

Anisotropic magnetoresistance and planar Hall effect in an antiferromagnetic insulator-topological insulator heterostructure

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The coupling between magnetism and topological states at a topological insulator (TI)-magnetic insulator interface can induce exchange gap opening and spin texture change, resulting in many emergent transport phenomena, including anisotropic magnetoresistance (AMR) and planar Hall effect (PHE). While AMR/PHE have been reported in several ferromagnetic insulator-TI heterostructures so far, such effects in antiferromagnetic insulator-TI heterostructure remain elusive. Here, we observe unique features of AMR and PHE in an antiferromagnetic insulator-TI heterostructure $\text{MnSe}/(\text{Bi}, \text{Sb})_2\text{Te}_3$. Specifically, at low magnetic fields (H), the in-plane AMR exhibits dips under H applied parallel to the current ($H//I$) but peaks under the perpendicular geometry ($H\perp I$), opposite to the zero AMR features in ferromagnetic insulator-TI heterostructures. The low-field PHE is most striking at $H//I$, but gradually suppressed when H deviates from parallel direction. At high magnetic fields, both AMR and PHE show prominent π -period oscillation. Gate-tuning and temperature-dependence measurements demonstrate that the observed AMR/PHE originate from the interplay between the topological surface state of TI with the spin canting and magnetic phase transition of MnSe. These results not only differentiate the AMR/PHE in TI-based magnetic heterostructure from the pristine TI, but also offer a feasible way to distinguish spin Hall effect and AMR in TI-based heterostructures.

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I. INTRODUCTION

Anisotropic magnetoresistance (AMR) and planar Hall effect (PHE, the in-plane off-diagonal version of AMR) were mainly observed in the ferromagnets since the first discovery by William Thomson in 1857 [1]. Starting from 3d ferromagnetic elements and their alloys, various kinds of materials have been verified experimentally to show AMR/PHE during the past two decades, such as dilute magnetic semiconductor (Ga, Mn)As [2], two-dimensional electron gases [3,4], Heusler alloys [5,6], antiferromagnets [7,8], topological insulators (TIs) [9–24], and Dirac/Weyl semimetals [25–29]. Unlike ferromagnets in which the mechanism of AMR/PHE has been well established [30–32], the origin of AMR/PHE in TIs remains controversial. Several mechanisms recently proposed for AMR/PHE in pristine TIs include anisotropic electron scattering by polarized impurities [12], hexagonal warping of surface states [33], and tilt of the Dirac cone by the in-plane magnetic field [34]. When introducing magnetism to TIs, the AMR/PHE become more complex and intriguing [9,11,13,18,21]. For the magnetically doped TI, Yasuda *et al.* identified a large unidirectional magnetoresistance (MR) and attributed it to the

asymmetric scattering of electrons by magnons [11]. Kandala *et al.* observed a giant out-of-plane AMR and a conventional in-plane AMR in the quantum anomalous Hall insulator $\text{Cr}_x(\text{Bi}, \text{Sb})_{2-x}\text{Te}_3$ [9]. Coupling a magnetic insulator to TI can also induce AMR and PHE phenomena, which has been reported for ferromagnetic insulator/TI heterostructures, such as $\text{EuS}/(\text{Bi}, \text{Sb})_2\text{Te}_3$ [13], $\text{TmIG}/\text{Bi}_2\text{Se}_3$ [18], and yttrium iron garnet (YIG)/TI [21,23,35]. Rakhmilevich *et al.* found a maximized (suppressed) PHE when the in-plane magnetic field is parallel (perpendicular) to the electric current and suggested two possible nonlinear contributions [13]. In the exfoliated TI flakes attached to YIG film, Banerjee *et al.* reported a fourfold symmetry pattern of AMR [35], and another work by Sklenar *et al.* reported a large (6.5%) AMR signal when magnetization is perpendicular to the surface [21]. Wang *et al.* observed nonlinear PHE in Bi_2Se_3 films grown on TmIG and YIG substrates [23].

The proximity-induced AMR and PHE in TI/magnet heterostructures could be more intriguing than that in the single-phase materials. In traditional 3d ferromagnets, PHE is attributed to anisotropic scattering and nonspherical Fermi surfaces, typically resulting in weaker effects at room temperature [36]. Dilute magnetic semiconductor systems offer tunable magnetic properties through carrier-mediated exchange interactions, though their low Curie temperatures and disorder present challenges [37]. Heusler alloys are known for high spin polarization and robust AMR, but they require complex synthesis and precise structural ordering [38–40]. In contrast, TI/magnet heterostructures benefit from proximity-induced effects and strong spin-orbit coupling,

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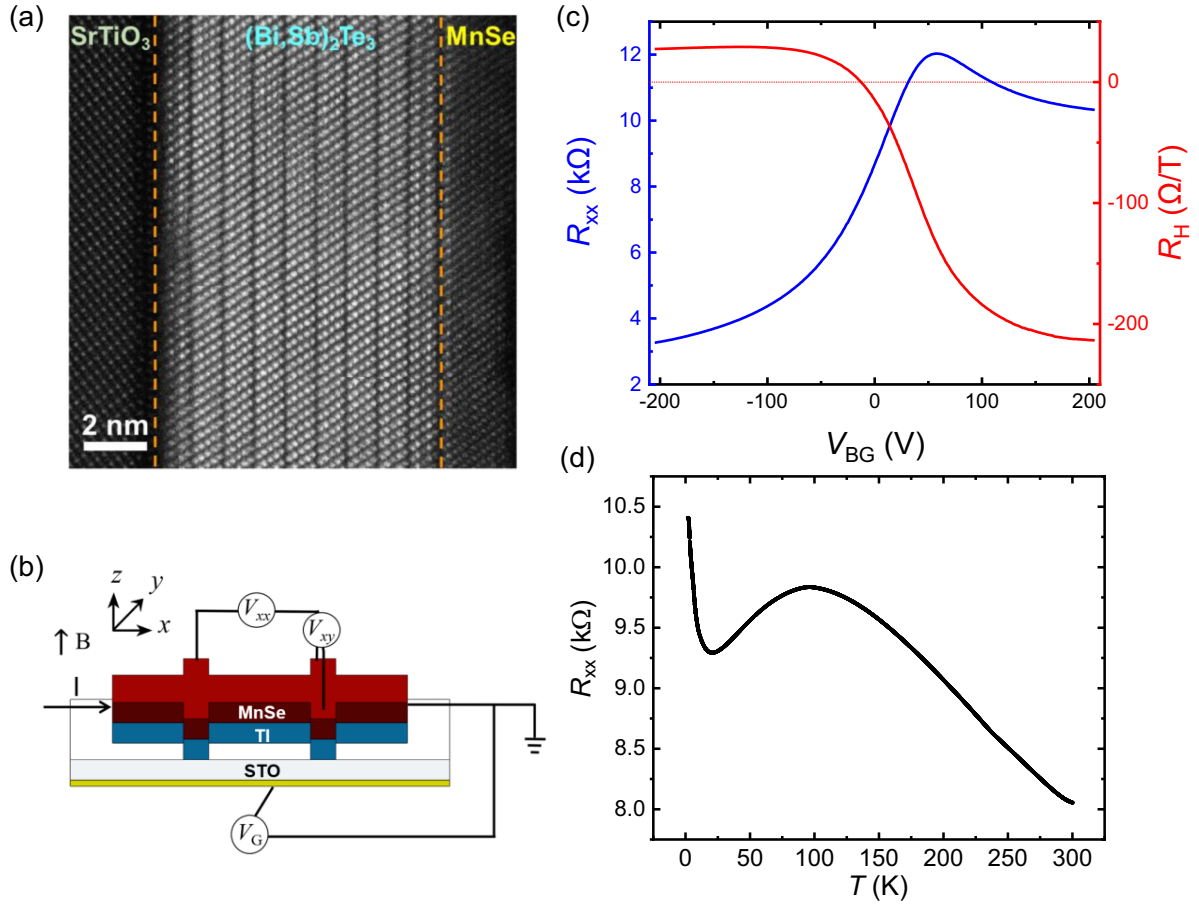


FIG. 1. Basic characterization of MnSe/(Bi, Sb)₂Te₃ heterostructures. (a) Cross-section scanning transmission electron microscopy image of the nominal MnSe/(Bi, Sb)₂Te₃ (3 nm/9 nm) grown on the SrTiO₃(111) substrate. (b) Schematic sketch of a back-gated Hall-bar device fabricated on the sample. (c) The gate voltage dependence of zero field R_{xx} (blue) and Hall coefficient R_H (red) in the MnSe/(Bi, Sb)₂Te₃ heterostructure at $T = 1.7$ K. (d) Temperature dependence of longitudinal resistance R_{xx} of MnSe/(Bi, Sb)₂Te₃ heterostructure.

which may lead to enhanced PHE and AMR responses. These heterostructures utilize interfacial interactions, such as the Dzyaloshinskii-Moriya interaction that can stabilize unique spin textures [41]. However, AMR and PHE in TI/magnet heterostructures have been largely underinvestigated up to now due to the rarity of ferromagnetic insulators. On the other hand, antiferromagnetic insulators would be a good candidate as the replacement of FI to couple with TIs. Although without macroscopic magnetization, the uncompensated spins in the basal plane of antiferromagnetic insulators can align the spin moments of TIs through short-range interfacial exchange coupling, similarly to the use of ferromagnetic insulators. Hence, integrating TIs with antiferromagnetic insulators is a feasible way for uncovering quantum phenomena induced by magnetic proximity effect on the TI surface states. In our recent work, a large proximity-induced anomalous Hall effect was observed in an antiferromagnetic insulator/TI heterostructure, MnSe/(Bi, Sb)₂Te₃ (MnSe/BST hereafter) [42]. For the particular antiferromagnetic spin structure in MnSe, we expect particular AMR and PHE phenomena in this system that differ from both the pristine TIs and ferromagnetic insulator/TIs.

In this work, we report the unique features of AMR and PHE in MnSe/BST. We investigate the low-field in-plane magnetoresistance, and also the high-field

AMR/PHE at different magnetic field directions. Based on the dependence of AMR/PHE on chemical potential and temperature, the AMR/PHE in this antiferromagnetic insulator/TI heterostructure is determined to originate from the magnetized topological surface states of BST induced by magnetic proximity effect. Our results could address important issues in this area, such as how to distinguish between the phenomena of AMR/PHE from the pristine TI and from the TI-based heterostructure, and how to differentiate AMR and the possible existing spin Hall magnetoresistance in TI-based heterostructures.

II. RESULTS AND DISCUSSION

A. Structure and basic transport characterization

The MnSe/BST (3 nm/9 nm) heterostructures were grown on 0.3-mm-thick heat-treated SrTiO₃(111) substrates by molecular beam epitaxy [42]. The atomically sharp interface was verified by the cross-section transmission electron microscopy image shown in Fig. 1(a) and the energy-dispersive X-ray spectroscopy mapping shown in Fig. S1 of the Supplemental Material [43]. The heterostructure samples were patterned into 200-μm-wide Hall-bar devices as schematically depicted in Fig. 1(b). With SrTiO₃ substrate as the dielectric

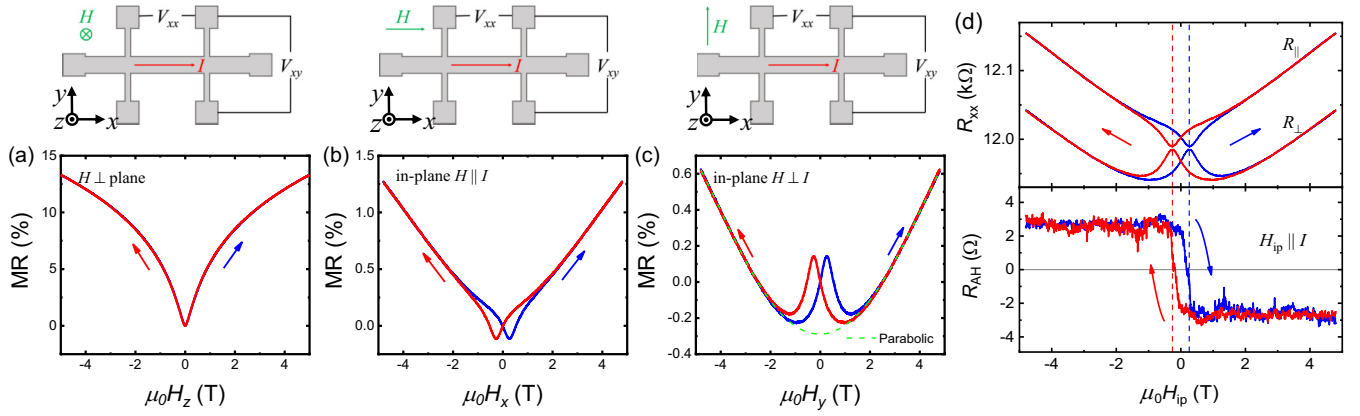


FIG. 2. MR curves of MnSe/(Bi, Sb)₂Te₃ heterostructure film at different magnetic field directions. (a) H is perpendicular to the sample plane (H_z). (b) H is in-plane and parallel to the current direction (H_x). (c) H is in-plane and perpendicular to current direction (H_y). The red and blue curves represent magnetic field sweeping to the negative and positive directions, respectively. (d) The longitudinal resistance ($R_{\parallel}$ and $R_{\perp}$) under in-plane magnetic field, parallel and perpendicular to the current, respectively, and the anomalous Hall resistance under in-plane magnetic field parallel to the current direction. $T = 1.7$ K. The red and blue curves represent magnetic field sweeping to the negative and positive directions, respectively.

layer, the carrier type and concentration of MnSe/BST can be effectively tuned, as shown in Fig. 1(c). The dominant charge carriers change from p -type to n -type with increasing gate voltage, and the zero-field longitudinal resistance reaches its maximum at 50 V, which corresponds to the Dirac point of the surface state. Figure 1(d) shows the temperature dependence of longitudinal resistance R_{xx} of the heterostructure. R_{xx} first increases monotonically as the temperature (T) decreases from room temperature to about 100 K for the thermal activation process. Then, below 100 K, R_{xx} decreases due to the increasing contribution from the surface states. The sharp upturn of R_{xx} below 20 K is due to strong T dependence at liquid helium temperature as broken time reversal symmetry suppresses the weak antilocalization effect. All the resistance values reported in this study refer to sheet resistance (resistance per square, $\Omega/\square$).

B. Low-field magnetoresistance and PHE

Figure 2 shows the magnetoresistance [$MR = (R_{xx}(H) - R_{xx}(0))/R_{xx}(0)$] with respect to varying magnetic field directions. When the magnetic field is applied perpendicular to the sample plane [Fig. 2(a)], MR is positive with a cusplike dip at zero magnetic field, which can be ascribed to the weak antilocalization effect. Under in-plane magnetic fields, significant hysteresis appears in the MR curves for both configurations of magnetic field applied parallel [$H \parallel I$ in Fig. 2(b)] and perpendicular to the current [$H \perp I$ in Fig. 2(c)], and anisotropic MR is observed. When the magnetic field is parallel to the current direction, the hysteresis loop shows a butterfly shape with two separate minima at the coercive field H_C [Fig. 2(b)]. In contrast, pronounced MR peaks emerge at H_C with the in-plane magnetic field applied perpendicular to the current [Fig. 2(c)]. Such MR signal is similar to that in 3d ferromagnetic systems [44], but different from that observed in ferromagnetic insulator/TI systems, such as EuS/TI [13] and garnet/TI [18,21]. In EuS/TI, MR shows V-shaped hysteretic dips for both $H \parallel I$ and $H \perp I$ directions (and hence zero AMR) [13], which were attributed to the perpendicular domain wall

forming at the interface and related one-dimensional chiral transport [45]. For YIG/Bi₂Se₃, Lang *et al.* observed square-shaped MR hysteresis loops at $H \parallel I$ [46], while Sklenar *et al.* [21] reported hysteretic MR at both $H \parallel I$ and $H \perp I$ with very weak anisotropy. The different signature of MR in these TI heterostructures should be related to the magnetic anisotropy of ferromagnetic insulator as well as the interfacial exchange coupling. For instance, evidence for perpendicular anisotropy has been found in the EuS/Bi₂Se₃ interface [47]. On the contrary, YIG possess in-plane anisotropy and no anomalous Hall effect has been observed in YIG/TI.

Different from EuS and YIG, MnSe is a type-II antiferromagnetic insulator with spins along $\langle 001 \rangle$ direction. As the epitaxial growth of MnSe film on the hexagonal TI is along $\langle 111 \rangle$ crystal orientation, the spins are canted about 35° away from the sample plane. The competition between the exchange coupling and the magnetic anisotropy may further tilt the spins and modulate the interfacial anisotropy of MnSe/BST heterostructure. Although the spin canting and the exact anisotropy at the interface are hard to detect, the transport measurements can give some information. Our recent work on MnSe/BST showed a large anomalous Hall effect with rather high saturation field, verifying the perpendicular magnetization and the effect of antiferromagnetism [42]. Here, the observed MR hysteresis loops with dips at $H \parallel I$ and peaks at $H \perp I$ should be correlated with the particular in-plane magnetization states at H_C .

By comparing the longitudinal resistance measured for the two geometries of $H \parallel I$ and $H \perp I$ (labeled as $R_{\parallel}$ and $R_{\perp}$) shown in the upper panel of Fig. 2(d), one can see that $R_{\parallel}$ is always larger than $R_{\perp}$ in the whole range of applied magnetic field, which leads to a positive AMR. Besides, a low-field hysteretic PHE is observed for $H \parallel I$ [lower panel of Fig. 2(d)]. The value of coercive field is consistent with that obtained from MR as marked by the dashed lines. This low-field PHE is the largest at $H \parallel I$ among all H directions but completely suppressed at $H \perp I$ (detailed data with respect to different in-plane magnetic field directions are presented in Fig. S3 of the Supplemental Material [43]), in contrast to that in the conventional ferro-

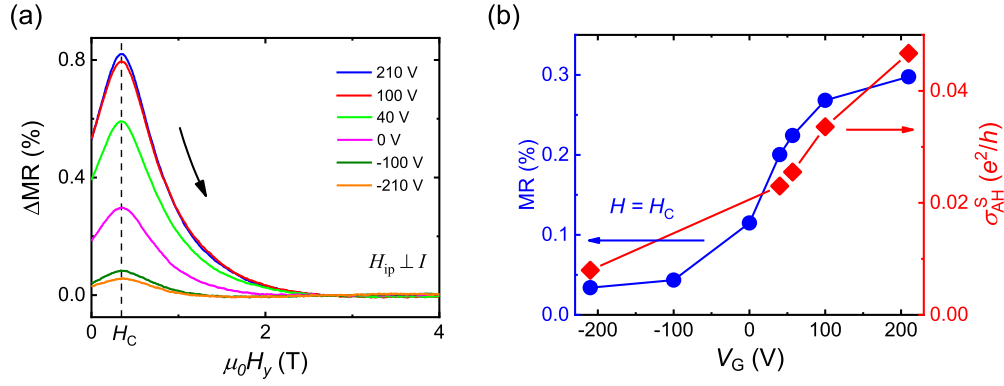


FIG. 3. Gate voltage dependence of low-field MR in MnSe/(Bi, Sb)₂Te₃ heterostructure film. (a) MR curves after subtracting the parabolic background. (b) gate voltage dependence of MR values at the coercive field under in-plane magnetic field perpendicular to the current and the saturation value of anomalous Hall conductance σ_{AH}^s under out-of-plane field. $T = 1.7$ K.

magnets that show zero PHE at both $H//I$ and $H \perp I$. We note that a similar PHE phenomenon was observed in EuS/TI, which was attributed to the nonlinear Hall mechanisms [13]. However, such mechanisms cannot be simply applied to our system since we have observed strong anisotropy of magnetoresistance [upper panel of Fig. 2(d)] that can contribute to this PHE, compared to no AMR appearing in EuS/TI.

To clarify the origin of low-field AMR, we did detailed study on the gate voltage and temperature dependence of MR. First, the back gate (V_G) was varied to examine the influence of carrier type and carrier concentration on MR. We found that the amplitude of MR can be effectively tuned by the electric field effect. The data at different V_G are presented in Fig. 3(a) after subtracting the parabolic background (the background is obtained by fitting the original MR curve at high magnetic field from 3 to 9 T). First, one can see that H_C remains unchanged within the whole gate range from -210 to 210 V. Such behavior excludes Mn-doping effect at the interface. As for Mn-doped TIs, the Ruderman-Kittel-Kasuya-Yosida interaction mediated by Dirac fermion would result in the coercive field changing with respect to the surface carrier density [48]. The independence of gate voltage of H_C in MnSe/BST suggests that H_C primarily originates from the magnetic anisotropy of the MnSe layer and its amplitude reflects the energy barrier required to reorient the magnetization of MnSe. On the other side, the amplitude of MR at H_C increases monotonically with increasing V_G , in accordance with the trend of saturation value of anomalous Hall conductance σ_{AH}^s under an out-of-plane magnetic field, as shown in Fig. 3(b) (the detailed extraction process of σ_{AH}^s was presented in our previous paper [42]). The Fermi level moves upward with increasing gate voltage and remains below the Dirac mass gap even at the maximum gate voltage of 210 V (see the band diagram in Ref. [42] and also Sec. 5 of the Supplemental Material [43]). As the gate voltage shifts the Fermi level upward, the surface carriers perform more contribution in the transport and the surface states interact more strongly with the canted MnSe moments, enhancing spin-dependent scattering. The gate dependence of MR at H_C is an interface-driven effect, indicating that the interfacially

magnetized surface states are responsible for the low-field AMR.

C. High-field AMR and PHE

At high fields, the magnetization of the samples is saturated; hence, the domain-wall-induced MR is suppressed, making the interpretation of MR simpler. We measured the angular dependence of in-plane MR and Hall resistance at 9 T [plotted in Fig. 4(b), upper and lower panels, respectively]. Both the in-plane MR and Hall resistance show a typical sinusoidal behavior. Normally, the angular dependence of R_{xx} and R_{xy} (AMR and PHE, respectively) could be expressed phenomenologically by the following equations [49]:

$$R_{xx} = R_{\perp} + (R_{\parallel} - R_{\perp})\cos^2\varphi, \quad (1)$$

$$R_{xy} = (R_{\parallel} - R_{\perp})\sin\varphi\cos\varphi, \quad (2)$$

where R_{xx} and R_{xy} are the longitudinal and transverse magnetoresistances, or the amplitude of AMR and PHE. φ is the angle between the direction of current and in-plane magnetic field. The high-field AMR and PHE observed in MnSe/BST exhibit an oscillatory behavior with a period of π in the form of $\cos^2\varphi$ and can be well described by the above equations. AMR remains positive as there is always $R_{\parallel} > R_{\perp}$ at different temperatures.

Because AMR can emerge in both the nonmagnetic pristine TIs and TI/magnet heterostructures, the mechanism of AMR in a heterostructure needs to be distinguished carefully. To figure out the true source of AMR/PHE in MnSe/BST, we measured not only the transport of the heterostructure (3-nm MnSe on 9-nm BST) but also the pristine 9-nm BST film. As a possible misalignment of the sample plane with the rotation plane of magnetic field would introduce a finite out-of-plane magnetic field component, an additional orbital magnetoresistance and ordinary Hall resistance may mix into the genuine AMR and PHE signals, respectively. The orbital magnetoresistance is difficult to be effectively eliminated, as Taskin *et al.* discussed in their work [12]. Instead, PHE is much more reliable since ordinary Hall resistance is antisymmetric to magnetic field and can be easily removed by sweeping field along reverse directions. Therefore, we use the PHE data to

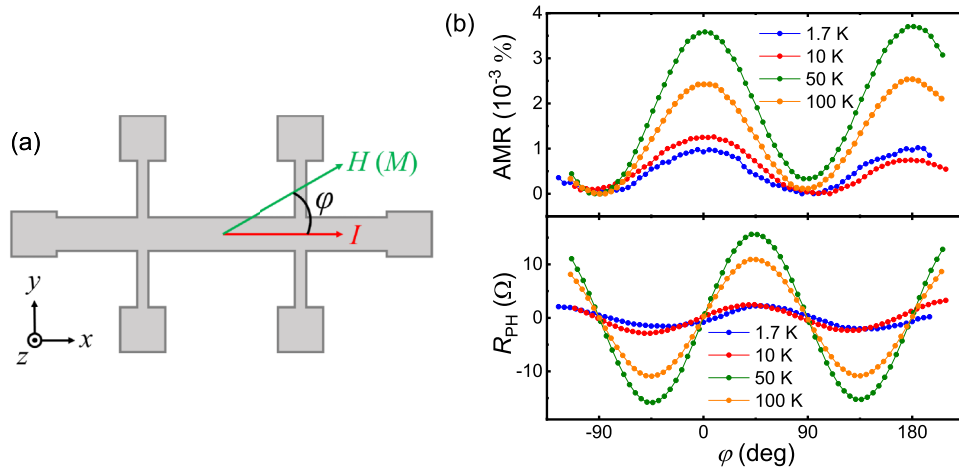


FIG. 4. In-plane angular dependence of MR and Planar Hall resistance in $\text{MnSe}/(\text{Bi, Sb})_2\text{Te}_3$ heterostructure film. (a) Schematic of the configuration of in-plane magnetic field and the current. (b) The angle dependence of in-plane AMR (top) and Planar Hall resistance R_{PH} (bottom) at 9 T and $T = 1.7, 10, 50$, and 100 K. $V_G = 0$ V.

analyze the magnetic field-induced anisotropy in the transport properties. We compared the temperature dependence of high-field PHE in MnSe/BST heterostructure and that in the pristine BST film (Fig. 5), and found a dramatic difference between the two systems. As shown in Fig. 5 (more data in Fig. S6 of the Supplemental Material [43]), PHE amplitude in the pristine 9-nm BST decreases monotonically with increasing temperature in the measured range from 1.7 to 70 K, and is almost suppressed above 70 K. In contrast, PHE amplitude in the heterostructure shows a nonmonotonic change with the maximum value at ~ 50 K, and persists up to a much higher temperature 250 K (Fig. 5 and more data in Fig. S5 of the Supplemental Material [43]).

The temperature behavior of pristine BST film should be attributed to the topological surface states. The temperature dependence of longitudinal resistance clearly shows an inflection point at ~ 75 K (Fig. S7 of the Supplemental Material [43]). Above this point, resistance decreases monotonically, which is due to the thermal activation process, and the bulk state dominates the transport. Below this point, with bulk carriers progressively frozen out, the metallic topological surface

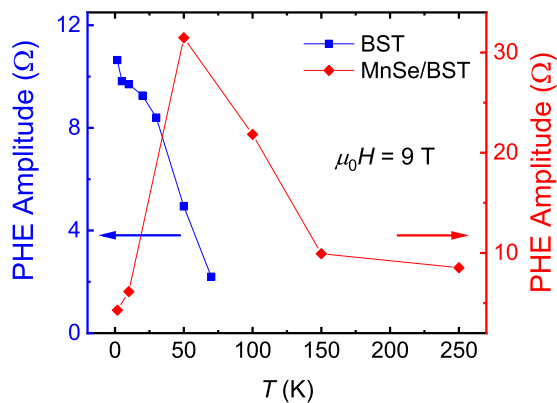


FIG. 5. Temperature dependence of PHE amplitudes in the 9-nm $(\text{Bi, Sb})_2\text{Te}_3$ film (blue squares) and $\text{MnSe}/(\text{Bi, Sb})_2\text{Te}_3$ (3 nm/9 nm) heterostructure (red diamonds). $V_G = 0$ V.

states arise and become the dominant contribution. Therefore, PHE in the pristine 9-nm BST should originate from the topological surface states, which explains the continuous suppression of PHE with increasing temperature. For the heterostructure, it is more complicated. We noted that a few works reported magnetic anomalies of bulk MnSe between 100 and 200 K [50–54]. According to a comprehensive study by Huang *et al.*, the bulk MnSe experiences a phase transition from α - MnSe to β - MnSe at 140 K and the two phases coexist until 270 K, leading to the huge magnetic susceptibility anomaly within a wide temperature range [54]. The Neel temperature (T_N) of α - MnSe is 120 K, while 270 K for β - MnSe . The high T_N of β - MnSe should be the reason for the persistent PHE to higher temperature in the heterostructure. On the other hand, the maximum PHE amplitude at the temperature of 50 K seems difficult to be explained by the phase transition temperature of either α - MnSe or β - MnSe . After a careful inspection into the literature, we found that an early work by Peng *et al.* reported an abrupt increase of susceptibility near 50 K in α - MnSe due to a spin-flop process under a high external magnetic field [52]. As the applied field is as large as 9 T in our high-field PHE measurement, the maximum PHE value at 50 K hence could correspond to the spin-flop process in the antiferromagnetic order state of α - MnSe . Therefore, the above observations clearly distinguish the high-field AMR and PHE in MnSe/BST from that in pristine BST, confirming that the magnetic proximity effect at the antiferromagnetic insulator/TI interface determines the AMR/PHE of this system.

D. Out-of-plane angular dependence of MR

Having studied in-plane angular dependence of AMR and PHE, we further measured the out-of-plane angular dependence of MR at 9 T (Fig. 6) aiming to discuss possible contributions from spin Hall effect. Normally, in a heterostructure with strong spin-orbital coupling, the spin Hall effect also gives rise to an anisotropic in-plane magnetoresistance, namely, spin Hall magnetoresistance [55]. Although spin Hall magnetoresistance gives rise to a similar $\cos^2\varphi$ de-

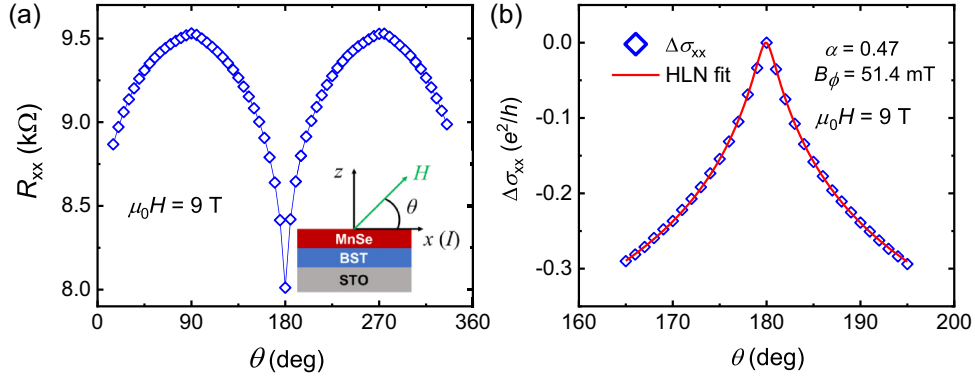


FIG. 6. (a) Out-of-plane angular dependence of MR in MnSe/(Bi, Sb)₂Te₃ at 1.7 K and 9 T. (b) The angular dependence of the longitudinal conductance in MnSe/(Bi, Sb)₂Te₃ at 1.7 K and 9 T. The red line is the HLN fitting curve. $V_G = 0$ V.

pendence on the angle between the current and the in-plane magnetic field as that of AMR, it can be differentiated with an out-of-plane magnetic field tilting from the current direction to the normal direction of the sample plane [55]. In this experimental configuration, spin Hall magnetoresistance remains constant while AMR oscillates in the form of a trigonometric function with the rotating magnetic field. However, we realize that this method does not apply to the systems with topological surface states protected by time reversal symmetry. In TIs, only the perpendicular component of magnetic field can break the time reversal symmetry and affect the transport of surface state. As a result, the MR should vary periodically as $B \sin \theta$ with the maximum value at $\theta = 90^\circ$ and minimum at $\theta = 0^\circ$ or 180° (θ is the angle between the out-of-plane magnetic field and the sample plane), characteristic of TIs. For MnSe/BST heterostructure studied here, the top TI surface is adjacent to the antiferromagnetic MnSe and the time reversal symmetry has already been broken, but the bottom TI surface is in contact with the nonmagnetic substrate SrTiO₃ and still under the protection of time reversal symmetry, which makes the MR of MnSe/BST follow a typical $|B \sin \theta|$ dependence under the out-of-plane magnetic field. The data exhibited in Fig. 6(a) show a period of 180° but deviates from the normal $|B \sin \theta|$ relationship with particularly sharp dips when the magnetic field lies in the sample plane. The deviation from $|B \sin \theta|$ should be attributed to the correction of weak antilocalization effect, a character of TIs induced by the nontrivial π Berry phase. Generally, weak antilocalization in TIs can be described by the simplified Hikami-Larkin-Nagaoka (HLN) equation [56]:

$$\Delta\sigma(B) \cong -\alpha \frac{e^2}{2\pi^2\hbar} \left[\psi\left(\frac{1}{2} + \frac{B_\phi}{B}\right) - \ln\left(\frac{B_\phi}{B}\right) \right], \quad (3)$$

where $\psi(x)$ is the digamma function and B_ϕ is the dephasing field. The prefactor α is an estimate of the number of independent channels. α is equal to 1/2 for single-channel transport in the weak antilocalization regime. Here, B should be replaced by the effective magnetic field $B \sin \theta$. Then, the formula is

$$\Delta\sigma(\theta) = \sigma_{xx}(\theta) - \sigma_{xx}(\pi) \simeq -\frac{\alpha e^2}{\pi h} \left[\psi\left(\frac{1}{2} + \frac{B_\phi}{|B \sin \theta|}\right) - \ln\left(\frac{B_\phi}{|B \sin \theta|}\right) \right]. \quad (4)$$

To analyze the sharp dips of MR at $\theta = 0^\circ$ or 180° , we fit the magnetoconductance data using Eq. (4) within the range 165° – 195° . As shown in Fig. 6(b), the fitting is in excellent agreement with the experimental data. The prefactor α is calculated to be ~ 0.46 , close to 0.5, indicating the single coherent channel from the bottom surface state contributing to the weak antilocalization correction. We noticed that our observation is similar to that reported in the pure TI [57,58] but different from that of exfoliated BiSbTeSe₂ flakes on YIG substrate [35]. The latter one shows a $|\cos \theta|$ dependence of magnetoconductance without sharp peak under the out-of-plane magnetic field, which may be due to the lack of device protection and hence a damage of the top surface state of the exfoliated BiSbTeSe₂ flakes.

E. Discussion

In this section, we would like to compare AMR/PHE in antiferromagnetic insulator/TI heterostructures with those in pristine TIs, and also in conventional ferromagnetic materials (e.g., 3d ferromagnetic elements, diluted magnetic semiconductors, and Heusler alloys).

The high-field PHE data in MnSe/BST show similarities with those reported in pure BST [12]. Under high magnetic fields, both systems exhibit π -period oscillations in AMR/PHE consistent with classical anisotropic transport theory. This similarity arises because in magnetization-saturated states (high fields), the MnSe layer in heterostructure behaves like a ferromagnetic system, analogous to the spin-polarized surface states in pristine TI. Both cases involve momentum-dependent scattering of Dirac fermions when time reversal symmetry is broken, leading to resistivity anisotropy. However, the mechanisms of PHE differ fundamentally in the two systems. For the MnSe/BST heterostructure, the AMR/PHE originates from MnSe-induced magnetic proximity at the interface. The low-field “butterfly” AMR and hysteresis (Fig. 2) directly correlate with MnSe’s spin reorientation. Also the observation of low-field AMR amplitude scaling with the anomalous Hall conductivity (Fig. 3) confirms interfacial magnetism as the driver. The tilted spin texture of MnSe induces interfacial spin polarization via exchange coupling, creating a magnetic anisotropy axis distinct from the current direction. The high-field PHE persists up to 250 K (Fig. 5), tied to MnSe’s magnetic ordering rather than pure topological protection. For the pristine TI BST, Taskin *et al.* attribute the origin of PHE to the peculiar time-reversal-breaking effect

of an in-plane magnetic field, which anisotropically lifts the protection of surface Dirac fermions from backscattering [12]. There exists no magnetic hysteresis or gate voltage correlation with anomalous Hall conductivity in pristine TIs, as it requires interfacial magnetic order. Therefore, in the high-field regime, the AMR/PHE of MnSe/BST resembles the pristine BST superficially but originates from proximity-induced spin polarization rather than intrinsic Dirac cone anisotropy. The apparent similarity in high-field angular dependence stems from shared symmetry constraints (C2 rotational symmetry for in-plane fields), but the scattering mechanisms differ. Taskin's Model indicates that field-induced time-reversal-symmetry breaking enables scattering via intrinsic Dirac state distortion. However, in the magnet/TI heterostructure, field-saturated moments generate extrinsic spin-polarized scatterers at the interface, mimicking anisotropic scattering without requiring Dirac cone tilt.

The AMR and PHE in the MnSe/BST system exhibit features similar to those found in conventional ferromagnetic materials, such as 3d ferromagnetic elements, diluted magnetic semiconductors, and Heusler alloys. These similarities include the dependence of the electrical resistance on the angle between the current direction and the applied magnetic field, band splitting induced by spin-orbit coupling, and spin-dependent scattering mechanisms. For example, *s-d* orbital scattering anisotropy induced by spin-orbit coupling in Fe, Co, Ni, and their alloys gives rise to their AMR at low temperature [31]. Spin-orbit coupling also plays a significant role in diluted magnetic semiconductors [59]. In our system, the strong spin-orbit coupling in the BST topological insulator and the spin-canted antiferromagnetism in MnSe together lead to a dependence of the AMR and PHE on the angle between the current and the magnetic field. Despite these similarities, there are also significant differences. In conventional ferromagnetic materials, the AMR and PHE mainly originate from their long-range ferromagnetic order, whereas in antiferromagnetic insulator/TI heterostructures they arise from magnetic proximity effects at the interface. That is, the topological surface states are influenced by the magnetic order of adjacent antiferromagnetic layers. These interactions can have a larger effect on the symmetry of the AMR and PHE than is found in conventional ferromagnets where it is largely determined by domain structures. In addition, there are differences in the electron scattering mechanisms between these systems. In antiferromagnetic insulator/TI heterostructures, the AMR and PHE are affected by the suppression of backscattering of the conduction electrons in topological surface states and the electrons' strong coupling to interfacial magnetic order. In contrast, in 3d ferromagnetic metals, the AMR arises from spin-polarized scattering of itinerant *d* electrons.

Our study may extend beyond the field of topological insulators and offer experimental approaches for other systems. First, the observed gate voltage dependence of AMR/PHE indicates that electric fields can be used to modulate spin-orbit coupling strength, which is highly relevant for spin-orbit torque devices based on the Rashba effect. Second, AMR in antiferromagnetic metals can be used to detect changes in Néel vector orientation. Our findings show that even in nonmagnetic topological materials, similar functionalities can be achieved through magnetic proximity effects, offering pathways for developing antiferromagnetic-order-

based memory devices. Also, the MnSe/BST heterostructure highlights the critical role of topology-magnetic order coupling in controlling magnetotransport, demonstrating the potential of antiferromagnets to regulate PHE through spin canting and phase transitions. Third, based on our results, we propose a magnet-topological insulator-magnet sandwich structure that can distinguish spin Hall magnetoresistance from AMR. This sandwich structure is potentially useful to enhance the spin Hall effect in 3d ferromagnetic metals for field-free switching [60].

III. CONCLUSION

In summary, we have performed systematic studies of AMR and PHE in the antiferromagnetic insulator/TI heterostructure MnSe/BST. The low-field MR at different in-plane field directions shows contrasting features, with two dips for $H//I$ but two peaks for $H\perp I$, which are induced by the particular spin-canted interfacial magnetism. This behavior appears similar to 3d ferromagnets but rather different from ferromagnetic insulator/TI heterostructures. On the other hand, the low-field PHE is most striking along $H//I$ direction but gradually suppressed when H deviates from parallel direction, which is quite different from ferromagnets. The high-field in-plane AMR and PHE both show a typical trigonometric function oscillation with π period in angle. The temperature dependence study proves the origin being magnetic proximity effect but not from the pristine BST itself. The out-of-plane AMR shows a significant deviation from $|B \sin \theta|$ as a result of the correction of weak antilocalization effect. However, we point out that it is difficult to rule out the existence of spin Hall magnetoresistance in the magnet/TI heterostructures as for the influence of weak antilocalization from the TI surface states. According to the theoretical study of Chiba *et al.* [61], the nonparamagnetic impurity at the interface should be considered as an important factor to generate MR depending on the magnetization orientation, and the induced AMR depends on $(m_x^2 - m_y^2)$, a combined result of both AMR and spin Hall magnetoresistance. We suggest future study on a magnet/TI/magnet sandwich heterojunction to better differentiate spin Hall magnetoresistance from AMR, because time reversal symmetry of the two surfaces is simultaneously broken in the sandwich structure, hence avoiding the interference of weak antilocalization effect, and one can easily identify spin Hall magnetoresistance from AMR through the out-of-plane angular dependence experiment.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The authors confirm that the data supporting the findings of this study are available within the article and its Supplemental Material [43].

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