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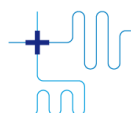
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ABSTRACT

Non-collinear chiral antiferromagnets, such as Mn_3X ($\text{X} = \text{Sn}, \text{Ge}$), have garnered significant interest in spintronics due to their topologically protected Weyl nodes and large momentum-space Berry curvatures. In this study, we report rapid chirality domain wall (CDW) motion in Mn_3Sn , driven by spin-orbit torque at over 545.3 m s^{-1} under a remarkably low current density of $9 \times 10^{10} \text{ A m}^{-2}$. The results demonstrate that the chirality of the domain wall and the direction of the current collectively determine the displacement direction of the CDW. Theoretically, we provide an analysis of the effective field experienced by the octupole moment, uncovering the underlying motion mechanism based on the unique profile of the chiral spin structure. Notably, CDWs with opposite chirality can coexist within the same sample containing the Dzyaloshinskii–Moriya interaction, where the formation of a Néel-like CDW is governed by the orientation of the kagome plane, rather than by the negligible magnetostatic energy of the small net magnetization. Additionally, the CDW, with a considerable width of 770 nm , is segmented into three 60° portions due to the sixfold anisotropy in Mn_3Sn . These emphasize that CDW motion in Mn_3Sn cannot be quantitatively studied using ferromagnetic frameworks. We also demonstrate that a small external field can effectively regulate CDW velocity. Our comprehensive results and theoretical analysis provide crucial guidelines for integrating antiferromagnet CDWs into functional spintronic devices.

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Magnetic domain walls (DWs) have been a subject of significant interest over the past decade, particularly in the context of their electrical manipulation enabled by advancements in spintronic materials and techniques.^{1–5} Utilizing spin-transfer torque (STT) or spin-orbit torque (SOT), ferromagnetic (FM) DW motion can be electrically manipulated at speeds of hundreds of meters per second, although this requires high current densities of up to 10^{12} A m^{-2} .^{6,7} In contrast, the velocity of ferrimagnetic DWs can be significantly improved to 5.7 km s^{-1} due to antiferromagnetic exchange coupling, although it still necessitates large current densities.^{8–11}

To achieve high-capacity racetrack memory, closely packed DWs are necessary. However, memory density is often limited by the magnetostatic interaction caused by the stray field of neighboring domains. Unlike FMs, antiferromagnets (AFMs) have magnetic moments that

are compensated on an atomic scale, resulting in zero stray fields.^{12–16} This property makes AFMs favorable for miniaturization and high-density integration, though it also presents challenges for the efficient manipulation and detection of AFM DWs.^{17,18} Recent research has seen substantial advancements in the area of non-collinear chiral AFMs, particularly in Mn_3X ($\text{X} = \text{Sn}, \text{Ge}$) systems.^{19–27} These materials have demonstrated large distinctive responses, including the anomalous Hall effect,^{15,28} anomalous Nernst effect,²⁹ and asymmetric magnetoresistance,³⁰ allowing efficient observation of domain structure in nanostructures. This advancement improves the ability to control AFM domain structures, thereby contributing to the broader exploration of AFM-based spintronic phenomena. Previous research has demonstrated field-assisted^{30,31} and STT-driven DW motion.³² SOT has attracted significant attention as a promising mechanism to

further improve energy efficiency and advance next-generation magnetic solid-state memory devices.^{25,33–37} Despite these advancements, SOT-driven chiral domain wall (CDW) motion in non-collinear AFM systems remains less explored.

In this work, we provide an in-depth understanding of the profile of CDWs with different chirality. Based on the rotation direction of the cluster magnetic octupole moment, the chirality is categorized into anti-clockwise and clockwise, both of which can be formed in the same sample. This behavior contrasts with FMs, where chirality is determined by the sign of the Dzyaloshinskii–Moriya interaction (DMI). This unique characteristic offers an alternative approach to advancing CDW studies.³⁸ The scale and structure of these CDWs are consistent with previous experimental observations and theoretical predictions.^{39–41} Importantly, we achieve SOT-driven CDW motion in both chirality systems with a small current density ($9 \times 10^{10} \text{ A m}^{-2}$), accelerating the speed up to 545.3 m s^{-1} in Mn_3Sn /heavy-metal (HM) bilayers. This velocity surpasses typical FM systems, even at lower current densities.^{42,43} The direction of motion is determined by the interplay between current and CDW chirality, consistent with our analysis that the motion is cooperatively facilitated by the damping-like SOT effective fields ($\mathbf{H}_{\text{DL}}$) and the vertical component of the exchange field ($\mathbf{H}_{\perp}$). Based on our results, it is worth noting that conventional FM frameworks are insufficient for quantitatively describing CDW motion in Mn_3Sn . We analyze this discrepancy from several perspectives. In Mn_3Sn , CDW type is dictated by the orientation of the kagome plane, not the competition between magnetostatic energy (E_{mag}) and other energy components as in FMs. Additionally, chirality is governed by initial formation conditions, allowing both clockwise and anti-clockwise CDWs to form under the same DMI constant. The unique triangular spin structure of Mn_3Sn , with six stable states, divides the CDW profile into three segments, leading to a larger CDW width than FM. These differences highlight the key distinctions arising from the intrinsic properties of Mn_3Sn . We also reveal an efficient control of CDW

velocity by combining a small external field ($\mathbf{H}_{\text{ext}}$) in the kagome plane. These findings provide insights into controlling CDW dynamics and advancing spintronics using AFMs.

To study the CDWs, we improve our previous macrospin model used in Ref. 19 to an atomistic model, enabling the investigation of spatially resolved CDW dynamics. Specifically, we construct a nanoribbon Mn_3Sn sample with a length of $5.7 \mu\text{m}$. The model captures the magnetic moments provided by Mn atoms. The simulation starts with identifying the Hamiltonian described as follows:^{44–46}

$$E = A \sum_{i,j} \mathbf{m}_i \cdot \mathbf{m}_j + \sum_{i,j} \mathbf{D}_{ij} \cdot (\mathbf{m}_i \times \mathbf{m}_j) - \sum_i (\mathbf{K}_i \cdot \mathbf{m}_i)^2 - \mu_0 M_s \sum_i (\mathbf{m}_i \cdot \mathbf{H}_{\text{ext}}),$$

where the exchange interaction constant $A = 9 \text{ meV}$,^{47,48} the DMI constant $D = 0.833 \text{ meV}$,²⁰ and the magnetic anisotropy constant $K = 0.196 \text{ meV}$.²⁰ The minimization of the DMI energy, characterized by the positive $\mathbf{D}$, favors a clockwise ordering of the vectors $\mathbf{m}_1$, $\mathbf{m}_2$, and $\mathbf{m}_3$.⁴⁹ The easy axis of crystalline anisotropy points to the nearest Sn atoms [the silver ball shown in Fig. 1(a)]. The magnetic moment $m_s = 3\mu_B$.²⁰ The last term is the Zeeman energy due to the external field $\mathbf{H}_{\text{ext}}$.

The dynamics of magnetic moments are modeled using a home-developed code that solves the Landau–Lifshitz–Gilbert (LLG) equation for every atom,^{50–52}

$$\frac{d\mathbf{m}_i}{dt} = -\gamma \mathbf{m}_i \times \mathbf{H}_{\text{eff},i} + \alpha \mathbf{m}_i \times \frac{d\mathbf{m}_i}{dt} - \gamma \frac{\hbar \theta_{\text{SH}} J_c}{2e M_s t} \mathbf{m}_i \times (\mathbf{m}_i \times \boldsymbol{\sigma}_i).$$

The first term on the right-hand side represents the precession of magnetic moment around the effective magnetic field $\mathbf{H}_{\text{eff},i} = -\frac{1}{m_i} \frac{\partial E}{\partial \mathbf{m}_i}$. The second term describes the Gilbert damping, and the last term is the SOT. γ is the gyromagnetic ratio, and $\alpha = 0.003$ is the damping constant. The spin-Hall angle $\theta_{\text{SH}} = 0.06$ is used in the simulation.^{12,20}

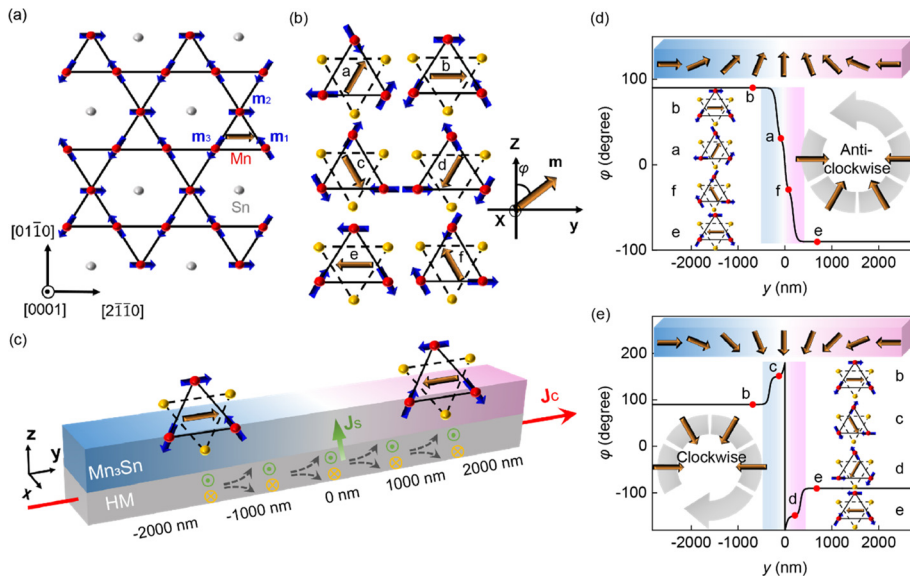


FIG. 1. (a) Atomic structure of Mn_3Sn . The Sn (silver circles) and Mn (red circles) atoms lie in the (0001) plane. (b) Six types of cluster $\mathbf{m}$ in Mn_3Sn , which are defined as state a, b, c, d, e, and f, respectively. The corresponding angles are $\varphi = 30^\circ, 90^\circ, 150^\circ, 210^\circ, 270^\circ, 330^\circ$. $\mathbf{m}$ is illustrated by brown arrows. (c) The structure of SOT-driven CDW motion in the $\text{Mn}_3\text{Sn}/\text{HM}$ bilayer. (d) Illustration of CDW with (d) anti-clockwise chirality and (e) clockwise chirality. The insets in (d) and (e) show the schematic diagram of the $\mathbf{m}$ state in the CDW.

In equilibrium, Mn_3Sn has six stable states, each differing by 60° within the kagome planes. As shown in Fig. 1(b), we define them as states a, b, c, d, e, and f, respectively. Each set of three spin sublattices, which takes ferroic order on the Kagome lattice, forms a cluster magnetic octupole. Importantly, there is a very small non-zero net magnetization ($\mathbf{m} = \frac{\mathbf{m}_1 + \mathbf{m}_2 + \mathbf{m}_3}{3}$), depicted as brown arrows, which is largely parallel to the cluster magnetic octupole moment.^{40,53} To study the SOT-driven CDW motion, a $\text{Mn}_3\text{Sn}/\text{HM}$ bilayer is constructed with two opposite states positioned at the ends of the sample along the longitudinal direction. As shown in Fig. 1(c), a 180° CDW forms at the interface between two domains, where the magnetic moments transition from the b state to the e state. A current flowing through the bottom HM layer generates a pure spin current by the spin-Hall effect (SHE) and the resulting spin polarization σ is perpendicular to the kagome plane. The CDW is formed by the gradual rotation of each triangular spin unit, manifesting as a twisted $\mathbf{m}$ in the kagome plane in a Néel-wall configuration. In conventional perpendicular magnetized FM films, Bloch walls typically form due to balanced E_{mag} , while large DMI tends to convert Bloch walls into Néel walls. For in-plane FM systems, as the sample thickness t decreases, E_{mag} becomes more dominant. When t approaches the DW width, the Bloch wall, with its out-of-plane magnetization, generates high E_{mag} and becomes unstable. To maintain a lower energy state, the DW transitions to a Néel wall, where the magnetization rotates parallel to the film surface, effectively reducing the influence of E_{mag} .^{54,55} However, in the case of Mn_3Sn , the finite anisotropy within the kagome plane constrains the rotation of $\mathbf{m}$ in this plane. Additionally, the small magnitude of $\mathbf{m}$ in Mn_3Sn , approximately $|\mathbf{m}| \approx 3.975 \times 10^{-3}$, leads to negligible E_{mag} , meaning that energy is not the primary factor governing CDW type. Consequently, the orientation of the kagome plane distinguishes between Bloch-like and Néel-like CDWs, rather than energy considerations. Interestingly, as illustrated in Figs. 1(d) and 1(e), there are two possible configurations distinguished by the profile of $\mathbf{m}$ within the CDW: anti-clockwise and clockwise. The chirality of the CDW corresponds to a clockwise or anti-clockwise rotation of $\mathbf{m}$ when viewed from left to right. For instance, if it consists of states b, a, f, and e [Fig. 1(d)], $\mathbf{m}$ rotates anti-clockwise. Conversely, if the CDW structure includes states b, c, d, and e [Fig. 1(e)], $\mathbf{m}$ rotates clockwise, defining it as a clockwise CDW. The origin of chirality in Mn_3Sn can be controlled by the prior residual minority domains history of the sample which depends on the history of the magnetic field orientation before CDW measurement, while in FM, it is determined by the sign of the DMI constant to minimize the DMI energy $\mathbf{H}_{\text{DMI}} = \mathbf{D}_{12} \cdot (\mathbf{m}_1 \times \mathbf{m}_2)$. In addition, the CDW, highlighted by the blue and red gradient band in the figure, exhibits a large width of approximately 770 nm, which is consistent with previous experimental and simulation results.^{30,56} This considerable width is primarily attributed to the ultralow energy density of the CDW, which is around three orders of magnitude lower than that of typical FM. The negligible $\mathbf{m}_{\text{net}}$ in Mn_3Sn eliminates magnetostatic constraints, further permitting a rotation of octupole moments across the kagome planes in the Néel type. However, estimating the CDW width using the formula $W = \pi \sqrt{A/K}$ for FM yields a width of only 12.05 nm,^{42,55} which is significantly smaller than the 770 nm observed in our results. This suggests that the triangular spin structure of Mn_3Sn requires a longer spatial extent for smooth rotation within the CDW. In terms of the internal profile of the CDWs, unlike conventional FM systems with a single easy axis, either perpendicular

or in-plane, $\mathbf{m}$ exhibits sixfold degeneracy. This causes the CDW to divide into three 60° segments, separated by stable states.³⁰ As a result, two small plateaus are formed, indicated by the red points in Figs. 1(d) and 1(e).

In thin FM materials, DWs generally tend to form into Néel walls, which can be driven by the SHE. Similarly, we achieved CDW motion driven by the SHE originating from the underlying HM layer. A current density of $J_c = 5 \times 10^{10} \text{ A m}^{-2}$ was applied along the $+\mathbf{y}$ direction in the sample with an anti-clockwise CDW at its center. As shown in the snapshot of Fig. 2(a), the white band representing the CDW moves in the direction opposite to the applied current J_c . When the current direction is reversed, as shown in Fig. 2(b), the CDW motion direction also reverses. This indicates that J_c directly determines the direction of CDW motion. Furthermore, we observe that the initial chirality of the CDW also plays a decisive role. As shown in Figs. 2(c) and 2(d), the CDW with clockwise chirality, illustrated by the blue and red bands, moves in the same direction as J_c , regardless of whether J_c is along $+\mathbf{y}$ or $-\mathbf{y}$. This indicates that the current direction and the initial chirality of the CDW jointly affect the direction of its displacement. Furthermore, we can determine the profile and chirality of the CDW based on the direction of the current and its motion. Corresponding to the snapshots above, we show φ at each position of the sample at different times in Figs. 2(e)–2(h). The center of the sample is defined as 0 nm. The equal spacing between each line indicates uniform motion, and the shape of the CDW remains consistent during its motion, with no noticeable shrinkage or expansion. In addition, the velocity of CDW motion in Mn_3Sn easily surpasses that of typical FM systems, where speeds are generally around 100 m s^{-1} .^{43,57} Recent studies have shown that STT-driven CDW motion can also reach several hundred meters per second and have attributed this to the large nonadiabatic torque.³² The stable characteristics and effective SOT manipulation of the CDW in non-collinear AFM are advantageous for potential device-level applications.

Figure 3 illustrates the mechanism of CDW motion. Although the neighboring atoms are antiferromagnetically coupled, $\mathbf{m}$ is often treated as a collective representation of three triangular spin units. Notably, this is analogous to perpendicular FM DW motion driven by SOT, where a perpendicular effective field along $+\mathbf{z}$ or $-\mathbf{z}$, generated by the SHE, is essential to induce DW propagation.⁵⁸ In Mn_3Sn , the perpendicular effective field is primarily governed by the exchange interaction, which dominates over the DMI and anisotropy due to its significantly larger magnitude as well as the unique crystal structure. It is important to note that the parallel component of the exchange field ($\mathbf{H}_{\parallel}$) relative to the local magnetic moment does not induce precession of the magnetic moment. Instead, the perpendicular component of the exchange field ($\mathbf{H}_{\perp}$), coupled with $\mathbf{H}_{\text{DL}}$, plays a critical role in driving the CDW motion. Figure 3(a) illustrates that $\mathbf{H}_{\perp}$ on the left side of the CDW works together with the $\mathbf{H}_{\text{DL}}$ to facilitate the reorientation of $\mathbf{m}$. Conversely, $\mathbf{H}_{\perp}$ on the right side compensates for $\mathbf{H}_{\text{DL}}$, limiting the expansion of the CDW on that side. Additionally, because of the strong in-plane magnetic anisotropy that keeps spins restricted in the $\mathbf{y}$ - $\mathbf{z}$ plane, behaving as a Néel-wall type and moving along the wire from right to left. Consequently, both our simulation results and analysis demonstrate that the direction of motion depends on the combined effect of $\mathbf{H}_{\text{DL}}$ and the perpendicular component of exchange field. When the chirality of the CDW is reversed to a clockwise fashion, the beneficial $\mathbf{H}_{\perp}$ shifts to the right side, aligning with the direction of

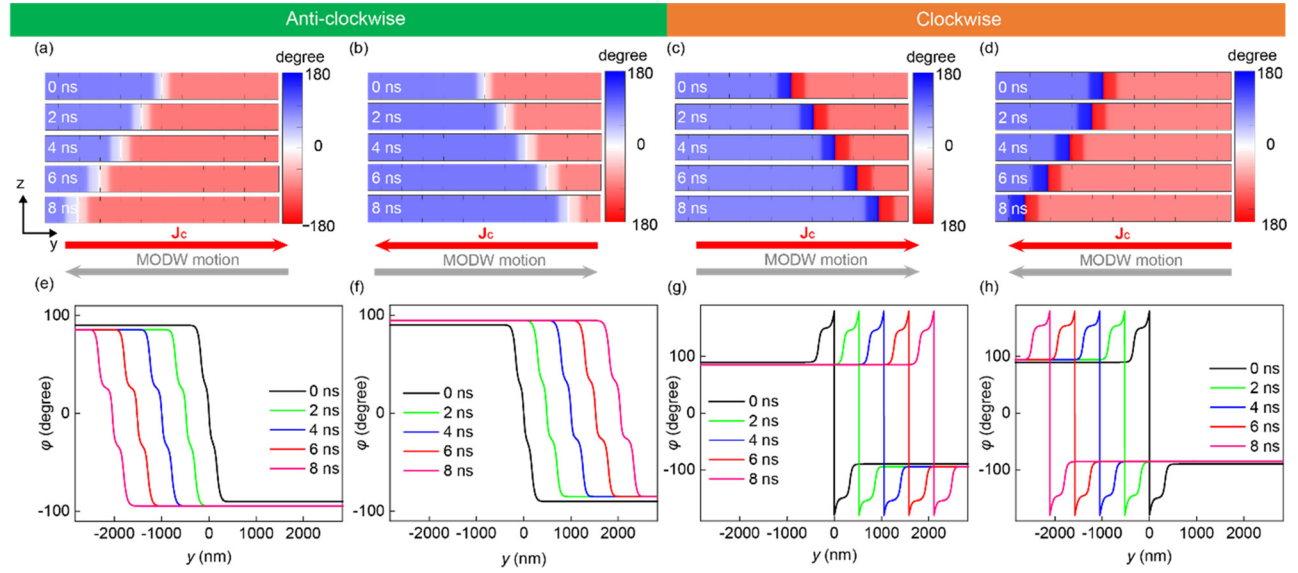


FIG. 2. (a)–(d) Time evolution of the CDW motion in AFM materials, showing both anti-clockwise [(a) and (b)] and clockwise [(c) and (d)] chirality. The horizontal axis represents the position along the nanotrack. The red arrows on the bottom indicate the current direction with $J_c = 5 \times 10^{10} \text{ A m}^{-2}$ and the gray arrows indicate the direction of the CDW motion. (e)–(h) Displacement of CDW at different times. The figures correspond to panels (a)–(d).

H_{DL} . The cooperation of these two torques results in the CDW moving in the $+y$ direction, i.e., the direction of J_c . Our analysis explains the simulation results and guides the direction of CDW motion. It is essential to emphasize that $\mathbf{m}$ should only serve as a qualitative descriptor of the direction of CDW motion, bearing in mind that the DW type, chirality, width, internal profile, and motion speed of Mn_3Sn differ significantly from those in FM systems. These distinctive characteristics highlight why quantitatively analyzing CDW motion by directly analogizing it to FM systems is inaccurate. The distinct behaviors observed in our results reflect the exceptional physical properties of Mn_3Sn .

To further investigate the CDW motion, we present the CDW velocity (v_{CDW}) as a function of J_c , where v_{CDW} is defined as the

displacement of the CDW per unit time. Figure 4(a) shows the v_{CDW} for right-to-left propagation under positive current and anti-clockwise chirality. We observe that the current-induced SOT can accelerate the CDW up to 545.3 m s^{-1} with a current density of only $9 \times 10^{10} \text{ A m}^{-2}$. This low current density results from the efficient interaction between the spin polarization and the kagome plane, which are perpendicular to each other. Furthermore, the sixfold in-plane anisotropy lowers the rotational energy barrier by offering multiple favorable orientations. In addition, v_{CDW} increases nearly linearly with current density. As current density continues to increase, the CDW motion abruptly disappears and is replaced by the oscillations throughout the sample. For instance, as shown in Fig. 4(b), the time evolution of a $\mathbf{m}$ located 2000 atoms away from the initial CDW center is depicted

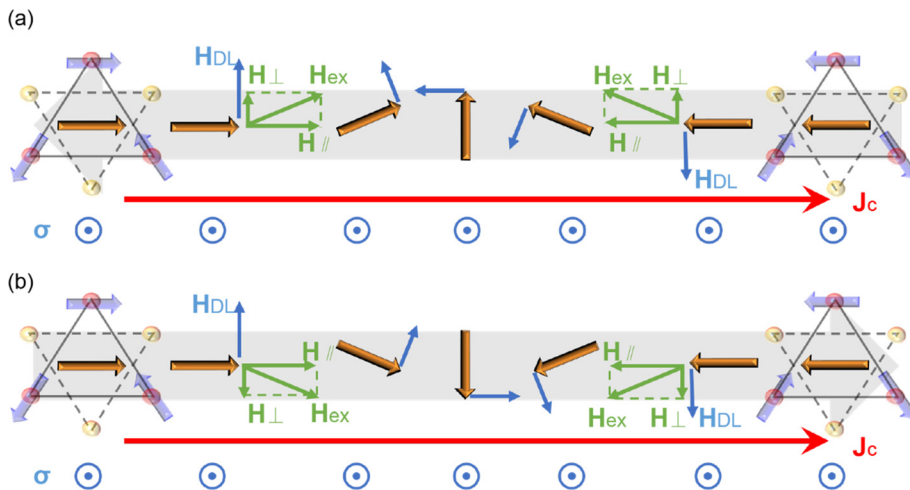


FIG. 3. The mechanism of CDW motion in the system with (a) anti-clockwise chirality and (b) clockwise chirality. Blue arrows represent the effective fields from the SOT, and green arrows represent the exchange field.

under $J_c = 1.3 \times 10^{11} \text{ A m}^{-2}$. This behavior is in agreement with previous research on the Mn_3Sn switching, which reported oscillation regions under large currents.^{19,59} Such oscillations indicate the presence of a “speed wall,” i.e., an intrinsic upper limit of SOT-driven CDW velocity, beyond which increasing current density no longer enhances the motion but instead leads to dynamic instability.

In addition to SOT, applying a small $\mathbf{H}_{\text{ext}}$ can also regulate the velocity of CDW motion. Based on the analysis above, $\mathbf{H}_{\text{DL}}$ generated by $\mathbf{J}_c$ along $+\mathbf{y}$ direction tends to rotate $\mathbf{m}$ anti-clockwise, regardless of the CDW chirality. However, the trajectory varies with the chirality of the CDW. Figure 4(c) shows the trajectory of $\mathbf{m}$ positioned along the path of the CDW motion when $\mathbf{J}_c$ is $+5 \times 10^{10} \text{ A m}^{-2}$. For the anti-clockwise CDW (red line), the initial position is marked by a star at -425 nm , and for the clockwise CDW (blue line), it is marked by a triangle at $+425 \text{ nm}$. Although the $\mathbf{H}_{\text{DL}}$ generated by the current drives magnetization to rotate anti-clockwise in both cases, the lateral paths differ due to the different CDW chirality. For the anti-clockwise CDW (red), the trajectory of $\mathbf{m}$ shifts toward negative y , while for the clockwise CDW (blue), it shifts toward positive y . These differences stem from the spatial configuration of the CDW and affect the direction of displacement. Importantly, the observed anti-clockwise rotation in both cases is consistent with the sign of $\mathbf{H}_{\text{DL}}$. This guides the design of regulating CDW displacement using current-driven torques. As seen in Fig. 4(d), when a small $\mathbf{H}_{\text{ext}}$ is applied along the $+\mathbf{y}$ direction, v_{CDW} changes significantly. The increase or decrease in velocity depends on whether $\mathbf{H}_{\text{ext}}$ assists in or hinders the rotation of $\mathbf{m}$. For an anti-clockwise CDW (red lines), $\mathbf{m}$ rotates from $+\mathbf{y}$ to $-\mathbf{y}$. When $\mathbf{H}_{\text{ext}}$ is aligned with the direction that supports magnetization rotation, the

CDW is accelerated. For example, when an anti-clockwise CDW undergoes a rotation from $+\mathbf{y}$ to $-\mathbf{y}$, an external field applied along $-\mathbf{y}$ reinforces this motion. As shown by the red line, this results in a significant increase in CDW velocity, with nearly double the speed achieved under a modest external field of 100 Oe. This dual regulation by current and $\mathbf{H}_{\text{ext}}$ opens possibilities for controlling CDW dynamics. However, unlike traditional FM where $\mathbf{H}_{\text{ext}}$ drives DW motion by expanding the specific domain, the presence of sixfold degenerate domains in Mn_3Sn makes $\mathbf{H}_{\text{ext}}$ -driven CDW motion configuration-dependent and often inefficient. For instance, CDWs can also form between various domain pairs such as configurations c–f or a–d, where the $\mathbf{H}_{\text{ext}}$ along the $\mathbf{y}$ direction may not align with the $\mathbf{m}$ of the domains, resulting in limited driving efficiency and potential disruption of the CDW structure. In contrast, SOT remains effective across different CDW patterns, providing a more robust and universal mechanism for CDW manipulation. In future studies, it would be interesting to explore how the large intrinsic spin-Hall conductivity of Mn_3Sn may influence the dynamics of the CDW.⁶⁰ Due to excellent plasticity of Mn_3Sn , it is anticipated to be a superior material platform for mimicking artificial synapses⁶¹ and developing various future spintronic devices.^{62–64}

In conclusion, we have demonstrated fast SOT-driven CDW in Mn_3Sn . Our comprehensive atomic-scale study reveals that CDW displacement is influenced by both CDW chirality and current direction. Theoretically, we analyzed how the exchange field and $\mathbf{H}_{\text{DL}}$ guide CDW motion. We argue that analogies between CDW motion in Mn_3Sn and FM systems are quantitatively inaccurate due to differences in Néel wall formation, chirality, CDW width internal profile,

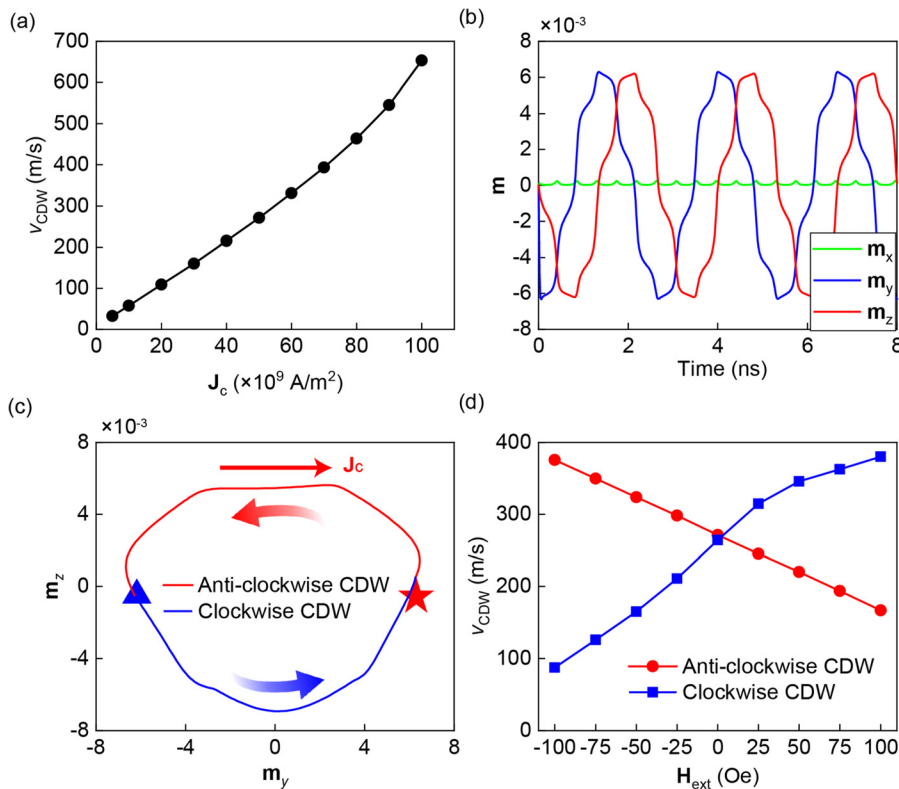


FIG. 4. (a) The velocity of steady CDW motion as a function of J_c . (b) Oscillation dynamics of $\mathbf{m}$ under large $J_c = 1.3 \times 10^{11} \text{ A m}^{-2}$. (c) Cross-sectional view of the $\mathbf{m}$ trajectory at positions -425 nm (initial point shown as a star) and $+425 \text{ nm}$ (initial point shown as a triangle) under J_c . (d) v_{CDW} as a function of $\mathbf{H}_{\text{ext}}$.

and motion speed. Notably, v_{CDW} easily exceeds 545.3 m s^{-1} , surpassing that of FM DWs, and increases linearly with current density. However, when J_c increases significantly and reaches the oscillation region, CDW motion ceases and is replaced by coherent oscillation. Additionally, the introduction of a small H_{ext} allows for precise modulation of v_{CDW} . Our study demonstrates an effective and flexible method for manipulating CDWs in Mn_3Sn , leveraging the absence of stray magnetic fields and the high CDW velocity. These findings provide insight for understanding the fundamental dynamics of CDWs in non-collinear AFM. The unique characteristics of Mn_3Sn CDWs and their effective manipulation highlight the potential of this approach for next-generation domain wall-based spintronic devices.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhengde Xu: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (equal); Methodology (equal); Project administration (equal); Software (equal); Validation (lead); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Yue Zhou:** Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (equal); Methodology (equal); Project administration (equal); Software (equal); Validation (lead); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Xue Zhang:** Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (equal); Methodology (equal); Project administration (equal); Software (equal); Validation (lead); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Yixiao Qiao:** Data curation (supporting); Formal analysis (supporting); Software (supporting); Visualization (supporting). **Zhuo Xu:** Software (supporting); Validation (supporting); Visualization (supporting). **Dingfu Shao:** Methodology (supporting); Supervision (equal); Validation (supporting). **Zhifeng Zhu:** Conceptualization (lead); Data curation (equal); Formal analysis (equal); Funding acquisition (lead); Investigation (lead); Methodology (equal); Project administration (lead); Resources (lead); Software (lead); Supervision (lead); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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