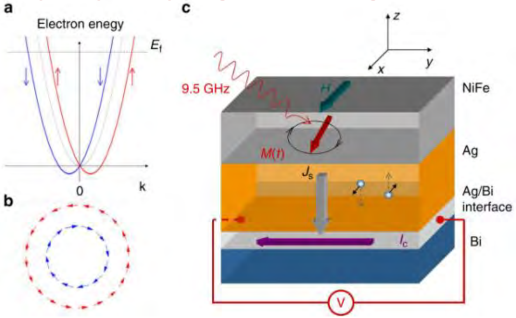
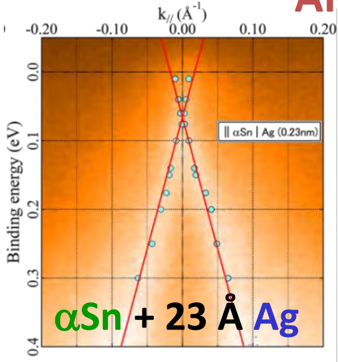
Interfacial spin-orbitronics: Large spin-current conversion in α-Sn topological insulator and potential for giant Spin Seebeck effect in YIG/α-Sn

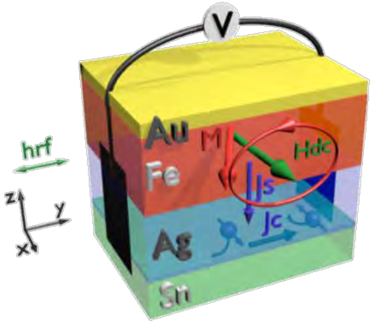
SP-FMR

(spin pumping ferromagnetic resonance)



ARPES & SP-FMR





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Acknowledgements

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CEA, Grenoble, F-38000 France

Y. Ohtsubo*, P. LeFevre, F. Bertran, A. Taleb-Ibrahimi

**Osaka Univ., Suita 565-0871,Japan*

Synchrotron SOLEIL, Gif, France

CEA-Eurotalents
(FP7 Marie-Skłodowska-Curie Actions)

SPINHALL + SOSPIN

Motivation: Spin-Orbit at surfaces and interfaces for SPINTRONICS

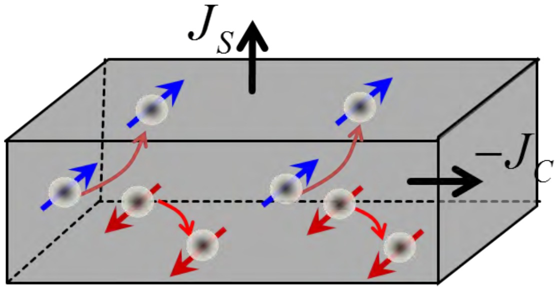
Use new Spin-Orbit (SO) effects towards
the creation, manipulation and detection of spin currents for potential applications in spintronics

- **SO effects in bulk materials: Spin Hall Effect**

- **SO effects at surfaces and interfaces (Rashba interfaces, interfaces between oxides, topological insulator)**

Examples of SO effect in bulk materials: Spin Hall Effect

Spin Hall effect (SHE) and ISHE
(bulk effects)



➔ **Efficiency of conversion:**

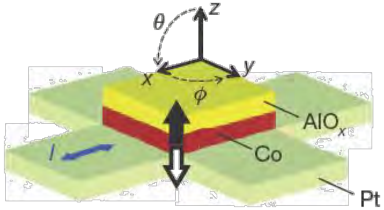
Spin hall angle $\theta_{SHE} = \dfrac{\textit{spin current density}}{\textit{charge current density}}$

(dimensionless)

Pt(0.056), Pd(0.01), βTa(-0.2), βW(-0.3), WO_x(-0.5), Mo(-0.001), Ge, CuBi (-0.11), CuIr(-0.02), Au(0.04), AuW(0.1), AuPt , AuTa (-0.5), CuPt

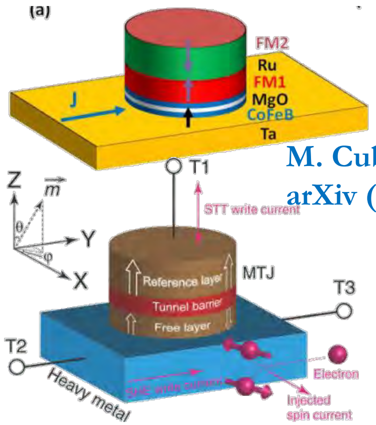
Applications

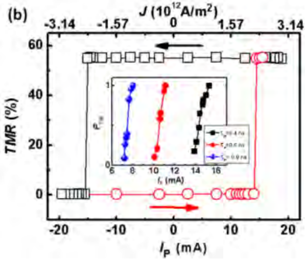
SOT- electrical switching



I. M. Miron *et al.*, Nature 476, 789 (2011)
Liu et al. Science 333, 555 (2012)
J.C R-S et al. APL 108, 082406 (2016)
T.H. Pham et al. (in preparation)

Ultrafast 3-terminal SOT MRAM





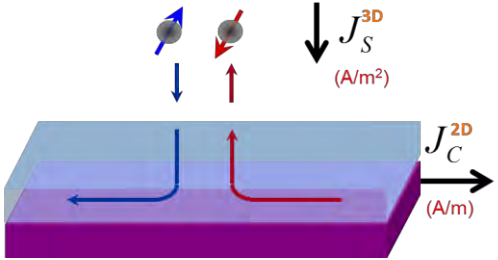
M. Cubukcu et al., arXiv (2015)

Z. Wang, W. S. Zhao *et al.*, J. Phys. D: 48, 065001 (2015)

Examples of SO effect in 2D materials: Edelstein Effect in Rashba interfaces and topological insulators

Edelstein effect (EE) and IEE

(interface effects)

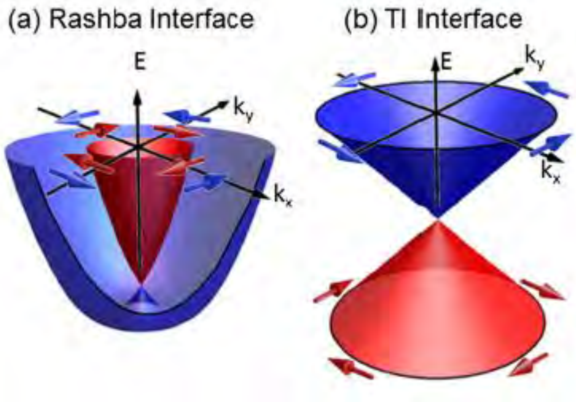


- ➔ Efficiency of EE conversion:

  $\lambda_{EE} = q_{ICS} = J_s^{3D}/J_c^{2D}$ (1/length units)

- ➔ **Efficiency of IEE conversion:**

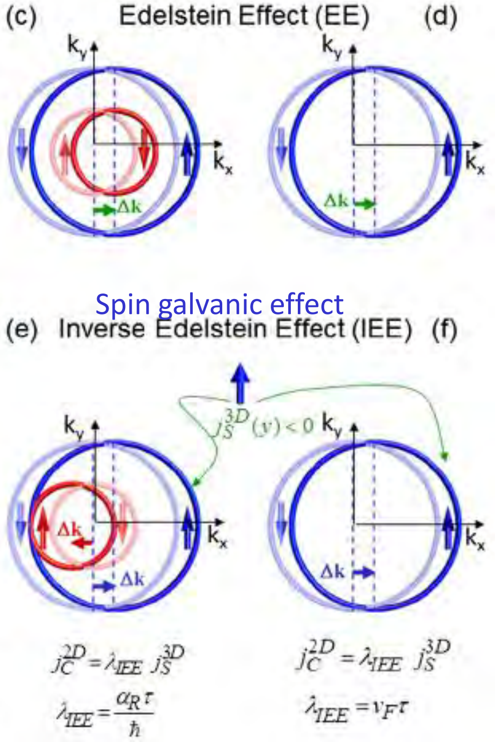
  $\lambda_{IEE} = J_c^{2D}/J_s^{3D}$ (length units)



SOC +
Inv. symm. Breaking:
Sub-band spin
splitting along k

SOC +
TRI symm.
Protection + band
inversion:
linear dispersion of
surface states (Dirac
cone)

Inverse spin galvanic effect

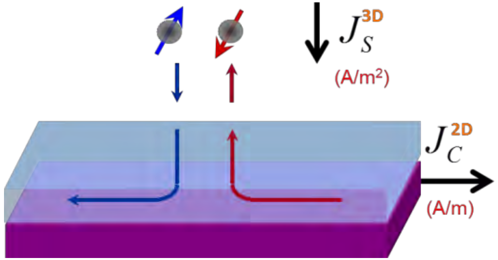


J.-C. R-S *et al.*, *Nat. Comm.* 4, 2944 (2013), *PRL.* 116, 096602 (2016), arXiv (2015)

Examples of SO effect in 2D materials: Edelstein Effect in Rashba interfaces and topological insulators

Edelstein effect (EE) and IEE

(interface effects)



➔ Efficiency of EE conversion:

$\lambda_{EE} = q_{ICS} = J_s^{3D}/J_c^{2D}$ (1/length units)

Sb_2Te_3 (1 nm^{-1}, 15 K)

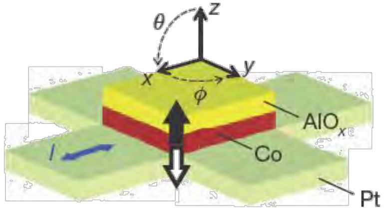
➔ **Efficiency of IEE conversion:**

$\lambda_{IEE} = J_c^{2D}/J_s^{3D}$ **(length units)**

Ag/Bi(0.3nm), Ag/Sb (0.01nm), Cu/BiOx (0.5nm), Ag/BiOx(0.3nm), Fe/Ge[111] (0.13nm, 20K), STO/LAO (6.1nm, 7 K) Fe/GaAs[001] (-0.11 nm), … **α-Sn (2.4 nm)**, …

Applications

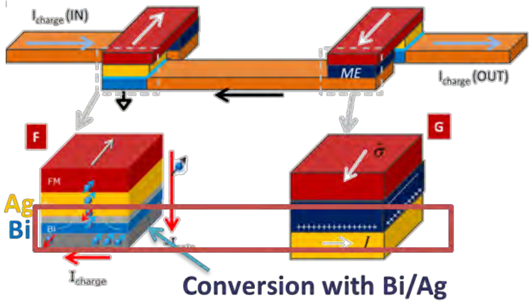
SOT- electrical switching



Y. Fan et al. Nat Mat (2014) @ 1.9 K
some reports in arXiv at RT
CFB/Bi_2Se_3; CoTb/Bi_2Se_3

F/NM/TI (using a spacer or barrier)

Spin-orbit logic



Conversion with Bi/Ag

(Manipatruni et al. arXiv 2015 INTEL)

spin battery

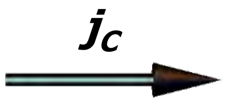
F. Mahfouzi *et al.*, PRB 82, 195440 (2010)

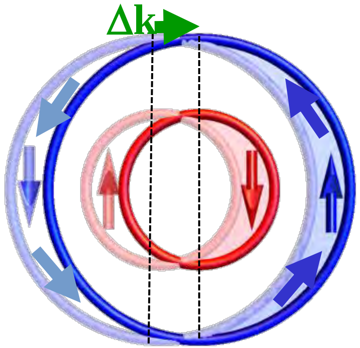
(a)

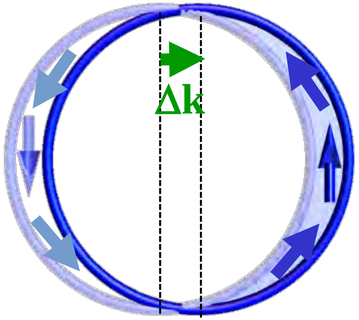
Edelstein and Inverse Edelstein Effect

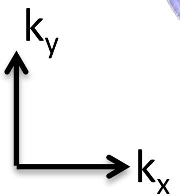
Rashba interfaces

Topological insulator interfaces/surfaces







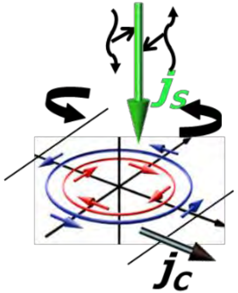


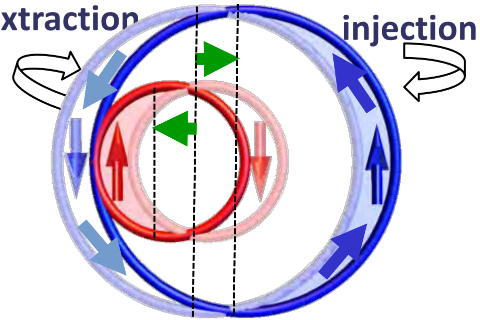
Inverse spin galvanic effect

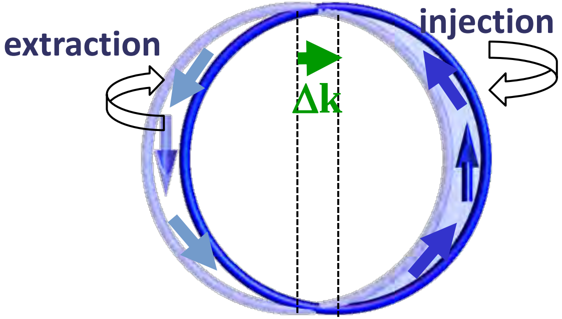
Edelstein Effect (EE)

Predicted in 1990 by Edelstein: Solid State Comm. **73**, v3, 233, (1990)

charge current j_C in 2DEG induces nonzero spin density σ_y







Spin galvanic effect

Inverse Edelstein Effect (IEE)

Injection of spin current j_s induces charge current j_C

length

A/m **A/m²**

$$j_c^{2D} = \lambda_{IEE}\; j_s^{3D}$$

$$\lambda_{IEE} = \alpha_R\, \tau / \hbar$$

J.C R-S, AF et al. Nat Comm. 4, 2944 (2013)
K. Sheng et al. PRL 112, 096601 (2014)

J.C R-S, AF et al. PRL 116, 096602 (2016)
S. Zhang and AF. PRB 94, 184423 (2016)

length

A/m **A/m²**

$$j_c^{2D} = \lambda_{IEE}\; j_s^{3D}$$

$$\lambda_{IEE} = v_F\, \tau$$

Outline

I. Background: Spin pumping voltage by FMR due to ISHE and IEE

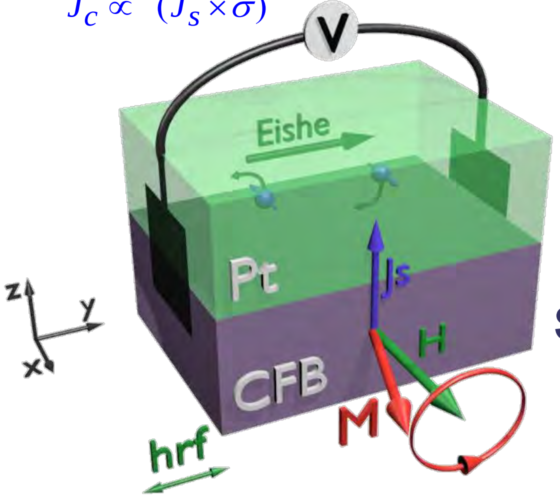
II. IEE in Bi/Ag/NiFe, Ge[111]/Fe, STO/LAO/NiFe and α-Sn/Ag/Fe/Au

III. ISHE vs IEE and perspective for low power applications

Summary

Spin pumping – Ferromagnetic resonance

$\vec{J}_C \propto (\vec{J}_S \times \vec{\sigma})$



Voltage **(charge current production)**

⇧

ISHE or IEE

⇧

Spin current

⇧

FMR

$$I_c = \frac{V_{SP}}{R}$$

Symmetrical voltage amplitude
Total resistance

$$I_c = \frac{V_{SP}}{R} = \mathrm{w}\,\theta_{\mathrm{SHE}}\, l_{sf}\, J_s^{3D}\, \mathrm{Tanh}\frac{t}{2l_{sf}}$$

Not only spin pumping yields symm. Voltage
M. Harder et al. Phys. Rep, 661, 1 (2016)

Spin pumping : generation of out of equilibrium spin distribution in FM and spin current injection in adjacent layer at FMR condition

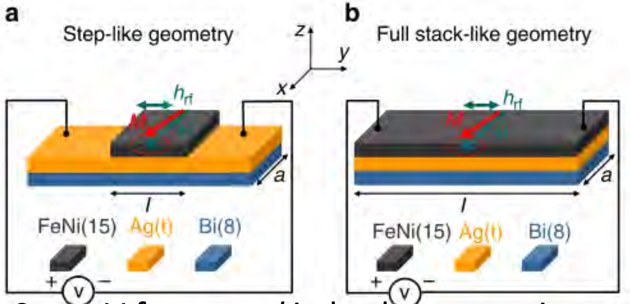
Tserkovnyak et al. PRL 88, 117601 (2002)
Silsbee et al. PRB 19, 4382 (1979)

$$J_s^{3D} = g_{\mathrm{eff}}^{\uparrow\downarrow}\frac{\hbar\gamma^2 h_{\mathrm{rf}}^2}{8\pi\alpha^2}\,\frac{4\pi M_s\gamma+\sqrt{(4\pi M_s\gamma)^2+4\omega^2}}{(4\pi M_s\gamma)^2+4\omega^2}\left(\frac{2e}{\hbar}\right)$$

K. Ando et al. JAP 108 , 113925 (2010)

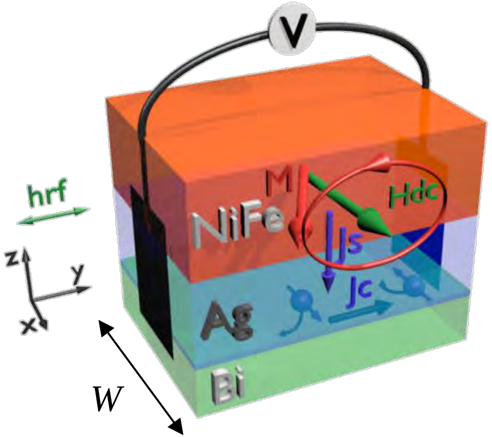
$$g_{\mathrm{eff}}^{\uparrow\downarrow} = \frac{4\pi M_s t_F}{g\,\mu_B}\left(\alpha_{FM/NM} - \alpha_{FM}\right)$$

Not only spin pumping enhances α

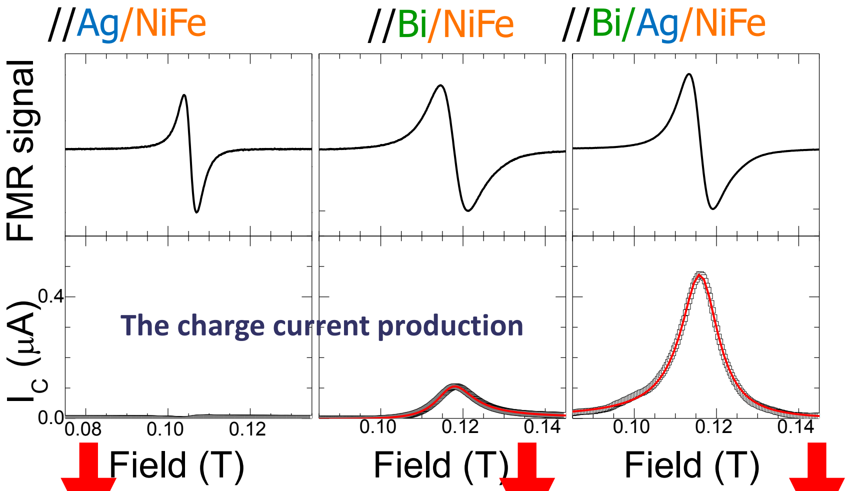


Same V for same *l* in both geometries

Ag/Bi interface : Inverse Edelstein Effect



Coll. J. M. De Teresa, Zaragoza, Spain



Room temperature

Bi/Ag[111] and Bi[111]
are very active Rashba interfaces
3.05 eV Å and 0.56 eV Å, resp.
C.R. Ast et al. PRL **98**, 186807 (2007)
Y.M. Koroteev et al. PRL **93**, 046403 (2004)

Ag and NiFe/Ag : transparent for spin injection

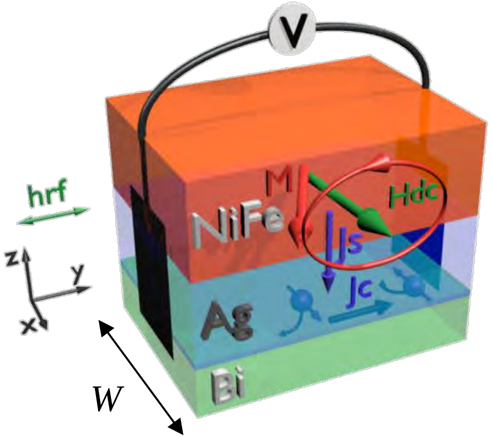
small I_c in Bi

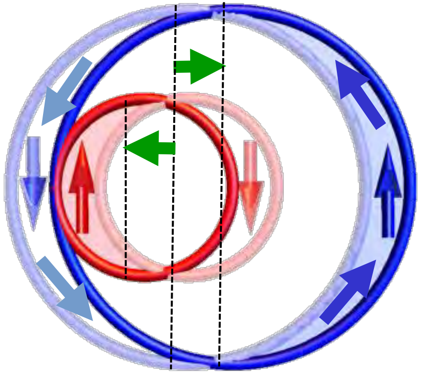
Similar to D. Hou et al. APL 101, 042403 (2012)

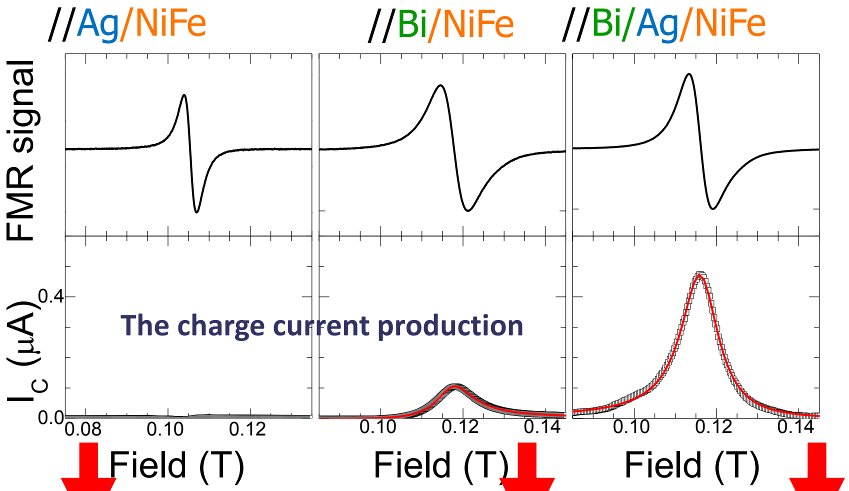
Ic is large only when there is a Ag/Bi interface

Ag/Bi interface : Inverse Edelstein Effect

Coll. J. M. De Teresa, Zaragoza, Spain







Room temperature

Ag and NiFe/Ag : transparent for spin injection

small I$_c$ in Bi

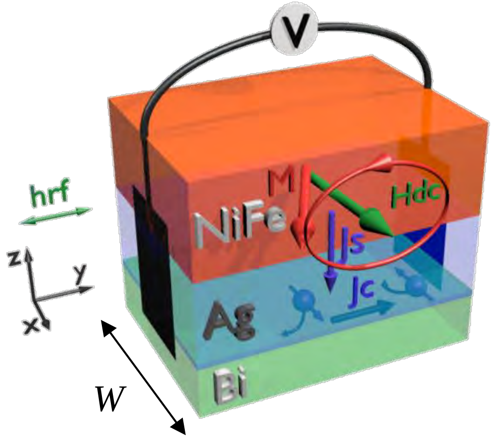
Ic is large only when there is a Ag/Bi interface

→large interfacial spin to charge current conversion : IEE

Previous demonstration in SC QW by

S. D. Ganichev et al. Nature 417, 153 (2002) – spin galvanic effect

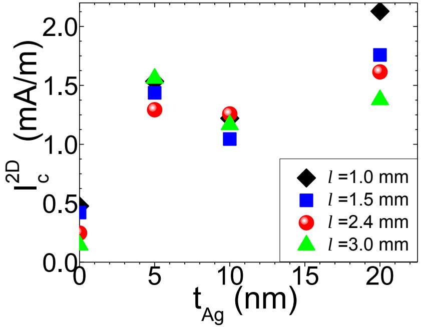
Ag/Bi interface : Inverse Edelstein Effect

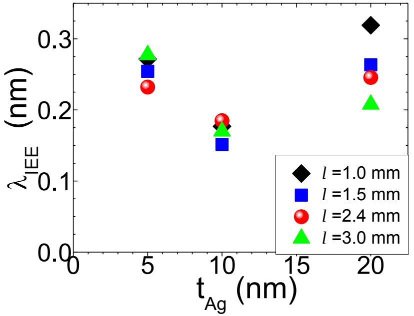


New parameter : λ_{IEE}

$$I_C^{2D} = \frac{V_{\text{IEE}}}{W\,R} \quad \text{(A/m)}$$

$$\frac{\text{(A/m)}}{\text{(A/m}^2\text{)}} \quad \frac{I_C^{2D}}{j_S} = \lambda_{\text{IEE}} \text{(m)}$$

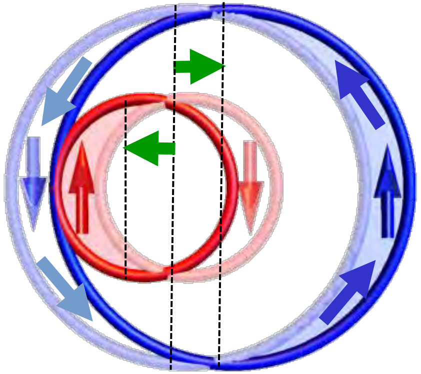




Ag/Bi λ_{IEE} ≈ 0.3 nm

Room temperature

The efficiency of SCC due to IEE :



From theory : λ_{IEE} $\quad |\lambda_{\text{IEE}}| \approx \frac{\alpha_R\ \tau}{\hbar}$

τ = relaxation of the out of equilibrium distribution

τ ≅ 5 fs

J-C. R-S et al. Nat. Comm. 2013

(Similar results by K. Shen, R. Raimondi et al, PRL. 2014)

➔ First experimental results of IEE by SP and its quantification

Inverse Edelstein Effect : some other results

$$\hat{H}_{SO} = \alpha_R \boldsymbol{\sigma} \cdot (\boldsymbol{k}_{\parallel} \times \mathbf{e}_z),$$

Recent results that support our statement of SCC at Rashba interfaces

The stacking order: Ag/Bi to Bi/Ag ➔ change the signs of Ic (α_R)

Spin pumping in Fe/Bi/Ag and Fe/Ag/Bi — S. Sangiao et al. APL 106, 172403 (2015)

Spin accumulation probed by positron beam at Ag/Bi and Bi/Ag — H. J. Zhang et al. PRL 114, 166602 (2015)

The Rashba coupling α_R sign

From ARPES: $\alpha_{R\ Ag/Bi} > 0$ $\alpha_{R\ Cu/Bi} < 0$ — H. Bentmann et al. PRB 84, 115426 (2011)

From Spin pumping-IEE: $\lambda_{IEE\ Ag/Bi} > 0$ $\lambda_{IEE\ Cu/Bi} < 0$ — S. Karube, APEX 9, 033001 (2016)

The Rashba coupling α_R strength

$\alpha_{R\ Ag/Bi} >> \alpha_{R\ Ag/Sb}$

Ag/Sb $\lambda_{IEE} \approx 0.01$ nm

Ag/Bi $\lambda_{IEE} \approx 0.1$ nm

W. Zhang et al. JAP 117, 17C727 (2015)

$$\lambda_{IEE} = \frac{\alpha_R \tau}{\hbar}$$

See also

A. Soumyanaryanan et al. Nature 539, 509 (2016)

Y. Ando and M. Shiraishi JPSJ 86, 011001 (2017)

I. Background: Spin pumping voltage by FMR due to ISHE and IEE

II. IEE in Bi/Ag/NiFe, Ge[111]/Fe, STO/LAO/NiFe and α-Sn/Ag/Fe/Au

III. ISHE vs IEE and perspective for low power applications

Summary

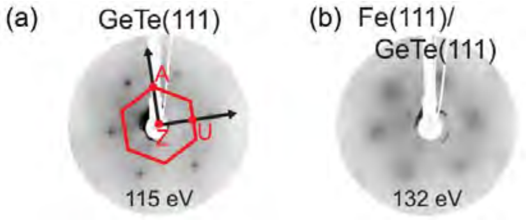
Evidence of spin-charge curent conversion at GeTe(111)

Ferroelectric Rashba Semiconductor

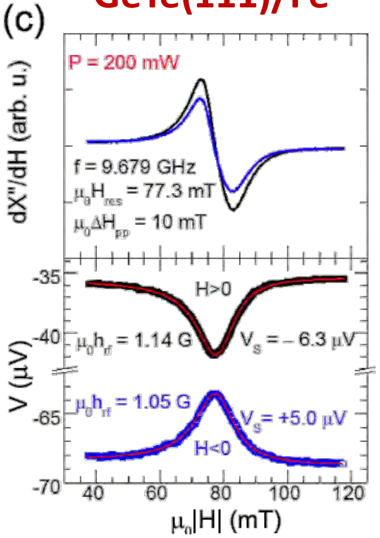
Intrinsic link between ferroelectric polarization and spin chirality in bulk Rashba-type bands

Coll. R. Calarco, Paul-Drude (Berlin)
R. Bertacco (Milan)

LEED pattern



Spin Pumping along ZA
GeTe(111)/Fe

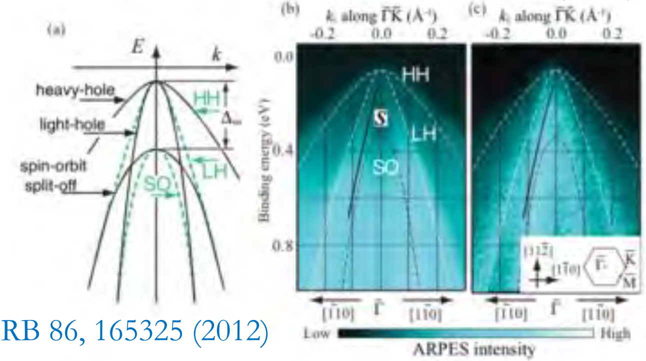


First (preliminary) results:
Spin pumping voltage detected
along ZA // [-110]
and not along ZU // [11-2]

C. Rinaldi *et al.*, *APL Mat.* 4, 032501 (2016)

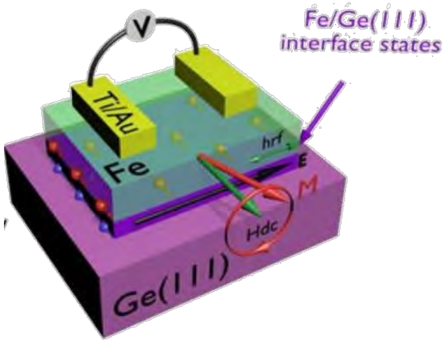
Spin-charge curent conversion at Fe/Ge(111) interface

Presence of sub-surface states at Ge(111) interface



PRB 86, 165325 (2012)

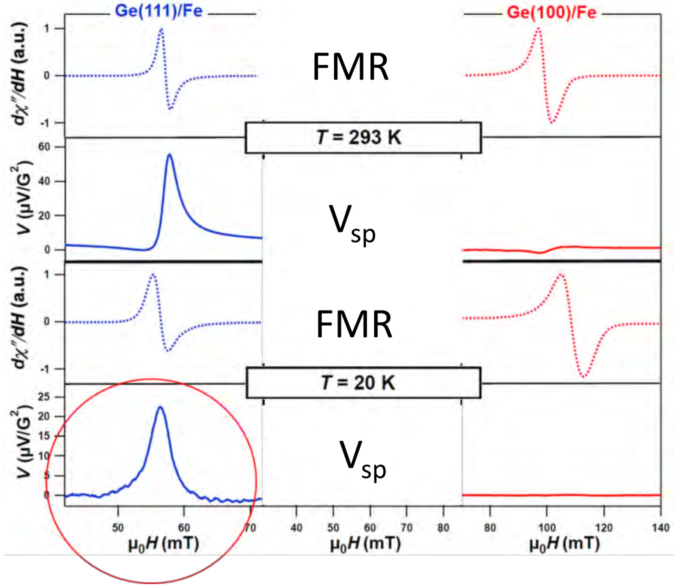
S. Oyarzun, M. Jamet (Grenoble)
Coll. A. K. Nandy, S. Blügel (Juliech)



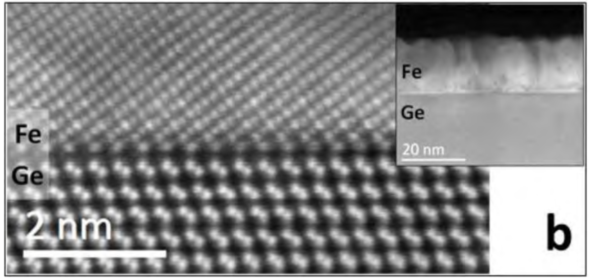
Hybridized states at the SC/metal interface having both exchange and SOC

λ_{IEE} = 0.13 nm (20 K)

Spin Pumping Ge(111)/Fe



20 nm of Fe deposited on Ge(111)



H. Okuno, CEA

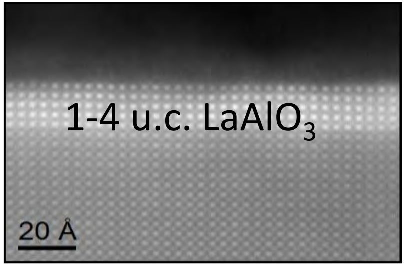
S. Oyarzun *et al.*, *Nat. Comm.* 7, 13857 (2016)

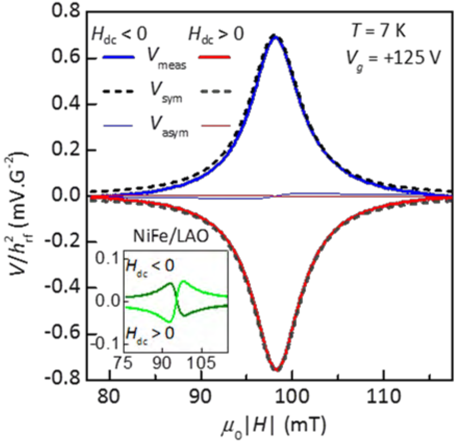
See also L. Chen et al. Nat Comm. 7, 13802 (2016) for Fe/GaAs(001) interface

LAO/STO system

$SrTiO_3$ and $LaAlO_3$: band insulators but $SrTiO_3/LaAlO_3$ interface conductive !

A. Ohtomo & H. Y. Hwang, *Nature* 423, 427 (2004)
N. Nakagawa *et al.*, *Nature Mater.* 5, 204–209 (2006)
T. Higuchi & H. Y. Hwang, *in* “Multifunctional Oxide Heterostructures”, *Oxford Univ. Press* (2011) [arXiv:1105.5779]
E. Lesne *et al.*, *Nature Comm.* 5, 4291 (2014)





Conductive tip AFM evidences the quasi-two-dimensional nature of the conduction.

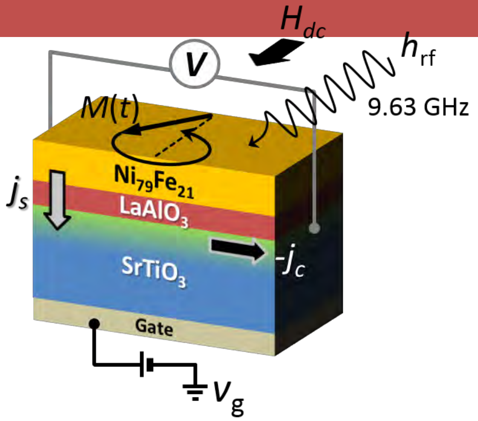
M. Basletic *et al.*, *Nature Mater.* 7, 621 (2008)
O. Copie *et al.*, *Phys. Rev. Lett.* 102, 216804 (2009)

E. Lesne *et al.*, *Nat. Mater.* 15, 261 (2016)

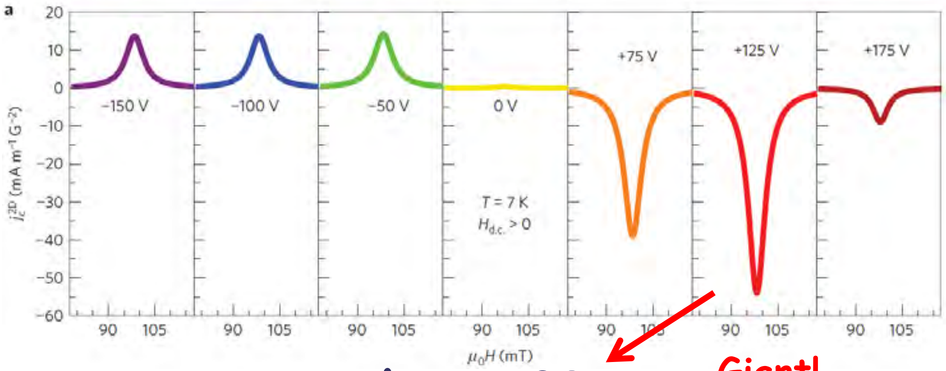
Larger effect in 2DEG at STO/LAO interface?

Tunable with gate voltage?

LAO/STO system : large Ic production and gate effect



- λ_{IEE} can be tuned (sign & amplitude) by gate voltage



T = 7 K

λ_{IEE} up to 6.4 nm **Giant!**

(definitely higher than with α-Sn and at Bi/Ag interfaces)

E. Lesne *et al.*, *Nat. Mater.* 15, 261 (2016)

See also J-Y Chauleau et al. EPL 116, 1706 (2016), Q. Song et al. Sci. Adv. 3, e1602312 (2017)

Rashba α_R~ 3x10^{-12} eV-m << α_R~ 3.5x10^{-10} eV-m for Ag/Bi

Caviglia et al, PRL (2010)
Hurand et al, Sc.Rep. (2015)

Ast et al. PRL 98, 186807 (2007)

$$\lambda_{IEE} = \frac{\alpha_R \, \tau}{\hbar}$$

τ~ 1 ps (OK with resistance) >> τ ~ 1-10 fs for Rashba (Bi/Ag) or TI (α-Sn) interfaces with a metal

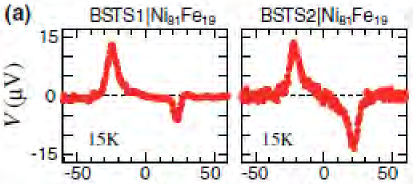
I. Background: Spin pumping voltage by FMR due to ISHE and IEE

II. **IEE in Bi/Ag/NiFe, Ge[111]/Fe, STO/LAO/NiFe and α-Sn/Ag/Fe/Au**

III. **ISHE vs IEE and perspective for low power applications**

Summary

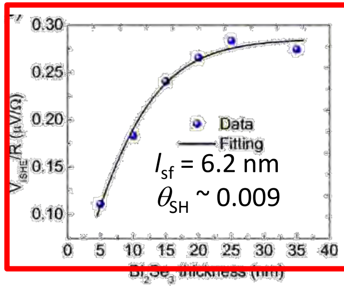
Spin to charge conversion by spin pumping voltage : some reports on FM/TI



$Bi_{1.5S}b_{0.5}Te_{1.7}Se_{1.3}$/NiFe
Y. Shiomi et al.
PRL 113, 196601 (2014)

Only at low T< 20 K

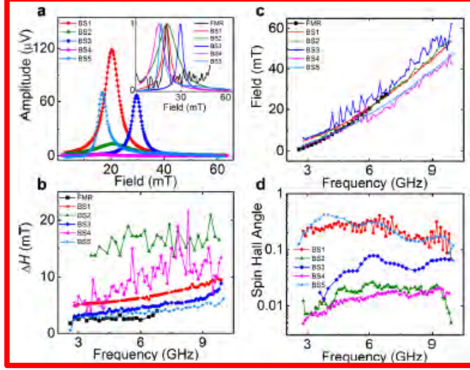
Also in SmB_6 K. Song et al.
Nat Comm, (2016) , T < 3K



Al_2O_3//Bi_2Se_3/NiFe(20nm)/SiO_2
P. Deorani et al. PRB 90, 094403 (2014)

Bulk-like behavior (ISHE)

$\theta_{SHE} \times l_{sf}$ = 0.056 nm



InP//Bi_2Se_3/CFB(5nm)/MgO
M. Jamali et al.
Nano Lett. 15, 7126 (2015)
ISHE is dominating

θ_{SHE} = 0.026 – 0.34
$\theta_{SHE} \times l_{sf}$ = 0.13 – 1.7 nm

➔ **Critical interface quality**

J. Zhang, Tsymbal et al. PRB 94, 014435 (2016)

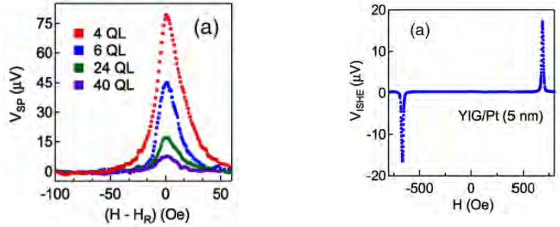
Bi_2Se_3/Co and Bi_2Se_3/Ni

"…The hybridization of the TI surface states with the metal bands destroys their helical spin structure."

No helical spin texture ➔ No Edelstein Effect (or IEE)

H. Wang et al. PRL 117, 076601 (2016) FMI/TI

GGG//YIG/Bi_2Se_3/MgO



Bigger signal in FMI/TI than FMI/Pt but λ_{IEE} still small (~0.035 nm)

See also
A. Soumyanaryanan et al. Nature 539, 509 (2016)
Y. Ando and M. Shiraishi JPSJ 86, 011001 (2017)

Spin to charge conversion by Dirac cone states with helical spin polarization of α-Sn

- ✓ Topological insulators with inversion symmetry

Liang Fu and C. L. Kane PRB 76, 045303 (2007)

Several reports in 2013-2014 account the TI behavior of α-Sn thin films

- ✓ Large-gap quantum Spin Hall Insulators in Tin films

Y. Xu et al. PRL 111, 136804 (2013)

- ✓ Elemental Topological Insulator with Tunable Fermi level: strained α-Sn on InSb(001)

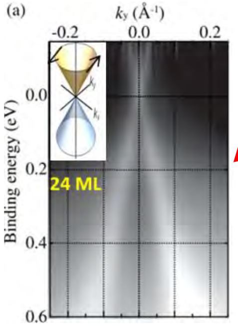
A. Barfuss et al. PRL 111, 157205 (2013)

- ✓ Dirac Cone with Helical Spin Polarization in Ultrathin α-Sn(001) films

Y. Othsubo et al. PRL 111, 216401 (2013)

- ✓ Topological α-Sn surface states versus films thickness and strain

S. Küfner et al. PRB 90, 125312 (2014)



Dirac-cone with helical spin polarization

ARPES

InSb//α-Sn(24-30ML)

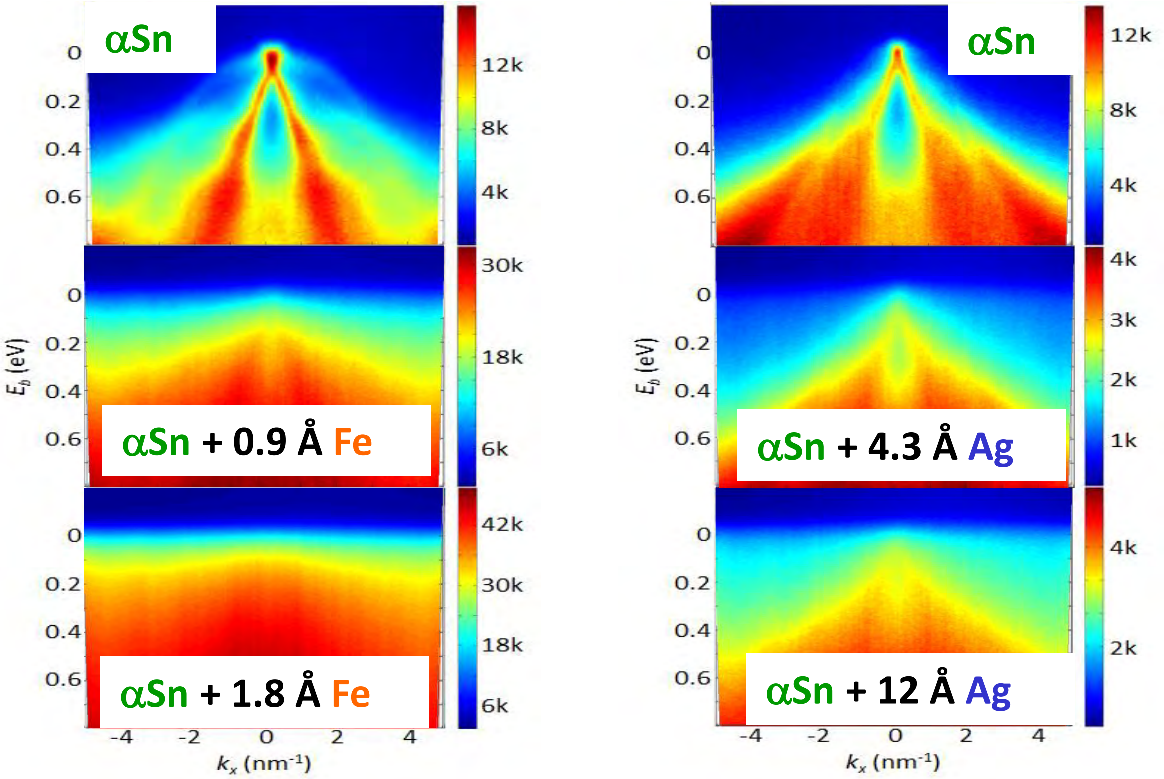
$\upsilon_F = 7.3\ 10^5$ m/s (4.8 evÅ)

Casiopee beam line at SOLEIL,
Room temperature

Our α-Sn/Fe and α-Sn/Ag/Fe samples (α-Sn: 30ML) have been grown in the same conditions in situ on the same beam line to check by ARPES if the topological states are or are not kept after depositing Fe or Ag for our spin pumping experiments

First stage : ARPES in α-Sn + Fe or αSn+Ag

Room temperature

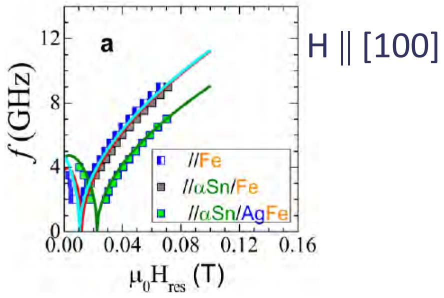


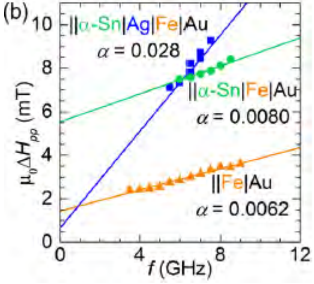
➔ The Dirac cone remains when adding Ag!! ☺

➔ IEE expected in spin pumping from Fe into Ag/α-Sn

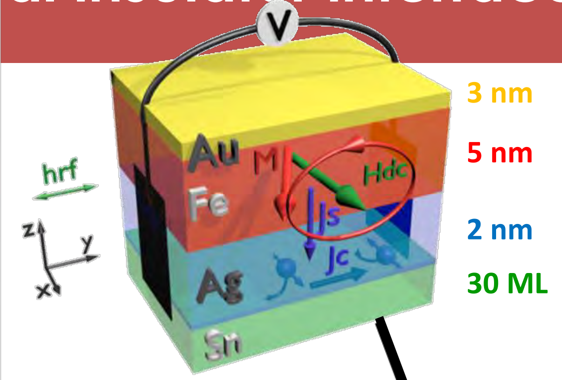
J.C. R.-S. et al, PRL 116, 096602 (2016)

Spin-to-charge conversion at topological insulator interfaces





α-Sn

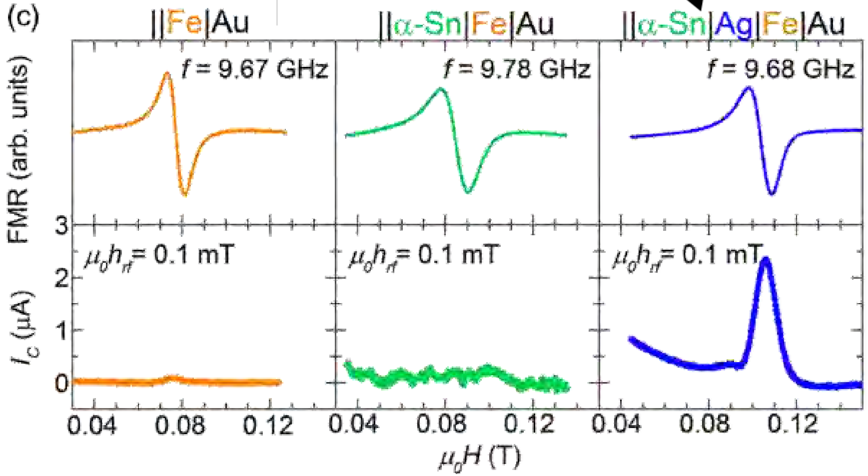


Enhancement of damping

//Fe $\alpha = 0.0062$

//αSn/Ag/Fe $\alpha = 0.028$

InSb//αSn(30ML)/Ag(2nm)/Fe(5nm)/Au(3nm)

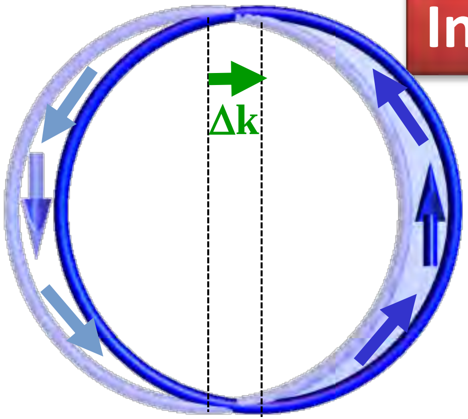


➔ **Large Ic^{2D} production at αSn/Ag**

J.C. R.-S. et al, PRL 116, 096602 (2016)

SCC at topological insulator interfaces : quantification

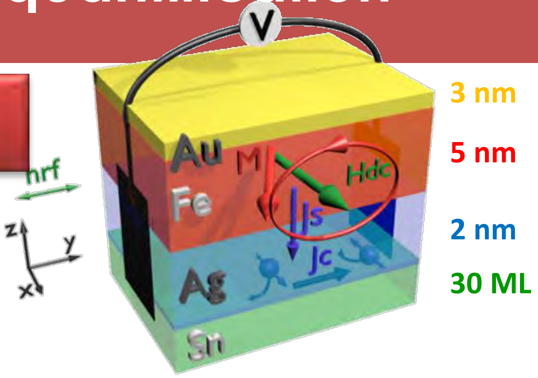
Inverse Edelstein Effect in α-Sn



A/m A/m²

$$j_c^{2D} = \lambda_{IEE} \; j_s^{3D}$$

$$\lambda_{IEE} = v_F \tau$$



InSb//αSn(30ML)/Ag(2nm)/Fe(5nm)/Au(3nm)

IEE length λ_{IEE} = 2.1 nm (at 300 K) ➔The largest at room temperature!

v_F = 7.3 10^5 m/s (4.8 evÅ)

τ = 3.7 fs << free TI surface (ps)
at room temperature

J.C. R.-S. et al, PRL 116, 096602 (2016)

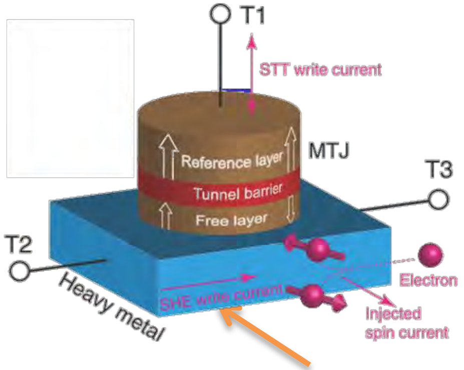
- ➔ **Large Ic^{2D} production at αSn/Ag**
- ➔ **Ag useful to keep surface states of TI**
- ➔ **But Ag reduces τ**

Perspective for exploiting the conversion between spin and charge by TI in low-power spintronic devices (Room Temp.), assessment of the advantage of TI

1) Charge to spin conversion: SHE already used in SOT-RAMS, Rashba and TI already proposed by INTEL, advantage of TI for spin-orbit logic (Manipatruni et al)

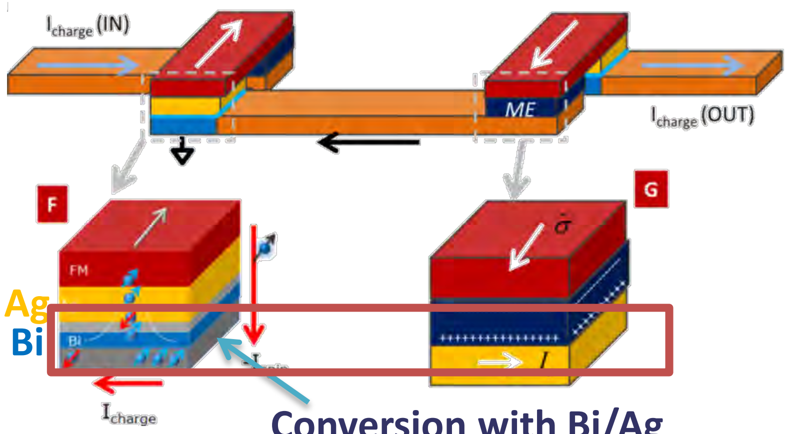
3-terminal SOT-MRAM

Z. Wang, W. S. Zhao *et al.*,
J. Phys. D: 48, 065001 (2015)



Version with conversion by Edelstein Effect on topological insulator

Spin-orbit logic



Conversion with Bi/Ag
(Manipatruni et al. arXiv 2015 INTEL)

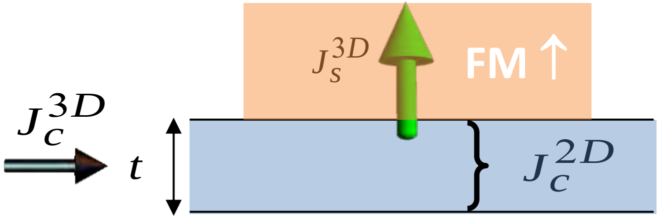
Spin Hall effect (SHE) vs Edelstein effect (EE)

3D layers

Charge-to-spin conversion by « bulk » spin-orbit effect through **spin hall effect** (SHE)

S.O. Valenzuela et al, Nature 442, 176 (2006)

SHE ($J_s^{3D} = \theta_{\text{SHE}} J_c^{3D}$)



Interface R << ρ×l_{sf}
the transferred spin current density is related to the total charge current j_c^{2D} in the SHE layer by

$$\boxed{\begin{gathered} J_s^{3D} = \theta_{\text{SHE}} \tanh\left(\frac{t}{2l_{sf}}\right)\frac{J_c^{2D}}{t} \\ \text{the max. value } (t \ll l_{sf}) \\ \frac{J_s^{3D}}{J_c^{2D}} = q^* = \frac{\theta_{\text{SHE}}}{2l_{sf}} \end{gathered}}$$

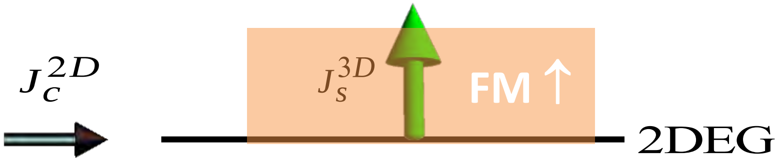
Interfaces and 2DEGs

Charge-to-spin conversion achieved through **Edelstein effect** (EE) *aka* Inverse spin galvanic effect

J.C. Rojas-Sanchéz et al, Nature Commun. 4, 2944 (2013)

K. Shen et al, PRL 102, 096601 (2014), K. Kondou et al, Nat. Phys. 2016

EE ($J_s^{3D} = q_{\text{EE}} J_c^{2D}$)



Maximum spin current induced by SHE characterized by the effective conversion reciprocal length

$$q^* = \frac{\theta_{\text{SHE}}}{2l_{sf}}$$ ***to be compared to q_{EE}***

From SHE to EE the gain in spin current production for the same charge current injected is at least q_{EE}/q^*_{SHE}

Compared charge to spin conversion yield of TI (Sb_2Te_3) and SHE (Pt and W)

The gain in spin current production J_s^{3D}

for the same injected charge current density J_c^{2D}

(for $t \ll l_{sf}$)

for Sb_2Te_3

$$\frac{J_s\,(\mathrm{EE})}{J_s\,(\mathrm{SHE})} = \frac{q_{\mathrm{EE}}}{q^*} = \frac{1\ \ \mathrm{nm}^{-1}}{\theta_{\mathrm{SHE}}\,/\,2l_{sf}}$$

Pt : θ_{SHE}= 0.056, l_{sf} = 3.4nm, $\theta_{\mathrm{SHE}}/2l_{sf}$ = 0.008 nm^{-1}
J.C.Rojas-Sánchez et al, PRL 112, (2014)

K. Kondou et al, Nat. Phys. 2016

W : θ_{SHE}= 0.33, l_{sf} = 1.26nm***, $\theta_{\mathrm{SHE}}/2l_{sf}$ = 0.13 nm^{-1}
Pai *et al, APL 101, (2012)*

W : θ_{SHE}= 0.27, l_{sf} = 1.26nm***, $\theta_{\mathrm{SHE}}/2l_{sf}$ = 0.11 nm^{-1}
*** Kim *et al, PRL 116, (2016)*

$$\frac{J_s\,(\mathrm{Sb_2Te_3})}{J_s\,(\mathrm{Pt})} \simeq 121$$

$$\frac{J_s\,(\mathrm{Sb_2Te_3})}{J_s\,(\mathrm{W})} \simeq 7.6$$

$$\frac{J_s\,(\mathrm{Sb_2Te_3})}{J_s\,(\mathrm{W})} \simeq 9.3$$

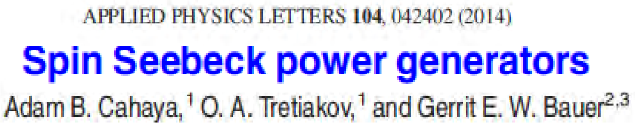
Reported charge current density to reverse Magnetization

3D:	β-W	J_c=1.2×10^{10} A/m^2	@ 300 K	Q. Hao et al. APL 106, 182403 (2015)
2D:	$(Bi_{0.5}Sb_{0.5})_2Te_3$	J_c=8.9×10^8 A/m^2	@ 1.9 K	Y. Fan et al. Nat. Matt (2014)

- ➔ **TI materials with larger q will reduce the charge current needed to reverse perpendicular M (toward application in MRAM)**
- ➔ **Perspective: measure q in α-Sn @ 300 K**

Perspective for exploiting the conversion between spin and charge by TI in low-power spintronic devices (Room Temp.), assessment of the advantage of TI

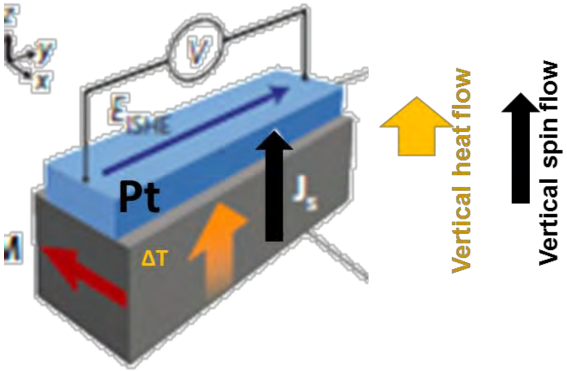
2) **Perspective for spin to charge conversion with TI, second exemple: conversion of heat flow into electrical power**



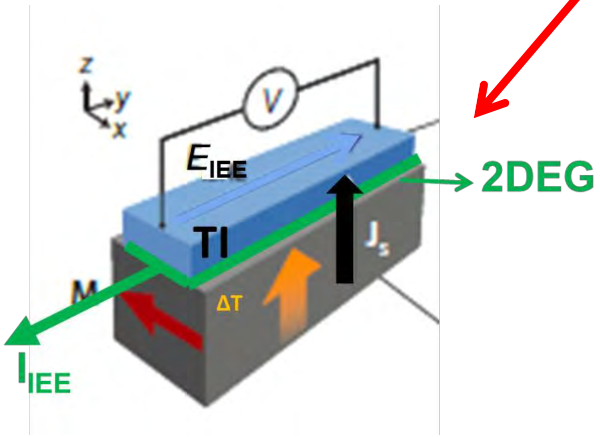
APPLIED PHYSICS LETTERS **104**, 042402 (2014)

Spin Seebeck power generators

Adam B. Cahaya,[1] O. A. Tretiakov,[1] and Gerrit E. W. Bauer[2,3]



Version with conversion by Inverse Edelstein Effect on topological insulator



Inverse spin Hall effect (ISHE) vs inverse Edelstein effect (IEE)

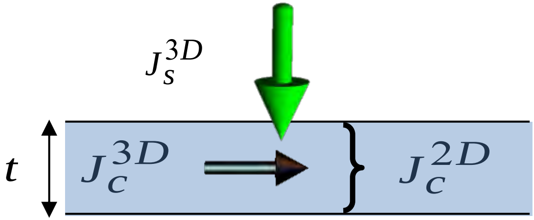
3D layers

Spin-to-charge conversion by « bulk » spin-orbit effect through **inverse spin hall effect** (ISHE)

E. Saitoh et al, APL 88, 182509 (2006)

S.O. Valenzuela et al, Nature 442, 176 (2006)

ISHE ($J_c^{3D} = \theta_{\mathrm{SHE}} J_s^{3D}$)



Optimal condition for

J_c^{2D} : $t \gg l_{sf}$

$$J_c^{2D} = \int_0^t J_c^{3D} dz \approx \theta_{\mathrm{SHE}} l_{sf} J_s^{3D}$$

then effectively

$$\frac{J_c^{2D}}{J_s^{3D}} = \lambda^* = \theta_{\mathrm{SHE}} l_{sf}$$

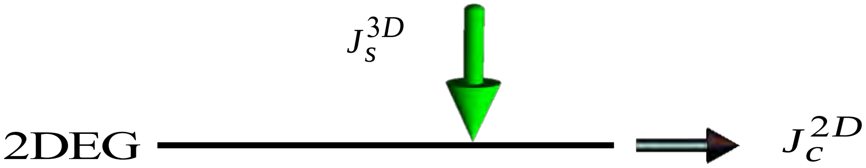
Interfaces and 2DEGs

Spin-to-charge conversion achieved through **inverse Edelstein effect** (IEE) *aka* spin galvanic effect

J.C. Rojas-Sanchéz et al, Nature Commun. 4, 2944 (2013)

K. Shen et al, PRL 102, 096601 (2014)

IEE ($J_c^{2D} = \lambda_{\mathrm{IEE}} J_s^{3D}$)



Maximum charge current induced by ISHE characterized by the effective conversion length

$\lambda^* = \theta_{\mathrm{SHE}} l_{sf}$ ***to be compared to λ_{IEE}***

From ISHE to IEE the gain in charge current for the same spin current is at least $\lambda_{IEE} / \lambda^*_{ISHE}$

Compared spin to charge conversion yield of TI (α-Sn) and ISHE (Pt and W)

The gain in charge current production J_c

for the same injected spin current density J_s

(for $t \gg l_{sf}$)

$$\frac{J_c(\text{IEE})}{J_c(\text{ISHE})} = \frac{\lambda_{\text{IEE}}}{\lambda^*} = \frac{2.1\ \text{nm}}{\theta_{\text{SHE}} l_{sf}}$$

for α-Sn

Pt : $\theta_{\text{SHE}} = 0.056$, $l_{sf} = 3.4$nm, $\theta_{\text{SHE}}\, l_{sf} = 0.19$ nm

J.C.Rojas-Sánchez et al, PRL 112, (2014)

Pt would be as efficient as **α-Sn**
with a θ_{SHE} of **62% (instead of 5.6%)**

W : $\theta_{\text{SHE}} = 0.33$, $l_{sf} = 1.26$nm***, $\theta_{\text{SHE}}\, l_{sf} = 0.41$ nm

Pai *et al, APL 101, (2012)*

W : $\theta_{\text{SHE}} = 0.27$, $l_{sf} = 1.26$nm***, $\theta_{\text{SHE}}\, l_{sf} = 0.34$ nm

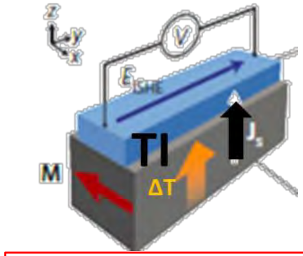
*** Kim *et al, PRL 116, (2016)*

W would be as efficient as **α-Sn**
with a θ_{SHE} of **150% (instead of 27-33%)**

$$\frac{J_c(\alpha\text{Sn})}{J_c(\text{Pt})} = 11.0$$

$$\frac{J_c(\alpha\text{Sn})}{J_c(\text{W})} = 4.9$$

$$\frac{J_c(\alpha\text{Sn})}{J_c(\text{W})} = 6.0$$



for α-Sn

The gain in electrical power P_c

for the same injected spin current density J_s

$$\frac{P_c(\text{IEE})}{P_c(\text{ISHE})} = \frac{R_\square J_c^2(\text{IEE})}{R_\square J_c^2(\text{ISHE})} = \frac{6\ \text{k}\Omega\ (2.1\ \text{nm})^2}{\frac{\rho}{l_{sf}}\left(\theta_{\text{SHE}} l_{sf}\right)^2}$$

$$\frac{P_c(\alpha\text{Sn})}{P_c(\text{Pt})} = 10^3$$

$$\frac{P(\alpha\text{Sn})}{P_c(\text{W})} = 10^2$$

➔The output power with α-Sn will be at least
1 000 larger than with Pt
100 larger than with W

Here our prediction of much larger output power using YIG/α-Sn

Perspective for exploiting the conversion between spin and charge by TI in low-power spintronic devices (Room Temp.), assessment of the advantage of TI

Toward longitudinal spin Seebeck effect in YIG/α-Sn

Sébastien
Petit-Watelot

Carlos

Olivier Copie
YIG (PLD)

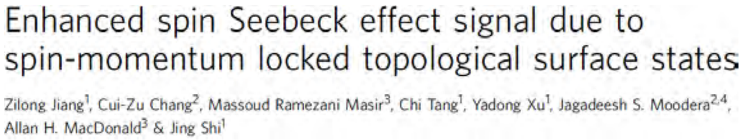
Stephane Andrieu
α-Sn (MBE)

CNRS *Cellule Energy funding*

Perspective for exploiting the conversion between spin and charge by TI in low-power spintronic devices (Room Temp.), assessment of the advantage of TI

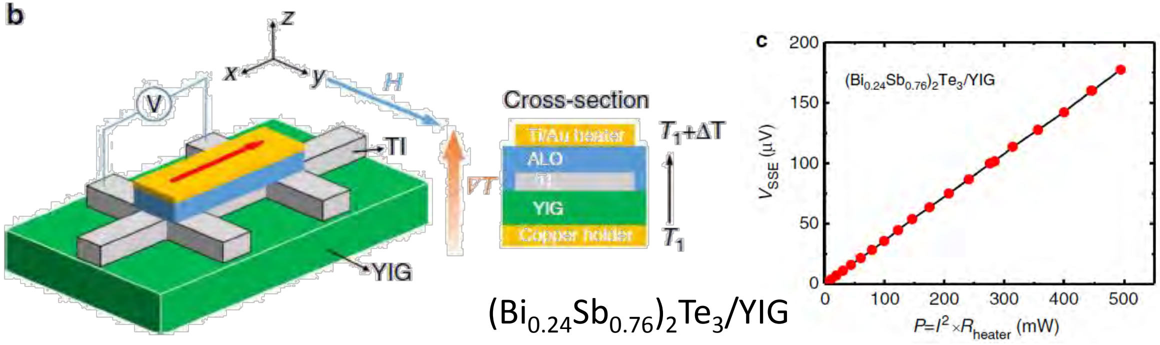
2) **Perspective for spin to charge conversion with TI, exemple: conversion of heat flow into electrical power**

Z. Jiang et al. Nat. Comm. 7, 11458 (2016)



Enhanced spin Seebeck effect signal due to spin-momentum locked topological surface states

Zilong Jiang[1], Cui-Zu Chang[2], Massoud Ramezani Masir[3], Chi Tang[1], Yadong Xu[1], Jagadeesh S. Moodera[2,4], Allan H. MacDonald[3] & Jing Shi[1]

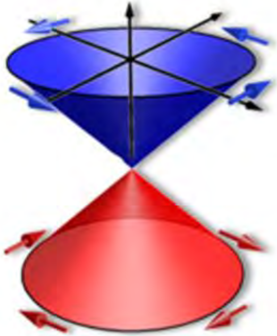


$(Bi_{0.24}Sb_{0.76})_2Te_3$/YIG

Large output voltage using $(Bi_{0.24}Sb_{0.76})_2Te_3$ TI: x100 than using Pt !

IEEE

MAGNETIC FRONTIERS
TOPOLOGICAL INSULATORS



September 18-21, 2017, Nancy, France

PLENARY SPEAKERS

Matthias Bode, *Univ. Würzburg*
Albert Fert, *Univ. Paris-Sud (Nobel Prize)*
Ingrid Mertig, *Martin Luther Univ. Halle-Wittenberg*
Nitin Samarth, *Penn State Univ.*
Zhi Xun Shen, *Stanford Univ.*
Qi-Kun Xue, *Tsinghua Univ.*

+13 Keynote speakers

https://topo-insulators.event.univ-lorraine.fr/

Summary

- ✓ **First experimental evidence by SP of IEE and its quantification**
- ✓ **Large efficiency of SCC at Ag/Bi interface λ_{IEE}= 0.3nm @ 300 K**

  J.-C. Rojas-Sánchez *et al.*, *Nat. Comm.* 4, 2944 (2013)

- ✓ **Promising results at oxides interfaces: STO/LAO λ_{IEE}= 6.2nm (7 K)**

  E. Lesne *et al.*, *Nat. Mater.* 15, 261 (2016)

- ✓ **Intriguing results on Ge(111)/Fe Rashba interface λ_{IEE}= 0.13nm (20 K)**

  S. Oyarzun *et al.*, *Nat. Comm.* 7, 13857 (2016)

- ✓ **Study of α-Sn topological insulator : λ_{IEE}= 2.1 nm @ 300 K**

  surface sates are suppressed in direct contact with Fe, αSn/Fe):

  but preserved with Ag layer, Ag/αSn ☺

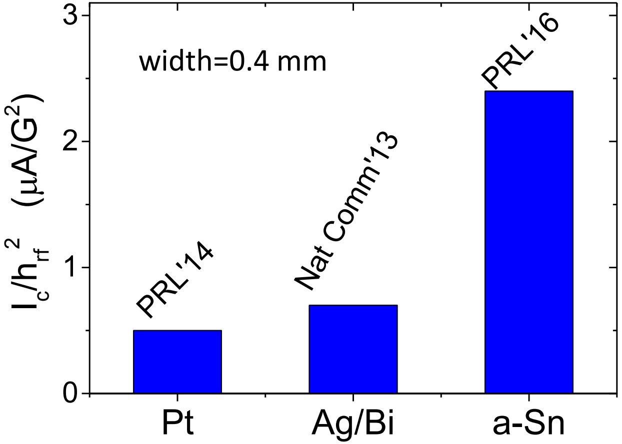
  τ with metallic spacer much smaller (~fs) than in free TI surface (~ps)

  ➔ a barrier will increase τ (and λ_{IEE})

  J.-C. Rojas-Sánchez *et al.*, *Phys. Rev.* Lett. 116, 096602 (2016), arXiv (2015)

Beyond any analysis

I_c charge current production @ 300 K



Spin-Orbit in 2D system is more efficient than in 3D (SHE) for spin-charge conversion and spintronic devices

email: juan-carlos.rojas-sanchez@univ-lorraine.fr