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

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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

• **\( \text{Bi}_2\text{Se}_3 \) / 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)
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    • Large negative shift in $H_{res}$ probed by ferromagnetic resonance (FMR)
(Bi, Sb)$_2$Te$_3$ / $\alpha$-Al$_2$O$_3$ & (Bi, Sb)$_2$Te$_3$ / TmIG

- Characterization of structural properties
  - Higher-temperature growth of Sb$_2$Te$_3$ & (Bi, Sb)$_2$Te$_3$
- 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)

- 3D TIs: Bi$_2$Se$_3$, Bi$_2$Te$_3$, and Sb$_2$Te$_3$
- 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)

Features

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

Cr-doped (Bi,Sb)$_2$Te$_3$

V-doped (Bi,Sb)$_2$Te$_3$

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


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


Breaking TRS by MPE

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Magnetic proximity effect

Advantages of MPE:
• Higher $T_C$ than that of magnetic doping
• No crystal defects
• Uniform magnetization

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:
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- Uniform magnetization

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)


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)

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

However,
- Complicated surface atomic arrangement
- Huge lattice mismatch with Bi$_2$Se$_3$

- Magnetic insulator
- High $T_c$ (above 500 K)
- Perpendicular magnetic anisotropy (PMA)

Conventional two-step growth

1\textsuperscript{st} step: \textbf{Low temp.}
\textbf{Ordered and smooth initial layer}

2\textsuperscript{nd} step: \textbf{High temp.}
\textbf{Atoms with more kinetic energy}  \rightarrow \textbf{Better film quality}

Applied on rare earth iron garnets (ReIGs):
\rightarrow \textbf{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

$T_C \sim 100 \text{ K}$

$T_C \sim 20 - 150 \text{ K}$
Manipulating $E_F$ toward Dirac point

- 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.

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

$\text{Bi}_2\text{Te}_3$

$\text{Sb}_2\text{Te}_3$

$k_{//}(\text{Å}^{-1})$

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


Manipulating $E_F$ toward Dirac point

Ways to eliminate/reduce the bulk contribution in TIs

Electric gating effect

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

J. S. Lee et al., npj Quantum Mater. 3, 51 (2018).
Manipulating $E_F$ toward Dirac point

Ways to eliminate/reduce the bulk contribution in TIs

- Electric gating effect
- Chemical doping / alloy

(Bi,Sb)$_2$Te$_3$ (BST)
- Tuning the position of the $E_F$
- Introducing different amounts of defects
- Modifying the band structure of TI

$\text{Bi}_2\text{Te}_3$
Te$_{\text{Bi}}$ anti-site  \downarrow  n-type doping

$\text{Sb}_2\text{Te}_3$
Sb$_{\text{Te}}$ anti-site  \downarrow  p-type doping


Manipulating the $E_F$ into the bulk band gap $\Rightarrow$ bulk insulating TI
Motivation

Molecular Beam Epitaxy (MBE)

$\alpha$-Al$_2$O$_3$

Bi$_2$Se$_3$

Base pressure: 4$\times$10$^{-10}$ torr (2$\times$10$^{-10}$ torr)

Reflection High-Energy Electron Diffraction (RHEED)

2D diffraction

Streaks: smooth surface & Great crystallinity

Rings or Spots: polycrystalline or rough surface
Motivation

- Adopting a new growth method (SBLT growth)
- Improvement of interface quality
- Toward bulk-insulating feature
- Exhibition of pure surface state
- Breaking time reversal symmetry
- Pushing the $T_C$ up to room temperature

Bi$_2$Se$_3$
\(\alpha\)-Al$_2$O$_3$

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


Quintuple layer (QL) (~ 1 nm)
I: \( \text{Bi}_2\text{Se}_3/\text{TmIG} \) & \( \text{Bi}_2\text{Se}_3/\text{YIG} \)

- \( \text{Bi}_2\text{Se}_3 \) / Rare earth iron garnet (ReIG)
  - Advantage of ReIGs
  - Growth method: \text{Se-buffered low-temperature (SBLT) growth}
  - Improvement in crystallinities (vs. conventional two-step growth)
  - Enhancement of interfacial exchange coupling
Thulium iron garnet (Tm$_3$Fe$_5$O$_{12}$, TmIG)
- Perpendicular magnetic anisotropy (PMA) (induced by tensile strain)

Yttrium iron garnet (Y$_3$Fe$_5$O$_{12}$, YIG)
- In-plane magnetic anisotropy (IMA) and low damping constant

ReIG substrate preparation

Sputter → MBE

- Without chemical cleaning

Outgassing

- Bi$_2$Se$_3$/YIG at 500°C
- (Bi,Sb)$_2$Te$_3$/YIG at 600°C, 1hr
  Z. Jiang et al., AIP Adv. 6, 055809 (2016).
- (Bi,Sb)$_2$Te$_3$/TmIG at 600°C, 1hr

Growth temp.

- 150 °C 15 min

RHEED patterns:
- 350°C↑ ring (polycrystalline)

Residual gas analysis:
- 300°C↑ C$_x$O$_x$ compounds

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Demand for a reproducible growth method

However,

• Complicated surface atomic arrangement
• Huge lattice mismatch with Bi$_2$Se$_3$

**Conventional two-step growth**

1$^{st}$ step: Low temp.

Ordered and smooth initial layer

2$^{nd}$ step: High temp.

Atoms with more kinetic energy
👉 Better film quality

Interlayer with poor crystallinity


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:

- $\text{Bi}_2\text{Se}_3$
- Amorphous Se
- TmIG

The substrate was covered by a layer of amorphous Se and $\sim1\text{ nm }\text{Bi}_x\text{Se}_{1-x}$.
The Se-buffered low-temperature (SBLT) growth:

The high-quality $\text{Bi}_2\text{Se}_3$ at the 1st QL serves as a great template for the further $\text{Bi}_2\text{Se}_3$ growth.
The Se-buffered low-temperature (SBLT) growth:

Sharper and brighter RHEED patterns were obtained in thicker Bi$_2$Se$_3$ films.
Comparison of RHEED patterns

Spotty ring feature
 poly crystalline

Grain growth,
 forming 2D surface

Reaching a good-quality surface

Two-step growth

TmIG

SBLT growth

Bi$_2$Se$_3$ (~1 QL)

Bi$_2$Se$_3$ (~3 QL)

Bi$_2$Se$_3$ (~7 QL)

Bi$_2$Se$_3$ (~1 QL)

Bi$_2$Se$_3$ (~3 QL)

Bi$_2$Se$_3$ (~7 QL)

Line feature
 better crystallinity
 and smooth surface

More distinct RHEED patterns
 achieving excellent crystallinity of thin films
Comparison of RHEED patterns

Two-step growth

Bi$_2$Se$_3$ (~1 QL) Bi$_2$Se$_3$ (~3 QL) Bi$_2$Se$_3$ (~7 QL)

TmIG

Bi$_2$Se$_3$ (~1 QL) Bi$_2$Se$_3$ (~3 QL) Bi$_2$Se$_3$ (~7 QL)

SBLT growth

Bi$_2$Se$_3$ (~1 QL) Bi$_2$Se$_3$ (~1 QL) Bi$_2$Se$_3$ (~1 QL)

It works on Bi$_2$Se$_3$/YIG!
Structural analyses

Two-step growth

Roughness = 2.58 nm

SBLT growth

Top surface:
• Smooth surface
• Clear triangular domain

Step height = ~1nm

Bi₂Se₃
7nm
TmgG
GGG

600 nm

Roughness = 0.43 nm

Roughness = 0.47 nm

GGG
TmgIG
Bi
2Se₃

Step height = ~1nm
Structural analyses

Two-step growth

- Bi$_2$Se$_3$
- TmIG
- YIG
- GGG

Roughness = 2.58 nm
Roughness = 1.29 nm

SBLT growth

- Bi$_2$Se$_3$
- TmIG
- GGG

Roughness = 0.43 nm
Roughness = 0.58 nm

Top surface:
- Smooth surface
- Clear triangular domain

GGG
TmIG
Bi$_2$Se$_3$

7nm
7nm

YIG
GGG

Two-step growth

Roughness = 2.58 nm
Roughness = 1.29 nm

SBLT growth

Roughness = 0.43 nm
Roughness = 0.58 nm

GGG
TmIG
Bi$_2$Se$_3$

7nm
7nm

YIG
GGG

Two-step growth

Roughness = 2.58 nm
Roughness = 1.29 nm

SBLT growth

Roughness = 0.43 nm
Roughness = 0.58 nm

GGG
TmIG
Bi$_2$Se$_3$

7nm
7nm

YIG
GGG

Two-step growth

Roughness = 2.58 nm
Roughness = 1.29 nm

SBLT growth

Roughness = 0.43 nm
Roughness = 0.58 nm

GGG
TmIG
Bi$_2$Se$_3$

7nm
7nm

YIG
GGG

Two-step growth

Roughness = 2.58 nm
Roughness = 1.29 nm

SBLT growth

Roughness = 0.43 nm
Roughness = 0.58 nm

GGG
TmIG
Bi$_2$Se$_3$

7nm
7nm

YIG
GGG
Structural analyses

Two-step growth

(Bi$_{0.3}$Sb$_{0.7}$)$_2$Te$_3$/YIG

Roughness = 0.77 nm

400 nm


SBLT growth

Top surface:
- Smooth surface
- Clear triangular domain

Roughness = 0.43 nm

600 nm

Bi$_2$Se$_3$/YIG

Roughness = 0.71 nm

1 μm


Roughness = 0.58 nm

200 nm

Bi$_2$Se$_3$/YIG

Roughness = 0.47 nm

1 μm
Structural analyses

HRTEM images

Two-step growth

Bi$_2$Se$_3$ (≈1 QL)

Bi$_2$Se$_3$ TmIG

5 nm

Cs-corrected STEM images

Interface:

➢ ~1nm amorphous interlayer

Films:

➢ Clear atomic structures

Interface:

➢ Se buffer layer evaporated

➢ Visible atoms in the 1$^{st}$ QL
Interfacial analyses

XPS spectra of 4 nm Bi$_2$Se$_3$ on TmlG

No elemental Se was detected at the interface!
Anomalous Hall effect (AHE) loops

Magnetic proximity effect (MPE):
Magnetization of the bottom topological surface state (TSS)

Spin current effect has been precluded in our other work

Enhanced exchange coupling at the interface!
Enhanced interfacial exchange coupling

**Two-step growth**

![Graph showing normalized dl/dH(a.u.) vs. H (Oe) for two-step growth.]

137 Oe

**SBLT growth**

![Graph showing normalized dl/dH(a.u.) vs. H (Oe) for SBLT growth.]

365 Oe

-- Our previous work

TSS-induced interfacial anisotropy

-卡通

**Ferromagnetic resonance (FMR)**

Spin dynamics at the interface

-卡通


Bi$_2$Se$_3$ grown on TmIG

Negative shift in $H_{res}$ of TmIG

Enhancement of IMA at the interface

Stronger interfacial exchange coupling!
Our **SBLT growth** attained:

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

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II: (Bi,Sb)$_2$Te$_3$/α-Al$_2$O$_3$ & (Bi,Sb)$_2$Te$_3$/TmIG

- (Bi,Sb)$_2$Te$_3$ / α-Al$_2$O$_3$ & (Bi,Sb)$_2$Te$_3$ / TmIG
  - Characterization of structural properties
  - Evidences of manipulating $E_F$ toward bulk-insulating features
  - Electronic transport & magnetoresistance analysis
Manipulating $E_F$ toward Dirac point

- 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: $(\text{Bi,Sb})_2\text{Te}_3$
- Tuning the position of the $E_F$
- Introducing different amounts of defects
- Modifying the band structure of TI

Bulk conduction band + Surface states

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

$\text{Bi}_2\text{Te}_3$
- $\text{Te}_\text{Bi}$ anti-site
- n-type doping

$\text{Sb}_2\text{Te}_3$
- $\text{Sb}_\text{Te}$ anti-site
- p-type doping


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
• Compositions of (Bi,Sb)$_2$Te$_3$ can be both \textit{in-situ} and \textit{ex-situ} calibrated by X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD), respectively.
**Te capping layer & R-T curves**

Our work

- **At 300 K**
  - \( n_{2D} = 3.37 \times 10^{12} \text{ cm}^{-2} \)
  - \( R_{\text{sheet}} = 45483 \ \Omega \)
  - Mobility = 39.8 cm\(^2\)/Vs

\(~20 \text{ nm Te} \)
\((\text{Bi,Sb})_2\text{Te}_3\)
\(\alpha-\text{Al}_2\text{O}_3\)

To prevent the oxidation of TIs

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

**Semiconductor-like**
- Resistance decreasing with the temperature decreasing

**Metal-like**
- Resistance increasing with the temperature decreasing

\(\sim 600 \ \text{k}\Omega \)
at 100 K

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\(\sim 20 \text{ nm Te} \)
\((\text{Bi}_0.29\text{Sb}_{0.71})_2\text{Te}_3\)
\((\text{Bi}_0.5\text{Sb}_{0.5})_2\text{Te}_3\)
\(\text{Sb}_2\text{Te}_3\)
\(\text{Bi}_2\text{Te}_3\)
Te capping layer & R-T curves

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

**Te capping layer & R-T curves**

\[ G_{total} = \frac{1}{R_0 + AT} + \frac{1}{R_1 \exp\left(\frac{\Delta}{kT}\right)} \]

- \( R_0 = 2172 \ \Omega \)
- \( A = 4.7 \ \Omega/T \)
- \( R_1 = 701 \ \Omega \)
- \( \Delta = 59 \text{ meV} \) ← 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

\[ G_{\text{total}} = \frac{1}{R_0 + AT} + \frac{1}{R_1 \exp\left(\frac{\Delta}{kT}\right)} \]

\begin{align*}
R_0 &= 2172 \ \Omega \\
A &= 4.7 \ \Omega/T \\
R_1 &= 701 \ \Omega \\
\Delta &= 59 \ \text{meV} \rightleftharpoons \text{activation energy}
\end{align*}

- Network of p-n junction
- Activation energy \approx \text{energy from } E_F \text{ to } E_e (\text{effective } E_c)
- Larger \Delta of a TI \Rightarrow \text{better quality}
- The largest achievable \Delta 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 $-1.2 \times 10^{12} \ cm^{-2}$ (15 nm) and $-1.5 \times 10^{12} \ cm^{-2}$ (5 nm)

\[ n_{2D} (x \times 10^{13} \ cm^{-2}) (2K)(15 \ nm) \]

\[ n_{2D} (x \times 10^{13} \ cm^{-2}) (2K)(5 \ nm) \]

- Without capping
- Te capping (LT)
- Te capping (HT)

\( \sim 15 \text{ nm (2K)} \)

\( \sim 5 \text{ nm (2K)} \)
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

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K. L. Wang's group 5 nm ($\text{Bi,Sb}_2\text{Te}_3$) $\mu \sim 500$ cm$^2$/Vs
8 nm ($\text{Bi,Sb}_2\text{Te}_3$) $\mu \sim 300$ cm$^2$/Vs (before applying field effect)

Our group 5 nm ($\text{Bi,Sb}_2\text{Te}_3$) $\mu = 917$ cm$^2$/Vs

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**Graphs:**

- **Right graph:**
  - ~15 nm (2K)
  - ~5 nm (2K)
  - Various symbols represent different capping layers and growth conditions.
  - **Legend:**
    - *without capping*
    - Te capping (LT)
    - Te capping (HT)
Two conductive transport channels

HLN equation:

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

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

\( \alpha \sim -1: \) two channel with WAL

\( l: \) phase coherence length

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

\[ \Delta \beta = \gamma \left( \frac{e^2}{\pi \hbar} \right) \left[ \psi \left( \frac{\hbar}{4e l^2 B} + \frac{1}{2} \right) - \ln \left( \frac{\hbar}{4e l^2 B} \right) \right] + cB^2 \]

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

\( \alpha \): phase coherence length

- \( \Delta G_{xx} \): conductive channel
- \( G_{xx} \): insulating channel

(1) \( \Delta \beta \): phase coherence length
(2) \( G_{xx} \): conductive channel

- \( \alpha \): phase coherence length
- \( \Delta \beta \): conductive channel
- \( G_{xx} \): insulating channel

(1) \( \Delta \beta \): phase coherence length
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- \( \alpha \): phase coherence length
- \( \Delta \beta \): conductive channel
- \( G_{xx} \): insulating channel
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
- At 300K
- Thickness = ~20 nm
- $K\rightarrow\Gamma\rightarrow K$
Low-temperature growth
(modified from Se-buffered low-temp. (SBLT) growth)

Breaking TRS by MPE

Observation of AHE up to RT

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

(Bi,Sb)$_2$Te$_3$/TmIG (in this work) vs Bi$_2$Se$_3$/TmIG (our previous work)
Observation of AHE up to RT

Factors affect the extent of $R_{AH}$:

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


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

\[ R(T) \]

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

MR analysis by HLN equation

\[ R_s (k\Omega) \]

\[ B (T) \]

2 K

\[ \sim 15 \text{ nm} \]

\[ \sim 5 \text{ nm} \]

\begin{itemize}
  \item Magnetization gap
  \[ R_s \geq h/e^2 \]
  \item Strong localization
  \item Hybridization gap
\end{itemize}

No negative MR

Bi\textsubscript{2}Se\textsubscript{3}/TmIG (our work)


Bi\textsubscript{2}Se\textsubscript{3} 9 nm/Sapphire
Bi\textsubscript{2}Se\textsubscript{3} 9 nm/TmIG
MR analysis by HLN equation

- No negative MR
- Suppressed WAL
- Smaller magnitude of $\alpha$ in $(Bi,Sb)_2Te_3/TmIG$ than those on Sapphire

$Bi_2Se_3/TmIG$ (our work)

$Bi_2Se_3 9$ nm/Sapphire
$Bi_2Se_3 9$ nm/TmIG

$(Bi,Sb)_2Te_3/TmIG$ (this work)

$BST 5$ nm/TmIG
$BST 15$ nm/TmIG
$BST 5$ nm/Sapphire
$BST 15$ nm/Sapphire

$\alpha$

Fitting Range (T)

$0.2$ $0.3$ $0.4$ $0.5$ $0.6$

$-1.0$ $-0.8$ $-0.6$ $-0.4$ $-0.2$ $0.0$

$R_{xx}(B)/R_{xx}(0)$

$B$ (T)

$-9$ $-6$ $-3$ $0$ $3$ $6$ $9$

$R_s(B)/R_s(0)$

$B$ (T)

$-9$ $-6$ $-3$ $0$ $3$ $6$ $9$
When the top surface and the bottom surface are decoupled,

\[ \Delta \sigma_{\text{total}} = \sigma_{\text{top surface}} + \sigma_{\text{bottom surface}} \]

- \( \sigma_{\text{top surface}} = \text{WAL} (\alpha = -0.5) \)
- \( \sigma_{\text{bottom surface}} = \text{WAL} (-0.5 < \alpha < 0) + \text{WL} (0 < \alpha < 0.5) \)
Excellent crystallinity in (Bi,Sb)$_2$Te$_3$ on $\alpha$-Al$_2$O$_3$

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

Excellent crystallinity in (Bi,Sb)$_2$Te$_3$ on TmIG

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

$T = 300K$
Conclusion
Conclusion

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

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

- Modifying the growth from Bi$_2$Se$_3$/RelG
- Pushing the $T_c$ up to room temperature (AHE)