Enhanced electron dephasing in three-dimensional topological insulators

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Study of the dephasing in electronic systems is not only important for probing the nature of their ground states, but also crucial to harnessing the quantum coherence for information processing. In contrast to well-studied conventional metals and semiconductors, it remains unclear which mechanism is mainly responsible for electron dephasing in three-dimensional topological insulators (TIs). Here, we report on using weak antilocalization effect to measure the dephasing rates in highly tunable (Bi,Sb)\textsubscript{2}Te\textsubscript{3} thin films. As the transport is varied from a bulk-conducting regime to surface-dominant transport, the dephasing rate is observed to evolve from a linear temperature dependence to a sublinear power-law dependence. Although the former is consistent with the Nyquist electron-electron interactions commonly seen in ordinary 2D systems, the latter leads to enhanced electron dephasing at low temperatures and is attributed to the coupling between the surface states and the localized charge puddles in the bulk of 3D TIs.
Three-dimensional topological insulators (TIs) have emerged as an important class of materials that are characterized by an insulator-like bulk and gapless surface states protected by time-reversal symmetry. Recent progresses in improving the quality and electrical gating of TI materials have led to remarkable observations of the quantum anomalous Hall effect, the quantum Hall effect, as well as many quantum coherent transport properties, such as weak antilocalization (WAL) and Aharonov-Bohm effects, and universal conductance fluctuations. It has also been proposed that quantum interference experiments can be used to probe Majorana zero modes formed on the TI surfaces due to superconducting interference. The nature of their ground states under the influence of fluctuation and electron-electron interactions. Electron dephasing rates obtained in experiments exhibit a variety of temperature-dependent behaviours. Some groups reported the linear temperature dependences that are often encountered in conventional 2D electron systems, whereas others found much weaker or stronger temperature dependences even in TI samples with presumably insulating bulk. The lack of consistency in the temperature dependences has precluded clear identification of the dephasing mechanisms, and brings an obstacle to the quantum coherent experiments that require long electron dephasing lengths.

Measurement of the magnetoresistance due to weak localization or WAL has proven a reliable technique to study the electron dephasing in diffuse electron systems of various dimensions. Similar magnetotransport measurements have been carried out on many types of TI thin films or microflakes. The low field magnetoconductivity is usually described very well with the Hikami-Larkin-Nagaoka (HLN) equation at the strong spin-orbit coupling limit:

\[
\Delta \sigma(B) = \sigma_{xx}(B) - \sigma_{xx}(0) = -2 \frac{e^2}{\pi h} \left[ \psi \left( \frac{1}{2} + \frac{B}{B_e} \right) - \ln \left( \frac{B}{B_e} \right) \right],
\]

where \(\psi(x)\) is the digamma function, \(B_e = \frac{\hbar}{2eD} = \frac{h}{eD} f_s\) is the dephasing field, \(D\) is the diffusion constant, and \(l_p\) is the dephasing length. For a single-channel WAL-type transport,

![Figure 1](image-url)  
**Figure 1** | Tunable electron transport in a 15 nm thick (Bi_{1-x}Sb_x)_{2}Te_3 topological insulator (TI) thin film (Sample #1). (a) Sketch of the Hall bar-shaped device with a back gate and a top gate. The width of the current path is 50 μm. (b,c) Hall coefficient \(R_h\) and longitudinal sheet resistivity \(\rho_{xx}\) rendered in a 2D map in top-gate voltage \(V_T\) and bottom-gate voltage \(V_B\). The thin dashed line in b marks the gate voltages for \(R_h = 0\). The sign of \(R_h\) is set to positive for electrons throughout this work. (d) Gate-voltage dependence of zero-field \(\rho_{xx}\) and Hall coefficient \(R_h\). The open circles represent the data for \(V_T = 0\), whereas the solid symbols stand for the case of dual-gating, in which the corresponding \((V_T, V_B)\) values are shown in b with solid diamonds. (e) Hall resistance curves for several set of top and bottom gate voltages. Data in (b-e) were taken at \(T = 1.6\) K. (f) Schematic band diagrams for the top and bottom surface states for the decoupled surface-transport regime (A) and the bulk-conducting regime (B).
prefactor $x$ would be equal to 1/2. In case of multi-channel WAL, the $x$ value can vary from 1/2 to $n_z/2$, where $n_z = 2x$ is the number of parallel conduction channels. The $n_z$ value obtained from the HLN fit is, however, often far from integers due to the difference in the dephasing fields or the coherent coupling between these channels. When the inter-channel coupling is not negligible, determination of the dephasing rate $\tau^{-1}_e$ becomes very challenging because the parameter $B_g$ extracted from the HLN fit is no longer a simple quantity proportional to $\tau^{-1}_e$. An ideal scenario is the surface-dominant transport with two symmetric channels (corresponding to $x = 1$, see Supplementary Note 1). It allows for straightforward extraction of the dephasing rate with a fit to Equation (1). This transport regime, however, requires not only the bulk is insulating, but also the top and bottom surfaces are decoupled and have identical dephasing fields. Unfortunately, most of the dephasing measurements reported so far have not fulfilled these conditions owing to inadequate control of the surface and bulk conductivities.

In this work, we present the measurements of electron dephasing rates in 3D TI thin films with highly tunable chemical potential. The phase coherent transport related to the WAL can be tuned continuously from a bulk-conducting regime with $x = 1/2$ to a decoupled surface-transport regime with $x = 1$ in a single device. Whereas the common Nyquist dephasing behaviour is observed in the former regime, the dephasing rate is found to have a sublinear power-law temperature dependence in the surface-transport regime. We propose that the coupling between the surface states and localized bulk states in a variable range hopping (VRH) regime is responsible for the enhanced electron dephasing and the sublinear temperature dependence in the surface-transport regime.

Results
Characterization of (Bi$_1_x$Sb$_x$)$_3$Te$_3$ field-effect devices. Our measurements were carried out in a set of field-effect devices based on 15–30 nm thick (Bi$_1_x$Sb$_x$)$_3$Te$_3$ (BST) films grown on SrTiO$_3$ substrates with molecular beam epitaxy. A high Sb composition ($x > 0.9$) was chosen to prevent the Dirac point being buried inside the bulk valence band. The un gated BST films have a conducting bulk with $p$-type carriers. As illustrated in Fig. 1 with a 15 nm thick BST film (Sample #1), the Hall-bar shaped device is equipped with both the top and bottom gates, which enable a large range tuning of the chemical potential. When a positive gate voltage is applied, the hole density is reduced and correspondingly the magnitude of Hall coefficient $R_H$ decreases. When the gate voltage is sufficiently high, the Fermi level passes the charge neutral point, which is manifested as a reversal of the sign of $R_H$ and appearance of a maximum in longitudinal resistivity $\rho_{xx}$. At large positive gate voltages, the Fermi level is shifted into the bulk band gap and the surface-dominant transport is achieved. For instance, with back-gate voltage $V_B = 210$ V and top-gate voltage $V_T = 25$ V, surface carrier densities as low as $n_T = 3.3 \times 10^{13}$ cm$^{-2}$ and $n_T = 4.0 \times 10^{13}$ cm$^{-2}$ can be obtained from a two-band fit of the Hall effect data. Such low electron densities indicate that the Fermi level in the BST film resides in the bulk band gap (See Supplementary Fig. 2 and Supplementary Note 2 for more details), consistent with angular resolved photoemission studies of similar BST films.

High tunable phase-coherent transport. Figure 2a shows the magnetoeconductivity curves of the BST film at several gate voltages at $T = 1.6$ K. All of them can be satisfactorily fitted with the HLN equation. Shown in Fig. 2b are the $x$ and $B_g$ values extracted from the fits. For small gate voltages, $x$ is close to 1/2, in agreement with previous measurements of TI thin films with conducting bulk. This can be attributed to strong surface-bulk coupling, which makes the sample, behaving like a single-channel system in the phase coherent transport despite the coexistence of multiple conduction channels. This transport regime is realized when the inter-channel scattering rate is much higher than the dephasing rates in individual channels (See Supplementary Note 1). It is also noteworthy that in this work the dephasing length $l_0 = (D\tau^{-1}_e)^{1/2} = (D/\pi)^{1/2}$ extracted from the fit to Equation (1) is always much longer than the corresponding film thickness. Therefore, even in the bulk-conducting regime, the phase coherent transport is two dimensional, justifying the application of the HLN equation for the data analysis. As the positive gate voltage increases, the depletion of hole carriers in the bulk leads to gradual decoupling between the top and bottom surfaces and accordingly the $x$ value becomes greater. When these two surfaces are fully decoupled and their dephasing fields are brought into equality, $x = 1$ is observed. For the BST thin films studied in this work, both $x \approx 1/2$ and $x \approx 1$ can be maintained for a wide range of temperatures at fixed gate voltages, as depicted in Fig. 2d. Such a good tunability in the phase coherent transport provides a solid foundation for studying the temperature dependence of dephasing rate in TIs.

Discussion
For a weakly disordered conventional 3D electron system, electron–phonon interactions are the dominant source of electron dephasing, which gives rise to a power-law temperature dependence of the dephasing rate: $\tau^{-1}_e \sim T^p$, with $p = 2$–4 (ref. 32). In low
Figure 2 | Tunable surface-bulk coupling in the BST thin film (Sample #1) revealed in the magnetotransport. (a) Low field magnetoconductivity and the best fits to the Hikami-Larkin-Nagaoka (HLN) equation. (b) Gate-voltage dependence of prefactor $\alpha$ and dephasing field $B_0$ extracted from the HLN fits. The gate voltages used for the dual-gating are same as those in Fig. 1. The error bars denote s.d.s of $B_0$ determined from various fitting ranges. (c,d) Temperature dependence of the prefactor $\alpha$ in both decoupled surface-transport regime ($\alpha \approx 1$) and bulk-conducting regime ($\alpha \approx 1/2$). Slight differences between different cool-downs were caused by exposure of the sample to atmosphere during the measurement intervals.

Figure 3 | Enhanced electron dephasing in the decoupled surface-transport regime. (a) Temperature dependence of dephasing field $B_0$ for a dual-gating case with $\alpha \approx 1$. The data can be well fitted to $B_0 \propto T^p$ with $p = 0.55$. (b) $T$-dependences of $B_0$ and the corresponding power-law temperature dependences of the bottom surface states as a function of temperature. (c) Power-law temperature dependence, $T^{-1}$, of the bottom surface states as a function of temperature. The dashed line shows the estimated dephasing times due to the Nyquist electron-electron interactions.

dimensional systems, the dominant dephasing mechanism at low temperatures is usually associated with small energy transfer processes owing to electron–electron interactions. This so-called Nyquist dephasing, first proposed by Altshuler et al., also leads to a power-law $T$-dependence, but with a smaller exponent: $p = 2/3$ and 1 for 1D and 2D electron systems, respectively. The Nyquist mechanism has been confirmed by numerous magnetotransport experiments on low dimensional metals or semiconductors. As shown above, the $p$ values for the decoupled surface-transport regime in TIs are in a range of 0.45–0.60, substantially lower than those of the known dephasing mechanisms for weakly disordered, nonmagnetic 2D electron systems. Figure 3c further shows that dephasing times estimated for the surface states are considerably shorter than the theoretical values for the Nyquist dephasing. This indicates the existence of an additional dephasing source in the topological transport regime.

Given the fact that decreasing the bulk conductivity in TIs can induce the crossover from the Nyquist dephasing to the sublinear power-law temperature dependence, it is reasonable that the evolution of bulk states with gating are involved in the crossover of the dephasing behaviour. As revealed by previous studies, TIs in the family of bismuth chalcogenides do not have truly insulating bulk. Even in the state-of-the-art materials, such as (Bi,Sb)$_2$(Te,Se)$_3$ single crystals, the bulk conductivity does not freeze out completely at low helium temperatures (typically on the order of $\Omega \cdot cm$). This was first explained by Skinner et al., who pointed out that the narrow band gaps and electrostatic fluctuations from the compensation doping result in the formation of localized nanometre-sized charge puddles in the bulk, and consequently the VRH of charge carriers between these puddles is energetically favoured over the thermal activation. In addition to the estimated bulk resistivities from
the transport of thick TI single crystals, the existence of surface and bulk charge puddles has been supported by scanning tunnelling microscopy\(^4^4\) and optical conductivity measurements\(^4^5\), respectively. In addition, the VRH transport has been directly observed in ultrathin BST films, in which the surface conductivity is suppressed by a hybridization gap\(^4^6\).

For the BST films with the bulk layer in the VRH regime, the transport is dominated by the diffusive Dirac fermions on the surfaces. If the films are sufficiently thick, the top and bottom surfaces do not couple to each other coherently owing to the lack of direct tunnelling. The phase coherent transport can be modelled as a decoupled two-channel system. Even though the localized charge puddles carry little electrical current due to the high resistivity, they can couple to the surface states via tunnelling. As the hopping transport is an inelastic process, the transport measurements of thick TI single crystals, the existence of surface and bulk charge puddles has been supported by scanning tunnelling microscopy\(^4^4\) and optical conductivity measurements\(^4^5\), respectively. In addition, the VRH transport has been directly observed in ultrathin BST films, in which the surface conductivity is suppressed by a hybridization gap\(^4^6\).

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As all known TIs have narrow band gaps in the bulk, the electron dephasing caused by the localized charge puddles should not be limited to the BST thin films studied in this work. At low temperatures, the enhanced dephasing severely shortens the dephasing length, and should be detrimental to the experiments requiring long phase coherent lengths, for instance, the interferometers proposed to detect Majorana zero modes. Therefore, it is highly desirable to search for the TI materials in which the dephasing caused by the charge puddles can be substantially suppressed. The electron dephasing measurement will play an unreplaceable role in such endeavours because it can probe the interaction between the surface and bulk states at a very small energy scale (down to the order of μeV). Such information is very difficult, if not impossible, to obtain from other transport or spectroscopic measurements. Finally, it is noteworthy that the coupling between the diffusive surface states and the bulk states in the hopping regime revealed in this work can be extended to non-topological bilayer systems. Such coupling can be utilized to offer a new method to measure electron dephasing rates in electron systems that are not in the weakly disordered regime. This could provide valuable information in the study of electron dephasing phenomena in non-diffusive systems, which have been challenged both experimentally and theoretically.

Methods

Thin film growth and device fabrication. TI BST thin films were grown on 500μm thick SrTiO3 (111) substrates in a molecular beam epitaxy (MBE) system with a base pressure of 1×10−10 Torr or lower. The BST films are single crystals and have large, atomically flat terraces on the surfaces, similar to those reported previously. They were capped with a 10 nm thick amorphous Te layer by chemical wet etching. A 35 nm thick AlOx thin film was deposited with atomic layer deposition onto the BST samples to serve as the dielectric material for top-gating. The SrTiO3 substrates, which have exceptionally large dielectric constants and high electrical breakdown strength, were used as the bottom-gate dielectric. Both top and bottom gate-contacts, as well as electrical contacts were prepared by thermal evaporation of Cr/ Au thin films with typical thicknesses of 5 nm/80 nm.

Electron transport measurements. The I–V characteristics of all electrical contacts and gates had been checked with Agilent source-measurement units with a current resolution of 100 pA before the electron transport measurements. All of the data presented in this manuscript were taken from the samples with good ohmic contacts. The leakage current is negligible for both top and bottom gates. The transport experiments were performed in a vapour-flow He flow cryostat. A He refrigerator and a top loading He3/He4 dilution refrigerator with magnetic fields up to 15 T. Electrical wirings of the dilution refrigerator are equipped with a variety of low pass filters at different temperature stages so that electron temperatures lower than 15 mK can be obtained. The electron temperature has been confirmed by the observations of activation gaps of fragile fractional quantum Hall states (for instance, the 5/2 state), and dephasing phenomena in the quantum Hall plateau transitions in high mobility GaAs/AlGaAs 2D electron systems, as well as the symplectic Anderson transition. The amplitude of excitation current was optimized to avoid electron heating effects while maintaining sufficient signal-to-noise ratios for the transport measurements. The data that support the findings of this study are available from the corresponding author upon request.

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Author contributions

Y.L. and K.H. initiated the project. Y.O. carried out the MBE growth of the samples. J.L. fabricated the Hall bar devices, performed the electron transport measurements. J.L., H.L. and Y.L. analysed the data and prepared the manuscript with contributions from all authors.

Additional information

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