Spin-electricity conversion induced by spin pumping into topological insulators

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Spin injection into "bulk-insulating" topological insulators

PRL **113,** 196601 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Spin-Electricity Conversion Induced by Spin Injection into Topological Insulators

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theory

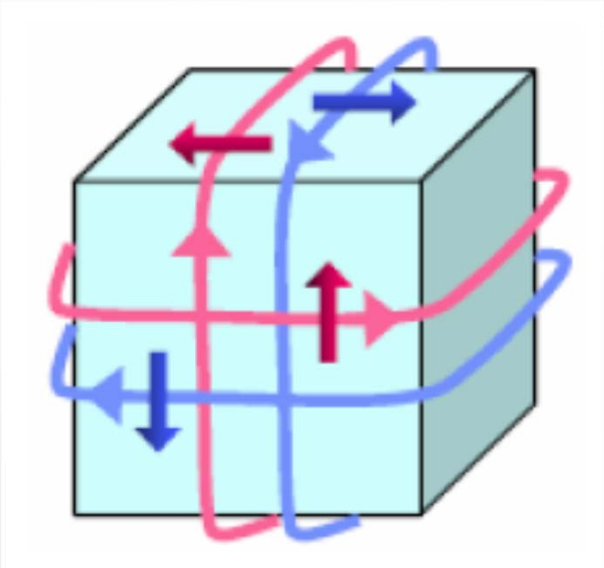
TI sample

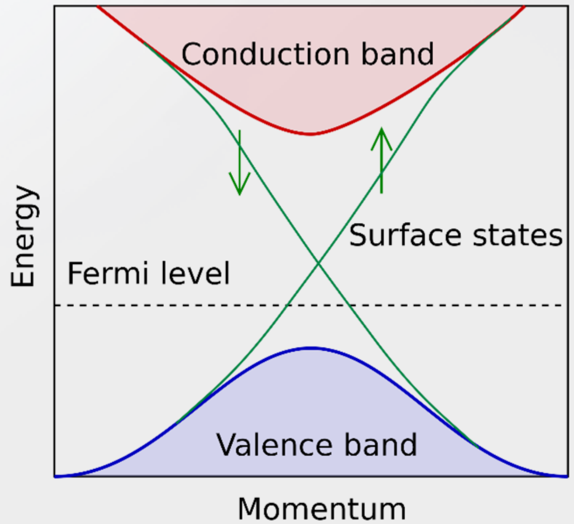
boss

arXiv:1312.7091 (2013)
Phys.Rev.Lett. **113**, 196601 (2014)

TI is a promising material for spintronics application

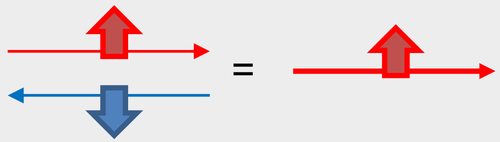
Topological Insulator (TI)





Surface: metal
Interior: Insulator

(1) spin current ≠ 0
electric current = 0

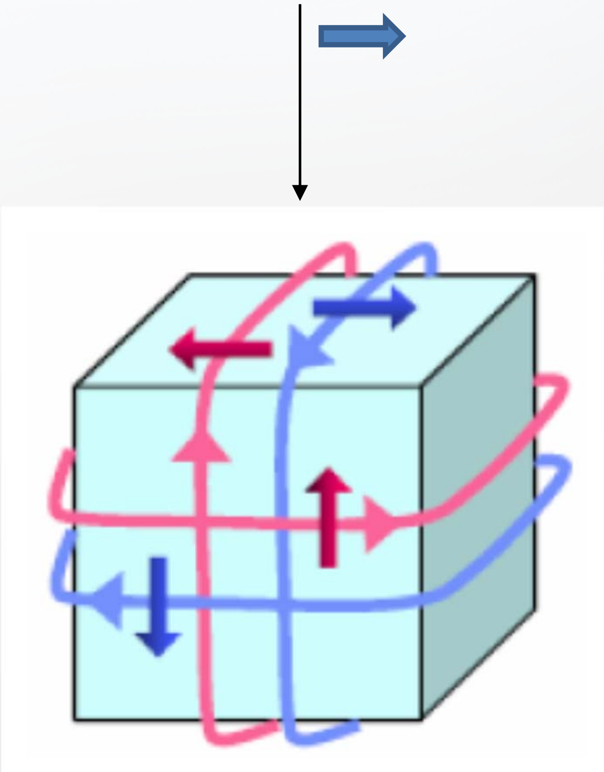


(2) spin-momentum locking

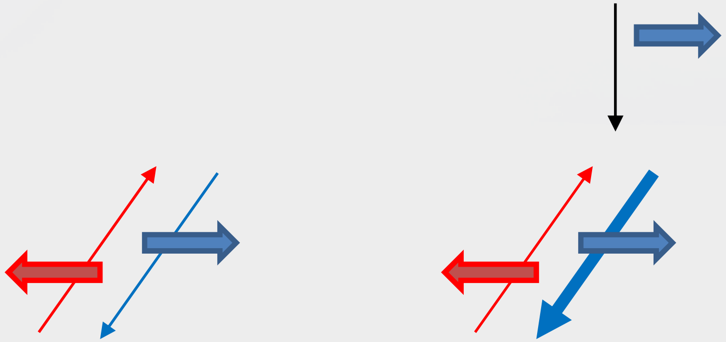
(3) surface property determined by bulk property

Spin injection into surface states of topological insulators

spin injection



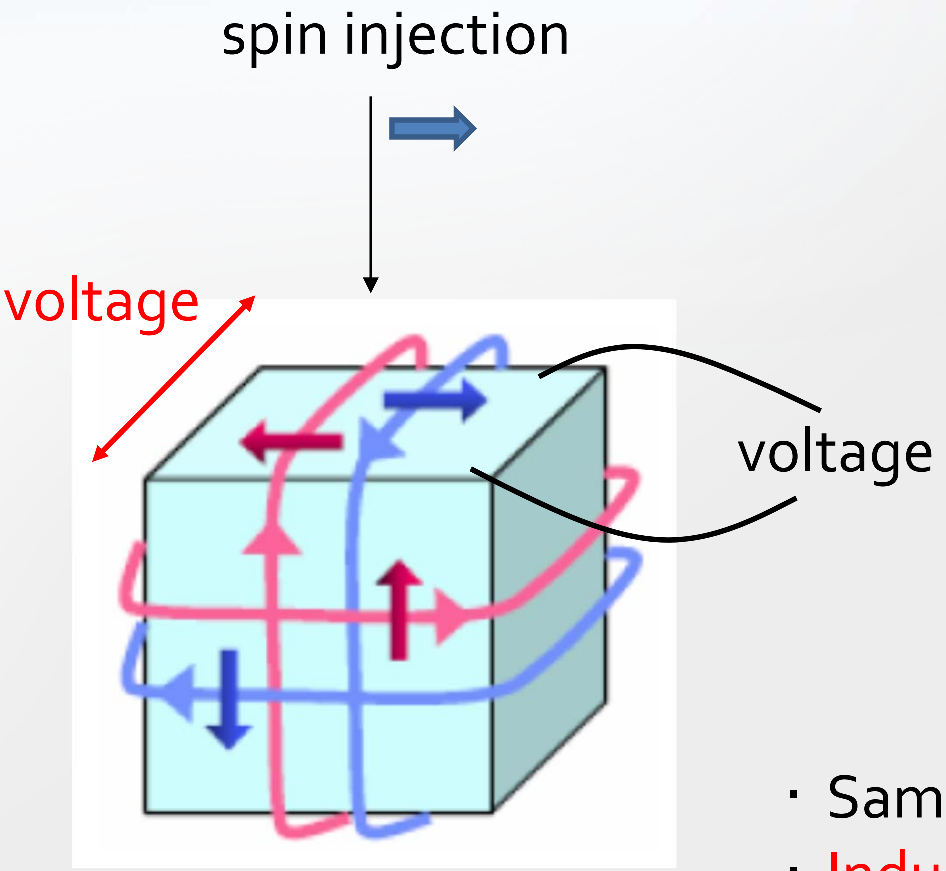
spin injection

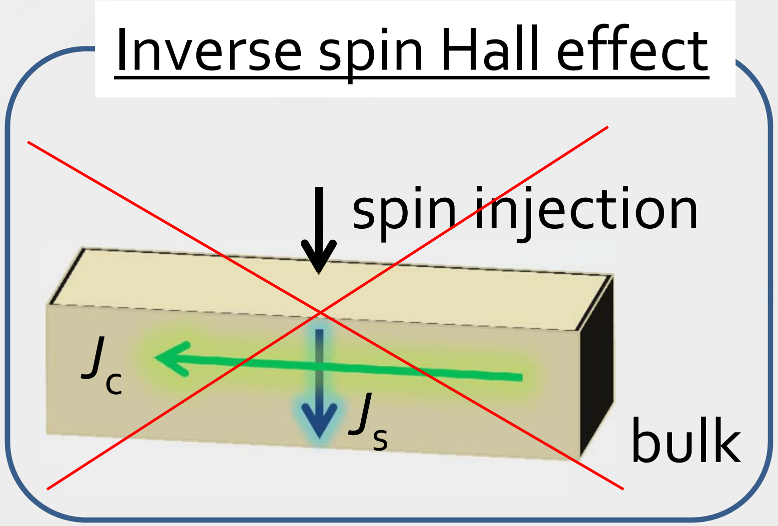


Electric current = 0   ≠ 0

Electric current induced by spin injection

Spin-electricity conversion induced by spin injection

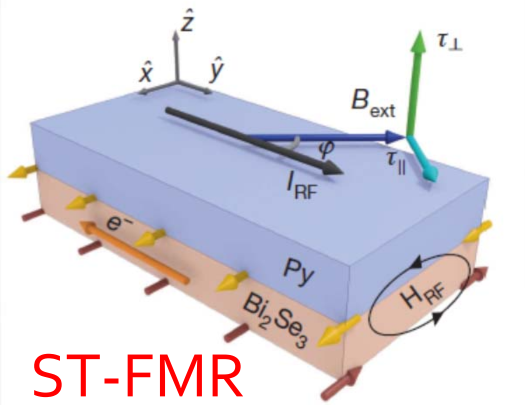




- Same symmetry as ISHE
- Induced by spin-momentum locking
  (in principle, perfect conversion)

Some trials for spintronics application of TI

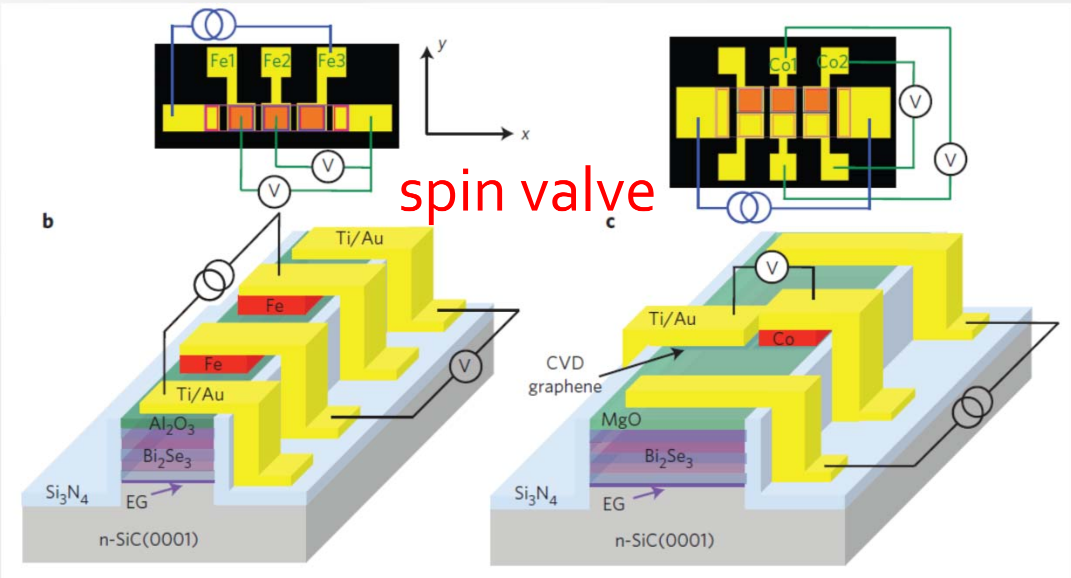
A.R.Mellnik, et al. Nature 511, 449-451 (2014)



Parameter	Bi_2Se_3 (this work)
$\theta_\parallel$	2.0–3.5
$\sigma_{S,\parallel}$	1.1–2.0

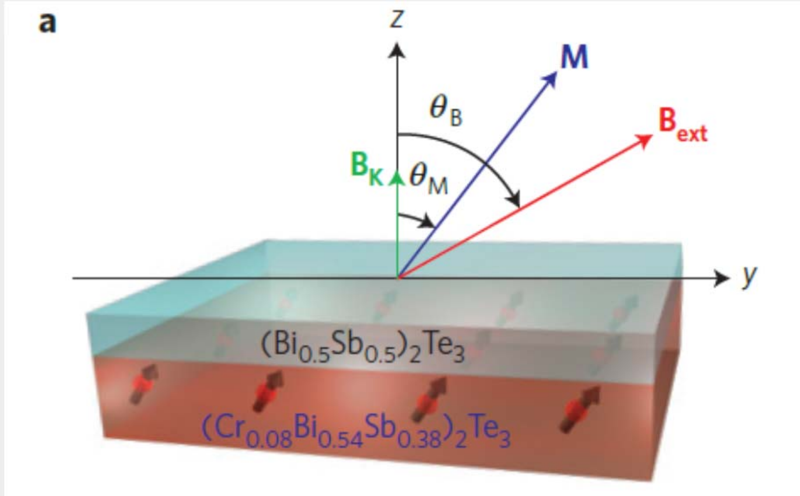
Hall angle > 1

C.H.Li, et al. Nature Nano. 9, 218-224 (2014)



Y. Fan, et al. Nature Mat. 13, 699-704 (2014)

Magnetization switching

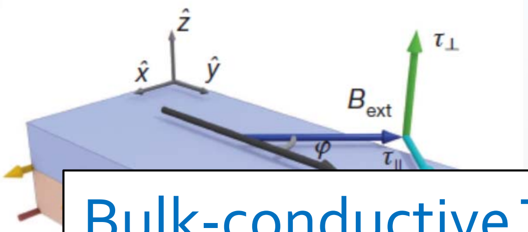


electric means

Bulk insulating
⇒ tiny electric current in TI

Some trials for spintronics application of TI

A.R.Mellnik, et al. Nature 511, 449-451 (2014)



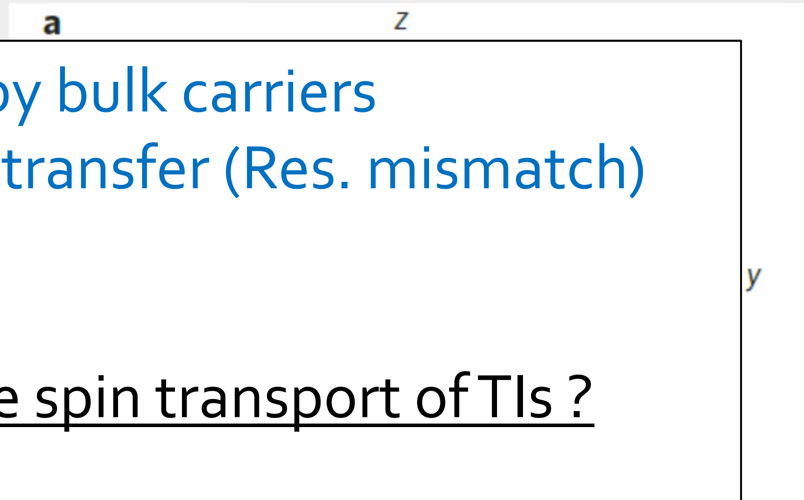
Parameter	Bi_2Se_3 (this work)

S

C.H

Y. Fan, et al. Nature Mat. 13, 699-704 (2014)

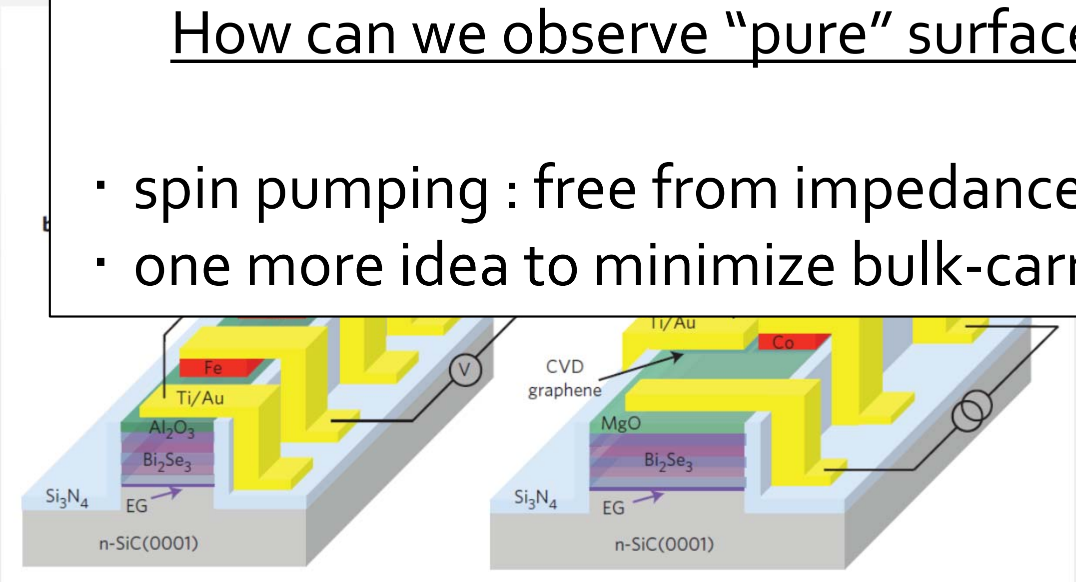
Magnetization switching



Bulk-conductive TI ⇒ contaminated by bulk carriers
Bulk-insulating TI ⇒ not-efficient spin transfer (Res. mismatch)

<u>How can we observe "pure" surface spin transport of TIs ?</u>

- spin pumping : free from impedance mismatch (K.Ando 2011)
- one more idea to minimize bulk-carrier contribution

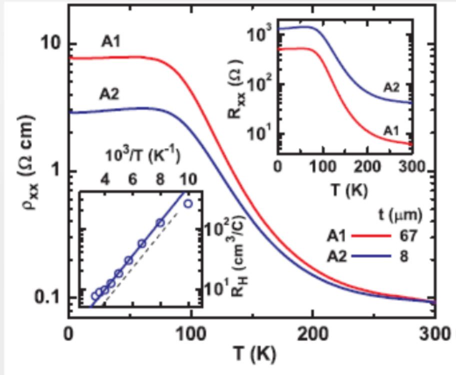


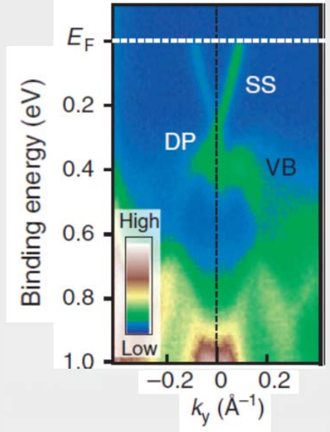
Bulk insulating
⇒ tiny electric current in TI

Our experimental setup: Use of "Bulk form" topological insulators

T.Arakane, et al. Nat. Commun. 3, 636 (2011)

A.A.Taskin, et al. PRL 107, 016801 (2011)





<u>Bulk-carrier compensated TIs</u>:

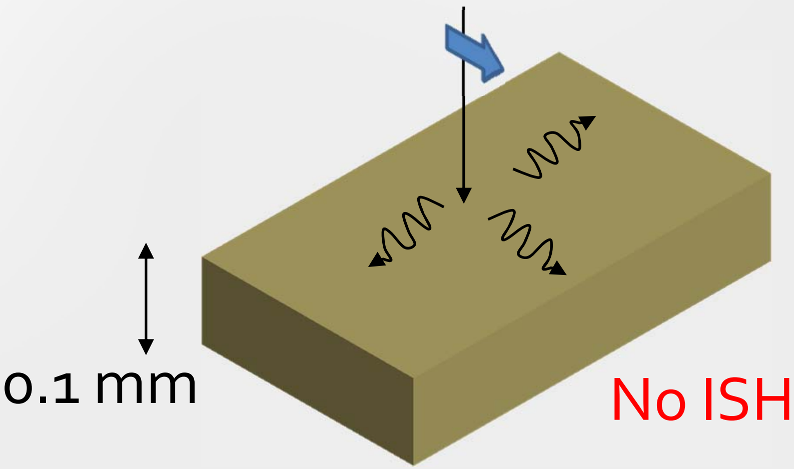
$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$, $BiSbTeSe_2$,

Sn-doped Bi_2Te_2Se

<u>Bulk-metallic TIs</u>:

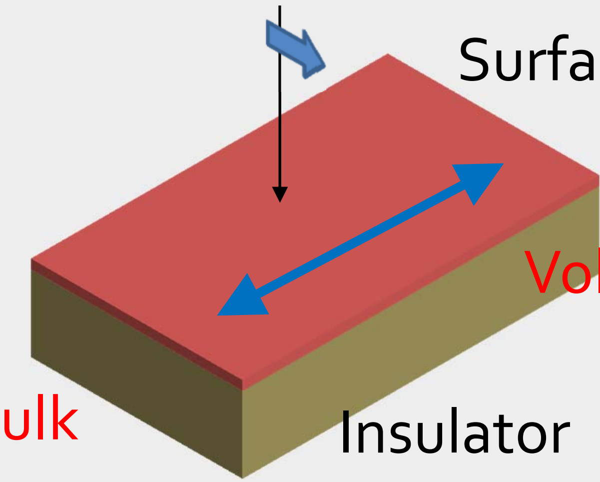
Bi_2Se_3

From Yoichi Ando (Osaka Univ.)



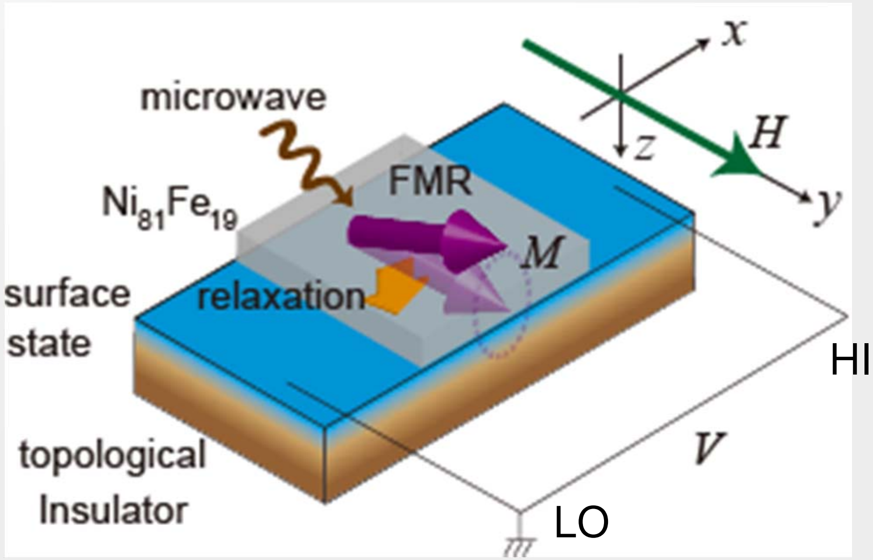
No ISHE from bulk

sample thickness >> spin diffusion length

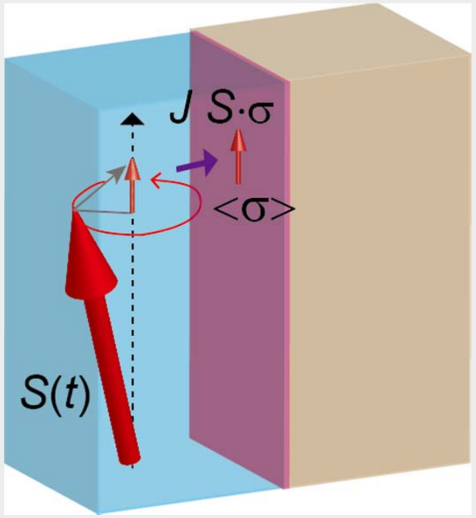


Methods and samples

- ferromagnet :permalloy ($Ni_{81}Fe_{19}$) 20nm thick
- coplanar-type wave guide, network analyser (typically, 5 GHz is used)
- measurement down to 15K (probe station)



Spin pumping



spin precession
⇒ spin current

Methods and samples

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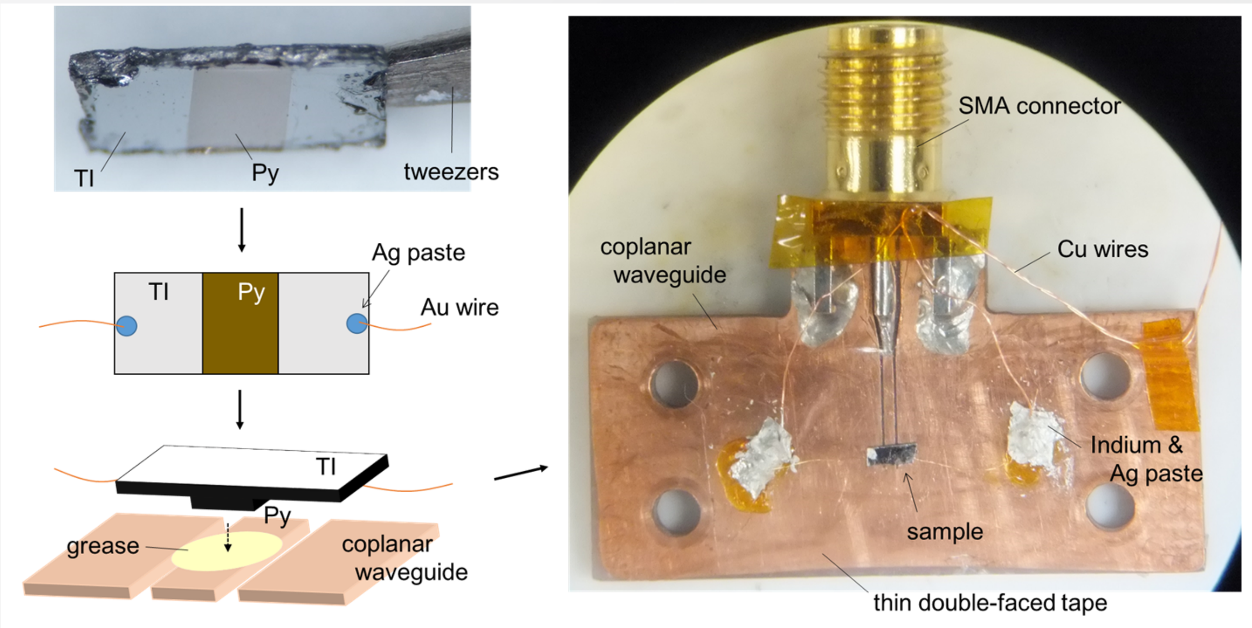
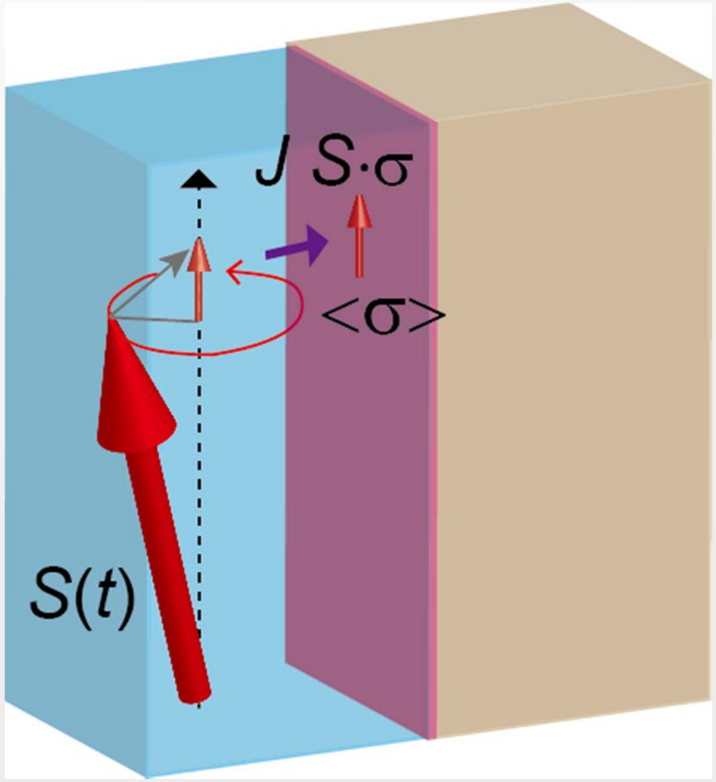


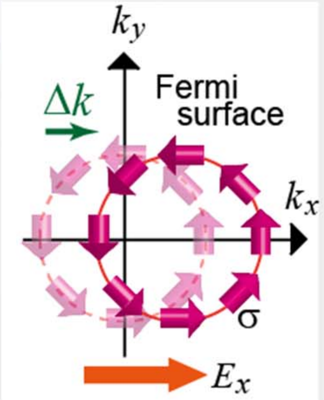
Spin pumping

Prof. Kentaro Nomura

$$H = v_F(\hat{z}\times\vec{\sigma})\cdot\vec{p} + J_{sd}\vec{S}\cdot\vec{\sigma} = v_F(\hat{z}\times\vec{\sigma})\cdot(\vec{p}+e\vec{a}) + J_{sd}S_z\sigma_z$$

Spin pumping





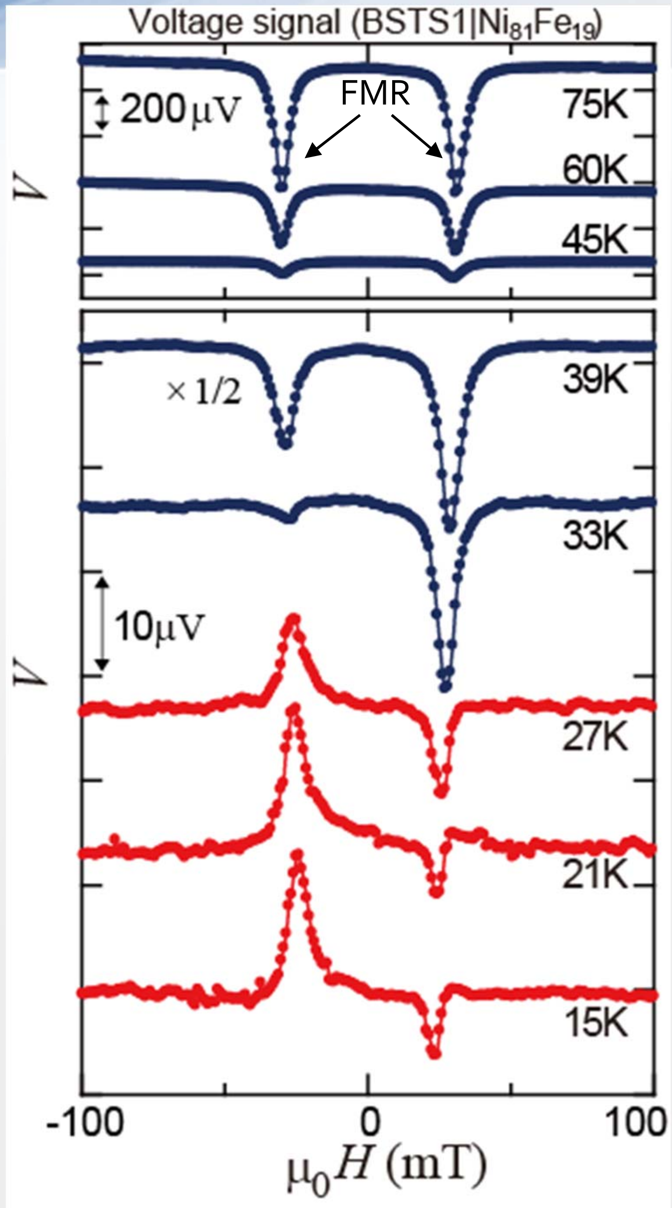
$\dot{\vec{a}}$ = voltage generation

spin exchange interaction
= torque

$$\vec{T}_{surface} = \gamma\vec{M}\times J_{eff}\langle\vec{\sigma}\rangle$$

damping enhancement

Voltage signals at FMR of Py at various temperatures for a $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ (BSTS) sample

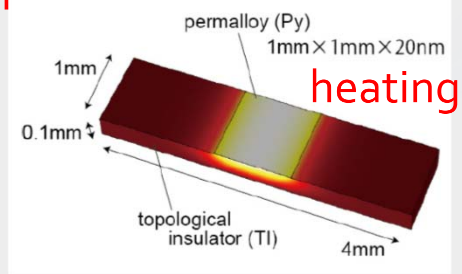


High-T : symmetric signal (Seebeck effect)

↓

Asymmetric signal

depend on environment



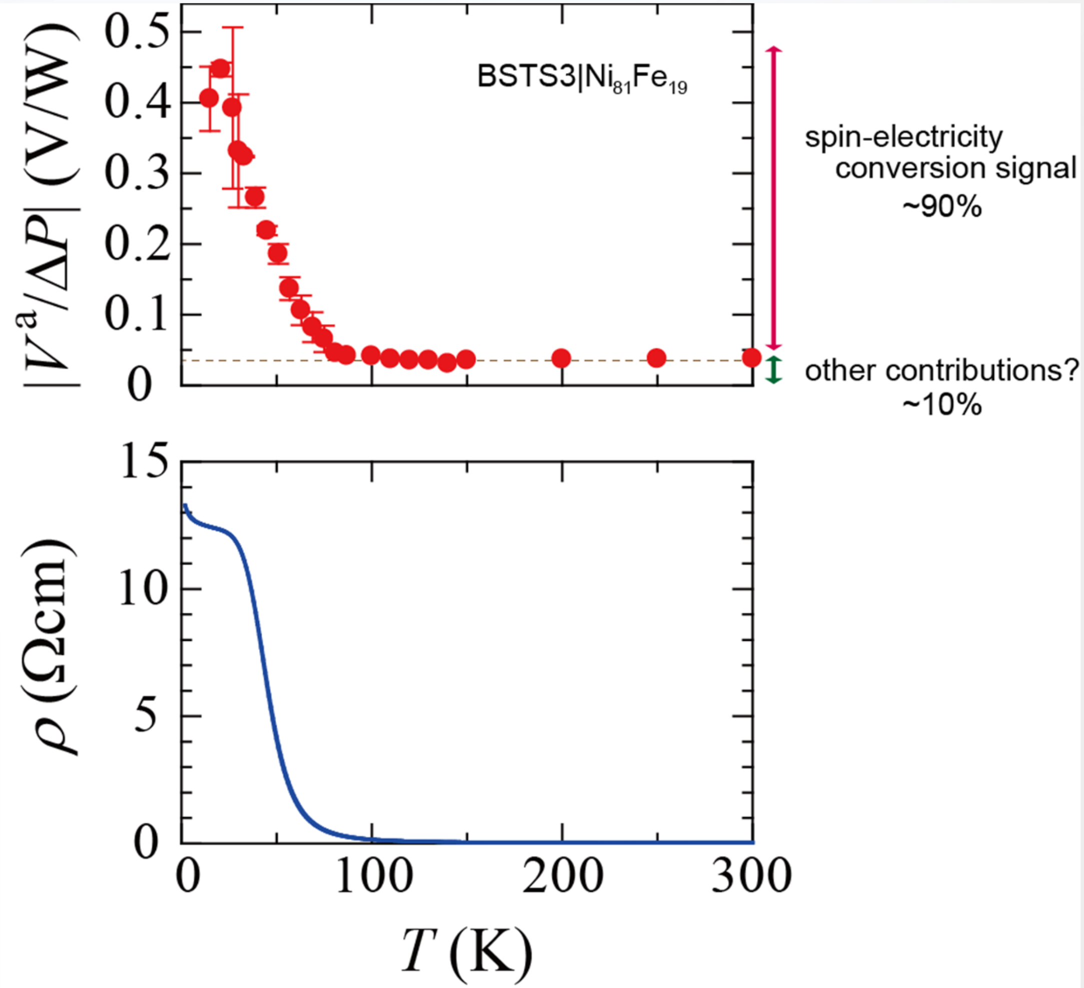
↓

Sign inversion between +H and -H

<u>Correlation to surface conduction being dominant at low *T*s</u>

Correlation between antisymmetric voltage signals and surface transport

$$V^a = [V(H) - V(-H)]/2$$



V^a increases with decreasing T

↗ ×10 !!

- NOT shunting of AMR

$$\frac{R_{\mathrm{BSTS}}}{R_{\mathrm{Py}} + R_{\mathrm{BSTS}}} V_{\mathrm{AMR}}$$ ↗ ×2

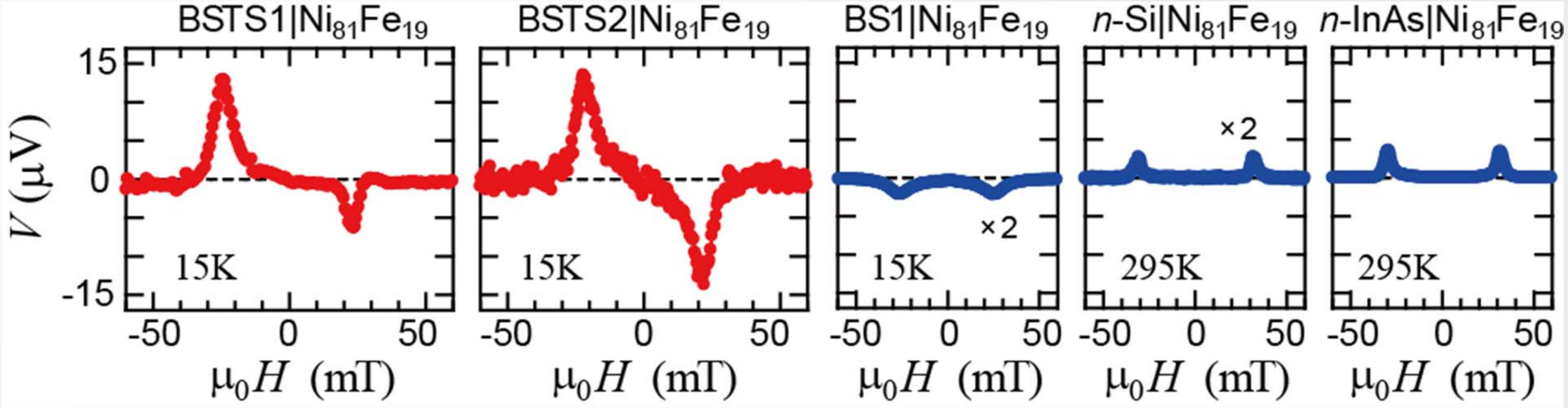
$R_{BSTS} \approx R_{py}$ (≈ 5Ω) at 300 K

$R_{BSTS} >> R_{py}$ at low Ts

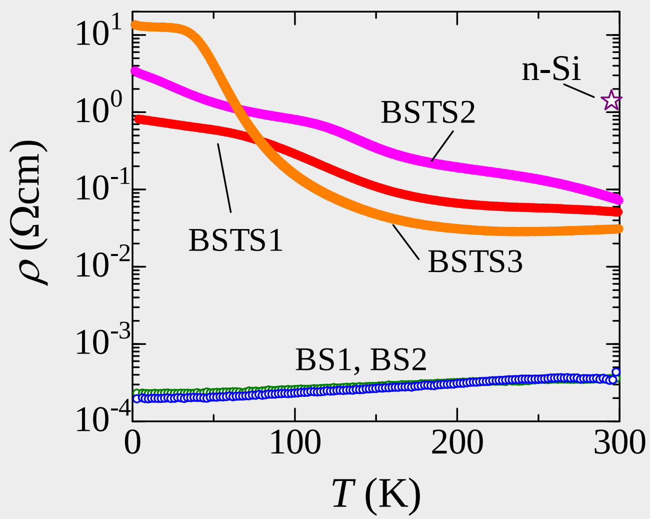
- NOT Nernst effect

∝ T at low Ts (Mott relation)

NO antisymmetric signal in control samples: bulk-metallic TIs (Bi_2Se_3); conventional semiconductors



- Reproducible for all BSTS samples
- not observed for BS1, *n*-Si, or *n*-InAs



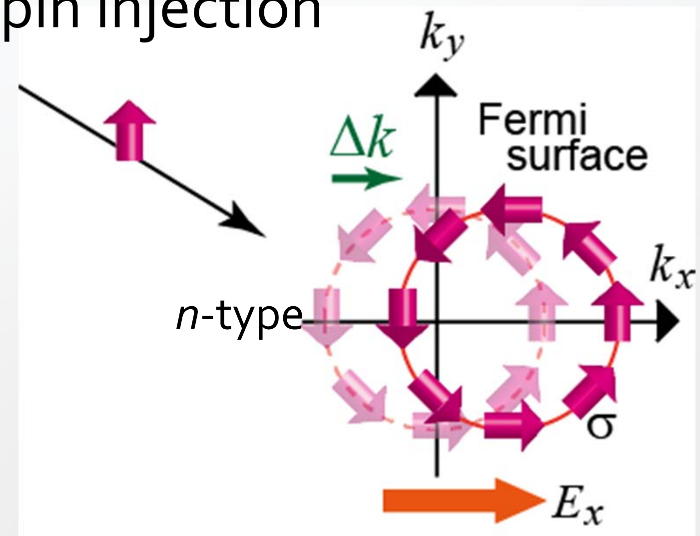
Anti-symmetric signals arise on topological surface states

Mechanism of spin-electricity conversion effect

Prof. Kentaro Nomura

"spin-momentum locking" ⇒ spin-electricity conversion

spin injection



shift of the Fermi circle

$$\Delta k_x = (e\tau/\hbar)E_x$$

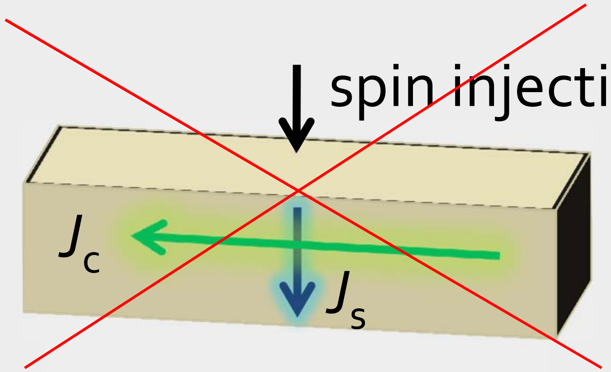
$$\frac{\langle \sigma_y \rangle}{A} = \frac{1}{A}\sum_{\vec{k}} f_{\vec{k}} \langle \vec{k},+ | \hat{\sigma}_y | \vec{k},+ \rangle$$

$$\Rightarrow \quad E_x = -\frac{4\pi\hbar}{e\tau k_F}\frac{\langle \sigma_y \rangle}{A}$$

same sign as the experiment

ISHE

spin injection



bulk

if Hall angle θ defined, θ~1%

Summary & perspective

Phys.Rev.Lett. **113**, 196601 (2014)

・ observation of anti-symmetric signals on millimeter-thick bulk-insulating TIs

・ anti-symmetric signals arise on surface states

・ build a model ： new spin-electricity conversion

the voltage sign is consistent

in principle, high efficiency up to 100%, but only ~ 1% now.

↓

・ improve the efficiency

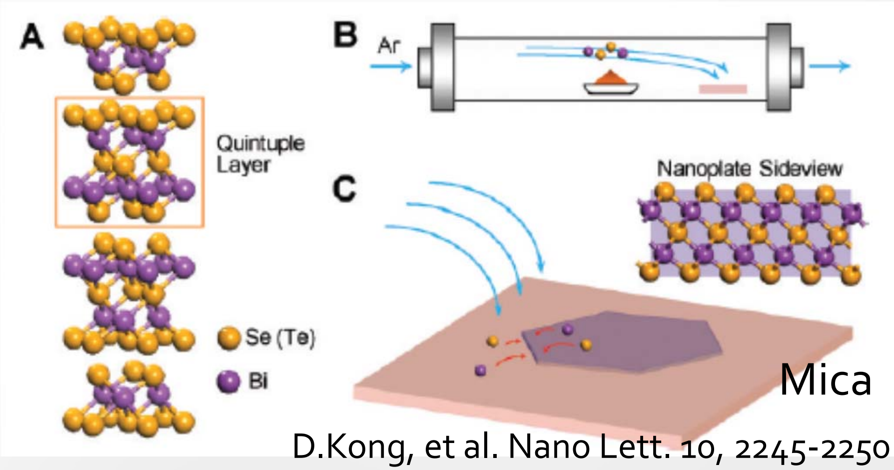
(improve interface quality, reduce magnetic proximity effect, etc.)

・ experiments in BSTS|YIG systems

Perspective: BSTS on YIG

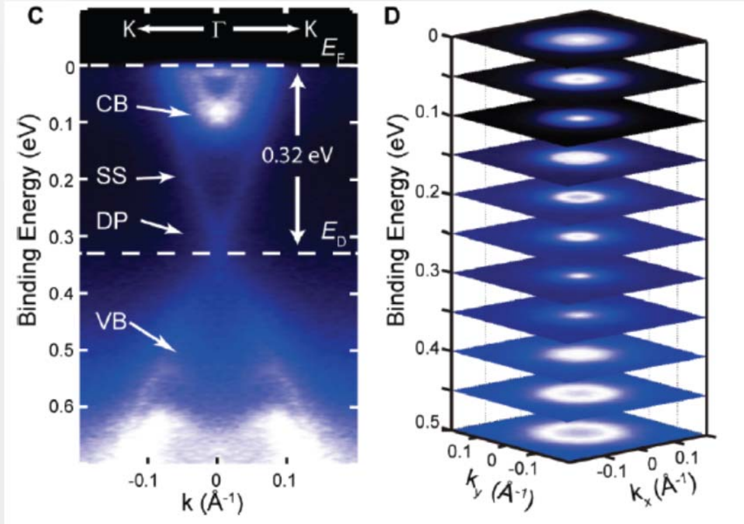
Growth of BSTS plates on Mica substrate ⇒ transfer onto YIG

Catalyst-free vapor solid method



D.Kong, et al. Nano Lett. 10, 2245-2250 (2010)

H.Li, et al. JACS. 134, 6132-6135 (2012)



BSTS plate (~ 1mm size)

⇒ transfer onto YIG

By Dr. Tanabe (Tohoku Univ.)

Au(20nm)|YIG

$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ plate
(50 nm thick)