Conversion between spin and charge currents by Rashba or Topological Insulator interfaces and perspective for low power spintronic devices

1) Introduction to spin-orbittronics.
2) Conversion between charge and spin current with Rashba or TI Interfaces.
3) Potential of TI for applications

A. Barhélémy, M. Bibes, A. Fert, J-M. George, H.Jaffres, E. Lesne, N. Reyren, J-C Rojas-Sánchez, CNRS/Thales, Palaiseau, France
L. Vila, J.-P. Attané, G. Desfond, Y. Fu, S. Gambarelli, M. Jamet, A. Marty, S. Oyarzun, L. Vila, CEA Grenoble, France
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P. LeFevre, F. Bertran, A. Taleb, SOLEIL Synchrotron, Gif, France
C.Rinaldi, R.Bertacco, Poli.Milan, R.Calarco, R.Wang, Drude Inst. Berlin
Conversion between spin and charge currents by Rashba or Topological Insulator interfaces at Room Temp. and perspective for low power spintronic devices

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Interface-induced skyrmions and chiral domain walls

Motion of skyrmion motion by SHE

Spin-orbitronics

Graphene + spin-orbit

Spin Hall effect

2D Oxide interfaces

2D Edelstein-type effects at Rashba and topological insulator interfaces
Bulk materials

3D charge current $\rightarrow$ 3D spin current conversion by **Spin Hall Effect (SHE)**
and 3D spin current $\rightarrow$ 3D charge current by **Inverse SHE (ISHE)**

\( J_S = \text{vertical spin current injected into an adjacent layer by SHE} \)

Switching of nanomagnet by the spin current \( J_S \) injected by the SHE in an adjacent SO layer

$\Rightarrow$ Yield of conversion between charge and spin current

**Spin hall angle** $\theta_{\text{SHE}} = \frac{\text{spin current density}}{\text{charge current density}}$

(dimENSIONLESS)
**Bulk materials**

3D charge current $\rightarrow$ 3D spin current conversion by **Spin Hall Effect (SHE)** and 3D spin current $\rightarrow$ 3D charge current by **Inverse SHE (ISHE)**

$J_S = $ vertical spin current injected into an adjacent layer by SHE

Switching of nanomagnet by the spin current $J_S$ injected by the SHE in an adjacent SO layer

M. Cubukcu et al., APL 2015: switching in 0.4 ns current pulse $\approx 10^8$ Amp/cm$^2$ in 1kOe

Z. Wang, W. S. Zhao et al., J. Phys. D 2015: STT + SOT < 1 ns, zero field, current densities $\approx 10^7$ Amp/cm$^2$
Spin/charge conversion by Rashba interfaces and topological insulators

Rashba interface

\[ \hat{H}_{SO} = \alpha_R \mathbf{\sigma} \cdot (\mathbf{k}_\parallel \times \mathbf{e}_z) \]

\( \alpha_R = \text{Rashba coefficient} \)

(example at the Bi/Ag interface 2DEG)

Topological insulator
Spin/charge conversion by Rashba interfaces and topological insulators

Rashba interface

\[ \hat{H}_{SO} = \alpha_R \sigma \cdot (k_\parallel \times e_z), \]

\[ \alpha_R = \text{Rashba coefficient} \]
(example at the Bi/Ag interface 2DEG)

Topological insulator

\[ E(k) \]

\[ E(k_x) \]

\[ E(k_y) \]

\[ E(eV) \]

\[ k_x (nm^{-1}) \]

\[ k_y (nm^{-1}) \]
Edelstein (EE) and Inverse Edelstein Effect (IEE)

Rashba interface

Topological insulator

Edelstein Effect

$\Delta k$

Charge Current $j_C$

$\Delta k$

depleted

overpopulated

$\Delta k$

depleted

overpopulated

charge current $j_C$ in 2DEG induces nonzero spin density $\sigma_y$
Edelstein (EE) and Inverse Edelstein Effect (IEE)

Rashba interface

Edelstein Effect

Topological insulator

Charge current $j_c$ in 2DEG induces nonzero spin density $\sigma_y$

Injection of spin current $j_s$ induces charge current $j_c$

Spin pumping
**Edelstein (EE) and Inverse Edelstein Effect (IEE)**

**Rashba interface**

**Edelstein Effect**

- Charge current $j_C$ in 2DEG induces nonzero spin density $\sigma_y$

**Topological insulator**

**Inverse Edelstein Effect**

- Injection of spin current $j_s$ induces charge current $j_C$

**Formulas**

- $j_{c}^{2D} = \lambda_{IEE} j_{s}^{3D}$

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

**References**

Rojas-Sanchez, AF et al, Nat.Com. 013, Shen et al, PRL014
**Edelstein (EE) and Inverse Edelstein Effect (IEE)**

**Rashba interface**

**Edelstein Effect**
- Charge current $j_C$ induces nonzero spin density $\sigma_y$
- Injection of spin current $j_S$ induces charge current $j_C$

**Topological insulator**

**Inverse Edelstein Effect**
- $j_C$ in 2DEG induces charge current $j_C$

**Equations**
- $j_C^{2D} = \lambda_{EE} j_S^{3D}$
- $j_C^{2D} = \lambda_{IEE} j_S^{3D}$

**Parameters**
- $\lambda_{IEE} = \frac{\alpha_R \tau}{\hbar}$
- $\lambda_{IEE} = v_F \tau$

Rojas-Sanchez et al, PRL 116, 096602 (2016), Culcer, Physica012
Edelstein (EE) and Inverse Edelstein Effect (IEE)

**Rashba interface**

- **Edelstein Effect**
  - Charge current \( j_C \) induces nonzero spin density \( \sigma_y \)
  - Injection of spin current \( j_s \) induces charge current \( j_C \)

**Topological insulator**

- **Inverse Edelstein Effect**
  - Charge current \( j_C \) in 2DEG induces non-zero spin density \( \sigma_y \)

- **Injection of spin current** \( j_s \) \( \Rightarrow \) **Extraction of charge current** \( j_C \)

**Equations**

- \( j_c^{2D} = \lambda_{IEE} j_s^{3D} \)
- \( \lambda_{IEE} = \frac{\alpha_R \tau}{\hbar} \)

**References**

Rojas-Sanchez et al, PRL 116, 096602 (2016), Culcer, Physica012
Bi/Ag interface* (J-C. Rojas-Sanchez, AF et al, Nature Communications, 4, 2944, 2013)

- Other examples presented today:
  - topological 2DEG: α-Sn and LAO/STO interface

* Before Bi/Ag, first observed in n-GaAs-AlGaAs QW, Ganichev et al, Nature 417, 153, 2002
Spin to charge conversion by Bi/Ag Rashba interfaces

\[ I_c = \frac{V}{Rl} \text{ is large} \]

only when there is a Bi / Ag interface

\[ \text{only Ag} \quad I_c \approx 0 \]

\[ \text{only Bi} \quad I_c \text{ is small} \]

\[ \text{Bi + Ag} \quad \text{large } I_c \]

J-C. Rojas-Sanchez, AF et al, Nature Communications, 4, 2944, 2013
Spin to charge conversion by Bi/Ag Rashba interfaces

\[ I_c = \frac{V}{R l} \] is large only when there is a Bi/Ag interface

S. Sangiao et al. APL 106, 172403 (2015) as expected by Rashba symmetry, \( I_c \) has opposite signs for, respectively, Ag above Bi and Ag under Bi

\[ I_c \approx 0 \] only Ag \( I_c \) is small

only Bi large \( I_c \)

J-C. Rojas-Sanchez, AF et al, Nature Communications, 4, 2944, 2013
\[ \frac{j_c}{j_s} = \frac{\lambda_{Bi/Ag}}{\lambda_{IEE}} = \frac{\alpha_R \tau}{\hbar} \]


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

Other results on Bi/Ag: Nomura et al, APL 2015

\[ \lambda_{Bi/Ag} \approx 0.2 - 0.3 \text{ nm} \]
More recent results on Bi/Ag, Sb/Ag.


$\lambda_{\text{IEE}}(\text{Ag/Bi}) \sim 0.1\text{nm} > \lambda_{\text{IEE}}(\text{Ag/Sb}) \sim 0.03\text{ nm} \ 0.1\text{nm}$

Sisasa et al, 2015, $\lambda_{\text{IEE}}(\text{Cu/Bi})$ derived from LSV is small and its sign changes with $T$

Spin to charge current conversion at Ag/IrO$_2$
(Fujiwara, Otani et al, Nat Comm. 2013,DOI: 10.1038/ncomms3893) and Cu/Bi$_2$O$_3$ interfaces
(Karube, Otani et al, App.Phys. Expr. 9,033001)

Zhang et al (PRL 2015), Jungfleisch et al (ArXiv 1500.0141): measurement of charge to spin conversion (direct EE) at Bi/Ag interface

J-C. Rojas-Sánchez et al.
Nature Comm. 2013

(Similar results by K. Shen,
R. Raimondi et al, PRL. 2014)
Spin to charge conversion by Dirac cone states with helical spin polarization of α-Sn

Elemental Topological Insulator with Tunable Fermi Level: Strained α-Sn on InSb(001)

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

InSb//α-Sn(24-30ML)  
υ_F = 7.3 \times 10^5 \text{ m/s} (4.8 \text{ evÅ})

ARPES: Y. Ohtsubo et al.  
PRL 11, 216401 (2013)

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

Casiopee beam line at SOLEIL, Room temperature
First stage: ARPES in $\alpha$-Sn(30ML) + Fe or $\alpha$Sn(30ML)+Ag

Room temperature

Rojas-Sanchez et al, PRL 116, 096602 (2016)
The Dirac cone remains when adding Ag on Sn.

IEE expected in spin pumping from Fe into Ag/Sn bilayers.

Room temperature

Rojas-Sanchez et al, PRL 116, 096602 (2016)
Spin pumping on $\alpha$-Sn/Fe and $\alpha$-Sn/Ag(2nm)/Fe

InSb/[$\alpha$Sn(24ML)/Ag(2nm)/Fe(5nm)/Au(3nm)]

strong spin absorption by pumping Fe on Ag/$\alpha$Sn, weak spin absorption by pumping directly from Fe an $\alpha$Sn

Rojas-Sanchez et al, PRL 116, 096602 (2016)
Spin pumping on $\alpha$-Sn/Fe and $\alpha$-Sn/Ag(2nm)/Fe

\[ \frac{J_c}{(A/m)} = \lambda_{IEE}^T = v_F \tau \]

\[ \frac{J_s}{(A/m^2)} \]

$\lambda_{IEE}^{\alpha-Sn} \approx 2.1 \text{ nm}$

InSb/\$\alpha$Sn(24ML)/Ag(2nm)/Fe(5nm)/Au(3nm)

Rojas-Sanchez et al, PRL 116, 096602 (2016)
Spin pumping on $\alpha$-Sn/Fe and $\alpha$-Sn/Ag(2nm)/Fe

\[ (A/m) \rightarrow \vec{j}_c = \lambda_{IEE}^{TI} = v_F \tau \]

\[ (A/m^2) \rightarrow \vec{j}_s = \lambda_{IEE}^{\alpha-Sn} \approx 2.1 \text{ nm} \]

Room temperature Rojas-Sanchez et al, PRL 116, 096602 (2016)
Spin pumping on $\alpha$-Sn/Fe and $\alpha$-Sn/Ag(2nm)/Fe

\[ \frac{j_c}{A/m} = \lambda^{TI}_{IEE} = v_F \tau \]

\[ \lambda^{\alpha-Sn}_{IEE} \approx 2.1 \text{ nm} \]

$\lambda_{IEE} > 0$ in agreement with CCW chirality in upper cone (from spin-resolved ARPES)

Rojas-Sanchez et al, PRL 116, 096602 (2016)

Room temperature

Precession angle $\approx 10^{-2}$
Spin pumping on $\alpha$-Sn/Fe and $\alpha$-Sn/Ag(2nm)/Fe

\[
\frac{j_c}{(A/m)} = \frac{\lambda_{IEE}^{TI}}{v_F \tau} = j_s (A/m^2)
\]

\[\lambda_{IEE}^{\alpha-Sn} \approx 2.1 \text{ nm} \]

In progress, dependence on T, $\alpha$-Sn thickness, gate voltage, applied field + inverse conversion

Other spin/charge conversions with TI, e.g. Shiomi et al, PRL014, Jamali et al, NanoLetters 015 (spin pumping), Tang et al, Nano Letters 014, (electrical spin inject.)
Relaxation time $\tau$ of out-of-equilibrium distribution in topological states

For circular contours

$$\lambda_{IEE} = v_F \tau = 2.1 \text{nm}, \quad v_F \cong 0.56 \times 10^6 \text{m/s}$$

$$\rightarrow \tau \cong 3.7 \text{fs} \quad (\text{Bi}/\text{Ag}: \tau \cong 5 \text{fs})$$

$v_F \cong 0.56 \times 10^6 \text{m/s}$

for cone at Ag/Sn with Ag = 0.23nm

(0.6 × 10^6 m/s for free Sn)

Dots correspond to maximum intensity in E=cst scans

Rojas-Sanchez et al, PRL 116, 096602 (2016)
Relaxation time $\tau$ of out-of-equilibrium distribution in topological states

For circular contours

$$\lambda_{IEE} = v_F \tau = 2.1 \text{nm}, \quad v_F \approx 0.56 \times 10^6 \text{ m/s}$$

$$\rightarrow \quad \tau \approx 3.7 \text{ fs} \quad (Bi/Ag: \tau \approx 5 \text{ fs})$$

ARPES intensity mapping in $(k_x, k_y)$ plane (low resolution)

Rojas-Sanchez et al, PRL 116, 096602 (2016)
Relaxation time $\tau$ of out of equilibrium states in Rashba or TI 2DEGs

1) Ultra-fast time-resolved ARPES (ex: $\text{Bi}_{2.2}\text{Te}_3$ Hajlaoui et al, Nat. Comm. 2013)

- $\tau$ in the ps range
  (ballistic length in the μm range)

2) Spin pumping

- $\tau$ in the fs range*
  (ballistic length in the nm range)

Additional relaxation of the spin+momentum accumulation by spin-flip scattering from 2D states to 3D metal

Additional relaxation by spin-flip scattering from 2DEG to metal

IEE (or EE) would more efficient ($\lambda_{\text{IEE}}$ longer) without proximity of the Rashba or TI states with a metal, i.e. with interface with an insulating ferromagnet (YIG, etc) or a tunnel interface

*The fs range is also the typical lifetime of QW states at the Fe/Ag interface QW, Ogawa et al, PRL 88
LAO/STO system: large Ic production and gate effect

Cylindrical cavity (INAC/CEA-Grenoble) allow for measurements down to few Kelvins, combined with voltage/current probe.

E. Lesne, Ph.D. Thesis, CNRS/Thales lab.
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-orbic logic (Manipatruni et al)

Ex: 3-terminal SOT MRAM

Conversion with Bi/Ag

Manipatruni et al, ArXiv (Intel)
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,

first exemple: spin battery,

Microwave-driven ferromagnet–topological-insulator heterostructures: The prospect for giant spin battery effect and quantized charge pump devices

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FIG. 1: (Color online) The proposed heterostructures consist of a 2D topological insulator (TI) attached to two normal metal (NM) electrodes where the ferromagnetic insulator (FI) with precessing magnetization (with cone angle \( \theta \)) under the FMR conditions induces via the proximity effect a time-dependent exchange field \( \Delta \neq 0 \) in the TI region underneath. In the absence of any applied bias voltage, these devices pump pure spin current into the NM electrodes in setup (a) or both charge and spin current in setup (b).
2) Perspective for spin to charge conversion with TI,

second exemple: conversion of heat flow into electrical power
Inverse spin Hall effect (ISHE) vs inverse Edelstein effect (IEE) WITH

3D layers
Spin-to-charge conversion by « bulk » spin-orbit effect through inverse spin hall effect (ISHE)

$$J_{s}^{3D} \rightarrow (A/m^2) \rightarrow ISHE: \quad j_{c}^{3D} = \Theta_{SHE} j_{s}^{3D}$$

Interfaces and 2DEGs
Spin-to-charge conversion achieved through inverse (Rashba-) Edelstein effect (IEE)

$$J_{s}^{3D} \rightarrow (A/m^2) \rightarrow IEE: \quad j_{c}^{2D} = \lambda_{IEE} j_{s}^{3D}$$

3D layers:
Spin-to-charge conversion by « bulk » spin-orbit effect through inverse spin hall effect (ISHE)

$$J_{c}^{2D} \rightarrow t \rightarrow ISHE: \quad J_{c}^{2D} = \int j_{c}^{3D} \, dz = \Theta_{SHE} l_{sf} \, th(t / 2l_{sf}) \, j_{s}^{3D}$$

reaches its maximum

$$J_{c}^{2D} = \Theta_{SHE} l_{sf} \, j_{s}^{3D} \text{ for } t \gg l_{sf}$$

which corresponds to an Inverse Edelstein Effect with, at the most, an effective

$$\lambda_{IEE}^{*} = \Theta_{SHE} l_{sf}$$
Inverse spin Hall effect (ISHE) vs inverse Edelstein effect (IEE) with spin-to-charge conversion by « bulk » spin-orbit effect through inverse spin hall effect (ISHE)

3D layers

\[ J^{3D}_c = \frac{(A/m^2)}{\Theta_{SHE}} J^{3D}_s \]

ISHE: \( J^{3D}_c \)

\[ J^{2D}_c = \frac{(A/m^2)}{\Theta_{SHE}} J^{3D}_s \]

\( J^{2D}_c \)

ISHE: \( J^{2D}_c = \int J^{3D}_c dz = \Theta_{SHE} l_{sf} \theta( t / 2 l_{sf} ) J^{3D}_s \)

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

\[ \lambda_{SHE}^* = \Theta_{SHE} l_{sf} \]

to be compared to

\[ \lambda_{IEE} \]

from ISHE to IEE the gain in current is at least \( \lambda_{IEE} / \lambda_{SHE}^* \)

Interfaces and 2DEGs

Spin-to-charge conversion achieved through inverse (Rashba-) Edelstein effect (IEE)

\[ J^{3D}_c = \frac{(A/m^2)}{\lambda_{IEE}} J^{3D}_s \]

IEE: \( J^{2D}_c \)

\[ J^{2D}_c \]

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

\[ \lambda_{SHE}^* = \Theta_{SHE} l_{sf} \]

to be compared to

\[ \lambda_{IEE} \]

from ISHE to IEE the gain in current is at least \( \lambda_{IEE} / \lambda_{SHE}^* \)
1) Gain in charge current $J_C$ for the same injected spin current density $j_s$ from SHE in Pt or W (for $t >> l_{sf}$) to $\alpha$-Sn (taken as an example of TI, $\lambda=2.1$nm)

- Gain from Pt ($\theta_{SHE} = 0.056^*$, $l_{sf} = 3.4$nm*) to $\alpha$-Sn: $J_C(\alpha$-Sn)/$J_C$(Pt) =11.03
  (Pt would be as efficient as $\alpha$-Sn if its SH-angle was 62% instead of 5.6%)

- Gain from W ($\theta_{SHE} = 0.33^{**}$, $l_{sf} = 1.4$nm*** ) to $\alpha$-Sn: $J_C(\alpha$-Sn)/ $J_C$(W) = 4.5
  or from W with $\theta_{SHE} = 0.19^{***}$, $l_{sf} = 1.4$nm*** to $\alpha$-Sn: $J_C(\alpha$-Sn)/$J_C$(Pt) = 7.9
  (W would be as efficient as $\alpha$-Sn if its SH-angle was 150% instead of 19-33%)

* from C.Rojas-Sanchez et al,PRL112, 2014
** from Pai et al, APL 101, 2012
*** from Kim et al, arXiv:150308903 2
Compared spin to charge conversion yield of TI (α-Sn) and ISHE (Pt and W)

2) Gain in electrical power $P_C$ for the same injected spin current density, 

with $P_C = R_{\square} J_C^2$

Optimal condition: $R_{\square} \approx 4k\Omega$ for α-Sn surface 2DEG between insulating materials

and $R_{\square} = \rho / t$ for the SHE metal layer (Pt, W) of optimal $t = l_{sf}$

- Gain from Pt ($\theta_{SHE} = 0.056$, $l_{sf} = 3.4$ nm, resistivity = 17 $\mu\Omega$cm) to α-Sn

$$P_C(\alpha\text{-Sn})/ P_C(\text{Pt}) \sim 10^4$$

- Gain from W ($\theta_{SHE} = 0.19-33$, $l_{sf} = 1.4$ nm, resistivity = 160 $\mu\Omega$cm) to α-Sn

$$P_C(\alpha\text{-Sn})/ P_C(\text{W}) \sim 10^3$$
Compared charge to spin (or charge to torque) conversion yields between 1) TI (Bi$_{1-x}$Sb$_x$)Te$_3$

with conversion factor $j_S/J_c \equiv q_{ICS} \approx 1$nm$^{-1}$

(Kondou et al, ArXiv:1510.03572)

and

2) SHE-Pt or - W layers with $j_S/J_c = \Theta_{SHE}/l_{sf}$

in the optimal conditions $t = l_{sf}$

1) Gain in ejected 3D spin current density $J_S$ for the same 2D charge current density $J_c$ in metal layer or 2D topological states between SHE with Pt or W (for $t \approx l_{sf}$) and (Bi$_{1-x}$Sb$_x$)Te$_3$ ($q_{ICS} \approx 1$nm$^{-1}$)

- Gain from Pt ($\Theta_{SHE} = 0.056$, $l_{sf} = 3.4$nm) to $\alpha$-Sn: $j_S$(BiSbTe)/ $j_S$(Pt) = 61

- Gain from W ($\Theta_{SHE} = 0.33$, $l_{sf} = 1.4$nm) to $\alpha$-Sn: $j_S$(BiSbTe)/ $j_S$(Pt) = 4.2

or with $\Theta_{SHE} = 0.19$, $l_{sf} = 1.4$nm: $j_S$(BiSbTe)/ $j_S$(Pt) = 7.4
Compared *charge to spin* conversion yields between

1) **TL (Bi$_{1-x}$Sb$_x$)Te$_3**

with conversion factor $j_s/J_c \equiv q_{ICS} \simeq 1\text{nm}^{-1}$

(Kondou et al, ArXiv:1510.03572) and

2) **SHE-Pt or - W** layers with $j_s/J_c = \theta_{SHE}/l_{sf}$

in the optimal conditions $t = l_{sf}$

1) Gain in ejected 3D spin current density $J_S$ for the same 2D charge current density $j_c$ in metal layer or 2D topological states between **SHE with Pt or W** (for $t \approx l_{sf}$) and (Bi$_{1-x}$Sb$_x$)Te$_3$ ($q_{ICS} \simeq 1\text{nm}^{-1}$)

- Gain from Pt ($\theta_{SHE} = 0.056$, $l_{sf} = 3.4\text{nm}$) to $\alpha$-Sn: $j_S(\text{BiSbTe})/j_S(\text{Pt}) = 61$

- Gain from W ($\theta_{SHE} = 0.33$, $l_{sf} = 1.4\text{nm}$) to $\alpha$-Sn: $j_S(\text{BiSbTe})/j_S(\text{Pt}) = 4.2$

or with $\theta_{SHE} = 0.19$, $l_{sf} = 1.4\text{nm}$: $j_S(\text{BiSbTe})/j_S(\text{Pt}) = 7.4$

**Remark:** simple calculations lead to $q_{ICS} = 1/v_F \tau$ and $\lambda_{IEE} = 1/v_F \tau = v_F \tau$

but $\tau$ has not exactly the same meaning in $q_{ICS}$ and $\lambda_{IEE}$
Summary

Spin-charge conversion in spintronics

- Spin-Orbit in 2D system (Rashba, TI, LAO/STO) more efficient than in 3D (SHE) for spin-charge conversion

- TI can work at RT (as well as Rashba interfaces)

- TI more efficient if topological 2DEG protected by interface with insulator (ex: LAO/STO)

- Other TI-based devices: spin-filtering p-n junctions, high-speed opto-spintronics, thermo-
Thanks to all my coworkers

K. Garcia, J-M. George, H.Jaffres, N. Reyren, **J-C Rojas-Sánchez**, CNRS/Thales


J.M. De Teresa, Un. Zaragoza, Y. Ohtsubo, A. Taleb, SOLEIL Synchrotron

C.Rinaldi, M.Cantoni, R.Bertacco, Milano, R.Wang, R.Calarco, Berlin (Drude)
Spin pumping from FMR

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

Tserkovnyak et al. PRL 88, 117601 (2002)

1) Increase of effective damping and FMR linewidth

\[ \alpha_{FM/NM} - \alpha_{FM} = \frac{g\mu_B}{4\pi M_s t_F} g_{eff} \]

Y. Tserkovnyak et al. RMP 77, 1375 (2005)

2) Injected spin current from \( g_{\uparrow\downarrow} \) derived from \( \Delta\alpha \)

\[ J_{\text{int}}^{\uparrow\downarrow} = \frac{g_{eff}^2 h_h^2 f}{8\pi\alpha^2} \left[ \frac{4\pi M_s \gamma + \sqrt{(4\pi M_s \gamma)^2 + 4\omega^2}}{(4\pi M_s \gamma)^2 + 4\omega^2} \right] \]


etc
Topological $\alpha$-Sn surface states versus film thickness and strain

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The theoretical prediction that gray tin represents a strong topological insulator under strain [L. Fu and C.L. Kane, Phys. Rev. B 76, 045302 (2007)] is proven for biaxially strained $\alpha$-Sn layers with varying thickness by means of a generalized density functional theory with a nonlocal exchange-correlation potential that widely simulates quasiparticle bands and a tight-binding method including intra- and interatomic spin-orbit interaction.

DFT-LDA for 44 ML of 0.23% biaxially strained $\alpha$-Sn(001)

Helical spin polarization
Topological $\alpha$-Sn surface states versus film thickness and strain

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The theoretical prediction that gray tin represents a strong topological insulator under strain [L. Fu and C.L. Kane, Phys. Rev. B 76, 045302 (2007)] is proven for biaxially strained $\alpha$-Sn layers with varying thickness by means of a generalized density functional theory with a nonlocal exchange-correlation potential that widely simulates quasiparticle bands and a tight-binding method including intra- and interatomic spin-orbit interaction.

They are localized near the slab surfaces. Apart from atomic oscillations in Fig. 2(c) the envelope shows a localization near the surface and an exponential decay into the bulk region of the slab with a decay constant of about 10.1 Å°. As consequence the overlap of envelope functions belonging to opposite surfaces of the slab with 40 ML is negligibly small.
\[ E_F - E_{DP} \] with Ag

\[ E_F - E_{DP} \] without Ag