$Sn$_2$S$_2$.

Another crucial parameter in DW dynamics is the threshold current density $J_c$, above which the current-induced DW motion can be achieved. In our experiments, even the lowest applied current density exceeds the threshold because a finite magnetic field and current are required to nucleate the DW and generate observable electrical signals. As a result, only the upper bound of $J_c$ can be given. We further calculate an effective actual threshold value $J_c^* = J_c + \left(\mu/\eta\right) H_z$, which is ensured by the field-like effect of the current. From Fig. 3j, we see that $J_c < 1.6 \times 10^5$ A/cm$^2$ under 0.2 kOe field, giving $J_c^* < 2.8 \times 10^5$ A/cm$^2$ at 167.5 K. A lower threshold is observed in device 5, with $J_c < 1.0 \times 10^5$ A/cm$^2$ under 0.2 kOe field and $J_c^* < 1.5 \times 10^5$ A/cm$^2$ at 160 K. In addition, DW nucleation is occasionally achieved without magnetic field in this device. Therefore, we obtain the maximum upper bound of $J_c < 5.1 \times 10^5$ A/cm$^2$ at 160 K (Supplementary Fig. S9), on the same order of magnitude as $J_c^*$, which is still two orders of magnitude smaller than the value of common metallic ferromagnets.

**Discussion**

In conclusion, we find that DC current significantly modulates the coercivity and thus magnetization reversal process in Co$_3$Sn$_2$S$_2$ nanoflakes with ultra-high efficiency. The mechanism is carefully studied and confirmed to be the current-assisted DW motion enabled by the giant STT efficiency in Co$_3$Sn$_2$S$_2$. The low threshold current density and the pure field-like effect of the current to drive the DWs coincides with microscopic spin-torque theory based on Weyl fermions – the topological band structure could lead to anomalous coupling between magnetism and transport, thereby greatly modifying the form of spin torques$^{22,23}$. It may explain why similar current modulation behavior has never been observed in conventional materials before. This work provides a new scheme of magnetism manipulation, demonstrates that STT in metallic systems can produce a large effective field comparable to the best results of SOT, and sheds light on the yet juvenile study of DW dynamics in magnetic Weyl semimetals$^{43,44}$. Direct control of magnetism by current injection into a single material with large perpendicular magnetic anisotropy may enable more flexible design on DW functional devices, which are more compact, stable, and power-saving. In addition, DW velocity in a larger range of current density is highly anticipated to better study the current threshold, Walker breakdown, and the non-adiabatic STT parameter $\beta$ in the magnetic Weyl semimetals.
Fig. 1 Current modulation of the 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 (device 1). c, The temperature dependence of the longitudinal (Rₓₓ) and transverse (Rᵧᵧ) resistance under 0.1 kOe field cooling along the c-axis. A Curie temperature of T_C ≈ 175 K is obtained. d, When the applied DC current exceeds the threshold, the coercive field H_C (red and blue points) begins to decrease rapidly, showing significant discrepancy from the pure thermal effect (orange lines, obtained by using the value of Rᵧᵧ as an internal thermometer). e, The hysteresis loops of Rᵧᵧ under different DC currents measured at 150 K. Each loop is measured twice to ensure repeatability.
**Fig. 2 Current-assisted domain wall motion model.**

**a,** Field angle dependence of $R_{yx}(H)$. The sample lies in the $xy$-plane. Magnetic field $H$ is applied in the $xz$-plane, and $\theta$ is the angle between $H$ and the $z$-axis.

**b,** Coercive field $H_C$ as a function of $\theta$. Error bars (both horizontal and vertical) are smaller than data points. The red dashed line represents $H_C(\theta=0)/\cos \theta$, the predicted value when the magnetization reversal process is dominated by DW motion.

**c-d,** $H_C$ and representative hysteresis loops of device 2 (40 $\mu$m×6 $\mu$m×92 nm) under different DC currents, showing features including the abnormal increase of $H_C$, asymmetric current thresholds, and multi-domain.

**e,** Schematic of device 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.

**f,** $H_C$ as a function of DC current and the current path in device 3.

**g,** The evolution of $H_C$ given by the current-assisted DW motion model in the simple case where two nucleation sites with different DW nucleation field $H_n$ located under source and drain electrodes. $H_n$ at the two sites are colored red and blue, respectively, and the smallest $H_n$ determines the coercive field (solid line). When the current reaches the value marked by the purple arrow, where $H_{n,1}=H_{n,2}$, the decisive nucleation site changes (also shown in d). All data in Fig. 2 are measured at 150 K.
Fig. 3 Domain wall velocity measurement. a, Schematic diagram of the domain wall velocity measurement and optical image of the tested nanowire device (device 4, 90 μm×1 μm×62 nm). The Hall voltage signals are transmitted to the oscilloscope through 1000× gain preamplifiers. b, Typical waveform obtained during a measurement. Black line shows the voltage pulse applied onto the heater. Red lines trace the change of $R_{yx}$. Domain wall velocity $v_{DW}$ equals the channel length between the two Hall bars divided by the time interval of $R_{yx}$ reversal. c-h, Control experiments to separate the contribution of Joule heating (by $I_{heater}$) and STT (by $I_{sd}$) in the magnetism modulation process. The $R_{yx}$ hysteresis loops are measured through 1 μA AC current that minimizes its influence on magnetization reversal. i, Contour map of $v_{DW}$ as a function of out-of-plane field $H_z$ and current density $J$. Black dashed lines show “iso-speed” lines with a spacing of 1 m/s. j, $v_{DW}$ as a function of $J$ and $T$, measured under $H_z = 0.2$ kOe. Inset, the current-dependent DW mobility $\eta$ as a function of $T$. k, $v_{DW}$ as a function of $H_z$ and $T$, measured at $J = 4.0 \times 10^5$ A/cm$^2$. Inset, the field-dependent DW mobility $\mu$ as a function of $T$. 
Fig. 4 The STT efficiency $\Delta H/\Delta J$ given by two independent methods. As described in the main text, devices 1-3 are Hall-bar devices, and the efficiency is given by the current modulation process of coercive field $H_C$, which is $\Delta H_C/\Delta J$. Device 4-5 are nanowire devices, and the efficiency is given by the current-induced effective field in DW velocity measurements, which is $\Delta H/\Delta J = \eta/\mu$ [\( \eta(\mu) \), current(field)-dependent DW mobility]. These data from different devices and methods show good consistency, providing strong evidence of the giant STT efficiency in Co$_3$Sn$_2$S$_2$. 

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Methods

Sample Growth and Device Fabrication  
Co3Sn2S2 nanoflakes are grown on sapphire or Si/SiO2 substrates via a modified chemical vapor transport method. Co3Sn2S2 powders are sealed in one end of an ampule as precursors with transport agents, and substrates are placed at the other end (see Supplementary Fig. S1). To reduce the transport rate, a neck of a diameter of 1 mm is introduced in the middle of the ampule. The source and the sink ends are gradually heated to 1000 °C and 800 °C in 3 hours, and the temperatures are kept for 1 hour. After natural cooling to room temperature, high-quality crystals are obtained, confirmed by high resolution transmission electron microscope and selected area electron diffraction patterns. The thicknesses of the samples are measured by atomic force microscopy. The nanoflakes are patterned into designed geometry by electron beam lithography and argon ion milling. After that, Cr/Au (10 nm/100 nm) electrodes are defined by electron beam lithography and evaporation.

Transport Measurement  
The device is loaded into a PPMS (Cryomagnetics, Inc.) with a magnetic field up to 14 T. For all-DC measurements (which is the case for devices 1-3), the current is applied by Keithley 2636B. Longitudinal and transverse voltage are measured by Keithley 2636B and 2182A, respectively. The devices show linear I-V curves in the measured current range, so the resistance can be directly obtained by dividing the voltage by the DC current. A small current of 100 μA is used to obtain the R-T and Hc-θ data. A self-made rotator probe is used for angular-dependent measurements. For current modulation measurements, the hysteresis loops can be obtained by directly sweeping the magnetic field or by holding the field but rotating the sample.

Domain Wall Velocity Measurement  
The schematic diagram to measure the DW velocity is shown in Fig. 3a. The AC signal is applied and measured by SR830 lock-in amplifier. The DC current is applied by Keithley 2636B. The current pulse is generated by AFG31000 arbitrary function generator. The Hall voltage signal is magnified 1000× by Signal Recovery 5186 preamplifier and is then traced by DPO2024B oscilloscope. The pulse duration on the heater is set to 10 μs to ensure DW generation, with rise/fall time set to be 5 μs to minimize interference on the Hall signal. As a result, clean jump signals are obtained when DW passes the Hall bar. Background signals are filtered by a 0.5 Hz cut-off frequency of the preamplifier.
Data availability
The datasets generated by the present study are available from the corresponding author upon request.

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Author contributions
Q.W. and Y.Y. conceived the project. Y.Z. grew the Co3Sn2S2 nanoflakes and fabricated the devices assisted by K.Y.. Q.Z. and E.L. provided the precursor Co3Sn2S2 powders and helpful discussion of preparing the nanoflake samples. Q.W. conducted the transport measurements assisted by Y.Z., K.Y., and P.G.. Q.W. analyzed the data. X.X. performed HRTEM measurements. E.L. and K.N. provided scientific discussions. Q.W. and Y.Y. wrote the manuscript, with input from all authors. Y.H. and Y.Y. supervised the project. All authors discussed the results, interpretation and conclusion.

Competing interests
The authors have filed a Chinese patent application for using direct current injection to modulate magnetism in magnetic semimetal thin films.

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