Whispers in Bedlam: Detecting the Dirac metal at a surface of a topological insulator by means of weak localization

Electrically tunable surface-to-bulk coherent coupling in topological insulator thin films.
arXiv:1104.1404 (2011)
Authors: H. Steinberg, J.-B. Laloö, V. Fatemi, J. S. Moodera, P. Jarillo-Herrero
and
Tunable surface conductivity in Bi_2Se_3 revealed in diffusive electron transport
Phys. Rev. B **83**, 241304/1-4 (2011)
Authors: J. Chen, X. Y. He, K. H. Wu, Z. Q. Ji, L. Lu, J. R. Shi, J. H. Smet, and Y. Q. Li

Recommended with a Commentary by Leonid Glazman, Yale University

The stunning theoretical discovery of 3D topological insulators [1–3] and the associated concrete material suggestions [4–6] touched off an avalanche of experiments aimed at detecting the signature behavior of these unconventional solids. The band structure characteristic for 3D topological insulators was seen in ARPES spectra [7]. Local STM probes also indicated the characteristic suppression of backscattering off the surface imperfections [8, 9]. However, the most desired observation of the hallmark metallic behavior of the dc conduction *confined to the surface layer* of a 3D topological insulator remains elusive. The main problem is the conduction through the bulk: in reality, these exotic insulators are narrow-gap semiconductors with the gap width in the ballpark of 0.3 eV. Apart from thermal excitation, the bulk carriers are provided by the crystalline lattice imperfections which act as a natural dopant. A popular material, Bi_2Se_3, is n-doped by the Se vacancies. Along with the attempts to reduce the bulk charge carriers density, experimentalists develop techniques which would allow them to register a *separate* conduction channel along the surface of a topological insulator. Measurements of the low-field magnetoresistance combined with electrostatic gating of thin-film samples became a burgeoning and promising direction of experiments; an incomplete list of works which appeared within a span of a year and devoted to Bi_2Se_3 include Refs. [10–14].

Making sample thinner mitigates the parasitic bulk conductance. Electrostatic gating may help in reducing the bulk density of charge carriers [10, 11, 13]. More importantly, it may affect the electron tunneling between the bulk and the putative surface 2D band [13, 14]. Measurement of the low-field magnetoresistance may hold the key in detecting the conduction along a separate surface band.

The low-field anomaly in the magnetoresistance is associated with the interference correction to the Drude conductivity σ_D. At low temperatures, σ_D is defined by independent acts of scattering of electrons off the imperfections of the crystal and is proportional to the classical electron diffusion constant D. If an electron wave preserves its coherence for a sufficiently long time $\tau_\varphi(T)$, then the interference between the electron partial waves scattered off different sites affects the conductivity. The sign of the interference correction to conductivity depends on spin-orbit interaction. In its absence, the correction is negative ("weak localization"). Spin-orbit interaction leads to suppression of backscattering, resulting in the weak anti-localization (WAL). Being an electron interference effect, WAL is degraded by a magnetic field [15, 16]. Its characteristic value B_φ corresponds to the flux quantum Φ_0 piercing a typical trajectory capable to contribute to the interference. The area under such trajectory is $l_\varphi^2 \sim D\tau_\varphi$, yielding $B_\varphi(T) \sim \Phi_0/[D\tau_\varphi(T)]$. For a diffusive 2D electron system, the resulting magnetoresistance $\Delta\sigma_{\mathrm{WAL}}(B) \equiv \sigma(B) - \sigma(0) = (Ae^2/\pi h)\ln(B_\varphi/B)$ at field $B \gg B_\varphi$ (here $\ln(\ldots)$ is an asymptote of a known function [15] valid at arbitrary B/B_φ; "weak" in WAL means $|\sigma_{WAL} - \sigma_D|/\sigma_D \ll 1$). As long as one deals with a single-component electron system, the coefficient A here is universal, $A = 1/2$; it is the same for a single-layer 2D system and for a thin film [15, 16] consisting of many atomic layers. The WAL corrections add for systems which are isolated from each other. Having two independent parallel conduction channels would yield $A = 1$, regardless the ratio of the Drude conductivities of the two sub-systems.

The relation between A and the number of parallel channels is at the heart of experiments [13, 14], and also was touched upon in Ref. [11]. The found $\Delta\sigma(B)$ dependence [13, 14] agrees well with the functional form provided by 2D WAL theory [15]. However, the coefficient A depends on the gate voltage V_G. For some devices [11, 13, 14], A changes from $A = 1/2$ all the way to $A = 1$.

A very plausible interpretation of that variation is presented in [14]: At zero or positive bias applied to the top gate of their devices (made of 20 nm thick Bi_2Se_3) electrons from the n-doped bulk reach the surface states easily; the entire film acts as a single electron system, and $A = 1/2$. At negative bias, the Dirac point of the gapless surface states emerges from under the Fermi level, and, in some window of V_G, a peculiar $p - n$ junction is formed. One side of the junction is the n-doped bulk, while the opposite side is the Dirac surface band populated with holes. The depletion region of the junction separates the film in two sub-systems, $A = 1$. A stronger negative bias apparently leads to the bulk inversion (accompanied by a precipitous drop in the resistance). Further confirmation of the crossover between the single-system transport and the parallel conduction of the surface and bulk comes from the analysis of the $l_\varphi(T)$ dependence [14].

To conclude, we mention here that the samples and data of Refs. [13, 14] look pretty similar, while interpretation is somewhat different: authors of Ref. [13] conclude that at the negative bias conduction occurs along the two surfaces of the film, while its bulk does not contribute to conductivity. Hopefully, future experiments will resolve this issue.

[1] L. Fu, C. L. Kane, and E. J. Mele, Phys. Rev. Lett. **98**, 106803 (2007).

[2] J. E. Moore and L. Balents, Phys. Rev. B **75**, 121306 (2007).

[3] R. Roy, Phys. Rev. B **79**, 195321 (2009).

[4] L. Fu and C. L. Kane, Phys. Rev. B **76**, 045302 (2007).

[5] H. Zhang, C.-X. Liu, X.-L. Qi, X. Dai, Z, Fang, and S.-C. Zhang, Nature Physics **5**, 438 (2009).

[6] H.-J. Zhang, C.-X. Liu, X.-L. Qi, X.-Y. Deng, X. Dai, S.-C. Zhang, and Z. Fang, Phys. Rev. B **80**, 085307 (2009).

[7] M. Z. Hasan, D. Hsieh, Y. Xia, L. A. Wray, S.-Y. Xu, and C. L. Kane, preprint arXiv:1105.0396 (2011).

[8] Z. Alpichshev, J. G. Analytis, J.-H. Chu, I. R. Fisher, Y. L. Chen, Z. X. Shen, A. Fang, and A. Kapitulnik, Phys. Rev. Lett. **104**, 016401 (2010).

[9] J. Seo, P. Roushan, H. Beidenkopf, Y. S. Hor, R. J. Cava, and A. Yazdani, Nature **466**, 343 (2010).

[10] J. Chen, H. J. Qin, F. Yang, J. Liu, T. Guan, F. M. Qu, G. H. Zhang, J. R. Shi, X. C. Xie, C. L. Yang, K. H. Wu, Y. Q. Li, and L. Lu, Phys. Rev. Lett. **105**, 176602 (2010).

[11] J. G. Checkelsky, Y. S. Hor, R. J. Cava, and N. P. Ong, Phys. Rev. Lett. **106**, 196801 (2011)

[12] H.-T. He, G. Wang1, T. Zhang1, I.-K. Sou, G. K. L. Wong, and J.-N. Wang, Phys. Rev. Lett.

106, 166805 (2011).

[13] J. Chen, X. Y. He, K. H. Wu, Z. Q. Ji, L. Lu, J. R. Shi, J. H. Smet, and Y. Q. Li, Phys. Rev. B **83**, 241304 (2011).

[14] H. Steinberg, J.-B. Laloë, V. Fatemi, J. S. Moodera, P. Jarillo-Herrero, preprint arXiv:1104.1404 (2011).

[15] S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[16] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).