Parallel Field Magnetoresistance in Topological Insulator Thin Films

C. J. Lin,1 X. Y. He,1 J. Liao,1 X. X. Wang,1,2 V. Sacksteder IV,1 W. M. Yang,1 T. Guan,1 Q. M. Zhang,1 L. Gu,1 G. Y. Zhang,1 C. G. Zeng,2 X. Dai,1 K. H. Wu,1 and Y. Q. Li1,∗

1Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
2Hefei National Laboratory for Physics at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

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We report that the finite thickness of three-dimensional topological insulator (TI) thin films produces an observable magnetoresistance (MR) in phase coherent transport in parallel magnetic fields. The MR data of Bi2Se3 and (Bi1−xSbx)2Te3 thin films are compared with existing theoretical models of parallel field magnetotransport. We conclude that the TI thin films bring parallel field transport into a unique regime in which the coupling of surface states to bulk and to opposite surfaces is indispensable for understanding the observed MR. The β parameter extracted from parallel field MR can in principle provide a figure of merit for searching TI compounds with more insulating bulk than existing materials.

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Much of the experimental effort on 3-dimensional (3D) topological insulators, an exotic class of quantum matter, has been devoted to obtaining samples with large bulk resistivities. This is essential to observing intrinsic transport properties of surface states and also a plethora of fascinating effects emerging from hybrid structures combining TIs with other materials. Observation of surface transport was once very challenging, since the first identified TI materials tend to exhibit a conducting bulk. Recent breakthroughs in material design have produced TI compounds with bulk resistivities over 1 Ω·cm (e.g. Bi2Te3 and (Bi1−xSbx)2Te3 thin films are compared with existing theoretical models of parallel field magnetotransport). We conclude that the TI thin films bring parallel field transport into a unique regime in which the coupling of surface states to bulk and to opposite surfaces is indispensable for understanding the observed MR. The β parameter extracted from parallel field MR can in principle provide a figure of merit for searching TI compounds with more insulating bulk than existing materials.

The latter is usually much more pronounced, and it has been a subject of intensive studies. The magnetic flux generated by the parallel field produces an Aharonov-Bohm phase which affects electrons when they make a closed loop and causes positive magnetoresistance (MR), similarly to the positive MR produced by a perpendicular field. The latter is usually much more pronounced, and it has been a subject of intensive studies. In contrast, the parallel field MR has not received systematic experimental effort despite a few theoretical predictions on novel quantum effects induced by the parallel magnetic fields.

The weak (anti)localization effect in parallel field transport was first predicted in 1981 by Altshuler and Aronov (AA) for dirty metal films, and was later generalized to cleaner films and bilayer systems. In this paper we show that none of these models developed for topologically trivial systems can fully describe the parallel field MR observed in Bi2Se3 and (Bi1−xSbx)2Te3 thin films. Our data point to qualitatively different regimes for phase coherent transport in parallel magnetic fields, and suggest that the essential ingredients include the existence of surface states, their coupling to the bulk, and coupling between opposite surfaces. Knowledge obtained from perpendicular field transport alone is insufficient to provide a satisfactory description of the complicated ele-
electron systems encountered in this work. For instance, the widely used two-channel model\textsuperscript{32,36,57,59} fails to explain the ambipolar transport in (Bi\textsubscript{1−x}Sb\textsubscript{x})\textsubscript{2}Te\textsubscript{3} thin films, and the parallel field transport suggests the importance of bulk conductivity in these films.

Fig. 1b illustrates several regimes of parallel field transport. These include the AA regime for thin films with mean free path much smaller than the film thickness (l\textsubscript{c} ≪ d)\textsuperscript{21} the Dugaev-Khmelnitskii (DK) regime for clean metal films (l\textsubscript{c} ≫ d)\textsuperscript{21} and the Beenakker-van Houten (BVH) regime\textsuperscript{64} which describes the crossover between the AA and DK regimes. The correction to the conductivity in all three regimes can be written in a unified form:

$$\Delta \sigma_\parallel(B) \simeq \alpha \frac{-e^2}{2\pi^2 h} \ln \left(1 + \beta \frac{e^2}{4\hbar B_\phi} B^2 \right), \quad (1)$$

where \(\Delta \sigma_\parallel(B) \equiv \sigma_{xx}(B) - \sigma_{xx}(0) \approx -\text{MR}/\rho_{xx}(0)\). The parameter \(\alpha\) takes values of 1/2 and −1 respectively for weak antilocalization and weak localization. In these traditional single layer systems the upper bound of \(\beta\) is reached in the AA regime with \(\beta_{AA} = 1/3\) while the DK regime gives the lower limit \(\beta_{DK} = (1/16)d/l\textsubscript{c} \ll 1\)\textsuperscript{21}. The dephasing field \(B_\phi\) can be obtained by fitting the perpendicular field magnetoconductivity (MC) to the Hikami-Larkin-Nagaoka (HLN) equation\textsuperscript{65} which in both strong and weak limits of the spin-orbit coupling (SOC) simplifies to:

$$\Delta \sigma_\perp(B) \simeq \frac{e^2}{2\pi^2 h} \left[\psi \left(\frac{1}{2} + \frac{B_\phi}{B}\right) - \ln \left(\frac{B_\phi}{B}\right)\right], \quad (2)$$

where \(\psi(x)\) is the digamma function.

A similar magnetoconductivity exists also in coupled bilayer systems, but its magnitude depends on the conductivity and dephasing time of each layer (\(\sigma_{xx,i}\) and \(\tau_{\phi,i}, i=1,2\)), as well as the interlayer tunneling (or transition) time \(\tau_s\). For symmetric bilayers (with \(\sigma_{xx,1}=\sigma_{xx,2}\) and \(\tau_{\phi,1}=\tau_{\phi,2}=\tau_\phi\)) \(\Delta \sigma_\parallel(B)\) follows the same form as Eq. (1) with \(\beta = 2(1+s)/(1+2s)−\ln(1+2s)/s\) and \(s = \tau_\phi/\tau_s\), according to Raichev and Vasilopoulos (RV)\textsuperscript{65}. In the weak coupling limit (\(\tau_\phi \ll \tau_s\)) \(\beta\) is suppressed quadratically \(\beta \simeq (4/3)(\tau_\phi/\tau_s)^2 \ll 1\), whereas in the strong coupling limit (\(\tau_\phi \gg \tau_s\)) \(\beta\) approaches 1 (see supplemental information\textsuperscript{65}).

Fig. 2 shows the magnetotransport results of Bi\textsubscript{2}Se\textsubscript{3} thin films with thicknesses of 7-45 nm for both perpendicular and parallel field orientations. The parallel field MC has a pronounced dependence on thickness, and its field dependence is drastically different from that of the perpendicular MC (Fig. 2a). Hall measurements show that the sheet carrier density \(n_s\) is in the range 1.8-4.6×10\textsuperscript{13} cm\textsuperscript{−2} which indicates that the Fermi level is located in the bulk conduction band, in agreement with previous studies\textsuperscript{16,21,56}. The perpendicular field MC can be fitted to the HLN equation (Fig. 2b), and \(\alpha\) is close to 1/2 for all films (Fig. 2c). This is consistent with previous measurements of Bi\textsubscript{2}Se\textsubscript{3} across a large range of electron densities\textsuperscript{36,38,59,66} mobilities\textsuperscript{36,38,59,66} and film thicknesses\textsuperscript{66}. At the electron densities encountered in this work both surface and bulk carriers are expected to contribute substantially to transport. Nonetheless the WAL manifested in perpendicular field transport does not show any qualitative difference from topologically trivial thin films with strong SOC\textsuperscript{36,38,59,66} such as Au thin films\textsuperscript{65}. It has been suggested that strong scattering between surface and bulk states makes the system behave as a single channel system when the dephasing rate is much smaller than the surface-bulk scattering rate\textsuperscript{36,38,59,66}. An angle-resolved photoemission spectroscopy (ARPES) experiment has found evidence for strong surface-bulk scattering in Bi\textsubscript{2}Se\textsubscript{3} when the Fermi level is located in the bulk conduction band\textsuperscript{36,38,59,66}.

Fig. 2d illustrates the strong thickness dependence of the parallel field MC. The data are fitted to Eq. (1) with \(\alpha\) fixed at 1/2. Since \(B_\phi\) can be obtained from the HLN fits, \(\beta\) is the only free parameter. In Fig. 2e we fix \(T \approx 2\) K and show that for all thicknesses studied here \(\beta\) is close to 1/3, the value predicted by AA for topologically trivial dirty metal films. The fact that \(\beta\) is nearly constant implies that \(\Delta \sigma_\parallel(B)\) is proportional to \(d^2\) in low fields [see Eq. (1)].

Even though these observations seem consistent with the AA prediction for a single bulk layer, this is only
films with (g) faces be separated by many scattering lengths, namely a coincidence, because the AA regime requires the surface states and their couplings to bulk may be key to the observed parallel field MC. A sizable portion of the current is carried by the surface states in these films, and this inhomogeneous current distribution can account for the discrepancy between the BVH prediction and the much larger experimental values. The T-dependence of $\beta$ can be attributed to the variation in the ratio $\tau_\phi/\tau_{sb}$, where $\tau_{sb}^{-1}$ is the scattering rate between surface and bulk carriers and $\tau_\phi$ is the dephasing time. As suggested in the ARPES experiment, $\tau_{sb}^{-1}$ is dominated by sample disorder at low $T$, and hence is expected to be nearly $T$-independent. Electron-electron interactions are the leading source of electron dephasing at low $T$ and hence $\tau_\phi^{-1} \propto T^{2/7}$. This implies that increasing $T$ causes the surface states to decouple from the bulk, resulting in decrease in the finite thickness effect.

In Bi$_2$Se$_3$ both the high density of selenium vacancies and various surface doping effects makes it difficult for back-gating to effectively suppress bulk transport. This difficulty is remedied in (Bi$_{1-x}$Sb$_x$)$_2$Te$_3$ compounds, which display much improved gate tunability. Ambipolar transport can be obtained reliably in (Bi,Sb)$_2$Te$_3$ films grown epitaxially on SrTiO$_3$. Fig. 3 shows transport data for an 18 nm (Bi,Sb)$_2$Te$_3$ sample at $T = 1.5$ K. At $V_G = 0$ the sample is p-type, but at large positive gate voltages ($V_G > 80$ V) it enters the
FIG. 4. (color online) (a) Temperature dependence of $\alpha$ at $V_G = -150$ V (hexagons) and +200 V (squares). (b) Schematic band diagrams for these two gate voltages. (c) $T$-dependencies of $\beta$ at $V_G = -150$ V and +200 V. (d) $\beta$ plotted as a function of $1/T$ (squares, $V_G = +200$ V) and as a function of the coupling strength $s = \tau_0/\tau_s$ (line, symmetric bilayer in RV theory).
In this work we neglect the magnetoconductivity of the side surfaces since the Hall bars’ width of 50 μm is three
orders of magnitude larger than their thickness ($\lesssim 50\text{ nm}$). Ref.\textsuperscript{51} finds that the finite penetration depth $\lambda$ of the surface state wavefunction leads to a positive parallel field MR proportional to $\ln(1 + bB^2)$ with $b \propto \lambda^2$. However, this effect is much smaller than the effects discussed in the main text as well as surface roughness effect\textsuperscript{52} since $\lambda$ is only about 2 nm or less for typical TIs.

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