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RAPID COMMUNICATION

Negative magnetoresistance in Dirac semimetal Cd_3As_2 with in-plane magnetic field perpendicular to current

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Topological insulators and semimetals have exotic surface and bulk states with massless Dirac or Weyl fermions, demonstrating microscopic transport phenomenon based on relativistic theory. Chiral anomaly induced negative magnetoresistance (negative MR) under parallel magnetic field and current has been used as a probable evidence of Weyl fermions in recent years. Here we report a novel negative MR result with mutually perpendicular in-plane magnetic field and current in Cd_3As_2 nanowires. The negative MR has a considerable value of -16% around 1.5 K and could persist to room temperature of 300 K with value of -1%. The gate tuning and angle dependence of the negative MR demonstrate the mechanism of the observed negative MR is different from the chiral anomaly. Percolating current paths induced by charge puddles and disorder might be involved to produce such considerable negative MR. Our results indicate the negative MR effect in topological semimetals involves synergistic effects of many mechanisms besides chiral anomaly.

Keywords: negative magnetoresistance, chiral anomaly, topological semimetals, quantum transport

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1. Introduction

The classical Drude model gives a magnetic field-independent conductivity formula $nq^2\tau/m$, which only considers carriers' collective drift and collision. Actually, a magnetic field could bend the motion paths of charged particles by Lorentz force and tend to localize the carriers in cyclotron orbits, corresponding to ordinary positive magnetoresistance (positive MR) with $\sigma_{xx} = \frac{\sigma_0}{1+(\mu B)^2}$, here σ_0 contributes to the zero-field conductivity.[1] When it comes to quantum well or topological system, unusual MR occurs and is generally considered as a signature of peculiar mechanism within quantum transport background,[2] such as linear MR and negative MR. Both of them are not limited to magnetic materials in view of moment scattering or transmission. As an instance, except for the negative MR source of quenching the Kondo effect[3,4] or magnetic phase transition,[5] nontrivial Berry curvature could revise relativistic particles' motion equation and contribute giant negative MR in topological semimetals or insulators.[6,7]

The topological semimetal is an analogue to graphene in three-dimensional situation, e.g., A_3Bi (A = Na, K, Rb)[8] and Cd_3As_2.[9–12] Band crossing formed by atom orbit's hybridization could be regarded as sources and drains of Berry curvature with higher degeneracy. Especially, Dirac semimetals are located at the center of phase transition to Weyl semimetals or strong/weak topological insulators.[13] Extra magnetic fields could break the time reversal symmetry and lift Dirac points to two-fold Weyl points. Considering the rectification of dynamic equation with Berry curvature, an extra axial current is induced by balancing charge pumping and intervalley relaxation, namely, chiral anomaly.[6,14] The negative MR induced by chiral anomaly is expected to be observed only in the longitudinal configuration with parallel electromagnetic fields, i.e., parallel B and I. Most angle-dependence experiments focus on out-of-plane magnetic fields, demonstrating positive MR transition with vanishing chiral anomaly.[15,16] For a sample above the substrate, out-of-plane and in-plane measurements own unequal symmetry or geometric configurations with collision paths of circling. Carriers' motion is related to the dimension and in-plane measurements could also provide additional insights, e.g., planar Hall effect.[17,18]

In this article, we report a considerable negative MR response by applying in-plane orthogonal electromagnetic fields

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in the Dirac semimetal Cd_3As_2. The amplitude of negative MR reaches -16% at 1.5 K and persists with -1% at room temperature. Such robust negative MR surviving to 300 K rules out the possible mechanisms such as quantum interference and alignment of random moments. Percolating current paths induced by charge puddles and disorder due to the inhomogeneous nanostructure and lattice disorder of Cd_3As_2 might be involved to produce such considerable negative MR. Our results indicate that the negative MR effect in topological semimetals involves synergistic effects of many mechanisms despite the chiral anomaly, even when the magnetic field is parallel to the current.

2. Experiment and method

The Cd_3As_2 nanowire is synthesized by chemical vapor deposition (CVD) method and transferred to silicon wafer with 285 nm SiO_2 oxide layer. Typical electron beam lithography technique is adopted to evaporate metal electrodes of Ti/Au with 10/200 nm. It is worth to note that the electrode regions are etched by Ar^+ before evaporation to reduce Schottky barrier and form Ohmic contact. Figure 1(a) shows an image of Cd_3As_2 nanowire growing along [112] crystal direction by scanning electron microscope (SEM). The quantum transport measurements are conducted by Oxford cryogenic refrigerator with the lowest temperature of 1.5 K. Traditional four-terminal configuration is used for measurement and lock-in amplifier SR830 provides alternating current with the amplitude $\sim$ 100 nA and frequency $\sim$ 17.777 Hz.

3. Results and discussion

Due to gapless energy bands around high degeneracy points and low density of relativistic Dirac fermions, thermal activation dominates the high temperature dependence of resistance. Metallic behavior appears after thermal energy is insufficient,[16] demonstrating a semiconductor-like R–T in Fig. 1(b). By tuning the carrier's density with back-gate voltage V_g at 1.7 K, a flat resistance kink is observed around -30 V, corresponding to the Dirac point in Fig. 1(c). The asymmetry feature indicates different carrier mobility and Fermi velocity in our Cd_3As_2 sample. Then, we focus on the main findings about negative MR under in-plane orthogonal electromagnetic fields as shown in Fig. 1(d). MR is calculated by $[R(B)-R(0)]/R(0)\times 100\%$. Either electron ($V_g = 0$ V) or hole ($V_g = -40$ V) side reveals negative MR feature, achieving maximum of -10% around 2–3 T. In addition, the value of negative MR is -16% when the Fermi level is closed to the Dirac point ($V_g = -30$ V), which means surface states and compensation of charges might dominate transport channels since bulk states are almost gapped with a lack of free particles. This novel negative MR is unlikely ascribed to the chiral anomaly, since here the magnetic field is in-plane orthogonal to the current. Besides, current jetting[19] with uneven density distribution along with the sample could also be excluded by considering the sample spanned by electrodes, i.e., uniform current injection.

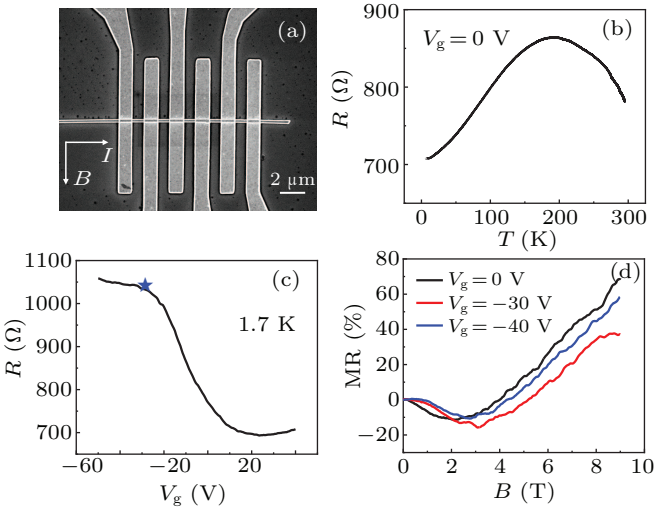


Fig. 1. (a) Image of Cd_3As_2 nanowire captured by SEM. (b) Temperature dependence of resistance probed by typical four-terminal configuration. (c) Back-gate voltage dependence of resistance at 1.7 K. Dirac point is marked around -30 V with a flat kink. (d) MR tuned by gate voltage with the magnetic field in-plane orthogonal to the current at 1.7 K.

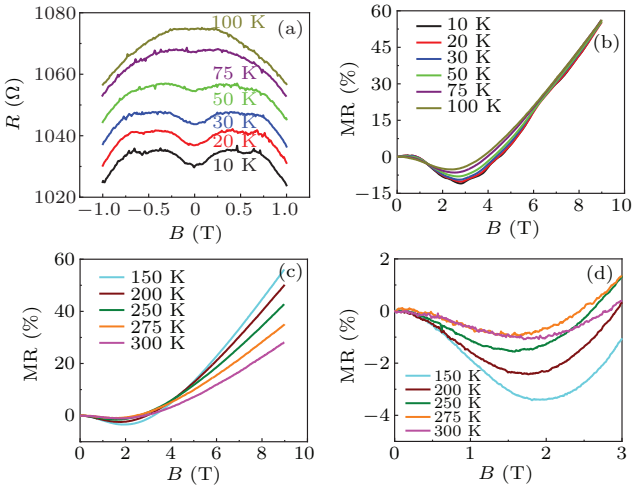


Fig. 2. (a) Magnetic field dependence of resistance from 10 K to 100 K under 1 T at the gate voltage $V_g = -30$ V, showing possible WAL feature with resistance dips around 0 T at lower temperature. (b) and (c) MR curves from 10 K to 300 K. (d) The enlarged area of (c) in order to observe the MR value and kink position clearly. All the measurements are taken at $V_g = -30$ V.

Subsequently, the temperature dependence of the negative MR with perpendicular in-plane magnetic field and current is measured from 10 K to 300 K at $V_g = -30$ V. A resistance dip is obviously observed around 0 T at 10 K, and gradually vanishes with increasing temperature to 75 K in Fig. 2(a). This low temperature behavior might be relevant to weak anti-localization (WAL) with nontrivial extra Berry phase suppressing of backscattering in semimetals.[20] All the amplitudes of negative MR achieve the extrema under 3 T,

with −11% at 10 K and decreases gradually by approaching room temperature, as shown in Figs. 2(b)–2(d). The negative MR unlikely comes from weak localization (WL) since the value is considerable at all the selected temperatures, even persisting to 300 K with −1%. Quantum interference, such as WAL and WL,[21,22] is very sensitive to phase coherence length, which diminishes quickly with increasing temperature and could hardly exist at 300 K.[20] The reason is that the dephasing process is usually dominated by inelastic collisions, i.e., electron–electron and electron–phonon scatterings, which implies higher temperature could enhance the relevant collisions and smear the quantum interference.

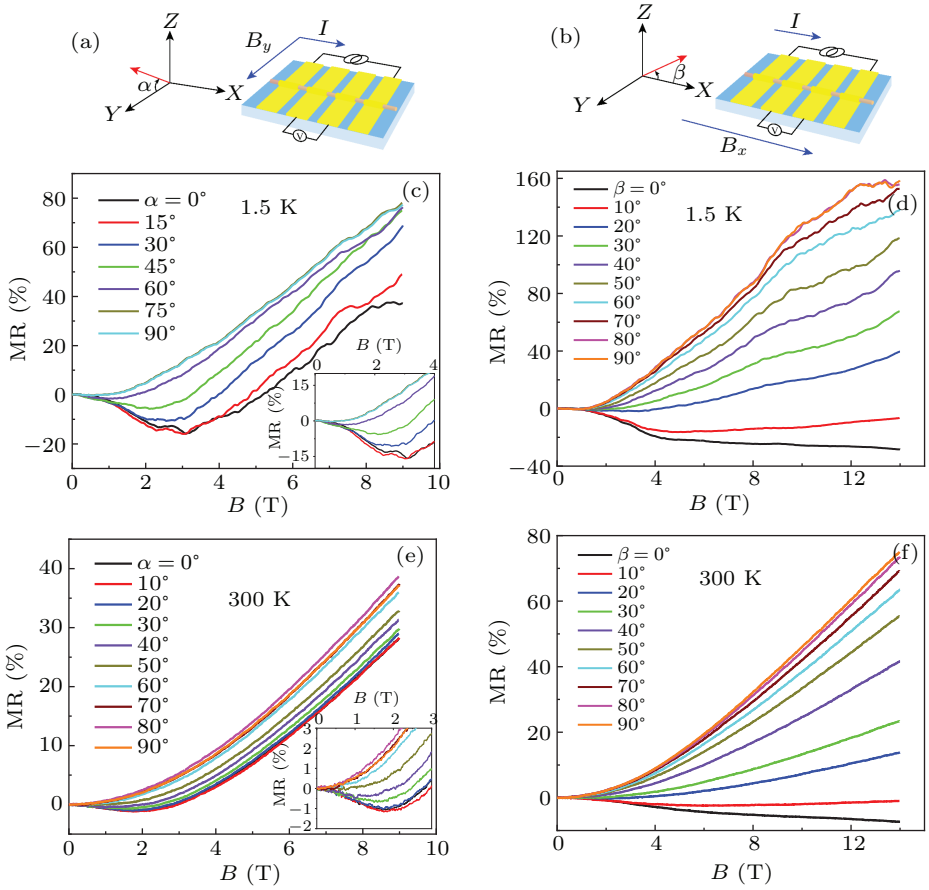


Fig. 3. (a), (c), (e) Angle dependence of MR at 1.5 K and 300 K with orthogonal configuration of the magnetic field and the current. The insets reveal the MR at small magnetic fields. (b), (d), (f) Angle dependence of MR at 1.5 K and 300 K with parallel configuration of the magnetic field and the current, corresponding to the typical chiral anomaly in topological semimetals. All the measurements are taken at $V_g = -30$ V.

Angle-dependence experiments are further conducted by applying the magnetic field along y–z plane and x–z plane respectively, corresponding to B_y vertical to I with $\alpha = 0°$ and B_x parallel to I with $\beta = 0°$, as shown in Figs. 3(a) and 3(b). Similar with earlier negative MR reports in semimetals,[15,16] Figs. 3(b), 3(d), 3(f) indicate a series of negative MR-to-positive MR transition with rotation contrasts from in-plane to out-of-plane at 1.5 K and 300 K, demonstrating a significant result of chiral anomaly in our Cd_3As_2 device. The maximum of $\beta = 0°$ negative MR could reach −28% (1.5 K) and −7% (300 K) at 14 T, respectively. It is worth to note that negative MR curves have no trend to positive MR by increasing the magnetic field, distinguishing from breakdown of C_4 rotation symmetry in Cd_3As_2.[16,21,23] This might be attributed to different energy band's stability by CVD growth method, or sufficient orbital-dependent part h_1 compared with the mass term.[8] The key finding of negative MR with orthogonal electromagnetic fields also indicates a process of gradual disappearance by rotating B_y to out-of-plane according to Figs. 3(a), 3(c), and 3(e). The insets amplify small field regions of the MR curves. It is interesting that the critical angles of negative MR-to-positive MR transition in orthogonal configuration are larger than he parallel ones, with 60° (1.5 K), 50° (300 K) in former and 20° (both 1.5 K and 300 K) in later. In addition, small angle misalignment of magnetic fields induced by measurement errors could be excluded as an origin of the negative MR in vertical in-plane magnetic fields by considering comparable values of the negative MR with parallel counterparts. Specifically, the negative MR of $\alpha = 0°$ (−16%) is even larger than the normal chiral anomaly of $\beta = 0°$ (−12%) in 3 T according to Figs. 3(c) and 3(d).

We could conclude that the novel negative MR with orthogonal electromagnetic fields is insusceptible to carrier types and still survives at room temperature. Metallic behavior in low temperature phase of Fig. 1(b) excludes strong localization or variable range hopping[24] as the origin of negative MR

in the Anderson localized system.[25] The fact of lower intrinsic carriers around Dirac points is contradicted with skipping-orbit effect observed in InSb films,[26] which claims classical surface boundary scattering brings to negative MR. Our results also rule out the conventional chiral anomaly with parallel configuration of fields in semimetals. Next, we discuss the possible mechanism of the observed MR in this work. Topological surface states provide spin–momentum locking for Fermi loops under time reversal symmetry of two-dimensional surface Hamiltonian. Extra fields could shift loops and cause a net spin-moment polarization, either through current density or Zeeman fields.[27] Earlier works[28,29] have proven that ion milling such as Ga^+ or Ar^+ could induce local magnetic moments by introducing disorder and lead to spin-dependent scattering process between surface and bulk states. Indeed, our Cd_3As_2 nanowire is fabricated by Ar^+ to form Ohmic contact as well, but only in electrode regions. It might not be possible that moment polarization-related scattering with disorder in such small areas covered by electrodes is able to cause an appreciable negative MR,[27] especially compared with the whole sample surface area. Besides, if net current brings spin polarization by spin–momentum locking, it seems that the relative direction of current and magnetic field should significantly influence the value of negative MR,[30,31] which is contradictory to our results.

In fact, such orthogonal configuration of negative MR is detected by an out-of-plane magnetic field in topological semimetals or insulators by several groups.[32–35] Percolating current path[32] induced by Zeeman energy is studied in theory and formed in abundant disorder bulk states. This perspective provides a possible mechanism for our negative MR results in the situation of vertical in-plane magnetic field and current. According to Fig. 1(c), we could roughly estimate electron's mobility with $\mu = \frac{\partial G}{\partial V_g} \times \frac{l^2}{C}$,[16] where G, l, C are the conductance, sample's length and the capacitance of SiO_2. The mobility is only around 5040 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at electron side, which is relatively small.[10] Thus the disorder due to intrinsic Cd vacancies or anisotropy of lattice should be considered.[9] Such defects might cause the Coulomb potential fluctuation among charge positions. Besides, the cross section of Cd_3As_2 nanowire is inhomogeneous due to its three-dimensional tetragonal crystal structure and might be tapered around tips.[36,37] Carriers' motion is restricted with varying dimension and might cause discrete energy level such as quantum confinement. Due to large Landé factor $g \sim 40$ in Cd_3As_2,[38] the Zeeman energy could provide an extra shift of electron clouds and bend current paths, causing the unexpected negative MR.

Although our negative MR is not detected by the out-of-plane magnetic field, it is related to specific simulation parameters of crystals, like different orientations of unit cells and Landé factors. The competition with orbit-related positive MR might also smear the mechanism. Nevertheless, the spatial disorder and distorted current paths exist in our sample, which would necessarily involve conductivity fluctuation[39–41] or carrier puddles.[32] In the meantime, microscopic disorder islands, anisotropy of lattice and Fermi velocity need to be carefully investigated in further research.

4. Conclusion

In summary, we display a distinct negative MR result with in-plane magnetic field orthogonal to the current in the Dirac semimetal Cd_3As_2. The amplitude of negative MR could reach -16% around 1.5 K and persist to room temperature. Moreover, such a phenomenon is different from the conventional chiral anomaly induced negative MR, demonstrating the complexity of the origins of negative MR in quantum transport. Here the extra conductance channels may play important roles due to percolating current paths, charge puddles and large Zeeman energy in disordered samples. Our results indicate the synergistic effects of chiral anomaly and other possible mechanisms such as disorders or percolating current path, Berry curvature, etc. in the negative MR effect observed in topological semimetals.

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References

[1] Dmitriev A, Dyakonov M and Jullien R 2001 *Phys. Rev. B* **64** 233321
[2] Lv B Q, Qian T and Ding H 2021 *Rev. Mod. Phys.* **93** 025002
[3] Andrei N, Furuya K and Lowenstein J H 1983 *Rev. Mod. Phys.* **55** 331
[4] Hanaki Y, Ando Y, Ono S and Takeya J 2001 *Phys. Rev. B* **64** 172514
[5] Ramirez A P 1997 *J. Phys.: Condens. Matter* **9** 8171
[6] Lu H Z and Shen S Q 2017 *Frontiers of Physics* **12** 127201
[7] Dai X, Du Z Z and Lu H Z 2017 *Phys. Rev. Lett.* **119** 166601
[8] Wang Z, Sun Y, Chen X Q, Franchini C, Xu G, Weng H, Dai X and Fang Z 2012 *Phys. Rev. B* **85** 195320
[9] Ali M N, Gibson Q, Jeon S, Zhou B B, Yazdani A and Cava R J 2014 *Inorg. Chem.* **53** 4062
[10] Liang T, Gibson Q, Ali M N, Liu M, Cava R J and Ong N P 2015 *Nat. Mater.* **14** 280
[11] Liu Z K, Jiang J, Zhou B, Wang Z J, Zhang Y, Weng H M, Prabhakaran D, Mo S K, Peng H, Dudin P, Kim T, Hoesch M, Fang Z, Dai X, Shen Z X, Feng L, Hussain Z and Chen Y L 2014 *Nat. Mater.* **13** 677
[12] Wang Z, Weng H, Wu Q, Dai X and Fang Z T 2013 *Phys. Rev. B* **88** 125427

[13] Liu Z K, Zhou B, Zhang Y, Wang Z J, Weng H M, Prabhakaran D, Mo S K, Shen Z X, Fang Z, Dai X, Hussain Z and Chen Y L 2014 *Science* **343** 864

[14] Nielsen H B and Ninomiya M 1983 *Phys. Lett. B* **130** 389

[15] Li H, He H, Lu H Z, Zhang H, Liu H, Ma R, Fan Z, Shen S Q and Wang J 2016 *Nat. Commun.* **7** 10301

[16] Li C Z, Wang L X, Liu H, Wang J, Liao Z M and Yu D P 2015 *Nat. Commun.* **6** 10137

[17] Li H, Wang H W, He H, Wang J and Shen S Q 2018 *Phys. Rev. B* **97** 201110

[18] Wu M, Zheng G, Chu W, Liu Y, Gao W, Zhang H, Lu J, Han Y, Zhou J, Ning W and Tian M 2018 *Phys. Rev. B* **98** 161110

[19] Liang S, Lin J, Kushwaha S, Xing J, Ni N, Cava R J and Ong N P 2018 *Phys. Rev. X* **8** 031002

[20] Zhao B, Cheng P, Pan H, Zhang S, Wang B, Wang G, Xiu F X and Song F Q 2016 *Sci. Rep.* **6** 22377

[21] Zheng W Z, Ye X G, Lin B C, Li R R, Yu D P and Liao Z M 2019 *Appl. Phys. Lett.* **115** 183103

[22] Yadav R, Bhattacharyya B, Pandey A, Kaur M, Aloysius R P, Gupta A and Husale S 2020 *J. Phys.: Condens. Matter* **33** 085301

[23] Jeon S, Zhou B B, Gyenis A, Feldman B E, Kimchi I, Potter A C, Gibson Q D, Cava R J, Vishwanath A and Yazdani A 2014 *Nat. Mater.* **13** 851

[24] Jiang H W, Johnson C E and Wang K L 1992 *Phys. Rev. B* **46** 12830

[25] Liao J, Ou Y, Feng X, Yang S, Lin C, Yang W, Wu K, He K, Ma X, Xue Q K and Li Y 2015 *Phys. Rev. Lett.* **114** 216601

[26] Ishida S, Takeda K, Okamoto A and Shibasaki I 2004 *Physica E* **20** 255

[27] Wang L X, Yan Y, Zhang L, Liao Z M, Wu H C and Yu D P 2015 *Nanoscale* **7** 16687

[28] Banerjee K, Son J, Deorani P, Ren P, Wang L and Yang H 2014 *Phys. Rev. B* **90** 235427

[29] Bhattacharyya B, Singh B, Aloysius R P, Yadav R, Su C, Lin H, Auluck S, Gupta A, Senguttuvan T D and Husale S 2019 *Sci. Rep.* **9** 7836

[30] Taskin A A, Legg H F, Yang F, Sasaki S, Kanai Y, Matsumoto K, Rosch A and Ando Y 2017 *Nat. Commun.* **8** 1340

[31] Cui Y, Chu Y, Pan Z, Xing Y, Huang S and Xu H 2021 *Nanoscale* **13** 20417

[32] Breunig O, Wang Z, Taskin A A, Lux J, Rosch A and Ando Y 2017 *Nat. Commun.* **8** 15545

[33] Miyazaki Y, Yokouchi T, Shibata K, Chen Y, Arisawa H, Mizoguchi T, Saitoh E and Shiomi Y 2022 *Phys. Rev. Res.* **4** L022002

[34] Pan H, Zhang K, Wei Z, Zhao B, Wang J, Gao M, Pi L, Han M, Song F, Wang X, Wang B and Zhang R 2016 *Appl. Phys. Lett.* **108** 183103

[35] Singh R, Gangwar V K, Daga D D, Singh A, Ghosh A K, Kumar M, Lakhani A, Singh R and Chatterjee S 2018 *Appl. Phys. Lett.* **112** 102401

[36] Schonherr P and Hesjedal T 2015 *Appl. Phys. Lett.* **106** 013115

[37] Zheng W Z, Zhao T Y, Wang A Q, Xu D Y, Xiang P Z, Ye X G and Liao Z M 2021 *Phys. Rev. B* **104** 155140

[38] Cao J, Liang S, Zhang C, Liu Y, Huang J, Jin Z, Chen Z G, Wang Z, Wang Q, Zhao J, Li S, Dai X, Zou J, Xia Z, Li L and Xiu F X 2015 *Nat. Commun.* **6** 7779

[39] Hu J, Rosenbaum T F and Betts J B 2005 *Phys. Rev. Lett.* **95** 186603

[40] Schumann T, Goyal M, Kealhofer D A and Stemmer S 2017 *Phys. Rev. B* **95** 241113

[41] Xu J, Ma M K, Sultanov M, Xiao Z L, Wang Y L, Jin D, Lyu Y Y, Zhang W, Pfeiffer L N, West K W, Baldwin K W, Shayegan M and Kwok W K 2019 *Nat. Commun.* **10** 287