How to manipulate pure spin current (淨自旋流) ?

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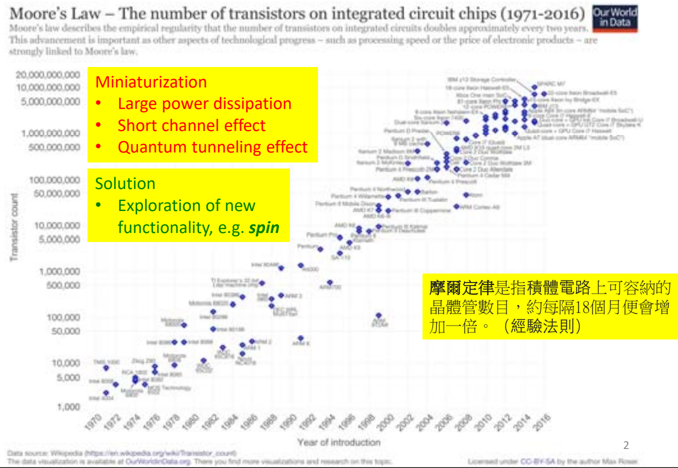
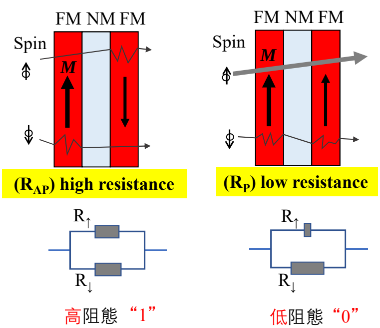
Moore's Law



2

Magnetic Memory Cell



Discovered (1987)

Nobel Prize in Physics (2007)

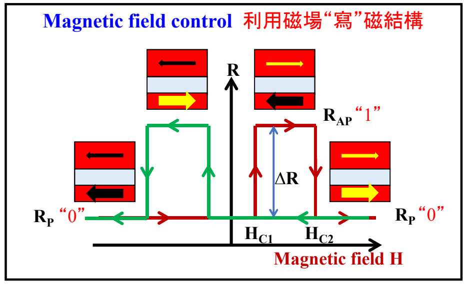
Peter Grünberg   Albert Fert

Giant magnetoresistance effect (GMR)
巨磁阻效應

Non-volatile memory: maintains data without power
(不需外加電壓)
Low power consumption

3

Magnetic Field Control

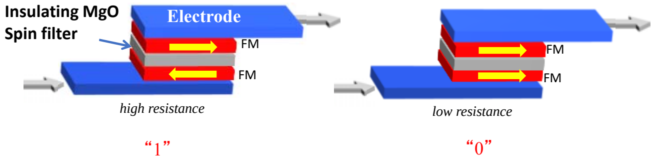


MR ratio: $\Delta R/R_P$
~30% for a GMR device
Magnetic field sensor
Read head

4

Tunneling Magnetoresistance (TMR)

兩層鐵磁材料中間夾一層非磁性絕緣體 (AlOx or MgO)

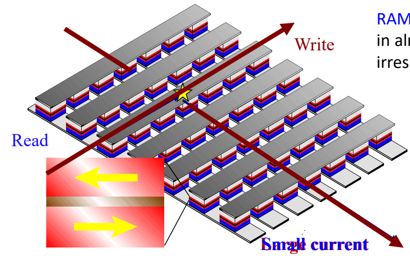


利用MgO的spin filtering，獲得較大的MR ratio

Magnetic Tunnel Junction (MTJ)
磁性隧道結

$\Delta R/R_p > 100\%$

Magnetic Random Access Memory (MRAM)



RAM: allows data to be read or written in almost the same amount of time irrespective of its physical location

小電流讀電阻

大電流產生的磁場寫磁結構

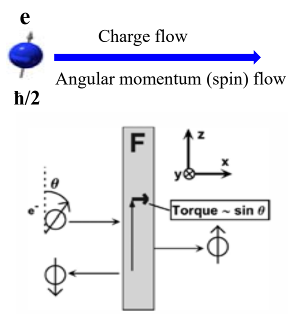
Key Challenge
Writing magnetic field is not site-specific:（磁場不局域）

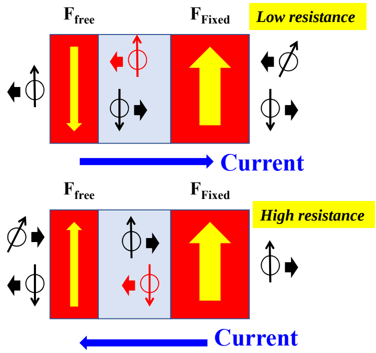
Accidental switching

Improve the writing process

Spin-Transfer Torque Effect: Current Writing

自旋極化電流可直接寫磁結構



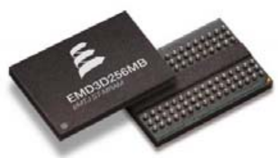


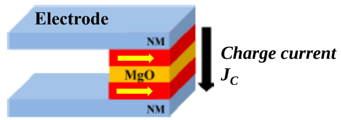
Large moment: FM layer as spin "filter"
Large spin current: FM moment switches

Current writing
（電流方向決定磁結構）

自旋轉移力矩

Spin Transfer Torque MRAM





Spin Transfer Torque-MRAM (STT-MRAM)
Non-volatile, Scalable

Key Challenge-- High writing current density: 10^7A/cm^2

Electro-migration, vulnerable under long operation

Can pure spin current provide a solution?

Outline

- Introduction of pure spin current (淨自旋流)
- Spin current generation and conversion
  - (Inverse) Spin Hall effect [(I)SHE (逆)自旋霍爾效應]
  - Spin pumping effect (SP 自旋幫浦效應)
  - Spin-orbit torque effect (SOT 自旋軌道力矩效應)
  - Spin Seebeck effect (SSE 自旋塞貝克效應)
- Self-consistent determination of spin Hall angle (自旋霍爾角) and spin diffusion length (自旋擴散長度) by SSE and ISHE
  - Non-magnetic materials (Au, Pt, Ta, and W)
  - Non-magnetic alloy (Au-Ta alloy)
  - Ferromagnetic materials (Py and Co)
  - Antiferromagnetic materials (Cr and Mn-Sn alloy)

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Spin-Polarized Current vs. Pure Spin Current

Electronics

(a) **Pure Charge Current 淨電荷流**

Spintronics

(b) **Spin polarized current 自旋極化電流**

Angular momentum current

Pure spin current devices

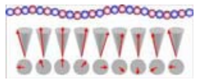
(c) **Pure Spin Current 淨自旋流**

Angular momentum current

Lower power consumption

Same j_s, but only **1/5 charge carriers**, thus dissipates **1/25** power

(d) Magnon in **magnetic insulators**



Magnon pure spin current

Pure Spin Current

No charge current

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Pure Spin Current Generation and Conversion

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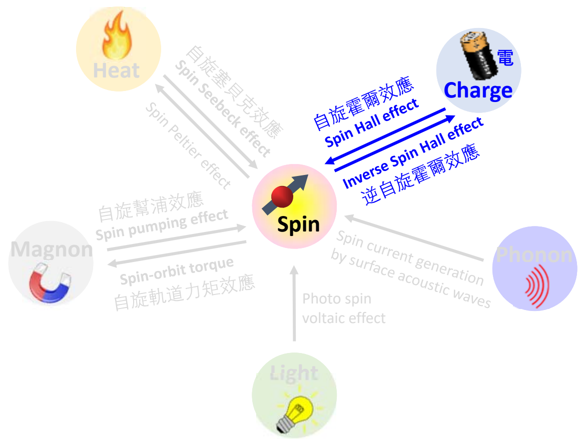
Charge and Spin Conversion



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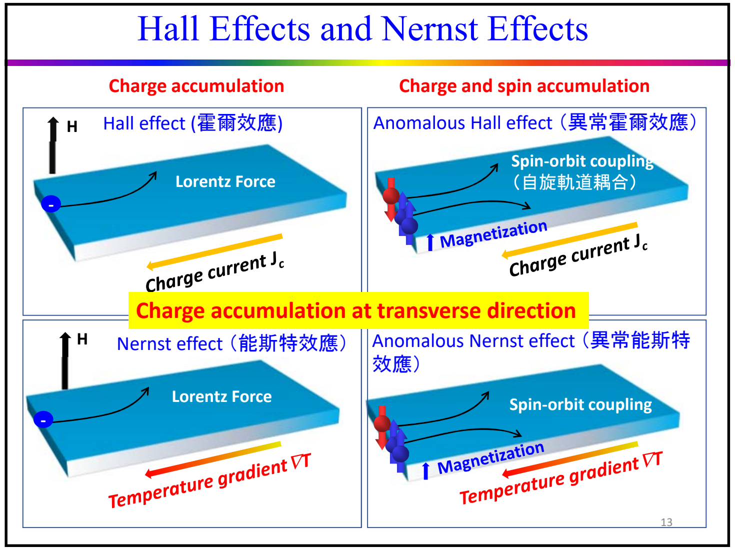
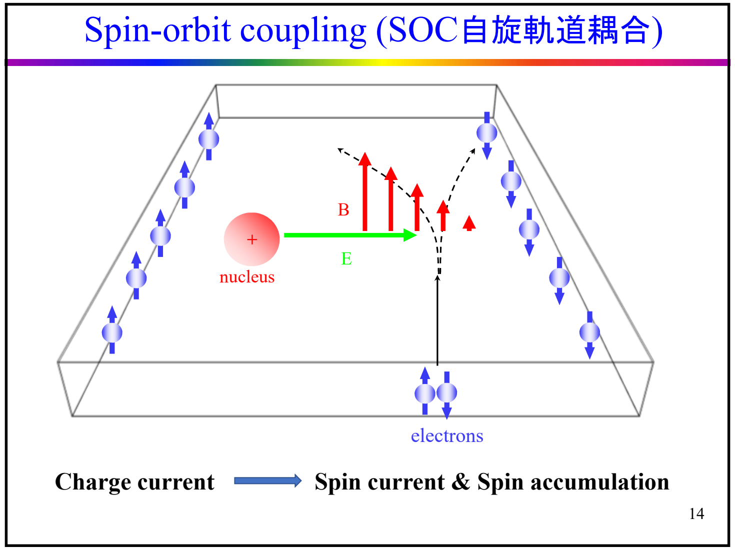
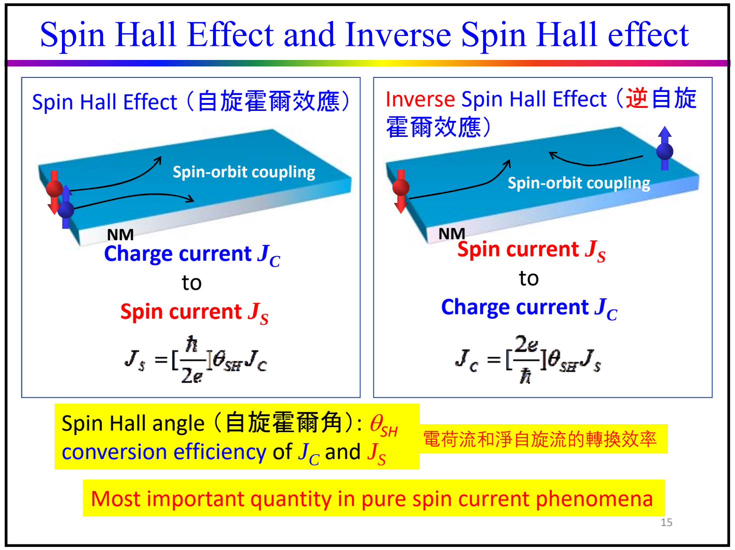


Hall Effects and Nernst Effects
Charge accumulation
Charge and spin accumulation
H
Hall effect (霍爾效應)
Lorentz Force
Charge current J_c
Anomalous Hall effect（異常霍爾效應）
Spin-orbit coupling（自旋軌道耦合）
Magnetization
Charge current J_c
Charge accumulation at transverse direction
H
Nernst effect（能斯特效應）
Lorentz Force
Temperature gradient ∇T
Anomalous Nernst effect（異常能斯特效應）
Spin-orbit coupling
Magnetization
Temperature gradient ∇T
13



Spin-orbit coupling (SOC自旋軌道耦合)
B
+
nucleus
E
electrons
Charge current → Spin current & Spin accumulation
14



Spin Hall Effect and Inverse Spin Hall effect
Spin Hall Effect（自旋霍爾效應）
Spin-orbit coupling
NM
Charge current J_C
to
Spin current J_S
$J_S = [\frac{\hbar}{2e}]\theta_{SH} J_C$
Inverse Spin Hall Effect（逆自旋霍爾效應）
Spin-orbit coupling
NM
Spin current J_S
to
Charge current J_C
$J_C = [\frac{2e}{\hbar}]\theta_{SH} J_S$
Spin Hall angle（自旋霍爾角）: θ_{SH}
conversion efficiency of J_C and J_S
電荷流和淨自旋流的轉換效率
Most important quantity in pure spin current phenomena
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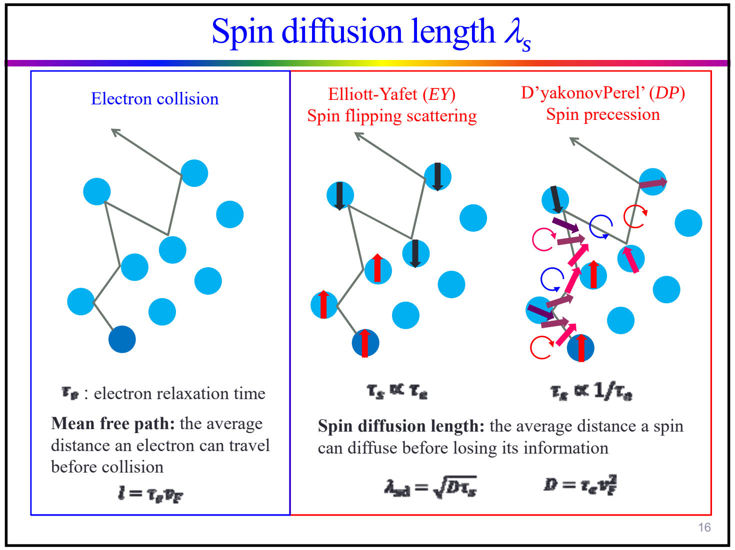

Spin diffusion length λ_s
Electron collision
Elliott-Yafet (EY)
Spin flipping scattering
D'yakonovPerel' (DP)
Spin precession
τ_e : electron relaxation time
Mean free path: the average distance an electron can travel before collision
$l = \tau_e v_F$
$\tau_s \propto \tau_e$
$\tau_s \propto 1/\tau_e$
Spin diffusion length: the average distance a spin can diffuse before losing its information
$\lambda_{sd} = \sqrt{D\tau_s}$
$D = \tau_e v_F^2$
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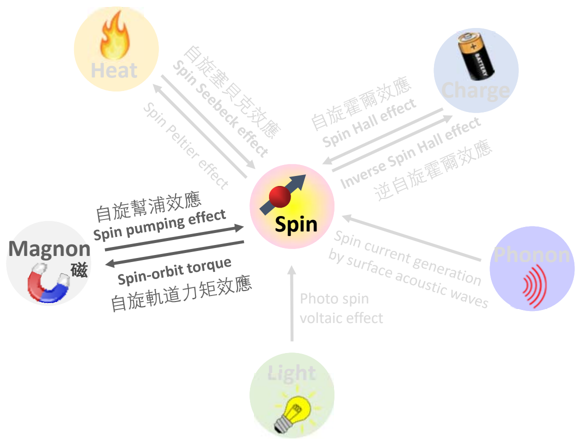
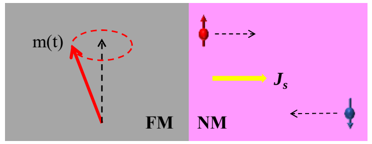
Magnon and Spin Conversion



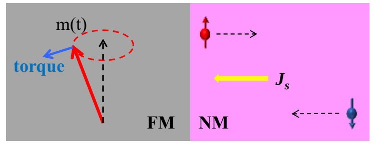
Spin Pumping and Spin Transfer/Spin-Orbit Torque

Spin pumping effect (自旋幫浦效應)



進動的磁矩 =>自旋流

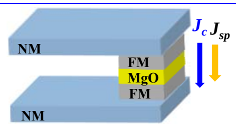
Spin transfer torque/Spin-orbit torque (自旋轉移/軌道力矩效應)



自旋流 => 進動的磁矩

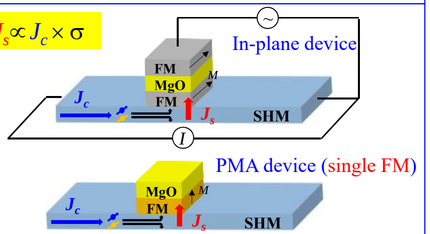
Spin-Orbit Torque Device

Spin-transfer torque (STT) switching
Current through device

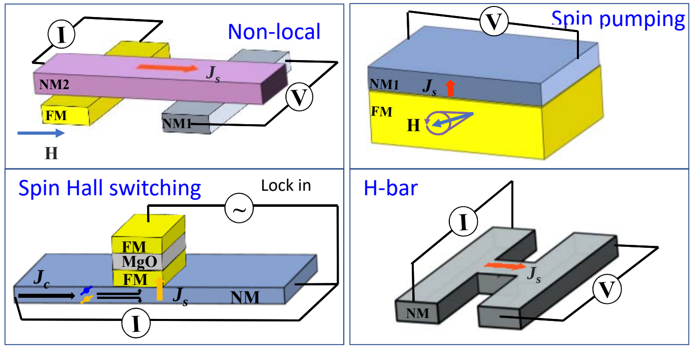


Spin-orbit torque (SOT) switching
Peripheral Current

$J_s \propto J_c \times \sigma$

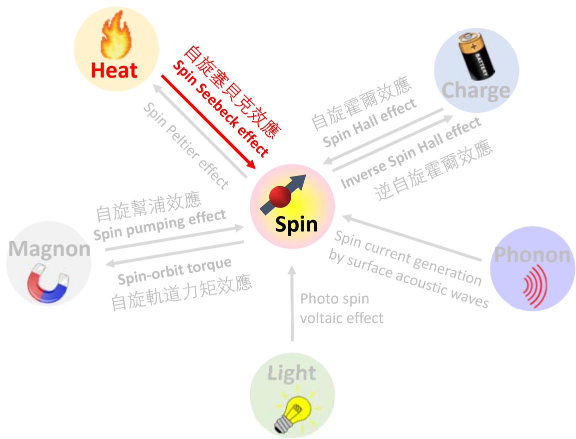


Pure spin current injection and detection



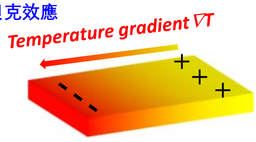
Challenges in complexity of structures, different number of interfaces and current distribution.

Heat and Spin Conversion



Seebeck and Spin Seebeck effect

塞貝克效應

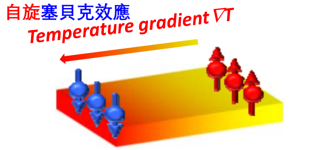


Charge Seebeck Effect in a **conductor**
∇T => *charge accumulation*

Discovered in 1821

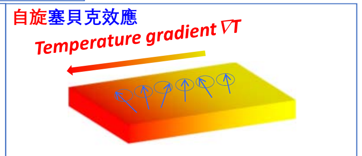
Thomas Johann Seebeck

自旋塞貝克效應



Spin Seebeck Effect in a **FM conductor**
∇T => *spin accumulation*

自旋塞貝克效應



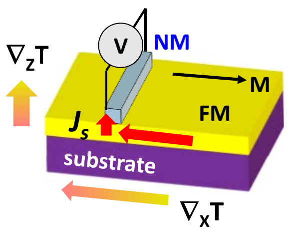
Spin Seebeck Effect in a **FM insulator**
∇T => *magnon*

K. Uchida et. al., Nature, **455**, 778 (2008)

K. Uchida *et al.*, Appl. Phys. Lett. **97**, 172505 (2010)

Spin Seebeck effect (SSE)

Transverse (TSSE)



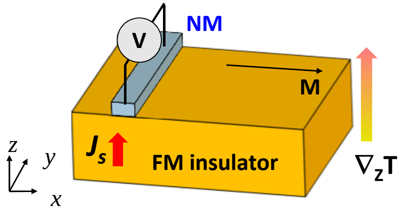
$(E_{\mathrm{ISHE}})_{\mathrm{NM}} \propto \boldsymbol{J}_s \times \boldsymbol{m}$

$(E_{\mathrm{ANE}})_{\mathrm{FM}} \propto \boxed{\nabla_z T} \times \boldsymbol{m}$

Entanglement of SSE and ANE!

S. Y. Huang *et. al*, Phys. Rev. Lett. 107, 216604 (2011)

Longitudinal (LSSE)



$(E_{\mathrm{ISHE}})_{\mathrm{NM}} \propto \boldsymbol{J}_s \times \boldsymbol{m}$

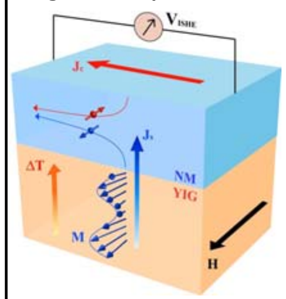
Unequivocal detection of SSE !

K. Uchida *et al.*, Appl. Phys. Lett. **97**, 172505 (2010)

D. Qu *et al*, Phys. Rev. Lett. **110**, 067206 (2013)

Advantages of metal/YIG bilayer structure

Longitudinal spin Seebeck effect (LSSE) in Yttrium Iron Garnet (YIG)



Metal/Insulator structure:
- No complication in current distribution

One interface:
- Reduced the loss of spin current

Self-consistency:
- Same experimental condition

Highly consistent approach to study the spin current

Yttrium Iron Garnet (YIG): Ferrimagnetic insulator
($4\pi M_s$=1740 G T_N=560 K)

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  - Non-magnetic *5d* materials (Au, Pt, Ta, and W)
  - Non-magnetic alloy (Au-Ta alloy)
  - Ferromagnetic materials (Py and Co)
  - Antiferromagnetic materials (Cr and Mn-Sn alloy)

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Outline

- Self-consistent determination of spin Hall angle (自旋霍爾角) and spin diffusion length (自旋擴散長度) by SSE and ISHE
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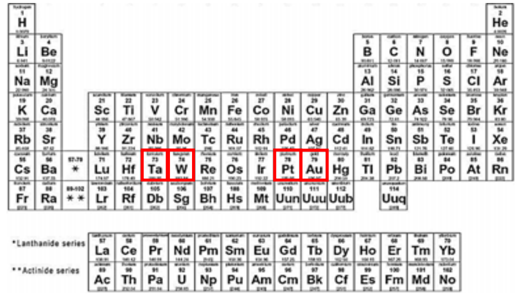

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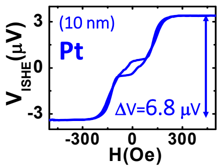
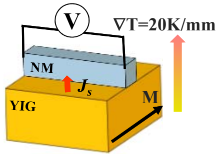
ISHE in different *5d* metals



$\vec{E}_{ISHE} \propto \vec{J}_S \times \hat{\sigma}$

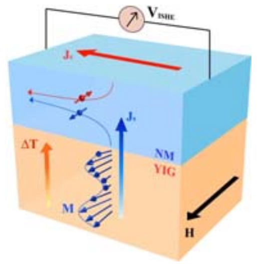


$t_{YIG} \approx 0.5$mm
$L_{NM} \approx 4.2$mm

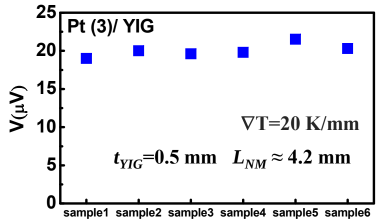
Instantly reveals the sign of spin Hall angle!
Pt and W have comparable V_{ISHE}

D. Qu *et al.* Phys. Rev. B 89 140407 (R) (2014) 27

Highly reproducible method



ISHE voltage of the **same thickness**



Highly reproducible!
Consistency in
- **injection efficiency**
- **interface quality**
- **spin mixing conductance**

	Sample 1	Sample 2
3 nm Pt	19 μV	20 μV
10 nm Au	0.74 μV	0.85 μV
4.5 nm Ta	7.2 μV	6.3 μV
5.2 nm W	8.6 μV	7.9 μV

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Determination of spin Hall angle

Spin current **C : spin injection coefficient** $C=\frac{2e}{\hbar}\frac{\gamma\hbar\rho' k_m^3 l_m}{4\pi M\pi^2}\frac{B_1 B_S}{B_2}\boxed{g_{eff}^{\uparrow\downarrow}}k_B$

$J_S^0 = C\nabla T$ (Magnetic property of the substrate & interface spin mixing conductance)

Spin current decays in z direction

$J_S(z)=J_S^0\frac{\sinh[(t-z)/\lambda_{sd}]}{\sinh(t/\lambda_{sd})}$ *λ: spin diffusion length* *Decay length*

$L\approx 4.2$mm

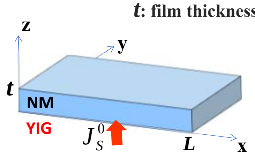
t: film thickness

Inverse spin Hall effect

$J_C=\frac{2e}{\hbar}\theta_{SH}J_S$

Charge accumulation

$V_{ISHE}(t)=2L\rho(t)\langle J_C\rangle$



$$V_{ISHE}(t)=2CL\nabla T\rho(t)\boxed{\theta_{SH}}\frac{\lambda_{sd}}{t}\tanh\left(\frac{t}{2\lambda_{sd}}\right)$$

D. Qu *et al.* Phys. Rev. B **89** 140407 (R) (2014) Rezende *et. al.*, Phys. Rev. B **89**, 014416 (2014)

Mosendz *et al*, Phys. Rev. Lett. **104** 046601 (2010)

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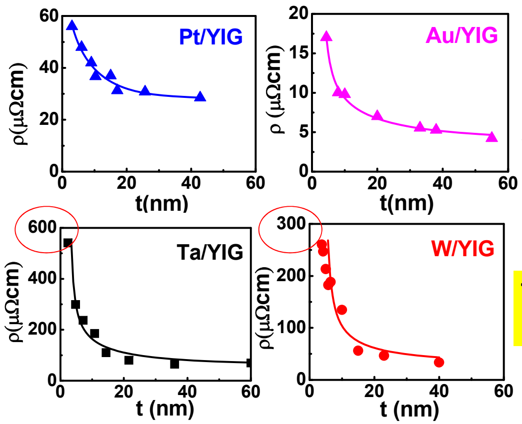
Resistivity (ρ)



Pt and **Au**: small ρ.

Ta and **W**: huge ρ.

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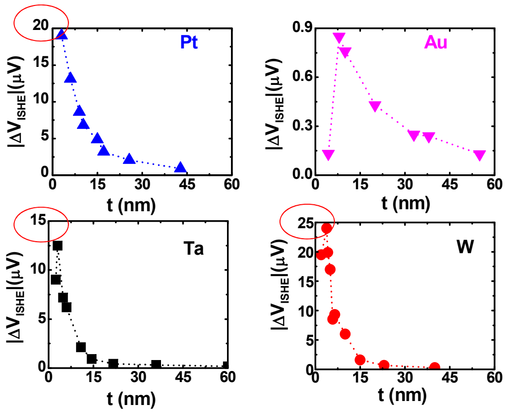
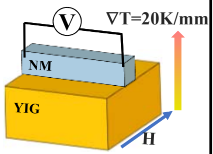
Thickness dependent voltage





$t_{YIG}\approx 0.5$mm
$L_{NM}\approx 4.2$mm

Systematically vary with thicknesses

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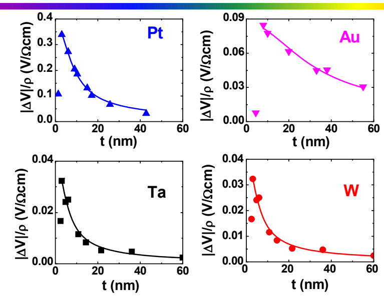
Relative spin Hall angle of 5d metals



D. Qu *et al.* Phys. Rev. B **89** 140407 (R) (2014)

Same C (spin injection coefficient)

$V_{ISHE}(t)=2CL\nabla T\rho(t)\theta_{SH}\frac{\lambda_{sd}}{t}\tanh\left(\frac{t}{2\lambda_{sd}}\right)$

$\frac{V_{ISHE}(t)}{\rho(t)}=2CL\nabla T\theta_{SH}\frac{\lambda_{sd}}{t}\tanh\left(\frac{t}{2\lambda_{sd}}\right)$

Use Au as reference

Consider different C: ($g_{\uparrow\downarrow}$)

$C=\frac{2e}{\hbar}\frac{\gamma\hbar\rho' k_m^3 l_m}{4\pi M\pi^2}\frac{B_1 B_S}{B_2}\boxed{g_{eff}^{\uparrow\downarrow}}k_B$

	Pt	Au (ref.)	Ta	W
$\theta_{SH}/\theta_{SH}(Au)$	4.3	1.0	-0.46	-1.43
λ_{sd} (nm)	2.5	9.5	1.7	1.5
$g_{\uparrow\downarrow}(10^{18}m^{-2})$	6.9	2.7	5.4	4.5
θ_{SH}	8%	3.4%	-1.6%	-4.7%

Rezende *et. al.*, Phys. Rev. B **89**, 014416 (2014) Wang *et. al.*, Phys. Rev. Lett. **112**, 197201 (2014) Du *et. al.*, Phys. Rev. B **90**, 140407(R) (2014)

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θ_{SH} by various methods

Metal	Technique	θ_{SH}
Pt	Non-local	0.021
Pt	Non-local	0.024
Pt	Spin-pumping	0.08
Pt	Spin-pumping	0.013
Pt	Spin-pumping	0.04
Pt	Spin-pumping	0.012
Pt	Spin-pumping	0.07
Pt	[illegible]	[illegible]
Pt	[illegible]	[illegible]
Pt	[illegible]	[illegible]
Pt	[illegible]	[illegible]
Au	Non-local	0.113
Au	Non-local	0.027
Au	Non-local	0.03~0.1
Au	Non-local	0.014
Au	Spin-pumping	0.0016
Au	Spin-pumping	0.0035
Au	Spin-pumping	0.058
Ta	Non-local	-0.0037
Ta	Non-local	-0.008
Ta	Spin-pumping	-0.049
Ta	Spin-torque FMR	-0.15
Ta	Spin-torque DW	-0.25
Ta	Spin Hall tunneling spectroscopy	-0.05~-0.11
W	Spin-pumping	-0.097
W	Spin-torque FMR	-0.3
W	Spin Hall switching	-0.07~-0.33

Spin Hall angle θ_{SH}

Pt	Au
0.012 ~ 0.16	0.0016 ~ 0.113

Ta	W

Consistent measurement is required to compare the **spin Hall angle** among different materials

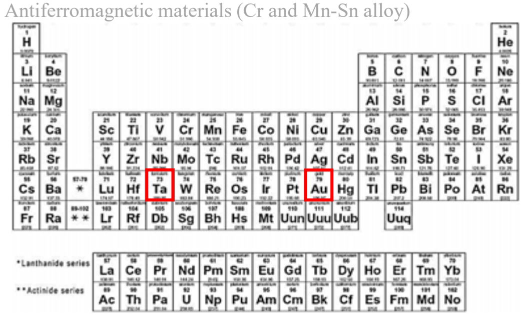
θ/θ_{Au}	Pt	Au (ref)	Ta	W
JHU	2.3	1.0 (0.034)	-0.48	-1.38
U Tokyo	1.7	1.0 (0.014)	-0.57	N/A
Ohio State U	1.2	1.0 (0.058)	-0.84	-1.67

Consistent relative values!

D. Qu *et al.* Phys. Rev. B **89** 140407 (R) (2014)
Y. Niimi *et al.* Phys. Rev. B **89** 054401 (2014)
H. L. Wang *et al.* Phys. Rev. Lett. **112** 197201 (2014)

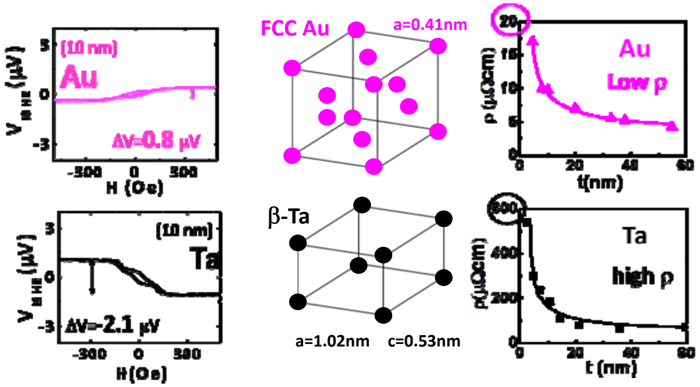
Outline

- Self-consistent determination of spin Hall angle (自旋霍爾角) and spin diffusion length (自旋擴散長度) by SSE and ISHE
  - Non-magnetic materials (Au, Pt, Ta, and W)
  - Non-magnetic alloy (Au-Ta alloy)
  - Ferromagnetic materials (Py and Co)
  - Antiferromagnetic materials (Cr and Mn-Sn alloy)



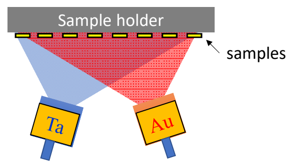
Au_xTa_{1-x} alloy (tunable spin Hall angle)

Opposite sign of θ_{SH} | **Different crystalline structure** | **Different resistivity**



Spin Hall angle dependence on composition

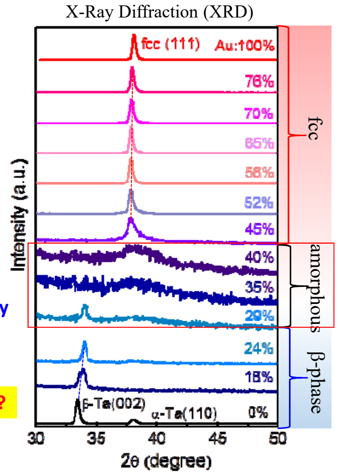
Au_xTa_{1-x} alloy – Crystalline structure



Co-sputtering at room-temperature
Vapor-quench method
Meta-stable crystalline/amorphous alloy

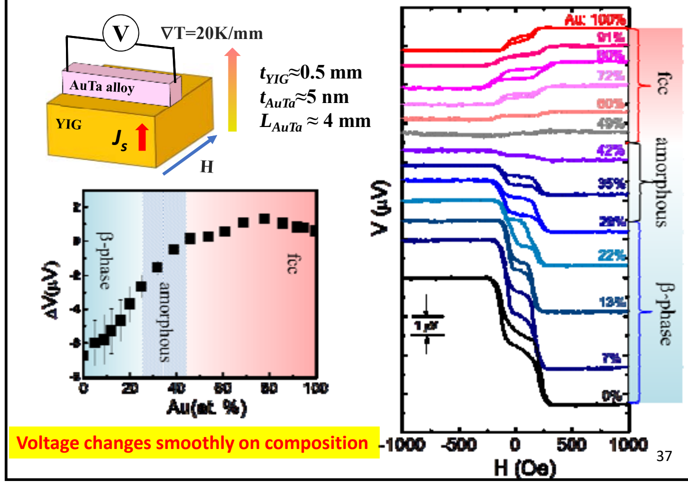
Changes of crystalline structure

How does it affect the spin Hall angle?



D. Qu et al, Phys. Rev. B **97**, 024402 (2018)

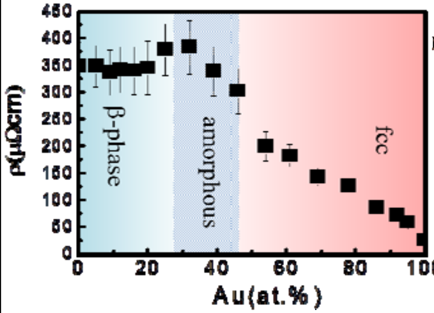
AuTa alloy - Inverse spin Hall voltage



Voltage changes smoothly on composition

37

AuTa alloy – Resistivity



$$V_{ISHE} = \boxed{2L\nabla T\rho\theta_{SH}}\boxed{C\frac{\lambda_{sd}}{t}\tanh(\frac{t}{2\lambda_{sd}})}$$

$$D = 2L\nabla TC\frac{\lambda_{sd}}{t}\tanh(\frac{t}{2\lambda_{sd}})$$

$$D(Ta)/D(Au) \approx 1.5$$

$$\theta_{SH} \propto V_{ISHE}/\rho$$

Large resistivity at Ta side/ small resistivity at Au side

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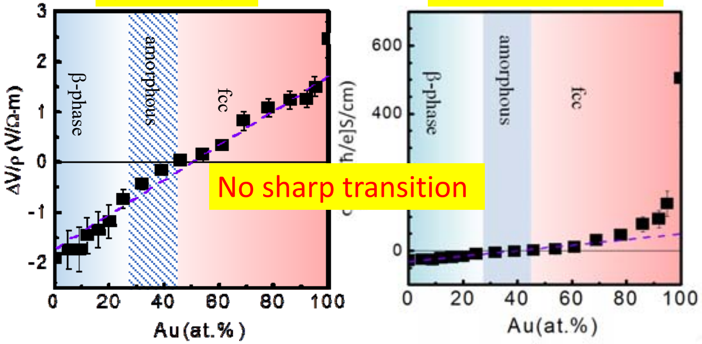
Spin Hall angle and spin Hall conductivity

$\theta_{SH} \propto V_{ISHE}/\rho$

spin Hall angle

$\sigma_{SH} \propto \theta_{SH}/\rho$

Spin Hall conductivity



Linear dependence

Monotonic dependence

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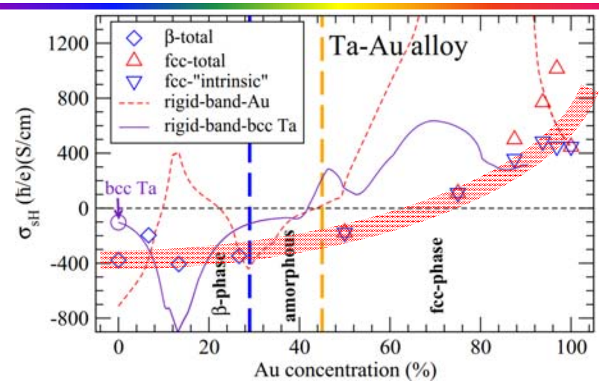
First-principle calculation



Importance of valence electron numbers over band structure in spin Hall effect

40

D. Qu et al, Phys. Rev. B **97**, 024402 (2018)

Outline

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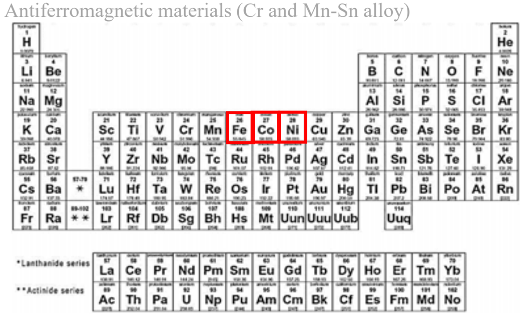

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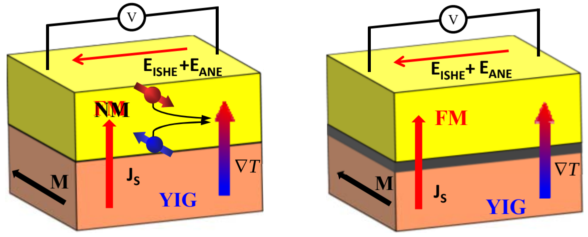
Observation of ISHE in FM



$E_{ISHE} + E_{ANE}$ — $E_{ISHE} + E_{ANE}$

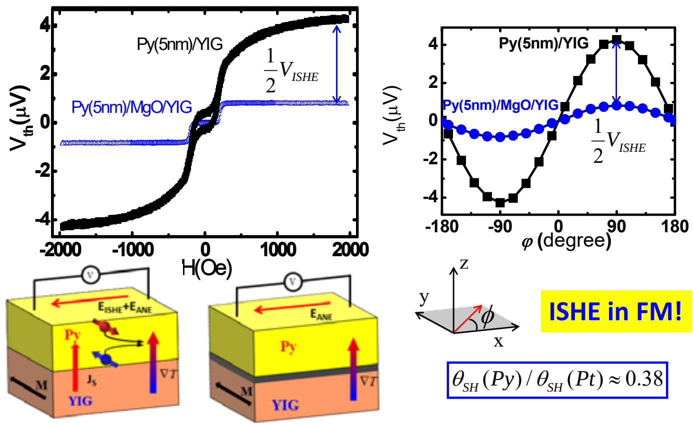
$E_{ISHE} \propto J_S \times M$ $\quad$ $E_{ANE} \propto \nabla T_Z \times M$

$J_S \parallel \nabla T_Z$

Same angular dependence!

B. F. Miao, S. Y. Huang, **D. Qu** and C. L. Chien, Phys. Rev. Lett.**111**, 066602 (2013) 42

Observation of ISHE in FM

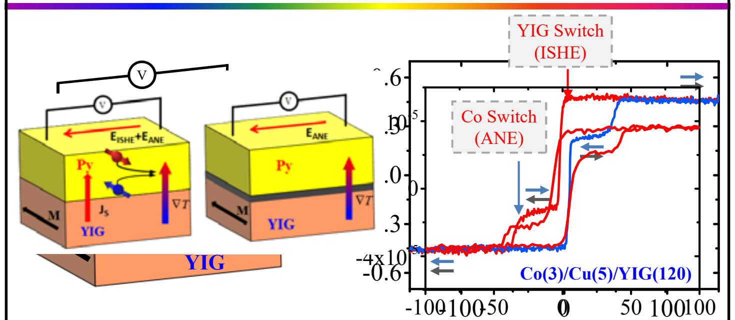


ISHE in FM!

$\theta_{SH}(Py)/\theta_{SH}(Pt) \approx 0.38$

B. F. Miao, S. Y. Huang, **D. Qu** and C. L. Chien, Phys. Rev. Lett.**111**, 066602 (2013) 43

Separation of SSE and ANE



Cu layer decouples the FM and YIG layer

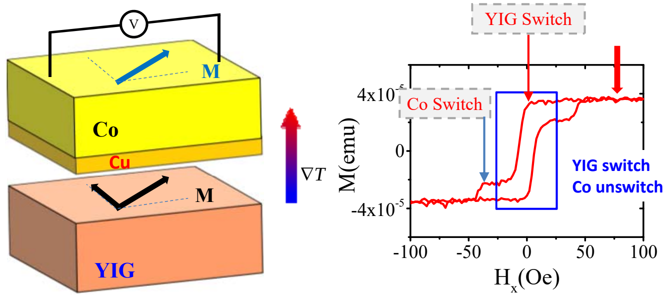
Separation of ISHE and ANE in FM from a **SINGLE** sample

$\theta_{SH}(Co)/\theta_{SH}(Pt) \approx 10\%$

44

Dai Tian, Yufan Li, **D. Qu**, Xiaofeng Jin, and C. L. Chien, Appl. Phys. Lett.**106**, 212407 (2015)

ISHE in Co

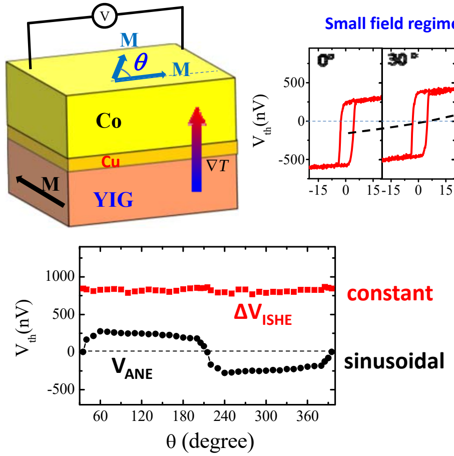


Between YIG and Co coercivity field, only YIG responses to magnetic field.

45

Dai Tian, Yufan Li, **D. Qu**, S. Y. Huang, Xiaofeng Jin, and C. L. Chien, Phys. Rev. B 94, 020403(R)

ISHE in Co



ISHE in Co independent of its magnetization

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Outline

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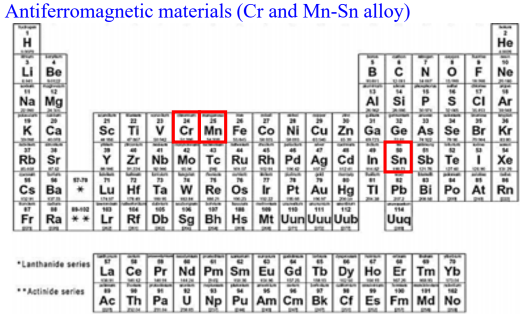

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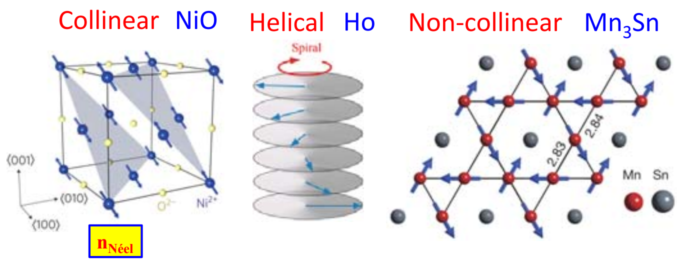
Fascinating AF Spin Structures ($\Sigma M_i \sim 0$)



- Negligible magnetization
- Weak response to magnetic field
- Generates no stray field
- High frequency magnetization dynamics
- Most AFs have no $n_{Néel}$

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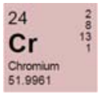
Collinear Antiferromagnet Chromium

3d metal



Spin Hall angle θ_{SH}

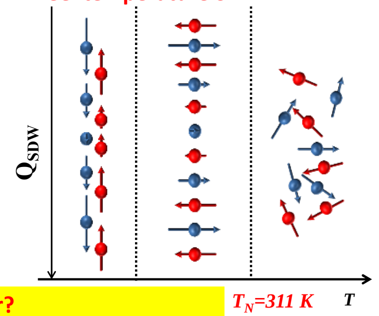
Theory: -0.15%

Frank Freimuth *et al.*, PRL **105**, 246602 (2010)

Spin Pumping: -5%

Chunhui Du *et al.*, PRB **90**, 140407 (2014)

Spin density wave Antiferromagnet
Spin flip temperature 123 K
Neel temperature 311 K



- **Large spin Hall angle in Cr?**
- **Dependence with antiferromagnetic ordering?**

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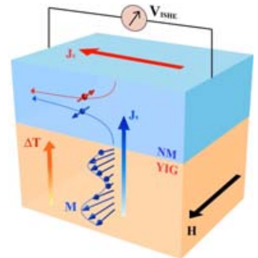
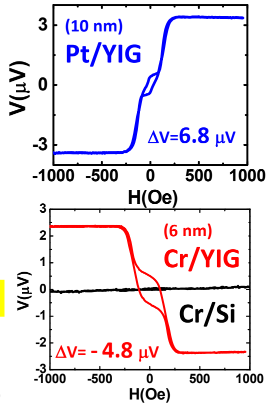
Inverse Spin Hall Effect in Cr

Longitudinal spin Seebeck effect (LSSE) ∇T=20 K/mm



Yttrium Iron Garnet (YIG)
Ferromagnetic insulator



Sizable θ_{SH}

θ_{SH} of Cr is opposite to Pt

D. Qu *et. al.*, Phys. Rev. B **92**, 020418 (R) (2015)

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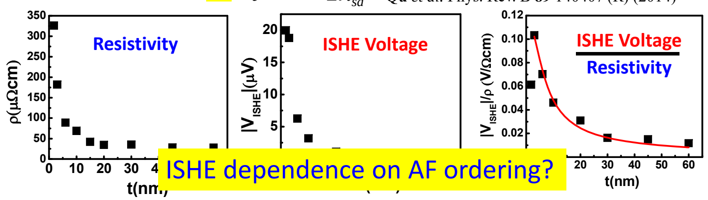
Giant spin Hall angle in Cr

$$V_{ISHE}(t) = 2CL\nabla T\rho(t)\theta_{SH}\frac{\lambda_{sd}}{t}\tanh(\frac{t}{2\lambda_{sd}})$$

Mosendz *et al*, Phys. Rev. Lett. **104** 046601 (2010)
Qu *et al.* Phys. Rev. B **89** 140407 (R) (2014)



ISHE dependence on AF ordering?

	Pt	Au (ref)	Ta	W	Cr
θ/θ_{Au}	4.33	1	-0.46	-1.43	-1.38
λ_{SF} (nm)	2.5	9.5	1.7	1.5	2.1
$g_{\uparrow\downarrow}(10^{18}m^{-2})$	6.91	2.66	5.35	4.54	1
θ	8%	3.4%	-1.6%	-4.7%	-12%

D. Qu *et. al.*, Phys. Rev. B **92**, 020418 (R) (2015)

Wang *et. al.*, Phys. Rev. Lett. **112**, 197201 (2014)
Du *et. al.*, Phys. Rev. B **90**, 140407(R) (2014)

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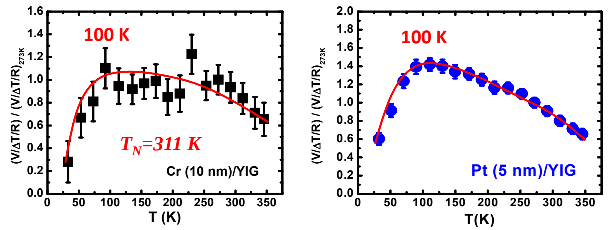
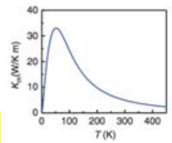
Temperature dependent measurement



Similar temperature dependence for Cr/YIG and Pt/YIG
=>intrinsic behavior originated from YIG
(thermal conductivity of YIG magnon)

Rezende *et al.*, PRB 89, 134406 (2014)

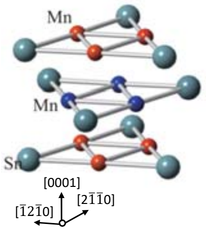


ISHE in Cr is independent on AF ordering

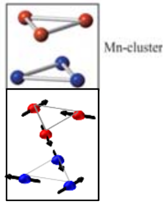
D. Qu *et. al.*, Phys. Rev. B **92**, 020418 (R) (2015)

52

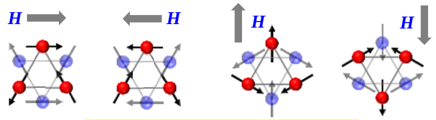
Non-Collinear Antiferromagnet Mn_3Sn



- Hexagonal crystalline structure
- a=5.67 Å c=4.53 Å
- Inverse triangular spin structure
- $M_s \sim 3\ \mathrm{m}\mu_B$/Mn
- T_N= 420 K



Cluster magnetic octupole in response to an external magnetic field in c plane

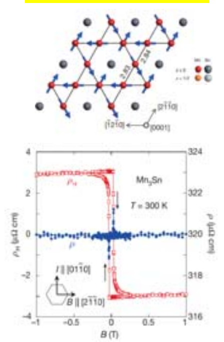


Inverse triangular spin structure

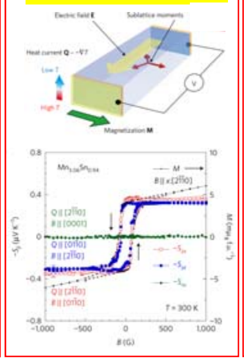
S. Nakatsuji, et al, Nature **527**, 212 (2015)
M. –T. Suzuki, et al, Phys. Rev. B 95, 094406 (2017)

Transverse Electrical and Optical Response at 300 K

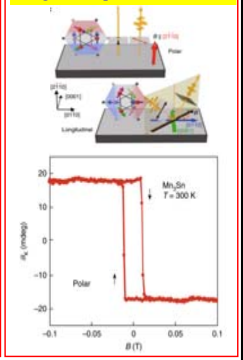
Anomalous Hall Effect



Anomalous Nernst Effect



Magnetic Optical Kerr effect



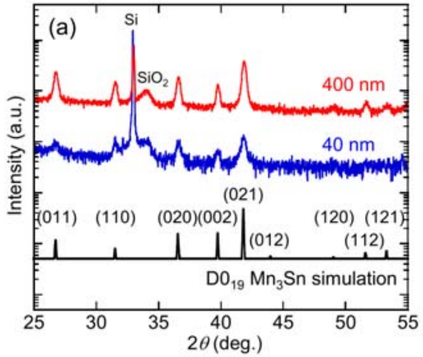
S. Nakatsuji et al. Nature **527**, 212 (2015) M. Ihklas et al. Nat. Phys. **13**, 1085 (2017) T. Higo et al. Nat. Phot. **12**, 74 (2018)

Weyl points => Berry Curvature => large SHE? K. Kuroda et al. Nat. Mater. **16**, 1090 (2017)

Mn_3Sn thin film?

Mn_3Sn Polycrystalline Thin Film

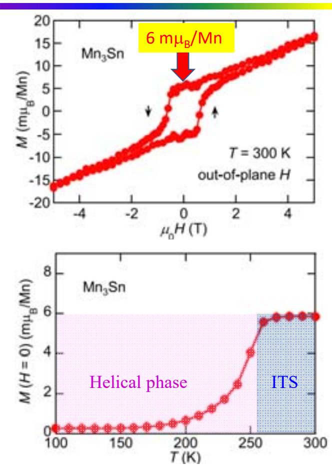
Polycrystalline Mn_3Sn thin film

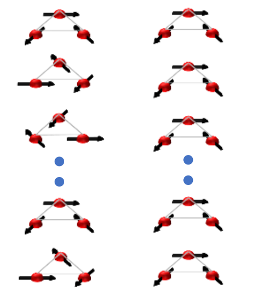


Synthesis of Mn_3Sn polycrystalline thin film

T. Higo, **D. Qu,** Y. Li, et. al, Appl. Phys. Lett. **113**, 202402 (2018)

Magnetization





Helical spin structure (TRS)

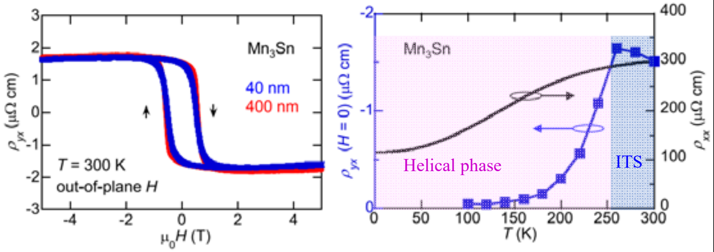
Inverse triangular spin structure (ITS) (TRS broken)

Magnetization comparable to bulk

Observation of helical phase transition near 260 K

T. Higo, **D. Qu,** Y. Li, et. al, Appl. Phys. Lett. **113**, 202402 (2018)

Anomalous Hall effect



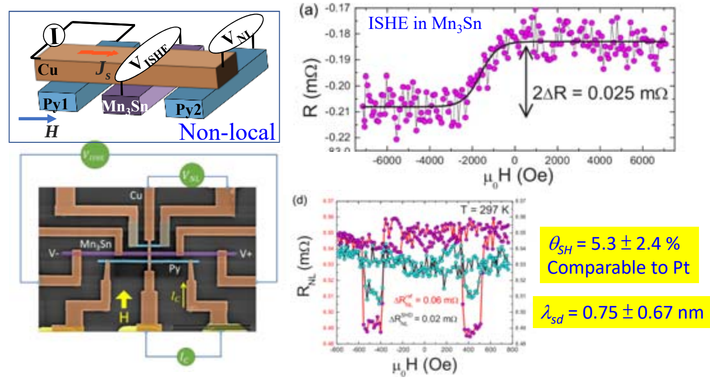
Large anomalous Hall effect for Mn_3Sn (Comparable to bulk)

No AHE for helical phase

Synthesis of high quality Mn_3Sn thin film

T. Higo, **D. Qu**, Y. Li, et. al, Appl. Phys. Lett. **113**, 202402 (2018)

ISHE in Poly-Mn_3Sn (Non-Local Spin Valve)



θ_{SH} = 5.3 ± 2.4 %
Comparable to Pt

λ_{sd} = 0.75 ± 0.67 nm

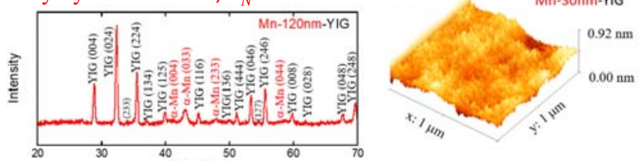
150 nm wide, 11.5 µm long, 70 nm thick

Sizable positive spin Hall angle

P. K. Muduli, T. Higo, T. Nishikawa, **D. Qu**, et al., Phys. Rev. B **99**, 184425 (2019)

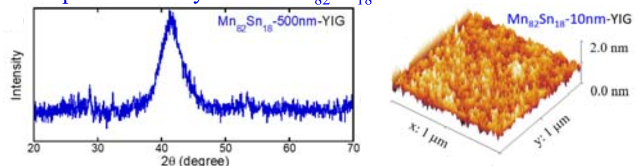
α-Mn and Amorphous Mn-Sn Alloy

Polycrystalline α-Mn, T_N=95 K



Mean roughness **0.07 nm**

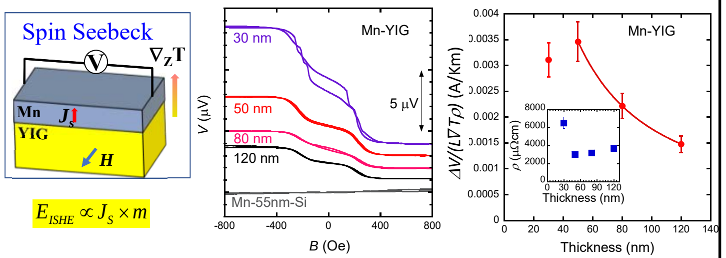
Amorphous/nanocrystalline $Mn_{82}Sn_{18}$



Mean roughness **0.15 nm**

D. Qu, *et al.*, Phys. Rev. Mater. 2, 102001(R) (2018) **Editor's suggestion**

ISHE in Mn (Spin Seebeck)



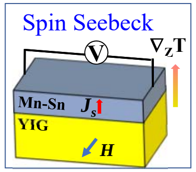
$E_{ISHE} \propto J_S \times m$

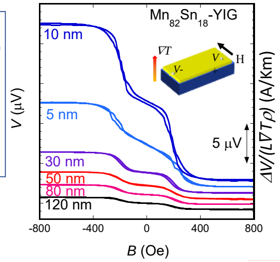
$V_{ISHE}(t) = 2CL\nabla T\rho(t)\theta_{SH}\frac{\lambda_{sd}}{t}\tanh(\frac{t}{2\lambda_{sd}})$

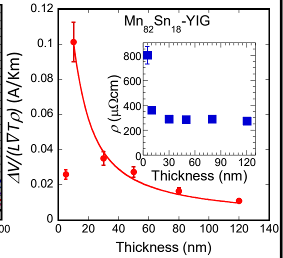
C: spin injection coefficient
L: distance between two terminals ~7 mm
∇T: temperature gradient ~6 mm/K

θ_{SH}(Mn)=- (0.23 ± 0.03)%
λ_{sd} (Mn)= 11.5 ± 0.15 nm

ISHE in Amorphous $Mn_{82}Sn_{18}$ (Spin Seebeck)







θ_{SH} = -(4.4 ± 0.7)%
λ_{sd} = 3.7 ± 0.8 nm

	Mn	$Mn_{82}Sn_{18}$
θ_{SH}	-0.23%	-4.4%
λ_{sd} (nm)	11.5	3.7
ρ (μΩcm)	3000	300

By doping 18% Sn, the θ_{SH} is enhanced by 20 times while ρ is reduced by 10 times

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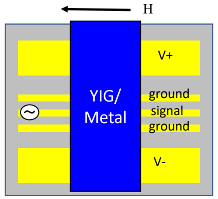
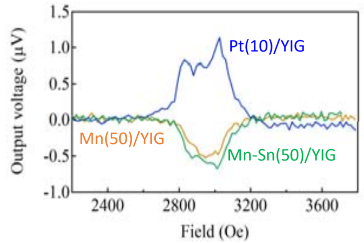
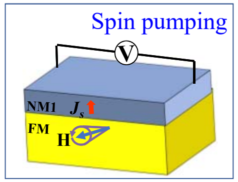
ISHE in $Mn_{82}Sn_{18}$ (Spin Pumping)







	Mn (SP)	$Mn_{82}Sn_{18}$ (SP)
θ_{SH}	-0.12%	-6.2%

Large spin Hall angle in Mn-Sn amorphous alloy!

	Mn_3Sn (NLSV)
θ_{SH}	+5.3%

Possible large contribution from the inverse triangular spin structure!

D. Qu, *et al.*, Phys. Rev. Mater. 2, 102001(R) (2018) **Editor's suggestion**

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Summary

✓Developed a new and consistent method to determine θ_{SH} and λ_{sd} through longitudinal spin Seebeck effect

✓Demonstrated importance of valence electron number over crystalline structure for spin Hall effect in alloys

✓Observed sizable spin Hall angle in non-magnetic material, ferromagnetic materials and antiferromagnetic materials

✓ISHE in FM Co and AFM Cr is independent on their magnetic ordering

✓ISHE in Mn_3Sn has possible large contribution from its inverse triangular spin structure

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Acknowledgement

- ***Johns Hopkins University:*** Prof. C.-L. Chien, Dr. S.X. Huang, Dr. Y. F. Lee, Dr. B.F. Miao, Dr. D. Tian
- ***ISSP, University of Tokyo:*** Prof. S. Nakatsuji, Prof. Y. Otani, Dr. T. Higo, Dr. P. K. Muduli, Dr. K. Kondou, Mr. K. Matsumoto, Mr. T. Nishikawa
- ***National Taiwan University:*** Prof. S.-Y. Huang, Prof. G.-Y. Guo

THANK YOU!

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