Giant Linear Magneto-resistance in Nonmagnetic PtBi$_2$

Xiaojun Yang,$^1$ Hua Bai,$^1$ Zhen Wang,$^1$ Yupeng Li,$^1$ Qian Chen,$^1$ Jian Chen,$^1$ Yuke Li,$^2$ Chunmu Feng,$^1$ Yi Zheng,$^1,3,4$ and Zhu-an Xu$^{1,3,4,5}$

$^1$Department of Physics and State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China
$^2$Department of Physics, Hangzhou Normal University - Hangzhou 310036, China
$^3$Zhejiang California International NanoSystems Institute, Zhejiang University, Hangzhou 310058, China
$^4$Collaborative Innovation Centre of Advanced Microstructures, Nanjing 210093, China
(Dated: 28 February 2018)

We synthesized nonmagnetic PtBi$_2$ single crystals and observed a giant linear magneto-resistance (MR) up to 684% under a magnetic field $\mu_0 H = 15$ T at $T = 2$ K. The linear MR decreases with increasing temperature, but it is still as large as 61% under $\mu_0 H$ of 15 T at room temperature. Such a giant linear MR is unlikely to be described by the quantum model as the quantum condition is not satisfied. Instead, we found that the slope of MR scales with the Hall mobility, and it can be well explained by a classical disorder model.

PACS numbers: 75.47.Gk; 72.15.Gd; 71.20.Lp; 85.75.Bb

Materials exhibiting large magneto-resistance (MR) can not only be utilized to enlarge the sensitivity of read/write heads of magnetic storage devices, e.g., magnetic memory and hard drives, but also stimulate many fundamental studies in material physics at low temperatures. Generally speaking, the ordinary MR in non-magnetic compounds and elements is a relatively weak effect and usually at the level of a few percent for metals. Moreover, a conventional conductor under an applied magnetic field exhibits a quadratic field dependence of MR which saturates at medium fields and shows a relatively small magnitude. Owing to the rich physics and potential applications, the large linear MR effect has drawn renewed interest recently. There are two predominant models used to explain the origin of such large linear MR effect, namely, the quantum model and the classical model. The quantum model is proposed for materials with zero band gap and linear energy dispersion, such as topological insulators, graphene, Dirac semimetals like SrMnBi$_2$, and the parent compounds of iron based superconductors. Quantum linear MR occurs in the quantum limit when all of the electrons fill the lowest Landau level (LL). In contrast, the classical linear MR is dominated by disorder. Materials showing the classical linear MR include highly disordered systems, and weakly disordered samples with high mobility, thin films, and quantum Hall systems. However, it is interesting that the classical linear MR has also frequently been reported in materials with linear dispersions, such as the topological insulator Bi$_2$Se$_3$, graphene, and the Dirac semimetal Cd$_3$As$_2$, which may be due to their large mobility. Even weak disorder could induce linear MR in high-mobility samples. When the carrier concentration is too high for the quantum limit, the linear MR may be described by classical model for disordered systems.

In this Letter, we synthesized high quality single crystals of nonmagnetic PtBi$_2$ and investigated the magneto-transport properties. We observed a giant positive linear MR up to 684% under $\mu_0 H = 15$ T at $T = 2$ K. MR decreases with increasing temperature, but MR of 61% is still achieved under a magnetic field of 15 T even at room temperature. Regarding the origin of the linear MR, the close relationship between the MR and the Hall mobility implies that the observed linear MR should not be attributed to the quantum origin, but may be explained by the classical model.

The PtBi$_2$ single crystals were synthesized using a self-flux method. Powders of the elements Pt (99.97%) and Bi (99.99%), both from Alfa Aesar, were thoroughly mixed together in an atomic ratio of Pt:Bi = 1:8, before being loaded into a small alumina crucible. The crucible was then sealed in a quartz tube in Argon gas atmosphere. During the growth, the quartz tube was slowly heated up to 1273 K and kept at the temperature for 10 h. Finally it was slowly cooled to 873 K at a rate of -3 K/h, followed by centrifugation to remove the excessive Bi. The resulting single crystals are large plates with a typical dimension of $3 \times 3 \times 0.05$ mm$^3$. We cut the single crystal into a rectangle of about $1 \times 0.4 \times 0.05$ mm$^3$ for transport measurements. The stoichiometry and structure of these single crystals were checked using Energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) measurements. All transport measurements were carried out in an Oxford-15 T cryostat with a He4 probe in a Hall-bar geometry, using Keithley 2400 sourcemeters and 2182A nanovoltmeters.

As illustrated in Fig. 1(a), PtBi$_2$ has a layered pyrite crystal structure with the space group of P3 (No. 147) and Fig. 1(b) shows the X-ray diffraction pattern of the PtBi$_2$ single crystals. Only multiple reflections of (0 0 l) planes can be detected, consistent with the layered crystal struc-

---

(a) Electronic mail: zhuan@zju.edu.cn
ture depicted in Fig. 1(a). The interplane spacing is determined to be 6.16 Å, agreeing well with the previous reported value.\(^{21}\)

The temperature dependence of in-plane resistivity curves under magnetic fields (\(|c|\)) of \(\mu_0H = 0, 5, 10\) and 15 T are displayed in Fig. 2(a). In zero field, the room temperature resistivity is 1.1 \(\mu\Omega \text{ m}\) and decreases to 0.13 \(\mu\Omega \text{ m}\) at 2 K, yielding a residual resistivity ratio (RRR) of 8.5. When a field is applied, the resistivity increases rapidly, corresponding to a large positive magnetoresistance. As a result, linear field dependence could appear even under high field along the magnetic field (not showing here) and thus MR would still show saturated behavior. In other directions MR would still show netoresistance (MR = \(\Delta\rho(H)/\rho(0) = \rho(H)/\rho(0) - 1\)) as a function of magnetic field \(\mu_0H\) at a series of temperatures \(T = 2, 20, 60, 100\) and 300 K.

We first consider a quantum explanation for the observed linear MR phenomenon in the framework developed by Abrikosov.\(^9\) Following this theory, linear MR will appear in the quantum limit, when \(\hbar\omega_c\) exceeds the Fermi energy \(E_F\) and all the electrons occupy the lowest LL. In such a limit, the quantum magnetoresistivity is calculated as \(\rho_{xx} = N_iB/\pi n^2e\), where \(n\) and \(N_i\) are the electron density and the concentration of scattering centers, respectively. The equation is valid under the condition, \(n \ll (eB/\hbar)^3/2\). That is, the quantum linear MR would appear when \(B \gg (\hbar/e)n^{3/2}\). In Fig. 3(a), we have plotted the temperature dependence of Hall coefficient (\(R_H\)). The Hall resistivity \(\rho_{yx}\) is linearly dependent on the magnetic field (not showing here) and thus we use a single-band model to estimate the charge carrier density, i.e., \(n = 1/eR_H\) and to calculate the critical magnetic field of \((\hbar/e)n^{3/2}\). We find that, even at 2K, it needs \(\sim271\) T to satisfy the quantum condition, which is far higher than the maximum field of 15 T in our experiments. Therefore, the observed linear MR in PtBi\(_2\)
is unlikely to be explained by the quantum model.

Instead, the classical disorder models\textsuperscript{19} may provide a reasonable explanation for the presence of linear MR in PtBi\textsubscript{2}. In the disorder network model, the linear MR appears when the local current density gains spatial fluctuations in both magnitude and direction, as a result of inhomogeneous carrier or mobility distribution\textsuperscript{10,17}. Such classical linear MR phenomena have been observed in various disordered systems, such as Bi\textsubscript{2}Se\textsubscript{3}, n-doped Cd\textsubscript{3}As\textsubscript{2}\textsuperscript{17}, and epitaxial graphene on SiC\textsuperscript{2}. In the classical model, the slope dMR/dB is predicted to be proportional to the Hall mobility: dMR/dB \propto \mu. Indeed, the dMR/dB, which is defined as the slope of the linearly fitting line of the linear region of MR at higher fields, exhibits the same temperature dependence (see the black solid squares in Fig. 3(b)) as the Hall mobility (red hollow circles). The curve of dMR/dB versus \mu can be fitted linearly very well, as shown in the inset of Fig. 3(b). This strongly suggests that the origin of the observed linear MR in our sample could be classical.

This classical origin can be further verified by scaling the inverse Hall mobility with the crossover magnetic field (B*)\textsuperscript{2}. We define the B*, marked by the arrow, as the crossing point of linear fits at the low and high field regimes, which are shown as blue dashed lines in the inset of Fig. 4. In the classical model, the crossover field is predicted to be linearly proportional to the inverse Hall mobility: B* \propto 1/\mu. Fig. 4 shows B* versus inverse Hall mobility, which displays good linear dependence, consistent with the classical model well. This further confirms that the origin of the observed linear MR could be classical. The disorder in the single-crystalline samples could come from the Bi-site vacancies. The occupation of Bi sites obtained by EDX is around 94%, which confirms the existence of Bi-site vacancies.

In summary, we performed detailed magnetotransport property measurements in the PtBi\textsubscript{2} single crystals. PtBi\textsubscript{2} exhibits very large linear magnetoresistance (684% in 15 T field at 2 K). The giant linear MR can scale well with the mobility. Our work indicates that the giant linear MR could arise from the classical origin, which makes PtBi\textsubscript{2} an appealing system for both practical use and further investigation on its physical properties.

This work is supported by the National Basic Research Program of China (Grant Nos. 2014CB921203 and 2012CB927404), NSF of China (Contract Nos. U1332209 and 11190023), the Ministry of Education of China (Contract No. 2015KF07), and the Fundamental Research Funds for the Central Universities of China.

\textsuperscript{1}Y. Moritomo, A. Asamitsu, H. Kuwahara, and Y. Tokura, Nature \textbf{380}, 141 (1996).
\textsuperscript{2}J. Daughton, J. Magn. Magn. Mater. \textbf{192}, 334 (1999).
\textsuperscript{3}A. Urushibara, Y. Moritomo, T. Arima, A. Asamitsu, G. Kido, and Y. Tokura, Phys. Rev. B \textbf{51}, 14103 (1995).
\textsuperscript{4}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 \textbf{514}, 205 (2014).
\textsuperscript{5}F. Y. Yang, K. Liu, K. Hong, D. H. Reich, P. C. Searson, and C. L. Chien, Science \textbf{284}, 1335 (1999).
\textsuperscript{6}A. Husmann, J. B. Betts, G. S. Boebinger, A. Migliori, T. F. Rosenbaum, and M. L. Saboungi, Nature \textbf{417}, 421 (2002).
W. J. Wang, K. H. Gao, Z. Q. Li, T. Lin, J. Li, C. Yu, and Z. H. Feng, Appl. Phys. Lett. 105, 182102 (2014).

N. V. Kozlova, N. Mori, O. Makarovskiy, L. Eaves, Q. D. Zhuang, A. Krier, and A. Patanè, Nat. Commun. 3, 1097 (2012).

A. A. Abrikosov, Sov. Phys. JETP 29, 746 (1969); A. A. Abrikosov, Phys. Rev. B 58, 2788 (1998); A. A. Abrikosov, EPL 49, 789 (2000).

M. M. Parish and P. B. Littlewood, Nature 426, 162 (2003).

X. Wang, Y. Du, S. Dou, and C. Zhang, Phys. Rev. Lett. 108, 266806 (2012).

A. L. Friedman, J. L. Tedesco, P. M. Campbell, J. C. Culbertson, E. Aifer, F. K. Perkins, R. L. Myers-Ward, J. K. Hite, C. R. EddyJr., G. G. Jernigan, and D. K. Gaskill, Nano Lett. 10, 3962 (2010).

J. Park, G. Lee, F. Wolff-Fabris, Y. Y. Koh, M. J. Eom, Y. K. Kim, M. A. Farhan, Y. J. Jo, C. Kim, J. H. Shim, and J. S. Kim, Phys. Rev. Lett. 107, 126402 (2011).

K. Huynh, Y. Tanabe, and K. Tanigaki, Phys. Rev. Lett. 106, 217004 (2011).

J. Hu, M. M. Parish, and T. F. Rosenbaum, Phys. Rev. B 75, 214203 (2007).

C. Herring, J. Appl. Phys. 31, 1939 (1960).

A. Narayanan, M. D. Watson, S. F. Blake, L. Bruyant, L. Drigo, Y. L. Chen, D. Prabhakaran, B. Yan, C. Felser, T. Kong, P. C. Canfield, and A. I. Coldea, Phys. Rev. Lett. 114, 117201 (2015).

J. Hu and T. F. Rosenbaum, Nat. Mater. 7, 697 (2008).

S. H. Simon and B. I. Halperin, Phys. Rev. Lett. 73, 3278 (1994).

Y. Yan, L. Wang, D. Yu, and Z. Liao, Appl. Phys. Lett. 103, 033106 (2013).

T. Biswas, and K. Schubert, Journal of the Less Common Metals 19, 223 (1969).

A. B. Pippard, *Magnetoresistance in Metals* (Cambridge University, Cambridge, 1989).

K. Wang, and C. Petrovic, Phys. Rev. B 86, 155213 (2012); K. Wang, and C. Petrovic, Appl. Phys. Lett. 101, 152102 (2012).

M. Ziman, *Principles of the Theory of Solids*, 2nd edn. (Cambridge University Press, Cambridge, 1972), p. 252.