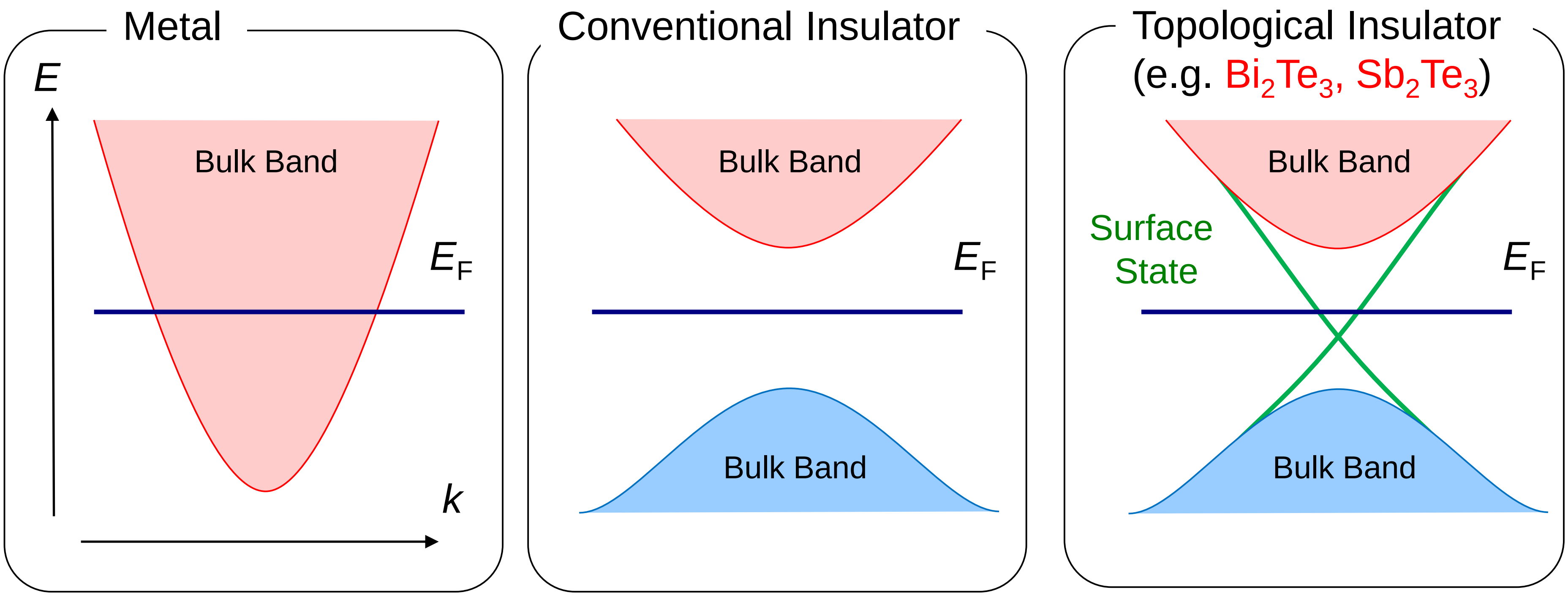
June 3rd 2015 Workshop on
"New Perspectives in Spintronic and Mesoscopic Physics"

Quantum transport phenomena in 3D topological insulator thin films

<u>Ryutaro Yoshimi</u> [A],
A. Tsukazaki [B], M. Mogi [A], K. Yasuda [A],
Y. Kozuka [A], J. Falson [A], J. G. Checkelsky [D], K. S. Takahashi [C],
N. Nagaosa [A, C], M. Kawasaki [A, C], and Y. Tokura [A, C]

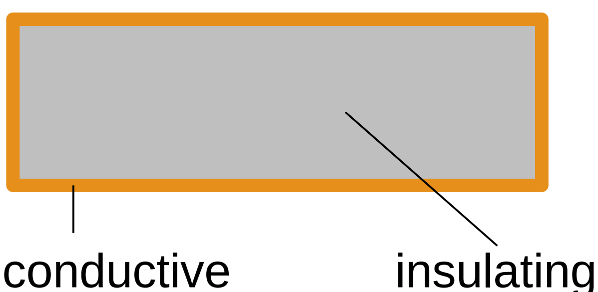
Univ. of Tokyo [A], Tohoku Univ. [B], RIKEN-CEMS [C], MIT [D]

Introduction to Topological Insulator



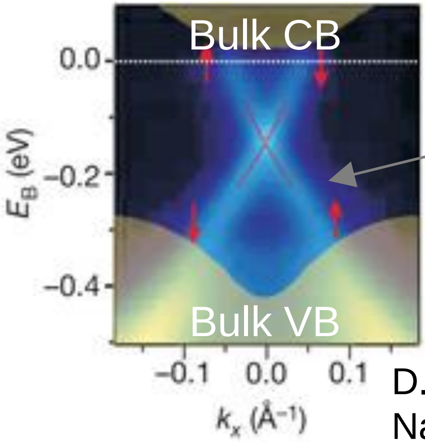
Topological Insulator

- Bulk (inside the sample) is insulating
- Surface is conductive



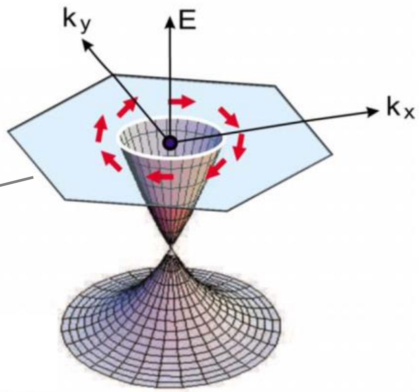
Characteristics of topological surface state

Momentum space



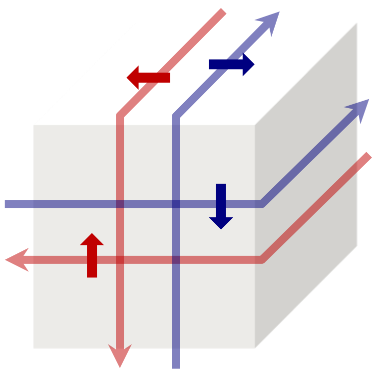
surface state

D. Hsieh *et al.*, Nature (2009)



Two-dimensional surface gapless band
- massless **Dirac** dispersion
- **spin** momentum locking
- **gapless** under time reversal symmetry

Real space



Spin
up
down

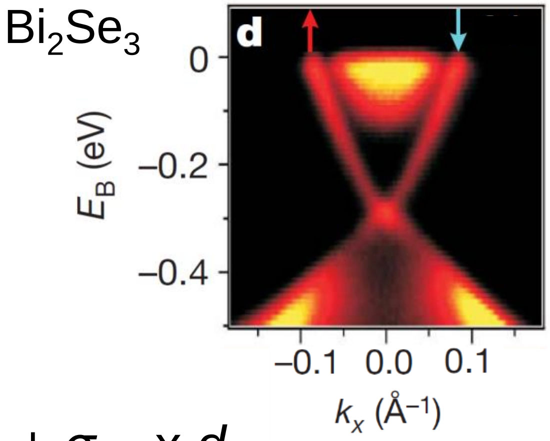
Dissipationless **spin-current** on the surface

Future application to spintronics device or quantum computation

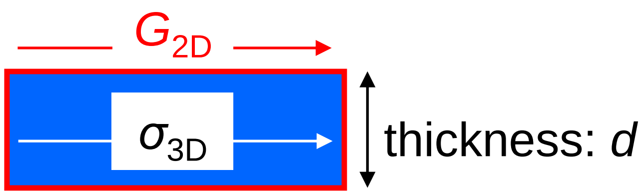
Experiment on bulk single crystal

<u>Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, …..</u>

- Small band gap (~ 250 meV)
- **Bulk residual carrier** by crystal defects



D. Hsieh *et al.*, Nature (2009)

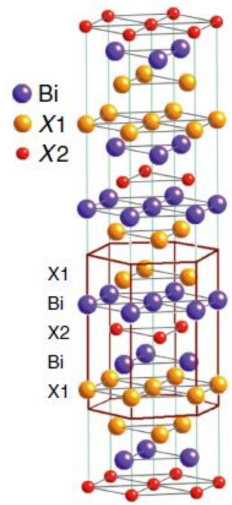


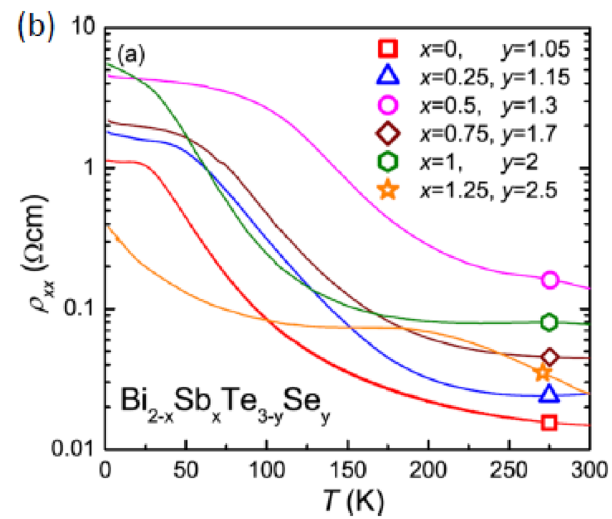
$$G_{total} = G_{2D} + \sigma_{3D} \times d$$

surface: G_{2D}; bulk conduction: $\sigma_{3D} \times d$

Reduction of bulk conduction

- Exfoliation (reduction in d)
- Find insulating compound (reduction in σ_{3D})

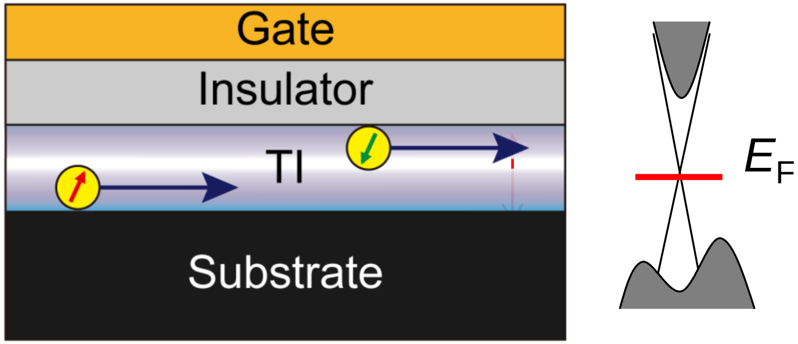




Y. Ando, Review in JPSJ (2013)

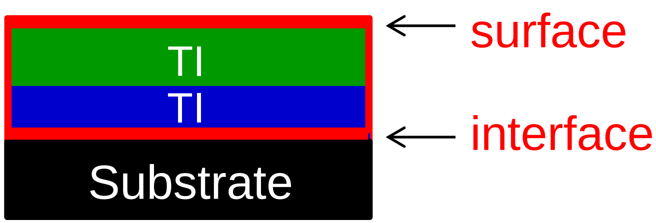
Complete suppression of bulk transport in thin film

Thin film + FET device



・**Surface dominant** transport
・***E_F* tuning** in the Dirac state

Surface/interface degrees of freedom

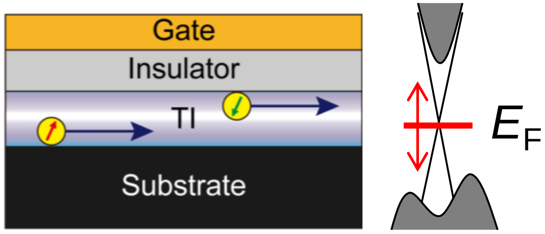


・Controlling surface/interface
(lift the degeneracy)
by **layered structure**

・Thin film device enable us to access the ideal Dirac states of TI without bulk state
・Surface/interface degrees of freedom shows up

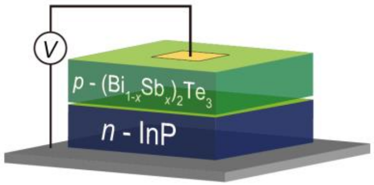
Quantum transport in surface/interface states of TI

Thin film device fabrication



Bulk insulating thin film
FET device for E_F tuning

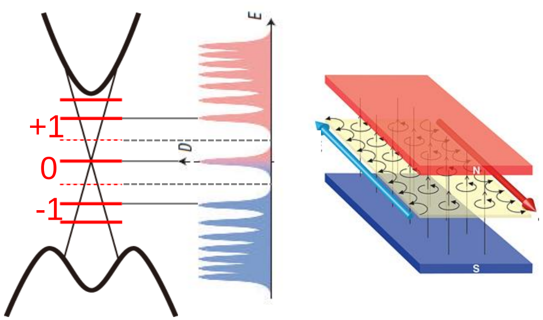
Tunneling Spectroscopy



R. Yoshimi *et al.*,
Nature Materials**13** 253 (2014)

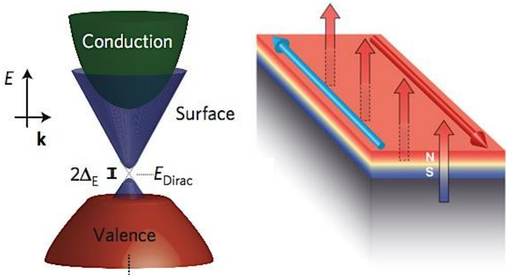
Detection of
interface Dirac state

Quantum Hall Effect



R. Yoshimi, *et. al*
Nature Commun. **6**,6627 (2015)

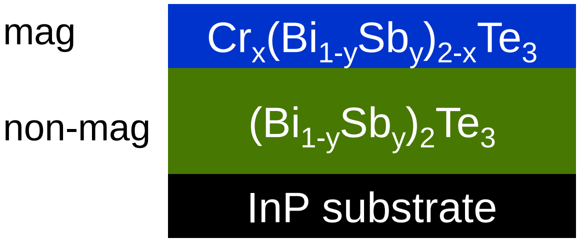
Quantum Anomalous Hall Effect



J. G. Checkelsky, R. Yoshimi *et.al.*
Nature Physics, **10**, 731 (2014)

Quantization at zero field

QHE in semi-magnetic TI bilayer



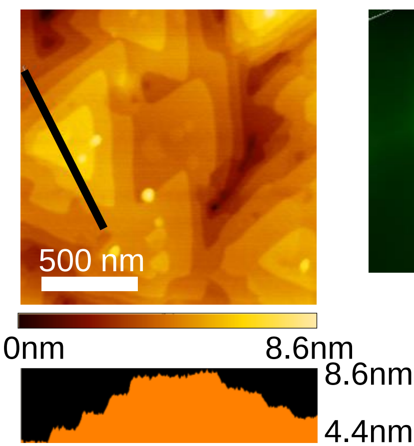
R. Yoshimi *et al.*, submitted.

QHE at higher temperature

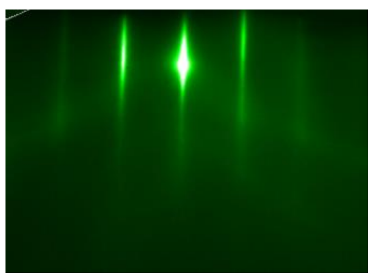
$(Bi_{1-x}Sb_x)_2Te_3$ (BST) thin film

Molecular Beam Epitaxy (MBE)

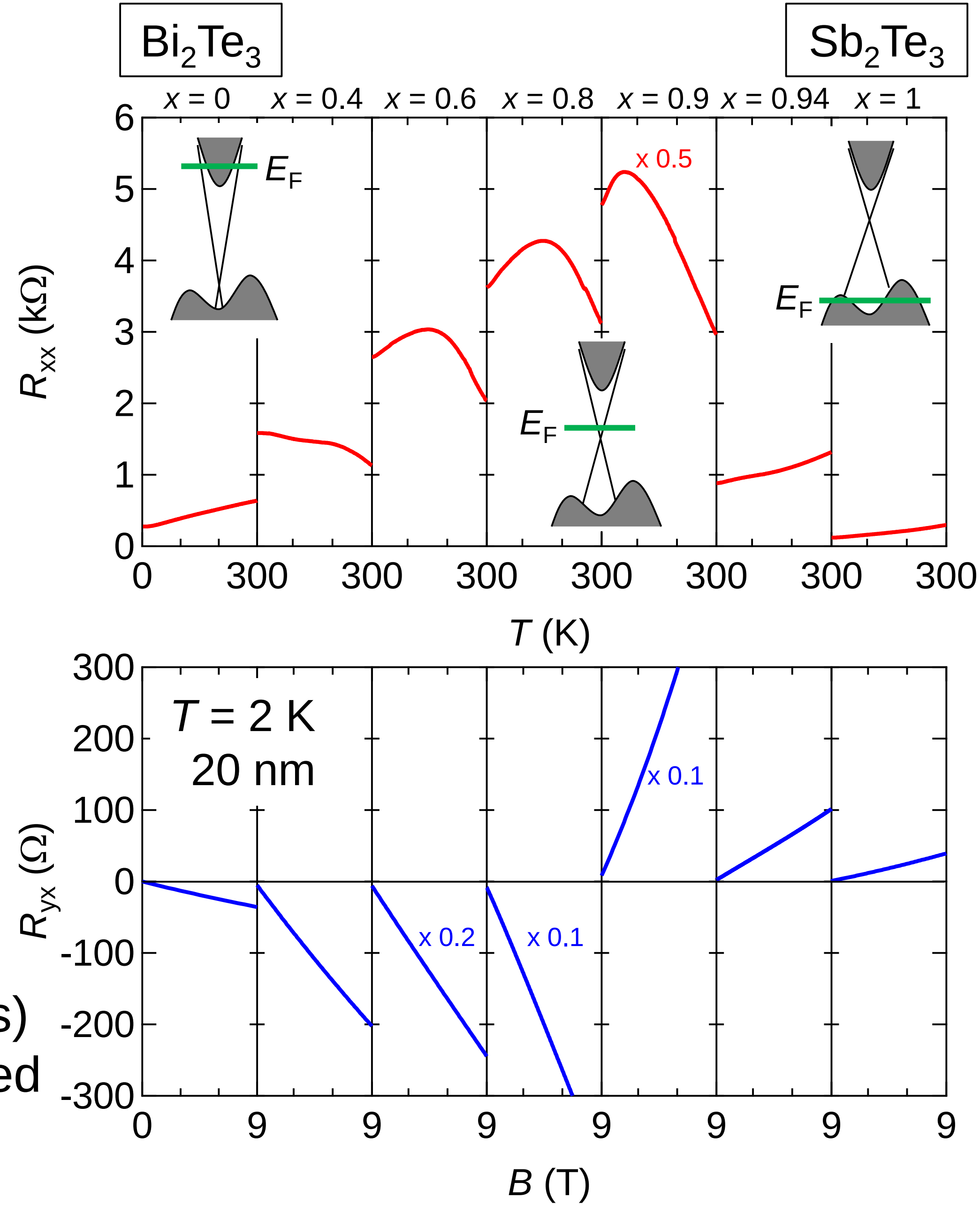
AFM



RHEED

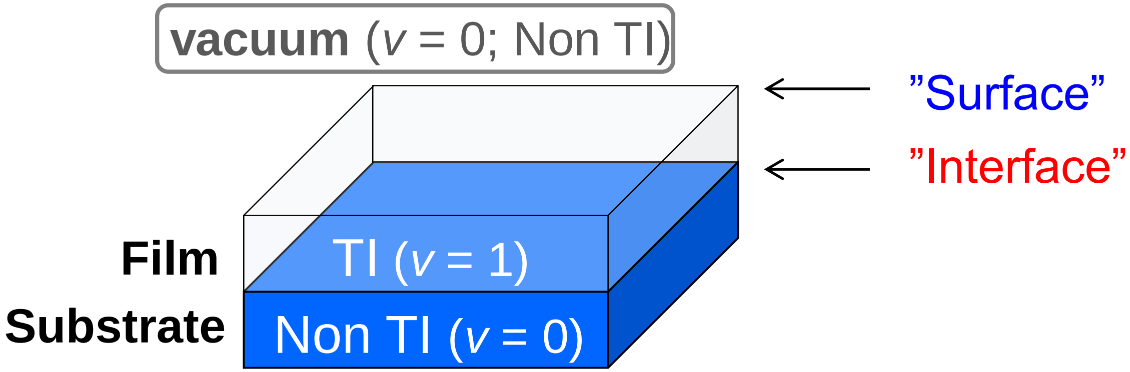


- Substrate: InP (lattice matches)
- Carrier density widely controlled with Sb content



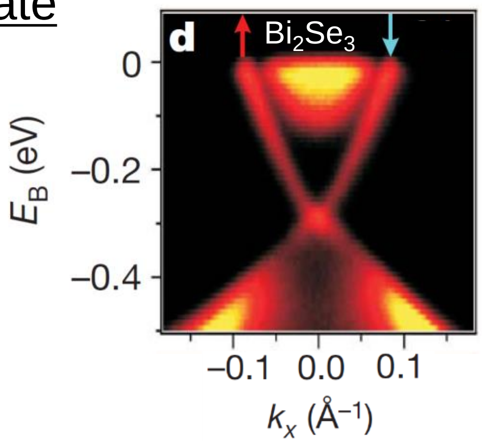
Surface/Interface Dirac states in topological insulator

Edge states at the boundary of TI



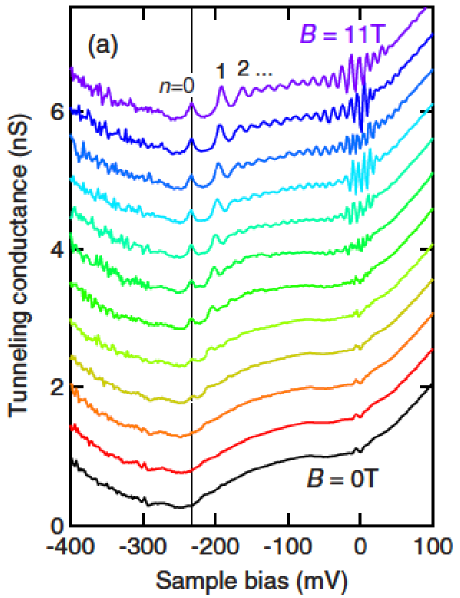
Surface Dirac state

ARPES



D. Hsieh *et al.*, Nature (2009)

STM

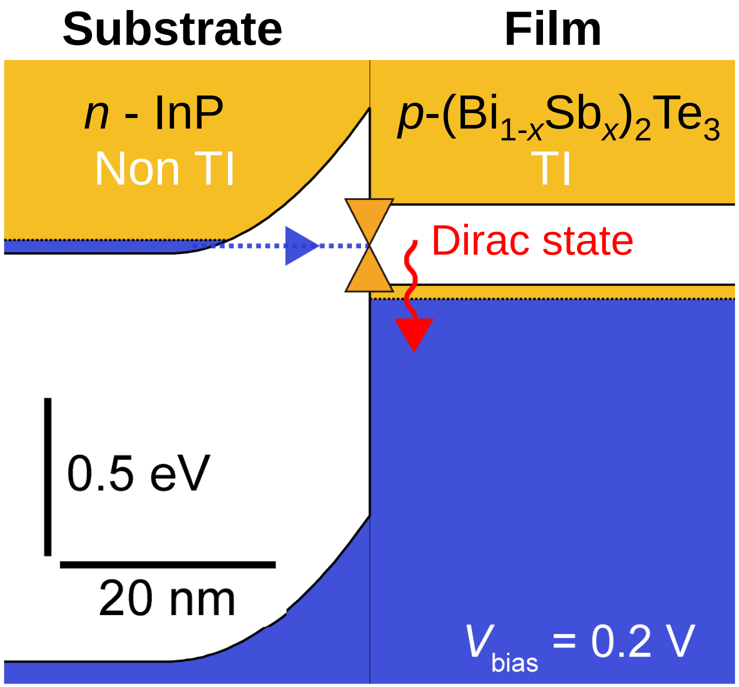


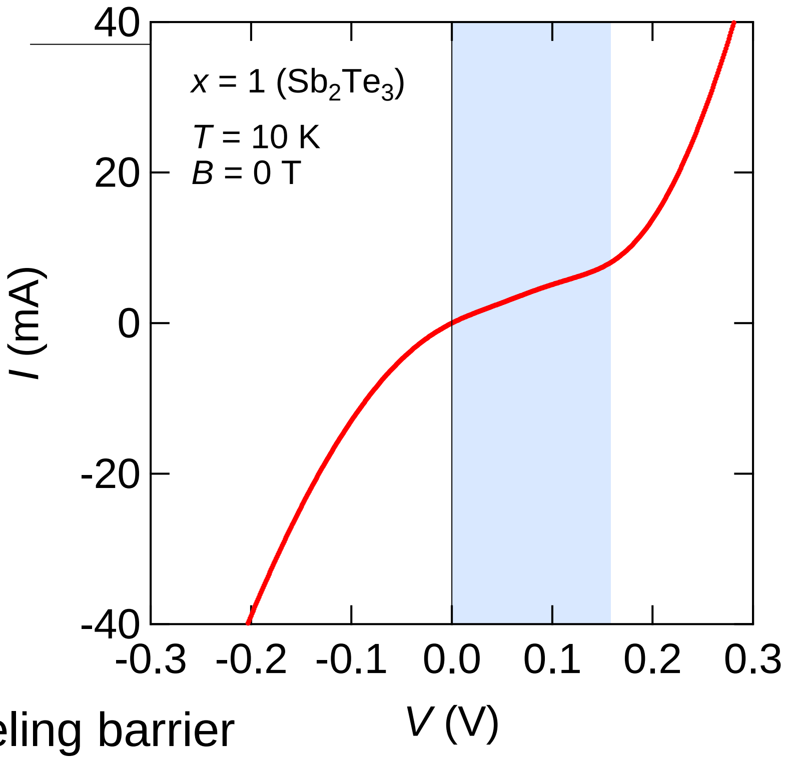
T. Hanaguri *et al.*, PRB (2010)

- Surface Dirac states are verified by ARPES and STM
- Dirac state at interface is not yet clearly observed

Detecting the interface Dirac state of TI

Tunneling spectroscopy on TI/non-TI *p-n* heterojunction

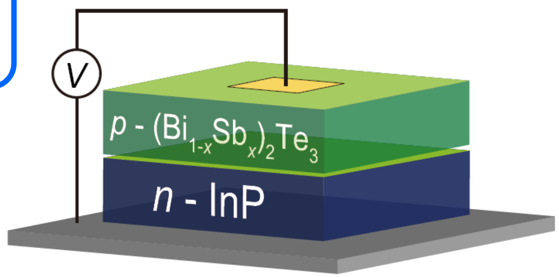




- Thin depletion layer acts as the tunneling barrier
- Tunneling conductance is proportional to the interface density of states

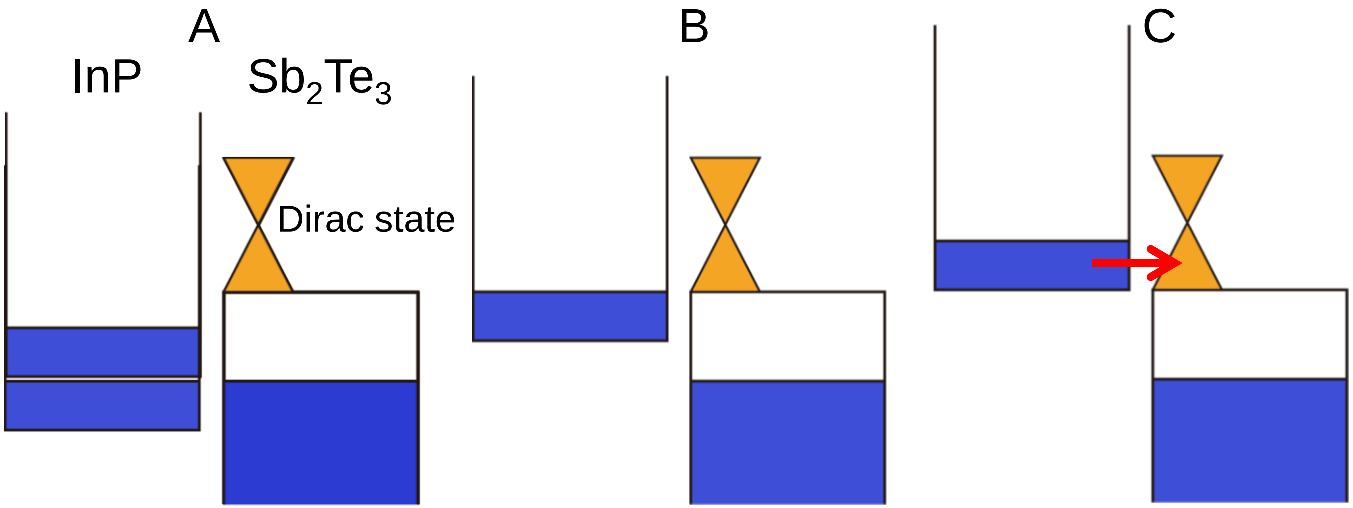
→ Interface Dirac states and its Landau level formation can be spectroscopically detected

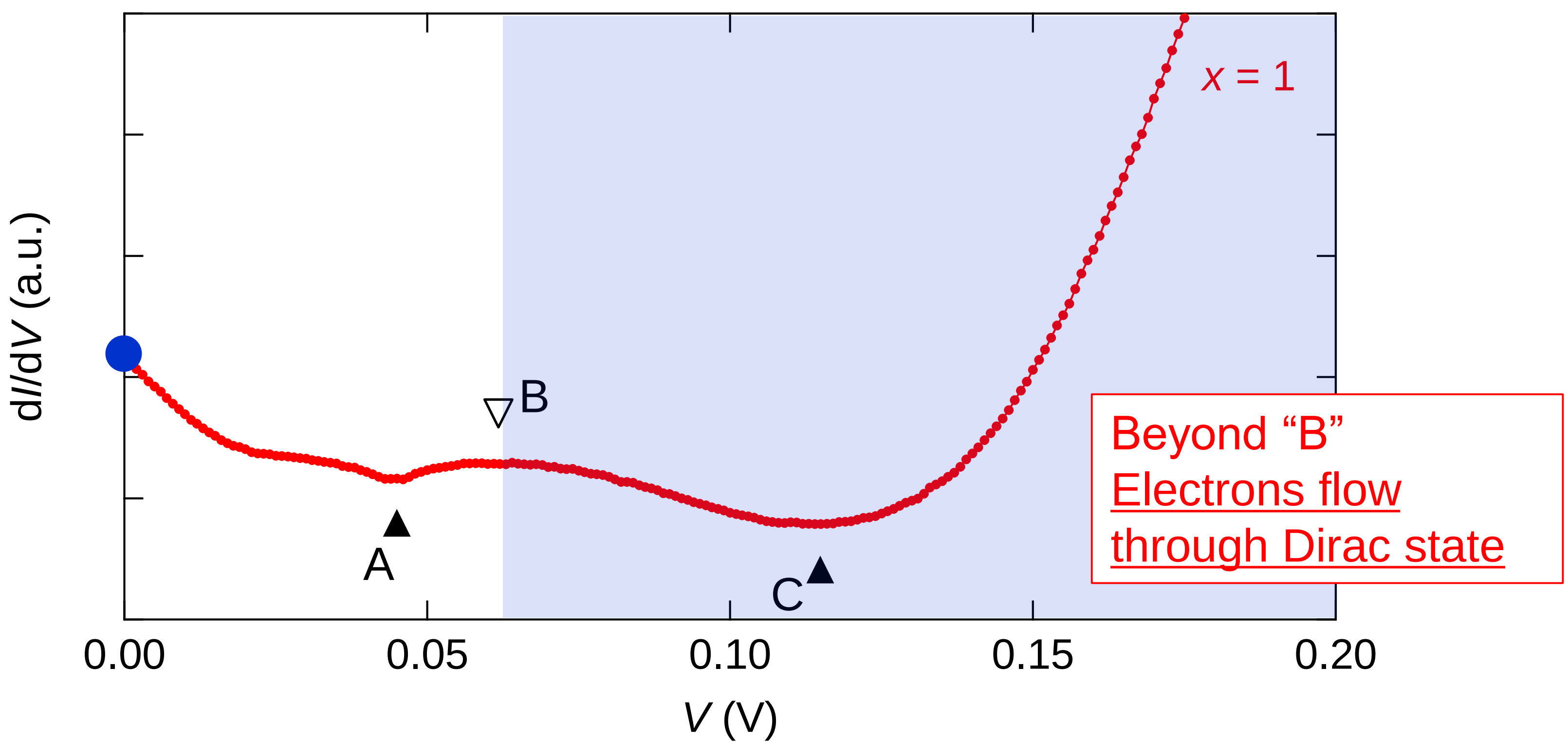
-Typical Esaki-diode character in *I*-*V* curve



R. Yoshimi *et al.*, Nature Materials **13** 253 (2014)

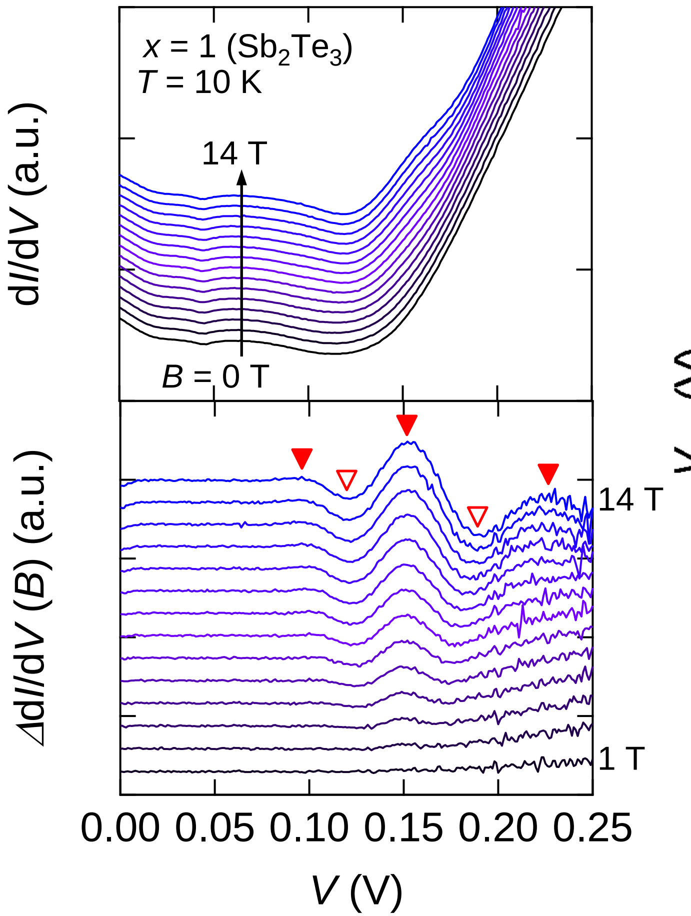
dI/dV in $(Bi_{1-x}Sb_x)_2Te_3$/InP junctions



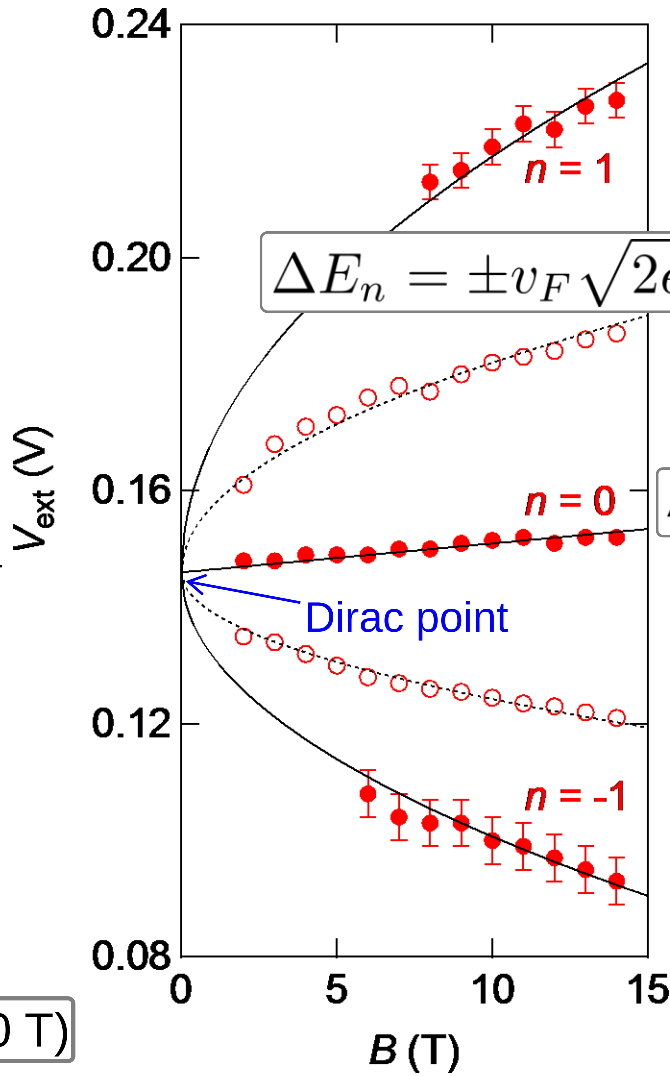


Landau level formation observed in tunneling spectra

Tunneling conductance d*I*/d*V*



$\Delta dI/dV\ (B) = dI/dV(B) - dI/dV(0\ T)$

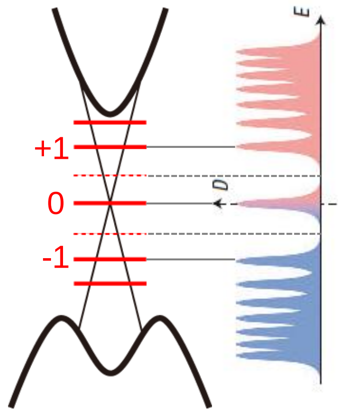


$$\Delta E_n = \pm v_F \sqrt{2e\hbar|n|B}$$

R. Yoshimi *et al.*, Nature Materials **13** 253 (2014)

$$\Delta E_0 = g\mu_B B/2$$

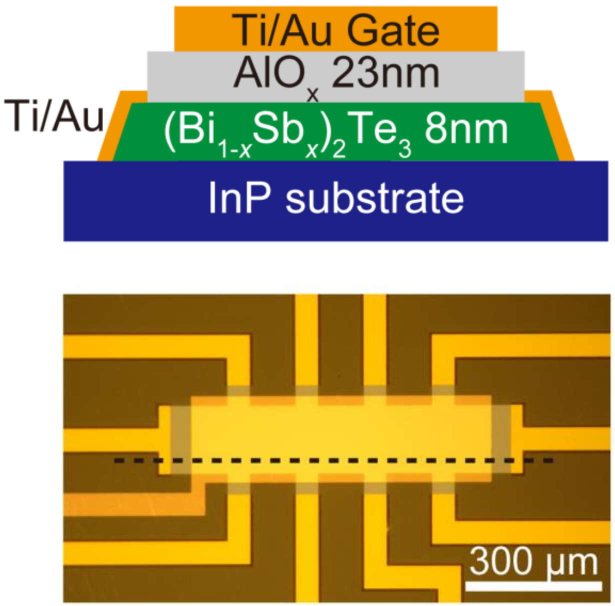
(g ~ 11)



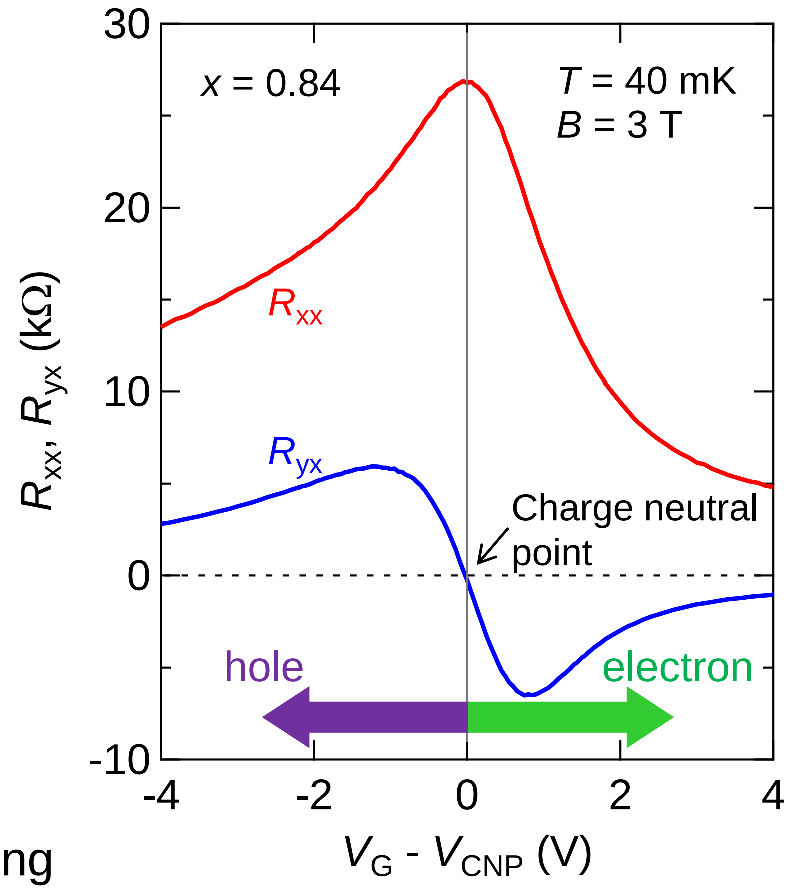
- Oscillatory feature in $\Delta dI/dV$
- Landau levels (n = 0, ±1) due to interface Dirac dispersion ($\propto B^{1/2}$)

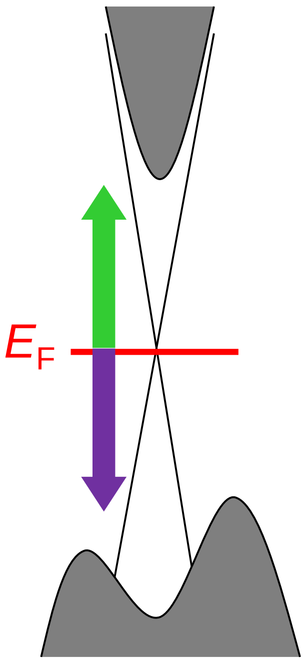
Ambipolar transport in FET device (x = 0.84)

FET device



Transport measurement in dilution fridge



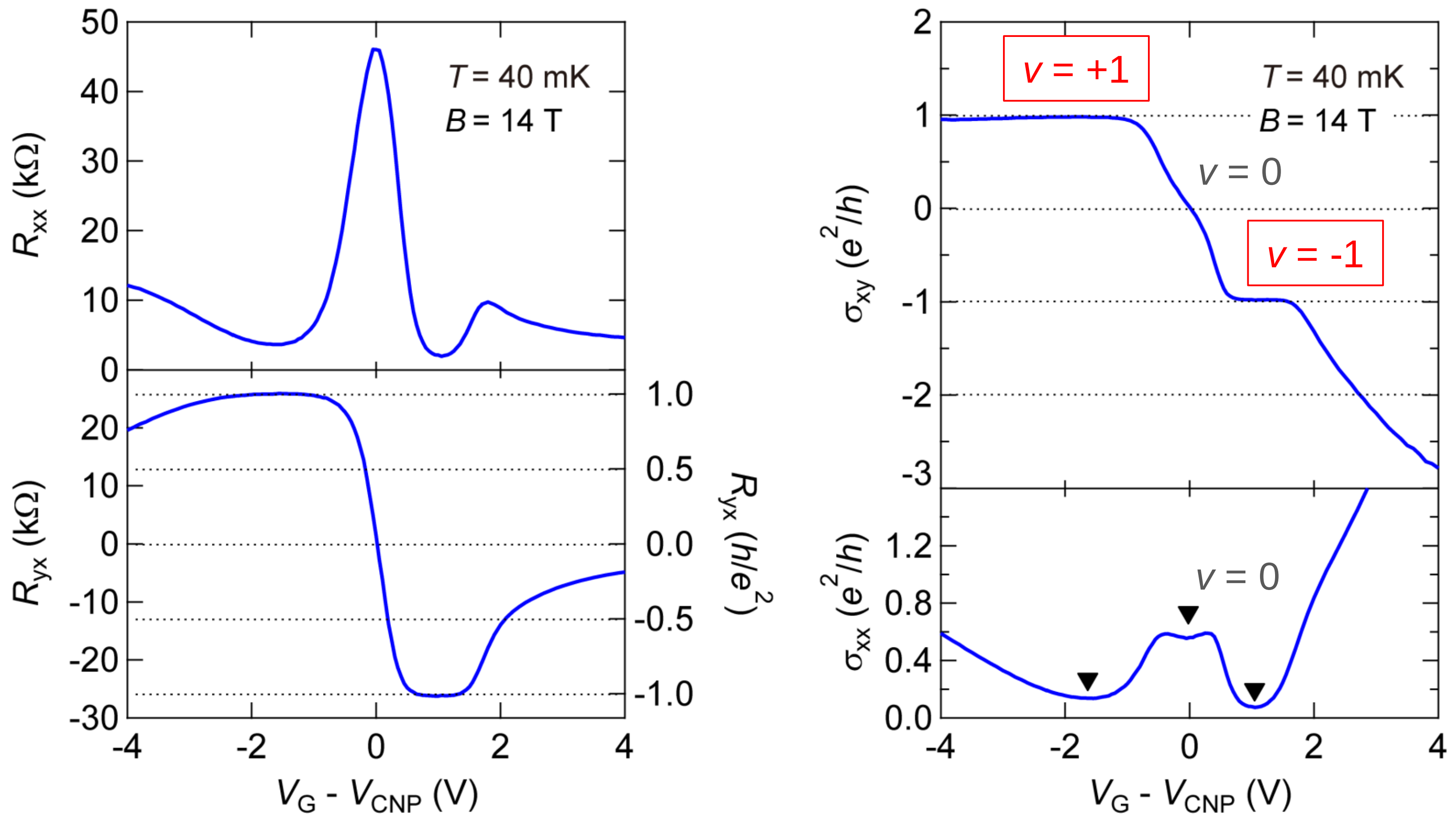


R. Yoshimi, *et. al* Nature Commun. **6**,6627 (2015)

- AlO_x capping before patterning
- Low temperature process (< 120 C°)
- Gate dielectric by ALD at R.T.

- Ambipolar conduction by gate tuning
  E_F is modulated across Dirac point
- mobility μ ~ 1,500 cm^2/Vs, n ~ 4 x 10^{11} cm^{-2}

Quantum Hall Effect in BST



- Quantum Hall plateau $\sigma_{xy} = \pm e^2/h$ (B = 14 T)
- 2D nature of Dirac states
- At charge neutral point, $\sigma_{xy} = 0$ ($v = 0$) QHE

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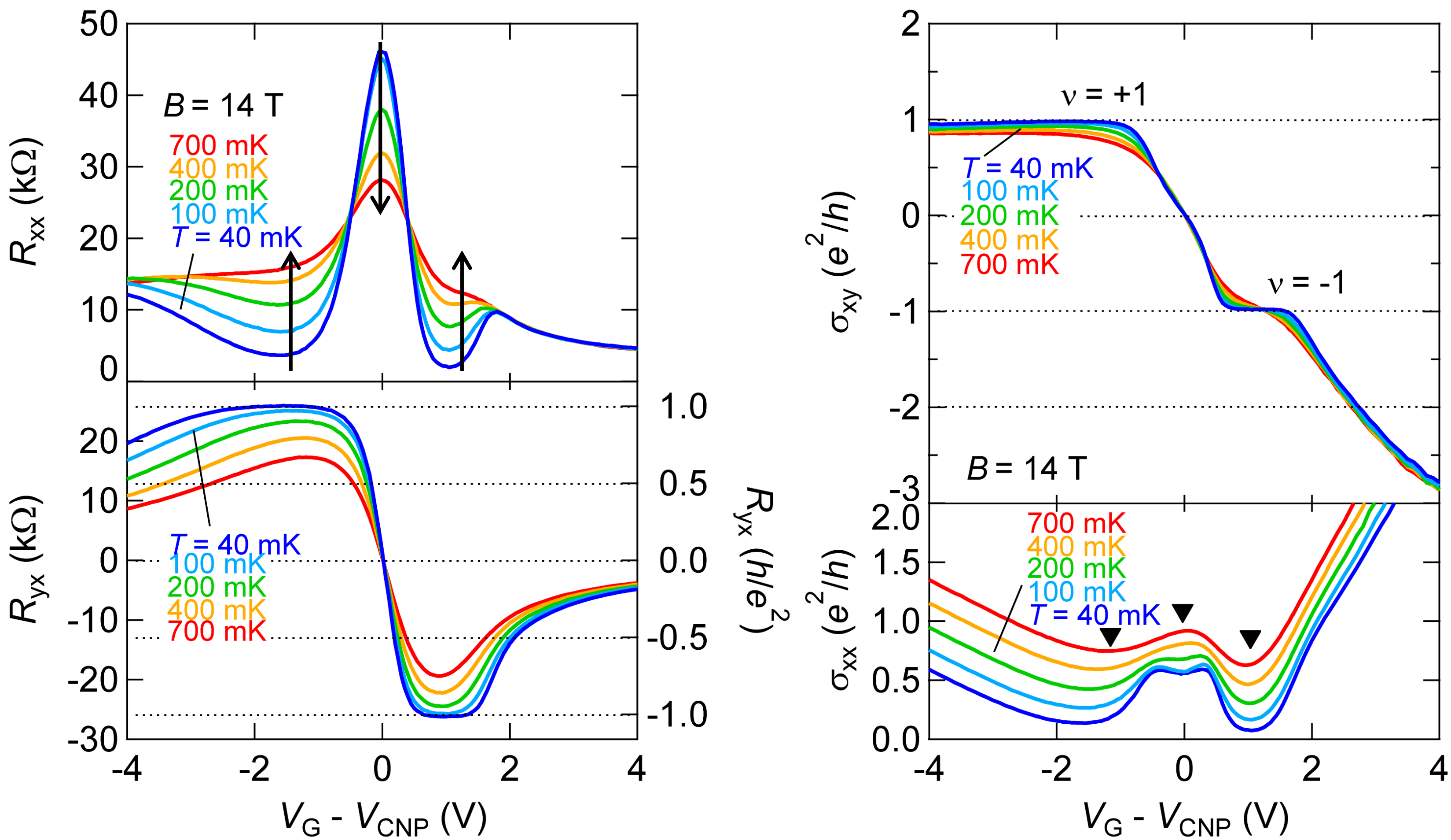
Temperature dependence



$\nu = \pm 1$: R_{xx} is metallic

$\nu = 0$: R_{xx} is insulating

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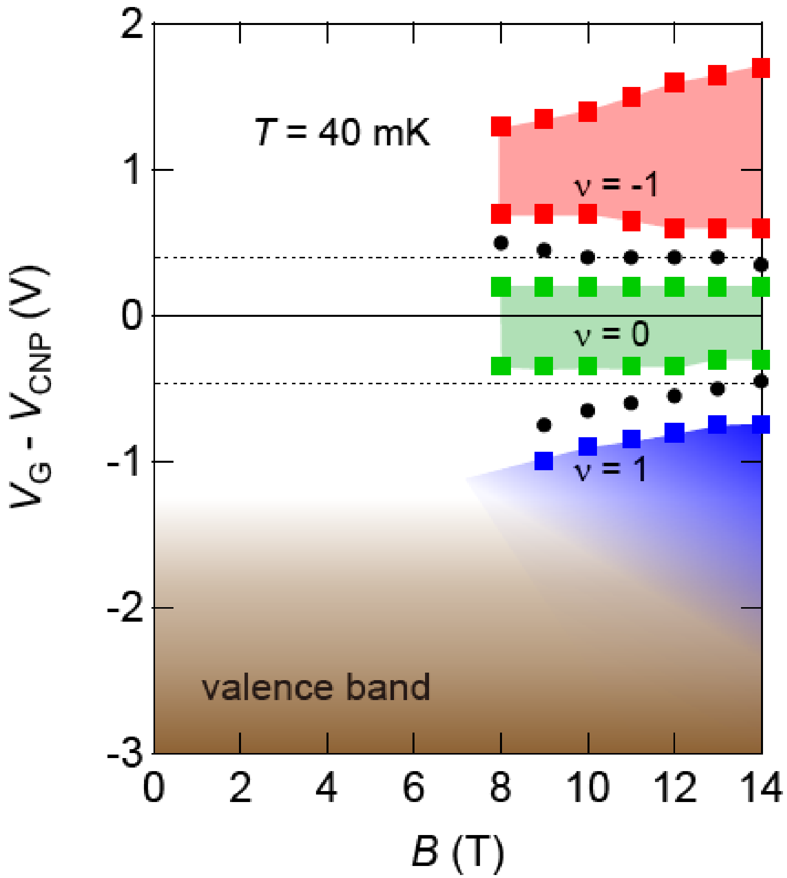
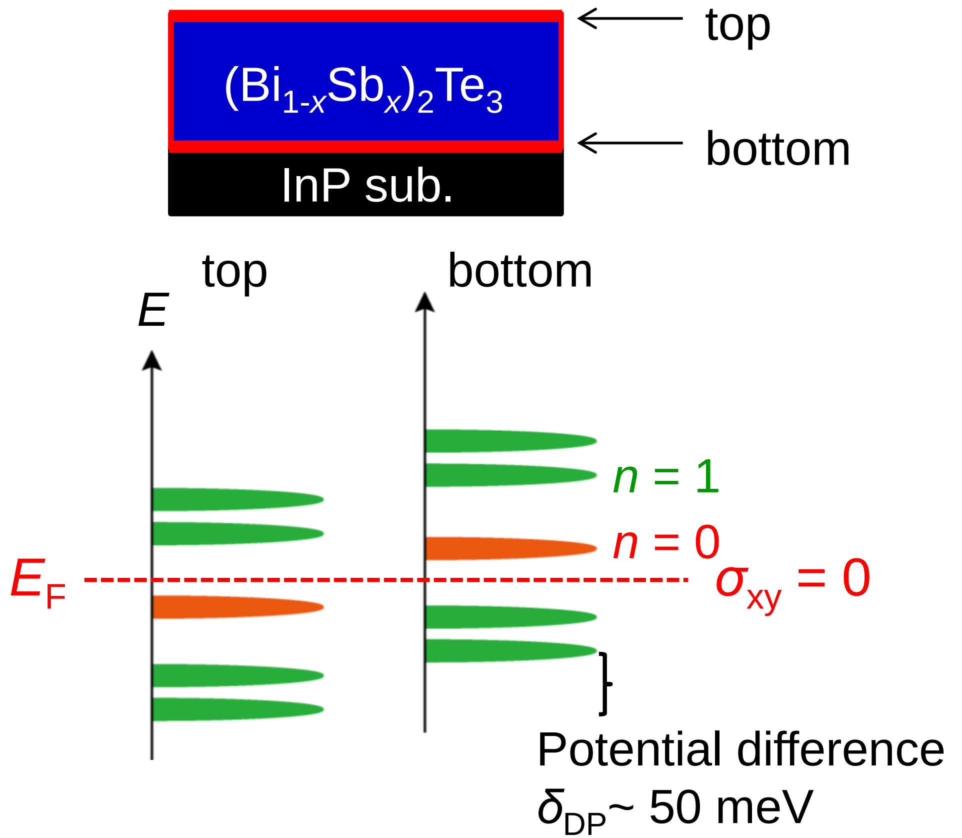
Nature Commun.
6,6627 (2015)

ν = 0 state by LL at top/botom Dirac state

Phase diagram of QH states



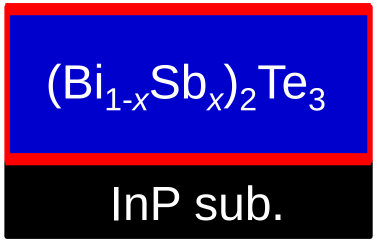
Landau levels at top and bottom surface

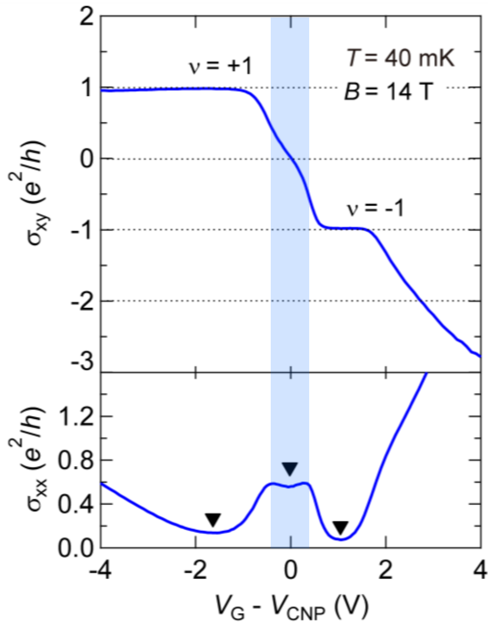


- weak B dependence in σ_{xy} plateau
- Different environment of top and bottom state→ δ_{DP}~ 50 meV

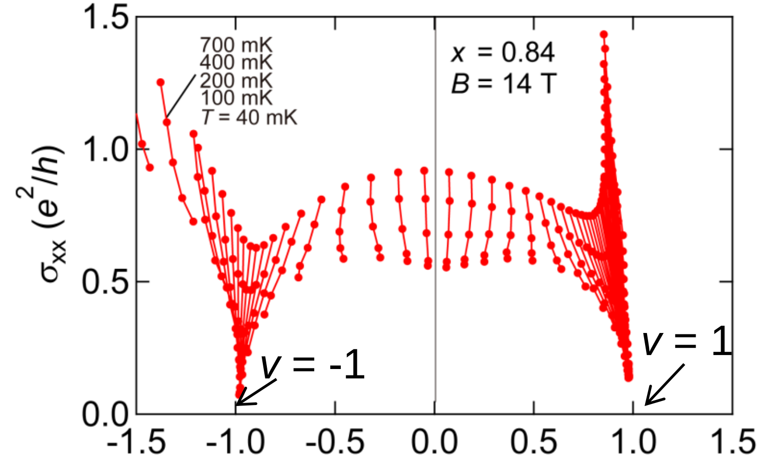
Stabilization of $\nu = 0$ state in layered structure

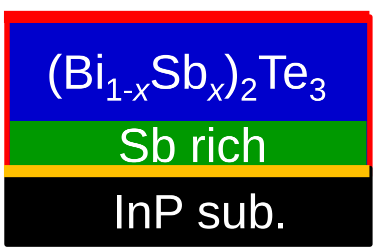
Structure

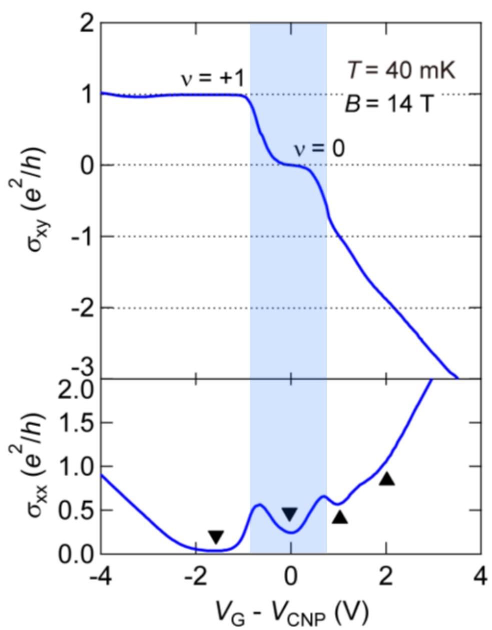


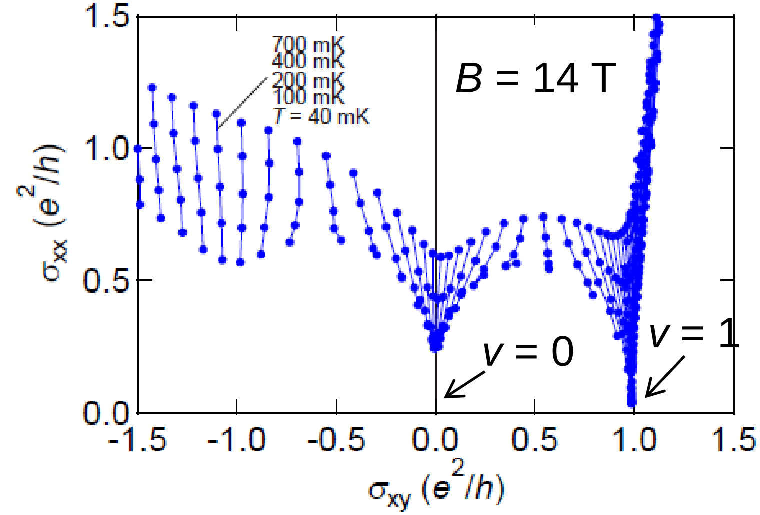


Conductivity mapping



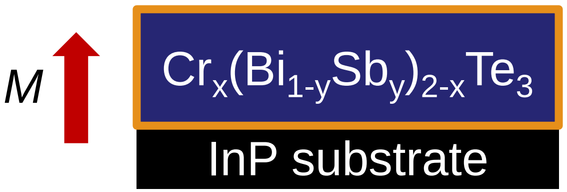


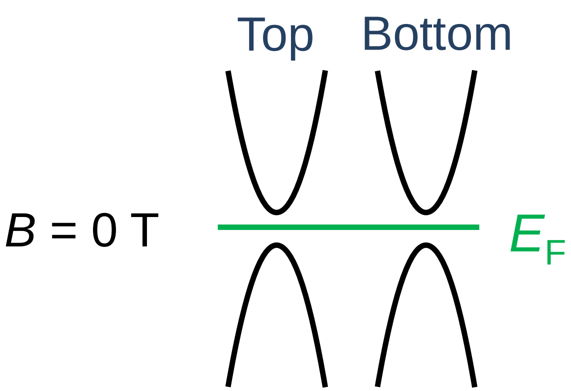




Observation of Quantum Anomalus Hall Effect

QAHE

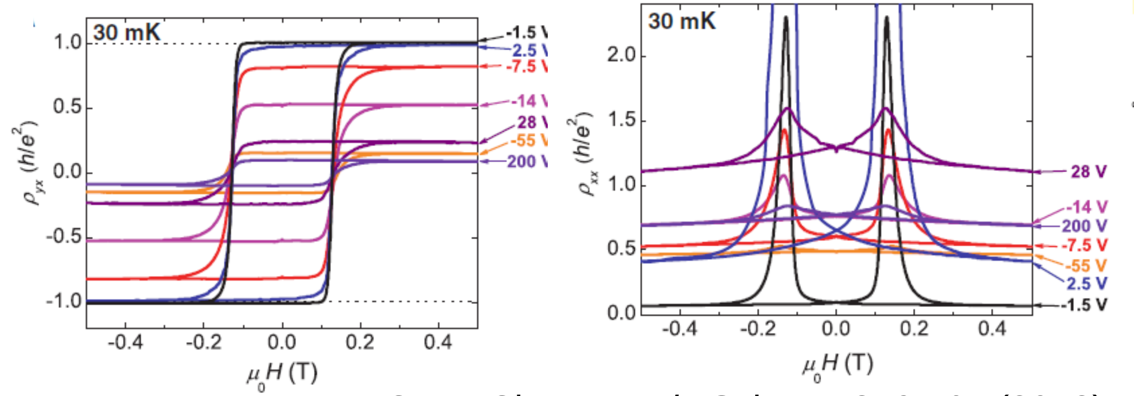




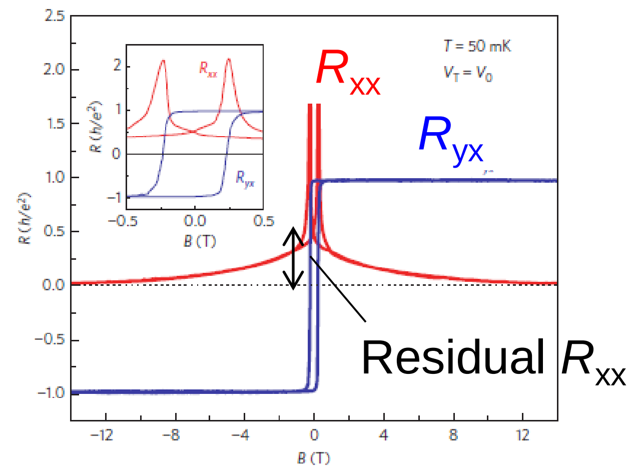
- Spontaneous gap opening by magnetism
- Quantization of Anomalous Hall term

$$\begin{cases} R_{yx} = R_{yx}^{A} = h/e^2 \\ R_{xx} = 0 \end{cases}$$

$Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$



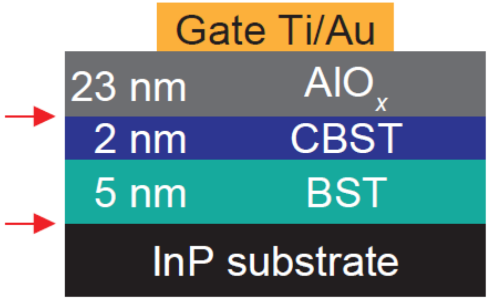
C-. Z. Chang *et al*., Science **340** 167 (2013).

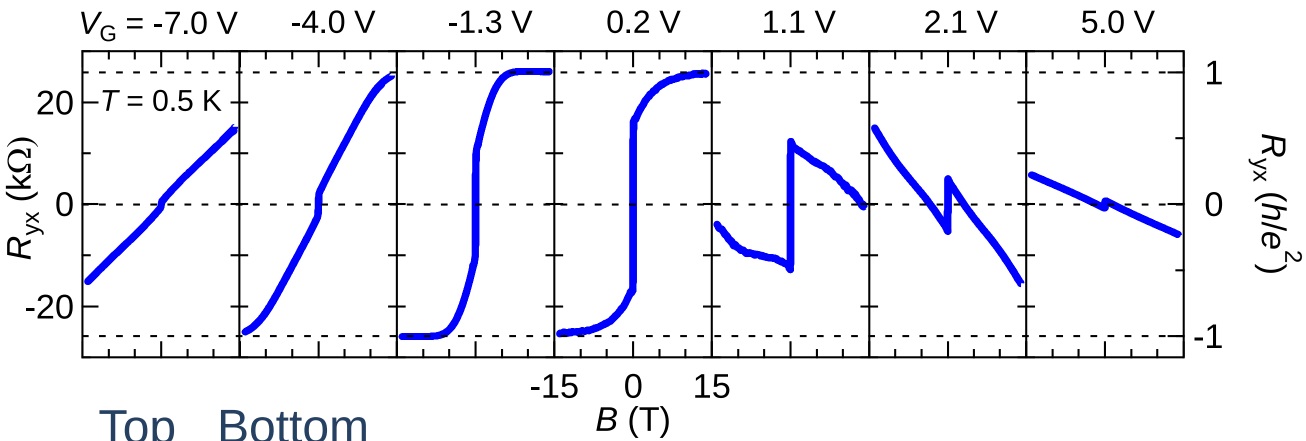


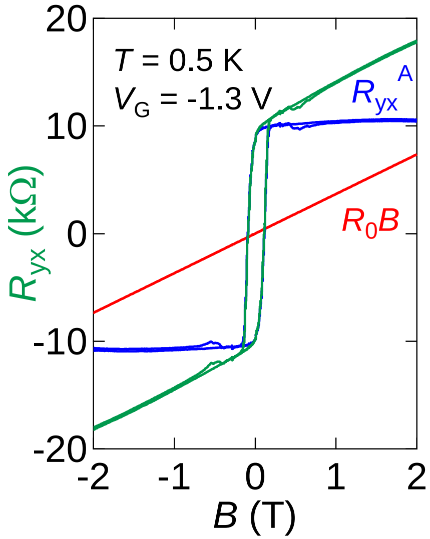
- QAHE with help of magnetic field (R_{xx} at 0 T ~ 0.5 h/e^2)

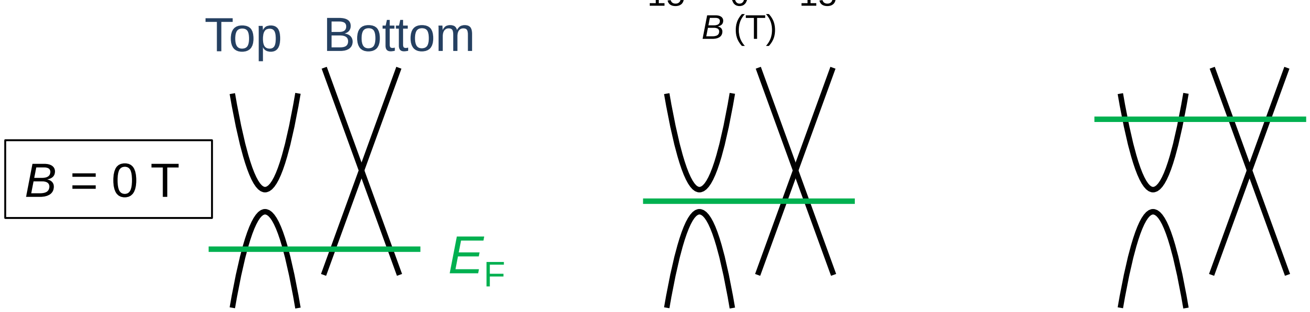
J. G. Checkelsky, R. Yoshimi *et al*., Nature Phys. (2014)

QHE in magnetic/non-magnetic TI bilayer









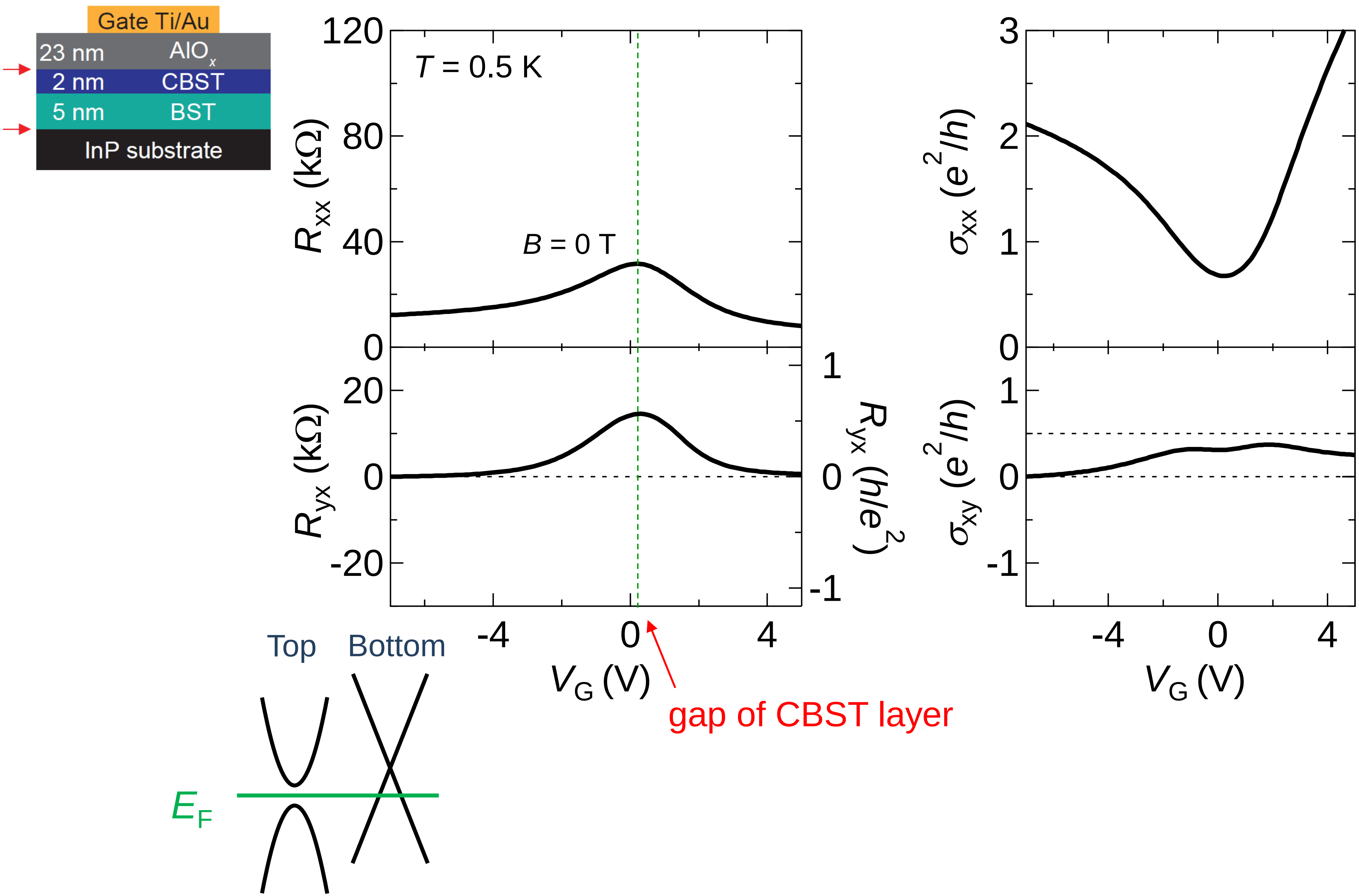
$R_{yx} = R_0 B + R_{yx}^{A}$

Ordinary Hall term ← BST

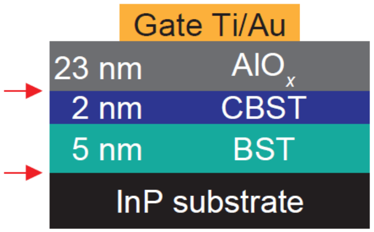
Anomalous Hall term ← CBST

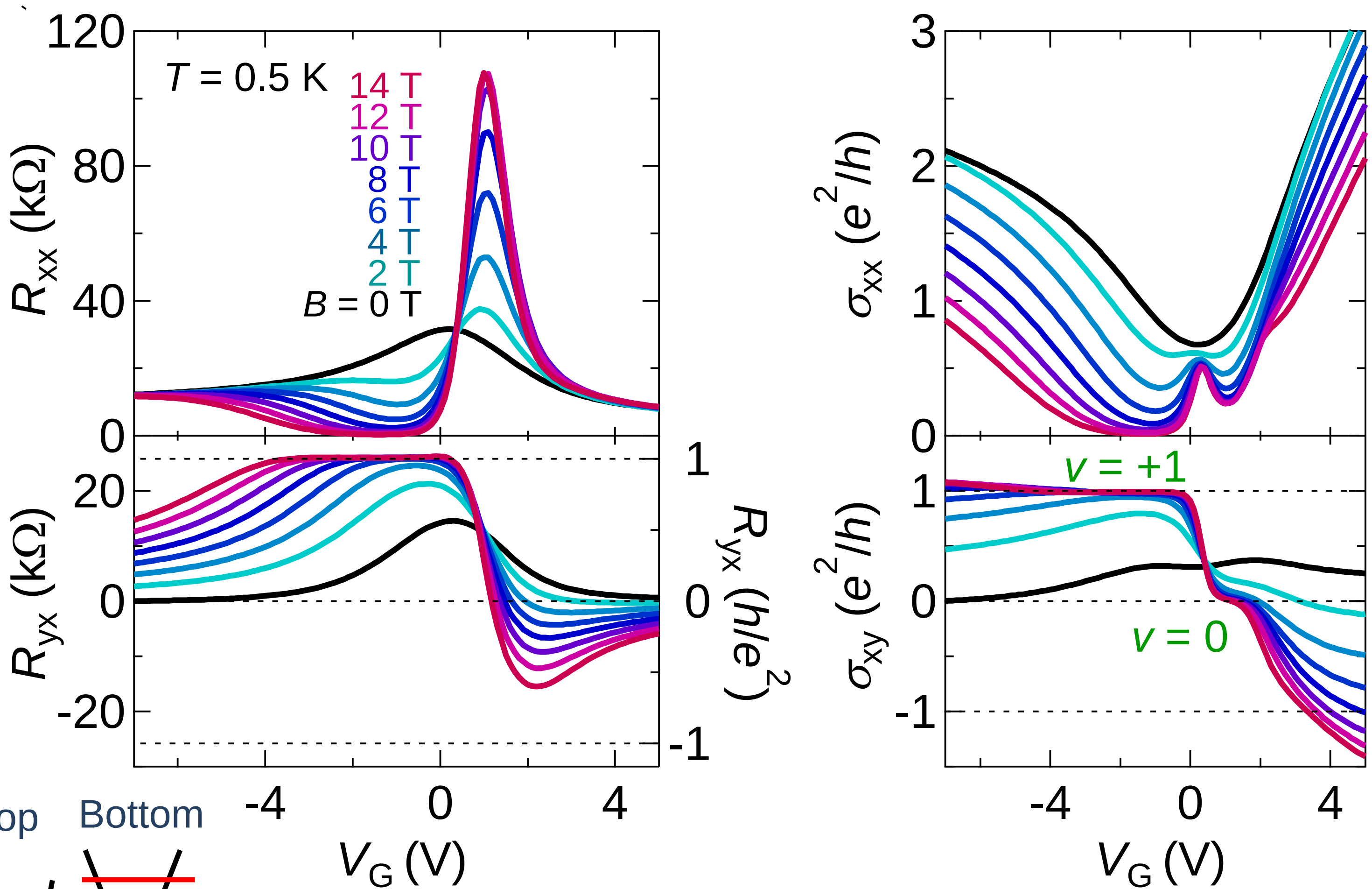
- R_{yx} reaches h/e^2 by adding up OHE and AHE
- Band structure
  - gapped CBST surface
  - gapless BST surface

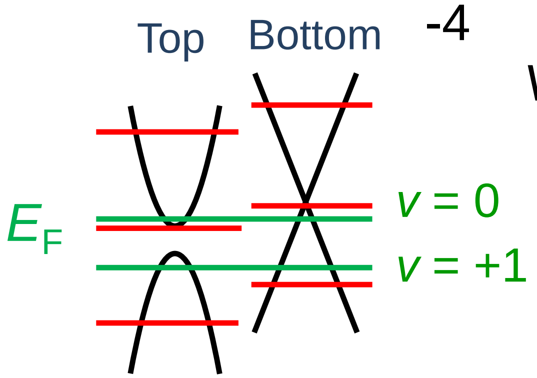
Transport Phenomena at 0T



Magnetic field dependence



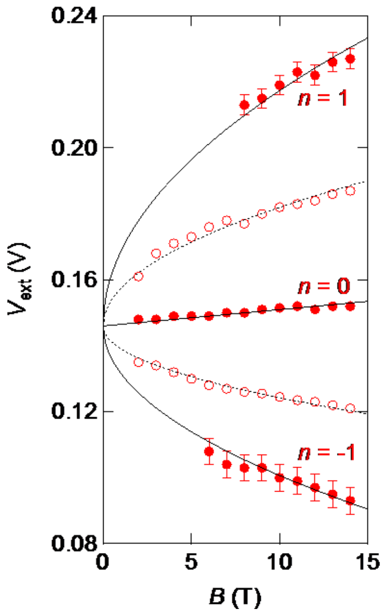




- $\nu = +1$, 0 states due to LL formation are observed

Summary

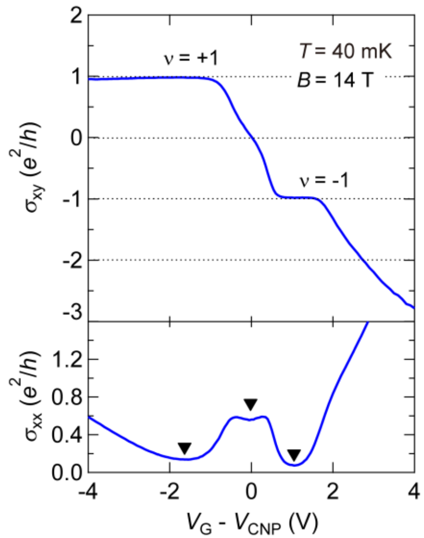
Tunneling Spectroscopy



R. Yoshimi *et al.*, Nature Materials **13** 253 (2014)

Detection of **interface** Dirac state

QHE in BST

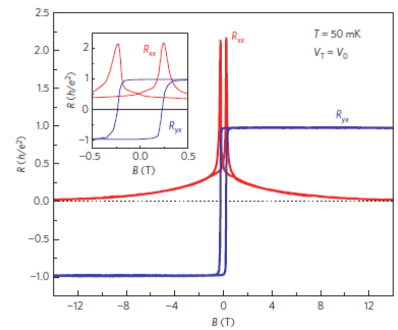


R. Yoshimi, *et. al* Nature Commun. **6**,6627 (2015)

FET device of **BST** thin film

QHE with $\nu = \pm 1, 0$

QAHE in CBST

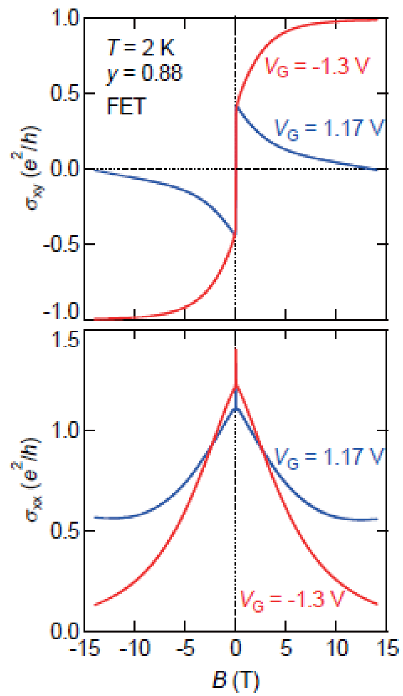


J. G. Checkelsky, R. Yoshimi *et al.*, Nature Phys. (2014)

Cr-doped BST

Quantization **at B = 0 T**

QHE in bilayer



R. Yoshimi *et al.*, submitted.

QHE **at higher temperature**