Ultrafast photoinduced terahertz dynamics of topological insulator $(Bi_{1-x}In_x)_2Se_3$

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Abstract: We present ultrafast terahertz dynamics in topological insulator $(Bi_{1-x}In_x)_2Se_3$. We find that photogenerated electrons suppress the increase of scattering at high temperature. The surface-bulk interaction strongly depends on the dynamic condition of topological phase transition.
OCIS codes: (300.6495) Spectroscopy, terahertz; (300.6530) Spectroscopy, ultrafast

Topological insulators (TIs) are new states of matter; the gapped bulk and gapless Dirac-like surface coexist. [1] In Bi_2Se_3 class of TIs, the strong spin-orbit coupling (SOC) induces the *k*-space reversal of the bulk conduction band minimum and the valence band maximum, resulting in topological Dirac-like dispersion at the surface. [2] Understanding the topological phase transition and related physical properties are important topics for developing novel optoelectronic applications. Recent studies have demonstrated that the topological phase can be tunable by controlling the strength of SOC via indium substitution, and have discovered several interesting phenomena such as transport–lifetime collapse during the topological phase transition. [3-4] However, it still has remained elusive to understand the dynamic nature of the Dirac surface scattering and the surface-bulk interaction (electron-photon coupling) on ultrafast time scale.

In this study, we present ultrafast terahertz (THz) dynamics in topological insulator $(Bi_{1-x}In_x)_2Se_3$ via optical-pump THz-probe measurement. First, we carried out temperature-dependent measurements on the bare Bi_2Se_3 topological insulator thin films without indium substitution in order to investigate the intrinsic Dirac-electron surface dynamics. Upon photoexcitation, the surface-scattering rate is increased due the metallic characteristics of the surface state. At high temperature, however, the photogenerated electrons relax from the bulk to the surface, which suppress the surface-scattering through screening of the long-range surface impurity potential. [5-9] Figure 1 summarizes these experimental observations.

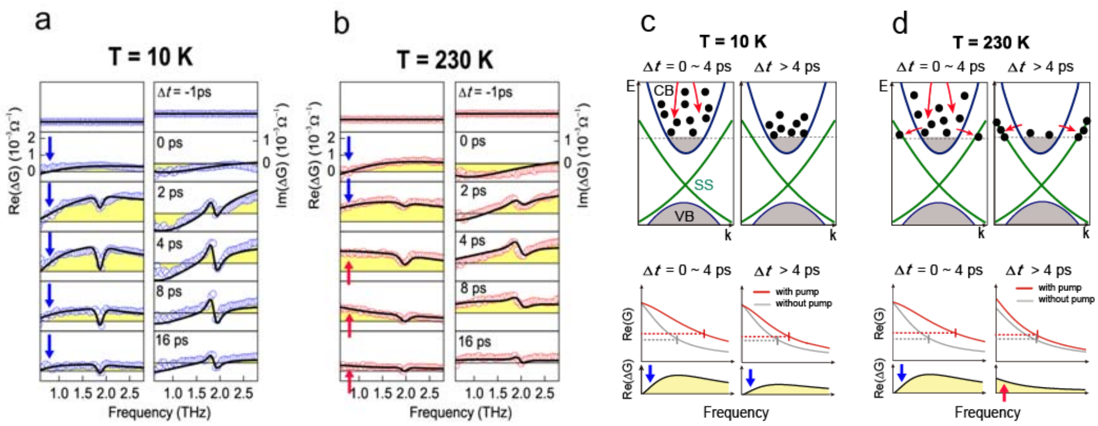

Figure 1. Suppression of surface-scattering due to bulk-to-surface electron scattering at high temperature. (a)(b) THz Dynamics of complex differential sheet conductnace for 32 QL Bi_2Se_3 thin film sample at 10 K (a) and 230 K (b) for several pump-probe time delays. (c)(d) Illlstrations on the relaxation pathway of photogenerated electrons and photoinduced change of real sheet conductance (Re(ΔG)). At low temperature, the photoexcitation leads to the broadening of Drude linewidth, resulting in a low-frequency spectral dip of Re(ΔG) shape. At high temperature, the broadening is suppressed due to the electron injected from the bulk to the surface state.

Second, we performed indium-concentration-dependent THz measurement of $(Bi_{1-x}In_x)_2Se_3$ thin films. As indium concentration increases, the SOC becomes weak, and the bottom and top surfaces are gradually coupled, resulting in gap-opened hybrid TIs (see the band structure in Figure 2(a)). [4] Because the surface-to-surface coupling opens up new scattering channels (which is forbidden in normal TIs), it is expected that the electron-phonon scattering will increase with increasing the indium concentration. Indeed, as shown in Figure 2(b) and 2(c), the asymmetric Fano resonance of bulk phonon at ~1.9 THz is clearly observed for the hybrid TI sample (indium = 4 %). Note that the Fano shape at low frequency dip is the result of interaction between bulk phonon mode and the surface continuum. [10] Because the low-frequency Drude response can be attributed to the surface Dirac-electron dynamics, [4] we conclude that the Fano resonance arises from the coupling between the bulk phonon mode and low-frequency Dirac-electron transitions. To understand details and further physics behind the phenomenon, we carried out optical-pump THz-probe of $(Bi_{1-x}In_x)_2Se_3$ (data not shown). There, we observed the Fano asymmetry variation depending on the topological phase transition condition, providing information on the strongly correlated free-carrier and electron-phonon coupling.

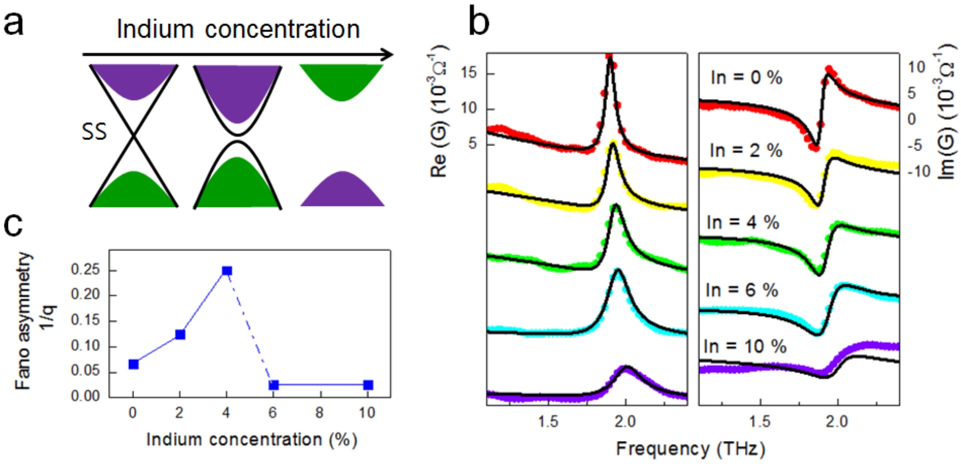

Figure 2. Fano resonance arsing from Dirac-electron phonon coupling (a) Schematics illustrating the topological phase transition. SS is surface state. (b) Equilibirum THz sheet conductance of $(Bi_{1-x}In_x)_2Se_3$ with varying indium concentration. (c) Indium concentration-dependent Fano asymmetry.

References

[1] M. Z. Hasan *et al.* “Colloguium: Topological insulators,” Rev. Mod. Phys. **82,** 3045 (2010)
[2] J. Liu *et al.* “Topological phase trainsitons in $(Bi_{1-x}In_x)_2Se_3$ and $(Bi_{1-x}Sb_x)_2Se_3$.” Phys. Rev. B **88,** 224202 (2013)
[3] M. Brahlek *et al.* “Topological-metal to band-insulator transition in $(Bi_{1-x}In_x)_2Se_3$ thin films.” Phys. Rev. Lett. **109**, 186403 (2012)
[4] L. Wu *et al.* “A sudden collapse in the transport lifetime across the topological phase transition in .” Nature Phys. **9,** 410 (2013)
[5] J. A. Sobota *et al.* “Ultrafast optical exciation of a persistent surface-state population in the topological insulator Bi_2Se_3,” Phys. Rev. Lett. **108,** 117403 (2012)
[6] M. Hajlaoui *et al.* “Ultrafast surface carrier dynamics in the topological insulator Bi_2Te_3,” Nano Lett. **12,** 3532-3536 (2012)
[7] Y. H. Wang *et al.* “Measurement of intrinsic Dirac fermion cooling on the surface of the topological insulator Bi_2Se_3 using time-resolved and angle-resolved photoemission spectroscopy,” Phys. Rev. Lett. **109,** 127401 (2012)
[8] A. Crepaldi *et al.* “Ultrafast photodoping and effective Fermi-Dirac distribution of the Dirac particles in Bi_2Se_3,” Phys. Rev. B **86,** 205133 (2012)
[9] C. W. Luo *et al.* “Snapshots of Dirac fermions near the Dirac point in topological insulators,” Nano Lett. **13,** 5797-5802 (2013)
[10] P. Di Pietro et al. “Optical conductivity of bismuth-based topological insualtors.” Phys. Rev. B **86,** 045439 (2012)