Topological phase transition controlled by electric field in two-dimensional ferromagnetic semiconductors

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To tune topological and magnetic properties of systems with band engineering by applying an electric field is of vital important both in physics and in practical applications. In this work, we find a topological phase transition from topologically trivial to nontrivial states at an external electric field of about 0.1 V/Å in ferromagnetic semiconductor MnBi2Te4 monolayer. It is shown that when electric field increases from 0 to 0.15 V/Å, the magnetic anisotropy energy (MAE) increases from 0.1 meV to about 5 meV, and the Curie temperature Tc increases from 20 to about 70 K. The increased MAE mainly comes from the enhanced spin-orbit coupling due to the applied electric field. The enhanced Tc can be understood from the enhanced p-d hybridization and decreased energy difference between p orbitals of Te atoms and d orbitals of Mn atoms. Moreover, we propose two novel Janus materials MnBi2S2Te2 and MnBi2S2Te2 monolayers with different internal electric polarizations, which can realize quantum anomalous Hall effect (QAHE) with Chern numbers C=1 and C=2, respectively. Our study not only exposes the electric field induced exotic properties of MnBi2Te4 monolayer, but also proposes novel materials to realize QAHE in ferromagnetic Janus semiconductors with electric polarization.

Introduction—Quantum anomalous Hall effect (QAHE) as a novel topological phase has attracted tremendous interest because of its potential applications in dissipationless spintronics [1–15]. The QAHE was firstly realized experimentally in Cr-doped (Bi, Sb)2Te3 thin film at 30 mK [6] and later in Cr-doped (Bi, Sb)2Te3 films at about 2 K [8]. Then, the QAHE was observed in V-doped (Bi, Sb)2Te3 thin film at 25 mK [9] and a Cr- and V-codoped (Bi, Sb)2Te3 system at about 300 mK [12]. In doped magnetic topological insulators, magnetic disorder is against to the observation of QAHE at higher temperatures. Thus, search for systems with stable QAHE at high temperatures is essential.

MnBi2Te4 as a new platform to realize QAHE has gained extensive studies both in theory and in experiments. MnBi2Te4 is composed of septuple TeBiTeMnTeBiTe sequences, and exhibits a van der Waals layered structure [16]. Bulk MnBi2Te4 is an antiferromagnetic insulator with the Neel temperature of 25 K [17, 18], which presents the axion state with quantized magnetoelectric effect [19]. Topological surface states with diminished gap forming a characteristic Dirac cone attributed to multidomains of different magnetization orientations were observed in antiferromagnetic topological insulator MnBi2Te4 [20]. (Bi2Te3)n(MnBi2Te4) with n=1 exhibits magnetic topological insulator with a strong out-of-plane ferromagnetic component at low temperatures and intrinsic net magnetization [21]. MnBi2Te4 monolayer is a topologically trivial ferromagnetic semiconductor [22–24], while its multilayers host the states alternating between QAH and zero plateau QAH for odd and even number of monolayers, respectively [24]. In a five-septuple-layer MnBi2Te4, the QAHE was observed at 1.4 K, and the quantization temperature can be raised up to 6.5 K by an external magnetic field to align all layers ferromagnetically [25]. High-Chern-number QHE without Landau levels was obtained in ten-septuple-layer MnBi2Te4 under applied magnetic field and back gate voltages [26]. In six-septuple-layer MnBi2Te4, the axion insulator state occurs over a wide magnetic field range and at relatively high temperatures, while a moderate magnetic field can drive the axion insulator phase to a Chern insulator phase with QAHE [27].

Band engineering is a powerful technology and plays an essential role in the study of electronic properties of materials. Band engineering can optimize the properties of materials, which may lead to materials to have better performance in devices. There are several ways to tune the energy bands, such as by an electric field [28–43], strain [44–46], doping [47–50], vacancy [51–53], surface modification [47, 54] and so on. Tuning energy bands by an external electric field has some advantages: it does not change the properties of the material itself; the magnitude and direction of the external electric field can be arbitrarily controlled; applying the external electric field is feasible and easy to realize in experiments. Graphene is a two-dimensional (2D) material with a zero band gap that restricts its application in electronic devices. After applying a gate voltage, the inversion symmetry is broken and a nonzero band gap is opened [55–59]. The band engineering by external electric fields was also performed in MoS2 [60].

In this work, we study novel properties of MnBi2Te4 monolayer controlled by an electric field. With the increase of electric field, the band gap decreases and the band inversion with a topological phase transition oc-
curs at an electric field of about 0.1 V/Å, and the system then enters into a topological state. With the electric field ranging from 0 to 0.15 V/Å, the magnetic anisotropy energy (MAE) increases from 0.1 meV to about 5 meV, and the Curie temperature $T_C$ increases from 20 to about 70 K. The increased MAE mainly comes from the enhanced spin-orbit coupling (SOC) due to the applied electric field. By means of the super-exchange picture, the enhanced Te can be understood from the enhanced $p$-$d$ hybridization and decreased energy difference between $p$ orbitals of Te atoms and $d$ orbitals of Mn atoms. Inspired by the electric field induced topological phase transition, we propose 2D Janus materials $\text{MnBi}_2\text{Se}_2\text{Te}_2$ and $\text{MnBi}_2\text{S}_2\text{Te}_2$ with different internal electric polarizations, which can realize QAHE. Our findings not only reveal the electric field induced exotic properties of $\text{MnBi}_2\text{Te}_4$ monolayer, but also present a new idea to realize QAHE in novel ferromagnetic Janus materials with electric polarizations.

**Monolayer $\text{MnBi}_2\text{Te}_4$**—Monolayer $\text{MnBi}_2\text{Te}_4$ can be grown in a quintuple layer of $\text{Bi}_2\text{Te}_3$ and a bilayer of $\text{MnTe}$ with the molecular beam epitaxy method [61]. The crystal structure of monolayer $\text{MnBi}_2\text{Te}_4$ is shown in Fig 1. The space group is $P\overline{3}m1$ (No. 164) with an optimized lattice constant $a = 4.37$ Å. Monolayer $\text{MnBi}_2\text{Te}_4$ is a ferromagnetic semiconductor with out-of-plane magnetization, and its Curie temperature $T_C$ is about 20 K [23]. Our calculated results of monolayer $\text{MnBi}_2\text{Te}_4$ are consistent with previous studies [22, 23] [see Supplemental Materials (SM)]. The atom projected band structure of monolayer $\text{MnBi}_2\text{Te}_4$ without electric field was plotted in Fig. 2(a), from which one can observe that the bottom of conduction band of monolayer $\text{MnBi}_2\text{Te}_4$ is mainly attributed to Bi-1 and Bi-2 atoms, while the main contribution to the top of valence bands is from Te-4 and Te-1 atoms. One may notice that the bands from Bi-1 and Bi-2 as well as Te-1 and Te-4 atoms are degenerate at $\Gamma$ point, because of the existence of inversion symmetry in monolayer $\text{MnBi}_2\text{Te}_4$.

**Monolayer $\text{MnBi}_2\text{Te}_4$ under an electric field**—By applying an electric field $E$ normal to the atoms plane, we can tune the properties of monolayer $\text{MnBi}_2\text{Te}_4$. The effect of electric field on the properties of monolayer $\text{MnBi}_2\text{Te}_4$ is summarized in Table S1. There are three main changes of the properties of monolayer $\text{MnBi}_2\text{Te}_4$ with increasing the electric field, including the changes of band gap, magnetic anisotropy and exchange integral.

**Evolution of band gap under an electric field**—The band structure of monolayer $\text{MnBi}_2\text{Te}_4$ varies with increasing the electric field without a big deformation of profiles but with a remarkable change of the band gap as shown in Fig. 2. The evolution of the band gap at $\Gamma$ point with the electric field was schematically plotted in Fig. 1 (c). The direct band gap at $\Gamma$ point [Fig. 2(e)] as well as the global band gap increases with increasing the electric field lower than 0.1 V/Å. This is intuitive,
because on one hand, the electric field E breaks the inversion symmetry of monolayer MnBi$_2$Te$_4$ resulting in the degeneracy broken of Bi-1 and Bi-2, Te-1 and Te-4 atoms at Γ point, respectively, and on the other hand, the effect of electric field on the upper triple Te-Bi-Te layers consisting of Te-1, Bi-1, and Te-2 atoms is equivalent to electron doping, while for the lower triple Te-Bi-Te layers consisting of Te-3, Bi-2, and Te-4 atoms it corresponds to hole doping. Thus, for the cation Bi-1, its energy level moves downward close to Fermi level, while for anion Te-4, its energy level moves upward close to Fermi level. This analysis is also verified by our DFT results as shown in Fig. 2. Therefore, the energy levels of Bi-1 and Te-4 atoms should be touched at a proper electric field, which is about 0.1 V/Å in our calculations. When the electric field continues to increase to 0.11 V/Å, an inversion occurs with E=0.15 V/Å near Fermi level as shown in Fig. 2(f).

*Figure 2.* In-plane magnetic anisotropy of MnBi$_2$Te$_4$ monolayer as a function of electric field. (a) the hopping matrix element between p orbitals of Te and d orbitals of Mn, and (b) the energy difference between them. By using maximally localized Wannier orbital projections, the energy difference per MnBi$_2$Te$_4$ formula unit between FM$^i$ and FM$^j$ configurations.

The schematic diagram of the micromechanism of enhanced Curie temperature under electric field.

Curie temperature under an electric field—The exchange integral $J$ shares the similar dependence on the electric field, i.e. the exchange integral increases with the increase of E as shown in Fig. 4(a). The increase of exchange integral $J$ can be interpreted by the superexchange interaction [62–64], where the FM coupling is expected since the Mn-Te-Mn bond angle is close to 90°. The indirect FM coupling between Mn atoms is proportional to the direct AFM coupling between neighboring Mn and Te atoms. The magnitude of this indirect AFM coupling can be roughly estimated as $J_{pd} = |V_{pd}|^2/|E_p - E_d|$, where $|V_{pd}|$ is the hopping matrix element between $p$ orbitals of Te and $d$ orbitals of Mn, and $|E_p - E_d|$ is the energy difference between them. By using maximally localized Wannier orbital projections, the

### Figure 3

Electric field enhanced spin-orbit coupling. The (a) electric field and (b) SOC strength dependent MAE, where MAE$_{ij}$ ($i \neq j = x, y, z$) means the energy difference per MnBi$_2$Te$_4$ formula unit between FM$^i$ and FM$^j$ configurations. The (c) electric field and (d) SOC strength dependent gap difference between the gaps with and without SOC.
dominant hopping matrix elements $|V_{pd}|$ and their corresponding energy differences $|E_p - E_d|$ can be obtained for monolayer MnBi$_2$Te$_4$ without E and with E=0.15V/A, respectively, as listed in Table S2. The enhanced direct AFM coupling with increasing the electric field comes from the enhanced $p$-$d$ hybridization owing to the increase of hopping and the decrease of energy difference between $p$ orbitals of Te and $d$ orbitals of Mn. It can be understood from that the energy levels of Mn atoms are relatively deep in MnBi$_2$Te$_4$, and the electric field drives the energy levels of the upper and lower Te layers near Mn layer to move downward, resulting in the decrease of the energy level difference and the enhancement of the overlaps between $p$ orbitals of Te and $d$ orbitals of Mn atoms as schematically depicted in Fig. 4(c).

The calculated Curie temperature based the isotropic Heisenberg model with the single ion anisotropy (SIA) using Monte Carlo (MC) simulation was listed in Table S1. It can be seen that for MnBi$_2$Te$_4$ with E=0.15 V/A the Curie temperature is three times greater than that without E as shown in Fig. 4(b).

**Novel monolayers MnBi$_2$Se$_2$Te$_2$ and MnBi$_2$S$_2$Te$_2$ for QAHE**—Inspired by the above study, where an electric field can tune the energy band and induce a topological phase transition in MnBi$_2$Te$_4$ monolayer, we propose a 2D Janus structure MnBi$_2$Se$_2$Te$_2$ monolayer based on MnBi$_2$Te$_4$ monolayer. Janus MnBi$_2$Se$_2$Te$_2$ monolayer can be obtained by substituting the upper triple Te-Bi-Te layers of MnBi$_2$Te$_4$ monolayer with a triple Se-Bi-Se layers. The stability of MnBi$_2$S$_2$Te$_2$ monolayer was checked by its phonon spectra, molecular dynamic simulation and formation energy. Because of different electronegativity of Se and Te, MnBi$_2$Se$_2$Te$_2$ monolayer possesses the spontaneous electric polarization of about 0.44 eÅ. MnBi$_2$Se$_2$Te$_2$ monolayer exhibits a ferromagnetic ground state with the out-of-plane magnetization, and its Curie temperature is estimated to be 25 K. The band structure of MnBi$_2$Se$_2$Te$_2$ monolayer shows a tiny full band gap of about 16 meV as shown in Fig. 5(a). The calculation on anomalous Hall conductivity shows a plateau at the Fermi level, which corresponds to a Chern number $C=1$, indicating QAHE state as shown in Fig. 5(b). As discussed above for MnBi$_2$Te$_4$ monolayer, when the system turns into the topological phase, the energy gap increases first and then decreases, and the Curie temperature keeps increasing with the increase of electric field. This is verified again in MnBi$_2$Se$_2$Te$_2$ monolayer, where the electric field enhances Curie temperature and changes the band gap as shown in Fig. 5(c).

For Janus material MnBi$_2$S$_2$Te$_2$ monolayer, its spontaneous electric polarization is about 0.73 eÅ, which is larger than that for MnBi$_2$Se$_2$Te$_2$ monolayer, thus a larger band gap and higher Curie temperature are expected in MnBi$_2$S$_2$Te$_2$ monolayer according to the above discussion. MnBi$_2$S$_2$Te$_2$ monolayer holds ferromagnetic ground state with out-of-plane magnetization, and its Curie temperature is estimated to be 48 K. MnBi$_2$S$_2$Te$_2$ monolayer has a global band gap of about 50 meV as shown in Fig. 5(d). The topologically nontrivial band structure of MnBi$_2$S$_2$Te$_2$ monolayer is characterized by a nonzero Chern number $C=2$ with a quantized charge Hall plateau of $2e^2/h$ and two gapless chiral edge states connecting the valence and conduction bands as shown in Figs. 5(e) and (f), respectively.

**Summary**—In this work, we systematically investigate the properties of monolayer MnBi$_2$Te$_4$ under electric
field. It is found that the electric field can induce a topological phase transition from a topologically trivial state to a nontrivial state. It is also observed that the MAE and Tc of MnBi\textsubscript{2}Te\textsubscript{4} monolayer are dramatically enhanced with the increase of electric field. The increased MAE and Tc of MnBi\textsubscript{2}Te\textsubscript{4} are mainly due to the enhanced SOC due to the enhanced hybridization and decreased energy difference between p orbitals of Te atoms and d orbitals of Mn atoms. In addition, we propose novel Janus monolayers MnBi\textsubscript{2}Se\textsubscript{2}Te\textsubscript{2} and MnBi\textsubscript{2}S\textsubscript{2}Te\textsubscript{2} with different spontaneous electric polarizations, which can realize the QAHE with Chern numbers C=1 and C=2, respectively. Our results will spur more studies on novel properties of MnBi\textsubscript{2}Te\textsubscript{4} monolayer under an electric field, and also provide new candidates to realize QAHE in ferromagnetic semiconductors with electric polarization that would be particularly interesting in electrically controlled spintronic devices.

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[1] F. D. M. Haldane, Phys. Rev. Lett. 61, 2015 (1988).
[2] M. Onoda and N. Nagaosa, Phys. Rev. Lett. 90, 206601 (2003).
[3] C.-X. Liu, X.-L. Qi, X. Dai, Z. Fang, and S.-C. Zhang, Phys. Rev. Lett. 101, 146802 (2008).
[4] C. Wu, Phys. Rev. Lett. 101, 186807 (2008).
[5] R. Yu, W. Zhang, H.-J. Zhang, S.-C. Zhang, X. Dai, and Z. Fang, Science 329, 61 (2010).
[6] C.-Z. Chang, J. Zhang, X. Feng, J. Shen, Z. Zhang, M. Guo, K. Li, Y. Ou, P. Wei, L.-L. Wang, Z.-Q. Ji, Y. Feng, S. Ji, X. Chen, J. Jia, X. Dai, Z. Fang, S.-C. Zhang, K. He, Y. Wang, L. Lu, X.-C. Ma, and Q.-K. Xue, Science 340, 167 (2013).
[7] J. Wu, J. Liu, and X.-J. Liu, Phys. Rev. Lett. 113, 136403 (2014).
[8] M. Mogi, R. Yoshimi, A. Tsukazaki, K. Yasuda, Y. Kozuka, K. S. Takahashi, M. Kawasaki, and Y. Tokura, Appl. Phys. Lett. 107, 182401 (2015).
[9] C.-Z. Chang, W. Zhao, D. Y. Kim, H. Zhang, B. A. Assaf, D. Heiman, S.-C. Zhang, C. Liu, M. H. W. Chan, and J. S. Moodera, Nat. Mater. 14, 473 (2015).
[10] C.-X. Liu, S.-C. Zhang, and X.-L. Qi, Annu. Rev. Condens. Matter Phys. 7, 301 (2016).
[11] L. Si, O. Janson, G. Li, Z. Zhong, Z. Liao, G. Koster, and K. Held, Phys. Rev. Lett. 119, 026402 (2017).
[12] Y. Ou, C. Liu, G. Jiang, Y. Feng, D. Zhao, W. Wu, X.-X. Wang, W. Li, C. Song, L.-L. Wang, W. Wang, W. Wu, Y. Wang, K. He, X.-C. Ma, and Q.-K. Xue, Adv. Mater. 30, 1703062 (2017).
[13] K. He, Y. Wang, and Q.-K. Xue, Annu. Rev. Condens. Matter Phys. 9, 329 (2018).
[14] J.-Y. You, Z. Zhang, B. Gu, and G. Su, Phys. Rev. Appl 12, 024063 (2019).
[15] Y. Li, J. Li, Y. Li, M. Ye, F. Zheng, Z. Zhang, J. Fu, W. Duan, and Y. Xu, Phys. Rev. Lett. 125, 086401 (2020).
[16] D. S. Lee, T.-H. Kim, C.-Y. Chung, Y. S. Lim, W.-S. Seo, and H.-H. Park, CrystEngComm 15, 5532 (2013).
[17] J. Cui, M. Shi, H. Wang, F. Yu, T. Wu, X. Luo, J. Ying, and X. Chen, Phys. Rev. B 99, 155125 (2019).
[18] H. Li, S. Liu, C. Liu, J. Zhang, Y. Xu, R. Yu, Y. Wu, Y. Zhang, and S. Fan, Phys. Chem. Chem. Phys. 22, 556 (2020).
[19] D. Zhang, M. Shi, T. Zhu, D. Xing, H. Zhang, and J. Wang, Phys. Rev. Lett. 122, 206401 (2019).
[20] Y. J. Chen, L. X. Xu, J. H. Li, Y. W. Li, H. Y. Wang, C. F. Zhang, H. Li, Y. Wu, A. J. Liang, C. Chen, S.W. Jung, C. Cacho, Y.H. Mao, S. Liu, M.X. Wang, Y.F. Guo, Y. Xu, Z.K. Liu, L.X. Yang, and Y.L. Chen, Phys. Rev. X 9, 041040 (2019).
[21] R. C. Vidal, A. Zeugner, J. I. Facio, R. Ray, M. H. Haghhi, A. U. B. Wolter, L. T. CorredorBohorquez, F. Cuglieris, S. Moser, T. Figge metier, T. R. F. Peixoto, H. B. Vasili, M. Valvidares, S. Jung, C. Cacho, A. Alfonso, K. Mehalwat, V. Kataev, C. Hess, M. Richter, B. Böchner, J. van den Brink, M. Ruck, F. Reiners, H. Bentmann, and A. Isaeva, Phys. Rev. X 9, 041065 (2019).
[22] J. Li, Y. Li, S. Du, Z. Wang, B.-L. Gu, S.-C. Zhang, K. He, W. Duan, and Y. Xu, Sci. Adv. 5, eaaw5685 (2019).
[23] Y. Li, Z. Jiang, J. Li, S. Xu, and W. Duan, Phys. Rev. B 100, 134438 (2019).
[24] M. M. Otrokov, I. P. Rusinov, M. Blan co-Rey, M. Hoffmann, A. Y. Vyazovskaya, S. V. Eremeev, A. Ernst, P. M. Echenique, A. Arnau, and E. V. Chulkov, Phys. Rev. Lett. 122, 107202 (2019).
[25] Y. Deng, Y. Yu, M. Z. Shi, Z. Guo, Z. Xu, J. Wang, X. H. Chen, and Y. Zhang, Science 367, 895 (2020).
[26] J. Ge, Y. Liu, J. Li, H. Li, T. Luo, Y. Wu, Y. Xu, and J. Wang, Natl. Sci. Rev. 7, 1280 (2020).
[27] C. Liu, Y. Wang, H. Li, Y. Wu, Y. Li, J. Li, K. He, Y. Xu, J. Zhang, and Y. Wang, Nat. Mater. 19, 522 (2020).
[28] M. Weisheit, S. Fähler, A. Marty, Y. Souché, C. Poinsignon, and D. Givord, Science 315, 349 (2007).
[29] Y. Sata, R. Moriya, S. Morikawa, N. Yabuki, S. Masubuchi, and T. Machida, Appl. Phys. Lett. 107, 023109 (2015).
Q. Liu, X. Zhang, L. B. Abdalla, A. Fazzio, and A. Zunger, Nano Lett. 15, 1222 (2015).
T. Chu and Z. Chen, Nano Res. 8, 3228 (2015).
J. Deng, Z. Chang, T. Zhao, X. Ding, J. Sun, and J. Z. Liu, J. Am. Chem. Soc. 138, 4772 (2016).
F. Liu, J. Zhou, C. Zhu, and Z. Liu, Adv. Funct. Mater. 27, 1602404 (2016).
A. Dankert and S. P. Dash, Nat. Commun. 8, 16093 (2017).
W. Xing, Y. Chen, P. M. Odenthal, X. Zhang, W. Yuan, T. Su, Q. Song, T. Wang, J. Zhong, S. Jia, X. C. Xie, Y. Li, and W. Han, 2D Mater. 4, 024009 (2017).
Y. Deng, Y. Yu, Y. Song, J. Zhang, N. Z. Wang, Z. Sun, Y. Yi, Y. Z. Wu, S. Wu, J. Zhu, J. Wang, X. H. Chen, and Y. Zhang, Nature 563, 94 (2018).
B. Huang, G. Clark, D. R. Klein, D. MacNeill, E. Navarro-Moratalla, K. L. Seyler, N. Wilson, M. A. McGuire, D. H. Cobden, D. Xiao, W. Yao, P. Jarillo-Herrero, and X. Xu, Nat. Nanotechnol. 13, 544 (2018).
S. Jiang, L. Li, Z. Wang, K. F. Mak, and J. Shan, Nat. Nanotechnol. 13, 549 (2018).
X.-B. Xiao, Q. Ye, Z.-F. Liu, Q.-P. Wu, Y. Li, and G.-P. Ai, Nanoscale Res. Lett. 14, 322 (2019).
S. Du, P. Tang, J. Li, Z. Lin, Y. Xu, W. Duan, and A. Rubio, Phys. Rev. Research 2, 022025 (2020).
S. I. Vishkayi, Z. Torbatian, A. Qaimzadeh, and R. Asgari, Phys. Rev. Materials 4, 094004 (2020).
C. Xu, P. Chen, H. Tan, Y. Yang, H. Xiang, and L. Bellaiche, Phys. Rev. Lett. 125, 037203 (2020).
Z. Wu and J. Hao, npj 2D Mater. Appl. 4, 4 (2020).
Z. H. Ni, T. Yu, H. H. Lu, Y. Y. Wang, Y. P. Feng, and Z. X. Shen, ACS Nano 2, 2301 (2008).
X. C. Liu, H. W. Zhang, and K. Lu, Science 342, 337 (2013).
X.-J. Dong, J.-Y. You, B. Gu, and G. Su, Phys. Rev. Appl 12, 014020 (2019).
D. M. Sim, M. Kim, S. Yim, M.-J. Choi, J. Choi, S. Yoo, and Y. S. Jung, ACS Nano 9, 12115 (2015).
J.-Y. You, B. Gu, and G. Su, Sci. Rep. 9, 20116 (2019).
T. Ahmed, N. A. Modine, and J.-X. Zhu, Appl. Phys. Lett. 107, 043903 (2015).
J.-Y. You, B. Gu, and G. Su, Phys. Rev. B 101, 184521 (2020).
Z. Chen, B. Ge, W. Li, S. Lin, J. Shen, Y. Chang, R. Hanus, G. J. Snyder, and Y. Pei, Nat. Commun. 8, 13828 (2017).
Y. Liu, C. Ma, Q. Zhang, W. Wang, P. Pan, L. Gu, D. Xu, J. Bao, and Z. Dai, Adv. Mater. 31, 1900062 (2019).
F. Hou, Q. Yao, C.-S. Zhou, X.-M. Ma, M. Han, Y.-J. Hao, X. Wu, Y. Zhang, H. Sun, C. Liu, Y. Zhao, Q. Liu, and J. Lin, ACS Nano (2020), 10.1021/acsnano.0c03149.
S. K. Nemani, R. K. Annavarapu, B. Mohammadian, A. Raiyan, J. Heil, M. A. Haque, A. Abdelaal, and H. Soudjoudi, Adv. Mater. Interfaces 5, 1801247 (2018).
T. Ohta, A. Bostwick, T. Seyller, K. Horn, and E. Rotenberg, Science 313, 951 (2006).
H. Min, B. Sahu, S. K. Banerjee, and A. H. MacDonald, Phys. Rev. B 75, 155115 (2007).
Y. Zhang, T.-T. Tang, C. Girit, Z. Hao, M. C. Martin, A. Zettl, M. F. Crommie, Y. R. Shen, and F. Wang, Nature 459, 820 (2009).
K. F. Mak, C. H. Lui, J. Shan, and T. F. Heinz, Phys. Rev. Lett. 102, 256405 (2009).
C. H. Lui, Z. Li, K. F. Mak, E. Cappelluti, and T. F. Heinz, Nat. Phys. 7, 944 (2011).
C.-P. Lu, G. Li, J. Mao, L.-M. Wang, and E. Y. Andrei, Nano Lett. 14, 4628 (2014).
Y. Gong, J. Guo, J. Li, K. Zhu, M. Liao, X. Liu, Q. Zhang, L. Gu, L. Tang, X. Feng, D. Zhang, W. Li, C. Song, L. Wang, P. Yu, X. Chen, Y. Wang, H. Yao, W. Duan, Y. Xu, S.-C. Zhang, X. Ma, Q.-K. Xue, and K. He, Chin. Phys. Lett. 36, 076801 (2019).
J. B. Goodenough, Phys. Rev. 100, 564 (1955).
P. W. Anderson, Phys. Rev. 115, 2 (1959).
J. Kanamori, J. Appl. Phys. 31, S14 (1960).