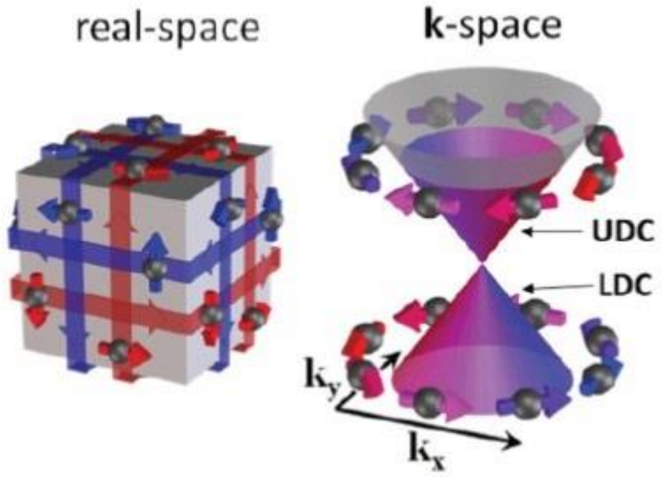
Spin transport and devices in topological insulators based magnetic heterostructures



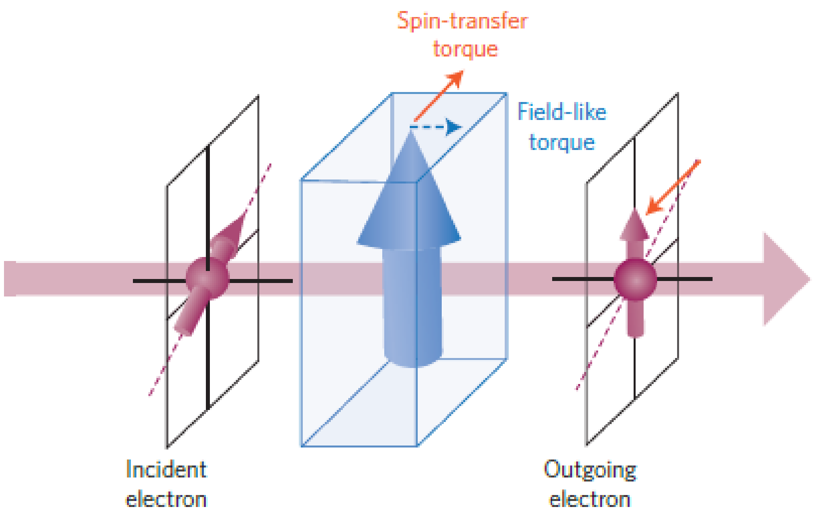
Outline

- 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)

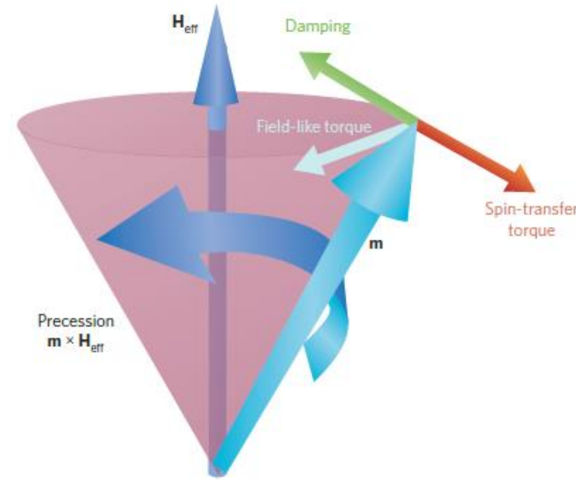
- Spin transport in TIs: paper review

Spin transfer torque



Ferromagnetic resonance (FMR)

Spin pumping



LLG equation with torque terms:

A. Brataas, et al., Nat. Mater. **11**, 372 (2012)

$$\frac{\partial \mathbf{m}}{\partial t} = -y\mathbf{m} \times H_{eff} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \boldsymbol{\tau}$$

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

$$\mathbf{Q} = \mathbf{v} \otimes \mathbf{s}$$

$$= \frac{\hbar^2}{2m} \mathrm{Im}\left(\psi^* \boldsymbol{\sigma} \otimes \nabla \psi\right)$$

For a spinor plane-wave wavefunction in x direction:

$$\psi = \frac{e^{ikx}}{\sqrt{\Omega}} \mathrm{Im}\left(a\left|\uparrow\right\rangle + b\left|\downarrow\right\rangle\right)$$

$$Q_{xx} = \frac{\hbar^2 k}{2m\Omega} 2\,\mathrm{Re}\left(ab^*\right)$$

$$Q_{xy} = \frac{\hbar^2 k}{2m\Omega} 2\,\mathrm{Im}\left(ab^*\right)$$

$$Q_{xz} = \frac{\hbar^2 k}{2m\Omega} 2\,\mathrm{Re}\left(\left|a\right|^2 - \left|b\right|^2\right)$$

Conservation of angular momentum

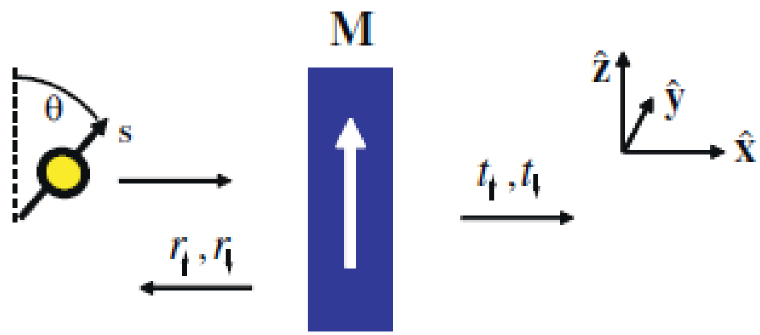
Spin transfer torque:

$$\mathbf{N}_{st} = -\int_{pillbox} d^2 R\, \hat{\mathbf{n}} \cdot \mathbf{Q}$$

$$= -\int_{pillbox} d^3 r \nabla \cdot \mathbf{Q}$$

D. C. Ralph, J. Magn. Magn. Mat. **320**, 1190 (2008)

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



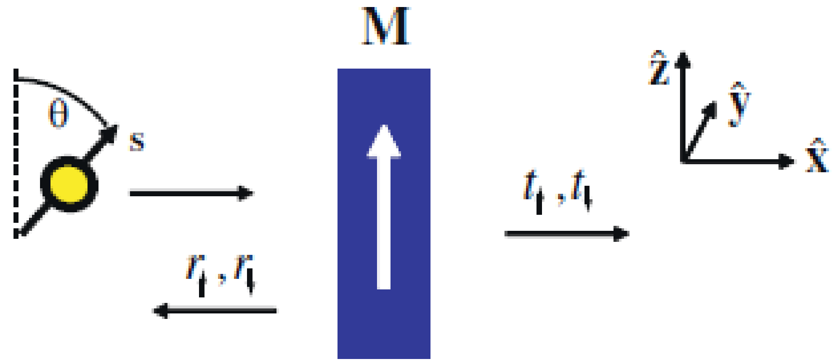
$$\psi_{trans} = \frac{e^{ikx}}{\sqrt{\Omega}}\left(t_\uparrow \cos(\theta/2)\left|\uparrow\right\rangle + t_\downarrow \sin(\theta/2)\left|\downarrow\right\rangle\right)$$

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

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

$$\mathbf{Q}_{trans} = \frac{\hbar^2 k}{2m\Omega}\sin(\theta)\,\mathrm{Re}\left(t_\uparrow t_\downarrow^*\right)\hat{\mathbf{x}} + \frac{\hbar^2 k}{2m\Omega}\sin(\theta)\,\mathrm{Im}\left(t_\uparrow t_\downarrow^*\right)\hat{\mathbf{y}}$$
$$+ \frac{\hbar^2 k}{2m\Omega}\left(\left|t_\uparrow\right|^2 \cos^2(\theta/2) - \left|t_\downarrow\right|^2 \sin^2(\theta/2)\right)\hat{\mathbf{z}}$$

$$\mathbf{Q}_{refl} = -\frac{\hbar^2 k}{2m\Omega}\sin(\theta)\,\mathrm{Re}\left(r_\uparrow r_\downarrow^*\right)\hat{\mathbf{x}} - \frac{\hbar^2 k}{2m\Omega}\sin(\theta)\,\mathrm{Im}\left(r_\uparrow r_\downarrow^*\right)\hat{\mathbf{y}}$$
$$- \frac{\hbar^2 k}{2m\Omega}\left(\left|r_\uparrow\right|^2 \cos^2(\theta/2) - \left|r_\downarrow\right|^2 \sin^2(\theta/2)\right)\hat{\mathbf{z}}$$



$$\mathbf{N}_{st} = A\hat{\mathbf{x}}\cdot\left(\mathbf{Q}_{in} + \mathbf{Q}_{refl} - \mathbf{Q}_{trans}\right)$$

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

Damp-like torque

$$-\frac{A\hbar^2 k}{2m\Omega}\sin(\theta)\,\mathrm{Im}\left(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\right)\hat{\mathbf{y}}$$

Field-like torque

$$(|t_\uparrow|^2 + |r_\uparrow|^2 = 1$$

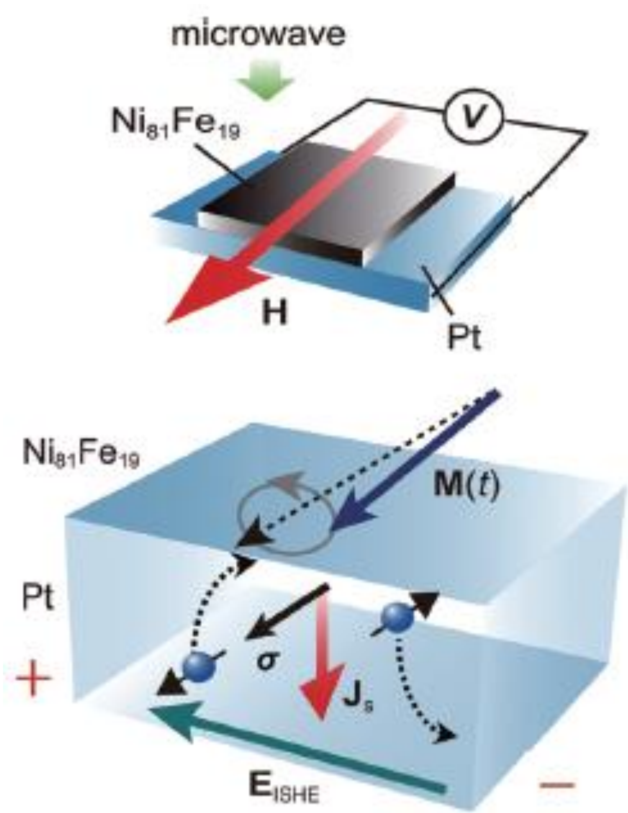
$$|t_\downarrow|^2 + |r_\downarrow|^2 = 1)$$

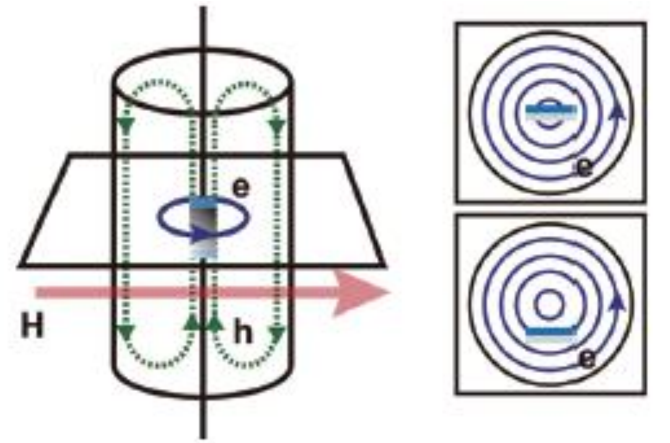
Spin mixing conductance

$$\begin{pmatrix} a' \\ b' \end{pmatrix} = \begin{pmatrix} G_{\uparrow\uparrow} & G_{\uparrow\downarrow} \\ G^*_{\downarrow\uparrow} & G_{\downarrow\downarrow} \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

$\mathrm{Re}\left(G_{\uparrow\downarrow}\right) >> \mathrm{Im}\left(G_{\uparrow\downarrow}\right)$ for metals

Spin pumping



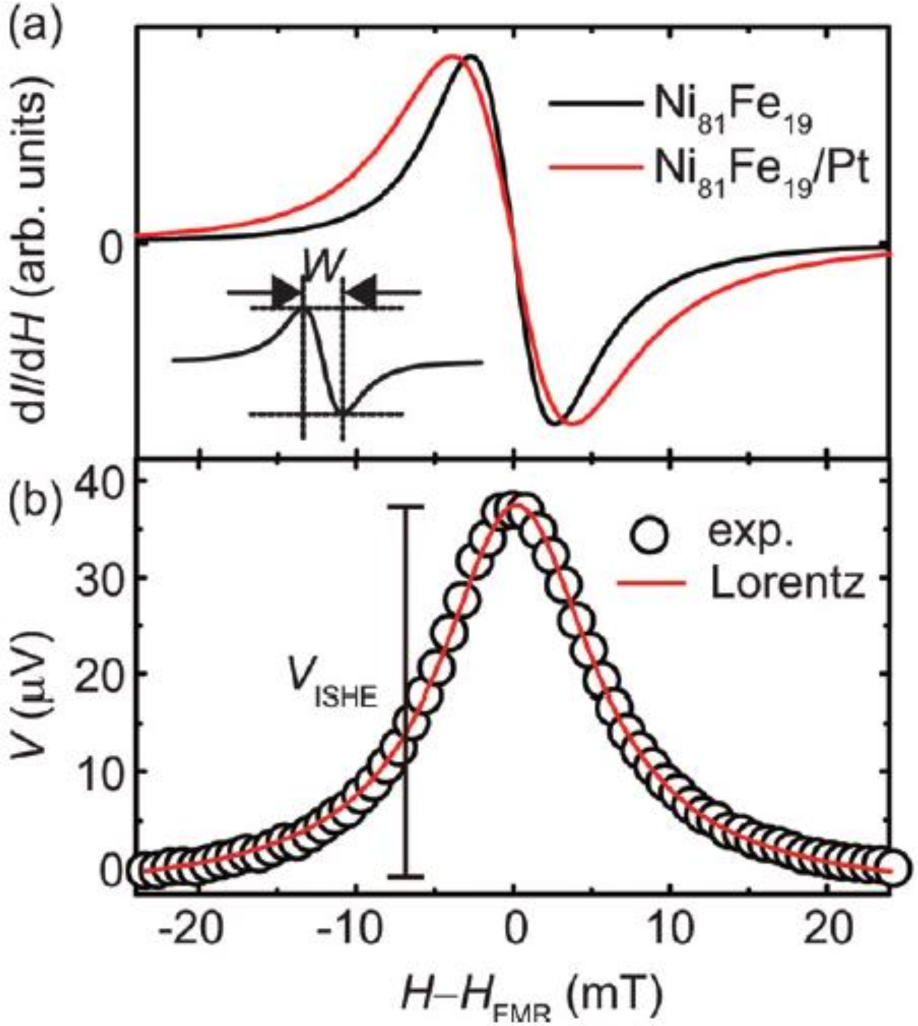


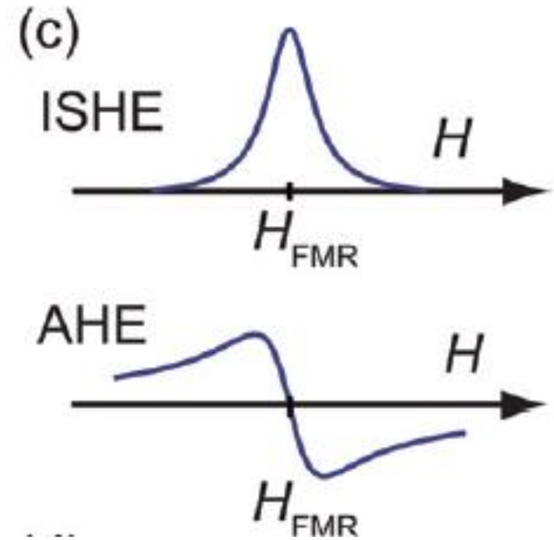
Spin current projected along H_{ext}:

$$j_s = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} \frac{\hbar}{4\pi} g_r^{\uparrow\downarrow} \frac{1}{M_s^2}\left[\mathbf{M}(t) \times \frac{d\mathbf{M}(t)}{dt}\right]_z dt$$

$$V_{\text{ISHE}} \propto \boldsymbol{J}_{\mathbf{c}} \propto \theta_{\text{SH}} \boldsymbol{J}_{\mathbf{s}} \times \boldsymbol{\sigma} \propto \theta_{\text{SH}} \boldsymbol{J}_{\mathbf{s}} \times \boldsymbol{M}$$
$$\propto \theta_{\text{SH}} \boldsymbol{J}_{\mathbf{s}} \times \boldsymbol{H} \propto \theta_{\text{SH}} \sin \theta_{\text{H}},$$

K. Ando, J. Appl. Phys. **109**, 103913 (2011)





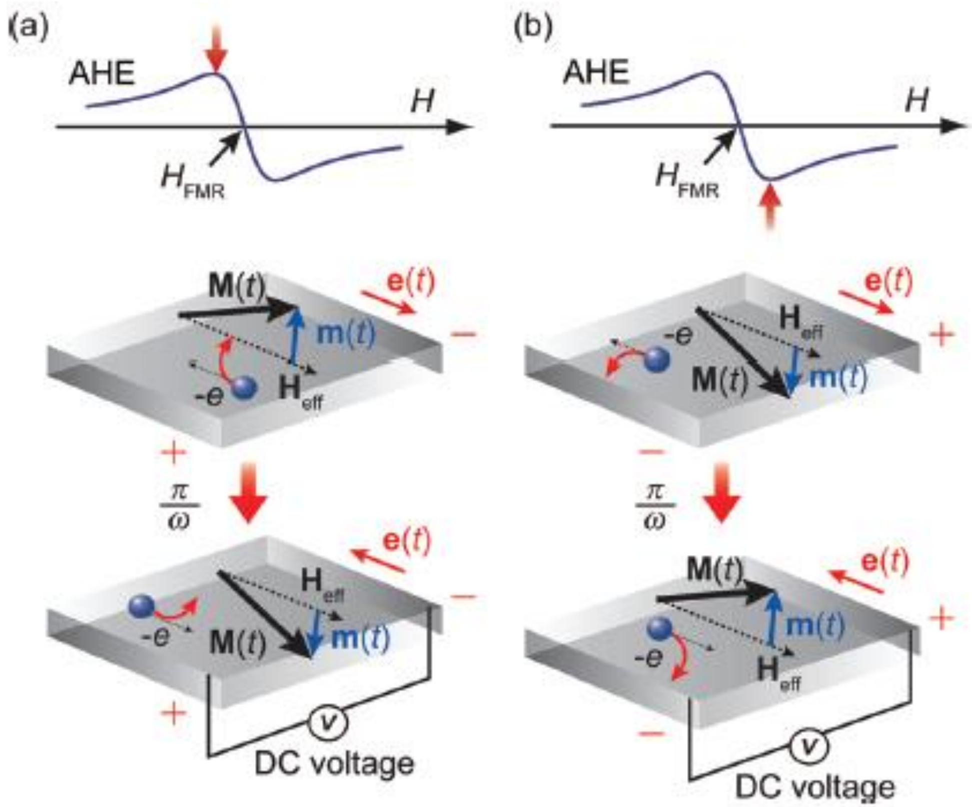
$$V = V_{ISHE}\frac{\Gamma^2}{\left(H-H_0\right)^2+\Gamma^2} + V_{AHE}\frac{-2\Gamma\left(H-H_0\right)}{\left(H-H_0\right)^2+\Gamma^2}$$

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

or $$g_r^{\uparrow\downarrow} = \frac{4\pi M_s d_F}{g\mu_B}\left(\alpha_{F/N}-\alpha_F\right)$$

A phenomenological model

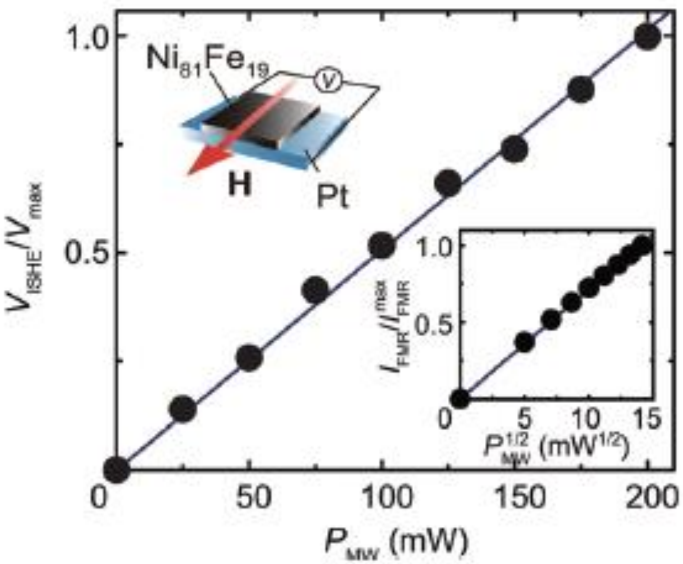
Antisymmetric line shape from AHE or AMR

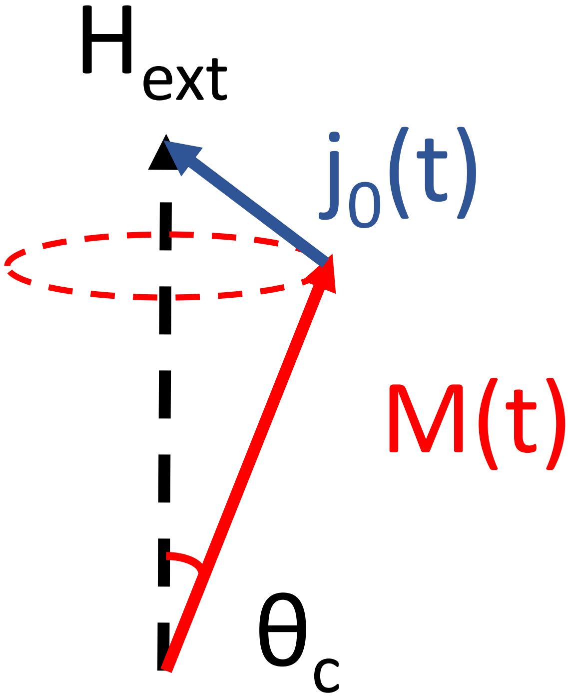


Phase shift between the microwave and magnetization determine the polarity.

Small cone angle (linear) regime

Linear power dependence





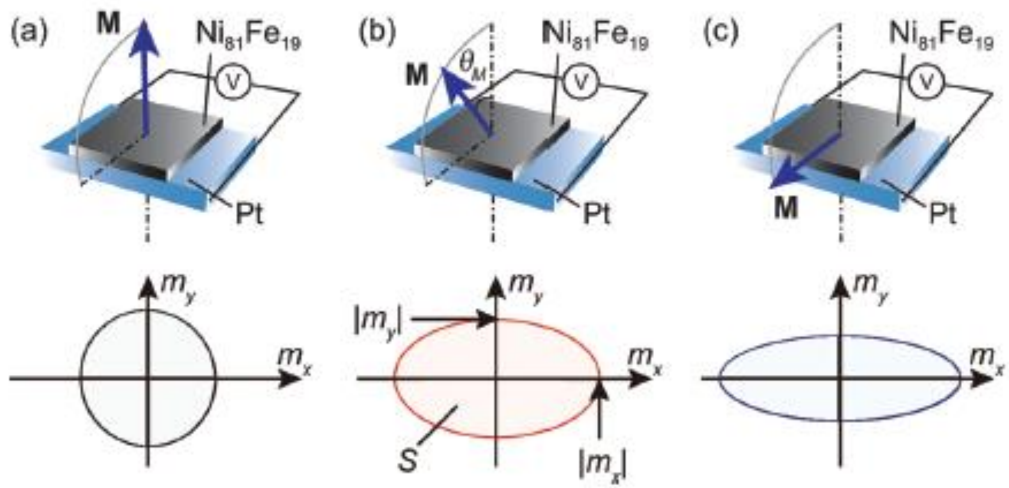
$$j_0 = \frac{g_r^{\uparrow\downarrow}\gamma^2 h_{rf}^2 \hbar \left[4\pi M_s \gamma + \sqrt{(4\pi M_s)^2 \gamma^2 + 4\omega^2} \right]}{8\pi\alpha^2 \left[(4\pi M_s)^2 \gamma^2 + 4\omega^2 \right]}$$

$$= g_r^{\uparrow\downarrow} fP \left(\frac{\gamma h_{rf}}{2\alpha\omega} \right)^2 = g_r^{\uparrow\downarrow} fP\theta_c^2$$, where $h_{rf}^2 \propto$ power

The P factor

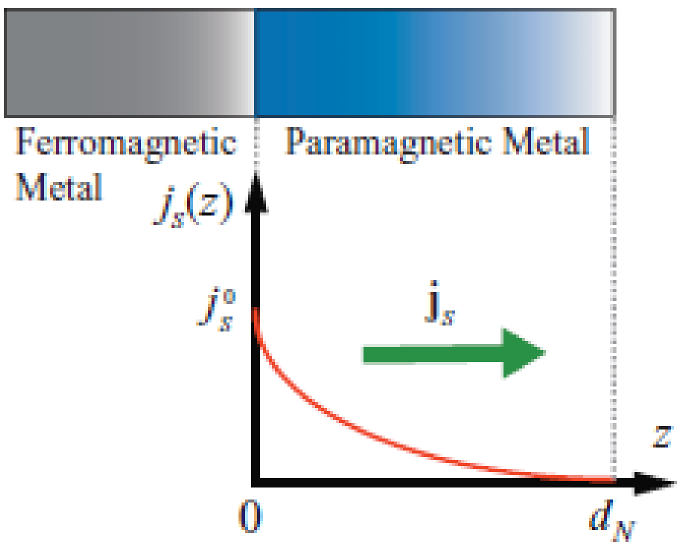
$$P = \frac{2\omega\left[4\pi M_s\gamma + \sqrt{(4\pi M_s)^2\gamma^2 + 4\omega^2}\right]}{(4\pi M_s)^2\gamma^2 + 4\omega^2}$$

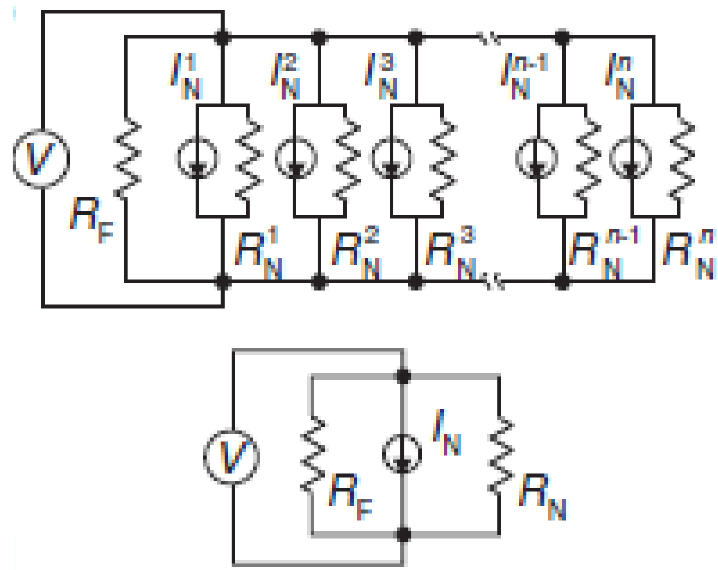
can be viewed as a correction factor.



The pumped spin current is proportional to the trajectory area.
Spin pumping is an adiabatic process.
(think about the Carnot engine.)

Spin distribution in normal metals



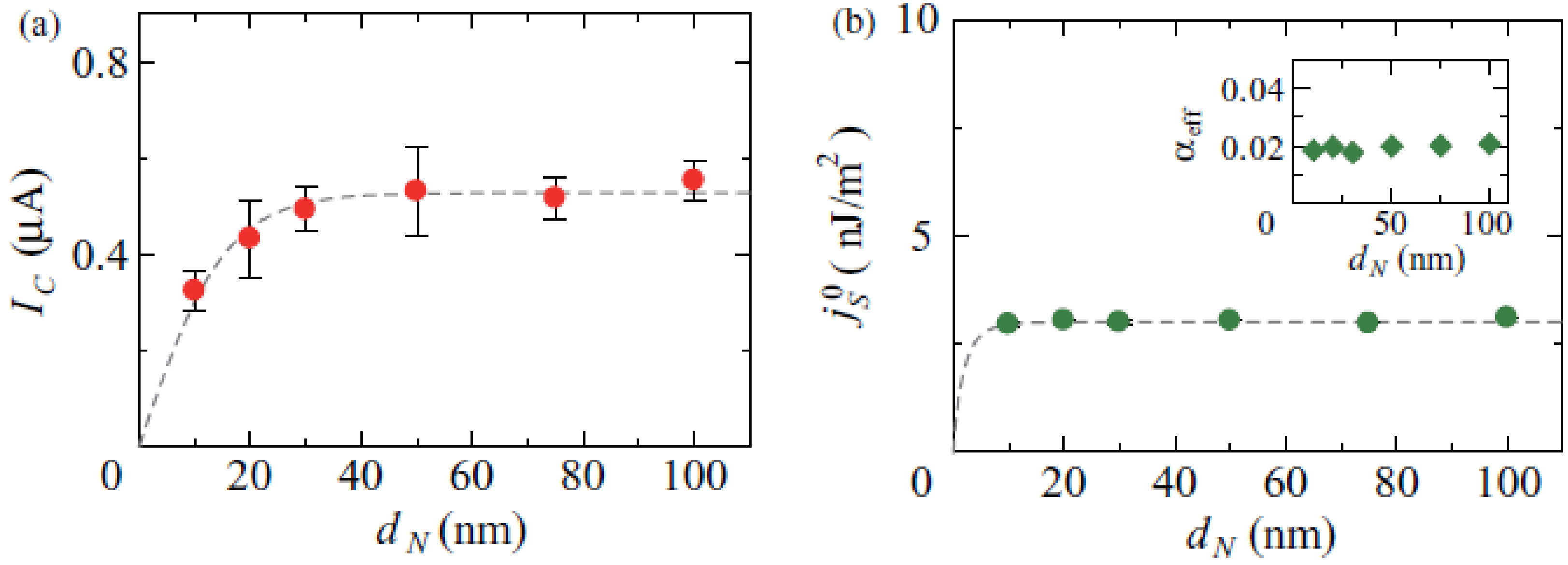


Spin Hall effect acts as a charge current source.

Solving the spin diffusion equation…

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

Thickness dependence



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

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

Spin backflow depends on the spin diffusion length.

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 $Y_3Fe_5O_{12}$/Metal Spin Pumping

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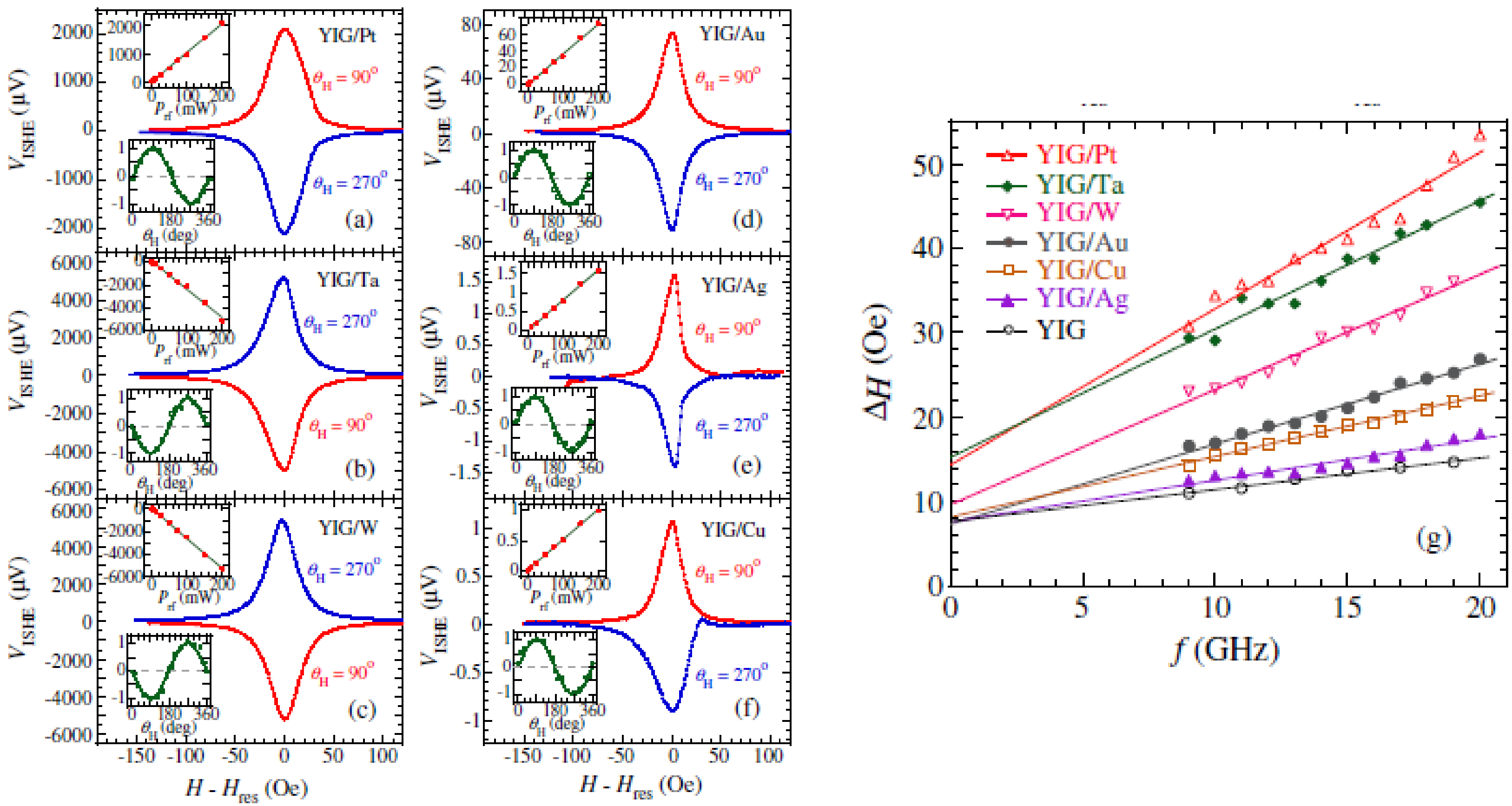
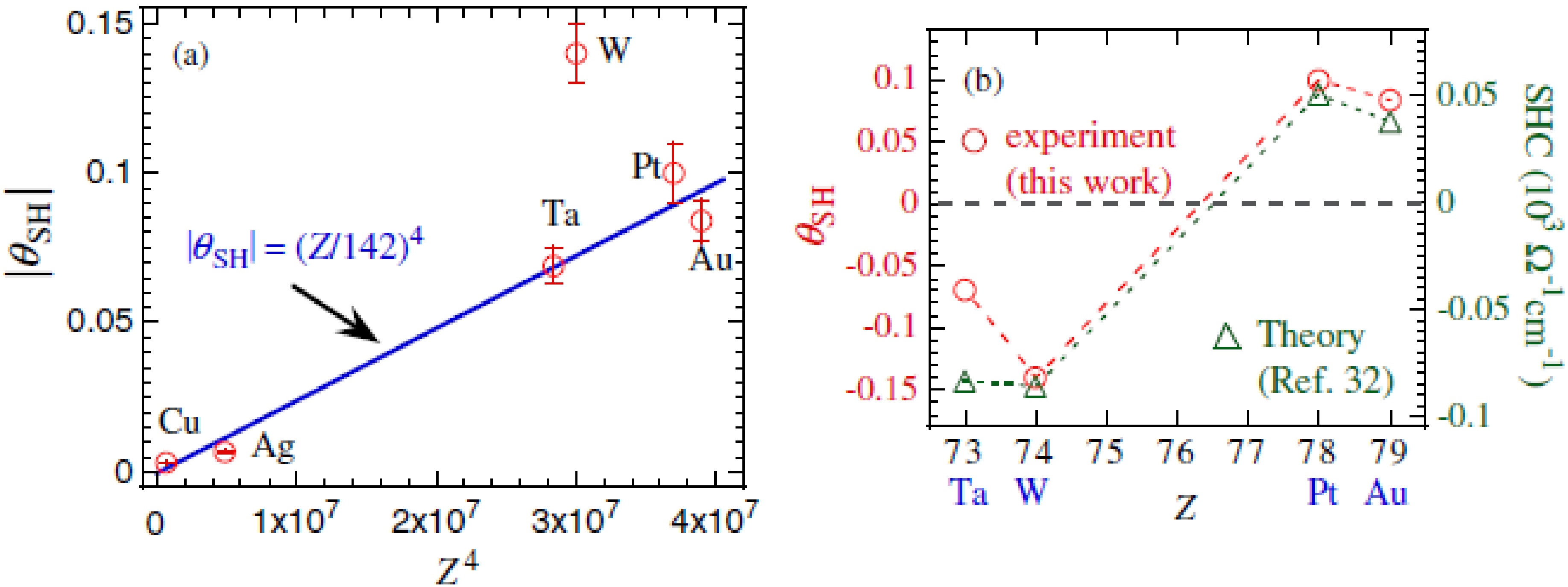
(Received 23 September 2013; revised manuscript received 24 December 2013; published 15 May 2014)



Bilayer	V_{ISHE}	ΔH change	α_{sp}	$\rho(\Omega m)$	$g_{\uparrow\downarrow}(\mathrm{m}^{-2})$	$\lambda_{\mathrm{SD}}(\mathrm{nm})$	θ_{SH}	$J_s(\mathrm{A/m}^2)$
YIG/Pt	2.10 mV	24.3 Oe	$(3.6 \pm 0.3) \times 10^{-3}$	4.8×10^{-7}	$(6.9 \pm 0.6) \times 10^{18}$	7.3	0.10 ± 0.01	$(2.0 \pm 0.2) \times 10^{7}$
YIG/Ta	−5.10 mV	16.5 Oe	$(2.8 \pm 0.2) \times 10^{-3}$	2.9×10^{-6}	$(5.4 \pm 0.5) \times 10^{18}$	1.9	-0.071 ± 0.006	$(1.6 \pm 0.2) \times 10^{7}$
YIG/W	−5.26 mV	12.3 Oe	$(2.4 \pm 0.2) \times 10^{-3}$	1.8×10^{-6}	$(4.5 \pm 0.4) \times 10^{18}$	2.1	-0.14 ± 0.01	$(1.4 \pm 0.1) \times 10^{7}$
YIG/Au	72.6 μV	5.50 Oe	$(1.4 \pm 0.1) \times 10^{-3}$	4.9×10^{-8}	$(2.7 \pm 0.2) \times 10^{18}$	60	0.084 ± 0.007	$(7.6 \pm 0.7) \times 10^{6}$
YIG/Ag	1.49 μV	1.30 Oe	$(2.7 \pm 0.2) \times 10^{-4}$	6.6×10^{-8}	$(5.2 \pm 0.5) \times 10^{17}$	700	0.0068 ± 0.0007	$(1.5 \pm 0.1) \times 10^{6}$
YIG/Cu	0.99 μV	3.70 Oe	$(8.1 \pm 0.6) \times 10^{-4}$	6.3×10^{-8}	$(1.6 \pm 0.1) \times 10^{18}$	500	0.0032 ± 0.0003	$(4.6 \pm 0.4) \times 10^{6}$



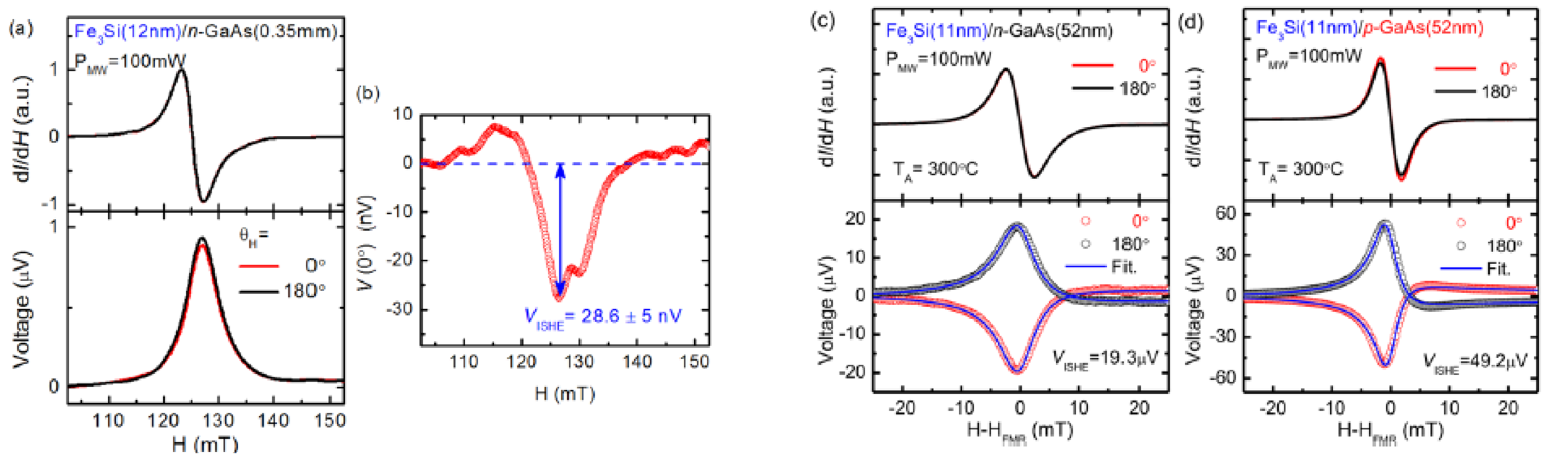
Spin Hall angles strongly depend on the d-electron count.

	T (K)	λ_{sd} (nm)	σ_{NM} (10^6 S/m)	α_{SH} (%)
Al	4.2	455 ± 15	10.5	0.032 ± 0.006
	4.2	705 ± 30	17	0.016 ± 0.004
Au	295	86 ± 10	37	11.3
	295	83	37	3
	4.5	65*	48.3	<2.3
	295	36*	25.7	<2.7
	295	35 ± 4	28	7.0 ± 0.1
	295	27 ± 3	14	7.0 ± 0.3
	295	25 ± 3	14.5	12 ± 4
	295	50 ± 8	16.7	0.8 ± 0.2
	<10	40 ± 16	25	1.4 ± 0.4
	295	35 ± 3*	25.2	0.35 ± 0.03
	295	35	20	0.25 ± 0.1
	295	35 ± 3*	5.25	1.6 ± 0.1
	295	35 ± 3*	7	0.335 ± 0.006
	295	35*		1.1 ± 0.3
	295	60	20.4	8.4 ± 0.7
AuW	295	1.9	1.75	>10
Ag	295	700	15	0.7 ± 0.1
Bi	3	0.3 ± 0.1	-	>0.3
	295	-	2.4 ± 0.3(I) 50 ± 12(V)	−(7.1 ± 0.8)(I) 1.9 ± 0.2(V)
Cu	295	500	16	0.32 ± 0.03
CuIr	10	5–30		2.1 ± 0.6
$CuMn_xT_y$				0.7(Ta); 2.6(Ir) 1.35(Au); 1.15(Sb) −1.2(Lu)
CuBi	10	~100; ~30 ~10; ~7		−11
Mo	10	10	3.03	−0.20
	10	10	0.667	−0.075
	10	8.6 ± 1.3	2.8	−(0.8 ± 0.18)
	295	35 ± 3*	4.66	−(0.05 ± 0.01)
Nb	10	5.9 ± 0.3	1.1	−(0.87 ± 0.20)
Pd	10	13 ± 2	2.2	1.2 ± 0.4
	295	9*	1.97	1.0
	295	15 ± 4*	4.0	0.64 ± 0.10
	295	5.5 ± 0.5	5	1.2 ± 0.3
	295	2.0 ± 0.1	3.7	0.8 ± 0.20
Pt	295		6.41	0.37
	5	8	8.0	0.44
	295	7	5.56	0.9
	10	11 ± 2	8.1	2.1 ± 0.5
	10	~10	8.1	2.4
	295	7*	6.4	8.0
	295	10 ± 2*	2.4	1.3 ± 0.2
	295	10*	2	4.0
	295	3.7 ± 0.2	2.42	8 ± 1
	295	8.3 ± 0.9	4.3 ± 0.2	1.2 ± 0.2
	295	7.7 ± 0.7	1.3 ± 0.1	1.3 ± 0.1
	295	1.5 − 10*	2.45 ± 0.1	$3^{+4}_{-1.5}$
	295	4	4	2.7 ± 0.5
	295	8 ± 1*	1.02	2.012 ± 0.003
	295	1.3*	2.4	2.1 ± 1.5
	295	1.2		8.6 ± 0.5
	295	1.4*		12 ± 4
	295	3.4 ± 0.4	6.0	5.6 ± 0.1
	295	7.3	2.1	10 ± 1
	295	1.2 ± 0.1	3.6	2.2 ± 0.4
	295	3(<6)	5.0	$7.6^{+8.4}_{-2.0}$
	295	2.1 ± 0.2	3.6	2.2 ± 0.8

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.



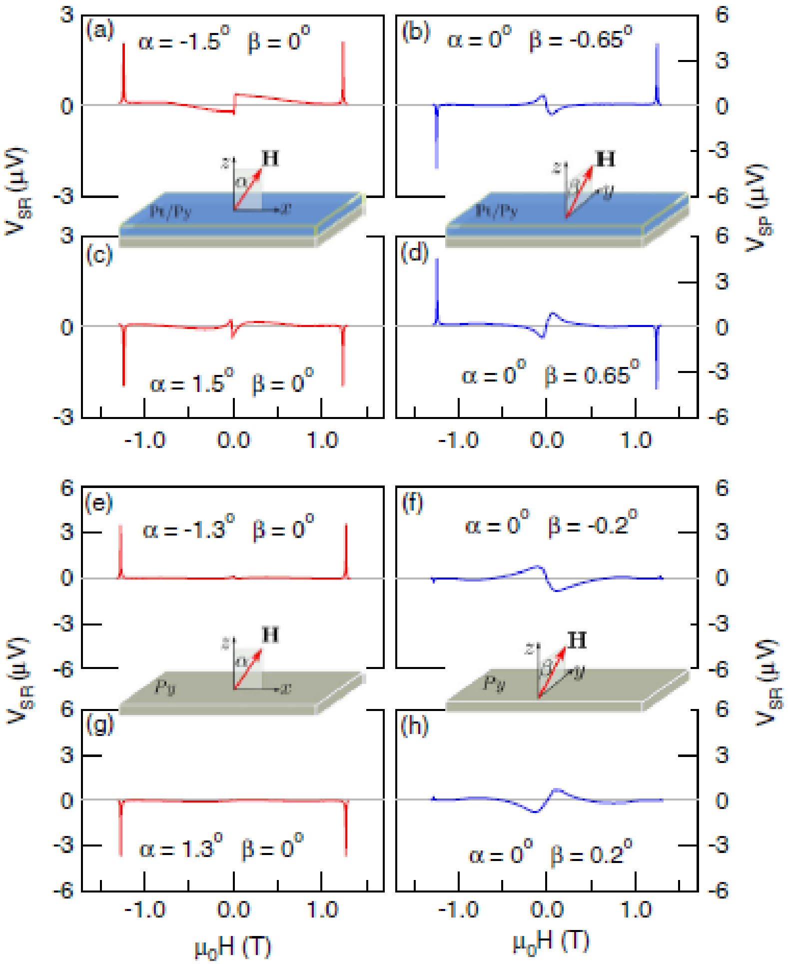
H. Hung et al., Appl. Phys. Lett. **105**, 152413 (2014)

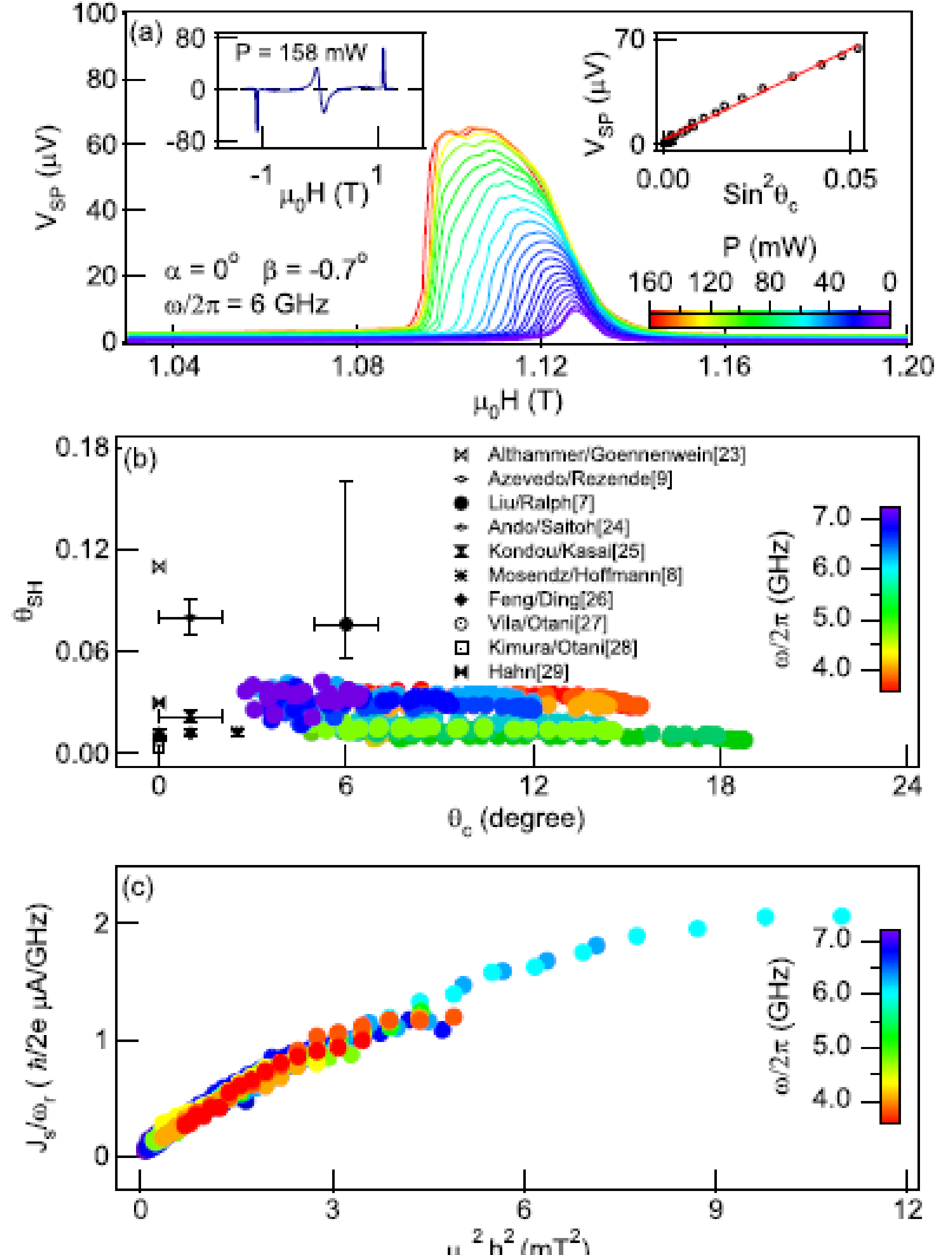
- Spin rectification effect. (can be prevented by YIG)

  - 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





Spin-torque ferromagnetic resonance (ST-FMR)

PRL 106, 036601 (2011) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2011

Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect

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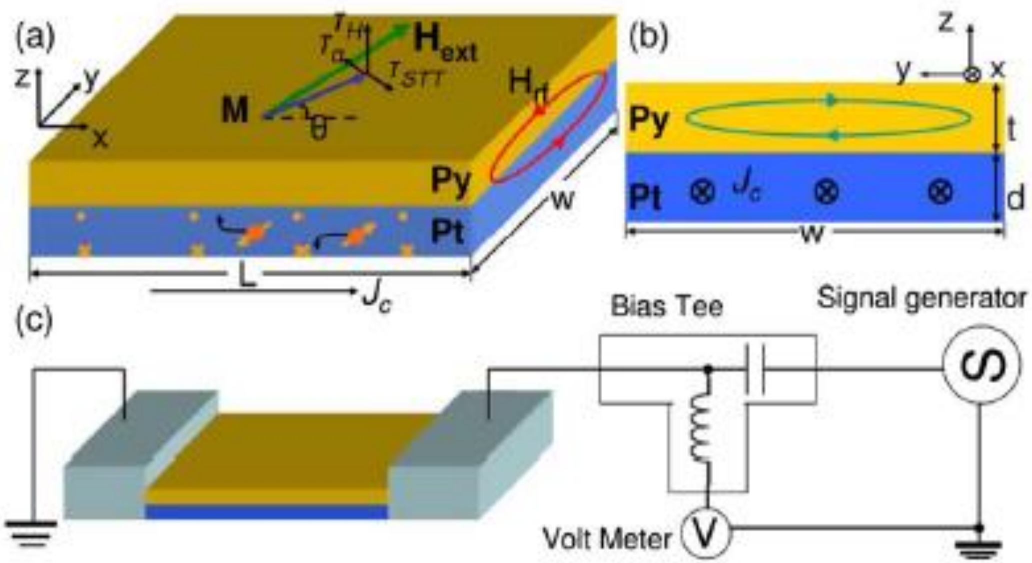
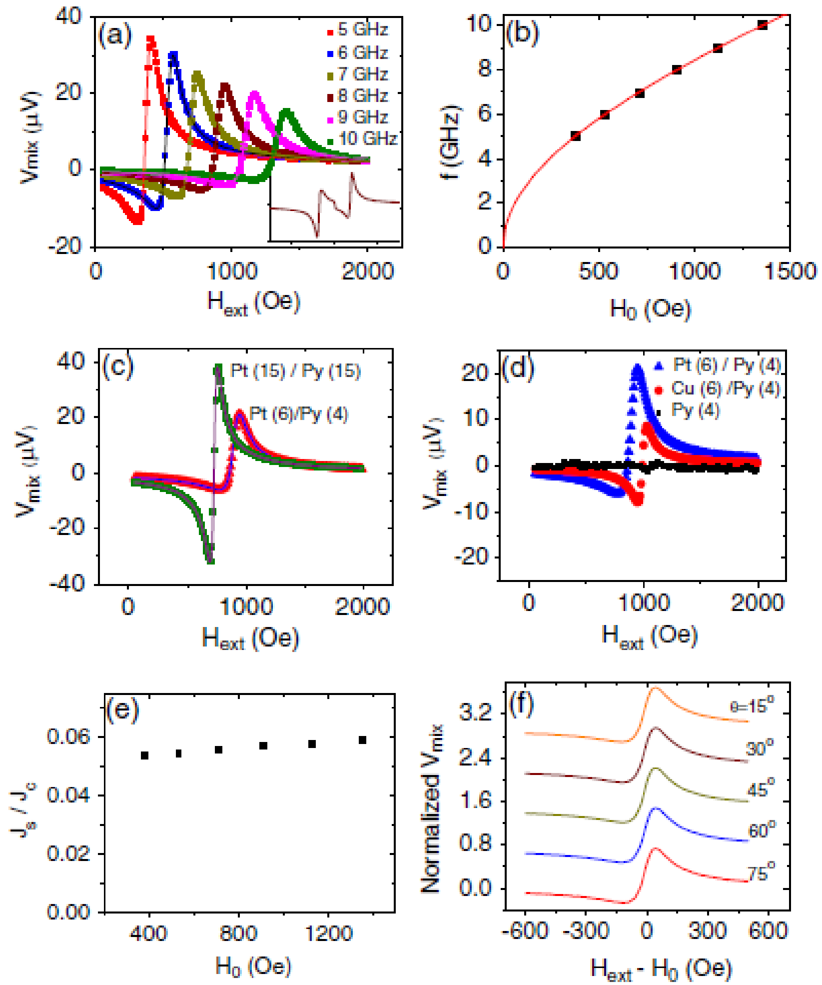
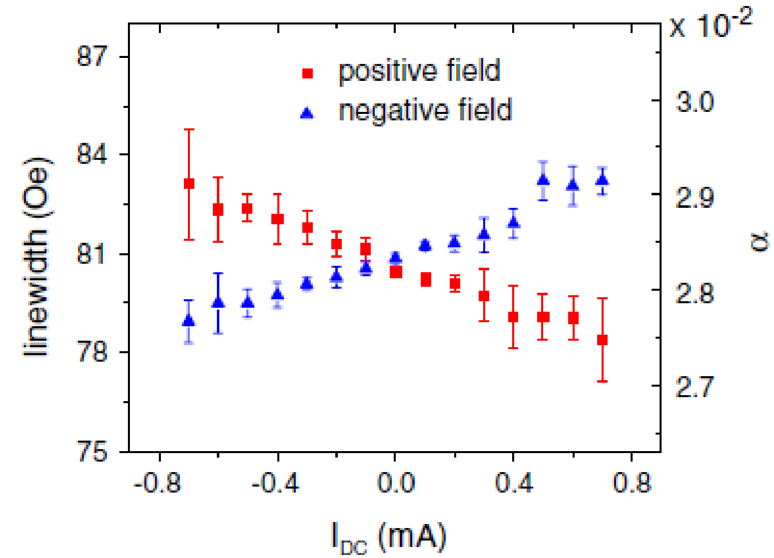
(Received 12 October 2010; published 20 January 2011)



$$\frac{d\hat{m}}{dt} - \gamma \hat{m} \times \vec{H}_{eff} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma \frac{\hbar}{2e\mu_0 M_S t} J_{s,rf} \left(\hat{m} \times \hat{\sigma} \times \hat{m} \right) - \gamma \hat{m} \times \vec{H}_{rf}$$

Anti-damp torques





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

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

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

The spin Hall angle can be determined from the relative magnitude of the two components.

Modulation of magnetization damping (MOD)

PRL **101,** 036601 (2008) PHYSICAL REVIEW LETTERS week ending 18 JULY 2008

Electric Manipulation of Spin Relaxation Using the Spin Hall Effect

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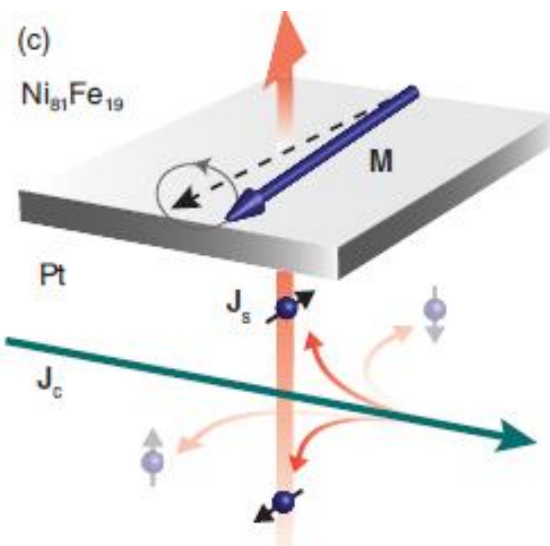
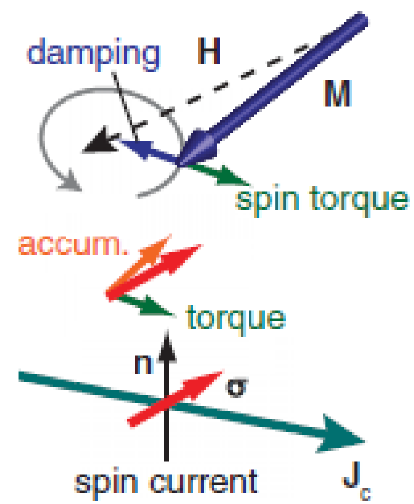
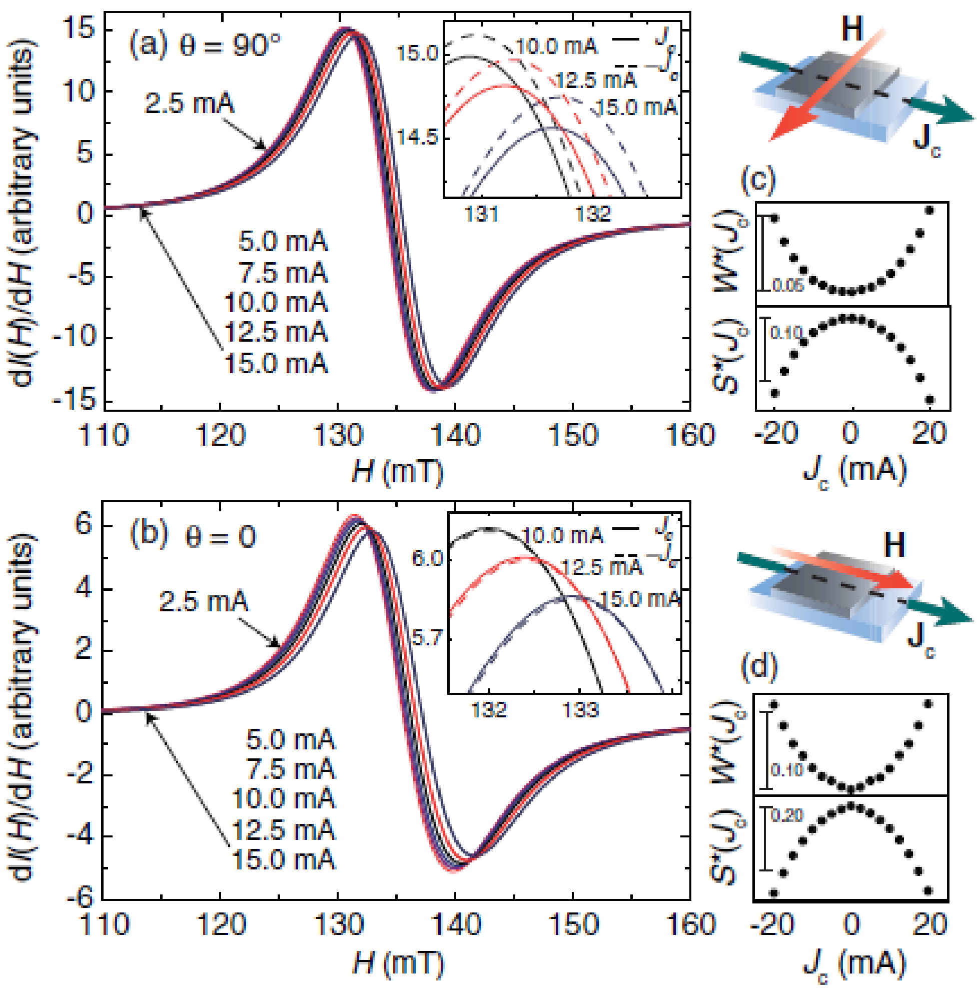
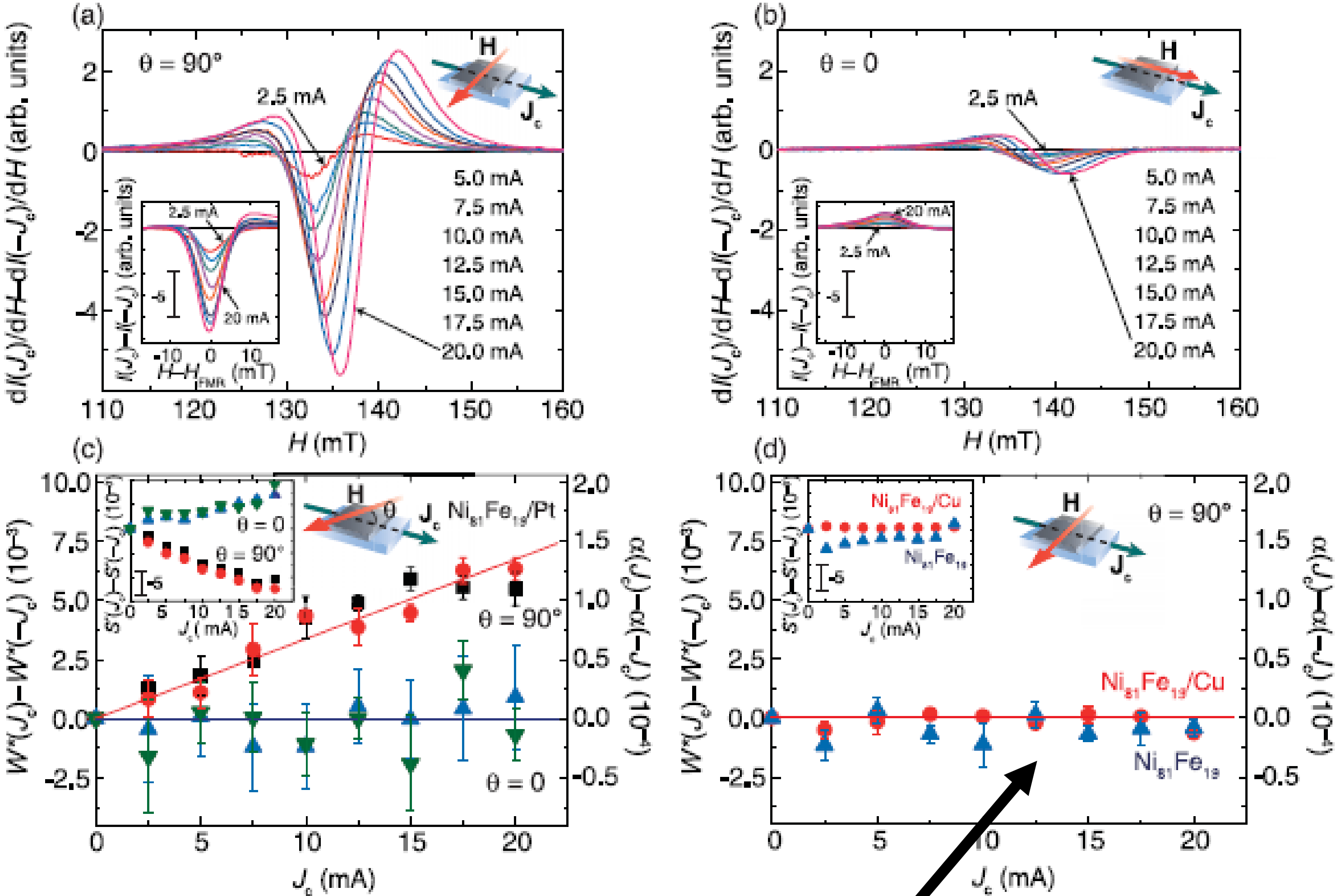






Thermal effects on FMR spectra can be serious.

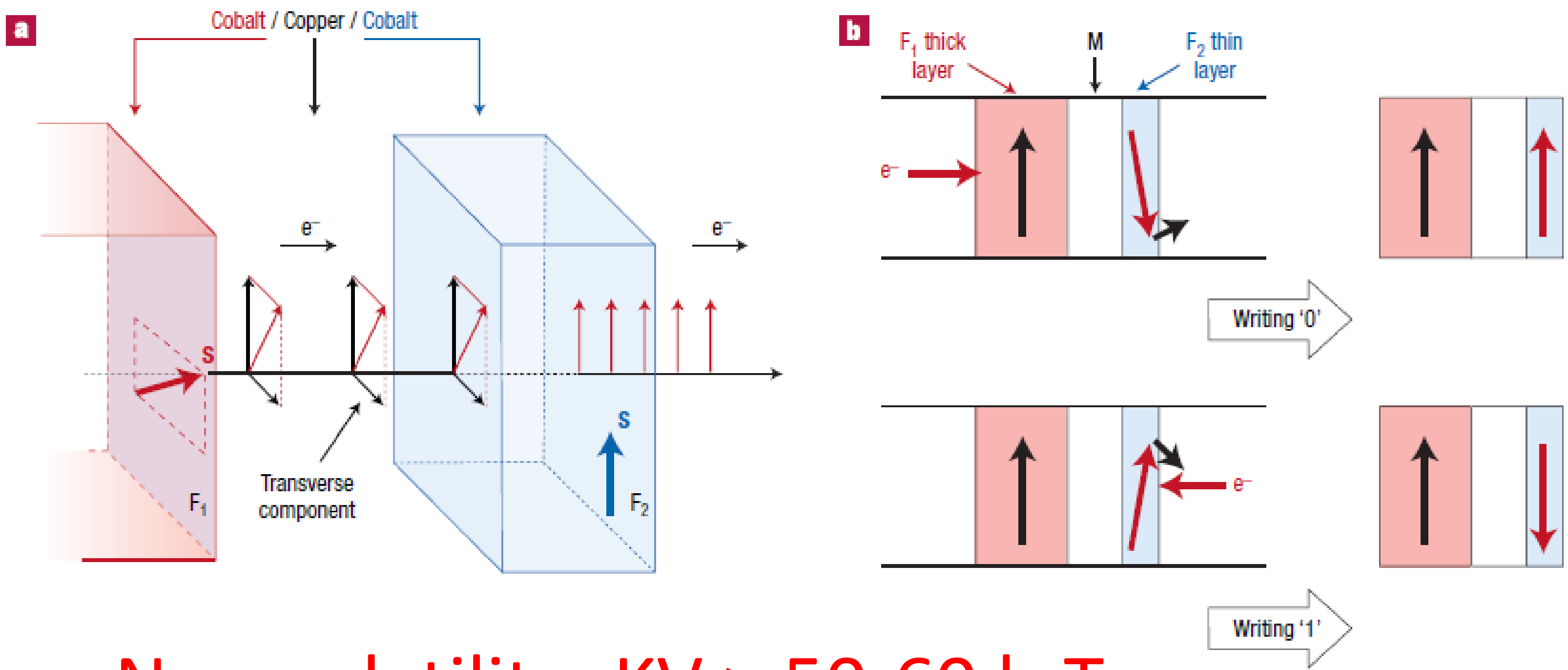
Need to change the in-plane field angle to separate the spin-transfer effect from the thermal effect.



Controlled sample Py/Cu:
Cu has small spin Hall angle.

Spin pumping to topological insulators

Application: *data storage*



Non-volatility: $KV > 50\text{-}60\ k_BT$

K: magnetic anisotropy constant

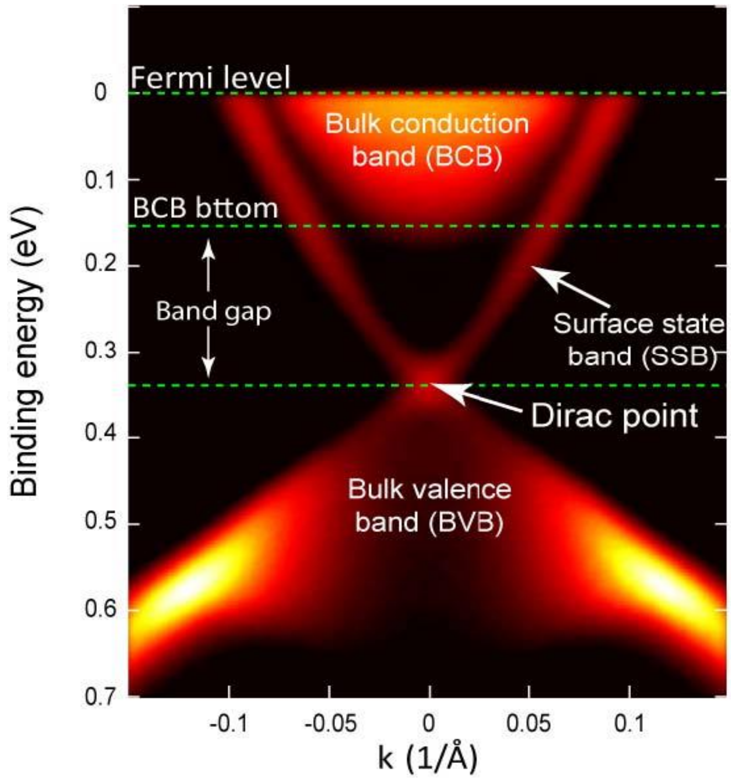
V: volume of nano-particle

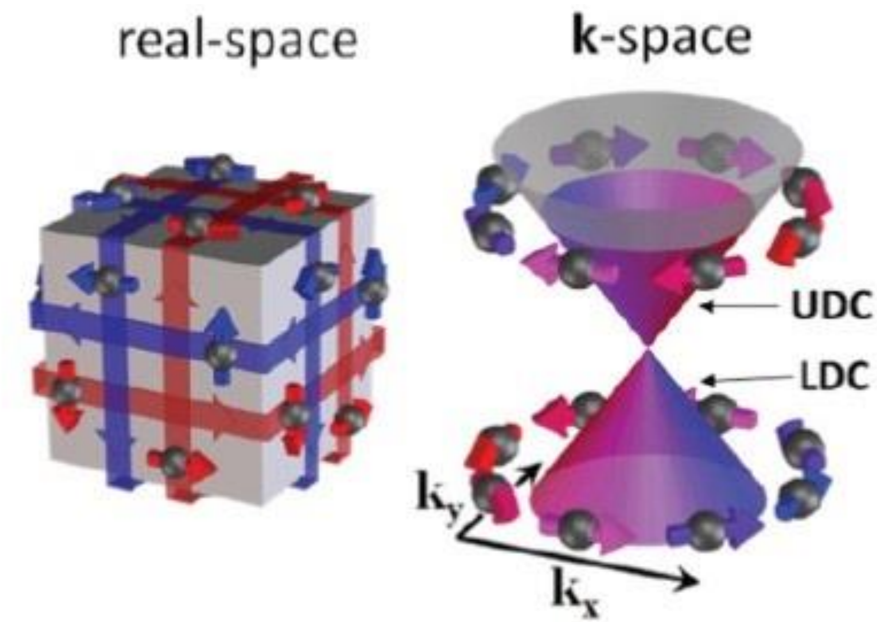
k_B: Boltzmann constant

Goal: Find a material that can generate maximum spin torques from a given charge current.

Topological insulators

ARPES spectra





Nearly 100 % spin polarization.

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

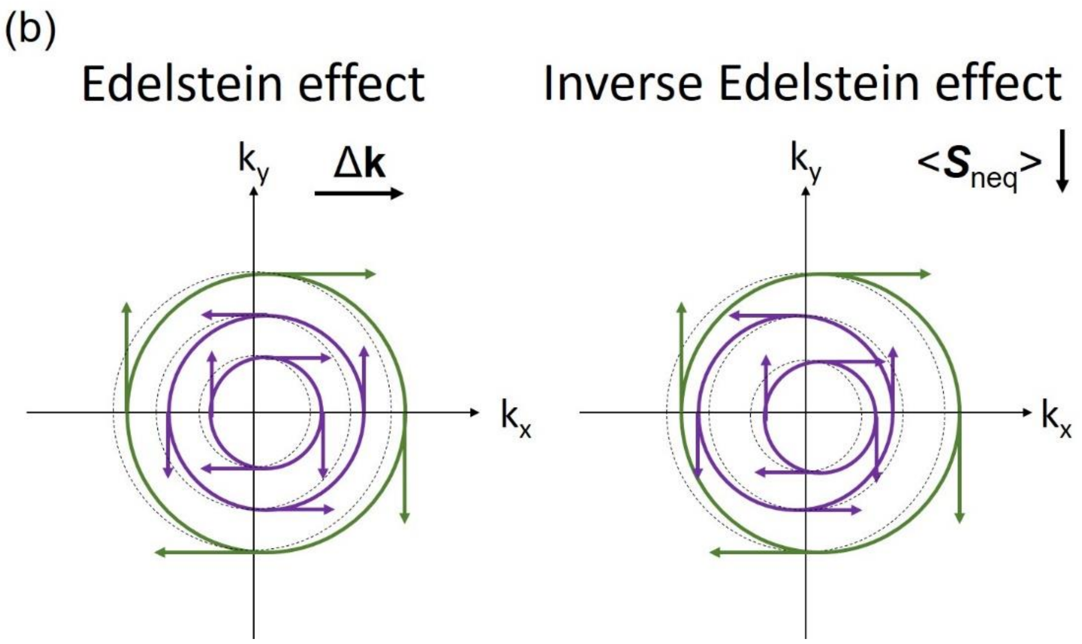
Challenges

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

- Large variation of reported effective spin Hall angle θ_{SH} (or conversion efficiency)
  - **0.022** in Bi_2Se_3/Py at 15 K (Deorani et al. (2014))
  - **~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_2Se_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)
location	bulk	surface
condition	Spin current normal to the interface	"non-equilibrium" spin density at interface
material	Normal metals and semiconductors including 3D TIs	TIs and Rasba materials possessing k-dependent spin-polarized states

Spin Hall angle and IEE length

$j_c = \lambda_{IEE}\, j_s$ (definition of IEE length)

$j_c = \theta_{SH} \lambda_N \tanh\left(\dfrac{d_N}{2\lambda_N}\right) j_s,$ 2D charge current from ISHE

$$\lambda_N >> d_N,\ \lambda_{IEE} = \frac{1}{2} d_N \theta_{SH}$$

$$\lambda_N << d_N,\ \lambda_{IEE} = \lambda_N \theta_{SH}$$

Using spin Hall angle to determine conversion ratio of 3D j_c and 2D j_s can lead to “unphysical” value (> 1).
Ex: θ_{SH} = 1.6 for α-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_2Se_3?

Structure	Journal	method	Spin-charge ratio	Importance
Py Ag Bi Si (001)	Nat. Commun. **4**, 2944 (2013) (A. Fert)	Spin pumping	300K: 0.09 ~ 0.2 0.3 nm	First demonstration of RT IEE with Rasba alloys Ag/Bi
Py Bi_2Se_3 Al_2O_3	Nature **511**, 449 (2014) (D. Ralph)	ST-FMR	300K: 2 ~ 3.5	Giant RT spin torque ratio of Bi_2Se_3 “Signature” of RT EE
Py Bi_2Se_3 Al_2O_3	PRB **90**, 094403 (2014) (S. Oh)	Spin pumping	300K: 0.009 15K: 0.02	ISHE of Bi_2Se_3
Py Bi_2Se_3, BSTS, and Sn-BTS	PRL **113**, 196601 (2014) (E. Saitoh)	Spin pumping	15K: ~10^{-4}	Low T IEE of TIs (crystal)
$Co_{40}Fe_{40}B_{20}$ Bi_2Se_3 Al_2O_3	PRL **114**, 257202 (2015) (S. Oh)	ST-FMR	300K: 0.047 50K: 0.42	Large Low T spin torque ratio of Bi_2Se_3 “Signature” of RT EE

Structure	Journal	method	Spin-charge ratio	Importance
Py Bi_2Se_3 $Co_{50}Fe_{50}$	Sci. Rep. **5**, 7907 (2015) (University of Oxford)	Spin pumping	--	Atypical thickness dependence of mixing conductance
$Co_{20}Fe_{60}B_{20}$ Bi_2Se_3 InP	Nano Lett. **15**, 7126 (2015) (Jian-Ping Wang, University of Minnesota)	Spin pumping	300K: 0.43	Giant RT ISHE of Bi_2Se_3
Fe Ag Sn InSb (001)	PRL **116**, 096602 (2016) (A. Fert)	Spin pumping	300K: 0.62 ~ 1.5 2.1 nm	Giant RT IEE of TI Sn
Py Bi_2Te_3 Al_2O_3	Submitted to PRB (S. F. Lee)	Spin pumping	5 K: 0.003 ~ 0.0062	"Signature" of low T IEE of Bi_2Te_3 Low T ISHE of Bi_2Te_3
Bi_2Se_3 YIG GGG	(our work)	Spin pumping	--	"Signature" of RT IEE of Bi_2Se_3 First study on FI/TI

Structure	Journal	method	Spin-charge ratio	Importance
Py Bi_2Se_3 Al_2O_3	PRB **90**, 094403 (2014) (S. Oh)	Spin pumping	300K: 0.009 15K: 0.02	ISHE of Bi_2Se_3

PHYSICAL REVIEW B 90, 094403 (2014)

Nothing new.

Observation of inverse spin Hall effect in bismuth selenide

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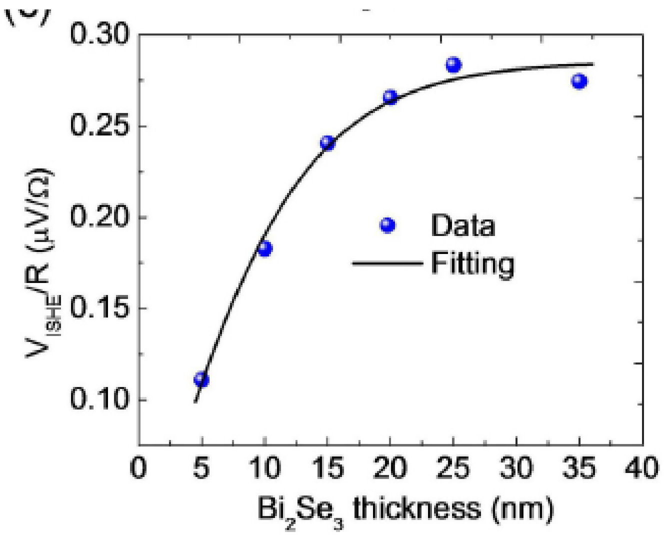
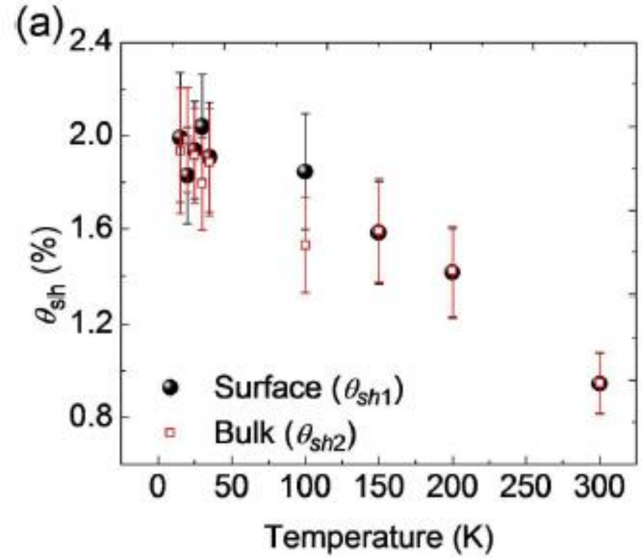
(Received 19 April 2014; revised manuscript received 20 August 2014; published 3 September 2014)

Bismuth Selenide (Bi_2Se_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_2Se_3 spin detector by injecting the pure spin current from a magnetic permalloy layer to a Bi_2Se_3 thin film and detect the inverse SHE in Bi_2Se_3. The spin Hall angle of Bi_2Se_3 is found to be 0.0093 ± 0.0013 and the spin diffusion length in Bi_2Se_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.





was taken to be of opposite signs. Fitting the measured data, we obtain θ_{sh1} at surface and θ_{sh2} at bulk for each temperature as shown in Fig. 4(a), which does not show any clear distinction between the surface and bulk value. Figure 4(b) shows the λ_{sf}

In order to distinguish the surface and bulk contributions, they assumed a spin Hall angle θ_{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.

Structure	Journal	method	Spin-charge ratio	Importance
Py Bi_2Se_3, BSTS, and Sn-BTS	PRL **113**, 196601 (2014) (E. Saitoh)	Spin pumping	15K: ~10^{-4}	Low T IEE of TIs (crystal)

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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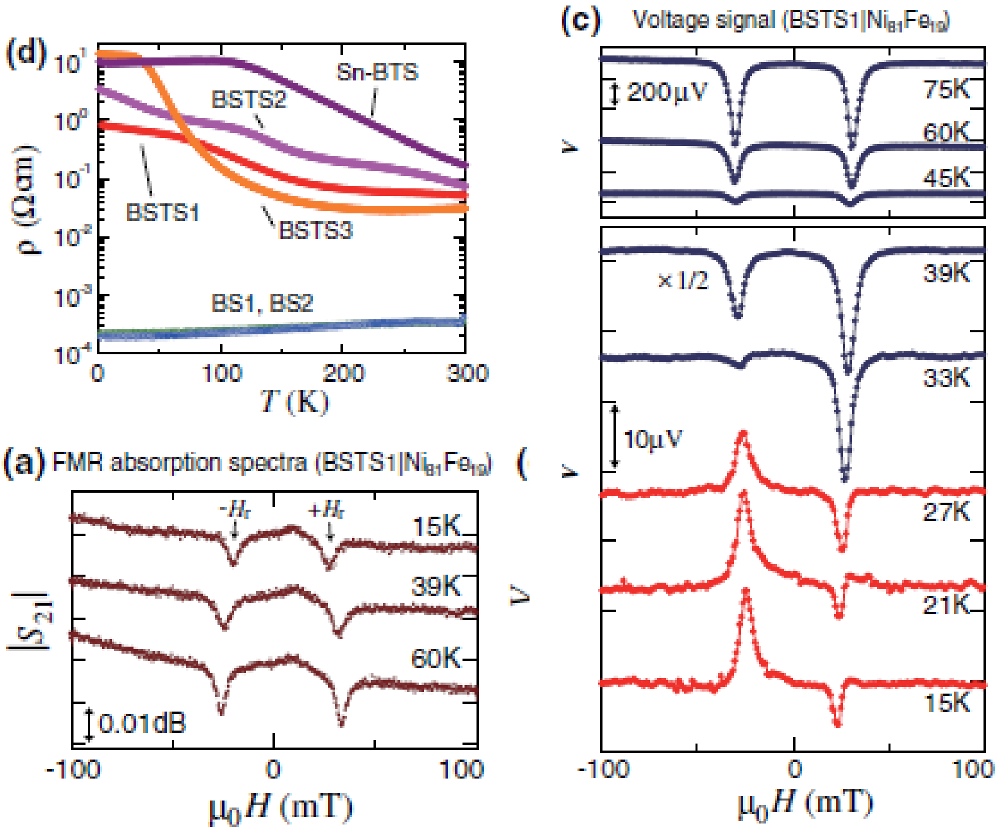
(Received 11 May 2014; published 3 November 2014)

We report successful spin injection into the surface states of topological insulators by using a spin pumping technique. By measuring the voltage that shows up across the samples as a result of spin pumping, we demonstrate that a spin-electricity conversion effect takes place in the surface states of bulk-insulating topological insulators $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ and Sn-doped Bi_2Te_2Se. In this process, the injected spins are converted into a charge current along the Hall direction due to the spin-momentum locking on the surface state.

DOI: 10.1103/PhysRevLett.113.196601 PACS numbers: 72.25.Pn, 72.25.Dc, 73.20.-r, 75.76.+j

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)



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.

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

to the spin-momentum locking. Though the efficiency of the spin-electricity conversion in the present work is as small as $\eta \sim 10^{-4}$, the spin-momentum locking on topological surface states can, in principle, lead to efficient conversion between spin and electricity.

The data show negative field shifts as T became lower, similar to Faris' data. However, they did not mention this.

Structure	Journal	method	Spin-charge ratio	Importance
$Co_{20}Fe_{60}B_{20}$ Bi_2Se_3 InP	Nano Lett. **15**, 7126 (2015) (Jian-Ping Wang, University of Minnesota)	Spin pumping	300K: 0.015 ~ 0.43	Giant RT ISHE of Bi_2Se_3

NANO LETTERS

Letter

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Nothing new in physics again.

Giant Spin Pumping and Inverse Spin Hall Effect in the Presence of Surface and Bulk Spin−Orbit Coupling of Topological Insulator Bi_2Se_3

Mahdi Jamali,[†] Joon Sue Lee,[‡] Jong Seok Jeong,[§] Farzad Mahfouzi,[∥] Yang Lv,[†] Zhengyang Zhao,[†] Branislav K. Nikolić,[⊥] K. Andre Mkhoyan,[§] Nitin Samarth,[*,‡] and Jian-Ping Wang[*,†]

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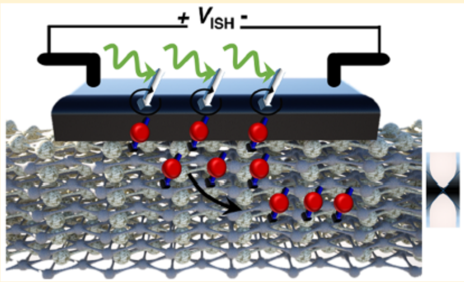
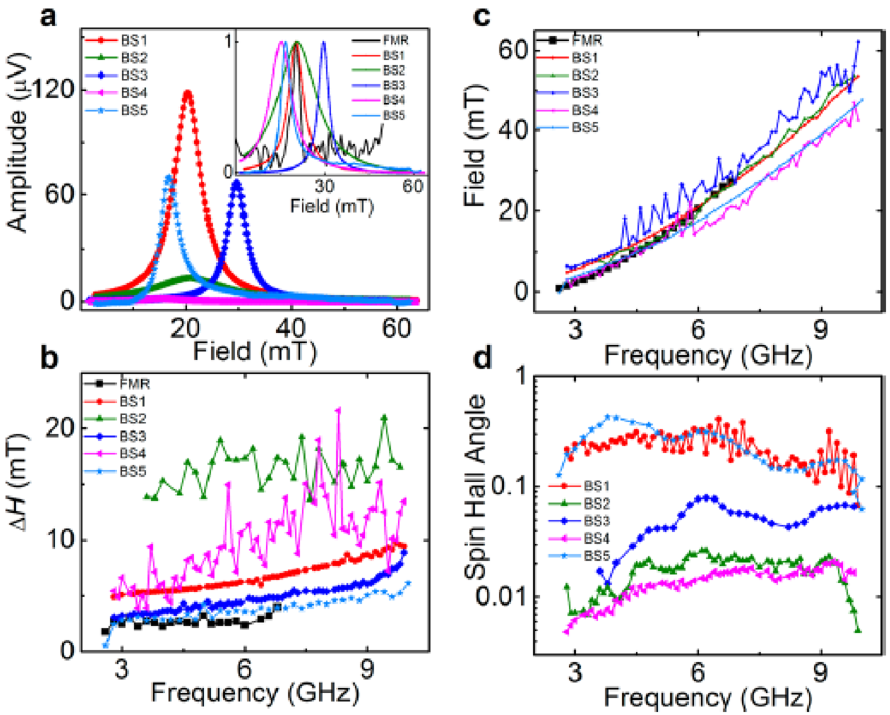
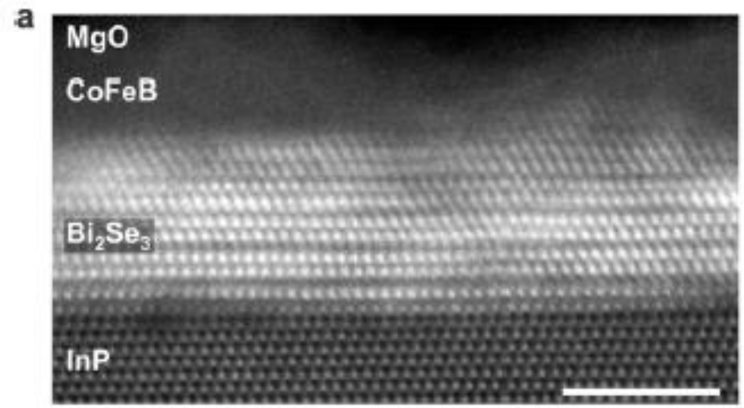
ABSTRACT: Three-dimensional (3D) topological insulators are known for their strong spin−orbit coupling (SOC) and the existence of spin-textured surface states that might be potentially exploited for "topological spintronics." Here, we use spin pumping and the inverse spin Hall effect to demonstrate successful spin injection at room temperature from a metallic ferromagnet (CoFeB) into the prototypical 3D topological insulator Bi_2Se_3. The spin pumping process, driven by the magnetization dynamics of the metallic ferromagnet, introduces a spin current into the topological insulator layer, resulting in a broadening of the ferromagnetic resonance (FMR) line width. Theoretical modeling of spin pumping through the surface of Bi_2Se_3, as well as of the measured angular dependence of spin-charge conversion signal, suggests that pumped spin current is first greatly enhanced by the surface SOC and then converted into a dc-voltage signal primarily by the inverse spin Hall effect due to SOC of the bulk of Bi_2Se_3. We find that the FMR line width broadens significantly (more than a factor of 5) and we deduce a spin Hall angle as large as 0.43 in the Bi_2Se_3 layer.





The samples had severely degraded. All of the curves should be smooth, so the calculated spin Hall angles are questionable.



The wide fluctuation of spin pumping signals from sample to sample could be explained based on the nonuniform composition of Bi_2Se_3 at its interface with the magnetic layer. Recently, it has been shown that surfaces of TIs are very nonuniform in terms of chemical potential and position of Dirac point.[53] Because the Bi_2Se_3/CoFeB interface plays the major role in the spin injection, the large variations of the spin pumping characteristics could be associated with nonuniform Bi_2Se_3 surface. Moreover, the decapping process could also be responsible for modification of the TI surface considering Bi_2Se_3 has strong thermoelectric properties.[54] Comparing the samples BS1−4 with BS5, BS5 is not involved in any high-temperature decapping process and we obtain the maximum spin Hall angle in this sample. This suggests that heat treatment temperature and a large spin Hall angle. In highly bulk-conductive Bi_2Se_3 TIs, the inverse Hall effect of the bulk seems to dominate over the inverse Edelstein effect of the surface state, at least in spin pumping experiments. Moreover, we find

(Question 2 ?)

Structure	Journal	method	Spin-charge ratio	Importance
Fe Ag Sn InSb (001)	PRL **116**, 096602 (2016) (A. Fert)	Spin pumping	300K: 0.62 ~ 1.5 2.1 nm	Giant RT IEE of TI Sn

PRL **116**, 096602 (2016) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2016

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

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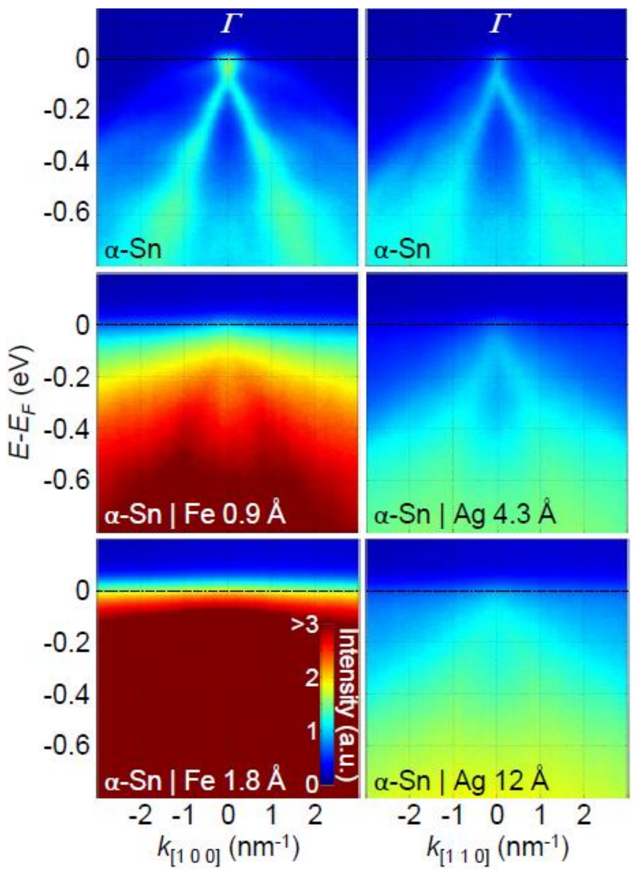
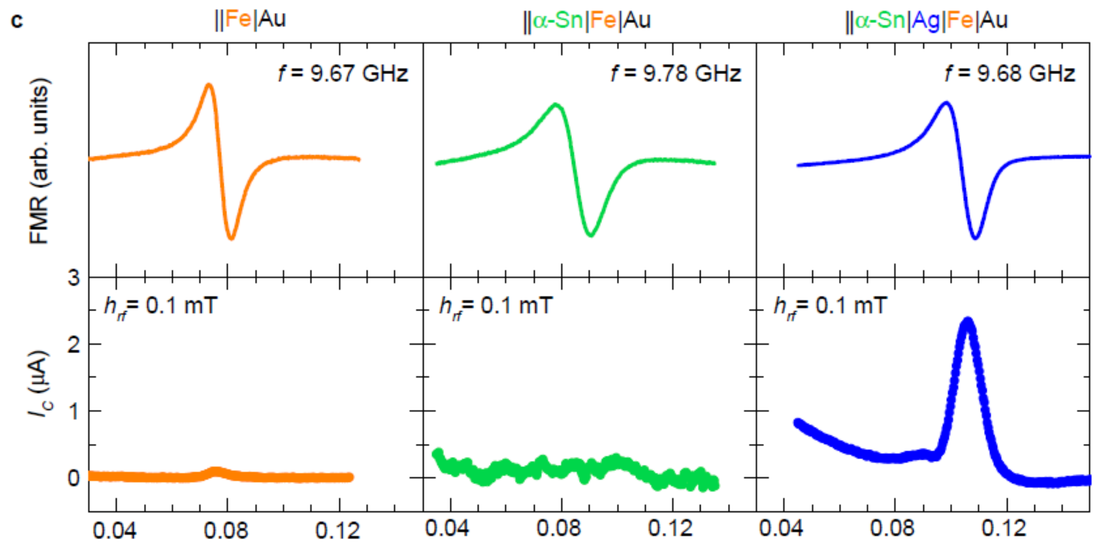
(Received 18 December 2015; published 1 March 2016)

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 (0 0 1) 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.





surfaces" of TI[22]. We believe that the long relaxation time on free topological surfaces characterizes the slow relaxation inside the 2D topological states whereas, by interfacing the TI (or Rashba) surface with a metal as Ag, we introduce a faster additional relaxation mechanism provided by exchanges of electrons with the adjacent 3D metal. We conclude that the best conditions for the exploitation of topological sates of TI in spintronics should be with TI interfaced with (trivial) insulators instead of metals, for example in experiments of spin-pumping or thermal[23] spin injection from an insulating ferromagnet. If one remarks that $v_F\,\tau$ is also the critical length for

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?

Structure	Journal	method	Spin-charge ratio	Importance
Py Bi_2Se_3 Al_2O_3	Nature **511**, 449 (2014) (D. Ralph)	ST-FMR	300K: 2 ~ 3.5	Giant RT spin torque ratio of Bi_2Se_3 “Signature” of RT EE

LETTER

doi:10.1038/nature13534

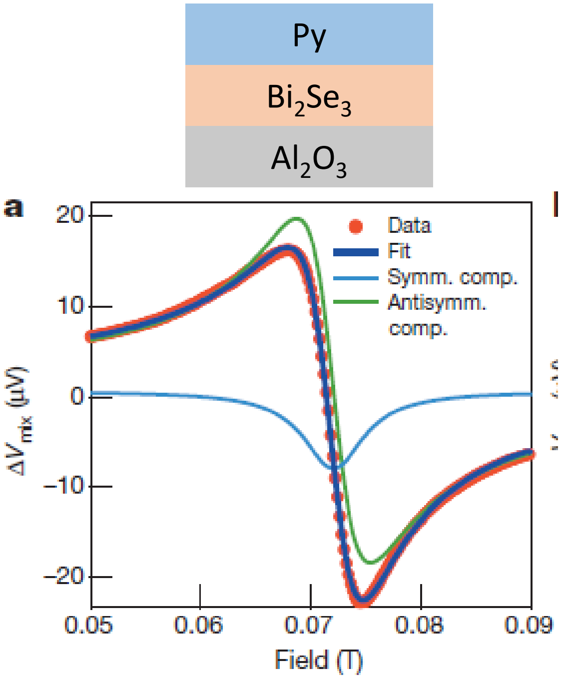
Spin-transfer torque generated by a topological insulator

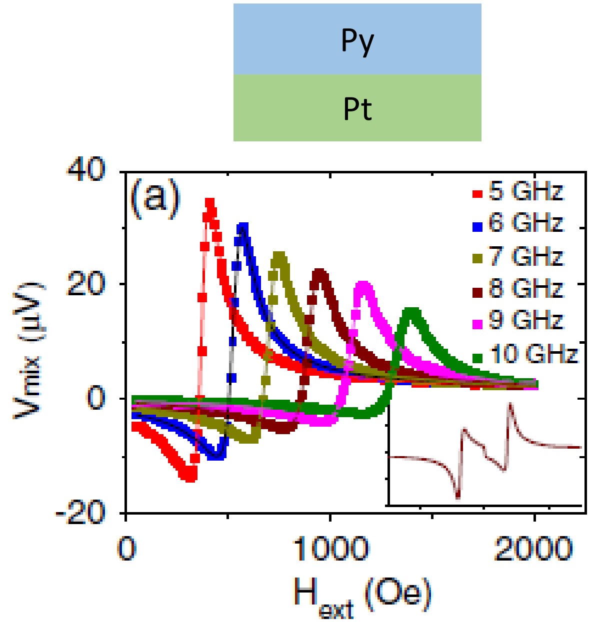
A. R. Mellnik[1], J. S. Lee[2], A. Richardella[2], J. L. Grab[1], P. J. Mintun[1], M. H. Fischer[1,3], A. Vaezi[1], A. Manchon[4], E.-A. Kim[1], N. Samarth[2] & D. C. Ralph[1,5]

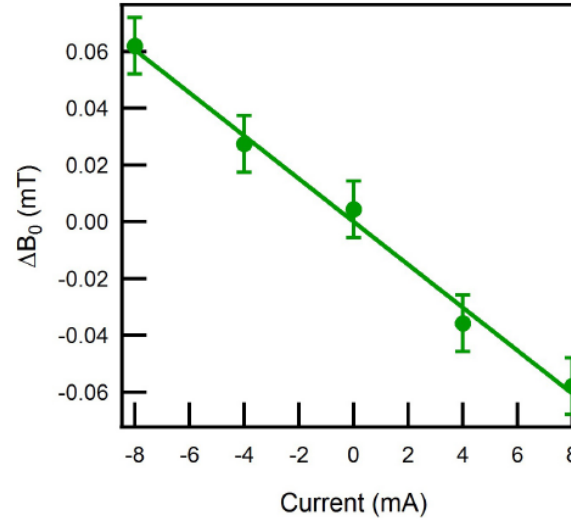
Signatures of Edelstein effect (EE):

1. Large anti-symmetric component of voltage signals.
2. Resonance field shifts.

The two features result from non-equilibrium spin density at TSS.







The resonance field shifted when applying dc current. From the shifts, magnitude of field-like torques can be determined.

Large antisymmetric component for Bi_2Se_3/Py. In contrast, symmetric signals dominate for Pt/Py (without EE).

any previously measured spin current source material. However, as noted above, for practical applications the specific layer structure of our devices (topological insulator/metallic magnet) does not make good use of this high intrinsic efficiency because most of the applied current is shunted through the metallic magnet and does not contribute to spin current generation within the topological insulator. Applications will probably require coupling topological insulators to insulating (or high-resistivity) magnets so that the majority of the current will flow in the topological insulator. Using insulating magnets may also have the advantage of providing much less Gilbert damping than do metallic magnets[29], which can yield an additional reduction in the levels needed at present for manipulation via the spin torque anti-damping mechanism. Additionally, using an insulating magnet would allow electrostatic gating of bilayer devices, thus allowing the chemical potential to be tuned to eliminate any deleterious effects of bulk conduction. Our results therefore point towards

They did not do Bi_2Se_3 thickness dependence measurement, so it's still hard to extract the EE.

Structure	Journal	method	Spin-charge ratio	Importance
$Co_{40}Fe_{40}B_{20}$ Bi_2Se_3 Al_2O_3	PRL **114**, 257202 (2015) (S. Oh)	ST-FMR	300K: 0.047 50K: 0.42	Large Low T spin torque ratio of Bi_2Se_3 “Signature” of RT EE

PRL **114**, 257202 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

Topological Surface States Originated Spin-Orbit Torques in Bi_2Se_3

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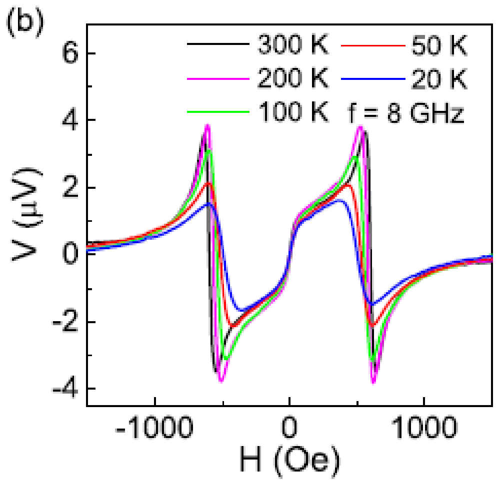
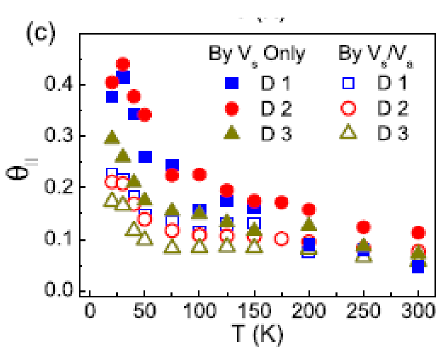
(Received 4 February 2015; revised manuscript received 27 April 2015; published 24 June 2015)

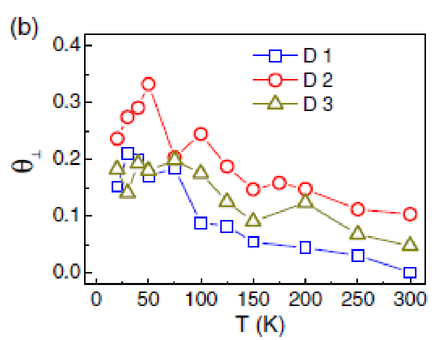
The three dimensional topological insulator bismuth selenide (Bi_2Se_3) is expected to possess strong spin-orbit coupling and spin-textured topological surface states and, thus, exhibit a high charge to spin current conversion efficiency. We evaluate spin-orbit torques in $Bi_2Se_3/Co_{40}Fe_{40}B_{20}$ devices at different temperatures by spin torque ferromagnetic resonance measurements. As the temperature decreases, the spin-orbit torque ratio increases from ~0.047 at 300 K to ~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_2Se_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_2Se_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 τ_{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_2Se_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_2Se_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?

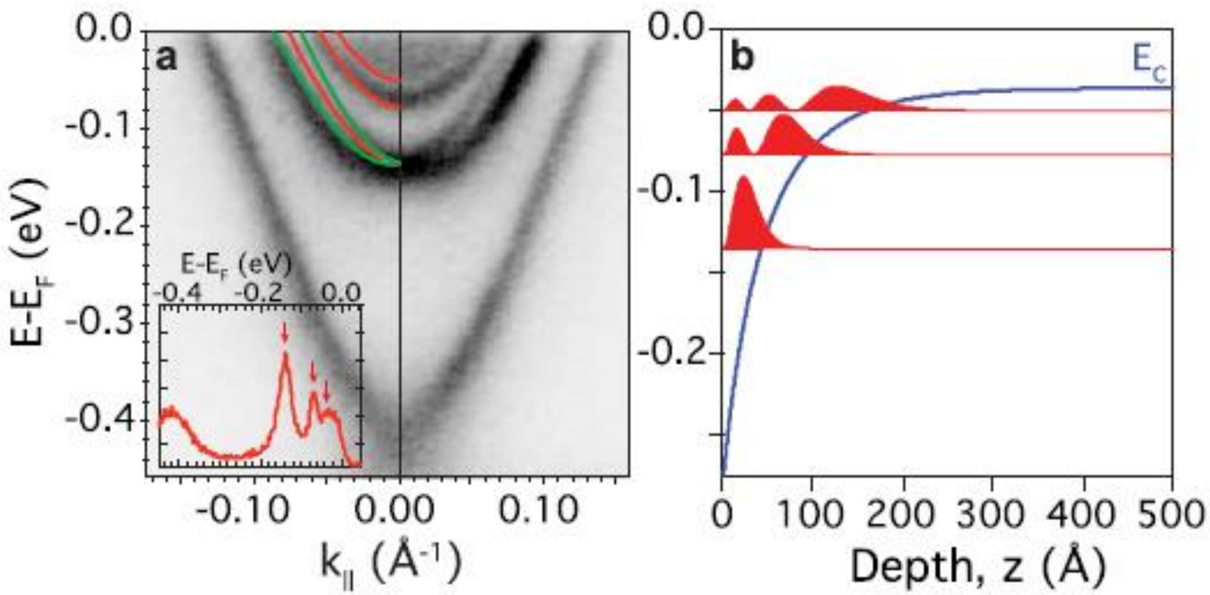
4. Note that in A. Fert's work they did not deposit Fe directly on Sn.

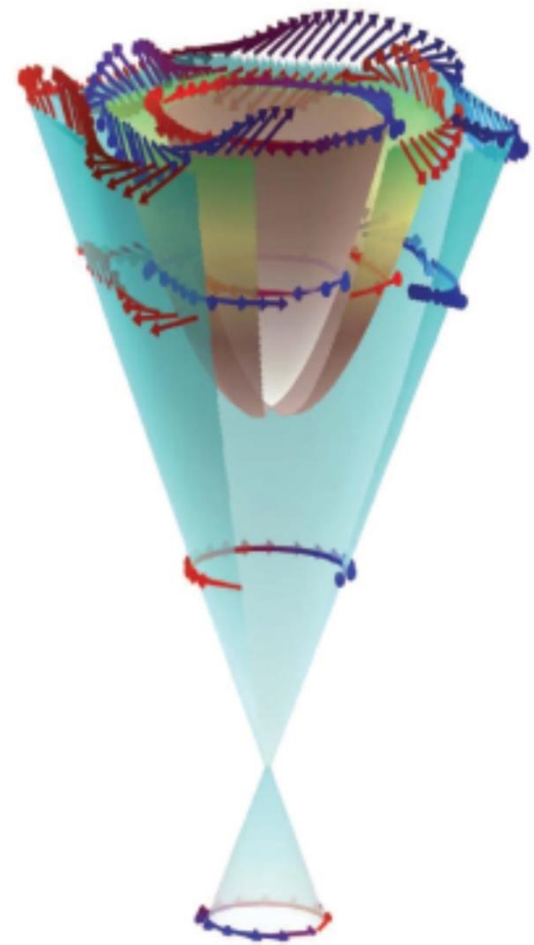
An Ag layer may weaken the effect of non-equilibrium spin density, which is localized, on Fe. That is, the Ag layer separate Fe and Sn out of the range of exchange coupling. Therefore, "signatures (negative field shift)" of IEE were not observed.

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_2Se_3





- Large Rashba splitting of 2DEG in Bi_2Se_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.

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Bahramy et. al., Nat. Commun. **3**, 1159 (2012)