Large Linear Magnetoresistance from Neutral Defects in Bi$_2$Se$_3$ Single Crystal

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The presence of large linear magnetoresistance in a Bi$_2$Se$_3$ single crystal is reported. The magnetoresistance has quadratic form at low fields which crosses over to linear dependence above 4 T. The temperature dependence of magnetoresistance scales with carrier mobility and inverse of carrier concentration while the crossover field scales with inverse of mobility. The magnetoresistance scaling shows that fluctuations in carrier mobility and carrier concentration cause the linear magnetoresistance. This analysis suggests that scattering of charge carriers from neutral crystalline defects is the main source of mobility fluctuation. Further, the carrier concentration exhibits a strong temperature dependence which is attributed to the thermal activation of charge carriers from defect states having activation energy $\approx 13$ meV.

The topological insulators are novel materials having spin polarized Dirac electrons at the conducting surface and an insulating bulk.$^{[1,2]}$ Among these topological insulators, the chalcogenide Bi$_2$Se$_3$ is most appealing because of simple gapless Dirac cone at the surface and the large topologically non-trivial gap of 0.3 eV between the bulk bands.$^{[3]}$ The massless Dirac fermions in two dimensional (2D) surface states of topological insulators exhibit interesting magnetotransport properties such as large linear magnetoresistance (MR),$^{[4-12]}$ non-trivial Berry phase in Shubnikov-de Haas (SdH) oscillations,$^{[13,14]}$ weak antilocalization (WAL),$^{[15,16]}$ and Aharonov–Bohm oscillations.$^{[17]}$ The linear MR in topological insulators is observed in thin films, nanoplates, nanoribbons of Bi$_2$Se$_3$, thin films, nanosheets, and in single crystals of Bi$_2$Te$_3$ where the surface state contribution dominates the overall transport of the system. MR of these materials is sensitive to chemical doping and gating.$^{[18]}$ The presence of large MR and understanding of its origin over a broad temperature range makes these materials interesting for applications in magnetic sensing and magnetoelectric devices.

The linear MR is observed in a number of materials, such as, silver chalcogenides,$^{[19]}$ single and multilayer graphene,$^{[20,21]}$ topological insulators,$^{[4-12]}$ Dirac$^{[22]}$ and Weyl semimetals$^{[23]}$ having a quantum or classical origin. The linear MR in nanosheets of Bi$_2$Te$_3$$^{[8]}$ and nanoribbons of Bi$_2$Se$_3$$^{[4]}$ have been ascribed to Abrikosov theory of quantum linear MR proposed for zero gap materials with linear dispersion. However the linear MR in nanoplates of Bi$_2$Se$_3$$^{[5]}$ thin films of Bi$_2$Se$_3$$^{[6]}$ and Bi$_2$Te$_3$$^{[9]}$ have been attributed to mobility fluctuations due to inhomogeneities suggesting a classical origin. The nature of MR in Bi$_2$Se$_3$ single crystals and its origin has not been investigated yet. The MR of Bi$_2$Se$_3$ crystals reported in literature have a large variation (MR $\approx 17%$$^{[24]}$ 15%$^{[25]}$ and 3.4%$^{[26]}$).

Therefore, it is important to explore the mechanism of MR in bulk crystals from the perspective of fundamental understanding as well as for optimizing the material for technological applications.

In this letter we present the magnetotransport study on a Bi$_2$Se$_3$ single crystal having large carrier concentration and bulk dominated magnetotransport properties. The MR increases with the application of field and becomes linear above 4 T. The linear MR scales with carrier mobility and inverse of carrier density. The MR values are large in comparison to those of previously reported.$^{[24-26]}$ Our results show a linear MR in our system which arises from deviation in current path due to fluctuations in carrier mobility and carrier concentration. We have also observed a strong temperature dependence in carrier density which is ascribed to the thermal activation of charge carriers from defect states.

**Experimental Details:** Bi$_2$Se$_3$ single crystal used in the present study is the same one as used in our earlier work.$^{[27-29]}$ This crystal has been well characterized by high resolution X-ray diffraction (HRXRD)$^{[28]}$ scanning electron microscopy (SEM)$^{[28]}$, energy diffractive X-ray analysis (EDX)$^{[28]}$ and extended X-ray absorption fine structure spectroscopy (EXAFS)$^{[29]}$. The sample used for resistivity and Hall measurements is a thin rectangular bar shaped crystal. Resistivity and Hall measurements are performed on a 9T PPMS AC Transport system (Quantum Design) using standard four probe and five probe techniques respectively.

**Results and Discussion:** Figure 1a displays the magnetoresistance MR = ($\rho(B)$ – $\rho(0)$)/$\rho(0)$ as a function of applied field upto 9 T at various temperatures. We note that MR of our system is large, approximately 50% at 1.8 K, in comparison to the previously reported for stoichiometric Bi$_2$Se$_3$ crystals (3–17%$^{[24-26]}$). The MR exhibits a weak temperature dependence upto 25 K, and thereafter decreases strongly on
increasing the temperature. The MR shows a quadratic field dependence at low fields which crosses over to linear dependence at high magnetic fields. Figure 1b shows the MR at 1.8 K along with the linear and quadratic fit. The crossover field $B_C$ is determined as the field at which the absolute value of the difference between the linear and quadratic functions is minimum. The existence of linear MR above $B_C$ cannot be understood on the basis of Lorentz deflection of carriers as the Lorentz deflection predicts a quadratic MR which may saturate in case of closed orbits.

The non-saturating linear MR at high fields could arise from quantum as well as classical effects. Abrikosov\cite{30,31} proposed a quantum interpretation of high field linear MR for materials processing a gapless linear energy dispersion in ultra quantum limit. In ultra quantum limit, only the first landau level is filled and this happens when $\hbar \omega_c > E_F$, and $E_F \gg k_B T$ where $\hbar \omega_c$ is the energy difference between two consecutive Landau levels, $E_F$ is the Fermi energy, and $k_B T$ is the thermal energy. The field dependent resistivity shown in Figure 1a exhibits SdH oscillations at low temperatures and the background subtracted SdH oscillations at 2 K is shown in Figure 2a. The SdH oscillations fit well with Lifshitz–Kosevich equation $\Delta \rho(B) = \Delta \rho_0(T) \frac{B^{1/2}}{(B^2 + \gamma^2)^1/2} \exp \left(-\frac{\pi \mu B}{\gamma} \cos \frac{\pi \delta}{B + \gamma} \right)$ giving $\mu = 8.6(9) \times 10^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $B_F = 219.8(6)$ T ($k_F = 0.0817(2)$ Å$^{-1}$), and $\gamma = 0.18(6)$. The analysis of SdH oscillations suggests that a large number of Landau levels are filled indicating that our system is not in ultra quantum limit. Moreover according to quantum model, MR is temperature independent until thermal energy is smaller than the Fermi energy and separation of Landau Levels. Figure 1a shows that MR starts dropping above 25 K whereas $\hbar \omega_c$ for our crystal is found to be $\approx 81$ K which further confirms that quantum model is not applicable in our case. Wang et al.\cite{32} have predicted that linear MR can also arise from topological surface states in systems having overlapped Landau levels with more than one filled levels. MR in this model

![Figure 1](image1.png)

*Figure 1.* a) The field dependence of magnetoresistance (MR) at different temperatures. b) The MR data at 1.8 K. The low field data is fitted with quadratic function while the high field data is fitted with the linear function to demonstrate their respective field dependence.

![Figure 2](image2.png)

*Figure 2.* a) Oscillatory part of longitudinal resistivity $\Delta \rho$ at 2 K. The solid line is fitting of Lifshitz–Kosevich equation. b) The temperature variation of carrier concentration $n$ (open circles) and mobility $\mu$ (open triangles). The solid lines represent the least square fitting of Equation (1) to $n$ and Equation (2) to $\mu$. The inset shows the variation of $\mu$ with $1/n$. 

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is robust against the temperature. Our system has bulk dominant transport behavior and linear MR weakens on increasing the temperature which rules out the possibility of this model.

Figure 2b shows the temperature variation of carrier concentration ($n$) and electron mobility ($\mu$) estimated from the Hall resistivity and longitudinal resistivity. The carrier concentration increases on increasing the temperature and fits well with the Arrhenius’s law:

$$n(T) = n_0 + n_1 \exp(-\Delta/k_B T)$$  \hspace{1cm} (1)

where $n_0$ is the carrier concentration at $T=0 K$, $n_1$ is thermally activated contribution, $\Delta$ is the activation energy, and $k_B$ is the Boltzmann constant. The obtained values are $n_0 = 1.13(4) \times 10^{19} cm^{-3}$, $n_1 = 4.3(2) \times 10^{19} cm^{-3}$, and $\Delta = 13(1) \text{meV}$. Since the activation energy is much smaller than the minimum activation energy expected for bulk valance band to conduction band charge transfer ($\sim 0.15 \text{eV}$), this thermal activation of charge carriers is expected to arise from defect states.$^{33,34}$ In contrast to carrier concentration, the carrier mobility exhibits a strong decay on enhancing the temperature as shown in Figure 2b. The temperature variation of mobility does not follow the power law dependence of normal metals/semiconductors instead fits well with the equation

$$\mu(T) = \mu(0)(1 - \exp(-C/T))$$  \hspace{1cm} (2)

where $\mu(0)$ is mobility at $T = 0$ and $C$ is a constant. The inset of Figure 2b shows the inverse variation of carrier mobility with carrier concentration i.e., $\mu \propto 1/n$.

The other mechanisms discussed in literature for the existence of linear MR are classical in nature and applicable to inhomogeneous systems with high carrier mobility. One such model by Herring$^{35}$ predicts that the small fluctuations in local conductivity can lead to linear MR at extremely high fields in the limit of weak disorder. For strong disorder limit, Parish and Littlewood (PL)$^{36,37}$ proposed that the distortion in current path due to inhomogeneous distribution of carrier concentration and mobility gives rise to linear MR. In weak disorder limit, the scale of inhomogeneities is small compared to the mean free path, while for strong disorder, scale of inhomogeneities is comparable/large compared to the mean free path. The PL model uses a random resistor network to simulate an inhomogeneous system where regions of different local carrier concentration and mobility are represented by a unique four terminal resistor. Each four terminal resistor accounts for the resistive as well as Hall voltage of a particular region. The MR in PL model strongly depends on the average mobility ($\langle \mu \rangle$) and the width of mobility disorder ($\Delta \mu$). At high fields, $MR \propto \langle \mu \rangle$ for $\Delta \mu / \langle \mu \rangle < 1$ and $MR \propto \Delta \mu$ for $\Delta \mu / \langle \mu \rangle > 1$. The crossover field ($B_c$) for quadratic to linear MR is $\propto \langle \mu \rangle^{-1}$ for $\Delta \mu / \langle \mu \rangle < 1$ and $\propto (\Delta \mu)^{-1}$ for $\Delta \mu / \langle \mu \rangle > 1$. According to recent theoretical studies on inhomogeneous materials, the carrier density fluctuations are more important than carrier mobility fluctuations in creating current distortion fields which predict that linear MR $\propto 1/n$ but insensitive to $\mu$.$^{38}$ In view of this, the behavior of MR with carrier mobility and carrier concentration is all the more significant in understanding the mechanism of linear MR.

Figure 3a displays the variation of total MR at 9 T with carrier mobility on changing the temperature. The magnitude of total MR increases linearly with carrier mobility. As MR of our system has quadratic form at lower fields, it is more appropriate to analyze the slope of linear part of MR ($dMR/dB$) to investigate the dependence of linear MR on carrier mobility. $dMR/DB$ is obtained by linear fitting of MR at high fields. The dependency of linear MR on carrier mobility is demonstrated in Figure 3b by scaling of temperature dependence of carrier mobility and $dMR/DB$. A remarkable similarity between the temperature evolution of $dMR/DB$ and carrier mobility confirms unambiguously that linear MR $\propto \mu$. Figure 3c exhibits the temperature dependence of crossover field ($B_c$) and compares it with that of inverse mobility ($\mu^{-1}$). $B_c$ increases on enhancing the temperature and its temperature dependence scales well with $\mu^{-1}$. The dependency of linear MR and $B_c$ on carrier mobility (i.e., linear MR $\propto \mu$ and $B_c \propto \mu^{-1}$) confirms the classical origin of MR which can be understood on the basis of PL model for narrow mobility distribution $\Delta \mu / \mu < 1$. The linear MR in inhomogeneous systems follow the PL model in a variety of materials such as Ag$_{2+y}$Se and Ag$_{2+y}$Te$^{39}$, epitaxial graphite,$^{39}$ graphene,$^{21,20}$...
and in the Dirac semimetal Cd$_3$As$_2$.[22] In Figure 3d the temperature dependence of MR and carrier concentration is compared. The MR decreases while the carrier concentration increases on increasing the temperature. Figure 3e shows that $dMR/\epsilon B \propto 1/n$. Similar scaling with $\mu$ and $1/n$ are also observed in the slope of magnetoresistivity suggesting the significant role of disorder in carrier concentration and carrier mobility in the origin of linear MR.

In the PL model, the linear MR in a high mobility inhomogeneous conductor arises due to multiple scattering of electrons from low mobility islands around inhomogeneities.[41] The inhomogeneity scattering decreases the average electron velocity along the applied voltage by deflecting the electron motion perpendicular to it. The inhomogeneities expected for the growth conditions of our crystal are ionized selenium vacancies and neutral crystalline defects.[33] The EDX spectrum of our sample gives atomic ratio of Bi:Se $\approx 2:2.8$ showing the presence of selenium vacancies.[27] For $n = 1.13 \times 10^{19}$ cm$^{-3}$ and considering that each selenium vacancy contributes two electrons, the average distance between the ionized selenium vacancies $l_{\text{imp}} \approx (n/2)^{-1/3} \approx 5.6$ nm. The Debye screening length of ionized selenium vacancies $l_{\text{Debye}} = (\epsilon_0 \epsilon_r k_B T/n e^2)^{1/2} \approx 0.3$ nm, where $\epsilon_0$ is the permittivity of free space and $\epsilon_r = 100$ is the relative permittivity of Bi$_2$Se$_3$. Each selenium vacancy affects the local electronic structure which can alter the electronic mobility in a nanometer region around it.[43] The lower mobility regions around the selenium vacancies can act as inhomogeneity islands for electron scattering. The distance between these inhomogeneity islands around the individual selenium vacancies ($l_{\text{imp}}$) is an order of magnitude smaller than the electronic mean free path $l = v_F/\tau \approx 52$ nm ($v_F = \hbar k_F/m^* \approx 6.2 \times 10^5$ m s$^{-1}$) suggesting that ionized selenium vacancies are not the main source of electron scattering, and are possibly screened by the free charge carriers. This leaves the neutral crystalline defects as the dominant source of inhomogeneity scattering. Williamson Hall analysis of the X-ray peak width of our crystal shows a positive slope indicating the presence of dominant local compressive strain field.[28] This suggests that microstrain in the crystal is not from Se vacancies but arises from crystalline disorder other than Se vacancies. The high resolution X-ray diffraction studies of our sample also shows the presence of crystalline disorders such as small angle grain boundaries and mosaic spread.[28] The Le Bail fitting of X-ray data gives larger $c$ suggesting a strain along the (003) axis. The existence of neutral crystalline defects is further confirmed by extended X-ray absorption fine structure spectroscopy (EXAFS) measurements which show the presence of shorter interlayer Bi-Se and Se-Se bond regions coexisting with the normal crystalline environment. The shorter interlayer bond distance is attributed to the modification in the strength of inter-layer coupling.[29] These neutral crystalline defects can create low mobility inhomogeneity islands around them acting as centers for electron scattering. The large linear MR at low temperatures is from the scattering of charge carriers from inhomogeneity islands around neutral defects.

The temperature evolution of magnetoresistance can be further analyzed by the Kohler’s scaling of isothermal MR: $\Delta\rho/\rho_0 = F(B/\rho_0)$, where $\Delta\rho$ is the change in isothermal resistance with field $B$ and $\rho_0$ is the zero field resistivity at the given temperature.[44] Figure 3f shows the Kohler plot for isothermal MR between 1.8 and 300 K. All MR data falls on the same curve showing the validity of Kohler scaling. This reconfirms the presence of single type of charge carrier and suggests that temperature dependence of electron scattering time does not vary significantly at different points of Fermi surface. This condition is satisfied if we have a single temperature dependent scattering rate which is the phonon scattering in our case.[45]

In conclusion, large linear MR is observed in Bi$_2$Se$_3$ crystal and its origin is discussed in detail. The observed MR is directly proportional to carrier mobility and inversely proportional to carrier density. The origin of such a large MR is explained from the extensive analysis of various models on our MR and Hall data and is found to be arising from the scattering of charge carriers from neutral crystalline defects instead of Se vacancies. These results and analysis are of significant importance in tailoring the topological materials for magnetoresistive devices.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

Bi$_2$Se$_3$, linear magnetoresistance, neutral defects, topological insulators

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References

[1] M. Z. Hasan, C. L. Kane, Rev. Mod. Phys. 2010, 82, 3045.
[2] X.-L. Qi, S.-C. Zhang, Rev. Mod. Phys. 2011, 83, 1057.
[3] H. Zhang, C.-X. Liu, X.-L. Qi, X. Dai, Z. Fang, S.-C. Zhang, Nat. Phys. 2009, 5, 438.
[4] H. Tang, D. Liang, R. L. J. Qiu, X. P. A. Gao, ACS Nano 2011, 5, 7510.
[5] Y. Yan, L.-X. Wang, D.-P. Yu, Z.-M. Liao, Appl. Phys. Lett. 2013, 103, 033106.
[6] H. T. He, H. C. Liu, B. K. Li, X. Guo, Z. J. Xu, M. H. Xie, J. N. Wang, Appl. Phys. Lett. 2013, 103, 031606.
[7] H. He, B. Li, H. Liu, X. Guo, Z. Wang, M. Xie, J. Wang, Appl. Phys. Lett. 2012, 100, 032105.
[8] X. Wang, Y. Du, S. Dou, C. Zhang, Phys. Rev. Lett. 2012, 108, 266806.
[9] Z. H. Wang, L. Yang, X. J. Li, T. Zhao, H. L. Wang, Z. D. Zhang, X. P. A. Gao, Nano Lett. 2014, 14, 6510.
[10] D.-X. Qu, Y. S. Hor, J. Xiong, R. J. Cava, N. P. Ong, Science 2010, 329, 821.
[11] S. Barua, K. P. Rajeev, A. K. Gupta, J. Phys.: Condens. Matter 2015, 27, 015601.
[12] K. Shrestha, M. Chou, D. Graf, H. D. Yang, B. Lorenz, C. W. Chu, Phys. Rev. B 2017, 95, 195113.
[13] Y. Yan, Z.-M. Liao, Y-B. Zhou, H.-C. Wu, Y.-Q. Bie, J.-J. Chen, J. Meng, X.-S. Wu, D.-P. Yu, Sci. Rep. 2013, 3, 1264.
[14] J. G. Analytis, R. D. McDonald, S. C. Riggs, J.-H. Chu, G. S. Boebinger, I. R. Fisher, Nat. Phys. 2010, 6, 960.
[15] Y. S. Kim, M. Braheke, N. Bansal, E. Edrey, G. A. Kapilevich, K. Iida, M. Tanimura, Y. Horibe, S.-W. Cheong, S. Oh, Phys. Rev. B 2011, 84, 073109.
[16] H.-T. He, G. Wang, T. Zhang, I.-K. Sou, G. K. L. Wong, J.-N. Wang, H.-Z. Lu, S.-Q. Shen, F.-C. Zhang, Phys. Rev. Lett. 2011, 106, 166805.
[17] H. Pan, K. Zhang, Z. Wei, J. Wang, M. Han, F. Song, X. Wang, B. Wang, R. Zhang, Appl. Phys. Lett. 2017, 110, 053108.
[18] a) B. F. Gao, P. Gehring, M. Burghard, K. Kern, Appl. Phys. Lett. 2012, 100, 212402; b) S. Singh, R. K. Gopal, J. Sarkar, A. Pandey, B. G. Patel, C. Mitra, J. Phys.: Condens. Matter 2017, 29, 505601; c) Z. Wang, L. Yang, X. Zhao, Z. Zhang, X. P. A. Gao, Nano Res. 2015, 29, 2963; d) J. Tian, C. Chang, H. Cao, K. He, X. Ma, Q. Xue, Y. P. Chen, Sci. Rep. 2014, 4, 4859.
[19] J. Hu, T. F. Rosenbaum, Nat. Mater. 2008, 7, 697.
[20] P. Li, Q. Zhang, X. He, W. Ren, H.-M. Cheng, X.-x. Zhang, Phys. Rev. B 2016, 94, 045402.
[21] W. J. Yang, K. H. Gao, Z. Q. Li, L. Lin, J. Li, C. Yu, Z. H. Feng, Appl. Phys. Lett. 2014, 105, 182102.
[22] A. Narayanan, M. D. Watson, S. F. Blake, N. Bruyant, L. Drigo, Y. L. Chen, D. Prabhakaran, B. Yan, C. Felser, T. Kong, P. C. Canfield, A. I. Coldea, Phys. Rev. Lett. 2015, 114, 177201.
[23] C. Shekhar, A. K. Nayak, Y. Sun, M. Schmidt, M. Nicklas, I. Leermakers, U. Zeitler, Y. Skourski, J. Wosnitza, Z. Liu, Y. Chen, W. Schnelle, H. Borrmann, Y. Grin, C. Felser, B. Yan, Nat. Phys. 2015, 11, 645.
[24] H. Cao, J. Tian, I. Miotkowski, T. Shen, J. Hu, S. Qiao, Y. P. Chen, Phys. Rev. Lett. 2012, 108, 216803.
[25] K. Eto, Z. Ren, A. A. Taskin, K. Segawa, Y. Ando, Phys. Rev. B 2010, 81, 195309.
[26] T. R. Devidas, E. P. Amaladass, S. Sharma, R. Rajaraman, D. Somadurai, N. Subramanian, A. Mani, C. S. Sundar, A. Bharathi, EPL 2014, 108, 67008.
[27] D. Kumar, A. Lakhani, Phys. Status Solidi RRL 2015, 9, 636.
[28] D. Kumar, A. Lakhani, Mater. Res. Bull. 2017, 88, 127.
[29] A. Tayan, D. Kumar, A. Lakhani, J. Phys.: Condens. Matter 2017, 29, 445704.
[30] A. A. Abrikosov, Phys. Rev. B 1998, 58, 2788.
[31] A. A. Abrikosov, Europhys. Lett. 2000, 49, 789.
[32] C. M. Wang, X. L. Lei, Phys. Rev. B 2012, 86, 035442.
[33] L. Xue, P. Zhou, C. X. Zhang, C. Y. He, G. L. Hao, L. Z. Sun, J. X. Zhong, AIP Adv. 2013, 3, 052105.
[34] a) D. Biswas, S. Thakur, G. Balakrishnan, K. Maiti, Sci. Rep. 2015, 5, 17351; b) T. Fang, A. Konar, H. Xing, D. Jena, Appl. Phys. Lett. 2007, 91, 092109; c) D. B. Farmer, V. Perebeinos, Y.-M. Lin, C. Dimitrakopoulos, P. Avouris, Phys. Rev. B 2011, 84, 205417; d) H. Li, H. He, H.-Z. Lu, H. Zhang, H. Liu, R. Ma, Z. Fan, S.-Q. Shen, J. Wang, Nat. Commun. 2016, 7, 10301.
[35] C. Herring, J. App. Phys. 1960, 31, 1939.
[36] M. M. Parish, P. B. Littlewood, Nature 2003, 426, 162.
[37] M. M. Parish, P. B. Littlewood, Phys. Rev. B 2005, 72, 094417.
[38] F. Kisslinger, C. Ott, H. B. Weber, Phys. Rev. B 2017, 95, 024204.
[39] M. A. Aamir, S. Goswami, M. Baenninger, V. Tripathi, M. Pepper, I. Farrer, D. A. Ritchie, A. Ghosh, Phys. Rev. B 2012, 86, 081203.
[40] W. Wang, Y. Du, G. Xu, X. Zhang, E. Liu, Z. Liu, Y. Shi, J. Chen, G. Wu, X.-x. Zhang, Sci. Rep. 2013, 3, 2181.
[41] N. V. Kozlova, N. Mori, O. Makarovski, L. Eaves, Q. D. Zhuang, A. Krier, A. Patané, Nat. Commun. 2012, 3, 1097.
[42] H. Köhler, C. R. Becker, Phys. Status Solidi B 1974, 61, 533.
[43] a) J. Dai, D. West, X. Wang, Y. Wang, D. Kwok, S.-W. Cheong, S. B. Zhang, W. Wu, Phys. Rev. Lett. 2016, 117, 106401; b) Z. Alpichshev, R. R. Biswas, A. V. Balatsky, J. G. Analytis, J.-H. Chu, I. R. Fisher, A. Kapitulnik, Phys. Rev. Lett. 2012, 108, 206402.
[44] A. P. Pippard, Magnetoresistance in Metals. Cambridge University Press, Cambridge, England 1989.
[45] M. K. Chan, M. J. Veit, C.-J. Dorow, Y. Ge, Y. Li, W. Tabs, Y. Tang, X. Zhao, N. Barisic, M. Greven, Phys. Rev. Lett. 2014, 113, 177005.