

Switchable Anomalous Hall Effects in Polar-Stacked 2D Antiferromagnet MnBi_2Te_4

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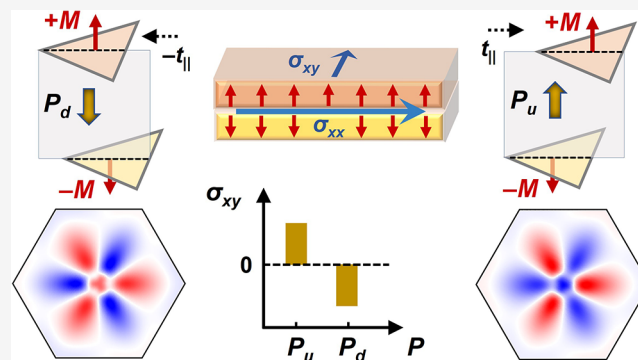
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ABSTRACT: van der Waals (vdW) assembly of two-dimensional (2D) materials allows polar layer stacking to realize novel properties switchable by the induced electric polarization. Here, based on symmetry analyses and density-functional calculations, we explore the emergence of the anomalous Hall effect (AHE) in antiferromagnetic MnBi_2Te_4 films assembled by polar layer stacking. We demonstrate that breaking $\hat{P}\hat{T}$ symmetry in an MnBi_2Te_4 bilayer produces a magnetoelectric effect and a spontaneous AHE switchable by electric polarization. We find that reversible polarization at one of the interfaces in a three-layer MnBi_2Te_4 film drives a metal–insulator transition, as well as switching between the AHE and quantum AHE (QAHE). Finally, we predict that engineering interlayer polarization in a three-layer MnBi_2Te_4 film allows converting MnBi_2Te_4 from a trivial insulator to a Chern insulator. Overall, our work emphasizes the topological properties in 2D vdW antiferromagnets induced by polar layer stacking, which do not exist in a bulk material.

KEYWORDS: two-dimensional material, layer stacking, anomalous Hall effect, antiferromagnetic, Chern insulator



Symmetry breaking plays an important role in generating quantum states in condensed matter, and thus its control allows manipulating these states and the associated transport properties, promising new functionalities.¹ For example, time-reversal ($\hat{T}$) symmetry breaking directly affects the spin-density distribution in material systems, producing novel spin-dependent transport properties.^{2–8} For low-power electronic applications, it would be desirable to have a method to control the spin-dependent properties of a material by an applied electric field, although such a method does not directly affect $\hat{T}$ symmetry.^{9–12} This would be especially advantageous for antiferromagnets—materials that have recently attracted increasing interest for application in next-generation spintronics.^{13–18}

In recent years, two-dimensional (2D) van der Waals (vdW) materials have become an extensively studied model system for exploring the new physics and potential applications at the nanoscale.^{19–26} A particular interest was stimulated by the recent discoveries of unexpected phenomena driven by interlayer stacking.^{27–31} Despite weak interlayer coupling, minor interlayer sliding^{28–30} or small-angle interlayer twisting^{27–33} can generate electronic and transport properties which do not exist in the bulk-like phases. This is largely due to the modification of the interlayer stacking pattern breaking crystal symmetries. Specifically, a combination of interlayer sliding and 180° twisting results in a noncentrosymmetric stacking pattern accompanied by the emergence of an out-of-plane electric polarization reversible by an external electric field.^{28–35}

This approach allows the design of 2D ferroelectrics out of parent nonpolar compounds to uncover new functionalities not existent in the bulk phase.³⁶

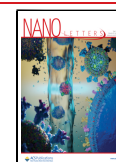
Such vdW polar stacking can be employed to engineer recently discovered 2D antiferromagnets.³⁷ Breaking space inversion symmetry in these materials could potentially induce novel spin-dependent properties controlled by the intrinsic ferroelectric polarization. Especially interesting are 2D materials derived from the antiferromagnet MnBi_2Te_4 , which exhibits nontrivial transport properties in the thin-film form.^{4,5,38–46} Although $\hat{T}$ symmetry is globally broken by magnetism of these antiferromagnetic materials, the magnetism is “hidden” by $\hat{T}\hat{O}$ symmetry that combines $\hat{T}$ and crystal symmetry $\hat{O}$ such as space inversion ($\hat{P}$) or mirror reflection ($\hat{M}$). Since the polar layer stacking affects crystal symmetry $\hat{O}$, it allows an indirect control of the $\hat{T}$ symmetry breaking in 2D magnets and thus spin-dependent properties, such as the anomalous Hall effect (AHE).

The intrinsic AHE is governed by the Berry curvature Ω , a property arising from the spin-dependent band structure of

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magnetic systems.⁴⁷ The anomalous Hall conductance (AHC) is quantized in 2D magnetic topological insulators due to formation of the topologically protected edge channels resulting in a dissipationless quantum AHE (QAHE).^{2,4,38} Ferromagnetic systems naturally support the AHE due to the intrinsic $\hat{T}$ symmetry breaking. Antiferromagnets also break $\hat{T}$ symmetry but usually preserve $\hat{T}\hat{O}$ symmetry that enforces the Berry curvature to be antisymmetric in k -space, i.e. $\hat{T}\hat{O}\Omega(\mathbf{k}) = -\Omega(\hat{T}\hat{O}\mathbf{k})$, prohibiting the AHE. The AHE can emerge in magnetically uncompensated antiferromagnets, where the combined $\hat{T}\hat{O}$ symmetry is broken by either noncollinear magnetic configurations or nonmagnetic atoms at low-symmetry positions.^{6,47–51} In the former case, the AHE is dependent on the orientation of the Néel vector, which can be changed by an applied magnetic field. In the latter case, the atomic structure of the nonmagnetic sublattice can influence the AHE; however, there are no straightforward means to control this structure by an external stimulus. While it is possible to break $\hat{T}\hat{O}$ symmetry by interfacing MnBi_2Te_4 with other materials,⁵² such an interface may not support bistable polar states and thus the nonvolatile control of the AHE.

In this letter, based on symmetry analysis and first-principles density functional calculations, we demonstrate that the AHE can be effectively induced in 2D vdW antiferromagnets by polar layer stacking. Using the recently discovered antiferromagnetic topological insulator MnBi_2Te_4 , as a representative material, we show that polar layer stacking breaks $\hat{P}\hat{T}$ symmetry and induces a magnetoelectric effect, a normal AHE, or QAHE, depending on the number of MnBi_2Te_4 layers and their stacking. These effects can be controlled by the switchable electric polarization of the polar stacked MnBi_2Te_4 , thus providing a route to manipulate the spin-dependent and quantum properties without an external magnetic field.

RESULTS AND DISCUSSION

Monolayer MnBi_2Te_4 represents a septuple layer, which can be viewed as a MnTe bilayer intercalated into the center of a Bi_2Te_3 quintuple layer (Figure 1a). Bulk MnBi_2Te_4 has $\hat{P}\hat{T}$ symmetry and an A-type antiferromagnetic order with collinear out-of-plane magnetic moments. A MnBi_2Te_4 film in bulk-like stacking inherits the bulk A-type antiferromagnetic order and exhibits quantum phenomena dependent on the number of layers.^{2,4,39} An MnBi_2Te_4 film with an even number of layers,

e.g., a bilayer, has intrinsic $\hat{P}\hat{T}$ symmetry, which not only prevents the net magnetic moment but also impedes both the AHE and QAHE. This can be seen from the expression for the Berry curvature

$$\Omega(\mathbf{k}) = -2\text{Im} \sum_{m \neq n} \frac{\langle n | \frac{\partial \hat{H}}{\partial k_x} | m \rangle \langle m | \frac{\partial \hat{H}}{\partial k_y} | n \rangle}{(E_{nk} - E_{mk})^2} \quad (1)$$

where $\hat{H}$ is the Hamiltonian of the system and E_{nk} is the energy of the n th band at wave vector $\mathbf{k}$. The AHC is determined by the integration of $\Omega(\mathbf{k})$ in the Brillouin zone (BZ) as follows:

$$\sigma_{xy} = -\frac{e^2}{h} \int_{\text{BZ}} \frac{d^2k}{2\pi} \Omega(\mathbf{k}) \quad (2)$$

According to eq 1, the Berry curvature is odd under the $\hat{P}\hat{T}$ symmetry operation, i.e., $\hat{P}\hat{T}\Omega(\mathbf{k}) = -\Omega(\mathbf{k})$, and thus is zero in any $\hat{P}\hat{T}$ -symmetric system enforcing σ_{xy} to vanish. On the contrary, due to the A-type antiferromagnetic order, an MnBi_2Te_4 film with an odd number of layers does not have the restriction of $\hat{P}\hat{T}$ symmetry, due to an uncompensated net magnetic moment. As a result, an intrinsic QAHE can occur in such a film where the number of quantum states is determined by the number of MnBi_2Te_4 layers, as was predicted theoretically⁴ and demonstrated experimentally.^{2,39,43} Here, we show that a polar-stacked MnBi_2Te_4 provides even a broader spectrum of quantum states and these states can be controlled by electric polarization.

Using the vdW assembly approach demonstrated in refs 28 and 29, a MnBi_2Te_4 bilayer can be engineered to be polar. This requires a top monolayer ($\bar{A}$) to be deposited as a mirror-reflected ($\hat{M}_z$) bottom monolayer. The resulting noncentrosymmetric AA stacking (Figure 1b) is unstable due to the proximity of the Te atoms across the interface. It spontaneously relaxes to the lower-energy AB or BA stacking with antiparallel magnetic moments (Figure 1c,d). The latter is distinguished by the lateral translation, $-t_{\parallel}$ or $t_{\parallel}$, along the $[1\bar{1}0]$ direction of the top monolayer with respect to the bottom ($t_{\parallel} = 1/3(a - b)$ in Figure 1a), placing the interfacial Bi atom atop the Te atom. The resulting two structures, AB and BA, have opposite polarizations, P_d or P_u , depending on the lateral translation, $-t_{\parallel}$ or $t_{\parallel}$, respectively (Figure 1c,d). The polarization can be switched by an applied electric field through interlayer sliding.

Depending on the number of monolayers, the interlayer polarization has different effects on quantum states of MnBi_2Te_4 films. In the case of a bilayer (Figure 2a), polar stacking breaks inversion symmetry and hence $\hat{P}\hat{T}$ symmetry. This lifts the $\hat{P}\hat{T}\Omega(\mathbf{k}) = -\Omega(\mathbf{k})$ constraint on the Berry curvature of the bulk phase, making AHC of a polar MnBi_2Te_4 bilayer nonzero. The two polarization states are related by the $\hat{M}_z\hat{T}$ symmetry transformation (Figure S2a), which changes sign of the Berry curvature, $\hat{M}_z\hat{T}\Omega(\mathbf{k}) = -\Omega(-\mathbf{k})$, and hence the sign of the AHC σ_{xy} in eq 2. Therefore, the switchable polarization of the polar MnBi_2Te_4 bilayer can serve as a control parameter for the AHE.

For a polar-stacked MnBi_2Te_4 trilayer, the net magnetic moment is nonzero and hence the AHE is always finite due to broken $\hat{P}\hat{T}$ symmetry. In the case of a trilayer with a polar MnBi_2Te_4 bilayer deposited on an MnBi_2Te_4 monolayer with bulk-like interface (Figure 2b), the interlayer polarization controls band bending across the layer stack and can lead to the AHE or QAHE depending on the polarization orientation.

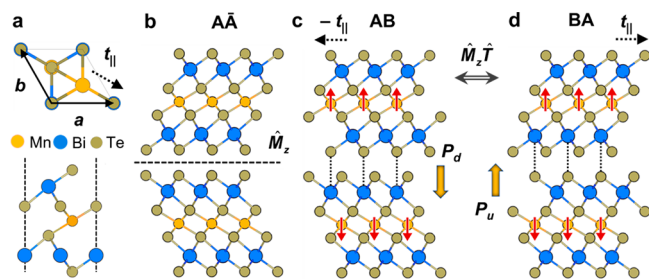


Figure 1. (a) Atomic structure of monolayer MnBi_2Te_4 (top and side views). (b) Unstable AA stacking of a MnBi_2Te_4 bilayer where the top monolayer is vdW assembled as a mirror reflection ($\hat{M}_z$) of the bottom monolayer. (c, d) A polar-stacked MnBi_2Te_4 bilayer with antiparallel magnetic moments and electric polarization pointing down P_d (c) and up P_u (d) due to the in-plane translation, $-t_{\parallel}$ (c) or $t_{\parallel}$ (d), of the top monolayer from the AA stacking in (b). The bilayer structures with opposite polarization are related by the $\hat{M}_z\hat{T}$ symmetry operation or equivalently by in-plane translation $2t_{\parallel}$.

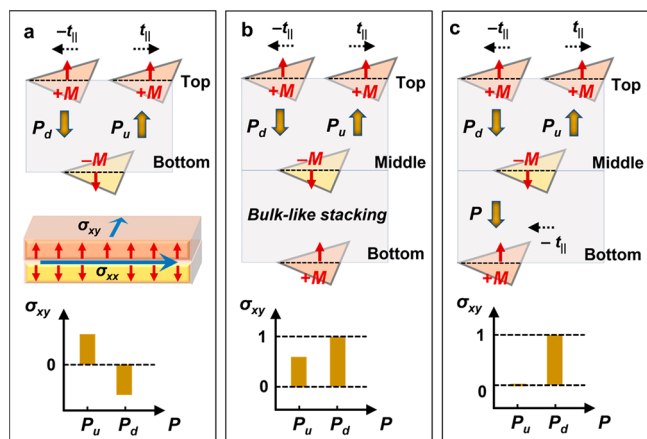


Figure 2. (a) Top: schematic of a polar-stacked MnBi_2Te_4 bilayer with polarization pointing up (P_u) or down (P_d). Middle and bottom: an AHE in a polar-stacked MnBi_2Te_4 bilayer switchable by ferroelectric polarization. (b) Top: schematic of a MnBi_2Te_4 trilayer with a single (top) polar interface. Bottom: switching between AHE and QAHE with polarization reversal. (c) Top: schematic of a MnBi_2Te_4 trilayer with two polar interfaces. Bottom: transition between trivial and Chern insulators driven by polarization switching.

In the case of a trilayer with two polar interfaces (Figure 2c), the polarization of the top interface can be switched to be parallel or antiparallel to the polarization of the bottom interface, resulting in a topological phase transition from a trivial band insulator to a nontrivial Chern insulator.

To explicitly demonstrate the anticipated properties, we apply density functional calculations, as described in the Supporting Information. Figure 3a shows the calculated energy profile and corresponding polarization for a polar MnBi_2Te_4

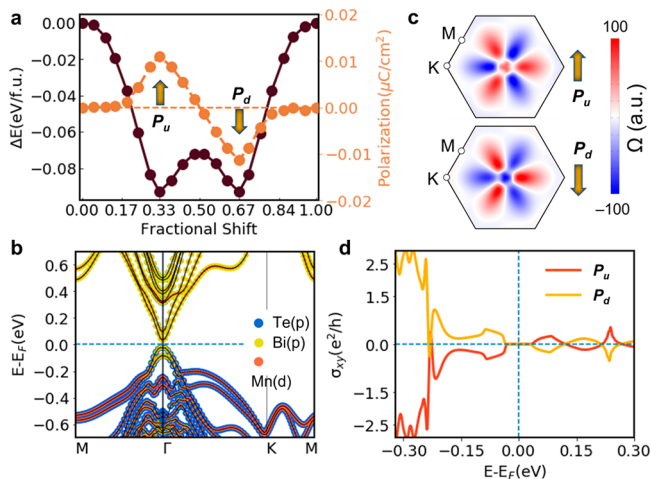


Figure 3. (a) Total energy and out-of-plane electric polarization of a polar MnBi_2Te_4 bilayer when sliding the top monolayer with respect to the bottom along the $[1\bar{1}0]$ direction. The two minima in the energy profile correspond to polarization pointing up (P_u) and down (P_d). (b) Electronic band structure of a polar MnBi_2Te_4 bilayer along the high-symmetry directions in the 2D Brillouin zone. (c) Berry curvature of a polar MnBi_2Te_4 bilayer in the 2D Brillouin zone calculated at $E = E_F - 0.05$ eV for polarization pointing up (top) and down (bottom). (d) Anomalous Hall conductivity σ_{xy} of a polar MnBi_2Te_4 bilayer as a function of electron energy for polarization pointing up and down. A dotted line indicates the energy at which the Berry curvature in (c) is calculated.

bilayer when sliding the top layer with respect to the bottom along the $[1\bar{1}0]$ direction (see Figure S1 for the sliding energy profile along the $[100]$ direction). Zero fractional shift matches to the AA stacking which has the highest energy and is thus unstable. The energy drops down with the shift and exhibits two local minima separated by an energy barrier of 0.09 eV/fu. These minima occur at a fractional shift of one-third and two-thirds the in-plane unit cell vector in the $[1\bar{1}0]$ direction (equivalent to the lateral translation, $t_{\parallel}$ and $-t_{\parallel}$, respectively). The two local energy minima correspond to the polar structures with polarization pointing up and down (Figure 3a). The interlayer polarization is mainly contributed by the charge transfer and associated displacements of the interfacial cation Bi and anion Te atoms, creating a dipole pointing from Bi to Te. The calculated out-of-plane polarization magnitude is $0.01 \mu\text{C}/\text{cm}^2$. This polarization induces the electrostatic potential energy drop across the MnBi_2Te_2 bilayer of 0.05 eV as shown in Figure S2b). Thus, the interlayer sliding transforms the polar structure with polarization pointing up to the structure with polarization pointing down or vice versa. Such sliding and the associated polarization reversal can be induced by an applied out-of-plane electric field of less than 1 V/nm, which is feasible under the experimental conditions.

The $\hat{P}\hat{T}$ symmetry broken by polar-layer stacking breaks the Kramers degeneracy of the energy bands for the bilayer. In the absence of spin–orbit coupling (SOC), the bands are exchange split into spin-up ($\sigma = \uparrow$) and spin-down ($\sigma = \downarrow$) states (Figure S3). The spin character of the bands $E^\sigma(k)$ is reversed with ferroelectric polarization, as follows from $\hat{M}_z\hat{T}E^\sigma(k) = E^\sigma(-k)$. Including SOC changes the band structure of a polar MnBi_2Te_4 bilayer. As seen from Figure 3b, similar to bulk MnBi_2Te_4 , the polar bilayer represents a direct band gap semiconductor with the conduction band minimum (CBM) and the valence band maximum (VBM) located at the Γ point. The states around the Fermi level are mainly composed of the p states of Bi and Te with the d states of Mn being relatively far away from the Fermi energy. Due to the presence of ferroelectric polarization, the band gap of the polar bilayer is reduced to about 0.06 eV from 0.08 eV obtained for a nonpolar bilayer and 0.16 eV known for bulk MnBi_2Te_4 .

We note that a polar-stacked MnBi_2Te_4 bilayer represents a magnetoelectric multiferroic. It has both a spontaneous electric polarization and an antiferromagnetic order. The magnetic moments of Mn atoms of about $4.47 \mu_B$ are aligned antiparallel on the top and bottom MnBi_2Te_4 monolayers. Importantly, due to broken $\hat{P}\hat{T}$ symmetry, the antiferromagnetism of the polar bilayer is not fully compensated. While the uncompensated net magnetic moment is small, about $0.002 \mu_B$ per formula unit, it is nonvanishing and reversible by ferroelectric polarization, as follows from $\hat{M}_z\hat{T}\mathbf{M} = -\mathbf{M}$, where $\mathbf{M}$ is the net magnetization. Potentially this functionality of the polar-stacked vdW antiferromagnets may be useful for applications.

The broken $\hat{P}\hat{T}$ symmetry causes the Berry curvature of a polar-stacked MnBi_2Te_4 bilayer to be nonvanishing. Figure 3c shows the Berry curvature $\Omega(k)$ calculated in the 2D Brillouin zone for up and down polarization states at the energy $E = E_F - 0.05$ eV close to the VBM. It is seen that $\Omega(k)$ exhibits a flower-like pattern with alternating red and blue colors of the petals indicating the alternating sign of $\Omega(k)$ and reflecting the 3-fold rotational symmetry of the trilayer around the z axis. This symmetry combined with $\hat{M}_z\hat{T}\Omega(k) = -\Omega(-k)$ makes the color of the petals independent of the polarization orientation. On the contrary, a persistent color around the Γ

point is reversed from blue to red when polarization is switched from up to down.

The nonvanishing Berry curvature implies finite AHC. Figure 3d shows the calculated AHC as a function of electron energy. It is evident that the AHC is zero within the band gap of an MnBi_2Te_4 bilayer, indicating that the bilayer represents a trivial insulator (semiconductor). However, with electron or hole doping, AHC becomes nonzero and, as expected, has the opposite sign for ferroelectric polarization pointing up and down. Thus, we observe the new functionality of a polar-stacked MnBi_2Te_4 bilayer which does not exist in bulk-like MnBi_2Te_4 .

The presence of a finite AHC in a polar-stacked MnBi_2Te_4 bilayer can be understood in terms of a layer-dependent Hall effect.^{44,46} While a bulk-like MnBi_2Te_4 bilayer represents an axion insulator where the top and bottom MnBi_2Te_4 monolayers spontaneously deflect electrons in opposite directions, resulting in zero net AHE, the presence of spontaneous polarization in a polar MnBi_2Te_4 bilayer breaks the AHE-compensating symmetry between the top and bottom monolayers, producing a finite AHC. This phenomenon is analogous to the effect of electric field on a bulk-like MnBi_2Te_4 bilayer.⁴⁴ However, while in the case of a bulk-like MnBi_2Te_4 bilayer the electric field needs to be maintained to have a nonzero AHC, the AHE in a polar MnBi_2Te_4 bilayer is spontaneous and nonvolatile with the sign of AHC being linked to the direction of electric polarization.

The polarization-controlled AHC emerges not only in a MnBi_2Te_4 bilayer that is composed of two polar-stacked MnBi_2Te_4 monolayers but also in MnBi_2Te_4 films assembled by polar stacking of two MnBi_2Te_4 layers formed of two or more monolayers. Figure S5 shows the results of calculations of the band structure and AHC for polar stacked four (Figure S5a)– and six– monolayer (Figure S5d) MnBi_2Te_4 films. It is seen that compared to the MnBi_2Te_4 bilayer, the band gap is reduced in the four-monolayer MnBi_2Te_4 (Figure S5b) and almost vanishes in the six-monolayer MnBi_2Te_4 (Figure S5e). The AHC as a function of energy (Figure S5c,f) exhibits trends similar to those of the bilayer. In particular, the AHC is reversed by switching the interlayer polarization. Thus, under the experimental conditions, vdW assembly can be used to engineer polar MnBi_2Te_4 films with an even number of monolayers to realize an AHE switchable by the intrinsic ferroelectric polarization.

Next, we consider effects of polar stacking in three-monolayer MnBi_2Te_4 films. Due A-type antiferromagnetism, such films have a large uncompensated magnetic moment of about $4.5 \mu_B$ per supercell. The presence of this magnetic moment breaks $\hat{P}\hat{T}$ symmetry of the parent bulk phase, producing a nonzero Berry curvature and the associated AHE. Following the schematic in Figure 2b, we assume that a three-monolayer MnBi_2Te_4 slab is composed of a polar-stacked bilayer deposited on a MnBi_2Te_4 monolayer with the bulk-like stacked bottom interface (Figure 4a,b left panels). We find a small band offset (~ 0.05 eV) between the polar and nonpolar stacked interfaces, resulting in a built-in electric field E_b across the trilayer pointing down (indicated by blue arrows in Figures 4a,b). The presence of this bias field independent of polarization orientation makes the transport behavior of the polar MnBi_2Te_4 trilayer different from that of a polar bilayer.

When polarization is pointing down (P_d), the associated depolarizing field is directed opposite to the bias field and effectively compensates it, thus maintaining the band gap

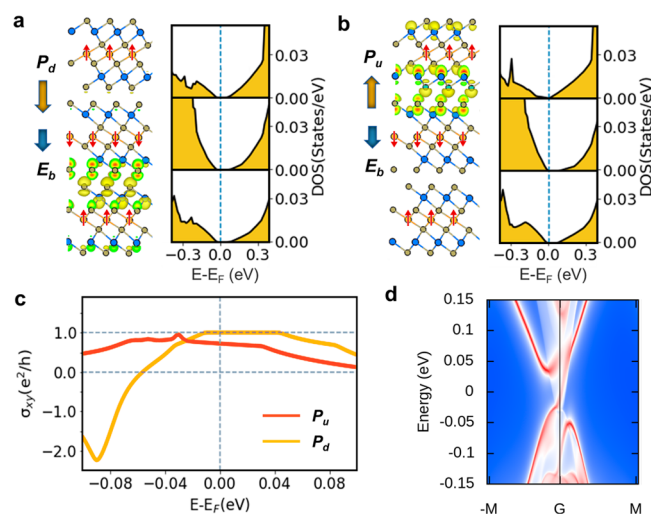


Figure 4. (a, b) Three-monolayer MnBi_2Te_4 film with a polar top interface with polarization pointing down (P_d) (a) or up (P_u) (b) and nonpolar bulk-like bottom interface (left panels), and the corresponding layer-resolved density of states (DOS) as a function of energy (right panels). In the left panels, blue arrows indicate a built-in electric field due to the band offset between top and bottom interfaces in the trilayer. The real-space distributions of the charge density at the conduction band minimum are shown by yellow isosurfaces of 10% of their maxima. (c) Anomalous Hall conductivity as a function of electron energy for P_u and P_d . (d) Surface band structure of the three-monolayer MnBi_2Te_4 film for P_u indicating the appearance of the topologically protected edge state at the Fermi energy. Red color intensity reflects the weight of the surface state contribution.

across the whole polar trilayer (~ 0.07 eV), as seen from the layer-resolved density of states (DOS) in Figure 4a. Also, as is evident from the real space distribution of the charge density at the CBM in this figure, the CBM lies away from the polar interface. In this case, the transport behavior of the polar trilayer in the P_d state is reminiscent of that of the bulk-like nonpolar trilayer. The latter is known to represent a Chern insulator exhibiting a QAHE.⁵ Likewise, we find that the polar MnBi_2Te_4 trilayer in the P_d state signifies a Chern insulator with a Chern number equal to 1 and exhibits an QAHE with AHC $\sigma_{xy} = e^2/h$ in the energy gap region (yellow curve in Figure 4c). The quantized AHC is associated with the nontrivial topological character of the system which is reflected in the topologically protected edge state shown in Figure 4 (d).

On the contrary, when polarization is pointing up (P_u), the associated depolarizing field is aligned in the direction of the bias field, which effectively doubles its effect, producing strong band bending across the trilayer, as seen from the layer-resolved DOS in Figure 4b. As a result, the band gap is closed at the polar interface of the trilayer, producing a nonzero charge density at the Fermi energy. The metallic character of the polar MnBi_2Te_4 trilayer in the P_u state makes the Chern number equal to 0, eliminates a topologically protected surface state, and changes the AHC to a smaller value at the Fermi energy (red curve in Figure 4c). Thus, the switchable electric polarization of the polar MnBi_2Te_4 trilayer can serve as a knob to control the transition between the nontrivial (associated with QAHE) and trivial (associated with AHE) electronic states in the MnBi_2Te_4 films.

A different type of stacking in a MnBi_2Te_4 trilayer occurs when a polar MnBi_2Te_4 bilayer is placed on a monolayer in such a way that the bottom interface is also polar and has

polarization pointing down (Figure 2c). In this case the trilayer has two polar interfaces and the polarization of the top interface can be switched up (P_u) to be antiparallel (AP) or down (P_d) to be parallel (P) to the polarization P of the bottom interface (Figure 5a,d, respectively). Depending on the

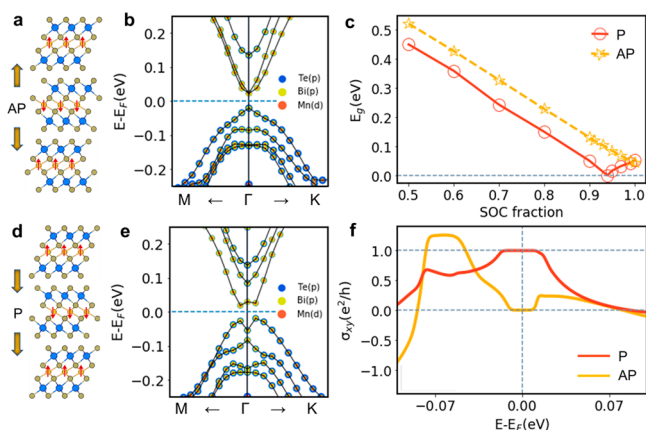


Figure 5. (a, b, d, e) Atomic structure (a, d) and energy bands near the Γ point (b, e) of a polar MnBi₂Te₄ trilayer with antiparallel (AP) (a, b) and parallel (P) (d, e) interface polarization. (c) Variation of the band gap for parallel (P) and antiparallel (AP) aligned MnBi₂Te₄ trilayer as a function of SOC strength given in units of a fraction of the actual SOC. (f) Anomalous Hall conductivity of the P- and AP-aligned MnBi₂Te₄ trilayer as a function of electron energy.

relative polarization orientation (AP or P), we find different topologies of the trilayer. While in both cases, we observe the presence of a band gap in the band structure of AP (Figure 5b)- and P-aligned (Figure 5e) trilayers, the nature of this gap is different. By comparing the band structures in Figure 5b and Figure 5e, we see for the former that the bands exhibit conventional dispersions typical for a normal semiconductor with the CBM and VBM located at the Γ point. On the contrary, for the latter, the valence bands reveal a “Mexican-hat” shape placing the VBM away from the Γ point and indicating a possible band inversion and thus a nontrivial character of the band gap.

To elucidate these different behaviors, we explore the evolution of the band gap for the AP- and P-aligned MnBi₂Te₄ trilayers as a function of SOC. Figure 5c shows the variation of the band gap for AP- and P-aligned aligned MnBi₂Te₄ trilayers as a function of SOC strength given in units of a fraction of the actual SOC (see Figures S6 and S7 for the associated band structures around the Γ point). It is seen that, with the increasing fraction of SOC, the band gap of the AP-aligned trilayer continuously decreases (yellow stars in Figure 5c and Figure S6), until it reaches the smallest value of 0.06 eV at the actual value of SOC. On the contrary, the band gap of the P-aligned trilayer first decreases with increasing SOC, so that the band gap reduces to zero at SOC = 0.93 (red circles in Figure 5c and Figure S7). A further increase of SOC reopens and then enlarges the band gap. This behavior indicates band inversion in the P-aligned MnBi₂Te₄ trilayer that is induced by SOC, reflecting the topologically nontrivial origin of the band gap. This is in contrast to the AP-aligned MnBi₂Te₄ trilayer, where there is no band inversion with increasing SOC, thus signaling the trivial character of the system. These conclusions are confirmed by the direct calculation of the Chern number.

While the Chern number is 0 for the AP-aligned trilayer, it is 1 for the P-aligned trilayer.

The nontrivial character of the AP-aligned MnBi₂Te₄ trilayer is reflected in the quantized AHC exhibiting a plateau of $\sigma_{xy} = e^2/h$ within the energy gap (red curve in Figure 5f), indicating that the trilayer represents a Chern insulator revealing an QAHE. On the contrary, $\sigma_{xy} = 0$ in the band gap region of the P-aligned MnBi₂Te₄ trilayer (yellow curve in Figure 5f), indicating that the trilayer represents a trivial insulator. In both cases, for electron energies above and below the band gap, the AHC is nonzero, reflecting the broken $\hat{P}\hat{T}$ symmetry of the system, and changes with reversal of ferroelectric polarization of the top interface. Therefore, a polar MnBi₂Te₄ trilayer can be switched between the trivial insulator and Chern insulator states by reversing electric polarization of the top interface, resulting in the antiparallel or parallel polarization alignment.

Overall, our results demonstrate that utilizing polar stacking of the 2D vdW antiferromagnet MnBi₂Te₄ with switchable interface polarization allows achieving new functional properties that are not available in the bulk form of this material. Polar layer stacking can be employed not only for MnBi₂Te₄ considered in this work but also for other 2D vdW antiferromagnets. Due to small vertical ion displacements, the out-of-plane electric polarization can be switched by a small applied electric field via in-plane interlayer sliding with an ultralow barrier. These characteristics are useful for potential applications of the polar-stacked 2D vdW antiferromagnets in data storage. We hope therefore that our theoretical results will stimulate experimental efforts to verify our predictions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.3c00047>.

Computational methods, sliding directions for a MnBi₂Te₄ bilayer and the sliding energy profile, the $\hat{M}_z\hat{T}$ symmetry for polar MnBi₂Te₄ bilayers, the electronic band structure of a polar-stacked MnBi₂Te₄ bilayer, effect of Mn–Bi intermixing, effect of magnetization orientation on the anomalous Hall effect, including the electronic structure and anomalous Hall conductivity for four- and six-monolayer MnBi₂Te₄ films, and the band structure of a polar MnBi₂Te₄ trilayer for different values of spin–orbit coupling (PDF)

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Notes

The authors declare no competing financial interest.

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