Large-scale epitaxy of two-dimensional van der Waals room-temperature ferromagnet Fe₅GeTe₂

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In recent years, two-dimensional van der Waals materials have emerged as an important platform for the observation of long-range ferromagnetic order in atomically thin layers. Although heterostructures of such materials can be conceived to harness and couple a wide range of magneto-optical and magneto-electrical properties, technologically relevant applications require Curie temperatures at or above room temperature and the ability to grow films over large areas. Here we demonstrate the large-area growth of single-crystal ultrathin films of stoichiometric Fe₅GeTe₂ on an insulating substrate using molecular beam epitaxy. Magnetic measurements show the persistence of soft ferromagnetism up to room temperature in 12 nm-thick films, with a Curie temperature of 293 K, and a weak out-of-plane magneto-crystalline anisotropy. The ferromagnetic order is preserved in bilayer Fe₅GeTe₂, with Curie temperature decreasing to 229 K. Surface, chemical, and structural characterizations confirm the layer-by-layer growth, 5:1:2 Fe:Ge:Te stoichiometric elementary composition, and single-crystalline character of the films.

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INTRODUCTION

Until recently, long-range magnetic ordering was not thought possible in two-dimensional (2D) systems. The Mermin-Wagner theorem states that thermal fluctuations in a low-dimensionality isotropic Heisenberg model block the emergence of ferromagnetism (FM). In 2017, ferromagnetism was observed in exfoliated flakes of the 2D van der Waals (vdW) materials Cr₃Ge₂Te₆ and CrI₃. These materials are electrical insulators, exhibit perpendicular magnetic anisotropy (PMA), and have Curie temperature (Tc) well below room temperature (RT). The prevailing understanding is that long-range ferromagnetic order in 2D vdW systems survives due to the spin-wave excitation gap opened by the strong intrinsic magneto-crystalline anisotropy (MCA). 2D vdW materials became a rich platform to explore low-dimensionality magnetism, and in a few years, the list of 2D vdW FMs increased with the addition of Fe₅GeTe₂, Fe₃GeTe₂, Fe₂GeTe₄, and Fe₅Ge₂Te₂. Fe₄Ge₁₇Te₂ (FGT) ternary compounds in particular stood out due to their itinerant ferromagnetism, which is of great interest for spintronic applications.

Among the family of 2D vdW FMs, FGT compounds host a variety of noticeable magnetic effects, namely large anomalous- and planar topological Hall effect, magnetic skyrmions, Kondo lattices, and giant tunneling magnetoresistance. To the best of our knowledge, the highest Curie temperatures of the Fe₅Ge₃Te₁₁ family are 310 K, Fe₃GeTe₂ exhibits a Tc of 230 K, and Fe₅Ge₂Te₂ with Tc~310 K. Fe₅GeTe₂ exhibits a Tc of 230 K in bulk form and 130 K for a single layer. In these systems, the Tc can be tuned via the use of extrinsic mechanisms such as ionic gating, doping, ion implantation, proximity to topological insulators, and patterning methods. Metastable states can be stabilized via temperature quenching and temperature cycles. From a technological standpoint, high Tc are among the magnetic properties of highest interest for next-generation spintronic applications integrating 2D vdW FMs. Fe₅Ge₂Te₂ is a Stoner-type itinerant ferromagnet, with asymmetric spin-up and spin-down density of states of the Fe 3d bands at the Fermi-level, spin-polarized metallic ligand bands, and near RT Tc. However, the mechanisms governing its magnetic properties are still unclear, with variable magnetic properties (Tc and anisotropy) being reported. Most experimental realizations have been done using Fe-deficient bulk crystals or micrometer-sized flakes exfoliated from them. The properties of Fe₅GeTe₂ films with exact 5:1:2 stoichiometry remain unexplored. Recent studies pointed out the role played by Fe vacancies and the different Fe sublattices on the complex range of magnetic behaviors observed. Additionally, magnetic critical exponents of bulk Fe₅Ge₂Te₂ are close to those of a 3D Heisenberg and 3D XY systems, remaining unclear if these models still hold in ultrathin regimes.

While many of the demonstrations of vdW FMs materials relied on bulk crystals and on exfoliated flakes in the 2D limit, growth by molecular beam epitaxy (MBE) has been pursued to expand the complexity of the designed heterostructures and large-area scalability. MBE is a well-established deposition technique for the realization of atomically thin single-crystal vdW materials and heterostructures with sharp interfaces. Any outlook on future heterostructures and device concepts based on 2D vdW FMs requires the large-area fabrication of high-quality ultrathin films, for which MBE is well suited.

Here we demonstrate the MBE growth of single-crystal thin films of stoichiometric Fe₅GeTe₂ on an insulating substrate, Al₂O₃(001). In situ reflection high-energy electron diffraction (RHEED) measurements demonstrate the layer-by-layer growth of single-crystalline films. Chemical and structural characterization using Rutherford backscattering spectroscopy (RBS), scanning transmission electron microscopy (STEM), and X-ray diffraction (XRD), confirm the 5:1:2 Fe₅GeTe stoichiometry and rhombohedral
Structure and chemical characterisation

The MBE growth of Fe₅GeTe₂ on Al₂O₃(001) was carried out in a home-built UHV deposition system with a base pressure in the low 10⁻¹⁰ mbar (see Methods for further information). Al₂O₃(001) is a conventional substrate used for epitaxy, electrically insulating, and has a hexagonal crystallographic structure. The substrates were first annealed in air at 1000 °C in a tube furnace to promote the formation of a terrace-and-step smooth surface, and again annealed in the UHV chamber at 800 °C for 20 min prior to the deposition. Ge and Te were co-deposited using Knudsen effusion and thermal cracker cells, respectively, and Fe using e-beam evaporation. The substrate temperature for the growth of Fe₅GeTe₂ was set to 350 °C, the flux ratio of Fe:Ge was kept to approximately twice the stoichiometric flux. After the deposition, the films were annealed for 20 min at 550 °C under Te flux, and then capped with a 3 nm-thick Al film at RT. The growth of Fe₅GeTe₂ on Al₂O₃(001) was monitored in situ using RHEED. We report mainly the growth of 12 nm of Fe₅GeTe₂. Similarly, the top and bottom surfaces before and after the growth of 12 Fe₅GeTe₂ layers, respectively, were measured along [100] (see Supplementary Fig. 1 for RHEED snapshots during the deposition and annealing of 12 and 2 nm-thick samples).

Despite the large lattice misfit with Al₂O₃(001) (~15 %), the sharp streaks and anisotropic RHEED patterns demonstrate the single-crystalline character of Fe₅GeTe₂, with c-axis perpendicular to the surface. The two azimuths are aligned with those of the Al₂O₃(001) surface, showing the Al₂O₃(001)[100]/Fe₅GeTe₂(001) [100] epitaxial relationship. The real-time monitoring of the RHEED intensity of the 1st order diffraction streaks allowed for the observation of periodical intensity oscillations characteristic of a layer-by-layer growth mode (Fig. 1b). By indexing the successive oscillations as the formation of a single layer, the rate of growth was estimated at 1.69 monolayers per minute of deposition. Atomic force microscopy (AFM) scans of the surface of 12 nm-thick films not capped with Al, taken within minutes of exposing the surface to the environment, show a smooth surface with root-mean-square roughness (RMS) of 0.5 nm, without clearly defined terraces, but with atomic steps corresponding to those of one or multiple monolayers (Fig. 1c).

To gather further information on the crystallographic structure, domain size, mosaic spread, and lattice parameter distribution of the films deposited, we performed in-plane (grazing incidence) and out-of-plane XRD measurements (see Methods for further details). Fe₅GeTe₂ is a highly anisotropic layered vdW ferromagnet with a trigonal crystal system. Typical lattice constants reported in the literature for bulk Fe₅GeTe₂ are a = 4.04 Å and c = 29.19 Å. Unit cells are typically represented with three stacked Fe₅GeTe₂ layers, with vdW gaps between adjacent Te planes. The complex atomic arrangement, the common presence of stacking faults and vacancy-induced disorder makes the precise determination of the crystallographic structure an open issue. In Fig. 2a, we depict the unit cell and three Fe₅GeTe₂ layers viewed along the [100] direction, according to the crystallographic model of ref. 7. The model considers Fe deficiency via fractional occupation probabilities of the Fe sites, and includes a split Ge and Fe1 site with half-occupation probability. Figure 2b shows the out-of-plane θ/2θ diffraction scan of a 12 nm-thick film, where we index the Al₂O₃(00 l) and Fe₅GeTe₂(00 l) Bragg peaks. The determined unit cell lattice constant c = 29.3 Å is in good agreement with previous reports (thickness of 1 ML = c/3). The fringes around the Bragg peaks of Fe₅GeTe₂(009) indicate low surface and interface roughness (also confirmed by the RMS of 0.5 nm measured by AFM in Fig. 1c), and allows for the estimation...
of a film thickness of 12.5 ± 0.3 nm, in strong agreement with the expected growth of 12 layers determined from the RHEED oscillations (See Supplementary Fig. 2 for the XRD analysis of a 2 nm-thick film). In Fig. 2c, we show in-plane radial scans \( \theta_{/2} \theta \) that were acquired along the \((hh0)\) and \((0h0)\) reciprocal directions, 30° apart from each other. The full width at half maximum (FWHM) is also displayed above the peaks. From these scans, we obtain an in-plane lattice parameter \( a = 4.068 \) Å, expanded by roughly 0.7% compared to the reference value of 4.04 Å. The mutually exclusive presence of the \((hh0)\) and \((0h0)\) peaks on each radial scan indicate the absence of domains rotated by at least 30°. This is further confirmed in Fig. 2d, which shows the azimuthal dependence of the intensity of the Bragg peaks identified in the radial scans (grey curves). The baseline of the azimuthal scans is the sum of the instrumental background and of the signal from misaligned crystallites with an isotropic distribution of orientations. The observed correspondence between the azimuthal and radial baselines implies that there is no isotropic component in the crystallites angular distribution. The film is single crystalline with the expected 60° periodicity of the basal plane of the crystal lattice. Noticeably, the FWHM for the Bragg peaks is substantially larger. From the study of the momentum transfer for each radial and azimuthal Bragg diffraction peak and its dispersion, one can estimate the domain size \( D \), lattice parameter distribution \( \Delta a/a \), and in-plane mosaic spread \( \Delta \xi \) of the film34,35 (see Supplementary Note 1 and Supplementary Fig. 3 for details on the calculations). For the 12 nm-thick film, \( D \) was determined to be 33 nm, which must be considered as a lower bound for the domain size due to the instrumental limited resolution, \( \Delta a/a \approx 0.66 \% \), and \( \Delta \xi \approx 3.34 ^\circ \), values that corroborate the single-crystalline character of the deposited films.

In order to take a closer look at the disorder and stacking of the Fe5GeTe2 ultrathin films, we recorded atomic-resolution real-space images by STEM (see Methods for further information). Figure 3a shows a high-angle annular dark-field (HAADF) cross-section image along [100]. The atomically flat Al2O3 promoted the epitaxy of well-oriented layers that are uniform over large areas, parallel to each other, and with no perceivable rotated domains. At the interface between the two materials, there is a thin amorphized gap of 6 Å, after which the first Fe5GeTe2 layer develops. The lattice parameters determined from Fourier transform analysis of the HAADF image, \( a = 4.07 \pm 0.02 \) Å and \( c = 29.4 \pm 0.3 \) Å, are in strong agreement with the ones obtained from XRD. Chemical analysis using RBS spectroscopy confirms the nominal 5:1:2 stoichiometry of the FeGeTe elementary composition of the film (inset of Fig. 3a). Energy-dispersive X-ray spectroscopy (EDX)
shows a homogenous distribution of each element in the film (Fig. 3b). In Fig. 3c, Z-contrast-enhanced HAADF over a smaller section of the film yields a site distribution with a clear indication of the presence of heavier atoms at the edges of the layers. Element resolved EDX over two layers shows the clear presence of Fe and Ge in between Te sites. Fe shows a broader dependence on position than Ge, as expected from its distribution in the cell. The presence of the Fe1 atom is not clearly resolved in our measurements, but the symmetry of the images points to a 50 % occupation probability in the two possible sites, as in the model of ref. 26. In order to confirm it, we performed simulations of Z-contrast HAADF images for several occupation probabilities (Fig. 3d). For a 100 % occupation probability, the simulation indicates that an STEM scan should be able to clearly resolve the site occupied by the Fe1 atom, while at 0 % the background strongly contrasts with the atomic sites. At 50 %, we observe a tail connecting the inner Fe2 atoms to Te. This reproduces well the experimental result, and strongly suggests that a crystallographic model with a Fe1 half-split site applies to our epitaxial films.

Characterization of the magnetic properties

The magnetic properties of the films were characterized using SQUID and XMCD (see Methods for further information). In Fig. 4a and Fig. 4b we plot isothermal magnetic hysteresis loops at different temperatures with the magnetic field applied in the ab basal plane, and along the c-axis of the layers, respectively, for 12 nm-thick films (12 ML). The data have been corrected by subtracting the magnetic background observed at temperatures well above \( T_C \) and a residual slope due to a paramagnetic contribution from the substrate below 50 K. The same slope was subtracted from the in-plane and out-of-plane field dependences. The subtraction of the magnetic background signal was justified from the comparative study of the XMCD and SQUID measurements, in which the latter had a systematic shift equivalent in magnitude to the parasitic magnetic background observed above \( T_C \), indicating that the SQUID was capturing a signal not related to the film. The insets show the raw magnetization curves and the considered background in gray. The in-plane hysteresis loops show low coercivity (~ 4 mT at 50 K) and saturation field (~ 200 mT at 50 K) (see Supplementary Fig. 4 for a zoom-in over a narrower field range of the in-plane magnetic hysteresis loops). The saturation magnetization averaged over in-plane and out-of-plane measurements amount to \( M_s = (644 \pm 54) \, \mu_B/\text{Fe} \). These values are in-line with those previously reported for Fe-deficient \( \text{Fe}_{x-\delta}\text{GeTe}_2 \) \( (\delta = 0.1-0.3) \) films exfoliated from bulk crystals23,25. Perpendicular to the surface, the saturation field largely increases, indicating an easy-plane magnetic anisotropy. We confirmed the consistency of the SQUID magnetic field dependences with polar magneto-optical Kerr effect and XMCD field dependences (see Supplementary Fig. 5).

In Fig. 4c, the temperature dependence of the remanent magnetization \( (M_r) \) closely follows the scaling behavior of an ordered ferromagnetic system, \( M_r \propto \left( \frac{T}{T_c} \right)^\beta \), yielding \( T_c = (292.6 \pm 2.6) \, \text{K} \) and \( \beta = 0.29 \pm 0.05 \). This behavior is in striking contrast to the complex temperature dependences observed in bulk and Fe-deficient \( \text{Fe}_{x-\delta}\text{GeTe}_2 \) films23,25, suggesting that MBE-grown films present a higher structural and chemical homogeneity. The \( M_r \) can be reasonably fitted with 3D models (see Supplementary Fig. 6). Our determined \( \beta \) significantly deviates from the one observed in bulk crystals \( \beta \approx 0.346 \)27. While the reduction in the magnitude of \( \beta \) might point towards an approach to the window of magnetic critical exponents of 2D systems, the analysis of the residuals of the fittings to different magnetic critical exponent models suggests that a 3D model is better suited to
describe the magnetic behavior of the films (Supplementary Fig. 6). Figure 4d shows the normalized in-plane and out-of-plane isothermal magnetic loops at 50, 100, 200, and 300 K. We determine the effective anisotropy $K_{\text{eff}}$ from the area enclosed between the curves. The uniaxial anisotropy $K_u$ is deduced from $K_{\text{eff}}$ and the measured $M_S$ with the relation $K_{\text{eff}} = K_u + K_d = K_u - (\mu_0/2)M_S^2$, where $K_d$ is the shape anisotropy and $\mu_0$ the vacuum permeability. The temperature dependence of $K_{\text{eff}}, K_u$
and $K_b$ is displayed in Fig. 4e. We estimate a small positive uniaxial anisotropy $K_u = 0.09$ J cm$^{-3}$ that favors an easy c-axis, but remains weaker than shape anisotropy at all temperatures. Figure 4f shows the magnetic moments of this sample (S1) determined by SQUID and compares it to the magnetic moment of a second sample (S2) measured by both SQUID and XMCD. Sample S2 was capped with 5 nm of Te instead of Al. For sample S2, the excellent agreement between SQUID and XMCD confirms the validity of the background correction of SQUID measurements. The smaller magnetic moment of sample S2 compared to that of sample S1 (whose S:1:2 Fe:Ge:Te composition was ascertained by RBS, in Fig. 3a) might originate from Fe deficiency. In Fig. 4g,h we detail the XMCD characterization of sample S2, and show the XMCD spectra at the Fe and Ge L$_2,3$ edges at 4 K (see Methods for further details). The measurements were performed in total electron yield mode, with X-ray incidence normal to the surface ($\alpha = 90^\circ$), and the ±T magnetic field parallel to the beam direction. Additional measurements were carried out at $\alpha = 30^\circ$ (not shown). We applied the conventional sum rules analysis$^{36,37}$ to the Fe absorption signal in order to determine the effective spin ($m_{S}^{\text{eff}} = m_{S} + m_{2D}^0$) and orbital ($m_{L}^0$) moments (see Supplementary Note 2 for further details on the determination of the Fe magnetic moments with XMCD sum rules). From those, we derive the isotropic spin ($m_{S}$) and orbital ($m_{L}$) moments, as well as the intraatomic dipole moment anisotropy $\Delta m_0 = m_{0}^0 - m_0$, and the orbital moment anisotropy $\Delta m_{L} = m_{l}^{0} - m_{l}^{\parallel}$ ($\parallel$ and $\perp$ denote the out-of-plane and in-plane components, respectively). We obtained $m_S = 1.54\, \mu_B$, $m_L = 0.08\, \mu_B$, $\Delta m_0 = 0.21\, \mu_B$, and $\Delta m_{L} = -0.01\, \mu_B$. The total magnetic moment amounts to $m_S + m_L = 1.62\, \mu_B$, in excellent agreement with the theoretical value determined from the first principles reported in Table 1 (see Methods for further details).

The small $m_L$ and $\Delta m_{L}$ are consistent with the weak out-of-plane uniaxial magnetic anisotropy deduced by SQUID measurements. We also observed a small polarization of Ge atoms, in agreement with ref.$^{25}$ and with our ab initio results (Table 1). As depicted in Fig. 4h, both 2p $\rightarrow$ 4d ($\Delta L = +1$) and 2p $\rightarrow$ 4s ($\Delta L = -1$) transitions present a finite XMCD signal. The sign of the XMCD for 4d (4s) final states is equal (opposite) to the one of Fe. Given the opposite sign of $\Delta L$ for these transitions, we deduce that the magnetic moment of both 4d and 4s bands is opposite to the Fe one. In ref.$^{25}$, a sizeable magnetic moment was also observed on Te atoms, but we could not confirm it in our film due to the use of a Te capping layer. Note that we neglected the Ge and Te contributions to determine the Fe magnetic moment by SQUID. According to Table 1, these assumptions lead to an underestimation of the Fe magnetic moment by only 2%.

Figure 5 shows the magnetic properties of 2 nm-thick films (2 ML of Fe$_5$GeTe$_2$) measured by SQUID. Figure 5a and Fig. 5b show isothermal magnetic hysteresis loops at different temperatures with the external magnetic field applied in the ab basal plane, and along the c-axis of the layers, respectively. Compared to the 12 nm-thick films, $M_c$ decreases by roughly 40%, with $M_S = (409 \pm 5)\, \mu_B$ m$^{-1}$ at 10 K (averaged over in-plane and out-of-plane measurements), corresponding to a magnetic moment $M = (1.21 \pm 0.01)\, \mu_B$/Fe. In Fig. 5c we plot the temperature dependence of $M$, and fit the results to $M_\lambda \propto (T_c - T)^{\delta}$. The fitting yields $T_c = (229.4 \pm 0.3)\, K$ and $\beta = 0.29 \pm 0.01$.

### DISCUSSION

The magnetic properties of the films ($M_\lambda$, $K_u$, and $T_c$) are in good general agreement with those reported for bulk crystals synthesized using chemical vapor transport (CVT). Nonetheless, some differences are noticed. More complex magnetic properties were reported in CVT Fe$_5$GeTe$_2$, which are not observed in our MBEGrown films. In particular, we do not observe PMA nor anomalies in the temperature dependence of $M_\lambda$.

Weak PMA has been reported in mono to few-layer flakes$^{7,38,39}$, while bulk crystals show in-plane magnetic anisotropy$^{27,30,42}$, or no magnetic anisotropy$^{23}$. When shape anisotropy is taken into account, all reports so far agree on the presence of a weak uniaxial anisotropy. We confirm the weak uniaxial anisotropy, but in our films it never overcomes shape anisotropy. It is possible that both $K_u$ and $M_S$ are affected by the 2% larger volume of the unit cell in our crystals ($a = 4.07\, \AA$, $c = 29.30\, \AA$) when compared to those of works reporting PMA ($a = 4.04\, \AA$, $c = 29.1 - 29.2\, \AA$)$^{7,38,39}$. Fe deficiency might also play a role. It is likewise possible that AlO$_x$ and Te capping layers induce a negative interface anisotropy that reduces the overall $K_u$.

Concerning the temperature dependence of $M_\lambda$, complex variations have been reported for CVT crystals$^{7,23}$. Quenched crystals produced by this method stabilize metastable states with higher $T_c$ and exhibit a first-order phase transition at $T \sim 110\, K$ originating from irreversible changes in the crystalline structure$^{27,29}$. In our case, it appears that the different growth method and thermal history prevents the formation of such metastable states. An additional anomaly around 100 K has been related to the ordering temperature and fluctuations of the Fe1 magnetic moments that are possibly sensitive to the Fe deficiency$^{26}$. An alternative interpretation involved the formation of “glassy clusters”$^{40}$ which are unlikely in our layers given the high crystalline quality. Since the body of literature points towards a high sensitivity of the magnetic properties on local inhomogeneities, we believe that the anomalies are of extrinsic origin and connected to the non-uniformity and disorder of the films. We speculate that our films simply do not show such complex behavior because of the higher homogeneity, uniformity and negligible Fe deficiency, as supported by our comprehensive characterization.

A striking result is the apparent 3D magnetic behavior of the films, even in the 2D limit. The $\beta = 0.29$ exponent hardly varies with the thickness (12 ML and 2 ML) and the $T_c$ remains surprisingly large (229 K) in bilayers. This may be related to the atomic coordination of Fe$_5$GeTe$_2$. Actually, a monolayer is composed of 6 atomic slabs of Fe stacked onto each other (4 fully occupied layers $- 2$ layers with 50% occupation). On top of that, the Te terminations also mediate the ferromagnetism in the system$^{26}$. Therefore, in contrast to 2D ferromagnets like CrI$_3$, where all magnetic atoms lie in the same plane, Fe$_5$GeTe$_2$ contains a 3D-like network of magnetic elements. This atomic configuration

| Atom | $m_S$ (μB/at.) | $m_L$ (μB/at.) | $m_S + m_L$ (μB/at.) |
|------|---------------|----------------|-----------------------|
| Te1  | 0.00          | 0.00           | 0.00                  |
| Fe1  | −0.16         | −0.03          | −0.19                 |
| Fe2  | 2.35          | 0.05           | 2.40                  |
| Fe3  | 2.10          | 0.04           | 2.14                  |
| Ge   | −0.06         | 0.00           | −0.06                 |
| Fe4  | 1.50          | 0.03           | 1.53                  |
| Fe5  | 2.60          | 0.08           | 2.68                  |
| Te2  | −0.10         | −0.02          | −0.12                 |
| Fe   | (averaged)    | 1.68           | 0.03                  |
| Fe   | (exp.)        | 1.54           | 0.08                  |

Spin ($m_S$), orbital ($m_L$), and total ($m_S + m_L$) magnetic moment per atom in Fe$_5$GeTe$_2$, estimated from first principles calculations. A single Fe1 site was considered to have 100% occupancy (see text). The last two lines give the calculated averaged Fe magnetic moments and the experimental values measured by XMCD, respectively.
implies a 3D-like exchange interaction, which results in the observed 3D magnetic behavior. This corroborates the idea developed in Ref. 6, that the large number of spin-pairs in Fe$_5$GeTe$_2$ enhances the exchange interaction and results in a large $T_c$ in spite of the weak magnetocrystalline anisotropy. The weak thickness dependences of $T_c$ and $\beta$ therefore point to sizable intralayer out-of-plane exchange interactions and suggest comparatively weak interlayer interactions, in consistency with the layered nature of Fe$_5$GeTe$_2$. Concerning the exact critical behavior of Fe$_5$GeTe$_2$ thin films, a further study of the $\gamma$ and $\delta$ critical exponents would be needed to unambiguously characterize the magnetic interactions.

In summary, we demonstrated the large-scale growth of few-layer, single-crystal Fe$_5$GeTe$_2$ on Al$_2$O$_3$(001) using molecular beam epitaxy, and provided a thorough structural and magnetic characterization. We showed that the MBE technique yields Fe$_5$GeTe$_2$ layers with high structural quality, layer-by-layer growth, virtually no Fe deficiency, and room-temperature ferromagnetism. STEM images and simulations clearly indicate a crystallographic structure with half-split occupation probability of the Fe1 atomic site. The 12 ML ultrathin films exhibit soft ferromagnetism, a large magnetization of about 644 kA m$^{-1}$ at 10 K, easy-plane magnetization, with a weak c-axis magnetocrystalline anisotropy $K_{c1} \approx 0.09$ J cm$^{-3}$. Bilayer Fe$_5$GeTe$_2$ retains the ferromagnetic order, with a lower magnetization of 409 kA m$^{-1}$ at 10 K, and a significant $T_c$ of 229 K. Analysis of the $\beta$ critical exponent indicates a thickness-independent 3D magnetic behavior, attributed to the 3D-like coordination between Fe sublattices inside vdW monolayers, and responsible for the high $T_c$.

Our work highlights the role of MBE as a key tool for the fine tailoring of 2D vdW FMs single crystals. In the particular case of Fe$_5$GeTe$_2$, we have grown a benchmark material with exact stoichiometry and well-defined crystalline structure to well-establish the magnetic properties of this vdW ferromagnetic material. It will serve as a platform to further unveil the complex dependence of the magnetic properties on the film composition and crystal structure, and as a stepping stone towards the integration in large-scale vdW multilayers for spintronics.

FIG. 5  Magnetic characterization of 2 nm-thick Fe$_5$GeTe$_2$. a Isothermal magnetic hysteresis loops with the external magnetic field $H$ in the $ab$ basal plane for different temperatures. b Same as a, with external magnetic field $H$ parallel to the $c$-axis. c Remanent magnetization as a function of temperature. Fitting to the scaling behavior of a magnetic system in an ordered state yields $T_c = 229$ K and $\beta = 0.29$. (see Supplementary Fig. 6 for a comparison with different 3D and 2D magnetic critical exponents).

METHODOLOGY

MBE

1 × 1 cm$^2$ Al$_2$O$_3$(001) substrates were cleaned prior to the tube furnace annealing with a standard isopropanol/acetone ultrasonic bath. For the growth of Fe$_5$GeTe$_2$, high-purity Ge (99.999%) was evaporated at 1060 °C, while high-purity Te (99.999%) was evaporated at 330 °C and cracked at 1000 °C. Fe (99.99%) was evaporated following standard e-beam procedures. Fe and Te deposition rates were calibrated by AFM on pre-patterned samples. The Ge deposition rate was calibrated with homoepitaxial RHEED oscillations on Ge(111). The Fe flux rate was monitored during the deposition using a quartz microbalance, while the Ge and Te flux rates were monitored before and after the depositions with a UHV pressure gauge.

XRD

In-plane XRD measurements were performed with a SmartLab Rigaku diffractometer operating at 45 kV and 200 mA. Collimators with a resolution of 0.5° were used both in the source and the detector. The measurements were done with a copper rotating anode beam tube ($K_{\alpha} = 1.54$ Å) at a grazing incident angle of 0.4°. The out-of-plane XRD measurements were performed using a Panalytical Epyrean diffractometer operated at 35 kV and 50 mA, with a cobalt source, ($K_{\alpha} = 1.79$ Å). A Pixelcel-3D detector allowed a resolution of 0.02° per pixel, in combination with a divergence slit of 0.125°.

AFM

The film topography was characterized with a Bruker Dimension-Icon microscope using a scanasyt-air cantilever, operated in ScanAsyst mode, and under ambient conditions. The root-mean-square roughness was evaluated on 1×1 µm$^2$ areas.

STEM

STEM measurements were performed using a Cs-corrected FEI Themis at 200 keV. HAADF-STEM images were acquired using a convergence semi-angle of 20 mrad and collecting scattering from >60 mrad. EDX was performed for elemental mapping using a Bruker EDX system consisting of four silicon drift detectors in the Themis microscope. STEM specimens were prepared by the focused ion-beam lift-out technique using a Zeiss DualBeam Cross Beam uSTEM750 at 30 kV. HAADF-STEM simulations were carried out using multislice simulation software, namely JEMS$^{43}$, and µSTEM$^{44}$ including the experimental conditions used for the image acquisition. The model structures were constructed based on the crystal information given in refs. 26,33.

RBS

Rutherford backscattering was done using an ion-beam of $^4$He$^+$ ions with 2 MeV, at a chamber pressure of 10$^{-6}$ mbar, with a 160° angle between the incident beam and the detector, and an angle of incidence of 75°.

SQUID

SQUID measurements were performed using a Quantum Design magnetic property measurement system MPMS®3 following standard procedures. Magnetic field sweeps were made in no-overshoot, persistent mode. The temperature sweeps were made at a rate of 5 K per minute. The estimated magnetic moments were determined from an average of two scans. For remanent magnetization measurements, the films were field-cooled from RT to 10 K with an external field of 2 T applied in-plane, and the superconducting magnet quenched before starting the temperature dependence.
**XMCD**

The XMCD measurements were performed on the DEIMOS beamline of the synchrotron SOLEIL. A XAS spectrum is obtained by continuously moving the energy of the monochromator over the energy range of interest while synchronizing the energy and polarization of the undulator to the energy of the monochromator. The XMCD spectrum is obtained from four measurements, where both the circular helicity and the direction of the applied magnetic field are flipped.

**Ab initio calculations**

First-principle calculations were performed using the Vienna Ab-initio Simulation Package (VASP)\(^1\)\(^2\), employing projector augmented wave (PAW)\(^3\)\(^4\) for potentials with the plane wave energy cutoff in all the calculations set to 550 eV, and the generalized gradient approximation (GGA)\(^5\) for the exchange-correlation energy. As a first step, ionic relaxation of Fe\(_3\)GeTe\(_2\) bulk structure was performed with \(k\)-point grids of 7 \( \times \) 7 \( \times \) 1 and 0.01 eV Å\(^{-1}\) force tolerance during optimization of the atomic positions. The in-plane (out-of-plane) lattice parameter was fixed to 4.07 (29.3) Å. Next, a self-consistent calculation with 21 \( \times \) 21 \( \times \) 3 \(k\)-point grids was realized to obtain the charge density wave and the atomic spin moments. Finally, the orbital moments were obtained by performing a non-self-consistent calculation with spin-orbit coupling included with the quantization axis set along [001].

**DATA AVAILABILITY**

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

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AUTHOR CONTRIBUTIONS

The sample preparation, growth, and the SQUID measurements were done by M.R., G. G., and F.B. XRD was performed by A.M. The AFM scans were made by G.G. The STEM cross-sections and simulations were done by H.O. and D.D. XMCD was done by F.B., G. G., D.L., and P.O. RBS was perform by C.V., J.-F.J., and D.J. A.H. and M.C. performed the ab initio simulations. The study was supervised by F.B., O.B., and M.J. M.R. and F.B. wrote the paper, and all authors contributed to the discussion of the results.

COMPETING INTERESTS

The authors declare no competing interests.