Phonon modes and Raman signatures of MnBi$_2$Te$_{3n+1}$($n = 1, 2, 3, 4$) magnetic topological heterostructures

Yujin Cho, Jin Ho Kang, Liangbo Liang, Madeline Taylor, Xiangru Kong, Subhajit Ghosh, Fariborz Kargar, Chaowei Hu, Alexander A. Balandin, Alexander A. Puretzky, Ni Ni, and Chee Wei Wong

$^1$Fang Lu Mesoscopic Optics and Quantum Electronics Laboratory, University of California, Los Angeles, California 90095, USA
$^2$Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
$^3$Phonon Optimized Engineered Materials (POEM) Center, Department of Electrical and Computer Engineering, University of California, Riverside, California 92521, USA
$^4$Department of Physics and Astronomy and California Nano Systems Institute, University of California, Los Angeles, California 90095, USA

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An intrinsic antiferromagnetic topological insulator MnBi$_2$Te$_4$ arises when intercalating a Mn-Te bilayer chain in a topological insulator, B$_2$Te$_3$. We present observations on the inter- and intralayer phonon modes of the generalized Mn Bi$_{2n}$Te$_{3n+1}$($n = 1, 2, 3, 4$) family using cryogenic low-frequency Raman spectroscopy with various polarization configurations. Two peaks at 66 and 112 cm$^{-1}$ show abnormal perturbation in Raman linewidths below magnetic transition temperature due to spin-phonon coupling. In MnBi$_4$Te$_7$, B$_2$Te$_3$ layers induce Davydov splitting of the $A_{1g}$ mode around 137 cm$^{-1}$ at 5 K. The out-of-plane interlayer force constant estimated using the linear chain model was $(3.98 \pm 0.14) \times 10^9$ N/m$^3$, three times weaker than that of B$_2$Te$_3$. Adding more B$_2$Te$_3$ layers, such as MnBi$_6$Te$_{10}$ and MnBi$_8$Te$_{13}$, makes B$_2$Te$_3$ layers more magnetic properties. Our work experimentally and theoretically discovers the dynamics of phonon modes of MnBi$_{2n}$Te$_{3n+1}$ family, facilitating utilization of magnetic topological heterostructures.

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The remarkable potentials of magnetic topological insulators, realizing exotic physical phenomena [1–3] like quantum anomalous Hall effect [4–7] or axion insulators [8–10], have led researchers striving to combine topological properties and magnetism by creating a proximity effect between a topological insulator and magnetic material [11], or by chemical doping [7,12,13]. However, synthesizing the material uniformly over a large area with well-controlled doping concentration has proven difficult. The recent discovery of MnBi$_2$Te$_4$ crystal structure. One unit layer consists of seven Mn, Bi, and Te elements, and a Mn-Te bilayer chain, of which the latter is shown in the dashed box. The top view of MnBi$_2$Te$_4$ crystal structure has threefold symmetry as illustrated in the middle panel of Fig. 1(a) [15]. We synthesize MnBi$_{2n}$Te$_{3n+1}$($n = 1, 2, 3, 4$) single crystals with B$_2$Te$_3$ flux [21,22,25,26,34], Mn, Bi, and Te elements.
FIG. 1. Polarized optical Raman spectroscopy of magnetic topological insulators, distinguishing E-mode and A-mode phonons. (a) Crystal structure of MnBi$_2$Te$_4$ (left), top view of MnBi$_2$Te$_4$ (middle), and exemplary optical image of samples (right). Scale bar: 20 μm. (b) The figure shows the layered structure of MBT families. (c) shows Raman spectrum (top) of MnBi$_2$Te$_4$ in the E mode (red) and A mode (blue), measured at 7 K. DFT calculation (bottom) shows corresponding Raman peak positions in each polarization configuration. The grey shaded area below 30 cm$^{-1}$ indicates the cut-off filter frequency. (d) Linear parallel polarization dependence of Raman signal at 7 K.

at a molar ratio of 15:170:270, are loaded in a crucible and sealed in a quartz tube under one-third atmospheric pressure of Ar. The ampule is heated to 900°C for 5 h, followed by air-quenching. It is then transferred to another furnace to cool it slowly from 595 °C to the decanting temperature, which varies for different n [21]. After resting the samples for one day, we centrifuge the ampule to separate the MnBi$_2$Te$_4$ and a differing number of Bi$_2$Te$_3$. For example, MnBi$_4$Te$_7$, MnBi$_6$Te$_{10}$, and MnBi$_8$Te$_{13}$ have one, two, and three Bi$_2$Te$_3$ layers, respectively. For the Raman measurements, we use a 532.2-nm laser, with an 80× objective lens at a power below 1 mW. Two Optical notch filters suppress the Rayleigh scattering and reveal low-frequency Raman peaks down to 30 cm$^{-1}$. The Raman spectrum is acquired with a Horiba 1000 M spectrometer with 1200 grooves/mm grating and the spectrometer was calibrated with a Mercury lamp and Si Raman peak at 520 cm$^{-1}$ before the measurements. To ensure the repeatability of the Raman signal, we probe several flakes, whose spectra are consistent within the experimental uncertainties. No laser-induced degradation of Raman peak intensities is observed over a few hours.

Figure 1(c) shows an example Raman spectrum of a bulk MnBi$_2$Te$_4$ at 7 K (top) and the calculated peak positions from the DFT (bottom). According to group theory, the crystal structure of bulk MnBi$_2$Te$_4$ belongs to the space group R$3\overline{m}$ (No. 166, point group D$_{3d}$) [34,36,37], and it has doubly degenerate $E_x$ and nondegenerate $A_{1g}$ symmetry Raman modes. To experimentally verify the $E$ and $A$ modes of the Raman peaks, we use circular polarization, the description of which can be found in Fig. S1 in the Supplemental Material (SM) [38]. From the Raman tensor analysis provided in the SM [38,39], $E$ modes only appear in $\bar{E}(\sigma^- - \sigma^+)_z$ configuration, while $A$ modes are only present in $\bar{E}(\sigma^- - \sigma^+)_z$ configuration. From our measurements, we assign Peaks II and III to $E$ modes (red) and Peaks I, IV, and V to A modes (blue), consistent with DFT calculations where red (blue) lines are $E$ ($A$) modes. The gray shaded area indicates the cutoff frequency in the polarized cryogenic Raman setup. The lowest frequency of the $E$ modes of 30.3 cm$^{-1}$ from theory was measured with Horiba T64000 Raman spectrometer in ambient, shown in Figure S2 in the SM. In Fig. 1(d), we present the incident linear polarization dependence of MnBi$_2$Te$_4$ at 7 K, maintaining the relative angle of the analyzer in the parallel polarization configuration. The polarization dependence remains isotropic, consistent with our theoretical analysis for the $R3m$ space group without considering the spin ordering (more details in the SM, Sec. 3). This means that in-plane magnetic anisotropy from spin-phonon coupling is not observed in the antiferromagnetic state. Vibrational modes and the temperature dependence of MnBi$_2$Te$_4$ Raman spectrum are discussed in depth later.

Figure 2 presents the Raman spectra of MnBi$_{2n}$Te$_{3n+1}$ $(n = 1, 2, 3, 4)$ at room temperature. Each sample has $(n-1)$ number of Bi$_2$Te$_3$ layers between two MnBi$_2$Te$_4$ layers. In all samples, we observe four distinctive peaks around 42 (peak I), 60 (II), 100 (III), and 135 cm$^{-1}$ (IV), and a shoulder peak around 110 cm$^{-1}$ (IV). The peak marked with * comes from the laser. As $n$ increases, the peak positions and the widths converge to those of Bi$_2$Te$_3$: light horizontal lines in Figs. 2(c)–2(d). Compared to the Raman spectrum of Bi$_2$Te$_3$, Peaks I, II, and IV uniquely exist in MnBi$_2$Te$_4$. Our DFT calculations show that the Mn atom of the Mn-Te bilayer chain remains static in all vibrational modes, while the Te atom oscillates in- or out-of-plane in Peaks I, II, and IV; see the inset in Fig. 2(b) for peak III as an example and all the vibrational modes in Fig. S3a in the SM. When $n \geq 2$, the additional Bi$_2$Te$_3$ layer either introduces a new peak or shifts the existing peaks (Fig. S3b in the SM). For example, the main contribution to the $E_g$ mode of Peak III in MnBi$_2$Te$_4$ comes from the vibrations of the top and the bottom Bi-Te atomic layers, similar to that of Bi$_2$Te$_3$. Therefore, the additional Bi$_2$Te$_3$ layer simply shifts the peak position, instead of creating a new mode.
In Peak II, the Bi$_2$Te$_3$ layer generates a new peak when it oscillates out-of-plane (A$_{1g}$) while the MnBi$_2$Te$_4$ layer remains almost static (calculated frequency of 58.8 cm$^{-1}$ in Fig. S3b, SM). This peak position overlaps with the $E_g$ vibration of MnBi$_2$Te$_4$ where the Bi$_2$Te$_3$ layer stays static (calculated frequency of 68.9 cm$^{-1}$ in Fig. S3b, SM). Therefore, Peak II with $E_g$ symmetry in the pure MnBi$_2$Te$_4$ bulk develops into two mixed peaks in the MnBi$_2$Te$_4$/Bi$_2$Te$_3$ heterostructure, i.e., one peak still with $E_g$ symmetry with the vibrating MnBi$_2$Te$_4$ layer, and the other one with $A_{1g}$ symmetry with the vibrating Bi$_2$Te$_3$ layer.

We use a circular polarization configuration to experimentally confirm the symmetries. In Fig. 2(b), the spectrum, measured in $\sigma^+ - \sigma^-$ circular polarization, shows only the $E$ modes. We observe that Peak II in MnBi$_2$Te$_4$ redshifts with increasing $n$. The decreased intensity is due to the reduced number of vibration entities in the unit area, owing to the static Bi$_2$Te$_3$ layers in the vibration patterns of Peak II. The dominating intensity around 60 cm$^{-1}$ above $n = 2$ in Fig. 2(a) is from the $A_{1g}$ mode of Bi$_2$Te$_3$, which is absent in MnBi$_2$Te$_4$, as expected from our theory. Polarization measurements in the parallel, cross, and $\sigma^+ - \sigma^-$ polarization configurations are shown in Fig. S4 in the SM, to further differentiate these two mixed peaks. The evolution of the peak positions and the widths with $n$ is presented in Figs. 2(c) and 2(d), respectively. The exact Raman peak positions from the experiment and the theory are given in the Table S1, SM. To observe the evolution of the peak II (orange dashed line), we fit the $E_g$ mode with Lorentzian in Fig. 2(b), where the $A_{1g}$ mode from the Bi$_2$Te$_3$ layer is suppressed. The orange solid line represents the $A_{1g}$ mode from the Bi$_2$Te$_3$. As expected, the peaks get closer to that of Bi$_2$Te$_3$ with increasing $n$. In this measurement, we observe a Davydov splitting of Peak V on MnBi$_4$Te$_7$ (blue dashed line, $n = 2$), which will be discussed further in Fig. 4.

To understand the effect of magnetic ordering on Raman spectrum of MnBi$_2$Te$_4$, we examine the temperature-dependent spectra from 294 to 5 K. Figure 3(a) shows no new peaks below the Néel temperature, indicating that the magnetic ordering does not significantly change the vibrational modes. Figure 3(b) displays the Raman peak shifts of Peak II ($E_g$), IV ($A_{2g}$) and V ($A_{3g}$), relative to those at room temperature. The rest can be found in the SM, Fig. S5. The peak shifts follow the general temperature-dependent anharmonicity model based on phonon decays into different number of phonons [40], i.e., monotonic blueshift down to ~40 K, followed by almost constant peak positions at lower temperatures. This model describes our experimental data well, represented by solid lines. In the same model, we would expect the widths of the Raman peaks to get narrower at lower temperatures, as observed in Peaks I, III, and V [e.g., Fig. 3(d) for Peak V and Fig. S5 in the SM for Peaks I and III] [40]. Interestingly, we find that Peaks II and IV behave differently. Peak IV widens by ~20% at low temperatures, as in Fig. 3(d), green scatter points. Peak II becomes broader below 20 K, while the width barely changes above 20 K, as shown in Fig. 3(e). The abnormal change of Peak II and IV is also demonstrated in thin samples. On 10-nm thickness MnBi$_2$Te$_4$ flake, the width of the Peak IV widens by ~16% at 7 K and Peak II remains unchanged within experimental uncertainties, as opposed to other peaks that become more than 20% narrower, as shown in Fig. S6 in the SM. This abnormal behavior is discordant with the anharmonicity model. For Peaks I, III, and V, the main contribution comes from the vibrations of the top and the bottom Bi-Te chains, not directly bonded to Mn atoms [Fig. 3(c), right panel, and Fig. S3a]. Conversely, the main contribution to Peaks II and IV comes from the vibrations of the Te atoms that are directly neighboring with Mn atoms [left two panels in Fig. 3(c)]. Therefore, below the $T_N$, the spin-phonon coupling would be more pronounced in Peaks II and IV, matching our measurements. We further confirmed the AFM ordering with DC magnetic susceptibility measurement, as shown in Fig. 3(e), right axis. The magnetic susceptibility peaks at 23.3 K, which is a signature of AFM. We do not expect the order-parameter-like temperature dependence here, because the net magnetization is close to zero in the ordered AFM phase. Hence, we attribute the observed broadening of the peaks, and therefore decreased phonon lifetime, to the spin-phonon coupling [27,41,42]. The temperature from which the Raman peak broadens is slightly lower than the $T_N$. This is because the change in the width is too small near the $T_N$.

FIG. 2. Effects of Bi$_2$Te$_3$ intercalation on Raman spectra of MnBi$_2$Te$_{n+1}$ topological heterostructures. (a), (b) Raman spectra measured at room temperature in linear polarization configuration without an analyzer and with circularly polarized light $\{\sigma^+ - \sigma^-\}z\}$, respectively. Inset shows example of in-plane vibration of structure corresponding to peak III. (c), (d) Evolution of Raman peaks positions and widths, respectively. Light horizontal lines indicate peak positions and widths of bulk Bi$_2$Te$_3$ measured at the same temperature.
FIG. 3. Temperature dependences and intralayer spin-phonon coupling of antiferromagnetic MnBi$_2$Te$_4$ topological insulator. (a) Raman spectra measured in temperatures ranging from 5 to 294 K. Peaks marked with * are from laser. (b) Change in Raman peak positions of II($E_{2g}^1$), IV($A_{2g}^1$), and V($A_{3g}^1$), relative to those measured at room temperature. Solid lines represent fitting based on anharmonicity model. (c) Vibrational patterns of the II, IV, and V modes. (d) Widths of peak V($A_{3g}^1$) and peak IV($A_{2g}^1$), obtained from Lorentzian fits. Blue solid line is fit with anharmonicity model. (e) Temperature dependent Raman linewidth of Peak II (red scatter points, left axis) and magnetic susceptibility of bulk MnBi$_2$Te$_4$ (black solid line, right axis). The shaded area in (b), (c), and (e) indicates the experimental errors.

and falls within the experimental uncertainties. In MnBi$_4$Te$_7$, we also observed a broader width of Peak IV (Fig. S7 in the SM), but could not isolate the $E_g$ mode from the MnBi$_2$Te$_4$ vibration due to dominating $A_{1g}$ mode from the Bi$_2$Te$_3$ layer near the same frequency.

When a Bi$_2$Te$_3$ layer forms a heterostructure with MnBi$_4$Te$_7$, it not only introduces an additional mode from Bi$_2$Te$_3$, e.g. $A_{1g}$ mode at 60 cm$^{-1}$, but also perturbs an intralayer vibration mode in bulk MnBi$_2$Te$_4$ and splits a peak, known as Davydov splitting [43], as presented in Fig. 4. Davydov splitting has been observed in other layered materials, such as MoSe$_2$ [44] and MoTe$_2$ [45]. Figure 4(a) shows the zoomed-in temperature-dependent spectra near Peak V, 135 cm$^{-1}$. The full spectrum can be found in the SM, Fig. S7. At room temperature, the large linewidths make the splitting less distinct. The narrower linewidths at cryogenic temperatures reveal Davydov splitting and the shoulder clearly. Figure 4(b) summarizes the central frequencies of these two peaks are related as $\omega_2^{1} = \omega_0^{1} + \omega_{LB}^{1}$ where $\omega_0^{1}$ is the original $A_{1g}$ peak (136.6 cm$^{-1}$; experiment at 5 K) and $\omega_1^{1}$ is its Davydov pair (140.2 cm$^{-1}$; experiment at 5 K) [46,47]. $\omega_{LB}^{1}$ is the frequency of layer breathing (LB) mode. From this expression, we experimentally find that $\omega_{LB}^{1}$ is 31.7 $\pm$ 0.6 cm$^{-1}$ at 5 K and 33.7 $\pm$ 2.5 cm$^{-1}$ at 297 K. Theoretically, we estimate the $\omega_{LB}^{1}$ ($A_{2u}$ mode; Raman inactive) to be 22.48 cm$^{-1}$ which deviates from our measurements due to the overestimated peaks from the DFT calculations. Using the linear chain model [45,46,48], we can estimate the out-of-plane interlayer force constant ($K^\perp$) using $\omega_{LB}^{1} = (1/\pi c)\sqrt{K^\perp/\mu}$; $c$ is the speed of light and $\mu$ is the effective mass per unit area. The estimated interlayer $K^\perp$ in MnBi$_4$Te$_7$ thus ranges from (3.98 $\pm$ 0.14) x 10$^{10}$ N/m$^2$ to (4.48 $\pm$ 0.66) x 10$^{10}$ N/m$^2$ between 5 K and room temperature, which is about a third of the value in Bi$_2$Te$_3$ [46]. In MnBi$_6$Te$_{10}$ and MnBi$_8$Te$_{13}$, it is difficult to observe such
MnBi$_4$Te$_7$, focusing on Peak V centered at 135 cm$^{-1}$. Two Lorentzian
MnBi$_2$Te$_4$, the anomalous broadening of the 66 cm$^{-1}$ peak
change in vibrational modes between MnBi$_2$Te$_4$ and MnBi$_4$Te$_7$
provides us the best contrast in the Raman phonon spectra
a splitting at this excitation wavelength because dominating
Bi$_2$Te$_3$ vibrational modes obscure the Davydov splitting.
In summary, we examined the phonon dynamics of the
layered MnBi$_n$Te$_{3n+1}$ magnetic topological insulator using polarized low-frequency Raman spectroscopy at cryogenic temperatures supported by first-principles DFT calculations of the phonon modes. Comparison of MnBi$_2$Te$_4$ and MnBi$_4$Te$_7$ provides us the best contrast in the Raman phonon spectra due to a newly introduced Bi$_2$Te$_3$ layer. From MnBi$_2$Te$_4$ to MnBi$_4$Te$_7$, the phonon spectrum changes more gradually. In MnBi$_2$Te$_4$, the anomalous broadening of the 66 cm$^{-1}$ peak is observed below the Néel temperature, the origin of which is explained by the intralayer spin-phonon coupling. When a Bi$_2$Te$_3$ layer is inserted between two MnBi$_2$Te$_4$ layers, an out-of-plane vibrational mode from Bi$_2$Te$_3$ dominates Peak II. We also observed and quantified the Davydov splitting of $A_{1g}$ mode at 136.6 cm$^{-1}$, arising from interlayer interactions between Bi$_2$Te$_3$ and MnBi$_2$Te$_4$. The estimated out-of-plane interlayer force constant is between (3.98 ± 0.14) to (4.48 ± 0.66) × 10$^{10}$ N/m$^2$, at 5 and 294 K, respectively, which is weaker than that of Bi$_2$Te$_3$ by a factor of 3. Our studies deepen the understanding of the phonon modes and layer interactions in the Mn Bi$_2$Te$_4$ magnetic topological insulator family, including circularly polarized excitations, anharmonic shifts and broadening, spin-phonon coupling, and Davydov splitting. It unveils the role of the intercalated Mn-Te bilayers in Bi$_2$Te$_3$ and supports the control of the physical processes in heterogeneous magnetic topological insulators.

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Y. C. designed and led the study of the Raman experiment on Mn Bi$_2$Te$_{3n+1}$ ($n = 1, 2, 3, 4$) including the measurements at low temperatures and building the low-frequency Raman setup. J.H.K. and M.T. performed the Raman experiments and obtained optical images. Y.C., J.H.K., and C.W.W. analyzed the experimental data. A.A.P., Y.C., S.G., F.K., A.A.B. measured preliminary Raman spectra at Oak Ridge National Laboratory (A.A.P. and Y.C.) and University of California, Riverside (S.G., F.K., A.A.B.). L.L., X. K. performed the DFT calculations to support the experimental Raman data. C.H. and N.N. provided the bulk single crystals used in this study. Y.C., J.H.K., L.L., A.A.P. and C.W.W. prepared the manuscripts. C.W.W. led and supported this research. All authors discussed the results.

The authors declare no competing interests.

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