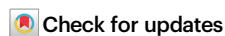


Real-space imaging and control of topological spin textures in a van der Waals antiferromagnet

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Layered magnetic systems with interlayer antiferromagnetic coupling are emerging as a promising platform for energy-efficient spintronic technologies, particularly in the form of van der Waals (vdW) magnets. The direct observation and manipulation of topological spin textures in perpendicularly magnetized 2D antiferromagnets, however, remain highly challenging due to their compensated magnetic states and rigid interlayer exchange, thereby hindering direct insight into spin ordering and functional exploration. Here, using spin-polarized low-energy electron microscopy, we directly visualize antiferromagnetic domains and emergent topological textures in the vdW antiferromagnet $(\text{Fe}_{1-x}\text{Co}_x)_3\text{GaTe}_2$. We uncover tuneable stripe-like domain configurations that can be reconfigured into antiferromagnetic skyrmions under external stimuli, despite the absence of remanent magnetization. These results provide direct insight into spin ordering in a perpendicularly magnetized layered two-dimensional antiferromagnet and open new avenues for next-generation antiferromagnetic spintronic devices.

Magnetic skyrmions, topologically protected nanoscale spin structures, have attracted immense interest owing to their emergent electrodynamics and potential applications in high-density, low-power-consumption spintronic devices¹. Their particle-like stability and extraordinary current-driven mobility enable information

encoding through their presence or absence, forming the foundation of the next-generation racetrack memories and neuromorphic architectures^{2,3}. The presence of the skyrmion Hall effect^{4,5}, which deviates its motion from the direction of the driving current, however, poses a significant challenge for device integration in

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ferromagnets⁶. Layered antiferromagnetic (AFM) coupling, as realized in multilayers and synthetic antiferromagnets (SAFs), can effectively suppress the skyrmion Hall effect and enhance the movement velocity, establishing coupling symmetry as a central tuning parameter for topological spin transport⁷.

The recent discovery of intrinsic magnetism in two-dimensional (2D) van der Waals (vdW) crystals has opened a new frontier for exploring low-dimensional spin textures⁸. Seminal works revealed intrinsic two-dimensional magnetism in $\text{Cr}_2\text{Ge}_2\text{Te}_6$ and CrI_3 with layer-dependent magnetic ordering^{9,10}, followed by itinerant ferromagnetism in layered Fe_3GeTe_2 ¹¹. These materials, with atomically sharp interfaces and tuneable stacking¹² or twisting¹³, provide unprecedented freedom to engineer magnetic properties, such as interlayer exchange, anisotropy, and symmetry breaking at the atomic scale^{14,15}. In parallel with these developments, skyrmionic spin textures have been observed exclusively in two-dimensional van der Waals ferromagnets. Such chiral spin structures can arise either from interfacial Dzyaloshinskii-Moriya interaction (DMI), as demonstrated in $\text{WTe}_2/\text{Fe}_3\text{GeTe}_2$ heterostructures¹⁶, or from bulk DMI originating from lattice asymmetry or Fe deficiency in intrinsic Fe-based tellurides^{17–19}. More recently, Fe_3GeTe_2 and Fe_3GaTe_2 have been shown to host tuneable-hybrid-type skyrmions above room temperature²⁰, with promising current-driven dynamics^{21,22}.

Interlayer exchange coupling fundamentally governs the magnetic ground states of layered systems, determining whether adjacent layers align ferromagnetically or antiferromagnetically as the interlayer spacing varies. The favored spin structures within each layer—uniform or multidomain—arise from a delicate competition among exchange, anisotropy, and dipolar energies²³, as experimentally observed in metallic multilayers²⁴. More recently, synthetic antiferromagnetic (SAF) trilayer structures have enabled compensated magnetic configurations while retaining strong spin-orbit coupling and interfacial DMI, leading to rich current-driven spin dynamics^{25,26}.

The van der Waals magnets provide a lattice-defined analog, in which atomic stacking and interlayer spacing intrinsically determine the key magnetic interactions, including exchange, anisotropy, and the microscopic origin of the DMI. Representative systems such as CrI_3 ¹⁰, CrBr_3 ¹², MnBi_2Te_4 ²⁷, and $(\text{Fe}_{1-x}\text{Co}_x)_3\text{GaTe}_2$ ^{28,29} exhibit diverse interlayer magnetic states, but are most often characterized macroscopically by hysteresis loop measurements or magneto-optical probes. As a result, it remains unclear whether the competition among these interactions can stabilize modulated or chiral spin textures, or instead favor a single-domain state, in intrinsic two-dimensional antiferromagnets, since high-spatial-resolution, layer-resolved magnetic imaging sensitive to antiferromagnetic order has remained elusive. Realizing and controlling such textures would mark a significant step toward all-antiferromagnetic spintronics, combining the topological protection of skyrmions with the robustness and scalability of 2D materials³⁰.

In this work, we address this question by employing high-resolution real-space magnetic imaging to directly visualize and control antiferromagnetic domains and skyrmion-like spin textures in a layered van der Waals antiferromagnet with strong perpendicular magnetic anisotropy. Despite the absence of remanent magnetization, we reveal tuneable stripe-like domain patterns that can be reconfigured into antiferromagnetic skyrmions under external stimuli. These results provide unambiguous evidence of topological spin textures in an intrinsic 2D antiferromagnet and establish van der Waals magnets as a robust platform bridging synthetic multilayers and atomically thin systems, paving the way for the next-generation all-antiferromagnetic spintronic technologies.

Results

Structure and magnetic properties of FCGT

Figure 1a, b shows the side and top views of the atomic structure of $(\text{Fe}_{0.81}\text{Co}_{0.19})_3\text{GaTe}_2$ (FCGT), where Fe and Co atoms share the same atomic sites. Previous X-ray diffraction studies indicate that FCGT

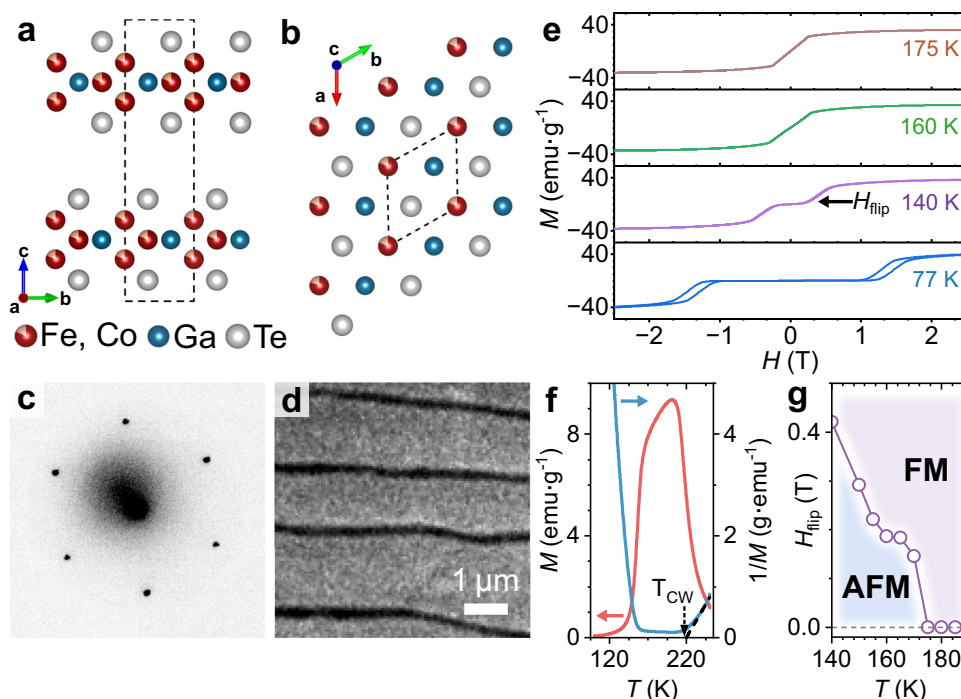


Fig. 1 | Structure and magnetic properties of Co-doped Fe_3GaTe_2 (FCGT). **a, b** Schematic illustrations of the atomic structure of FCGT. **c** LEED pattern of FCGT acquired with an incident electron energy of 27 eV. **d** Surface morphology of FCGT measured by LEEM. The scale bar is 1 μm. **e** Temperature-dependent magnetic hysteresis loops of FCGT. **f** Magnetization as a function of temperature

measured after zero-field cooling, together with the inverse magnetization ($1/M$) versus temperature, proportional to the inverse magnetic susceptibility. A linear fit to the high-temperature data (black dashed line) yields a Curie-Weiss temperature T_{CW} of -220 K. **g** Temperature dependence of the critical field for the spin-flip transition from the AFM to the FM phase, where dots represent experimental data.

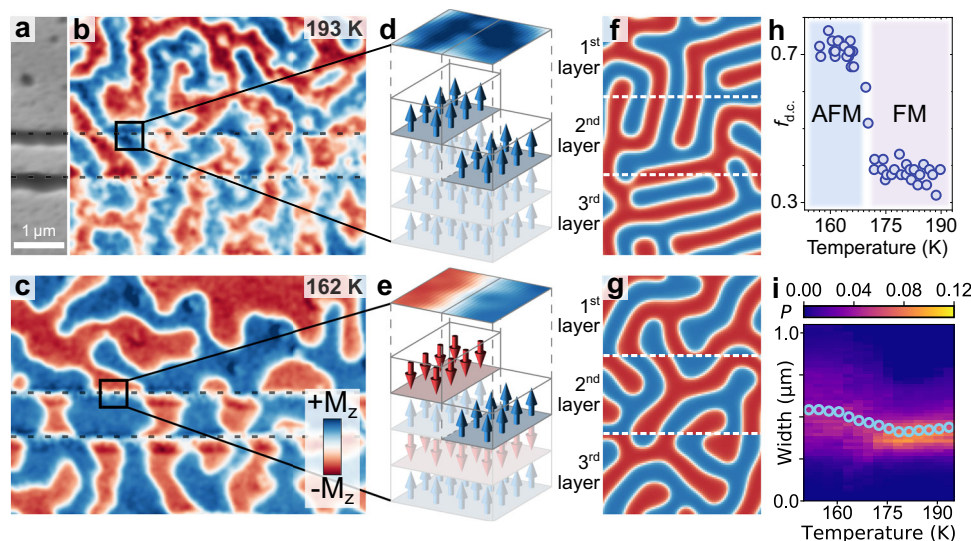


Fig. 2 | SPLEEM observation of antiferromagnetic domain patterns in FCGT. **a** Surface morphology measured by LEEM, highlighting two atomic steps (scale bar, 1 μm). **b**, **c** SPLEEM images of the same area at 193 K (**b**, FM phase) and 162 K (**c**, AFM phase), distinguished by the continuity of the domain patterns across single-atomic-height steps (marked by dashed lines). **d**, **e** Schematics illustrating the near-surface magnetization vectors in the black boxes in (**b**, **c**), respectively.

Simulated domain patterns in different layers in the FM phase (**f**) and the AFM phase (**g**); white dashed lines indicate the boundaries between various layers, and the changes in domain discontinuities are consistent with the experimental observations. Temperature-dependent evolution of the discontinuity fraction (**h**) and the averaged domain width (**i**) near the AFM-FM transition.

crystallizes in the $P6_3/mmc$ structure^{28,29,31,32}, which is the same structure as pristine Fe_3GaTe_2 ¹⁹. The threefold symmetry of the crystal is captured by the low-energy electron diffraction (LEED) pattern (Fig. 1c). The surface morphology of the sample is shown in low-energy electron microscopy (LEEM) images (Fig. 1d, highlighting different layer terraces (brighter areas) separated by step edges (darker lines)). The magnetic properties of the FCGT sample at different temperatures were characterized using a Physical Property Measurement System (PPMS) (Fig. 1e–g). After cooling the samples below 100 K in the absence of a magnetic field, a perpendicular magnetic field of 1000 Oe was applied to record the temperature-dependent magnetization (M - T) curve (Fig. 1f). A Curie–Weiss fit to the high-temperature susceptibility yields a characteristic temperature T_{CW} of ~ 220 K.

We further examined the temperature-dependent evolution of magnetic hysteresis. At high temperatures, the loops show a paramagnetic response. Upon cooling, they become ferromagnetic-like with very small coercivity and remanence. Below 175 K, the slope of the hysteresis begins to change near zero field and develops into a plateau at even lower temperatures (Fig. 1e and Supplementary Fig. S1), followed by a rapid increase in magnetization at higher fields, revealing an AFM ground state and a field-induced AFM-FM transition. To quantify this transition, the differential magnetic susceptibility (dM/dH) was derived from the hysteresis loops (Supplementary Fig. S1), and the critical fields were determined from the local maxima of the dM/dH curves (Fig. 1g). Non-zero critical fields appear below ~ 170 K, indicating a temperature-driven FM-AFM transition near this temperature, consistent with previous work³¹. Overall, the system exhibits distinct PM, FM-like, and AFM regimes in magnetization measurements.

Observation of domain pattern in A-type AFM FCGT

We first consider the possible domain configurations in A-type AFM multilayers with intralayer FM and interlayer AFM coupling. Although adjacent layers remain antiferromagnetically aligned, the domain configuration within each layer is not uniquely determined. Each layer may host either a single-domain state that avoids domain-wall energy but only partially reduces dipolar energy, or periodic labyrinthine or stripe domains that further lower dipolar energy at the cost of forming

domain walls. Which of these configurations is realized is governed by the competition between dipolar energy, domain-wall energy, and interlayer exchange. Depending on material parameters, either configuration may therefore be stabilized. Indeed, single-domain states have been observed in $[(\text{Co}/\text{Pt})_{x-1}/(\text{Co}/\text{Ru})_n]$ multilayers²⁴, whereas both configurations can be energetically stable depending on material parameters.

For van der Waals A-type AFM materials, however, the magnetic ground-state domain configuration has remained largely unexplored. To directly access the magnetic domain structure of FCGT, the samples were prepared by in situ cleavage followed by annealing under UHV conditions (see “Methods”) and subsequently imaged using spin-polarized low-energy electron microscopy (SPLEEM). Owing to the very low incident electron energy, which is only a few eV above the work function³³, the magnetic contrast predominantly originates from the topmost FCGT layer because of the very limited probing depth.

During cooling, the domain evolution of FCGT was monitored using SPLEEM with an out-of-plane spin-polarized beam. At the early stage of cooling, no magnetic contrast is observed above the Curie–Weiss temperature (Supplementary Fig. S2). At intermediate temperatures below ~ 200 K, SPLEEM reveals a layer-aligned out-of-plane spin configuration, indicating a ferromagnetic-like interlayer coupling between adjacent FCGT layers. A representative image acquired at 193 K is shown in Fig. 2b. The domain boundaries are zigzag rather than straight, and small bubble-like structures appear within the stripes, consistent with previous observations of the FM phase in Fe_3GeTe_2 ³⁴. One key piece of evidence is provided by the spin configuration at the location highlighted in Fig. 2d, which reveals the same-oriented out-of-plane magnetization in adjacent layers near single-layer-height steps, as indicated by the LEEM morphology in Fig. 2a. This indicates a ferromagnetic-like interlayer alignment across atomic steps, underscoring the temperature-dependent evolution of interlayer magnetic coupling in a van der Waals antiferromagnet.

The AFM phase of FCGT was then examined with the same out-of-plane spin-polarized beam at lower temperatures. Near ~ 170 K, the domain pattern at a fixed location changes noticeably. A representative stripe-like magnetic domain pattern is observed at ~ 162 K (Fig. 2c).

Further cooling to lower temperatures does not lead to appreciable changes in the AFM stripe domain pattern (Supplementary Fig. S3). Within each terrace, the stripe domain boundaries remain continuous. In contrast, sign reversals of the magnetic contrast occur at single-layer-height steps at the exact location described above (Supplementary Fig. S4). The spin configuration near such a step, marked by the black square in Fig. 2c, is illustrated in Fig. 2e and reveals the characteristic A-type AFM stacking^{35,36}. These contrast reversals appear exclusively at odd-layer step edges and are absent at even-layer step edges (Supplementary Fig. S5), further confirming the A-type AFM nature of the low-temperature phase of FCGT. Similar AFM stripe-domain patterns are also observed in thinner FCGT flakes (~600 nm).

These observations indicate that periodic stripe or labyrinthine domains are favored over a single-domain state within each AFM FCGT layer. Previous theoretical studies have shown the importance of the relative weight of dipolar energy compared with other interactions, for example, by varying the thickness of the magnetic layer²³ or the interlayer spacing³⁷. In particular, thinner magnetic layers tend to stabilize single-domain states, whereas thicker layers with larger magnetic moments favor periodic domain formation due to enhanced dipolar interactions²³. Along the same lines, a large ratio of interlayer spacing to magnetic layer thickness may also favor periodic domain states, reflecting an increased relative weight of dipolar interactions.

To examine the stability of the observed AFM stripe domains in FCGT, we performed three-dimensional Monte Carlo simulations (Methods), which reproduce the experimentally observed domain patterns (Fig. 2f, g). For a large negative interlayer exchange coupling, together with interaction parameters consistent with the considerations above, the simulations stabilize an AFM-coupled state, in which domains reverse between adjacent layers and become discontinuous across steps (Fig. 2g). As the interlayer exchange strength is increased toward positive values, a first-order AFM-FM phase transition is reproduced, leading to an FM state where the domains remain continuous across the step edges (Fig. 2f). This correspondence establishes a direct connection between the simulated interlayer coupling and the experimentally observed domain continuity.

To quantify the interlayer coupling across steps, we define a discontinuity factor $f_{d,c}$, which characterizes the continuity of two-dimensional domains across steps with an odd number of layer-height differences (see “Methods”). In a fully AFM-coupled system, $f_{d,c}$ equals one, whereas $f_{d,c}$ equals zero corresponds to a fully FM-coupled system. In practice, values slightly below one can occur even in a fully AFM-coupled state, owing to the finite width of step edges and the irregular shapes of magnetic domains. Such deviations do not indicate lateral shifts of domains between adjacent layers but rather reflect geometric and morphological effects at the steps. The temperature dependence of $f_{d,c}$ shows a sharp drop near -170 K (Fig. 2h), providing a quantitative indication of a temperature-driven AFM-FM transition.

The magnetic domain pattern changes drastically during the AFM-FM transition (Supplementary Movie S1). Defects occasionally observed in LEEM images show little influence on the overall domain pattern or the magnetic phase transition, except for locally reducing or blocking the magnetic contrast. The evolution of domain morphology was further quantified by analyzing the domain size and shape (Fig. 2i). In the AFM phase, the domains exhibit greater shape variation, with an average domain width of approximately 0.54 μm . As the temperature increases, the domain width decreases and becomes more uniform. The temperature at which this morphological change occurs coincides with the AFM-FM transition identified from $f_{d,c}$, indicating a consistent evolution of domain morphology and interlayer coupling.

Identify the chirality of FCGT

Topologically nontrivial spin textures are of broad interest owing to their enhanced stability and potential applications. In two-dimensional

magnetic systems, magnetic chirality typically originates from the DMI. To explore possible topological spin structures in FCGT, we employed SPLEEM to resolve the three-dimensional spin configuration at the surface.

We utilized the ferromagnetic phase of bulk Fe_3GaTe_2 (FGT) as a reference system and investigated its magnetic structure, where the layer-dependent local spin configuration within magnetic domains is illustrated in Fig. 3a. The out-of-plane and in-plane magnetization components were resolved by SPLEEM (Fig. 3b, c, respectively). The domain walls consistently point from the $+M_z$ domains toward the $-M_z$ domains, revealing a right-handed chiral feature^{38,39} (Fig. 3c). Pronounced domain and domain-wall signals were observed experimentally, as evidenced by the line profiles (Fig. 3c, d). Considering the ferromagnetic nature and the relatively large thickness of the FGT sample, these right-handed domain walls are attributed to Néel caps^{40,41}, whose domain structure is stabilized by dipolar interactions.

We then examined FCGT in its antiferromagnetic phase, with the spin configuration schematically shown in Fig. 3e. Stripe-like out-of-plane domains are clearly observed in the SPLEEM images of AFM-FCGT (Fig. 3f), whereas no discernible in-plane magnetization component is detected at the domain boundaries, as confirmed by the absence of an in-plane signal in the corresponding line profiles (Fig. 3g, h). The lack of a resolvable in-plane domain-wall signal indicates that the system does not host dipolar interaction stabilized Néel caps, which are naturally suppressed in the antiferromagnetically stacked phase of FCGT due to the nearly quenched dipolar interaction resulting from antiparallel pairs of magnetic moments. Consequently, any chiral signal subsequently observed in FCGT cannot originate from dipolar Néel caps.

To enhance the sensitivity to domain-wall spin textures in FCGT, 0.5 monolayers (ML) of Co were deposited on the FCGT surface at approximately 100 K, while maintaining the FCGT in the antiferromagnetic phase. The magnetic domain pattern remains unchanged after Co deposition (Fig. 3j and Supplementary Fig. S6), indicating that the Co overlayer is ferromagnetically coupled to the topmost FCGT layer and follows its local magnetization. Following Co deposition, domain walls become clearly visible in the SPLEEM images (Fig. 3k). The ultrathin Co overlayer is ferromagnetically coupled to the topmost FCGT layer and follows its local magnetization (Supplementary Fig. S6). The enhanced domain-wall visibility may originate from a modification of the near-surface magnetic properties induced by the Co overlayer. Line profiles across the domain walls reveal correlated variations of the out-of-plane and in-plane magnetization components (Fig. 3l), enabling a direct real-space access to the right-handed chiral spin textures in van der Waals antiferromagnetic FCGT. We note that the additional dipolar effects introduced by the 0.5 ML thick Co overlayer are expected to be very weak, given that its thickness is significantly smaller than that of the FCGT under investigation. The observed chiral domain walls are therefore attributed to an intrinsic DMI, which can originate from the vertical displacement of Fe atoms, a mechanism previously identified in FGT systems and also observed in our samples^{18–20} (Supplementary Fig. S7).

Manipulate the domain patterns in AFM FCGT

To enable potential applications of FCGT in antiferromagnetic spintronic devices, a practical route to modulate its antiferromagnetic domain configuration is required. As shown by the magnetic hysteresis loop in Fig. 1e, the magnetization of FCGT remains zero and the hysteresis is closed within ± 1 T, indicating that the AFM domain structure in this fully compensated system cannot be efficiently manipulated by an external magnetic field (Supplementary Fig. S8), owing to strong interlayer antiferromagnetic coupling.

To overcome this intrinsic limitation, we exploit the temperature-driven AFM-FM phase transition in FCGT as an indirect control channel. In the ferromagnetic phase at relatively higher temperatures, the

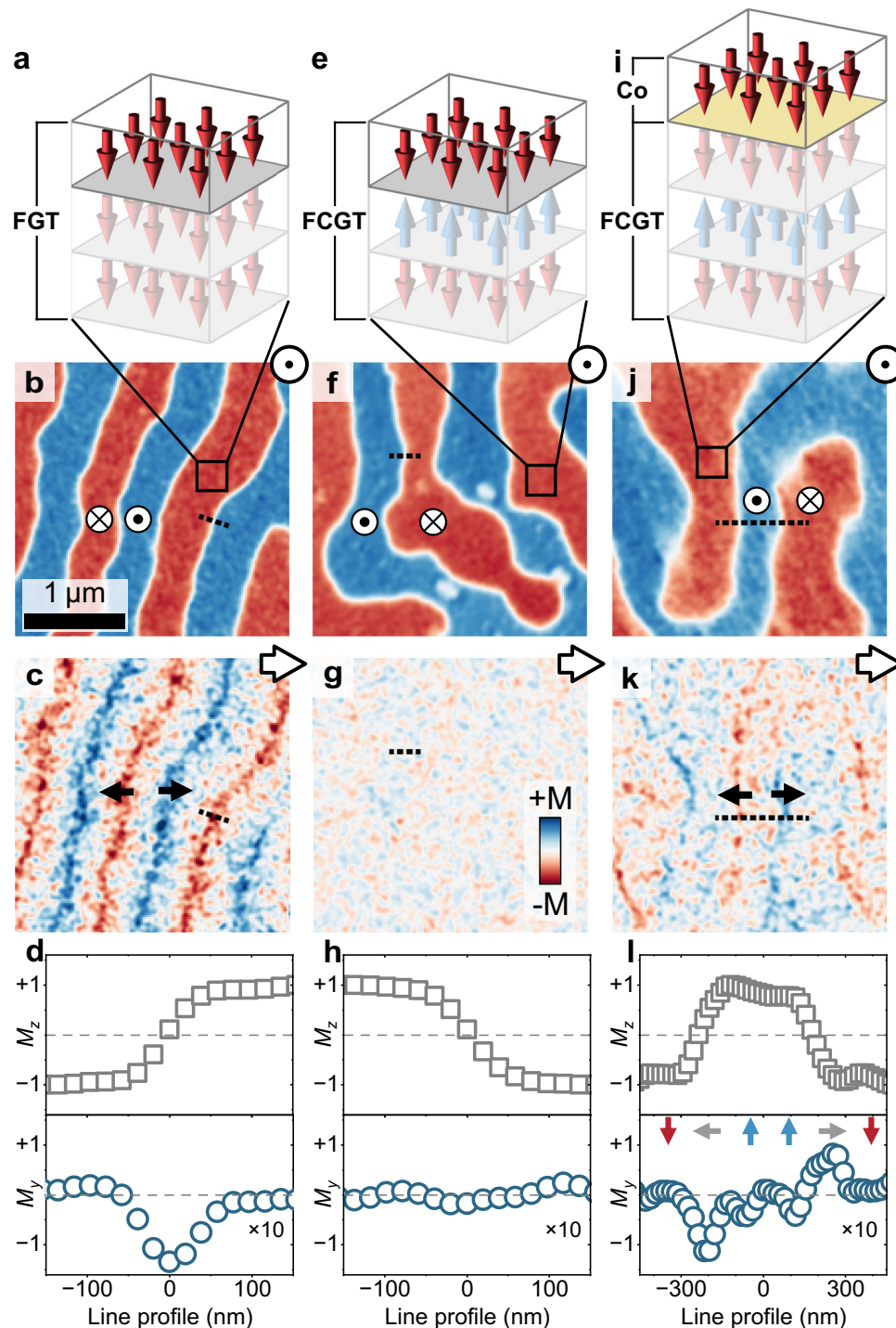


Fig. 3 | Chiral spin textures in van der Waals magnets. **a** Schematic illustrations of the near-top spin structures for FGT. **b, c** SPLEEM images of FGT at room temperature acquired with different incident electron polarizations; the polarization directions are indicated in the upper-right corners of the images, and the directions of domain magnetization are overlaid. Scale bar, 1 μm . **d** Line profiles of

magnetization across the domain boundaries, where M_z and M_y are extracted from the regions marked by dashed lines in (**b, c**). **e–l** Schematic illustrations, spin textures, and line profiles similar to those in (**a–d**) but for FCGT (**e–h**) and 0.5 ML Co/FCGT (**i–l**) at $\sim 100\text{ K}$.

magnetic domain pattern becomes susceptible to external magnetic fields, enabling deterministic modification of the domain morphology. To implement this approach, a perpendicular magnetic field of approximately 170 mT was applied using permanent magnets at selected temperatures, and the remanent magnetic states were subsequently imaged (see “Methods”).

Figure 4a summarizes the temperature and magnetic-field protocol that enables writing magnetic textures in the FM phase and

transferring them into the antiferromagnetic phase upon cooling. In the absence of an external field, the ground state of FCGT in the AFM phase consists of stripe domains (Fig. 4b), which remain insensitive to magnetic fields. In contrast, when the sample was heated into the paramagnetic phase and subsequently cooled into the FM phase under a perpendicular field, the FM domain pattern evolves from stripes into bubble-like domains with hollow cores (Fig. 4c). The hollow cores are similar to the cone-like central regions reported in the van der Waals

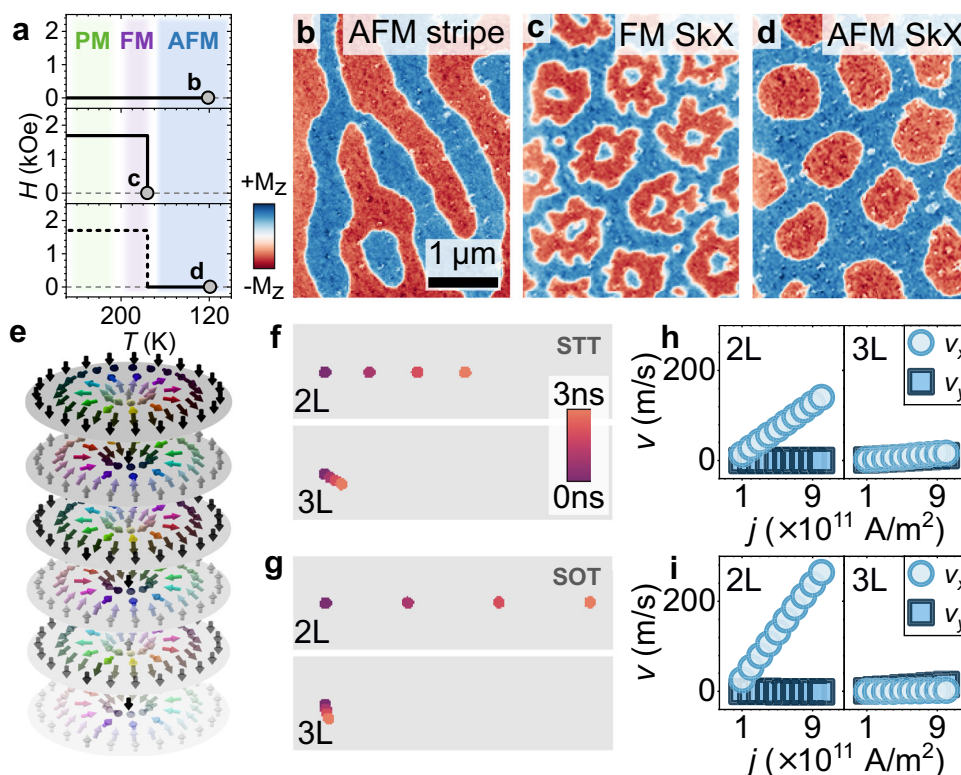


Fig. 4 | Generation and dynamics of AFM skyrmions. **a** Cooling history with an out-of-plane magnetic field used in **(b–d)**. **b** Stripe domains observed in the AFM phase of FCGT after zero-field cooling (scale bar, 1 μm). **c** Skyrmion lattice formed after field cooling into the FM phase. **d** AFM skyrmion lattice obtained by cooling

from **(c)** to the AFM phase under zero-field conditions. **e** Schematic illustration of an AFM skyrmion in A-type AFM multilayers. Trajectories of AFM skyrmions driven by **(f)** STT and **(g)** SOT in racetracks with different layer thicknesses. Skyrmion velocity driven by STT **(h)** and SOT **(i)**.

ferromagnet Fe_3GeTe_2 , which have been attributed to strong dipolar interactions and described as locally topologically trivial^{34,42}. Although the out-of-plane magnetization profile (Fig. 4c) may appear skyrmion-like, the corresponding magnetic texture remains topologically skyrmion-like^{40,43}. Reversing the field polarity leads to a corresponding reversal of the bubble contrast.

Upon further cooling through the FM-AFM transition, the bubble domains persist while their internal structure evolves. The bubbles become more circular and their hollow cores disappear as the system enters the AFM phase, resulting in an antiferromagnetic bubble lattice (Fig. 4d). This zigzag-to-smooth domain-boundary transition can be attributed to the strong suppression of dipolar interactions in the antiferromagnetic phase due to interlayer magnetic compensation. These results demonstrate that magnetic textures written in the ferromagnetic phase can be deterministically transferred and stabilized in the antiferromagnetic phase via the AFM-FM phase transition. Combined with the right-handed chiral spin textures identified earlier, the observed surface domain patterns are consistent with a two-dimensional skyrmion-like texture at the surface of FCGT. Because the intrinsic DMI has the same sign in each layer and the layers are antiferromagnetically coupled, the chirality is expected to be preserved along the stacking direction. Monte Carlo simulations of the subsurface spin structure reveal a layer-resolved chiral spin texture with antiparallel coupling between adjacent layers, supporting an antiferromagnetically coupled skyrmion configuration (Supplementary Fig. S9).

To further investigate antiferromagnetic skyrmion dynamics, micromagnetic simulations were performed based on this configuration (Fig. 4e), where both the polarity and the topological charge are reversed between adjacent layers. Simulations of current-driven motion show that skyrmions in racetracks with an even number of magnetic layers exhibit a vanishing skyrmion Hall effect due to

complete compensation of the topological charge⁴⁴, whereas a finite skyrmion Hall effect persists for odd numbers of layers (Fig. 4f, g). The current-driven skyrmion motion is significantly more efficient in compensated systems (Fig. 4h, i). While skyrmion velocities driven by spin-transfer torque are nearly independent of thickness in compensated systems, spin-orbit torque-driven motion shows a pronounced thickness dependence, with the velocity decreasing as the number of layers increases (Supplementary Fig. S10).

Discussion

Our results show that periodic multidomain states and chiral spin textures can be realized in intrinsic A-type van der Waals antiferromagnets, thereby addressing a previously unresolved question regarding their stability in the compensated phase. The present work focuses on the simplest magnetic configuration in layered A-type antiferromagnets, namely a fully antiferromagnetically coupled state between adjacent layers. Such imprinting of FM domain patterns into the AFM phase (Fig. 4d) requires an FM-AFM phase transition. In FCGT layered magnets, such transitions occur over a broad compositional range in both $(\text{Fe}_{1-x}\text{Co}_x)_3\text{GaTe}_2$ and $(\text{Fe}_{1-x}\text{Co}_x)_5\text{GeTe}_2$ ^{31,45}. In the A-type antiferromagnet MnBi_2Te_4 , surface anisotropy may stabilize domain boundaries at odd-even layer steps during magnetic-field-induced spin-flop transitions⁴⁶. We expect that similar AFM domain imprinting may also be possible in layered antiferromagnets with accessible FM-AFM phase transitions. Beyond this approach, antiferromagnetic domain configurations may also be controlled through alternative approaches, including intercalation⁴⁷, strain engineering⁴⁸, electrostatic gating⁴⁹, or interface design in heterostructures³², providing additional routes for tailoring antiferromagnetic spin textures. In the present work, antiferromagnetic skyrmion-like states are realized in FCGT, although their characteristic size remains relatively large⁵⁰. Materials design and optimization in van der Waals antiferromagnets

may therefore provide a pathway toward more compact and robust antiferromagnetic skyrmions. Finally, the present work focuses on the simplest magnetic configuration, namely a fully antiferromagnetically coupled state between adjacent layers. More complex magnetic textures may emerge under different conditions, such as antiferromagnetic stripe states with lateral shifts between neighboring layers or other nontrivial interlayer modulations^{23,24,51}. Whether such configurations can be stabilized in van der Waals antiferromagnets, and whether they host distinct or useful spin textures, remains an important question.

In summary, we directly access and control antiferromagnetic domain states in the two-dimensional van der Waals magnet FCGT. By combining surface-sensitive imaging, controlled magnetic phase transitions, and theoretical modeling, we reveal complex antiferromagnetic spin textures and demonstrate a practical route for engineering antiferromagnetic skyrmion-like states. Our work establishes a general strategy for accessing and manipulating antiferromagnetic spin textures in layered magnetic materials.

Methods

Sample preparation

The single-crystalline $(\text{Fe}_{0.81}\text{Co}_{0.19})_3\text{GaTe}_2$ (FCGT) samples were grown by a self-flux method³². High-purity Fe powders (99.95%), Co powders (99.998%), Ga lumps (99.9999%), and Te powders (99.99%) were mixed in a molar ratio of 1.7:0.3:1:2. The mixture was sealed in an evacuated quartz tube and heated to 1273 K at a rate of 5 K/min, and kept at this temperature for one day to ensure sufficient reaction. Subsequently, the temperature was slowly decreased to 1053 K at a rate of 1.8 K/h, followed by natural cooling to room temperature. Plate-like single crystals with a typical thickness of ~20 μm were obtained. The magnetic properties of the FCGT samples (Fig. 1e, f) were measured using a PPMS.

SPLEEM measurements were performed using an Elmitec SPLEEM III at the National Laboratory of Solid State Microstructures and the Department of Physics at Nanjing University. The bulk-like FCGT samples were mounted on a standard Elmitec cartridge, and fresh surfaces were prepared by in situ cleavage in the load-lock chamber under high vacuum before transfer into the main chamber. The pressure during cleavage was maintained below 10^{-7} Torr. The cleaved sample was annealed under ultra-high vacuum at 623 K for more than two hours to improve the surface cleanliness. The sample was controlled using a liquid-nitrogen-based cooling system by adjusting both the nitrogen flux and the heating current during measurements. A K-type thermocouple was used to measure the sample temperature. Co layers were deposited obliquely onto the sample surface by molecular beam epitaxy in the SPLEEM chamber (approximately 75° with respect to the surface normal). The Co film thickness was determined from oscillations of the LEEM intensity on a single-crystal Cu(001).

SPLEEM imaging and domain pattern analysis

In SPLEEM measurements, the sample was illuminated by spin-polarized electrons. Two images (LEEM_{up} and $\text{LEEM}_{\text{down}}$) were obtained using electrons with opposite spin polarization. The magnetic contrast in SPLEEM images was quantified by the spin asymmetry A , defined as $A = (\text{LEEM}_{\text{up}} - \text{LEEM}_{\text{down}}) / ((\text{LEEM}_{\text{up}} + \text{LEEM}_{\text{down}}))$. A is proportional to $\mathbf{P} \cdot \mathbf{M}$, where $\mathbf{P}$ is the spin polarization of the incident electrons and $\mathbf{M}$ is the surface magnetization of the sample. In the presence of strong spin-independent LEEM contrast (e.g., due to surface morphology), the spin asymmetry was further improved by normalization with a non-spin-polarized LEEM background. The energy of the incident electrons was 2.2–2.7 eV for FCGT and 1.5–1.6 eV for FGT, chosen to optimize the magnetic contrast. At this energy, the SPLEEM signal is expected to be dominated by the topmost layer of FCGT³².

To calculate the discontinuity of 2D domains crossing steps $f_{\text{d.c.}}$, the steps were extracted from the morphology LEEM image. Each

SPLEEM image was first binarized and smoothed, then down-sampled by a factor of 5 along the horizontal direction. $f_{\text{d.c.}} = (l_{+, -} + l_{-, +}) / L$ was calculated by comparing the sign of M_z on two sides of the steps (Supplementary Fig. S5). The lengths of the steps with two different configurations of M_z on each side are $l_{+, -}$ and $l_{-, +}$, respectively. The total length of the steps is L . The results plotted in Fig. 2h are based on the lower step in Fig. 2a. Domain widths were calculated by skeletonizing the binarized SPLEEM images and applying a straight-line Hough transform to extract lines representing domain orientation. The width of the domains was calculated by measuring the distance between the domain boundaries perpendicular to the lines.

Monte Carlo simulations

To investigate the transition between different magnetic ground states, Monte Carlo simulations were carried out. A 3D simulation space consisting of a cubic grid was built, and both intralayer and interlayer exchange interactions, perpendicular uniaxial anisotropy, dipolar interaction, and Néel-type DMI were taken into account. The Hamiltonian is written as:

$$H = -J_{\text{intra}} \sum_{\text{intralayer} < i, j >} \mathbf{S}_i \cdot \mathbf{S}_j - J_{\text{inter}} \sum_{\text{interlayer} < i, j >} \mathbf{S}_i \cdot \mathbf{S}_j - K_z \sum_i S_{z,i}^2 - D_{\text{dip}} \sum_{i,j} \frac{3(\mathbf{S}_i \cdot \mathbf{r}_{ij})(\mathbf{S}_j \cdot \mathbf{r}_{ij}) - \mathbf{S}_i \cdot \mathbf{S}_j}{r_{ij}^3} - \sum_{< i, j >} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) \quad (1)$$

where $\mathbf{S}_i$ and $\mathbf{S}_j$ are the spins at grid sites i and j , respectively, and $\mathbf{r}_{ij}$ is the position vector pointing from grid site i to j . The ground state was modulated by the parameters J_{intra} , J_{inter} , K_z , D_{dip} and D , which correspond to intralayer exchange, interlayer exchange, perpendicular magnetic anisotropy, dipolar interaction, and DMI, respectively. In the simulations, the temperature represents spin fluctuations according to Boltzmann statistics. The initial state is set to be completely random at a finite temperature, followed by annealing to a zero temperature. The simulation geometry is $150 \times 150 \times 4$ with an interlayer distance of 4. Periodic boundary conditions were applied in the in-plane directions, while open boundary conditions were used along the stacking direction. The truncation of dipolar interaction is set as 10. All simulations were iterated over 100,000 steps. The total energy versus iteration steps was checked, and the ground state was obtained when the energy changed less than 1×10^{-5} between successive iterations.

For the simulations presented in Fig. 2, $J_{\text{intra}} = 1$, $D_{\text{dip}} = 0.15$ and $D = 0.2$ were set. The FM phase (Fig. 2f) resulted from $J_{\text{inter}} = 0.50$, $K_z = 0.84$, while the AFM phase (Fig. 2g) was generated from $J_{\text{inter}} = -0.24$, $K_z = 1.04$.

Micromagnetic simulations

Micromagnetic simulations were carried out using MuMax3⁵³. The racetrack geometry is $512 \times 64 \times n$, where n is the number of layers. The size of each cell is $2.5 \text{ nm} \times 2.5 \text{ nm} \times 4 \text{ nm}$. Spin-orbit torque was introduced to the simulations using the method described in ref. 53. The simulation parameters were selected as follows: saturation magnetization $M_s = 1.4 \text{ MA/m}$, intralayer exchange stiffness $A_{\text{intra}} = 30 \text{ pJ/m}$, interlayer exchange stiffness $A_{\text{inter}} = -15 \text{ pJ/m}$, perpendicular magnetic anisotropy $K_z = 0.85\mu_0 \cdot M_s^2 \sim 0.90\mu_0 \cdot M_s^2$, interfacial DMI $D_{\text{Néel}} = 5 \text{ mJ/m}^2$, and damping constant $\alpha = 0.02$. For the STT condition, the non-adiabaticity of spin-transfer torque $\beta = 0.2$ and electrical current polarization $P = 0.4$. For the SOT condition, spin Hall angle $\theta_H = 0.2$, and the ratio of field-like torque to damping-like torque $\xi = -2$. The current density range is from $1 \times 10^{10} \text{ A/m}^2$ to $8 \times 10^{12} \text{ A/m}^2$ in both conditions. The magnetization in simulations was initially set to form skyrmions with different polarities and topological charges in adjacent layers. It was then relaxed to obtain the initial state. This initial state was then used in a series of simulations with the same geometry

and driving mechanism but different current values. The skyrmion's velocity is calculated from the center's displacement.

Data availability

The data supporting the findings of this study are available in the paper and its Supplementary Information. Raw SPLEEM data (including LEEM spin-up and spin-down images) are available from the corresponding authors upon reasonable request.

References

- Fert, A., Reyren, N. & Cros, V. Magnetic skyrmions: advances in physics and potential applications. *Nat. Rev. Mater.* **2**, 17031 (2017).
- Tokura, Y. & Kanazawa, N. Magnetic skyrmion materials. *Chem. Rev.* **121**, 2857–2897 (2021).
- Zhou, Y., Li, S., Liang, X. & Zhou, Y. Topological spin textures: basic physics and devices. *Adv. Mater.* **37**, e2312935 (2025).
- Jiang, W. et al. Direct observation of the skyrmion Hall effect. *Nat. Phys.* **13**, 162–169 (2017).
- Litzius, K. et al. Skyrmion Hall effect revealed by direct time-resolved X-ray microscopy. *Nat. Phys.* **13**, 170–175 (2017).
- Nagaosa, N. & Tokura, Y. Topological properties and dynamics of magnetic skyrmions. *Nat. Nanotechnol.* **8**, 899–911 (2013).
- Reichhardt, C., Reichhardt, C. J. O. & Milosevic, M. V. Statics and dynamics of skyrmions interacting with disorder and nanostructures. *Rev. Mod. Phys.* **94**, 035005 (2022).
- Gong, C. & Zhang, X. Two-dimensional magnetic crystals and emergent heterostructure devices. *Science* **363**, eaav4450 (2019).
- Gong, C. et al. Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals. *Nature* **546**, 265–269 (2017).
- Huang, B. et al. Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit. *Nature* **546**, 270–273 (2017).
- Deng, Y. et al. Gate-tunable room-temperature ferromagnetism in two-dimensional Fe_3GeTe_2 . *Nature* **563**, 94–99 (2018).
- Chen, W. et al. Direct observation of van der Waals stacking-dependent interlayer magnetism. *Science* **366**, 983–987 (2019).
- Xie, H. C. et al. Twist engineering of the two-dimensional magnetism in double bilayer chromium triiodide homostructures. *Nat. Phys.* **18**, 30–36 (2022).
- Burch, K. S., Mandrus, D. & Park, J. G. Magnetism in two-dimensional van der Waals materials. *Nature* **563**, 47–52 (2018).
- Blei, M. et al. Synthesis, engineering, and theory of 2D van der Waals magnets. *Appl. Phys. Rev.* **8**, 021301 (2021).
- Wu, Y. et al. Néel-type skyrmion in $\text{WTe}_2/\text{Fe}_3\text{GeTe}_2$ van der Waals heterostructure. *Nat. Commun.* **11**, 3860 (2020).
- Chakraborty, A. et al. Magnetic skyrmions in a thickness tunable 2D ferromagnet from a defect driven Dzyaloshinskii-Moriya interaction. *Adv. Mater.* **34**, e2108637 (2022).
- Li, Z. et al. Room-temperature sub-100 nm Néel-type skyrmions in non-stoichiometric van der Waals ferromagnet $\text{Fe}_{3-x}\text{GaTe}_2$ with ultrafast laser writability. *Nat. Commun.* **15**, 1017 (2024).
- Zhang, C. et al. Above-room-temperature chiral skyrmion lattice and Dzyaloshinskii-Moriya interaction in a van der Waals ferromagnet $\text{Fe}_{3-x}\text{GaTe}_2$. *Nat. Commun.* **15**, 4472 (2024).
- Lv, X. et al. Distinct skyrmion phases at room temperature in two-dimensional ferromagnet Fe_3GaTe_2 . *Nat. Commun.* **15**, 3278 (2024).
- Zhang, W. et al. Current-induced domain wall motion in a van der Waals ferromagnet Fe_3GeTe_2 . *Nat. Commun.* **15**, 4851 (2024).
- Guan, Y. et al. Highly efficient current-induced domain wall motion in a room temperature van der Waals magnet. *Nat. Commun.* **16**, 10790 (2025).
- Kiselev, N. S., Dragunov, I. E., Rössler, U. K. & Bogdanov, A. N. Exchange shift of stripe domains in antiferromagnetically coupled multilayers. *Appl. Phys. Lett.* **91**, 132507 (2007).
- Hellwig, O., Berger, A., Kortright, J. B. & Fullerton, E. E. Domain structure and magnetization reversal of antiferromagnetically coupled perpendicular anisotropy films. *J. Magn. Magn. Mater.* **319**, 13–55 (2007).
- Duine, R. A., Lee, K. J., Parkin, S. S. P. & Stiles, M. D. Synthetic antiferromagnetic Spintronics. *Nat. Phys.* **14**, 217–219 (2018).
- Pham, V. T. et al. Fast current-induced skyrmion motion in synthetic antiferromagnets. *Science* **384**, 307–312 (2024).
- Otrokov, M. M. et al. Prediction and observation of an antiferromagnetic topological insulator. *Nature* **576**, 416–422 (2019).
- Zhu, K. et al. Effect of Co or Ni substitution on magnetism in the layered van der Waals ferromagnet Fe_3GaTe_2 . *Phys. Rev. B* **109**, 104402 (2024).
- Wang, M. et al. Layer-number-dependent magnetism in the Co-doped van der Waals ferromagnet Fe_3GaTe_2 . *Nano Lett.* **24**, 4141–4149 (2024).
- Baltz, V. et al. Antiferromagnetic spintronics. *Rev. Mod. Phys.* **90**, 015005 (2018).
- Ahn, H. B. et al. Metamagnetic transition and meta-stable magnetic state in Co-doped Fe_3GaTe_2 . *Nanoscale* **16**, 20252–20259 (2024).
- Guo, H. et al. Layer-dependent spin-orbit torque switching of Néel vector in a van der Waals antiferromagnet. *Nat. Commun.* **16**, 8911 (2025).
- Rougemaille, N. & Schmid, A. K. Magnetic imaging with spin-polarized low-energy electron microscopy. *Eur. Phys. J. Appl. Phys.* **50**, 20101 (2010).
- León-Brito, N., Bauer, E. D., Ronning, F., Thompson, J. D. & Movshovich, R. Magnetic microstructure and magnetic properties of uniaxial itinerant ferromagnet Fe_3GeTe_2 . *J. Appl. Phys.* **120**, 083903 (2016).
- Konoto, M. et al. Direct imaging of temperature-dependent layered antiferromagnetism of a magnetic oxide. *Phys. Rev. Lett.* **93**, 107201 (2004).
- Sass, P. M., Kim, J., Vanderbilt, D., Yan, J. & Wu, W. Robust A-type order and spin-flop transition on the surface of the antiferromagnetic topological insulator MnBi_2Te_4 . *Phys. Rev. Lett.* **125**, 037201 (2020).
- Kiselev, N. S., Dragunov, I. E., Neu, V., Rössler, U. K. & Bogdanov, A. N. Theoretical analysis of magnetic force microscopy contrast in multidomain states of magnetic superlattices with perpendicular anisotropy. *J. Appl. Phys.* **103**, 043907 (2008).
- Chen, G. et al. Novel chiral magnetic domain wall structure in Fe/Ni/Cu(001) films. *Phys. Rev. Lett.* **110**, 177204 (2013).
- Chen, G. & Schmid, A. K. Imaging and tailoring the chirality of domain walls in magnetic films. *Adv. Mater.* **27**, 5738–5743 (2015).
- Legrand, W. et al. Hybrid chiral domain walls and skyrmions in magnetic multilayers. *Sci. Adv.* **4**, eaat0415 (2018).
- Hubert, A., Schäfer, R. *Magnetic Domains: The Analysis of Magnetic Microstructures* (Springer Berlin Heidelberg, 1998).
- Rybakov, F. N., Borisov, A. B., Blugel, S. & Kiselev, N. S. New type of stable particlelike states in chiral magnets. *Phys. Rev. Lett.* **115**, 117201 (2015).
- Zheng, F. et al. Experimental observation of chiral magnetic bobbles in B20-type FeGe. *Nat. Nanotechnol.* **13**, 451–455 (2018).
- Zhang, X. C., Zhou, Y. & Ezawa, M. Magnetic bilayer-skyrmions without skyrmion Hall effect. *Nat. Commun.* **7**, 10293 (2016).
- Tian, C. et al. Tunable magnetic properties in van der Waals crystals ($\text{Fe}_{1-x}\text{Co}_x$) $_5\text{GeTe}_2$. *Appl. Phys. Lett.* **116**, 202402 (2020).
- Yang, X. et al. Tailoring néel orders in layered topological antiferromagnet MnBi_2Te_4 . *Phys. Rev. Lett.* **135**, 266704 (2025).
- Wu, J. et al. Toward 2D magnets in the $(\text{MnBi}_2\text{Te}_4)(\text{Bi}_2\text{Te}_3)_n$ bulk crystal. *Adv. Mater.* **32**, e2001815 (2020).
- Das, J. & Menon, K. S. R. On the evolution of antiferromagnetic nanodomains in NiO thin films: a LEEM study. *J. Magn. Magn. Mater.* **449**, 415–422 (2018).

49. Tan, C. et al. Gate-controlled magnetic phase transition in a van der Waals magnet Fe₅GeTe₂. *Nano Lett.* **21**, 5599–5605 (2021).
50. Mishra, K. K., Lone, A. H., Srinivasan, S., Fariborzi, H. & Setti, G. Magnetic skyrmion: from fundamental physics to pioneering applications. *Appl. Phys. Rev.* **12**, 011315 (2025).
51. Kiselev, N. S., Rössler, U. K., Bogdanov, A. N. & Hellwig, O. Magnetic ground and remanent states of synthetic metamagnets with perpendicular anisotropy. *J. Phys. Conf. Ser.* **303**, 012051 (2011).
52. Bauer, E. Spin-polarized low energy electron microscopy. In: *Handbook of Magnetism and Advanced Magnetic Materials* (Wiley, 2007).
53. Leliaert, J. et al. Fast micromagnetic simulations on GPU—recent advances made with mumax³. *J. Phys. D Appl. Phys.* **51**, 123002 (2018).

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Author contributions

G.C. and Z. Luo conceived the study and coordinated the project. G.C. and H.D. supervised the SPLEEM facility. Z.C. carried out the experiments and analyzed the data. Z. Lin, H.G. and Z. Luo grew the FCGT crystals and performed the magnetic characterization. M.Y. grew the FGT crystals. H.G. and L.P. performed the TEM measurements. Z.J. and Y. Hao performed AFM characterization of the samples. H.Y.K. and C.W. performed Monte-Carlo simulations. Z.C. performed the Mumax3 micromagnetic simulations. Y. Han, Z.D., R.D. and G.Y. assisted with the

exploration of sample surface preparation. Z.C., H.Z., H.N., L.S., B.M., T.M., J.Y., Y.W., C.W., H.D, Z. Luo, and G.C. discussed and interpreted the results. Z.C. and G.C. prepared the manuscript. All authors commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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