Spin transport and devices in topological insulators based magnetic heterostructures
Outline

• Introduction to spin current and spin transfer torques

• Measuring spin Hall angle and IEE length
  - Spin pumping
  - Spin-torque ferromagnetic resonance (ST-FMR)
  - Modulation of magnetization damping (MOD)

• Spin transport in TIs: paper review
**Spin transfer torque**

Ferromagnetic resonance (FMR)  
Spin pumping

**LLG equation with torque terms:**

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \tau$$

Damp-like torque:

$$- \frac{\gamma \hbar}{2eM_s V} \mathbf{m} \times (\mathbf{m} \times I_s)$$

Field-like torque:

$$- \frac{\gamma \hbar}{2eM_s V} \mathbf{m} \times I_s$$

Spin current

\[ Q = v \otimes s \]

\[ = \frac{\hbar^2}{2m} \text{Im} \left( \psi^* \sigma \otimes \nabla \psi \right) \]

For a spinor plane-wave wavefunction in x direction:

\[ \psi = \frac{e^{ikx}}{\sqrt{\Omega}} \text{Im} \left( a \uparrow + b \downarrow \right) \]

\[ Q_{xx} = \frac{\hbar^2 k}{2m\Omega} 2 \text{Re} \left( ab^* \right) \]

\[ Q_{xy} = \frac{\hbar^2 k}{2m\Omega} 2 \text{Im} \left( ab^* \right) \]

\[ Q_{xz} = \frac{\hbar^2 k}{2m\Omega} 2 \text{Re} \left( |a|^2 - |b|^2 \right) \]

Conservation of angular momentum

Spin transfer torque:

\[ N_{st} = -\int_{\text{pillbox}} d^2 R \hat{n} \cdot Q \]

\[ = -\int_{\text{pillbox}} d^3 r \nabla \cdot Q \]
\[ \psi_{in} = \frac{e^{ikx}}{\sqrt{\Omega}} \left( \cos(\theta/2)|\uparrow\rangle + \sin(\theta/2)|\downarrow\rangle \right) \]

\[ \psi_{trans} = \frac{e^{ikx}}{\sqrt{\Omega}} \left( t_{\uparrow} \cos(\theta/2)|\uparrow\rangle + t_{\downarrow} \sin(\theta/2)|\downarrow\rangle \right) \]

\[ \psi_{refl} = \frac{e^{-ikx}}{\sqrt{\Omega}} \left( r_{\uparrow} \cos(\theta/2)|\uparrow\rangle + r_{\downarrow} \sin(\theta/2)|\downarrow\rangle \right) \]

\[ Q_{in} = \frac{\hbar^2 k}{2m\Omega} \left[ \sin(\theta)\hat{x} + \cos(\theta)\hat{z} \right] \]

\[ Q_{trans} = \frac{\hbar^2 k}{2m\Omega} \sin(\theta) \text{Re}(t_{\uparrow} t_{\downarrow}^*)\hat{x} + \frac{\hbar^2 k}{2m\Omega} \sin(\theta) \text{Im}(t_{\uparrow} t_{\downarrow}^*)\hat{y} \]

\[ + \frac{\hbar^2 k}{2m\Omega} \left( |t_{\uparrow}|^2 \cos^2(\theta/2) - |t_{\downarrow}|^2 \sin^2(\theta/2) \right) \hat{z} \]

\[ Q_{refl} = -\frac{\hbar^2 k}{2m\Omega} \sin(\theta) \text{Re}(r_{\uparrow} r_{\downarrow}^*)\hat{x} - \frac{\hbar^2 k}{2m\Omega} \sin(\theta) \text{Im}(r_{\uparrow} r_{\downarrow}^*)\hat{y} \]

\[ - \frac{\hbar^2 k}{2m\Omega} \left( |r_{\uparrow}|^2 \cos^2(\theta/2) - |r_{\downarrow}|^2 \sin^2(\theta/2) \right) \hat{z} \]
\[ N_{st} = A \hat{x} \cdot \left( Q_{in} + Q_{refl} - Q_{trans} \right) \]

\[
= \frac{A \hbar^2 k}{2m\Omega} \sin(\theta) \left[ 1 - \text{Re} \left( t_{\uparrow \downarrow}^* t_{\downarrow \uparrow} + r_{\uparrow \downarrow}^* r_{\downarrow \uparrow} \right) \right] \hat{x} 
\]

Damp-like torque

\[
- \frac{A \hbar^2 k}{2m\Omega} \sin(\theta) \text{Im} \left( t_{\uparrow \downarrow}^* t_{\downarrow \uparrow} + r_{\uparrow \downarrow}^* r_{\downarrow \uparrow} \right) \hat{y} 
\]

Field-like torque

Spin mixing conductance

\[
\begin{pmatrix}
  a' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  G_{\uparrow \uparrow} & G_{\uparrow \downarrow} \\
  G_{\downarrow \uparrow}^* & G_{\downarrow \downarrow}
\end{pmatrix} \begin{pmatrix}
  a \\
  b
\end{pmatrix}
\]

\[ \text{Re} \left( G_{\downarrow \uparrow} \right) \gg \text{Im} \left( G_{\downarrow \uparrow} \right) \text{ for metals} \]

\[ \left| t_{\uparrow} \right|^2 + \left| r_{\uparrow} \right|^2 = 1 \]

\[ \left| t_{\downarrow} \right|^2 + \left| r_{\downarrow} \right|^2 = 1 \]
Spin pumping

Spin current projected along $H_{\text{ext}}$:

$$j_s = \frac{\omega}{2\pi} \left[ \frac{\hbar}{4\pi} g_r^{\uparrow\downarrow} \frac{1}{M_s^2} \left[ \mathbf{M}(t) \times \frac{d\mathbf{M}(t)}{dt} \right] \right]_z dt.$$

$$V_{\text{ISHE}} \propto J_c \propto \theta_{\text{SH}} J_s \times \sigma \propto \theta_{\text{SH}} J_s \times M$$

$$\propto \theta_{\text{SH}} J_s \times H \propto \theta_{\text{SH}} \sin \theta_H,$$

A phenomenological model

\[ V = V_{\text{ISHE}} \frac{\Gamma^2}{(H - H_0)^2 + \Gamma^2} + V_{\text{AHE}} \frac{-2\Gamma(H - H_0)}{(H - H_0)^2 + \Gamma^2} \]

\[ g_r^{\uparrow\downarrow} = \frac{2\sqrt{3}\pi M_s \gamma d_F}{g \mu_B \omega} (W_{F/N} - W_F) \]

or

\[ g_r^{\uparrow\downarrow} = \frac{4\pi M_s d_F}{g \mu_B} (\alpha_{F/N} - \alpha_F) \]
Antisymmetric line shape from AHE or AMR

Phase shift between the microwave and magnetization determine the polarity.
Small cone angle (linear) regime

Linear power dependence

\[
\dot{j}_0 = \frac{g_r^{\uparrow\downarrow} \gamma^2 h_{rf}^2 \hbar \left[ 4\pi M_s \gamma + \sqrt{(4\pi M_s)^2 \gamma^2 + 4\omega^2} \right]}{8\pi \alpha^2 \left[ (4\pi M_s)^2 \gamma^2 + 4\omega^2 \right]}
\]

\[
= g_r^{\uparrow\downarrow} fP \left( \frac{\gamma h_{rf}}{2\alpha \omega} \right)^2 = g_r^{\uparrow\downarrow} fP \theta_c^2, \text{ where } h_{rf}^2 \propto \text{power}
\]
The \( P \) factor

\[
P = \frac{2\omega \left[ 4\pi M_s \gamma + \sqrt{(4\pi M_s)^2 \gamma^2 + 4\omega^2} \right]}{(4\pi M_s)^2 \gamma^2 + 4\omega^2}
\]

can be viewed as a correction factor.

The pumped spin current is proportional to the trajectory area. Spin pumping is an adiabatic process. (think about the Carnot engine.)
Spin Hall effect acts as a charge current source.

Solving the spin diffusion equation...

\[ j_s(z) = \frac{\sinh \left[ \left( d_N - z \right) / \lambda_N \right]}{\sinh \left( d_N / \lambda_N \right)} j_s^0 \]
Thickness dependence

Spin backflow depends on the spin diffusion length.

\[
\langle j_c \rangle = \frac{1}{d_N} \int_0^{d_N} j_c(y) \, dy
\]

\[
= \theta_{SH} \left( \frac{2e}{\hbar} \right) \frac{\lambda_N}{d_N} \tanh \left( \frac{d_N}{2\lambda_N} \right) j_s^0
\]

Need to get the thickness dependence data to calculate the spin Hall angle.
Scaling of Spin Hall Angle in 3d, 4d, and 5d Metals from Y$_3$Fe$_5$O$_{12}$/Metal Spin Pumping


Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

(Received 23 September 2013; revised manuscript received 24 December 2013; published 15 May 2014)
Spin Hall angles strongly depend on the d-electron count.

<table>
<thead>
<tr>
<th>Bilayer</th>
<th>$V_{\text{SHE}}$</th>
<th>$\Delta H$ change</th>
<th>$\alpha_{\text{sp}}$</th>
<th>$\rho(\Omega m)$</th>
<th>$g_{\uparrow\downarrow}$ (m$^{-2}$)</th>
<th>$\lambda_{\text{SD}}$ (nm)</th>
<th>$\theta_{\text{SH}}$</th>
<th>$J_s$ (A/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YIG/Pt</td>
<td>2.10 mV</td>
<td>24.3 Oe</td>
<td>$(3.6 \pm 0.3) \times 10^{-3}$</td>
<td>$4.8 \times 10^{-7}$</td>
<td>$(6.9 \pm 0.6) \times 10^{18}$</td>
<td>7.3</td>
<td>$0.10 \pm 0.01$</td>
<td>$(2.0 \pm 0.2) \times 10^{7}$</td>
</tr>
<tr>
<td>YIG/Ta</td>
<td>$-5.10$ mV</td>
<td>16.5 Oe</td>
<td>$(2.8 \pm 0.2) \times 10^{-3}$</td>
<td>$2.9 \times 10^{-6}$</td>
<td>$(5.4 \pm 0.5) \times 10^{18}$</td>
<td>1.9</td>
<td>$-0.071 \pm 0.006$</td>
<td>$(1.6 \pm 0.2) \times 10^{7}$</td>
</tr>
<tr>
<td>YIG/W</td>
<td>$-5.26$ mV</td>
<td>12.3 Oe</td>
<td>$(2.4 \pm 0.2) \times 10^{-3}$</td>
<td>$1.8 \times 10^{-6}$</td>
<td>$(4.5 \pm 0.4) \times 10^{18}$</td>
<td>2.1</td>
<td>$-0.14 \pm 0.01$</td>
<td>$(1.4 \pm 0.1) \times 10^{7}$</td>
</tr>
<tr>
<td>YIG/Au</td>
<td>72.6 $\mu$V</td>
<td>5.50 Oe</td>
<td>$(1.4 \pm 0.1) \times 10^{-3}$</td>
<td>$4.9 \times 10^{-6}$</td>
<td>$(2.7 \pm 0.2) \times 10^{18}$</td>
<td>60</td>
<td>0.084 $\pm 0.007$</td>
<td>$(7.6 \pm 0.7) \times 10^{6}$</td>
</tr>
<tr>
<td>YIG/Ag</td>
<td>1.49 $\mu$V</td>
<td>1.30 Oe</td>
<td>$(2.7 \pm 0.2) \times 10^{-4}$</td>
<td>$6.6 \times 10^{-8}$</td>
<td>$(5.2 \pm 0.5) \times 10^{17}$</td>
<td>700</td>
<td>0.0068 $\pm 0.0007$</td>
<td>$(1.5 \pm 0.1) \times 10^{6}$</td>
</tr>
<tr>
<td>YIG/Cu</td>
<td>0.99 $\mu$V</td>
<td>3.70 Oe</td>
<td>$(8.1 \pm 0.6) \times 10^{-4}$</td>
<td>$6.3 \times 10^{-8}$</td>
<td>$(1.6 \pm 0.1) \times 10^{18}$</td>
<td>500</td>
<td>0.0032 $\pm 0.0003$</td>
<td>$(4.6 \pm 0.4) \times 10^{6}$</td>
</tr>
</tbody>
</table>
1. The larger spin Hall angles, the shorter spin diffusion lengths.
2. Depending on techniques, materials preparation and geometry, the calculated spin Hall angle can vary by 1 order of magnitude.
3. Rashba effect (broken inversion symmetry) at the interface adds complexity to analyses.
Spurious effects?

- Microwave induced Seebeck effect in semiconductor.
  
  - Spin rectification effect. (can be prevented by YIG)
    - the boundary conditions, phase shift between E and B field can strongly affect voltage signals.
  
  - Self-induced ISHE and spin backflow. (can be prevented by YIG)

Universal Method for Separating Spin Pumping from Spin Rectification Voltage of Ferromagnetic Resonance

(a) $\alpha = -1.5^\circ$, $\beta = 0^\circ$
(b) $\alpha = 0^\circ$, $\beta = -0.65^\circ$
(c) $\alpha = 1.5^\circ$, $\beta = 0^\circ$
(d) $\alpha = 0^\circ$, $\beta = 0.65^\circ$
(e) $\alpha = -1.3^\circ$, $\beta = 0^\circ$
(f) $\alpha = 0^\circ$, $\beta = -0.2^\circ$
(g) $\alpha = 1.3^\circ$, $\beta = 0^\circ$
(h) $\alpha = 0^\circ$, $\beta = 0.2^\circ$

$V_{SR} (\mu V)$

$\tan \theta_{SH}$

$\omega/2\pi = 6 \text{ GHz}$

$P = 158 \text{ mW}$

$\mu_0 H (\text{T})$

$\omega/2\pi$ (GHz)

$\mu^2 H^2 (\text{mT}^2)$

$J/\omega^2$ (h/2e$\mu$A/GHz)

$\theta_c$ (degree)

$\mu_0 H (\text{T})$

$\tan \theta_{SH}$

$\omega/2\pi$ (GHz)

$\mu^2 H^2 (\text{mT}^2)$
Spin-torque ferromagnetic resonance (ST-FMR)

Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect

Luqiao Liu, Takahiro Moriyama, D. C. Ralph, and R. A. Buhrman
Cornell University, Ithaca, New York, 14853
(Received 12 October 2010; published 20 January 2011)

\[
\frac{d\hat{m}}{dt} - \gamma \hat{m} \times \vec{H}_{\text{eff}} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma \frac{\hbar}{2e \mu_0 M_s t} J_{s,\text{rf}} (\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma \hat{m} \times \vec{H}_{\text{rf}}
\]

Anti-damp torques
Rely on AMR to generate voltage signals. Not suitable for magnetic insulator.
Special case: Pt/YIG, Ta/YIG...

\[
V_{\text{mix}} = -\frac{1}{4} \frac{dR}{d\theta} \frac{\gamma I_{\text{rf}} \cos \theta}{\Delta 2\pi \left(df / dH\right)} \left|_{H_{\text{ext}}=H_0} \right. \left[ S \frac{\Delta^2}{\Delta^2 + (H_{\text{ext}} - H_0)^2} + A \frac{(H_{\text{ext}} - H_0)\Delta}{\Delta^2 + (H_{\text{ext}} - H_0)^2} \right]
\]

\[
\frac{J_{S,\text{rf}}}{J_{C,\text{rf}}} = \frac{S e \mu_0 M_{\text{std}}}{A \hbar} \left[ 1 + \left( 4\pi M_{\text{eff}} / H_{\text{ext}} \right) \right]^{1/2}
\]

The spin Hall angle can be determined from the relative magnitude of the two components.
Electric Manipulation of Spin Relaxation Using the Spin Hall Effect

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2Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
3CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan
4PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama 332 0012, Japan

(Received 17 March 2008; published 18 July 2008)
Thermal effects on FMR spectra can be serious.

Need to change the in-plane field angle to separate the spin-transfer effect from the thermal effect.
Controlled sample Py/Cu: Cu has small spin Hall angle.
Spin pumping to topological insulators
Goal: Find a material that can generate maximum spin torques from a given charge current.

Non-volatility: \( KV > 50-60 \, k_B T \)

- \( K \): magnetic anisotropy constant
- \( V \): volume of nano-particle
- \( k_B \): Boltzmann constant

Application: data storage
Topological insulators

Nearly 100 % spin polarization.

Spin-momentum locking: the direction of electron motion determines the spin direction.
Challenges

• Bulk conduction of TIs obscures the effect of topological surface states

• Large variation of reported effective spin Hall angle $\theta_{\text{SH}}$ (or conversion efficiency)
  - $0.022$ in Bi$_2$Se$_3$/Py at 15 K (Deorani et al. (2014))
  - $\sim 10^{-4}$ in bulk insulating Bi$_{1.5}$Sb$_{0.5}$Te$_{1.7}$Se$_{1.3}$ at 15 K (Shiomi et al. (2014))
  - $0.021$-$0.43$ in Bi$_2$Se$_3$/CoFeB at RT (Jamali et al. (2015))

• Current shunting effect by ferromagnetic metals in ST-FMR measurement

Ferrimagnetic insulator YIG with high thermal stability is an ideal spin source.
Inverse spin Hall effect (ISHE)

Inverse Edelstein effect (IEE)

<table>
<thead>
<tr>
<th>location</th>
<th>bulk</th>
<th>surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>condition</td>
<td>Spin current normal to the interface</td>
<td>“non-equilibrium” spin density at interface</td>
</tr>
<tr>
<td>material</td>
<td>Normal metals and semiconductors including 3D TIs</td>
<td>TIs and Rasba materials possessing k-dependent spin-polarized states</td>
</tr>
</tbody>
</table>
**Spin Hall angle and IEE length**

\[ j_c = \lambda_{IEE} j_s \quad \text{(definition of IEE length)} \]

\[ j_c = \theta_{SH} \lambda_N \tanh \left( \frac{d_N}{2\lambda_N} \right) j_s , \quad \text{2D charge current from ISHE} \]

\[ \lambda_N \gg d_N, \quad \lambda_{IEE} = \frac{1}{2} d_N \theta_{SH} \]

\[ \lambda_N \ll d_N, \quad \lambda_{IEE} = \lambda_N \theta_{SH} \]

Using spin Hall angle to determine conversion ratio of 3D \( j_c \) and 2D \( j_s \) can lead to “unphysical” value (> 1). Ex: \( \theta_{SH} = 1.6 \) for \( \alpha \)-Sn if compared with W.
Questions

1. Does ferromagnetic metal suppress topological surface states?

2. Can spin pumping distinguish surface and bulk effects (IEE and ISHE) of Bi$_2$Se$_3$?
<table>
<thead>
<tr>
<th>Structure</th>
<th>Journal</th>
<th>method</th>
<th>Spin-charge ratio</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi (001)</td>
<td>Nat. Commun. 4, 2944 (2013) (A. Fert)</td>
<td>Spin pumping</td>
<td>300K: 0.09 ~ 0.2</td>
<td>First demonstration of RT IEE with Rasba alloys Ag/Bi</td>
</tr>
<tr>
<td>Bi</td>
<td>Nature 511, 449 (2014) (D. Ralph)</td>
<td>ST-FMR</td>
<td>300K: 2 ~ 3.5</td>
<td>Giant RT spin torque ratio of Bi$_2$Se$_3$ “Signature” of RT EE</td>
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<tr>
<td>Py, Bi$_2$Se$_3$, Al$_2$O$_3$</td>
<td>PRB 90, 094403 (2014) (S. Oh)</td>
<td>Spin pumping</td>
<td>300K: 0.009 15K: 0.02</td>
<td>ISHE of Bi$_2$Se$_3$</td>
</tr>
<tr>
<td>Py, Bi$_2$Se$_3$, Al$_2$O$_3$, Bi$_2$Se$_3$, BSTS, and Sn-BTS</td>
<td>PRL 113, 196601 (2014) (E. Saitoh)</td>
<td>Spin pumping</td>
<td>15K: $\sim 10^{-4}$</td>
<td>Low T IEE of TIs (crystal)</td>
</tr>
<tr>
<td>Co$<em>{40}$Fe$</em>{40}$B$_{20}$</td>
<td>PRL 114, 257202 (2015) (S. Oh)</td>
<td>ST-FMR</td>
<td>300K: 0.047 50K: 0.42</td>
<td>Large Low T spin torque ratio of Bi$_2$Se$_3”Signature” of RT EE</td>
</tr>
<tr>
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<td><strong>Atypical thickness dependence of mixing conductance</strong></td>
</tr>
<tr>
<td>Co$<em>{20}$Fe$</em>{60}$B$_{20}$</td>
<td>Nano Lett. 15, 7126 (2015) (Jian-Ping Wang, University of Minnesota)</td>
<td>Spin pumping</td>
<td>300K: 0.43</td>
<td>Giant RT ISHE of Bi$_2$Se$_3$</td>
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<tr>
<td>Bi$_2$Se$_3$</td>
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<td>InP</td>
<td></td>
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<tr>
<td>Fe</td>
<td>PRL 116, 096602 (2016) (A. Fert)</td>
<td>Spin pumping</td>
<td>300K: 0.62 ~ 1.5 2.1 nm</td>
<td>Giant RT IEE of TI Sn</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
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<tr>
<td>Sn</td>
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<tr>
<td>InSb (001)</td>
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<tr>
<td>Py</td>
<td>Submitted to PRB (S. F. Lee)</td>
<td>Spin pumping</td>
<td>5 K: 0.003 ~ 0.0062</td>
<td>“Signature” of low T IEE of Bi$_2$Te$_3” Low T ISHE of Bi$_2$Te$_3”</td>
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<tr>
<td>Bi$_2$Te$_3$</td>
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<tr>
<td>Al$_2$O$_3$</td>
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<tr>
<td>Bi$_2$Se$_3$</td>
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<tr>
<td>YIG</td>
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<tr>
<td>GGG</td>
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</tbody>
</table>

**Summary:**
- Spin pumping is a method used to study the spin-charge ratio of various structures.
- The spin-charge ratio varies depending on the structure and experimental conditions.
- Importance notes highlight the significance of these findings in the field of spintronics.
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<td>15K: 0.02</td>
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<td>Al$_2$O$_3$</td>
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</tbody>
</table>

Nothing new.

**Observation of inverse spin Hall effect in bismuth selenide**

Praveen Deorani,¹ Jaesung Son,¹ Karan Banerjee,¹ Nikesh Koirala,² Matthew Brahlek,² Seongshik Oh,² and Hyunsoo Yang¹,* ¹Department of Electrical and Computer Engineering, National University of Singapore, 117576, Singapore ²Department of Physics & Astronomy, Rutgers Center for Emergent Materials, Institute for Advanced Materials, Devices and Nanotechnology, The State University of New Jersey, New Jersey 08854, USA (Received 19 April 2014; revised manuscript received 20 August 2014; published 3 September 2014)

Bismuth Selenide (Bi$_2$Se$_3$) is a topological insulator exhibiting helical spin polarization and strong spin-orbit coupling. The spin-orbit coupling links the charge current to spin current via the spin Hall effect (SHE). We demonstrate a Bi$_2$Se$_3$ spin detector by injecting the pure spin current from a magnetic permalloy layer to a Bi$_2$Se$_3$ thin film and detect the inverse SHE in Bi$_2$Se$_3$. The spin Hall angle of Bi$_2$Se$_3$ is found to be 0.0093 ± 0.0013 and the spin diffusion length in Bi$_2$Se$_3$ to be 6.2 ± 0.15 nm at room temperature. Our results suggest that topological insulators with strong spin-orbit coupling can be used in functional spintronic devices.
In order to distinguish the surface and bulk contributions, they assumed a spin Hall angle $\theta_{sh1}$ for TSS, believing that TSS would give far larger spin Hall angle than the bulk. However, the fitting results show that $\theta_{sh1} \approx \theta_{sh2}$. That is, no TSS features were revealed in this work.
Obviously, they have realized the difficulties of separating surface and bulk effects. So they choose bulk-insulating BSTS to rule out ISHE. However, the very small spin-charge ratio is very puzzling. (Question 1)
The data show negative field shifts as $T$ became lower, similar to Faris’ data. However, they did not mention this.

Q1: The thing is, are TSS still “robust” in this structure?

unit vector perpendicular to the plane. Here, due to the strictly 2D nature, spins do not “flow” along the $z$ direction within the surface state and the converted charge current $J_c$ has the 2D nature. Hence, the mechanism of this spin-electricity conversion is different from that in the inverse spin Hall effect, where a spin current flowing within a finite thickness of a sample is converted into a 3D charge current along the Hall direction.

samples [Fig. 3(a)]. It is worth mentioning that the present spin-electricity conversion effect is rather similar to that reported in Rashba-split systems [31,32], but the efficiency is, in principle, much higher in TIs than that in the Rashba-split system [33]. The spin-momentum locking on a single Dirac cone predicts efficient spin-electricity conversion in TIs even at room temperature as long as the surface state is robust, while in the Rashba-split systems where a pair of bands exist, one of the bands counteracts the effect of the other.
<table>
<thead>
<tr>
<th>Structure</th>
<th>Journal</th>
<th>method</th>
<th>Spin-charge ratio</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co$<em>{20}$Fe$</em>{60}$B$_{20}$</td>
<td>Nano Lett. 15, 7126 (2015) (Jian-Ping Wang, University of Minnesota)</td>
<td>Spin pumping</td>
<td>300K: 0.015 ~ 0.43</td>
<td>Giant RT ISHE of Bi$_2$Se$_3$</td>
</tr>
<tr>
<td>Bi$_2$Se$_3$</td>
<td></td>
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</tr>
<tr>
<td>InP</td>
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</table>

Nothing new in physics again.
The samples had severely degraded. All of the curves should be smooth, so the calculated spin Hall angles are questionable.
<table>
<thead>
<tr>
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<th>Journal</th>
<th>method</th>
<th>Spin-charge ratio</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>PRL 116, 096602 (2016) (A. Fert)</td>
<td>Spin pumping</td>
<td>300K: 0.62 ~ 1.5 2.1 nm</td>
<td>Giant RT IEE of TI Sn</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td></td>
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<tr>
<td>Sn</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>InSb (001)</td>
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</tbody>
</table>

Spin to Charge Conversion at Room Temperature by Spin Pumping into a New Type of Topological Insulator: α-Sn Films

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We present results on spin to charge current conversion in experiments of resonant spin pumping into the Dirac cone with helical spin polarization of the elemental topological insulator (TI) α-Sn. By angle-resolved photoelectron spectroscopy (ARPES), we first check that the Dirac cone (DC) at the α-Sn (001) surface subsists after covering Sn with Ag. Then we show that resonant spin pumping at room temperature from Fe through Ag into α-Sn layers induces a lateral charge current that can be ascribed to the inverse Edelstein effect by the DC states. Our observation of an inverse Edelstein effect length much longer than those generally found for Rashba interfaces demonstrates the potential of TIs for the conversion between spin and charge in spintronic devices. By comparing our results with data on the relaxation time of TI free surface states from time-resolved ARPES, we can anticipate the ultimate potential of the TI for spin to charge conversion and the conditions to reach it.
Fermi level is very closed to the Dirac point of Sn. TSS disappeared when Fe was deposited on top. (Question 1)

Q3: Could this explain the small spin-charge ratio from the Japanese group’s work?
<table>
<thead>
<tr>
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<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Py</td>
<td>Nature <strong>511</strong>, 449 (2014) (D. Ralph)</td>
<td>ST-FMR</td>
<td>300K: 2 ~ 3.5</td>
<td>Giant RT spin torque ratio of Bi$_2$Se$_3$ “Signature” of RT EE</td>
</tr>
<tr>
<td>Bi$_2$Se$_3$</td>
<td></td>
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<tr>
<td>Al$_2$O$_3$</td>
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</table>

**LETTER**

doi:10.1088/nature13534

**Spin-transfer torque generated by a topological insulator**

A. R. Mellnik$^1$, J. S. Lee$^2$, A. Richardella$^2$, J. L. Grab$^1$, P. J. Mintun$^1$, M. H. Fischer$^{1,3}$, A. Vaezi$^1$, A. Manchon$^4$, E.-A. Kim$^1$, N. Samarth$^2$ & D. C. Ralph$^{1,5}$

Signatures of Edelstein effect (EE):
1. Large anti-symmetric component of voltage signals.
2. Resonance field shifts.

The two features result from **non-equilibrium spin density** at TSS.
Large antisymmetric component for $\text{Bi}_2\text{Se}_3$/Py. In contrast, symmetric signals dominate for Pt/Py (without EE).

They did not do $\text{Bi}_2\text{Se}_3$ thickness dependence measurement, so it’s still hard to extract the EE.
Topological Surface States Originated Spin-Orbit Torques in Bi$_2$Se$_3$

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The three dimensional topological insulator bismuth selenide (Bi$_2$Se$_3$) is expected to possess strong spin-orbit coupling and spin-textured topological surface states and, thus, exhibit a high charge to spin current conversion efficiency. We evaluate spin-orbit torques in Bi$_2$Se$_3$/Co$_{40}$Fe$_{40}$B$_{20}$ devices at different temperatures by spin torque ferromagnetic resonance measurements. As the temperature decreases, the spin-orbit torque ratio increases from $\sim$0.047 at 300 K to $\sim$0.42 below 50 K. Moreover, we observe a significant out-of-plane torque at low temperatures. Detailed analysis indicates that the origin of the observed spin-orbit torques is topological surface states in Bi$_2$Se$_3$. Our results suggest that topological insulators with strong spin-orbit coupling could be promising candidates as highly efficient spin current sources for exploring the next generation of spintronic applications.

DOI: 10.1103/PhysRevLett.114.257202

PACS numbers: 75.76.+j, 72.25.Dc, 73.20.-r, 85.75.-d
Large antisymmetric component of voltage.

Spin-charge ratio was greatly enhanced at low T. But the RT values are two order of magnitudes smaller than that from the Cornell group.

On the other hand, a possible out-of-plane spin polarization in the TSS has been theoretically predicted [55,56] and experimentally observed in Bi$_2$Se$_3$ [57,58], which is attributed to the hexagonal warping effect in the Fermi surface [55,59]. This out-of-plane spin polarization in the TSS can account for the observed $\Delta \tau$ especially in the low temperature range (<50 K), and the $\Delta \tau$ adds to the $\tau_{\text{Oe}}$ [27,31]. Moreover, as shown in Figs. 3(a) and 4(a), the out-of-plane torque ($\Delta \tau$) has the same order of magnitude comparable to the in-plane torque ($\tau_{\parallel}$) below 50 K ($\Delta \tau/\tau_{\parallel} \sim 60\%$) [37], which is in agreement with the behavior of hexagonal TSS in TI [55,56]. With the analysis from different aspects, our findings especially in the low temperature range (<50 K) indicate a TSS origin of spin-orbit torques in Bi$_2$Se$_3$ and CFB.

They explained the origin of field-like torques with spin texture only qualitatively. They did not resort to the model proposed by the Cornell group.
Questions?

1. Does ferromagnetic metal suppress topological surface states?
   Yes. (A. Fert and E. Saitoh)

2. Can spin pumping distinguish surface and bulk effects (IEE and ISHE) of Bi$_2$Se$_3$?
   It’s difficult for TI/FM, but how about FI/TI?

3. Now that ST-FMR have shown the signature of EE with large field-like torques, which come from non-equilibrium spin density, is it possible to observe similar effect (IEE) with spin pumping?

4. Note that in A. Fert’s work they did not deposit Fe directly on Sn.
   An Ag layer may weaken the effect of non-equilibrium spin density, which is localized, on Fe. That is, the Ag layer separate Fe and Sn out of the range of exchange coupling. Therefore, “signatures (negative field shift)” of IEE were not observed.
More questions

• How does the ac component of the pumped spin current affect the TSS?

• How does spin canting of TSS affect the spin transport properties?
Spin texture of Bi$_2$Se$_3$

- Large Rashba splitting of 2DEG in Bi$_2$Se$_3$ has been confirmed by ARPES. The interplay between TSS and 2DEG leads to intricate spin texture.
- The spin pumping effect strongly depends on the interface electronic structure and spin texture.
- The spin transport of topological interface state near a magnetic layer is of further interest to investigate.

King et. al., PRL 107, 096802 (2011)