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Topological Insulators for Next Generation Electronics and Photonics

3rd International Conference and Exhibition on Materials Science & Engineering, San Antonio, USA

Oct. 8 2014

Dongxia Qu

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXXX
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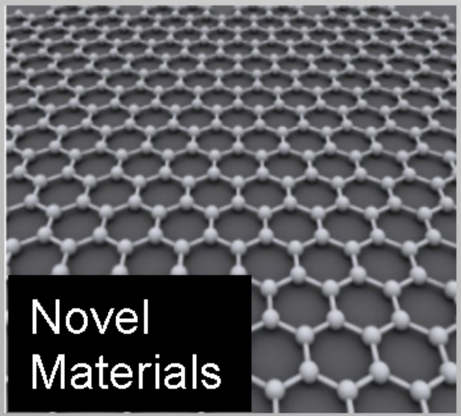
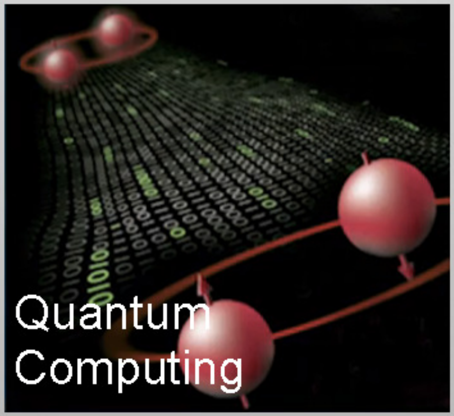
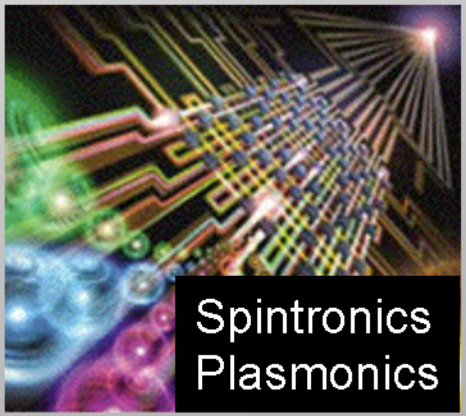
Search for new materials or ideas toward "dissipationless" transport

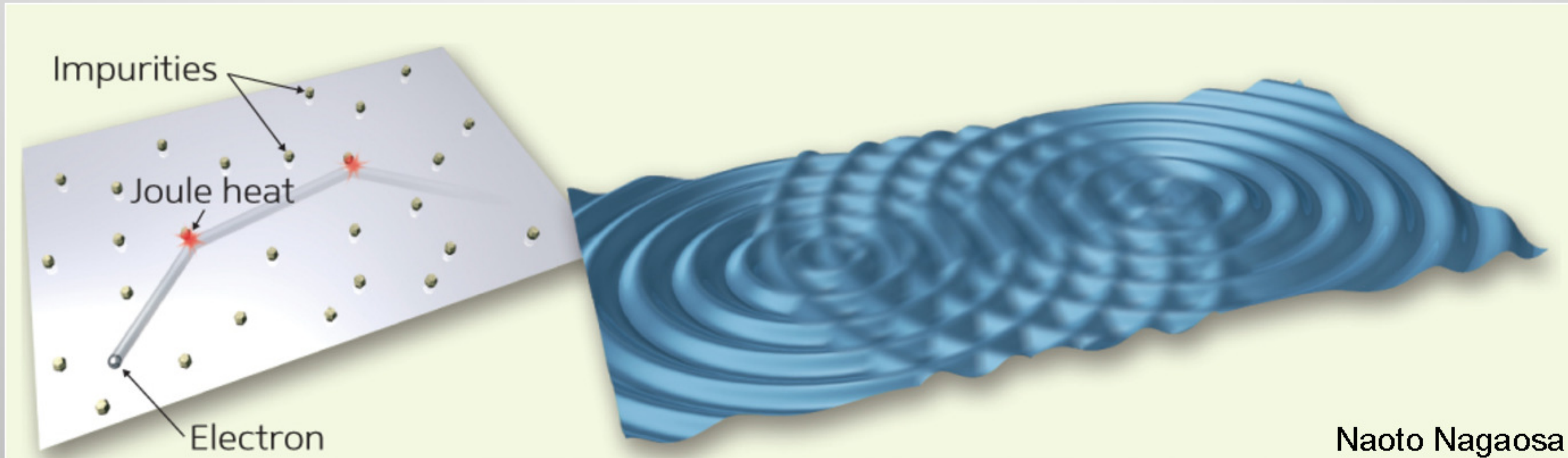
- We are always searching for alternatives to silicon chips
  - **Novel Materials:** III-V compounds; group IV elements; III-V semiconductor and silicon substrate integration, graphene…
  - **Quantum Computing**: Superconducting logic chips; spin qubits; topological quantum computation…
  - **Emerging Technology**: Plasmonic circuits, spintronics, metamaterials…







Ohmic current vs. topological current

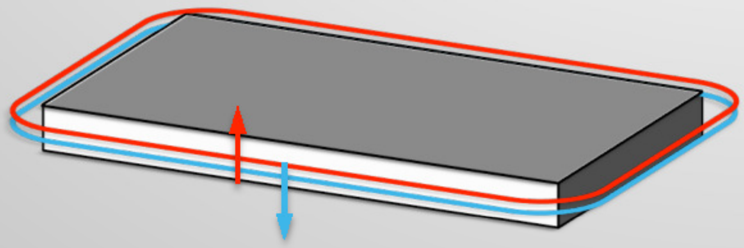


- Ohmic current
- Joule heat is produced

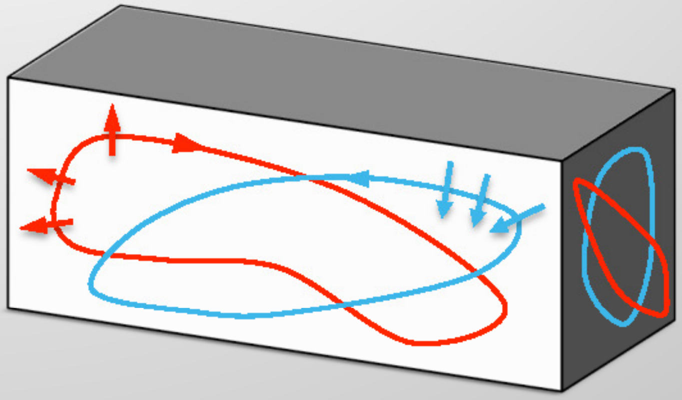
- Topological current
- Dissipationless, e.g. edge currents in quantum Hall effect

What is a topological insulator?

A topological insulator is an insulating material that allows electrons to flow along its boundary in spin-polarized channels that are topologically protected from impurity scattering.



2D topological insulator

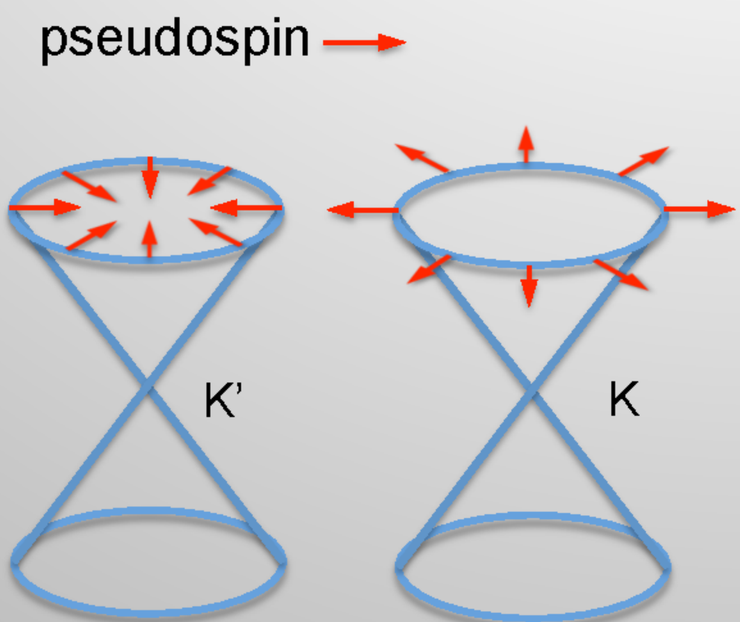


3D topological insulator

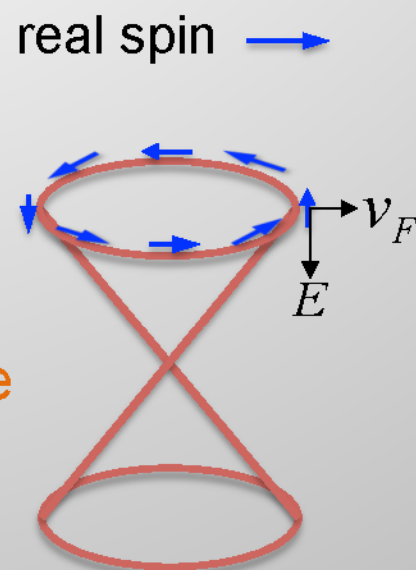
These materials have been named topological insulators because they are insulators in the 'bulk' but have exotic metallic states present at their surfaces owing to the topological order.

Hassan and Kane, *RMP* (2010) J. E. Moore, *Nature* (2010). H. C. Manoharan, *Nature Nano*. (2010)

Chiral Dirac fermions in a topological insulator



¼ Graphene



Graphene

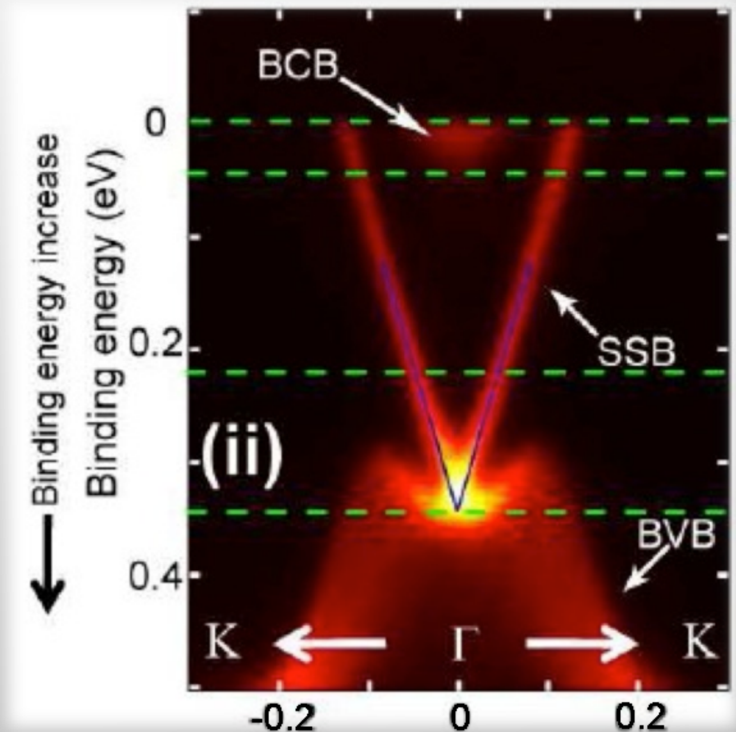
$$H_{eff} = \hbar v_F \vec{\sigma} \cdot \hat{p}$$

Topological Insulator

$$H_{eff} = \hbar v_F (\sigma_y p_x - \sigma_x p_y)$$

Properties of topological surface states

- Linear energy-momentum dispersion
- One Dirac cone on each surface
- No spin degeneracy
- Tunable chemical potential
- Robust against disorder

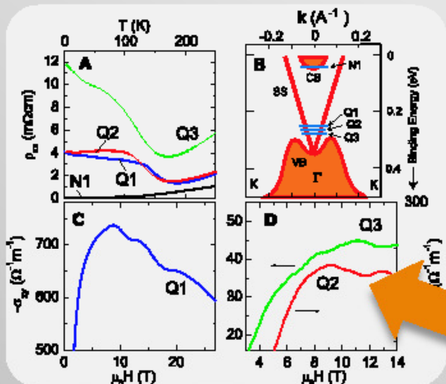


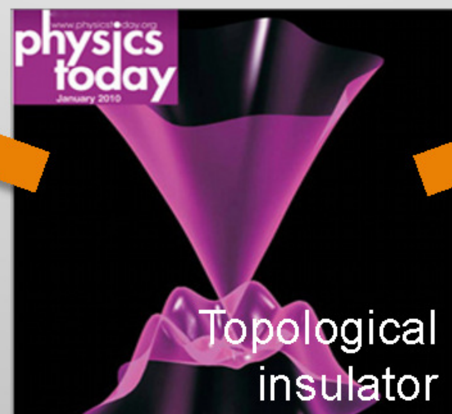
Experiment: Y. Chen *et al.*, *Science* (2009)
Y. Xia *et al.*, *Nature Phys.* (2009)

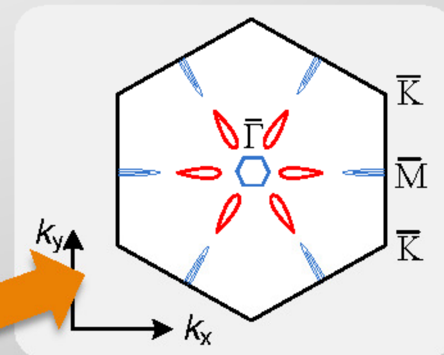
Theory : H. Zhang *et al*, *Nature Phys.* (2009)

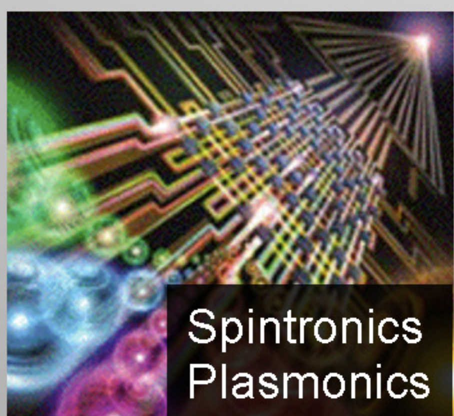
New two dimensional electron gas – topological surface states

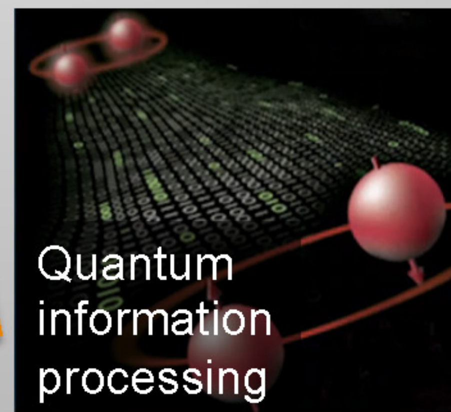
- Topological surface states offer new opportunities for manipulating energy and information in powerful ways











Outline

- Search of topological surface states in 3D materials
  - Why and how to search for topological surface states?
  - Single crystal growth of bulk topological insulators
- Electrical transport investigation of topological insulators
  - Detect topological surface states in Bi_2Te_3
  - High mobility and mean free path of surface holes in Bi_xSb_{1-x}
- Future applications

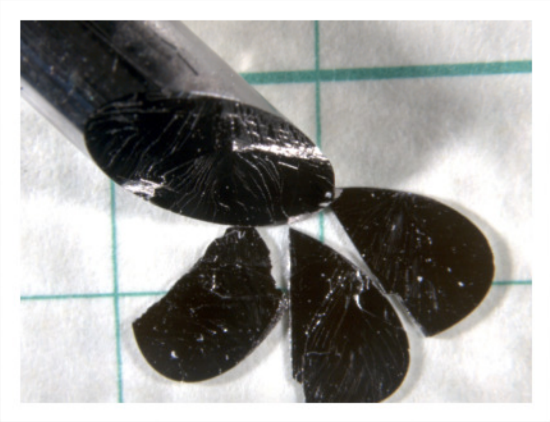
Compounds identified to be topological insulators

$Hg_{1-x}Cd_xTe$
Bi_xSb_{1-x}
Bi_2Se_3
$Bi_{2-x}Ca_xSe_3$
$Bi_{2-x}Sb_xSe_3$
Bi_2Se_2Te
Bi_4Se_3
$TlBiSe_2$
$TlBiSe_{1-x}S_x$
$(PbSe)_5(Bi_2Se_3)_6$
$(Bi_2)_n(Bi_2Se_3)_m$
Sb_2Te_3
Sb_2Te_2Se…

Bi_2Te_3
$Bi_{2-x}Sb_xTe_3$
Bi_2Te_2Se (BTS)
$Bi_{2-x}Sb_xTe_{3-y}Se_y$
$Bi_2(Te_{0.8}S_{0.2})_2S$
$Bi_{1.1}Sb_{0.9}Te_2S$
$PbBi_2Te_4$
$GeBi_2Te_4$(GBT124)
$PbBi_4Te_7$
$Pb(Bi_{1-x}Sb_x)_2Te_4$
$TlBiTe_2$
BiTe
$(Bi_2)_n(Bi_2Te_3)_m$ …

Goal of Crystal Growth

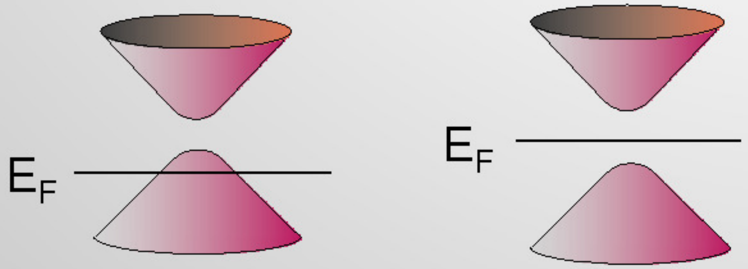
- Defect control
  - Low bulk conductivity
  - High surface mobility



R. J. Cava *et al*, *J. Mater. Chem. C* (2013)
Y. Ando *J. Phys. Soc. Jap* (2013)

Challenges in transport measurements

Anti-site defects and vacancy defects



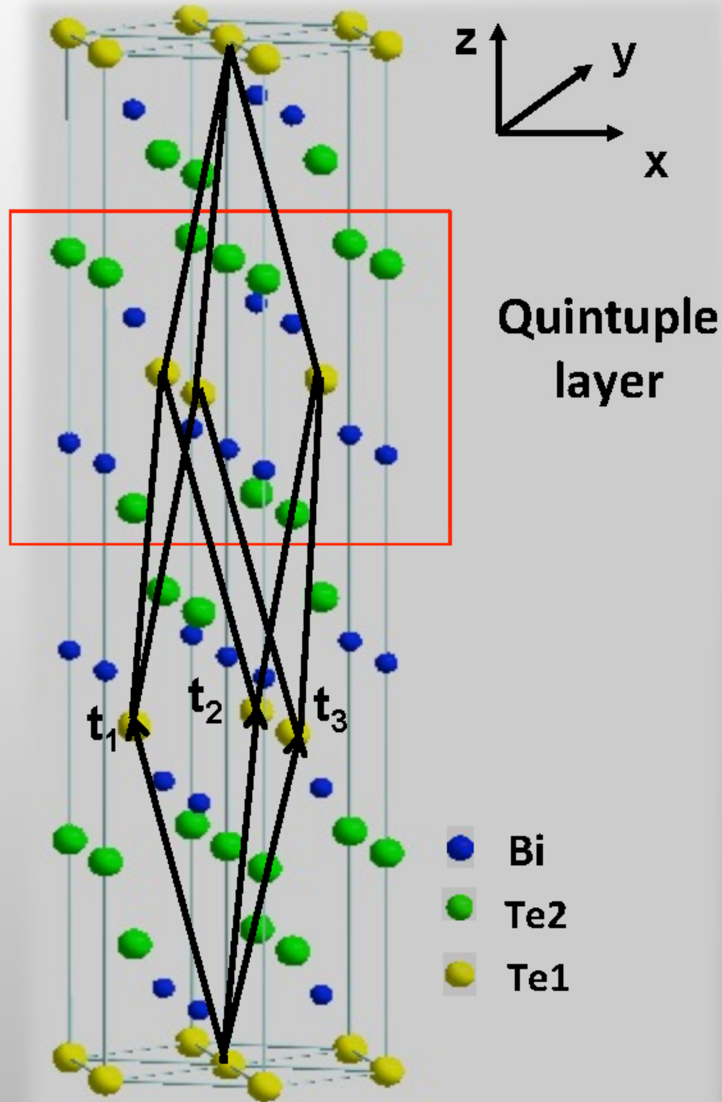
Metallic Crystal   Non-metallic Crystal

- As-grown crystals tend to be metallic due to defects
- Doping tunes E_F but significantly degrades the crystal quality

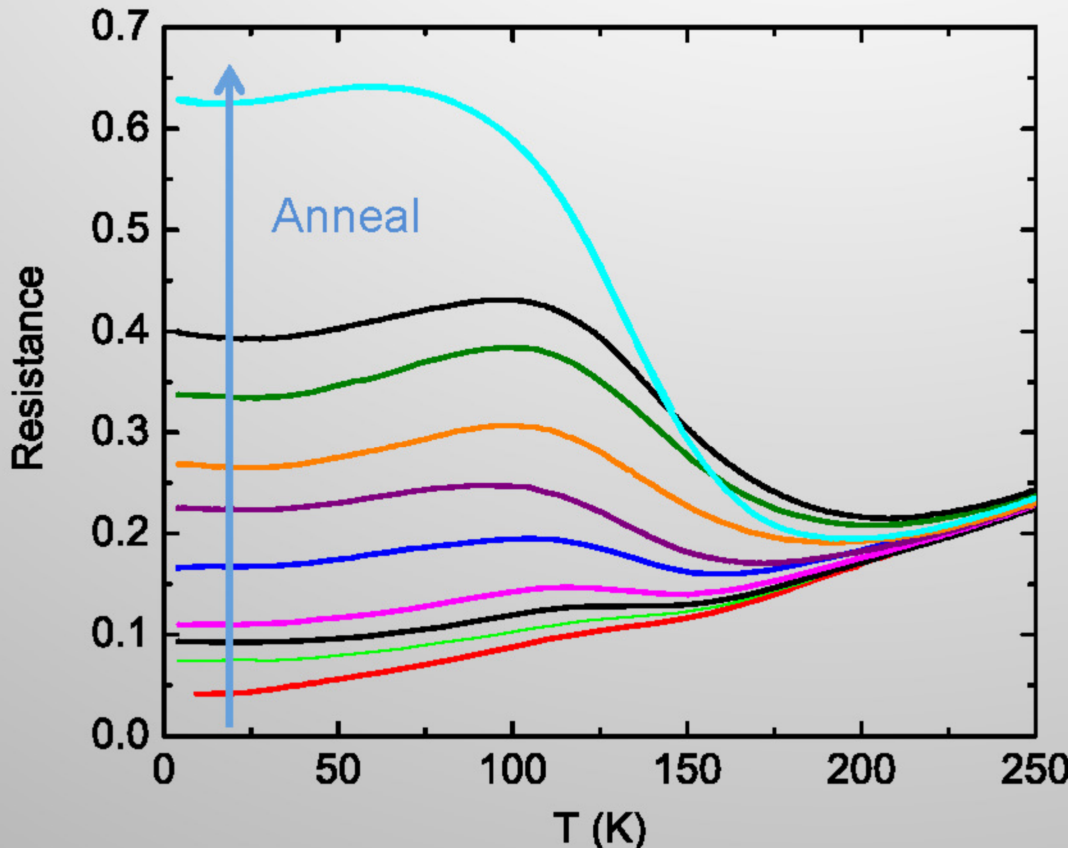
$Bi_{Bi} \rightarrow Bi_{Te}' + h^{\cdot} + Te$ (anti-site defects)

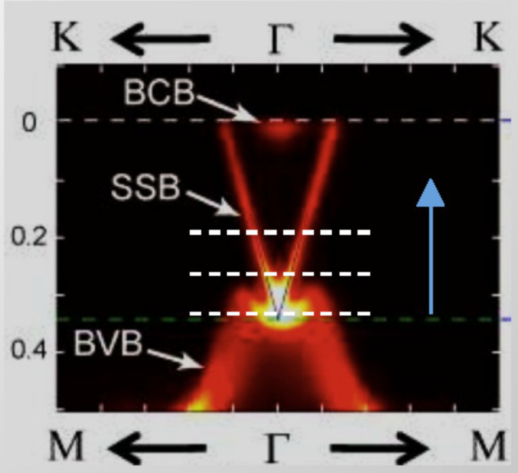
$Te_{Te} \rightarrow V_{Te}^{\cdot\cdot} + 2e' + Te$ (vacancy defects)

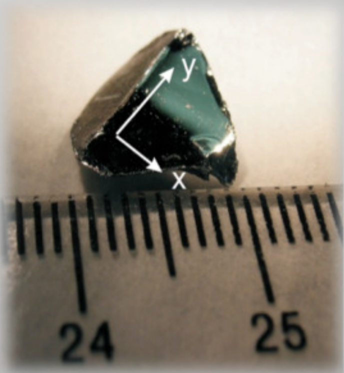
Q: How to tune E_F into the gap without degrading the surface electron mobility?



Our approach
1. heat treatment to fine tune E_F in Bi_2Te_3



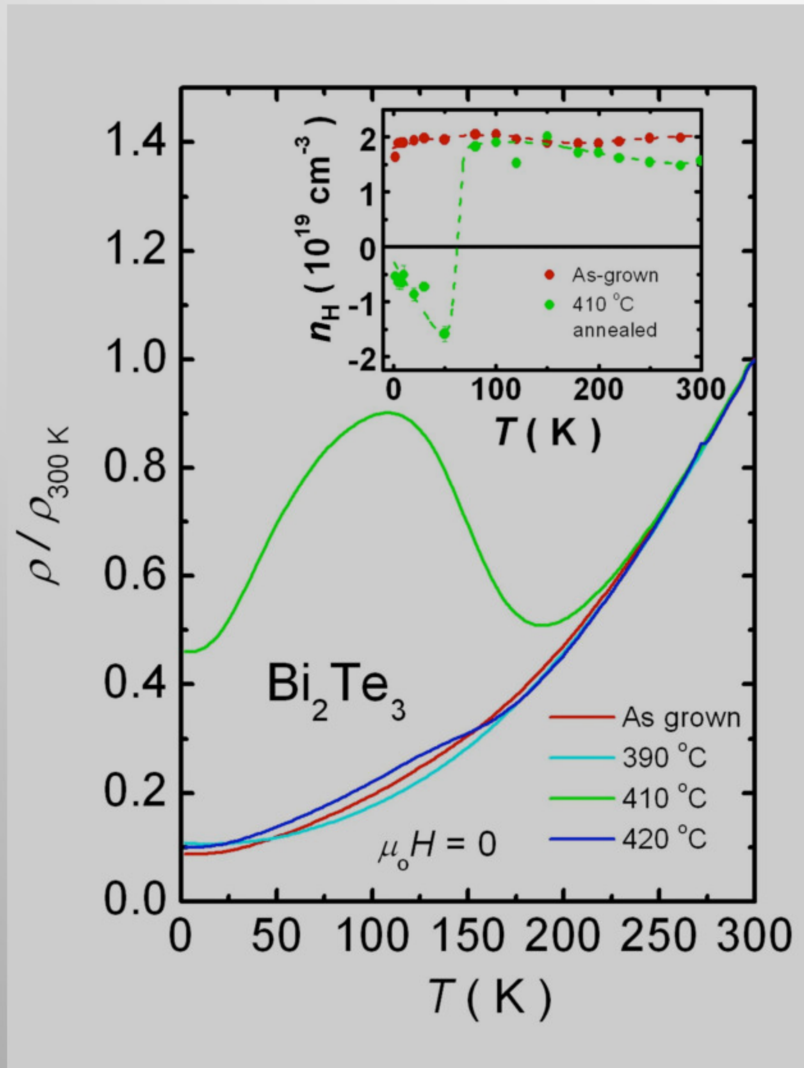


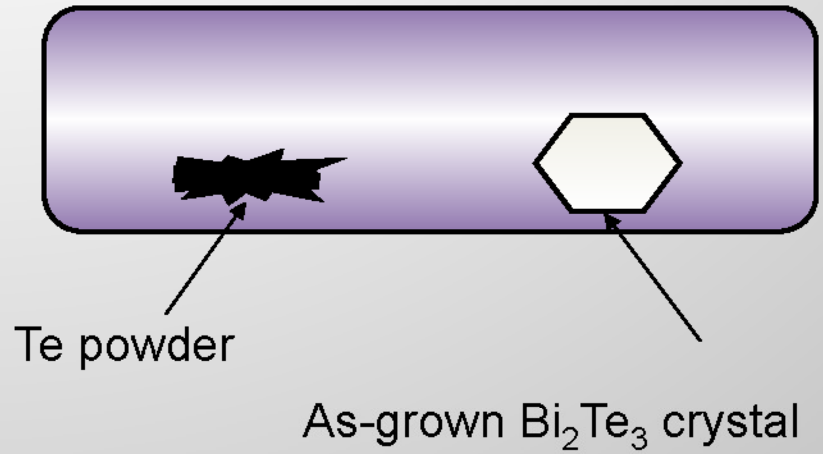


- Anneal the as-grown crystal can vary the defect concentration
- Fine-tuning brings the chemical into the gap

Our approach

2. Anneal the Bi_2Te_3 in Te vapor



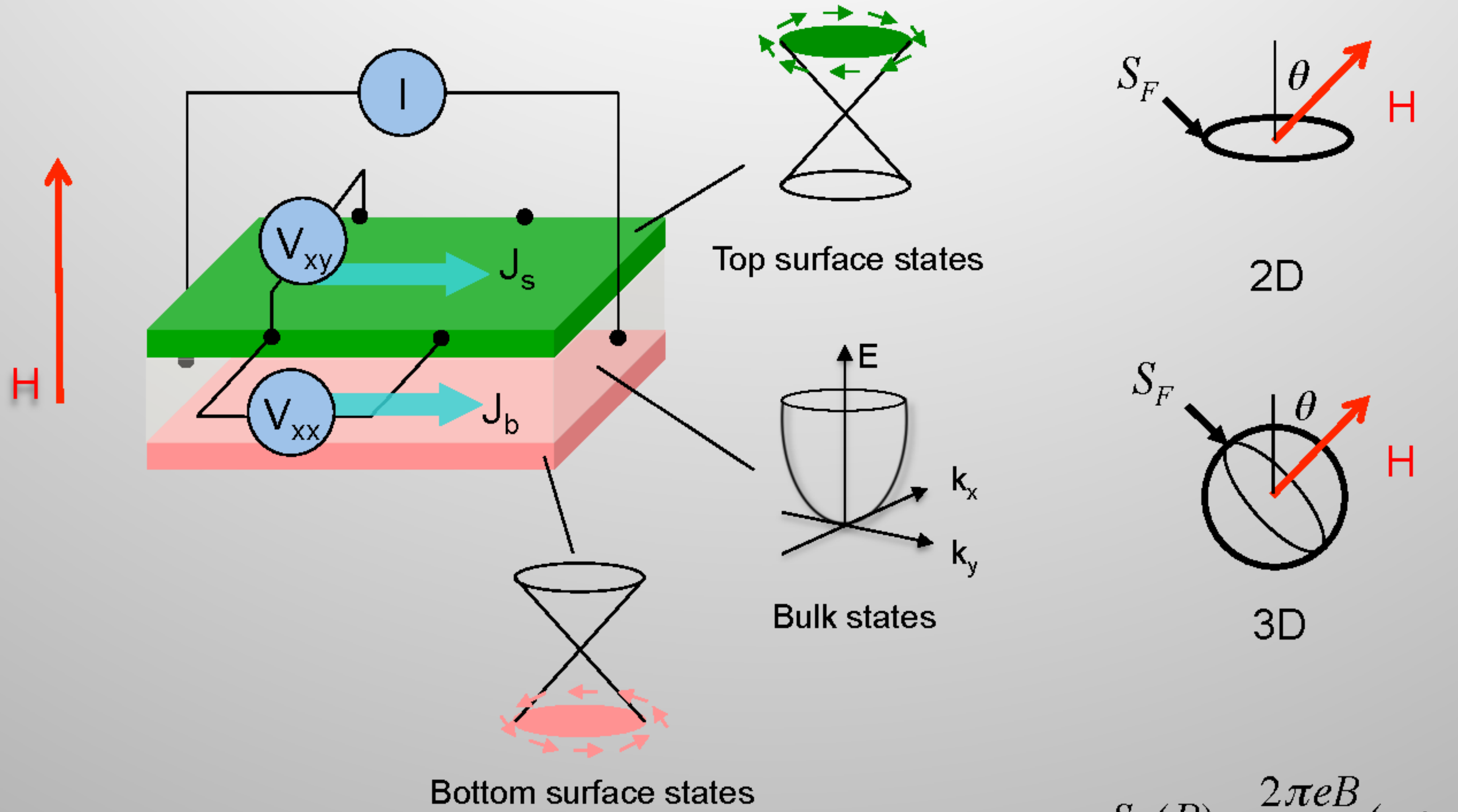


Annealing temperature:

400 – 440 °C (1 week)

Y. S. Hor, **D. Qu**, N. P. Ong and R. J. Cava, J. Phys.: Condens. Matter, **22**, 375801 (2010)

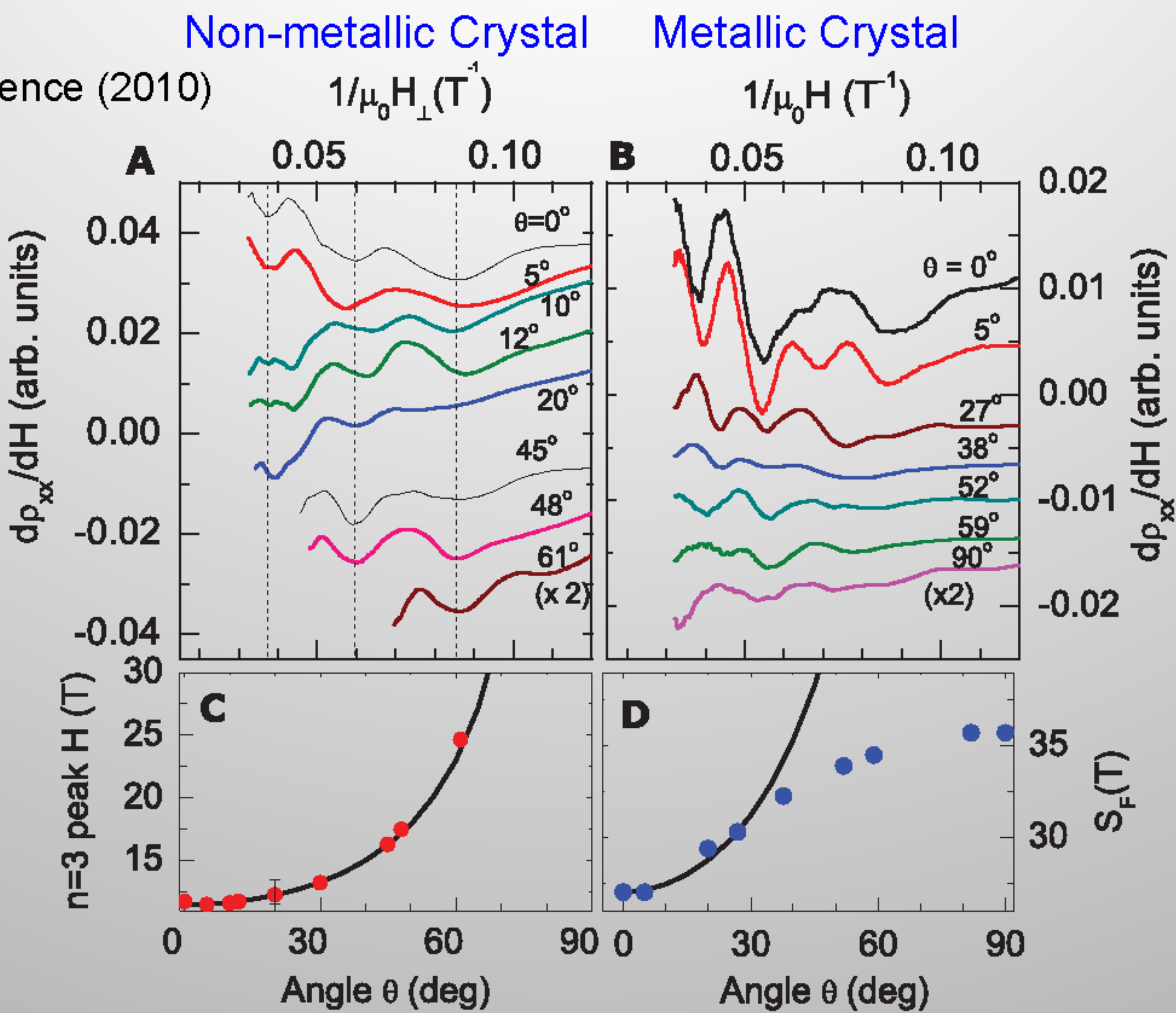
How to measure surface states in a topological insulator?



$$S_F(B) = \frac{2\pi eB}{\hbar}(n+\gamma)$$

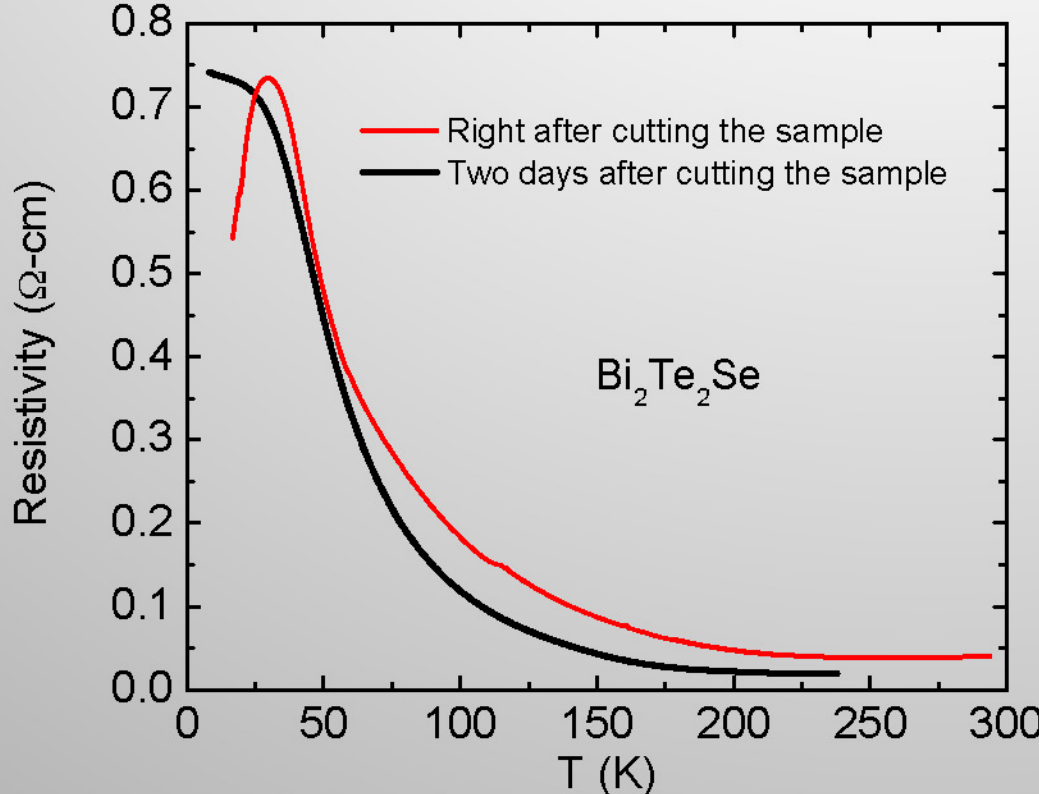
Angle dependent shubnikov de Haas oscillations

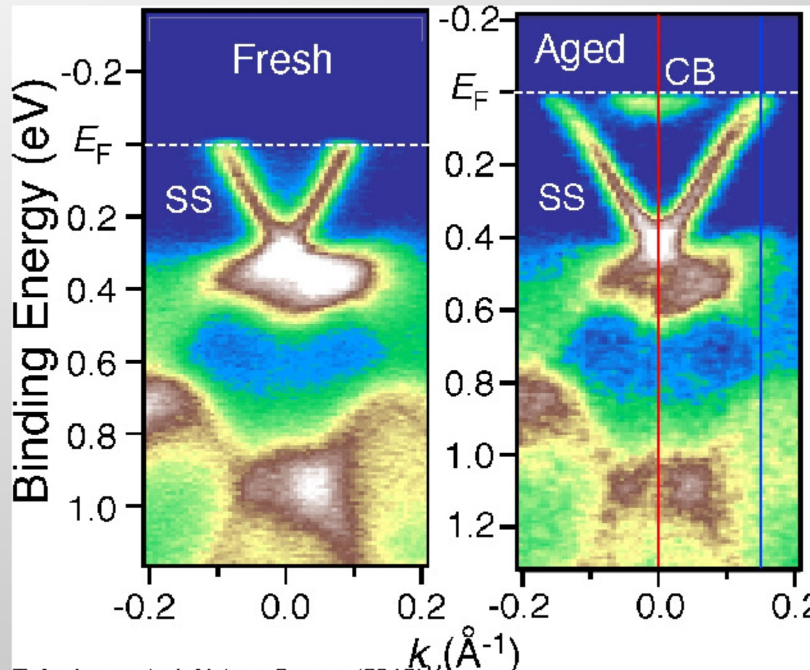
D.-X Qu *et al*, Science (2010)



- First demonstration of the 2D surface states in TI Bi_2Te_3

Aging effect in bismuth-based stoichiometric topological insulators



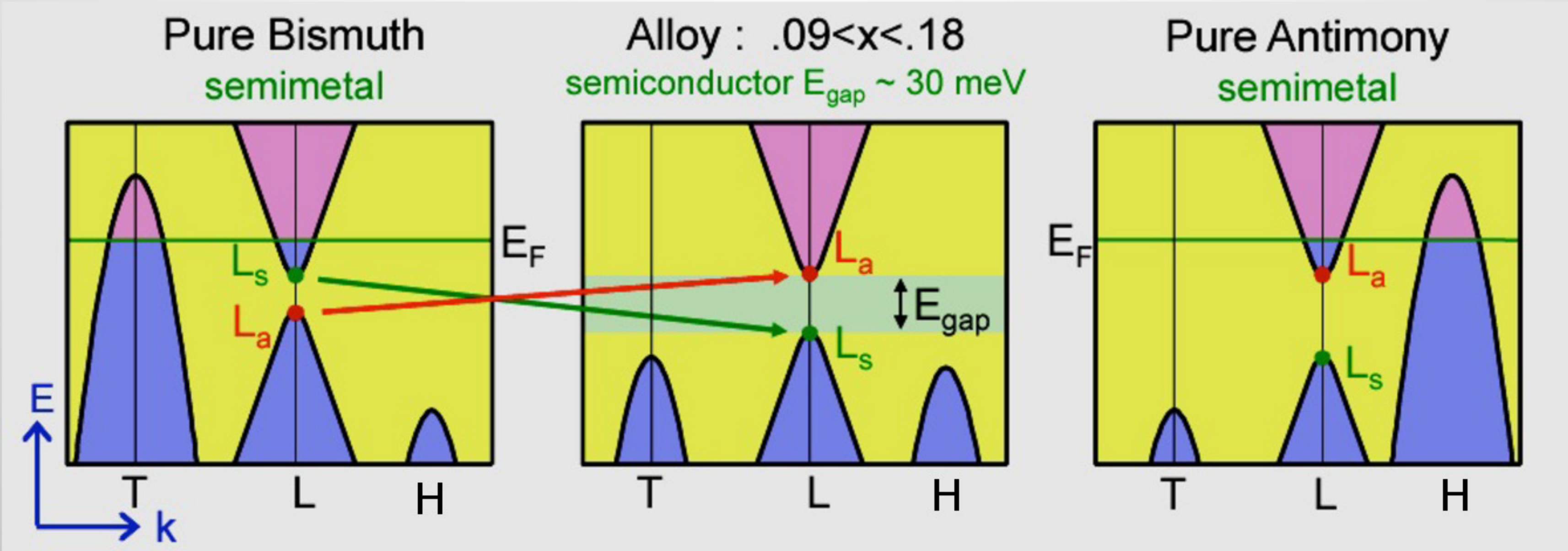


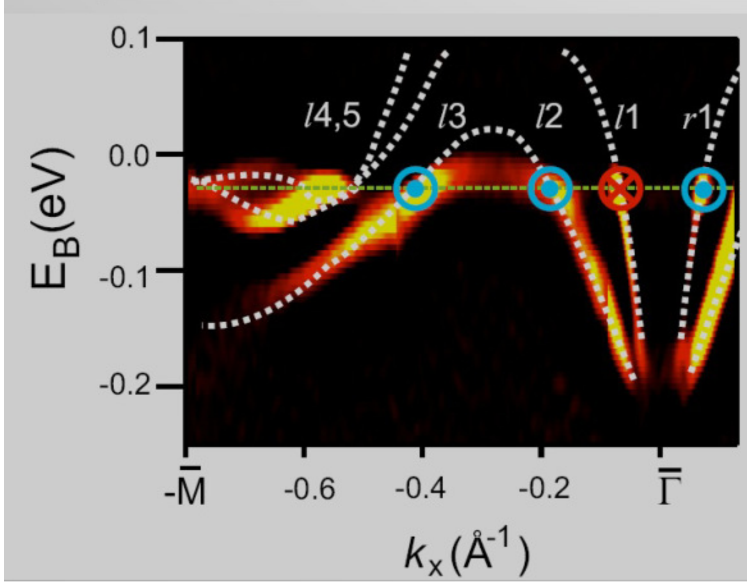
T. Arakane *et al*, *Nature Comm.* (2012)

- A thermally activated process induces a spontaneous Bi termination atop the original bulk terminated structure after cleavage.

Low energy ion scattering measurements: X. He *et al*, *PRL* (2013).

Phase Diagram of $Bi_{1-x}Sb_x$

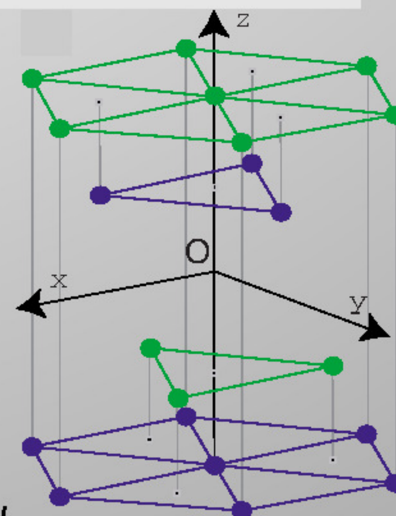




$Bi_{1-x}Sb_x$ is a strong topological insulator with 0.07 <x< 0.22

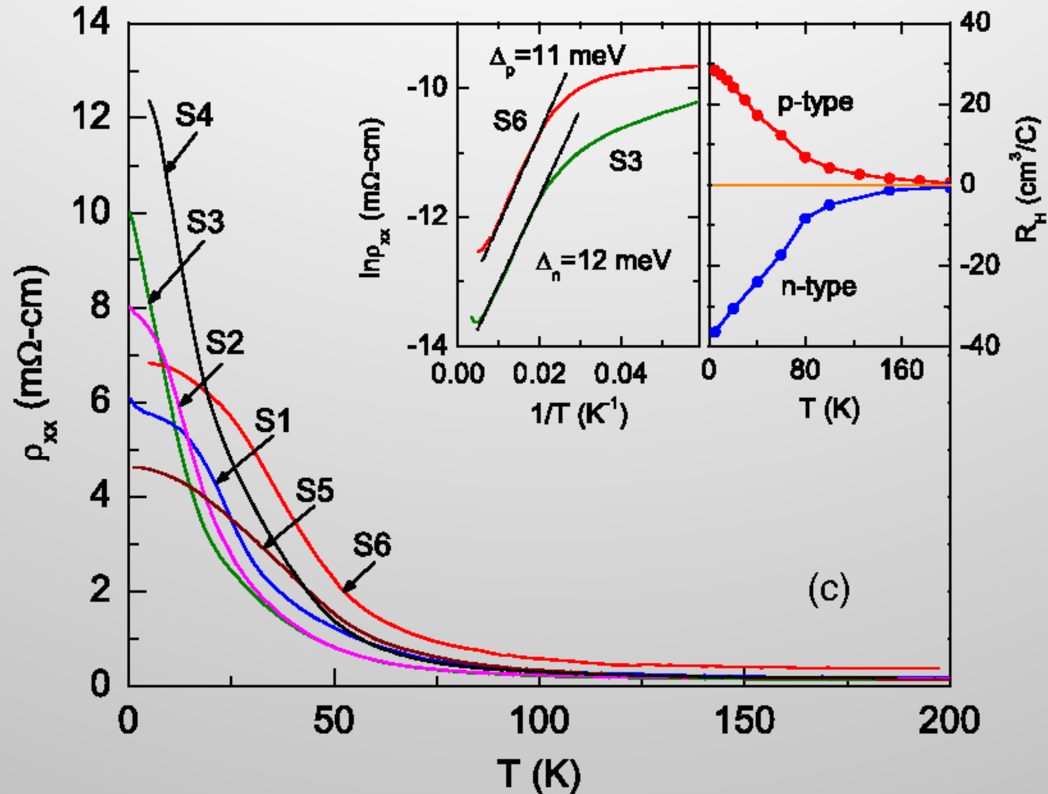
No aging effect due to surface reconstruction in $Bi_{1-x}Sb_x$

Fu and Kane, PRB (2007) J. C. Y. Teo *et al* PRB (2008)D. Hsieh *et al* Nature (2008)



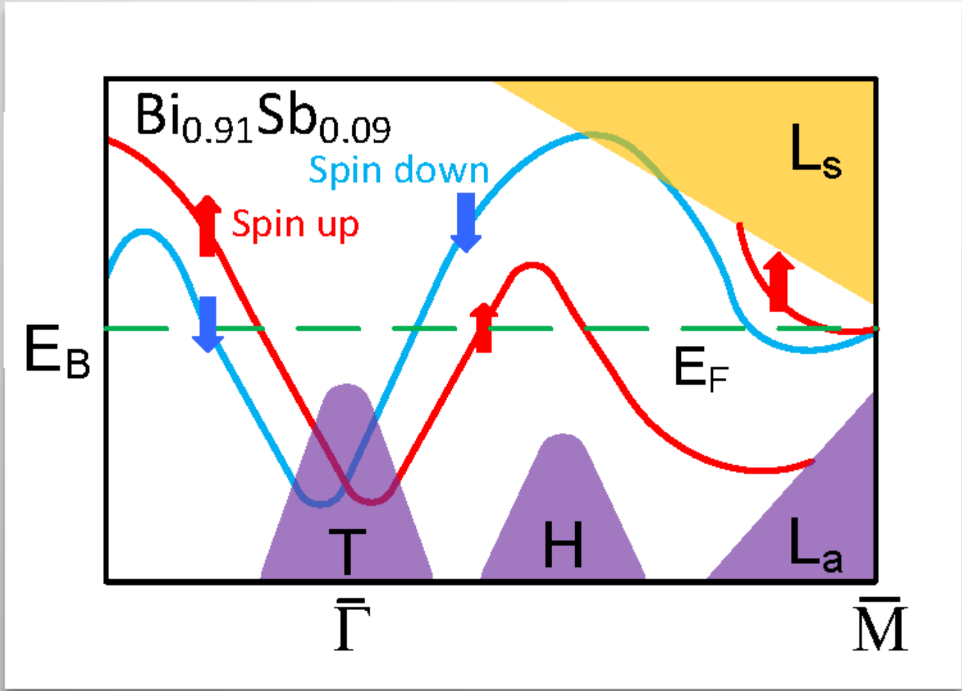
$Bi_{1-x}Sb_x$

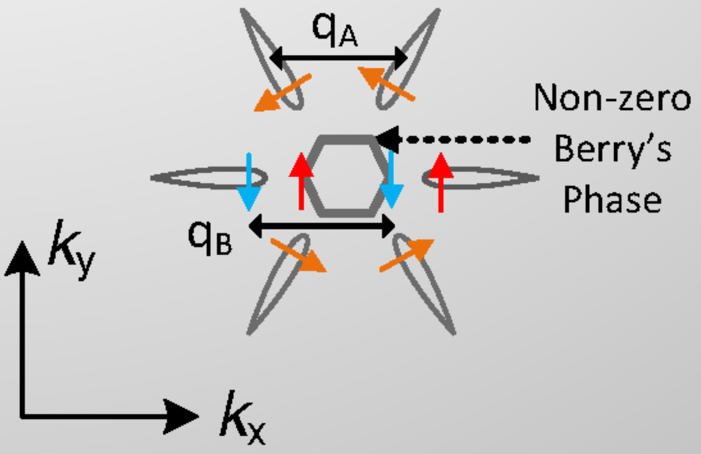
Resistivity vs. temperature properties



- Bulk crystals can be either n- or p- type doped
- Electron and hole bulk conduction are comparable and compensated

Surface band structure of $Bi_{0.91}Sb_{0.09}(111)$





- There are 5 surface bands crossing the Fermi level – complicated band structure
- Interband scattering into the Dirac band centered around Γ indirectly protects the holelike bands against defects

Low field Hall anomaly in $Bi_{0.91}Sb_{0.09}(111)$

- Hole-like Hall anomaly is observed in *n*-type samples
- Fitting the conductivity tensors

$$\sigma_{ij} = \sigma_{ij}^{b} + \sigma_{ij}^{sp} + \sigma_{ij}^{sn}$$

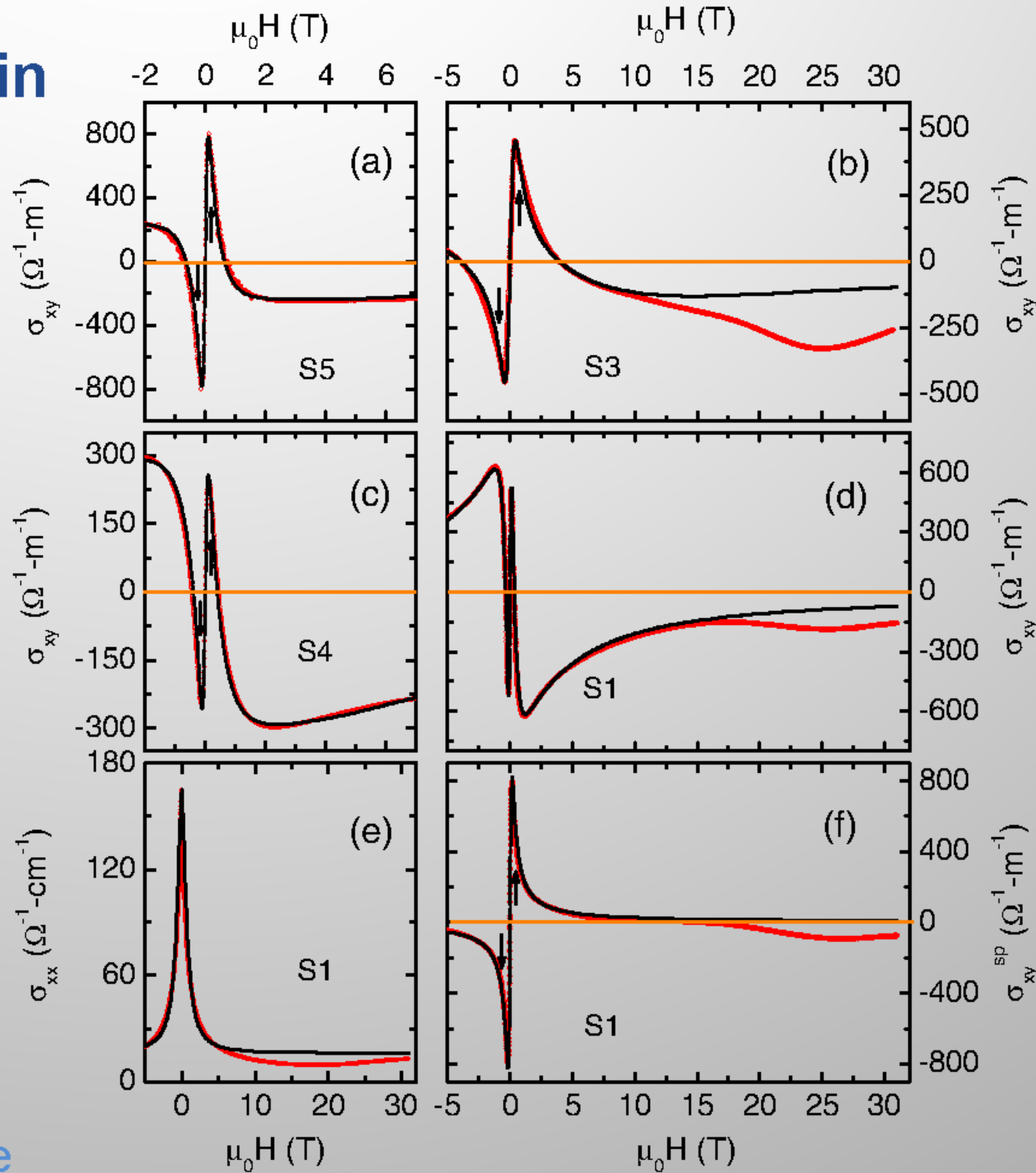
$$\mu_s = 85,000 \quad cm^2/V\ s$$

$$\mu_b = 13,000 \quad cm^2/V\ s$$

$$n_b^{tot} = 6.8\times10^{16} \quad cm^{-3}$$

Comparable to n_b of BTS

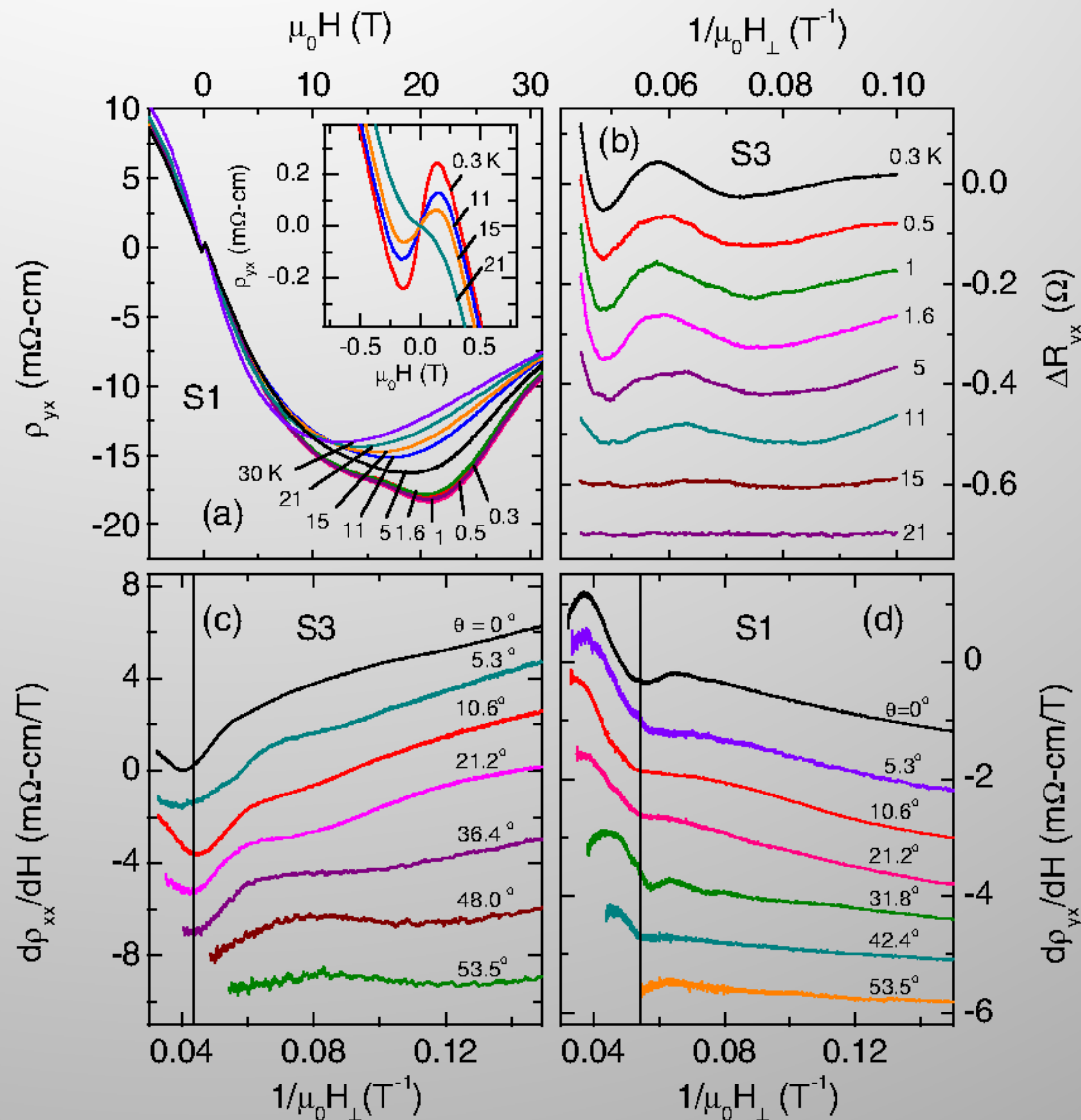
Alloy disorder decreases surface mobility by less than 43%



D.-X. Qu, S. K. Roberts, G. F. Chapline, PRL (2013)

Observation of SdH oscillations from 2D Fermi gas

- First transport detection of surface states in topological insulator $Bi_{1-x}Sb_x$ (111)
- The hole-like surface band displays the highest mobility, so far reported in bismuth-based topological insulators



Conclusion

- The big picture story
  - Topological insulator is a new quantum state of matter useful for a wide range of applications
  - The search for perfect topological insulators is on going
- Transport and optical investigations of topological insulators
  - Limited knowledge on the optical properties of TI
  - Realization of TI based diverse functional devices

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