

Thin Film Growth of Topological Insulators Bi_2Se_3 and $(\text{Bi,Sb})_2\text{Te}_3$ toward Bulk-insulating Features and Enhanced Interfacial Exchange Coupling on Rare Earth Iron Garnets

Chun-Chia Chen (陳俊嘉)

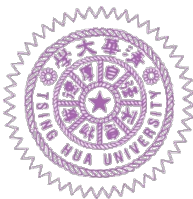
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Department of Physics, National Tsing-Hua University, Taiwan

Advisor: Minghwei Hong (洪銘輝)

Department of Physics, National Taiwan University, Taiwan



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- **MBE**

C. C. Chen and K. H. M. Chen

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C. C. Tseng, M. X. Guo, and
Dr. C. N. Wu

- **XRD**

C. K. Cheng

- **TEM**

Dr. C. T. Wu

- **Transport**

S. R. Yang, J. S. Wei,
Y. T. Fanchiang, and W. J. Zou

- **XPS**

S. W. Huang and K. Y. Lin

- **ARPES**

S. W. Huang and K. Y. Lin

- **FMR**

Y. T. Fanchiang

- **Spin pumping**

Y. T. Fanchiang

- **Discussion & suggestion**

Dr. C. N. Wu, Dr. Y. K. Liu,
and Y. H. Lin

Outline

- **Introduction**

- 3D topological insulators (TIs)
- Breaking time reversal symmetry by magnetic proximity effect (MPE)
 - Demand for a reproducible growth method
- Manipulating the Fermi level (E_F) toward the Dirac point
- Motivation

- **Bi_2Se_3 / Rare earth iron garnet (ReIG)**

- Advantage of ReIGs
 - Yttrium iron garnet (YIG) & thulium iron garnet (TmIG)
- Growth method: Se-buffered low-temperature (SBLT) growth
- Improvement in crystallinities (vs. conventional two-step growth)
- Enhancement of interfacial exchange coupling
 - Observation of anomalous Hall effect (AHE)
 - Large negative shift in H_{res} probed by ferromagnetic resonance (FMR)

Outline

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- Motivation

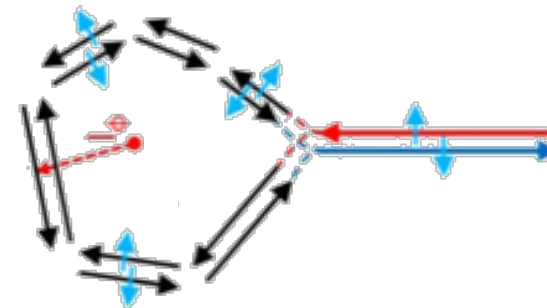
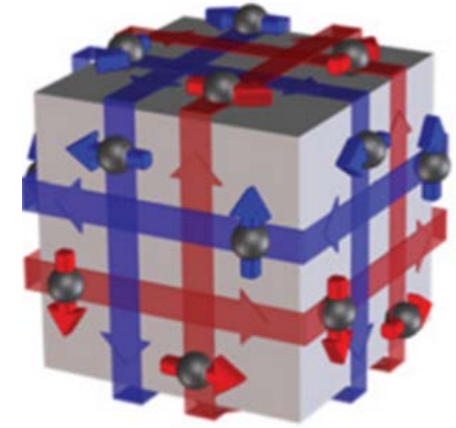
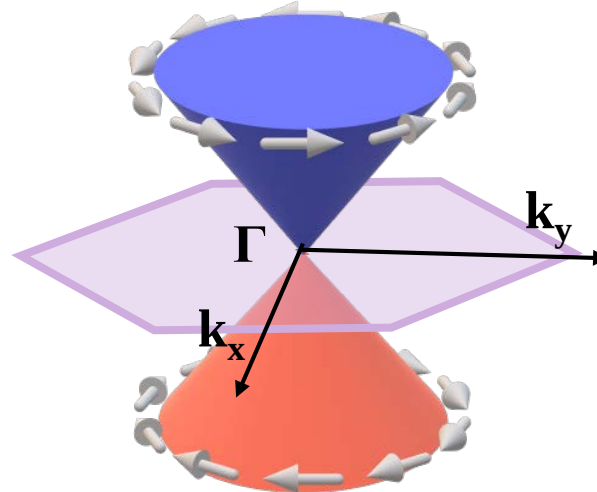
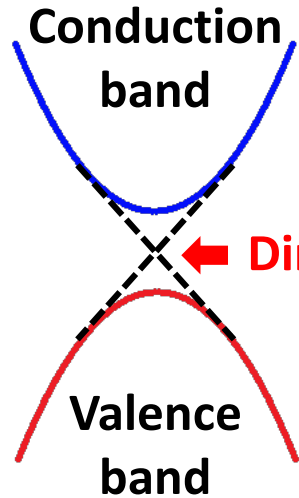
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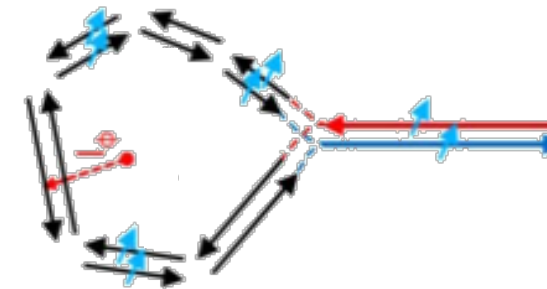
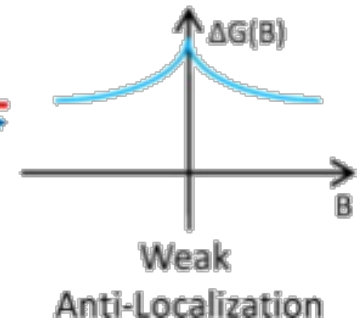
Outline

- **(Bi,Sb)₂Te₃ / α -Al₂O₃ & (Bi,Sb)₂Te₃ / TmIG**
 - Characterization of structural properties
 - Higher-temperature growth of Sb₂Te₃ & (Bi,Sb)₂Te₃
 - Evidences of manipulating E_F toward bulk-insulating features
 - Detection of two conductive transport channels
 - Band structure engineering revealed by ARPES
 - Electronic transport & magnetoresistance analysis
 - Observation of room-temperature AHE
- **Conclusion**

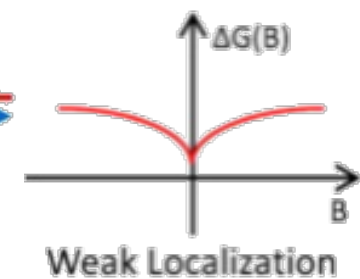
3D topological insulators (TIs)



Spin-momentum locked



No Spin-momentum locking

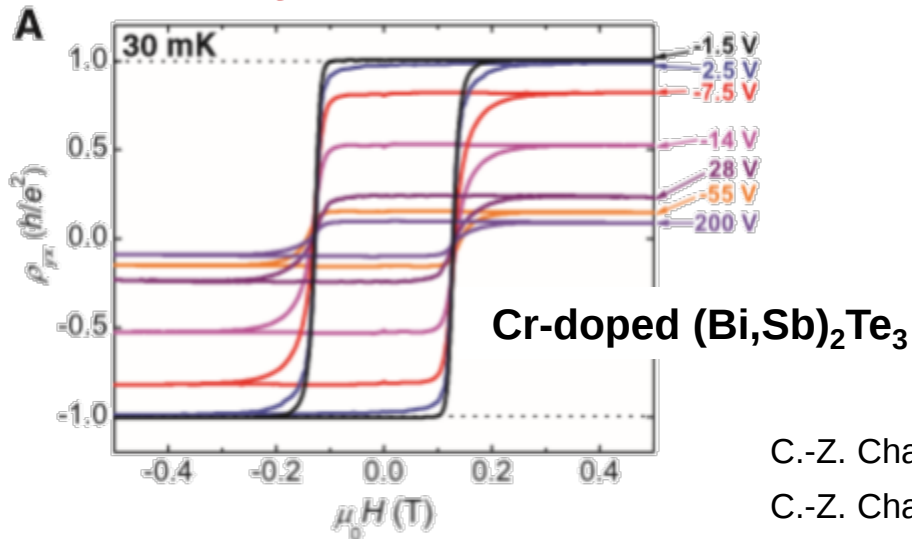


- 3D TIs: Bi_2Se_3 , Bi_2Te_3 , and Sb_2Te_3
- Band inversion induced by strong SOC
- Protected by time-reversal symmetry
- Topological surface states (TSSs)
 - Spin-momentum locking
 - Massless Dirac fermion
- More...
 - High spin-to-charge conversion
 - Weak anti-localization (WAL) effect
 - Forbidden-back-scattering transport

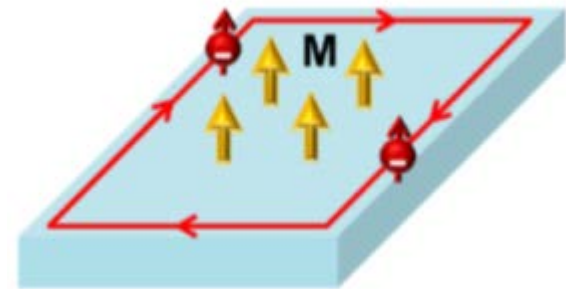
Breaking TRS by MPE

Breaking Time Reversal Symmetry (TRS) in TIs

➡ Quantum anomalous Hall effect (QAHE)



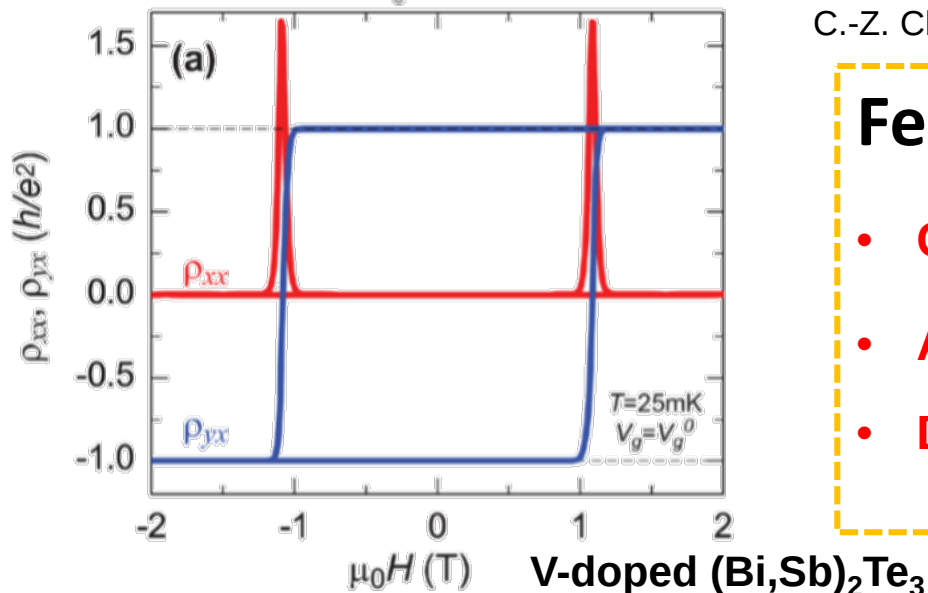
(e) QAHE (2013)



C.-Z. Chang *et al.*, Science **340**(6129), 167-170 (2013).

C.-Z. Chang *et al.*, Nat. Mater. **14**, 473–477 (2015).

C.-Z. Chang *et al.*, J. Phys.: Condens. Matter **28**, 123002 (2016).



Features

- Quantized plateau ($\frac{h}{e^2}$) in ρ_{xy}
- Approaching zero resistivity in ρ_{xx}
- Dissipationless transport

Breaking TRS by MPE

Breaking Time Reversal Symmetry (TRS) in TIs

➡ Quantum anomalous Hall effect (QAHE)

Ways to break TRS in TIs:
Introducing magnetic moments

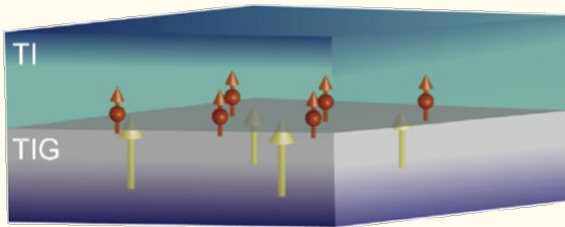
Transition metal doping

Magnetic proximity effect (MPE)

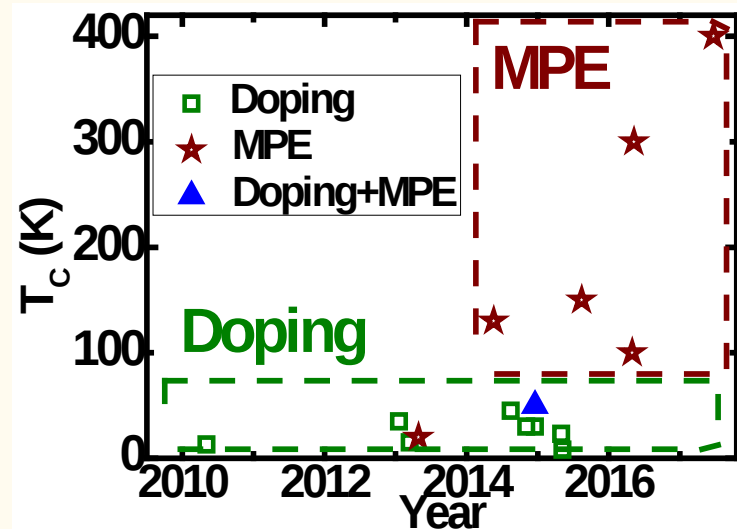
Magnetic proximity effect

Advantages of MPE:

- Higher T_C than that of magnetic doping
- No crystal defects
- Uniform magnetization



C. Tang *et al.*, Sci. Adv. **3** (6), e1700307 (2017).



E

$$= \pm \sqrt{\left(\hbar v_F k_x + \frac{J}{2} M_y \right)^2 + \left(\hbar v_F k_y - \frac{J}{2} M_x \right)^2 + \left(\frac{J}{2} M_z \right)^2}$$

H. Z. Lu *et al.*, Phys. Rev. Lett. **107**, 076801 (2011).

Breaking TRS by MPE

Breaking Time Reversal Symmetry (TRS) in TIs

➡ **Quantum anomalous Hall effect (QAHE)**

Ways to break TRS in TIs:
Introducing magnetic moments

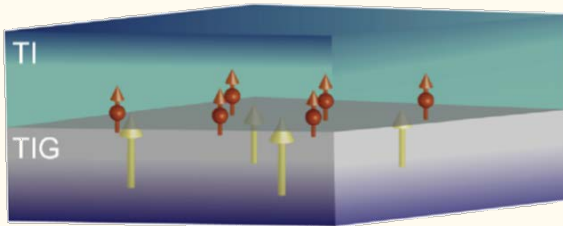
Transition metal doping

Magnetic proximity effect (MPE)

Magnetic proximity effect

Advantages of MPE:

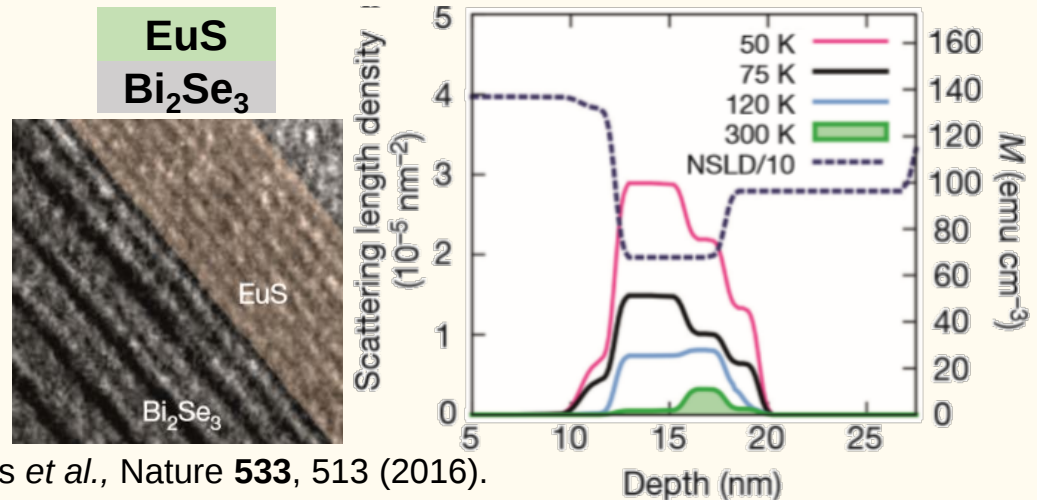
- Higher T_C than that of magnetic doping
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- Uniform magnetization



C. Tang *et al.*, *Sci. Adv.* **3** (6), e1700307 (2017).

TI/MI hetero-structure with a very small lattice mismatch

- Persistence of MPE to room temperature
- Low T_C (~17 K)
- In-plane magnetic anisotropy (IMA) of EuS



F. Katmis *et al.*, *Nature* **533**, 513 (2016).

Breaking TRS by MPE

Breaking Time Reversal Symmetry (TRS) in TIs

➡ **Quantum anomalous Hall effect (QAHE)**

Ways to break TRS in TIs:
Introducing magnetic moments

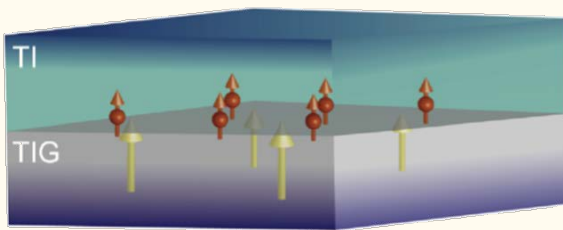
➡ **Transition metal doping**

➡ **Magnetic proximity effect (MPE)**

Magnetic proximity effect

Advantages of MPE:

- **Higher T_C than that of magnetic doping**
- **No crystal defects**
- **Uniform magnetization**



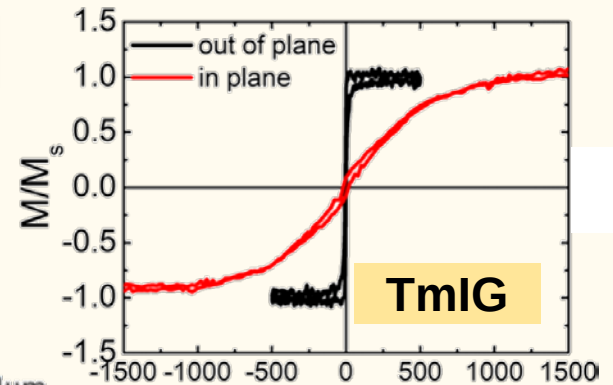
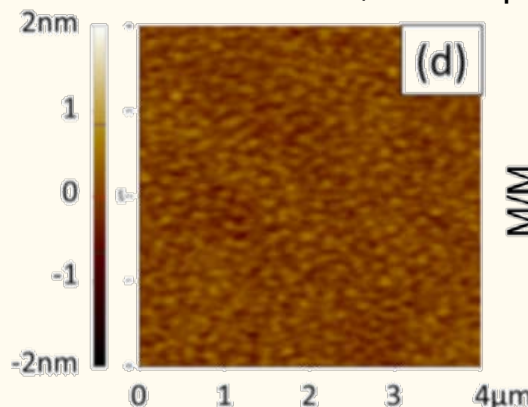
C. Tang *et al.*, *Sci. Adv.* **3** (6), e1700307 (2017).

Tensile-strained $\text{Tm}_3\text{Fe}_5\text{O}_{12}$ (thulium iron garnet, TmIG)

- **Magnetic insulator**
- **High T_C (above 500 K)**
- **Perpendicular magnetic anisotropy (PMA)**

C. N. Wu *et al.*, *AIP Adv.* **8** (5), 055904 (2018).

C. N. Wu *et al.*, *Sci. Rep.* **8** (1), 11087 (2018).



Breaking TRS by MPE

Breaking Time Reversal Symmetry (TRS) in TIs

➡ Quantum anomalous Hall effect (QAHE)

Ways to break TRS in TIs:
Introducing magnetic moments

Transition metal doping

Magnetic proximity effect (MPE)

However,

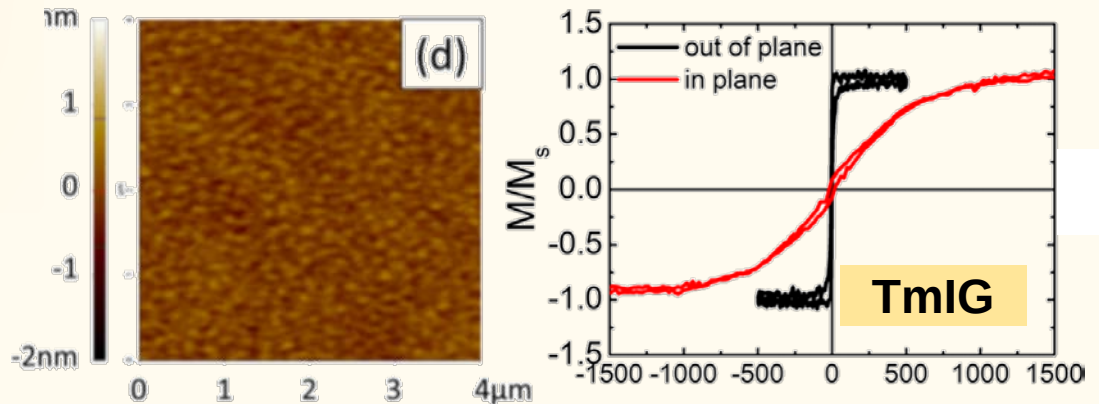
- Complicated surface atomic arrangement
- Huge lattice mismatch with Bi_2Se_3

Tensile-strained $\text{Tm}_3\text{Fe}_5\text{O}_{12}$
(thulium iron garnet, TmIG)

- Magnetic insulator
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- Perpendicular magnetic anisotropy (PMA)

C. N. Wu *et al.*, AIP Adv. **8** (5), 055904 (2018).

C. N. Wu *et al.*, Sci. Rep. **8** (1), 11087 (2018).



Breaking TRS by MPE

Conventional two-step growth

1st step: **Low temp.**

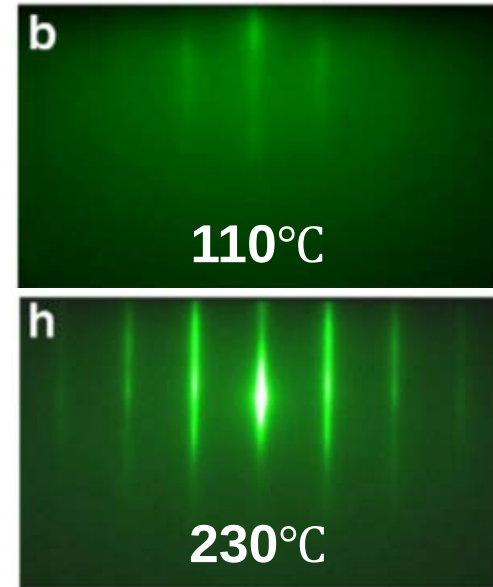
Ordered and smooth initial layer



2nd step: **High temp.**

Atoms with **more kinetic energy**

➡ **Better film quality**



N. Bansal *et al.*, Thin Solid Films **520** (1), 224 (2011).

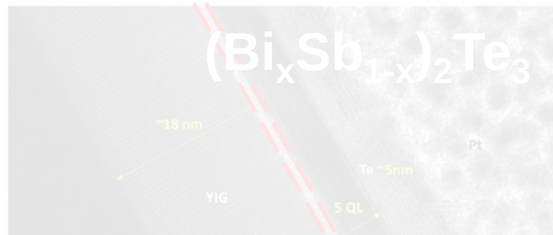
Applied on rare earth iron garnets (ReIGs):

➡ Atoms tend to **bond to the surface dangling bonds first**

Breaking TRS by MPE

Conventional two-step growth leads to:

Interlayer with poor crystallinity



Large variation of T_C of MPE properties



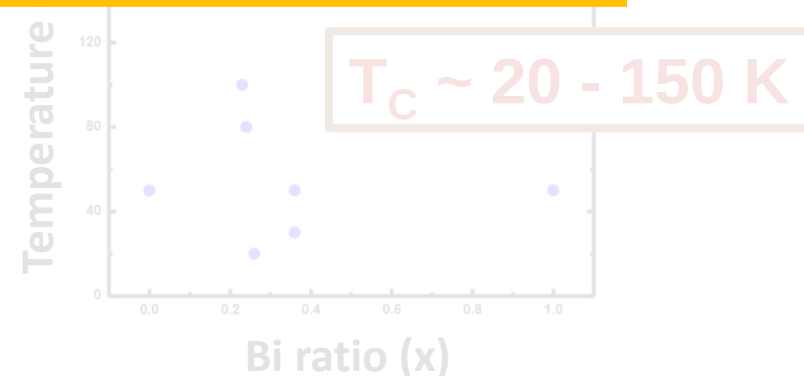
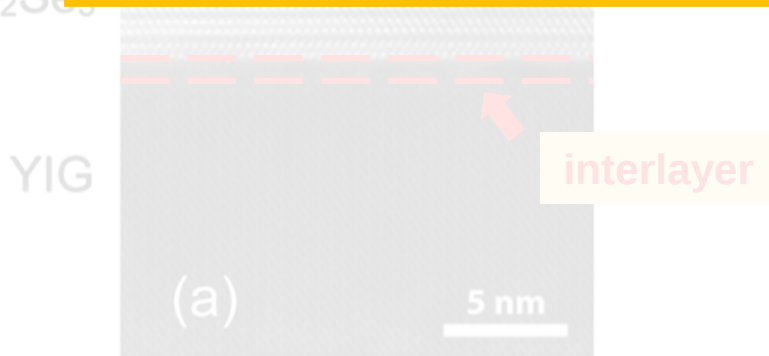
Urgent demand for a **reproducible growth method**

- **Narrowing the variation of film qualities**
- **High-quality interface**
- **Strong exchange coupling**

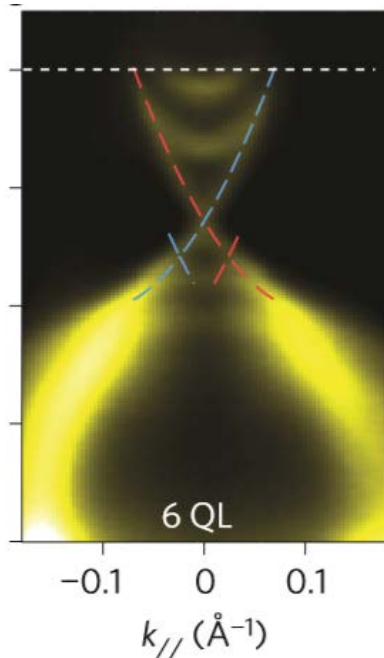
Z. Jia

(2016).

Bi_2Se_3

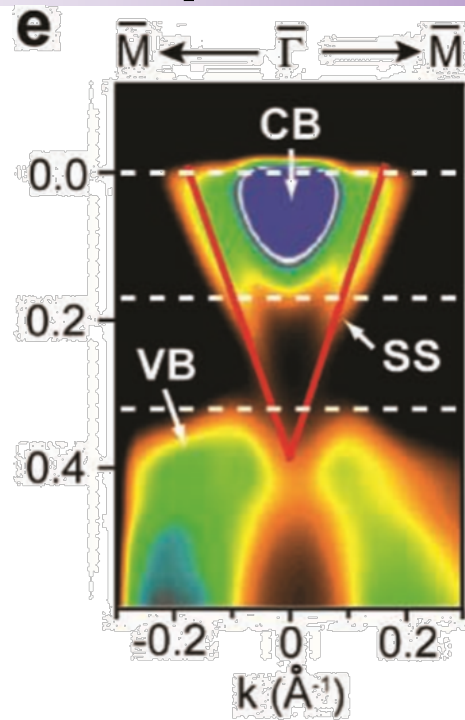


Manipulating E_F toward Dirac point



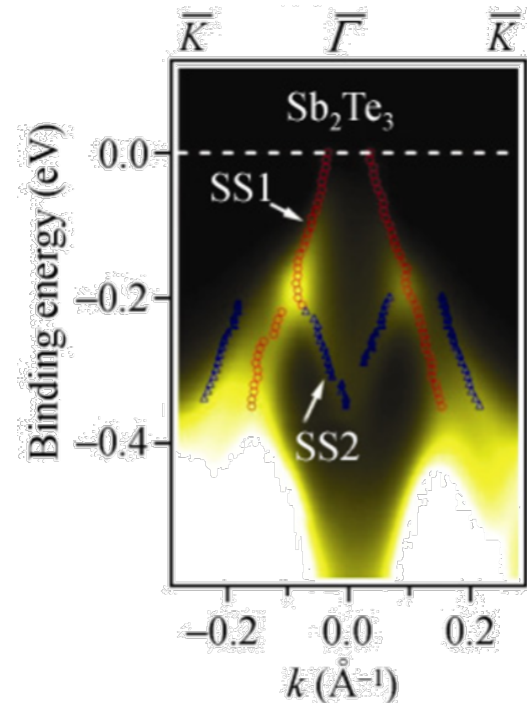
Y. Zhang et al., Nat. Phys. **6**, 584-588 (2010).

Bi₂Se₃



Y.-Y. Li et al., Adv. Mater. **22**, 4002-4007 (2010).

Bi₂Te₃



G. Wang et al., Nano Res. **3**(12), 874-880 (2010).

Sb₂Te₃

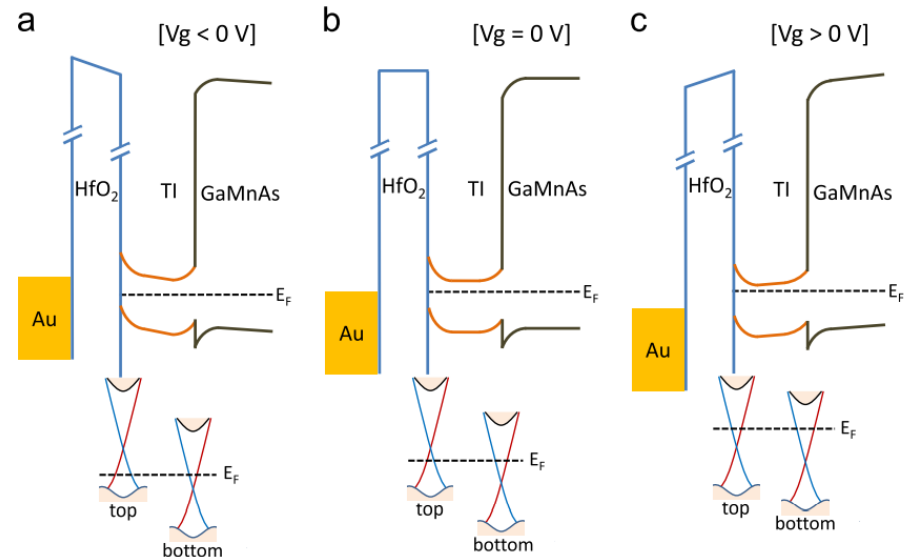
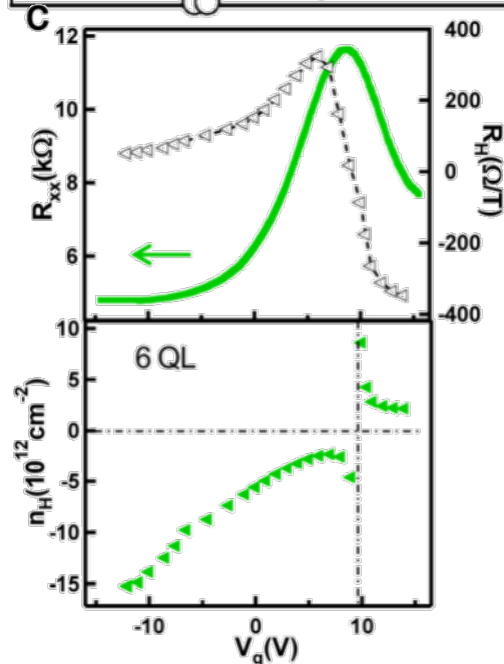
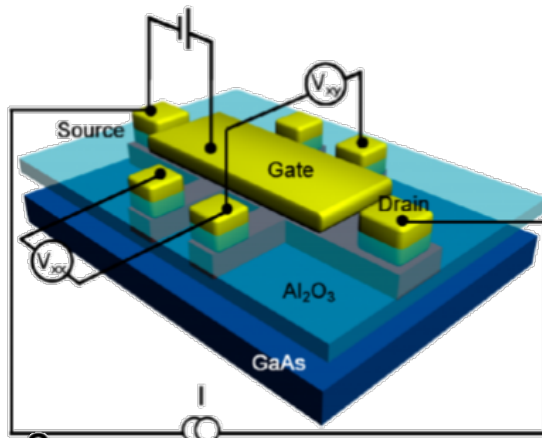
- **Bulk states dominate** the transport properties.
- **TSS features are diluted** by the bulk contribution.
- It is **hard to distinguish the contributions** between the TSS and the bulk.

Manipulating E_F toward Dirac point

Ways to **eliminate/reduce the bulk contribution** in TIs



Electric gating effect



J. S. Lee *et al.*, npj Quantum Mater. **3**, 51 (2018).

M. Lang *et al.*, Nano Lett. **13**, 48–53 (2013).

Electric gating effect

- Tuning E_F by the field effect
- Affecting only one side of the TI
- No modification on the band structure

Manipulating E_F toward Dirac point

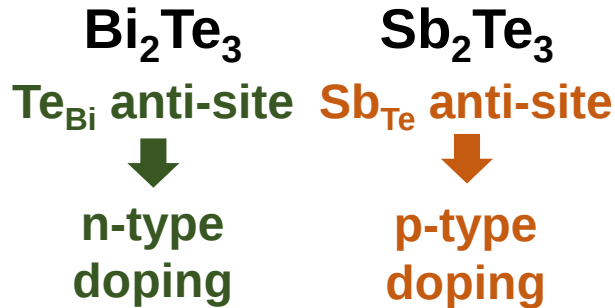
Ways to **eliminate/reduce the bulk contribution** in TIs

Electric gating effect

Chemical doping / alloy

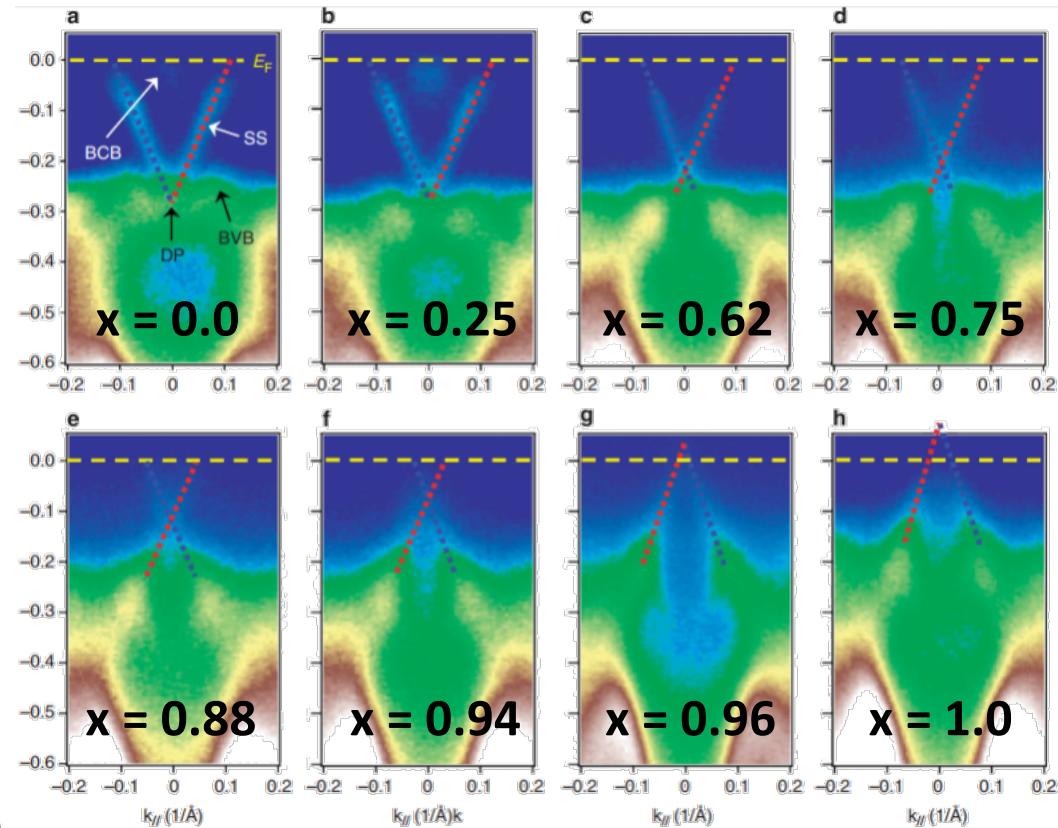
$(\text{Bi,Sb})_2\text{Te}_3$ (BST)

- Tuning the position of the E_F
- Introducing different amounts of defects
- Modifying the band structure of TI



J. Zhang, *et al.*, Nat. Commun. **2**, 574 (2011).

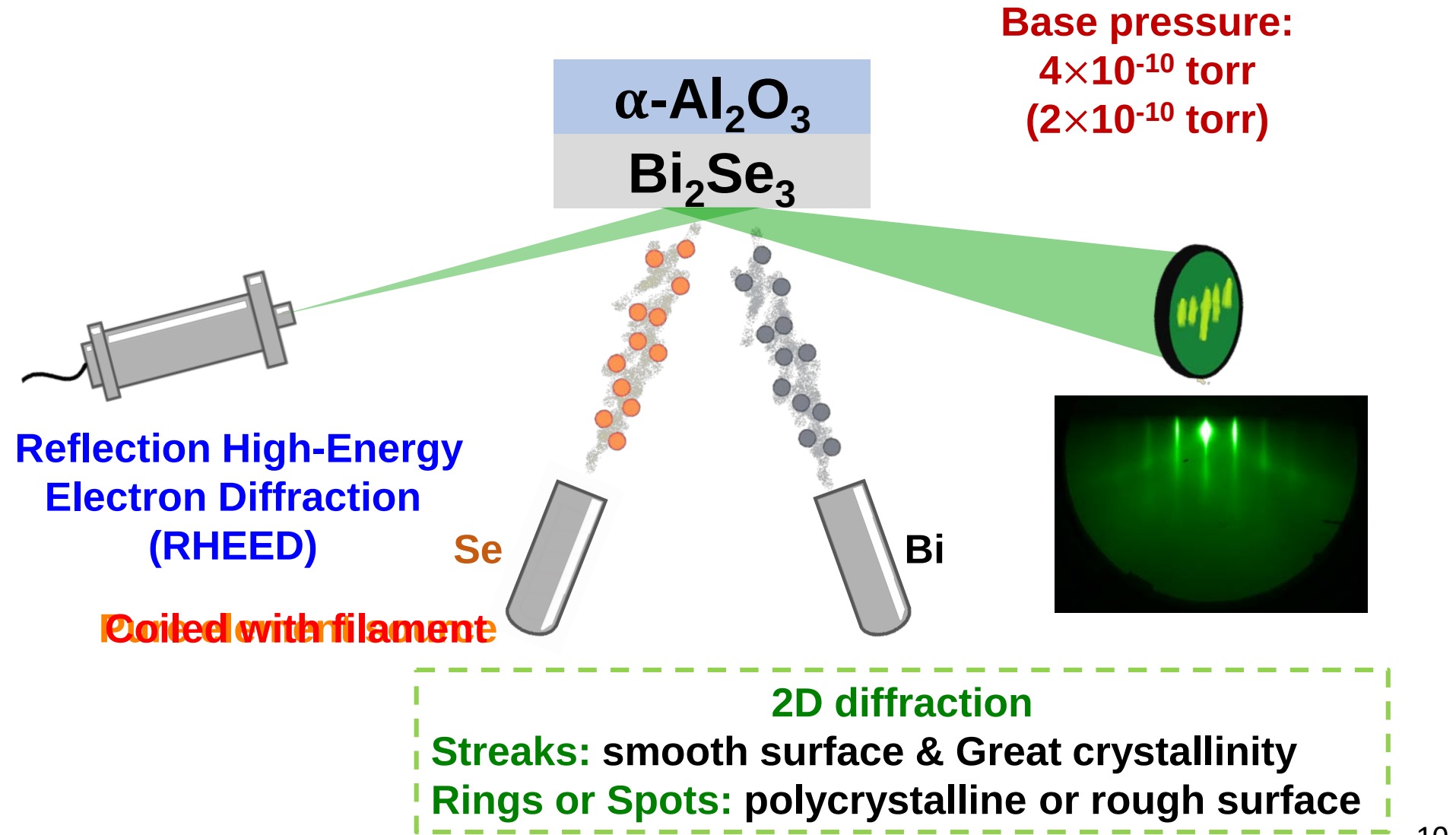
J. M. Zhang *et al.* Phys. Rev. B **88**, 235131 (2013)



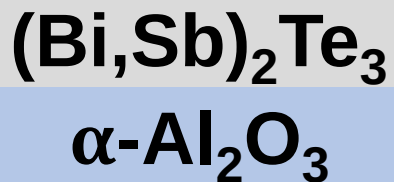
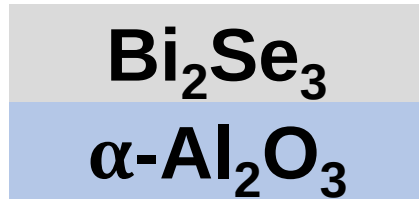
Manipulating the E_F into the bulk band gap ➡ **bulk insulating TI**

Motivation

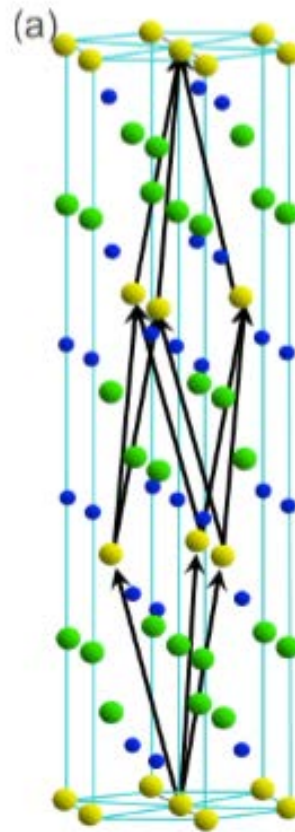
Molecular Beam Epitaxy (MBE)



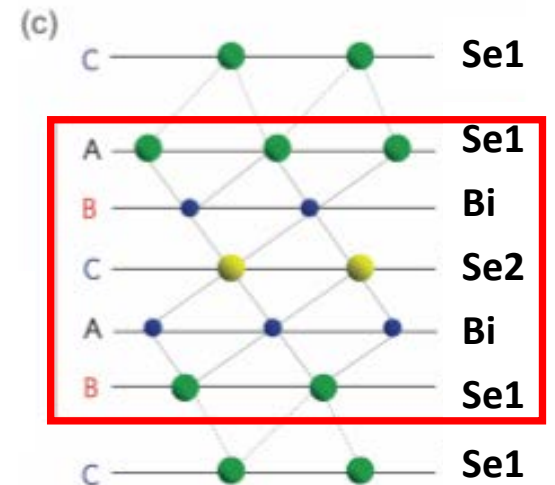
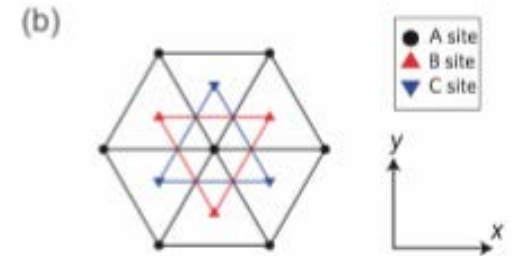
Motivation



- Toward **bulk-insulating feature**
- Exhibition of pure surface state



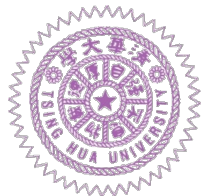
● Bi
● Se1
● Se2



H. Zhang et al., Nat. Phys. 5 (6), 438 (2009).

TmIG Quintuple layer (QL)
(~ 1 nm)

- **Breaking time reversal symmetry**
- Pushing the T_c up to room temperature



I: $\text{Bi}_2\text{Se}_3/\text{TmIG}$ & $\text{Bi}_2\text{Se}_3/\text{YIG}$

- Bi_2Se_3 / Rare earth iron garnet (ReIG)
 - Advantage of ReIGs
 - Growth method: **Se-buffered low-temperature (SBLT) growth**
 - Improvement in crystallinities (vs. **conventional two-step growth**)
 - Enhancement of interfacial exchange coupling

RelG substrate preparation

- Thulium iron garnet ($\text{Tm}_3\text{Fe}_5\text{O}_{12}$, **TmIG**)
 - **Perpendicular magnetic anisotropy (PMA)** (induced by tensile strain)
- Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, **YIG**)
 - **In-plane magnetic anisotropy (IMA)** and low damping constant

Sputter

Without
chemical
cleaning

MBE

a)

Outgassing

150 °C 15 min

Growth temp.

Garnet structure

Outgassing

$\text{Bi}_2\text{Se}_3/\text{YIG}$

at 500°C

H. Wang *et al.*, Phys. Rev. Lett. **117**, 076601 (2016).

$(\text{Bi,Sb})_2\text{Te}_3/\text{YIG}$

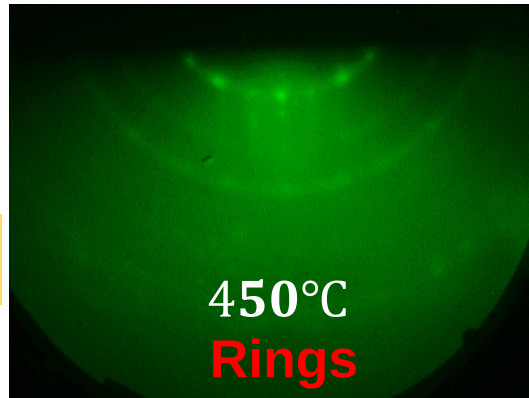
at 600°C, 1hr

Z. Jiang *et al.*, AIP Adv. **6**, 055809 (2016).

$(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$

at 600°C, 1hr

C. Tang *et al.*, Sci. Adv. **3** (6), e1700307 (2017).



RHEED patterns:

350°C ↑ **ring (polycrystalline)**

Residual gas analysis:

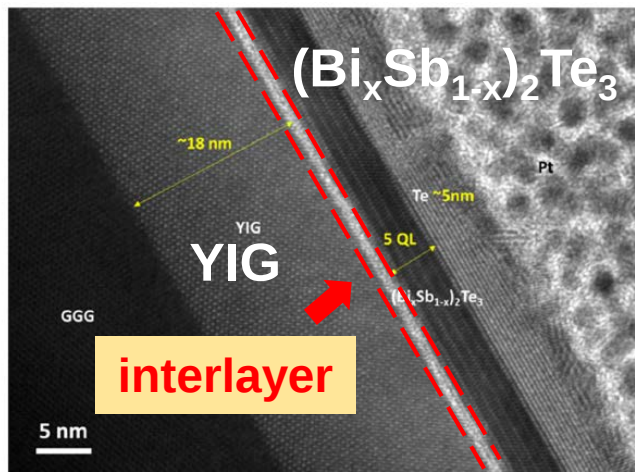
300°C ↑ **C_xO_x compounds**

Demand for a reproducible growth method

However,

- **Complicated surface** atomic arrangement
- **Huge lattice mismatch** with Bi_2Se_3

Interlayer with poor crystallinity



Z. Jiang *et al.*, AIP Adv. **6** (5), 055809 (2016).

Conventional two-step growth

1st step: **Low temp.**

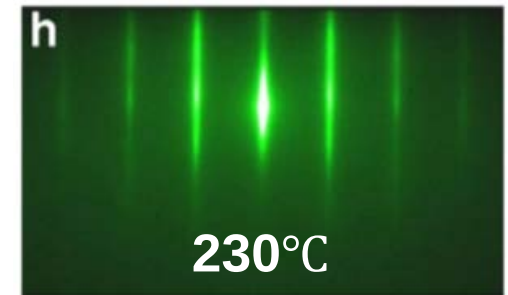
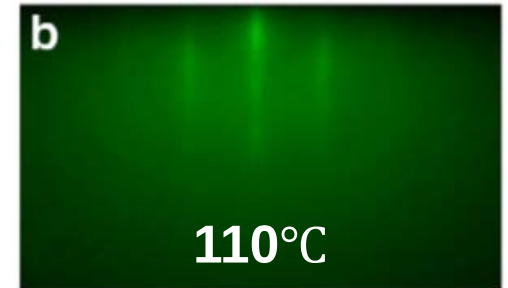
Ordered and smooth initial layer



2nd step: **High temp.**

Atoms with **more kinetic energy**

➡ **Better film quality**



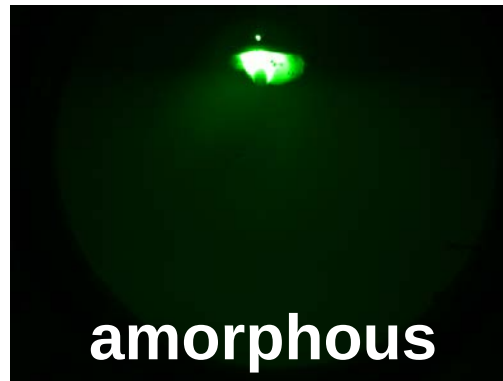
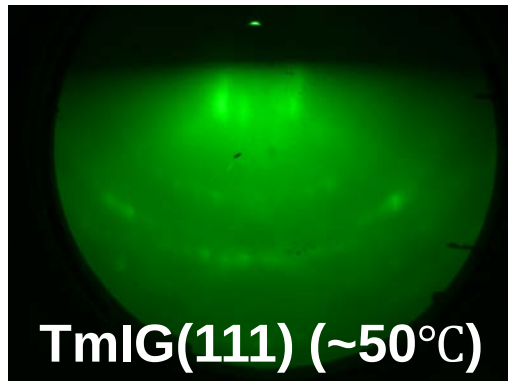
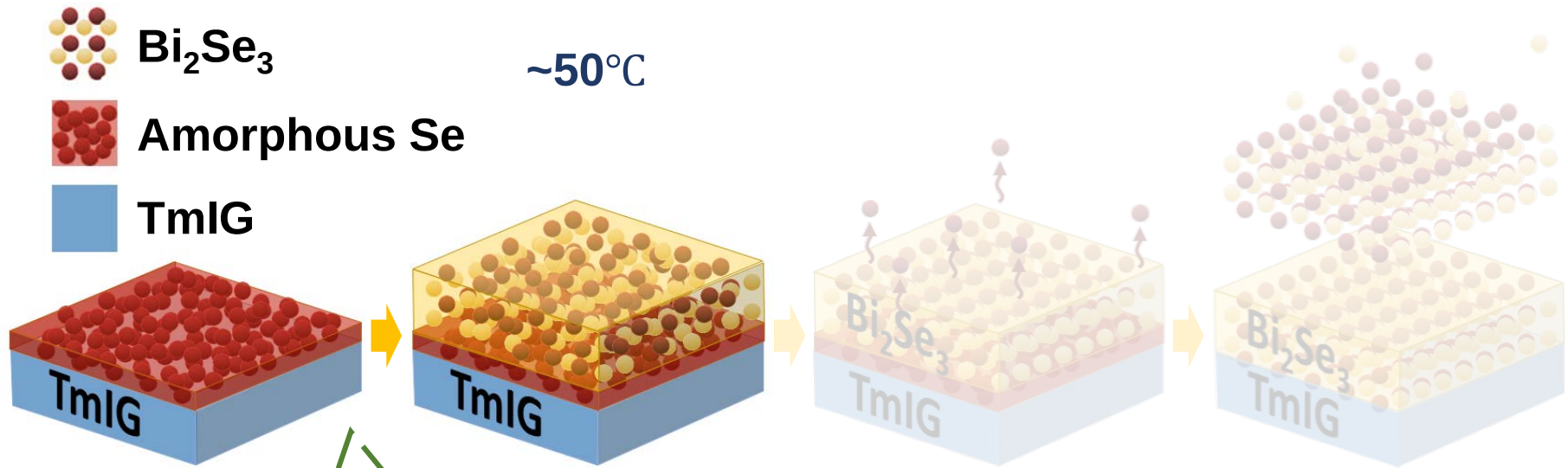
N. Bansal *et al.*, Thin Solid Films **520** (1), 224 (2011).

Urgent demand for a reproducible growth method

- **Narrowing the variation of film qualities**
- **High-quality interface**
- **Strong exchange coupling**

The SBLT growth

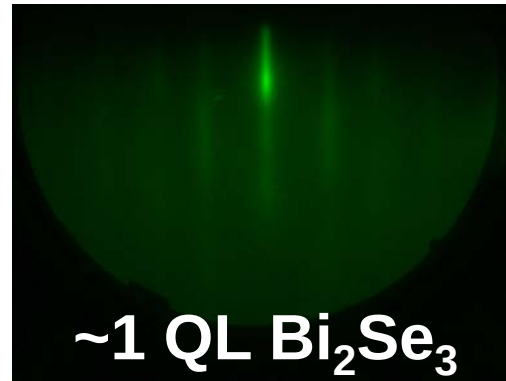
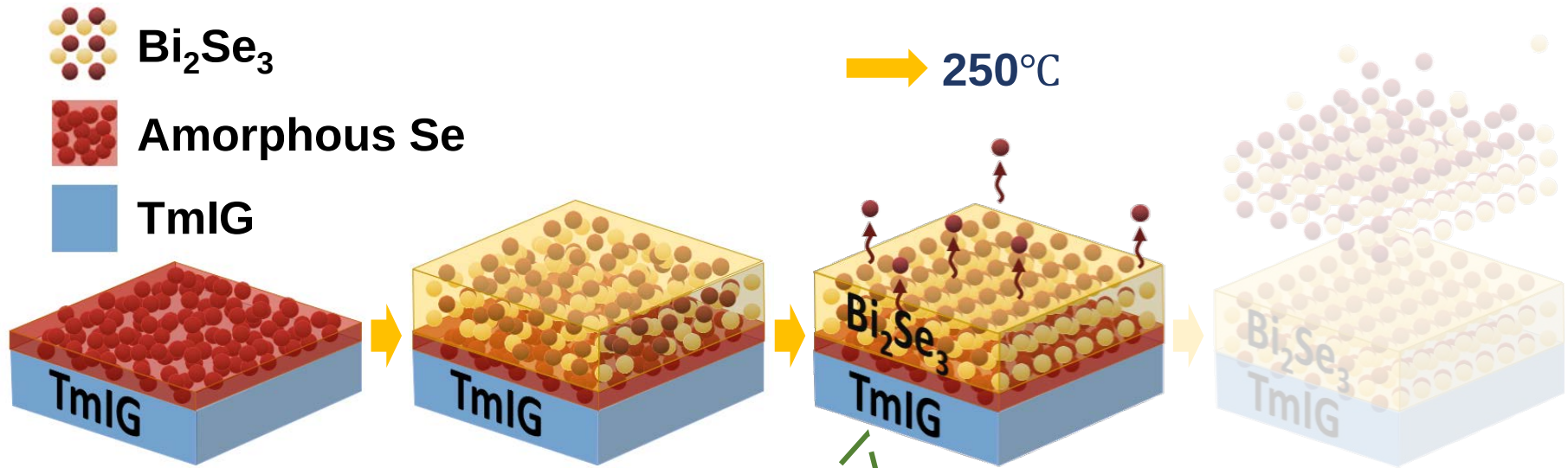
The Se-buffered low-temperature (SBLT) growth:



The substrate was covered by a layer of **amorphous Se** and **$\sim 1 \text{ nm Bi}_x\text{Se}_{1-x}$** .

The SBLT growth

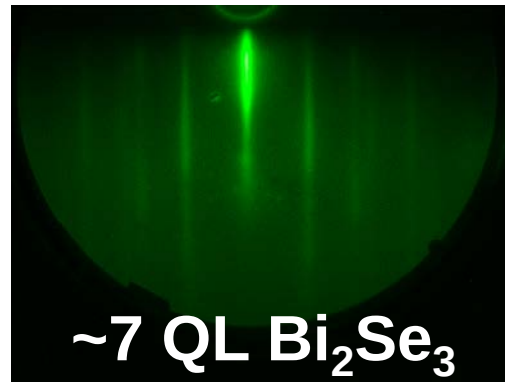
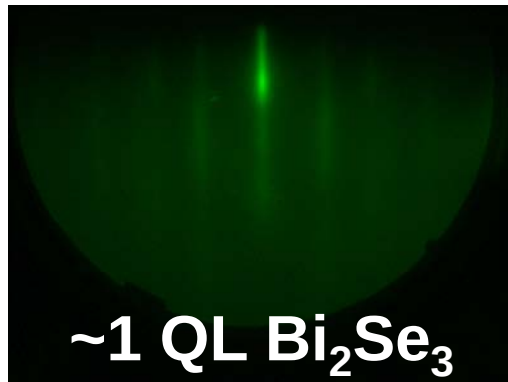
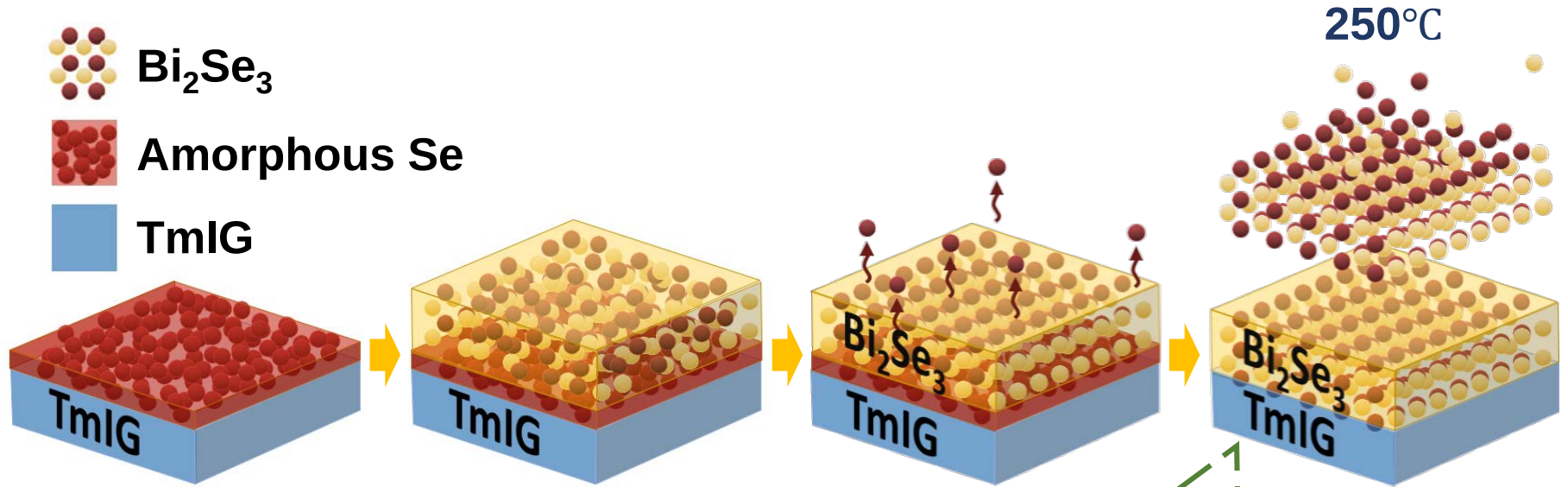
The Se-buffered low-temperature (SBLT) growth:



The **high-quality Bi_2Se_3 at the 1st QL** serves as a **great template** for the further Bi_2Se_3 growth.

The SBLT growth

The Se-buffered low-temperature (SBLT) growth:



Sharper and brighter RHEED patterns were obtained in thicker Bi_2Se_3 films.

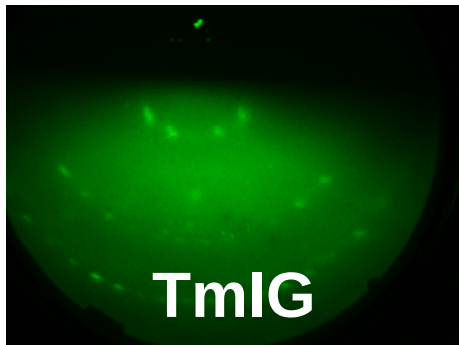
Comparison of RHEED patterns

Spotty ring feature
→ poly crystalline

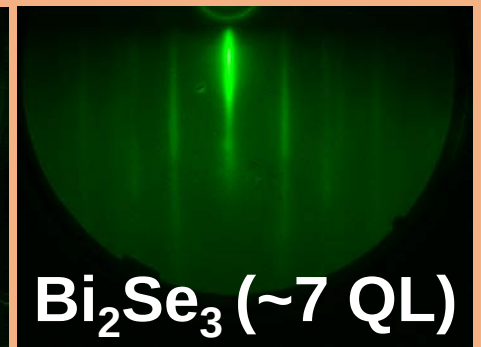
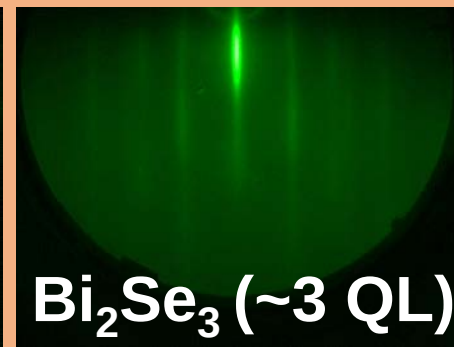
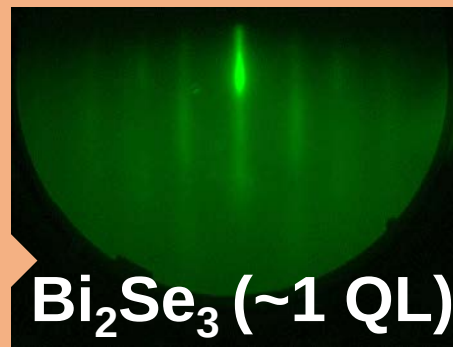
Grain growth,
forming 2D surface

Reaching a good-
quality surface

Two-step growth



SBLT growth

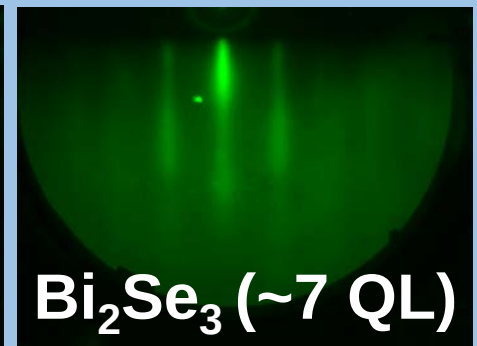


Line feature
→ better crystallinity
and smooth surface

More distinct RHEED patterns
→ achieving excellent
crystallinity of thin films

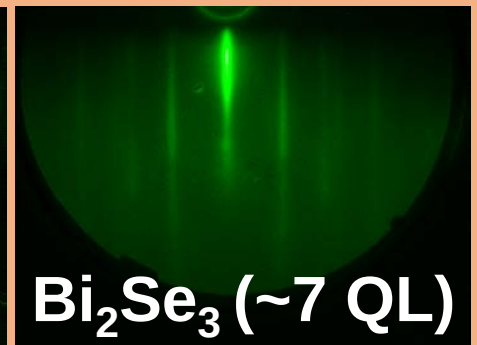
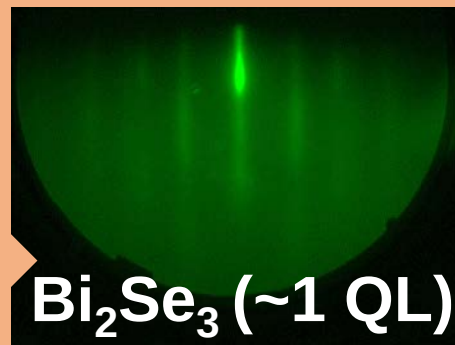
Comparison of RHEED patterns

Two-step growth

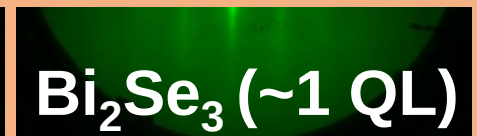
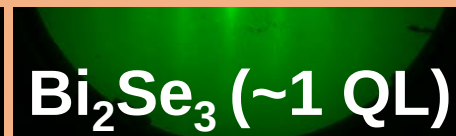
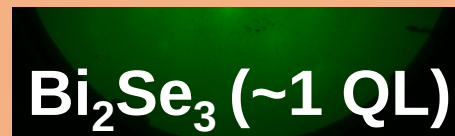


TmIG

SBLT growth



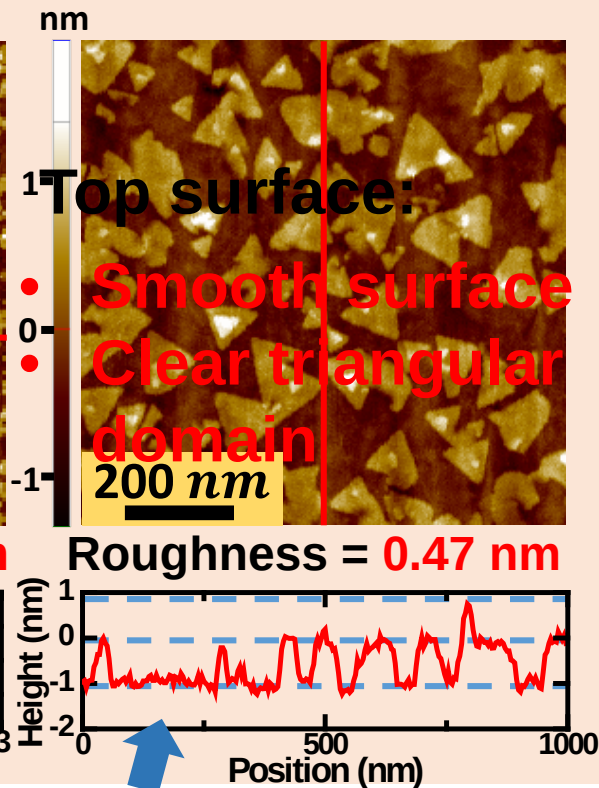
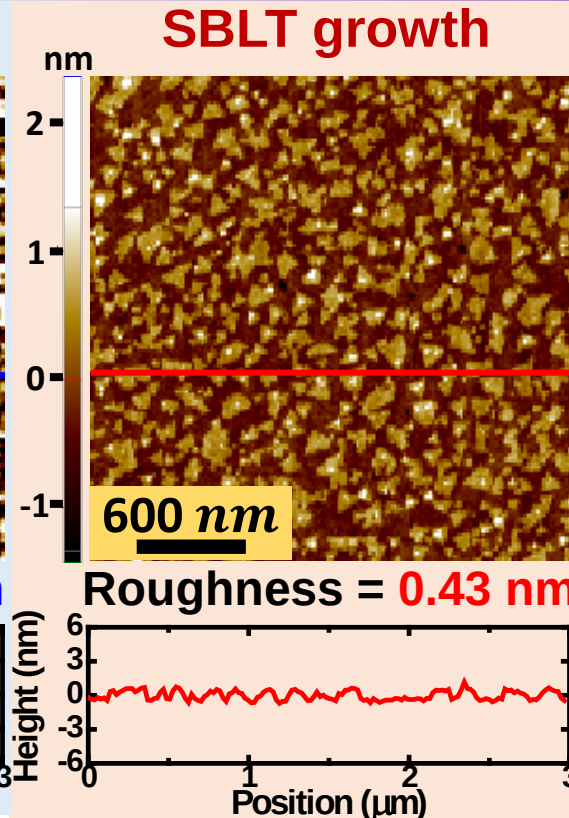
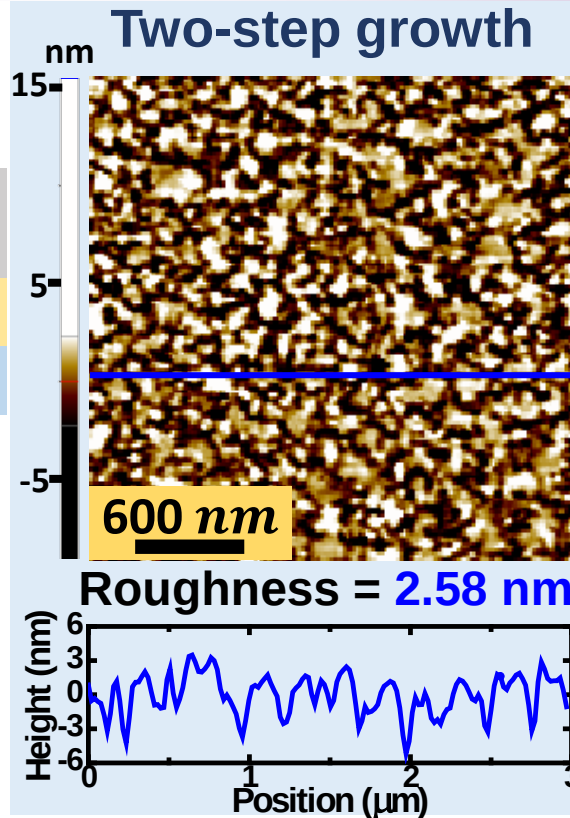
YIG



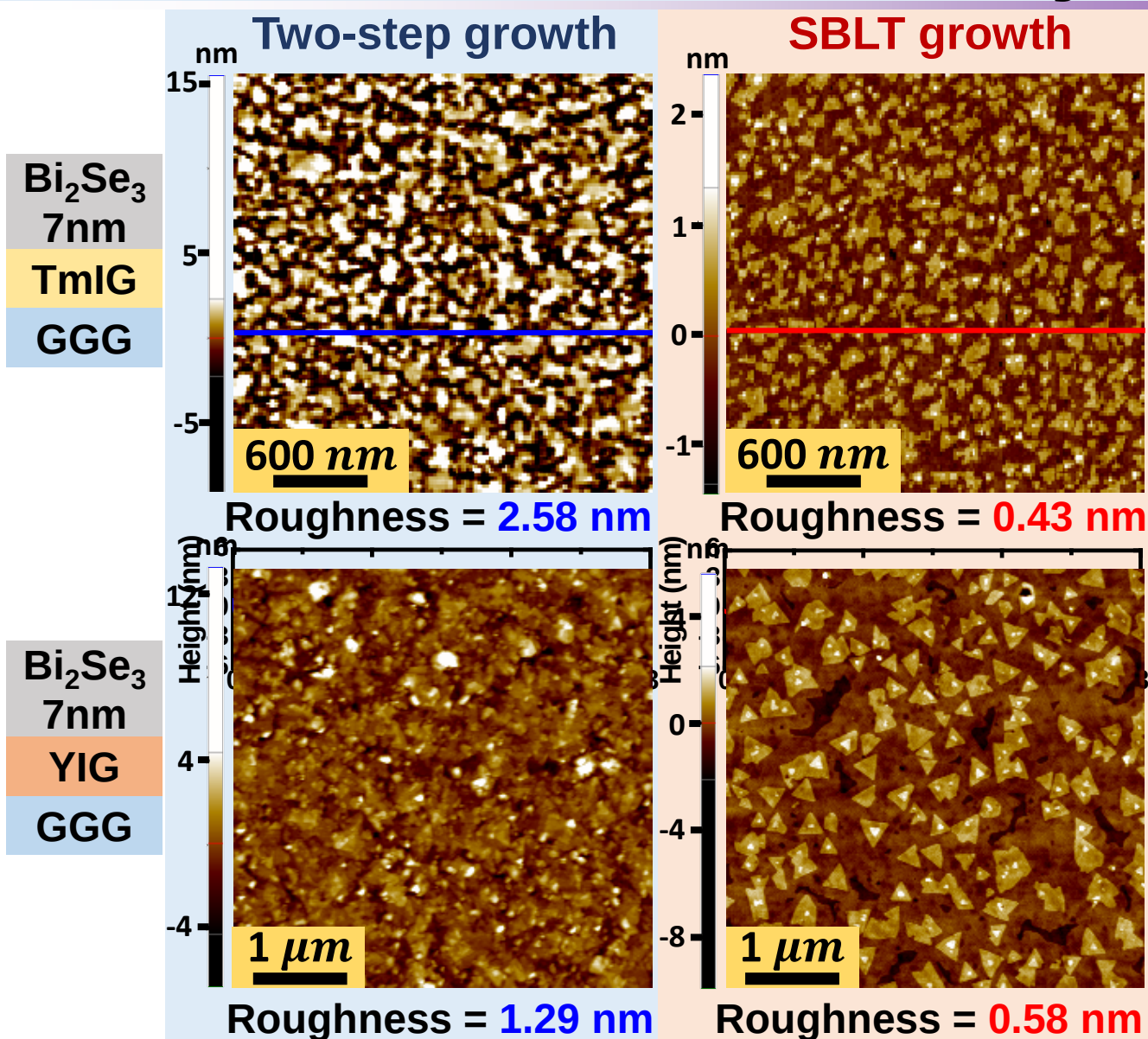
It works on Bi₂Se₃/YIG !

Structural analyses

Bi₂Se₃
7nm
TmIG
GGG

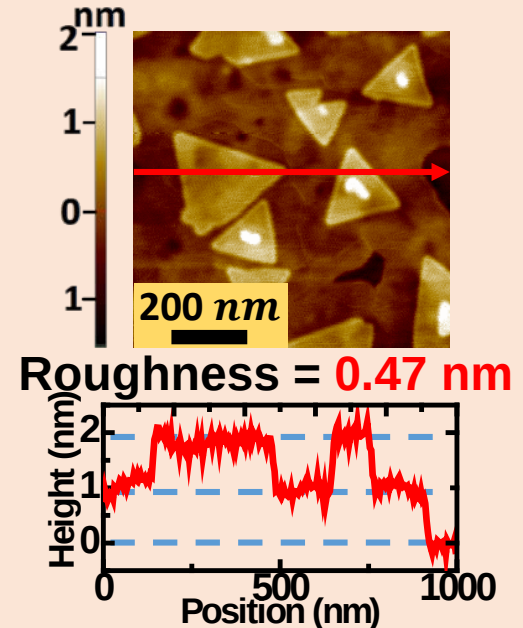


Structural analyses



Top surface:

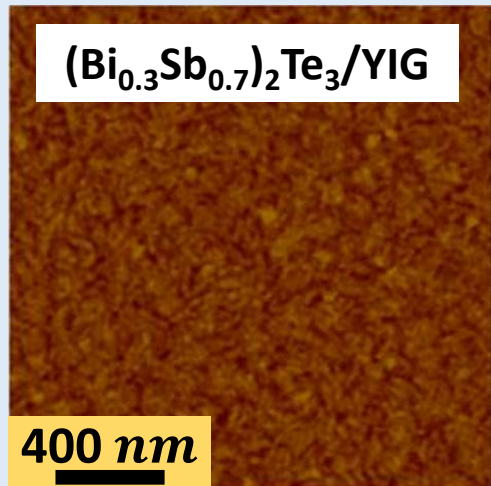
- Smooth surface
- Clear triangular domain



Structural analyses

Two-step growth

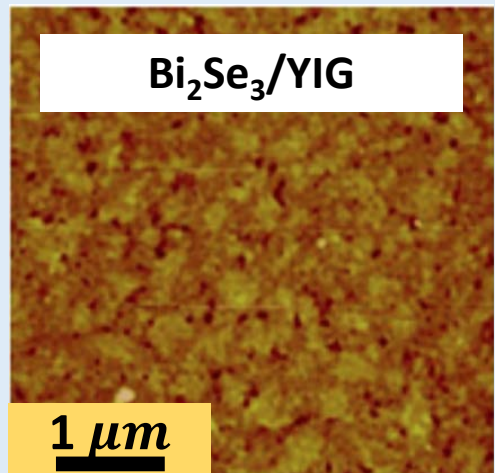
Bi₂Se₃
7nm
TmIG
GGG



Roughness = 0.77 nm

C. Tang *et al.*, Sci. Adv. 4, eaas8660 (2018).

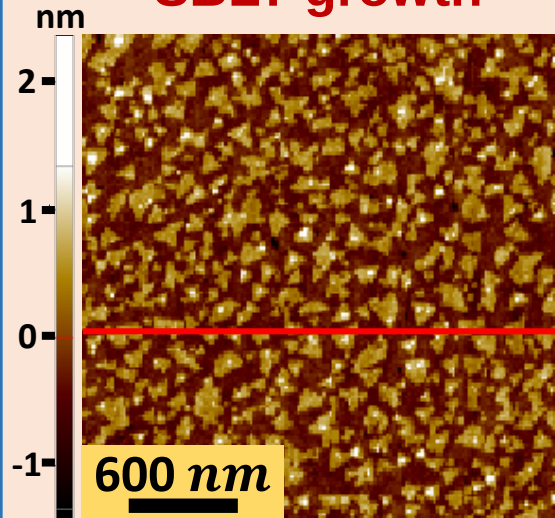
Bi₂Se₃
7nm
YIG
GGG



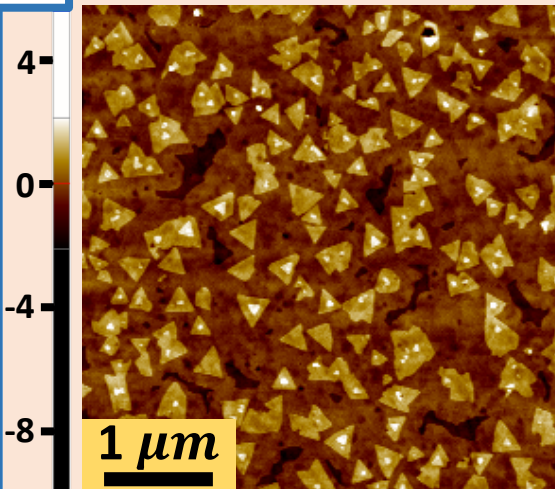
Roughness = 0.71 nm

H. Wang *et al.*, Phys. Rev. Lett. 117 (7), 076601 (2016).

SBLT growth



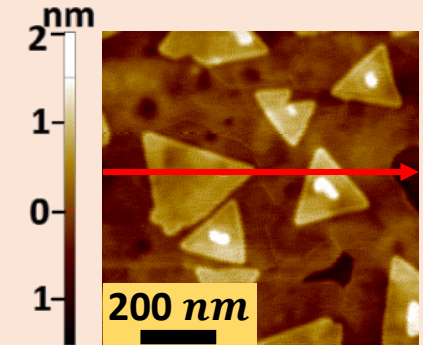
Roughness = 0.43 nm



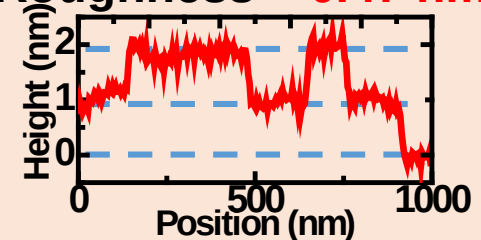
Roughness = 0.58 nm

Top surface:

- Smooth surface
- Clear triangular domain



Roughness = 0.47 nm



Structural analyses

HRTEM images

Two-step growth

Bi_2Se_3

YIG

Bi_2Se_3 (~1 QL)

5 nm

SBLT growth

Bi_2Se_3

TmIG

5 nm

Cs-corrected STEM images

0.5 nm

0.5 nm

Bi_2Se_3

TmIG

Interface:

- ~1nm amorphous interlayer

Films:

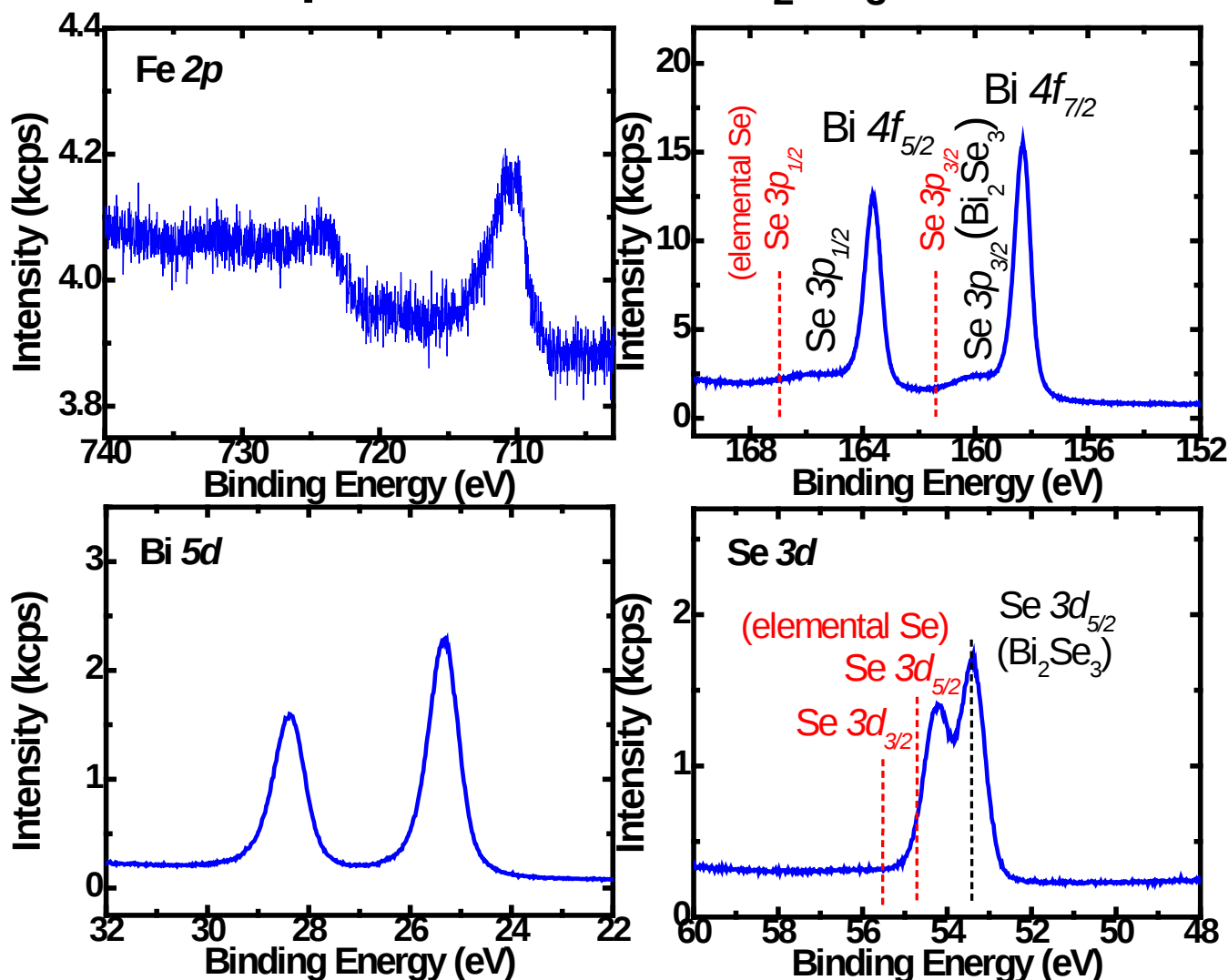
- Clear atomic structures

Interface:

- Se buffer layer evaporated
- Visible atoms in the 1st QL

Interfacial analyses

XPS spectra of 4 nm Bi_2Se_3 on TmIG



Bi₂Se₃ 4 nm
TmIG
GGG

No elemental Se was detected at the interface!

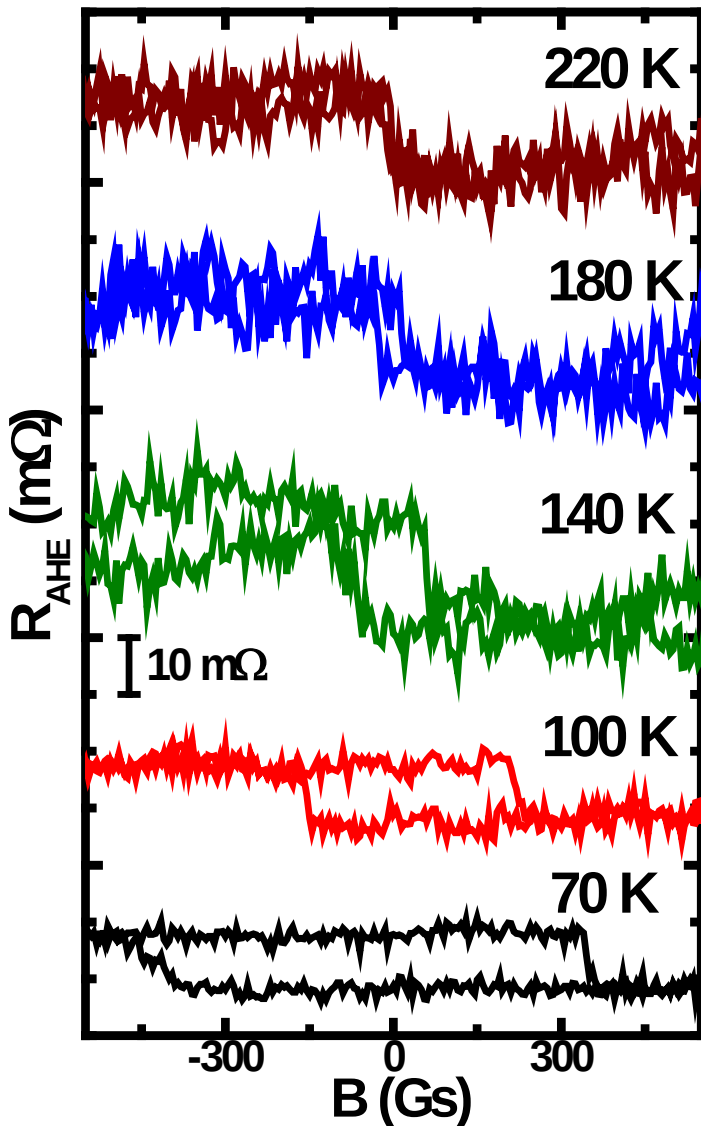
Observation of AHE

Bi₂Se₃

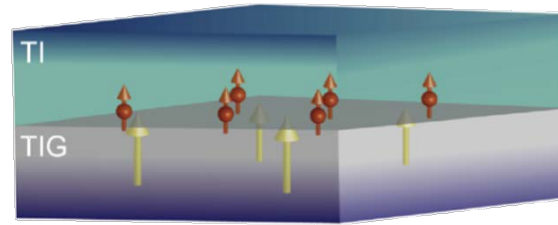
TmIG

GGG

**Anomalous Hall
effect (AHE) loops**



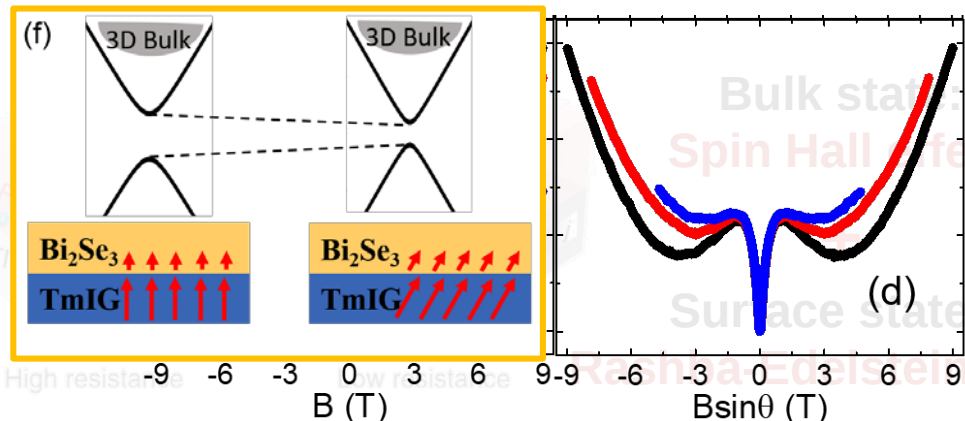
Magnetic proximity effect (MPE):



**Magnetization of
the bottom
topological surface
state (TSS)**

C. Tang et al., Sci. Adv. **3** (6), e1700307 (2017).

**Spin current effect has been precluded
in our other work**

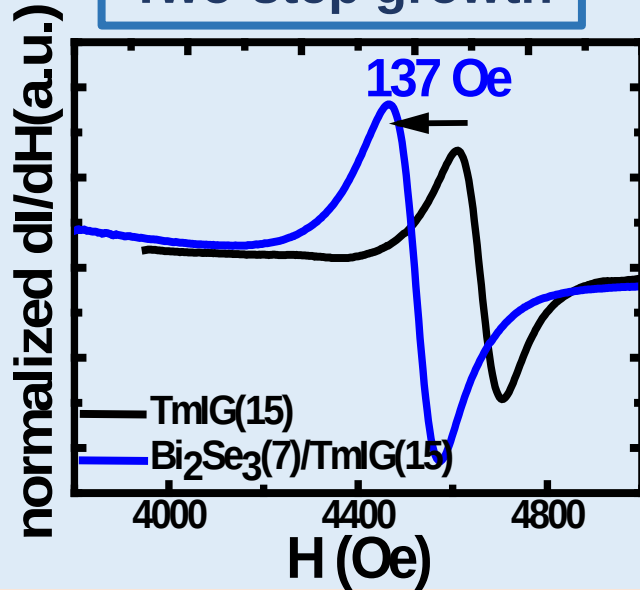


S. R. Yang et al., arXiv: 1811.00689 (2018).
(Accepted by Phys. Rev. B)

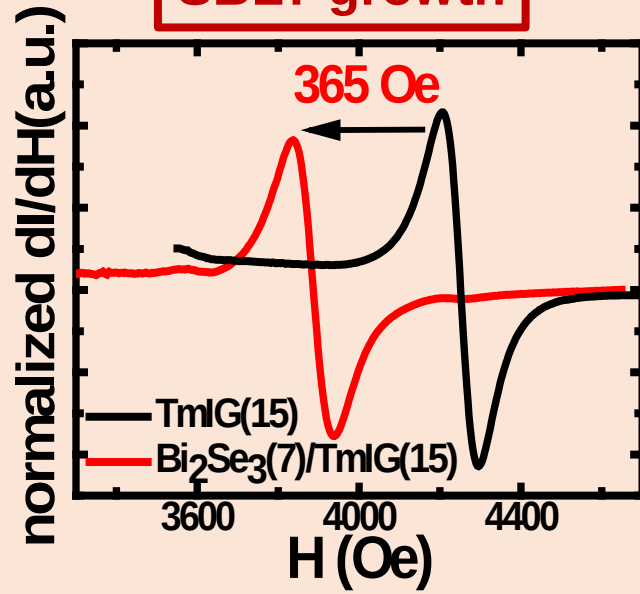
Enhanced exchange coupling at the interface!

Enhanced interfacial exchange coupling

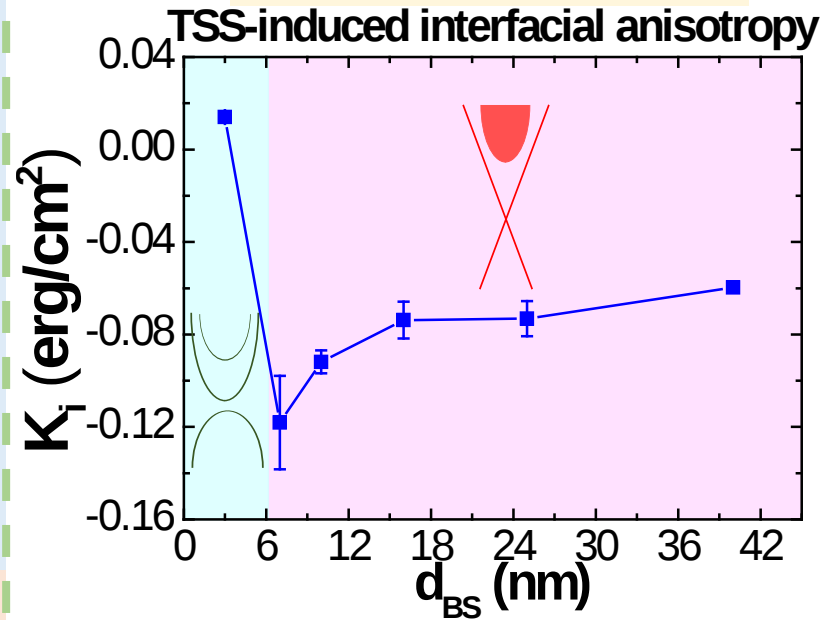
Two-step growth



SBLT growth



Our previous work



Ferromagnetic resonance (FMR)



Spin dynamics at the **interface**

Y. T. Fanchiang et al., Nat. Commun. **9**, 223 (2018)

Bi_2Se_3 grown on TmIG



Negative shift in H_{res} of TmIG



Enhancement of **IMA** at the interface



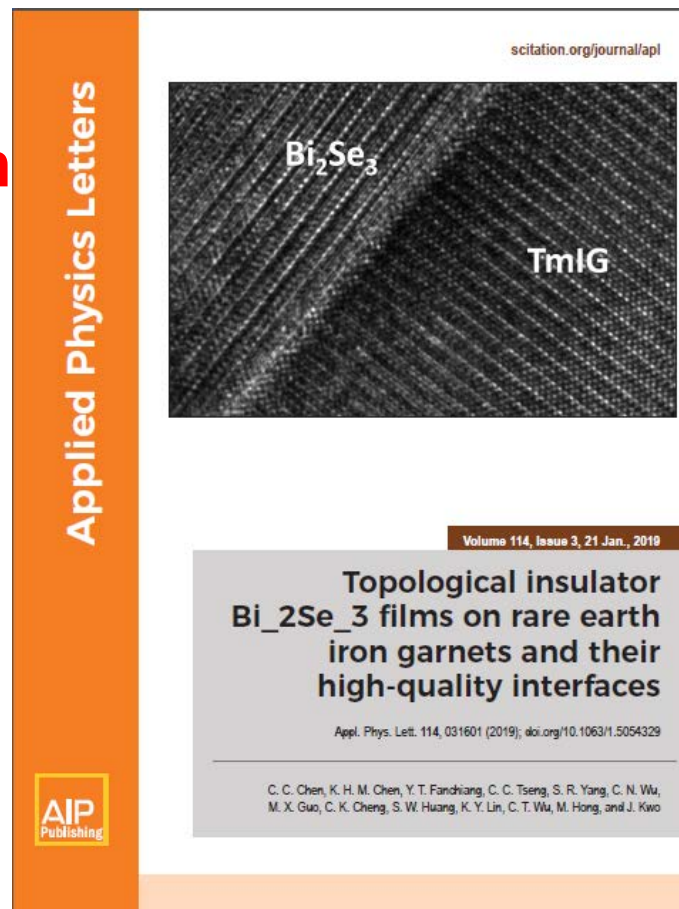
Stronger interfacial exchange coupling !

Summary I

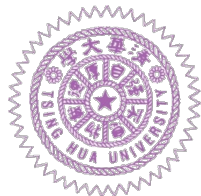
Our **SBLT growth** attained:

- Bright and distinct RHEED at the 1st QL
- Smoother surface and sharp triangular domains
- High-quality interface
- Observation of AHE
- Larger shift in H_{res}

Enhance



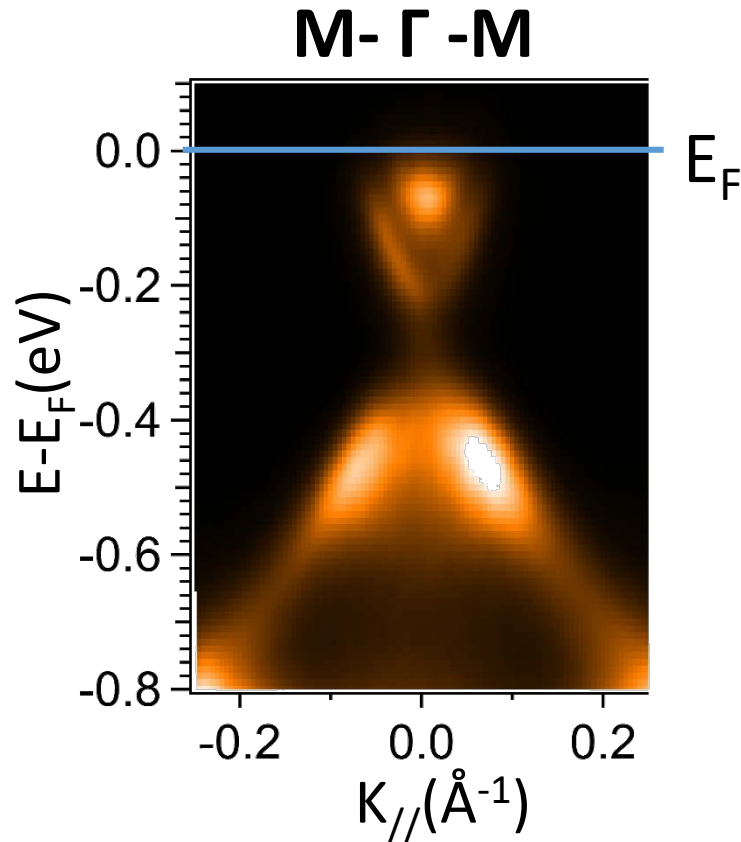
C. C. Chen *et al.*, Appl. Phys. Lett. **114**, 031601 (2019).
(Featured, cover story)



II: $(\text{Bi,Sb})_2\text{Te}_3/\alpha\text{-Al}_2\text{O}_3$ & $(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$

- $(\text{Bi,Sb})_2\text{Te}_3 / \alpha\text{-Al}_2\text{O}_3$ & $(\text{Bi,Sb})_2\text{Te}_3 / \text{TmIG}$
 - Characterization of structural properties
 - Evidences of **manipulating E_F** toward **bulk-insulating features**
 - Electronic transport & magnetoresistance analysis

Manipulating E_F toward Dirac point



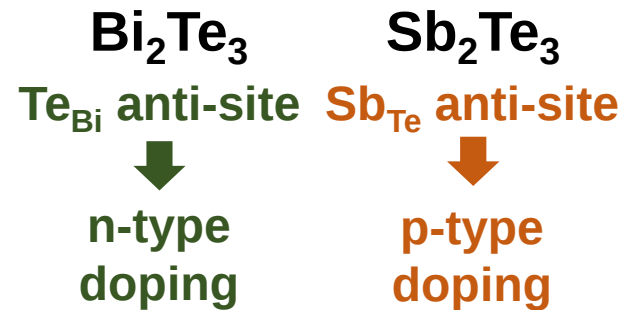
Bi₂Se₃ (our work)

Bulk conduction band
+
Surface states

- Bulk states dominate the transport properties.
- It is hard to distinguish the contributions between the TSS and the bulk.

Ways to eliminate/reduce the bulk contribution in TIs: (Bi,Sb)₂Te₃

- Tuning the position of the E_F
- Introducing different amounts of defects
- Modifying the band structure of TI

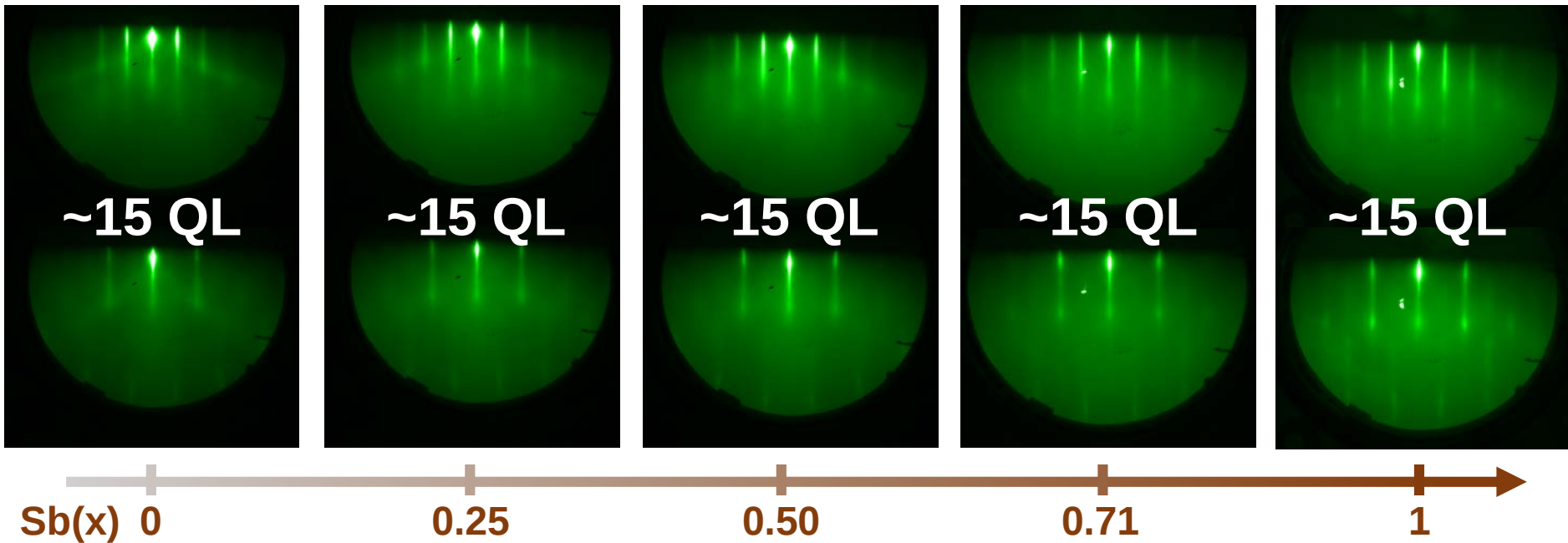


J. M. Zhang *et al.* Phys. Rev. B **88**, 235131 (2013)

Manipulating the E_F into the bulk band gap

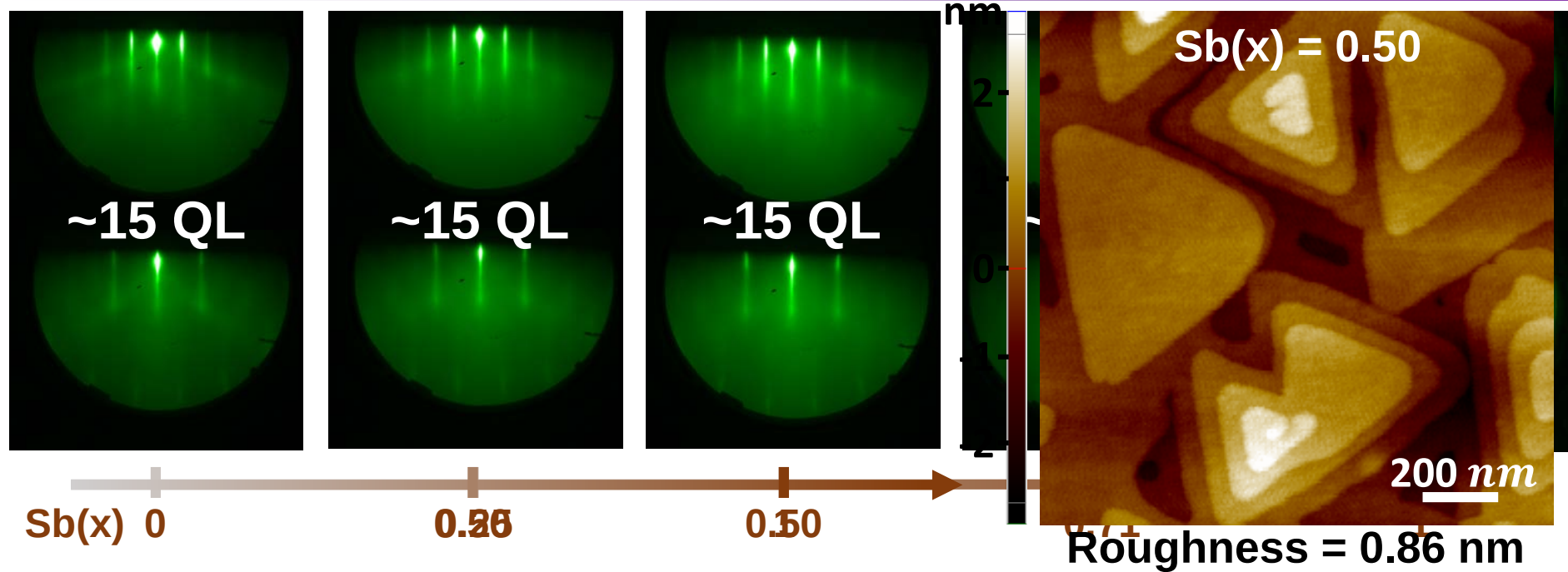
bulk insulating TI

Excellent crystallinities of BST films

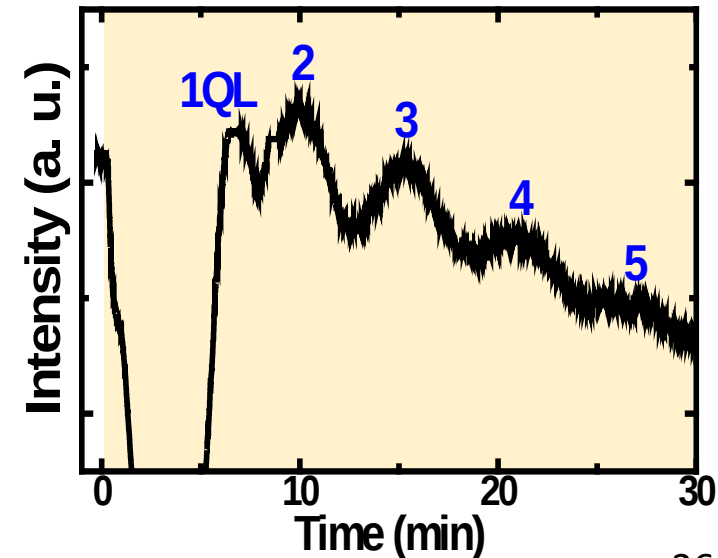


- **Streaky RHEED patterns** from the **very first quintuple layer** (QL) to ~15 QL grown by **MBE**

Excellent crystallinities of BST films

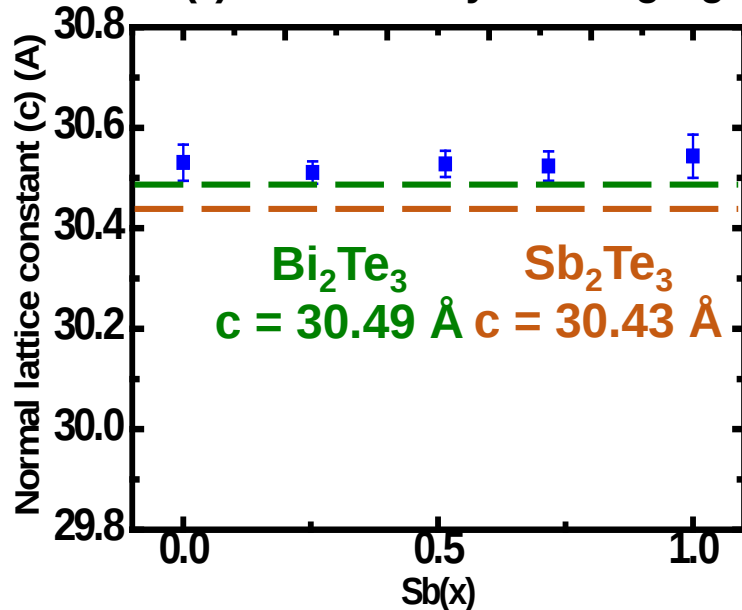
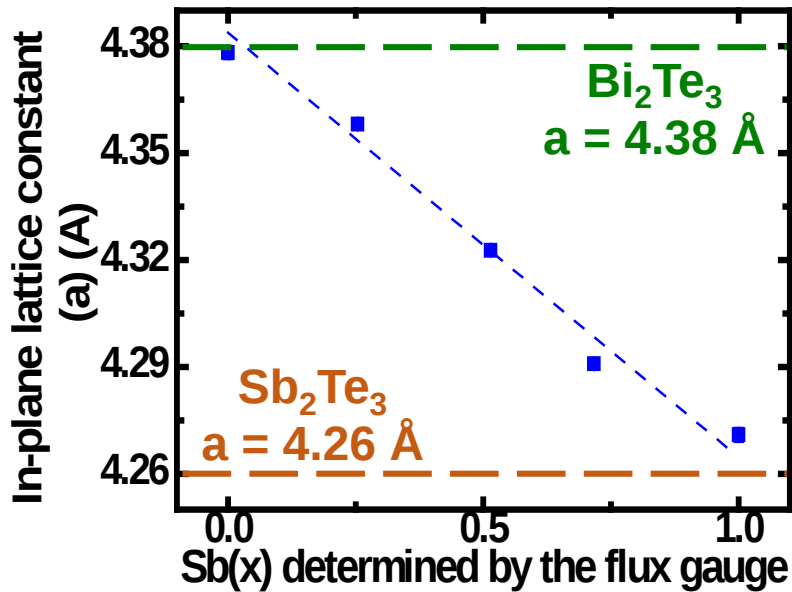


- **Streaky RHEED patterns** from the **very first QL** to ~15 QL grown by **MBE**
- **Large domains** with **sharp triangular shapes**
- **Clear RHEED oscillations** indicating **the layer-by-layer growth**

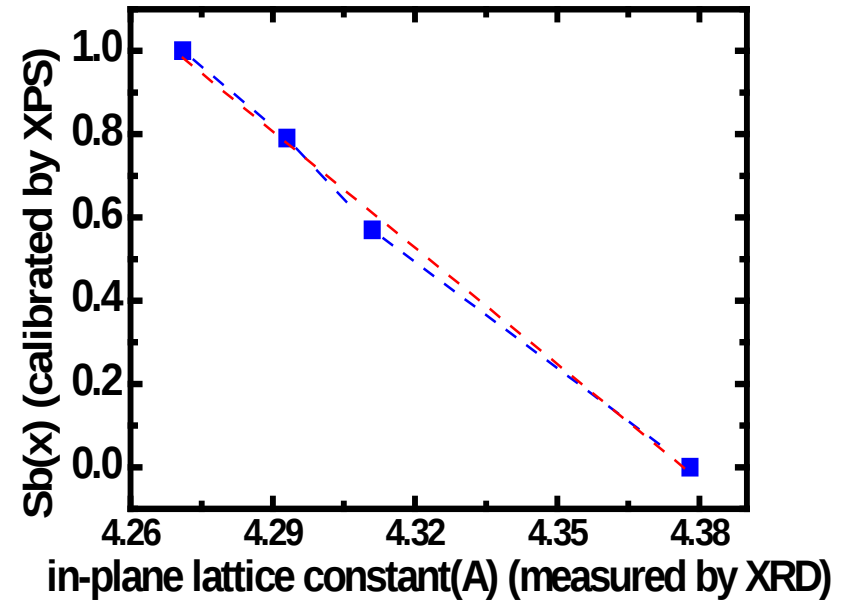


Composition characterization

XRD (*ex-situ*)

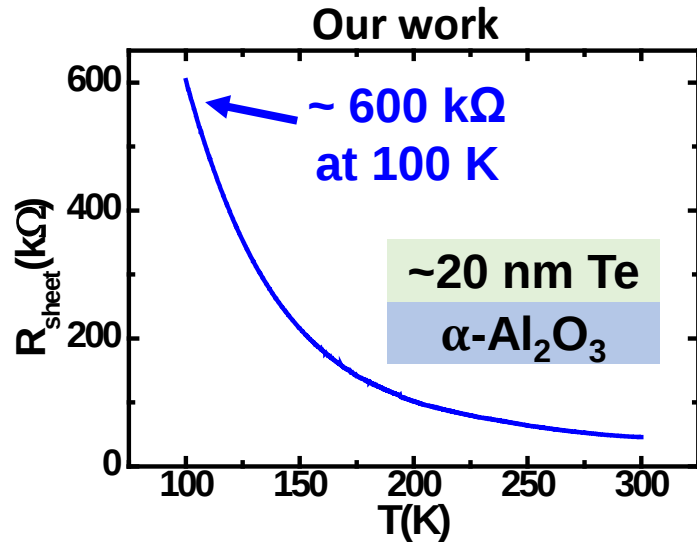


XPS (*in-situ*)



- Compositions of $(\text{Bi,Sb})_2\text{Te}_3$ can be both *in-situ* and *ex-situ* calibrated by **X-ray photoelectron spectroscopy (XPS)** and **X-ray diffraction (XRD)**, respectively.

Te capping layer & R-T curves



At 300 K

$$n_{2D} = 3.37 \times 10^{12} \text{ cm}^{-2}$$

$$R_{\text{sheet}} = 45483 \Omega$$

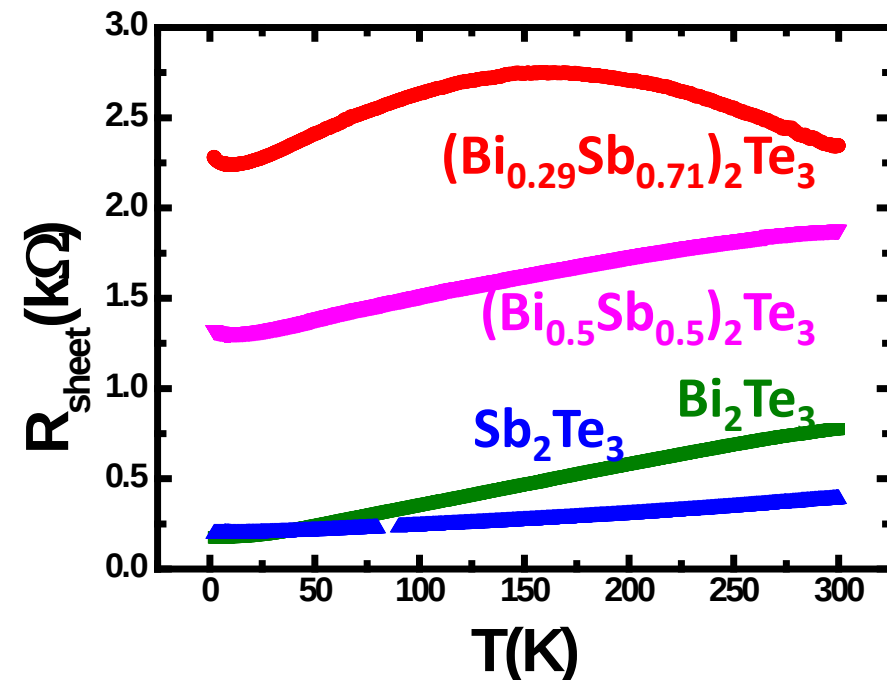
$$\text{Mobility} = 39.8 \text{ cm}^2/\text{Vs}$$

~ 20 nm Te

$(\text{Bi,Sb})_2\text{Te}_3$

$\alpha\text{-Al}_2\text{O}_3$

To prevent the oxidation of TIs



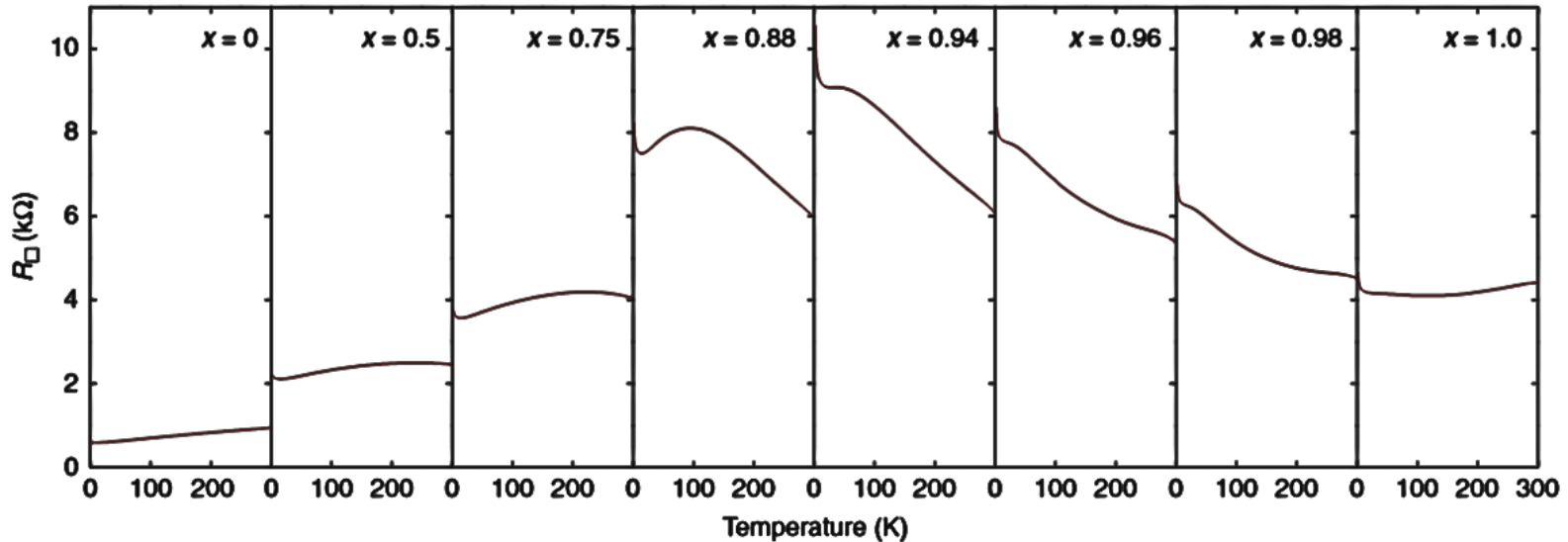
Semiconductor-like

- Resistance increasing with the temperature decreasing
- Higher value of resistance

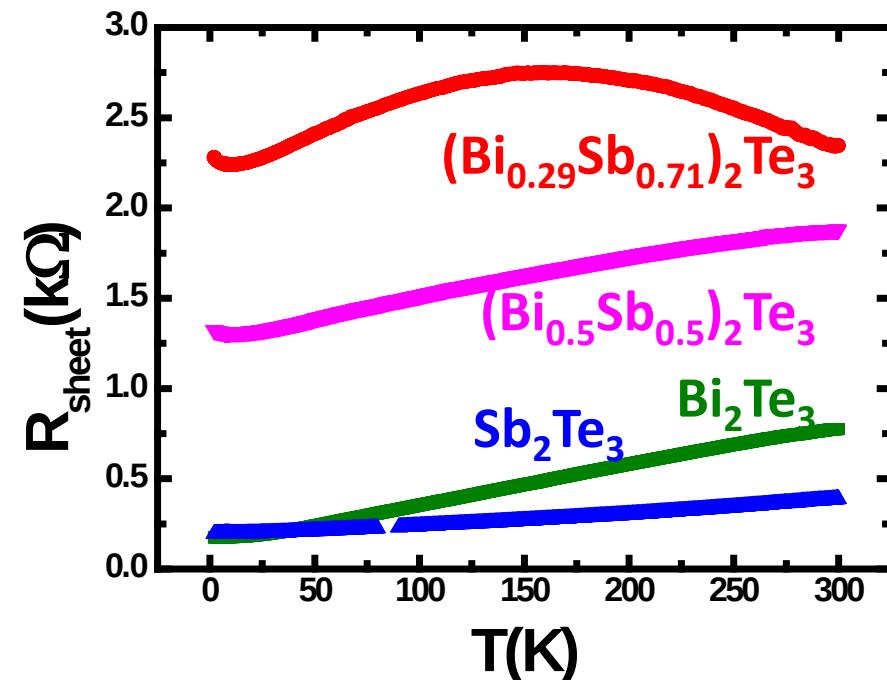
Metal-like

- Resistance decreasing with the temperature decreasing

Te capping layer & R-T curves



J. Zhang et al., Nat. Commun. **2**, 574 (2011).



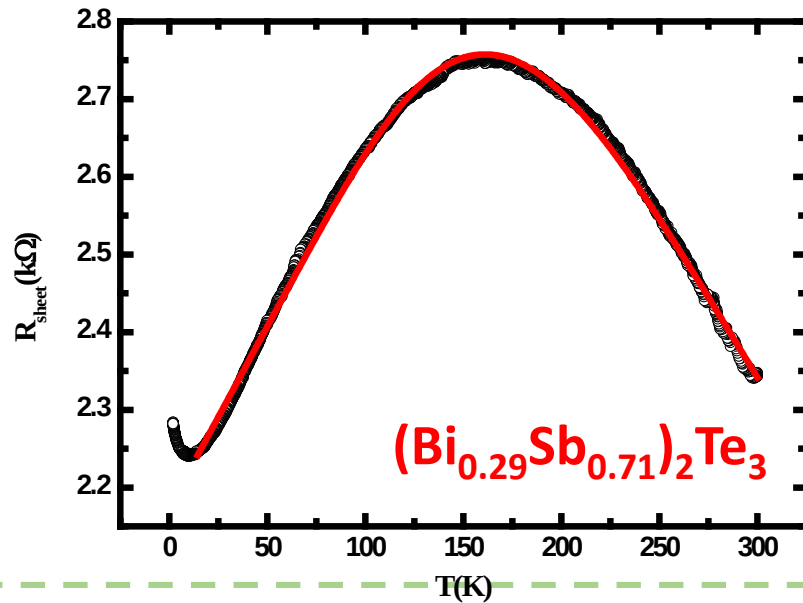
Semiconductor-like

- Resistance increasing with the temperature decreasing
- Higher value of resistance

Metal-like

- Resistance decreasing with the temperature decreasing

Te capping layer & R-T curves



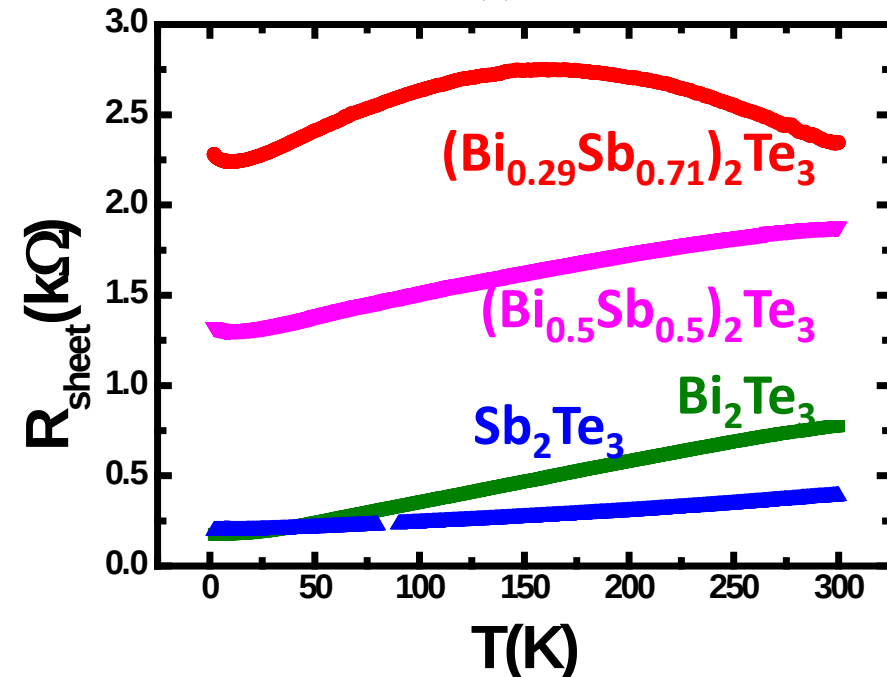
$$G_{\text{total}} = \frac{1}{R_0 + AT} + \frac{1}{R_1 \exp(\frac{\Delta}{kT})}$$

$$R_0 = 2172 \Omega$$

$$A = 4.7 \Omega/\text{T}$$

$$R_1 = 701 \Omega$$

$$\Delta = 59 \text{ meV} \leftarrow \text{activation energy}$$



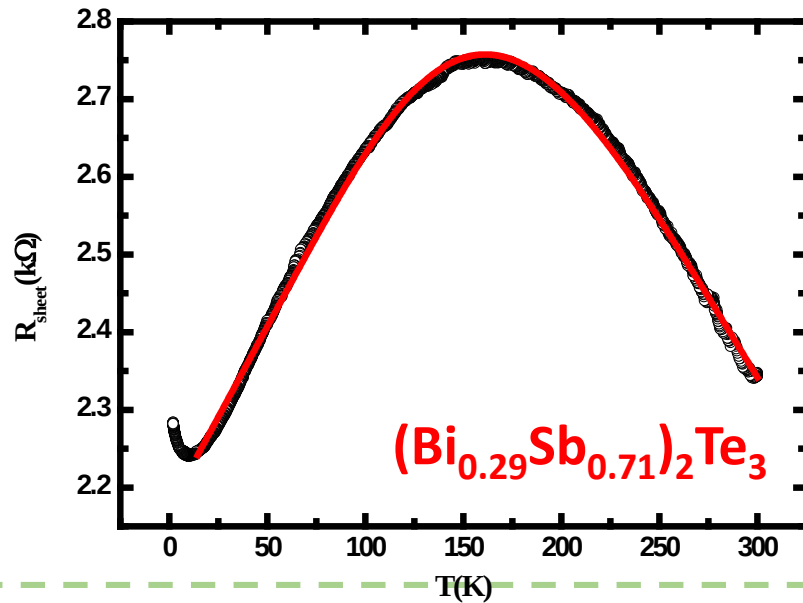
Semiconductor-like

- Resistance increasing with the temperature decreasing
- Higher value of resistance

Metal-like

- Resistance decreasing with the temperature decreasing

Te capping layer & R-T curves



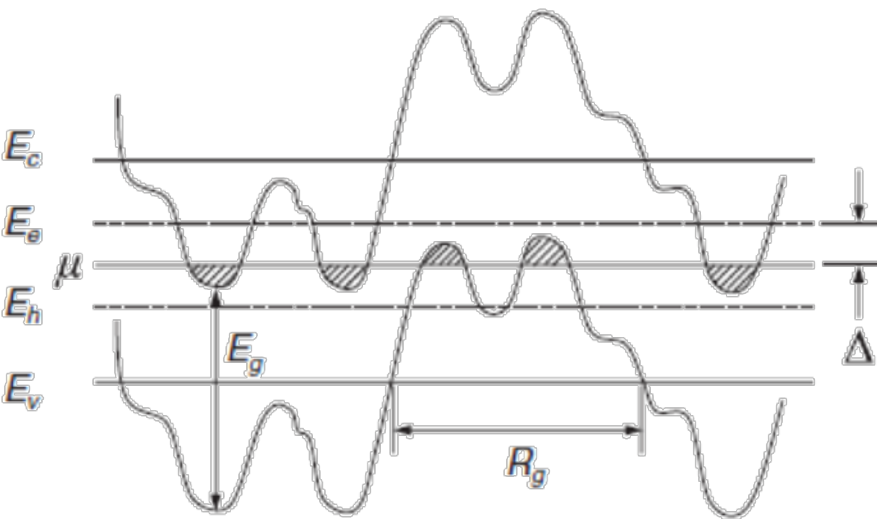
$$G_{total} = \frac{1}{R_0 + AT} + \frac{1}{R_1 \exp(\frac{\Delta}{kT})}$$

$$R_0 = 2172 \, \Omega$$

$$A = 4.7 \, \Omega/\text{T}$$

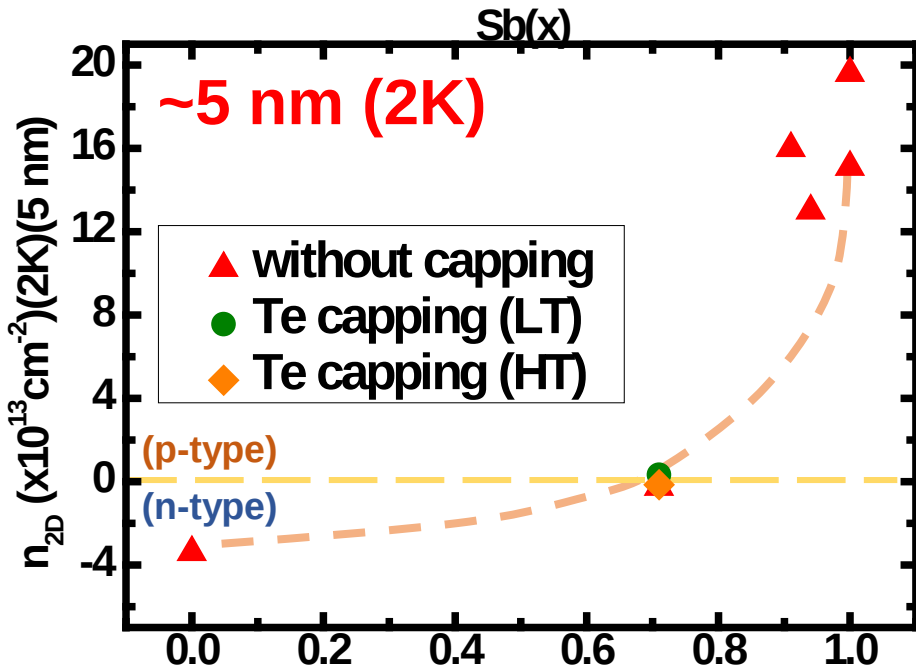
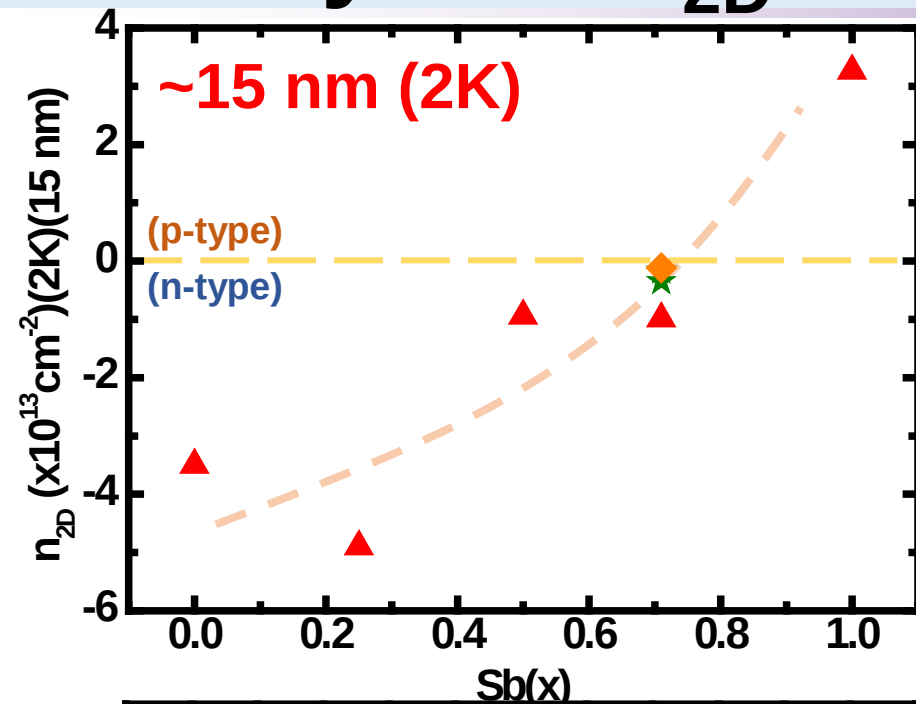
$$R_1 = 701 \, \Omega$$

$$\Delta = 59 \, \text{meV} \leftarrow \text{activation energy}$$



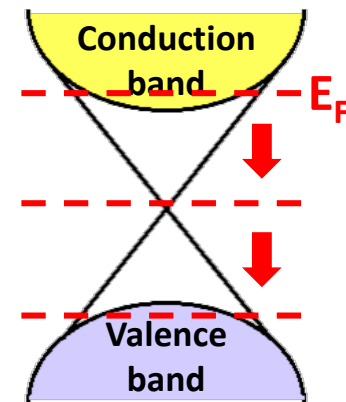
- Network of p-n junction
- Activation energy $\approx$ energy from E_F to E_e (effective E_c)
- Larger Δ of a TI $\Rightarrow$ better quality
- The **largest achievable Δ** of doped TI is **$0.15E_g \approx 50\text{meV}$** according to simulations.

Very low n_{2D} & boosted mobility



n_{2D} :

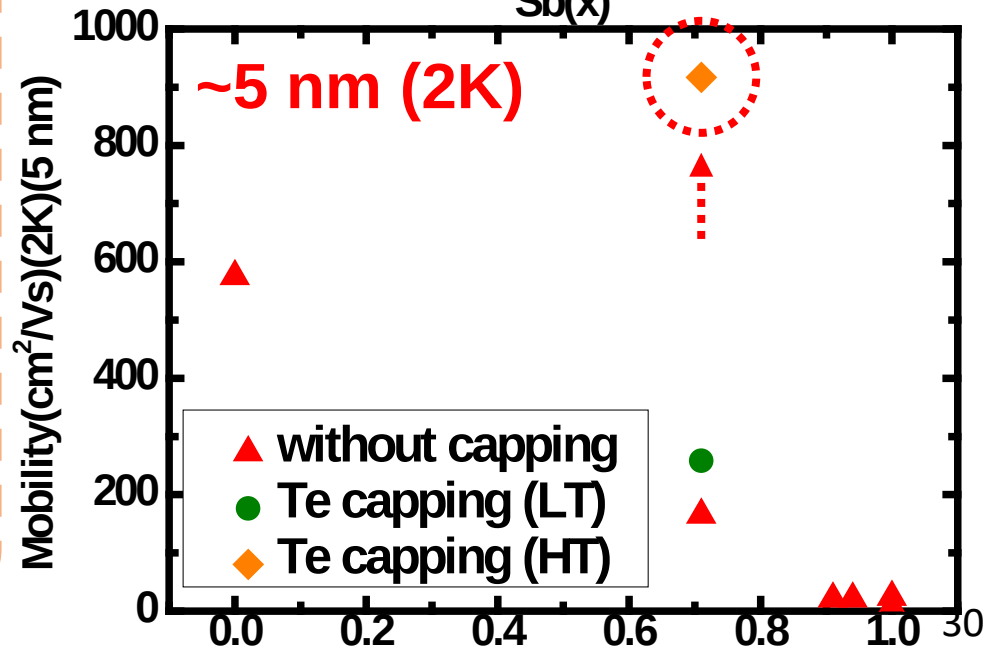
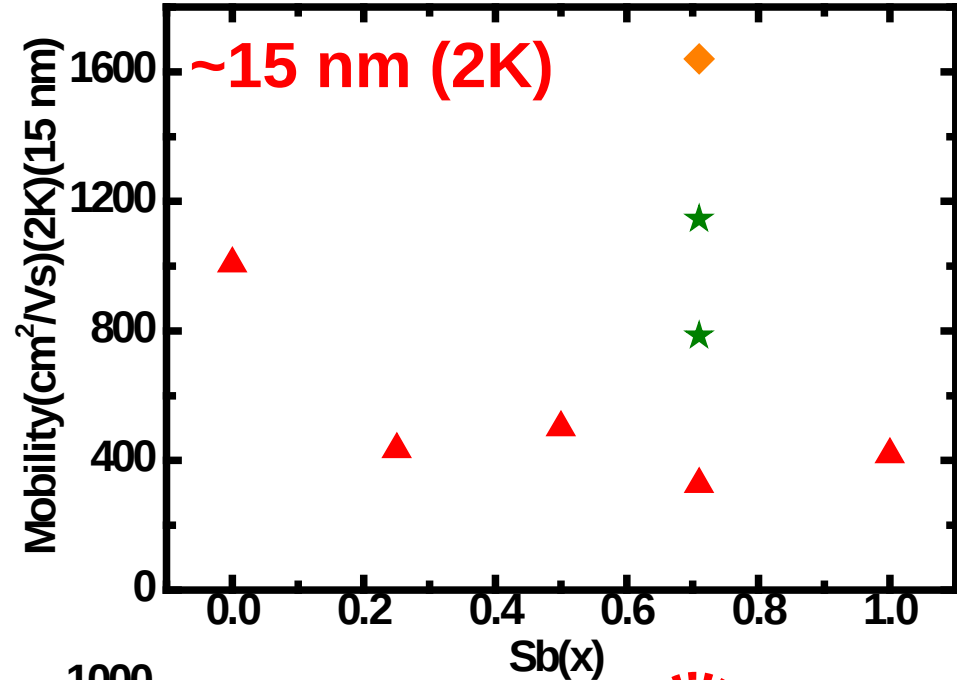
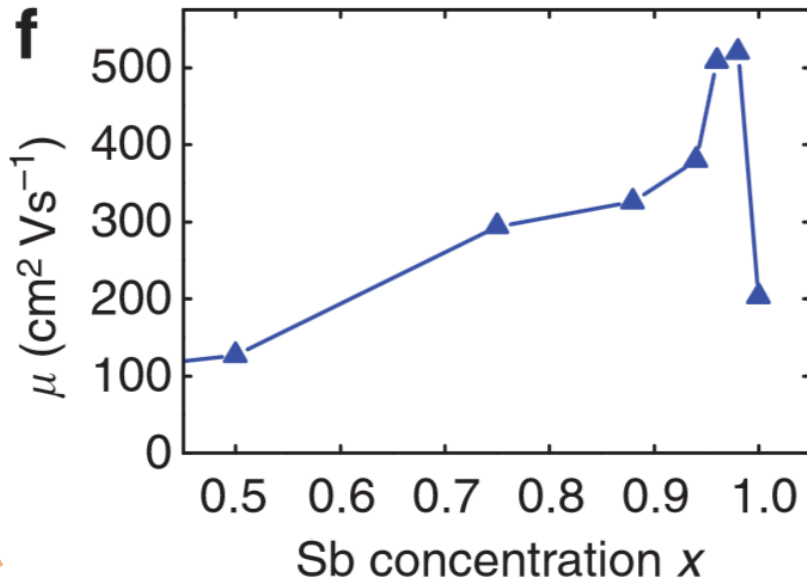
- Demonstration from **n-type to p-type**
- The lowest value of
 $-1.2 \times 10^{12} \text{ cm}^{-2}$ (15 nm)
and $-1.5 \times 10^{12} \text{ cm}^{-2}$ (5 nm)



Very low n_{2D} & boosted mobility

Mobility:

- **Enhanced value** with capping layers
- Boosted value with **high-temp. growth**
- **Higher value** at Dirac point stemmed from the feature of **Dirac fermion**



Two conductive transport channels

HLN equation:

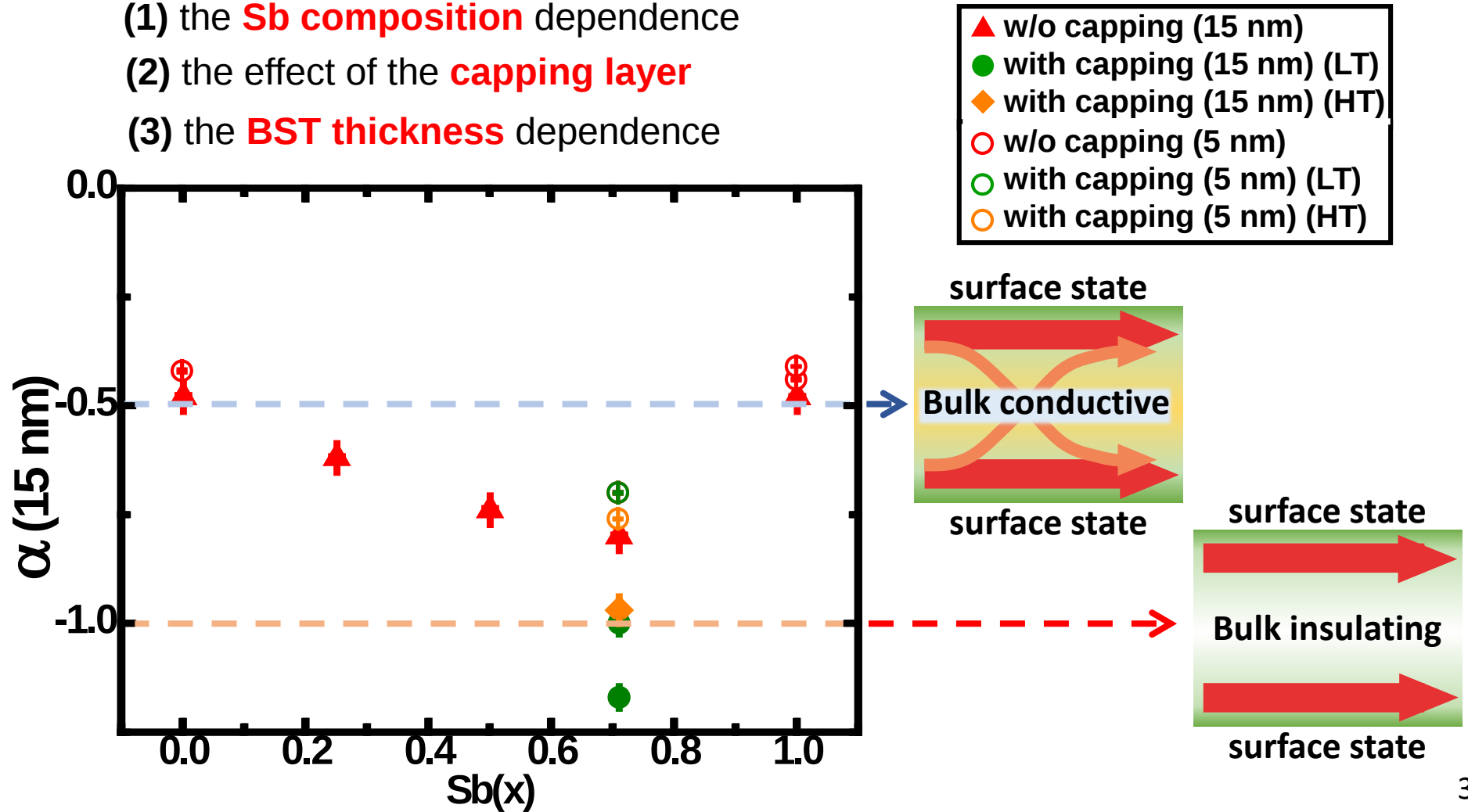
$$\Delta G_{xx} = \alpha \left(\frac{e^2}{\pi h} \right) \left[\psi \left(\frac{\hbar}{4el^2B} + \frac{1}{2} \right) - \ln \left(\frac{\hbar}{4el^2B} \right) \right] + cB^2$$

- (1) the **Sb composition** dependence
- (2) the effect of the **capping layer**
- (3) the **BST thickness** dependence

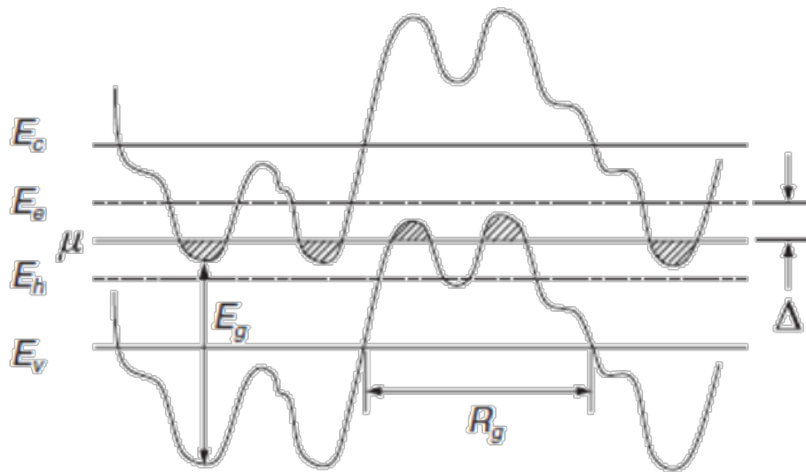
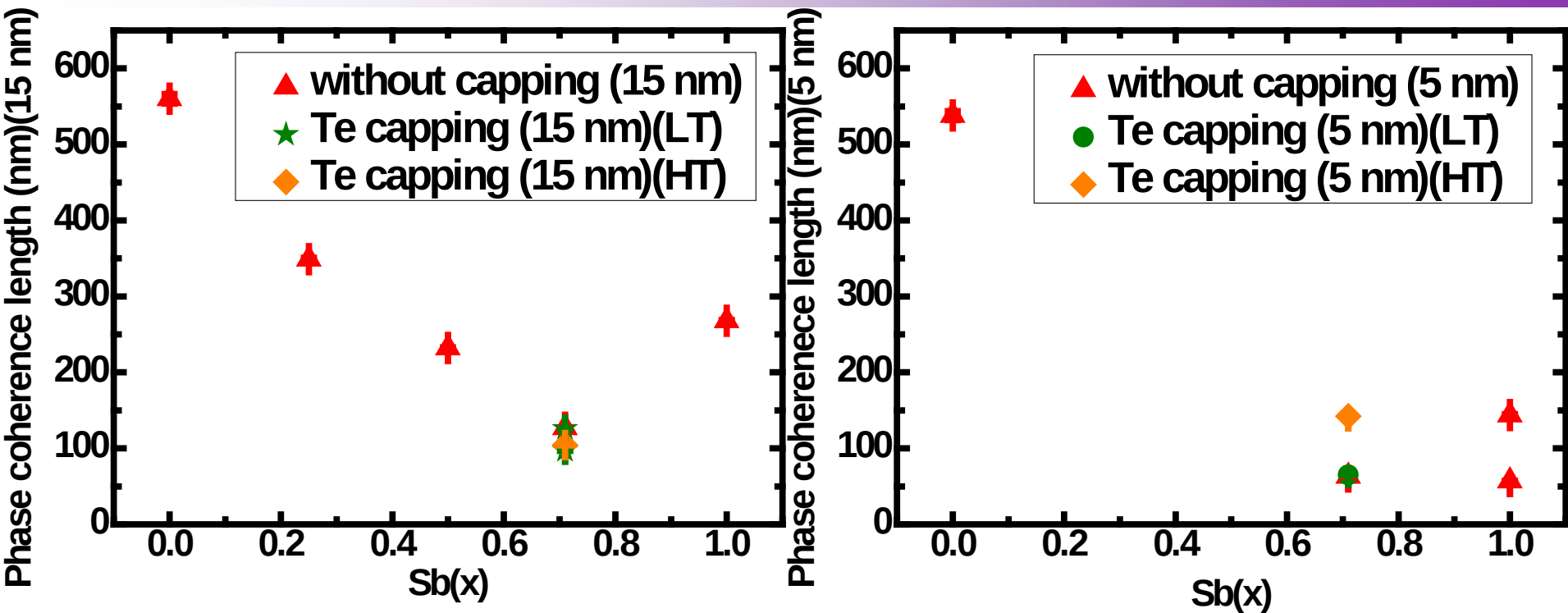
$\alpha \sim -0.5$: **one channel** with weak anti-localization (WAL)

$\alpha \sim -1$: **two channel** with WAL

l : **phase coherence length**



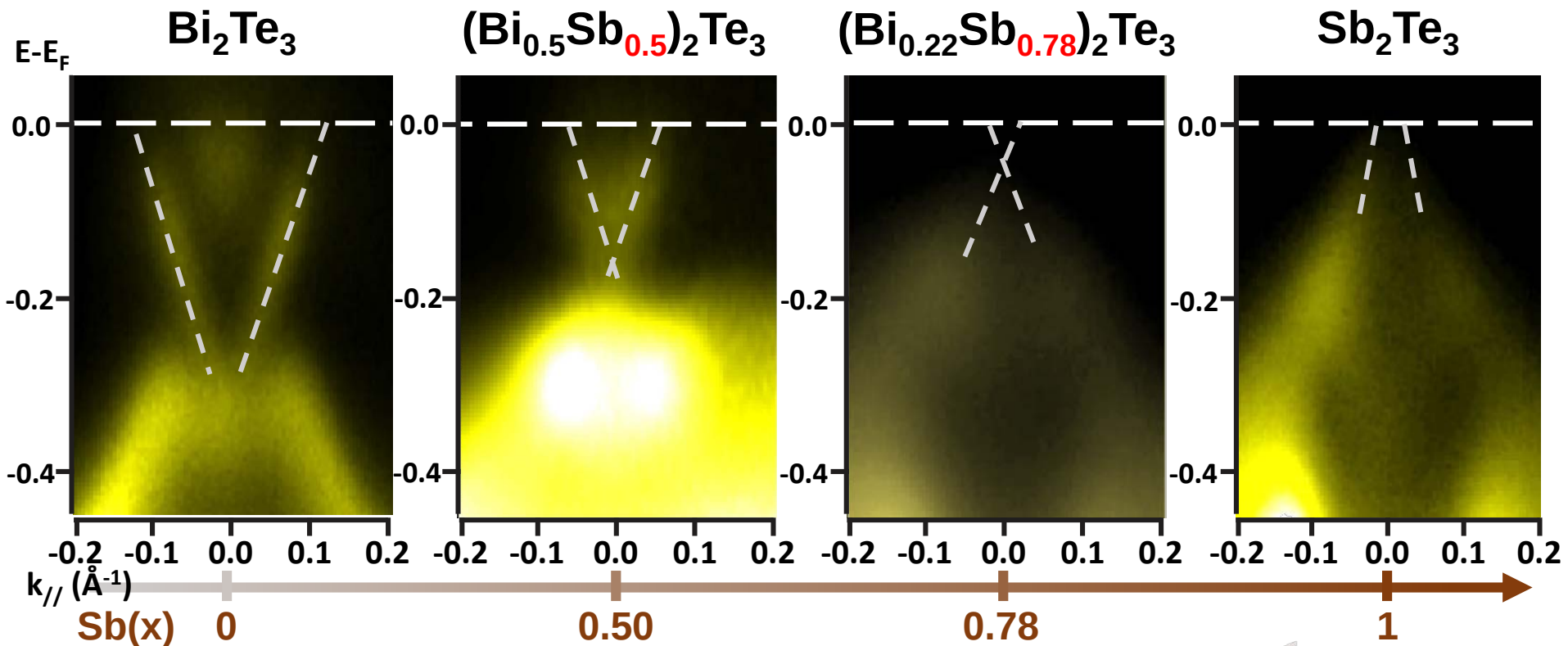
Two conductive transport channels



Low phase coherence length of $(\text{Bi,Sb})_2\text{Te}_3$

- **Network of p-n junction**
- Transport by means of **hopping** or **tunneling between charge puddles**
- **Enhanced coherence length with the high-temperature growth**

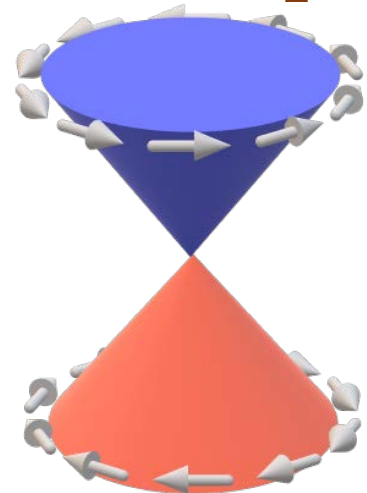
Tuning E_F and band structures



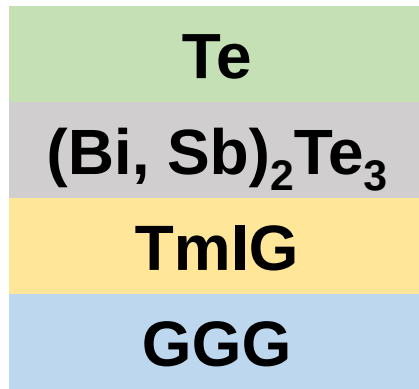
- **Tuning E_F** across the Dirac point
- **Clear surface states** shown in all samples

Condition:

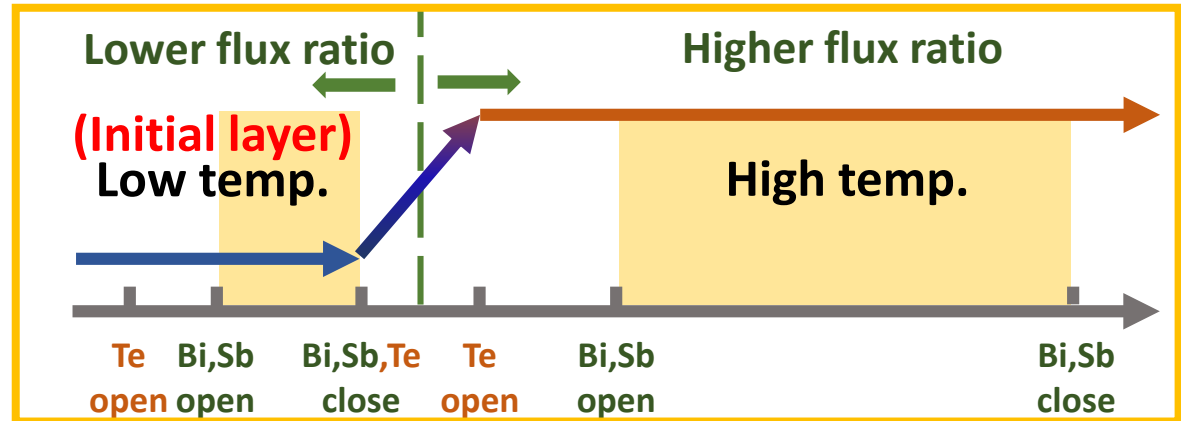
- He I $h\nu = 21.2$ eV
- Thickness = ~ 20 nm
- At 300K
- K- Γ -K



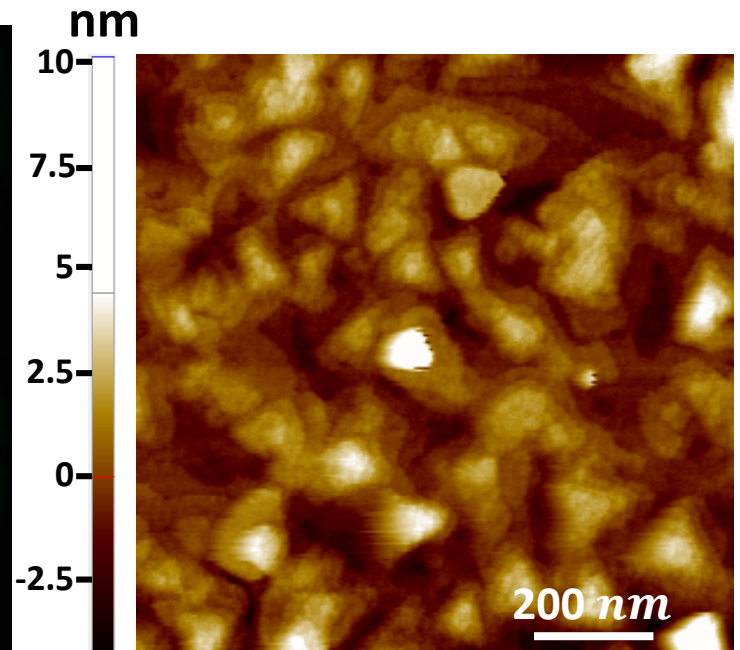
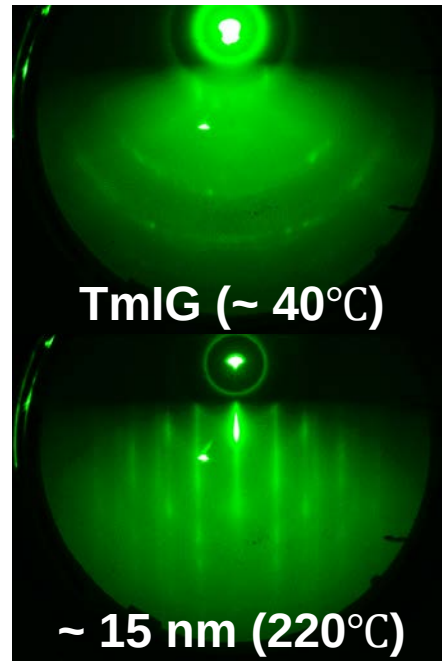
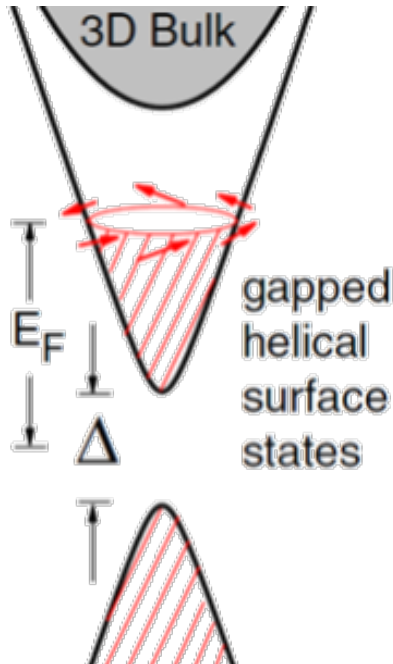
Modified SBLT growth (Te-based TI)



Low-temperature growth
(modified from **Se-buffered low-temp. (SBLT) growth**)

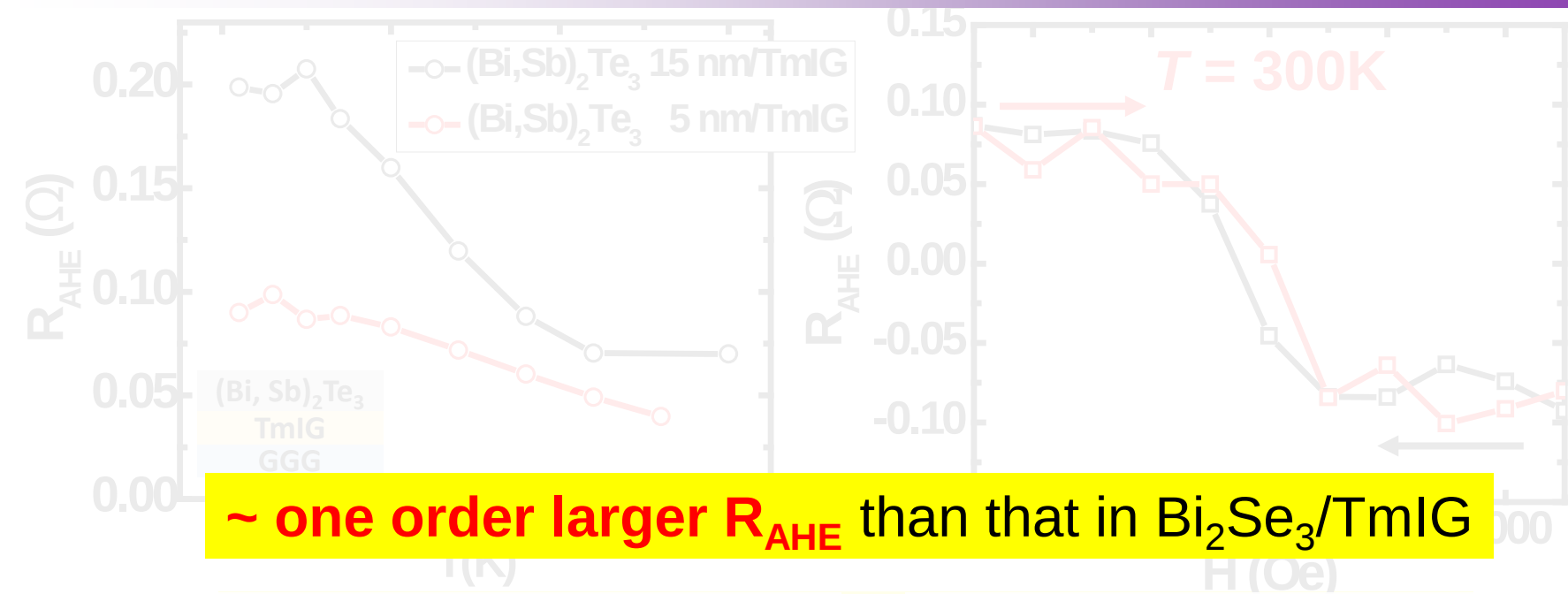


Breaking TRS by **MPE**



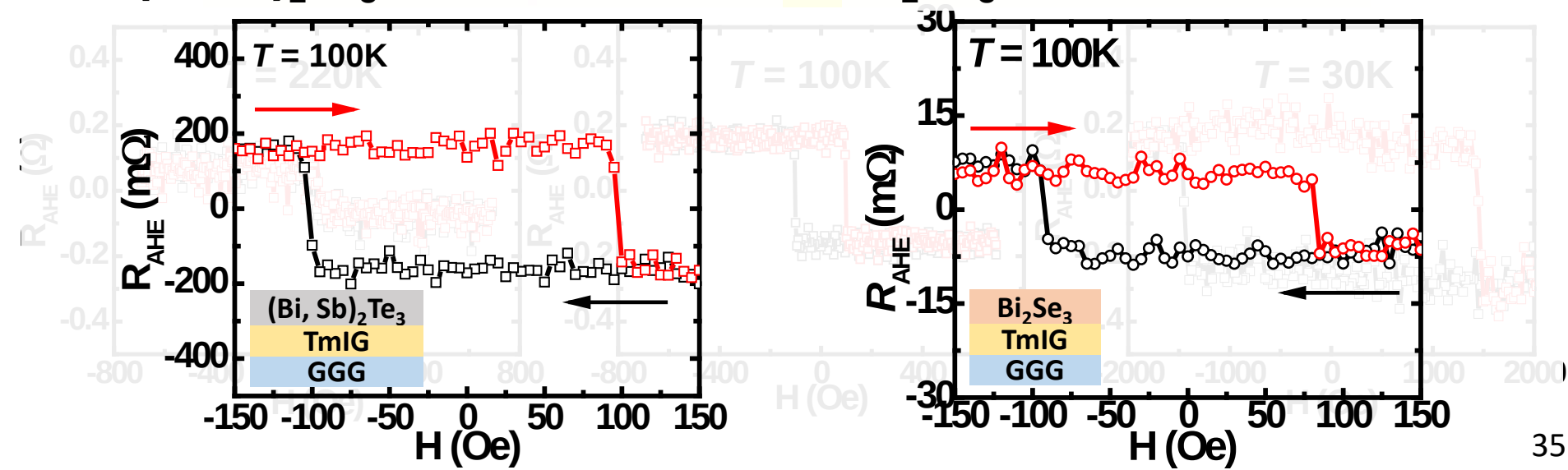
Roughness = 1.42 nm

Observation of AHE up to RT

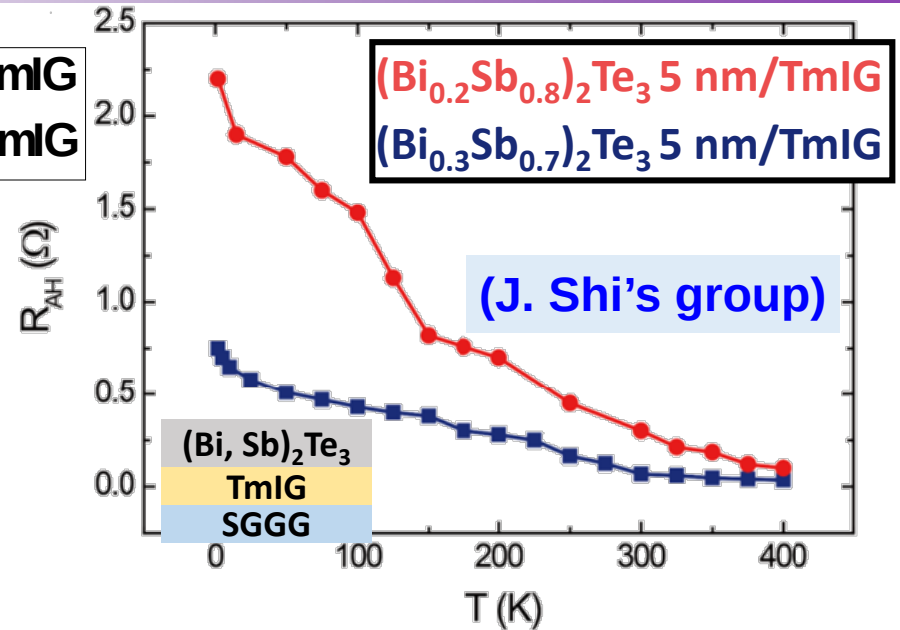
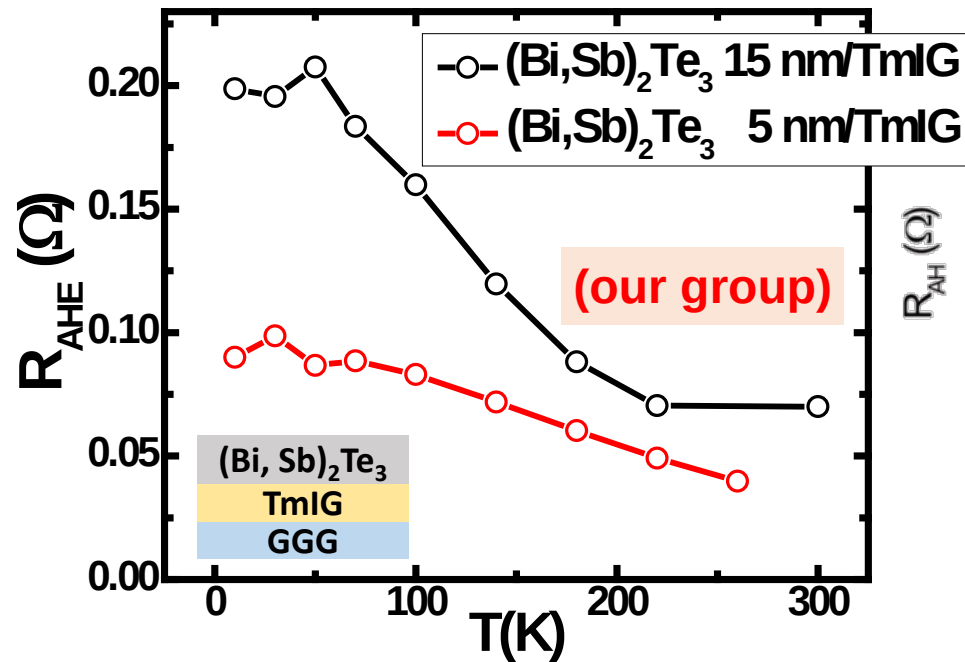


~ one order larger R_{AHE} than that in $\text{Bi}_2\text{Se}_3/\text{TmIG}$

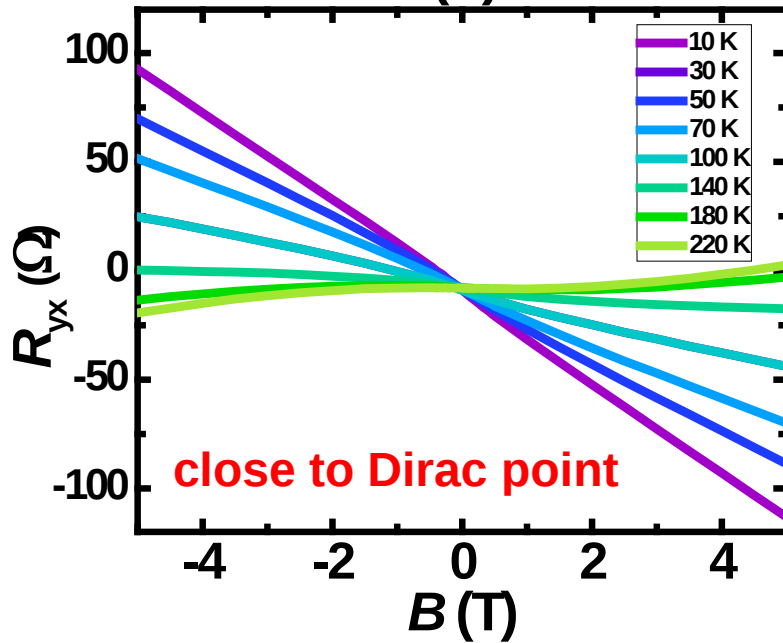
$(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$ (in this work) **$\text{Bi}_2\text{Se}_3/\text{TmIG}$ (our previous work)**



Observation of AHE up to RT



C. Tang *et al.*, Sci. Adv. **3** (6), e1700307 (2017).



Factors affect the extent of R_{AH} :

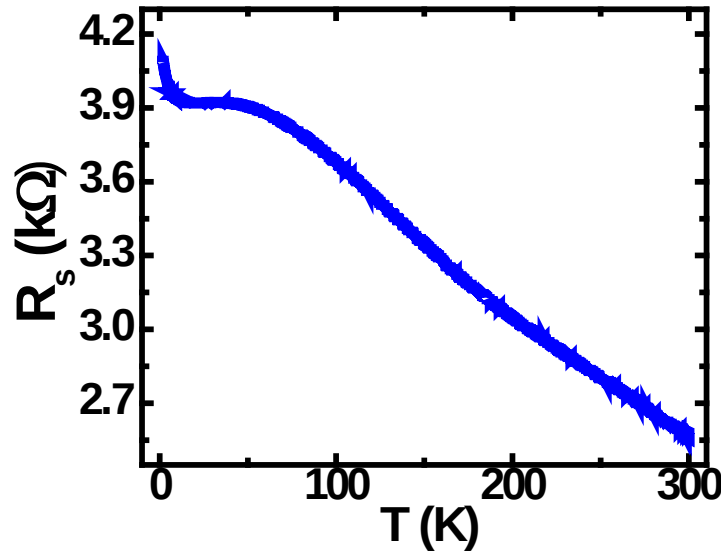
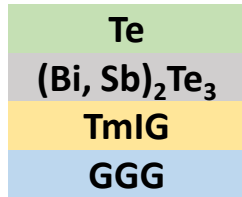
- Stronger PMA induced by SGGG
 - Larger tensile strain
- E_F closer to Dirac point
- Interface quality

M. Li *et al.*, Phys. Rev. B **96**, 201301(R) (2017).

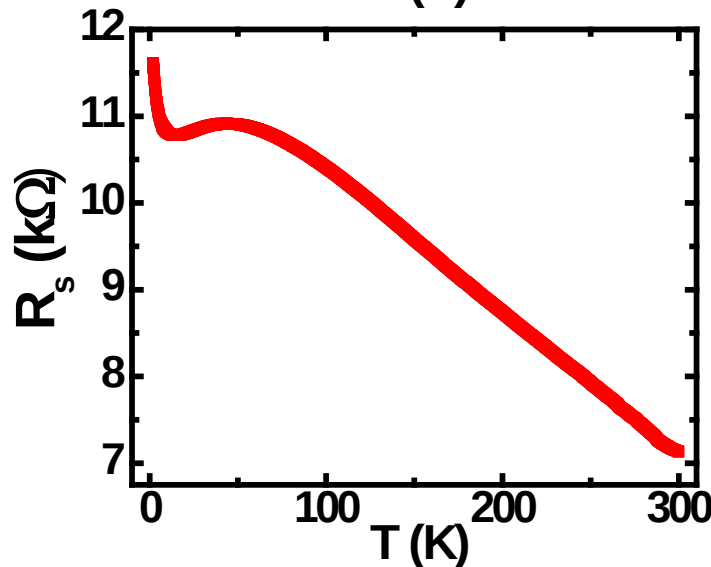
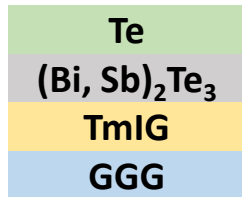
R-T curves of $(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$

R-T curve

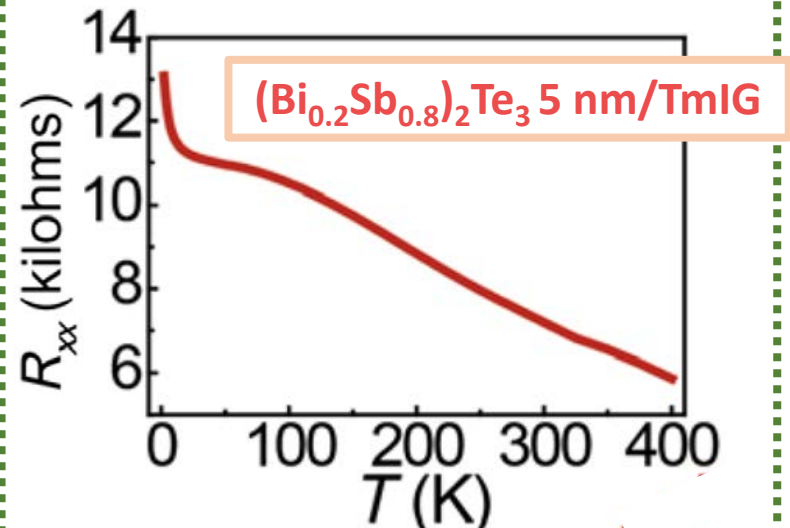
~ 15 nm



~ 5 nm



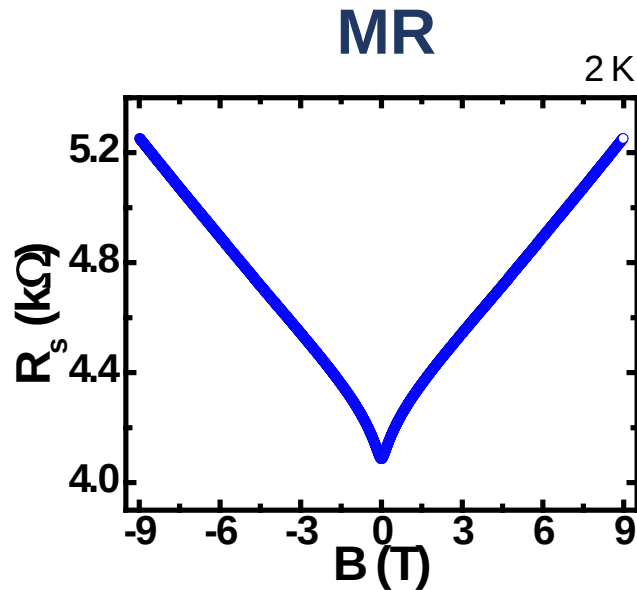
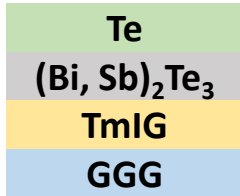
- **Semiconductor-like feature in both samples**
- Similar to the previous work



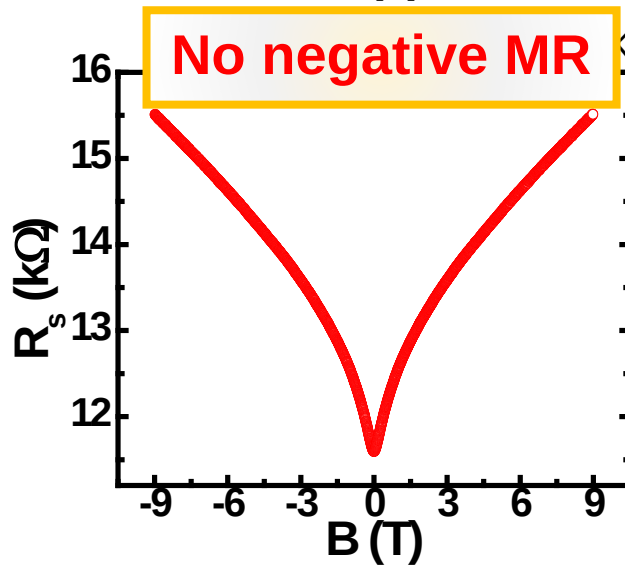
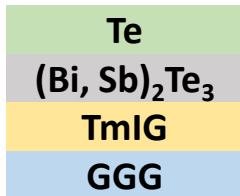
C. Tang *et al.*, Sci. Adv. **3** (6), e1700307 (2017).

MR analysis by HLN equation

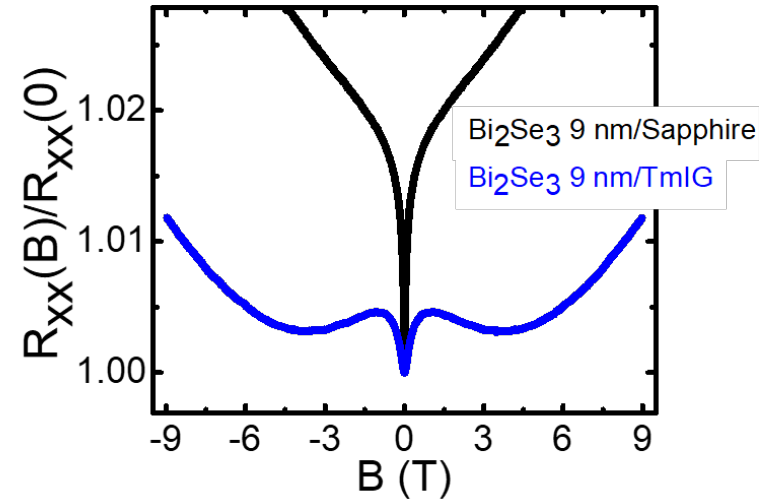
~ 15 nm



~ 5 nm



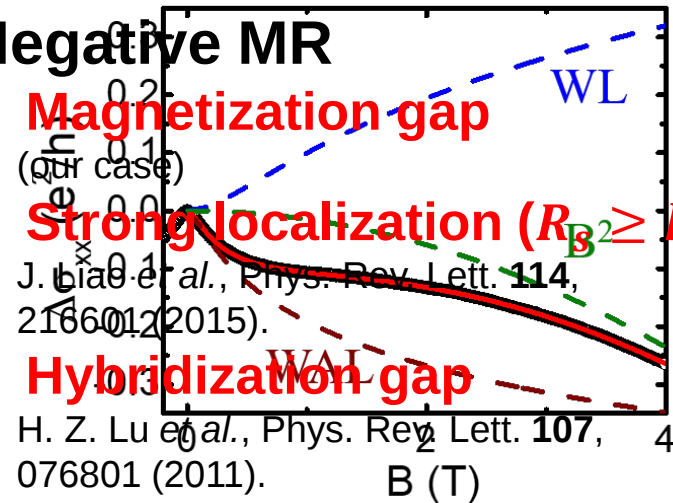
Bi₂Se₃/TmIG (our work)



S. R. Yang et al., arXiv: 1811.00689 (2018).

Negative MR

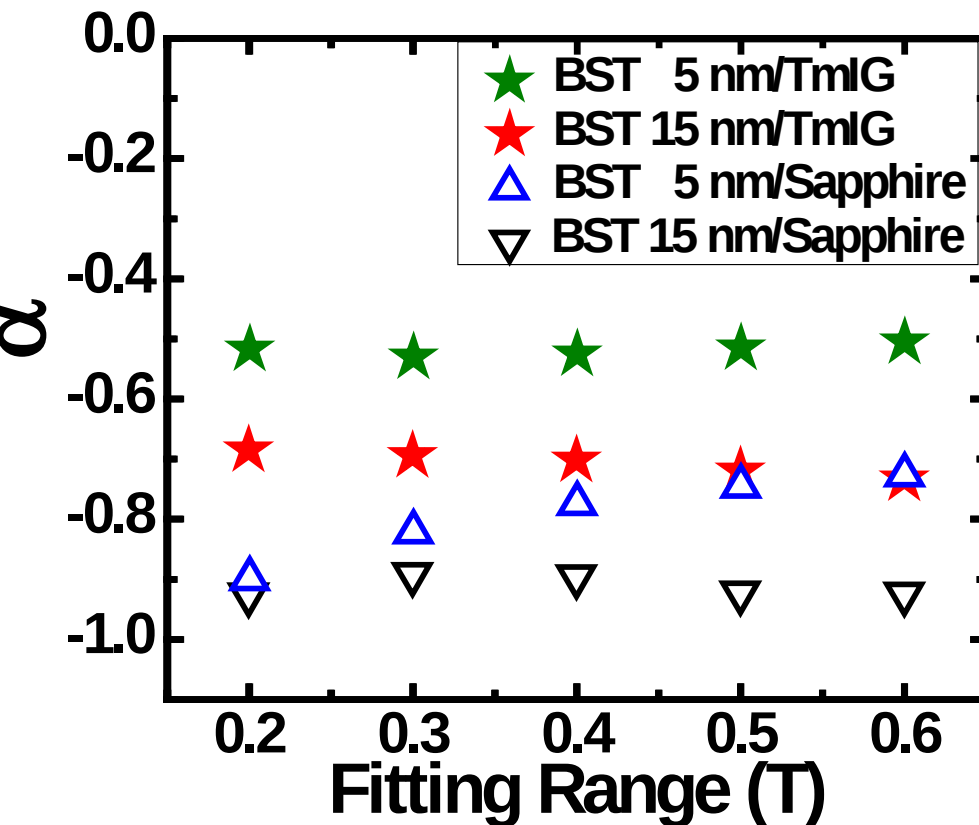
- **Magnetization gap**
- **Strong localization ($R_B \geq h/e^2$)**
- **Hybridization gap**



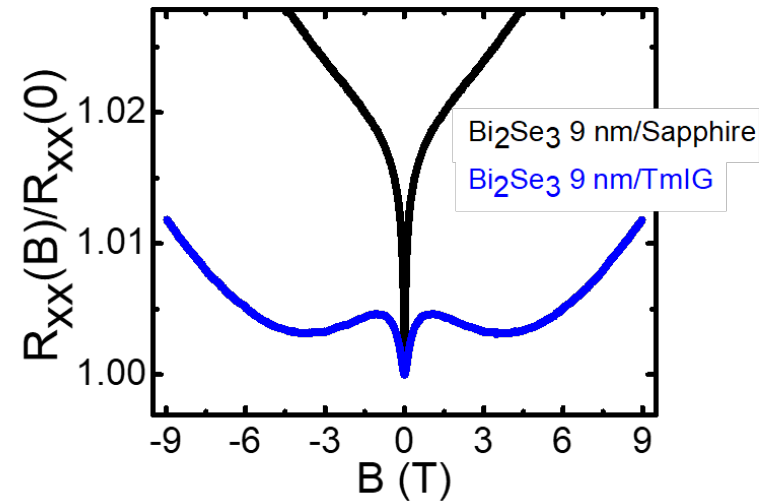
H. Z. Lu et al., Phys. Rev. Lett. **107**, 076801 (2011).

MR analysis by HLN equation

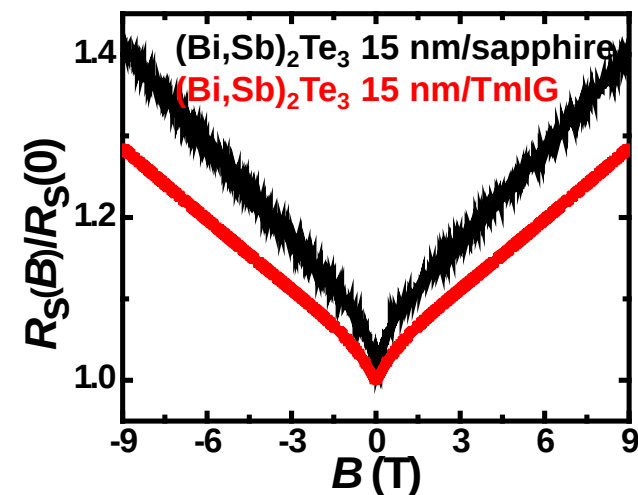
- No negative MR
- Suppressed WAL
- Smaller magnitude of α in $(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$ than those on Sapphire



$\text{Bi}_2\text{Se}_3/\text{TmIG}$ (our work)



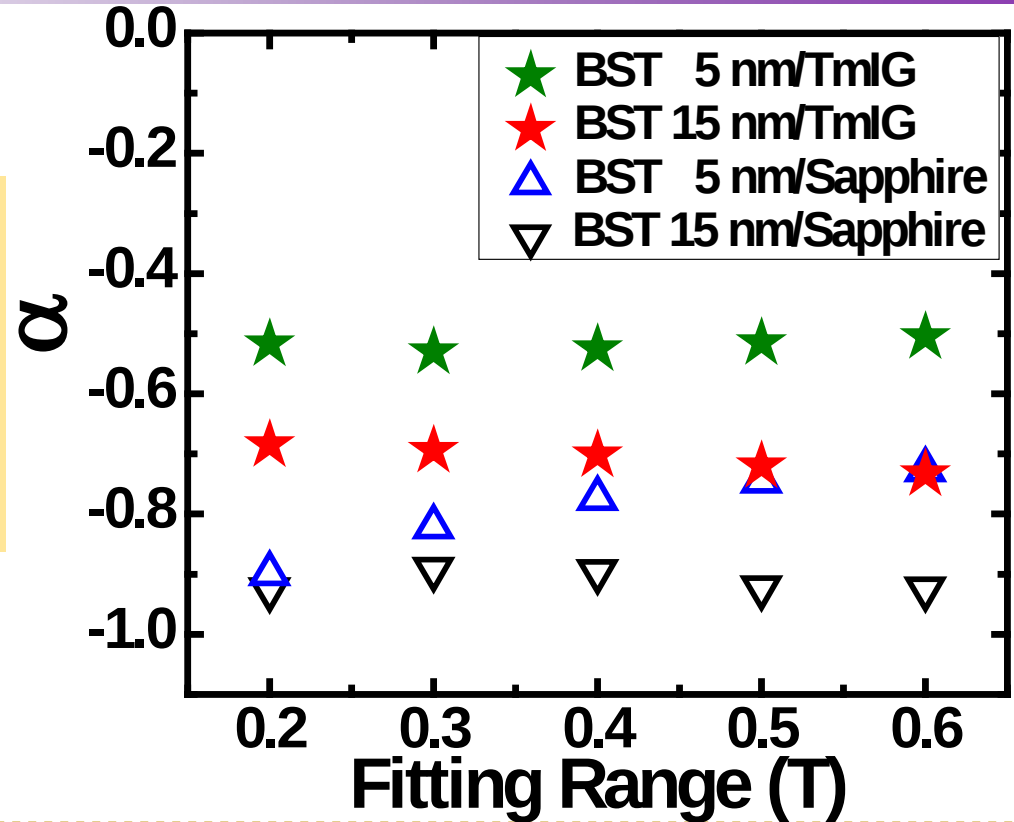
$(\text{Bi,Sb})_2\text{Te}_3/\text{TmIG}$ (this work)



MR analysis by HLN equation

When the **top surface** and the **bottom surface** are decoupled,

$$\Delta\sigma_{total} = \sigma_{top\ surface} + \sigma_{bottom\ surface}$$



surface state



$$\rightarrow \sigma_{top\ surface} = \text{WAL} (\alpha = -0.5)$$

Bulk

insulating



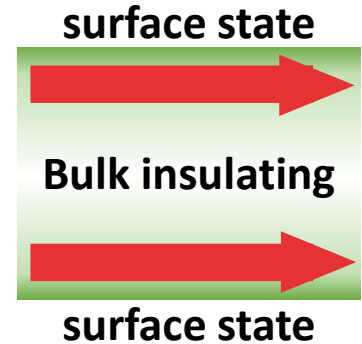
$$\rightarrow \sigma_{bottom\ surface} = \text{WAL} (-0.5 < \alpha < 0) + \text{WL} (0 < \alpha < 0.5)$$

surface state

Summary II

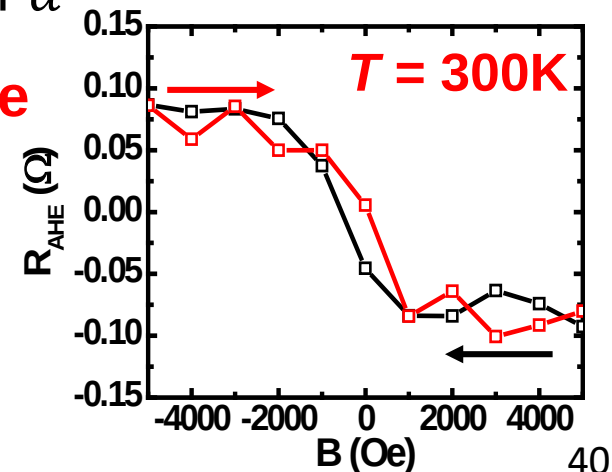
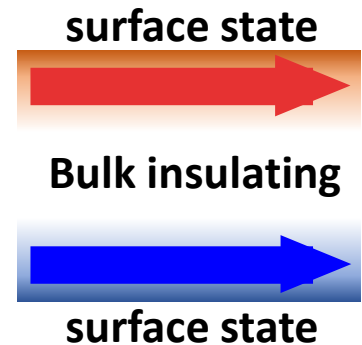
Excellent crystallinity in $(\text{Bi,Sb})_2\text{Te}_3$ on $\alpha\text{-Al}_2\text{O}_3$

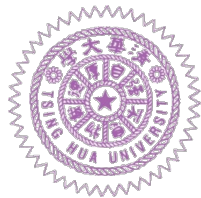
- Transport: **lowest n_{2D} , two conducting channels**
- ARPES: closer to **Dirac point**



Excellent crystallinity in $(\text{Bi,Sb})_2\text{Te}_3$ on **TmIG**

- **Room-temperature AHE**
- Weak thickness dependence $\Rightarrow$ **insulating bulk**
- **No negative MR** with smaller magnitude of α
 $\Rightarrow$ **MPE only affected the bottom surface**





Conclusion

Conclusion

Bi_2Se_3
ReIG

- **Breaking time reversal symmetry**
- Improvement of the **interface quality**
- Enhancement of the **interfacial exchange coupling**

$(\text{Bi,Sb})_2\text{Te}_3$
 $\alpha\text{-Al}_2\text{O}_3$

- **Toward insulating bulk state**
- Two conductive transport channels
- Band engineering revealed by ARPES

$(\text{Bi,Sb})_2\text{Te}_3$
TmIG

- Modifying the growth from $\text{Bi}_2\text{Se}_3/\text{ReIG}$
- Pushing the **T_C up to room temperature** (AHE)