7th ISSP International Symposium
“**Emergent Quantum Phases in Condensed Matter**”
Kashiwa Chiba, Japan, June 12, 2013

Transport Studies of Epitaxial Thin Films of Topological Crystalline Insulators

Alexey Taskin

Institute of Scientific and Industrial Research,
Osaka University

ISIR OSAKA UNIVERSITY

OSAKA UNIVERSITY

Outline

- Topological Crystalline Insulator (TCI)
- MBE growth of SnTe on Bi_2Te_3
- Transport properties of SnTe thin films

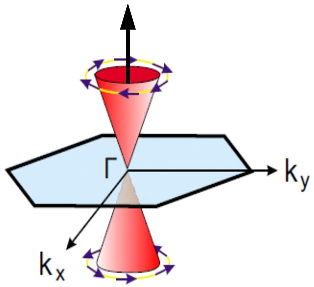
Collaborators at Osaka Univ.

Yoichi Ando

Kouji Segawa

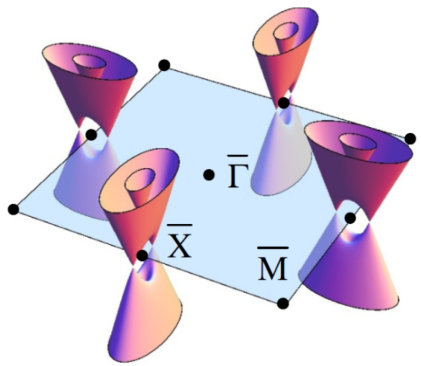
Satoshi Sasaki

Z_2 Topological Insulator
vs.
Topological Crystalline Insulator



Two important ingredients for TI:

1) Spin-Orbit Coupling ⇒ band inversion
2) Time Reversal Symmetry ⇒ Kramers' degeneracy at TRIMs

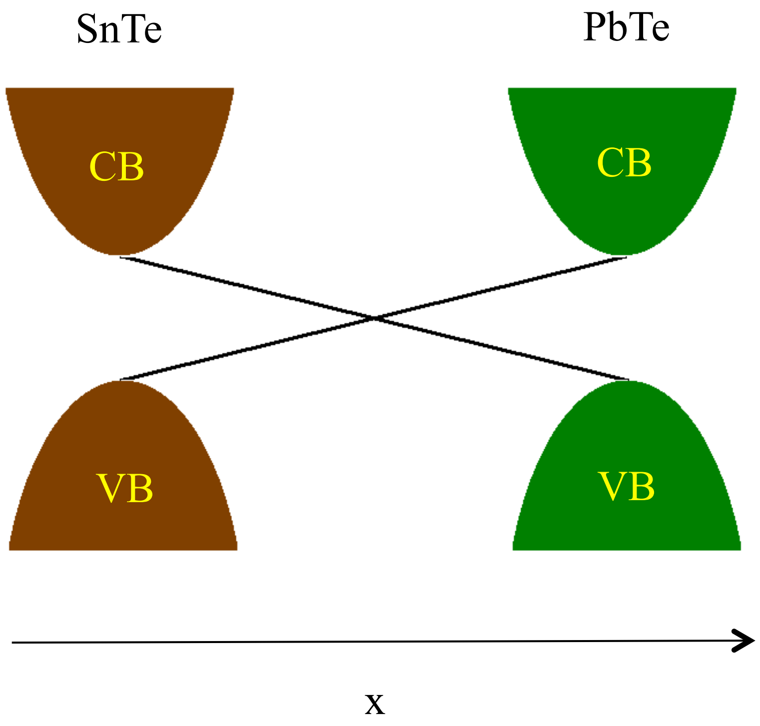


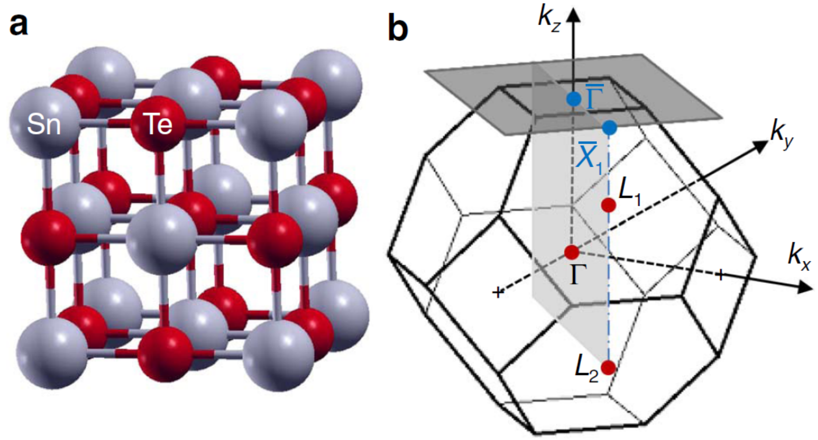
Two important ingredients for TCI:

1) Spin-Orbit Coupling ⇒ band inversion
2) Symmetry of the crystal lattice ⇒ degeneracy at mirror planes, etc.

SnTe as a topological crystalline insulator (prediction)

• Band inversion in $Pb_{1-x}Sn_xTe$ with x



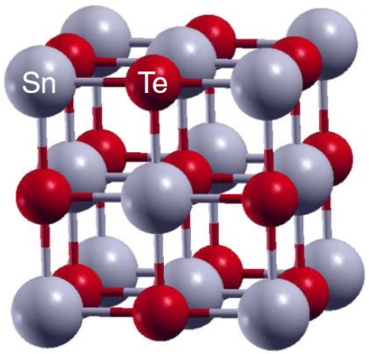


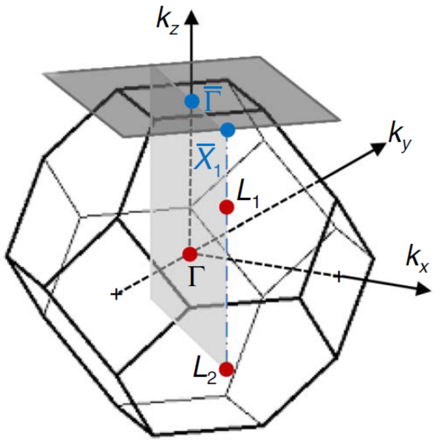
• Band inversion at even number of time-reversal-invariant momenta

Hsieh *et al*., Nature Commun. 2012

SnTe as a topological crystalline insulator (prediction)

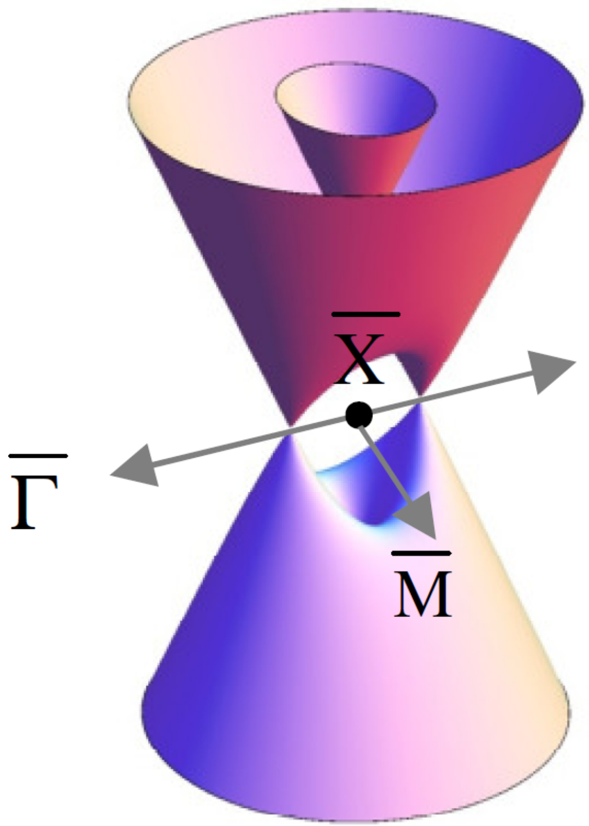
- Band inversion in $Pb_{1-x}Sn_xTe$ with x
- **Mirror plane symmetry**





SnTe is predicted to be a topological crystalline insulator with mirror symmetry having robust surface states with an even number of Dirac cones on crystal surfaces such as {001}, {110} or {111}, which are symmetric about {110} mirror planes.

The [001] surface states of SnTe

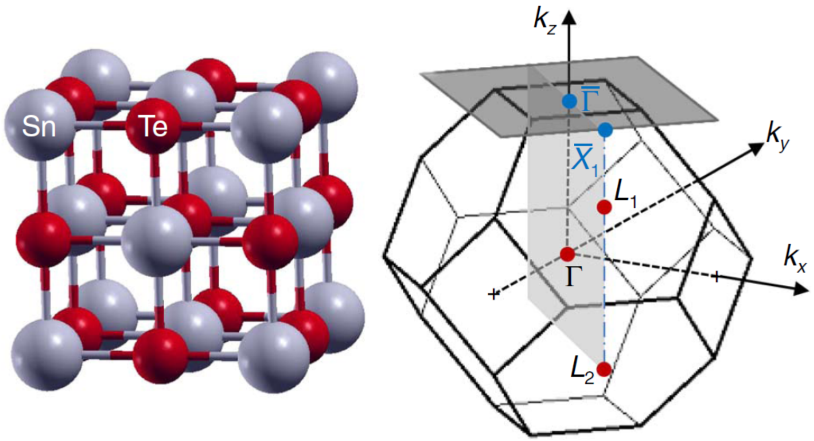


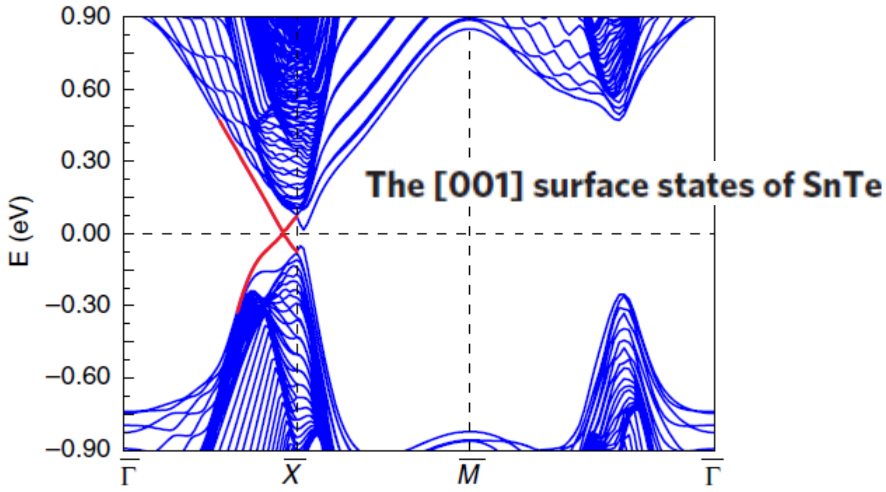
Hsieh *et al*., Nature Commun. 2012

Okada *et al*., arxiv 1305.2823

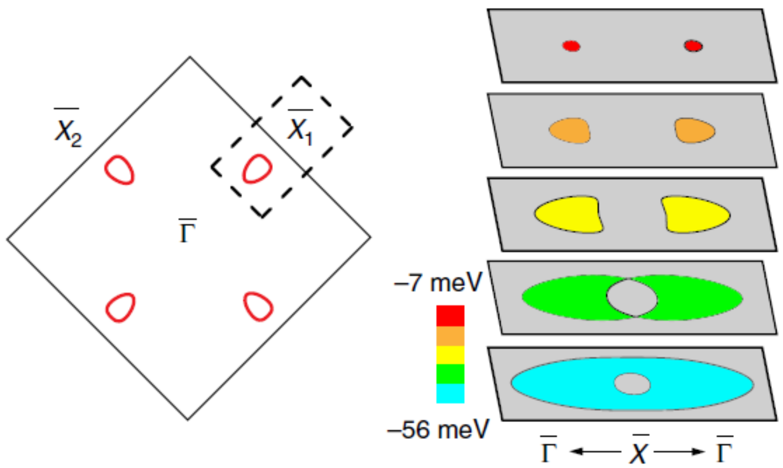
SnTe as a topological crystalline insulator (prediction)

- Band inversion in $Pb_{1-x}Sn_xTe$ with x
- Mirror plane symmetry



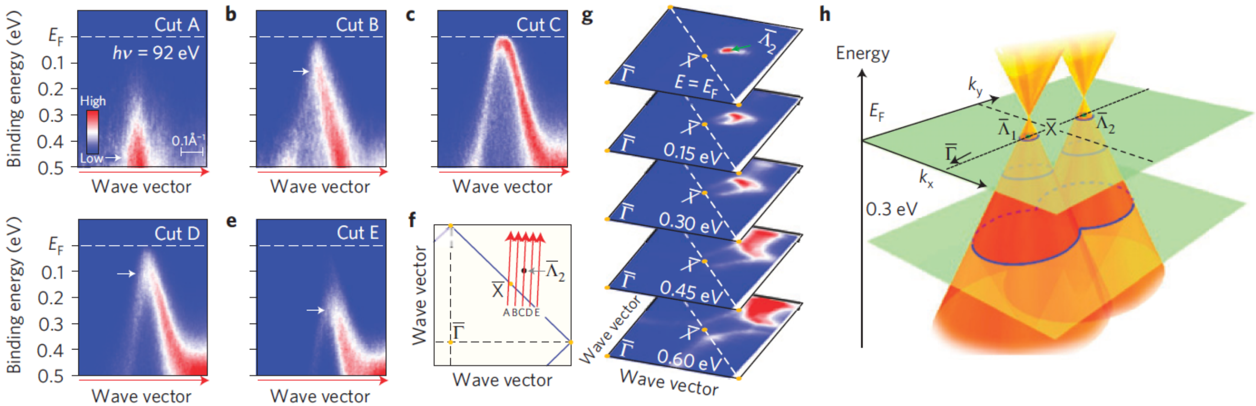


SnTe is predicted to be a topological crystalline insulator with mirror symmetry having robust surface states with an even number of Dirac cones on crystal surfaces such as {001}, {110} or {111}, which are symmetric about {110} mirror planes.



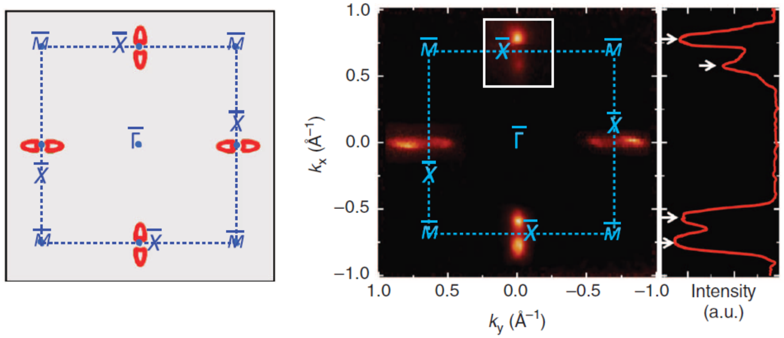
Hsieh *et al.*, Nature Commun. 2012

SnTe as a topological crystalline insulator (ARPES)



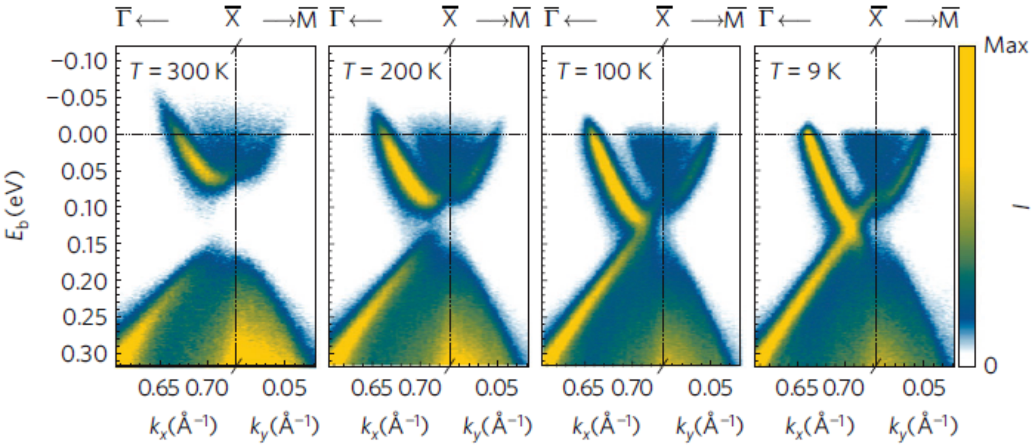
SnTe

Tanaka *et al.*,
Nature Phys. 2012



$Pb_{0.6}Sn_{0.4}Te$

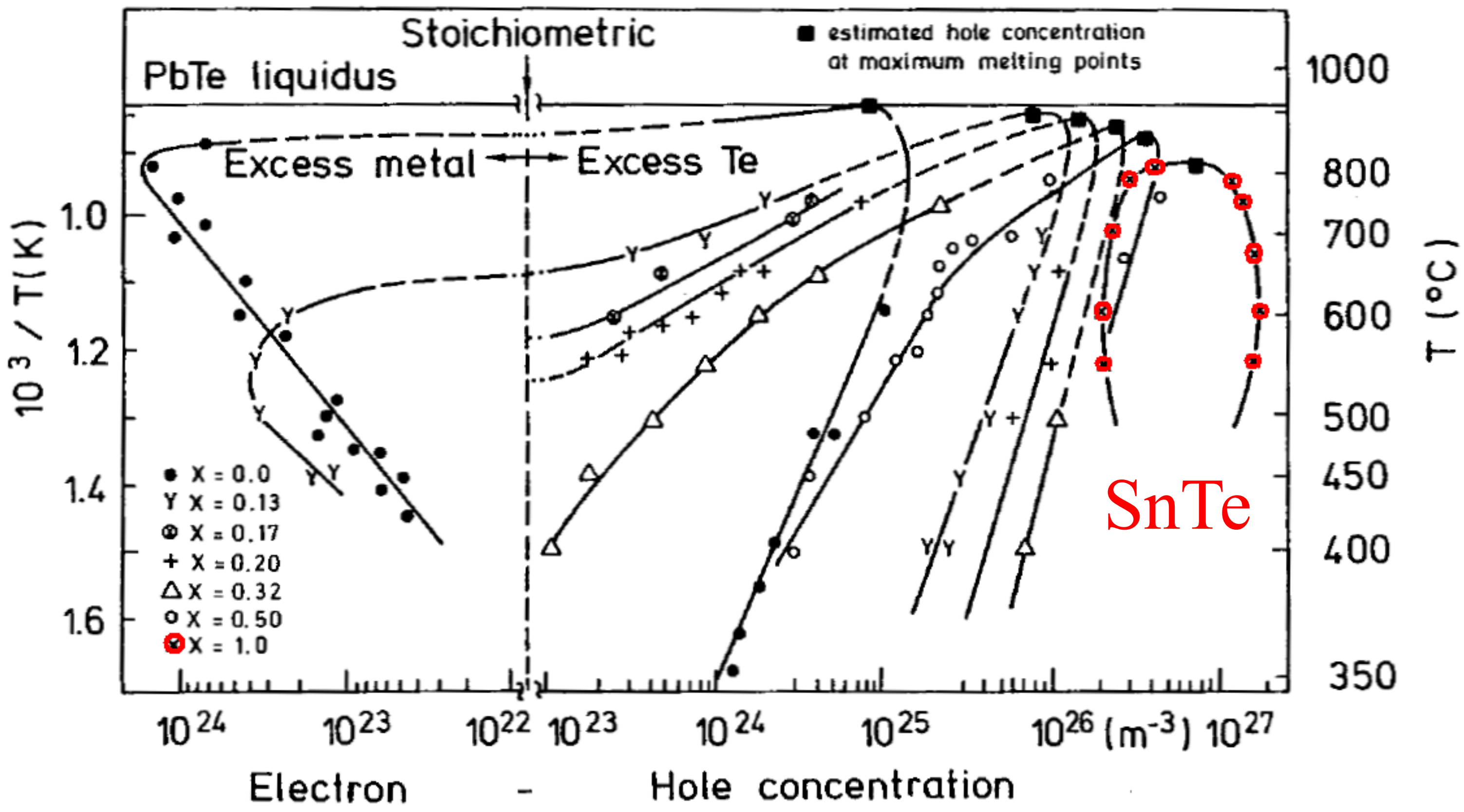
Xu *et al.*,
Nature Commun. 2012



$Pb_{0.77}Sn_{0.23}Se$

Dziawa *et al.*,
Nature Mater. 2012

2D transport in SnTe?

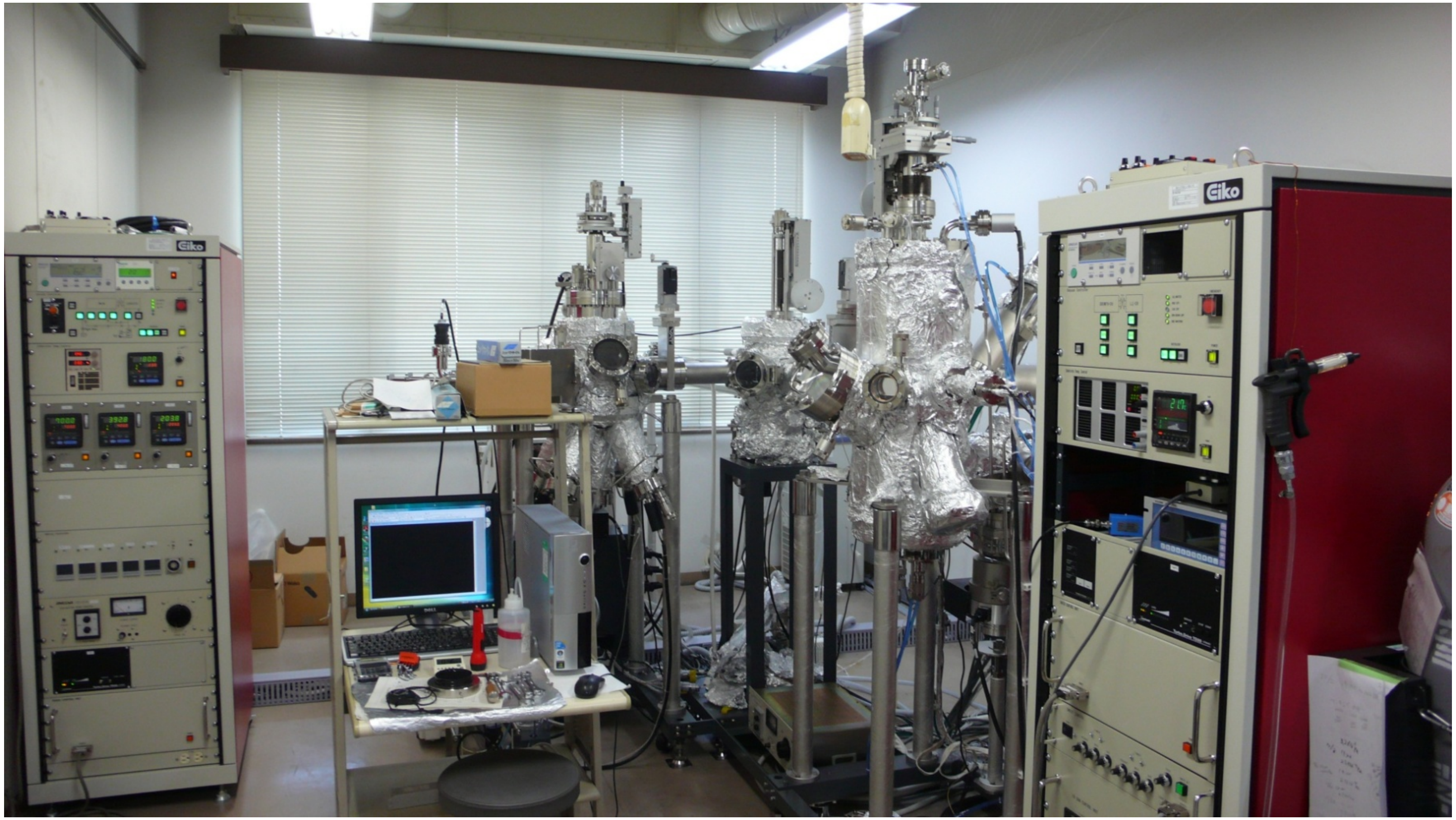


For SnTe concentration of **holes** is ~ $10^{20} \div 10^{21}$ cm^{-3}

→ it should be a problem to probe 2D transport

Nimtz & Schlicht, Narrow-Gap Semiconductors, 1983

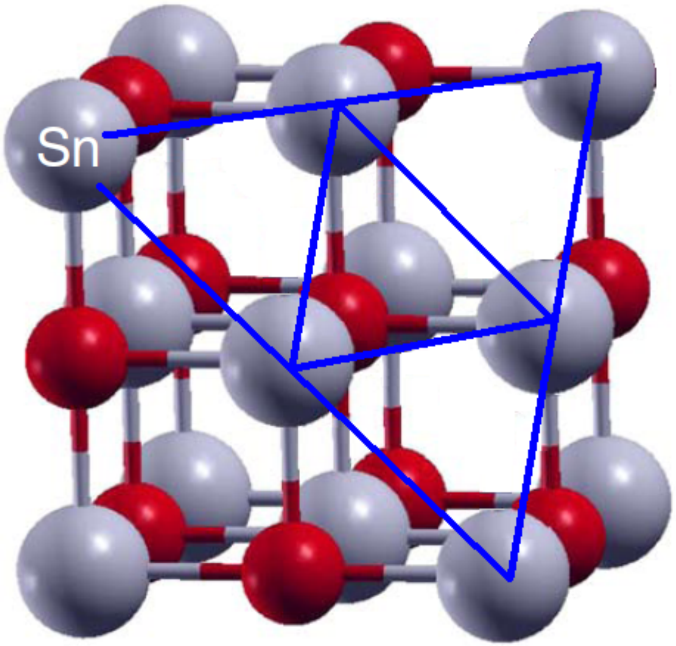
Molecular Beam Epitaxy (MBE)



• surface-to-bulk ratio

MBE growth of SnTe (111) thin films on Bi_2Te_3

(111) plane

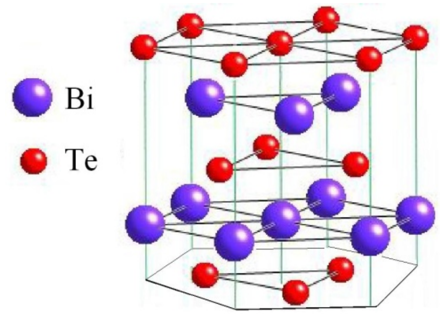


cubic

SnTe $\boldsymbol{a} = 6.3$ Å

BaF_2 $\boldsymbol{a} = 6.2$ Å (~1.6%)

"hexagonal"

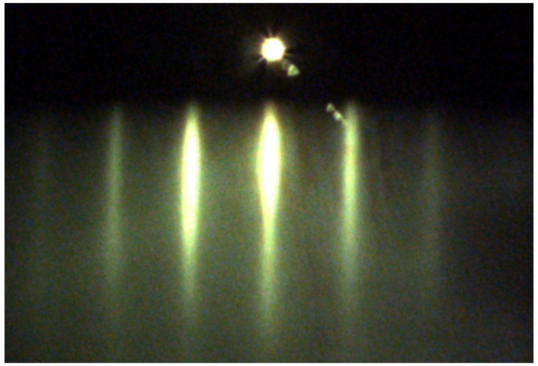


Bi_2Te_3 $\boldsymbol{a}^* = 4.386$ Å

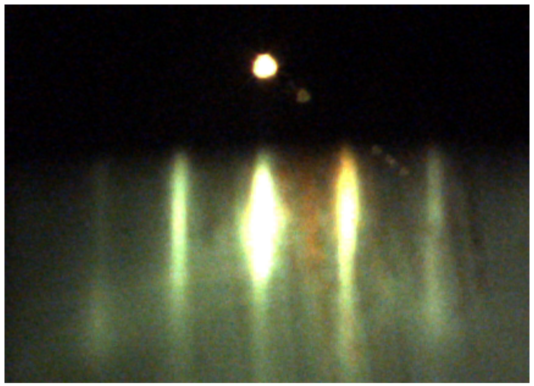
SnTe $\boldsymbol{a}^* = \boldsymbol{a}/\sqrt{2} = 4.45$ Å (~1.5%)

- Close lattice match
- Natural continuation for growth of Sn layer on Te-terminated layer
- p-type SnTe on n-type Bi_2Te_3

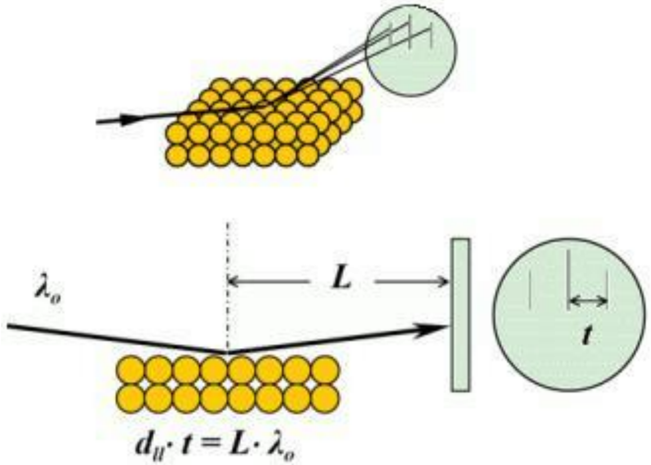
MBE growth of SnTe (111) thin films on Bi_2Te_3



Bi_2Te_3



SnTe

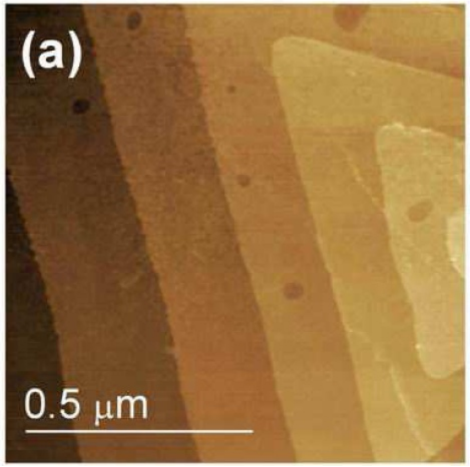


Reflection High-Energy Electron Diffraction (RHEED)

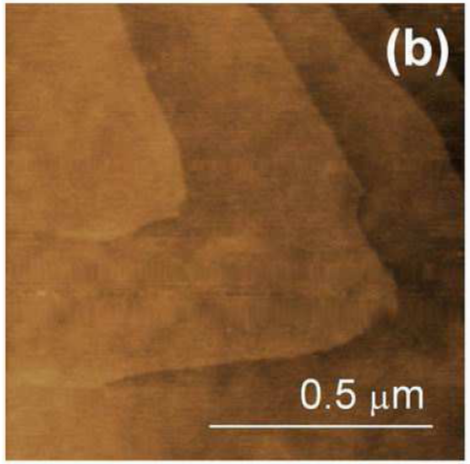
- 2D growth mode

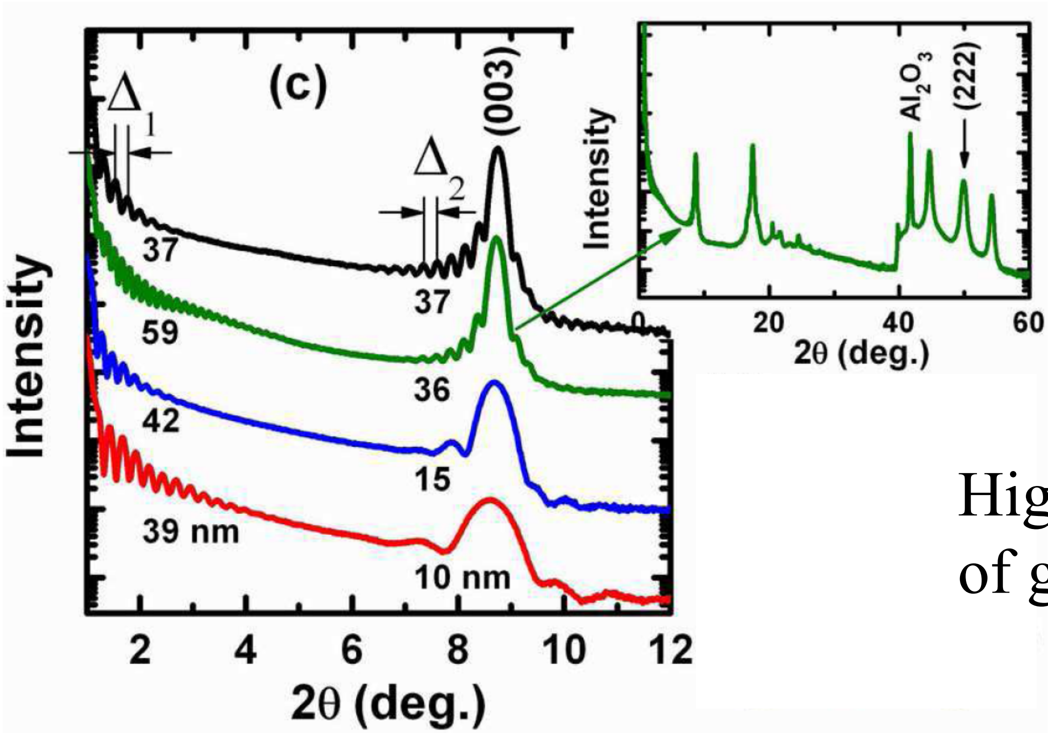
MBE growth of SnTe (111) thin films on Bi_2Te_3

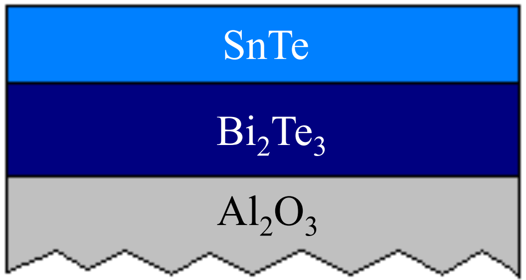
Bi_2Te_3



SnTe

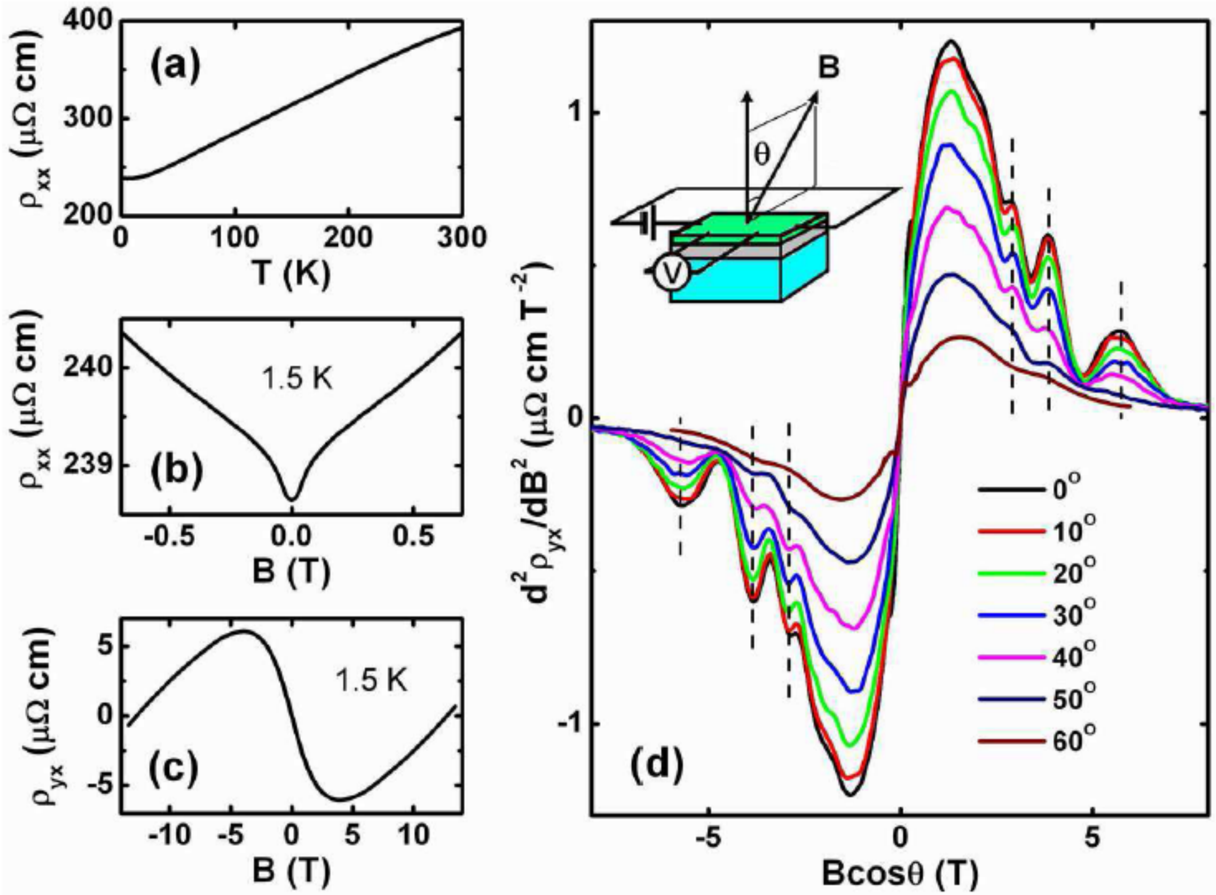






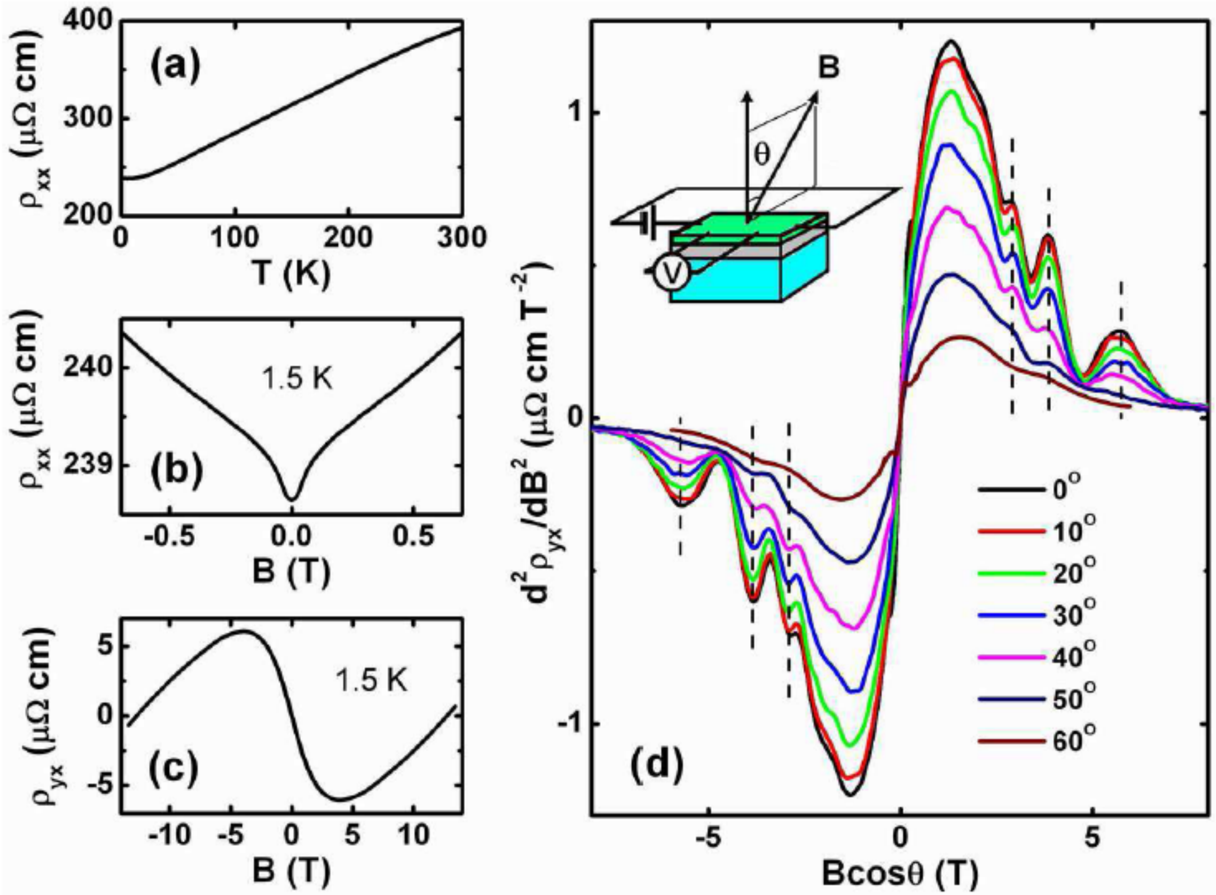
High structural quality of grown films

2D transport in SnTe thin films grown on Bi_2Te_3



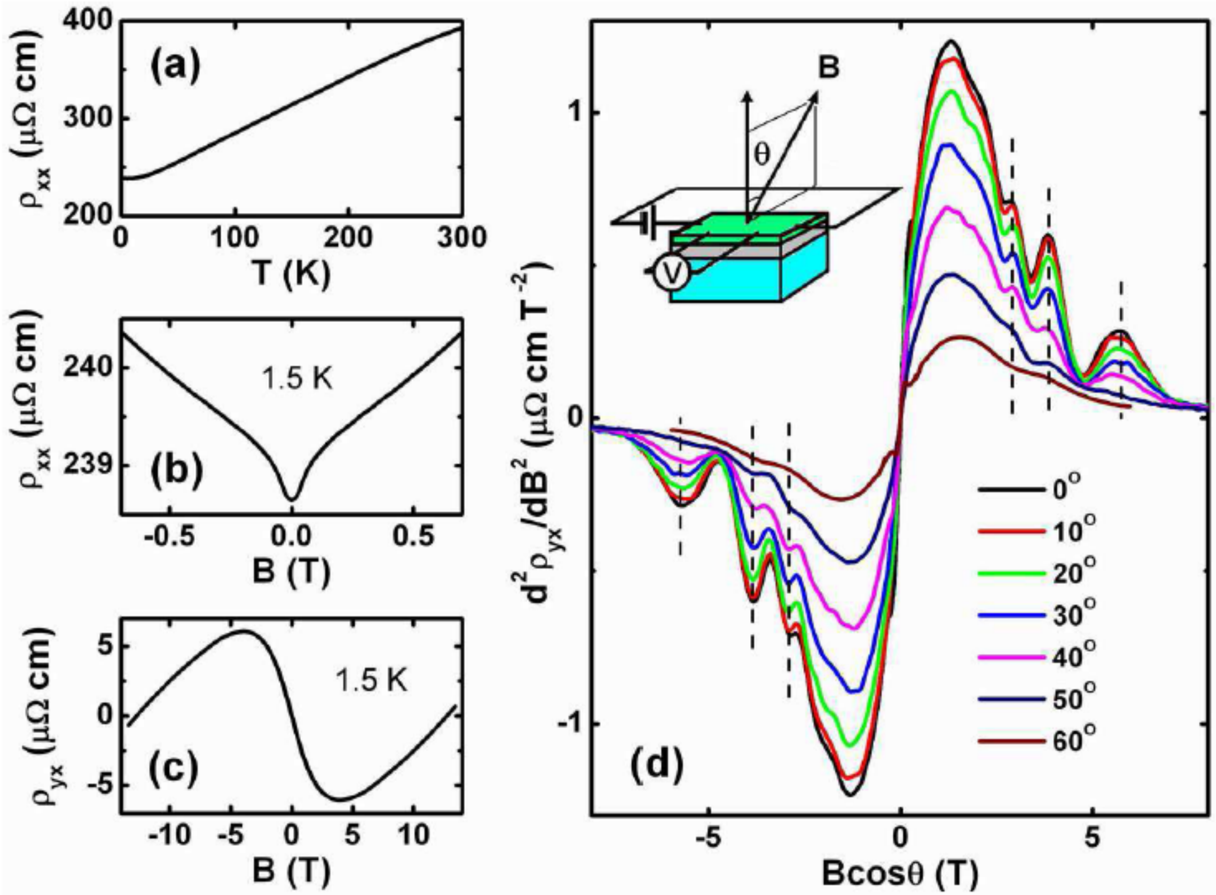
- ➢ No sign of the cubic-to-rhombohedral phase transition

2D transport in SnTe thin films grown on Bi_2Te_3



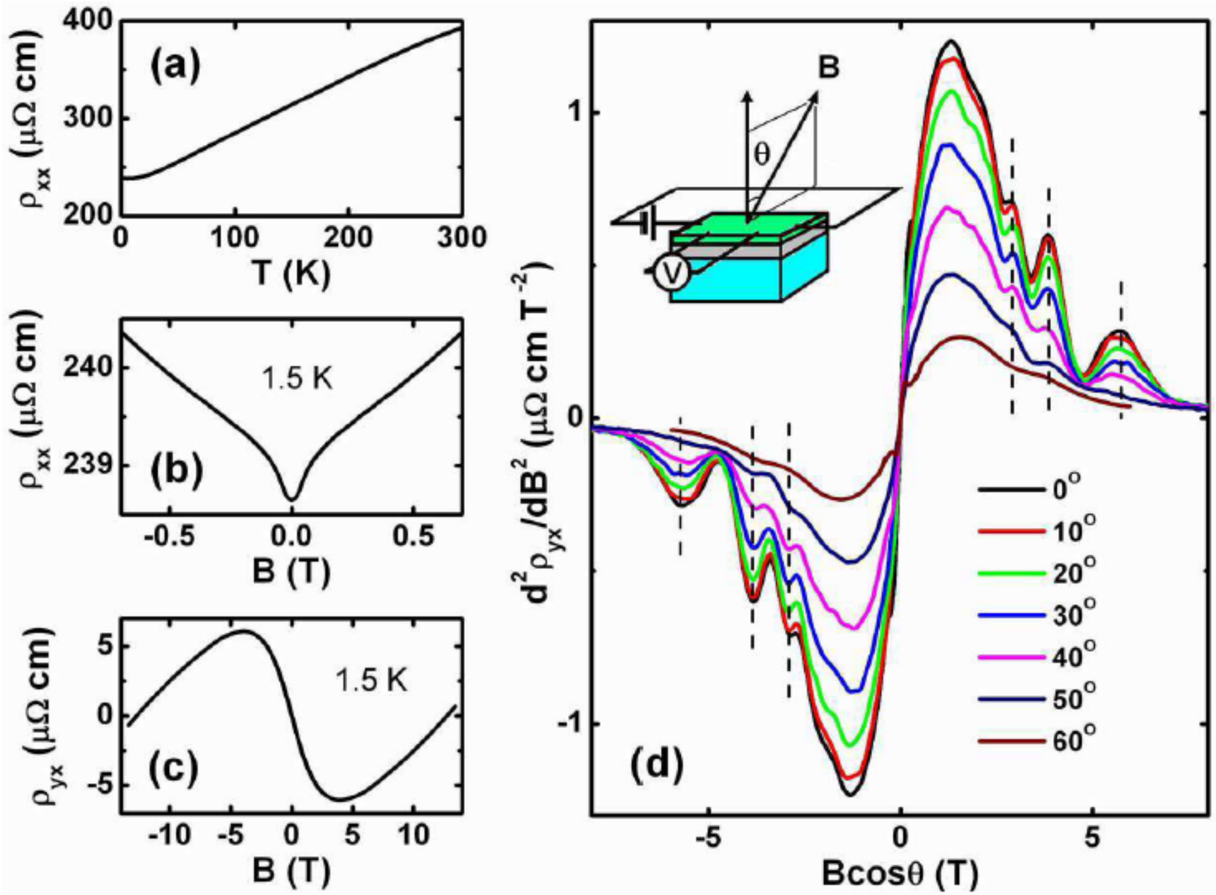
- ➢ No sign of the cubic-to-rhombohedral phase transition
- ➢ WAL

2D transport in SnTe thin films grown on Bi_2Te_3



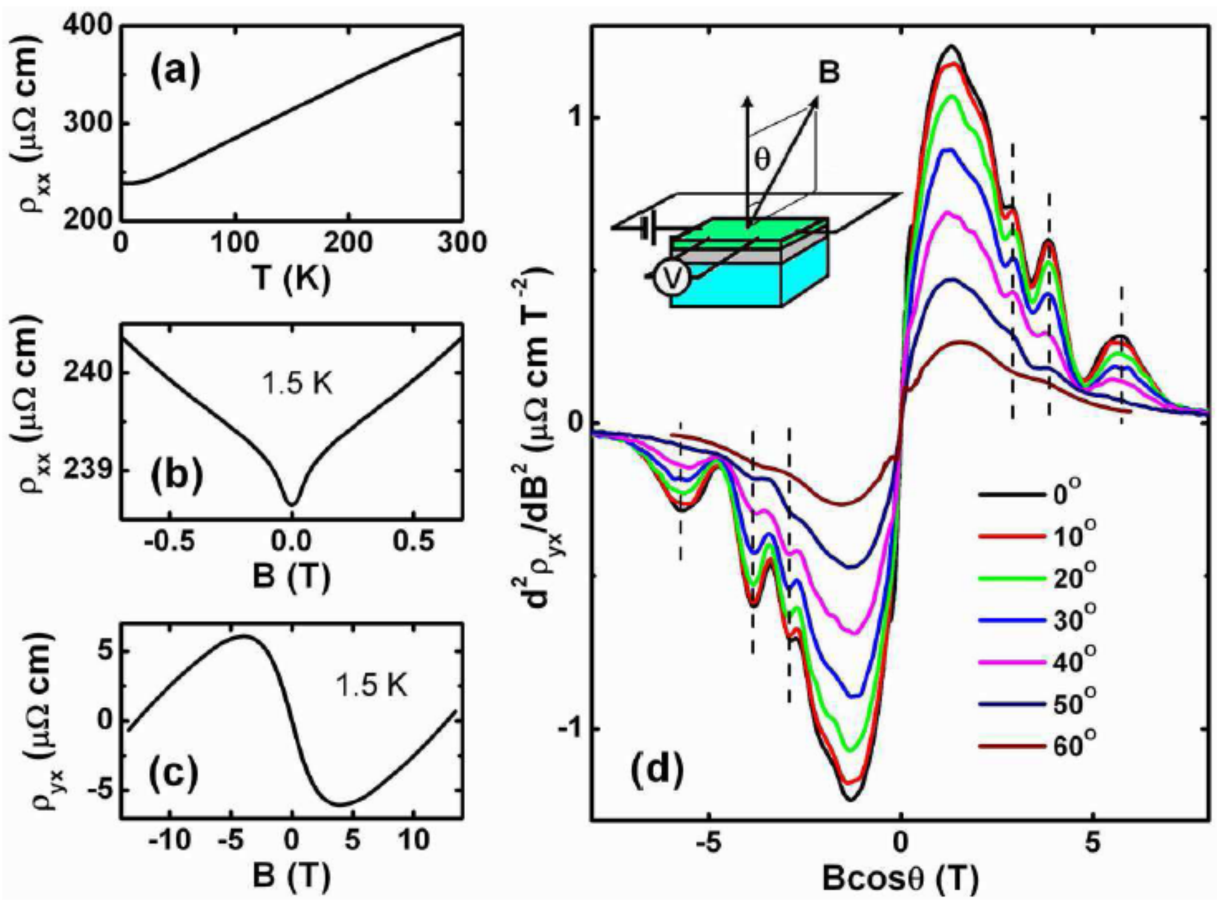
- No sign of the cubic-to-rhombohedral phase transition
- WAL
- Coexistence of p- and n-type carriers

2D transport in SnTe thin films grown on Bi_2Te_3



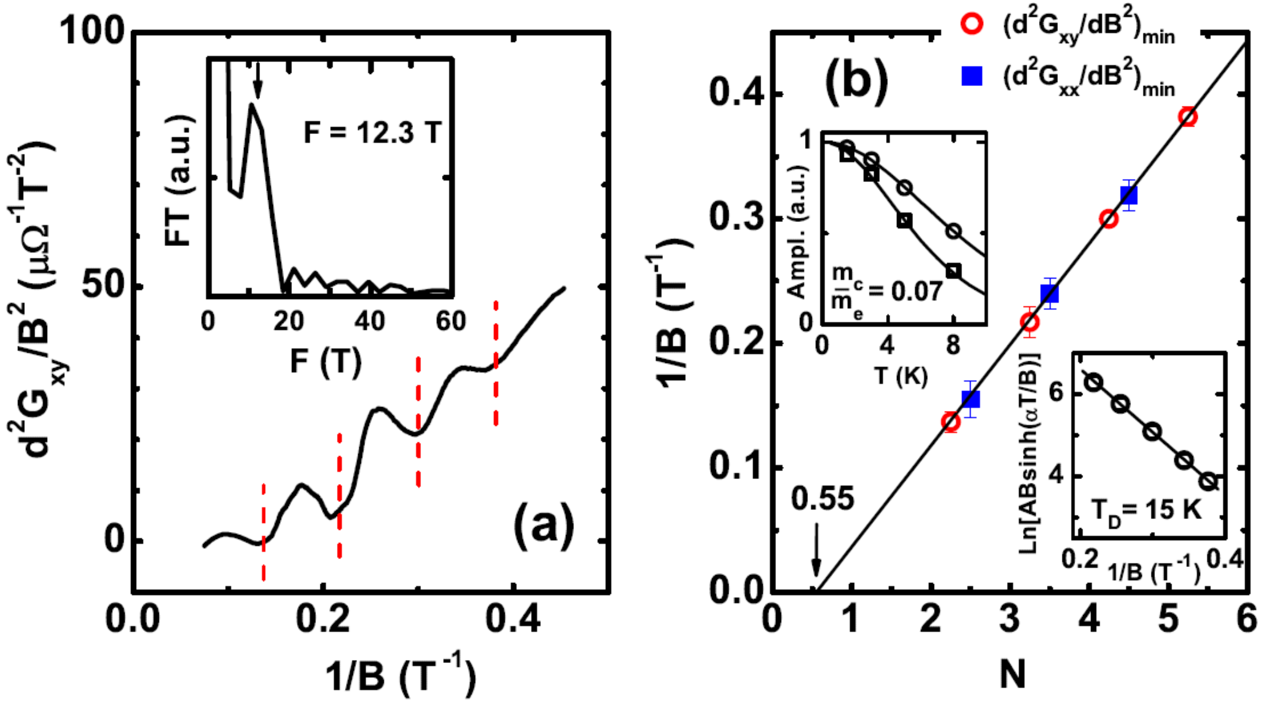
- ➢ No sign of the cubic-to-rhombohedral phase transition
- ➢ WAL
- ➢ Coexistence of p- and n-type carriers
- ➢ SdH oscillations in both $\rho_{xx}(B)$ and $\rho_{yx}(B)$

2D transport in SnTe thin films grown on Bi_2Te_3



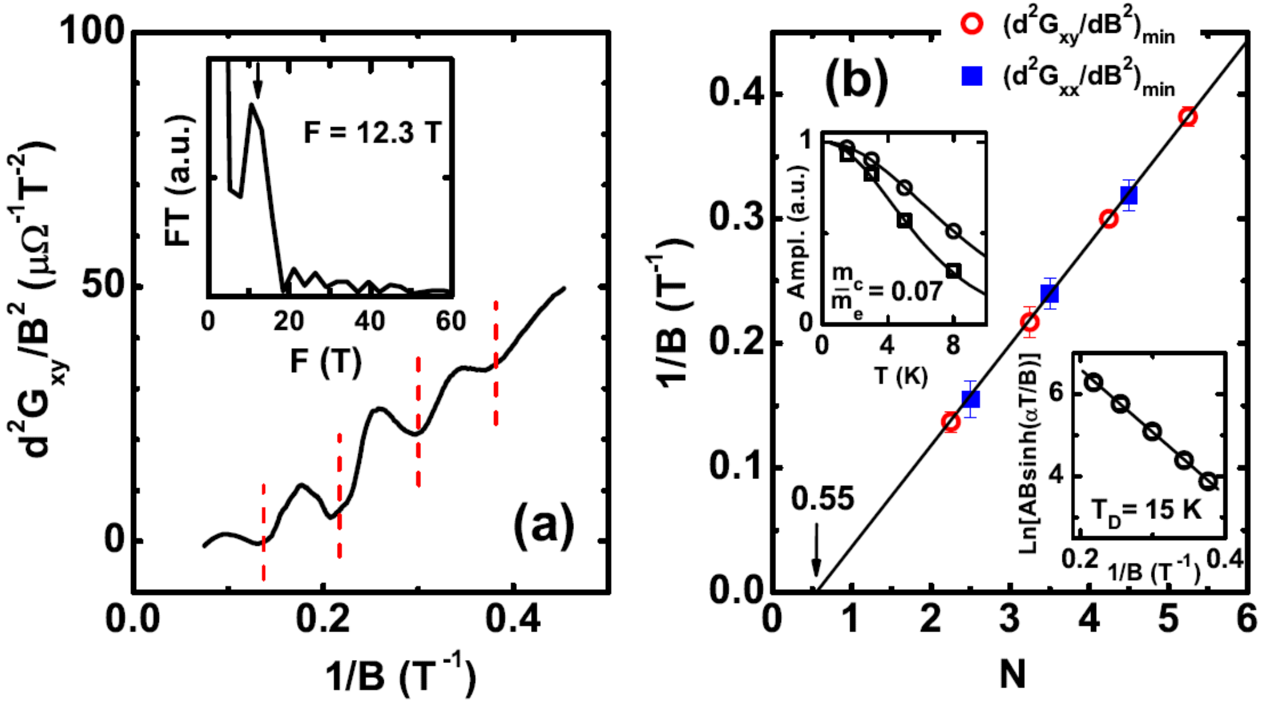
- No sign of the cubic-to-rhombohedral phase transition
- WAL
- Coexistence of p- and n-type carriers
- SdH oscillations in both $\rho_{xx}(B)$ and $\rho_{yx}(B)$
- **2D character of quantum oscillations**

2D transport in SnTe thin films grown on Bi_2Te_3



- $k_F = 1.9\times10^6$ cm^{-1},
  $n_s = 3\times10^{11}$ cm^{-2}
  for each FS (each spin)

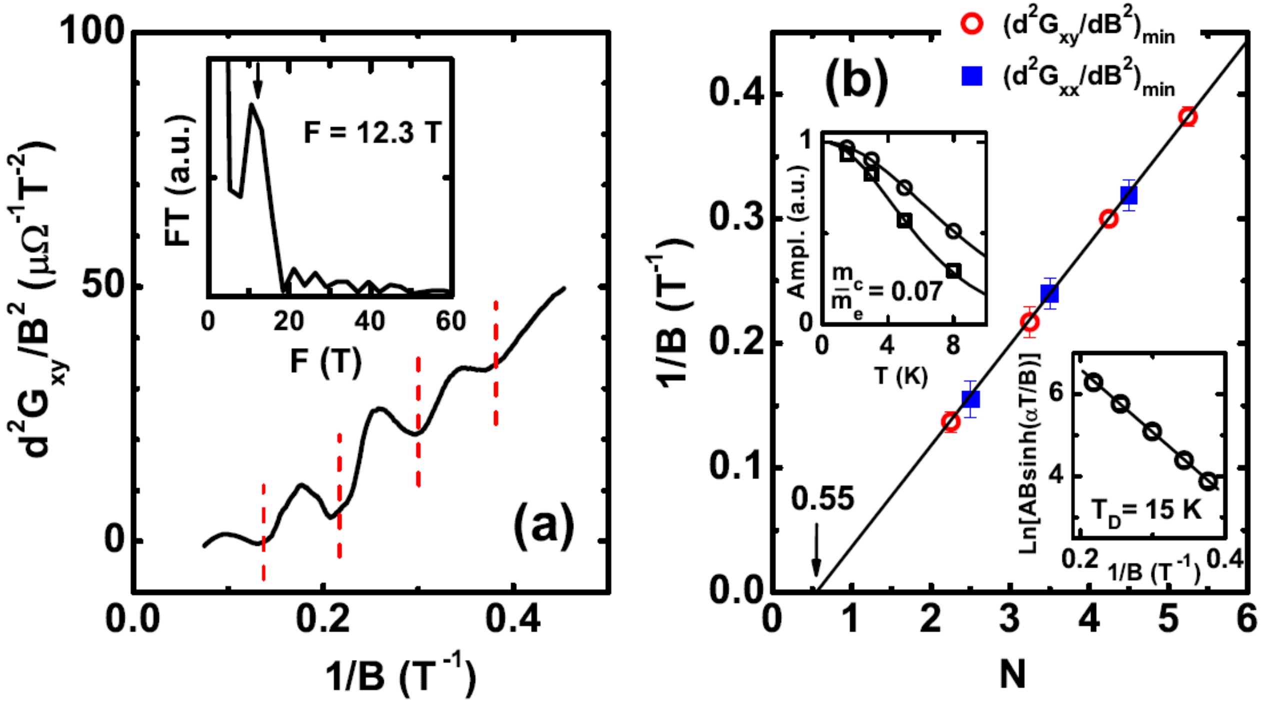
2D transport in SnTe thin films grown on Bi_2Te_3



- k_F = 1.9×10^6 cm^{-1},
  n_s = 3×10^{11} cm^{-2}
  for each FS (each spin)

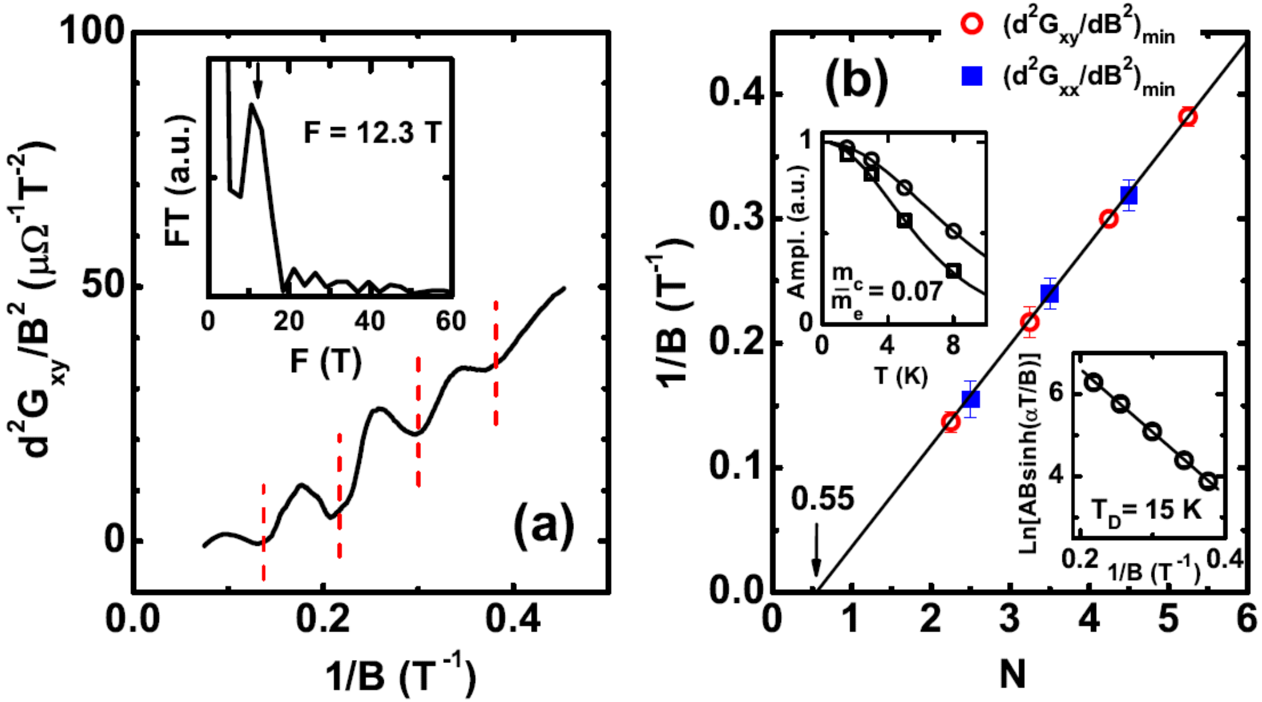
- π Berry phase → Dirac fermions

2D transport in SnTe thin films grown on Bi_2Te_3



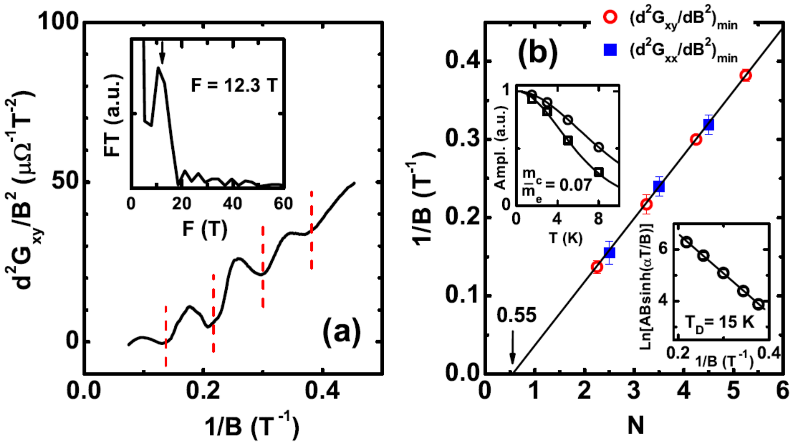
- k_F = 1.9×10^6 cm^{-1}, n_s = 3×10^{11} cm^{-2} for each FS (each spin)
- π Berry phase → Dirac fermions
- v_F = 3.2×10^7 cm/s
- ℓ = 26 nm, μ^{SdH}=2000 cm^2/Vs

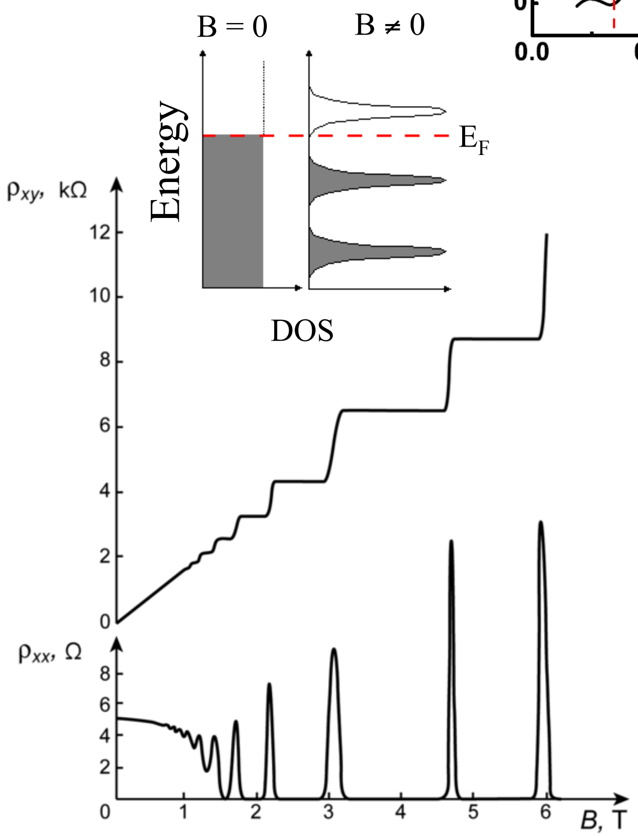
2D transport in SnTe thin films grown on Bi_2Te_3

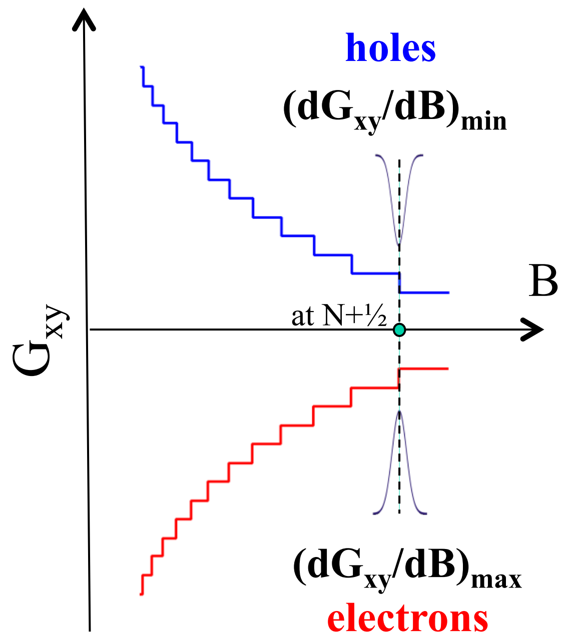


- $k_F = 1.9\times10^6$ cm^{-1}, $n_s = 3\times10^{11}$ cm^{-2} for each FS (each spin)
- π Berry phase → Dirac fermions
- $v_F = 3.2\times10^7$ cm/s
- ℓ = 26 nm, μ^{SdH}=2000 cm^2/Vs
- **2D Dirac fermions are of n-type (electrons)**

2D transport in SnTe thin films grown on Bi_2Te_3

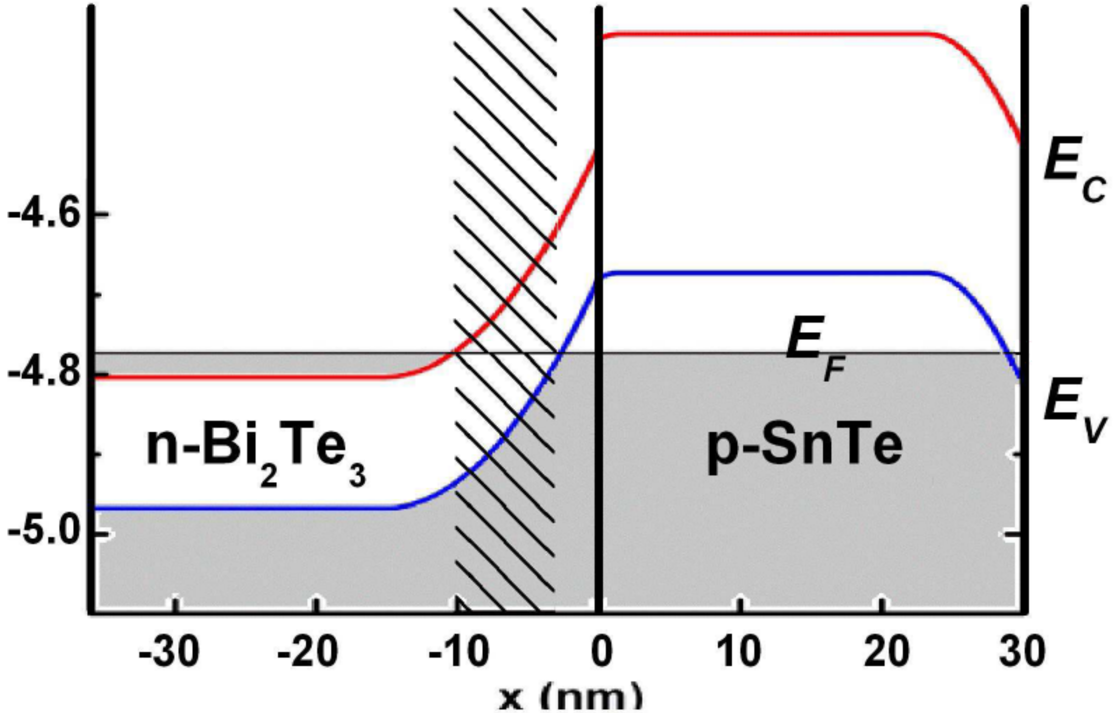






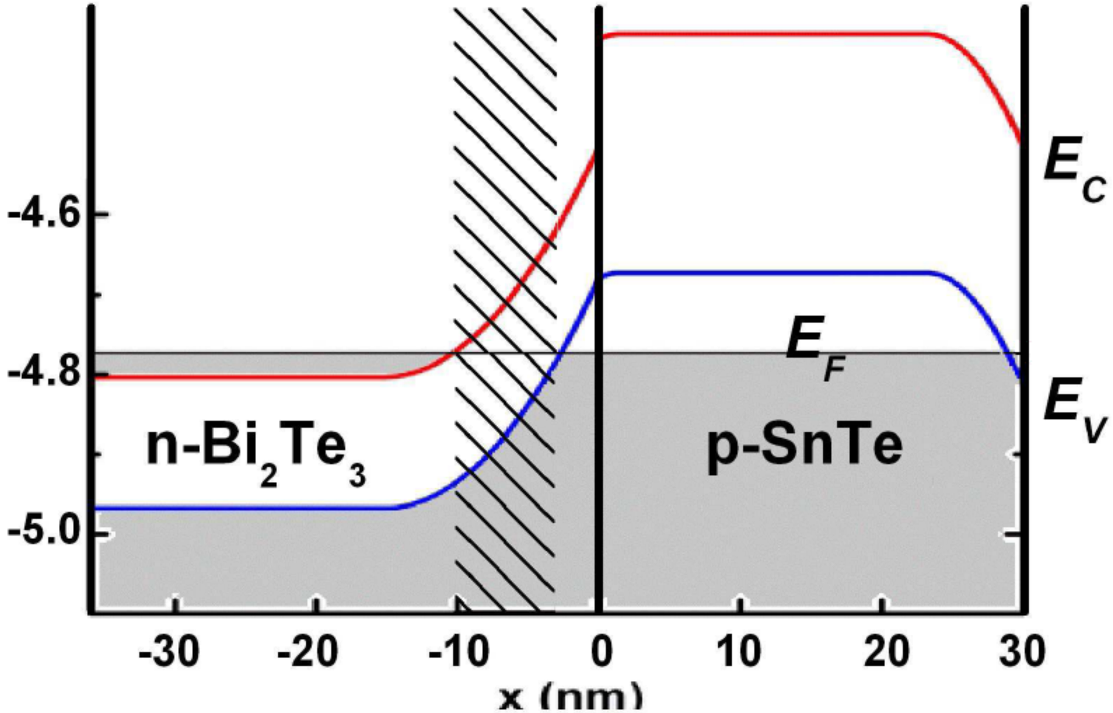
- $k_F = 1.9\times10^6$ cm^{-1},
  $n_s = 3\times10^{11}$ cm^{-2}
  for each FS (each spin)
- π Berry phase → Dirac fermions
- $v_F = 3.2\times10^7$ cm/s
- ℓ = 26 nm,
  μ^{SdH}=2000 cm^2/Vs
- **2D Dirac fermions are of n-type (electrons)**

Origin of surface Dirac electrons



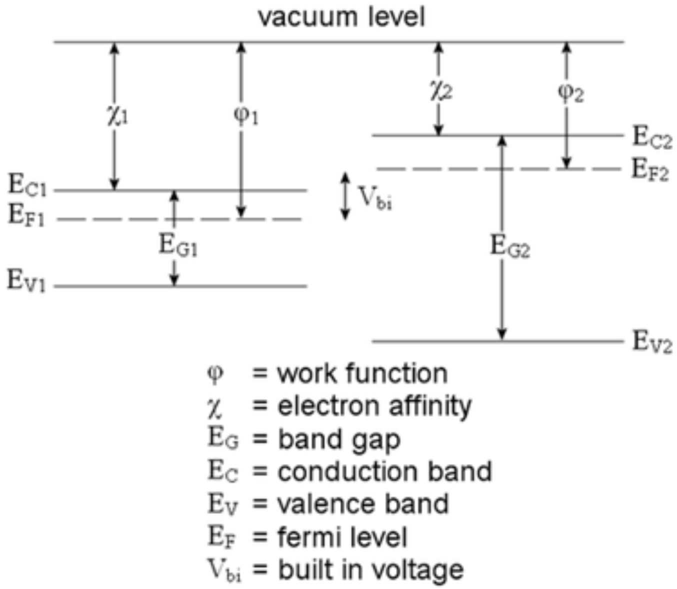
- both SnTe and Bi_2Te_3 have topological SS

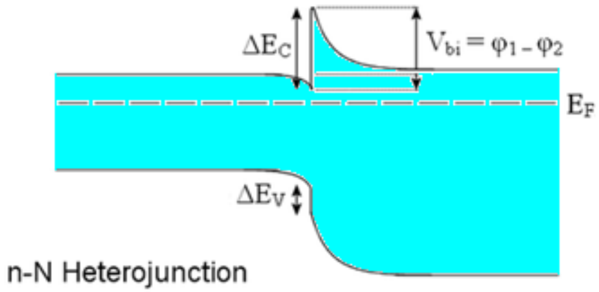
Origin of surface Dirac electrons



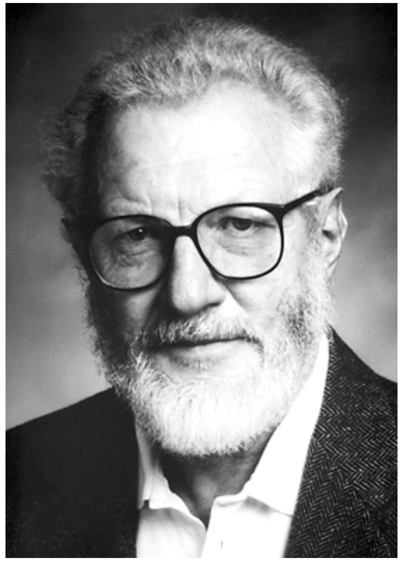
- both SnTe and Bi_2Te_3 have topological SS
- heterostructure (common anion rule)

Band lineups in heterostructures



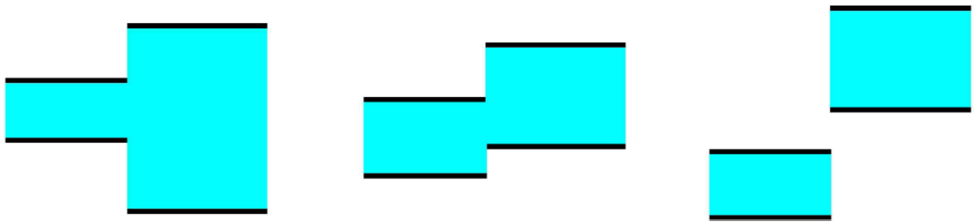


Zhores I. Alferov



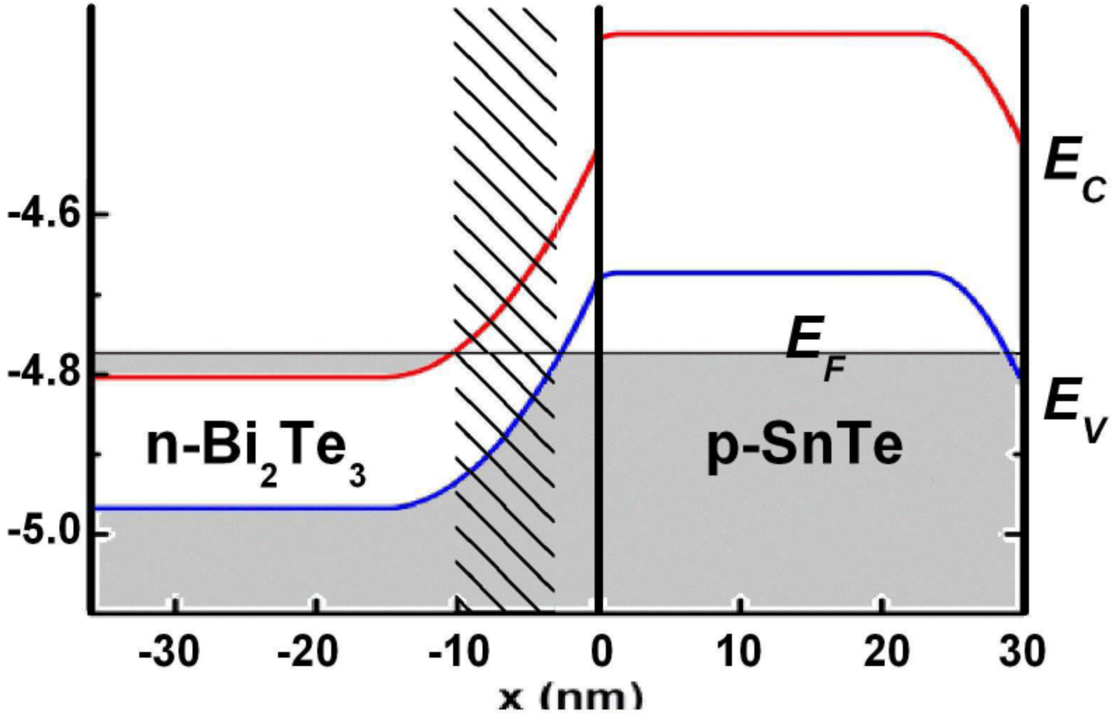
Herbert Kroemer

The Nobel Prize in Physics 2000



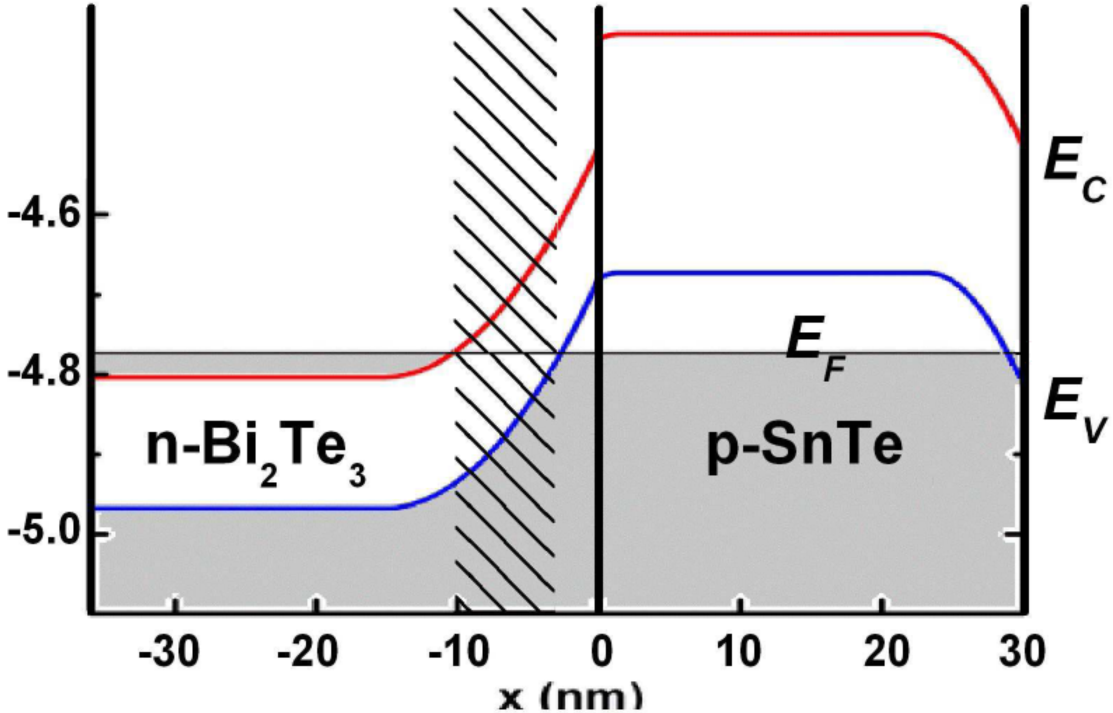
straddling staggered broken-gap

Origin of surface Dirac electrons



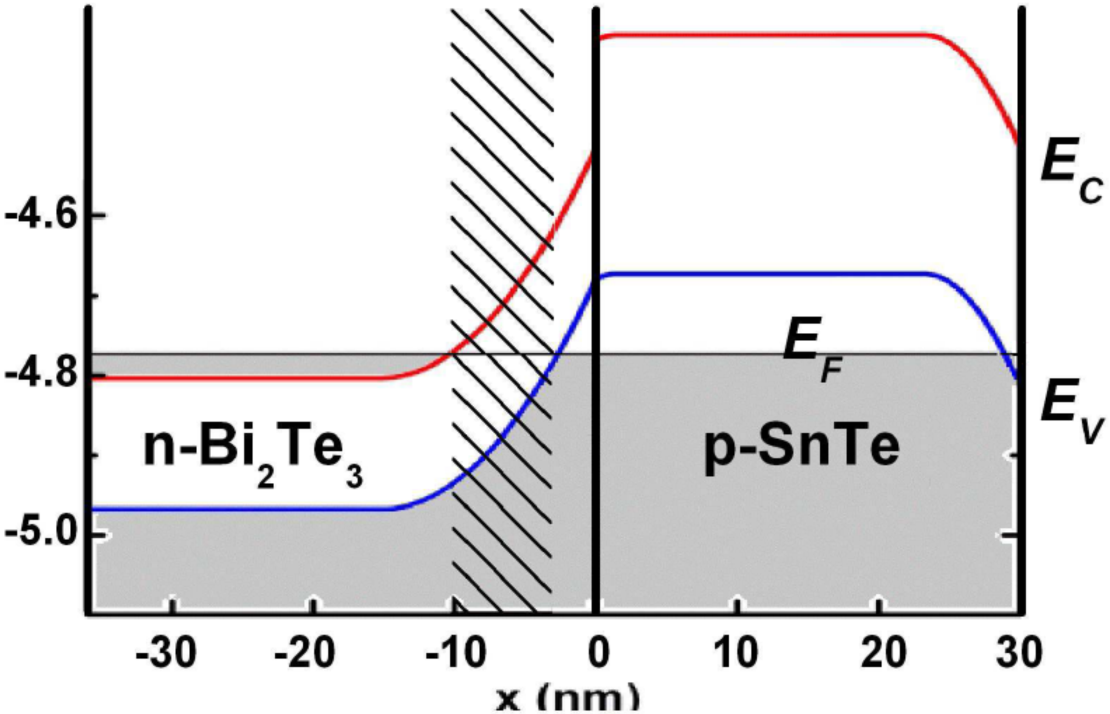
- both SnTe and Bi_2Te_3 have topological SS
- heterostructure (common anion rule)
- p^+- n^+ tunneling junction

Origin of surface Dirac electrons



- both SnTe and Bi_2Te_3 have topological SS
- heterostructure (common anion rule)
- p^+- n^+ tunneling junction
- SnTe and Bi_2Te_3 are electrically isolated

Origin of surface Dirac electrons

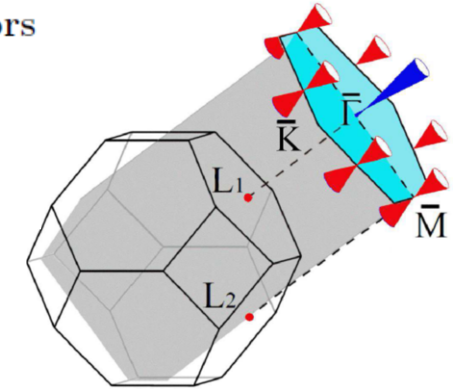


- both SnTe and Bi_2Te_3 have topological SS
- heterostructure (common anion rule)
- p^+- n^+ tunneling junction
- SnTe and Bi_2Te_3 are electrically isolated
- SS is most likely on the free surface of SnTe

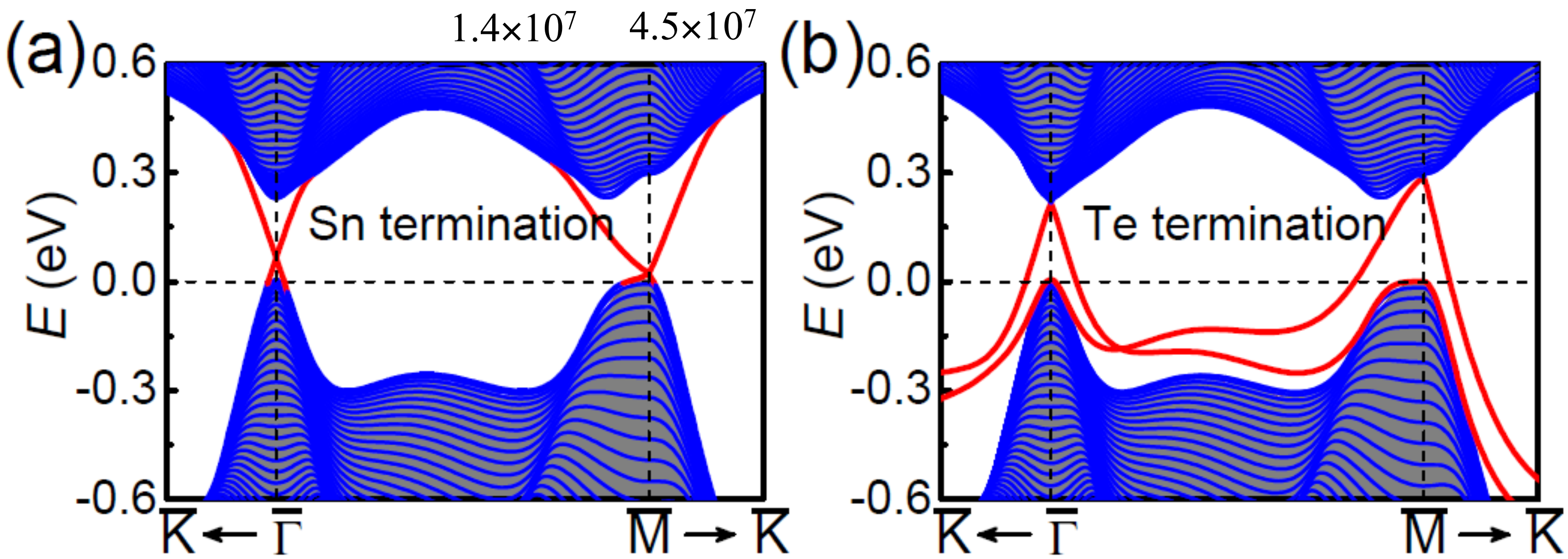
SS on the (111) plane of SnTe

Surface States of Topological Crystalline Insulators in IV-VI Semiconductors

Junwei Liu[1,2], Wenhui Duan[1] and Liang Fu[2]
[1] *Department of Physics and State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing 100084, People's Republic of China*
[2] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139*

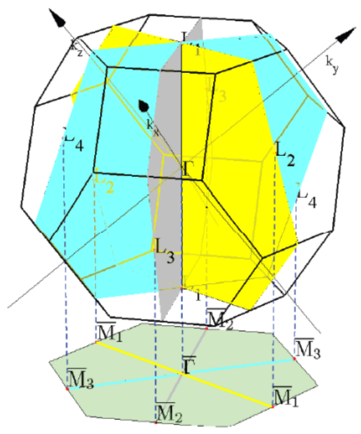


$v_F = 5.6\times10^7$ cm/s $\langle v_F \rangle = 2.5\times10^7$ cm/s



ArXiv 1304.0430

SS on the (111) plane of $Pb_{0.6}Sn_{0.4}Te$



The topological-crystalline-insulator (Pb,Sn)Te - surface states and their spin-polarization

S. Safaei,[1] P. Kacman,[1] and R. Buczko[1,*]

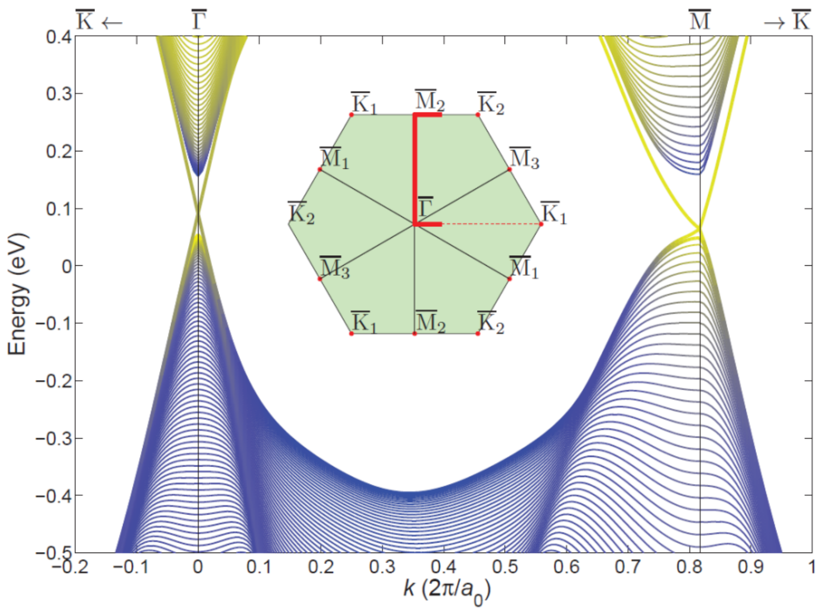
[1] *Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland*

(Dated: March 27, 2013)

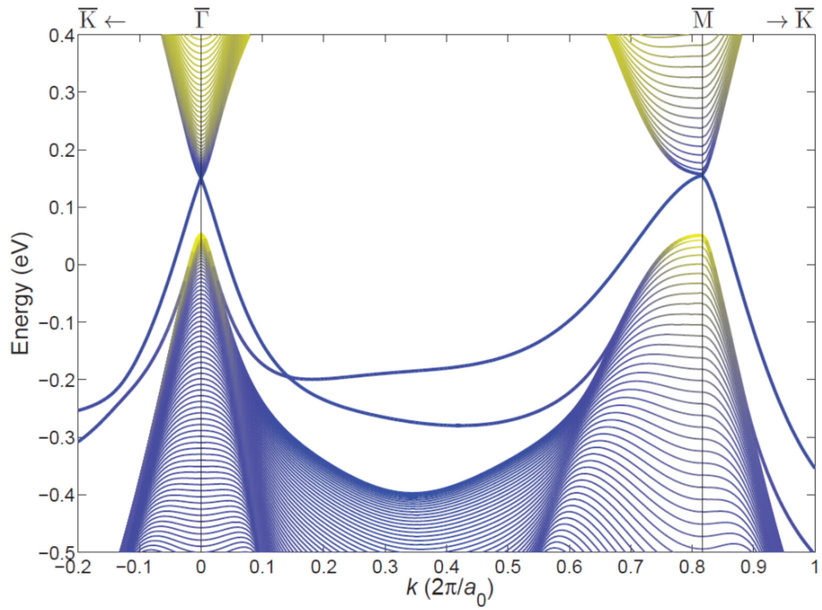
$v_F = 7\times10^7$ cm/s

$\langle v_F \rangle = 3.1\times10^7$ cm/s

2.5×10^7 5×10^7



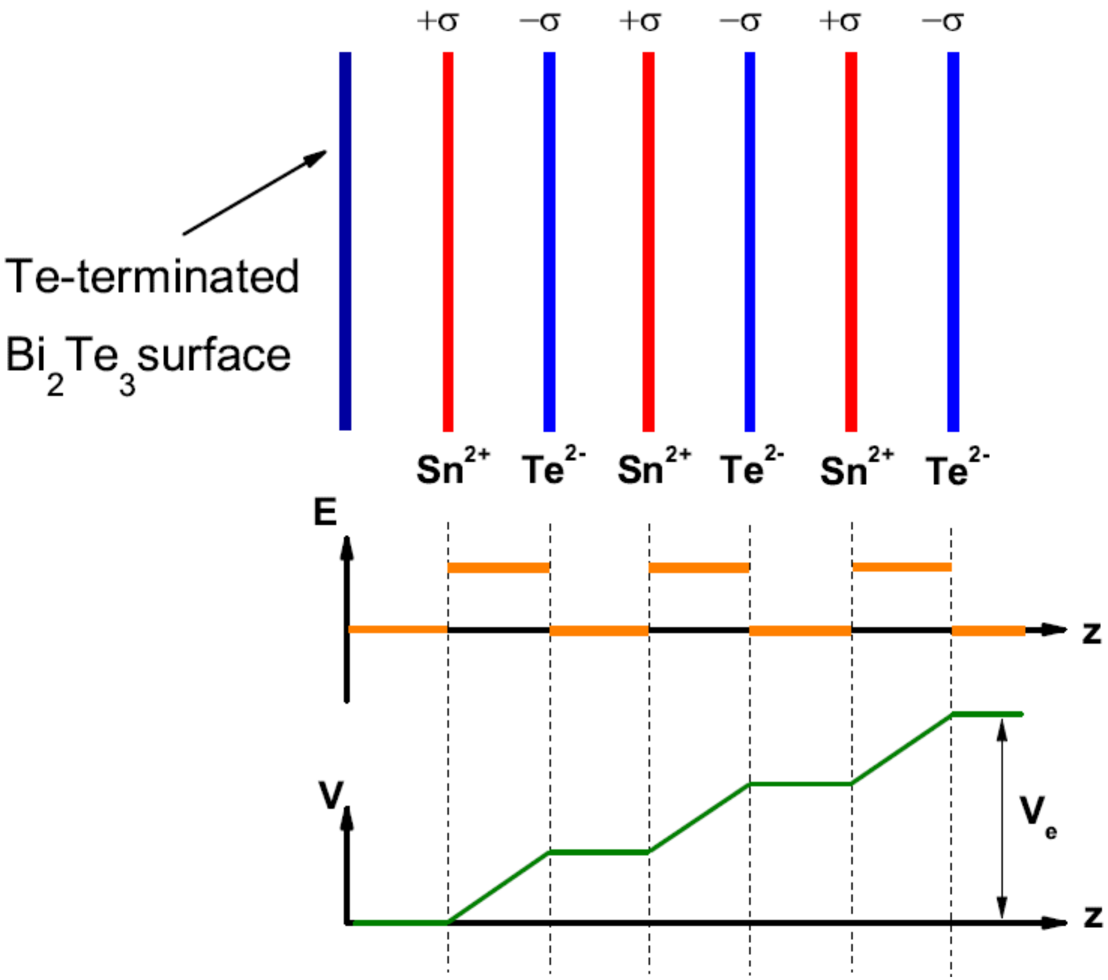
Sn-terminated



Te-terminated

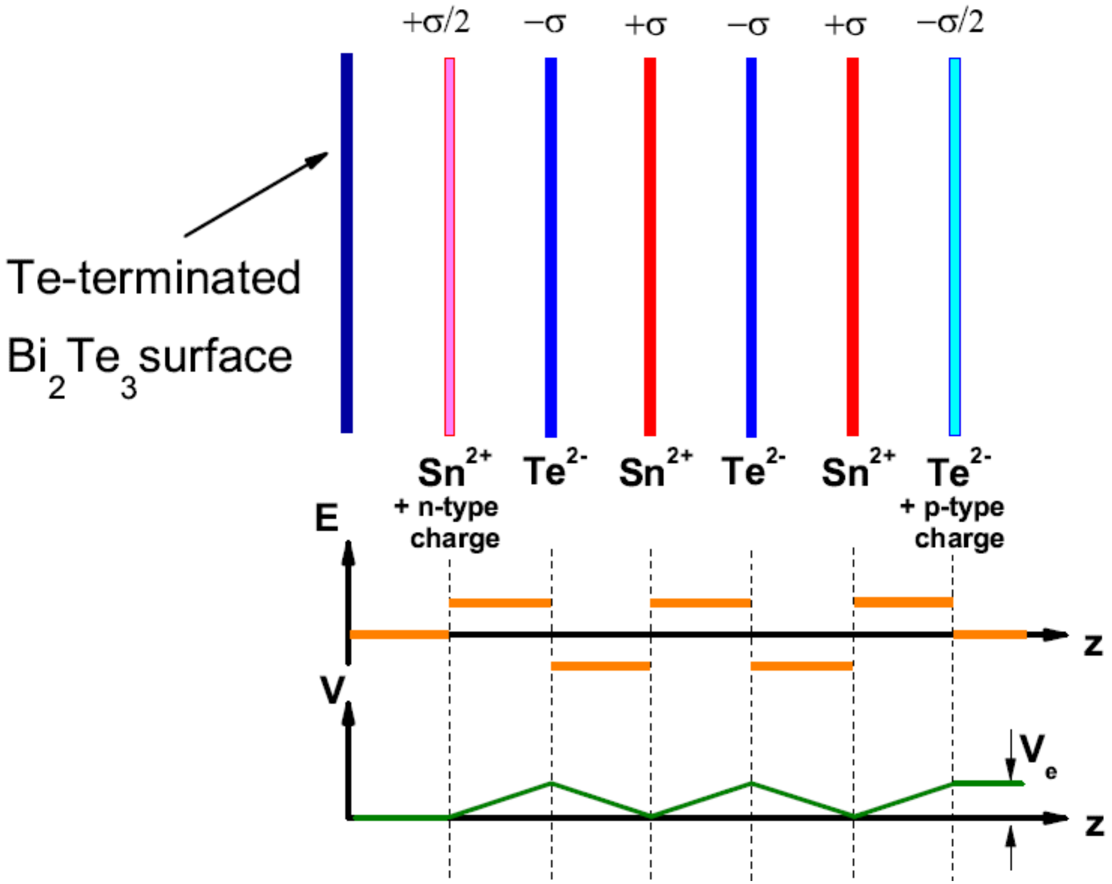
ArXiv 1303.7119

Surface termination



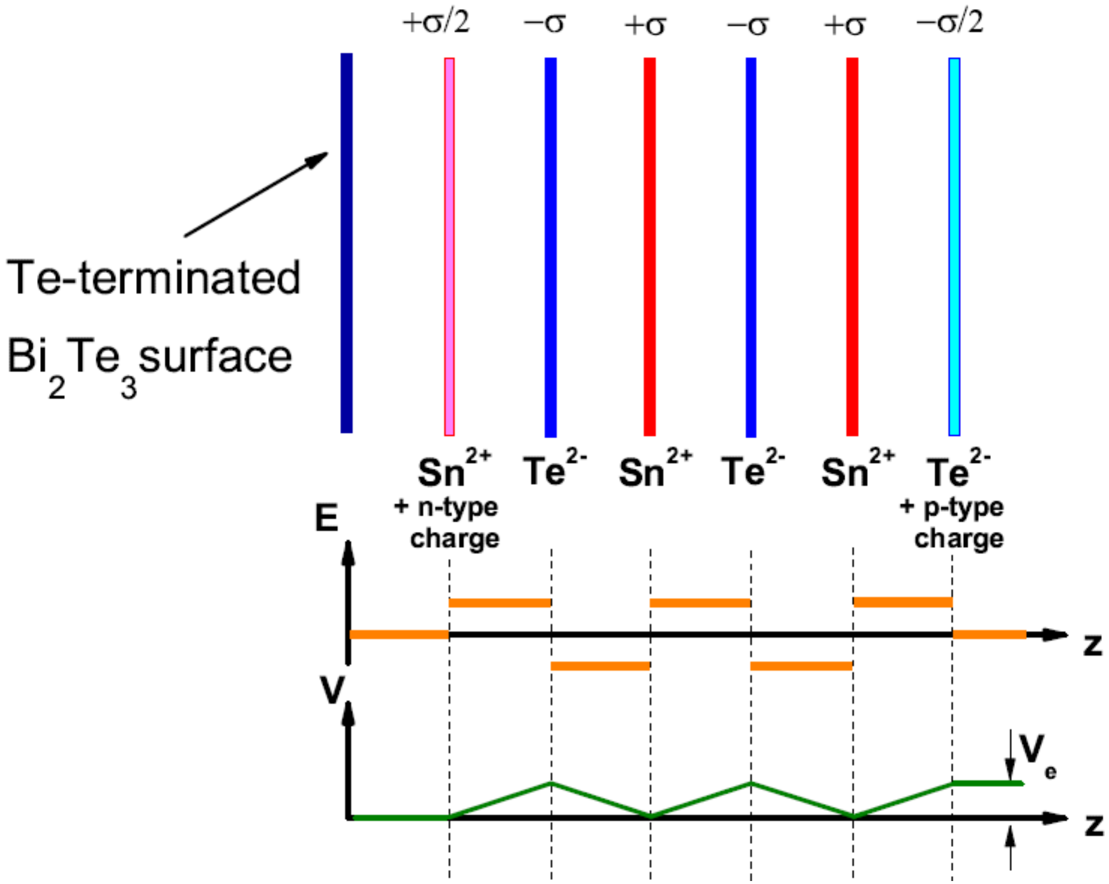
- polar catastrophe in SnTe films grown along the (111) direction

Surface termination (Te)



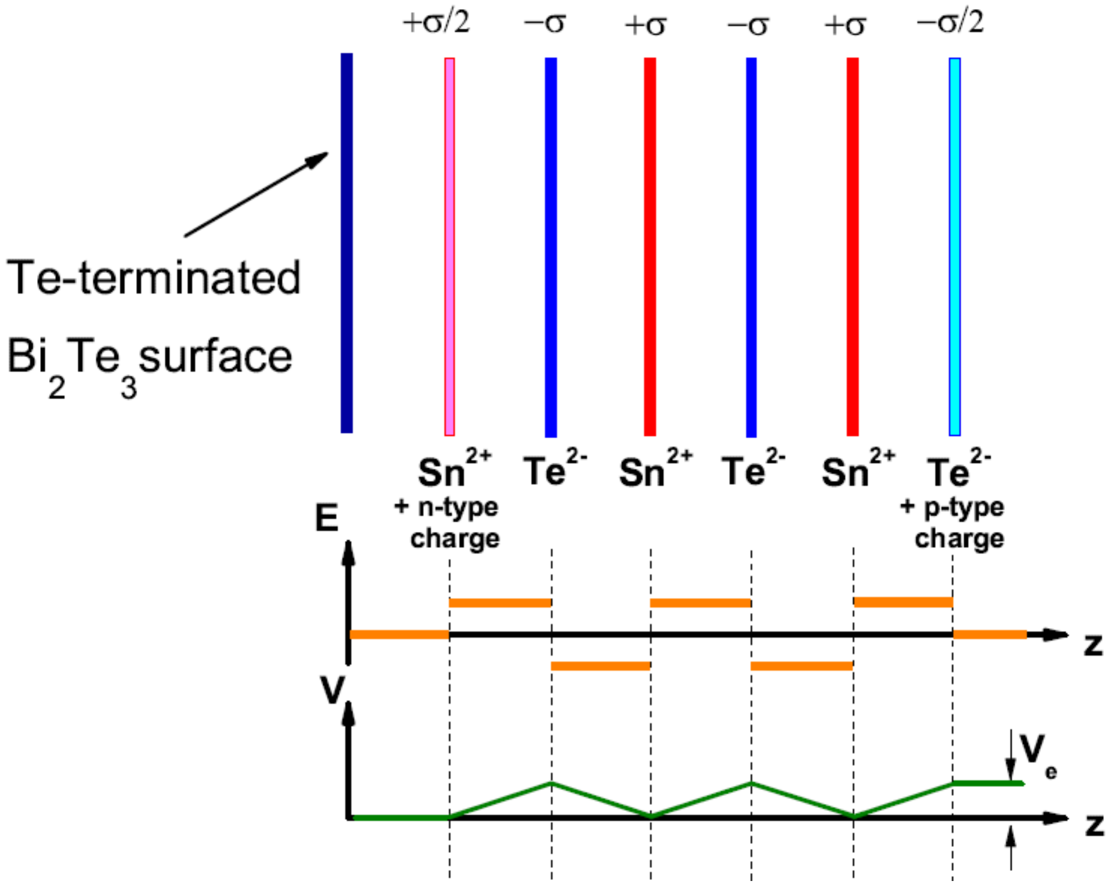
- ➢ polar catastrophe in SnTe films grown along the (111) direction
- ➢ partially compensated charge on the surfaces

Surface termination (Te)



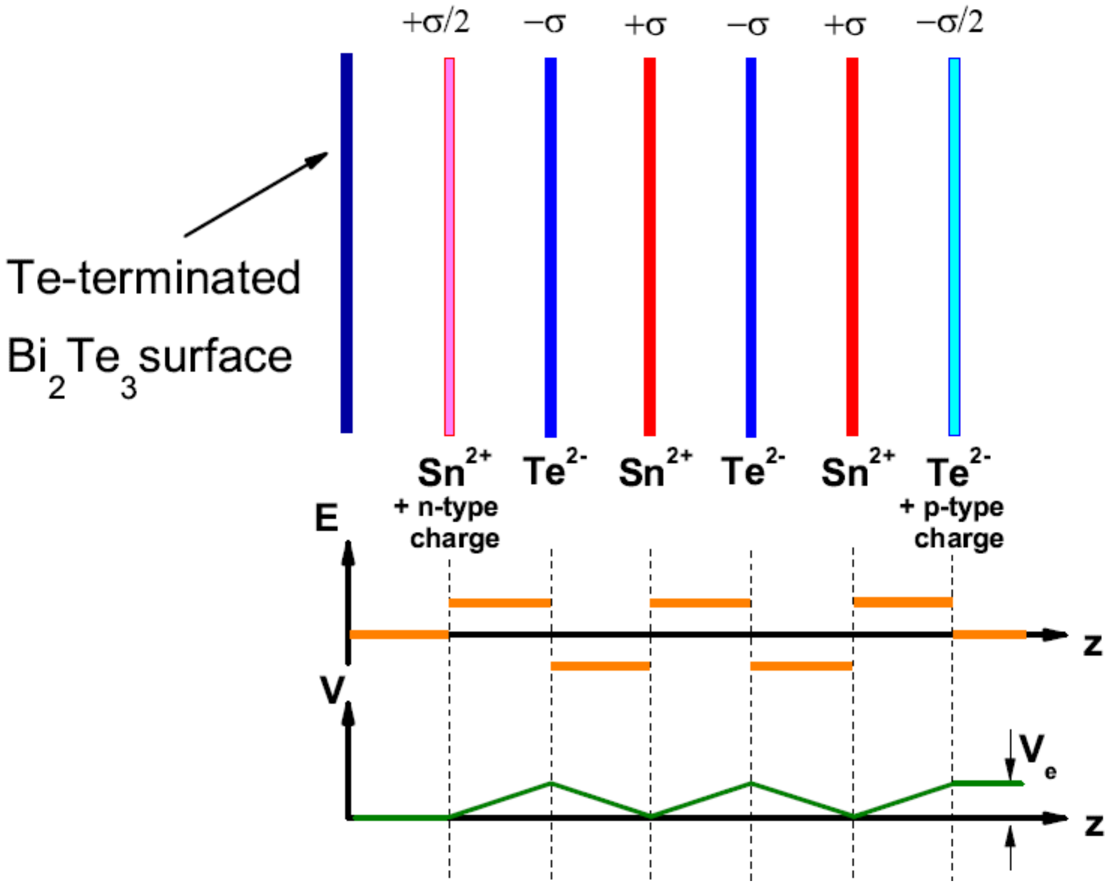
- polar catastrophe in SnTe films grown along the (111) direction
- partially compensated charge on the surfaces
- natural compensation at the interface (p-n junction)

Surface termination (Te)



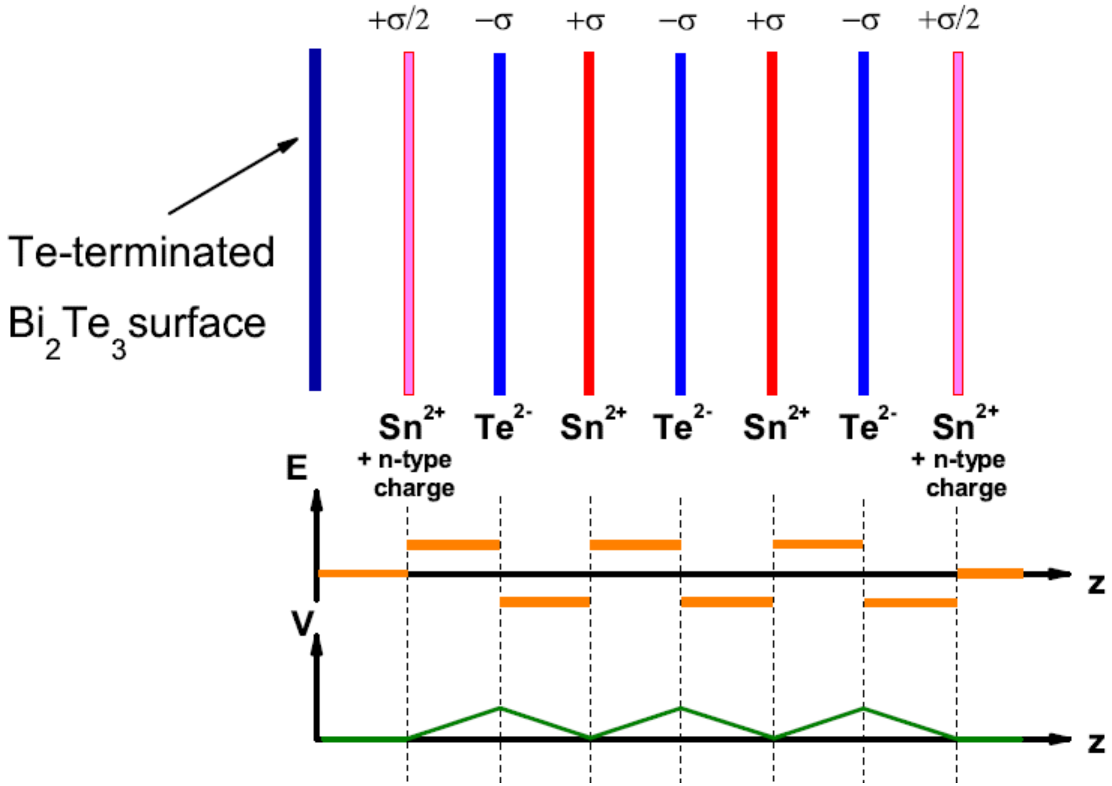
- ➢ polar catastrophe in SnTe films grown along the (111) direction
- ➢ partially compensated charge on the surfaces
- ➢ natural compensation at the interface (p-n junction)
- ➢ **upward** band bending for Te-terminated surface

Surface termination (Te)



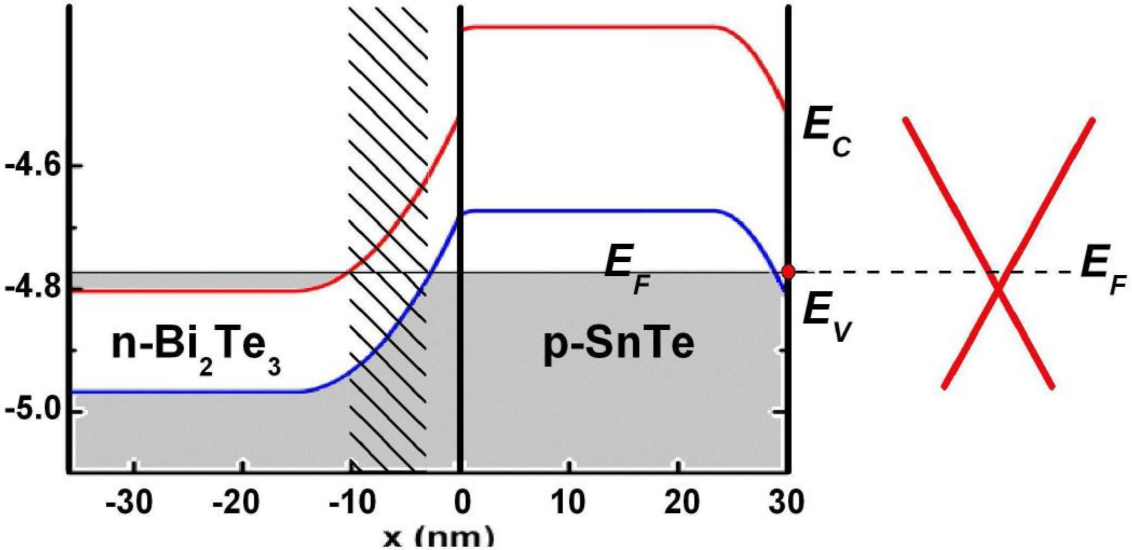
- ➢ polar catastrophe in SnTe films grown along the (111) direction
- ➢ partially compensated charge on the surfaces
- ➢ natural compensation at the interface (p-n junction)
- ➢ **upward** band bending for Te-terminated surface
- ➢ **finite** electrostatic potential for Te-terminated surface

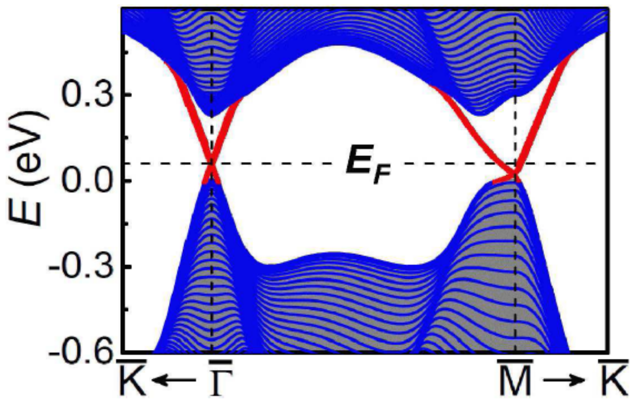
Surface termination (Sn)



- polar catastrophe in SnTe films grown along the (111) direction
- partially compensated charge on the surfaces
- natural compensation at the interface (p-n junction)
- **zero** electrostatic potential for Sn-terminated surface
- **downward** band bending for Sn-terminated surface

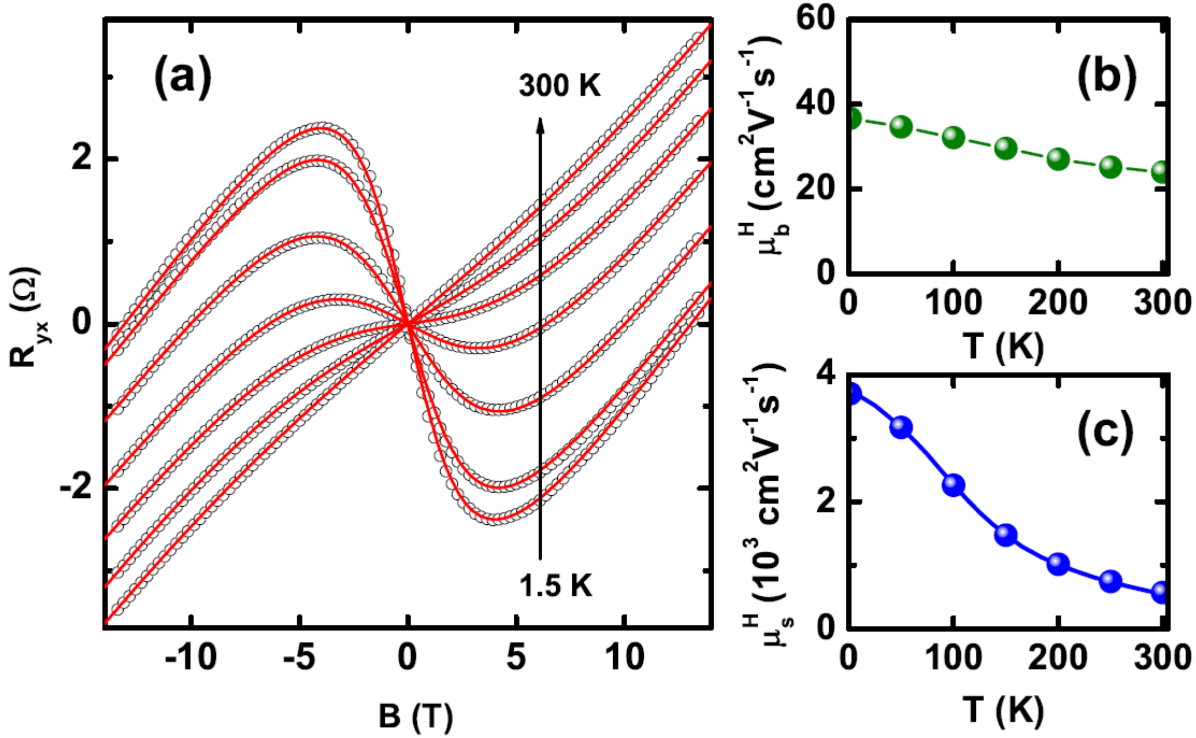
Origin of surface Dirac electrons





- **Sn-terminated surface**
- **downward band bending**
- **Fermi level crosses Dirac cones at ~0 ($\bar{\Gamma}$) and ~40 meV ($\bar{M}$)**
- **single frequency F =12.3 T of SdH oscillations**
- **$v_F = 3.2\times10^7$ cm/s (SdH)**

Nonlinear Hall effect



- two-band fitting
- $n_s = 3 \times 3\times10^{11}$ cm^{-2} (from SdH oscillations) is fixed
- $p_{3D} = 6.4 \times10^{20}$ cm^{-3} (from 300K Hall meas.) is fixed
- **high mobility of surface Dirac electrons**

Summary

- High quality epitaxial SnTe films have been grown on Bi_2Te_3 buffer layer.
- n- and p-type carriers are found to coexist in SnTe film, which is electrically decoupled from Bi_2Te_3 layer due to a p-n junction at the interface.
- SdH oscillations combined with the Hall resistivity data provide evidence that the n-type carriers are **Dirac fermions** residing on the top SnTe (111) surface.