Supplementary Materials for

Surface-bulk coupling in a Bi_2Te_3 nanoplate grown by van der Waals epitaxy

Xiaobo Li[1,2], Mengmeng Meng[1], Shaoyun Huang[1], Congwei Tan[3], Congcong Zhang[3], Hailin Peng[3], and H. Q. Xu[1,4,*]

[1]*Beijing Key Laboratory of Quantum Devices, Key Laboratory for the Physics and Chemistry of Nanodevices, and School of Electronics, Peking University, Beijing 100871, China*

[2]*Academy for Advanced Interdisciplinary Studies, Peking University, Beijing 100871, China*

[3] *Center for Nanochemistry, Beijing National Laboratory for Molecular Sciences (BNLMS), College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, China*

[4] *Beijing Academy of Quantum Information Sciences, Beijing 100193, China*

[*] Corresponding authors: H. Q. Xu (hqxu@pku.edu.cn)

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Contents

Supplementary note I. Characteristic transport parameters that would be obtained by fits of the measured magnetoconductivity data to the Hikami-Larkin-Nagaoka (HLN) formula

In this supplementary note, we show the fits of the measured magnetoconductivity data at different top-gate voltages V_g and temperatures T based on the Hikami-Larkin-Nagaoka (HLN) theory. The HLN theory does not take inter-channel scattering into account. For a two-dimensional (2D) disordered conducting system, the theory predicts that the quantum correction to the classical conductivity can be written as[1]

$$\Delta\sigma_{xx}(B) = -\alpha\frac{e^2}{\pi h}\left[\Psi\left(\frac{\hbar}{4eBL_{\varphi}^{*2}}+\frac{1}{2}\right) - \ln\left(\frac{\hbar}{4eBL_{\varphi}^{*2}}\right)\right], \quad (1)$$

where prefactor α refers to the number of 2D conduction channels in the system, with $\alpha\sim 1/2$ representing one 2D conduction channel and $\alpha\sim 1$ representing two separated 2D conduction channels, and L_{φ}^{*} is the dephasing length of electrons in the system. To clearly present the fits of our experimental data to the HLN theory, we show in Fig. S1(a) again the magnetoconductivity data (opened circles) measured for the device at different gate voltages V_g at $T=2\ K$ as in Fig. 2(a) of the main article. Again, the black open circles are obtained at $V_g=11\ V$ and the ones at other values of V_g are successively vertically offset for clarify. Opened circles in Fig. S1(c) show the same magnetoconductivity data measured for the device at different temperatures T at $V_g=-10\ V$ as in Fig. 3(a) of the main article. Here, the dark green circles are obtained at $T=2\ K$ and the ones at other values of T are again successively vertically offset for clarify. The dashed lines in Figs. S1(a) and S1(c) show the fits of the measured magnetoconductivity data based on the HLN theory. Figure S1(b) displays the extracted L_{φ}^{*} and α from the fits shown in Fig. S1(a), while Fig. S1(d) displays the extracted L_{φ}^{*} and α from the fits shown in Fig. S1(c). It is seen that both L_{φ}^{*} and α are top-gate voltage or temperature dependent. The extracted value of α increases with decreasing top-gate voltage or increasing temperature, reflecting that the electron transport at the 2D top surface channel and in the 2D bulk channel is gradually coherently decoupled in the Bi_2Te_3 nanoplate. The dephasing length L_{φ}^{*} is shown to decrease as the top-gate voltage decreases, which is a result of an enhancement in electron-electron interaction[2] at a lower electron density. These results are qualitatively in agreement with the results obtained based on the Garate-Glazman theory as presented in the main article. However, the extracted L_φ^* exhibits a power-law temperature dependence, $L_\varphi^* \sim T^{-0.38}$. This power-law temperature dependence is incompatible with the well-established dephasing process caused by electron-electron scattering with small-energy transfers in a 2D system at low temperatures.

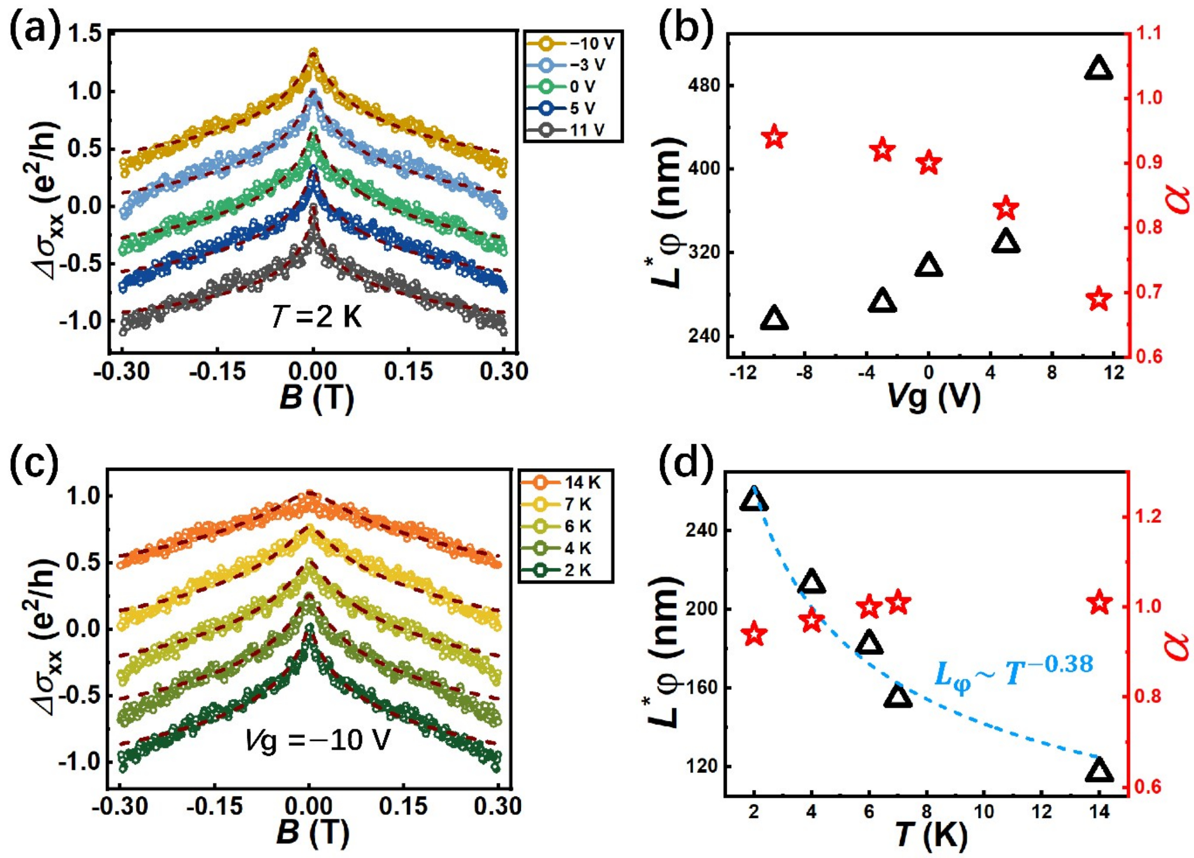

FIG. S1. (a) Magnetoconductivity $\Delta\sigma_{xx}$ of the device at different top-gate voltages at $T = 2\ K$. The opened circles show the measured data. The black ones are obtained at $V_g = 11\ V$ and the ones at other top-gate voltages are successively vertically offset for clarify. The dashed lines show the fits of the measured data based on the HLN theory. (b) Extracted dephasing length L_φ^* and prefactor α vs. top-gate voltage V_g. (c) Magnetoconductivity $\Delta\sigma_{xx}$ of the device at different temperatures *T* at $V_g = -10\ V$. Again, the opened circles show the measured data. The dark green ones are obtained at $T = 2\ K$ and the ones at other temperatures are successively vertically offset for clarify. The dashed lines show the fits of the measured data based on the HLN theory. (d) Extracted dephasing length L_φ^* and prefactor α vs. temperature *T*.

Supplementary note II. Surface-bulk inter-channel scattering rates, $\tau_{SB_1}^{-1}$ and $\tau_{SB_2}^{-1}$, and the diffusion coefficients in the bulk and at the top surface, D_1 and D_2

In this supplementary note, we discuss how the surface-bulk inter-channel scattering rates, $\tau_{SB_1}^{-1}$ and $\tau_{SB_2}^{-1}$, and the diffusion coefficients, D_1 and D_2, are changed with changing top-gate voltage V_g. In the simple Fermi golden role approximation, the bulk-to-surface electron inter-channel scattering rate is proportional to the density of states (DOS) at the top surface, $\tau_{SB_1}^{-1}(E_F) \propto DOS_2(E_F)$, where the density of states at the top surface $DOS_2(E_F)$ is given by

$$DOS_2(E_F) = \frac{E_F}{\pi\hbar^2 v_F^2}, \qquad (2)$$

with $\hbar$ being the reduced Planck Constant, E_F the top-surface electron Fermi energy measured with respect to the Dirac point, and v_F the electron Fermi velocity at the top surface. It is seen that $DOS_2(E_F)$ is a linear function E_F and is thus decreased with decreasing V_g. As a result, the bulk-to-surface electron inter-channel scattering rate $\tau_{SB_1}^{-1}$ is decreased with decreasing V_g, leading to an increase in the bulk electron mobility with decreasing V_g at low temperatures.

The surface-to-bulk electron scattering rate is proportional to the DOS in the bulk, $\tau_{SB_2}^{-1}(E_F) \propto DOS_1(E_F)$, where the DOS in the bulk $DOS_1(E_F)$ is given by

$$DOS_1(E_F) = \frac{m^*}{\pi\hbar^2}, \qquad (3)$$

with E_F being the bulk electron Fermi energy measured with respect to the bulk conduction band bottom and m^* the electron effective mass in the bulk. Here, in deriving $DOS_1(E_F) = \frac{m^*}{\pi\hbar^2}$, we assume there is only one 2D subband in the bulk. Evidently, since $DOS_1(E_F)$ is independent of the Fermi energy, the surface-to-bulk electron inter-channel scattering rate $\tau_{SB_2}^{-1}$ is V_g-independent, which could imply that the surface-to-bulk electron scattering would not give a visible change in the surface electron mobility with a change in V_g.

Now we discuss the dependences of the diffusion coefficients D_1 and D_2 on the top-gate voltage V_g. Based on the Einstein relation for the conductivity σ and the diffusion coefficient D in a conductor, $\sigma = e^2 DOS(E_F)D$, the diffusion coefficient D of electrons in the conductor can be expressed as $D = \frac{n\mu}{eDOS(E_F)}$, where n and μ are the electron density and mobility in the conductor, and e the elementary charge. More specifically, for the 2D bulk channel in our Bi_2Te_3 nanoplate (with the occupation of the lowest 2D subband assumed), the electron density $n_1(E_F)$ and the density of states $DOS_1(E_F)$ are related by $n_1(E_F)/DOS_1(E_F) = E_F$. Thus, the diffusion coefficient D_1 of electrons in the bulk is expressed as

$$D_1 = \frac{\mu_1 E_F}{e}, \tag{4}$$

where μ_1 denotes the electron mobility in the bulk. For the 2D top surface channel, the electron density $n_2(E_F)$ and the density of states $DOS_2(E_F)$ are related by $n_2(E_F)/DOS_2(E_F) = E_F/2$. The diffusion coefficient D_2 of electrons at the top surface can then be expressed as

$$D_2 = \frac{\mu_2 E_F}{2e}, \tag{5}$$

where μ_2 denotes the electron mobility at the top surface.

The above analyses show that the diffusion coefficients D_1 and D_2 in the bulk and at the top surface could be expressed as a function of a product of the mobility and the Fermi energy of electrons in their respective subsystems. In the experiment, each mobility value of μ shown in the inset of Fig. 1(c) of the main article is in fact an averaged value over the electrons at the top surface and in the bulk and is an outcome of the presence of all scattering events (including both intra-channel and inter-channel scatterings). If we take the experimentally measured μ for both μ_1 and μ_2, which is increased with decreasing V_g [see the inset of Fig. 1(c) of the main article], and consider the fact that the Fermi energies E_F at the top surface and in the bulk are decreased with decreasing V_g, we expect that both D_1 and D_2 would exhibit a weak V_g-dependence, which is consistent with our experimental observations shown in the inset of Figs. 2(b) and 2(c) of the main article.

References:

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