Evidence of the Ferroelectric Polarization in Charge Transport through WTe₂ Weyl Semimetal Surface

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We investigate electron transport along the surface of WTe₂ three-dimensional single crystals, which are characterized by the coexistence of the conductivity and ferroelectricity of a Weyl semimetal at room temperature. We find that a nonlinear behavior of the differential resistance \( \frac{dV}{dI} \) of WTe₂ is accompanied by a slow relaxation process, which appears as the \( \frac{dV}{dI} \) dependence on the sign of the current change. This observation is confirmed by direct investigation of time-dependent relaxation curves. While strongly nonlinear differential resistance should be expected for zero-gap WTe₂, the slow relaxation in transport is very unusual for well-conducting semimetals at room temperature. We establish that a nonmonotonic dependence of the amplitude of the effect on the driving current \( \frac{dV}{dI} \) well corresponds to the known Sawyer–Tower’s ferroelectric hysteresis loop. The possibility to induce polarization current by source-drain field variation is unique for WTe₂, since it is a direct consequence of the coexistence of ferroelectricity and metallic conduction. This conclusion is also confirmed by gate voltage dependencies, so our results can be understood as a direct demonstration of the ferroelectric behavior of WTe₂ in charge transport experiment.

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The layered transition metal dichalcogenides (TMDCs) are attracting significant research interest due to their extraordinary electronic and optical properties. For instance, band gap varies from indirect to direct one in single layers of MoS₂, MoSe₂, WS₂ and WSe₂, which allows different possible applications like transistors, photodetectors and electroluminescent devices [1–3]. The recent discovery of the memristor effect (or nonvolatile resistance switching) in monolayers TMDC structures has added a new field of fundamental and applied activities [4]. For MoS₂ monolayers, the effect is based on the gold adatom absorption at native vacancy defects [5].

WTe₂ is a special member among the TMDC family. It has been extensively studied [6–9] as realization of a Weyl semimetal with broken inversion symmetry for three-dimensional samples [10–12], while monolayer WTe₂ is known to be quantum spin Hall insulator [13, 14]. In ambient conditions WTe₂ is characterized by phase distorted 1T’ (Td) crystal structure in a wide temperature range [15–17], in contrast to typical TMDCs, where several (2H or 1T) phases can be observed [18]. At low temperatures, WTe₂ is characterized by extremely large unsaturated magnetoresistance [19] and even superconductivity [20] at high pressures.

Recently, three-dimensional WTe₂ single crystals were found to demonstrate coexistence of metallic conductivity and ferroelectricity at room temperature [21]. The latter usually belongs to the insulators [22–26], but it occurs in WTe₂ due to the strong anisotropy of the non-centrosymmetric crystal structure. The spontaneous polarization of ferroelectric domains is found to be bistable; it can be affected by high external electric field [21]. Scattering of the charge carriers on the domain walls is known to provide noticeable contribution to the sample resistance [27]. Thus, coexistence of metallic and ferroelectric properties should produce new physical effects [28] for electron transport in TMDCs, and, therefore, it should be important for nanoelectronic applications.

Here, we investigate electron transport along the surface of WTe₂ three-dimensional single crystals, which are characterized by the coexistence of Weyl semimetal conductivity and ferroelectricity at room temperature. We find that nonlinear behavior of \( \frac{dV}{dI} \) WTe₂ differential resistance is accompanied by slow relaxation process, which appears as the \( \frac{dV}{dI} \) dependence on the sign of the current change. This observation is confirmed by direct investigation of time-dependent relaxation curves. While strongly nonlinear differential resistance should be expected for the zero-gap WTe₂, the slow relaxation in transport is very unusual for well-conducting semimetals at room temperature. We establish that nonmonotonic dependence of the amplitude of the effect on
driving current $dV/dI(I)$ well corresponds to the known Sawyer–Tower’s ferroelectric hysteresis loop. The possibility to induce polarization current by source-drain field variation is unique for WTe$_2$, since it is a direct consequence of the coexistence of ferroelectricity and metallic conduction. This conclusion is also confirmed by gate voltage dependencies, so our results can be understood as a direct demonstration of WTe$_2$ ferroelectric behavior in charge transport experiment.

WTe$_2$ compound was synthesized from elements by reaction of metal with tellurium vapor in the sealed silica ampule. The WTe$_2$ crystals were grown by the two-stage iodine transport [29] that previously was successfully applied [29, 30] for growth of other metal chalcogenides like NbS$_2$ and CrNb$_3$S$_6$. The WTe$_2$ composition is verified by energy-dispersive X-ray spectroscopy. The X-ray diffraction confirms $Pmn_2_1$, orthorhombic single crystal WTe$_2$ with lattice parameters $a = 3.48750(10)$ Å, $b = 6.2672(2)$ Å, and $c = 14.0629(6)$ Å. We check by standard magnetoresistance measurements that our WTe$_2$ crystals demonstrate large, non-saturating positive magnetoresistance in normal magnetic field, which goes to zero in parallel one, as it has been shown for WTe$_2$ Weyl semimetal [19], see [8] for details of magnetoresistance measurements.

The single-crystal flakes of WTe$_2$ are obtained by regular mechanical exfoliation, also known as scotch-tape technique. Next, the exfoliated samples were transferred on the insulating SiO$_2$ substrate. While we need thick three-dimensional flakes to preserve WTe$_2$ semimetal properties, we use two different techniques for Ohmic contacts fabrication for the flakes of different thicknesses.

For the thinnest, 300–600 nm flakes, the Au leads are defined over the flake surface by standard photolithography and lift-off technique after thermal evaporation of 70 nm Au, see the AFM image in Fig. 1. As usual, thin flakes are about 10–30 μm in the lateral size, so only two or three Au leads can be placed over the flake to form Ohmic contacts with 5 μm distance (which should exceed the mean free path in WTe$_2$, $l_e = 1$ μm). These samples are mostly suitable for the two-point transport measurements.

The thicker (1–3 μm) flakes are about 100 μm in lateral size, which allows different multiple contact geometries. However, standard 70–100-nm-thick Au leads cannot be formed across the 1–3 μm step, so we use different contact technique. Thick flakes are transferred to SiO$_2$ substrate with pre-defined Au leads pattern, the flake is slightly pressed to the leads by another oxidized silicon substrate. Weak pressure is applied with a special metallic frame, which keeps the substrates strictly parallel. This procedure has been verified to provide electrically stable contacts with high quality interfaces [8, 9, 31, 32]. In addition, WTe$_2$ surface with Au contacts is protected from any contamination by SiO$_2$ substrate in this case.

Typical sample resistance is about 10–50 Ω. For correct measurement of low-resistance samples one have to directly define current $I$ and measure the resulting voltage drop $V$. For the two-point measurements (small flakes), one of the contacts is grounded, dc current varies within ±3 mA range at the neighbor contact (see Fig. 1). To obtain $dV/dI(I)$ curves, the dc current $I$ is additionally modulated by a small ac component (0.03 mA) at the 1600 Hz frequency. The ac voltage component is measured by lock-in, it is proportional to the differential resistance $dV/dI(I)$ at a given $I$ value. We verify that the obtained $dV/dI(I)$ curves are independent of the modulation frequency in the range 1–10 kHz, which is determined by the applied filters. For large flakes we use a standard four-point scheme with two separate potential probes.

These measurements can be carried out in external electric field by applying gate voltage to the silicon wafer, separated from the flake by 300 nm SiO$_2$ layer. The measurements are performed at room temperature for WTe$_2$ samples of different thicknesses and lateral sizes, since ferroelectric domains have been previously observed in WTe$_2$ semimetal at room temperature [21].

Figure 2 shows the examples of experimental $dV/dI(I)$ curves for the thinnest, 400 nm sample from Fig. 1. Differential resistance $dV/dI(I)$ is a maximum (42 Ω) at zero bias, it falls symmetrically at positive and negative currents by about 20% in a full current range. To our surprise, we observe small but noticeable hysteresis in the experimental $dV/dI$ with
current sweep direction, as demonstrated by red and blue curves. It is important that \( dV/dI \) curves coincide perfectly if they are obtained for the same sweep direction, see the inset to Fig. 2. Thus, WTe\(_2\) differential resistance is affected by the sign of the current change in the main field of Fig. 2.

The hysteresis is clearly not symmetric in Fig. 2, the maximum difference between the \( dV/dI \) curves is shifted to positive currents due to extremely low sweep rate (60 min for the full ±3 mA range). This well corresponds to the measurement procedure: the blue curve (current sweep from –3 mA to +3 mA) is obtained immediately after the red one (from +3 mA to –3 mA).

\( dV/dI \) curves are shown in Fig. 3a for higher sweep rate (20 min for the full ±3 mA range) for the same 400 nm sample. The hysteresis can be seen for both \( dV/dI \) branches, so it obviously depends on the sweep rate and reflects some slow relaxation process. Time-dependent relaxation curves \( dV/dI(t) \) for fixed currents \( I = (b) 0 \) and \( c) -2 mA \) obtained after keeping the sample for 10 min at two different dwelling currents ±3 mA. The relaxation curves \( dV/dI(t) \) are clearly different in these cases, so \( dV/dI \) depends on the sign of the current change.

For a single pair of the curves, the sample is kept at a fixed dwelling current (3 mA or –3 mA) for 10 min. Then, the current is abruptly set to the required value (e.g., \( I = 0 \) in (b)), and time dependence of \( dV/dI \) is traced immediately after that. As a result, we observe slow relaxation in \( dV/dI \), while there is clear difference between the curves for dwelling current ±3 mA (see Figs. 3b and 3c). Thus, there is time-dependent relaxation of \( dV/dI \) differential resistance, which depends on the sign of the current change. We can estimate relaxation time as about 300 s from the curves in Figs. 3b and 3c. This behavior well correlates with the hysteresis in \( dV/dI \) curves in Figs. 2 and 3a.

These results can be reproduced for samples of different thicknesses and lateral sizes, and, therefore, of different contact preparation techniques (see Fig. 4). \( dV/dI \) curves are shown in Fig. 4a for the 600-nm-thick sample, the Au leads are still evaporated over the WTe\(_2\) flake. The overall sample behavior is quite similar to one in Figs. 2 and 3a: \( dV/dI \) curves also depend on the current sweep direction, there is a well-defined difference between the \( dV/dI(t) \) relaxation curves at \( I = 0 \) for two dwelling currents ±3 mA, as depicted in the inset. Similar results can be obtained for the 3-μm-thick WTe\(_2\) flake, which is pressed to the pre-defined Au leads pattern (see Fig. 4b).

These effects are intrinsic to bulk WTe\(_2\), which can be confirmed by measurements in a standard four-point connection scheme, see the inset to Fig. 4b for the large-area 3-μm-thick WTe\(_2\) flake. In this case, the
Au–WTe₂ interfaces are excluded, which leads to much lower $dV/dI(I)$ values. Nevertheless, both the overall $dV/dI(I)$ shape and the dependence on the current sweep direction are well reproduced in the inset.

We can also study effect of the normal-to-the-plane electric field on $dV/dI(I)$ curves by using silicon substrate as a gate electrode. We check that for the 300-nm-thick SiO₂ flake, there is no gate leakage at least in the ±50 V range. Experimental $dV/dI(I)$ curves are shown for a single current sweep direction in Figs. 5a and 5b for two gate voltage polarities, respectively. Increasing the gate voltage value shifts $dV/dI(I)$ curves down irrespective of the gate voltage sign, so the level is in a maximum at zero gate voltage and falls symmetrically both to positive and negative gate voltage values, in contrast to the standard asymmetric accumulation/depletion field-effect transistor behavior.

The hysteresis amplitude can be demonstrated directly by subtracting two $dV/dI(I)$ curves for opposite current sweep directions at fixed gate voltage. The result is shown as $ΔdV/dI(I)$ in Fig. 5 for the 4-μm-thick flake with pre-defined contacts (c), and for the 600 nm one with evaporated contacts (d). The curves are even quantitatively similar in (c) and (d): in both cases, $ΔdV/dI(I)$ shows a maximum at the −1 mA negative current and a minimum at the +1 mA positive one. The curves are shifted vertically for different gate voltages, but one can not see any systematic dependence on $V_g$, in contrast to a single-sweep $dV/dI(I)$ curves in Figs. 5a and 5b.

All five WTe₂ samples demonstrate symmetric $dV/dI(I)$ curves, which can be expected for zero-gap semiconductors. In this case, even low electrochemical potential shift leads to the noticeable change of the carrier concentration even away from the charge neutrality point. Electrochemical potential difference appears between the potential contacts at finite $I$, so the decrease in $dV/dI(I)$ reflects the increased concentration near the high-potential probe. The effect is symmetric due to the overall symmetry of the sample.

On the other hand, one can not expect the observed dependence of $dV/dI$ differential resistance on the sign of the current change.

For all five WTe₂ samples, $dV/dI(I)$ demonstrates smooth behavior, there are no special points which could be associated with phase transitions due to the Joule heating of the sample. It well corresponds to the known WTe₂ properties, since WTe₂ crystal structure (Td) is known to be stable in a wide temperature range [15–17] at ambient pressure. Phase transitions can
only be observed in WTe$_2$, subjected to high pressures [33–35], so one cannot associate the observed hysteresis in $dV/dI(I)$ with any phase-change effects.

In addition, Au–WTe$_2$ interfaces have no contribution to the hysteresis in $dV/dI(I)$, since it can be reproduced by the four-point measurements, as shown in the inset to Fig. 4b. Thus, the observed effects cannot be connected with previously reported [5] gold adatom absorption at defects.

Surprisingly, even well-conducting WTe$_2$ single crystals demonstrate ferroelectricity at room temperature, which has been shown by direct visualization of ferroelectric domains [21]. The spontaneous polarization of these domains is normal to the WTe$_2$ layers, it can be affected by external electric field [21]. Due to the presence of the metallic conduction, there are two possible directions of the external electric fields in our setup (see Fig. 6): (i) gate field, $E_{\text{gate}} = V_{\text{g}}/d$, where $d = 300$ nm is the SiO$_2$ oxide thickness, $E_{\text{g}}$ is directed normally to the WTe$_2$ surface; (ii) source–drain field $E_{\text{sd}} = \rho j/I$, which is connected with the flowing current, $E_{\text{sd}}$ is parallel to the WTe$_2$ surface. The achievable values of the fields ($\sim 10^4–10^6$ V/m) are too small to align polarization of the whole WTe$_2$ flake, so they mostly affect the domain wall regions. Due to the field direction, $E_{\text{gate}}$ moves the position of the wall, while $E_{\text{sd}}$ changes the wall region width (see Fig. 6). Thus, any variation of electric fields leads to the additional polarization current. The latter we observe as slow relaxation in $dV/dI$, since polarization current is connected with lattice deformation in ferroelectrics.

The proposed mechanism is quite natural to explain the observed effects in $dV/dI$ both for the driving current and for the gate voltage behavior:

(i) By changing the driving current $I$ (i.e., $E_{\text{sd}}$ electric field in Fig. 6), one should expect a standard ferroelectric hysteresis loop, like in the Sawyer–Tower’s circuit [36, 37]. Due to the modulation technique, we obtain the first derivative of this $I$–$V$ loop, which leads to the maximum $\Delta dV/dI(I)$ at the negative cur-

**Fig. 5.** (Color online) (a, c) Gate-voltage dependence of $dV/dI(I)$, obtained for a single current sweep direction for the 4-μm-thick sample. The curves are shifted symmetrically for two different gate voltage polarities, which contradicts to the standard asymmetric field-effect transistor behavior. There is no gate leakage in the present gate voltage range. (b, d) Hysteresis amplitude $\Delta dV/dI(I)$, obtained by subtracting two curves for opposite current sweep direction at fixed gate voltage. The $\Delta dV/dI(I)$ curves are shown for the 4-μm-thick sample in (b) and for the thinner, 600 nm one (d). The curves are even quantitatively similar for different samples, they are of odd behavior with a maximum at the $-1$ mA negative current and a minimum at the $+1$ mA positive one. There is no any systematic dependence on $V'_{\text{g}}$ for $\Delta dV/dI(I)$ in (d).
Fig. 6. (Color online) Schematic diagram of the domain wall region, arrows indicate ferroelectric polarization direction. Due to the coexistence of metallic conductivity and ferroelectricity [21], there are two possible directions of the external electric fields in our setup. Gate field \( E_{\text{gate}} = V_g / d \) is directed normally to the WTe\(_2\) surface, while source-drain field \( E_{\text{sd}} \) is parallel to it, being induced by the flowing current \( E_{\text{sd}} = \rho j \). The achievable values of the fields are too small to align polarization of the whole WTe\(_2\) flake, so they mostly affect the domain wall regions. Thus, any variation of the electric fields leads to the additional polarization current. The latter we observe as slow relaxation in \( dV/dI \), since polarization current is connected with lattice deformation in ferroelectrics.

current \((-1 \text{ mA})\) and the minimum \( \Delta dV/dI(I) \) at the positive one \((+1 \text{ mA})\).

(ii) Gate voltage is fixed for any curve in Fig. 5, so gate electric field \( E_{\text{gate}} \) is stable and it does not induce an additional polarization current in this regime. Instead, we observe symmetric \( dV/dI \) shift in Figs. 5a and 5b, which reflects the overall symmetry of \( dV/dI(I) \) curves due to the strong coupling between the carrier concentration and the electrochemical potential position in zero-gap WTe\(_2\).

The possibility to induce polarization current by source-drain field variation is unique for WTe\(_2\), since it is a direct consequence of ferroelectricity and metallic conductivity coexistence [21].

The observed effects are nearly independent of the sample thickness in Figs. 2–4 and 5a–5c, which should be connected with the planar experimental geometry: current is mostly concentrated near the surface between the Au leads, where the ferroelectric domains have been observed previously by scanning techniques [21]. For thick \((1–4 \mu\text{m})\) WTe\(_2\) samples, Au leads are pre-defined at SiO\(_2\) surface (for typical sample images see [8, 31]), so current is concentrated near the WTe\(_2\)/SiO\(_2\) interface. In this case, we observe well-defined gate electric field effect in Figs. 5a–5c. For thin samples, \( E_{\text{gate}} \) should be partially screened by bulk WTe\(_2\) carriers, because of Au contacts at the upper WTe\(_2\) surface, see the image in Fig. 1. However, the electric field penetration length can be expected to be high in WTe\(_2\) semimetal, due to the perfect carrier compensation [38, 39]. It can be crudely estimated as \(0.1 \mu\text{m} \), which is comparable with the sample thickness in Fig. 5d.

In conclusion, we investigate electron transport along the surface of WTe\(_2\), three-dimensional single crystals, which are characterized by coexistence of Weyl semimetal conductivity and ferroelectricity at room temperature. We find that nonlinear behavior of \( dV/dI(I) \) WTe\(_2\) differential resistance is accompanied by slow relaxation process, which appears as the \( dV/dI(I) \) dependence on the sign of the current change. This observation is confirmed by direct investigation of time-dependent relaxation curves. While strongly nonlinear differential resistance should be expected for the zero-gap WTe\(_2\), the slow relaxation in transport is very unusual for well-conducting semimetals at room temperature. We establish that non-monotonic dependence of the amplitude of the effect on driving current \( \Delta dV/dI(I) \) well corresponds to the known Sawyer–Tower’s ferroelectric hysteresis loop. The possibility to induce polarization current by source-drain field variation is unique for WTe\(_2\), since it is a direct consequence of ferroelectricity and metallic conductivity coexistence. This conclusion is also confirmed by gate voltage dependencies, so our results can be understood as a direct demonstration of WTe\(_2\) ferroelectric behavior in charge transport experiment.

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REFERENCES

1. H. S. Lee, S. W. Min, Y. G. Chang, M. K. Park, T. Nam, H. Kim, J. H. Kim, S. Ryu, and S. Im, Nano Lett. 12, 3695 (2012).
2. N. Perea-López, A. L. Elías, A. Berkdemir, A. Castro-Beltran, H. R. Gutiérrez, S. Feng, R. Lv, T. Hayashi, F. López-Urías, S. Ghosh, B. Muchharla, S. Talapatra, H. Terrones, and M. Terrones, Adv. Funct. Mater. 23, 5511 (2013).
3. Q. Wang, K. Kalantar-Zadeh, A. Kis, J. N. Coleman, and M. S. Strano, Nat. Nanotechnol. 7, 699 (2012).
4. R. Ge, X. Wu, M. Kim, J. Shi, S. Sonde, L. Tao, Y. Zhang, J. C. Lee, and D. Akinwande, Nano Lett. 18, 434 (2018).
5. S. M. Hus, R. Ge, P.-A. Chen, M.-H. Chiang, G. E. Donnelly, W. Ko, F. Huang, L. Liang, A.-P. Li, and D. Akinwande, arXiv: 2002.01574.
6. S. Y. Xu, I. Belopolski, N. Alidoust, et al., Science (Washington, DC, U.S.) 349, 613 (2015).
7. Y. Wu, D. X. Mou, N. H. Jo, K. W. Sun, L. N. Huang, S. L. Bud’ko, P. C. Canfield, and A. Kaminski, Phys. Rev. B 94, 121113 (2016).
8. A. Kononov, O. O. Shvetsov, S. V. Egorov, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Eur. Phys. Lett. 122, 27004 (2018).
9. O. O. Shvetsov, A. Kononov, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Eur. Phys. Lett. 124, 47003 (2018).
10. A. A. Soluyanov, D. Gresch, Z. Wang, Q. Wu, M. Troyer, X. Dai, and B. A. Bernevig, Nature (London, U. K.) 527, 495 (2015).
11. J. Jiang, Z. Liu, Y. Sun, et al., Nat. Commun. 8, 13973 (2017).
12. Ch. Wang, Y. Zhang, J. Huang, et al., Phys. Rev. B 94, 241119(R) (2016).
13. Y. Ma, L. Kou, X. Li, Y. Dai, and Th. Heine, Phys. Rev. B 93, 035442 (2016).
14. S.-Y. Xu, Q. Ma, H. Shen, et al., Phys. Rev. B 93, 180101(R) (2017).
15. J. Zhou, F. Liu, J. Lin, et al., Adv. Mater. 29, 1603471 (2017).
16. W. G. Dawson and D. W. Bullett, J. Phys. C: Solid State Phys. 20, 6159 (1987).
17. N. Lu, Ch. Zhang, Ch.-H. Lee, J. P. Oviedo, M. An T. Nguyen, X. Peng, R. M. Wallace, Th. E. Mallouk, J. A. Robinson, J. Wang, K. Cho, and M. J. Kim, J. Phys. Chem. C 120, 8364 (2016).
18. M. N. Ali, J. Xiong, S. Flynn, J. Tao, Q. D. Gibson, L. M. Schoop, T. Liang, N. Haldolaarachchige, M. Hirschberger, N. P. Ong, and R. J. Cava, Nature (London, U. K.) 514, 205 (2015).
19. X.-Ch. Pan, X. Chen, H. Liu, Ya. Feng, Zh. Wei, Yo. Zhou, Zh. Chi, L. Pi, F. Yen, F. Song, X. Wan, Zh. Yang, B. Wang, G. Wang, and Yu. Zhang, Nat. Commun. 6, 7805 (2015).
20. P. Sharma, F.-X. Xiang, D.-F. Shao, D. Zhang, E. Y. Tsymbal, A. R. Hamilton, and J. Seidel, Sci. Adv. 5, eaax5080 (2019).
21. A. N. Morozovska, E. A. Eliseev, G. I. Dovbeshko, M. D. Glinchuk, Y. Kim, and S. V. Kalinin, Phys. Rev. B 102, 075417 (2020).
22. A. Urru, F. Ricci, A. Filippetti, J. Íñiguez, and V. Fiorentini, Nat. Commun. 11, 4922 (2020).
23. C. Ferreyra, M. Rengifo, M. J. Sánchez, A. S. Everhard, B. Noheda, and D. Rubi, Phys. Rev. Appl. 14, 044045 (2020).
24. M. V. Stern, Y. Waschitz, W. Cao, I. Nevo, K. Watanabe, T. Taniguchi, E. Sela, M. Urbakh, O. Hod, and M. Ben Shalom, arXiv: 2010.05182 (2020).
25. K. Yasuda, X. Wang, K. Watanabe, T. Taniguchi, and P. Jarillo-Herrero, arXiv: 2010.06600 (2020).
26. T. Hou, Ya. Ren, Yu. Quan, J. Jung, W. Ren, and Zh. Qiao, Phys. Rev. B 101, 201403(R) (2020).
27. W. X. Zhou, H. J. Wu, J. Zhou, et al., Commun. Phys. 2, 125 (2019).
https://doi.org/10.1038/s42005-019-0227-4
28. E. B. Borisenko, V. A. Berezin, N. N. Kolesnikov, V. K. Gartman, D. V. Matveev, and O. F. Shakhlevich, Phys. Solid State 59, 1310 (2017).
29. A. Sidorov, A. E. Petrova, A. N. Pinyagin, N. N. Kolesnikov, S. K. Khasanov, and S. M. Stishov, JETP 122, 1047 (2016).
30. O. O. Shvetsov, V. D. Esin, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Phys. Rev. B 99, 125305 (2019).
31. V. D. Esin, D. N. Borisenko, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Phys. Rev. B 101, 155309 (2020).
32. X.-Ch. Pan, X. Chen, H. Liu, Ya. Feng, Zh. Wei, Yo. Zhou, Zh. Chi, L. Pi, F. Yen, F. Song, X. Wan, Zh. Yang, B. Wang, G. Wang, and Yu. Zhang, Nat. Commun. 6, 7805 (2015).
33. M. N. Ali, J. Xiong, S. Flynn, J. Tao, Q. D. Gibson, L. M. Schoop, T. Liang, N. Haldolaarachchige, M. Hirschberger, N. P. Ong, and R. J. Cava, Nature (London, U. K.) 514, 205 (2015).
https://doi.org/10.1038/nature13763