One-dimensional weak antilocalization in single-crystal Bi$_2$Te$_3$ nanowires

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Angle-dependent magnetoconductance was measured on an individual surface-curved Bi$_2$Te$_3$ single-crystal nanowire fabricated by electrochemical deposition, where the evolution of surface conduction with wire diameters was investigated. It was found that the magnetoconductance of these nanowires in low field regime can be well described by one-dimensional (1D) weak antilocalization (WAL) model, where the dephasing length of the electrons follows $T^{-2/3}$ dependence but insensitive to the wire diameter. Meanwhile, such a 1D surface WAL was found to be enhanced significantly with the decrease of the wire diameter.

Topological insulator (TI) is a new state of matter. It is characterized by a full insulating gap in the bulk and gapless spin-resolved surface state (SS) in which the spin of the electrons is locked perpendicular to its momentum by the strong spin-orbit interaction. These spin helical properties of Dirac fermions in SS have made them relevant for exotic new physics and applications on improved spintronic devices and potentially useful for quantum computing. In three-dimensional (3D) TIs, the topological surface states have been proved by angle-resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy (STM) and electrical transport measurements including two-dimensional (2D) weak antilocalization (WAL), Shubnikov-de Haas (SdH) or quantum Hall (QH) effect, where a 2D character was determined due to a fact that all of these effects were found only sensitive to the perpendicular component of the magnetic field. However, direct probing the surface state of an individual nanowire by ARPES is almost impossible because of the limitation of sample size. Instead, electrical transport measurement become the most efficient way to obtain the surface information due to its unique geometry and extreme large surface to volume ratio. Several quasi-1D nanoribbons have been synthesized, including Bi$_2$Se$_3$, Bi$_2$Te$_3$ and Bi$_2$(Se$_x$Te$_{1-x}$)$_3$-type nanoribbons, where the Aharonov-Bohm and Aharonov-Aronov-Spivak effect and 2D WAL of the SS were found. Compared with the TI nanoribbons with two well-defined parallel surfaces, the nature of the surface state in a surface-curved 1D cylindrical nanowire has not been well explored experimentally although a number of unique and fascinating properties have been predicted theoretically, such as the possible helical Luttinger liquid that was ever described as the edge mode of the 2D quantum spin Hall (QSH) topological insulator.

In this work, we report angle-dependent magnetoresistance (MR) studies on an individual surface-curved Bi$_2$Te$_3$ nanowire fabricated by electrochemical deposition. The evolution of the surface conduction with wire diameters was carefully investigated. It was found that the nanowires of different diameters showed similar positive MR behavior, where the variations of their magnetoconductance at different angles, $\Delta G(\theta, B)$, by subtraction of the magnetoconductance at $\theta = 0^\circ$ can be surprisingly normalized to one curve with the perpendicular component, $B_{\perp} = B \sin \theta$, of the magnetic field, where $\theta$ is the angle between $B$ and the wire axis as shown schematically in the inset of Fig. 3(a). Such a behavior is a direct indication of the WAL of the surface states of nanowire. Theoretical analysis based on the WAL model showed that the dephasing length of electrons in these thin curved nanowires follows $T^{-2/3}$ temperature dependence but insensitive to the wire diameter, indicating the 1D WAL character from the surface channels of the nanowire instead of the expected 2D WAL reported in nanoribbons and bulk. These results are also consistent with our observation that the upper limit for the range of the magnetic fields which is appropriate for fitting the observed 1D WAL increases significantly with the decrease of the wire diameter, i.e., an enhancement of quasi-one dimensionality in electrical transport of surface states in small diameter wire.
Results

All of Bi$_2$Te$_3$ nanowires used in this work were synthesized by electrochemical deposition via customer-made porous anodic aluminum oxide (AAO) membrane. The wire diameter was exactly controlled by the pore size of the template$^{29}$ so that we are able to carry out a systematic comparative study on wires of various diameters by selecting the templates with proper pore size. While the diameter of each wire along its length is uniform, it shows variations from wire to wire within an uncertainty of $\pm 20\%$, verified by both scanning electron microscopy (SEM) and transmission electron microscopy (TEM). It was shown that the majority of the nanowires have a length of 8–15 $\mu$m with single-crystal morphology as shown in Figs. 1 (a), 1(b) and 1(c). An oxidation layer of approximately $\sim 5.0$ nm, which was probably formed after the nanowires were released from the membrane, is visible on the surface. All samples of different diameters, such as 300 nm, 100 nm and 50 nm showed very similar structure, verified by x-ray diffraction measurements on the nanowire arrays (see Fig. 1d), where the (110) diffraction is the dominant peak in the spectra.

Standard 4-probe transport measurements were carried out on an individual nanowire using a physical property measurement system (PPMS). Four platinum (Pt) strips of 100 nm (width) $\times$ 100 nm (thickness) as shown in the lower inset of Fig. 2 (a) were deposited onto the wire as the contact electrodes using FEI Helios NanoLab 600i FESEM/FIB dual beam system. Resistance as a function of temperature for three individual Bi$_2$Te$_3$ nanowires of 300 nm, 100 nm and 50 nm showed very similar transport behavior in high temperature range (see Fig. 2a), such as a resistance hump near 220 K and a subsequent metallic behavior down to $\sim 25$ K. We noticed that the hump behavior of the resistance usually appears in TI-samples with the reduction of bulk carrier density less than $10^{17}$/cm$^3$ by element-doping (e.g., Na$^{30}$, Pb$^{16}$ or Sb$^{18}$ doping and so on), where the surface contribution to the total conduction become significant. Therefore, the similar hump behavior observed in our nanowires might have the same origin due to the competition of conduction between the surface and bulk. When the temperature decreases, the contribution of the bulk conductivity decreases sharply and thus the surface conductivity will be dominant in low-$T$ range. Below about 25 K, both larger diameter wires ($W = 100$ nm and 300 nm) show slightly an upturn in resistance while the small diameter wire ($W \sim 50$ nm) displays a plateau down to 2 K. It was also noted that the upturn behavior becomes more significant with the increase of the wire diameter, as shown in the upper inset of Fig. 2 (a). The tendency of the weakened insulating feature with the decrease of the wire diameter at low temperatures means that the contribution of the metallic surface states to the total conduction might be enhanced in such a thinner nanowire.

Figure 1 | (a) and (b) are respectively the low magnification SEM and TEM images of nanowires with $W = 50$ nm. The inset of (b) shows an enlargement of an individual nanowire. (c) High-resolution TEM image of 50 nm wire selected randomly. An oxidation layer of approximately $\sim 5.0$ nm is visible on the surface. (d) x-ray diffraction spectra carried out on the nanowire arrays, where the (110) diffraction is the dominant peak in the spectra.
positive MR curves were observed. The amplitude of the MR oscillations Fig. 2 (b) shows the normalized resistance as a function of the mag-

Figure 2 | (a) Resistance versus temperature for three nanowires of surface states32,33. The WAL is a negative quantum cor-

low temperatures. The lower inset is the SEM image of the four-probe wire was much larger than those of 100 nm or 300 nm wires. The MR oscillations superimposed on the positive MR curves were observed. The amplitude of the MR oscillations was enhanced when the diameter decreases from 300 nm to 50 nm. Fig. 2 (b) shows the normalized resistance as a function of the mag-

The overall MR behavior as shown in Fig. 2 (b) is very similar to those reported in TI-bulk, films and nanoribbons, namely all three wires display a positive MR over entire magnetic field regime we measured and a valley in low-H range. Such a positive MR in TIs is usually attributed to the weak antilocalization (WAL) of the surface states because of the strong spin-orbit coupling and the heli-

Discussion
To quantitatively understand the size dependent properties of the MR in these thin surface curved TI nanowires, Figure 3 (a), 3(c) and 3(e), respectively, show the angle-dependent magnetoconductance, $G(\theta, B) = 1/R(\theta, B)$, of three samples with diameters of $W = 300$ nm, 100 nm and 50 nm. It was known that the WAL induced by 2D surface states is characterized by a sole dependence on the perpen-

the weak localization correction at a magnetic field $B$ that includes the electron-electron ($e-e$) interactions and spin-orbit ($s-o$) interactions to the conductance is given by

$$\Delta G = \sqrt{2e^2 L_n} \pi \hbar L \left[ \frac{5 A(2L_n^2)}{2 L_1^2} - \frac{A(2L_n^2)}{2 L_2^2} \right]$$

where $\Delta G$ is the conductance quantum correction in 1D, $L_n$ and $L_0$ are the wire length and the Nyquist length, respectively, $A$, represents the Airy function, $L_1 = (4/3L_n^2 + L_n^2)^{-1/2}$, and $L_2 = (1/L_n^2 + W^2 / 3L_n^2)^{-1/2}$. Here, $L_n = \sqrt{D \tau_n}$, $\tau_n = (\hbar eB/L_n)$ is the spin-orbit length that charac-

the oxide layer of nanowires, the actual widths, $W$, of the three wires quoted by 300 nm, 100 nm, and 50 nm were selected as 290 nm, 90 nm and 40 nm in the theoretical fitting, respectability. The solid red curves in Fig. 3 (b), 3(d) and 3(f) are the fitting results with 1D localization theory, yielding $L_n = 27.1$ nm, $L_0 = 396.0$ nm, $L_{so} = 20.8$ nm for nanowire of 300 nm, $L_n = 34.8$ nm, $L_0 = 395.9$ nm, $L_{so} = 26.1$ nm for nanowire of 100 nm, and $L_n = 34.0$ nm, $L_0 = 400.1$ nm, $L_{so} = 25.9$ nm for nanowire of 50 nm. It was noted that $L_n < L_{so}$, which means the spin-orbit scattering time $\tau_{so}$ is significantly shorter than $\tau_n$, being consistent with the results obtained from other similar topological insulators34,35. Obviously, the fitting is more successful for small diameter wire, and the upper limit for the range of the magnetic field which is appropriate for the 1D WAL increases significantly with the decrease of the wire diameter. Since the dephasing length $L_{so}$ shows no clear diameter dependence, indicating the surface nature of the 1D WAL (If the bulk contribution to the WAL effect were significant, $L_{so}$ should change with the diameter). These observations are consistent
with our expectation that quasi-one dimensionality in electrical transport of surface state is significantly enhanced in small diameter wire. A deviation of the 1D WAL fitting for 300 nm wire can be understood from a fact that the 300 nm is almost comparable to the phase coherence length, $L_Q$. We have also tried the fitting with 2D WAL model for 300 nm wire, but unfortunately we obtained unphysical small fitting parameters compared with those reported for TI- bulk or film samples. A possible reason might be related to its cylindrical geometry with a curved surface or the diameter of 300 nm is just on the order of between 1D and 2D dimensionality.

To further investigate the observed WAL, the magnetoconductance as a function of temperature was also measured in several other Bi$_2$Te$_3$ nanowires of different diameters ($W = 50$ nm, 100 nm and 300 nm) in the field aligned perpendicular to the wire axis, as shown in Figs. 4 (a), 4(c) and 4(e), respectively. As $T$ increases, the cusp of the magnetoconductance in low field range is gradually broadened and finally disappears. Fitting the data at different $T$ with eq.(1), the observed characteristic lengths of $L_n$, $L_Q$ and $L_{so}$ as a function of temperatures are shown in Fig. 4 (b), 4(d) and 4(f) for nanowires with $W = 50$ nm, 100 nm and 300 nm, respectively. All characteristic lengths decrease with the increase of temperatures due to the increased thermal scattering.

It was well-known that the Nyquist length $L_n$ and coherence length $L_Q$ are proportional to $T^{-2/3}$ for the two dimensional system and $T^{-1/3}$ for the one-dimensional one$^{24,30,37}$. Fig. 4(b) shows that the Nyquist length $L_n$, coherence length $L_Q$ and spin-orbit length $L_{so}$ for 50 nm wire are proportional to $T^{-0.37}$, $T^{-0.32}$ and $T^{-0.37}$ which are very close to the exponent, $-1/3$, expected for the one-dimensional system, i.e., the electron conduction in Bi$_2$Te$_3$ nanowires follows the quasi-one-dimensionality. Similar fitting were also done for nanowires with...
respectively. It is noted that, as shown in Fig. 4(f), Au film evaporated on one side of the AAO membrane prior to the electrodeposition of magnetoconductance in the surface curved Bi$_2$Te$_3$ nanowires.

**SCIENTIFIC METHODS**

**Synthesis.** Bi$_2$Te$_3$ nanowires were fabricated by direct-current electrodeposition into porous anodic aluminum oxide membrane (AAO). The plating solution was prepared by dissolving 10 mM Te (powder: 99.9998% purity) and 7.5 mM Bi (shots: 99.999% purity) elements into concentrated nitric acid (69.1%), and then the solution was diluted to 1 M final concentration with distilled water. The electrodeposition was carried out at a constant potential of $-62$ mV, relative to an Ag/AgCl reference electrode at room temperature. A pure Pt-wire was used as the counter electrode and Au film evaporated on one side of the AAO membrane prior to the electrodeposition was used as the working electrode. Freestanding nanowires were obtained by dissolving the membrane with 2 M aqueous NaOH solution, followed by precipitating the wires via centrifugation.

**Device fabrication and characterization.** To make standard four-probe devices on an individual Bi$_2$Te$_3$ NW for transport measurement, we dispersed the NWs on a silicon substrate with a 1 m thick Si$_3$N$_4$ insulating layer. Then, the sample was transferred into FEI NanoLab 600i SEM/FIB dual beam system for the deposition of Pt-electrodes. The size of the four Pt-stripe electrodes has a nominal width of 100 nm and a thickness of 100 nm deposited. Usually, the film by FIB-induced Pt deposition is amorphous consisting of Pt, C, Ga or O depending on the deposition condition. While the maximum spreading or diffusion distance of the actual Pt along the wire is longer than the spreading distance.

$W = 100$ nm and 300 nm. The obtained results indicate that $L_n$, $L_p$, and $L_{so}$ decay as $-T^{-0.33}$, $-T^{-0.37}$, and $-T^{-0.26}$ for $W = 100$ nm, and $-T^{-0.28}$, $-T^{-0.32}$ for $W = 300$ nm, as shown in Fig. 4 (d) and 4 (f), respectively. It is noted that, as shown in Fig. 4(f), $L_p < W$ at $T > 10$ K for nanowires with $W = 300$ nm, which indicates that the transport behavior of electrons is beyond quasi-one-dimensional channel, but two or three dimensionally above this temperature.

In summary, single crystal Bi$_2$Te$_3$ nanowires with diameters ranging from 50 nm to 300 nm were fabricated by electrodeposition. Both MR oscillations and weak antilocalization (WAL) behavior were observed for nanowires with different diameters, and both properties were enhanced with the decrease of wire diameters, indicating the enhancement of surface states in thinner nanowires. The obtained dephasing length $L_n$ shows independence of diameter but follows $T^{-1/3}$ dependence, suggesting the quasi-one-dimensional nature of magnetoconductance in the surface curved Bi$_2$Te$_3$ nanowires.

**Figure 4** (a), (c) and (e) respectively show magnetoconductance at different temperatures with magnetic fields aligned perpendicular to the wire axis for nanowires with $W = 50$ nm, 100 nm and 300 nm. (b), (d) and (f) respectively show the characteristic lengths of $L_n$, $L_p$ and $L_{so}$ as a function of temperatures obtained from the fitting with the 1D localization theory. The solid lines in each plot show the power-law dependence on temperatures, yielding $L_n$, $L_p$ and $L_{so}$ decay as $-T^{-0.37}$, $-T^{-0.32}$, $-T^{-0.26}$ for 50 nm wire, and $-T^{-0.34}$, $-T^{-0.37}$, $-T^{-0.33}$ for 100 nm wire, and $-T^{-0.26}$, $-T^{-0.25}$, $-T^{-0.28}$ for 300 nm wire. The exponent of $L_n$ and $L_p$ closes to $-1/3$ expected for the one-dimensionality in Bi$_2$Te$_3$ nanowires.

In the following, we report the properties of Bi$_2$Te$_3$ nanowires with diameters ranging from 50 nm to 300 nm. The obtained results indicate that $L_n$, $L_p$, and $L_{so}$ decay as $-T^{-0.33}$, $-T^{-0.37}$, and $-T^{-0.26}$ for $W = 100$ nm, and $-T^{-0.28}$, $-T^{-0.32}$ for $W = 300$ nm, as shown in Fig. 4 (d) and 4 (f), respectively. It is noted that, as shown in Fig. 4(f), $L_p < W$ at $T > 10$ K for nanowires with $W = 300$ nm, which indicates that the transport behavior of electrons is beyond quasi-one-dimensional channel, but two or three dimensionally above this temperature.

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Author contributions
M.T. supervised the research. W.N., H.D., Y.H., F.K. and J.Y. synthesized the Bi$_2$Te$_3$ nanowires, fabricated the devices and carried out the transport measurement in high magnetic field and performed structural analysis. Y.Z. contributed to the analysis. W.N. and M.T. wrote the paper, together with the help of all other co-authors.

Additional information
Competing financial interests: The authors declare no competing financial interests.
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