

Large Fieldlike Spin-Orbit Torque and Magnetization Manipulation in a Fully Epitaxial van der Waals Two-Dimensional-Ferromagnet/Topological-Insulator Heterostructure Grown by Molecular-Beam Epitaxy

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With the development of technologies taking advantage of emerging quantum phenomena under extreme conditions of dimensionality and temperature, the search for alternative materials and heterostructure engineering has opened up on several fronts. Here, we report the magnetotransport properties of topological-insulator/two-dimensional-ferromagnet (TI/2D-FM) heterostructures composed of $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ stacks grown by molecular-beam epitaxy. The electrical transport measurements reveal high levels of fieldlike effective torques, up to 115 mT at a current density of 10^7 A/cm²; the occurrence of interfacial magnetoresistance effects, such as the anisotropic interfacial magnetoresistance; and anomalies in the anomalous Hall effect. Furthermore, we report on complementary characterization with scanning tunneling microscopy, angle-resolved photoemission spectroscopy, and superconducting quantum interference device measurements. Finally, magnetization reversal induced by current pulses is also reported. The reported results make the relevance of the TI/2D-FM interface evident and indicate the preservation of polarized surface states at the interface.

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I. INTRODUCTION

Efficient manipulation of magnetization states is a key goal in modern spintronics and materials science research in general [1]. To this end, various mechanisms have been explored, from the use of actual magnetic fields to the use of spin-polarized currents in spin-transfer-torque (STT) phenomena. More recently, emerging technology based on the use of pure spin currents has been intensively studied. This mechanism, called spin-orbit torque (SOT), takes advantage of spin accumulation and spin-dependent scattering effects arising in materials and interfaces with high spin-orbit coupling to generate pure spin currents and torques [2]. One class of such materials is the topological insulators (TI), which have attracted interest in recent years based on predictions [3,4], and experimental observations

[5,6] of their functionality as a source of high values of SOT. Spin Hall angle values for TIs are reported to be at least an order of magnitude larger than those found for metallic alloys; this could lead to reduced critical currents for magnetization switching, a key requirement for the widespread adoption of spintronic memory cells [7,8]. The integration of metallic magnetic materials into TIs brings its own challenges, particularly with respect to the stability of the topological surface states at the TI/ferromagnet interface [9,10]. In addition, metallic films are much less resistive than the TI layer, resulting in less-efficient spin-current generation, since much of the applied current flows in the more conductive magnetic layer than in the TI. In the last decade, however, room-temperature ferromagnetic ordering in metallic two-dimensional (2D) van der Waals materials has been demonstrated on the scale of a few atomic layers or less [11–14]. In particular, the integration of 2D ferromagnets (FMs) on chemically and structurally compatible TIs may benefit from the sharply defined van der Waals FM/TI interfaces, which ensures optimal coupling for the generation of SOT. In addition, the higher resistivity of these 2D-FM layers could enable electrical probing of the magnetization state with limited current

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shunting and exploitation of the full SOT efficiency. Moreover, several 2D-FM layers may host skyrmions that are directly evidenced in magnetic imaging experiments [15, 16] or reveal their presence indirectly via the topological Hall effect (THE) [17, 18], opening the way for different skyrmion-based spintronic applications.

Here, we report the integration of TIs and 2D-FM materials in the form of $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ heterostructures. Bi_2Te_3 is a layered TI material and $\text{Cr}_{1+\delta}\text{Te}_2$ is a 2D-FM material with a low Curie temperature, where each chemically ordered Te/Cr/Te trilayer (CrTe_2 TL) is weakly coupled to the next TL through additional interlayer Cr atoms. δ represents, in this case, the extra self-intercalated Cr atoms. Magnetic and electrical properties of molecular-beam epitaxy (MBE) grown sapphire (substrate)/ WS_2 (1 ML)/ $\text{Cr}_{1+\delta}\text{Te}_2$ (7 or 10 TL)/ Bi_2Te_3 (10 QL) (ML stands for monolayer, QL for quintuple layer) layers are characterized using superconducting quantum interference device magnetometry and low-temperature transport measurements. Other samples covered with Al(1 nm) or W(19 nm) are also studied and used for comparison. A list of the samples used in this study can be found in the Supplemental Material (Table T1) [19]. Second-harmonic techniques are used to investigate the spin-to-charge conversion and subsequent SOT at the TI/2D-FM interfaces. This system proves to be a suitable framework to probe the spin-current-generation efficiency at the topological-insulator interface due to the high resistivity of the $\text{Cr}_{1+\delta}\text{Te}_2$ films. The torque measurements show the occurrence of current-induced magnetic torques with a large contribution from the fieldlike (FL) torque component, which has not been reported before. It is found that the FL effective field in $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ is 10 times larger than the dampinglike (DL) component. Such a large value is compatible with the expected results of charge-to-spin conversion induced by the Rashba-Edelstein effect at the TI/2D-FM interface [20–22]. Additional evidence for the presence of polarized interface states comes from the observation of a positive angular dependence for the longitudinal resistance with in-plane saturating fields. This positive magnetoresistance component is inconsistent with the usual spin-Hall magnetoresistance (SMR) and is associated with an interfacial contribution to the spin-to-charge interconversion [23]. Furthermore, magnetization-switching experiments induced by a pulsed current are performed for the $\text{Bi}_2\text{Te}_3/\text{Cr}_{1+\delta}\text{Te}_2$ bilayer, showing partial but consistent reversal with field and current symmetries, as expected from SOT. We also observe a large THE-like signal in $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ bilayers up to 110 K.

II. RESULTS AND DISCUSSION

A. MBE growth

Chromium telluride 2D van der Waals ferromagnetic thin films are grown by molecular-beam epitaxy on

different substrates in the temperature range between 220 and 490 °C with a Cr deposition rate of 0.06 Å/s. The chromium telluride films are covered with the topological insulator Bi_2Te_3 , which serves as a SOT material for spin-torque measurements, while others are covered with W and Al(AlO_x) for comparison. The phase diagram of chromium telluride is complex, ranging from CrTe_2 to Cr-rich Cr_5Te_8 , Cr_2Te_3 , and Cr_3Te_4 phases [24], obtained by spontaneous Cr self-intercalation in the interlayer van der Waals gaps. The Cr-rich compounds tend to form at higher temperatures and larger thicknesses and typically result in a multiphase material. At low-temperature growth (220 °C), chromium telluride films adopt a 1×1 CrTe_2 surface phase, as opposed to higher-temperature growth where extra phases (see the Supplemental Material [19]), coexisting with the previous one, appear. These high-temperature phases are identified from the 2×1 and 2×2 superstructures attributed to Cr_3Te_4 and Cr_5Te_8 , respectively [24]. In this work, we focus our attention to the low-temperature-grown chromium telluride magnetic films, which are single-phase materials with well-defined magnetic properties, exhibiting strong perpendicular magnetic anisotropy (PMA), about 0.04 MJ/m³ at 100 K; large saturation magnetization (0.2 MA/m at 10 K); and high coercivity, up to 1 T at 10 K (see the Supplemental Material [19]).

Reflection high-energy electron diffraction (RHEED) and high-resolution scanning tunneling microscopy (STM), shown in Figs. 1(a) and 1(b), reveal relatively sharp 1×1 reconstruction patterns, pointing to the occurrence of the CrTe_2 phase [24]. The angle-resolved photoelectron spectroscopy (ARPES) measurements and Raman spectra [two characteristic peaks (98 and 135 cm⁻¹)] are also comparable to reported results for the 1T- CrTe_2 phase [13, 25, 26]. However, the particular magnetic properties observed in these samples, namely, the low-temperature ferromagnetic transition and out-of-plane anisotropy, are mostly associated with the Cr_2Te_3 phase ($\delta = 1/3$) [27, 28], even though strained CrTe_2 could also exhibit PMA phases [25, 29]. This conflict reflects the inherent difficulty in distinguishing the two phases, since the additional interlayer Cr atoms preserve the periodicity along the normal of the CrTe_2 TLs. Additionally, the lower density of Cr atoms in the interlayers result in black contrast in high-resolution transmission electron microscopy images, which can be mistakenly interpreted as van der Waals gaps [30, 31]. In the next section, we discuss the magnetotransport results for the low-temperature-grown Cr-Te-based 2D-FM irrespective of the specific concentration of self-intercalated Cr atoms, if any.

B. Topological Hall effect

At low temperatures, Hall measurements performed on either the Al-capped $\text{Cr}_{1+\delta}\text{Te}_2$ films or on the $\text{Cr}_{1+\delta}\text{Te}_2$ (7 or 10 TL)/ Bi_2Te_3 bilayer heterostructures grown on

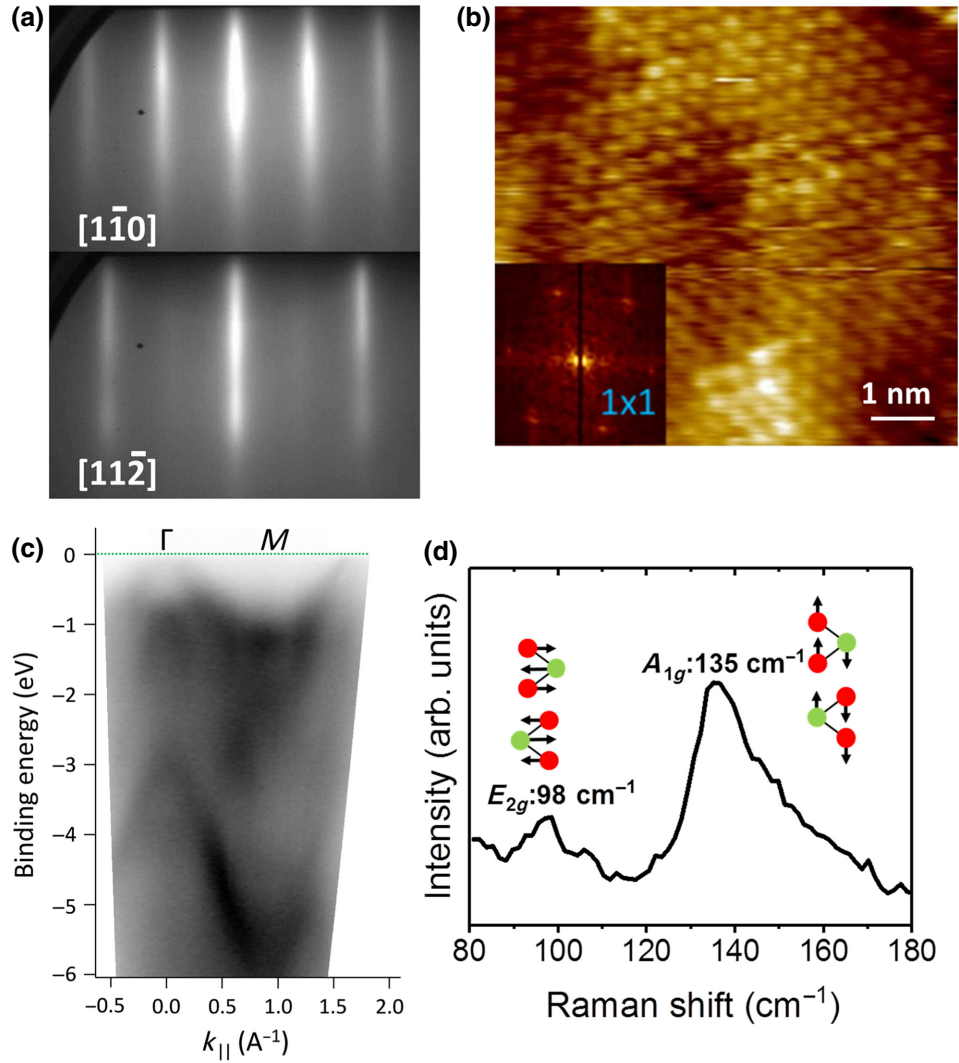


FIG. 1. (a) RHEED patterns of the low-temperature-grown $\text{Cr}_{1+\delta}\text{Te}_2$ phase. (b) High-resolution STM real-space image along with the FFT, showing a 1×1 pattern of hexagonal $\text{Cr}_{1+\delta}\text{Te}_2$. (c) *In situ* ARPES image using a He I excitation energy, 21.22 eV, along the Γ - M direction of the Brillouin zone. (d) Raman spectra for the low-temperature-grown $\text{Cr}_{1+\delta}\text{Te}_2$ film with characteristic peaks at 98 (E_{2g}) and 135 cm^{-1} (A_{1g}).

sapphire/ WS_2 (1 ML) are characterized by an anomalous Hall effect (AHE) signal typically observed for materials with PMA, i.e., square hysteretic resistance curves with clear saturation values, as seen in Fig. 2(a). The AHE amplitudes, however, depend strongly on temperature and even changes its sign at several temperatures. At inversion points, the Hall data display anomalies that are characterized by peaks of transversal resistance with amplitudes surpassing the saturation value, Fig. 2(b). Such anomalies are explained by the emergent magnetic field due to the phase gained by electrons flowing through skyrmions, giving rise to the THE [32–34]. In our system, symmetry breakage at the interface may enhance the interfacial Dzyaloshinskii–Moriya interaction (DMI), making the stabilization of skyrmions possible. Sharp potential

gradients at the interface may also provide additional contributions to the AHE, resulting in features similar to the THE [35,36].

For Al-capped $\text{Cr}_{1+\delta}\text{Te}_2$, THE-like features are observed around 50 K, reaching peak values of about 1 $\mu\Omega\text{ cm}$. This is comparable to recent observations of a giant THE in $\text{Bi}_2\text{Te}_3/\text{Cr}_{1+\delta}\text{Te}_2$ bilayers, where THE values are reported to reach up to 1.5 $\mu\Omega\text{ cm}$ at 10 K [17]. Here, however, the peak of the THE for Bi_2Te_3 -capped Cr-Te films occurs at higher temperatures, at about 100 K. The maximum THE values are found to be 259 and 193 $\text{n}\Omega\text{ cm}$ for samples consisting of 7 and 10 trilayers, respectively. The skyrmion sizes are estimated to be about 42, 175, and 190 nm for $\text{Cr}_{1+\delta}\text{Te}_2$ (7 TL)/Al, $\text{Cr}_{1+\delta}\text{Te}_2$ (7 and 10 TL)/ Bi_2Te_3 , respectively, which compares well with the

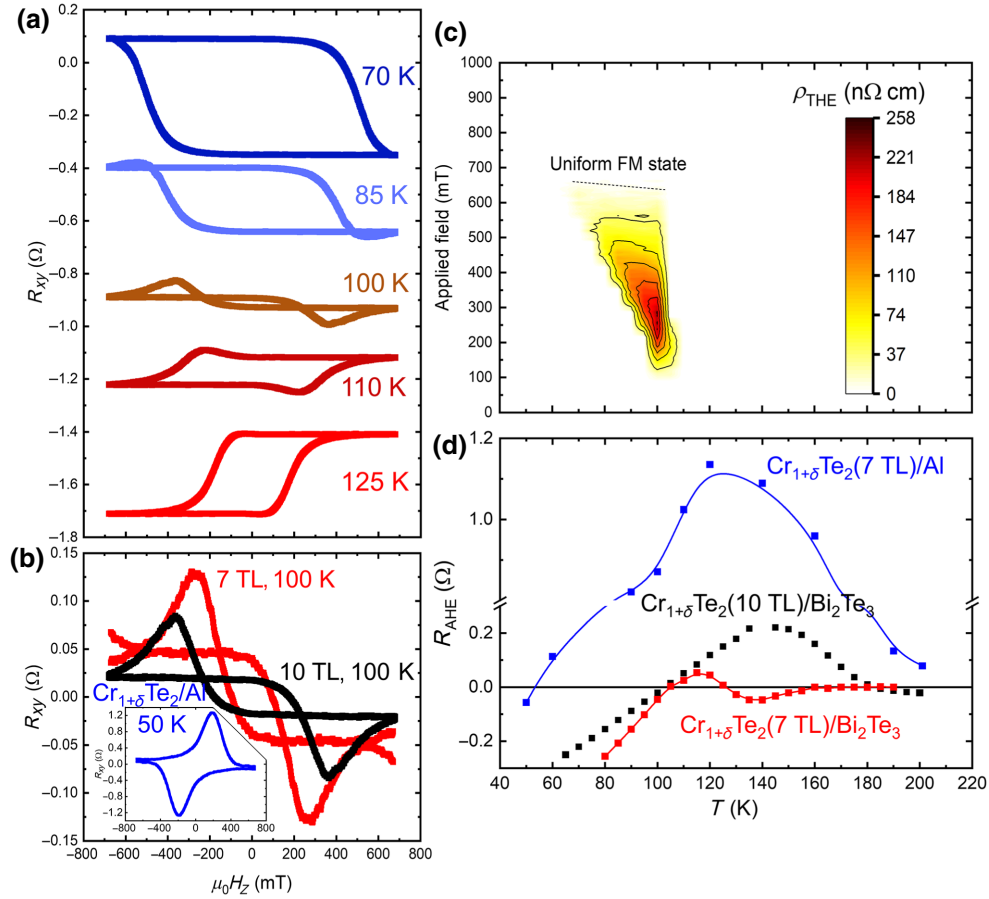


FIG. 2. (a) AHE curves at low temperatures for $\text{Cr}_{1+\delta}\text{Te}_2(10 \text{ TL})/\text{Bi}_2\text{Te}_3$. (b) AHE curves for $\text{Cr}_{1+\delta}\text{Te}_2(7 \text{ or } 10 \text{ TL})/\text{Bi}_2\text{Te}_3$ and $\text{Cr}_{1+\delta}\text{Te}_2(7 \text{ TL})/\text{Al}$ samples close to the respective AHE inversion points. The signal in Al and Bi_2Te_3 -capped samples are reversed due to opposite signs of the ordinary Hall effect in these structures. (c) THE amplitude as a function of applied positive field and temperature after negative saturation for a sample of $\text{Cr}_{1+\delta}\text{Te}_2(7 \text{ TL})/\text{Bi}_2\text{Te}_3$. (d) Amplitude of the AHE for different samples as a function of temperature.

previously reported value of 34 nm in the $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ heterostructure [18] and with our numerical estimations for single-layer $\text{Cr}_{1+\delta}\text{Te}_2$. Details on the atomistic simulations and size estimation can be found in the Supplemental Material [19]. The inversion of THE polarity observed in $\text{Cr}_{1+\delta}\text{Te}_2/\text{Al}$ when compared with $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ samples arises from the change in charge carrier from p type, in the first system, to n type in 2D-FM/TI [18]. Figure 2(c) shows the amplitude of the THE as a function of applied field and temperature for the $\text{Cr}_{1+\delta}\text{Te}_2(7 \text{ TL})/\text{Bi}_2\text{Te}_3$ sample. The white regions in the resulting phase diagram may be attributed to either the absence of a chiral texture or to a low THE-to-AHE ratio far from the temperature of AHE sign inversion. It is also worth noting that this diagram is very reminiscent of the magnetic phase diagrams of B20 materials, where it is possible to find pockets of stability of skyrmion lattices [37]. They are, however, located near the Curie temperature, unlike in the $\text{Cr}_{1+\delta}\text{Te}_2$ case. The temperature profile of the AHE amplitude as a function of temperature is shown in Fig. 2(d). During preparation

of this manuscript, direct imaging of a skyrmion lattice in $\text{Cr}_{1+\delta}\text{Te}_2$ has been reported through Lorentz microscopy at 100 K for $\delta = 0.3$ [38].

The fact that the THE-like signal peaks at the temperature at which the AHE changes sign (50 K for Al, 100 K for Bi_2Te_3 capping) suggests that another explanation is possible. If one assumes a potential gradient due to interfaces, the temperature dependence of the AHE might vary, and the AHE sign reversal can occur at slightly different temperatures for an interfacial portion of $\text{Cr}_{1+\delta}\text{Te}_2$. A model considering bulk and interfacial $\text{Cr}_{1+\delta}\text{Te}_2$ “layers” with slightly different AHE temperature dependence allows all the observed signals [$R_{xy}(H)$, $R_{\text{AHE}}(T)$ and the phase diagram] to be well reproduced (see the Supplemental Material, Sec. 5 [19]). The success of such a crude model indicates that such effects cannot be ignored and signals attributed to the THE must be very carefully considered. A possible interfacial component of the AHE would be heavily dependent on the interface composition because of doping or even spin-charge interconversion phenomena.

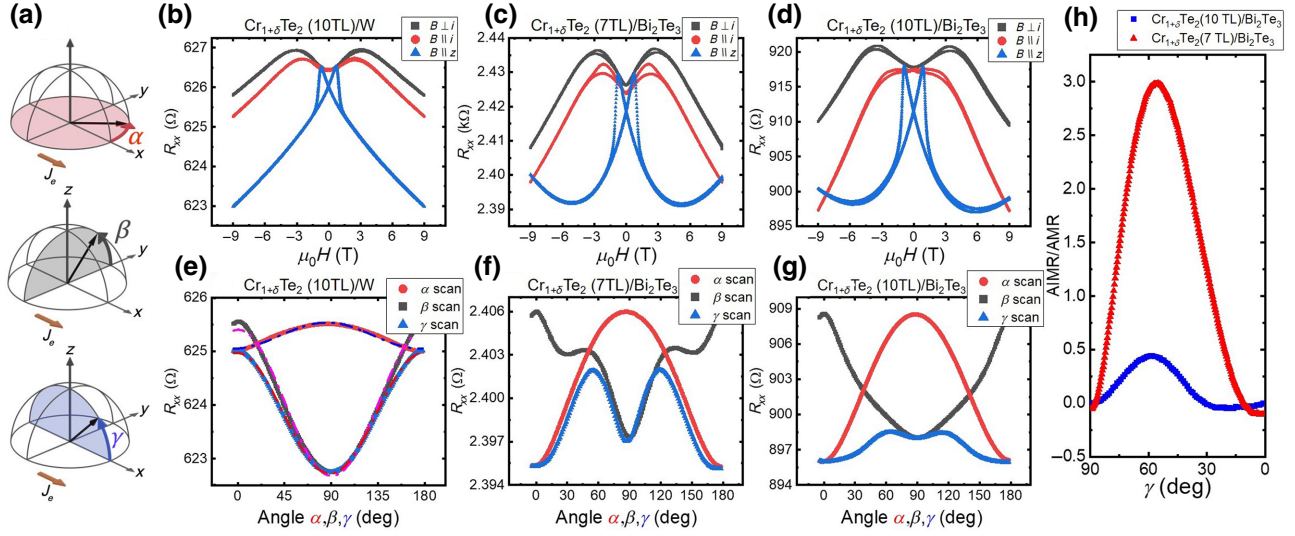


FIG. 3. (a) Schematics defining the angle conventions of magnetoresistance measurements. (b)–(d) Longitudinal resistance (R_{xx}) as a function of applied field for $\text{Cr}_{1+\delta}\text{Te}_2(10\text{TL})/\text{W}$, $\text{Cr}_{1+\delta}\text{Te}_2(7\text{TL})/\text{Bi}_2\text{Te}_3$, and $\text{Cr}_{1+\delta}\text{Te}_2(10\text{TL})/\text{Bi}_2\text{Te}_3$, respectively. (e)–(g) Longitudinal resistance for different angular sweeps following the conventions of panel (a) and a constant field of 9 T. Panel (e) also shows the best cosine-squared fittings for experimental points. (h) AIMR component as a function of γ for two different $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ bilayers. All measurements are conducted at 15 K.

These effects could lead then to an effective shift in the temperature dependence of the interfacial component of the AHE. It may explain the temperature dependence of AHE inversion as a function of interface composition, as observed in Fig. 2(d).

Although the simulation shows that a THE-like signal can be produced without topological effects arising from a chiral magnetization texture, the exact nature of the spin texture and the electronic band structure, in general, at the TI/2D-FM interface is unknown. We show, however, in the next sections, that these interfacial effects are relevant for both magnetoresistance and spin-current generation phenomena in $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ stacks. The relative importance of interfacial effects to the electrical transport phenomena at $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ bilayers points towards the possible preservation of polarized surface states at the TI/2D-FM interface.

C. Angular-dependent magnetoresistance

Figure 3 shows longitudinal magnetoresistance, R_{xx} , curves for $\text{Cr}_{1+\delta}\text{Te}_2/\text{W}$ and $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ bilayers for different orientations of the external magnetic field at 15 K. For all samples, the magnetoresistance curves exhibit a linear decrease for in-plane fields above saturation [Figs. 3(b)–3(d)], as is the case for the perpendicular orientation on the film capped by W. For $\text{Cr}_{1+\delta}\text{Te}_2/\text{Bi}_2\text{Te}_3$ samples, however, the magnetoresistance curve exhibits a quadratic field dependence at high perpendicular field, which is a characteristic of the magnetoresistance response of the topological-insulator film. The Lorentz magnetoresistance

is only visible for fields perpendicular to the planes, strongly suggesting that conduction mostly occurs in the plane. Magnetoresistance curves for isolated Bi_2Te_3 films can be found within the Supplemental Material [19]. Apart from the linear negative magnetoresistance, Figs. 3(b)–3(d) also make it clear which orientation leads to the highest resistance state at saturation. Disregarding the cases displaying quadratic behavior of the perpendicular high fields, which are associated with the TI layer, higher resistance is found when the magnetization points in plane but transverse to the current. This is clearly not compatible with conventional anisotropic magnetoresistance (AMR) behavior nor standard SMR [39], as we discuss hereafter. Angular scans of the longitudinal resistance (R_{xx}) are carried out to directly probe contributions from AMR and SMR or additional magnetoresistance effects. Figures 3(e)–3(g) show R_{xx} for scans in the x - y , x - z , and y - z planes for two different thicknesses of $\text{Cr}_{1+\delta}\text{Te}_2$ in the heterostructure.

Scans in the x - y , x - z , and y - z planes follow the convention expressed in the schematics of Fig. 3(a). Often, the magnetoresistance can be split into different components, the contributions of which are proportional to the square of the magnetization projection along orthogonal in-plane axes, either m_x^2 or m_y^2 , resulting in cosine-squared dependence of the angle of magnetization relative to the current direction [see Fig. 3(a)]. The most common contributions are the AMR, proportional to $+m_x^2$, and the SMR, proportional to $-m_y^2$. From the results of the $\text{Cr}_{1+\delta}\text{Te}_2/\text{W}$ bilayer, shown in Fig. 3(e), we can observe that resistance curves can be reasonably fitted by functions proportional

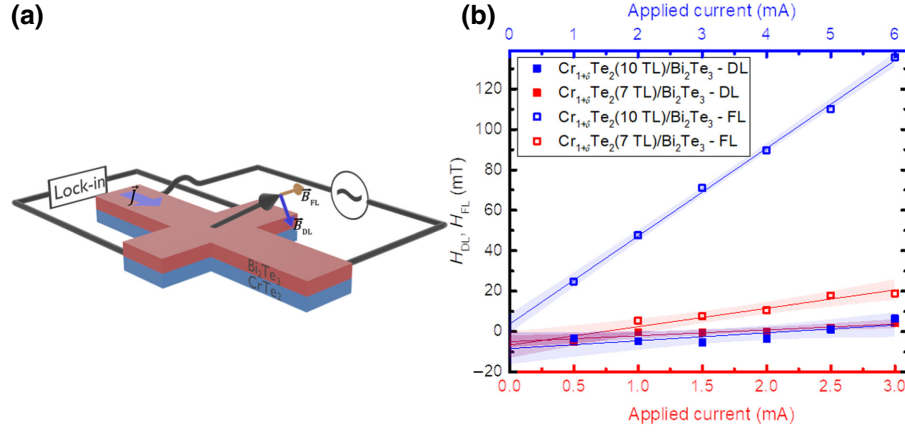


FIG. 4. (a) Schematic view of the experimental setup and torque effective-field geometry. (b) DL and FL amplitudes extracted from second-harmonic torque measurements at 15 K as a function of applied current. Shaded areas around the linear fittings represent 95% confidence intervals.

to the cosine square of the respective angles. In the γ scan, i.e., magnetic rotation in the x - z plane, the maximum of resistance occurs for $\gamma = 0^\circ/180^\circ$ ($\mathbf{m}$ is parallel to x). This behavior is compatible with a conventional *positive* contribution from AMR. Our β scan also exhibits a *positive* cosine-squared contribution to the magnetoresistance, that is, the state of maximum resistance also occurs when the magnetization is in plane, specifically when $\mathbf{m}$ is parallel to y . A previous report [13] on the magnetoresistance of $Cr_{1+\delta}Te_2$ described a large negative AMR, but their measurement did not take into account transversal magnetoresistance terms, such as the SMR. Indeed, scanning in the x - y plane, i.e., α scans, mixes the two components and a larger positive contribution of the transversal component, as observed in our results, leads to higher resistance state when $\mathbf{m}$ is parallel to y , which can be confused as a negative AMR when considering α scans alone. The same large positive transversal magnetoresistance (β scan) is also observed for samples of $Cr_{1+\delta}Te_2/Bi_2Te_3$ bilayers, shown in Figs. 3(f) and 3(g). This positive transversal component is not compatible with traditional SMR, which is generally proportional to $-m_y^2$. Similar behavior has been recently observed in Ta/Ni-Fe and Pt/Ni-Fe bilayers and was associated with a purely interfacial contribution to the spin-to-charge interconversion phenomena [23].

The AMR contribution (γ scan) appears to be negative due the crossover of the $R(H_x)$ and $R(H_z)$ at high fields caused by the quadratic component of the magnetoresistance of Bi_2Te_3 , as observed in Figs. 3(c) and 3(d) around 8.5 T. However, on top of the cosine-squared behavior on β and γ scans, peaklike features can be observed at about 60° and 120° . These features may arise from the anisotropic interfacial magnetoresistance (AIMR) [40], which is described by a higher order of even-powered cosine terms. This effect is mainly associated with scattering at ferromagnetic/paramagnetic interfaces

and may point to the occurrence of a magnetic phase at the 2D-FM/TI interface. The interfacial characteristic of the observed peaklike features is clear when we consider the AIMR-to-AMR ratio for samples with different thicknesses, as shown in Fig. 3(h). The sample with a thinner FM layer displays a much larger effect, as expected from a purely interfacial effect.

D. Spin-orbit torques

The charge-to-spin conversion in the $Cr_{1+\delta}Te_2/Bi_2Te_3$ heterostructures is probed by current-induced SOT measurements. Torque magnitudes are obtained using the second-harmonic technique [41–43]. Figure 4(a) shows a schematic view of the second-harmonic experiment and the SOT effective fields. For more details, the complete protocols for measurements can be found within the Supplemental Material, as well as the experimental curves and modeling for all the results discussed subsequently [19].

Figure 4(b) shows the amplitude of FL- and DL-torque effective fields versus applied current for different bilayers, thus unambiguously demonstrating the SOT mechanism. The extracted current-induced DL- and FL-torque effective fields are $H_{DL} = 12.5$ mT and $H_{FL} = 38$ mT at an average current density of 10^7 A/cm² for the sample with 7 TL of $Cr_{1+\delta}Te_2$, and $H_{DL} = 10$ mT and $H_{FL} = 115$ mT at 10^7 A/cm² for the sample with 10 TL of $Cr_{1+\delta}Te_2$. While the magnitude of the dampinglike field remains basically constant, on the order of a dozen mT at 10^7 A/cm², the FL-to-DL-torque ratio increases to be almost 4 times larger with an increase in the FM layer thickness. The obtained DL-torque values are marginally above the torque magnitudes found in transition-metal systems, such as Co/Pt, Co/Ta, or Co/ β -W, which are also on the order of a few mT [42,44]. However, the measured FL-torque component is significantly larger, well beyond the corresponding

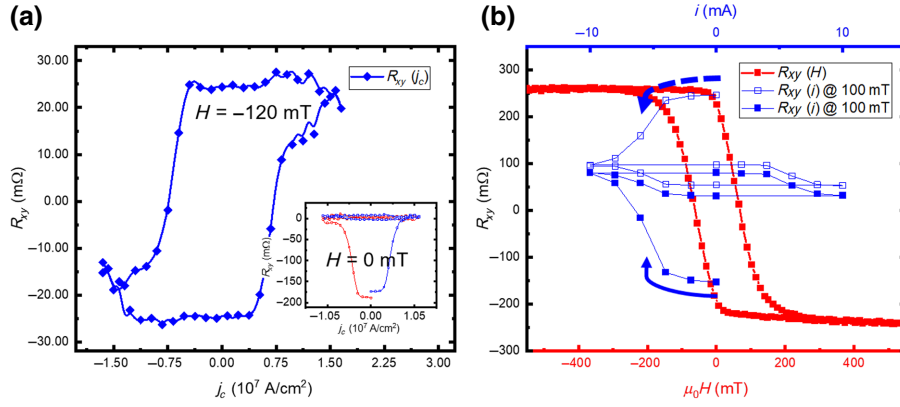


FIG. 5. (a) Hall voltage as a function of pulsed-current intensity at 140 K. (b) Complete switching curve departing from two different initial conditions for experiments, namely, remanent states after either positive or negative saturation. AHE curve at the same temperature is also shown for comparison. For panel (a), the applied in-plane field is -120 mT, while there is no field for curves in the inset. Hall bars are patterned from the complete sapphire/WS₂(1 ML)/Cr_{1+δ}Te₂(10 TL)/Bi₂Te₃(10 QL) stack.

values observed in the conventional SOT systems. Its large value provides evidence for the predominance of the Rashba-Edelstein mechanism in charge-to-spin conversion, in line with theoretical predictions [20]. This result supports the interfacial origin of spin-current generation from polarized surface states reported for the topological insulator Bi₂Te₃ [10,45], even after deposition of the quasi-2D ferromagnetic material.

E. Magnetization reversal induced by SOT

Current-induced switching experiments are also carried out successfully on the Cr_{1+δ}Te₂/Bi₂Te₃ bilayers. The reversal experiments are monitored via AHE measurements between pulses of current applied to samples patterned by optical lithography. The curves shown in Fig. 5(a), showing a clear current-induced magnetization reversal, are obtained for the Cr_{1+δ}Te₂(10 TL)/Bi₂Te₃ sample using pulses of 100 μ s in 5- μ m-wide Hall bars. Nevertheless, similar to current-induced-switching experiments reported for quasi-2D Fe₃GeTe₂/Pt [46,47] and Cr₂Ge₂Te₆/Pt [48], we are unable to achieve complete reversal. Only part of the resistance curve describes a hysteretic loop as a function of current with the SOT symmetries. Even though the change in resistance is about 40 m Ω , which is comparable to the change in resistance found in all-metallic stacks, this value represents only 8% of the change in resistance between remanent states. The switching seems to be limited by thermally induced magnetic domain nucleation, since intermediary magnetic states can be reached regardless of the polarity of the current, and even in the absence of an in-plane field, as shown in the inset of Fig. 5(a). Once these intermediary states are achieved, partial SOT-induced switching can be achieved, as evidenced by the hysteric behavior of the AHE resistance seen in Fig. 5(b). The Supplemental Material also

contains an optical microscopy image of the devices used in this work, as well as theoretical details of the second-harmonic technique for SOT evaluation [17,19,24,39,41,43,49–53].

III. CONCLUSIONS

Here, by adopting low-temperature MBE growth of CrTe₂/Bi₂Te₃ heterostructures, we achieve a Cr_{1+δ}Te₂ epitaxial phase on sapphire substrates/WS₂ with well-defined ferromagnetic properties and PMA. Evaluation of the magnetic properties and the charge-to-spin-conversion efficiency shows the important role of interface states. First, magnetotransport reveals the presence of an interfacial AIMR and an unexpectedly large positive transversal magnetoresistance attributed to spin-to-charge interconversion phenomena induced by interface electronic states. Second, the heterostructures show an unexpectedly large FL torque in second-harmonic spin-torque measurements, dominating the overall SOT effect. The latter result points to either the persistence of the topological surface states from the topological insulator film or the emergence of Rashba states in the 2D-FM/TI interface. The high efficiency of charge-to-spin conversion results in current-induced magnetization reversal in Cr_{1+δ}Te₂/Bi₂Te₃, which is similar to other SOT systems, making this heterostructure suitable for spintronic devices. We hope that these results will stimulate research on the large-scale growth of van der Waals heterostructures, including topological insulators and 2D ferromagnets dedicated to spintronic applications.

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