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

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and

Tunable surface conductivity in Bi$_2$Se$_3$ revealed in diffusive electron transport

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$_2$Se$_3$, 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$_2$Se$_3$ 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 $\sigma_D$. At low temperatures, $\sigma_D$ 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 $B_\varphi$ corresponds to the flux quantum $\Phi_0$ piercing a typical trajectory capable to contribute to the interference. The area under such trajectory is $l^2_\varphi \sim D \tau_\varphi$, yielding $B_\varphi(T) \sim \Phi_0 /[D \tau_\varphi(T)]$. For a diffusive 2D electron system, the resulting magnetoresistance $\Delta \sigma_{WAL}(B) \equiv \sigma(B) - \sigma(0) = (A e^2/\pi \hbar) \ln(B_\varphi/B)$ at field $B \gg B_\varphi$ (here $\ln(\ldots)$ is an asymptote of a known function [15] valid at arbitrary $B/B_\varphi$; "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$_2$Se$_3$) 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 $I_{\varphi}(T)$ 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.


