Origin of exceptional magneto-resistance in Weyl semimetal TaSb$_2$

P Kumar, Sudesh and S Patnaik ©
School of Physical Sciences, Jawaharlal Nehru University, New Delhi-110067, Delhi, India
E-mail: spatnaik@mail.jnu.ac.in
Keywords: Weyl semimetal, Magnetoresistance, Kohler’s scaling, Topological insulators

Abstract
We study magneto-transport properties in single crystals of TaSb$_2$, which is a topological semimetal. In the presence of magnetic field, the electrical resistivity shows onset of insulating behaviour followed by a plateau at low temperature. Such resistivity saturation is generally assigned to topological surface states but we find that aspects of extremely large magneto resistance and resistivity plateau are well accounted by classical Kohler’s scaling. In addition, magneto-resistance in TaSb$_2$ shows non-saturating field dependence. Evidence for anomalous Chiral transport is provided with observation of negative longitudinal magneto-resistance. Shubnikov-de Haas oscillation data reveal two dominating frequencies, 201 T and 455 T. At low temperature, the field dependence of Hall resistivity shows non-linear behaviour that indicates the presence of two types of charge carriers in consonance with reported electronic band structure. Analysis of Hall resistivity implies extremely high electron mobility.

The nascent classification of materials in accordance with the topological states of quantum matter has yielded a radically new technological paradigm [1, 2]. This relates to the discovery of several material systems belonging to topological insulators (TI) and topological semimetals (TSM) that exhibit extremely large magnetoresistance (XMR) [3–9]. Quite generally, the study of electrical resistance in the presence of external magnetic field renders deep insight into electronic transport mechanism [10] that collaterally leads to several technological applications such as in magnetic sensors, magnetic switches and magnetic storage devices. To bring in a prospective, the reported [6, 11–19] magnetoresistance in TSMs could be two orders of magnitude higher than the giant magnetoresistance (GMR) or colossal magnetoresistance (CMR) observed in metallic thin films [20], perovskite manganites [21] or Cr-based chalcogenide spinels [22]. At the core of such exceptional magneto-resistance is the peculiar band structure of three-dimensional TIs and TSMs that yields conducting surface states. Recent studies reveal extremely large magnetoresistance (XMR) in Dirac semimetals (with linear band crossing at the Fermi level e.g. Na$_x$Bi [23] and Cd$_x$As$_2$ [24]) that extends to Weyl semimetals like TaAs family [25, 26]. Such properties are also seen in compensated layered semimetals like WTe$_2$ [27] and MoTe$_2$ [28]. The XMR exhibited by topological materials make them very interesting from the prospective of technological applications. However, several recent works in a wide variety of these novel materials have raised a fundamental question; whether the XMR can be explained by classical magneto-resistance theories without considering the topological aspects [15, 29].

In terms of theories for topological insulators, the associated symmetry principles restrict the quantum states to be robust against disorder due to time reversal symmetry invariance [30]. Experimentally this is manifested as a low temperature plateau in electrical resistivity. The plateau at low temperature is understood to have origin in conducting surface states that negate the insulating bulk behaviour, and are protected against backscattering due to time-reversal symmetry (TRS) invariance. The observation of large magneto-resistance in rare-earth monopnictides like R(Sb, Bi)(R = La, Y, Pr etc) [18, 19, 31, 32] and transition-metal dipnictides TM$_2$(T = Nb, Ta and M = Sb, As) [33, 34] have been analysed under such perspectives. In particular, TM$_2$ dipnictides are peculiar in the sense that at zero magnetic field they behave as weak topological insulators but with the application of external field, they can be classified as Type-II Weyl materials [35]. Several recent works have inferred that the plateau in these materials can also be explained by classical magneto-resistance theories without
invoking topological surface states [15, 18, 31, 33, 36, 37]. In this paper, we present a detailed study of magneto-
transport behaviour in single crystalline TaSb2. We observe XMR and metal-insulator like transition at low
temperatures under external magnetic field. The resistivity plateau is observed at temperatures below 13 K. Our
data on XMR and resistivity plateau is well accounted by Kohler’s scaling. Further we observe unambiguous
signatures of negative longitudinal magneto-resistance that can be assigned to Weyl phase in TaSb2 in the
presence of external magnetic field. Moreover, clear Shubnikov-de Haas (SdH) oscillations are observed
revealing two major Fermi pockets.

Single crystals of TaSb2 were synthesized by a two-step iodine vapour transport technique. In the first step,
polycrystalline TaSb2 was synthesized by solid-state reaction method. Stoichiometric amounts of Ta powder
(3 N, Alfa Aesar) and Sb shots (6 N, Alfa Aesar) were reacted together by heating at 700 °C for 3 days. The
polycrystalline sample was then vacuum sealed with Iodine (50 mg cm⁻¹ [3]) in quartz ampoule and put in a
tubular furnace with sample at 1000 °C and temperature gradient of ~100 °C across the sealed tube for one
week. Shiny needle like single crystals were obtained in the size range 2–6 mm. The crystallinity and structure
of the sample were analyzed using single crystal x-ray diffractometer (Bruker D8 Quest single crystal x-ray
diffractometer). The crystal structure of the sample was also studied using high resolution transmission electron
microscope (HRTEM). Magnetotransport measurements in the temperature range 2–300 K and field range
0–6 T were performed with single crystal x-ray diffractometer (J. Phys. Commun. 3 (2019) 115007).

The XRD data analysis suggests a monoclinic (C12/m13) structure with lattice constants a = 10.39(±0.03) Å,
b = 3.66(±0.01) Å, c = 8.42(±0.03) Å, β = 121.38(±13) and V = 273(±2) Å³ which are in agreement with the
reported data for TaSb2 [17]. Inset (i) in figure 1(a) shows the HRTEM image of the single crystal. The lattice
fringes reveal excellent crystalline nature of the specimen. The inter-planar spacing is ~0.286 nm which
residual resistivity value reflects negligible defect scattering in the sample. The residual resistivity ratio (RMR = ρ
(300 K)/ρ(2 K)) of the sample is observed to be ~260. Three different crystal of about same size were studied
and we are reporting the data from highest RMR specimen. We note that the magnitude of resistivity is lower
than that in good metals and this is clear reflection of role played by topological states where impurity and defect
scattering become oblivious to current flow. At low temperatures, ρxx(T) can be fitted with ρxx = ρ0xx + ATn
with n ~ 2.56, where ρ0xx is the residual resistivity (=0.538 μΩcm) and A = (4.29 × 10⁻¹⁰ ΩcmK⁻ⁿ). Such
extremely low resistivity has also been observed in other topological semimetals such as WTe2 and LaSb45. The
exponent value n is reflective of dominant scattering mechanism in the system with limiting values n = 2 for
strong electron-electron scattering and n = 5 for conventional electron-phonon scattering processes. The
observed value for TaSb2 would imply dominance of limiting electron–electron scattering as was observed in
NbP [38].

An extensively studied aspect of magneto-transport in TSM is the reported negative magnetoresistance when
magnetic field is applied parallel to current direction. Such observations are a common feature in several Weyl
and Dirac semimetal such as TaAs, Cd3As2, and ZrSiS. Dirac semimetals are essentially gapless semiconductors
with linear dispersion that become Weyl semimetals when Dirac point splits into two Weyl points due to either
spatial inversion or time reversal symmetry breaking. The chiral transport current between the Weyl points is
not conserved in this case leading to what is referred to as Adler–Bell–Jackiw (ABJ) anomaly [39]. The
experimental manifestation of this is negative magnetoresistance (for B || 1). Figure 1(b) shows the transverse
(B ⊥ 1) magnetoresistance at several temperatures with current along a-axis and magnetic field along c-axis. At 2 K
and 6 T, the sample shows extremely large magnetoresistance (MR = |[ρ(B) - ρ(0)]/ρ(0)| × 100 with ρ(B) and ρ
(0) being electrical resistivity at applied B field and 0 field, respectively), with magnitude ~3.55 × 10⁻³%, without
any trace of saturation. With increase in temperature, MR decreases to 300% at 50 K, 6 T. Inset in figure 1(b)
compares the field dependence of transverse and longitudinal magnetoresistance (LMR) at 2 K. In the
longitudinal configuration, magnetic field and current are applied along the a-axis of the sample. This is
figuratively elucidated in the inset of figure 1(b). We observe negative magnetoresistance above ~5.5 T below
which a parabolic field dependence is seen. The possible reasons for the negative LMR could be (i) the
magnetism in the sample that can be ruled out in TaSb2, (ii) Improper contact geometry (non-uniform current)
may also give rise to negative LMR [40]. Importantly, the specimen was needle-like thus eliminating such
possibilities, and (iii) The emergence of Weyl points with application of magnetic field leading to Chiral anomaly
in current transport. In agreement with band structure of TaSb2, we find the negative LMR observation to be a
clear signature of ABJ anomaly. A recent theoretical report [35] confirms the possibility of hidden Weyl points in
TaSb$_2$ that appear under applied magnetic field resulting in anisotropic chiral anomaly and consequent Type-II Weyl semimetal characterization [41].

In figure 2(a) we show Kohler’s scaling with regard to constant temperature field scans. Kohler’s rule gives a classical description of electronic motion that can provide insight into the MR behaviour in the sample. According to Kohler’s scaling: $\text{MR} = \alpha (B/\rho_0)^m$ where $\alpha$ and $m$ are sample dependent constants, $B$ is the applied field strength and $\rho_0$ is the zero field resistivity. Employing the Kohler’s rule: $\text{MR} = \alpha (B/\rho_0)^m$, MR($B$) data are fitted for all temperatures against $\alpha (B/\rho_0)$ and $\text{MR}(B)$ data are fitted for all temperatures against $\alpha (B/\rho_0)$ (with $\alpha = 1.13 \times 10^5$). Inset (i) of figure 2(a) shows MR as a function of $B/\rho_0$ (at 2 K) from which $\alpha$ and $m$ were determined. The collapse of MR data at all temperatures to a single line in the Kohler plot (main frame of figure 2(a)) implies that the sample shows similar power law for MR at all temperatures. This means similar scattering mechanism is followed by the carriers at all temperatures. Inset of figure 2(b) shows resistivity $\rho_{xx}(T)$ in applied perpendicular magnetic fields ranging from 0 to 6 T. We note that in the presence of magnetic field, above $\sim$100 K, TaSb$_2$ shows metallic temperature dependence similar to the zero field $\rho_{xx}(T)$ behaviour. In the presence of magnetic field, the resistivity shows sharp upturn and drastic increase at temperatures below $\sim$100 K. Moreover, below around 13 K, the resistivity starts to saturate, leading
to a plateau-like behaviour in the \( \rho_{xx}(T) \) curve. The temperature where the sample starts showing saturation remains unchanged at all applied magnetic fields. Such sharp upturn in resistivity below a particular temperature has been seen in several topological semimetals. The associated XMR \([7, 31, 39, 42–44]\) has been widely reported. The microscopic explanation of such phenomena has been attempted with theories that include, (a) magnetic field induced metal to insulator (MIT) transition, (b) electron-hole compensation, and (c) high mobility transport in metallic surface states of topological materials. However, as recently reported for LaSb \([29]\), the upturn in resistivity and its eventual saturation can also be ascribed to classical magnetoresistance theories involving Kohler scaling without invoking topological surface states.

Inset in (b) shows temperature dependence of \( \rho_{xx} \) at various magnetic fields. Kohler scaling can be written as:

\[ \rho_{xx}(T, B) = \rho_0 + \alpha B^m / (\rho_0)^{m-1} \]

Since \( \rho_0 \) is the only temperature dependent term in this equation, the temperature variation of \( \rho_{xx}(T, B) \) is mainly governed by \( \rho_0 \). Evidently, the second term \( (\Delta \rho = \alpha B^m / (\rho_0)^{m-1}) \) and \( \rho_0 \) have opposite dependence on temperature, leading to a minimum in total resistivity, \( \rho_{xx}(T, B) \), at a
particular temperature. The main panel of figure 2(b) shows the temperature dependent behaviour of \( \rho_{xx}(6 \text{ T}) \), \( \rho_0(=\rho_{xx}(0 \text{ T})) \) and \( \Delta \rho(=\rho_{xx}(6 \text{ T}) - \rho_0) \). The Kohler fitting to \( \rho_{xx}(6 \text{ T}) \) is shown by dark blue line and the fitting parameters \( \alpha \) and \( m \) are taken as \( 1.13 \times 10^4 \) and 1.78 respectively. Evidently, the \( \rho_{xx}(6 \text{ T}) \) in this figure fits well in the entire temperature range down from 2 K to 150 K that includes the plateau region as well. The correct crossover temperature of \( \sim 13 \text{ K} \) is also verified from Kohler scaling. At low temperature, since \( \rho_0 \) is small and independent of temperature variation, it implies \( \Delta \rho \gg \rho_0 \) and \( \rho_{xx}(T, B) \approx \Delta \rho \times 1/\rho_0 \). In summary, the low temperature emergence of plateau and XMR in TaSb2 can be explained with the help of Kohler’s scaling. In conjunction with the observation of AB anomaly, we conclude that Kohler’s analysis is applicable to Magnetoresistance in Weyl semimetal and there is no apparent contradiction between Kohler scaling and existence of surface transport in TSMs. We emphasize that in the case of Dirac semimetal Cd3As2, the magnetic field can lead to a bulk gap due to the magnetic-field-induced rotational symmetry breaking. Recent work by Liu et al confirms anisotropic magneto-resistivity in TaSb2, that imply breaking of two fold rotational symmetry in the presence of magnetic field [41]. There are two key results of our data analysis; 1. TaSb2 is a Weyl semimetal that is proven by longitudinal negative magnetoresistance and, 2. Kohler’s scaling is followed for transverse magneto-resistance data. The case is similar to WTe2 which is a well known Weyl semimetal [6] that follows Kohler’s scaling [43]. The point that we want to emphasize is that Kohler’s scaling takes into account magnetoresistance of normal metals that does not require peculiar surface states of topological systems. Therefore, while the edge modes are present in single crystals of TaSb2, one does not need to invoke this to explain metal-insulator like upturn on application of magnetic field and its eventual saturation at low temperature. Simply said, TaSb2 is one more example (like WTe2) that questions the general assignment of topological states to its exceptional magnetoresistance.

The Hall resistivity measurements were performed to investigate the carrier type, concentration and mobility. The field dependence of Hall resistivity \( \rho_{xy} \) is shown in the inset (iii) of figure 2(a). The negative sign of \( \rho_{xy} \) indicates possible dominance of electronic transport although a large difference in mobilities can also give rise to same result. The Hall resistivity at 2 K is fitted with the two-band model [46] (inset ii) to evaluate the charge carrier concentration and mobility:

\[
\rho_{xy} = \frac{B}{|e|} \left( n_e \mu_h^2 - n_h \mu_e^2 \right) + \left( n_h - n_e \right) \left( \mu_h \mu_e B^2 \right)
\]

where \( n_e(n_h) \) and \( \mu_e(\mu_h) \) are density and mobility of electrons (holes), respectively. The constraint: \( \rho_{xx}(B = 0) = 1/|e| (n_e \mu_h + n_h \mu_e) \) is used to fit the Hall resistivity. The obtained values of electron and hole carrier concentrations are estimated to be \( \sim 1.02 \times 10^{18} \text{ cm}^{-3} \) and \( 1.01 \times 10^{18} \text{ cm}^{-3} \), respectively, revealing TaSb2 to be a compensated semimetal. From the fitting parameters, the obtained electron and hole mobilities are estimated as \( \sim 5.1 \times 10^4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) and \( 1.36 \times 10^4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \), respectively. In essence, the resistivity upturn and low temperature saturation can be well accounted by strong temperature dependence of the high mobilities of the charge carriers in this compensated semimetal [45].

Further, the magnetoresistance measurements show clear Shubnikov-de Haas (SdH) oscillations at low temperatures and high magnetic fields (figure 3(a)). Inset (i) shows zoomed data between 11 T-13 T. The oscillation component (dR) of the MR is extracted by subtracting a higher order polynomial fit from the high field oscillation data. The oscillations can be identified from the plots of dR versus \( B^{-1} \), as shown in the inset (ii) of figure 3(a). In figure 3(b) we show Fast Fourier transformation (FFT) of the data shown in inset (ii) of figure 3(a). The oscillation frequencies are identified as 201 T \((\beta)\) and 455 T \((\gamma)\). From these SdH oscillation frequencies, the extremal cross-sectional area, \( A_F \), of the Fermi surface can be extracted using the Onsager relation: \( F = (\Phi_0/2\pi^2)A_F \). The frequency of \( F = 201 \text{ T} \) corresponds to \( A_F = 0.019 \text{ Å}^2 \) and \( F = 455 \text{ T} \) corresponds to \( A_F = 0.043 \text{ Å}^2 \). Also, we obtain Fermi wave vector, \( \kappa_F = (A_F/\pi)^{1/2} = 0.078 \text{ Å}^{-1} \) and 0.117 \text{ Å}^{-1} \) corresponding to frequencies 201 T and 455 T, respectively. The FFT amplitude decreases with increasing temperature. In the inset of figure 3(b) we show FFT amplitude with increasing temperature for \( \beta \) and \( \gamma \) peaks. From the temperature damping of SdH oscillation amplitude, the effective quasiparticle mass \( (m^*) \) can be extracted. The value of \( m^* \) is extracted from the fit of temperature dependence of FFT amplitude with Lifshitz-Kosevich (LK) equation: \( \Delta \rho / \rho \propto A T / \sinh(\text{AT}) \), where \( A = 2 \pi^2 \xi_0 m^*/\hbar B \). The LK fit is shown in the inset of figure 3(b). The value of \( m^* \) obtained from the LK fit for frequency 201 T is \( 0.17m_e \), and that for frequency 455 T is \( 0.15m_e \), where \( m_e \) is the free electron mass. The Fermi velocity \( v_F = h/\sqrt{2m^*} \) is estimated to be \( 5.29 \times 10^5 \text{ m s}^{-1} \) and \( 7.94 \times 10^5 \text{ m s}^{-1} \), respectively corresponding to frequencies 201 T and 455 T. The SdH oscillatory component was further analysed using the expression: \( dR \propto \cos[2\pi(F/B-\gamma)] ^0 \), here \( F \) is the frequency of oscillation and \( \gamma \) is the Onsager phase. From corresponding Landau fan diagram (not shown), the obtained \( \gamma \) was estimated to be zero confirming non-trivial Berry phase in TaSb2 [17].

To summarize, we present a magneto-transport study in the topological semimetal TaSb2. At 2 K and 6 T a large transverse MR (\( \sim 3.55 \times 10^4 \% \)) is observed without any sign of saturation. The magnetic field induced turn-on behaviour and plateau like feature at low temperature are well explained with Kohler scaling.
Significantly we find evidence for negative longitudinal magnetoresistance that signifies the presence of topological Weyl points. Non-trivial Berry phase is also indicated from analysis of SdH oscillation measurements. The high field SdH oscillations show two dominant frequencies at 201 T and 455 T. The Hall measurements confirm compensated semi-metallic behaviour with exceptionally high mobilities. We find that applicability of classical Kohler’s scaling to magneto-resistance and low temperature plateau in TaSb₂ is surprisingly accommodative with underlying topological Weyl states.

Acknowledgments

Sudesh and P Kumar acknowledges DSK-PDF fellowship from UGC (Government of India) and JNU (New Delhi) fellowship, respectively, for financial support. Authors are thankful to AIRF (JNU) for access to the PPMS and TEM facilities. Low–temperature high magnetic field at JNU is supported under the FIST and PURSE program of DST, Government of India. SP thanks SERB-DST for the project EMR/2016/003998/PHY. We thank Dr Dinabandhu Das for advice on single crystal diffraction data analysis.

ORCID iDs

S Patnaik  https://orcid.org/0000-0003-4984-9243
References

[1] Hasan M Z and Kane C L 2010 Rev. Mod. Phys. 82 3045
[2] Bernevig B A, Hughes T L and Zhang S-C 2006 Science (80-.), 314 1757
[3] Yan Y, Wang L X, Yu D P and Liao Z M 2013 Appl. Phys. Lett. 103 33106
[4] Liang T, Gibson Q, Ali M N, Liu M, Cava R J and Ong N P 2015 Nat. Mater. 14 280–84
[5] Kumar N et al 2017 Nat. Commun. 8
[6] Ali M N, Xiong J, Flynn S, Gibson Q, Schoop L, Haldolaarachchige N, Ong N P, Tao J and Cava R J 2015 Europhysics Lett. 110 arXiv
[7] Tafit F F, Gibson Q D, Kushwaha S K, Krizan J W, Haldolaarachchige N and Cava R J 2016 PNAS 113 E3475–E3481 arXiv
[8] Klier J, Gorniy I V and Mirlin A D 2017 Phys. Rev. B-Condens. Matter Mater. Phys. 96 214209
[9] Sudesh, Kumar P, Neha P, Das T and Patnaik S 2017 Sci. Rep. 7 46062
[10] Abrikosov A A 1972 Introduction to the Theory of Normal Metals (New York: Academic)
[11] Wang Z, Weng H, Wu Q, Dai X and Fang Z 2013 Phys. Rev. B 88 125427
[12] Shekhar C et al 2015 Nat. Phys. 11 1
[13] Du J et al 2016 Sci. China Physics, Mech. Astron. 59 657406
[14] Guo P, Yang H-C, Zhang B-J, Liu K and Lu Z-Y 2016 Phys. Rev. B 93 235142
[15] Singhia R, Satpati B and Mandal P 2017 Phys. Rev. B 95 445138
[16] Ali M N, Schoop L, Xiong J, Flynn S, Gibson Q, Hirscherberger M, Ong N P and Cava R J 2015 EPL (Europhysics Lett. 110 67002
[17] Li Y, Li L, Wang J, Wang T, Xu X, Xi C, Cao C and Dai J 2016 Phys. Rev. B 94 121115(R)
[18] Pavlovskii O, Swatek P and Wiśniewski P 2016 Sci. Rep. 6 38691
[19] Wu F, Guo C Y, Smidman M, Zhang J L and Yuan H Q 2017 Phys. Rev. B 96 125122
[20] Egelhoff W F et al 1995 J. Appl. Phys. 78 275
[21] Jin S, McCormack M, Tiefel T H and Barmash R 1994 J. Appl. Phys. 76 6929
[22] Ramirez A P, Cava R J and Krajewski J 1997 Nature 386 156
[23] Wang Z, Sun Y, Chen X Q, Franchini C, Xu G, Weng H, Dai X and Fang Z 2012 Phys. Rev. B-Condens. Matter Mater. Phys. 85 1
[24] Liu Z K et al 2014 Nat. Mater. 13 677
[25] Huang S-M et al 2015 Nat. Commun. 6 7373
[26] Yang L X et al 2015 Nat. Commun. 11 728
[27] Ali M N et al 2014 Nature 514 203
[28] Jiang J et al 2017 Nat. Commun. 8 13973
[29] Han F et al 2017 Phys. Rev. B 96 125312
[30] Fu L and Kane C L 2007 Phys. Rev. B-Condens. Matter Mater. Phys. 76 1
[31] Tafit F F, Gibson Q D, Kushwaha S K, Haldolaarachchige N and Cava R J 2016 Nat. Phys. 12 272–77
[32] Singhia R, Satpati B and Mandal P 2017 PNAS 114 2468–2473
[33] Wang Y, Yu Q, Guo P, Liu K and Xia T 2016 Phys. Rev. B 94 041103(R)
[34] Wang K, Graff D, Li L, Wang L and Petrovic C 2014 Sci. Rep. 4 7328
[35] Gresch D, Wu Q, Winkler G W and Soluyanov A A 2017 New J. Phys. 19 35001
[36] Sun S, Wang Q, Guo P- J, Liu K and Lei H 2016 New Journal of Physics 18 arXiv
[37] Wang L, You W, Wang T, Cao C, Dai J and Li Y 2017 Sci. Rep. 7 15669
[38] Wang Z, Zheng Y, Shen Z, Lu Y, Fang H, Sheng F, Zhou Y and Yang X 2016 Phys. Rev. B 93 121112(R)
[39] Kim H J, Kim K S, Wang J, Sasaki M, Sato N, Ohnishi A, Kitamura M, Yang M and Li L 2013 Phys. Rev. Lett. 111 246603
[40] Hu J, Rosenbaum T F and Ketten J 2005 Phys. Rev. Lett. 95 186603
[41] Liu Y-K, Xu Y, Wang J-L, You W, Wang T-T, Yang H-Y, Jiao W-H, Mao H-Y, Zhang L and Cheng J 2017 Chinese Phys. Lett. 34 3
[42] Luo Y, McDonald R D, Rosa P F S, Scott B, Wakeham N, Ghimire N J, Bauer E D, Thompson J D and Ronning F 2016 Sci. Rep. 6 27294
[43] Ghimire N J, Botana A S, Phelan D, Zheng H and Mitchell J F 2016 Journal of Physics: Condensed Matter 28 Arxiv
[44] Khveshchenko D V 2001 Phys. Rev. Lett. 87 206401
[45] Wang Y L et al 2015 Phys. Rev. B 91 180402(R)
[46] Colin M 1972 The Hall Effect in Metals and Alloys (Cambridge University Press)