THz conductivity of nanograined Bi_2Te_3 pellets

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THz spectroscopy www.uni-due.de/ag-mittendorff

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Offen im Denken

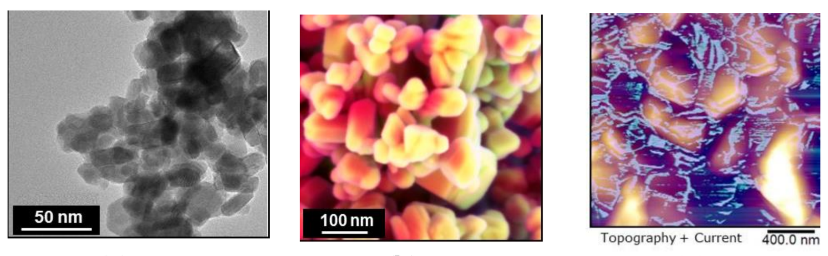
Introduction

- **Topological insulators (TI)**

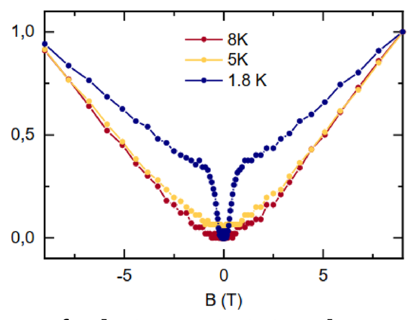
  - host Dirac carriers at the surface with a very high mobility
  - spin–momentum locking ➡ no backscattering between states of opposite momentum which would otherwise need a spin flip
  - transport properties of bulk crystals being dominated by bulk carriers which outnumber the surface carriers by orders of magnitude

- **Material studied**

  - Bi_2Te_3 nanoparticles (with different Te doping) compacted by hot pressing to nanograined bulk samples with a high surface to volume ratio
  - give access to surface properties even in extended dimensions
  - percolating channel of Dirac carriers along grain boundaries and interfaces
  - band gap ~ 0.165 eV
  - signatures of spin-orbit coupled transport associated with the phenomenon of weak anti-localization at low temperatures (<5K)



(a) Transmission Electron Microscopy(TEM) (b) Scanning Electron Microscopy(SEM) and (c) Atomic Force Microscopy(AFM) images of Bi_2Te_3 nanoparticles (taken from [1])



Comparison of relative resistivity-change versus magnetic field at three different temperatures(taken from[1])

- **Method**

  - THz time-domain spectroscopy (TDS) in reflection geometry is the method employed
  - two parabolic mirrors guide THz pulse generated by photo-conductive antenna (PCA) to the sample
  - two more parabolic mirrors focus the reflected THz radiation onto the detector
  - the detector being gated by near infrared pulse which allows the sampling of electric field evolution of THz pulse.

Theoretical models

- Fermi Energy E_F is calculated from the relation

$$\int_{E_c}^{\infty} D(E)\, f(E, E_f)\, dE = n_H(1.8K) \quad \text{(n-doped system)}$$

$$\int_{-\infty}^{E_v} D(E)\left(1 - f(E, E_f)\right) dE = n_H(1.8K) \quad \text{(p-doped system)}$$

where, D(E) – density of states
$f(E,E_f)$ – Fermi-Dirac distribution
n_H (1.8 K) – carrier density from hall measurements at 1.8K
E_c – Energy at conduction band minimum
E_v – Energy at valence band maximum

- Chemical potential (μ(T)) is calculated from the concept of particle number conservation

Three different contributions are employed to analyze the reflectivity spectra

- free carrier absorption by bulk carriers (bulk conductivity)

$$\sigma_B(\omega) = \frac{p' n_B e^2 \tau_B}{m^*}\left(\frac{1}{1 - i\omega\tau_B}\right)$$

τ_B: momentum scattering time of bulk carriers
m^*: Effective mass of bulk carriers
p': scaling factor accounting for the fact that sample is not a bulk crystal

- free carrier absorption by surface carriers (surface conductivity)

The Dirac carriers behave as massless fermions, so the Drude formula differs from the bulk as

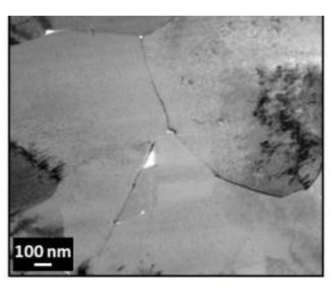
$$\sigma_S(\omega) = \frac{i q' e^2 \sqrt{\pi n_S}\, v_F}{\pi\hbar(i\gamma_S + \omega)}$$

q': surface to volume ratio
γ_S: scattering rate of surface carriers
v_F: Fermi velocity

- plasmonic contribution of surface carriers (plasmonic conductivity)

$$\sigma_P(\omega) = \frac{i q' r' e^2 \sqrt{\pi n_S}\, v_F}{\pi\hbar\left(i\gamma_S + \frac{\omega^2 - \omega_p^2}{\omega}\right)}$$

ω_p : plasmon frequency
r' : ratio of surface plasmons to free surface carriers



AFM image of compacted Bi_2Te_3 pellet

$$\sigma_{total}(\omega)(total\ conductivity) = \sigma_B(\omega) + \sigma_S(\omega) + \sigma_P(\omega)$$

When the frequency of electric field is resonant to the plasmon (associated with strong mobility offered in the domain of surface carriers), strong light-matter interaction occurs.
Two samples with different Te doping are studied as discussed in cases I and II.

References

[1]: Izadi, S., Han, J. W., Salloum, S., Wolff, U., Schnatmann, L., Asaithambi, A., Matschy, S., Schlörb, H., Reith, H., Perez, N., Nielsch, K., Schulz, S., Mittendorff, M., Schierning, G., Interface-Dominated Topological Transport in Nanograined Bulk Bi_2Te_3. *Small* 2021, 17,2103281.

Results

Case I (E_F is 0.078 eV above conduction band minimum)

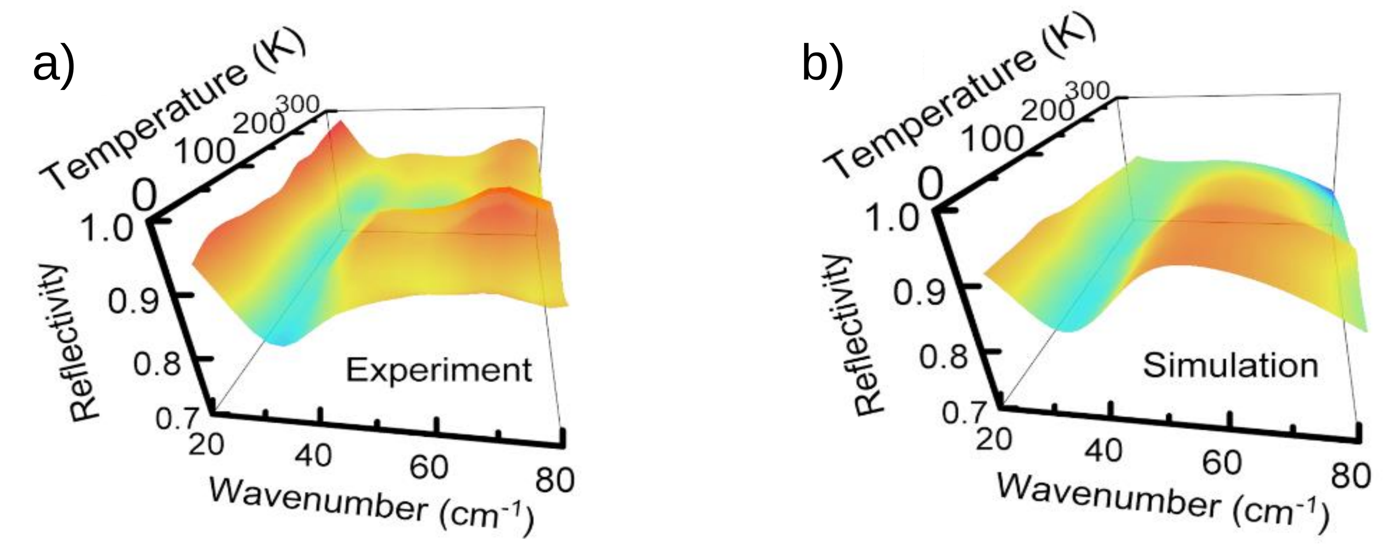


Fig.I.1. Reflectivity as a function of temperature and wavenumber from (a) experiment and (b) simulation (taken from [1])

- strong plasmonic response at 45 cm^{-1} at low temperatures
- decrease in plasmonic contribution with increase in temperature owing to increased scattering at high temperatures ($\gamma_S(T) = \gamma_0 + AT^2$, where $A = 3.33 \times 10^{-4}\ cm^{-1}K^{-2}$)

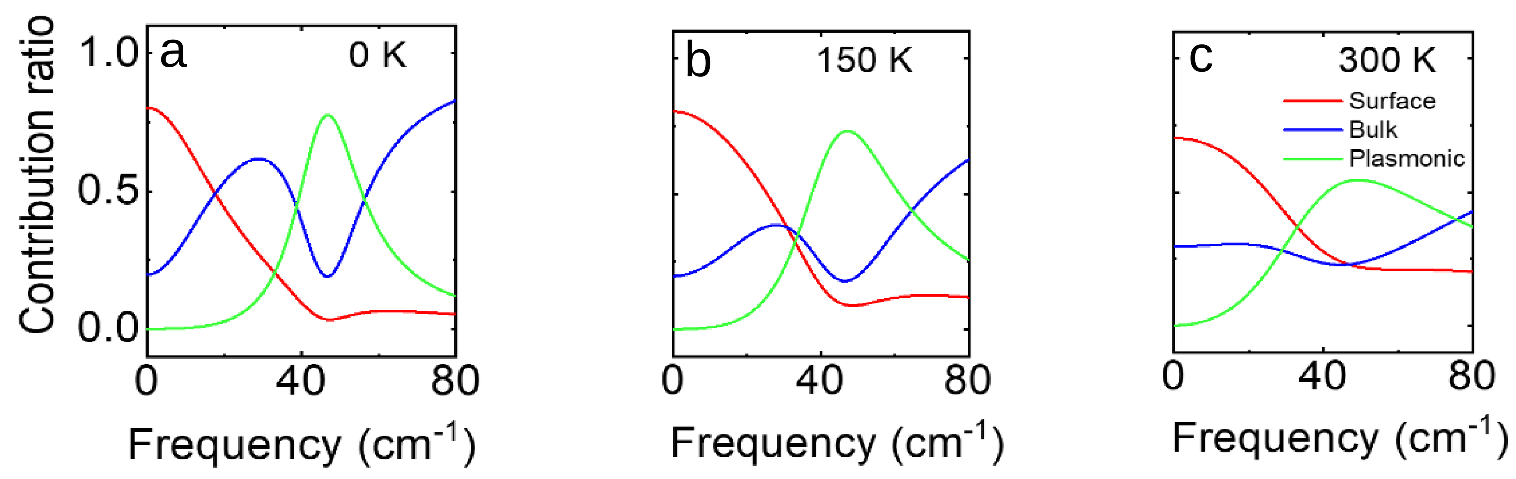


Fig.I.2. Ratio of contribution of bulk, surface and plasmonic conductivity as a function of frequency at (a) 0K, (b) 150K and (c) 300K (taken from [1])

- dominance of surface transport below plasmonic frequency accounting for roughly 60 % of the net conductivity even at room temperature

Case II (E_F is 0.052 eV above conduction band minimum)

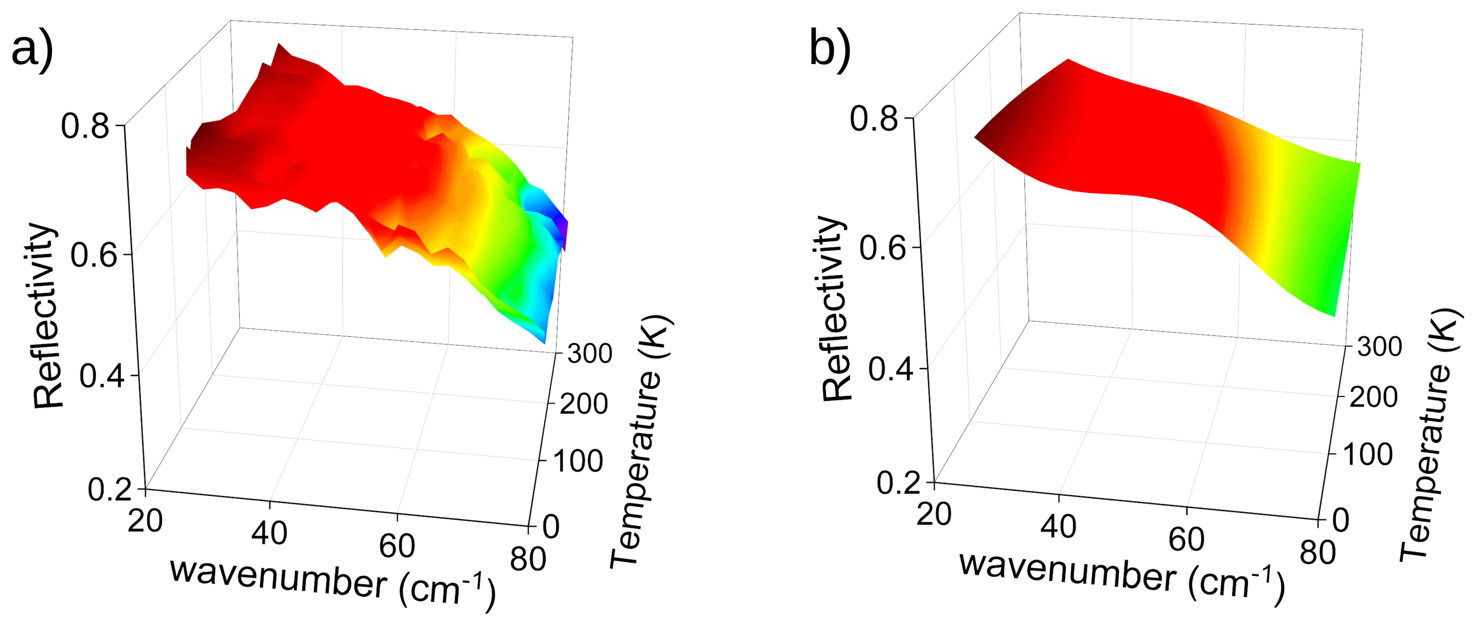


Fig II.1. Reflectivity as a function of temperature and wavenumber from (a) experiment and (b) simulation

- weaker plasmonic response (compared to case I) even at low temperatures
  ➡ weaker localisation
  ➡ weaker light-matter coupling

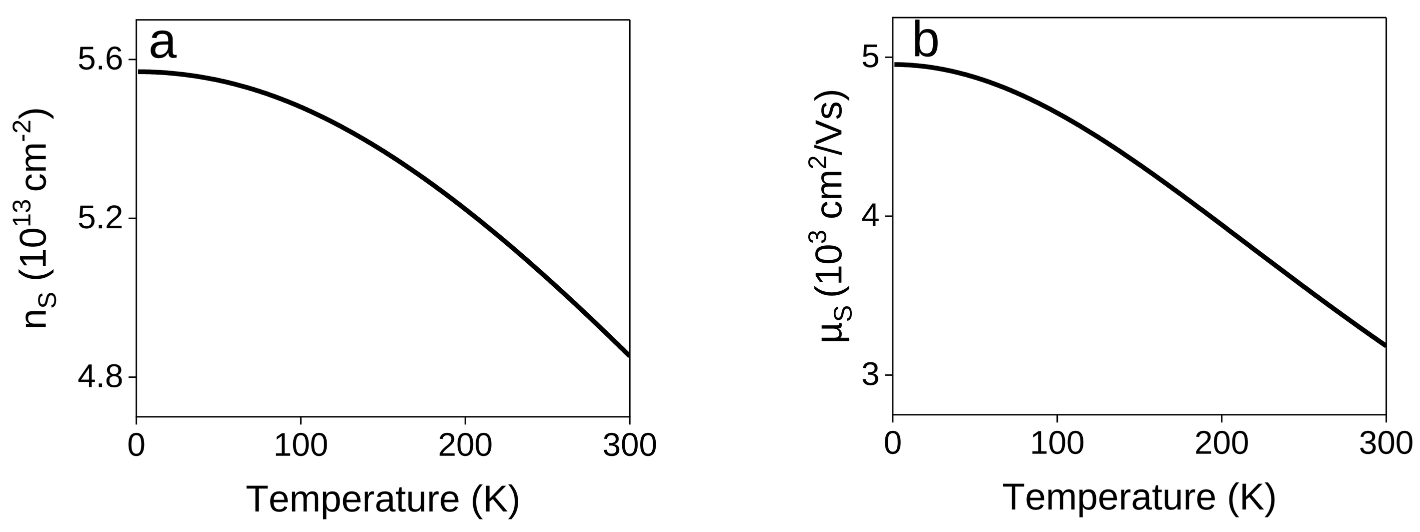


Fig II.2 . Temperature variation of (a) carrier density and (b) mobility of surface carriers

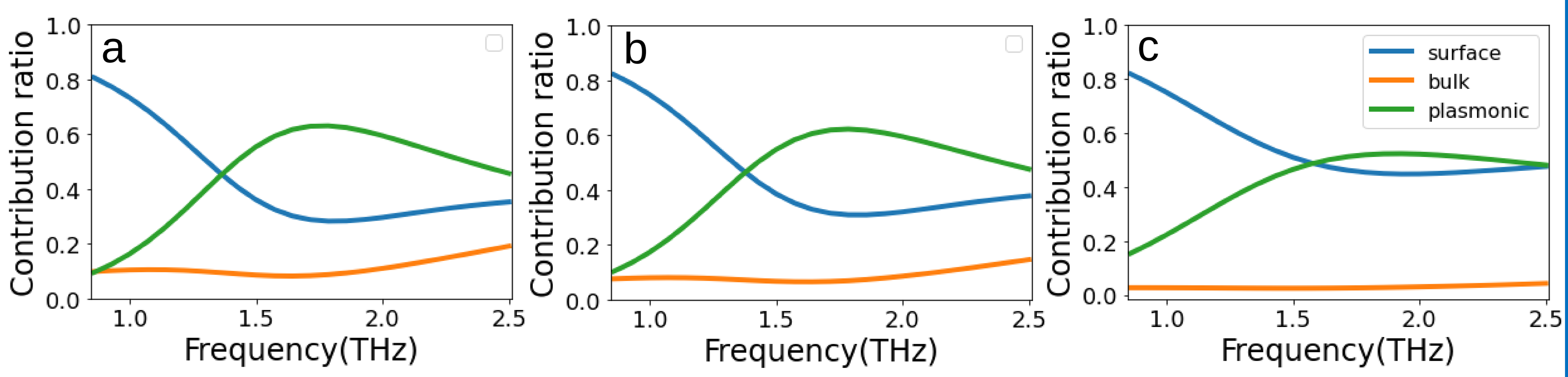


Fig II.3 Ratio of contribution of bulk, surface and plasmonic conductivity as a function of frequency at (a) 4K, (b) 100K and (c) 300K

Despite high bulk carrier density of the order of 10^{19}-10^{20} cm^{-3} compared to surface carrier density of the order of 10^{13} cm^{-2} (Fig.II.2.(a)), surface carriers dominate the net conductivity(~80 percent) with a mobility above 10^3 cm^2/Vs (Fig.II.2.(b)) even at room temperature ➡ high mobility of surface carriers exploited!

Conclusions and outlook

- Using hot-pressed Bi_2Te_3 nanograined pellets help exploit the properties (high mobility and thereby, high conductivity) of surface carriers which are otherwise outnumbered by bulk carriers in bulk crystals.
- Surface carriers with high mobility have a strong frequency dependence unlike bulk carriers whose reflectivity profiles show a flat response.
- Non-equilibrium carrier dynamics of bulk and surface carriers can be further exploited by optical pump-THz probe and THz pump-THz probe spectroscopy respectively.