

Tunable artificial topological Hall effects in van der Waals heterointerfacesMeri Algarni,^{1,2,*} Cheng Tan,^{1,*} Guolin Zheng,^{1,†} Sultan Albarakati,¹ Xiangde Zhu,³ James Partridge[ⓧ],¹ Yanglin Zhu,⁵ Lawrence Farrar,¹ Mingliang Tian,^{3,4} Jianhui Zhou,³ Xiaolin Wang,⁶ Zhiqiang Mao,⁵ and Lan Wang[ⓧ]^{1,‡}¹*ARC Centre of Excellence in Future Low-Energy Electronics Technologies (FLEET),**School of Science, RMIT University, Melbourne, VIC 3001, Australia*²*Physics Department, School of Science, Albaha University, Albaha, Alaqiq 4781, Saudi Arabia*³*Anhui Province Key Laboratory of Condensed Matter Physics at Extreme Conditions, High Magnetic Field Laboratory, Chinese Academy of Sciences (CAS), Hefei 230031, Anhui, China*⁴*Department of Physics, School of Physics and Materials Science, Anhui University, Hefei 230601, Anhui, China and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China*⁵*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*⁶*ARC Centre for Future Low-Energy Electronics Technologies (FLEET) and Institute for Superconducting & Electronic Materials, University of Wollongong, Wollongong, NSW 2500, Australia*

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The topological Hall effect (THE) originating from a real-space Berry phase is a significant transport signal for chiral spin textures and has been extensively investigated recently due to its potential applications in topological spintronics. Recently, chiral spin textures and THE were realized in heterointerfaces where spatial inversion symmetry is naturally broken. However, multichannel transport in heterointerfaces can mask the intrinsic THE associated with chiral spin textures. Here, we systematically investigate multichannel transport in two different kinds of van der Waals (vdW) heterointerfaces. In ferromagnetic-ferromagnetic (FM-FM) heterointerfaces with two opposite anomalous Hall effects, multichannel transport has mimicked both positive and negative THE without involving any topological charges, which is dubbed as an artificial THE. Moreover, artificial THEs were also observed in FM-metal heterointerfaces consisting of a single FM layer stacked onto a nodal-line semimetal; this was attributed to the presence of multichannel transport as well. Our findings provide an alternative explanation for THE-like features in heterointerfaces. They also reveal exotic multichannel transport properties in vdW heterointerfaces which could facilitate the development of multifunctional nanodevices based on vdW heterointerfaces.

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The anomalous Hall effect (AHE) is an important phenomenon in condensed matter physics that usually occurs in systems with broken time-reversal symmetry, such as in magnetic materials [1]. Experimental and theoretical studies have provided a means to understand the AHE by the Berry curvature of electronic bands [2]. In addition to the Berry phase in reciprocal space, it has been established that the real-space Berry phase (e.g., skyrmion) adopted by conducting electrons can also result in a Hall response—topological Hall effect (THE) [3,4], as shown in Fig. 1(a), that resembles the AHE dominated by the Berry phase in the reciprocal space. The real-space topology widely exists in chiral spin textures, which have promising applications in topological spintronics. The THE has thus been experimentally employed to detect chiral spin textures in chiral magnets [5–9] or in heterointerfaces with naturally broken spatial inversion symmetry (SIS) [10–16]. Importantly, hybrid Hall effects observed in

heterointerfaces usually arise from multichannel transport which can mask the intrinsic THE associated with chiral spin textures. Further investigation in this area would significantly inspire the study of the associated novel phenomena.

Previous studies have demonstrated that magnetic heterointerfaces prepared by pulsed laser deposition or molecular beam epitaxy can mimic the skyrmionlike Hall effect due to the competition of two opposite AHEs [17–21]. THE-like signals raised from the film inhomogeneities [22] and multiple magnetotransport channels in multilayers [23,24] have also been reported recently. The observed skyrmionlike Hall effect in those heterointerfaces with similar lattice structures usually exhibit only either a “hump” or a “dip” in anomalous Hall loops, as shown in Fig. 1(b). In this article, we demonstrate that the artificially stacked magnetic van der Waals (vdW) heterointerfaces with significantly differing lattice structures and magnetic properties can reproduce both hump and dip structures in a single anomalous Hall loop, due to the competition of two opposite AHEs. Our magnetic heterointerfaces consist of a ferromagnetic (FM) Fe_3GeTe_2 (FGT) layer with a positive AHE and a FM $\text{Fe}_{0.26}\text{TaS}_2$ (FTS) layer with an opposite AHE separated by a thin graphite (Gr) layer. The hump structures near the coercivities were observed to evolve into dip structures as the temperature was altered. Within a

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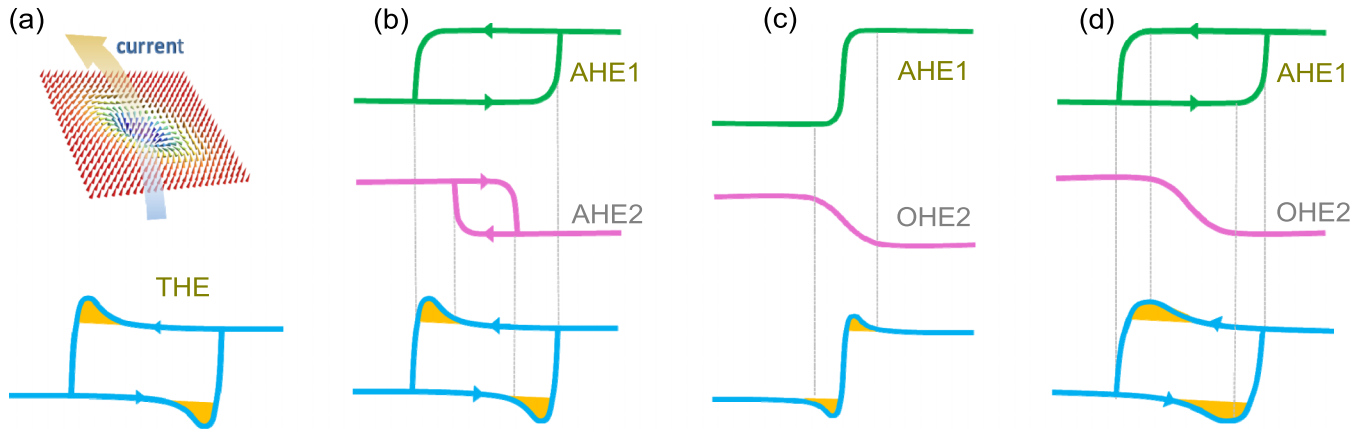


FIG. 1. Possible origins of skyrmionlike Hall effects. (a) An intrinsic topological Hall effect in chiral magnets. (b) Hybrid anomalous Hall effect in a heterointerface constructed with two decoupled magnetic layers with opposite signs. (c), (d) Two-channel Hall effects in a FM-metal heterointerface. The metallic layer is a two-band metal with a nonlinear, ordinary Hall effect (OHE). The FM layer might exhibit no hysteresis (c) or a large hysteresis loop (d).

certain temperature range, both hump and dip structures coexist in a single Hall loop, resembling the respective positive and negative THE observed in a chiral magnetic system [25]. Since the two magnetic layers are decoupled and separated by a graphite layer, the observed hump or dip features exhibited by the FGT/Gr/FTS heterointerfaces are not involved in any real-space topology. These peak structures were also found to vary with the thicknesses of the FGT and FTS layers, suggesting the potential tunability of the multichannel transport properties in the vdW heterointerfaces by controlling the layer thicknesses within them. Notably, the hump structures in the Hall trace were even reproduced in a FM-metal heterointerface by assembling a single magnetic layer with a two-band metallic layer, as illustrated in Figs. 1(c) and 1(d). The nodal-line semimetal ZrSiSe (ZSS) was chosen for these experiments and incorporated into FTS/Gr/ZSS interfaces indeed exhibited hump anomalies over a large temperature range, which can be attributed to multichannel transport as well. Our findings reveal that THE-like features may widely exist in vdW heterointerfaces due to their characteristic multichannel transport which may not necessarily involve any topological charges or two magnetic layers with opposite AHEs.

II. MULTICHANNEL TRANSPORT IN FM-FM HETEROINTERFACES

We first focus on a FM-FM heterointerface with two opposite AHEs. Figure 2(a) shows the layout of our device. The device consists of an upper FGT layer and a lower FTS layer separated by a spacer. A graphite layer (around 10 nm) was chosen as the spacer because the Hall response of graphite is almost linear over a large temperature range. Since graphite has a negligible spin-orbit coupling (SOC), it does not support a Dzyaloshinskii-Moriya interaction (DMI) and the resultant chiral spin textures at its interfaces. Figure 2(b) illustrates the AHEs under different temperatures in a typical FGT nanoflake with thickness around 70 nm. FGT is a typical vdW ferromagnet with large perpendicular magnetic anisotropy and high

Curie temperature (around 220 K) [26–28]. As we can see, the AHEs of FGT are proportional to the magnetization curves (see the Appendix), revealing a positive AHE. Figure 2(c) demonstrates the AHEs of a typical FTS nanoflake with a thickness of around 90 nm from 30 to 70 K. FTS is also a ferromagnetic metal but with a much lower Curie temperature of around 100 K and very large coercivities (see the Appendix).

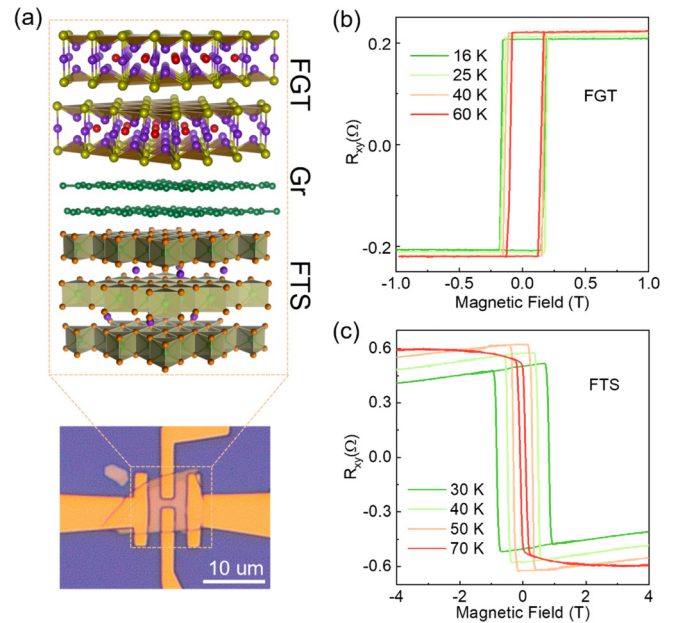


FIG. 2. Device structure and anomalous Hall effects in FGT and FTS. (a) The structure of the FGT/Gr/FTS heterostructure device. (b) shows positive AHEs in a typical FGT nanoflake in the temperature range 16–60 K. Due to the strong FM order and high Curie temperature of FGT, both coercivities and anomalous Hall resistances are relatively unchanged in this temperature range. (c) shows negative AHEs in a typical FTS nanoflake in the temperature range 30–70 K. In sharp contrast to AHEs in FGT, both coercivities and anomalous Hall resistances changed dramatically with the increase of temperature.

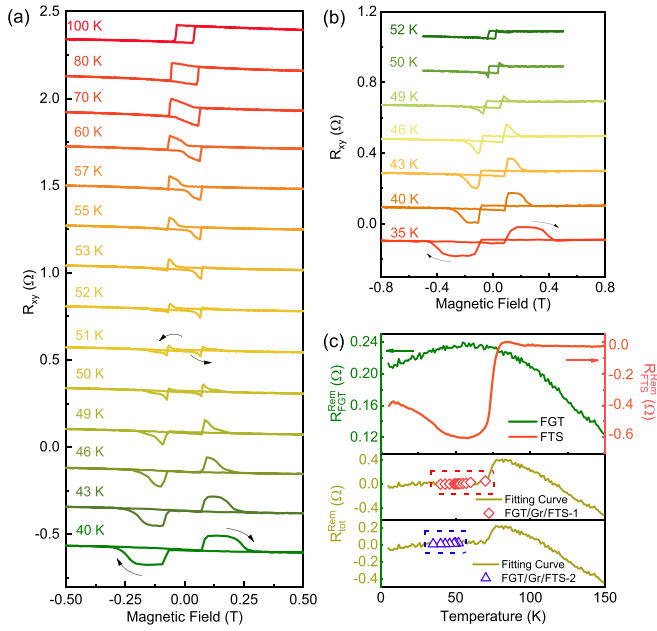


FIG. 3. Multichannel anomalous Hall effect in FGT/Gr/FTS heterointerfaces and the remanence fitting. (a) The multichannel AHE in sample 1 with the thickness of the FTS layer (95 nm) significantly exceeding that of the FGT layer. The two-channel transport shows that $|R_{xy}^{\text{FGT}}|$ equals $|R_{xy}^{\text{FTS}}|$, causing R_{xy}^{tot} to vanish at $B = 0$ T between 40 and 46 K. (b) The multichannel transport in sample 2. Increasing the anomalous Hall contribution of the FGT layer (both FTS layer and FGT layer are 60 nm thick in sample 2) ensures that the hybrid anomalous Hall effects are always positive. Both samples exhibit skyrmionlike hump or dip features in their Hall traces. All Hall traces are vertically shifted for clarity. (c) Linear regression analysis of the remanences in device 1 (FGT/Gr/FTS-1) and device 2 (FGT/Gr/FTS-2). Two typical remanence curves of FGT (red, 40 nm) and FTS (green, 80 nm) were utilized to linearly fit the remanence of devices 1 and 2.

In contrast to FGT, the AHEs in FTS oppose the magnetization process (see the Appendix), indicating a negative AHE. It has been reported that both FGT and FTS are dominated by intrinsic AHE at low temperatures [29,30]. For the intrinsic AHE, the anomalous Hall conductivity is determined by the integration of Berry curvature in reciprocal space [2]. The positive AHE indicates a positive integration and vice versa. Due to the different coercivities and different Curie temperatures of the layers, the hybrid AHE of FGT/Gr/FTS heterostructures is expected to exhibit interesting phenomena.

Figure 3 shows the multichannel Hall effects in FGT/Gr/FTS heterointerfaces. Since FGT and FTS have different coercivities and anomalous Hall resistivities, the trace of hybrid anomalous Hall resistance would strongly depend on the current ratio passing through the two different magnetic layers. For clarity but without loss of generality, we fabricated two FGT/Gr/FTS heterostructure devices with different FGT and FTS thicknesses. In sample 1, the thickness of the FGT was 35 nm while the FTS was 95 nm thick. The two magnetic layers were separated by a graphite spacer (around 10 nm thick). In sample 2, the thicknesses of the FGT and FTS layers were nearly identical (60 nm) while the graphite layer was

again 10 nm thick. Figure 3(a) demonstrates the multichannel AHEs in sample 1 under different temperatures. Interestingly, the anomalous Hall resistance of FGT, R_{xy}^{FGT} , is similar in amplitude to R_{xy}^{FTS} between 40 and 50 K. Due to the opposite signs, the combined anomalous Hall resistance R_{xy}^{tot} in sample 1 approaches zero when the magnetic field $B \leq |H_c^{\text{FGT}}|$ (with H_c^{FGT} being the coercivity of FGT) in this temperature range. However, extra positive hump structures were observed for the magnetic field $|H_c^{\text{FGT}}| \leq B \leq |H_c^{\text{FTS}}|$ (H_c^{FTS} is the coercivity of FTS), resembling the positive THE arising from positive topological charges. Note that, due to the dramatic change of H_c^{FTS} with respect to the temperatures, the hump structures diminished rapidly as the temperature was increased from 40 to 49 K. Above 49 K, the amplitude of R_{xy}^{FGT} surpassed the amplitude of R_{xy}^{FTS} , $|R_{xy}^{\text{FGT}}| > |R_{xy}^{\text{FTS}}|$. The combined AHE above 49 K then became positive, as seen in Fig. 3(a). Moreover, both hump and dip structures were observed in a single Hall loop between 50 and 52 K, resembling both positive and negative THE induced by topological charges. Further elevating the temperature, the hump structures disappeared while the dip structures became more intense. Hence, a transformation from hump structures at low temperatures to dip structures occurred above 52 K. Meanwhile, due to the suppression of R_{xy}^{FTS} , the combined anomalous Hall resistance R_{xy}^{tot} at $B = 0$ T gradually increased. When the temperature exceeded 80 K, ferromagnetism in the FTS layer was suppressed and the AHE of FTS vanished. The combined AHE was then dominated by the contribution from the FGT layer. As shown in Fig. 3(a), the total anomalous Hall loop measured from this heterointerface at 100 K features square-shaped hysteresis that is characteristic of the intrinsic AHE in FGT at this temperature.

If the thicknesses of both FGT and FTS layers are altered, the combined Hall trace can be tuned. Figure 3(b) shows the two-channel Hall effect of sample 2 (in which both FGT and FTS layers were around 60 nm thickness). With the significant increase in the thickness of the FGT relative to sample 1, the combined Hall resistance R_{xy}^{tot} in sample 2 should be much larger than that exhibited by sample 1 near $B = 0$ T. Indeed, it can be seen from Fig. 3(b) that the hybrid AHEs are always positive from 35 to 52 K. Additionally, the observed hump structures do not transform to dip structures over that temperature range. These two-channel Hall effects appear to be very similar to previously reported THE [10–16] induced by the large DMI due to the strong SOC and broken SIS at heterointerfaces. However, due to the ignorable SOC in graphene, the FGT/Gr or Gr/FTS heterointerfaces do not support a nonzero DMI as well as any real space topological spin textures. We conclude that for heterointerfaces that support two opposite AHEs, two-channel transport can indeed mimic both positive and negative THE. This could mask the intrinsic THE associated with chiral spin textures.

III. LINEAR REGRESSION ANALYSIS ON REMANENCE OF FM-FM HETEROINTERFACES

To distinguish between the two possible origins, careful analysis of the AHEs in the separate magnetic layers should be performed. To further validate the two-channel scenario, we conduct linear regression analysis on the remanences of

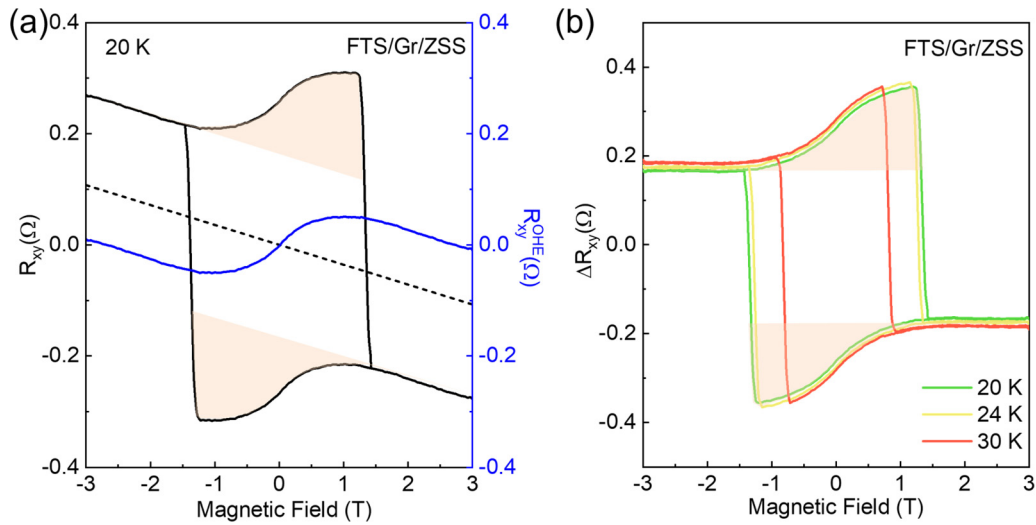


FIG. 4. Multichannel transport in FTS/Gr/ZSS heterointerfaces. (a) The hybrid Hall effect in a typical FTS/Gr/ZSS sample at 20 K (black curve). Due to the two-band character of ZrSiSe, the hybrid Hall resistance contains a hump structure (shaded light yellow) and a linear Hall contribution (dashed line). The blue curve indicates the possible two-band Hall component of ZrSiSe after subtracting the anomalous Hall part (light blue part). (b) shows the hybrid Hall component ΔR_{xy} at different temperatures after subtracting the linear Hall contribution.

anomalous Hall traces. Figure 3(c) displays the fitting curves for the remanences of devices 1 and 2. Note that the remanence discussed here refers to the value of R_{xy} ($B = 0$ T) after the magnetic field decreases from saturated fields. Here, two typical remanence curves of FGT [$R_{\text{FGT}}^{\text{Rem}}(T)$, 40 nm] and FTS [$R_{\text{FTS}}^{\text{Rem}}(T)$, 80 nm] nanoflakes [see the upper figure of Fig. 3(c)] were utilized to perform linear regression analysis. The detailed measurements of the temperature-dependent remanence curve were discussed previously [23]. The remanence values of both samples 1 and 2 now conform to $R_{\text{tot}}^{\text{Rem}} =$

$a + bR_{\text{FTS}}^{\text{Rem}} + cR_{\text{FGT}}^{\text{Rem}}$, where $R_{\text{tot}}^{\text{Rem}}$, $R_{\text{FGT}}^{\text{Rem}}$, and $R_{\text{FTS}}^{\text{Rem}}$ represent the remanence of the heterointerface, FGT, and FTS, respectively, and the fitting parameter a is a contributing factor from the graphene; it is close to zero due to the paramagnetic characteristic of graphene. b , c are the respective contributing factors of the FTS and FGT, which might depend on the sizes, resistivity, and metal electrode contact of each layer. However, the tendency of $R_{\text{tot}}^{\text{Rem}}(T)$ is almost the same in device 1 and device 2. As we can see in the lower two figures of Fig. 3(c), the remanences of device 1 and device 2 can be well fitted by the

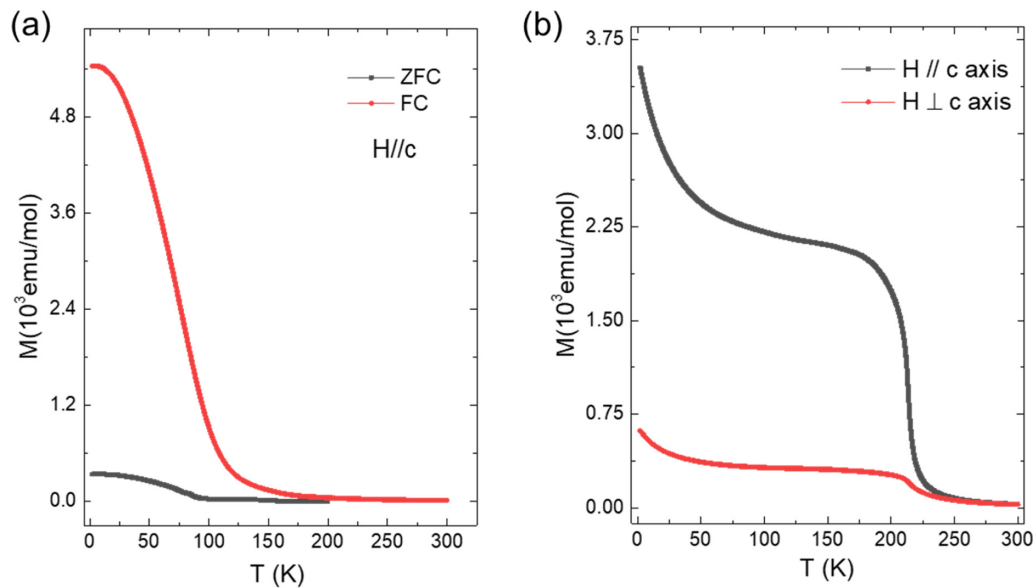


FIG. 5. Temperature-dependent magnetization (M - T) in $\text{Fe}_{0.26}\text{TaS}_2$ and Fe_3GeTe_2 single crystals. (a) Field cooling (FC) (1 T) and zero field cooling (ZFC) M - T curves in single crystal $\text{Fe}_{0.26}\text{TaS}_2$. From the M - T curves, we can get the Curie temperature of $\text{Fe}_{0.26}\text{TaS}_2$ which is around $T_c = 100$ K. (b) M - T curves in a single crystal Fe_3GeTe_2 with different magnetic field directions with cooling field $B = 500$ Oe. As we can see from the M - T curves, the Curie temperature of Fe_3GeTe_2 is around 220 K, much higher than that of $\text{Fe}_{0.26}\text{TaS}_2$.

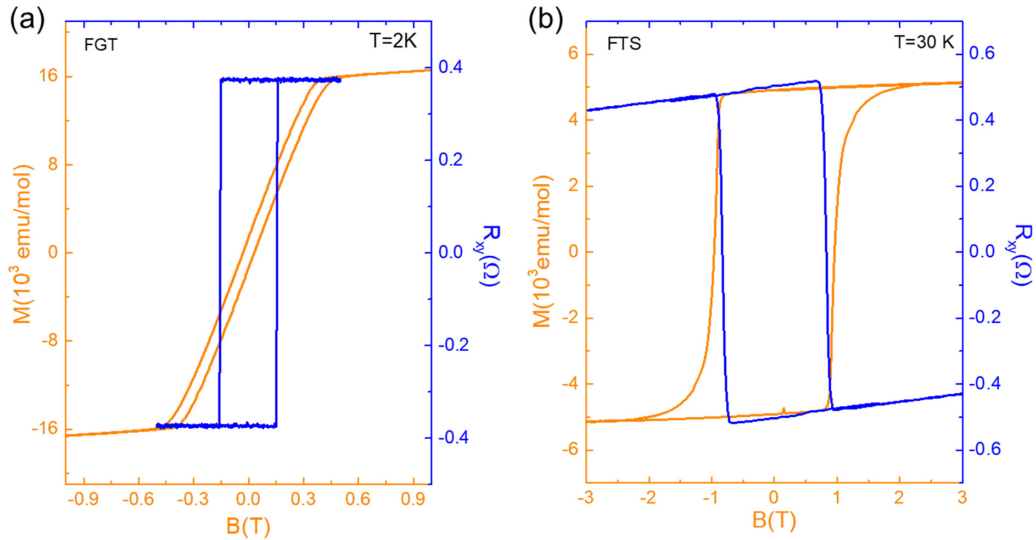


FIG. 6. A comparison between field-dependent magnetization (M - H) and anomalous Hall effects in $\text{Fe}_{0.26}\text{TaS}_2$ and Fe_3GeTe_2 . (a) M - H curve in FGT single crystal (orange) and anomalous Hall effect in FGT nanoflake (blue) at 2 K. Note that the M - H loop is different from the AHE loop; this is because in bulk FGT, the motion of multidomain will cause a gradual magnetization under magnetic field, while in FGT nanoflake, single domain will dominate and the anomalous Hall usually exhibits a square-shaped loop. However, both M - H and AHE exhibit a similar tendency, revealing a positive AHE in FGT. (b) M - H curve in FTS single crystal (orange) and anomalous Hall effect in FTS nanoflake (blue) at 30 K. In sharp contrast to FGT, the AHE in FTS is opposite to the M - H curve, indicating a negative AHE.

linear superposition of remanence from FGT and FTS layers, which further supports the multichannel transport scenario. Note that the resistivities of FTS, graphite, and FGT are quite different, which might lead to an inhomogeneous distribution of current in each layer. Since FGT has higher resistivity, we put it on top of the heterostructures to ensure that enough current could flow through FGT and generate sizable AHE signals in both FGT and FTS layers. Despite the different resistivities in each layer, however, these discrepancies are almost unchanged in our fitting temperature range (typically between 40 and 80 K) which validates the fittings in Fig. 3.

IV. MULTICHANNEL TRANSPORT IN FM-METAL HETEROINTERFACES

Besides the two-AHE scenario, we found that a single magnetic layer stacked onto a two-band nodal-line semimetal (ZrSiSe) also generated a skyrmionlike Hall trace, as illustrated in Figs. 1(c) and 1(d). It is well established that ZrSiSe is a two-band Dirac semimetal with a “nonlinear” Hall trace [31] resembling an AHE without hysteresis. Figure 7 shows the Hall resistances of a typical ZrSiSe nanoflake at different temperatures. Figure 4 shows the two-channel transport properties in one of our FTS/Gr/ZSS devices with layer thicknesses 70 nm (FTS), around 10 nm (Gr), and 110 nm (ZSS). The solid black curve in Fig. 4(a) shows the total Hall resistance at 20 K, which, at first glance contains a linear ordinary Hall contribution (dashed linear curve) and extra hump structures near the coercivities (shaded light yellow). However, this hump structure merely originates from the two-band character of ZrSiSe, and the corresponding two-band Hall component is shown by the blue curve in Fig. 4(a). The linear ordinary Hall contribution is subtracted to reveal the Hall component ΔR_{xy} at different temperatures, as

shown in Fig. 4(b). Due to the two-band character of Dirac semimetal ZrSiSe, the hybrid Hall effect in the FTS/Gr/ZSS heterointerface also exhibits hump features which resemble skyrmionlike THE. This multichannel transport in artificial FM-metal heterointerfaces has been overlooked so far and as a result, similar hump features observed in Hall traces might be mistakenly attributed to THE raised by chiral spin textures. Our experiments therefore provide an alternative explanation for unconventional AHEs that may be observed in a variety of heterointerfaces.

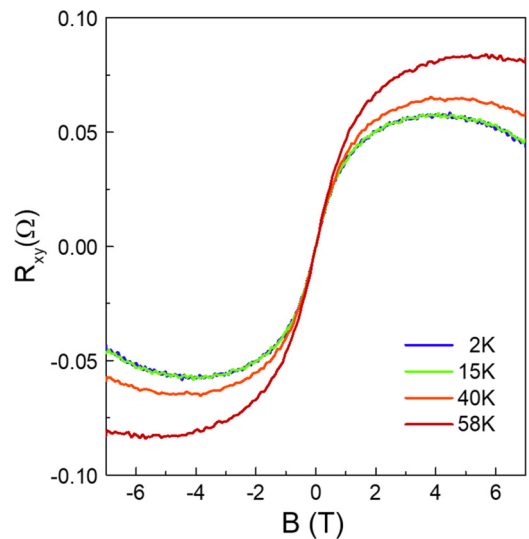


FIG. 7. Hall effects in a typical ZrSiSe nanoflake at different temperatures. As we can see, the Hall effects in Dirac semimetal ZrSiSe exhibit a two-band character, resembling the anomalous Hall resistance without hysteresis.

V. CONCLUSION

In conclusion, we systematically studied the multichannel Hall effects in different kinds of van der Waals heterointerfaces. We unveiled both hump and dip structures near the coercivities in anomalous Hall loops in FM/Gr/FM heterointerfaces with two opposite AHEs and the hump features in the FM/Gr/metal heterointerface even without the two opposite AHEs. These features, resembling skyrmionlike THE in chiral magnets, can be well captured by multichannel transport without involving any chiral spin textures. Our findings advance the understanding of the multichannel transport properties in artificial heterointerfaces.

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APPENDIX

1. Methods

a. Single crystal growth

Fe_3GeTe_2 single crystals were purchased from HQ graphene. $\text{Fe}_{0.26}\text{TaS}_2$ crystals were grown by the chemical vapor transport method with iodine as the transport agent. First, granular Fe, Ta powder, and S sponges with a mole ratio of 0.26:1:2 were mixed and sealed in an evacuated quartz tube. The tube was heated at 1173 K for 1 week. Second, the powder was obtained and 120 mg of iodine was sealed in an evacuated quartz tube with 15 mm inner diameter and 18 cm length. The

tube was then placed in a horizontal two-zone furnace with the source zone kept at 1223 K and the growth zone kept at 1123 K for 10 days. The as-grown crystals were cleaned in ethanol under ultrasonic agitation. The ZrSiSe single crystals were prepared using a chemical vapor transport method as described in Ref. [28].

b. Device fabrication and transport measurements

All nanoflakes, including $\text{Fe}_{0.26}\text{TaS}_2$, Fe_3GeTe_2 and ZrSiSe, were mechanically exfoliated from bulk crystals in a glove box filled with high-purity Ar gas with $\text{O}_2 < 0.1$ ppm, $\text{H}_2\text{O} < 0.1$ ppm. Nanoflakes with suitable thicknesses were then dry transferred using a polymer-based dry transfer technique. Note that FGT and FTS nanoflakes with smooth surfaces were chosen to construct the FTS/FGT heterostructure. Afterwards, the polymer was dissolved in chloroform. Hall-bar structures were fabricated by standard electron-beam lithography (EBL) methods followed by Cr/Au (10 nm/100nm) evaporation in a high-vacuum sputtering system with a base pressure less than 10^{-8} Torr. Transport measurements were performed using the electric transport option in a commercial magnetic property measurement system (Quantum Design, MPMS3).

2. Characterization of Fe_3GeTe_2 , $\text{Fe}_{0.26}\text{TaS}_2$, and ZrSiSe

See Figs. 5–7. The M - T curves in Fig. 5 show that the Curie temperature of FTS and FGT is around 100 K and 220 K, respectively. Different from the $R_{xy}(B)$ curve of FGT in Fig. 6(a), the $R_{xy}(B)$ curve of FTS is opposite to its M - H curve, which can be utilized to mimic the THE. Figure 7 shows a two-band character of the Hall effect in ZrSiSe, which resembles the AHE without hysteresis.

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- [1] E. H. Hall, On the “rotational coefficient” in nickel and cobalt, *Philos. Mag.* **12**, 157 (1881).
- [2] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, Anomalous Hall effect, *Rev. Mod. Phys.* **82**, 1539 (2010).
- [3] J. Ye, Y. B. Kim, A. J. Millis, B. I. Shraiman, P. Majumdar, and Z. Tešanović, Berry Phase Theory of the Anomalous Hall Effect: Application to Colossal Magnetoresistance Manganites, *Phys. Rev. Lett.* **83**, 3737 (1999).
- [4] P. Bruno, V. K. Dugaev, and M. Taillefumier, Topological Hall Effect and Berry Phase in Magnetic Nanostructures, *Phys. Rev. Lett.* **93**, 096806 (2004).
- [5] A. Neubauer, C. Pfleiderer, B. Binz, A. Rosch, R. Ritz, P. G. Niklowitz, and P. Böni, Topological Hall Effect in the A Phase of MnSi, *Phys. Rev. Lett.* **102**, 186602 (2009).
- [6] N. Kanazawa, Y. Onose, T. Arima, D. Okuyama, K. Ohoyama, S. Wakimoto, K. Kakurai, S. Ishiwata, and Y. Tokura, Large Topological Hall Effect in a Short-Period Helimagnet MnGe, *Phys. Rev. Lett.* **106**, 156603 (2011).
- [7] Y. Li, N. Kanazawa, X. Z. Yu, A. Tsukazaki, M. Kawasaki, M. Ichikawa, X. Jin, F. Kagawa, and Y. Tokura, Robust Formation of Skyrmions and Topological Hall Effect Anomaly in Epitaxial Thin Films of MnSi, *Phys. Rev. Lett.* **110**, 117202 (2013).
- [8] C. Franz, C. Freimuth, F. Bauer, A. Ritz, R. Schnarr, C. Duvinage, C. Adams, T. Blügel, S. Rosch, A. Mokrousov, and C. Pfleiderer, Real-Space and Reciprocal-Space Berry Phases in the Hall Effect of $\text{Mn}_{1-x}\text{Fe}_x\text{Si}$, *Phys. Rev. Lett.* **112**, 186601 (2014).
- [9] D. Liang, J. P. DeGrave, M. J. Stolt, Y. Tokura, and S. Jin, Current-driven dynamics of skyrmions stabilized in MnSi nanowires revealed by topological Hall effect, *Nat. Commun.* **6**, 8217 (2015).
- [10] K. Yasuda, R. Wakatsuki, T. Morimoto, R. Yoshimi, A. Tsukazaki, K. S. Takahashi, M. Ezawa, M. Kawasaki, N. Nagaosa, and Y. Tokura, Hall effects in topological insulator heterostructures, *Nat. Phys.* **12**, 555 (2016).
- [11] J. Matsuno, N. Ogawa, K. Yasuda, F. Kagawa, W. Koshibae, N. Nagaosa, Y. Tokura, and M. Kawasaki, Interface-driven topological Hall effect in SrRuO_3 - SrIrO_3 bilayer, *Sci. Adv.* **2**, e1600304 (2016).
- [12] C. Liu, Y. Zang, W. Ruan, Y. Gong, K. He, X. Ma, Q.-K. Xue, and Y. Wang, Dimensional Crossover-Induced Topological Hall Effect in a Magnetic Topological Insulator, *Phys. Rev. Lett.* **119**, 176809 (2017).
- [13] Y. Ohuchi, J. Matsuno, N. Ogawa, Y. Kozuka, M. Uchida, Y. Tokura, and M. Kawasaki, Electric-field control of anomalous

- and topological hall effects in oxide bilayer thin films, *Nat. Commun.* **9**, 213 (2018).
- [14] Q. L. He, G. Yin, A. J. Grutter, L. Pan, X. Che, G. Yu, D. A. Gilbert, S. M. Disseler, Y. Liu, P. Shafer, B. Zhang, Y. Wu, B. J. Kirby, E. Arenholz, R. K. Lake, X. Han, and K. L. Wang, Exchange-biasing topological charges by antiferromagnetism, *Nat. Commun.* **9**, 2767 (2018).
- [15] M. Raju, A. Yagil, A. Soumyanarayanan, A. K. Tan, A. Almoalem, F. Ma, O. Auslaender, and C. Panagopoulos, The evolution of skyrmions in Ir/Fe/Co/Pt multilayers and their topological Hall signature, *Nat. Commun.* **10**, 696 (2019).
- [16] J. Jiang, D. Xiao, F. Wang, J.-H. Shin, D. Andreoli, J. Zhang, R. Xiao, Y.-F. Zhao, M. Kayyalha, L. Zhang, K. Wang, J. Zang, C. Liu, N. Samarth, M. H. W. Chan, and C.-Z. Chang, Concurrence of quantum anomalous Hall and topological Hall effects in magnetic topological insulator sandwich heterostructures, *Nat. Mater.* **19**, 732 (2020).
- [17] D. J. Groenendijk, C. Autieri, T. C. van Thiel, W. Brzezicki, J. Hortensius, D. Afanasiev, N. Gauquelin, P. Barone, K. van den Bos, S. van Aert, J. Verbeeck, A. Filippetti, S. Picozzi, M. Cuoco, and A. D. Caviglia, Berry phase engineering at oxide interfaces, *Phys. Rev. Res.* **2**, 023404 (2020).
- [18] D. Zheng, Y.-W. Fang, S. Zhang, P. Li, Y. Wen, B. Fang, X. He, Y. Li, C. Zhang, W. Tong, W. Mi, H. Bai, H. N. Alshareef, Z. Q. Qiu, and X. Zhang, Berry phase engineering in SrRuO₃/SrIrO₃/SrTiO₃ superlattices induced by band structure reconstruction, *ACS Nano* **15**, 5086 (2021).
- [19] K. M. Fijalkowski, M. Hartl, M. Winnerlein, P. Mandal, S. Schreyeck, K. Brunner, C. Gould, and L. W. Molenkamp, Coexistence of Surface and Bulk Ferromagnetism Mimics Skyrmion Hall Effect in a Topological Insulator, *Phys. Rev. X* **10**, 011012 (2020).
- [20] P. Chen, Y. Zhang, Q. Yao, F. Tian, L. Li, Z. Qi, X. Liu, L. Liao, C. Song, J. Wang, G. Li, D. M. Burn, G. van der Laan, T. Hesjedal, S. Zhang, and X. Kou, Tailoring the hybrid anomalous Hall response in engineered magnetic topological insulator heterostructures, *Nano Lett.* **20**, 1731 (2020).
- [21] F. Wang, X. Wang, Y.-F. Zhao, D. Xiao, L.-J. Zhou, W. Liu, Z. Zhang, W. Zhao, M. H. W. Chan, N. Samarth, C. Liu, H. Zhang, and C.-Z. Chang, Interface-induced sign reversal of the anomalous Hall effect in magnetic topological insulator heterostructures, *Nat. Commun.* **12**, 79 (2021).
- [22] D. Kan, T. Moriyama, K. Kobayashi, and Y. Shimakawa, Alternative to the topological interpretation of the transverse resistivity anomalies in SrRuO₃, *Phys. Rev. B* **98**, 180408 (2018).
- [23] A. Gerber, Interpretation of experimental evidence of the topological Hall effect, *Phys. Rev. B* **98**, 214440 (2018).
- [24] L. Yang, L. Wysocki, J. Schöpf, L. Jin, A. Kovács, F. Gunkel, R. Dittmann, P. H. M. van Loosdrecht, and I. Lindfors-Vrejoiu, Origin of the hump anomalies in the Hall resistance loops of ultrathin SrRuO₃/SrIrO₃ multilayers, *Phys. Rev. Mater.* **5**, 014403 (2021).
- [25] W. Wang, Y.-F. Zhao, F. Wang, M. W. Daniels, C.-Z. Chang, J. Zang, D. Xiao, and W. Wu, Chiral-bubble-induced topological Hall effect in ferromagnetic topological insulator heterostructures, *Nano Lett.* **21**, 1108 (2021).
- [26] C. Tan, J. Lee, S.-G. Jung, T. Park, S. Albarakati, J. Partridge, M. R. Field, D. G. McCulloch, L. Wang, and C. Lee, Hard magnetic properties in nanoflake van der Waals Fe₃GeTe₂, *Nat. Commun.* **9**, 1554 (2018).
- [27] S. Albarakati, C. Tan, Z.-J. Chen, J. G. Partridge, G. Zheng, L. Farrar, E. L. Mayes, M. R. Field, C. Lee, Y. Wang, Y. Xiong, M. Tian, F. Xiang, A. R. Hamilton, O. A. Tretiakov, D. Culcer, Y.-J. Zhao, and L. Wang, Antisymmetric magnetoresistance in van der Waals Fe₃GeTe₂/graphite/Fe₃GeTe₂ trilayer heterostructures, *Sci. Adv.* **5**, eaaw0409 (2019).
- [28] G. Zheng, W.-Q. Xie, S. Albarakati, M. Algarni, C. Tan, Y. Wang, J. Peng, J. Partridge, L. Farrar, J. Yi, Y. Xiong, M. Tian, Y.-J. Zhao, and L. Wang, Gate-Tuned Interlayer Coupling in van der Waals Ferromagnet Fe₃GeTe₂ Nanoflakes, *Phys. Rev. Lett.* **125**, 047202 (2020).
- [29] K. Kim, J. Seo, E. Lee, K.-T. Ko, B. Kim, B. G. Jang, J. M. Ok, J. Lee, Y. J. Jo, W. Kang, J. H. Shim, C. Kim, H. W. Yeom, B. I. Min, B.-J. Yang, and J. S. Kim, Large anomalous Hall current induced by topological nodal lines in a ferromagnetic van der Waals semimetal, *Nat. Mater.* **17**, 794 (2018).
- [30] J. G. Checkelsky, M. Lee, E. Morosan, R. J. Cava, and N. P. Ong, Anomalous Hall effect and magnetoresistance in the layered ferromagnet Fe_{1/4}TaS₂: The inelastic regime, *Phys. Rev. B* **77**, 014433 (2008).
- [31] J. Hu, Z. Tang, J. Liu, X. Liu, Y. Zhu, D. Graf, K. Myhro, S. Tran, C. N. Lau, J. Wei, and Z. Mao, Evidence of Topological Nodal-Line Fermions in ZrSiSe and ZrSiTe, *Phys. Rev. Lett.* **117**, 016602 (2016).