Transient Fano Resonance in topological insulators observed by coherent phonon spectroscopy

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Abstract. We report upon observation of a transient Fano resonance, a quantum interference between coherent phonon and Dirac plasmons, that persisted for up to 1 picosecond in the topological insulator Sb_2Te_3 investigated using coherent phonon spectroscopy.

1 Introduction

Fano resonances in optical spectra are one of the most intriguing quantum mechanical processes in solid state physics [1]. They occur when a discrete optical transition overlaps with continuum states and interference occurs. Fano resonances have been extensively investigated in atoms [1], solids [2] and quantum well structures [3], etc. A transient Fano resonance in the newly discovered topological insulators (TIs) has not been observed to date. TIs, a quantum phase of matter, are characterized by a bulk band gap like normal insulators (NIs), but possess metallic gapless surface states that are protected from backscattering [4]. TIs have been shown to be promising candidates for application in spintronic and optoelectronic devices, since spin is locked orthogonally to momentum. The investigation of phonon dynamics in TIs is an intriguing research topic to understand fundamental electron-phonon interactions. The phonon properties in TIs have been extensively studied using Raman scattering measurements [5], although the electron-phonon interaction in the time-domain is less well understood in TIs. In this work, we report on the dynamics of coherent phonons [6], generated by ultrashort laser pulses in a prototypical TI, Sb_2Te_3, and discuss quantum interference between discrete (phonons) and continuum states (Dirac-plasmons).

2 Experiment

The samples used in this study were highly-oriented Sb_2Te_3 polycrystalline films with five quintuple layers (QL) thick grown on Si (100) substrates by self-organized van der

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Waals epitaxy using helicon-wave radio-frequency (RF) magnetron sputtering [7]. To study the coherent phonon dynamics induced by an ultrashort laser pulse, we employed reflection-type time-resolved pump-probe measurement. The experiment was carried out using near-infrared optical pulses from a Ti:sapphire laser oscillator with a pulse duration of ≈20 fs, a central wavelength of ≈830 nm, and a repetition rate of 80 MHz. The pump and probe beams were orthogonally polarized to each other and were co-focused onto the sample to a spot size of ≈70 μm in diameter. The transient reflectivity change (*ΔR/R*) of the samples was recorded using balanced silicon photo diodes as a function of the pump-probe delay over a time range up to 15 ps [8]. The measurements were carried out in air at room temperature.

3 Results and discussion

Figure 1(a) shows the time evolution of the *ΔR/R* signal observed for a 5 QL thick sample of Sb_2Te_3. The *ΔR/R* signal shows an oscillatory component in combination with a non-oscillatory background. The non-oscillatory background is attributed to excitation and relaxation of hot electrons and lattice heating effects, while the oscillatory signal is attributed to coherent phonons. The oscillatory signal was extracted by subtracting the background. To explore the coherent phonon dynamics in the time-frequency domain, the residual oscillatory signal was analyzed based on the discrete wavelet transform (DWT) [9]. The DWT analysis was carried out using the Gabor wavelet function given by a Gaussian function. The DWT chronogram was obtained by a series of FFTs carried out on different time windows scanned over the entire time domain. The DWT chronogram spectrum is shown in Fig. 1(b), in which two dominant peaks were observed at 1.92 THz and 5.04 THz.

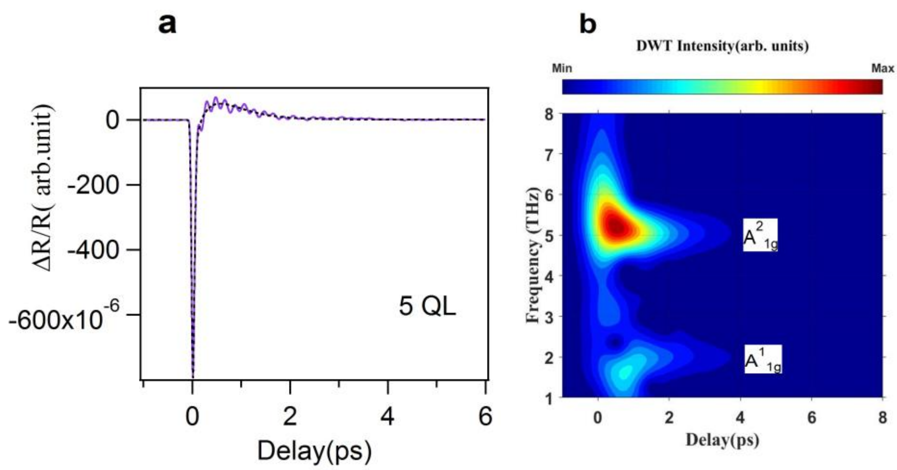

Fig. 1. (a) Time evolution of the reflectivity signal obtained for a 5 QL thick Sb_2Te_3 TIs film. The non-oscillatory signal represents a background indicated by a dotted line, while oscillatory component is due to coherent phonons. **(b)** The coherent phonon spectrum in time and frequency domain obtained based on the DWT analysis performed on the residual oscillatory signal. The two dominant phonon modes assigned to $A_{1g}{}^1$ and $A_{1g}{}^2$, respectively.

These peaks are assigned to the $A_{1g}{}^1$ and $A_{1g}{}^2$ optical phonon modes, respectively, as indicated in Fig. 1(b), which is in good agreement with those observed by Raman measurements [5]. It is interesting to note that an anti-symmetric line shape on the higher frequency side of the $A_{1g}{}^2$ mode is clearly observable. The anti-symmetric line shape is attributed to quantum interference between the discrete $A_{1g}{}^2$ mode and photo-generated coherent Dirac-plasmons, referred to as a Fano resonance [1]. The A_{1g}^2 mode shows a strong Fano-like line shape at nearly zero time delay, while with increasing time delay, the Fano-like line shape changes to a Lorentzian line shape. The transient Fano resonance survives for up to ≈1 ps as clearly observed in the DWT spectrum. Recently a second Dirac surface state (SS_2) was discovered at ≈1.5 eV above the first Dirac surface state (SS_1) [10]. Therefore, optical excitation with a 1.5 eV photon can excite a Dirac plasmons via the SS2 state. Thus, at near zero time delay, the wave function of the continuum, i.e., Dirac plasmons in SS_2 band, and the bulk coherent phonon (A_{1g}^2 mode) are strongly coupled to each other leading quantum interference, resulting in a Fano-like line shape. The coupling between these two states decreases with increasing time delay, as the photogenerated coherent Dirac plasmons dephase within ≈1 ps through the energy distribution within the SS_2 band [11].

3 Conclusion

In summary, we have investigated the coherent phonon dynamics in a 5 QL thick Sb_2Te_3 topological insulator, using reflection type pump-probe spectroscopy. We have observed two dominant optical phonon modes at 1.92 THz and 5.04 THz, which were assigned to the A_{1g}^1 and A_{1g}^2 modes. Interestingly, we found that the A_{1g}^2 mode exhibits a Fano-like line shape, which is persistent for up to ≈1 ps. The transient Fano-like line shape of the A_{1g}^2 phonon mode observed in Sb_2Te_3 is due to quantum interference between the continuum-like Dirac plasmons in the SS_2 band and the discrete coherent phonon mode.

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