YIG-Based FMR Spin Pumping in Metals and Insulators

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Lake Shore Cryotronics

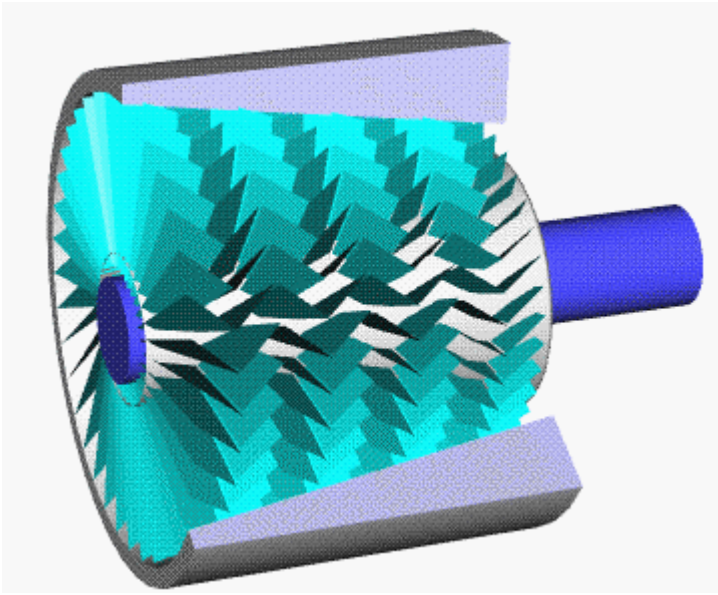
Outline

- Introduction to spin pumping
- *Inverse* Spin Hall effect & spin-orbit coupling
- Deposition and characterization of $Y_3Fe_5O_{12}$ (YIG) films
- ISHE measured in YIG/metal bilayers
  - Spin Hall angle of 3*d*, 4*d*, 5*d* transition metals
  - Spin-orbit coupling: the effect of *Z* and *d*-orbitals
- Spin transport in antiferromagnetic insulators
- Summary

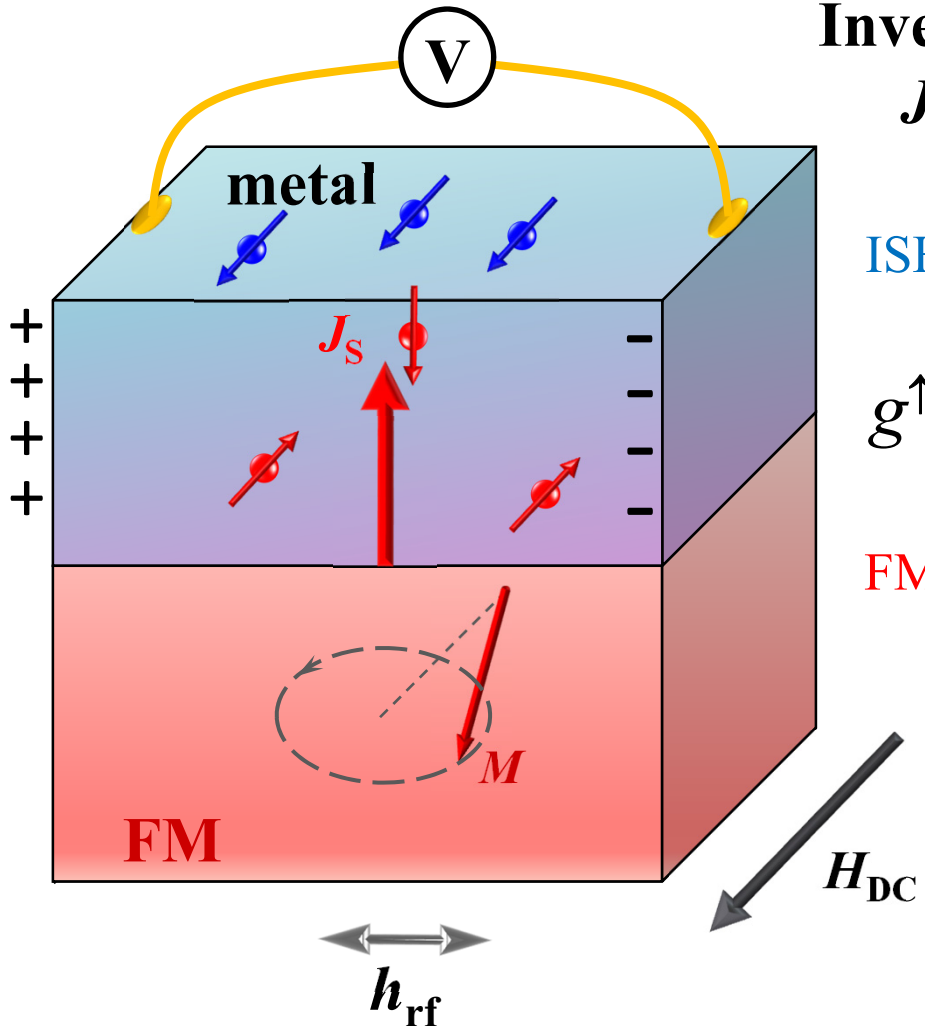
Spin Pumping

Turbo pump





FMR spin pumping



Inverse Spin Hall Effect

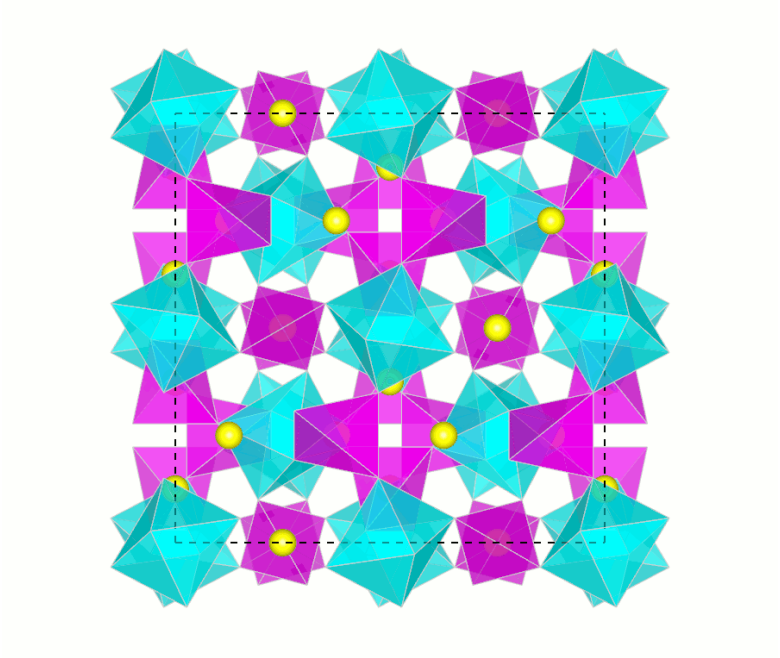
$$J_C \propto J_S \times \sigma \text{ (SOC)}$$

ISHE ⟶ Large spin Hall angle

$g^{\uparrow\downarrow}$ ⟶ Clean, sharp interface

FMR ⟶ $\theta_{\text{cone}} = \dfrac{\gamma h_{rf}}{2\alpha\omega}$

$Y_3Fe_5O_{12}$



$Y_3Fe_2Fe_3O_{12}$ (8 f.u.)

octahedral Fe ↓
tetrahedral Fe ↑
} Corner sharing

YIG: exceptionally low damping

→ large θ_{cone}

→ large angular momentum transfer

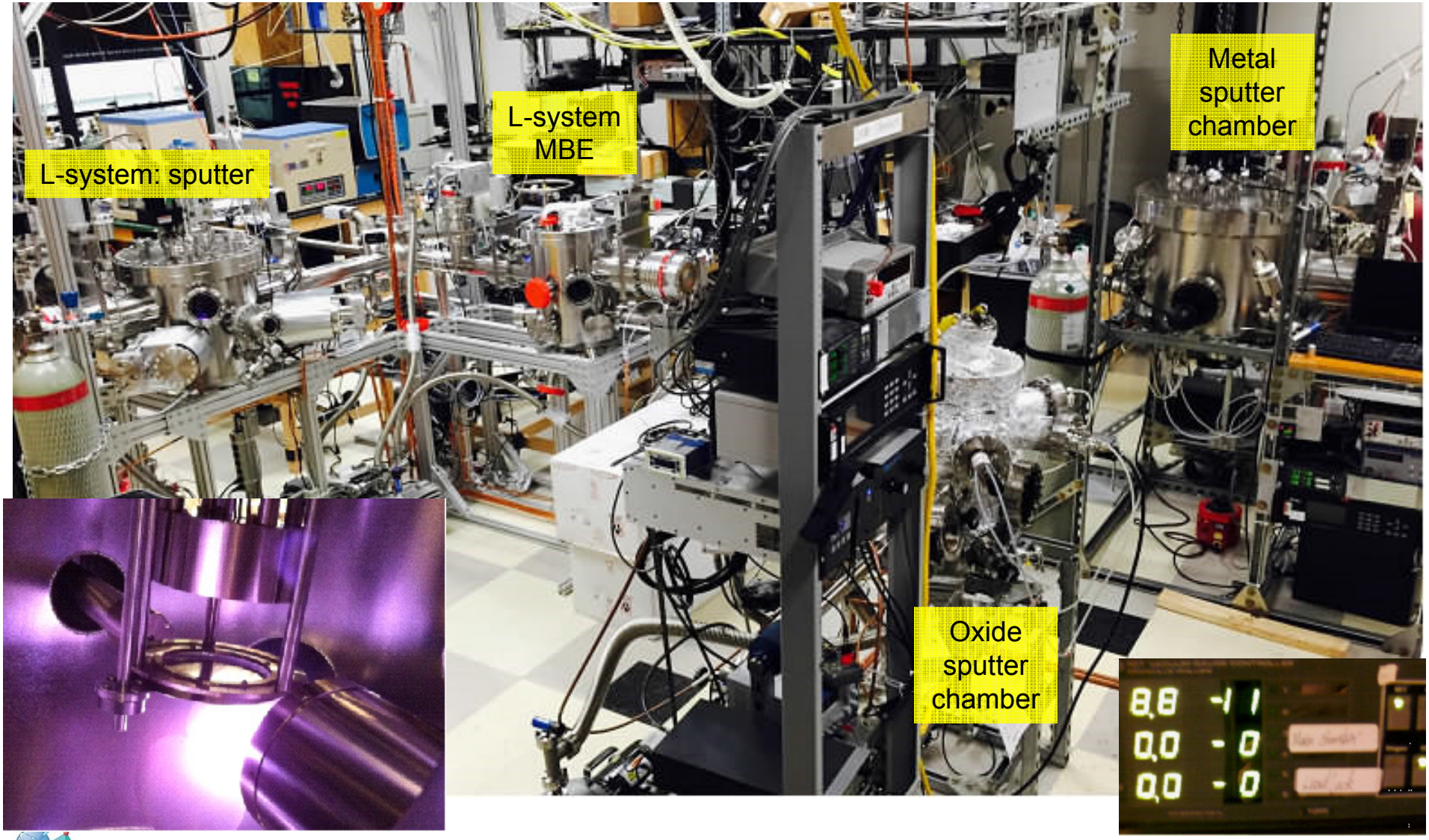
→ large pure spin current

→ large ISHE voltage

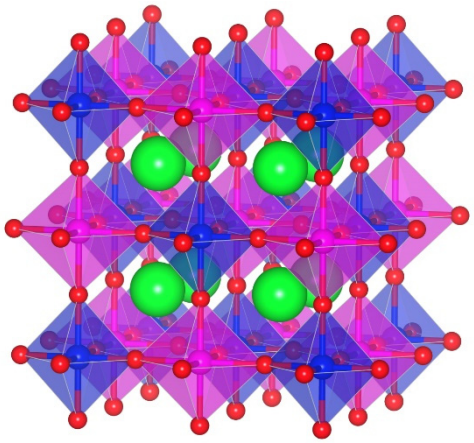
$\mathbf{Y_3^{3+}Fe_5^{3+}O_{12}^{2-}}$ → highly stable

→ clean interface

Deposition of YIG Epitaxial Thin Films: Off-axis UHV sputtering

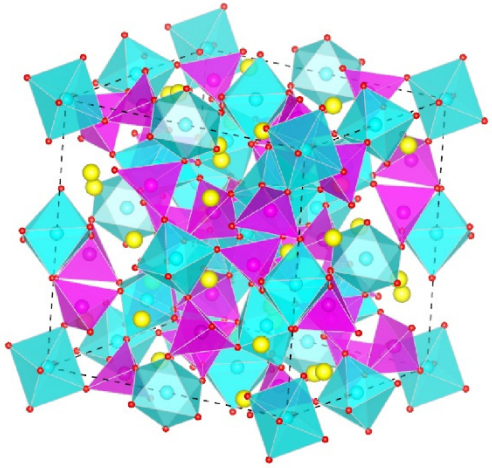


Materials deposited by off-axis sputtering



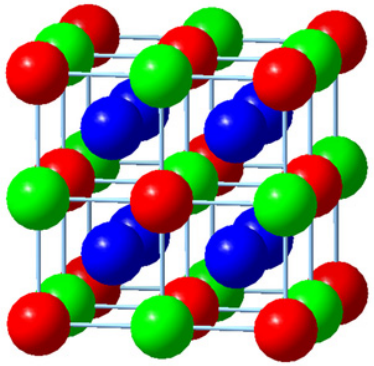
$A_2BB'O_6$ double perovskite
(Sr_2FeMoO_6)

Lucy, *et al. PRB* **91**, 094413 (2015)
Lucy, *et al. PRB* **90**, 180401(R) (2014)
Liu, *et al. PRB* **90**, 104416 (2014)
Hauser, *et al. PRB* **89**, 180402(R) (2014)
Lucy, *et al. APL* **103**, 042414 (2013)
Du, *et al. PRL* **110**, 147204 (2013)
Hauser, *et al. APL* **102**, 032403 (2013)
Hauser, *et al. PRB* **85**, 161201(R) (2012)
Hauser, *et al. PRB* **83**, 014407 (2011)
Rutkowski, *et al. JVSTA* **28**, 1240 (2010)



$A_3B_5O_{12}$ garnet
($Y_3Fe_5O_{12}$)

Du, *et al. JAP* **117**, 172603 (2015)
Adur, *et al. JAP* **117**, 172604 (2015)
Adur, *et al. JAP* **117**, 17E108 (2015)
Du, *et al. PRB* **90**, 214428 (2014)
Du, *et al. PRB* **90**, 140407(R) (2014)
Adur, *et al. PRL* **113**, 176601 (2014)
Wang, *et al. PRL* **113**, 097201 (2014)
Wang, *et al. APL* **104**, 202405 (2014)
Du, *et al. PR Appl.* **1**, 044004 (2014)
Wang, *et al. PRL* **112**, 197201 (2014)
Wolfe, *et al. PRB* **89**, 180406(R) (2014)
Wang, *et al. PRB* **89**, 134404 (2014)
Du, *et al. PRL* **111**, 247201 (2013)
Wang, *et al. PRB* **88**, 100406(R) (2013)

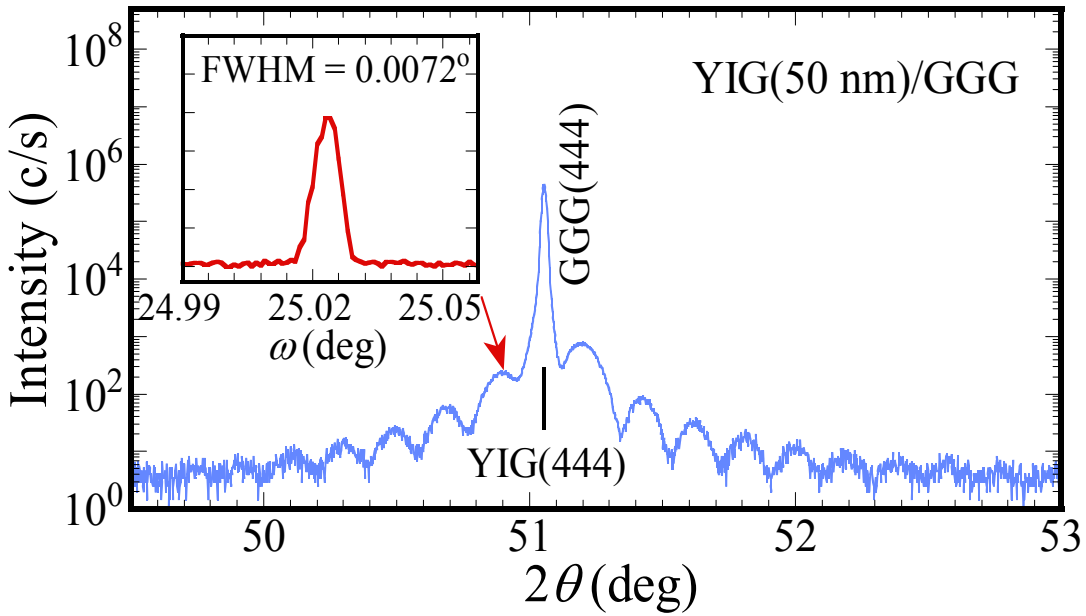


X_2YZ Heusler
(Co_2FeSi)

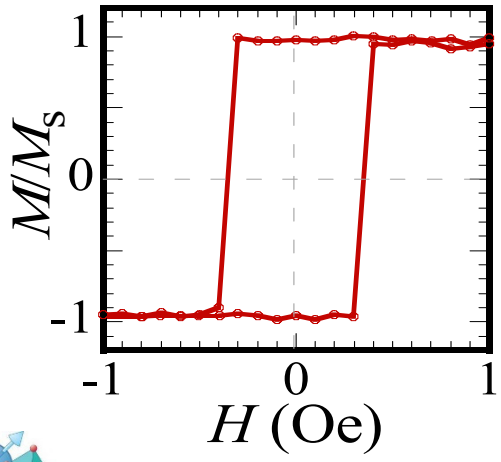
Alfonsov, *et al. PRB* **91**, 064421 (2015)
Peters, *et al. APL* **103**, 162404 (2013)

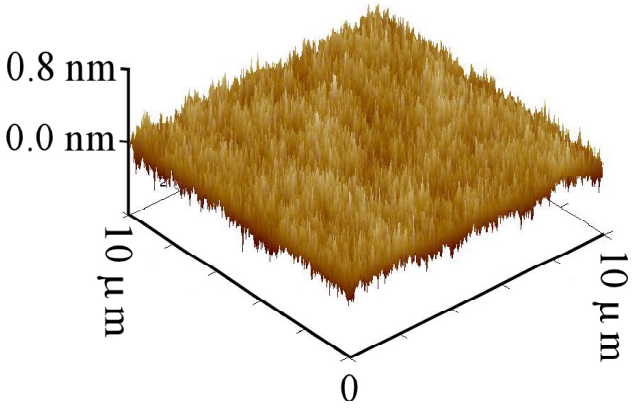
- AB_2O_4 spinels
  ($MgAl_2O_4$)
- Skyrmion intermetalics
  (FeGe)
- Binary oxides
  (NiO)
- Simple metals
  (Pt)

Crystalline quality of YIG films



- Phase pure
- Epitaxial
- High crystalline quality
- Sharp interface
- Smooth surface
- Magnetically uniform & soft

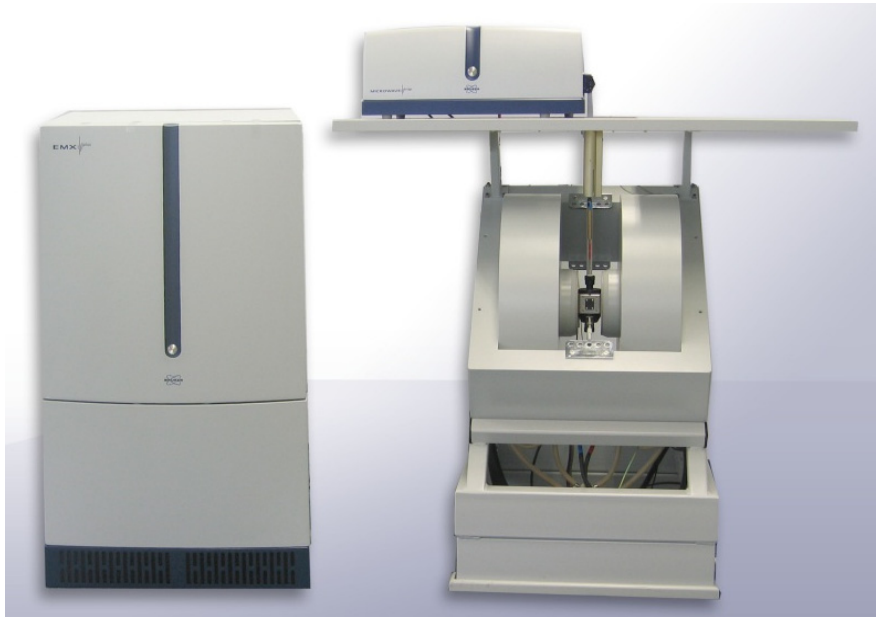




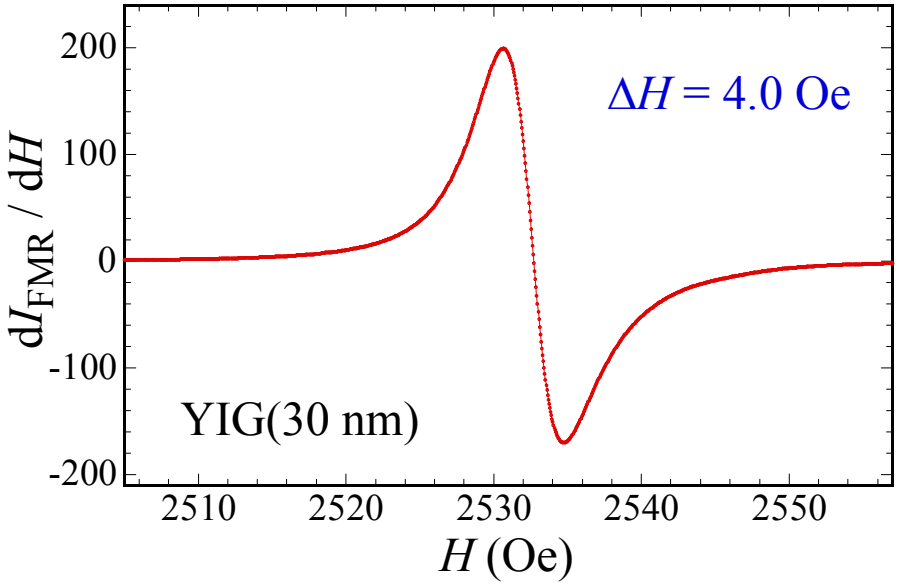
- Wang, *et al*. *PRB* **88**, 100406(R) (2013)
- Du, *et al*. *PRL* **111**, 247202 (2013)
- Wang, *et al*. *PRL* **112**, 197201 (2014)
- Du, *et al*. *PR Applied* **1**, 044004 (2014)
- Wang, *et al*. *PRL* **113**, 097202 (2014)

FMR absorption of YIG films

Cavity FMR



Bruker EPR spectrometer



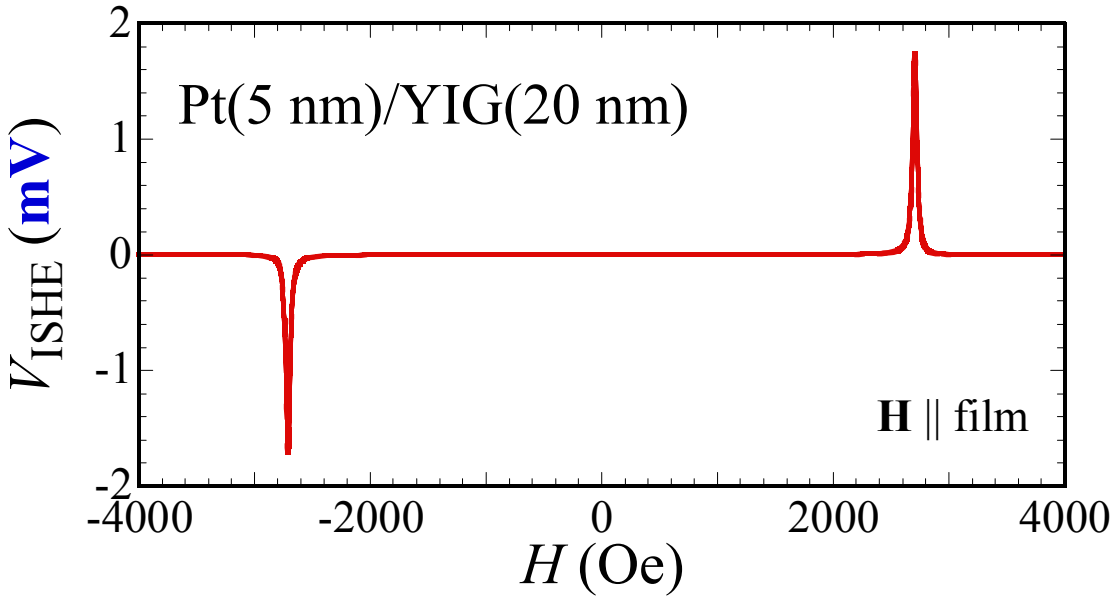
Very narrow FMR linewidth

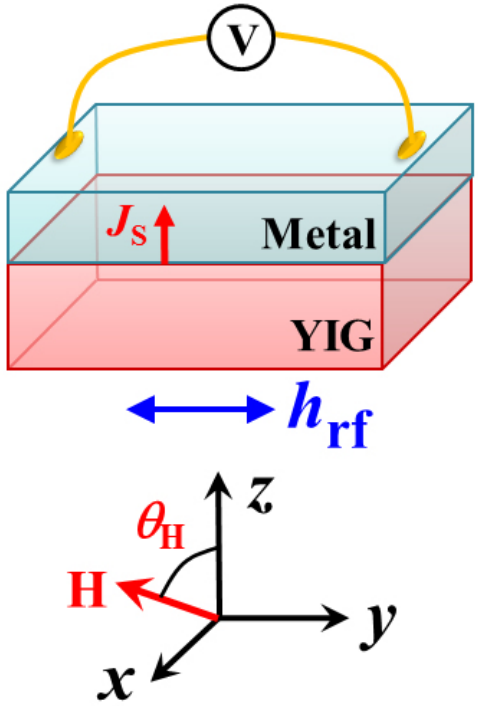
→ Low Gilbert damping

→ High spin pumping efficiency

Hammel's group

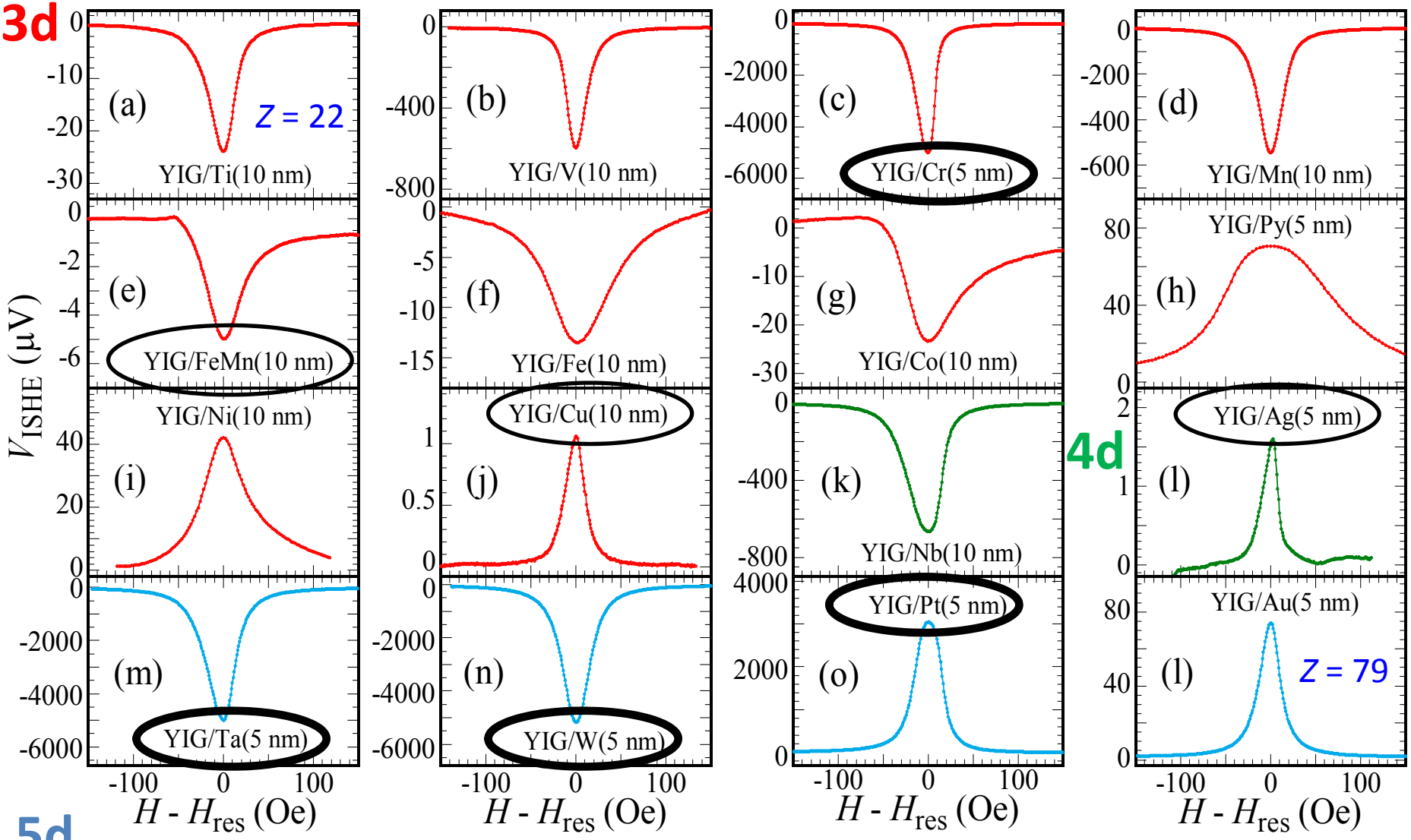
FMR spin pumping in YIG/Pt





- Exceptionally large ISHE signals:
  - ➢ mV as compared to μV reported previously
- Signals are from ISHE
  - ➢ No spurious effects: YIG is an insulating FM
- Powerful platform for studying other materials

Spin pumping in other YIG/metal bilayers



Wang, *et al*. *PRL* **112**, 197201 (2014)
Du, *et al*. *PRB* **90**, 140407(R) (2014)

Spin Hall angle & spin mixing conductance

$$V_{\mathrm{ISHE}} = \frac{-e\theta_{\mathrm{SH}}}{\sigma_{\mathrm{NM}} t_{\mathrm{NM}}} \lambda_{\mathrm{SD}} \tanh\left(\frac{t_{\mathrm{NM}}}{2\lambda_{\mathrm{SD}}}\right) g^{\uparrow\downarrow} f LP \left(\frac{\gamma h_{\mathrm{rf}}}{4\pi\alpha f}\right)^2$$

Mosendz, *et al*. *PRB* **82**, 214403 (2010).

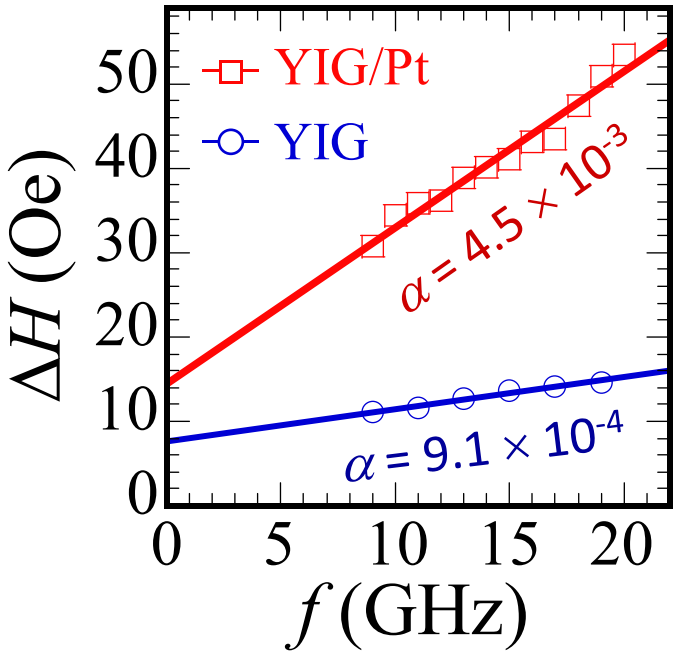
$$g^{\uparrow\downarrow} = \frac{4\pi M_{\mathrm{s}} t_{\mathrm{YIG}}}{g\mu_{\mathrm{B}}} (\alpha_{\mathrm{YIG/NM}} - \alpha_{\mathrm{YIG}})$$

To find θ_{SH} and $g^{\uparrow\downarrow}$, we need to determine λ_{SD} and α

- Wang, *et al*. *PRL* **112**, 197201 (2014)
- Wang, *et al*. *APL* **104**, 202405 (2014)
- Du, *et al*. *PRB* **90**, 140407(R) (2014)

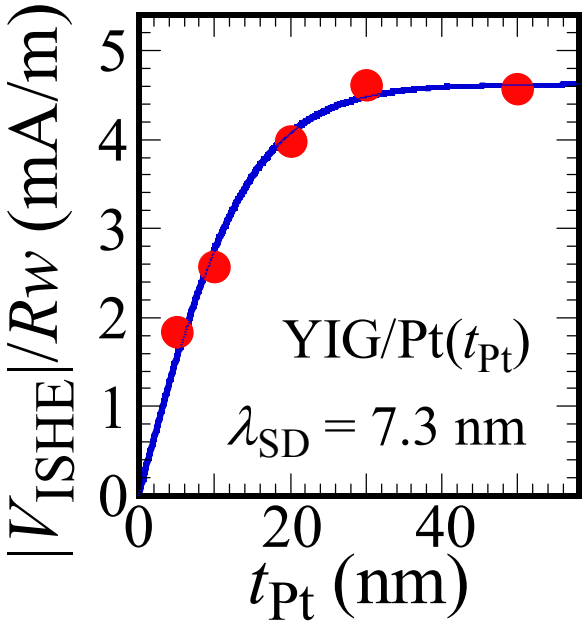
Gilbert damping & spin diffusion length of Pt

$$\Delta H = \Delta H_0 + \frac{4\pi\alpha f}{\sqrt{3}\gamma}$$



$g^{\uparrow\downarrow} = 6.9 \times 10^{18}\ \mathrm{m}^{-2}$

$$\frac{V_{\mathrm{ISHE}}}{Rw} \propto \lambda_{\mathrm{SD}} \tanh\left(\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\right)$$



$$V_{\mathrm{ISHE}} = \frac{-e\theta_{\mathrm{SH}}}{\sigma_{\mathrm{NM}} t_{\mathrm{NM}}} \lambda_{\mathrm{SD}} \tanh\left(\frac{t_{\mathrm{NM}}}{2\lambda_{\mathrm{SD}}}\right) g^{\uparrow\downarrow} fLP \left(\frac{\gamma h_{\mathrm{rf}}}{4\pi\alpha f}\right)^2$$

$$\theta_{\mathrm{SH}} = 0.10 \pm 0.01$$

cem Center for Emergent Materials

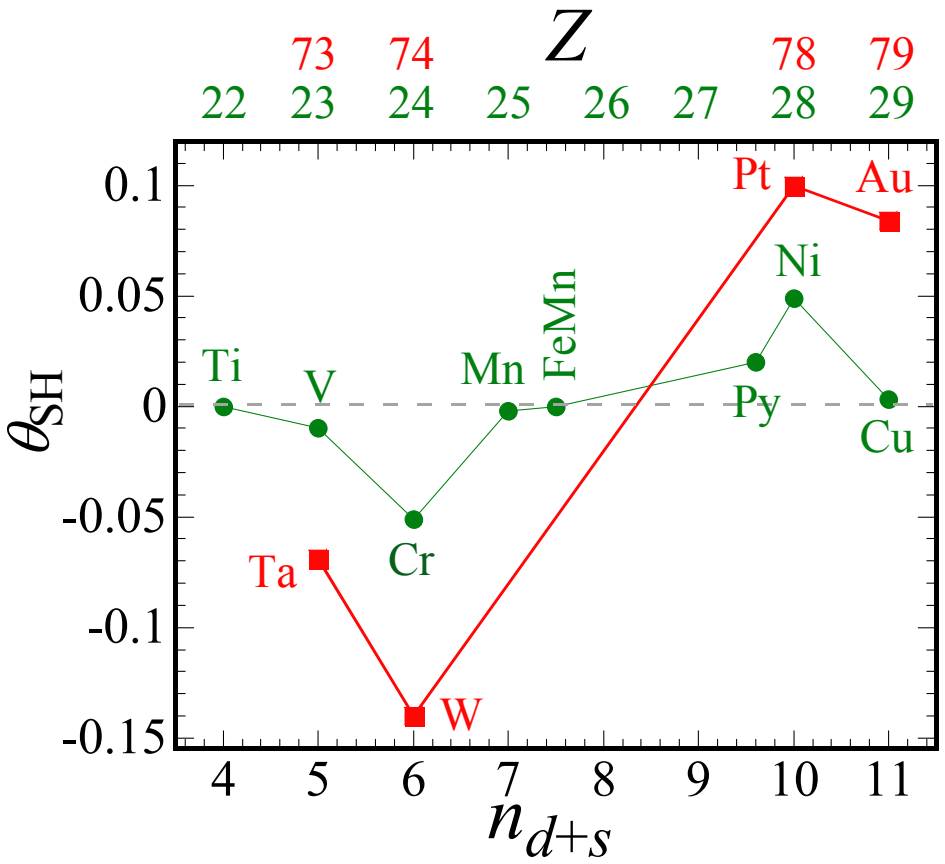
The Ohio State University

θ_{SH} and $g^{\uparrow\downarrow}$ in 3d, 4d, 5d Transition metals

	Structure	$g^{\uparrow\downarrow}$ (m^{-2})	λ_{SD} (nm)	θ_{SH}	n_{d+s}
3d	YIG/Ti	3.5×10^{18}	13.3	-3.6×10^{-4}	4
	YIG/V	3.1×10^{18}	14.9	-1.0×10^{-2}	5
	YIG/Cr	8.3×10^{17}	13.3	-5.1×10^{-2}	6
	YIG/Mn	4.5×10^{18}	10.7	-1.9×10^{-3}	7
	YIG/FeMn	4.9×10^{18}	3.8	-7.4×10^{-5}	7.5
	YIG/Cu/Py	6.3×10^{18}	1.7	2.0×10^{-2}	9.6
	YIG/Cu/Ni	2.0×10^{18}	3.2	4.9×10^{-2}	10
	YIG/Cu	1.6×10^{18}	500	3.2×10^{-3}	11
4d	YIG/Ag	5.2×10^{17}	700	6.8×10^{-3}	11
	YIG/Ta	5.4×10^{18}	1.9	-6.9×10^{-2}	5
5d	YIG/W	4.5×10^{18}	2.1	-1.4×10^{-1}	6
	YIG/Pt	6.9×10^{18}	7.3	1.0×10^{-1}	10
	YIG/Au	2.7×10^{18}	60	8.4×10^{-2}	11

Wang, *et al*. *PRL* **112**, 197201 (2014)
Wang, *et al*. *APL* **104**, 202405 (2014)
Du, *et al*. *PRB* **90**, 140407(R) (2014)

Spin Hall effect & spin-orbit coupling

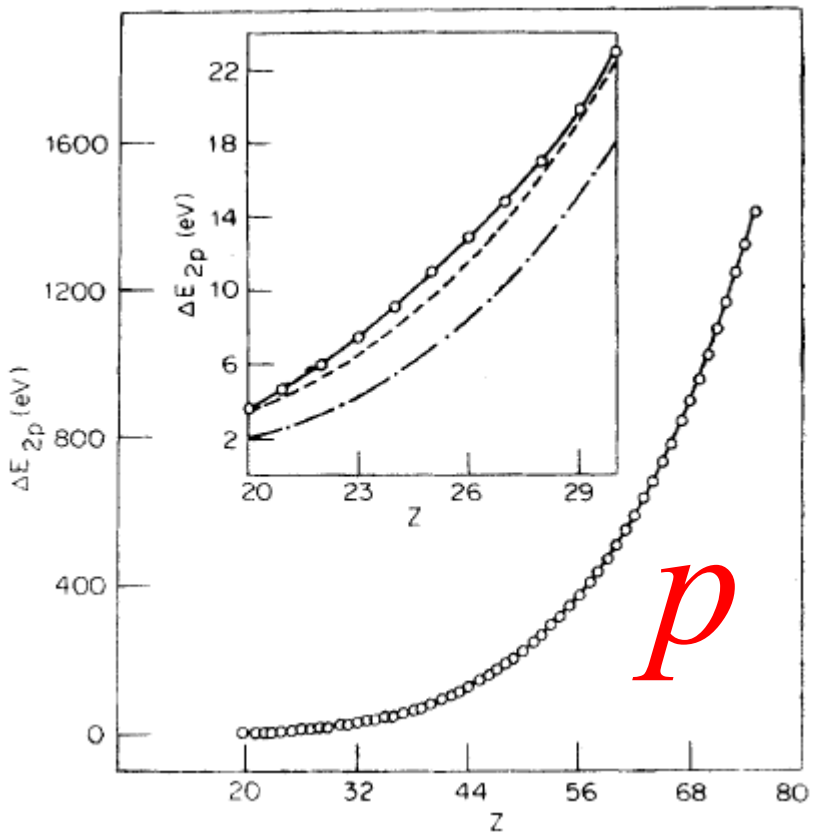


- θ_{SH} changes sign at $n_{d+s} \approx 7$
  - $n_{d+s} = 7 \rightarrow n_d = 5$: half fill
- Surprisingly large θ_{SH} for 3*d* metals
- Largest θ_{SH} observed at:
  - $n_{d+s} =$ 6: Cr, W
  - $n_{d+s} = 10$: Ni, Pt

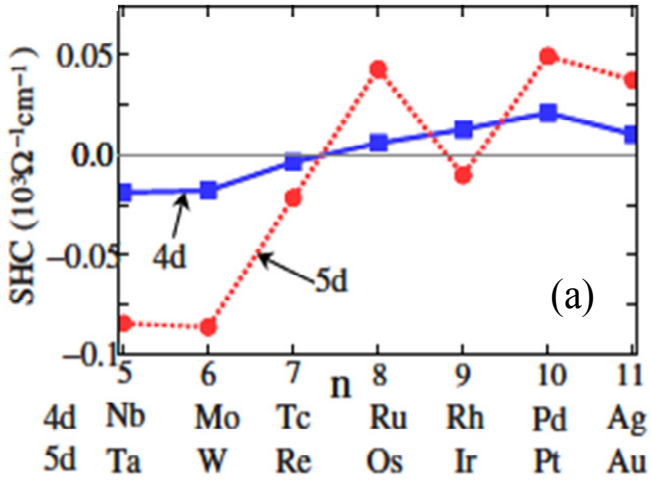
Spin-orbit coupling

D. D. Sarma, *Proc. Indian Acad. Sci. (Chem. Sci.)* **90**, 19 (1981).

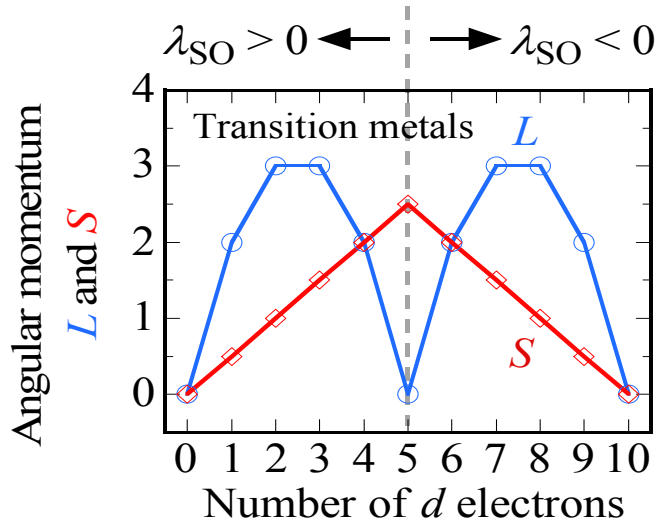
$$\triangle E_{nl} = a\,(Z - Z_0)^4$$



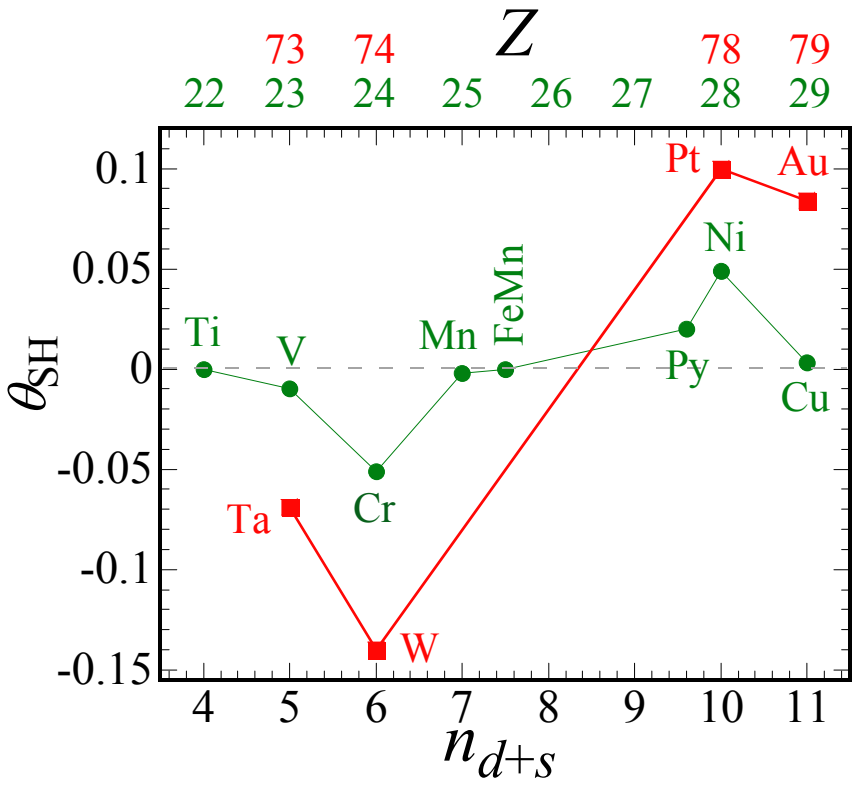
Tanaka, *et al*. *PRB* **77**, 165117 (2008).



Hund's rules



spin-orbit coupling: *Z* vs. *d*



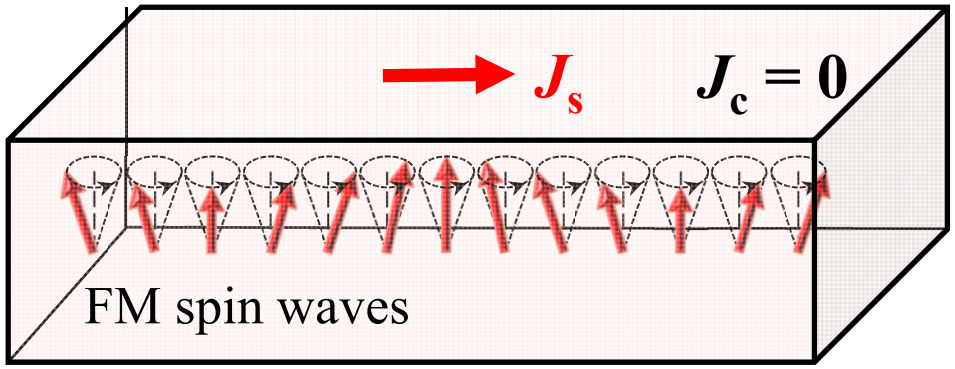
For spin-orbit coupling:

- Both Z^4 and *d*-count are important
- Z^4 and *d*-count are additive, not multiplicative

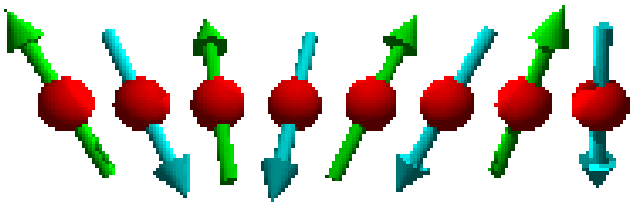
$$\lambda_{SOC} \propto aZ^4 + f(n_d)$$

~~$$\lambda_{SOC} \propto [aZ^4] \times [f(n_d)]$$~~

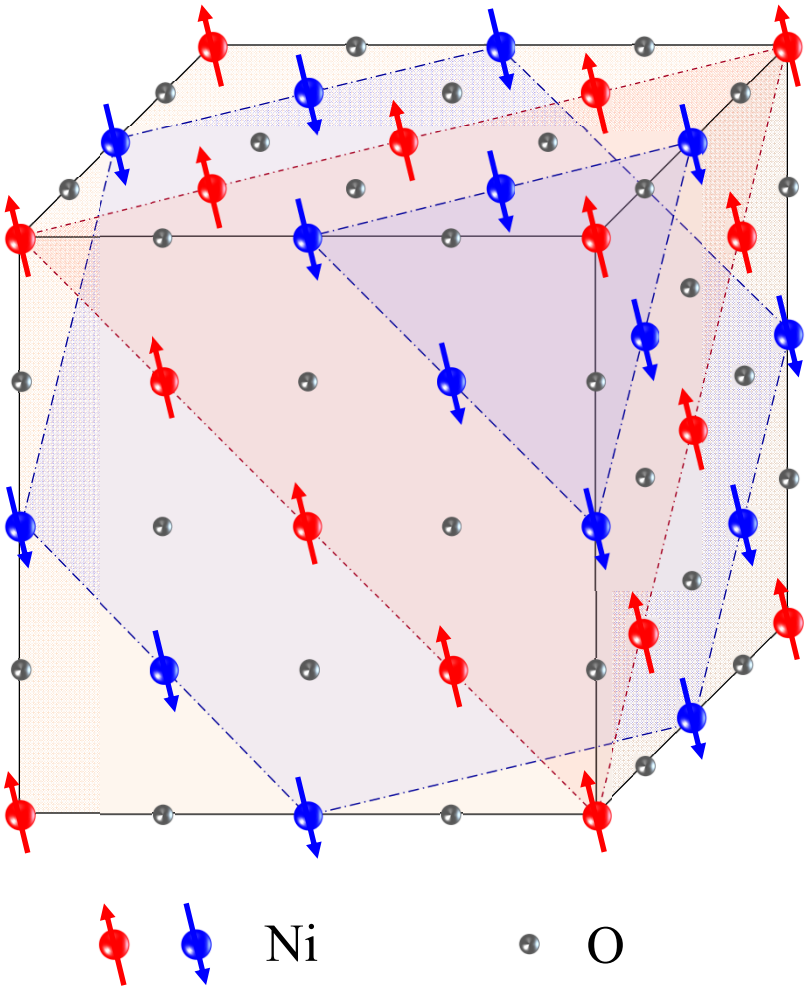
Spin Current in Antiferromagnetic Insulators



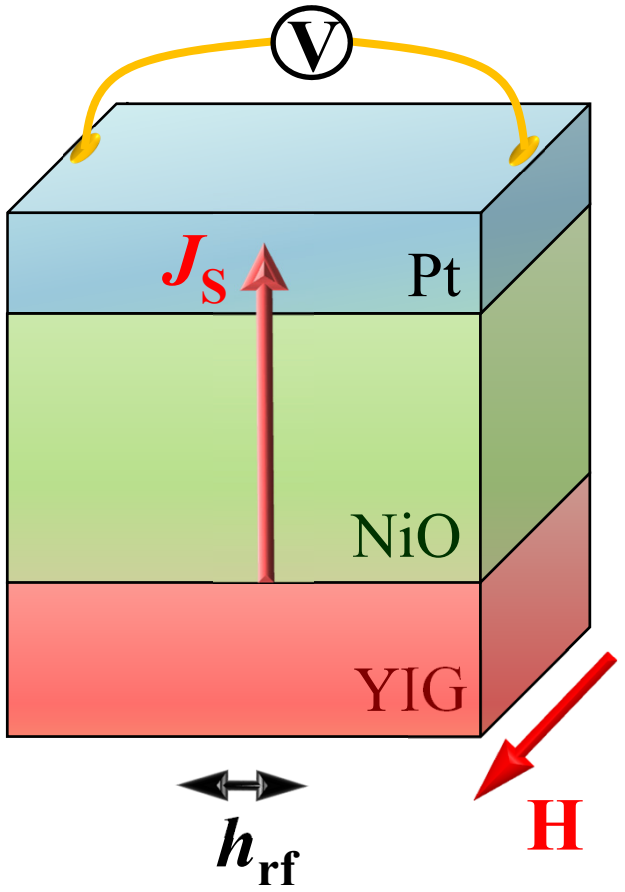
AF



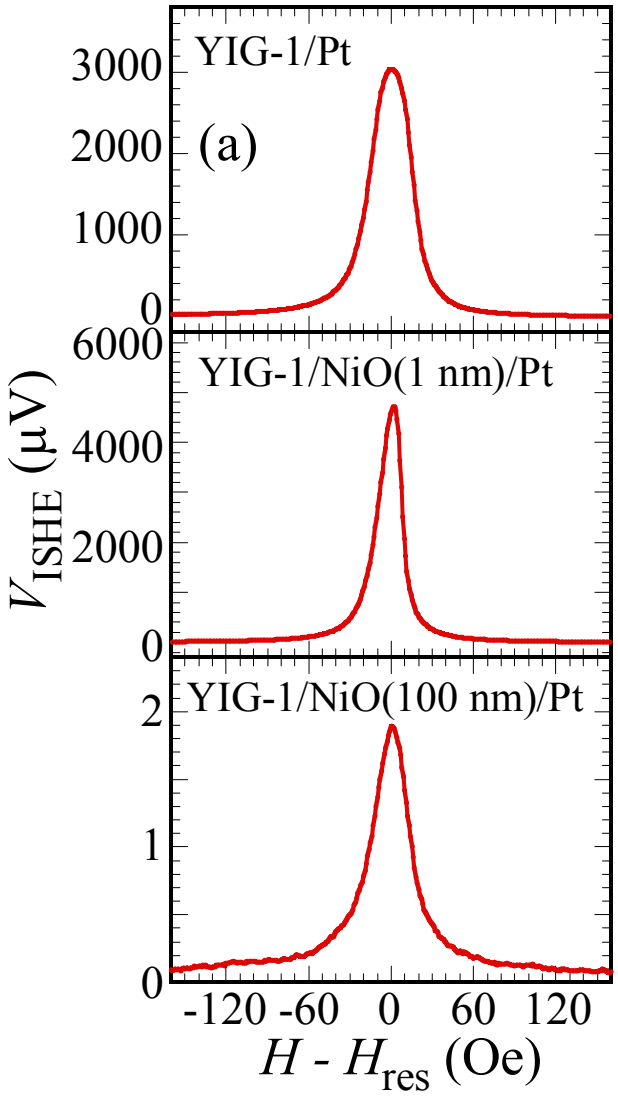
Antiferromagnetic Insulator: NiO



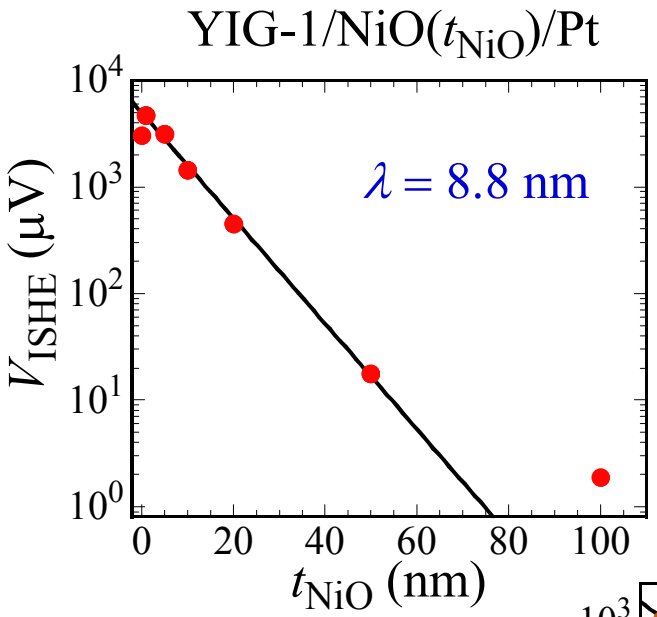
- Rock-salt crystal structure
- AF with T_N = 525 K
- AF resonance: 1 THz, 140 GHz

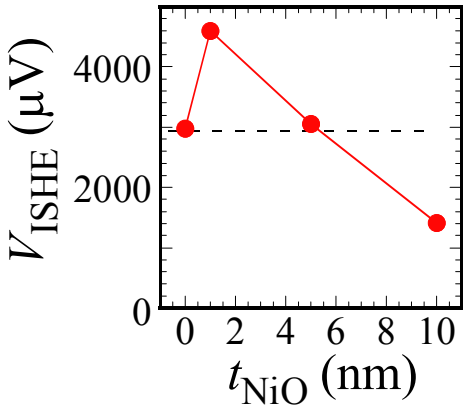


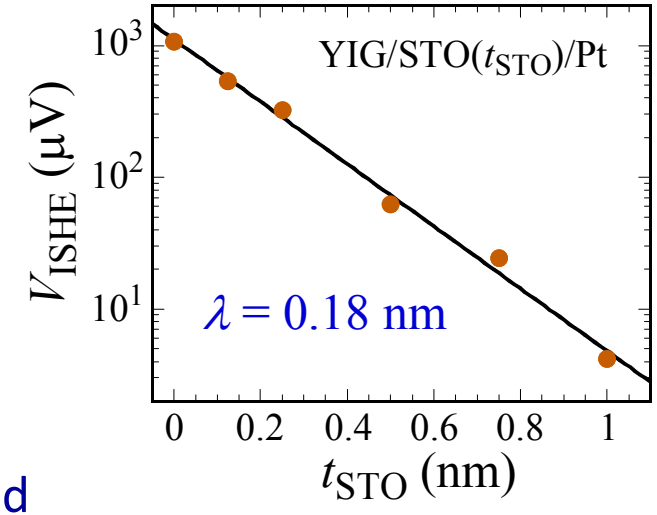
Spin Current in Pt/NiO(*t*)/YIG Trilayers



Wang, *et al*. *PRL* **113**, 097202 (2014).



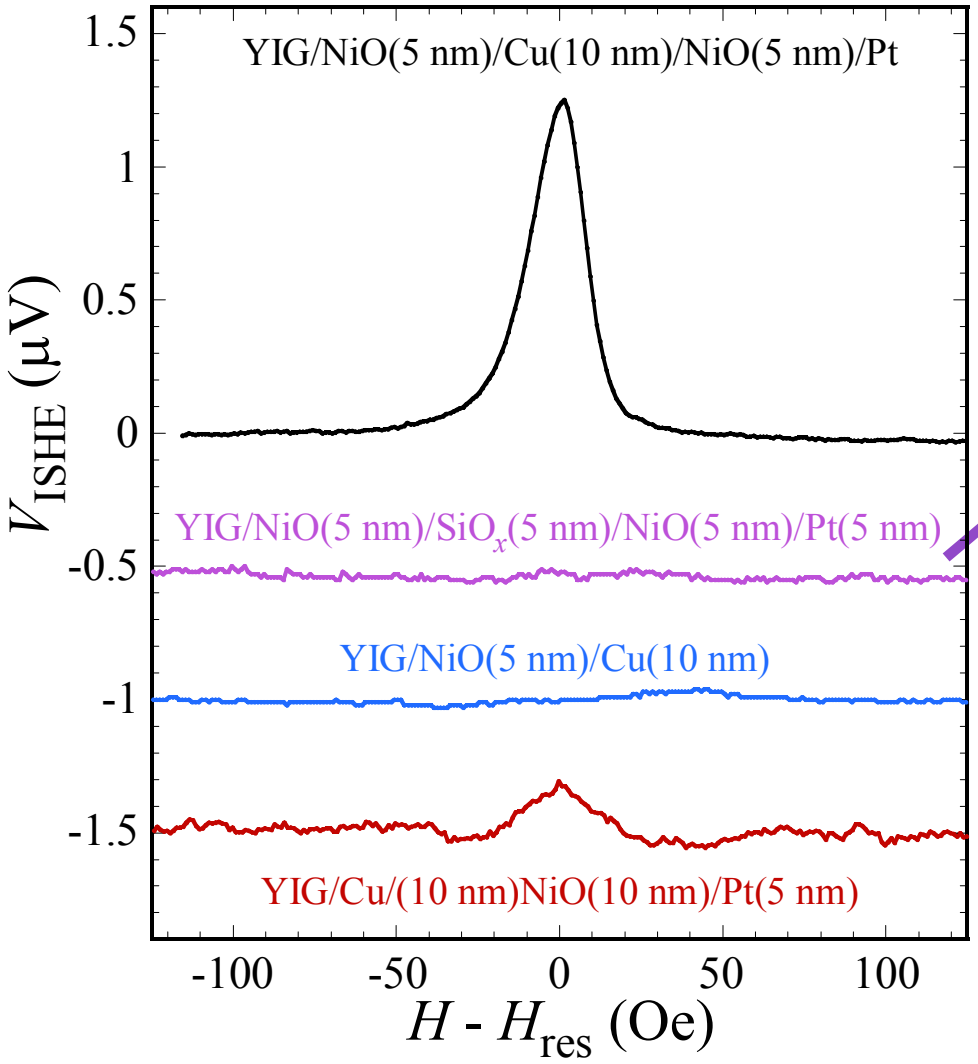




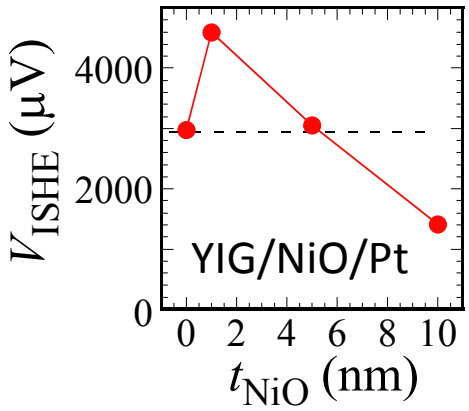
- J_s enhancement
- Spin current detected over 100-nm NiO

Du, *et al*. *PRL* **111**, 247202 (2013).

Spin Current in NiO: Control Experiments

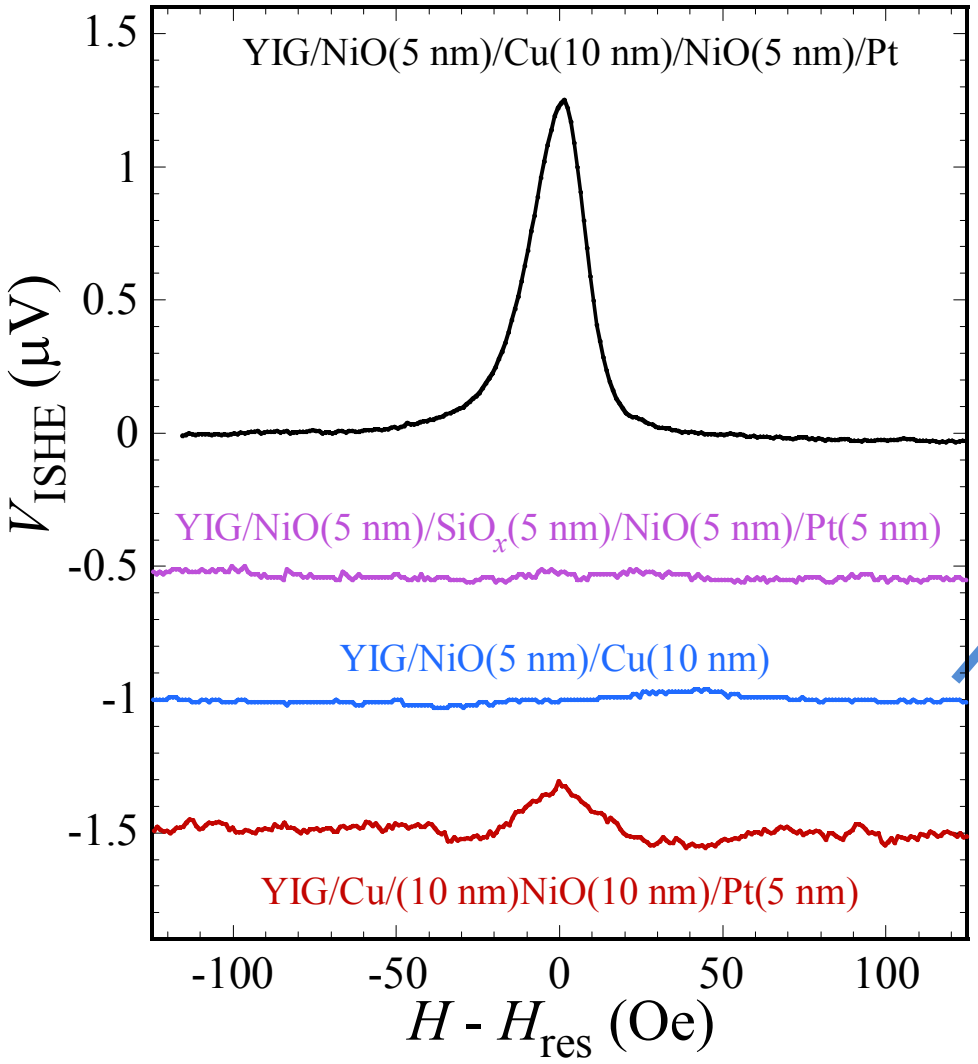


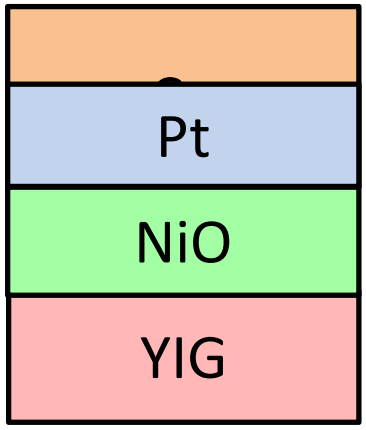


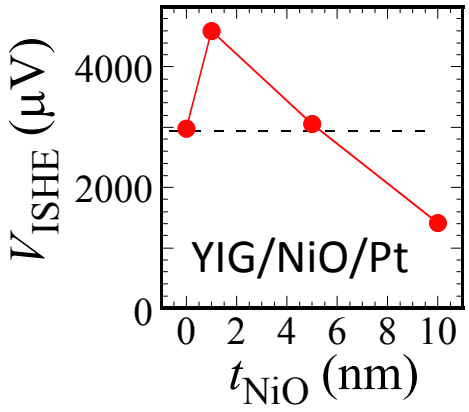


Wang, *et al. PRL* **113**, 097202 (2014)

Spin Current in NiO: Control Experiments

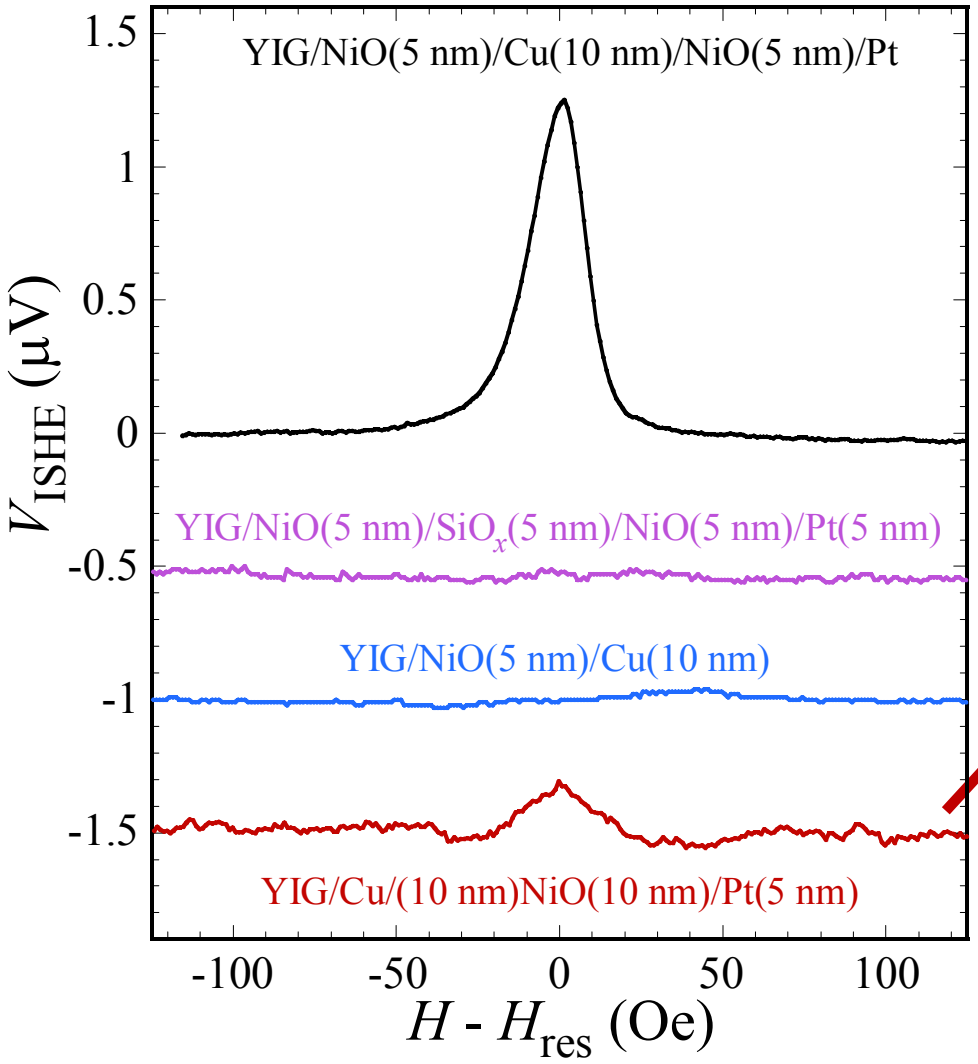


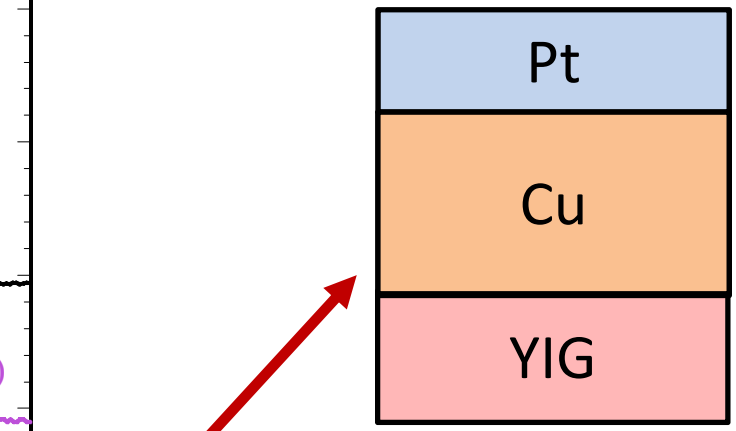


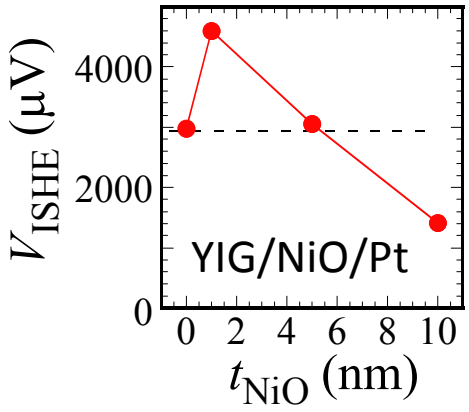


Wang, *et al. PRL* **113**, 097202 (2014)

Spin Current in NiO: Control Experiments

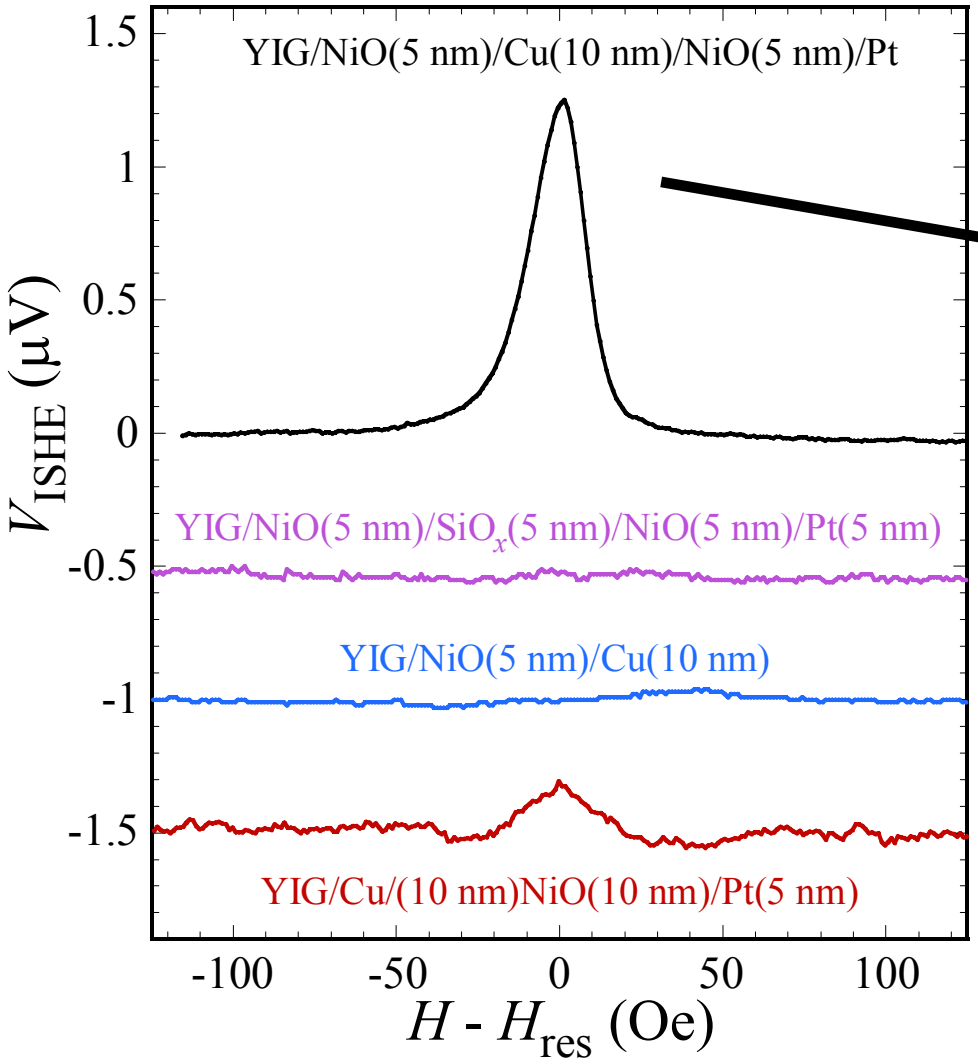


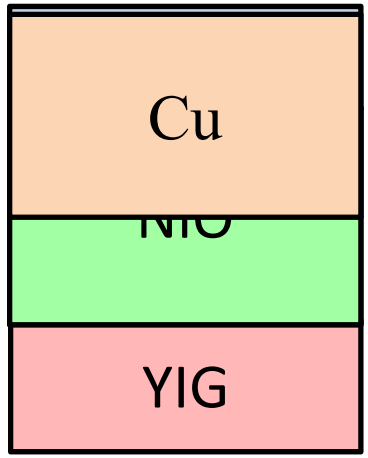


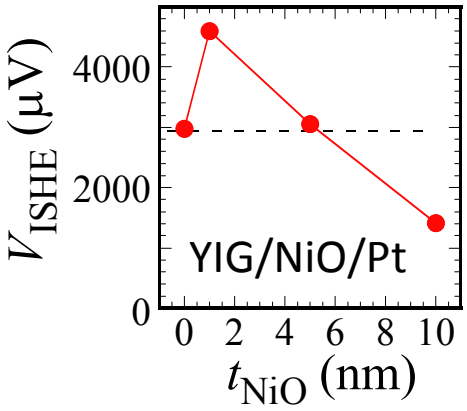


Wang, *et al. PRL* **113**, 097202 (2014)

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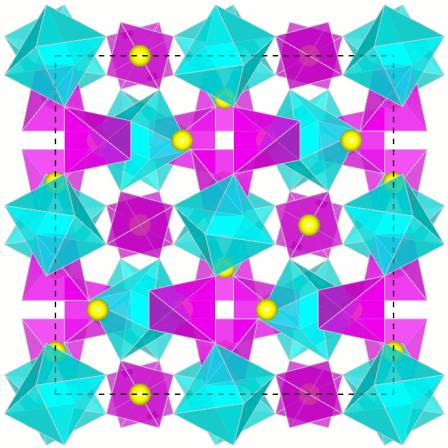


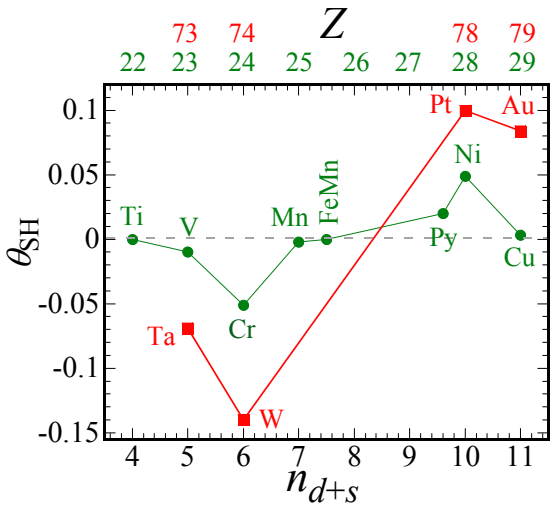


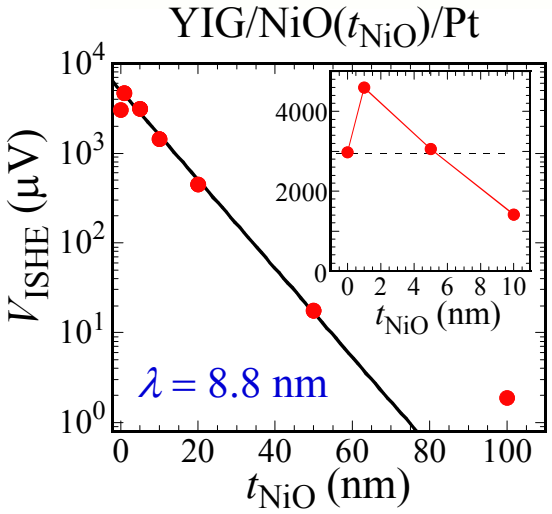
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Summary

- High quality YIG epitaxial films & large spin pumping signals
- Determination of spin Hall angle in 3*d*, 4*d*, 5*d* transition metals
- Robust spin transport in AF insulators







✓ critical role of *d*-orbitals in SOC

✓ Z^4 and *d*-count are additive

✓ Enhancement of spin current

✓ Long spin propagation distance

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