Observation of helical surface transport in topological insulator nanowire interferometer

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The discovery of three dimensional (3D) topological insulators opens a gateway to generate unusual phases and particles made of the helical surface electrons, proposing new applications using unusual spin nature. Demonstration of the helical electron transport is a crucial step to both physics and device applications of topological insulators. We report an observation of a topologically-protected 1D mode of surface electrons in topological insulator nanowires, which serves as a transport evidence of spin-momentum locking nature. Helical 1D mode exists at half magnetic quantum flux due to a spin Berry’s phase ($\pi$), robust against disorder and a change of Fermi level, but fragile against a perpendicular magnetic field breaking time-reversal-symmetry. This result demonstrates a device with new 1D helical electronic states from 3D topological insulators, a unique electronic system to study topological phenomena.

On the surface of topological insulators (TIs), electron spin is locked perpendicular to momentum, resulting in the suppression of electron backscattering from nonmagnetic impurities.[1–4] Such spin textured surface states have been studied extensively by surface probing techniques such as angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy (STM).[5–12] Electronic device demonstrating topologically distinctive properties, crucial to both physics and device applications, however, has lagged behind in part due to the dominance of large bulk carrier concentration. Recent studies on Shubnikov de Haas (SdH)[13–16] and Aharonov-Bohm (AB)[17, 18] oscillations have provided evidence of surface electron conduction although the unique spin nature remains undemonstrated in transport.

In a TI nanowire device, the Aharonov-Bohm (AB) effect, quantum interference of surface state electrons winding around the nanowire, offers a unique opportunity to detect topological protection in the helical surface electrons (Fig. 1a). Following the initial experimental works showing evidence of the surface electronic states,[17, 18] several theoretical works described the AB effect in the context of 1D modes in TI nanowires.[19, 20] 2D Dirac Fermions on the TI nanowire surface form 1D subbands due to the periodic boundary condition along the perimeter direction (Fig. 1b), in a similar manner to the transition from graphene to a carbon nanotube. The gap spacing between subbands depends on the dimension of the nanowire. In our typical TI nanowire (50nm height and 100nm width) with rectangular cross-sectional area, the estimated energy gap is 6-7meV.

An important difference of TI nanowires from carbon nanotubes is the existence of a spin Berry’s phase. Along the TI nanowire perimeter, the electron spin rotates by a 2$\pi$ angle due to the spin-momentum locking nature of electrons, leading to a Berry’s phase of $\pi$ (Fig. 1a). This spin Berry’s phase makes every 1D mode at zero magnetic flux gapped and spin-degenerated (Fig. 1b left). However, at half quantum flux ($h/2e$), the AB phase shift induced by the magnetic flux ($\pi$) cancels the spin Berry’s phase ($\pi$) resulting in a single, gapless 1D mode (Fig. 1b right).
right, red 1D subband) \[^{19, 20}\]. This gapless 1D mode, key in manifesting topologically-protected electrons, is not spin-degenerate and is protected by time reversal symmetry (TRS) from backscattering (localization). In this letter, we provide experimental results predicted in theoretical works from weak disorder to strong disorder and across a wide range of Fermi energy. Both the 1D band structure of the nanowire and the topological robustness of the helical 1D mode are demonstrated, providing an evident signature of topological protection in spin-momentum locked surface electrons.

Three main experimental observations are presented here to prove the topological nature of surface electrons. First, in the nanowires with least disorder, we observe oscillations of both h/e and h/2e periodicities. We attribute the former to the density of state (DOS) oscillations of the quasi-1D surface states and the latter to the electron interference in diffusive motion. Second, we induce stronger disorder by sample aging. Only one gapless helical mode peaking at half quantum flux survives while other topologically-trivial modes are suppressed by disorder. This is the manifestation of the topologically-protected 1D mode of the surface electrons. Finally, by applying perpendicular magnetic fields, we find that the helical mode is fragile to TRS breaking.

A heterostructure nanowire consisting of a Bi\(_2\)Se\(_3\) \[^{21, 22}\] core and an amorphous Se shell is synthesized by vapor-liquid-solid growth of a Bi\(_2\)Se\(_3\) nanowire \[^{23}\] followed by in-situ Se coating. A 2 nm-thick Se layer protects the Bi\(_2\)Se\(_3\) surface from environmental contamination and maintains a chemically stable surface (Fig. 1a). In addition, Cu doping (<1\%) and field effect gating (SiO\(_2\) 300nm) are used to manipulate the chemical potential of the nanowire. We believe that the insulating, inert Se layer is the key to preserve the high mobility of the TI surface electrons, as it suppresses the surface degradation. The high quality core-shell TI nanostructures, as quantum interferometers, are investigated systematically from the quasi-ballistic regime to the strong disorder limit.

In transport experiments of clean core-shell TI devices subject to a parallel magnetic field (Fig. 2a), we see periodic oscillations of conductance peaks, with a period of either h/2e flux or h/e flux (Fig. 2b-d). To investigate the physical origin of oscillations of two different periods, we monitor the evolution of the oscillations by tuning the Fermi level of the nanowire device with a back gate (Fig. 2f). All devices are n-type conductors due to the crystalline defects in Bi\(_2\)Se\(_3\) \[^{24, 25}\]. In device B (Fig. 2c-f), h/e period oscillations are the dominant features at small negative gate voltage (-40V). Interestingly, the location of conductance maxima in the h/e period component alternate between half quantum flux and integer quantum flux, by changing the Fermi level (Fig. 2c-e). That is, the h/e period component, deduced by subtracting conductance at two different fluxes (Fig. 2e top), has a phase switch depending on the Fermi level. On the other hand, h/2e period oscillations (Fig. 2e bottom) become stronger at larger negative gate voltage when the carrier density is lower (Fig. 2f).

While oscillations with h/2e period are understood as the interference between clockwise and counterclock-
FIG. 3. Quantum interference of the surface states with strong disorder. (a) A schematic of the band structure of 1D modes in the topological insulator nanowire in the strong disorder limit. Inset left. The helical 1D mode (red) at half quantum flux (h/2e) is protected from localization. (b) Numerical simulation of the localization length (λ) at different fluxes, with disorder strengths W=2Δ (Δ is the bulk energy gap). (c) A representative quantum interference of a disordered nanowire device (sample C) in parallel field, at different temperatures (2K-15K). Two strong conductance peaks are observed at half quantum flux, in addition to the suppressed oscillations and the zero flux peak from WAL of bulk carriers. (d) Quantum interferences from sample D at different Fermi levels tuned by a back gate voltage (V_G) (after aging). Background magneto-conductance is subtracted. (e) The conductance peak amplitude (ΔG) versus gate voltage (V_G) from (d). Electronic modes at the first half quantum flux (Φ=±h/2e) persist in the entire range of the Fermi level, while there is no conductance peak observed at integer quantum flux (Φ=±h/e). (f) Conductance change by applying back gate voltage. All the conductance values are rescaled by the device length/the nanowire perimeter.

Wise propagating electrons\[^{26}\], oscillations with h/e period can be described as 1D DOS oscillations versus the magnetic flux. When the Fermi level is far from the Dirac point, both the helical mode and many other spin-degenerate modes contribute to the transport. Therefore the phase of magneto-oscillations would depend on the flux dependence of the net DOS at the Fermi level contributed by many 1D modes\[^{19}\]. Conductance maxima will appear at the flux having more number of electronic states than other flux at the Fermi level (i.e. the Fermi level crossing a 1D band edge). Either half or integer quantum flux becomes maxima (minima), resulting h/e period oscillations with opposite phases. The experimentally observed switching of conductance maxima (Fig. 2e) is consistent with the 1D bandstructure of surface states due to periodic boundary condition\[^{19}\].

Because all 1D modes at the Fermi level contribute to quantum interference in the quasi-ballistic regime (Fig. 2), it is difficult to observe the unpaired helical mode at half quantum flux. The strongly disordered limit is expected to suppress all spin-degenerate 1D modes except the helical mode, providing an opportunity to manifest the spin Berry’s phase and topological protection against localization (Fig. 3a)\[^{20}\]. This implies that, in spite of strong disorder, the quantum interference from the topologically protected 1D mode, which only exists at half quantum flux due to the additional π spin Berry’s phase, should remain. The numerical simulation supports this picture, as the calculated localization length (λ) increases at the first half quantum flux (±h/2e) even if strong disorder suppresses all other quantum modes (Fig. 3b). The detection of the conductance peak at ±h/2e flux in the strongly disordered limit will provide conclusive evidence of a spin Berry’s phase as well as topological protection from localization\[^{20}\]. The peak position should be independent from the Fermi level since there is only one helical mode participating in the interference.

One important premise here is that such strong disorder should not create inelastic scattering events, which can break TRS and thus also the topological protection. From the TI nanowires without a protective layer, we only observe the conductance peak at zero flux corresponding to weak antilocalization of bulk carriers. We believe that the chemically modified Bi₂Se₃ surface introduces many inelastic impurities destroying TRS in the surface states. To induce strong disorder without affecting the Bi₂Se₃ surface, we kept core-shell nanowire de-
ices under inert atmosphere where aging at room temperature would create more disorder in the TI nanowire core but the surface would remain chemically stable under the Se shell.

From the core-shell TI nanowires with more disorder, we observe two strong conductance peaks at ±h/2e flux while other oscillations are suppressed (Fig. 3c). These half quantum flux peaks are even larger than the zero-field peak, and thus unlikely the remains of h/2e period oscillations. In another device, which showed both h/e and h/2e period oscillations before aging, we also observed half quantum flux peaks after sample aging (Fig. 3d-f). The half quantum flux peaks do not change location in the wide range of the Fermi level as tuned by the gate voltage, excluding the possibility of the h/e oscillations from DOS effect (Fig.2e). Therefore, we expect that the half quantum flux peaks observed from strongly disordered samples are from the 1D helical mode protected against backscattering[20]. This result clearly demonstrates that the surface electrons are protected from Anderson localization due to the spin-momentum locking. We note that in addition to the suppression at the integer quantum fluxes, no conductance peak is observed at higher orders of half quantum flux (i.e. 3h/2e) in both the experiments and the numerical results (Fig. 3b-d). This can be understood as a local TRS breaking effect at strong disorder under a large parallel magnetic field.

Finally, the quantum interferences in both the clean regime and disordered limit are studied under TRS breaking condition, by a perpendicular magnetic field[3]. The nanowire devices, initially aligned along the magnetic field direction, are tilted to create a small perpendicular field (Fig. 4a). We observe that h/e period oscillations do not change much by the perpendicular field within a few hundreds millitesla (Fig. 4b). This is consistent with the theoretical explanation that the h/e period oscillations are not from interference but from the 1D bandstructure which is insensitive to the TRS breaking. In contrast, the h/2e oscillations are from the interference between electrons along two different time-reversed paths, therefore these oscillations would be affected by TRS breaking. The experimental data show that the amplitude of h/2e oscillations decrease as the perpendicular field increases (∼100mT) (Fig. 4b,d). The most fragile feature observed under the TRS breaking condition is the helical 1D mode peaks at the first half quantum flux persisting in the disordered limit. They disappear at the perpendicular magnetic field of ∼20mT (Fig. 4b-c). The fragileness against TRS breaking further confirms the topological nature of the half flux peak, which is very similar to the magneto-conductance of the HgTe quantum spin Hall edge state[3].

The robustness of 3D TI surface states against disorder is shown via AB conductance oscillations. A 1D nanostucture and sufficiently strong (elastic) disorder are the key requirements to observe quantum nature of surface electrons via robust helical 1D mode[20]. The detected conductance peak not only manifests topological protection originated from the spin texture, but is, itself, of fundamental interest. For example, the helical 1D mode is expected to host 1D topological superconducting states immune to disorder[27], serving as an attractive candidate for Majorana zero-modes[28]. Appropriate material design was critical to study the exotic properties of the topological surface states. The clean TI surface protected by an in-situ Se coating allows us to explore high mobility transport in the wide range of the Fermi level and shows the coherent topological nature in a long range exceeding the nanowire perimeter. This core-shell heterostructure nanowire device offers an ideal candidate for a topological quantum device, making use of the exotic nature of the surface electrons.

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