spin Hall angle dispersion induced Hall effect

— Hall detection of spin accumulation in normal metal

Dazhi Hou (侯达之), Z. Qiu, R. Iguchi, K. Sato,
E. K. Vehstedt, K. Uchida, G. E. W. Bauer, E. Saitoh

the outline

- $\partial\theta_{\mathrm{SHE}}/\partial\varepsilon$ —> Hall probe of spin accumulation
- Hall detection of the spin accumulation due to:
  - spin pumping
  - spin Seebeck
- T-dependence of spin transport in AFM

the outline

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  - spin pumping
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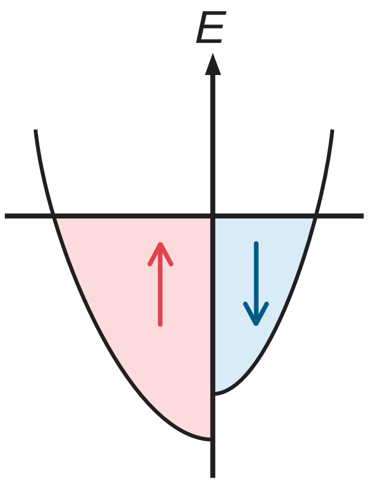
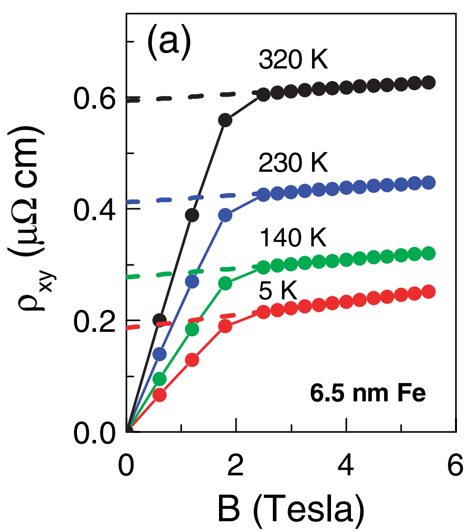
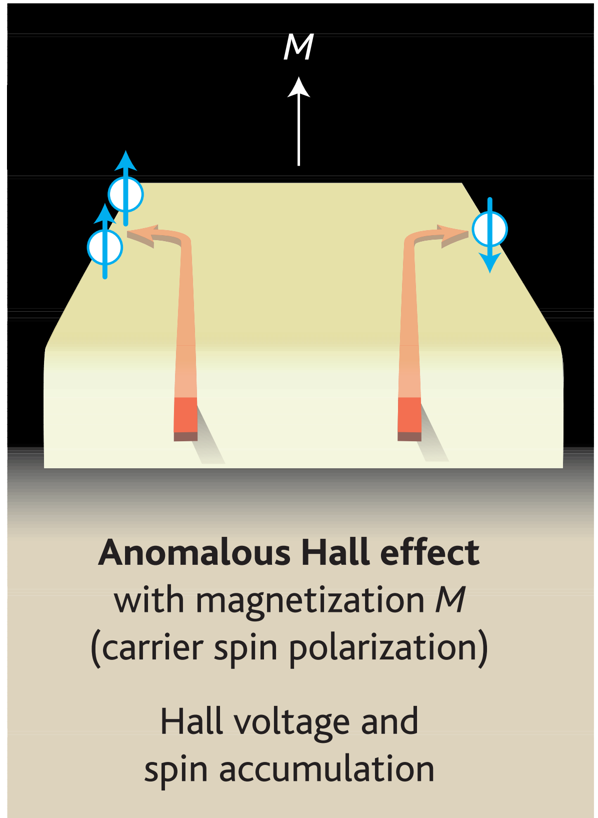
Hall detection of spin polarization in ferromagnets



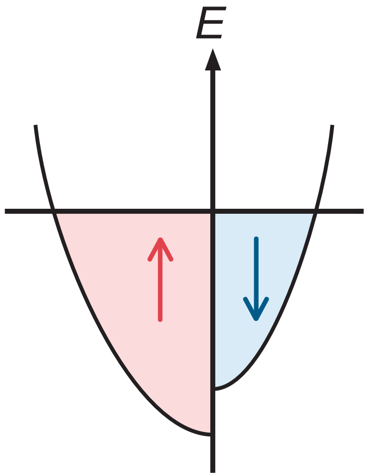


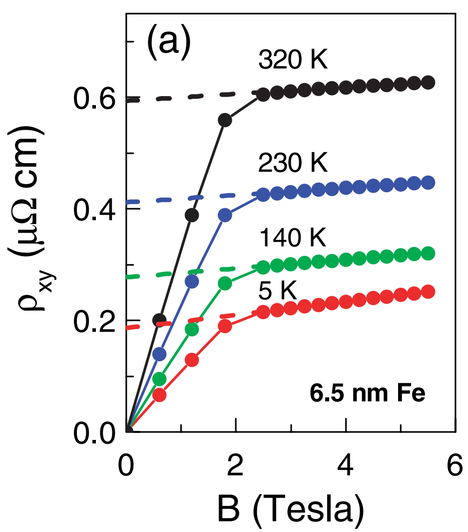


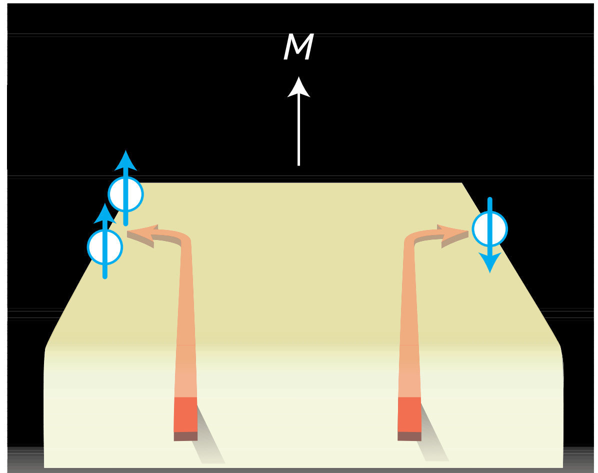
Junichiro Inoue and Hideo Ohno, SCIENCE VOL 309 (2005)

Yuan Tian, Li Ye, and Xiaofeng Jin, PRL 103, 087206 (2009)

Hall detection of spin polarization in ferromagnets

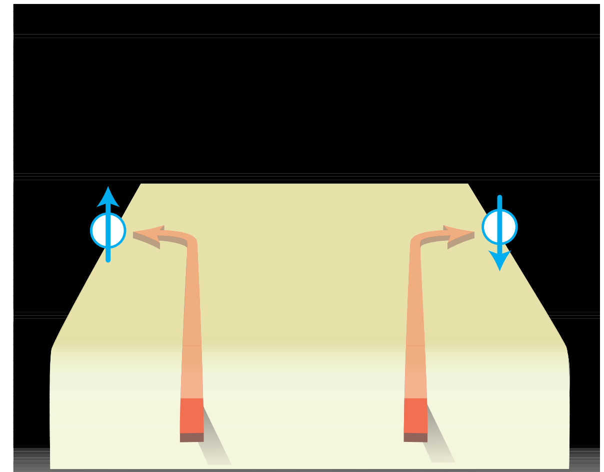






Anomalous Hall effect
with magnetization *M*
(carrier spin polarization)

Hall voltage and
spin accumulation



(Pure) spin Hall effect
no magnetic field necessary

No Hall voltage but
spin accumulation

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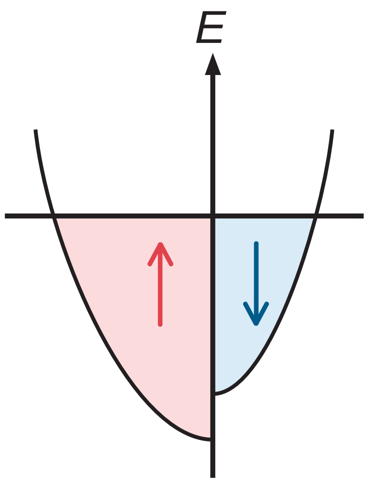
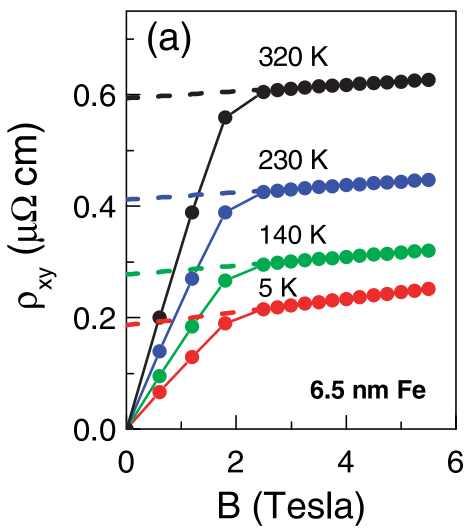
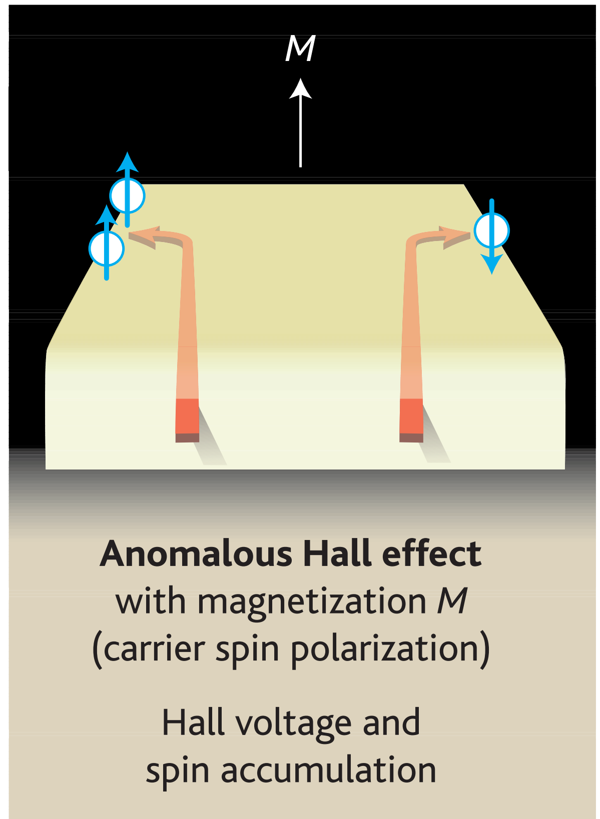
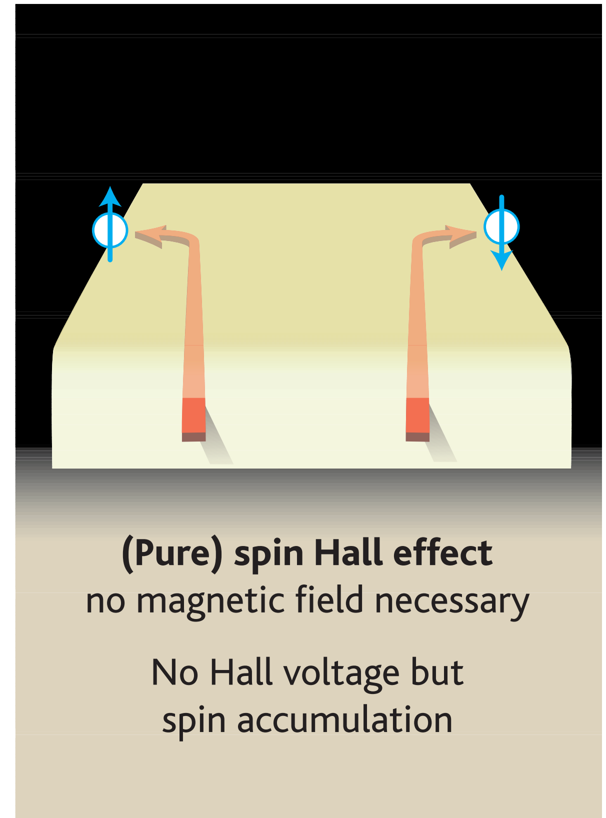
Yuan Tian, Li Ye, and Xiaofeng Jin, PRL 103, 087206 (2009)

Hall detection of spin polarization in ferromagnets









spin Hall angle:

$$\theta_{\mathrm{SHE}} = j_s / j_c$$

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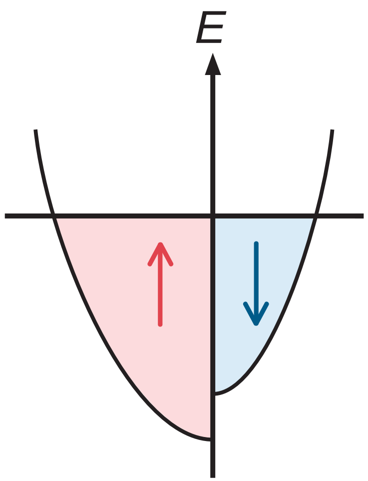

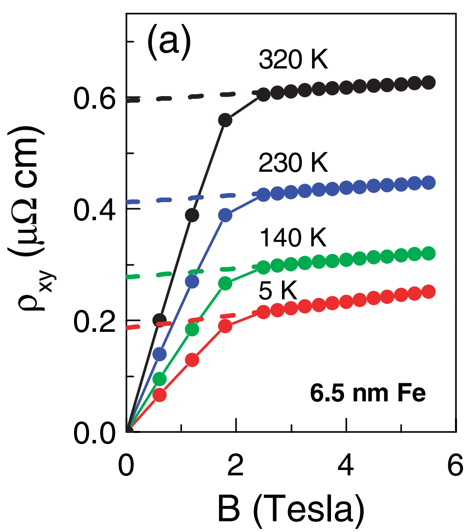

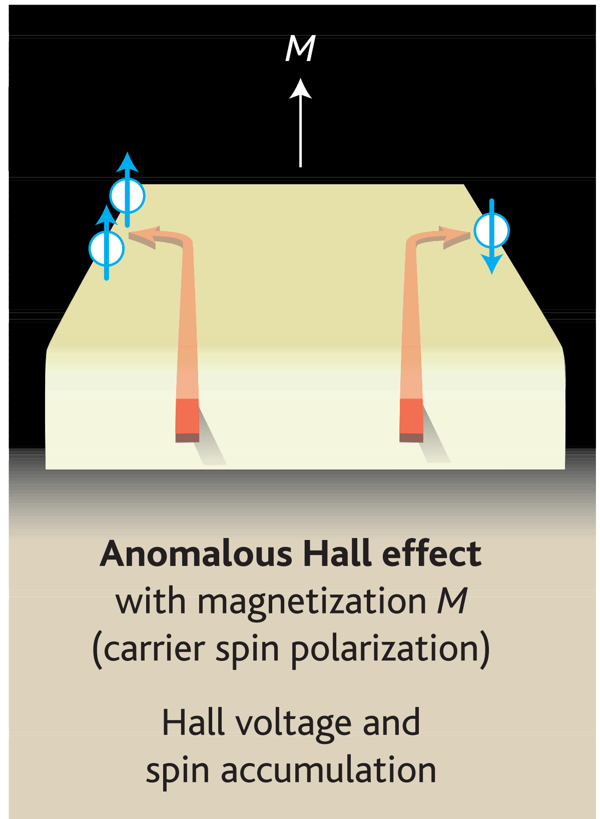

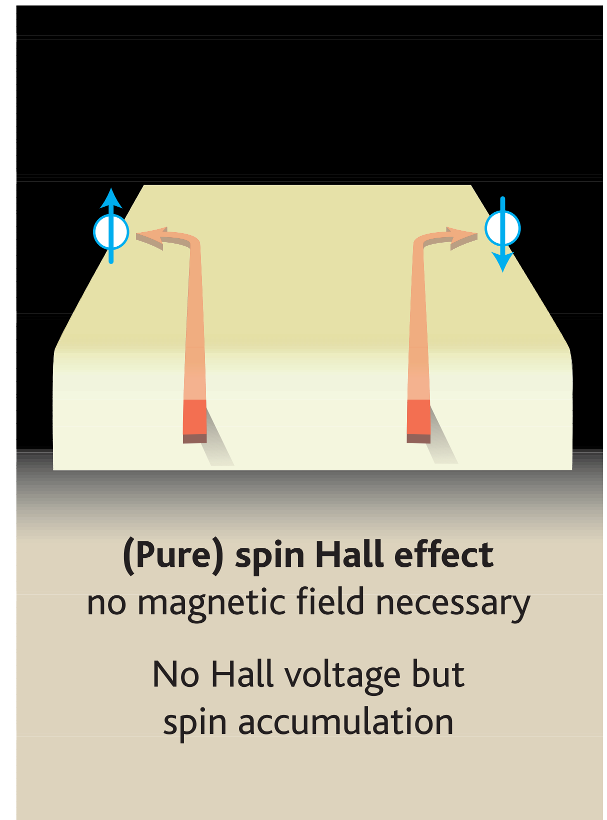

spin Hall angle:

$$j_H = P\theta_{\mathrm{SHE}} j_c$$

$$\theta_{\mathrm{SHE}} = j_s / j_c$$

$$P = \frac{j^{\uparrow} - j^{\downarrow}}{j^{\uparrow} + j^{\downarrow}}$$

Junichiro Inoue and Hideo Ohno, SCIENCE VOL 309 (2005)
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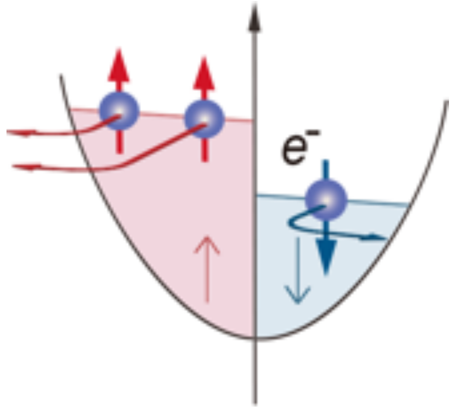
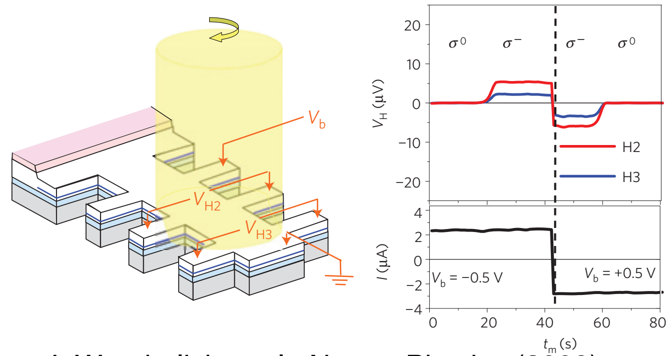
Hall detection of spin polarization in nonmagnetics





J. Wunderlich et al., Nature Physics (2009)

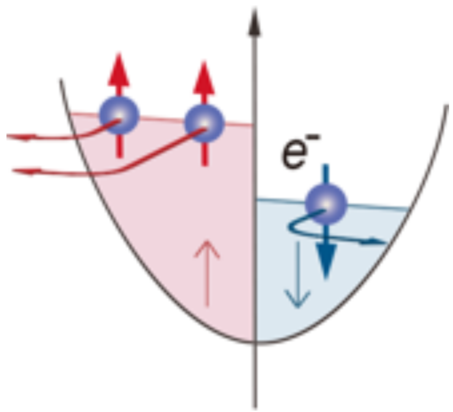
"spin injection Hall effect"

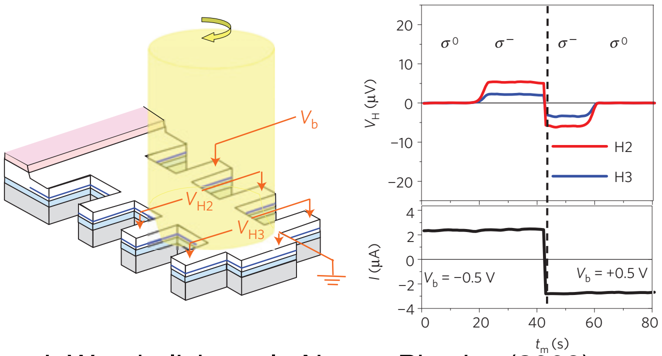
shared formula of Hall current:

$P > 1\%$

$$j_H = P\theta_{\mathrm{SHE}} j_c$$

Hall detection of spin polarization in nonmagnetics





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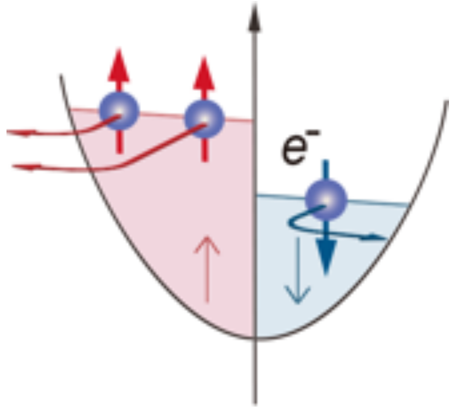
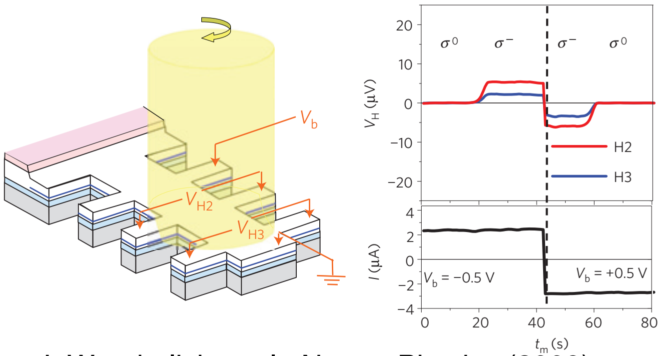
☆ to detect P in metal~ 0.0001%, $\theta_{\mathrm{SHE}} > 1$ needed

Hall detection of spin polarization in nonmagnetics





J. Wunderlich et al., Nature Physics (2009)

"spin injection Hall effect"

shared formula of Hall current:

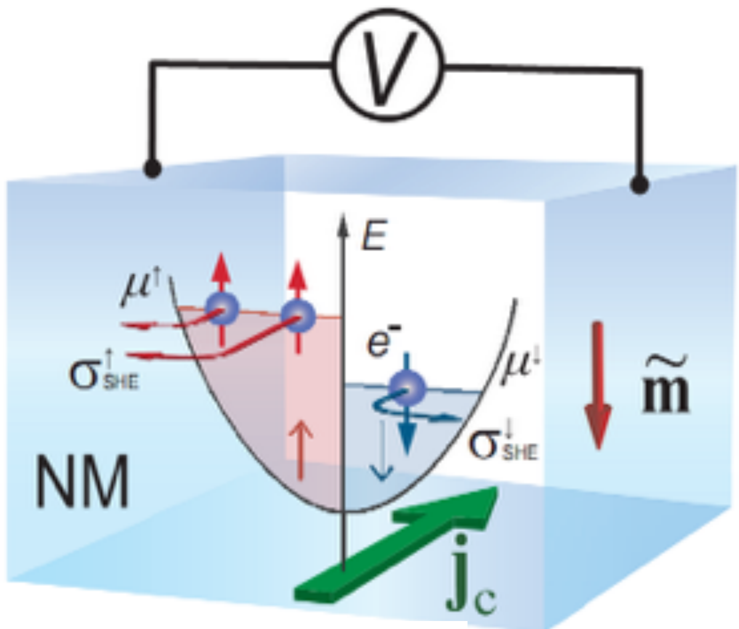
$P > 1\%$

$$j_H = P\theta_{\rm SHE} j_c + \ldots$$

☆ to detect P in metal $\sim 0.0001\%$, $\theta_{\rm SHE} > 1$ needed

☆ sensitivity down to 0.0001% spin polarization in metals

Hall current in metals with spin accumulation



$$\mu_s = \mu^{\uparrow} - \mu^{\downarrow}$$

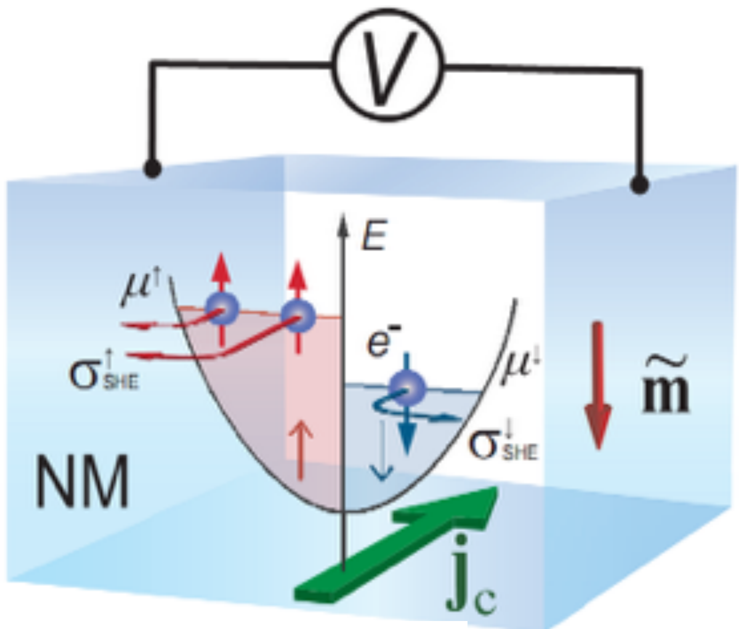
total Hall current:

$$\mathbf{j}_{\mathrm{AHE}} = \mathbf{j}_{\mathrm{H}}^{\uparrow} + \mathbf{j}_{\mathrm{H}}^{\downarrow}$$

Hall current in two sub-bands:

$$\mathbf{j}_{\mathrm{H}}^{\uparrow(\downarrow)} = \sigma_{\mathrm{SHE}}^{\uparrow(\downarrow)} \boldsymbol{\sigma} \times \mathbf{E}$$

Hall current in metals with spin accumulation



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for small μ_s, we have:

$$\sigma_{\mathrm{SHE}}^{\uparrow(\downarrow)} = 1/2[\sigma_{\mathrm{SHE}} \pm (\partial\sigma_{\mathrm{SHE}}/\partial\varepsilon)\mu_s/2]$$

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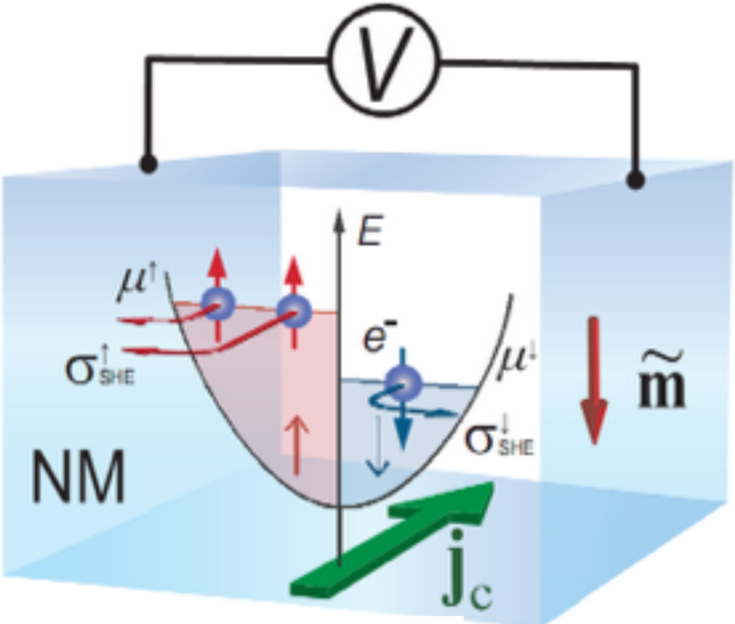

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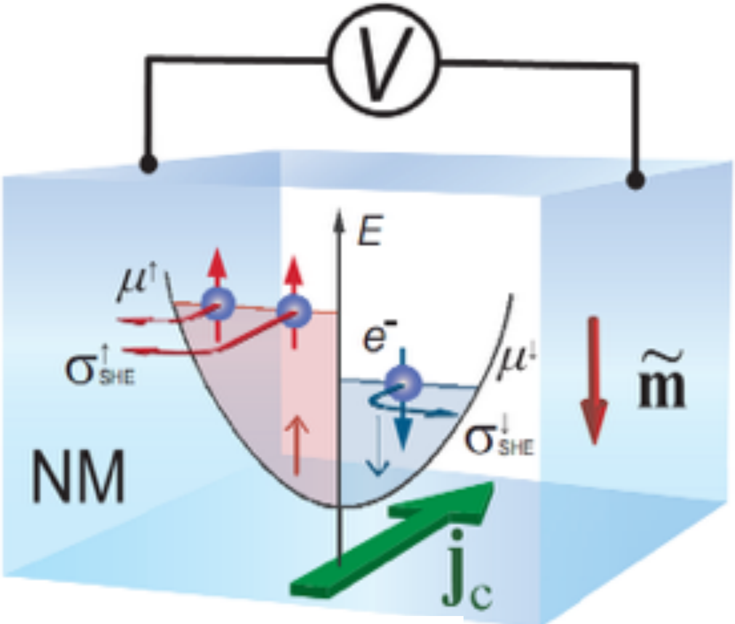
spin accumulation Hall effect (SaHE)

$$\mathbf{j}_{\mathrm{SaHE}} = \frac{\mu_s}{2} \frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} \frac{-\widetilde{\mathbf{m}}}{|\widetilde{\mathbf{m}}|} \times \mathbf{E}$$

Hall current in metals with spin accumulation



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conventional AHE in ferromagnet

$$\mathbf{j}_{\mathrm{AHE}} = \sigma_{\mathrm{AHE}} \frac{-\mathbf{M}}{|\mathbf{M}|} \times \mathbf{E}$$

spin accumulation Hall effect (SaHE)

$$\mathbf{j}_{\mathrm{SaHE}} = \frac{\mu_s}{2} \frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} \frac{-\widetilde{\mathbf{m}}}{|\widetilde{\mathbf{m}}|} \times \mathbf{E}$$

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$$\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} = \frac{\partial \sigma}{\partial \varepsilon} \theta_{\mathrm{SHE}} + \frac{\partial \theta_{\mathrm{SHE}}}{\partial \varepsilon} \sigma$$

Hall current in metals with spin accumulation

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$$P = \frac{\mu_s}{2} \frac{\partial \sigma / \partial \varepsilon}{\sigma}$$

Hall current in metals with spin accumulation

$$\mathbf{j}_{\mathrm{SaHE}} = \frac{\mu_s}{2}\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon}\frac{-\widetilde{\mathbf{m}}}{|\widetilde{\mathbf{m}}|} \times \mathbf{E} \qquad \theta_{\mathrm{SHE}} = \sigma_{\mathrm{SHE}}/\sigma$$

$$\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} = \frac{\partial \sigma}{\partial \varepsilon}\theta_{\mathrm{SHE}} + \frac{\partial \theta_{\mathrm{SHE}}}{\partial \varepsilon}\sigma$$

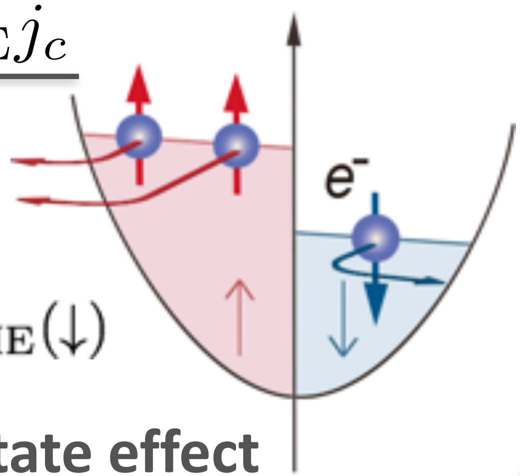
$$P = \frac{\mu_s}{2}\frac{\partial \sigma / \partial \varepsilon}{\sigma}$$

conventional AHE scenario

$$j_H = P\theta_{\mathrm{SHE}} j_c$$

$$\sigma(\uparrow) > \sigma(\downarrow)$$

$$\theta_{\mathrm{SHE}}(\uparrow) = \theta_{\mathrm{SHE}}(\downarrow)$$



equilibrium state effect

Hall current in metals with spin accumulation

$$\mathbf{j}_{\text{SaHE}} = \frac{\mu_s}{2} \frac{\partial \sigma_{\text{SHE}}}{\partial \varepsilon} \frac{-\widetilde{\mathbf{m}}}{|\widetilde{\mathbf{m}}|} \times \mathbf{E} \qquad \theta_{\text{SHE}} = \sigma_{\text{SHE}}/\sigma$$

$$P = \frac{\mu_s}{2} \frac{\partial \sigma / \partial \varepsilon}{\sigma} \qquad \frac{\partial \sigma_{\text{SHE}}}{\partial \varepsilon} = \frac{\partial \sigma}{\partial \varepsilon} \theta_{\text{SHE}} + \frac{\partial \theta_{\text{SHE}}}{\partial \varepsilon} \sigma$$

conventional AHE scenario

$$j_H = P \theta_{\text{SHE}} j_c$$

$\sigma(\uparrow) > \sigma(\downarrow)$

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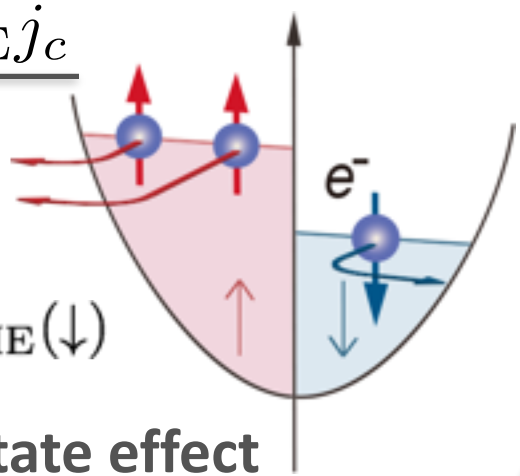


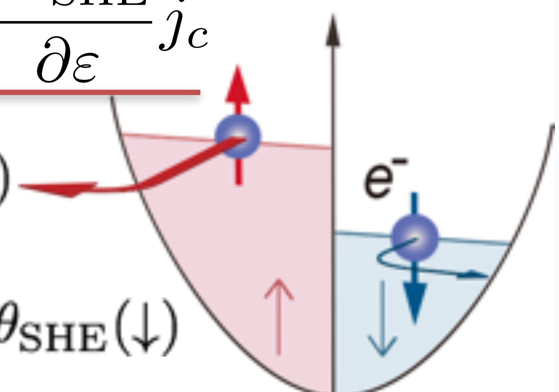
equilibrium state effect

new scenario

$$j_H = \frac{\mu_s}{2} \frac{\partial \theta_{\text{SHE}}}{\partial \varepsilon} j_c$$

$\sigma(\uparrow) = \sigma(\downarrow)$

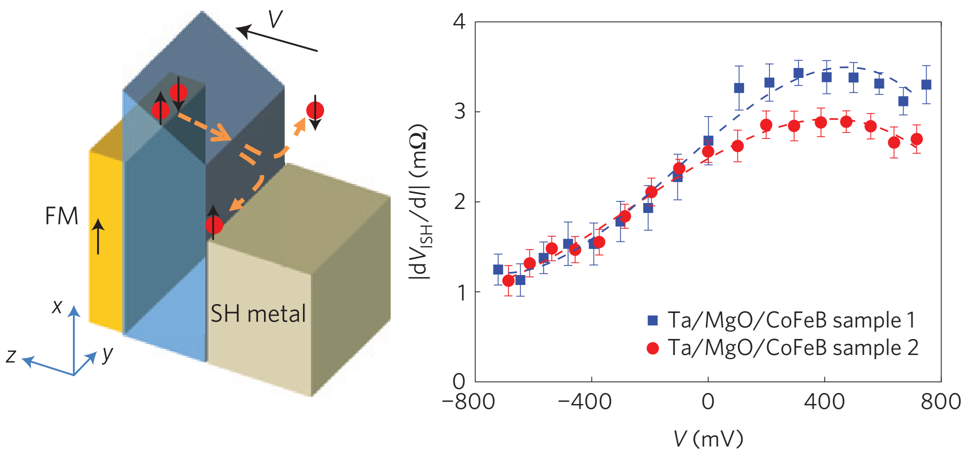
$\theta_{\text{SHE}}(\uparrow) > \theta_{\text{SHE}}(\downarrow)$



only when $\mu^{\uparrow} \neq \mu^{\downarrow}$

Hall contribution from spin Hall angle dispersion

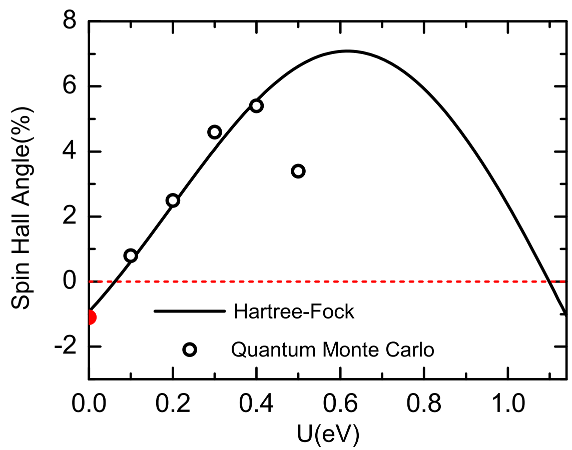
experiment:



Luqiao Liu ,Ching-Tzu Chen & J. Z. Sun, Nature Physics (2014)

$$|\partial\theta_{\mathrm{SHE}}/\partial\varepsilon| > 0.4/\ \mathrm{eV}$$

theoretical calculation:



Zhuo Xu et al., PRL 114, 017202 (2015)

$$|\partial\theta_{\mathrm{SHE}}/\partial\varepsilon| \sim 0.3/\ \mathrm{eV}$$

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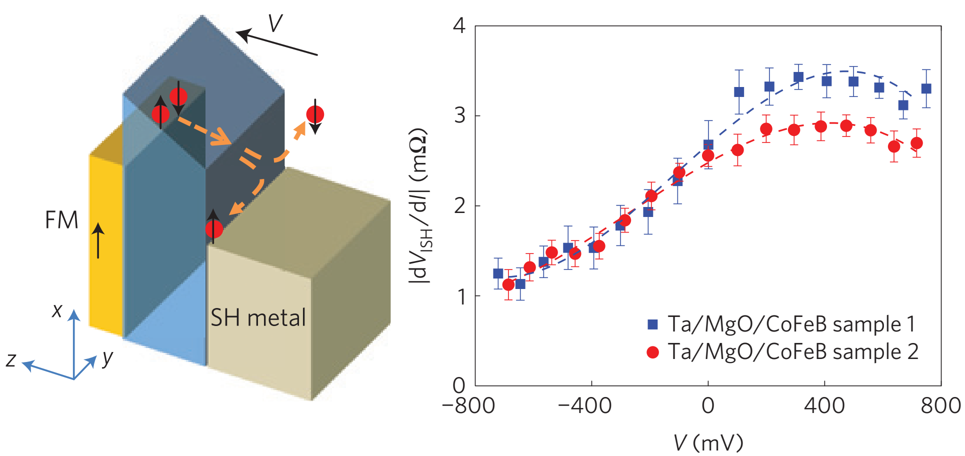

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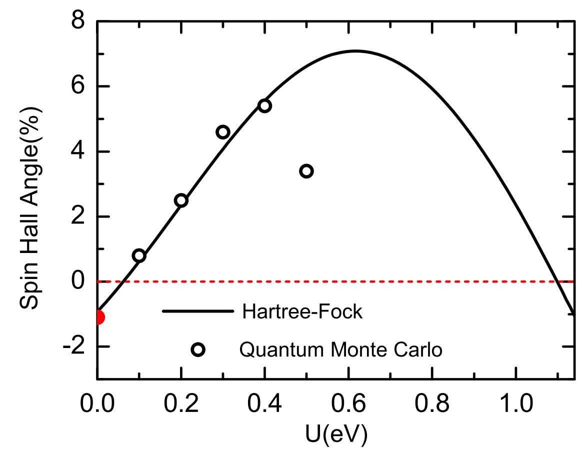


Zhuo Xu et al., PRL 114, 017202 (2015)

$$|\partial\theta_{\mathrm{SHE}}/\partial\varepsilon| \sim 0.3/\ \mathrm{eV}$$

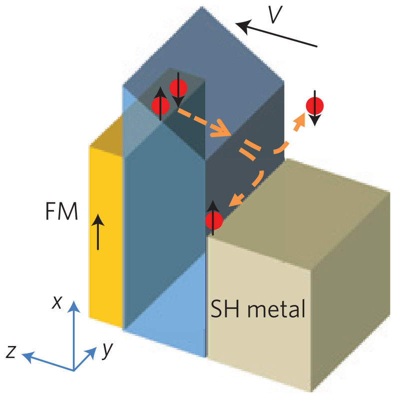
Hall resistance estimation for 20 nm CuIr alloy:

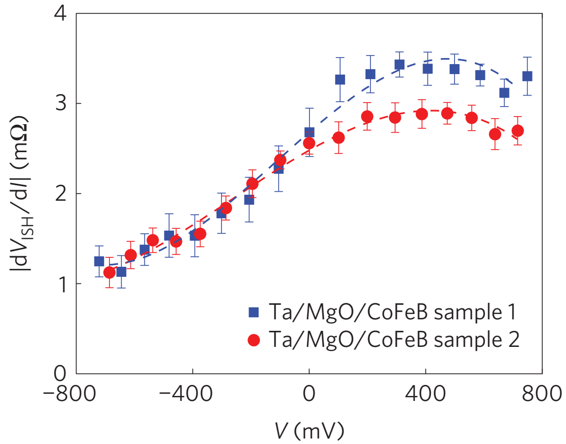
$$P = 0.0001\% = 1ppm$$

$$R_H^{\theta_{\mathrm{SHE}}} \sim 0.3\mu\Omega \ll R_H^{\partial\theta_{\mathrm{SHE}}/\partial\varepsilon} \sim 15\mu\Omega$$

Hall contribution from spin Hall angle dispersion

experiment:





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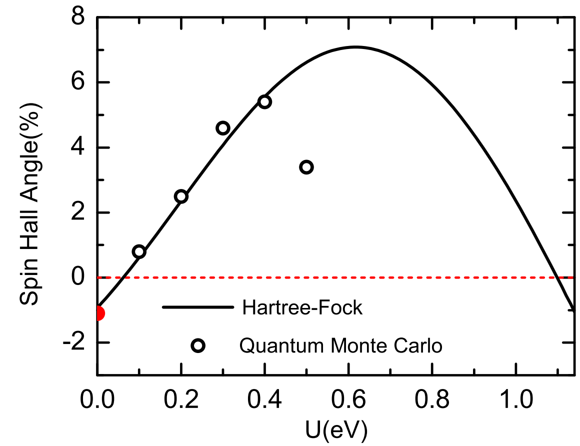

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$$R_H^{\theta_{\mathrm{SHE}}} \sim 0.3\mu\Omega \ll R_H^{\partial\theta_{\mathrm{SHE}}/\partial\varepsilon} \sim 15\mu\Omega$$

Detectable experimentally!

Experiment part

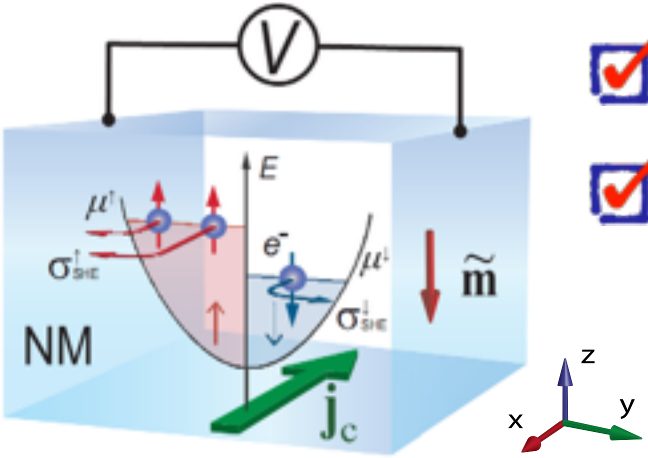
- $\partial\theta_{\mathrm{SHE}}/\partial\varepsilon$ —> Hall probe of spin accumulation

- Hall detection of the spin accumulation by:
  - spin pumping
  - spin Seebeck

- T-response of spin current transport in AFM

Hall measurement setup

$$\mathbf{E}_{\mathrm{SaHE}} \sim \mathbf{j}_c \times \widetilde{\mathbf{m}}$$

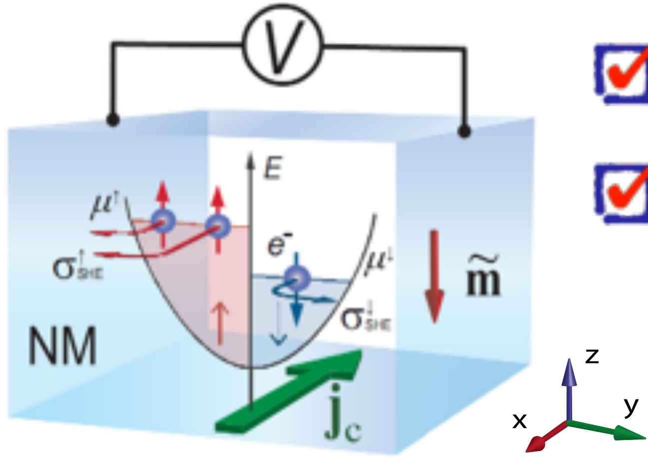


Device design:

- ☑ strong $\partial\theta_{\mathrm{SHE}}/\partial\varepsilon$ material: CuIr
- ☑ out-of-plane spin accumulation

Hall measurement setup

$$\mathbf{E}_{\mathrm{SaHE}} \sim \mathbf{j}_c \times \tilde{\mathbf{m}}$$



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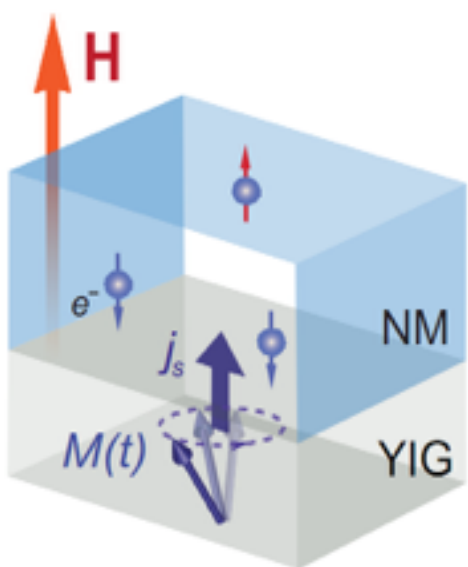

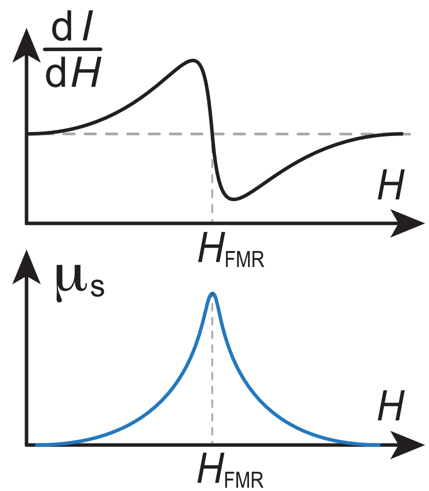

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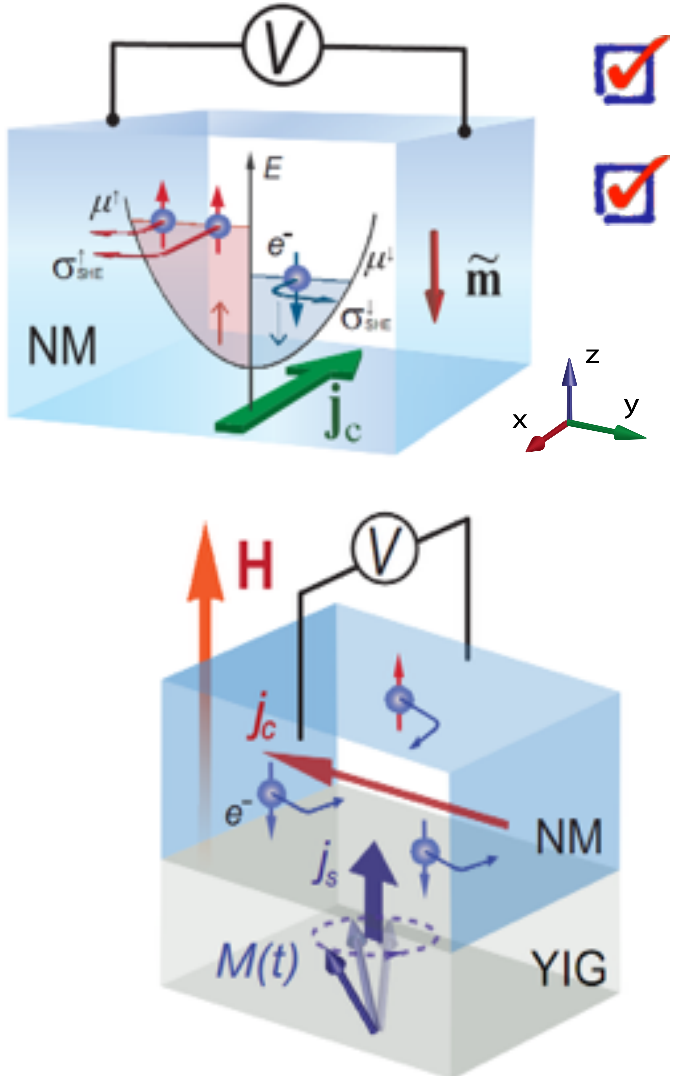
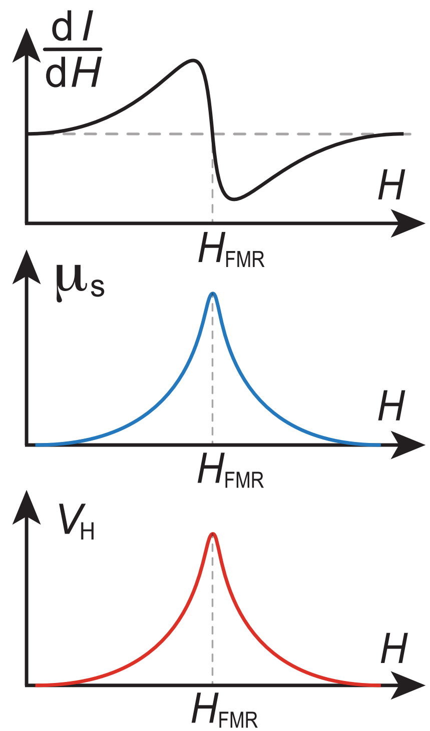
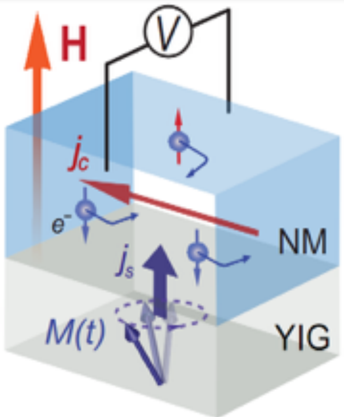




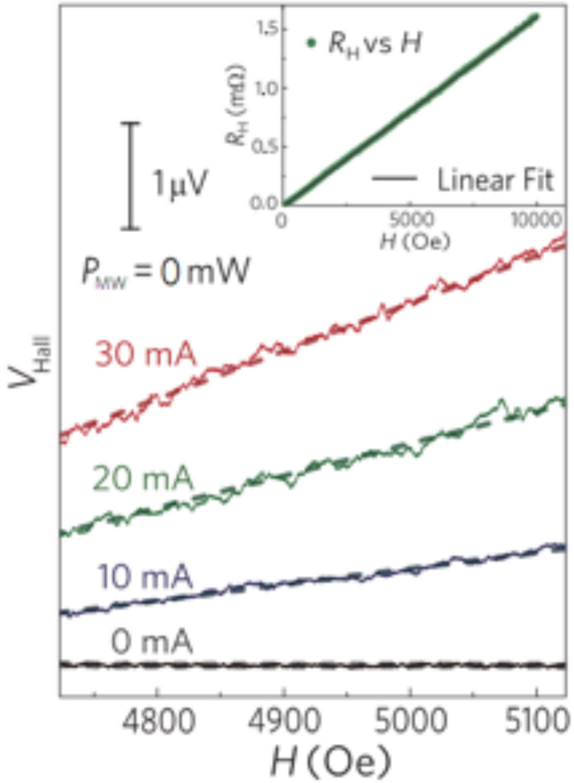
Experiment: Hall signal in $Cu_{95}Ir_5$/YIG

$$\mathbf{E}_{\text{SaHE}} \sim \mathbf{j}_c \times \tilde{\mathbf{m}}$$

CuIr thin film
on 2mm*3mm YIG



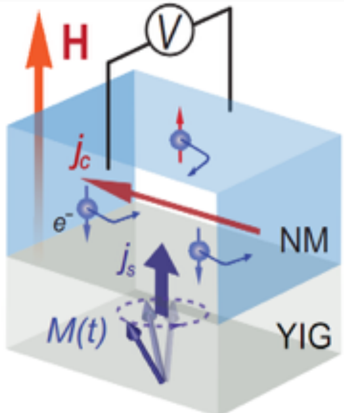
microwave off: only normal Hall



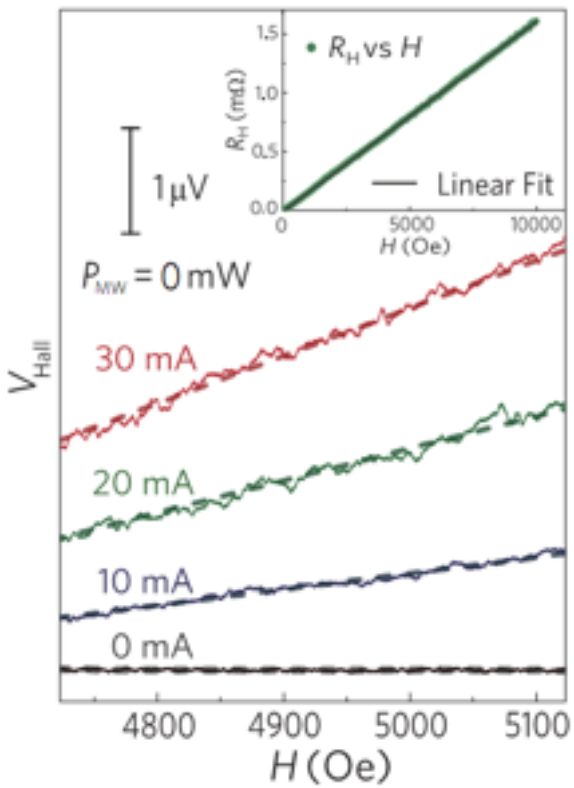
Experiment: Hall signal in $Cu_{95}Ir_5$/YIG

$$\mathbf{E}_{\mathrm{SaHE}} \sim \mathbf{j}_c \times \widetilde{\mathbf{m}}$$

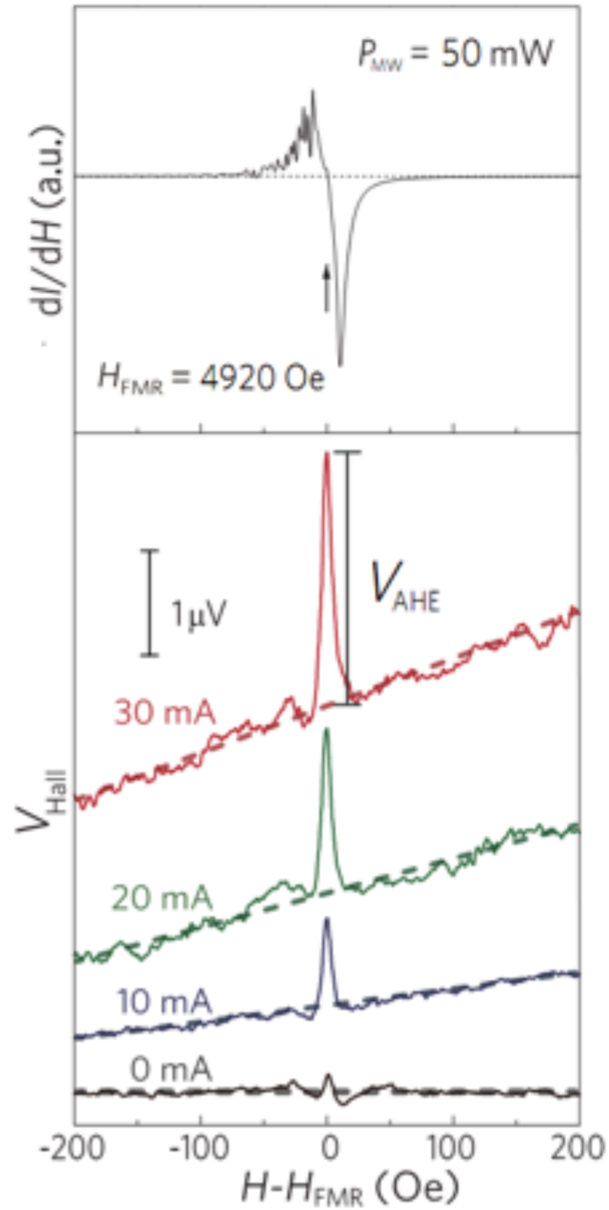
CuIr thin film
on 2mm*3mm YIG



microwave off: only normal Hall



microwave on: additional signal at FMR



$\mathbf{j}_c$ and $\widetilde{\mathbf{m}}$ symmetry of the Hall signal

$$\mathbf{E}_{\mathrm{SaHE}} \sim \mathbf{j}_c \times \widetilde{\mathbf{m}}$$

$\mathbf{j}_c$ and $\widetilde{\mathrm{m}}$ symmetry of the Hall signal

$$\mathbf{E}_{\mathrm{SaHE}} \sim \mathbf{j}_c \times \widetilde{\mathbf{m}}$$

$$\mathbf{E}_{\mathrm{SaHE}}(\mathbf{j}_c) = -\mathbf{E}_{\mathrm{SaHE}}(-\mathbf{j}_c) \qquad \mathbf{E}_{\mathrm{SaHE}}(\widetilde{\mathbf{m}}) = -\mathbf{E}_{\mathrm{SaHE}}(-\widetilde{\mathbf{m}})$$

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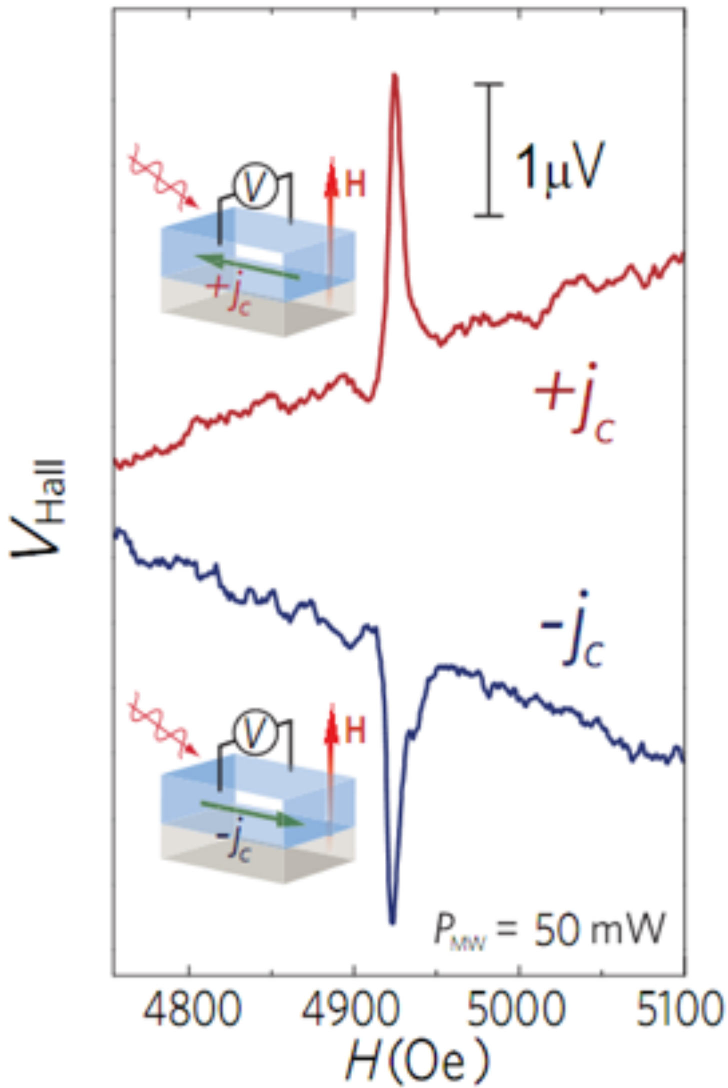

$\mathbf{j}_c$ and $\widetilde{\mathbf{m}}$ symmetry of the Hall signal

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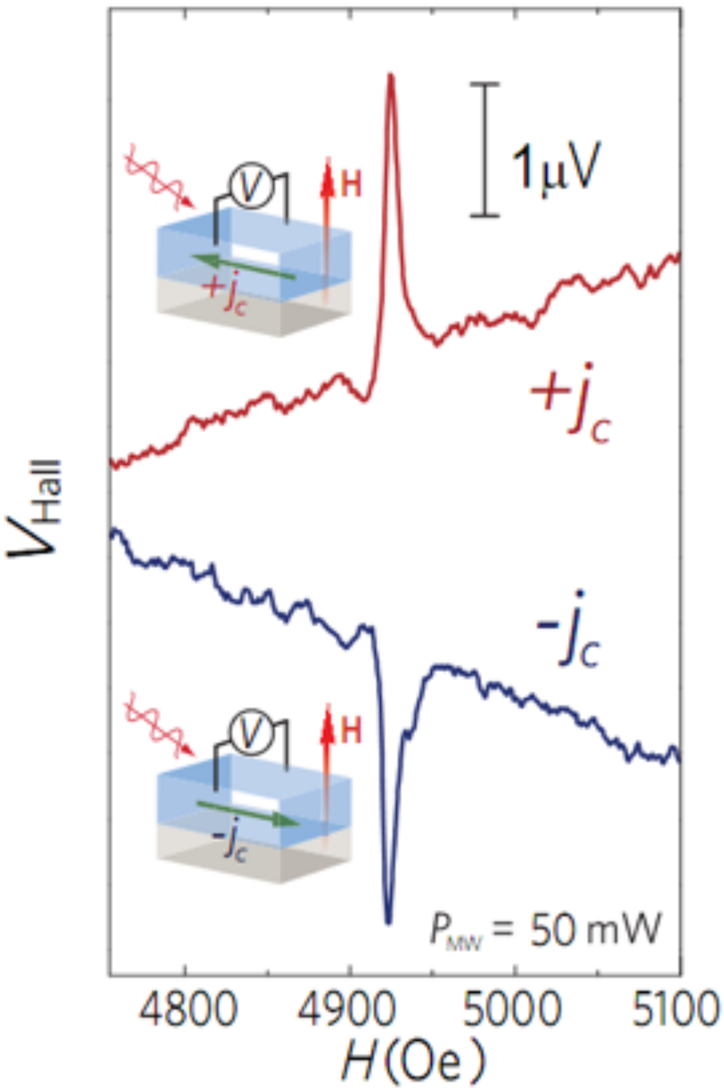
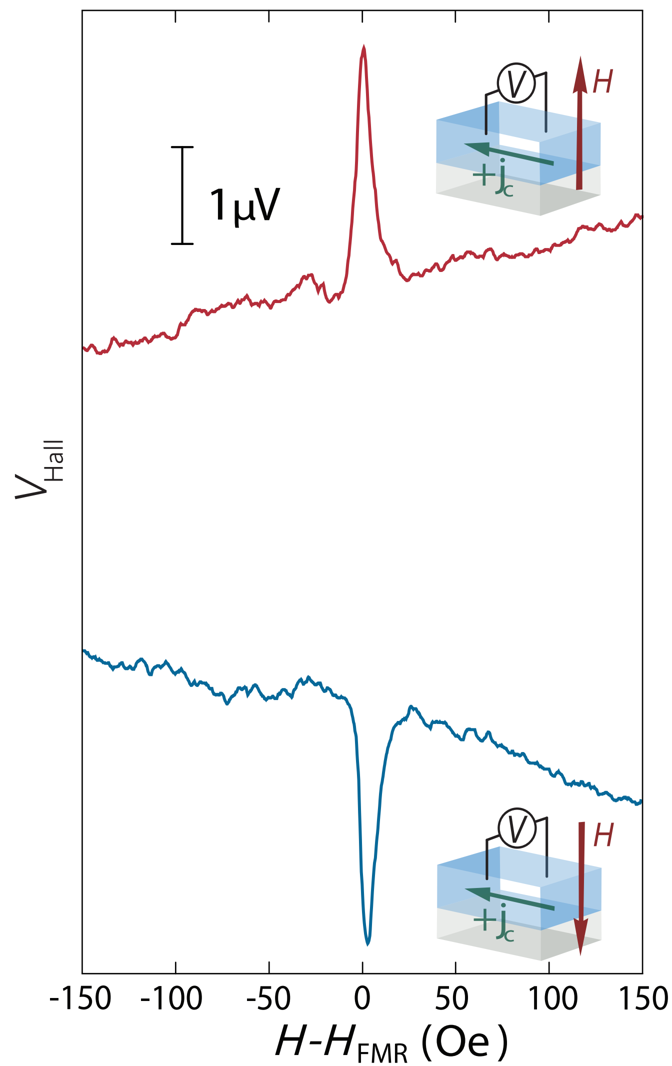


$$\mathbf{E}_{\mathrm{SaHE}}(\widetilde{\mathbf{m}}) = -\mathbf{E}_{\mathrm{SaHE}}(-\widetilde{\mathbf{m}})$$



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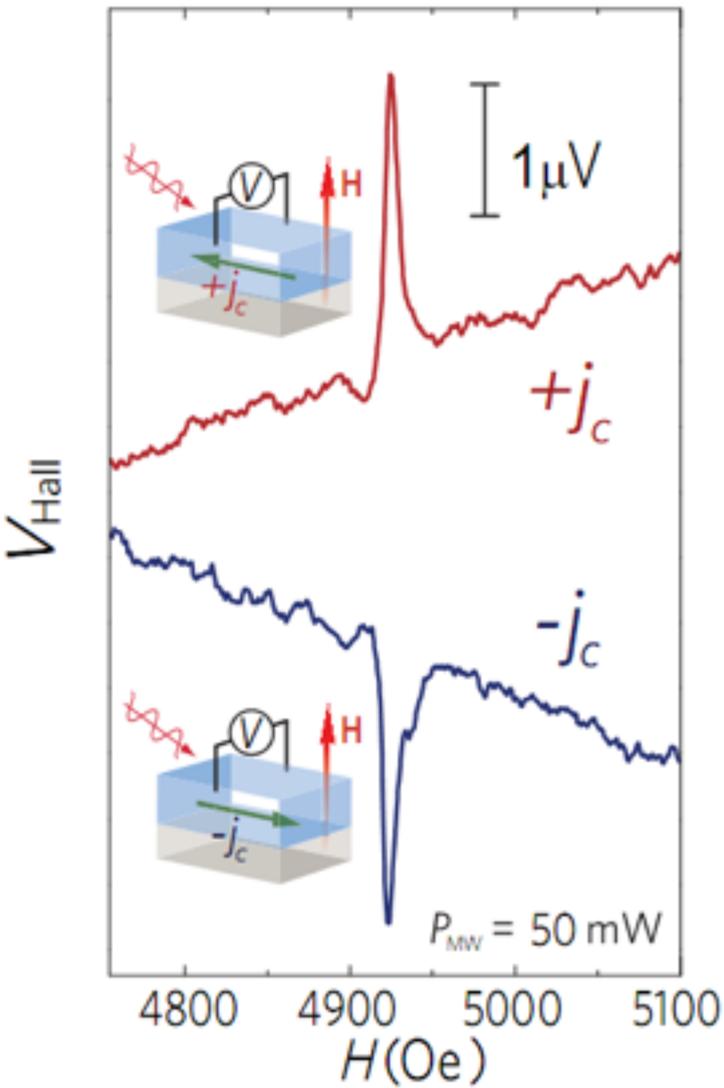

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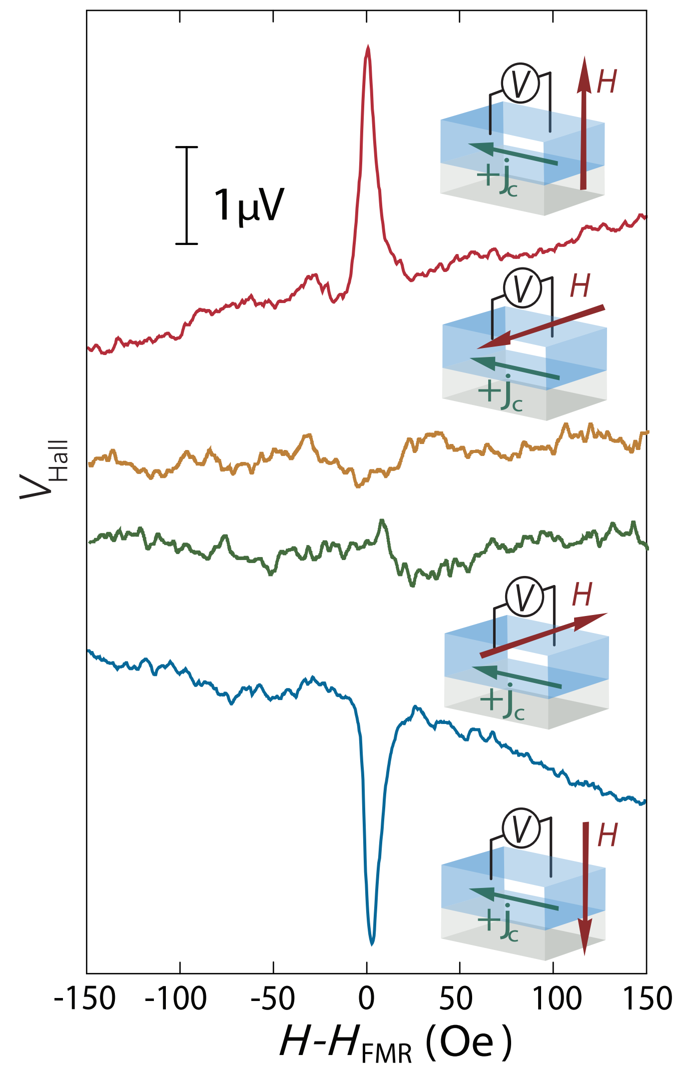
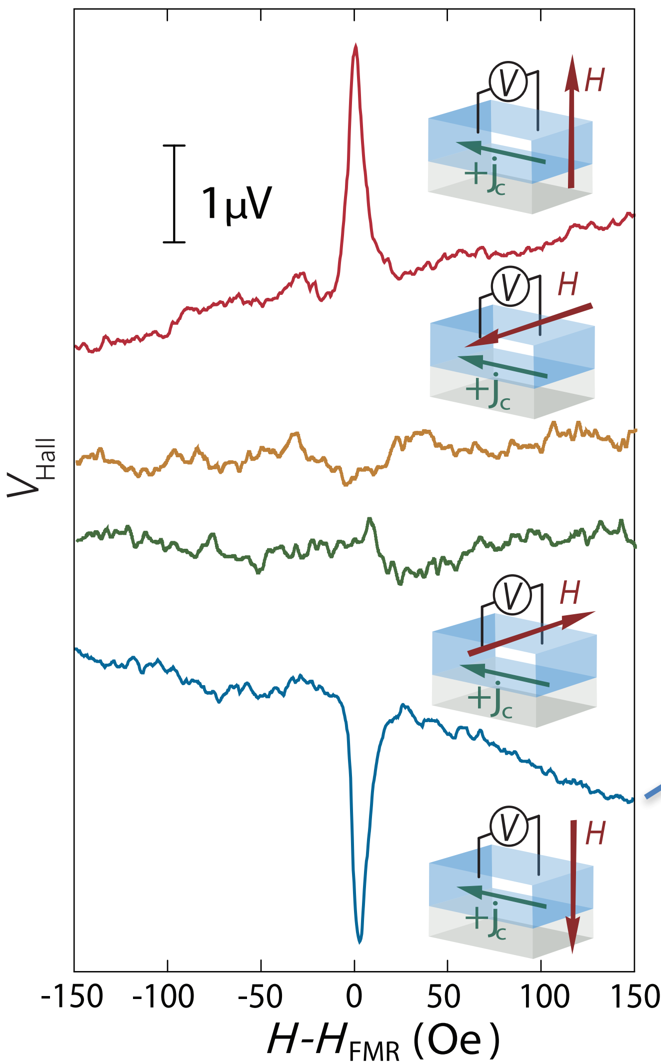
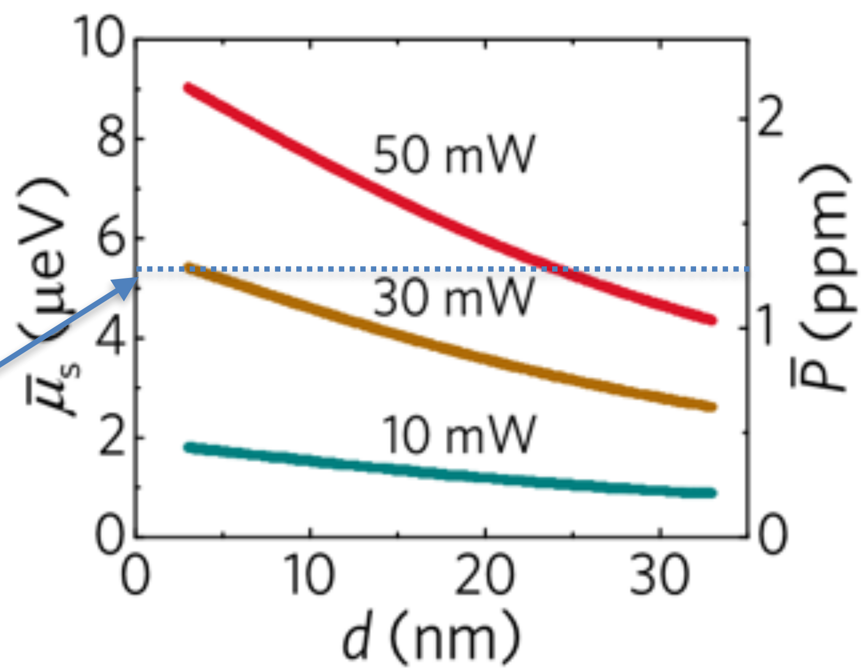


Hall detection of ppm spin polarization



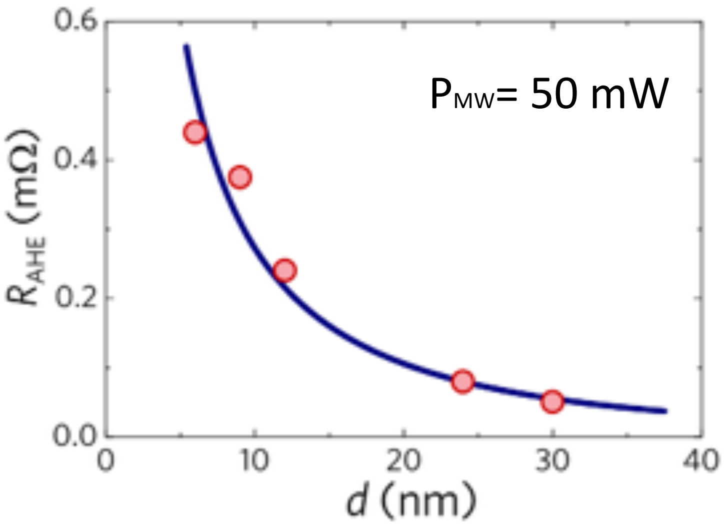
$$\bar{P} = \frac{\partial\sigma/\partial\varepsilon}{\sigma}\frac{\bar{\mu}_s}{2}$$



Thickness dependence

Hall resistance of spin accumulation AHE:

$$R_{\mathrm{AHE}} = \frac{V_{\mathrm{AHE}}}{I} = -\frac{1}{2\sigma^2 d}\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon}\bar{\mu}_{\mathrm{s}} \sin\theta_{\mathrm{M}}$$



fitting result:

$$\partial \sigma_{\mathrm{SHE}}/\partial \varepsilon = -9620\ \Omega^{-1}\mathrm{m}^{-1}/\mathrm{meV}$$

$$\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} = \frac{\partial \sigma}{\partial \varepsilon}\theta_{\mathrm{SHE}} + \frac{\partial \theta_{\mathrm{SHE}}}{\partial \varepsilon}\sigma$$

evaluate the first term:

$$\theta_{\mathrm{SHE}}\partial \sigma/\partial \varepsilon = -35\ \Omega^{-1}\mathrm{m}^{-1}/\mathrm{meV}$$

Dazhi Hou et al., arXiv:1503.00816

Thickness dependence

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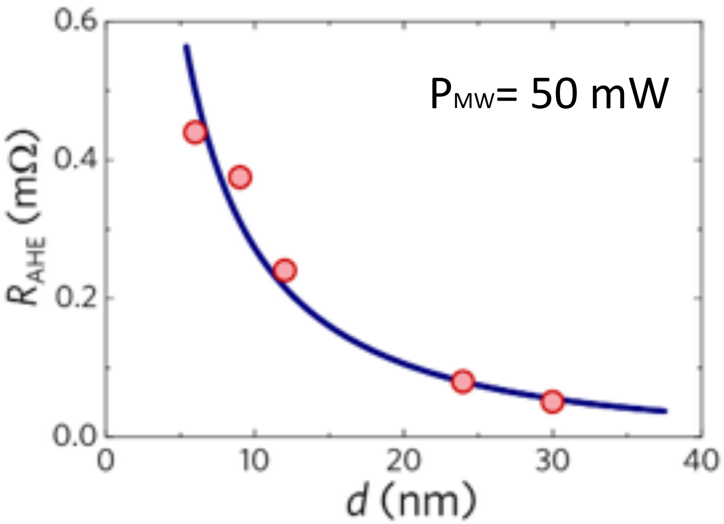

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spin Hall angle energy derivative

$$\partial\theta_{\mathrm{SHE}}/\partial\varepsilon = -2.6\ /\mathrm{eV}.$$

Dominent Contribution in CuIr

Dazhi Hou et al., arXiv:1503.00816

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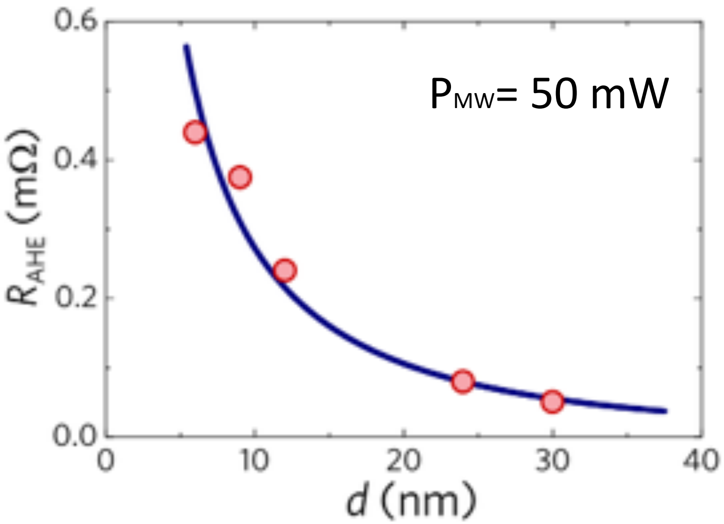

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evaluate the first term:

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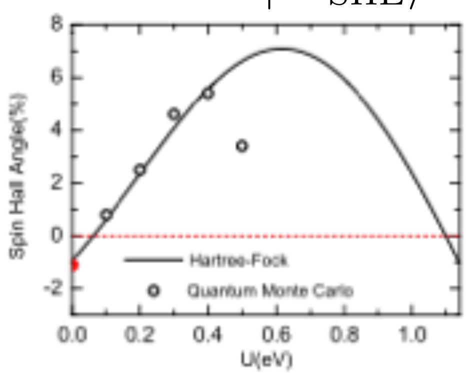
larger than calculation $|\partial\theta_{\rm SHE}/\partial\varepsilon| \sim 0.3/\ {\rm eV}$



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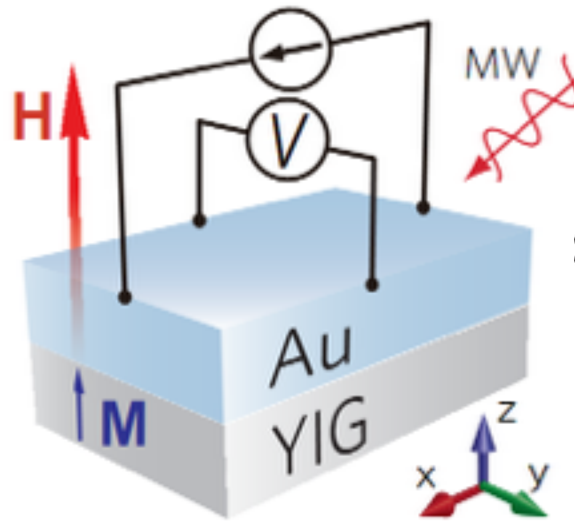
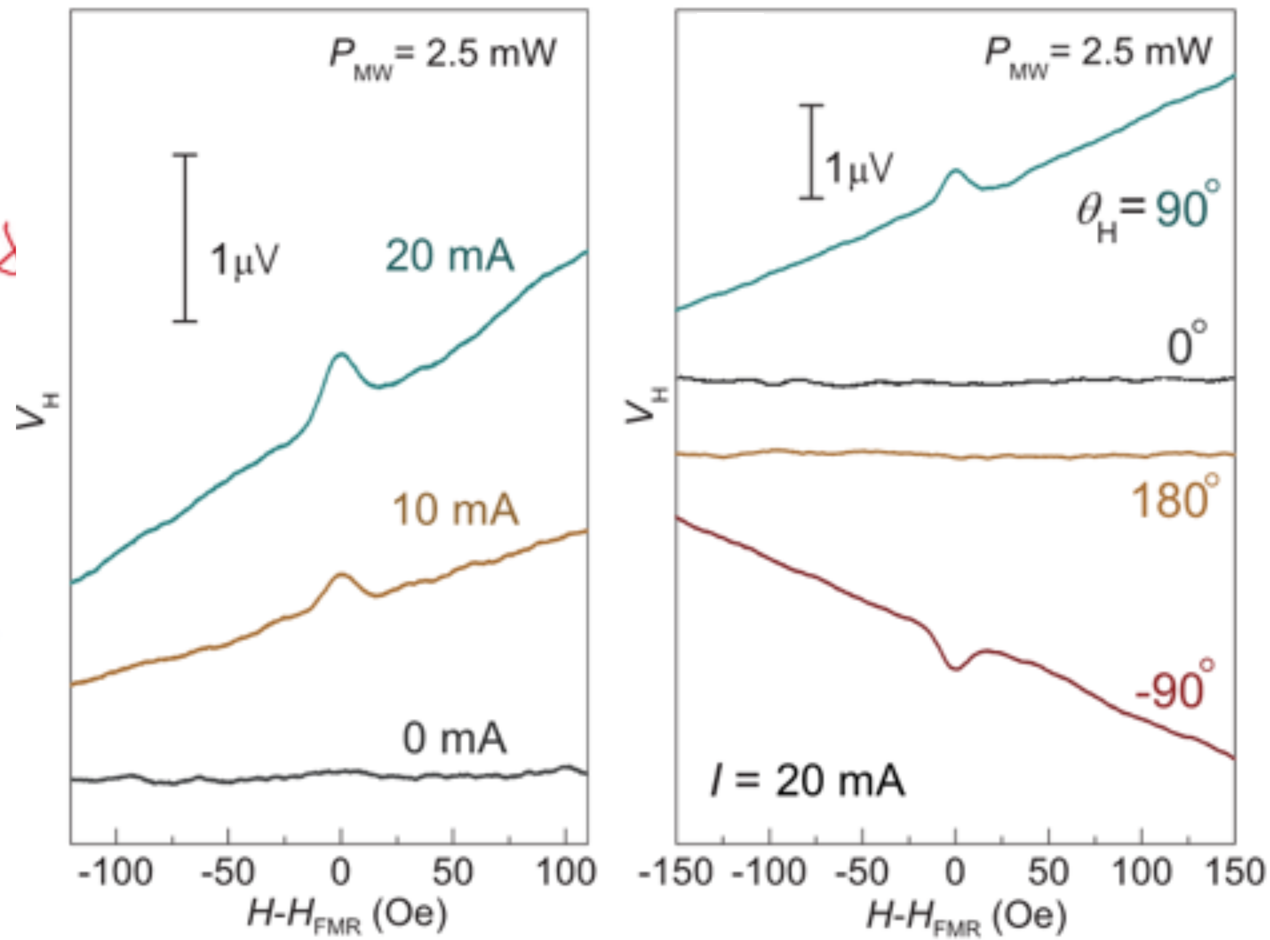
Dominent Contribution in CuIr

Zhuo Xu et al., PRL 114, 017202 (2015)

Dazhi Hou et al., arXiv:1503.00816

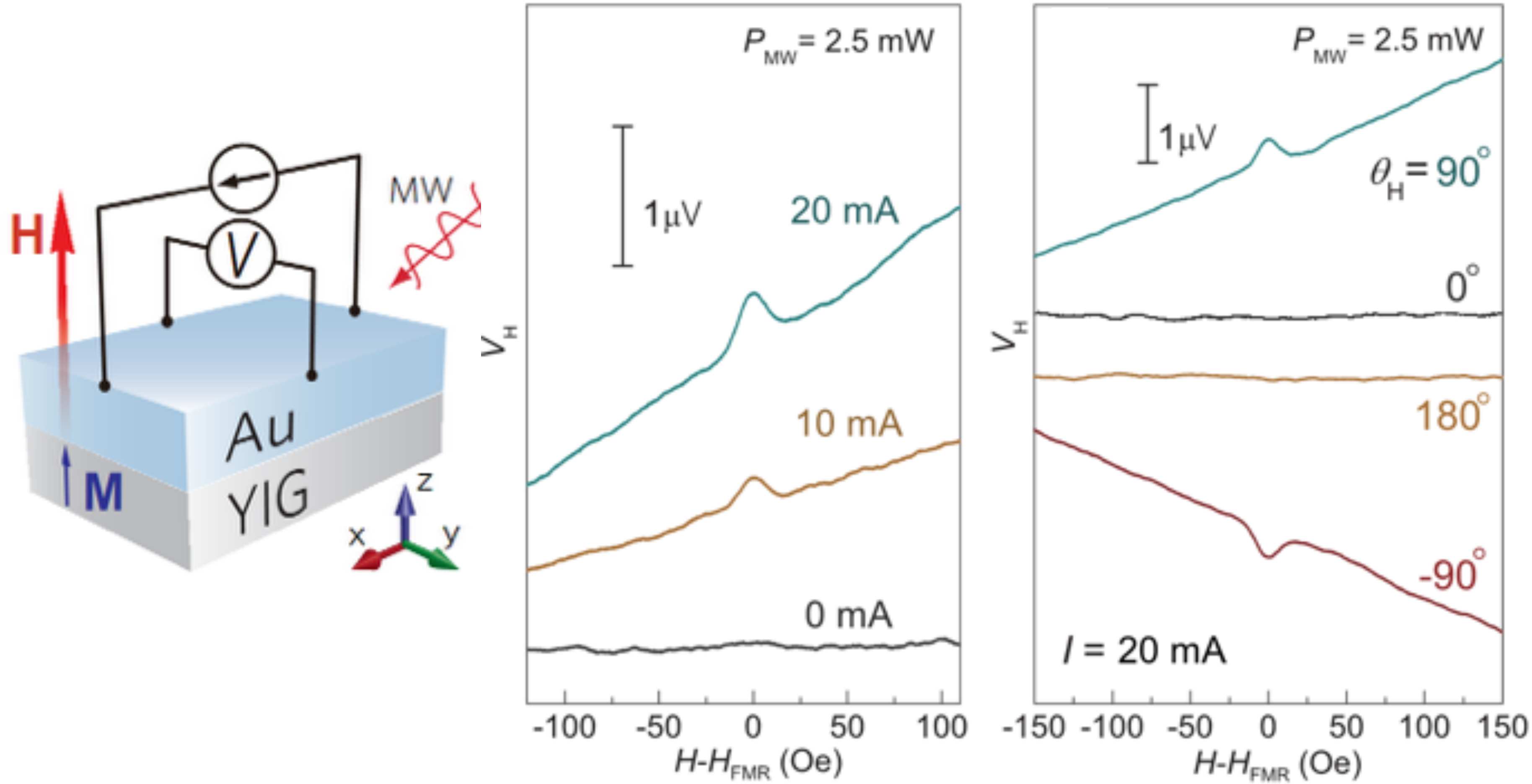
Experiment: Hall signal in Au





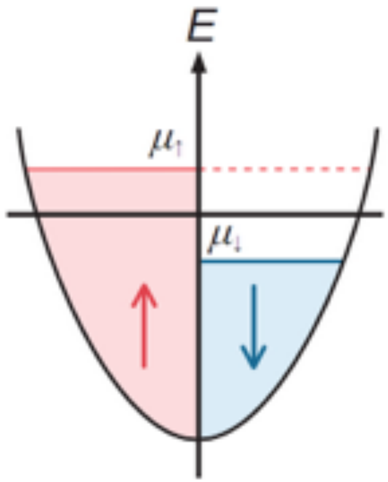
Experiment: Hall signal in Au

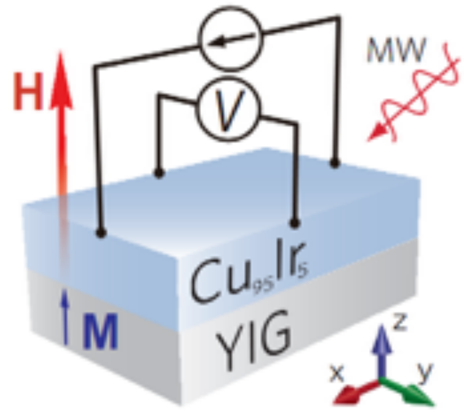
Not only in CuIr!



Summary

- ☑ Hall detection of ppm spin polarization





Summary

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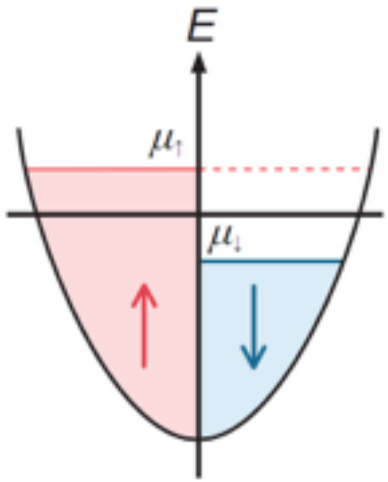

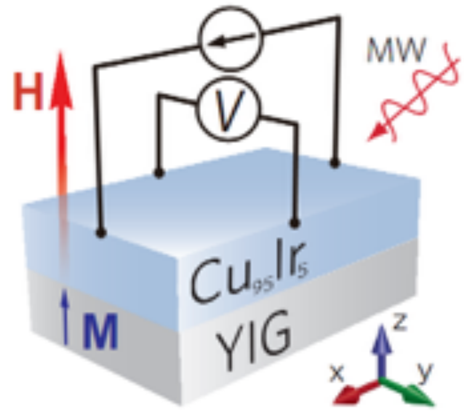

☑ spin accumulation Hall effect is **NOT** anomalous Hall effect

$$\mathbf{j}_{\mathrm{SaHE}} = \frac{\mu_s}{2}\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon}\frac{-\widetilde{\mathbf{m}}}{|\widetilde{\mathbf{m}}|} \times \mathbf{E}$$

$$\frac{\partial \sigma_{\mathrm{SHE}}}{\partial \varepsilon} = \frac{\partial \sigma}{\partial \varepsilon}\theta_{\mathrm{SHE}} + \frac{\partial \theta_{\mathrm{SHE}}}{\partial \varepsilon}\sigma$$

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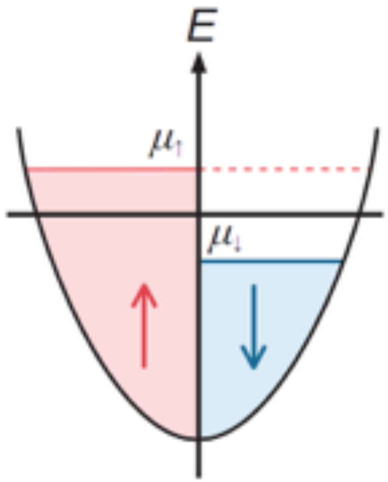

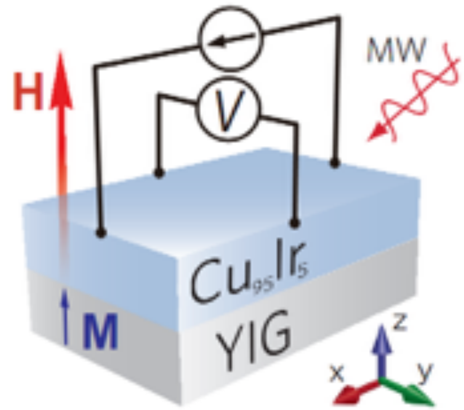

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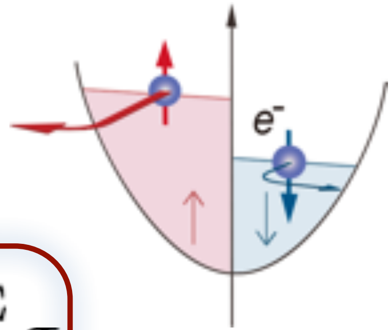


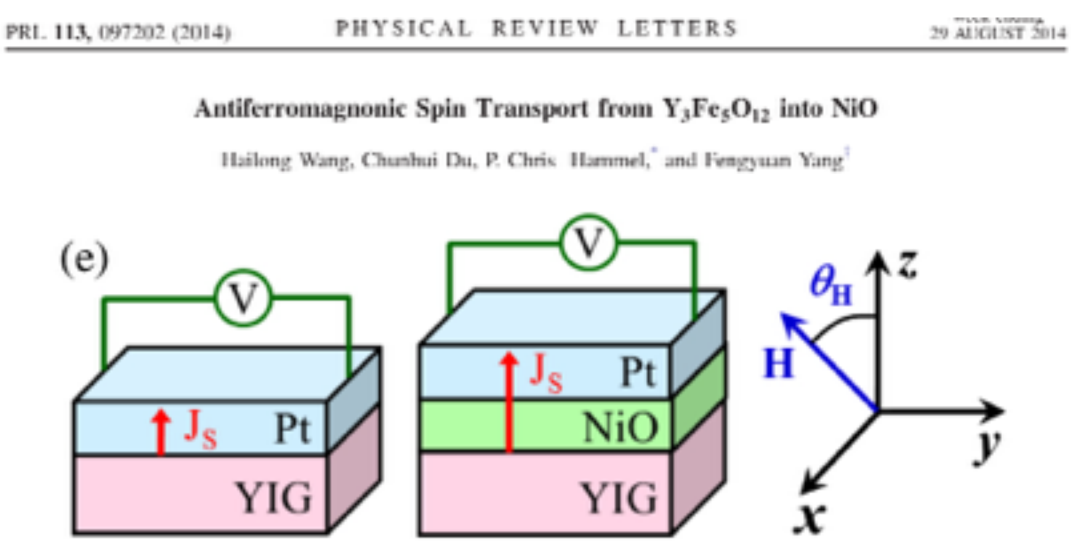
Experiment part

- $\partial\theta_{\mathrm{SHE}}/\partial\varepsilon$ —> Hall probe of spin accumulation

- Hall detection of the spin accumulation by:
  - spin pumping
  - spin Seebeck

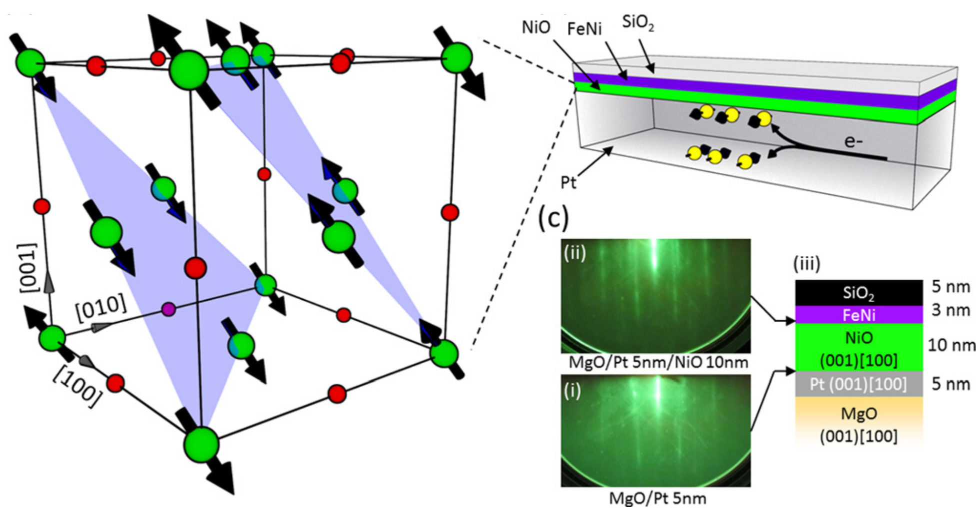
- T-response of spin current transport in AFM

spin current in antiferromagnetic insulator


PRL 113, 097202 (2014) PHYSICAL REVIEW LETTERS 29 AUGUST 2014

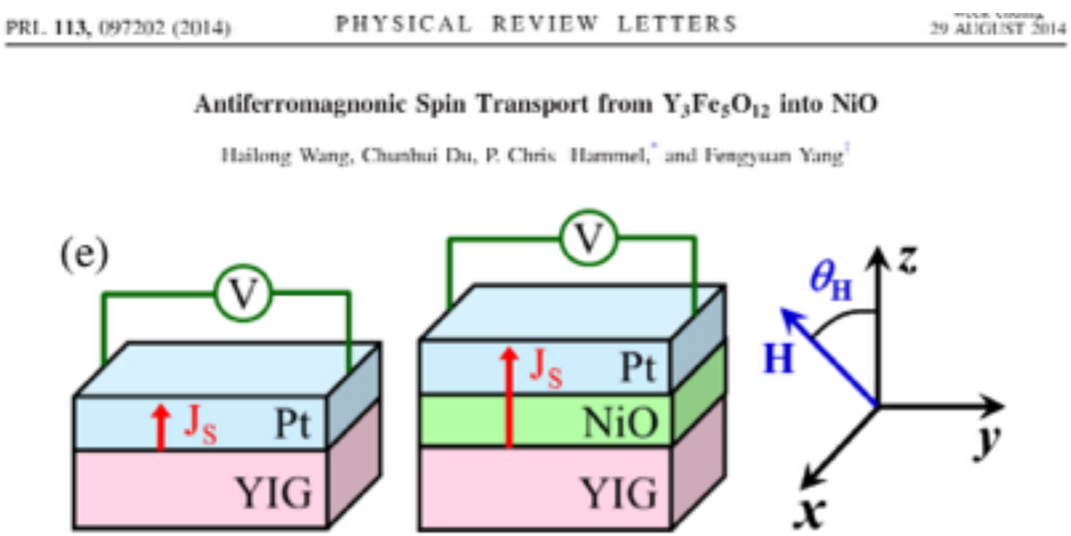
Antiferromagnonic Spin Transport from $Y_3Fe_5O_{12}$ into NiO

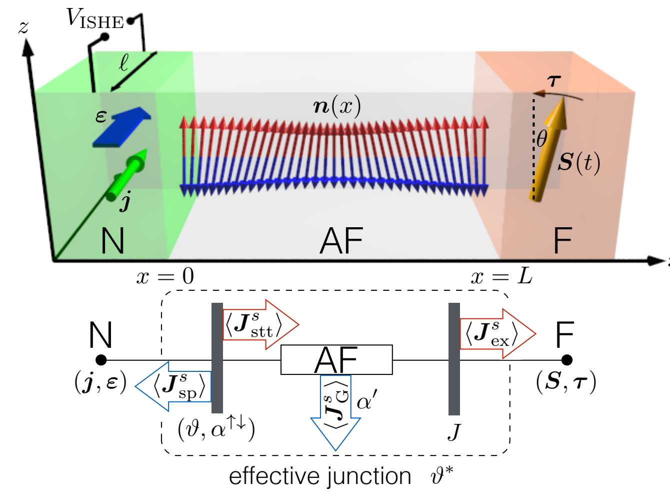
Hailong Wang, Chunhui Du, P. Chris Hammel,* and Fengyuan Yang†



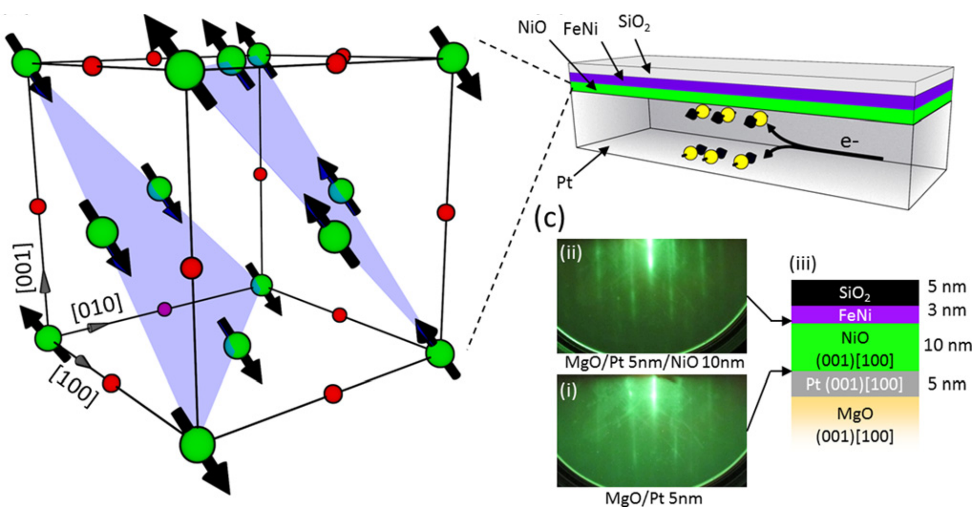
T. Moriyama et al., Appl. Phys. Lett. 106, 162406 (2015)

spin current in antiferromagnetic insulator





S. Takei et al., arXiv:1502.04128

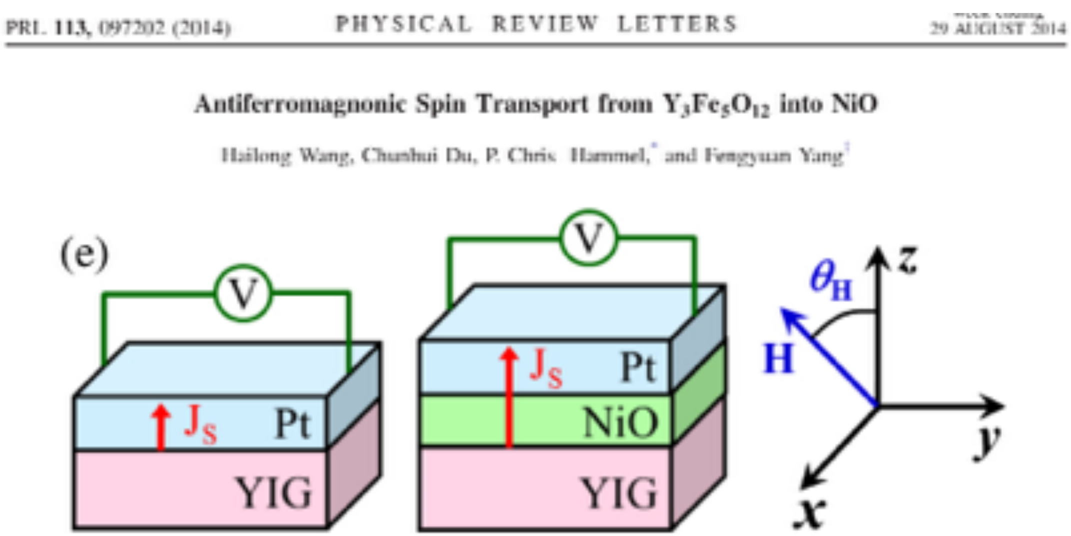


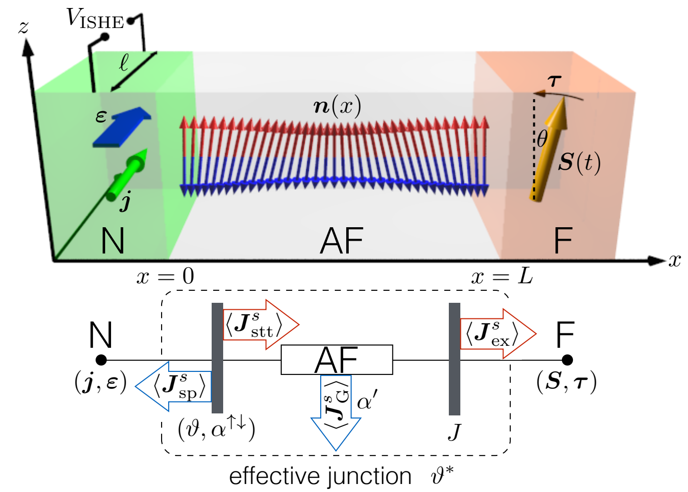
T. Moriyama et al., Appl. Phys. Lett. 106, 162406 (2015)

spin transport mechanisms

- coherent Neel dynamics
- incoherent thermal magnons

spin current in antiferromagnetic insulator





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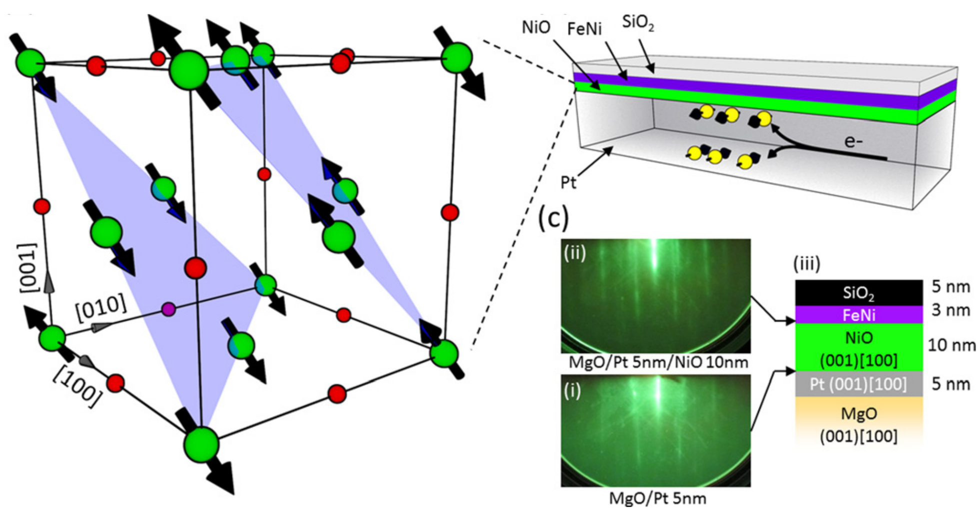


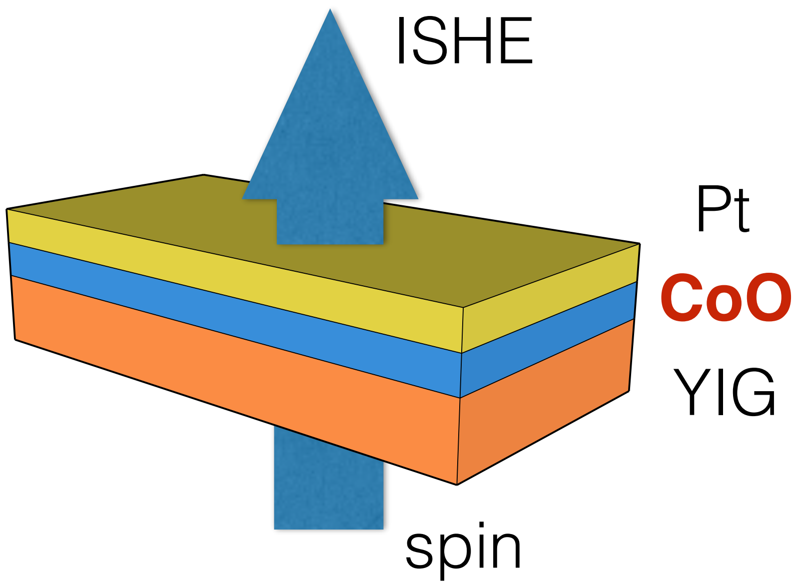
T. Moriyama et al., Appl. Phys. Lett. 106, 162406 (2015)

spin transport mechanisms

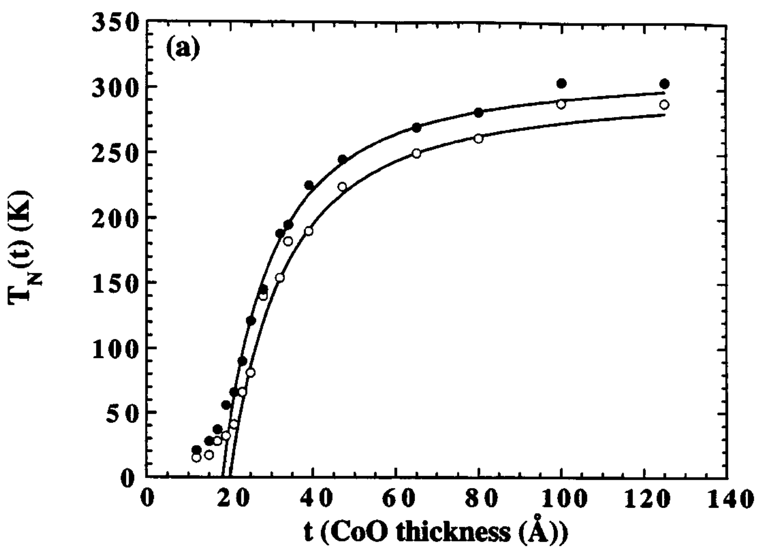
- coherent Neel dynamics
- incoherent thermal magnons

Temperature dependence?

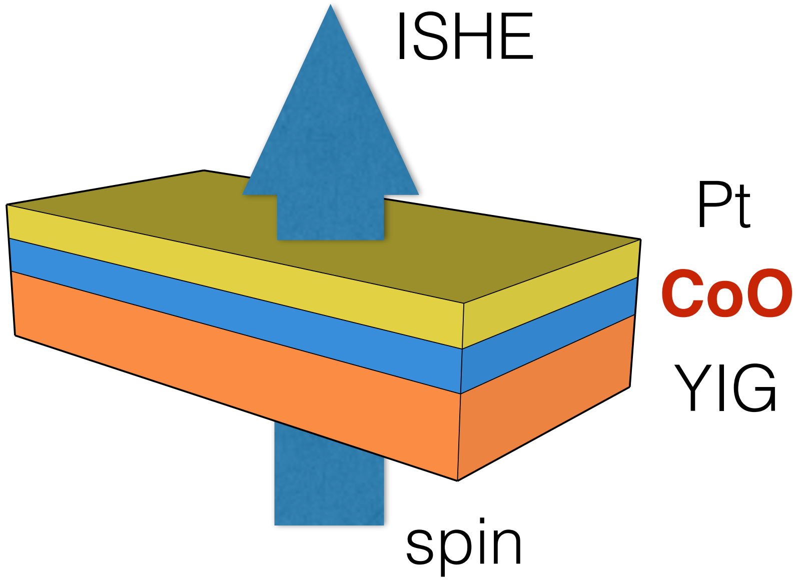
T-range covering Neel point



reduced Neel temperature in thin films



T. Ambrose and C. L. Chien, Phys. Rev. Lett. (1996)



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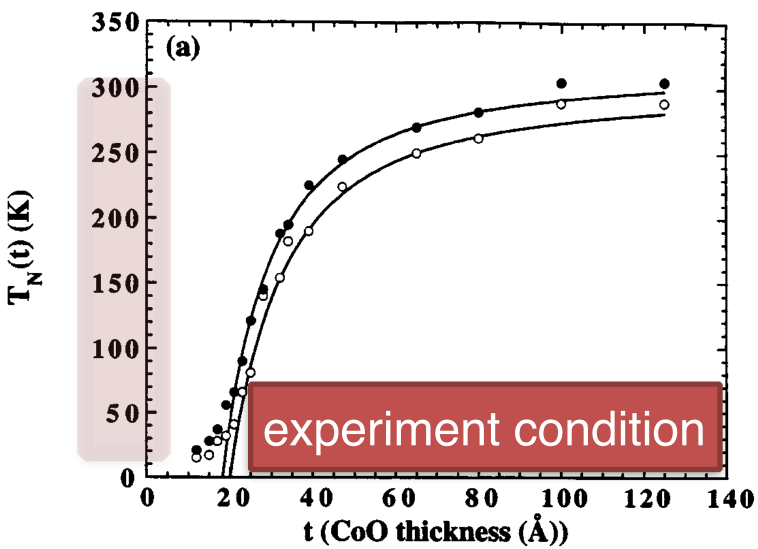

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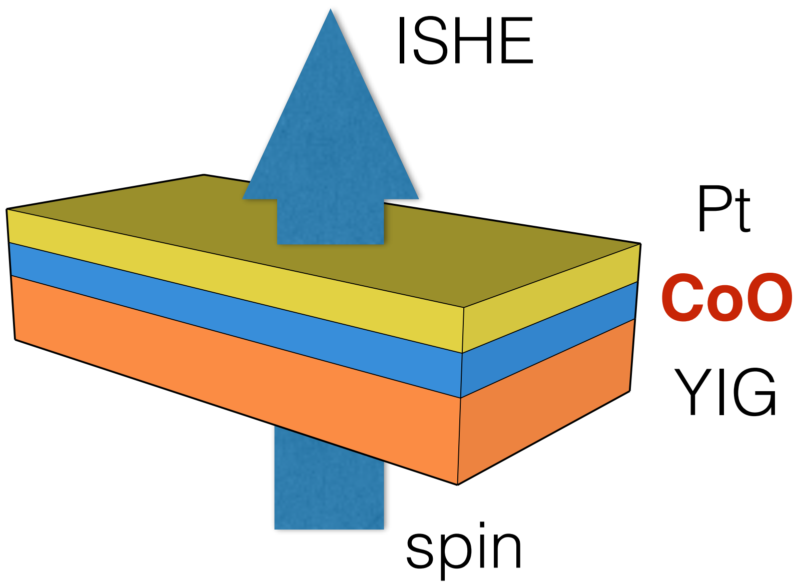

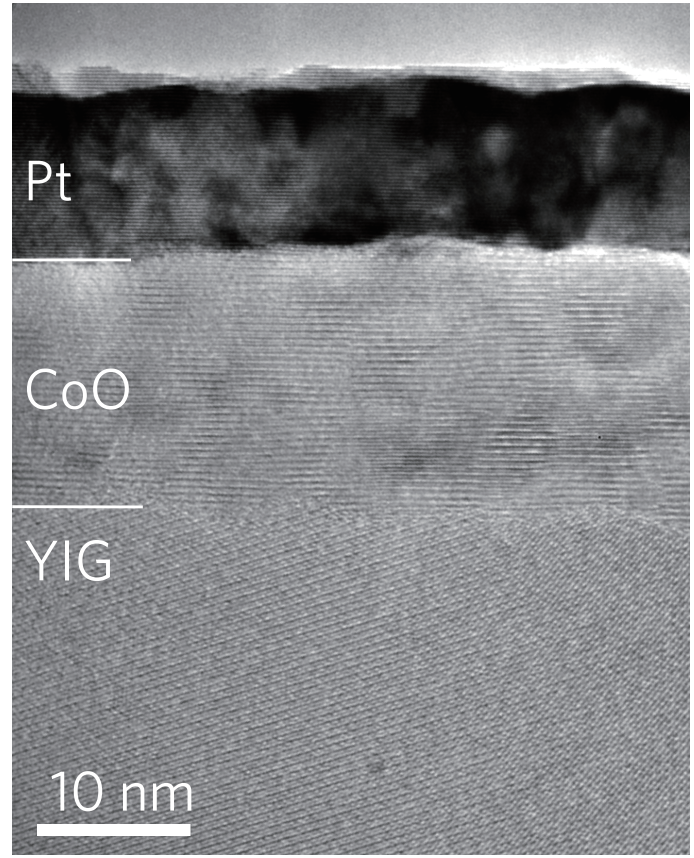

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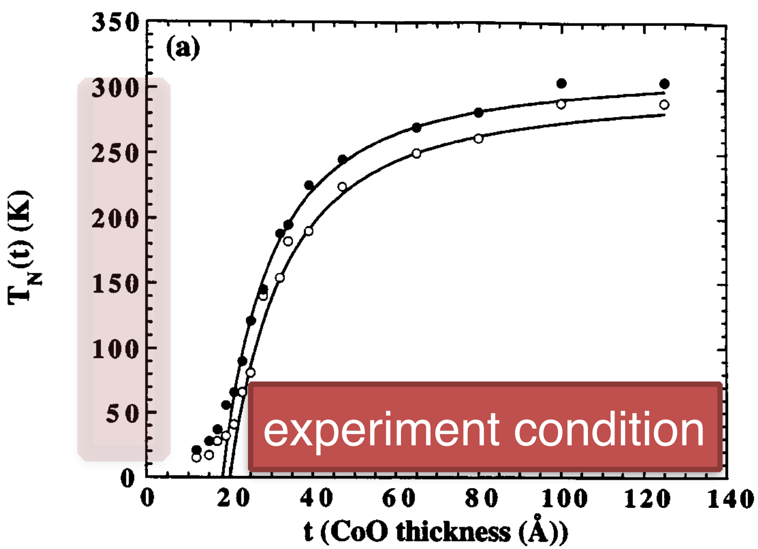

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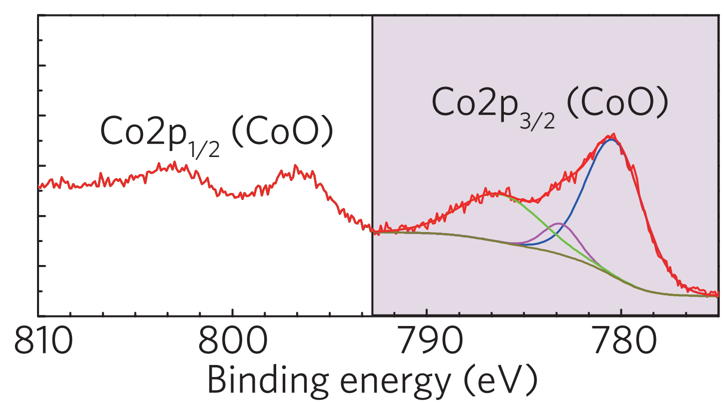
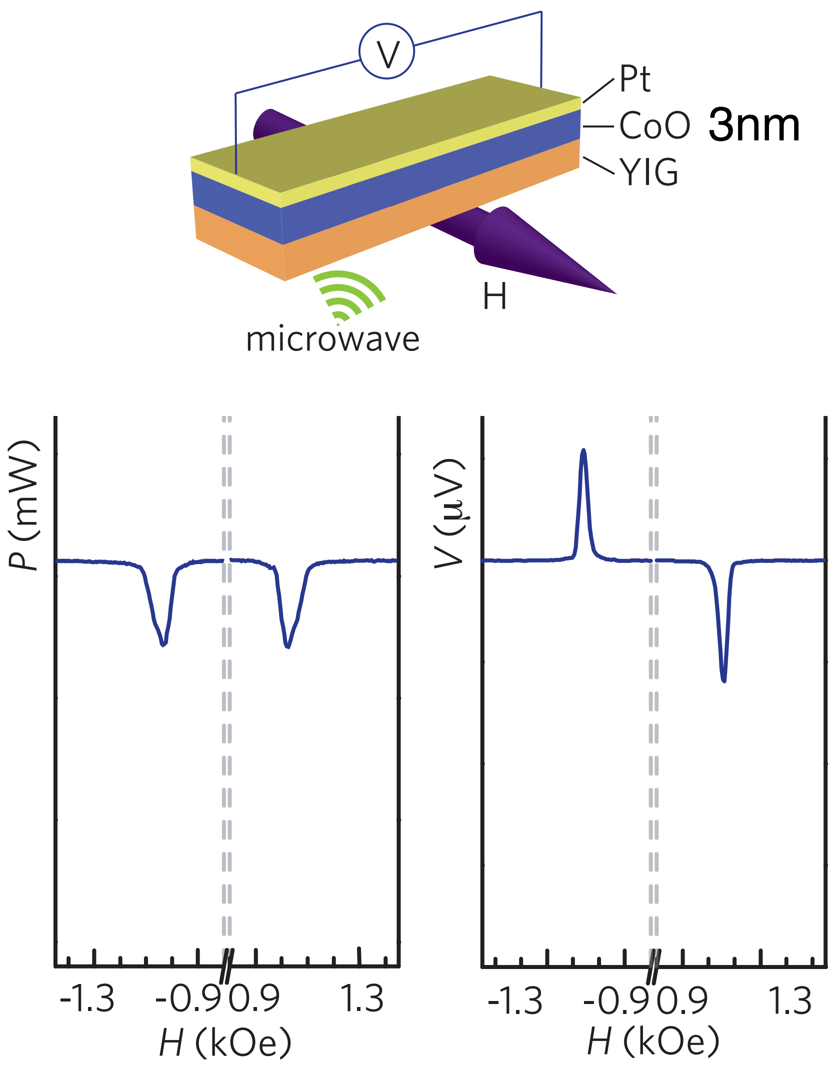
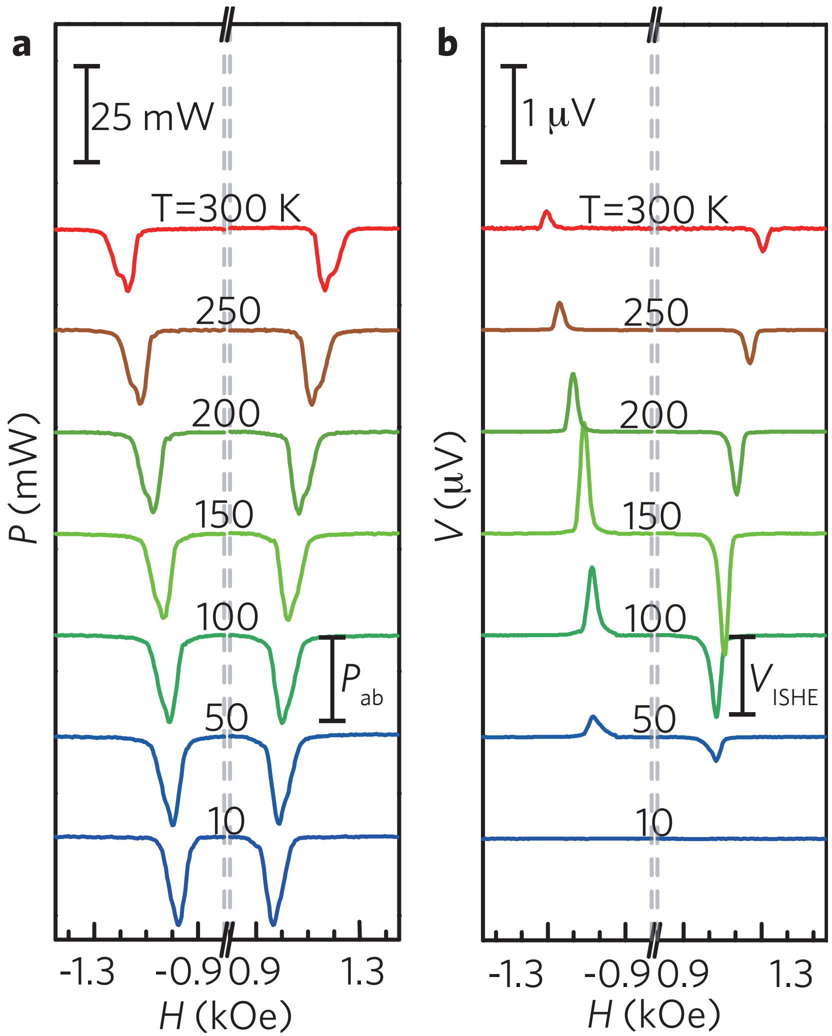


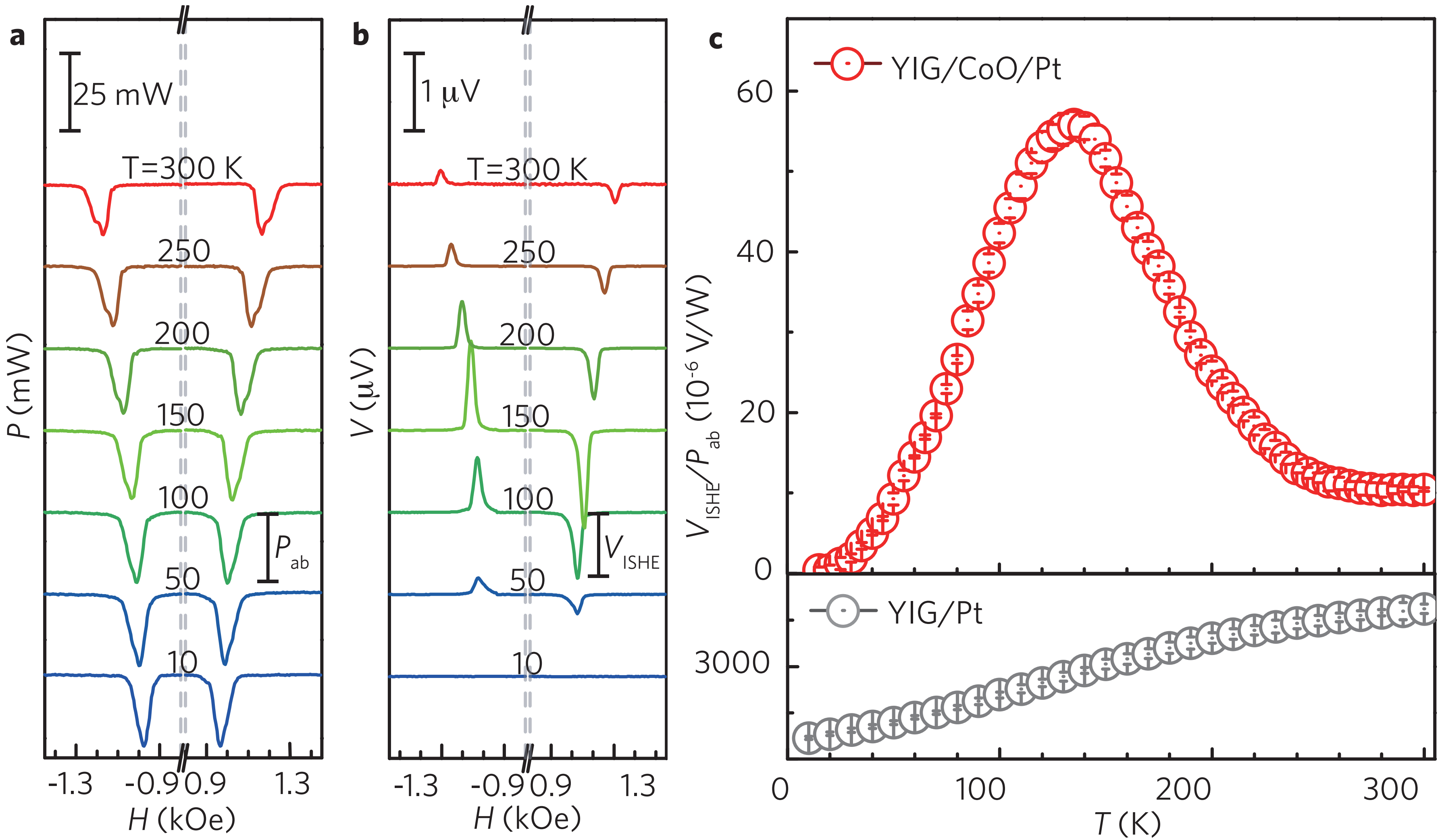
Results and discussion



Results and discussion

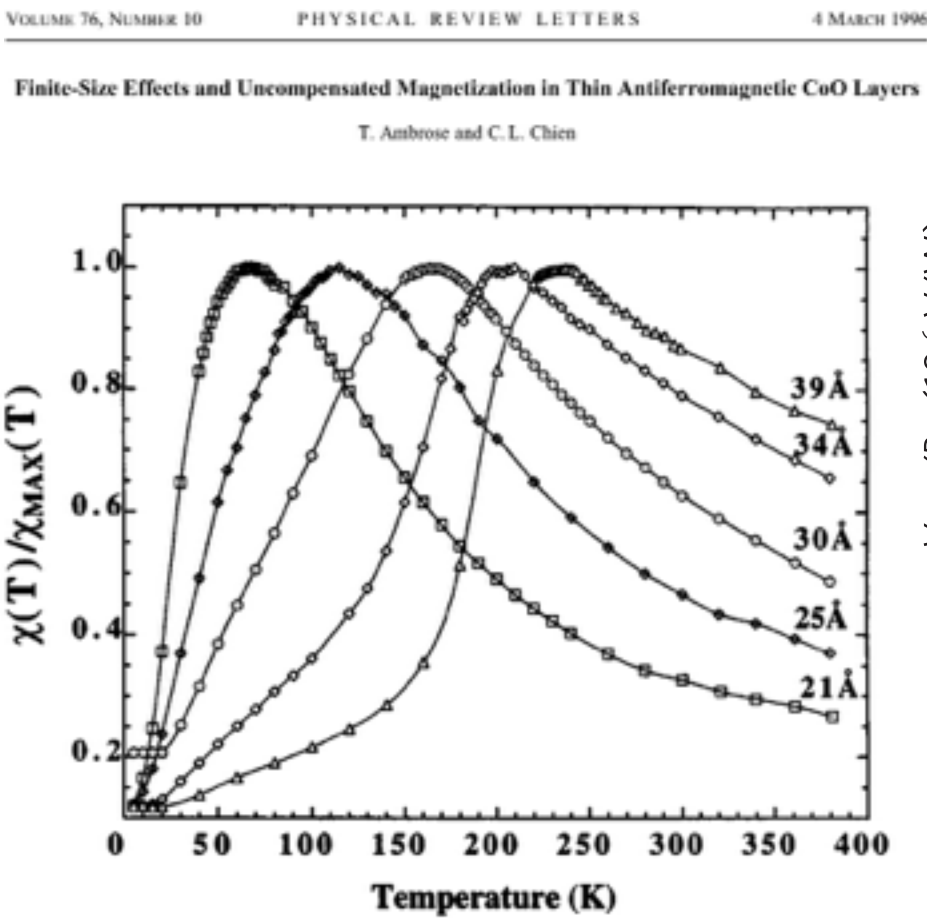


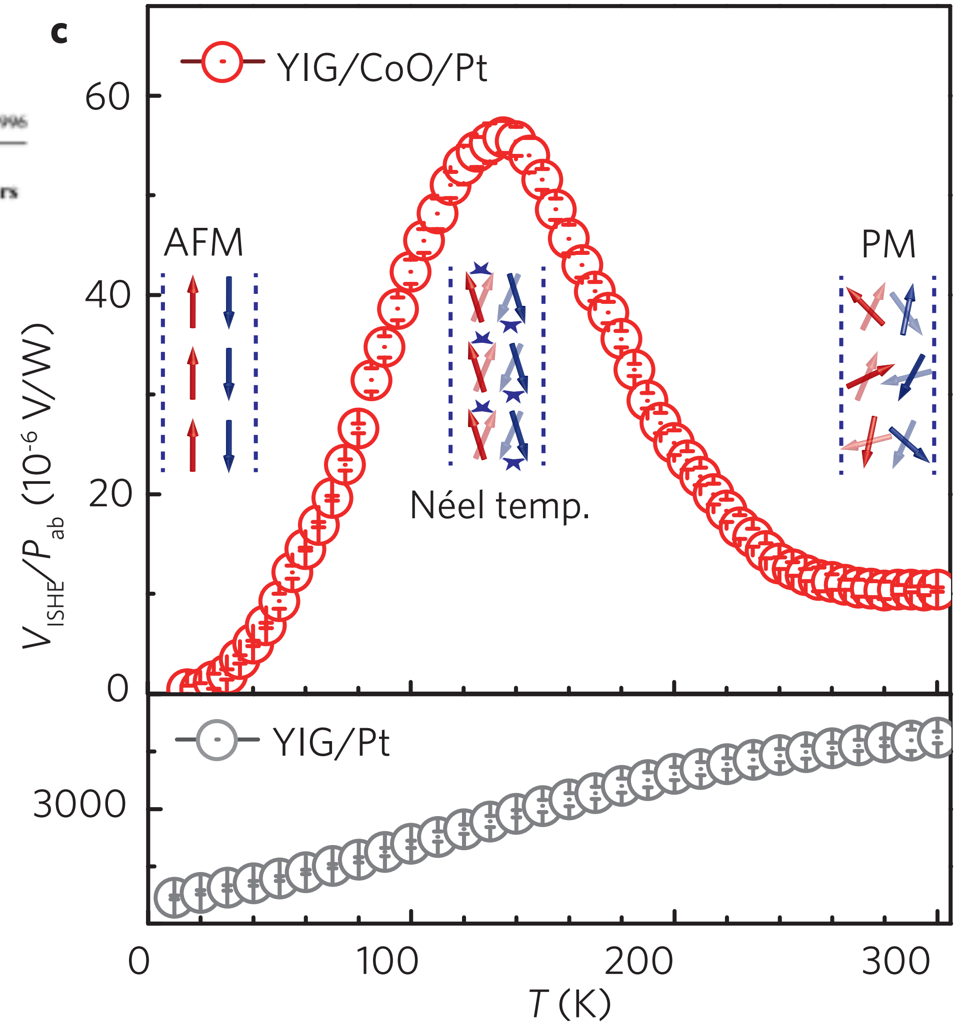
Results and discussion



Results and discussion

- **Susceptibility of CoO film**





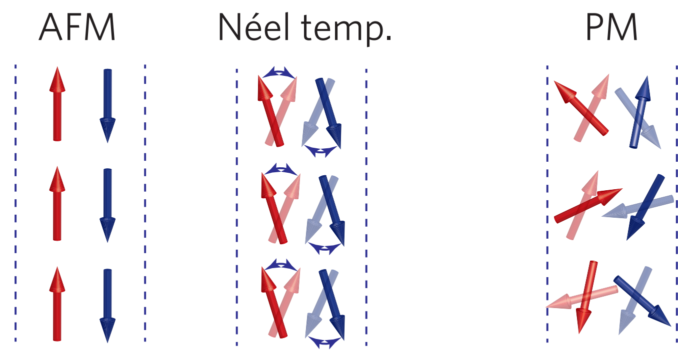
Results and discussion

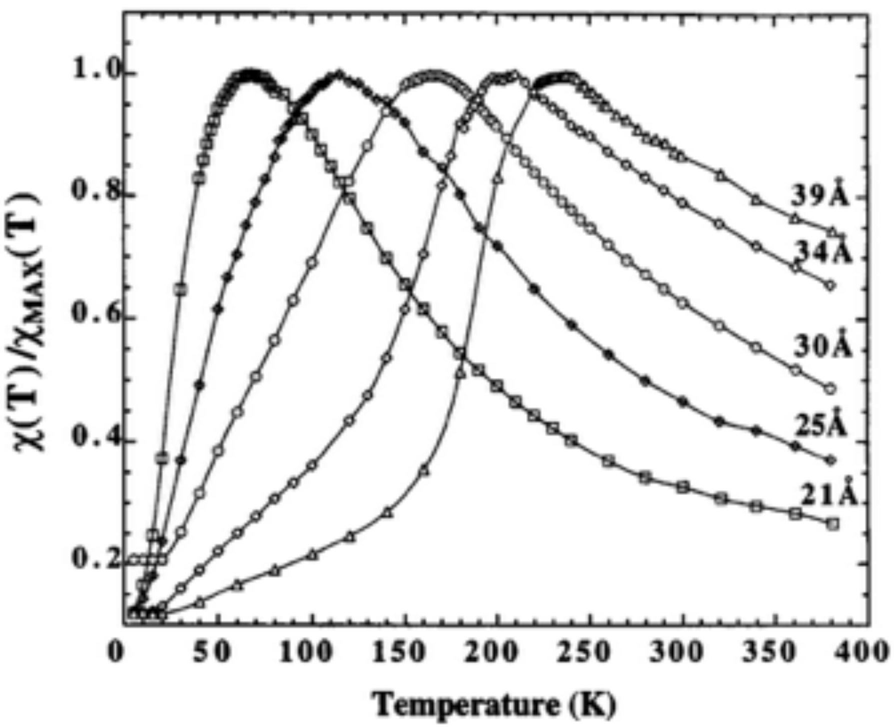
- **Susceptibility of CoO film**
- **Finite size effect**

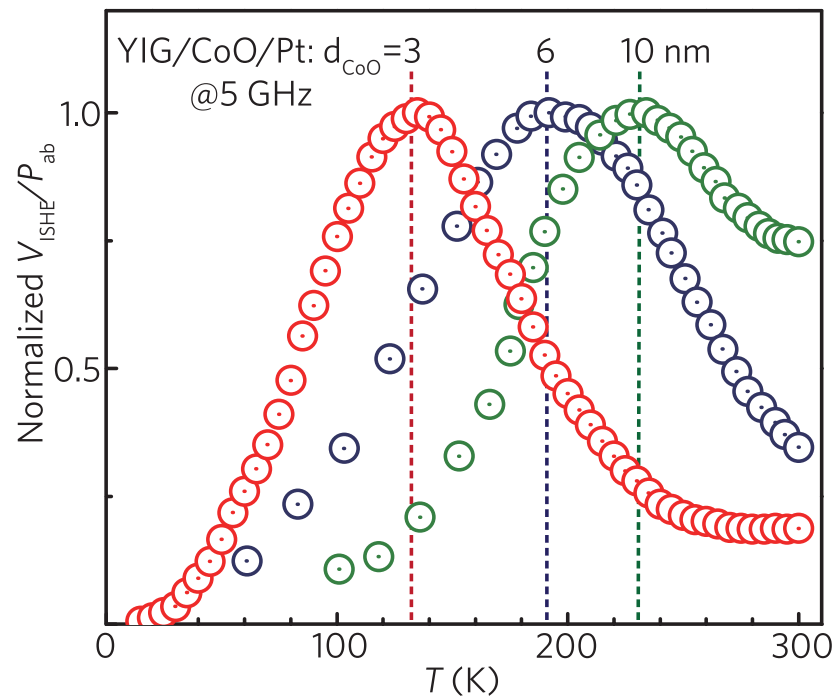
VOLUME 76, NUMBER 10 PHYSICAL REVIEW LETTERS 4 MARCH 1996

Finite-Size Effects and Uncompensated Magnetization in Thin Antiferromagnetic CoO Layers

T. Ambrose and C. L. Chien

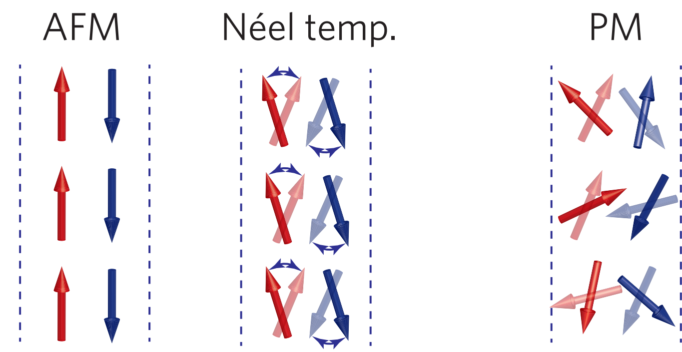


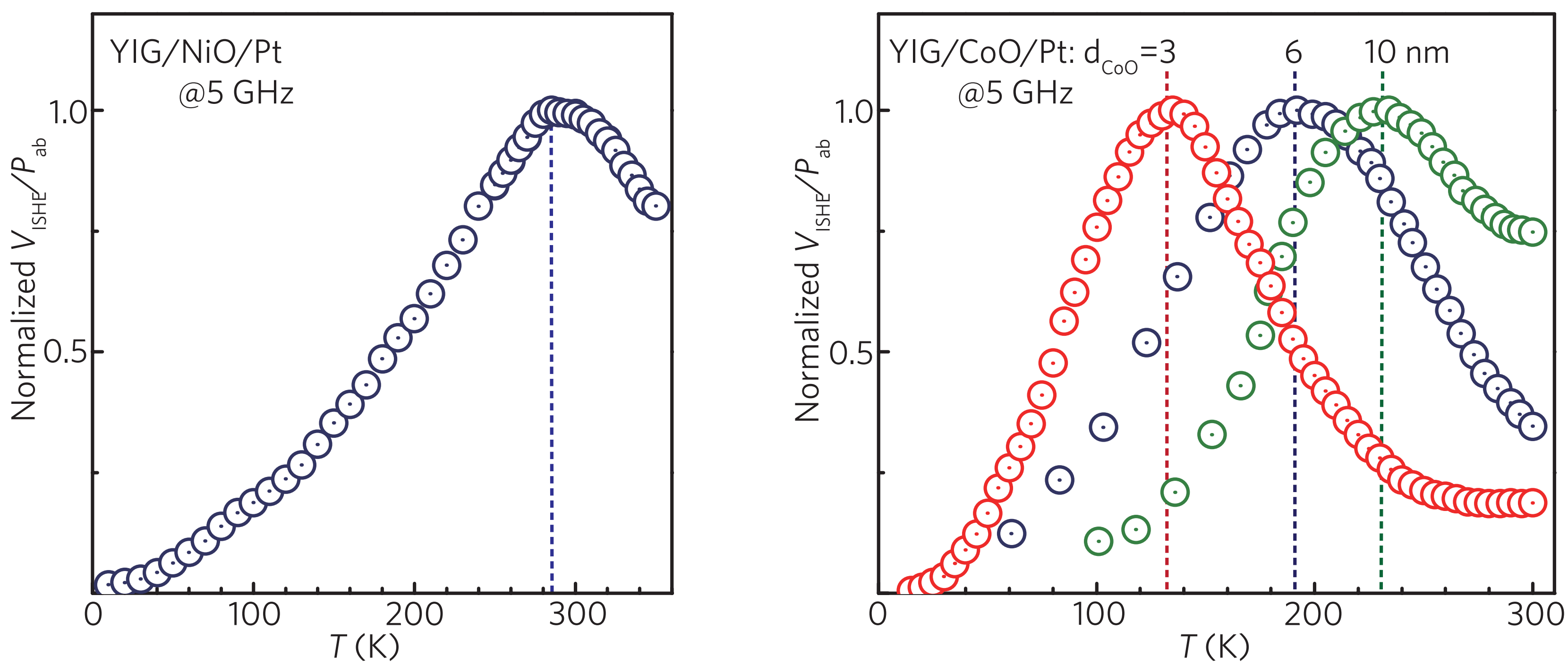




Results and discussion

- **Susceptibility of CoO film**
- **Finite size effect**
- **Double check**

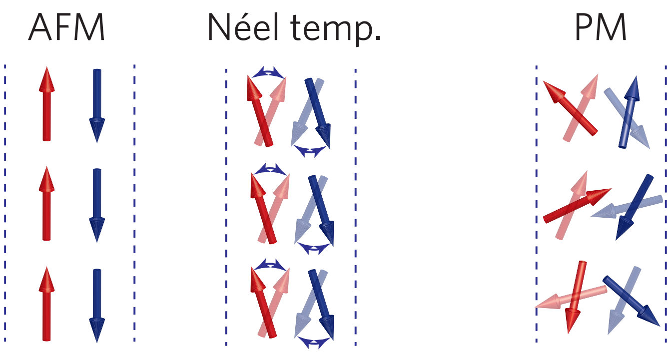


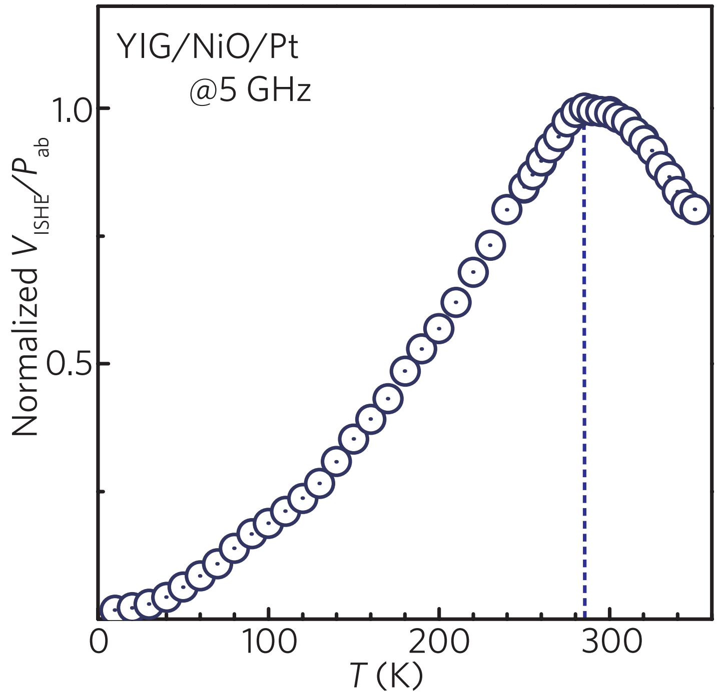


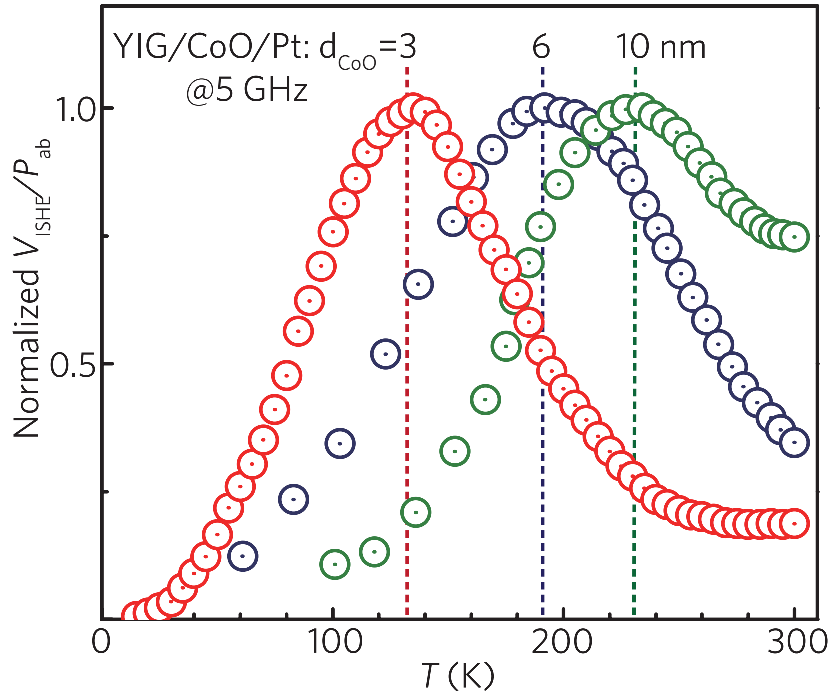
Results and discussion

- **Susceptibility of CoO film**
- **Finite size effect**
- **Double check**

spin transmission maximized around T_N







Thank you!