Indications of topological transport by universal conductance fluctuations in Bi$_2$Te$_2$Se microflakes

Zhaoguo Li$^1$, Yuze Meng$^1$, Jian Pan$^2$, Taishi Chen$^1$, Xiaochen Hong$^2$, Shiyian Li$^2$, Xuefeng Wang$^1$, Fengqi Song$^*$$^*$, and Baigeng Wang$^*$$^*$

$^1$National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, P. R. China
$^2$Department of Physics, Fudan University, Shanghai 200433, P. R. China
E-mail: songfengqi@fudan.edu.cn; bgwang@nju.edu.cn

Received April 30, 2014; accepted May 19, 2014; published online June 5, 2014

Universal conductance fluctuations (UCFs) are extracted in the magnetoresistance responses in bulk-insulating Bi$_2$Te$_2$Se microflakes. Their two-dimensional character is demonstrated by field-tilting magnetoresistance measurements. Their origin from the surface electrons is determined by the fact that the UCF amplitudes remain unchanged while applying an in-plane field to suppress the coherence of bulk electrons. After considering the ensemble average in a batch of micrometer-sized samples, the intrinsic UCF magnitude of over 0.37$\sqrt{\Omega}$ is obtained. This agrees with the theoretical prediction on topological surface states. All the lines of evidence point to the successful observation of the UCF of topological surface states. © 2014 The Japan Society of Applied Physics

The quantum interference transport of topological insulators (TIs) has been arousing much interest$^{1-3}$ owing to the free-of-scattering and spin-blocking properties of surface carriers protected by the time reversal invariance; however, the pin down of the transport of the topological surface state (TSS) is still questionable$^4$. Universal conductance fluctuation$^{12-14}$ (UCF), as an important manifestation of mesoscopic electronic interference, has been found in TIs recently. Giant conductance fluctuation (CF) amplitudes of 200–500 times over the expected value have been observed in millimeter-sized crystals. The UCFs are further identified in some microflakes and demonstrated to be from two-dimensional (2D) interference by the field-tilting magnetoconductance (MC) measurements$^{10}$ and have been confirmed recently$^{25,26,28}$. However, the question still exists whether such 2D UCFs originate from a TSS since a few critical issues have to be taken care of. In a previous work on the 2D UCF, the bulk electrons fall into a crossover region between 2D and 3D interferences. This leads to the question as to whether the 2D transport may arise from the bulk electrons. Such suspicion is further strengthened by the possible bulk-surface coupling, which merges all the electronic states to a single 2D state.$^{10,31}$ Another critical concern is the UCF contribution from the topologically trivial 2D electron gas (2DEG) due to the surface band bending, which has been shown by both spectroscopic$^{25}$ and calculation approaches$^{33}$ in practical TI samples. Here, we tackle the questions by studying the UCF effect in many samples of bulk insulating Bi$_2$Te$_2$Se (BTS) microflakes. The sample thickness is chosen to eliminate the bulk–surface coupling and the 3D effects. A novel in-plane field measurement is proposed to exclude the bulk 2D interference. The intrinsic UCF is successfully extracted, supporting the TSS origin of the observed UCFs.

The BTS single crystals are grown by a high-temperature sintering method.$^{10}$ Then, all the microflakes are exfoliated from the same mother crystal and deposited on the SiO$_2$/Si substrates. The Au electrodes are applied on the microflakes by a standard lift-off technique. The thicknesses ($H$) of all the samples are measured by atomic force microscopy (AFM). Typical samples can be seen in the insets of Figs. 1(a) and 2(a). The resistances of all the samples are measured in four-probe configurations, as shown in the left inset of Fig. 1(a). All the magnetotransport measurements are carried out using the Quantum Design physical property measurement systems. The in-plane field tuning is performed using an Oxford vector rotate magnet system.

The UCF can be extracted from the magnetoresistance data. Figure 1 shows the transport data of a typical microflake with a thickness of 60 nm (sample S4). The temperature-dependent resistance ($R$–$T$) reveals the bulk insulation of the microflake$^{25,34,35}$ [Fig. 1(a)]. Figure 1(b) shows the MC as a function of magnetic field. We can see an MC peak around the zero field, which is from the weak anti localization$^9$ (WAL). In the high-field range, there are some CF patterns. After subtracting a polynomial background curve [red curve in Fig. 1(b)], we can clearly observe the aperiodic CF patterns [red curve in Fig. 1(b)]. Such CF patterns can be observed repeatedly at different temperatures, as shown in Fig. 1(c). Please see the bottom curves in Fig. 1(c) for the two CF patterns, one of which is measured during the up-sweeping and the other is measured during the down-sweeping of the field $B$ [the arrows in Fig. 1(c) indicate the field-sweeping directions]. Despite the fact that the time interval between the two measurements is longer than 20 h, the two CF curves still coincide with each other. In addition, the nearly same fluctuation features in $\delta G$–$B$ curves measured at different temperatures confirm the retracability of the CFs. Such irregular but repeatable CFs are attributed to the UCFs of mesoscopic transport.$^{36,37}$ Figure 1(d) shows the measured $\delta G$–$B$ curves at various $\theta$ values. We can find that the CF peaks in the $\delta G$–$B$ curves shift towards the high-$B$ direction and their widths are monotonically broadened with increasing $\theta$, as guided by the circle-marked lines. The circle markers represent the expected maxima for a 2D interference system, given by $B_{\perp} = B \cos \theta$. This indicates that the UCF is from a 2D electronic interference.

An important reservation appears that the bulk interference can provide a 2D interference (UCF) in the case that the thickness is close to or less than the dephasing length of the bulk electrons. Actually, we have observed an MC curve at $\theta = 90^\circ$ where the bulk electrons are dominant in the MC response. According to the traditional WAL theory,$^{38}$ we can obtain the dephasing length of the bulk of approximately 60 nm. It implies that the bulk state falls into a crossover regime between the 2D and 3D interferences. Hence, more
evidence is required to distinguish the origin of the 2D UCF. The in-plane field \(B_\parallel\) tuning is an effective tool for excluding such bulk quasi-2D interference. As shown in the inset of Fig. 2(d), the UCF signal is adopted from the polynomial background. \(\delta G - \delta B\) curves at various temperatures \(\theta = 0^\circ\). The arrows indicate the field-sweeping direction in the MC curves at 2 K. \(B\)-tilting \(\delta G - \delta B\) data measured at 2 K. The black, red, and blue circle markers represent the expected shift of the maxima in the magnetic field for a 2D system, given by \(B_\perp = B \cos \theta\). For clarity, adjacent curves in (c) and (d) are displaced vertically.

**Fig. 1.** UCF of BTS sample with \(H = 60\) nm. (a) Temperature dependence of its resistance. The left inset shows the measurement configuration. The right inset shows its AFM image. (b) Typical MC curve at \(T = 2\) K. The red curve is the polynomial fitting result. The blue curve is the CF curve after subtracting the polynomial background. (c) \(\delta G - \delta B\) curves at various temperatures \(\theta = 0^\circ\). The arrows indicate the field-sweeping direction in the MC curves at 2 K. (d) \(B\)-tilting \(\delta G - \delta B\) data measured at 2 K. The black, red, and blue circle markers represent the expected shift of the maxima in the magnetic field for a 2D system, given by \(B_\perp = B \cos \theta\). For clarity, adjacent curves in (c) and (d) are displaced vertically.

Then, we can obtain the RMS of CFs using \(\delta G_{\text{rms}} = \sqrt{\langle F(0) \rangle}\). The dephasing length \(L_\phi\) can be extracted using the relation \(L_\phi = \sqrt{\langle F(0) \rangle} B_\perp \sim h/\epsilon e\), where \(B_\phi\) is the half width at half maximum of the CF autocorrelation function. Figure 2(c) shows \(\delta G_{\text{rms}}\) as a function of \(B_\parallel\), which can be seen that \(\delta G_{\text{rms}}\) is independent of \(B_\parallel\) in our samples. \(L_\phi\) is determined to be \(~50\) nm by analyzing the \(R - B\) data.\(^{39,40}\) It will be reduced to \(~17\) nm while \(B_\parallel = 1\) T, corresponding to a strong suppression of \(\delta G_{\text{rms}}\) if the 2D UCF is contributed by the bulk electrons. This is contradictory to our results in Fig. 2(c).

**Fig. 2.** Tuning UCF by \(B_\parallel\) in sample with \(H = 47\) nm. (a) Temperature dependence of its resistance. The inset shows its optical micrograph. (b) \(\delta G - \delta B\) curves at various \(B_\parallel\) values. The adjacent curves are displaced vertically. (c) \(B_\parallel\) dependence of \(\delta G_{\text{rms}}\). (d) \(B_\parallel\) dependence of \(L_\phi\). The inset shows the magnetic field configuration. The data in (b-d) are measured at \(T = 1.5\) K.
Table I. Basic parameters of devices. \(L\) is the distance between the two voltage probes in a four-probe configuration. \(W\) and \(H\) are the width and height (thickness), respectively. \(\delta G_{\text{rms}}\) is the measured RMS value of CFs at \(T = 2\) K. The resistances \((R)\) of the samples at \(T = 2\) and \(300\) K are also shown.

| Sample | \(L\) (µm) | \(W\) (µm) | \(H\) (nm) | \(R\) at 2 K (kΩ) | \(R\) at 300 K (kΩ) | \(\delta G_{\text{rms}}\) \((e^2/h)\) |
|--------|-----------|-----------|----------|----------------|------------------|------------------|
| S1     | 1.46      | 0.85      | 47       | 5.92           | 5.78             | 0.0149           |
| S2     | 1.40      | 1.20      | 50       | 4.07           | 3.66             | 0.0141           |
| S3     | 1.36      | 0.60      | 59       | 5.40           | 4.99             | 0.0074           |
| S4     | 1.66      | 1.20      | 60       | 5.55           | 5.45             | 0.0056           |
| S5     | 1.48      | 1.40      | 60       | 3.29           | 2.78             | 0.0201           |
| S6     | 1.80      | 1.54      | 61       | 5.90           | 5.55             | 0.0043           |
| S7     | 1.50      | 1.20      | 62       | 6.14           | 3.89             | 0.0082           |
| S8     | 1.40      | 0.88      | 98       | 7.86           | 6.67             | 0.0107           |
| S9     | 1.76      | 0.71      | 57       | 8.38           | 6.58             | 0.0070           |
| S10    | 1.90      | 0.56      | 47       | 17.09          | 16.76            | 0.0065           |
| S11    | 1.25      | 0.78      | 45       | 9.60           | 8.60             | 0.0148           |
| S12    | 1.53      | 1.59      | 70       | 7.62           | 6.41             | 0.0147           |
| S13    | 1.55      | 1.06      | 45       | 5.17           | 3.47             | 0.0117           |
| S14    | 1.79      | 0.95      | 58       | 6.70           | 4.28             | 0.0093           |

TSS or trivial 2DEG. In Fig. 2(d), \(L_\phi\) is plotted against \(B_{\parallel}\), where no significant dependence between \(L_\phi\) and \(B_{\parallel}\) can be seen. This further confirms that the 2D UCF originates from SSs. The \(L_\phi\) extracted from the UCF therefore describes the coherence of SSs.

We have investigated the magnetotransport of 14 BTS microflakes in this work. The device parameters of all the samples are listed in Table I. The bulk insulating behaviors are identified in all the samples [Fig. 3(c) and Table I]. The \(\delta G\)–\(B\) curves of several samples are shown in Fig. 3(a). Figure 3(b) shows the low-field MC \([\Delta G(B) = G(B) - G(0)]\) curves, which are identified as the WAL response originating from the \(\pi\) Berry phase of TSS.1,2,14,15 Similar 2D UCF and 2D WAL are observed in all the samples. The magnitudes of the UCF features fluctuate in different samples with different dephasing lengths.

The topological nature of the UCF can be demonstrated here. It has been suggested that the topological origin of the SS can be studied from the amplitudes of the 2D UCF in TI samples.12,15,17,19 When the sample size \(L\) is less than the dephasing length \(L_\phi\), a recent theory has shown a UCF amplitude \(\delta G_{\text{rms}} = (0.43 – 0.54) e^2/h\) for Dirac fermions (i.e., TSS),17,19 while \(\delta G_{\text{rms}} = 0.86 e^2/h\) for a normal 2DEG.12–14 This indicates that we can distinguish the TSS from the 2DEG by directly measuring \(\delta G_{\text{rms}}\) of TIs. However, the condition \(L < L_\phi\) fails in the experiments so far.10,20–29 The sample dimensions are normally a few micrometers while the dephasing lengths are often an order smaller. One may see very small \(\delta G_{\text{rms}}\) values of approximately \(0.01 e^2/h\) in the experiments, which cannot be directly compared with the theoretical predictions.

To obtain the intrinsic UCF amplitudes in our samples, we consider the classical self-averaging effect, which often occurs in some independent phase-coherence segments in the mesoscopic samples. Note that the energy averaging may also have an effect on the experimental UCF amplitudes; however, the effect can be neglected because the thermal diffusion lengths are comparable to the dephasing lengths in our samples.42 The classical self-averaging modifies the UCF amplitudes as12–14

\[
\delta G_{\text{rms}} \simeq \beta \frac{\delta G_{\text{rms}}^\text{cl}}{\sqrt{N}} \frac{W}{L} = \delta G_{\text{rms}}^\text{cl} \cdot \frac{L_\phi W^{1/2}}{L^{3/2}},
\]

where \(\beta\) is a suppression factor that is related to the symmetry of the system and \(\beta = 1/2\sqrt{2}\) in this work.13,43

\(N \simeq L \times W/L_\phi^2\) is the number of independent phase-coherence
segments, and $L$ and $W$ are the length and width of the microflake, respectively. The sheet conductance of a microflake $G_{\text{rms}} = G - (L/W)$ is also considered. $\delta G_{\text{rms}}$ and $L_0$ can be extracted from the measured $\delta G - B$ curves, and $L$ and $W$ are identified by AFM. Then, applying this formula to our samples, we can obtain the intrinsic UCF amplitude $\delta G_{\text{rms}}$ of a single phase-coherence segment. We prepare 14 samples, which are exfoliated from the same BTS crystal. All the data are measured using a configuration similar to that described above and processed after considering the ensemble average. The results are shown in Fig. 3(d), where $\delta G_{\text{rms}}$ is plotted against $L/W$. Theoretically, the UCF amplitude of TSSs with a 2D geometry can be written as:

$$\delta G_{\text{rms}} = \frac{e^2}{\pi^2 h} \left( \frac{12}{\sum_{n_x=1}^{\infty} \sum_{n_y=-\infty}^{\infty}} \left[ n_x^2 + 4 \left( \frac{L}{W} \right)^2 n_y^2 \right] \right)^{1/2}. \quad (2)$$

Please see Fig. 3(d); the solid curve is the theoretical prediction according to Eq. (2). We can see that the UCF amplitude decreases with increasing $L/W$. It soon saturates to 0.37 $e^2/h$ while $L/W > 1$ regime, $\delta G_{\text{rms}}$ seems independent of $L/W$. These experimental data seem slightly spread, but it can be explained by considering the impurity concentrations that are different in these samples or some nonuniformity of the electronic configurations. Moreover, the difference in the Fermi level also affects $\delta G_{\text{rms}}$. Please note that the experimental data are evenly distributed on both sides of the theoretical curve of TSS, and all data points are far below the theoretical value of a trivial 2DEG (dashed line). This excludes the contribution of the topologically trivial 2DEG and reveals that the experimental results trivially agree with the theoretical tendency of TSS. This essentially suggests that we have accessed the UCF of a real TSS. To the best of our knowledge, the measurement of the intrinsic UCF amplitudes of TSS in the bulk-insulating Tl samples has not been reported.

In summary, the UCF and its physical origin have been investigated in the bulk-insulating BTS microflakes. The 2D UCF features are demonstrated by field-tilting analysis. In-plane field tuning further excludes the contribution of the bulk electrons. We also investigate the classical self-averaging of the BTS UCF to obtain the intrinsic UCF amplitude of over 0.37 $e^2/h$. All the results suggest that the UCF originates from the TSSs.

Acknowledgments  We thank the National Key Projects for Basic Research of China (grant numbers: 2013CB922103, 2011CB922103, and 2010CB923401), the National Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the PAPD project, the NCET project, and the Fundamental Research Funds for the NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054), the National Natural Science Foundation of China (grant numbers: 11023002, 11134005, 60825402, 61176088, 11075076, and 21173040), NSF of Jiangsu province (Nos. BK2011592, BK20130016, and BK20130054).