Topological Antiferromagnetic Van der Waals Phase in Topological Insulator/Ferromagnet Heterostructures Synthesized by a CMOS-Compatible Sputtering Technique

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1. Introduction
Magnetic order in topological insulators (TIs) and breaking of time-reversal symmetry\(^1,2\) has been achieved through magnetic doping of TIs,\(^3\text{–}11\) magnetic proximity effect,\(^12\text{–}18\) and synthesis of intrinsic magnetic TI (MTI) compounds such as, MnBi\(_2\)Te\(_4\) that supports the quantum anomalous Hall (QAH) state at low temperatures.\(^19\text{–}28\) These exotic quantum states can help realize topological quantum computers and energy-efficient spintronic devices. Introducing impurity atoms in TIs can also lead to the emergence of new phases with exotic properties, such as superconductivity.\(^29\) TIs in van der Waals (vdW) materials are promising systems in this connection due to the tunability and diversity of their optical, electronic, and magnetic properties. Recently, TI thin films have been shown to form new material phases at the interface when coupled with metallic thin films\(^30\text{–}32\) resulting from the diffusion of elements. Notably, an AFM...
order in TIs in these interfacial material phases has not been reported. Much of these existing experimental works have been performed on c-axis-oriented Bi$_2$Se$_3$-based systems. However, theoretical calculations have shown an order of magnitude larger superexchange interaction strength in Te-based TI material systems compared to those based on Se$_2$ making the latter more promising for creating topological magnetic materials.

Ti thin films grown using magnetron sputtering have been reported recently as promising candidates for energy-efficient spintronic devices. Sputtering is the semiconductor industry’s accepted manufacturing process for growing thin films with high film quality, large throughput, and ability for large area uniform thin film deposition. However, high-quality c-axis ordering in sputter-deposited TIs has been elusive, which is required for realizing the topological properties. This has prevented the study of many fascinating materials phases emerging in heterostructure interfaces and also has hindered the integration of TI-based spintronic devices in industrial complementary metal–oxide–semiconductor (CMOS) processes.

Here, the discovery of a vdW antiferromagnetic (AFM) phase of NiBi$_2$Te$_4$ at the Ni-Bi$_2$Te$_3$ interface, which emerges as a distinct interfacial layer when a highly c-axis-oriented Bi$_2$Te$_3$ thin film is coupled with the ferromagnetic (FM) alloy, Ni$_{80}$Fe$_{20}$ (Py) as a result of the diffusion of Ni into Bi$_2$Te$_3$. Growth of the Py layer following Bi$_2$Te$_3$ growth is carried out in the same sputtering chamber without breaking vacuum. This ensures access to a topologically nontrivial surface of Bi$_2$Te$_3$ for the creation of the AFM Ni-Bi$_2$Te$_3$ layer. Measurements of the magnetic hysteresis loops show the appearance of a large spontaneous exchange bias (EB), signaling an AFM phase in proximity to the FM layer of Py having substantial exchange interaction between the AFM–FM layers.

2.1. Characterization of Crystal Structure and Interface Morphology

Heterostructures were grown by depositing 40 nm of c-axis-oriented crystalline-textured Bi$_2$Te$_3$ on thermally oxidized Si/SiO$_2$ substrates using RF magnetron sputtering, followed by a 20 nm layer of Py (see Experimental Section for details). Reference samples were prepared with Bi$_2$Te$_3$ (40 nm)/TiO$_x$ (3 nm) for X-ray diffraction (XRD) analysis. The wide-angle XRD plot in Figure 1a clearly shows the Bi$_2$Te$_3$ phase with a significant crystalline orientation along the c-axis. The surface roughness of the Bi$_2$Te$_3$ layer was measured to be $\sim$1 nm using X-ray reflectivity (Figure S1, Supporting Information) for the Bi$_2$Te$_3$/TiO$_x$ sample. This value of surface roughness is typical of sputter-grown thin films. These results show that high-quality, c-axis-oriented, crystalline-ordered TI can be grown using sputtering on an amorphous substrate, enabling us to study the interface phases in TI/FM heterostructures.

The microstructure of the interface was studied extensively using several techniques. High-resolution transmission electron microscopy (HRTEM) was used to image the cross-section of the Bi$_2$Te$_3$/Py heterostructure, as shown in Figure 1b. Four distinct layers are identified: Bi$_2$Te$_3$, Ni$_x$Bi$_{2-x}$Te$_3$, Py* (Ni-depleted Py), and Py. The HRTEM and scanning transmission electron microscopy–high-angle annular dark-field (STEM-HAADF) images in Figure 1b,c clearly show vdW layers, which confirms the crystalline-textured, c-axis-oriented growth of the Bi$_2$Te$_3$ thin film. Energy-dispersive X-ray spectroscopy (EDS) was used to characterize the elemental composition of the heterostructure as presented in Table 1 (details of analysis in Figure S4, Supporting Information). The obtained Bi:Te ratio of 2.3 confirms a stoichiometric composition of the sputtered Bi$_2$Te$_3$ thin film. It is important to note that a significant diffusion of Ni occurs within the interface, as illustrated in the normalized EDS depth profile in Figure 1d. This diffusion of Ni is accompanied by a substantial loss of magnetic moment, $m$, by $\approx$40% compared to a control sample of Py as shown in the room temperature $m(H)$ loop in Figure 1d. The constancy of this significant moment loss is further verified using the PNR measurements (Section 7, Supporting Information). The diffused Ni in Bi$_2$Te$_3$ undergoes a solid-state chemical reaction, possibly catalyzed by the topological surface state (TSS) electrons. A second interface layer also forms because of depletion of Ni from Py, wherein trace amounts of Bi and Te are also detected, which is referred to as the Py* layer. The 5 nm thick Ni$_x$Bi$_{2-x}$Te$_3$ AFM layer is clearly a vdW material phase which is evident from the STEM-HAADF image in Figure 1b,c and will be further verified using several techniques.

2.2. Exchange Bias due to FM/AFM Interaction

To study the magnetic properties in the sputter-deposited Bi$_2$Te$_3$/Py heterostructure, $m(H)$ loop measurements were carried out with the field in the plane of the sample with a superconducting quantum interference device (SQUID) magnetometer. As expected, the in-plane hysteresis loops measured at room temperature, $T = 300$ K are centered with a small coercive field, $\mu_0H_c \approx 0.5$ mT, which is comparable to the Py control sample in Figure 1e. In contrast, the zero-field-cooled (ZFC) and field-cooled (FC) low-temperature measurements exhibit a sizable spontaneous EB along with a significant enhancement of $\mu_0H_c$ as shown in Figure 2a. This EB shift and $\mu_0H_c$ enhancement is
characteristic of a large exchange interaction in the FM/AFM interface.\textsuperscript{[40–43]} A high energy of the exchange interaction between the FM and AFM layers not only shifts the loop $m(H)$ loop along the axis of the $H$-field (exchange bias), but often also leads to an increase in coercive field.\textsuperscript{[40,41]} This possibly happens due to the pinning of domains in a magnetic frustrated interface. The ZFC $m(H)$ loop measured at 6 K is shifted by 8 mT off-center and an enhanced coercive field was determined to be $\mu_0 H_c = 9.5$ mT. FC hysteresis loops were also measured where the samples were cooled with an applied field of $\pm 1$ T. As shown in Figure 2b, EB field switched from $-18.0$ mT to $+18.0$ mT for FC of $+1$ T and $-1$ T, respectively. This confirms the presence of a large exchange coupling that exists between the FM, Py, and the AFM, Ni-Bi$_2$Te$_3$ layers, with a large in-plane magnetic anisotropy\textsuperscript{[45]} indicative of a vdW layered A-type AFM\textsuperscript{[19,20]} material (more evidence of A-type AFM order in Section S8, Supporting Information). The Neél temperature at which the AFM phase emerges was obtained from $m(T)$ measurements performed in both FC and ZFC conditions using a constant applied field of 5 mT as shown in Figure 2c,d. Figure 2d plots the derivative, $dm/dT$ of the ZFC $m(T)$, showing a sharp peak at 63 K, which is the Neél transition temperature of the AFM phase.\textsuperscript{[42,43]} This

| Element | Bi$_2$Te$_3$ [%] | Ni-Bi$_2$Te$_3$ [%] | Py* [%] | Py [%] |
|---------|-----------------|---------------------|--------|-------|
| Bi      | 39.03 (5.17)    | 22.25 (4.05)        | 3.21 (1.05) | 0.03 (0.05) |
| Te      | 60.28 (4.87)    | 34.31 (3.82)        | 5.24 (1.04) | 0.20 (0.07) |
| Ni      | 0.38 (0.03)     | 39.38 (3.63)        | 69.90 (1.89) | 80.79 (2.47) |
| Fe      | 0.31 (0.03)     | 4.11 (0.09)         | 21.65 (0.58) | 18.99 (0.58) |

Table 1. Atomic % of the Bi$_2$Te$_3$/Ni-Bi$_2$Te$_3$/Py*/Py heterostructure shown in Figure 1. The numbers in parantheses represent their standard deviation in each layer.
Neél temperature of the Ni-Bi$_2$Te$_3$ AFM phase is higher than the transition temperatures of MTIs reported in the literature.\cite{54}

### 2.3. Confirmation of AFM Order in Ni-Bi$_2$Te$_3$ Layer Using PNR

The location of the layer with AFM ordering in the Ni-Bi$_2$Te$_3$ layer present in the heterostructure was confirmed by performing depth-sensitive PNR measurements\cite{56,57} at the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source using the MagRef reflectometer.\cite{58} The experiments were performed at $T = 7$ K under ZFC conditions using 1 T and 5 mT applied fields. The theoretical model was fit to the PNR profiles using Refl1D software for the reflectivity and spin-asymmetry experimental data, $SA = (R^+ - R^-)/(R^+ + R^-)$ as shown in Figure 3a,b. The structural and magnetic depth profiles were parameterized using the nuclear and magnetic scattering length densities (NSLD and MSLD, respectively) as shown in Figure 3c (full PNR profile in Figure S7, Supporting Information). The NSLD and MSLD depth profiles obtained from the fit to the reflectivity represent the structural and magnetic depth profiles of the heterostructure, respectively. Note that the reduction in NSLD by $\approx 2 \times 10^{-6}$ Å$^{-2}$ in the Py$^\#$ layer is compensated by a gain in NSLD by approximately the same value in the Ni-Bi$_2$Te$_3$ layer. This suggests that the Ni lost by the Py in the Py$^\#$ layer forms the distinct Ni-Bi$_2$Te$_3$ interfacial layer, which is in agreement with the STEM-HAADF image in Figure 1c.

For the applied field of 1 T, most of the moment vectors are aligned along the field direction, including the moments in the interfacial layer, illustrated in Figure 3d. But at a low applied field of 5 mT, the AFM order in the Ni-Bi$_2$Te$_3$ vdW layers yields largely compensated moments. From the MSLD depth profile in Figure 3c, the Ni-Bi$_2$Te$_3$ layer was observed to have an order of magnitude larger value of $0.26 \times 10^{-6}$ Å$^{-2}$ at 1 T compared to $0.034 \times 10^{-6}$ Å$^{-2}$ at 5 mT. The reduction in the value of moments by an order of magnitude at a low applied field confirms the AFM ordering in the Ni-Bi$_2$Te$_3$ interfacial layer. A lower value of MSLD can also mean that the moments are oriented out of the film plane, as PNR is insensitive to the perpendicular component of moments. However, the large exchange bias for in-plane $m(H)$ loop measurements as shown in Figure 2 and significantly low remnant magnetization in out-of-plane $m(H)$ loop measurement (Figure S7, Supporting Information) provides clear evidence of largely in-plane easy-axis AFM order in the Ni-Bi$_2$Te$_3$ layer with small canting of moments out-of-plane.
2.4. Evidence of Topologically Nontrivial Compounds in AFM Ni-Bi₂Te₃ Phase

The c-axis crystalline-oriented texture of the vdW-layered Bi₂Te₃ and the Ni-Bi₂Te₃ AFM layers are clearly identified in the HRTEM and STEM-HAADF images in Figure 1b,c and SAED patterns in Figure 4a–c. In order to understand the structural and chemical properties of the Ni-Bi₂Te₃ layer, SAED followed by cross-section EELS and depth-dependent XPS measurements were performed. These measurements provide strong evidence of formation of topologically nontrivial vdW compounds in the AFM Ni-Bi₂Te₃ layer as a result of diffusion and solid-state reaction between the diffused Ni and Bi₂Te₃. The SAED measurements clearly demonstrate a vdW-layered structure in the Ni-Bi₂Te₃ layer as shown by the single line of diffraction spots in Figure 4a, as well as in the Bi₂Te₃ of Figure 4b. Figure 4c contains the diffraction intensities extracted from Figure 4a,b, for both the Bi₂Te₃ and Ni-Bi₂Te₃ layers, where additional peaks emerge in the Ni-Bi₂Te₃ layer compared to the peaks representing quintuple layers (QL) of Bi₂Te₃. These additional diffraction peaks confirm formation of new planes parallel to the crystalline c-axis and support the diffusion of Ni and reaction with Bi₂Te₃. A similar pattern of the SAED peaks in the Ni-Bi₂Te₃ layer compared to the Bi₂Te₃ layer further confirms the vdW nature of the Ni-Bi₂Te₃ layer. These key pieces of information are strong indications of the formation of a Ni-based vdW-layered magnetic topological material phase in the interfacial Ni-Bi₂Te₃ layer. Theoretical calculations of NiBi₂Te₄, which belongs to the MBi₂Te₄ (M = Mn, Ni, V, Eu etc.) family, have shown it to be an intrinsic MTI compound with large exchange energy.[19,20] With this in mind, the emergence of a large exchange-bias from the AFM-ordered Ni-Bi₂Te₃ layer points toward the emergence of Ni-based AFM phases with topologically nontrivial properties. Qualitative comparison of the positions of the c-axis-oriented SAED peaks with theoretical diffraction peak positions of possible Ni, Bi, and Te based vdW materials, raises the possibility of the presence of topologically nontrivial compounds such as NiBi₂Te₄, (Ni,Bi)₂Te₃, NiTe, and NiTe₂ in the Ni-Bi₂Te₃ AFM layer.[19,20,52] Of these, however, NiTe and NiTe₂ are known to be paramagnetic.[48] This makes the topological magnetic compounds, NiBi₂Te₄ and (Ni,Bi)₂Te₃ (substitution of Bi sites by Ni) highly probable candidates for the AFM ordering in the Ni-Bi₂Te₃ layer. The average c-axis length was calculated as 40.63 Å from the SAED data of the Ni-Bi₂Te₃ layer which is close to the theoretical value of 41.01 Å for NiBi₂Te₄. This further supports the presence of the MTI compound NiBi₂Te₄ in the Ni-Bi₂Te₃ layer making it the most likely candidate for the AFM order in the layer (Section 9, Supporting Information). The presence of a few diffraction peaks that deviate beyond the measurement error limits of SAED in Figure 4c (also Figure S10a,d, Supporting Information) also suggests presence of other materials phases in addition to Bi₂Te₃ and NiBi₂Te₄ in the Ni-Bi₂Te₃ layer. Presence of disorder and resultant diffraction peak shifts and broadening is however
expected in such an interfacial layer formed by diffusion and solid-state reaction between Ni and Bi₂Te₃.

Further evidence supporting the formation of compounds in the AFM Ni-Bi₂Te₃ layer is provided by cross-sectional EELS and depth-dependent XPS measurements, shown in Figure 4d–g. The EELS measurements for core shell electrons were performed on the layers marked in the STEM-HAADF cross-section images shown in Figure 1c. For the Ni-Bi₂Te₃ layer, Figure 4d shows new pre-edge features emerging at 30 eV lower binding energies (BE) prior to Ni and Fe L-shell edges, which were absent for the Py reference layer. In addition to these pre-edge features, a change in L3:L2 peak ratio of Ni from
and an A-type AFM ordering.\textsuperscript{[19,20,49–51]} Of further interest is the high Neél transition temperature of 63 K measured for the Ni-Bi\textsubscript{2}Te\textsubscript{3} AFM layer, which is higher than the MTIs\textsuperscript{[54]} reported in literature. This makes the present Ni-Bi\textsubscript{2}Te\textsubscript{3} phase an appealing candidate for high-temperature QAH and other topological phases that are required for realizing energy-efficient spintronics and topological quantum computing applications.

3. Conclusion

Sputtered TI/FM heterostructures of highly c-axis-oriented Bi\textsubscript{2}Te\textsubscript{3} coupled with the FM alloy Py were shown to exhibit a large exchange bias field at low temperatures that arise from the emergence of a novel AFM phase in the vdW Ni-Bi\textsubscript{2}Te\textsubscript{3} layer in the interface. The Bi\textsubscript{2}Te\textsubscript{3}/Ni\textsubscript{90}Fe\textsubscript{20} heterostructures were grown on amorphous thermally oxidized Si substrates. Using PNR measurements, the AFM ordering in the Ni-Bi\textsubscript{2}Te\textsubscript{3} layer was confirmed. The diffused Ni undergoes a solid-state reaction with Bi\textsubscript{2}Te\textsubscript{3}, which is believed to be catalyzed by delocalized TSS electrons of the Bi\textsubscript{2}Te\textsubscript{3}. SAED diffraction patterns for the Ni-Bi\textsubscript{2}Te\textsubscript{3} layer exhibited new peaks in addition to the Bi\textsubscript{2}Te\textsubscript{3} QL peaks, confirming the formation of additional planes oriented along the crystalline c-axis. Furthermore, using cross-section EELS and depth-dependent XPS measurements, spectral changes were observed for Ni, Fe, Bi, and Te in the Ni-Bi\textsubscript{2}Te\textsubscript{3} layer, as compared to the reference Bi\textsubscript{2}Te\textsubscript{3} and Py layers. These are attributed to the formation of Ni–Te bonds in the interface layer. Comparison of diffraction data and the detection of Ni–Te bonds provide strong experimental evidence of presence of AFM TI compound, NiBi\textsubscript{2}Te\textsubscript{4} in the interfacial Ni-Bi\textsubscript{2}Te\textsubscript{3} layer. Using first principles DFT calculations, the NiBi\textsubscript{2}Te\textsubscript{4} compound was found as the most likely candidate contributing to the AFM order in the Ni-Bi\textsubscript{2}Te\textsubscript{3} layer. Band structure calculations determined the NiBi\textsubscript{2}Te\textsubscript{4} compound to be topological with a Z\textsubscript{2} topological number of 2. Furthermore, the \textasciitilde 63 K Neél transition temperature of the Ni-Bi\textsubscript{2}Te\textsubscript{3} phase is considerably higher than the magnetic transition temperatures of recent experimentally synthesized MTIs, which makes the present interfacial phase in sputtered TI/FM heterostructures promising candidates for high-temperature QAH and other topological quantum devices. These results open the path for further exploration of industrial CMOS compatible sputter-grown TIs and TI/FM material systems for high-temperature topological material systems and the realization of energy-efficient topological spintronics devices.

4. Experimental Section

Material Growth: Heterostructures of 30 nm Bi\textsubscript{2}Te\textsubscript{3} were grown by co-sputtering a composite Bi\textsubscript{2}Te\textsubscript{3} target with a Te target using RF magnetron sputtering at 90 W and 20 W, respectively, with 4 mTorr (0.53 Pa) Ar pressure on thermally oxidized Si substrates. The base pressure of the sputtering chamber was \textasciitilde 2 \times 10^{-7} \text{Torr} (2.67 \times 10^{-5} \text{Pa}). The samples were grown with substrates maintained at 250 °C. Samples were further annealed inside the chamber at 45 mTorr (6 Pa) Ar pressure for 25 min at 250 °C to achieve high-quality crystalline c-axis-oriented textured growth. The samples were cooled to room temperature in a high vacuum for \textasciitilde 5 h before deposition of other layers. For the magnetic samples, 20 nm Py and 3 nm Ti capping layer were deposited at

Table 2. XPS peak positions in units of eV of interest for Ni, Fe, Bi, and Te for Ni-Bi\textsubscript{2}Te\textsubscript{3} layer compared to reference Py and Bi\textsubscript{2}Te\textsubscript{3} layers.

| Element | Py [eV] | Ni-Bi\textsubscript{2}Te\textsubscript{3} [eV] | Bi\textsubscript{2}Te\textsubscript{3} [eV] | \(\Delta E\) [eV] |
|---------|---------|-----------------------------------------|---------------------------------|----------------|
| Ni      | 858.7   | 859.6                                   | –                               | 0.9            |
| Fe      | 712.1   | 713.0                                   | –                               | 0.9            |
| Te      | –       | 572.8                                   | 572.3                           | 0.5            |
| Bi      | –       | 157.1                                   | 157.4                           | –0.3           |
...polarized neutrons penetrate the entire structure of the film and generate no magnetic moment in the system. Electrically neutral, spin-$\Delta$ polarized neutrons with a wavelength band $\lambda_1$ T. In the time-of-flight method, a collimated polychromatic beam of field using a Bruker electromagnet with a maximum magnetic field of.

Sputtering occurred in 1 min intervals, while the sample was moved by a 2D charged-coupled device (CCD). The Bragg reflections were indexed highly collimated beam of CuK$\alpha$ radiation (wavelength $\lambda$ = 0.154056 Å).

The Nanobeam diffraction (Figure 4a,b) and STEM/EELS (Figure 4c) studies were performed using an aberration-corrected (image) Titan operated at an accelerating voltage of 200 kV. The EELS data acquisition was performed using a GIF-Quantum (Gatan, Inc) spectrometer and processed using the DigitalMicrograph 2.10 (Gatan, Inc.) software.

**Hysteresis Loop Measurements:** Magnetization $m(H)$ and $m(T)$ measurements were obtained using a Quantum Design superconducting quantum interference device (SQUID) magnetometer. Hysteresis loop $m(H)$ measurements were carried out at various temperatures between 6 and 300 K. The ZFC and FC $m(T)$ measurements were obtained while increasing the temperature in an applied field of 5 mT, and FC measurements were performed after cooling the sample under an applied field of 1 T. Room-temperature $m(H)$ measurements in Figure 1e were taken using a vibrating sample magnetometer (VSM).

**PNR Characterization:** PNR experiments were carried out on the Magnetism Reflectometer at the Spallation Neutron Source at Oak Ridge National Laboratory. A neutron beam with a wavelength band of 2.6–8.6 Å and a high polarization of 98.5% was used. Measurements were performed in a closed cycle refrigerator in an applied external magnetic field using a Bruker electromagnet with a maximum magnetic field of 1 T. In the time-of-flight method, a collimated polychromatic beam of polarized neutrons with a wavelength band $\Delta\lambda$ impinges on the film at a grazing incidence angle $\theta$. The neutrons interact in the film with atomic nuclei and the spins of unpaired electrons. The reflected intensity was measured as a function of wave vector transfer, $Q = 4\pi\sin(\theta)/\lambda$, for two neutron polarizations $R$ and $R_-$, with the neutron spin parallel (+) or antiparallel (−) to the direction of the external field, $H_{ext}$. To separate nuclear contribution from magnetic scattering, the data were presented in the form of the spin-asymmetry ratio $SA = (R^+ - R^-)/(R^+ + R^-)$ as shown in Figure 3b and Figure 57b, Supporting Information, where $SA = 0$ indicates that there is no magnetic moment in the system. Electrically neutral, spin-polarized neutrons penetrate the entire structure of the film and generate a depth profile of magnetic and structural composition of the film interfaces down to the substrate with a resolution of 0.5 nm. The depth profiles of the nuclear and magnetic scattering length densities (NSLD and MSLD) correspond to the depth profile of the chemical and in-plane polarization vector distributions on the atomic scale, respectively.

Based on these neutron scattering merits, PNR serves as the powerful technique to simultaneously and nondestructively characterize chemical and magnetic nature of buried interfaces. Neutron scattering measurements were performed on a 2 × 2 cm$^2$ surface samples.

**XPS Depth Profile:** Valence state of elements near the surface of the sample was characterized using a PHI VersaProbe II X-ray photoelectron spectrometer with a scanning monochromated Al source (1486.6 eV, 100 W, spot size 200 μm). The instrument’s C$\omega_{2p}$ ion source was used to perform depth profiling. A takeoff angle of 45° between the sample surface and analyzer was used. The X-ray beam collected Ni2p, Fe2p, Te3d, and Bi4f elemental information whilst rastering over a 200 × 1400 μm$^2$ area. Sputtering occurred in 1 min intervals, while the sample was moved using concentric Zalar rotation at 0.10 rad s$^{-1}$. The operation power of the C$\omega_{2p}$ source was maintained at 1 kV and 0.5 μA and rastered over a 2 × 2 mm$^2$ area at an angle 70° to the surface normal. Valence states of elements were determined by comparing the shift in XPS peaks in BE, and the relative sensitivity factors were provided in PHI’s Multipak software. Background-subtraction and smoothing of the data were performed using a five-point quadratic Savitzky–Golay algorithm. The relative position of the layers was based on amplitude of the spectra and relative shift in peak positions. Spectra peaks were fit in CasaXPS, and data were plotted and analyzed using Matlab.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

ferromagnets, interface, magnetic topological insulators, topological insulators, van der Waals materials

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