Observation of magnetic skyrmion crystals in a van der Waals ferromagnet Fe₃GeTe₂

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Since the discovery of long-range magnetic orders in the two-dimensional (2D) van der Waals (vdW) crystals, significant interest on such 2D magnets has emerged, inspired by their appealing physical properties and integration with other 2D family for unique heterostructures. In known 2D magnets such as CrGe₂Te₆, CrI₃ and Fe₃GeTe₂, spin-orbit coupling (SOC) stabilizes perpendicular magnetic anisotropy (PMA) down to one or few monolayers. Such a strong SOC could also lift the chiral degeneracy, leading to the formation of topological magnetic textures such as skyrmions through the Dzyaloshinskii-Moriya interaction (DMI). Here, we report the experimental observation of magnetic skyrmions and their ordered crystal structures in a vdW ferromagnet Fe₃GeTe₂ flake. Using high-resolution scanning transmission X-ray microscopy (STXM) and Lorentz transmission electron microscopy (LTEM) measurements, we demonstrate that a skyrmion crystal (SkX) state in Fe₃GeTe₂ can be generated by both dynamically using current pulses and statically using magnetic field-cooling process, where our LTEM measurements suggest that the observed skyrmions in SkX state are Néel-type. We also present the current-driven motion of these skyrmions in Fe₃GeTe₂, which is the essential requirement for any skyrmion-based spintronic device. Using first principle calculations, we further unveil the possible origin of DMI being the oxidized FGT (O-FGT) at interfaces. Otherwise Bloch-type magnetic textures appear in a FGT heterostructure without any interface oxidation. Our finding opens the door to chiral magnetism and topological spin textures in the 2D vdW magnet, which will pave a new avenue towards 2D magnet-based topological spintronics.

I. INTRODUCTION

Two dimensional (2D) van der Waals (vdW) crystals have been significantly highlighted as a unique material platform, mainly due to their fascinating physical properties, low-cost fabrication and high integrability to produce appealing artificial heterostructures [1,2]. Recent addition of magnetic vdW crystals, where intrinsic long-range magnetic orders were observed in CrGe₂Te₆ and CrI₃, offered a new building block to this platform, opening a whole new door to vdW magnet-based spintronics [3–10]. Therefore, significant following interests have emerged and rapidly demonstrated few key elements for applications, including the magnetoresistance (MR) effects [5,6] and gate-tunable room-temperature magnetism [7].

Whereas the long-range magnetic order is often suppressed in vdW crystals due to thermal fluctuations given by Mermin-Wagner theorem [11], strong spin-orbit coupling (SOC) in vdW magnets plays an essential role in stabilizing the perpendicular magnetic anisotropy (PMA) and thus
overcomes the thermal fluctuations down to a monolayer limit [4,7]. In a material with such large SOC and broken inversion symmetry, the anti-symmetric exchange interaction, so called Dzyaloshinskii-Moriya interaction (DMI) [12,13], can emerge and be strong enough to stabilize topological magnetic configurations including skyrmions [14,15]. Recent theoretical works have also discussed the emergence of DMI in vdW magnets with various possible origins, e.g. crystal symmetry or sample boundary, as well as resulting skyrmion stabilization [16–18]. However, experimental demonstration of chiral magnetic configurations or skyrmions in such vdW magnets has remained elusive and challenging.

Here we present the observation of magnetic skyrmions and their ordered crystal structures in a vdW ferromagnetic Fe$_3$GeTe$_2$ (FGT hereafter). Among various types of vdW magnets, FGT exhibits relatively high ferromagnetic transition temperature ($T_C$), large PMA, and metallic nature that enables efficient charge/spin transport suitable for spintronic applications [7,19]. In this study, we utilize high spatial resolution magnetic imaging techniques, scanning transmission X-ray microscopy (STXM), Lorentz transmission electron microscopy (LTEM) and differential phase contrast microscopy (DPCM) to directly observe magnetic structures in the FGT flake. We first show the dynamic generation and stabilization of skyrmion crystal (SkX, also referred to as skyrmion lattice) state in the FGT flake, where strong pulse-induced thermal fluctuations transform magnetic domains into SkX. We then examine the stability of SkX against thermal fluctuation and magnetic fields, which eventually constitutes experimental phase diagram of SkX state. Moreover, we demonstrate the static generation of magnetic skyrmions and SkX using a magnetic field applied along an oblique direction. Taking advantage of in-plane magnetization sensitivity in LTEM and DPCM measurements, we further evidence the chiral nature of skyrmions stabilized in the SkX state. Moreover, we present the current-driven motion of skyrmions, where we drive isolated individual skyrmions by short current pulses along a FGT racetrack at speeds approaching a meter per second. Finally, using first principle calculations, we demonstrate the presence of significant interfacial DMI at partially oxidized FGT crystals and interfaces, which may have contributed to skyrmion stabilization observed in experiments.
II. RESULTS

A. Crystal structure and domain configuration

Figure 1a schematically shows the crystal structures of mono-layered FGT viewed from $xy$ and $yz$ planes and bi-layered FGT exhibiting vdW bonding between monolayers. Each FGT monolayer consists of a Fe$_3$Ge covalently bonded slab and two Te layers placed above and underneath the Fe$_3$Ge, and each layer is separated by a 2.95 Å vdW gap in multi-layered stack [20]. Within a Fe$_3$Ge slab, two inequivalent Fe sites exist, Fe$^{II}$ (the valence states of Fe$^{2+}$) and Fe$^{III}$ (the valence states of Fe$^{3+}$). Overall, the reduced bulk crystal symmetry in FGT is known to provide a magnetocrystalline anisotropy in FGT due to increased thermal fluctuations. Using this slanted area, we can drive the magnetization into multi-domain states where the domain state, where the reduced magnetic anisotropy of FGT at higher temperature range, 100 K $\leq T \leq 200$ K, and the slanted area becomes more prominent as temperature increases. This area indicates the presence of multi-domain state, where the initially nucleated domains at sharp but incomplete switching propagate across the film, originating from the reduced magnetic anisotropy of FGT at higher temperature due to increased thermal fluctuations. Using this slanted area, we can drive the magnetization into multi-domain states at low temperatures and near zero magnetic fields, as shown in Fig. 1d. Red and blue curves indicate down-to-up and up-to-down switching at 120 K, respectively. For example, at a down-(up-) magnetization saturation state, increasing (decreasing) magnetic field just enough to generate multi-domain states and then subsequently reversing the field drives the overall magnetization into multi-domain states near zero magnetic field. This technique was employed to generate multi-domains during STXM, which require large moments and multi-domain states for high contrast observations.
Figure 2a shows the schematic of STXM experimental setup, where the temperature of cooling stage was controlled between 100 K ≤ T ≤ 300 K using liquid nitrogen (LN₂) and heat-exchanger. The scanning electron microscopy (SEM) image of measured FGT device with Hall-cross geometry and the electrical circuit diagram is also included in Fig. 2a [see Methods for details]. The magnetization state of FGT device was imaged by probing the intensity of transmitted circularly-polarized X-ray at the Fe-edge (L₃ absorption edge), where X-ray magnetic circular dichroism (XMCD) provides contrasts corresponds to the out-of-plane magnetization. Figure 2b shows the magnetic domain configurations in the FGT device as a function of out-of-plane magnetic field, Bₕ, at 120 K, which confirms strong magnetic contrast observable in FGT from STXM measurements. Note that the alternative field-sweep procedure (Bₕ = +200 mT → −60 mT → 0 mT) described in Fig. 1d was used to generate the initial magnetic configuration at zero field, Bₕ = 0 mT. The dark and bright contrasts in STXM images correspond to downward (−M₀) and upward (+M₀) out-of-plane magnetization direction of Fe atoms in FGT, respectively. With increasing out-of-plane field Bₕ > 0, the up domains expand while the down domains shrink into narrow domains, vanishing at the saturation field of Bₕ = +80 mT.

B. Dynamic generation and stabilization of SkX

Having established that multi-domain states can be readily stabilized and observed in FGT, we then examined the current-induced generation of magnetic skyrmions, as summarized in Fig. 3. In our previous study using conventional chiral ferromagnetic multi-layers, Pt/CoFeB/MgO, we demonstrated that the application of bipolar pulses could transform labyrinth domains with chiral domain walls into multiple skyrmions [23], and the recent study by Lemesh et al. [ref. [24]] unveiled the mechanism to be current-induced thermal transformation into skyrmions, because the energy barrier towards the global skyrmionic ground state decreases with increasing temperature. To utilize the same technique on the FGT device, we applied the burst of 100 bipolar pulses, where the pulse frequency of 1 MHz, the peak-to-peak voltage of Vpp = 2.96 V and the pulse width of 10 ns were used at Bₕ = −40 mT and 120 K. As shown in Fig. 3a, it is obvious that the bipolar pulse injection transformed the labyrinth random domain state into multiple circular domain state, where these circular domains turn out to be chiral magnetic skyrmions in Fig. 4. We performed the same procedure at slightly lower temperature, 100 K, and the consistent transformation into multiple skyrmions is observed and the generated skyrmions remain stable at zero magnetic field, Bₕ = 0 mT (highlighted in a blue-boxed area in Fig. 3a). As was observed in ferromagnetic chiral multi-layers, the thermal excitation induced by the bipolar pulses may have opened a path towards global skyrmionics state [23,24]. We examined and observed the consistent domain transformation in another sample capped by graphite, as shown in Supplementary Fig. S3 [22]. This demonstration with graphite-capping is significant, as it excludes two possible contributions from Pt: i) the spin-orbit torques (SOTs) by transmitted spin current caused by the spin-Hall effect (SHE) in Pt [25] and ii) the DMI contribution from Pt/O-FGT interface. Additional Hall measurements presented in Supplementary Fig. S4 also confirm the negligible influence from capping materials on the magnetic properties of studied FGT structure [22]. Further analysis reveals that the average size of zero-field skyrmion is ~123 nm at 120 K, and the size decreases down to ~80 nm with increased density at 160 K [see Supplementary Fig. S5 [22] for details].

At such disordered multi-skyrmion state at 100 K, we applied alternative positive and negative magnetic fields with increasing magnitude up to Bₕ = ±80 mT with the step of Bₕ = ±10 mT, as the application of static fields could annihilate pinned weak skyrmions and rearrange them driven by inter-skyrmion repulsive forces, leading to the stabilization of ordered skyrmion state [26,27]. Figure 3b shows the zero-field magnetic configuration after the field sweep, and surprisingly, the initial disordered magnetic skyrmions transformed into ordered hexagonal SkX. The inset of Fig. 3b presents the enlarged STXM images at a magnetic field, Bₕ = −80 mT, where the ordered SkX state is more clearly observable (few SkXs are highlighted with blue colors and white lines for guide). The symmetry of SkX also agrees with the symmetry observed in non-centrosymmetric B20-type chiral magnets [14,15]. After stabilizing the SkX state, we then plotted the experimental phase diagram of magnetic configurations in FGT, based on the real-space STXM measurements as summarized in Fig. 3c. We observed three magnetic configuration phases: i) SkX, ii) the co-existence of SkX and multi-domains, and iii) saturated ferromagnetic states, where the representative STXM images of each state are included in the right panel of Fig. 3c. It should be noted that, once generated, SkX in FGT can be stabilized at a wide range of magnetic field and temperature. Moreover, SkX state remains stable at zero magnetic field. Together with the recent discovery of gate-tunable room-temperature magnetization in the same material [7], it might also be possible to harness and manipulate magnetic skyrmions and their lattice at room temperature and zero magnetic fields, which may constitute a major step towards room-temperature skyrmion applications based on vdW magnets.

C. Lorentz transmission electron microscopy (LTEM) study of SkX

To deeply understand magnetic configurations observed by STXM measurements, we first performed the LTEM measurement as summarized in Fig. 4 (see Methods for details [22]). Note here that Fresnel-LTEM is useful to detect the in-plane components of Bloch-type spin spirals at
FIG. 3. Generation and stabilization of magnetic skyrmion lattice phase. (a) The two images on the left side were acquired at \( B_z = -40 \text{ mT} \) at 120 K and 100 K after the initial saturation at \( B_z = +200 \text{ mT} \), respectively, where an initial labyrinth domain states were stabilized. The right two images at \( B_z = +40 \text{ mT} \) were acquired after the application of bipolar pulse bursts at 120 K and 100 K, respectively, and the other two images at \( B_z = 0 \text{ mT} \) were acquired after removing magnetic fields. Scale bar, 1 μm. (b) Representative STXM image of skyrmion crystal (SkX) stabilized over the whole FGT device at \( B_z = 0 \text{ mT} \) and \( T = 100 \text{ K} \). Scale bar, 2 μm. For clarity, the enlarged image of SkX was obtained at \( B_z = -80 \text{ mT} \). Scale bar, 1 μm. The hexagonal white lines are drawn to guide eye for the ordered SkX, and the inset schematic represents the exemplary magnetic configuration of SkX found in chiral magnets for comparison. Note that skyrmion polarity in b (-M\(_z\) core) is different from a (+M\(_z\) core), as the initial field-sweep procedure of reversed field direction was used before the pulse application: \( B_z = -200 \text{ mT} \rightarrow +40 \text{ mT} \). (c) Experimental phase diagram of magnetic configurations as a function of temperature and magnetic field. Experimentally measured positions are marked with open circles, and star symbols correspond to exemplary images shown on the right side of the phase diagram. Three representative images show each magnetic configuration state: SkX, SkX + multi-domains, and saturated ferromagnet (FM). Scale bar, 1 μm. Black dashed lines in phase diagram are guide to the eyes to indicate the phase boundaries.

defocused modes, whereas it cannot directly observe Néel-type magnetic configurations with zone-axis beam irradiation, due to the cancellation of magnetic inductions between electrons and symmetric in-plane magnetic moments with opposite directions projected by Néel-type spin textures [28–30]. However, when samples are tilted away from the zone-axis, the projected configurations of up-down magnetic domains should contribute to the LTEM contrasts at defocused modes, therefore, Néel-type magnetic configurations can be observed [27–30].

Figure 4a first shows in- and de-focus LTEM images of the FGT sample tilted about −20° along the x-axis at zero field and 160 K, where dark/bright contrasts are only visible in defocused images. Moreover, as shown in the red-boxed areas in the left and right images in Fig. 4a, under- and over-focus LTEM images exhibit the labyrinth domain structures with reserved domain wall contrasts, indicating a multi-domain state in the FGT flake at zero field [29–31], in agreement with STXM results. To generate SkX, we then performed the field cooling (FC) of FGT flake with an
oblique magnetic field of $B = -40$ mT (the oblique angle is 20° to the zone-axis). Figure 4b shows LTEM images observed at 160 K. Noticeably, the FC generated quasi-static (metastable) chiral SkX state in FGT crystal, which magnetic configurations as well as in-plane magnetization profiles agrees well with simulated LTEM results as shown in Fig. 4c (see Methods and Fig. S6 [22] for details). Considering that the oblique field applied during the LTEM measurements could have contributed to the in-plane alignment of magnetic moments within FGT domain walls, we have performed LTEM observations of SkX at zero field after the same FC process as described above, which confirmed the robustness of FC-driven static SkX (Fig. S7 [22]).

D. Current-driven motion of isolated skyrmions

To further highlight the potential of FGT-based skyrmion devices, we next demonstrate the current-driven motion of skyrmions in this material, as summarized in Fig. 5. Figure 5a shows a schematic image of the FGT track and electric contacts fabricated on Si$_3$N$_4$ membrane for STXM measurements. Note that a thin h-BN vdW flake is used as a capping material on FGT, where the FGT layer is sandwiched by two O-FGT as was also shown in Fig. 1b. In this experiment, we first generated initial few-skyrmion-state (as shown in the first image of Fig. 5b) by applying external magnetic field to the multi-skyrmion state acquired by the current-driven skyrmion generation process described in Fig. 3, while an oblique magnetic field of $B = -50$ mT (the oblique angle is 30° to the zone-axis) was applied at $T = 100$ K. In Fig. 5b, each image was obtained after injecting 5 current pulses with $J_d = 1.4 \times 10^{11}$ A/m$^2$ and $t_{\text{pulse}} = 50$ ns. The current was applied along the +x direction, opposite to the electron flow along -x direction as schematically indicated in each image.

It is first noteworthy that skyrmions move upon the application of current pulses, and the propagation direction is along the electron-flow direction (against current flow), where this directionality indicates that skyrmion are driven by spin-transfer torques (STTs) arising within the FGT. This is also expected from the HRTEM image shown in Fig. 5a, exhibiting no possible interface of FGT that could provide vertical spin current by e.g. SHE. As shown in Fig. 5c, the average skyrmion velocity was measured to be ~ 1 m/s at a current density $J_r = 1.4 \times 10^{11}$ A/m$^2$, below which no skyrmion motion is observed. The current-driven motion of skyrmion shows the potential of using skyrmions in FGT for functional device applications, such as the racetrack-type memory [32], where skyrmions act as moveable information carriers.

It should also be noted that, although we initially observed three stabilized skyrmions (Sk1-3), only one skyrmion (Sk2) remains stable and propagates along the track during the their motion. We speculate such non-ideality may come from the interplay between various magnetic parameters in FGT that sharply changes with temperature, which then alters skyrmion stability as was experimentally navigated in Fig. 3c. However, we believe that further experimental studies of skyrmion motion in FGT using more efficient torques, e.g. SOTs, could substantially improve their electrical controllability and current-velocity relation [32].
broken inversion symmetry of sublayers in FGT could result in the DMI that stabilizes Néel-type skyrmions, all possible DMI contributions in the whole FGT monolayer structure cancel each other as discussed and summarized in Supplementary Fig. S8 and Supplementary Table S1 [22]. For example, similar to the case of 2D hexagonal boron nitride structure with buckling [35], the top FeIII sublayer and neighboring Te layer form a lattice of C3v point group with broken inversion symmetry, the interfacial DMI could be induced at the top FeIII sublayer via the superexchange along the FeIII-Te-FeIII path. However, due to the reflection symmetry of the system, the DMI contributions induced at the top and bottom FeIII sublayers are cancelled with each other and the net DMI in the whole FGT structure vanishes.

In order to elucidate the possible origin of DMI at atomic level, we performed first principles calculations employing the approach used for multi-layers comprising magnetic and heavy metals [36], oxides [37] and graphene [38] (see Methods for details [22]). We first verified that the DMI for symmetric FGT structure indeed vanishes as discussed above. For FGT crystal monolayer the calculated DMI, arising at both Fe/Te interfaces is of almost equal magnitude with opposite sign yielding negligible DMI as expected from aforementioned crystal symmetry analysis (Fig. S9a [22]). This in agreement with SOC energy difference associated with the total DMI, \( \Delta E_{SOC} \) for the same FGT crystal monolayer presented in Fig. S9b [22].

We next investigated other possible mechanisms of induced DMI by examining global and local atomic distributions along FGT crystal and its interfaces. Figure 6a shows atomic concentrations across the sample acquired using the quantitative high-angle annular dark field detector (HAADF) installed in scanning transmission electron microscopy (STEM) (see Supplementary Fig. S2 [22] for elemental mapping images). One can note first that the concentration of each atom along the thickness of sample within the pure FGT crystal region is symmetric and homogeneous, implying that the DMI owing to asymmetric distribution of elemental content in bulk material, as presented in ref. [39], can be excluded in this case. However, it is noteworthy that there exists significant atomic concentration fluctuation at two FGT/O-FGT interfaces. In particular, the concentration of Te atom at both interfaces rapidly decreases and vanishes upon oxidation, while Fe and Ge concentrations only fluctuate and recover their original values near the largest oxidation areas (oxygen peaks). Fig. 6b shows the relative atomic concentration distribution between Te and O atoms, where their sum and difference are plotted. It becomes clearer that, while their total concentration (Te+O) fluctuates within 10–15%, their concentration difference (Te-O) rapidly decreases from the initial bulk value of Te, ~ 30%, to its negative value, ~ -30%,
around oxygen concentration peaks. This distribution variation between Te and O elemental contents strongly implies that Te atoms are likely substituted by O atoms, forming Fe₄GeTe₂ₓOₓ over few nanometers of oxidized interfacial regions. Furthermore, one cannot exclude oxygen addition scenario at the interfaces as well. Therefore, we performed systematic calculations of microscopic and micromagnetic DMI parameters (d and D), for both O-substitution and O-addition scenarios using single crystal monolayer and bulk FGT structures (Figs. 6c-j). In both scenarios, we found that the DMI is anisotropic in plane yielding \( d_{[100]} \neq d_{[110]} \) (Figs. 6c-i). Of note, similar behavior was also reported for out-of-plane magnetized bcc Au/Co/W structures [40]. For O-substitution case, we find that the single crystal monolayer DMI is nonmonotonic as a function of oxygen concentration, being weakly anticlockwise (resp. strongly clockwise) for low (resp. high) concentrations (Figs. 6d-f). As for the case of O-addition scenario, the DMI strength monotonically increases as a function of oxygen concentration, although \( d_{[100]} \) and \( d_{[110]} \) configurations give opposite DMI chirality (Fig. 6g-i). Regarding the DMI in the bulk O-substituted FGT structures, very importantly, we found additional DMI contributions arising from the proximity of pure FGT cell with the oxidized layer O-FGT. For instance, it follows from \( \Delta E_{SOC} \) distribution shown in Fig. 6j, that O-FGT and FGT parts of this bulk structure provide clockwise [100] DMIs with -0.6 meV and -0.8 meV contributions, respectively, resulting in total value of -1.4 meV indicated by black solid square in Fig. 6f. The difference of about -1 meV between the total DMI values for the bulk O-FGT/FGT and O-FGT fully oxidized single crystal monolayer (open square in Fig. 6f), clearly indicates the large clockwise DMI contribution associated with the bulk FGT part in this structure. Similar conclusions can be deduced for [110] structure. As for O-addition scenario, these net FGT bulk contributions in O-FGT/FGT resulting from oxygen gradient within the structure are significantly smaller (Fig. 6i).

Using these theoretical findings, we can now analyze the resulting DMI in our samples supposing that these oxidation scenarios occur within interfacial areas with transient Te-O concentration represented by shaded areas in Fig. 6b, with top (5.9 nm) oxidized region being thicker compared to the bottom one (3.3 nm). These relatively thick regions with variable oxidation rate within them suggest that the DMI is not “localized” at narrow interfaces between atomic layers. Instead, the whole thickness regime with a finite oxidation gradient serves as DMI-enhancing layer across few nanometers, which works together with Heisenberg exchange, dipolar energy and anisotropy, leading to the formation of chiral magnetic skyrmions and their lattices observed here. Although two O-FGT/FGT interfaces are

FIG. 6. First principles calculations of Dzyaloshinskii-Moriya interaction (DMI) in FGT crystal and interfaces. (a) Atomic concentration distribution of Fe, Ge, Te and O atoms across sample thickness within the FGT crystal used for STXM measurements. (b) Relative distribution of Te and O atomic concentrations, i.e. their sum and difference across the FGT sample thickness. (c) Top views of relaxed crystal of oxygen-substituted Fe₄GeTe₂ₓOₓ (x = 1) relaxed structure showing DMI vectors in (d) [100] and (e) [110] directions. (f) The calculated DMI parameters in [100] and [110] in-plane directions as a function of oxygen substitution concentration of Fe₄GeTe₂ₓOₓ monolayer (x = 0, 0.25, 0.5, 0.75, 1). Solid symbols show the DMI values for O-FGT/FGT bulk structures. (g) and (h) The side view of oxygen-added FGT structures along [110] and [110] directions. (i) The same as (f) for oxygen addition concentration. (j) Side view of bulk O-FGT/FGT[100] structure and layer-resolved SOC energy difference, \( \Delta E_{SOC} \), associated with DMI distribution.
symmetrically present in our FGT sample and therefore may counteract, the magnitudes of DMI in these interfaces may be very different due to largely asymmetric oxidation profile and aforementioned scenarios (substitution and addition). In fact, even in case of only substitution scenario present, the overall net clockwise DMI will be present due to oxidation region asymmetry. Moreover, both O and Te interfacial gradients favors O-substitution scenario which gives rise to clockwise DMI provided by FGT adjacent layers.

To further corroborate our ab-initio study, we performed additional microscopy imaging experiments on another FGT flake heterostructure without any O-FGT interfaces, as shown in Fig. S10. In this experiment, we used DPCM by configuring the TEM in low-mag. scanning mode (STEM), which enables the direct measurement of the in-plane magnetic components in focus and at zero-tilt [41]. The DPCM measurement and analysis suggest that the observed magnetic textures are Bloch-type, where the same magnetization textures were confirmed to be Bloch-type in LTEM measurements as well, as presented in Fig. S11. The marked absence of Neél-type skyrmions suggests that there is no interfacial DMI present.

Nevertheless, we believe further systematic experimental studies probing the dependence of spin textures on the total FGT thickness, and/or the internal magnetization profile of skyrmions from top to bottom layers in FGT considering the role of van der Waals interactions could shed light into more precise tailoring of DMI and resulting magnetic textures in FGT crystal and heterostructures.

III. CONCLUSIONS

In summary, we observed chiral magnetic skyrmions and their lattice phase stabilization in a vdW ferromagnet FGT using high resolution magnetic microscopy. We examined the stability of SkX in FGT over a wide range of temperatures and magnetic fields, including its zero-field manifestation. We also demonstrated current-driven motion of individual skyrmions in FGT, highlighting its potential for device applications. We performed symmetry analysis and first principles calculations to unveil the origins of the emergent Neél-type spin textures, namely DMI in the FGT crystal at its oxidized interfaces. The possibility to achieve magnetic skyrmions and their lattice phase in vdW magnets marks a significant advance in vdW magnet-based spintronics. Along with the large potential of skyrmions for future spintronic devices to store, process, and transmit data with extremely low power cost, this work will pave a road towards vdW magnet-based topological spintronics.

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Author contributions
S.W. designed and conceived the study. T.-E.P. prepared films, fabricated devices and performed device characterizations with the support from S.J.K. K.M.S., K.K.
and Y.D.K., T.-E.P., K.M.S., K.K., M.W., S.F., J.R. and S.W. performed STXM experiments at BESSY II in Berlin, Germany and at Swiss Light Source in Villigen, Switzerland. L.P. and X.Z.Y. performed Lorentz-TEM experiments and analyzed the data. F.S.Y. performed DPCM and Lorentz-TEM experiments on non-oxidized FGT and analyzed the data. J.L., A.H., A.F., M.C. and H.Y. performed the ab initio calculations on DMI in FGT crystal, and analyzed the results. X.Z., J.X., Y.Z., M.E. and X.L. provided symmetry analysis on DMI in FGT crystal. T.-E.P. drafted and L. P., X.Z., X.Z.Y., F.S.Y. and S.W. revised the manuscript and all authors reviewed the manuscript.

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Competing Interests.
The authors declare no competing interests.

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