Topological insulator interfaced with ferromagnetic insulators: Bi₂Te₃ thin films on magnetite and iron garnets

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We report our study about the growth and characterization of Bi₂Te₃ thin films on top of Y₃Fe₅O₁₂(111), Tm₃Fe₅O₁₂(111), Fe₃O₄(111), and Fe₃O₄(100) single-crystal substrates. Using molecular-beam epitaxy, we were able to prepare the topological insulator/ferromagnetic insulator heterostructures with no or minimal chemical reaction at the interface. We observed the anomalous Hall effect on these heterostructures and also a suppression of the weak antilocalization in the magnetoresistance, indicating a topological surface-state gap opening induced by the magnetic proximity effect. However, we did not observe any obvious x-ray magnetic circular dichroism (XMCD) on the Te *M*₄₅ edges. The results suggest that the ferromagnetism induced by the magnetic proximity effect via van der Waals bonding in Bi₂Te₃ is too weak to be detected by XMCD, but still can be observed by electrical transport measurements. This is in fact not inconsistent with reported density-functional calculations on the size of the gap opening.

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I. INTRODUCTION

The quantum anomalous Hall effect (QAHE) is expected and observed when magnetic ordering is introduced in a topological insulator (TI) system [1–5]. This effect is due to time-reversal symmetry breaking and can be experimentally achieved by doping transition metals into the TI. There is also the possibility to use the magnetic proximity effect in TI/ferromagnetic insulator (FI) heterostructures to magnetize the topological surface state at the interface. Although the QAHE has not yet been experimentally observed for such TI/FI heterostructures, the magnetic proximity effect in TI/FIs has the advantage compared to doping with magnetic ions that it will not introduce defects in the TI. Moreover, the Curie temperatures of FIs are much higher than those of magnetically doped TIs so that one can hope to obtain the QAHE over a larger temperature window. To study the gap opening of the topological surface state induced by the magnetic proximity effect, one can measure the magnetoresistance and fit the Hikami-Larkin-Nagaoka (HLN) equation [6] to the data. The gap opening suppresses the weak antilocalization

(WAL) and induces weak localization (WL) [7]. The anomalous Hall effect (AHE) of a magnetized TI, on the other hand, has been observed in several TI/FI heterostructures, such as in (Bi, Sb)₂Te₃ on Tm₃Fe₅O₁₂ for temperatures of up to 400 K [8], (Bi_xSb_{1-x})₂Te₃ on Y₃Fe₅O₁₂ [9], Bi₂Te₃ on Cr₂Ge₂Te₆ [10], and Bi₂Se₃ on EuS [11]. X-ray magnetic circular dichroism (XMCD) measurements have been performed to provide information on the magnetic properties for each of the different elements in the TI. XMCD effects on the Cr-doped (Sb, Bi)₂Te₃ [12] and Cr-doped Sb₂Te₃ [13] systems have been observed, showing that the Sb and Te are magnetized. An XMCD experiment on a (Bi_{0.25}Sb_{0.75})₂Te₃ film interfaced with Tm₃Fe₅O₁₂ claims to have detected that the Te is magnetized [14].

In order to study the magnetic proximity effect in TI/FI heterostructures, we have grown Bi₂Te₃ thin films by molecular-beam epitaxy (MBE) on magnetic Y₃Fe₅O₁₂(111) substrates, Tm₃Fe₅O₁₂(111) thin films, Fe₃O₄(111) substrates, and Fe₃O₄(100) thin films as well as on nonmagnetic Al₂O₃(0001) substrates as a reference. X-ray photoelectron spectroscopy (XPS) was utilized to examine the interface very carefully, and to ascertain that the Bi₂Te₃ films on the magnetite and iron garnets have no or minimal chemical reaction at the interface since this is a crucial aspect for the short-range magnetic proximity effect to be well defined. We conducted electrical transport measurements and observed the AHE as well as a suppression of the weak antilocalization, indicating a topological surface-state gap opening induced by the magnetic proximity effect. Moreover, the XMCD was examined on the Te *M*₄₅ edges of our Bi₂Te₃ heterostructures. As reference, we

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also conducted XMCD measurements on a “Te on Fe” film and a Fe_xTe film, which showed clear and substantial XMCD effects at the Te M_{45} edges.

II. EXPERIMENT

Magnetic insulators for the Bi_2Te_3 film growth were prepared in various ways. $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG) substrates were ultrasonically cleaned by acetone and isopropanol, and were annealed *in situ* at 600 °C for 2 h in an oxygen pressure of 1×10^{-6} mbar prior to the Bi_2Te_3 growth. $\text{Tm}_3\text{Fe}_5\text{O}_{12}$ (TmIG) films (16 nm) were grown on $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ substrates by off-axis sputtering [15,16]. The TmIG films were annealed at 150 °C to remove the moisture after being loaded into the MBE chamber. $\text{Fe}_3\text{O}_4(100)$ films were grown *in situ* by MBE on $\text{MgO}(100)$ substrates [17–20]. The Fe_3O_4 single crystal was grown by the floating-zone method and cut and polished into substrates with the surface normal along the (111) direction. The Fe_3O_4 (111) substrates were then loaded into the MBE chamber and annealed at 250 °C for 2 h in an oxygen pressure of 1×10^{-5} mbar. Nonmagnetic $\text{Al}_2\text{O}_3(0001)$ substrates were also prepared using the same cleaning procedure as for the YIG substrates.

Bi_2Te_3 films were grown on the magnetic oxides using MBE with a base pressure of about 2×10^{-10} mbar [21]. Bi and Te were evaporated from LUXEL Radak effusion cells at temperatures of about 458 and 228 °C, respectively. The flux rates were measured by a quartz crystal monitor at the growth position. The Bi flux rate was set at 0.5 Å/min, while the Te flux rate was kept at 1.5 Å/min, giving a typical growth rate of Bi_2Te_3 of about 0.15 quintuple layer per minute (~ 0.15 QL/min). We first deposited 2 QLs of Bi_2Te_3 at room temperature and then annealed the film at 240 °C for 30 min to crystallize the material [22]. For the second step, we used 220 °C as the substrate temperature to grow the Bi_2Te_3 to the desired thickness (6–10 QLs). For the Bi_2Te_3 films on nonmagnetic $\text{Al}_2\text{O}_3(0001)$ substrates, 3 QLs of Bi_2Te_3 were deposited at 160 °C and then annealed at 240 °C for 30 min. For the second step, we used 220 °C as the substrate temperature to grow the Bi_2Te_3 to 10 QLs.

Real-time monitoring of the growth was performed by reflection high-energy electron diffraction (RHEED) measurements at 20 keV using a STAIB Instruments RH35 system. *In situ* XPS and angle-resolved photoelectron spectroscopy (ARPES) measurements were conducted after the annealing of the 2 QLs and after the deposition of the 6–10 QLs using 1486.6-eV photons (monochromatized Al $K\alpha$ light) for XPS and using a nonmonochromatized He discharge lamp with 21.2-eV photon energy (He I line) for ARPES. XPS and ARPES were performed at room temperature with a Scienta R3000 electron energy analyzer.

A Te film of 12 nm was used as a capping layer for the Bi_2Te_3 films which was deposited at room temperature before taking the samples out of vacuum for the transport measurements [23]. We cut and pressed indium balls with copper wires on the four corners of the samples to form electrodes with standard Van der Pauw configuration. AHE and magnetoresistance measurements were then performed using a Physical Property Measurement System from Quantum Design.

X-ray absorption spectroscopy and x-ray magnetic circular dichroism (XAS/XMCD) measurements were conducted *in situ* at the 11A Dragon beam line of the Taiwanese Light Source at the National Synchrotron Radiation Research Center (NSRRC) (Taiwan) to probe the magnetic properties of the heterostructure selectively for each element. We connected an MBE system to the XAS/XMCD chamber at the beamline end station. 1–2-QL Bi_2Te_3 thin films were grown on YIG(111), TmIG(111), and $\text{Fe}_3\text{O}_4(111)$ at room temperature and then annealed at 240 °C for 30 min to crystallize the films, and 1-ML Te was grown on $\text{Fe}_3\text{O}_4(100)$ at room temperature. The samples were transferred *in situ* to the XAS/XMCD chamber. In order to establish reference XMCD spectra of magnetized Te, Te and Fe were codeposited into an Fe_xTe film onto a $\text{MgO}(100)$ substrate with a Te flux rate of 2.1 Å/min and an Fe flux rate of 1 Å/min at a substrate temperature of 250 °C. Moreover, a 1-ML Te film was deposited on an Fe film with a Te flux rate of 4 Å/min at a substrate temperature of 220 °C. The spectra were recorded in the total electron yield mode at around 80 and 300 K. All spectra have their photon energies aligned using reference samples measured simultaneously (Cr L_{23} edges of Cr_2O_3 for Te M_{45} edges; Fe_2O_3 for Fe L_{23} edges). A magnetic field of about 0.28 T was applied for the XMCD measurements.

III. RESULTS AND DISCUSSION

Figure 1 shows the reflection high-energy electron diffraction (RHEED) patterns of various magnetic oxides and the Bi_2Te_3 films deposited on top of those. All the magnetic substrates showed good and sharp RHEED patterns after the *in situ* annealing, providing a very good starting condition for the growth of the Bi_2Te_3 films. 2 QLs of Bi_2Te_3 were grown at room temperature and annealed at 240 °C for 30 min. The RHEED patterns showed streaky lines (except 2-QLs Bi_2Te_3 on TmIG), indicating a flat surface and good crystallinity of Bi_2Te_3 on the magnetic oxides. In Fig. 1(b), the 2-QLs RHEED pattern shows spots and powder ring features on top of the diffraction streaks, indicating a worse growth quality at the Bi_2Te_3 /TmIG interface. Afterwards the Bi_2Te_3 films were grown thicker to 6–10 QLs, and the RHEED patterns became even more streaky and intense, indicating a better flatness and crystalline order.

The quality of the interface and the topological surface state of the Bi_2Te_3 films of these heterostructures were investigated by XPS and ARPES measurements (Figs. 2 and 3). In order to determine the chemical states of the Bi_2Te_3 at the interface, we compared the line shapes of the Te 3d and Bi 4f XPS core-level spectra. The spectra of the 2-QL Bi_2Te_3 films in Figs. 2(a)–2(c) are slightly shifted in energy to overlap with those of the reference data, namely of the 10-QL Bi_2Te_3 film on $\text{Al}_2\text{O}_3(0001)$. The small change of the line shape indicates a minimal reaction at the TI/oxide interface. The extra peaks in Fig. 2(a) for the 2-QL Bi_2Te_3 on YIG(111) near the Bi 4f peaks are the Y 3d peaks from the substrate which are visible because of the small thickness of only 2 QLs. The substrate peaks vanished when the films were grown thicker. The binding energy shifts (~ 0.10 – 0.14 eV) in the 2-QL Bi_2Te_3 films might be due to the band bending in the heterostructure such as observed at oxide/semiconductor interfaces. These shifts became smaller after the Bi_2Te_3 films were grown thicker to

FIG. 1. RHEED patterns of Bi_2Te_3 on magnetic substrates (a) YIG(111); (b) TmIG(111); (c) Fe_3O_4 (111); (d) Fe_3O_4 (100), and the corresponding substrates. The thickness of the Bi_2Te_3 films is indicated.

6 QLs, and the line shapes of the spectra are identical to that of the 10-QL Bi_2Te_3 films on Al_2O_3 (0001). In Fig. 2(d), one can observe small shoulders on the higher binding energy sides of the Te and Bi peaks, indicating stronger Bi–O and Te–O bonds at the $\text{Bi}_2\text{Te}_3/\text{Fe}_3\text{O}_4$ (100) interface, in contrast to those of Bi_2Te_3 on Fe_3O_4 (111) and iron garnets. However, there is still no sign of a strong chemical reaction between the Bi_2Te_3 films and the Fe_3O_4 such as the formation of TeO_2 , Te_2O_3 , FeTe , Bi_2O_3 , or Bi metal. Also, for the Fe_3O_4 (100), the shape of the XPS spectra became identical after the Bi_2Te_3 films were grown thicker to 10 QLs.

FIG. 2. XPS measurements of Bi_2Te_3 on (a) YIG(111); (b) TmIG(111); (c) Fe_3O_4 (111); (d) Fe_3O_4 (100). The XPS spectra are shifted to have a better comparison of the peak shapes. “+0.1 eV” means that the measured spectra are shifted by 0.1 eV towards lower binding energy. The black lines are the spectra from the reference sample, namely, 10-QL Bi_2Te_3 on Al_2O_3 (0001). The red lines are the spectra of 2-QL Bi_2Te_3 on the respective magnetic oxides. The blue lines are the spectra of thicker Bi_2Te_3 (6–10 QLs) on the respective magnetic oxides.

In Fig. 3, the ARPES images show clear and well-defined topological surface states for all heterostructures with the Fermi surface located in the Bi_2Te_3 band gap and intercepting with only the surface state. This not only shows a good quality of the TI films but also indicates intact top topological surface states. We plotted a zoom-in of the ARPES images with emphasized color to locate the topological surface states. The red lines are plotted and aligned along the intensity maxima below the Fermi surface, and the Dirac points are then determined at the intersections, as 0.11, 0.15, 0.14, and 0.12 eV below the Fermi surface, for the Bi_2Te_3 films grown on the YIG(111), TmIG(111), Fe_3O_4 (111), and Fe_3O_4 (100) substrates, respectively. The Dirac cone angles of the films are consistently similar. We note that the intensity of the surface states of the Bi_2Te_3 films grown on the YIG(111) is weaker [Fig. 3(a)], but one can still locate the surface states

FIG. 3. ARPES measurements of Bi_2Te_3 on (a) YIG(111); (b) TmIG(111); (c) Fe_3O_4 (111); (d) Fe_3O_4 (100). The corresponding zoom-in ARPES images in emphasized color are shown on the right side of each spectrum. The dashed black lines indicate the Fermi level, and the red lines indicate the surface states.

FIG. 4. Temperature-dependent sheet resistance and magnetoconductance of the Bi_2Te_3 films on (a) YIG(111); (b) TmIG(111); (c) Fe_3O_4 (111); (d) Fe_3O_4 (100). The insets show the fine structure at low temperature and the Verwey transition temperature for Fe_3O_4 .

with the same Dirac cone angle and the intensity maxima of the image with emphasized color. Compared to former thickness-dependent ARPES results of Bi_2Te_3 films grown on Si [24], where one can see the clear paraboliclike band when the surface states are gapped, we conclude that there is no gap formed in the top topological surface states in our films. We would like to note that for Bi_2Se_3 films below 6 QLs, a gap opens in the surface state due to the hybridization of top and bottom surface states [25]. For Bi_2Te_3 , the hybridization gap does not form when the thickness is larger than 2 QLs [24]. In our study, we used a thickness of 6–10 QLs of Bi_2Te_3 which is much larger than the critical thickness, consistent with our observation that there is no hybridization gap for our films.

The results of the transport measurements of the Bi_2Te_3 heterostructures are shown in Fig. 4. For the Bi_2Te_3 on YIG(111) shown in Fig. 4(a), the sheet resistance decreases with lowering the temperature, and has a minimum at about 8 K. For the Bi_2Te_3 on TmIG(111) shown in Fig. 4(b), the Bi_2Te_3 film shows a rather insulating behavior with a dip at around 26 K. The sheet resistance of the Bi_2Te_3 film grown on TmIG is one order of magnitude larger than that grown on YIG. This might be due to a worse growth quality at the Bi_2Te_3 /TmIG interface, as indicated by the 2-QL RHEED pattern in Fig. 1(b). On the other hand, for the Bi_2Te_3 on Fe_3O_4 , Figs. 4(c) and 4(d) show that the sheet resistance increases with decreasing temperature for higher temperatures. At 120 K for the Fe_3O_4 (100) film and at 124 K for the Fe_3O_4 (111) bulk (see insets), the magnetite undergoes the Verwey transition. When the temperature is below the Verwey transition temperature (T_v), the sheet resistance decreases with decreasing temperature, and has a minimum at about 10 K. The results indicate that the conduction contribution from the Bi_2Te_3 film dominates when the Fe_3O_4 is insulating, i.e., below T_v .

For the magnetoconductance at low temperature and low magnetic field, the Hikami-Larkin-Nagaoka formula (HLN

formula) can be fitted to the data:

$$\Delta G_{xx} = \alpha \frac{e^2}{\pi h} \left[\ln \left(\frac{B_\phi}{B} \right) - \psi \left(\frac{1}{2} + \frac{B_\phi}{B} \right) \right] + \beta B^2,$$

where ΔG_{xx} is the difference between the magnetoconductance at a certain magnetic field and the zero-field magnetoconductance, $B_\phi = \frac{\hbar}{8\pi e l_\phi}$, B is the applied magnetic field, l_ϕ is the phase coherence length. The prefactor $\alpha = -1$ for weak localization and $\alpha = 1/2$ for weak antilocalization [6], and β is the coefficient of the magnetic field. For the magnetoconductance in Fig. 4, the weak antilocalization dominates and forms the cusplike shape.

The thickness-dependent magnetoconductance of the Bi_2Te_3 on Fe_3O_4 (100) together with the fitting parameters are summarized in Fig. 5(a). The data can be fitted well by introducing only one set of α and l_ϕ , like for the reference data of the 10-QL Bi_2Te_3 on Al_2O_3 (0001). The values for α and l_ϕ of the reference sample are 0.51 and 437 nm, respectively. These values are typical for a topological insulator with one WAL conduction channel, where the top topological surface state and interface topological surface state are coupled through the bulk carriers [26]. Compared to the reference data, the coherence length of the 10-QL Bi_2Te_3 is suppressed from 437 to 100 nm when grown on the Fe_3O_4 (100) substrate. And, when we further reduce the thickness to 6 QLs, the prefactor α is reduced from 0.58 to 0.39, indicating a suppression of the WAL by competition between WL and WAL in the topological surface states [7,27], although we did not observe a negative resistance as for Bi_2Se_3 on YIG(111) in Ref. [27]. Here we use only one set of α and l_ϕ for the fit of the HLN equation to the magnetoconductance curves of the 10-QL Bi_2Te_3 on Fe_3O_4 (100) sample since the resulting values of l_ϕ for the WL and WAL are comparable. In this case we cannot separate the two effects by fitting. The prefactor α is then a combination of α_{WL} and α_{WAL} , which is between 0.5 and -1 , or in other words the reduced prefactor of $\alpha = 0.39$

FIG. 5. (a) Thickness-dependent magnetoconductance of the Bi_2Te_3 films on $\text{Fe}_3\text{O}_4(100)$. The black line is the magnetoconductance of the reference sample, 10-QL Bi_2Te_3 on $\text{Al}_2\text{O}_3(0001)$. The results of the fittings of the HLN formula are denoted for each curve. (b) Magnetoconductance of 6-QL Bi_2Te_3 on YIG(111). The red line is the fitting of the HLN formula. The orange, blue, and green lines are the contributions from WAL, WL, and B^2 of the HLN formula, respectively.

indicates a “suppression of the WAL.” Figure 5(b) shows the magnetoconductance of a 6-QL Bi_2Te_3 film on YIG(111). The data can now be fitted with two sets of prefactors α and l_ϕ ($\alpha_{\text{WL}} = -1$, $\alpha_{\text{WAL}} = 0.5$ and their respective l_ϕ : $l_{\phi\text{WL}} = 33$ nm, $l_{\phi\text{WAL}} = 383$ nm) because the difference of the coherence lengths is larger. The observation of the WL indicates a gap opening possibly caused by a magnetization of the Bi_2Te_3 on $\text{Fe}_3\text{O}_4(111)$ [Fig. 4(c)] is rounded at low field, or “less cusplike” compared to the other films, indicating a weaker or more suppressed WAL effect already at low fields. The magnetoconductance can be fitted by the HLN formula if we only include a smaller range of the H field (500 Oe rather than 3000 Oe used for the other films). The fitted parameters are $\alpha_{\text{WAL}} = 0.5$ with $l_{\phi\text{WAL}} = 70$ nm. Considering the good crystallinity at 2 QLs as shown by RHEED and no chemical reactions as shown by XPS, the suppressed WAL coherence length might be due to the magnetic proximity effect from the substrate.

The results of the Hall measurements are summarized in Fig. 6. The AHE was observed for the Bi_2Te_3 on YIG(111) for temperatures up to 300 K with a saturation field of about 2000 Oe, for the Bi_2Te_3 on TmIG(111) for temperatures of up to 80 K with a saturation field of <100 Oe (due to the magnetic perpendicular anisotropy of the TmIG, the saturation field at hard axis is $4\pi M_s \sim 1382$ Oe, $M_s \sim 110$ emu/c.c. for TmIG), and for the Bi_2Te_3 on $\text{Fe}_3\text{O}_4(111)$ for temperatures of up to 80 K with a saturation field of about 5000 Oe. For temperatures greater than 80 K, the conduction of the Fe_3O_4 becomes non-negligible and the contribution of the TI layer is overwhelmed. Surprisingly, no AHE was observed for the Bi_2Te_3 on $\text{Fe}_3\text{O}_4(100)$. This might be explained by the dead magnetic layer that is known to form at the surface of $\text{Fe}_3\text{O}_4(100)$ films [20,28–30].

FIG. 6. Hall resistance of the Bi_2Te_3 films on (a) YIG(111); (b) TmIG(111); (c) $\text{Fe}_3\text{O}_4(111)$; (d) $\text{Fe}_3\text{O}_4(100)$. The left figures of (a)–(c) show the raw data, and the right figures of (a)–(c) emphasize the anomalous Hall effect with the linear background (ordinary Hall effect) subtracted.

FIG. 7. XAS and XMCD spectra of the Te M_{45} and Fe L_{23} edges on the Te and Bi_2Te_3 films deposited on the magnetic insulators. The measuring temperature and the x-ray incident angle (parallel to magnetic field) with respect to the surface normal are indicated in each figure. $\sigma+$ and $\sigma-$ denote the two XAS spectra taken at opposite applied magnetic fields. The XMCD of Te M_{45} was multiplied by 100 to emphasize the tiny features.

To study the origin of the AHE, we performed Te M_{45} and Fe L_{23} XAS and XMCD measurements on the Te and Bi_2Te_3 films deposited on the magnetic insulators (see Fig. 7). Although the Fe L_{23} edges show decent XMCD spectra for all the magnetic insulators, the Te M_{45} edges, consisting of two absorption edges located at about 571 eV for the M_5 edge and 581 eV for the M_4 edge, show no XMCD for all the samples. The small signal at 576 eV in Fig. 7(a) might be from the light shining on the Cr stripes grown on the edges of the YIG substrate for grounding. The results indicate that the effect of magnetic proximity might be too weak to be measured by XMCD.

In order to establish a reference XMCD spectrum of magnetized Te, XMCD spectra were also measured on a Fe_xTe film and 1-ML Te deposited on a Fe film. Figures 8(a) and 8(b) show that the Te in the Fe_xTe film was magnetized, as indicated by the XMCD (18 and 15% of the XAS edge jump measured at 78 and 300 K, respectively). The XMCD signal shows opposite directions of the magnetization of the M_5 and M_4 edges, which is due to the spin-orbit splitting. Figure 8(c) shows that also a 1-ML Te layer can be magnetized by being deposited on an Fe film, as indicated by the XMCD (7% of the XAS edge jump measured at 300 K). The positions of the Te M_{45} edges are comparable to those of the Fe_xTe film shown in Figs. 8(a) and 8(b). The XMCD spectra are noisier due to the smaller size of the effect, but the opposite directions of magnetization at the M_4 and M_5 edges agree with those of the Fe_xTe film. Figure 8(d) shows the XAS and XMCD of 1-QL Bi_2Te_3 grown on the 1-ML Te layer on the Fe film shown in Fig. 8(c). Although the positions of the Te M_{45} edges remained, the XMCD intensity was reduced to a value smaller than 1% of the XAS edge height, which is comparable to the

noise level, showing that the magnetization as detected by XMCD is much weaker.

Analyzing the results of the transport and XMCD measurements, we noticed that we have observed the AHE but not the XMCD on the Te M_{45} edges. One possible reason could be that the XMCD effect is too small to be detected. If we look at the previous reported magnitude of the XMCD on Cr-doped $(\text{Bi}, \text{Sb})_2\text{Te}_3$ [12], one can find that the magnitude of the XMCD on the Te M_{45} edges is only $\sim 2.5\%$ of the XAS peak. And, this is the result from a doped sample where there is presumably a chemical bonding between the Cr and the Te. However, for the heterostructures studied here, the XMCD is relying on the presence and strength of the magnetic proximity effect, an issue that we will elaborate further below.

Now we first need to note that an earlier study [14] has claimed the observation of an XMCD signal at the Te $M_{4,5}$ edges from a TI magnetized by the proximity effect. We would like to point out, however, that the reported spectra consist of two white lines for each of the M_4 and M_5 edges, namely at 572 and 576 eV for the M_5 , and at 582 and 586 eV for the M_4 . This is different from our results, which show only a single white line per edge, namely at 571 eV for the M_5 and at 581 eV for the M_4 , and not only for the Bi_2Te_3 heterostructures but also for the Fe_xTe and Te on Fe films. There is no XMCD in the 572- and 582-eV features of the earlier study, nor in the 571- and 581-eV features in ours. In fact, the claimed XMCD occurs only for the 576- and 586-eV features in the earlier study. In our opinion, these 576- and 586-eV features do not belong to the Te of the Bi_2Te_3 but rather to oxidized Te [31]. Moreover, the claimed XMCD seems to be not due to an XMCD effect but rather due to an artifact since the difference spectrum of the two features has the same sign,

FIG. 8. XAS and XMCD spectra of the Te M_{45} and Fe L_{23} edges on (a), (b) the Fe_xTe film measured at 78 and 300 K, respectively; (c) 1-ML Te deposited on 12-nm Fe; (d) 1-QL Bi_2Te_3 on 1-ML Te deposited on 12-nm Fe. The measuring temperature and the x-ray incident angle (parallel to magnetic field) with respect to the surface normal are indicated in each figure. $\sigma+$ and $\sigma-$ denote the two XAS spectra taken at opposite applied magnetic field. The XMCD spectra were multiplied to emphasize the features.

which is completely different from that of the magnetized Te exhibiting opposite signs as shown in Fig. 8.

Returning to the issue of not observing an XMCD effect but nevertheless observing the AHE, we need to understand how the magnetic exchange energy gap (E_g) affects the XMCD. To this end we perform a rough estimation of the influence of a band gap by assuming that the Te M_5 absorption edge is shifted due to the magnetic exchange by $\pm E_g/2$ for circular polarized light with positive and negative helicity, respectively, neglecting any influence of change in line shape or occupation. In Fig. 9(a), we plot the energy-shifted XAS of the Te M_5 edge of 1-QL Bi_2Te_3 on YIG(111) with ± 50 meV to simulate the spectrum with a large magnetic exchange energy gap $E_g = 100$ meV. The calculated difference spectrum shows a 17% effect at the M_5 edge, which is a comparable value to our Fe_xTe XMCD results in Figs. 8(a) and 8(b). Figure 9(b)

FIG. 9. (a) XAS of the Te M_5 edge on 1-QL Bi_2Te_3 on YIG(111). The energy was shifted by ± 50 meV for the black and red curves, respectively. The difference spectrum of the XAS curves with 100-meV energy gap is shown in green. (b) Difference spectra of the shifted Te M_5 edges on 1-QL Bi_2Te_3 on YIG(111) for various energy gaps.

shows the simulated difference spectra for various smaller exchange energy gaps, where the spectrum with energy gap $E_g = 5$ meV shows only a 0.8% difference and the spectrum with $E_g = 10$ meV shows only a 1.6% difference.

Considering the small band gap of 9 meV obtained from density-functional theory calculations for $\text{EuS}/\text{Bi}_2\text{Te}_3$ [32], the estimation indicates that our results with $\text{XMCD} < 1\%$ on the Te M_5 edge for Bi_2Te_3 on various FIs could be indeed related to a small size of the magnetic exchange energy gap. As an energy gap $E_g = 10$ meV shows only a 1.6% difference [Fig. 9(b)], and considering that only a very thin layer of Bi_2Te_3 at interface contributes to the XMCD (for an estimation we assume that 1 ML of the 1-QL Bi_2Te_3 layer is magnetized), the XMCD effect is then decreased to 0.3%, which is below our XMCD detection limit. The van der Waals bonding between TI and FI seems to yield only a small transferred magnetic entity, which is very different from the direct exchange or the superexchange via chemical bonding. Thus, we infer that seeing an XMCD effect exceeding 1% might actually indicate that the interface is not sharp and clean, but that there are rather chemical reactions and intermixing present as observed, e.g., in Fe_xTe [see Figs. 8(a) and 8(b)]. For good interfaces, the magnetic proximity effect across the van der Waals bonding is too small to be detected by XMCD but still sufficient to create a small gap opening for the AHE to be observed by transport measurements since the conducting topological surface state contributes to the conduction channel.

IV. CONCLUSION

In conclusion, we have successfully grown Bi_2Te_3 on magnetite and iron garnets by molecular-beam epitaxy with

no or minimal chemical reactions. The transport results showed a gap opening indicated by the suppression of the weak antilocalization and observation of the weak localization in the magnetoconductance. The anomalous Hall effect was observed in Bi_2Te_3 on YIG(111) (up to 300 K), TmIG(111) and Fe_3O_4 (111) (up to 80 K), while we did not observe any x-ray magnetic circular dichroism on the Te M_{45} edges for such heterostructures. Our findings suggest that the ferromagnetism induced by the magnetic proximity effect via van der Waals bonding in Bi_2Te_3 is too weak to be detected by x-ray magnetic circular dichroism, but still can be measured by transport experiments. This is consistent with previous density-functional theory calculations for $\text{EuS}/\text{Bi}_2\text{Se}_3$ [32] indicating an opening of a band gap of only 9 meV due to the magnetic proximity effect.

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