2017/10/16 @ KITS

Thermal effects in spintronics

Yuichi Ohnuma

Japan Atomic Energy Agency

Collaborators:

Mamoru Matsuo (JAEA)

Hiroto Adachi (Okayama Univ.)

Sadamichi Maekawa (JAEA)

Curriculum vitae

EXPERIENCE

2016–present **Postdoctoral Fellow, Advanced Science Research Center, Japan Atomic Energy Agency**

EDUCATION

March 2016 **Ph.D. in Physics, Tohoku University, Japan**
Thesis Topic: “Microscopic theory of spin current generation in magnetic insulator/ metal bilayer system”
Advisor: Professor Eiji Saioth

March 2013 **M.S. in Physics, Tohoku University, Japan**

March 2011 **B.A. in Physics, Tohoku University, Japan**

HONORS AND AWARDS

Nov. 2016 **Student Award of the Physical Society of Japan**
“Linear response theory of spin current generated by magnons”

Mar. 2010 Aoba-science promotion award of Tohoku University
For excellent scores in undergraduate course

Achievements

Publications…7 papers

Selected papers:

[*] Theory of the spin Peltier effect
Y. Ohnuma, et al., Phys. Rev. B **96**, 134412 (2017).

[*] Origin of the spin Seebeck effect in compensated ferrimagnets
S. Geprägs and Y. Ohnuma et al., Nat. Commun., **7**, 10452 (2016).

[*] Spin Seebeck effect in antiferromagnets and compensated ferrimagnets
Y. Ohnuma et al., Phys. Rev. B, **87**, 014423 (2013).

Invited talks (International conference)

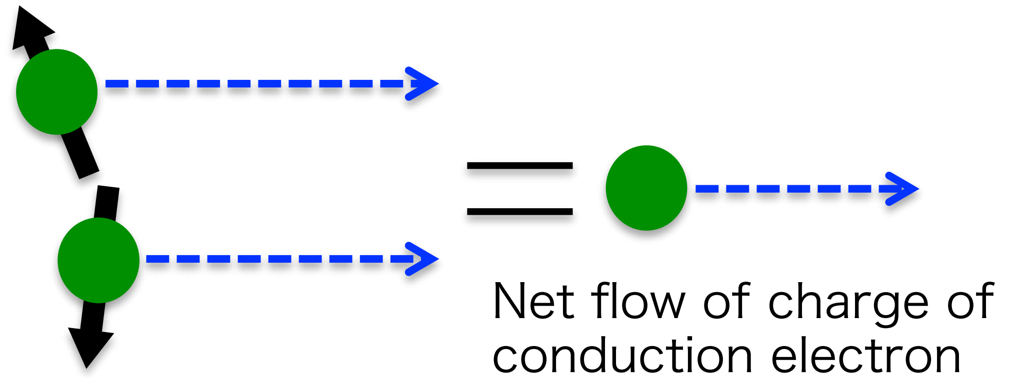
- **Kanazawa, Japan, Feb. 2017**
- **Hawaii, USA, Dec. 2016**

Funding

2017	A Grant-in-Aid for Young Scientists B from MEXT, Japan “Theory of spin Peltier effect” 2017—2019 Declined according to the regulations of Japan Atomic Energy Agencey
2014/04/01–-2016/03/31	Grant from Japan Society for the Promotion of Science, Japan “Theory of the modulated magnetization dynamics by the heat current” Total Direct Costs: 2,000,000 JPY

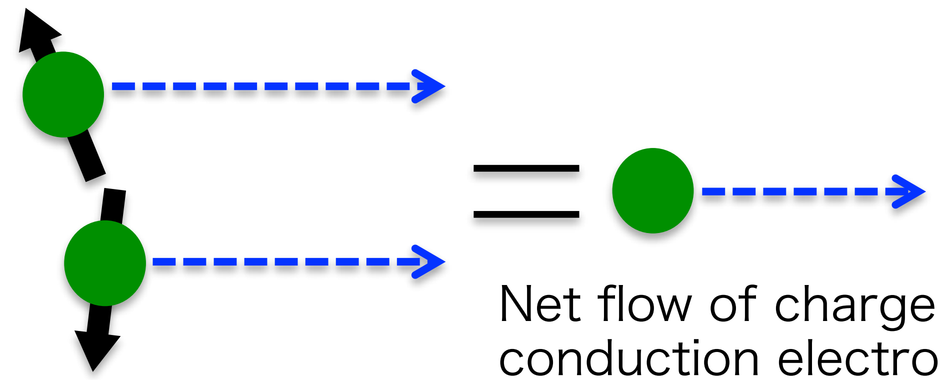
Spin current

Charge current



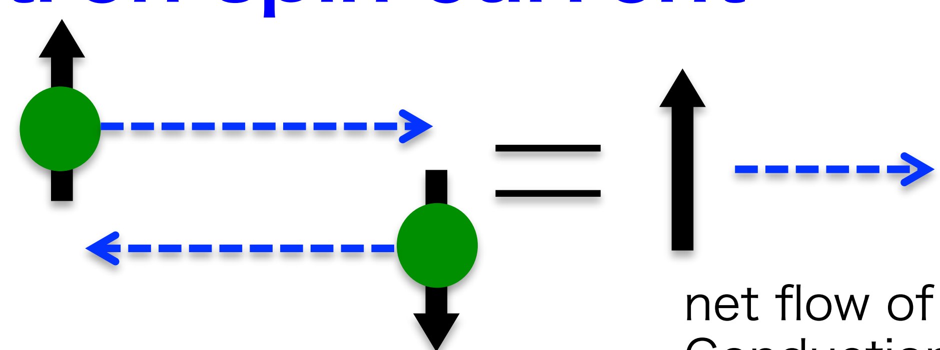
Spin current

Charge current



Net flow of charge of
conduction electron

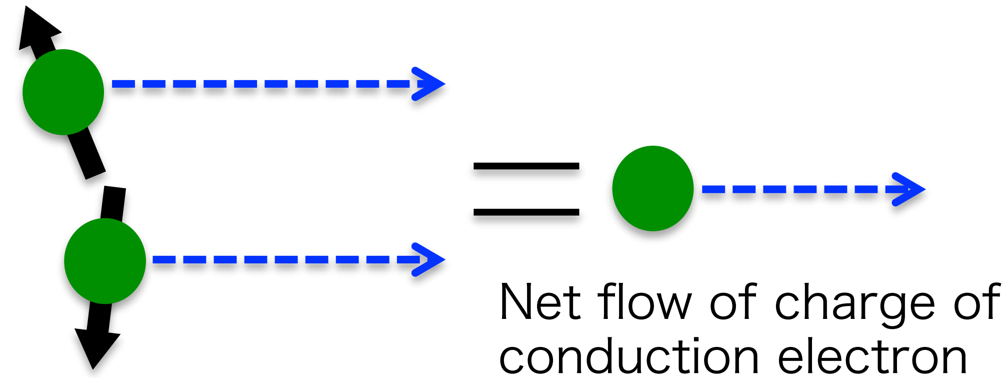
Conduction electron spin current



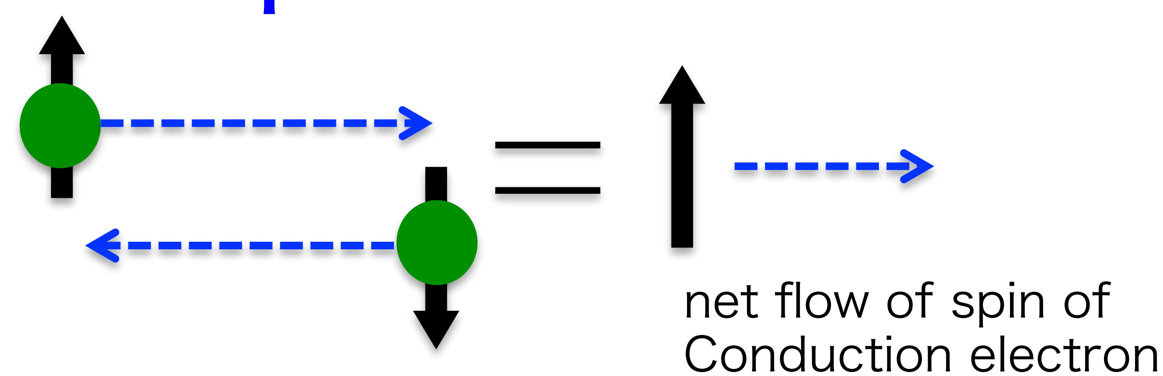
net flow of spin of
Conduction electron

Spin current

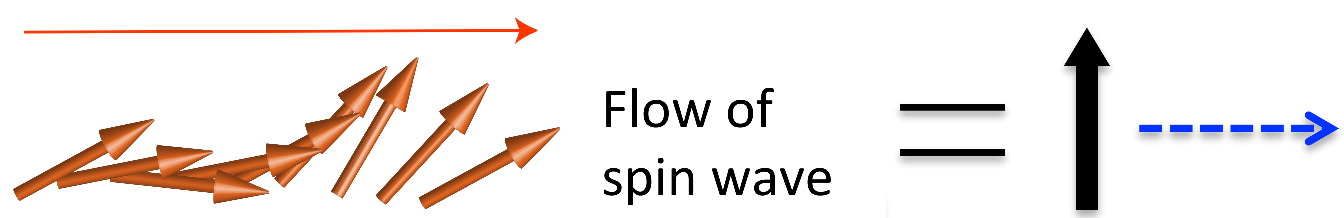
Charge current



Conduction electron spin current

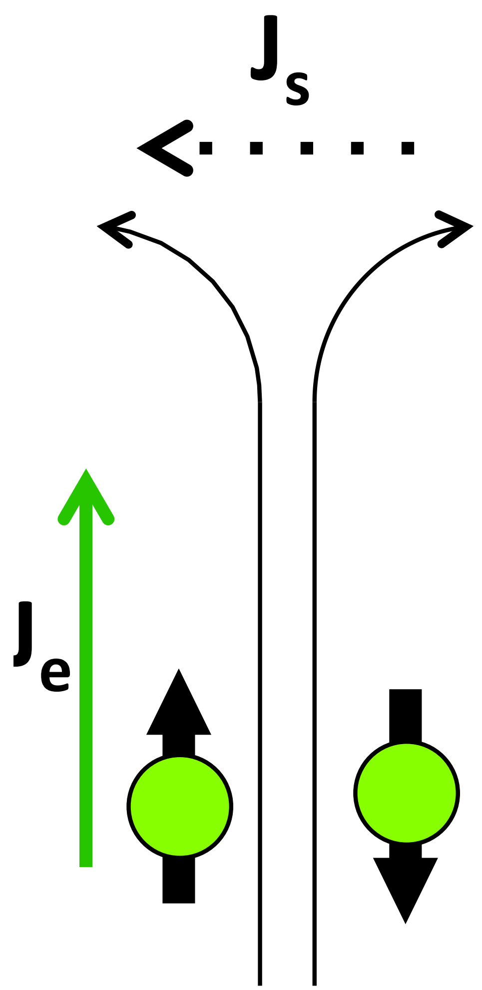


Magnon spin current

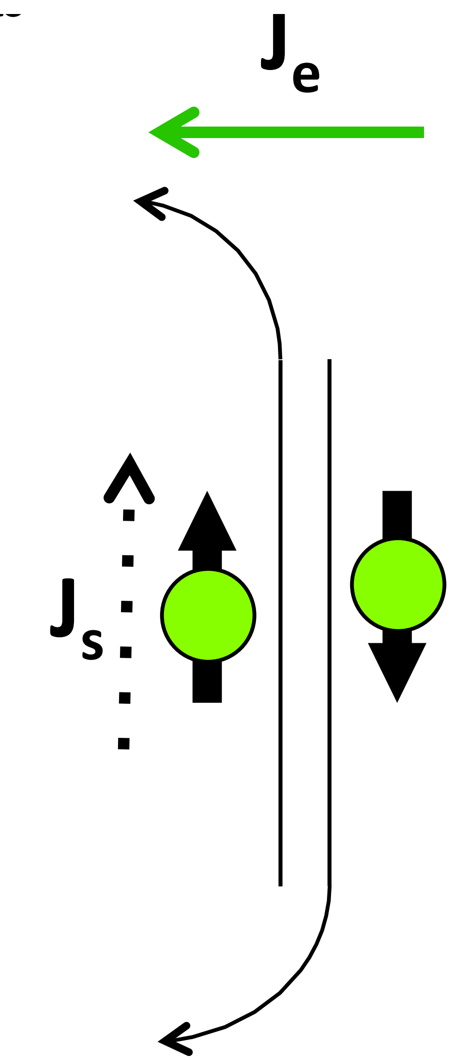


Interconversion of spin and charge currents

Spin Hall effect

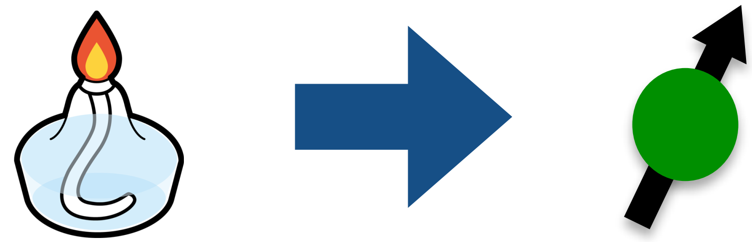
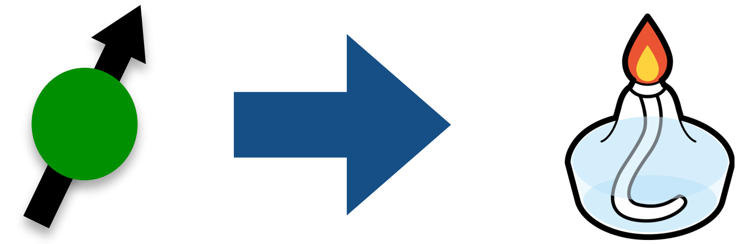
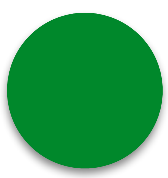


Inverse spin Hall effect

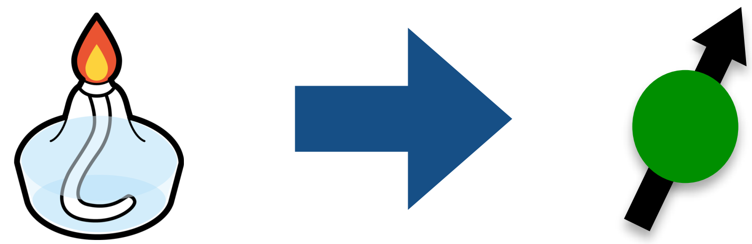
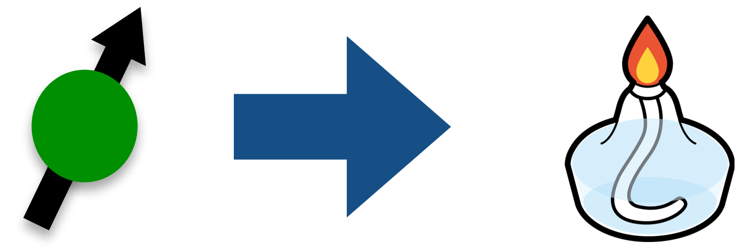
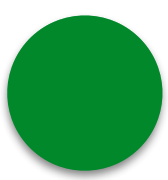
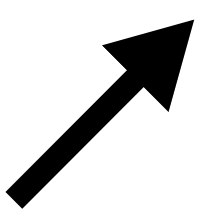


We can detect spin current.

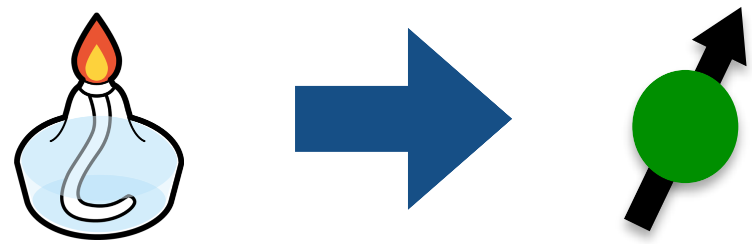
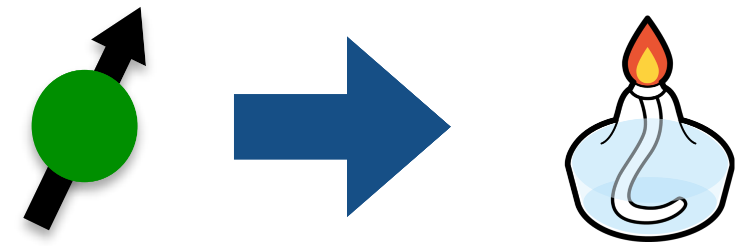
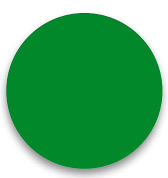
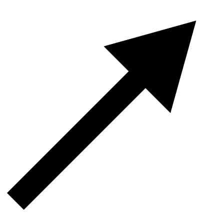
Interconversion of spin and heat currents

		
Charge 	Seebeck effect	Peltier effect

Interconversion of spin and heat currents

		
Charge 	Seebeck effect	Peltier effect
Spin 	**Spin Seebeck effect** Uchida 2008	

Interconversion of spin and heat currents

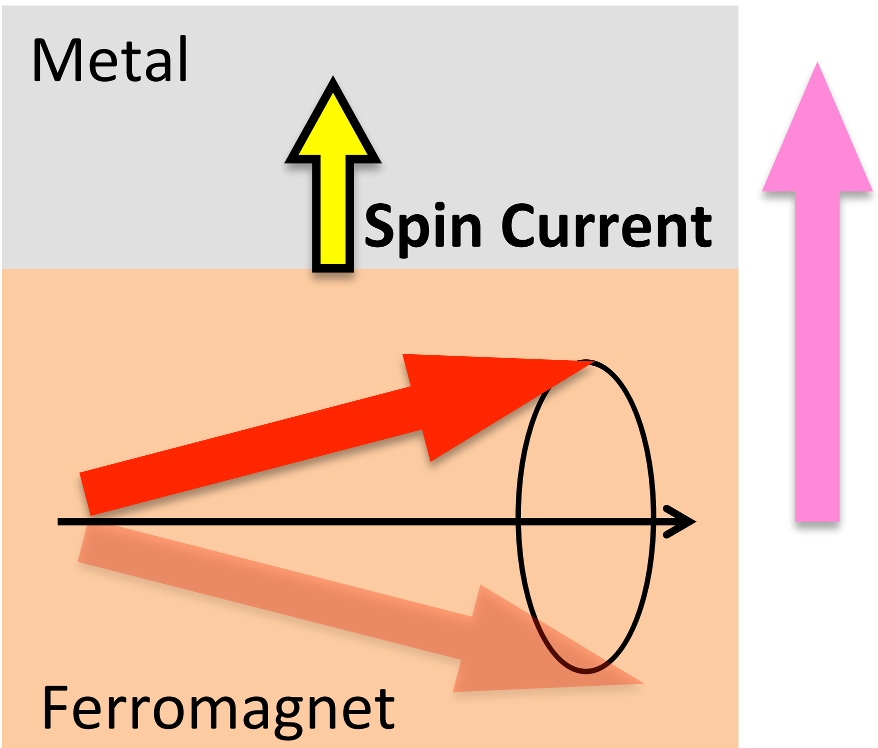
		
Charge 	Seebeck effect	Peltier effect
Spin 	**Spin Seebeck effect** Uchida 2008	**Spin Peltier effect** Flipse 2014 Daimon 2016

Contents

- Spin Seebeck effect [heat -> spin]
- Spin Peltier effect [spin -> heat]
- Summary

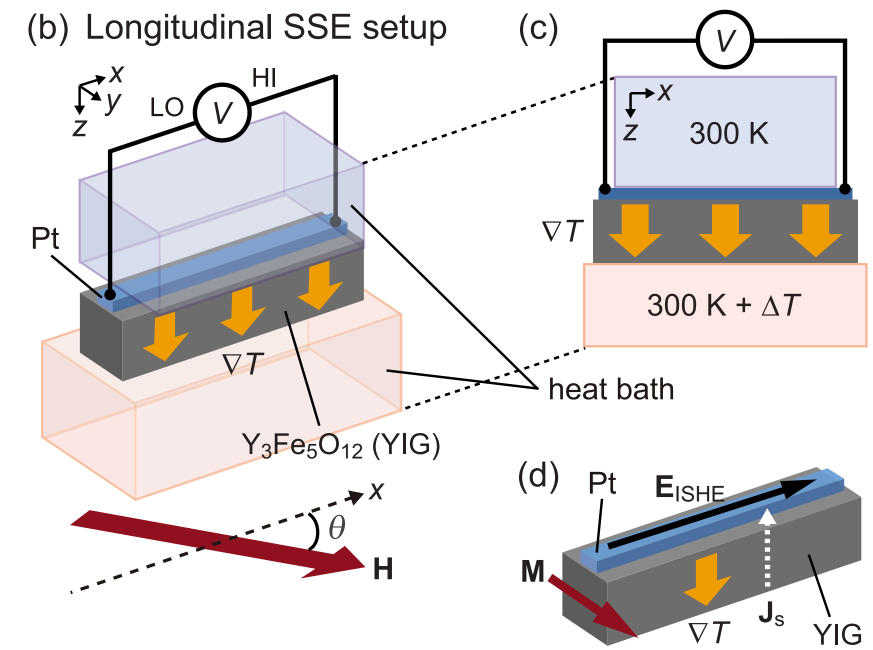
Spin Seebeck effect

Short review of spin Seebeck effect



Temperature gradient

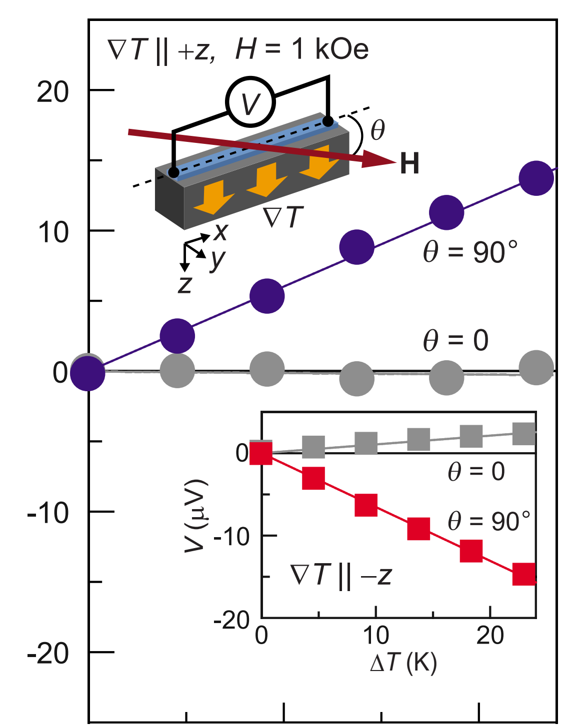
Metal(Platinum)
/ Ferrimagnetic Insulator($Y_3Fe_5O_{12}$) system



Temperature gradient

Spin current

V[μV]

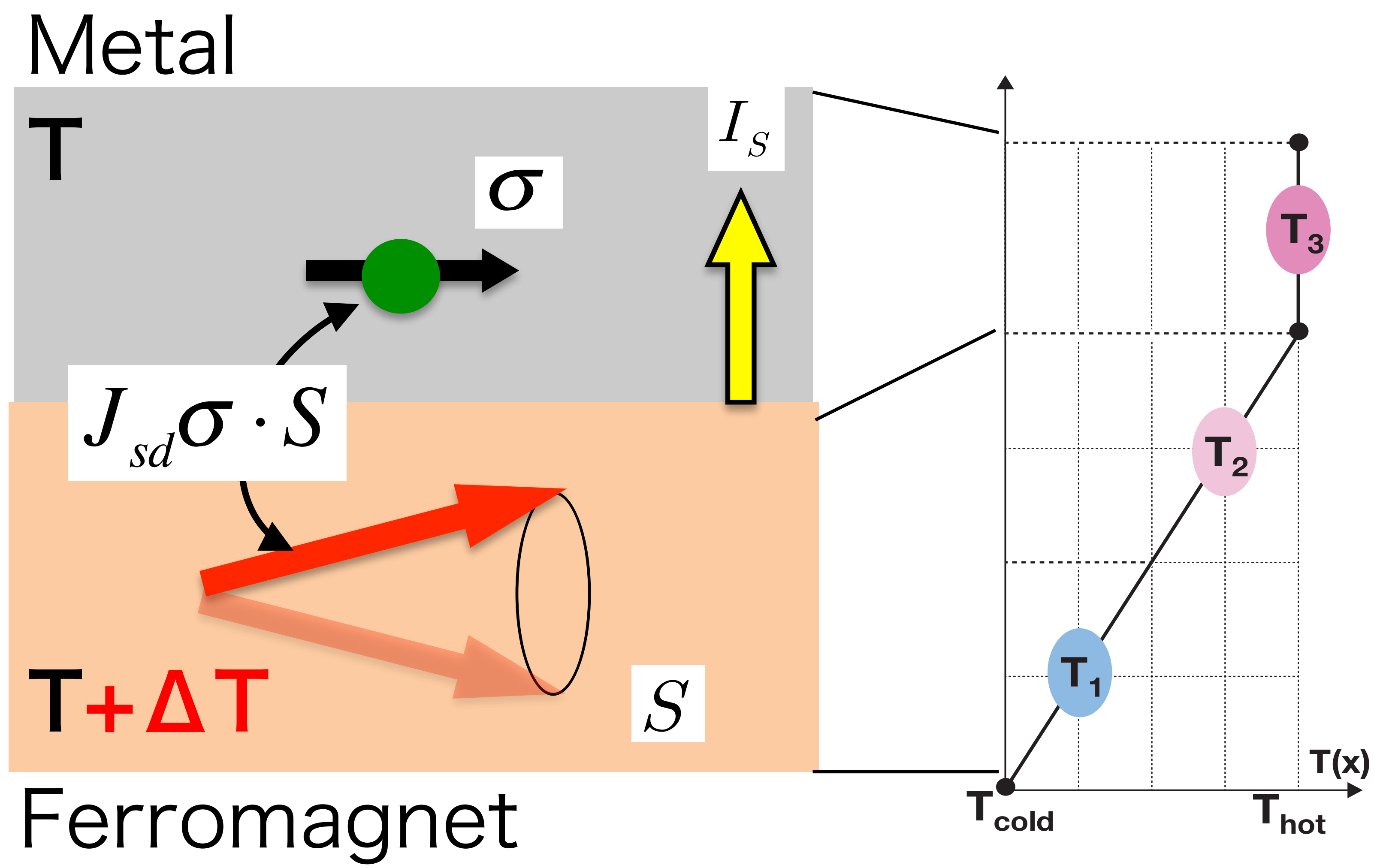


0 ΔT[K] 20

Uchida 2010

Spin Seebeck effect in metal/ferromagnet

Adachi PRB (2011)



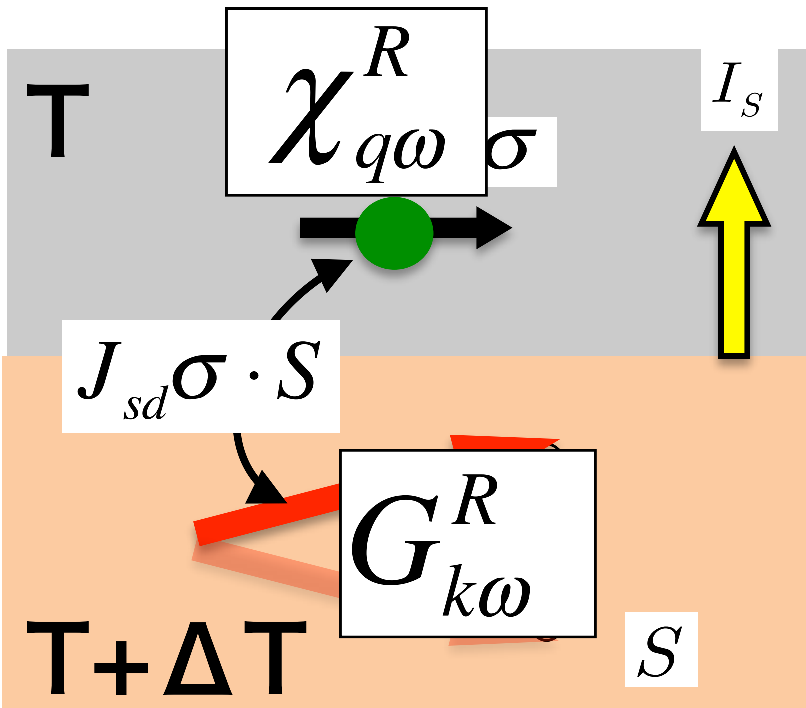
Spin current: $I_S \equiv \sum_{i \in \mathrm{int}} \left\langle \partial_t \sigma_i^z \right\rangle$ spin density in Pt

König and Martinek 2003

Adachi 2011

Ohnuma 2013, 2016, 2017

Spin Seebeck effect in metal/ferromagnets



$$H = J_{sd}\sum_i \sigma_i \cdot S_i$$

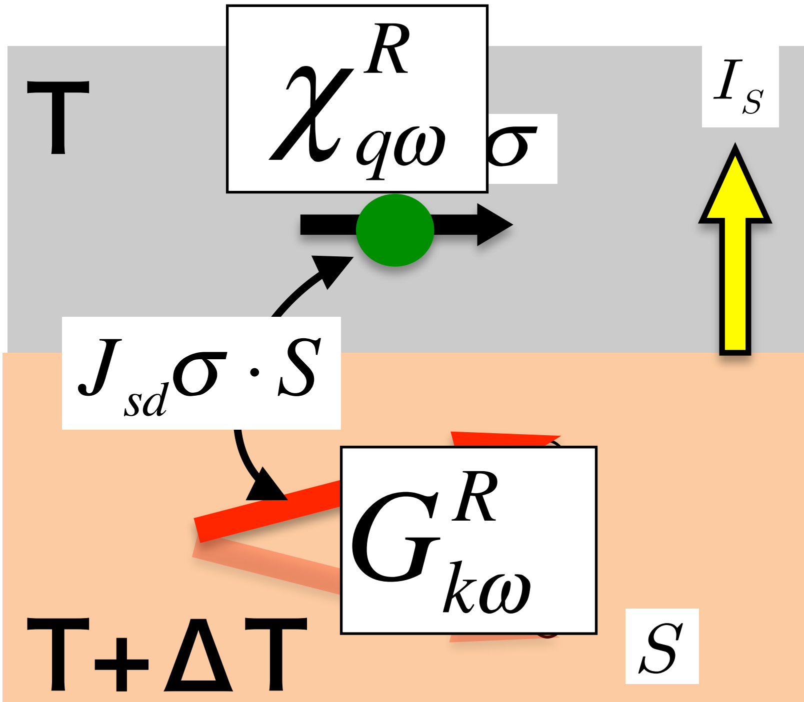
Expression of spin Seebeck effect

$$I_S = \Delta T \times \int_{kq\omega}\left[J_{sd}^2 \times \mathrm{Im}\,\chi^R_{q\omega} \times \mathrm{Im}\,G^R_{k\omega} \times \frac{\partial f}{\partial T}\right]$$

Spin current = **Temeprature difference** × interfacial interaction × **Spectral function in M** × **Spectral function in F** × **Distribution functions**

$$\chi = \langle \sigma^+\sigma^- \rangle \quad G = \langle S^+S^- \rangle$$

Spin Seebeck effect in metal/ferromagnets



$$I_S = \Delta T \int_{kq\omega} \left[J_{sd}^2 \, \mathrm{Im}\,\chi^R_{q\omega} \, \mathrm{Im}\, G^R_{k\omega} \frac{\partial f}{\partial T} \right]$$

Quasiparticle approximation for FI (magnon)

$\mathrm{Im}\, G^F_{k\omega} \sim -\pi\delta(\omega - \omega_k)$

Spectral function in FI

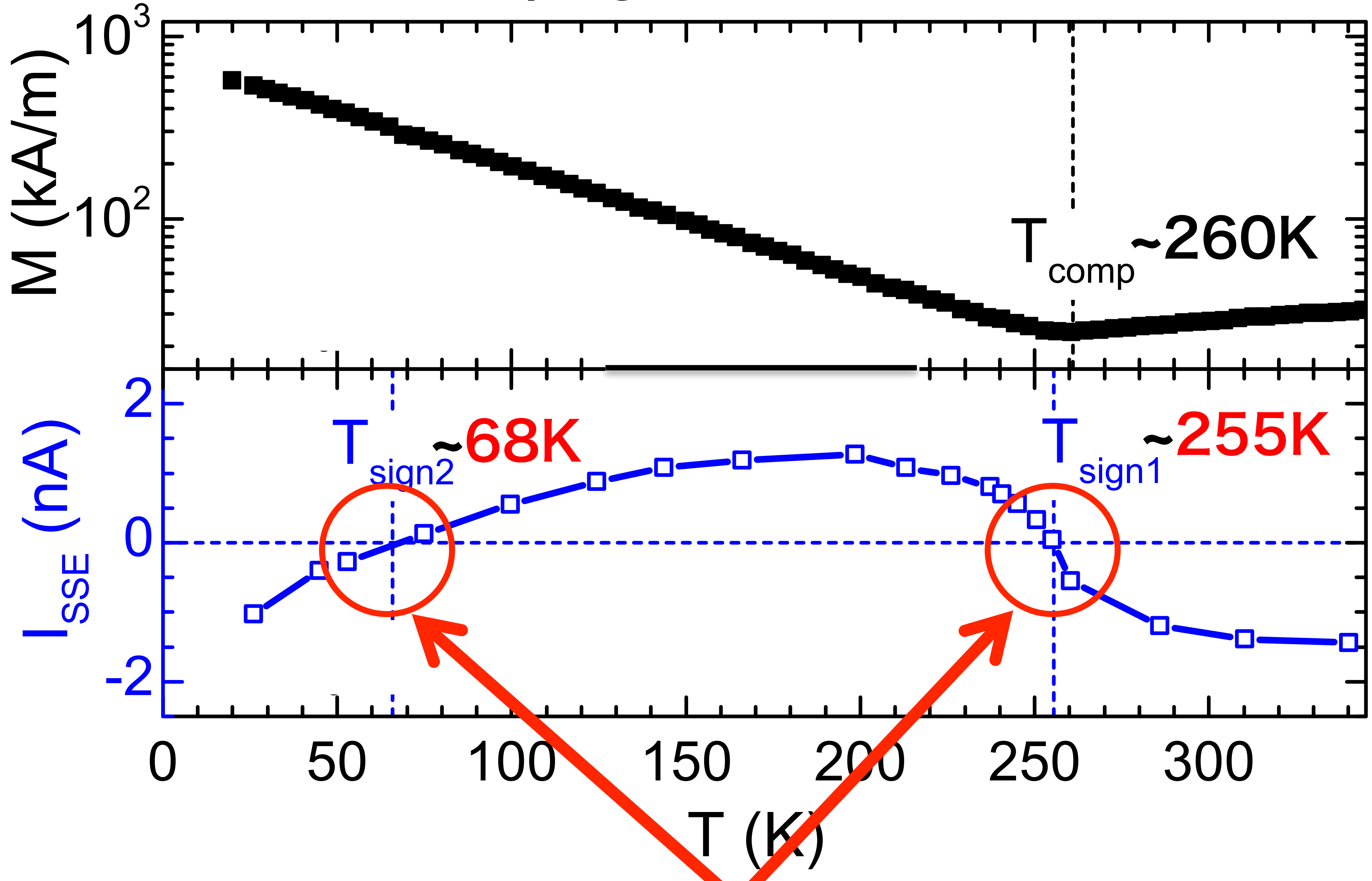
$$\boxed{I_S = \Delta T \int_{\omega} \tilde{J}_{sd}(\omega) D(\omega) \frac{\partial f(\omega)}{\partial T}}$$

Spin current = Temeprature difference × Effective exchange at interface × Number of magnons

$\tilde{J}_{sd}(\omega) = J_{sd}^2 S \, \mathrm{Im}\,\chi^R_{q\omega}$

Two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

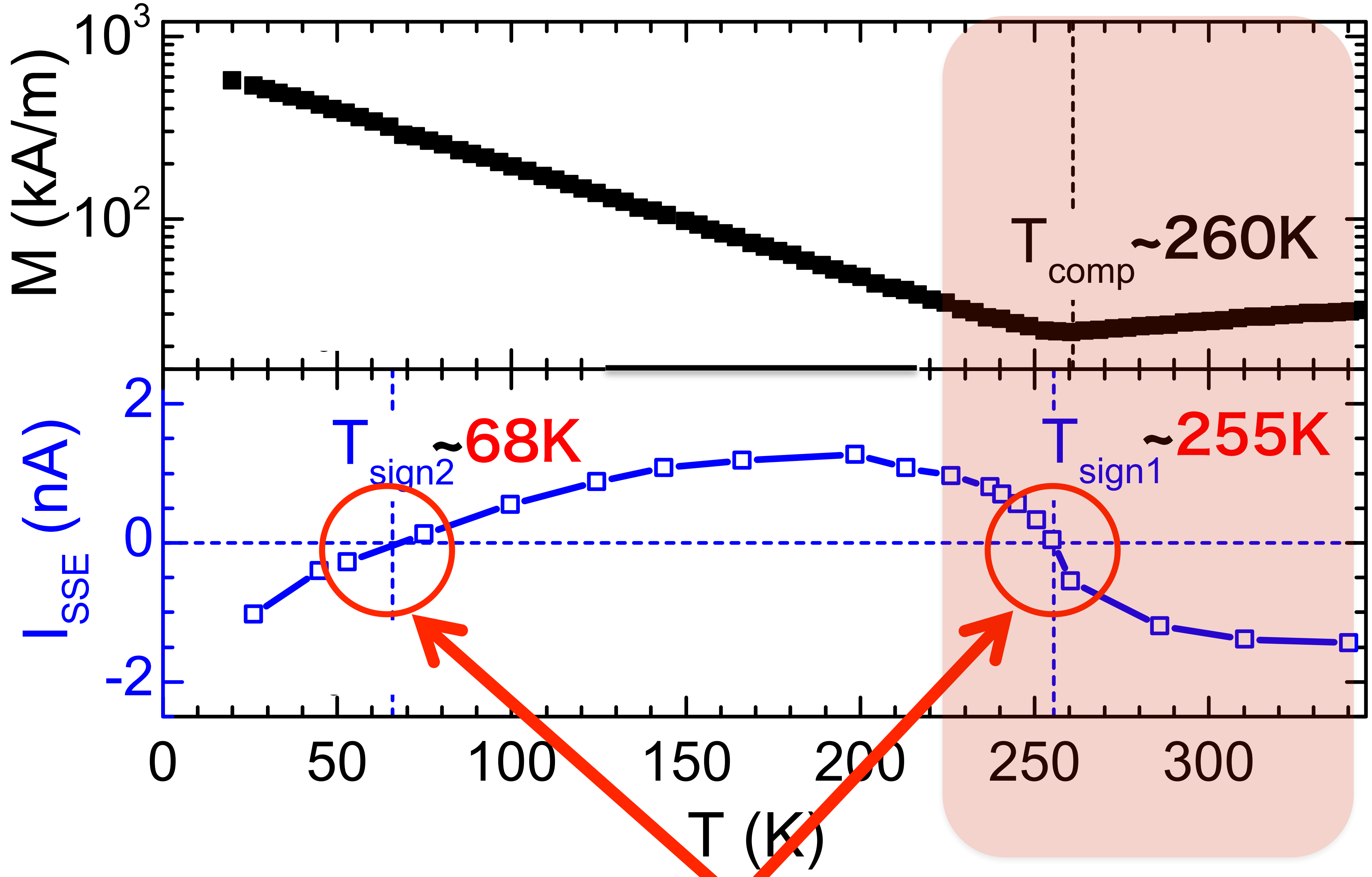
Geprägs and Ohnuma et al., Nat. Commun. 2016



Two sign changes

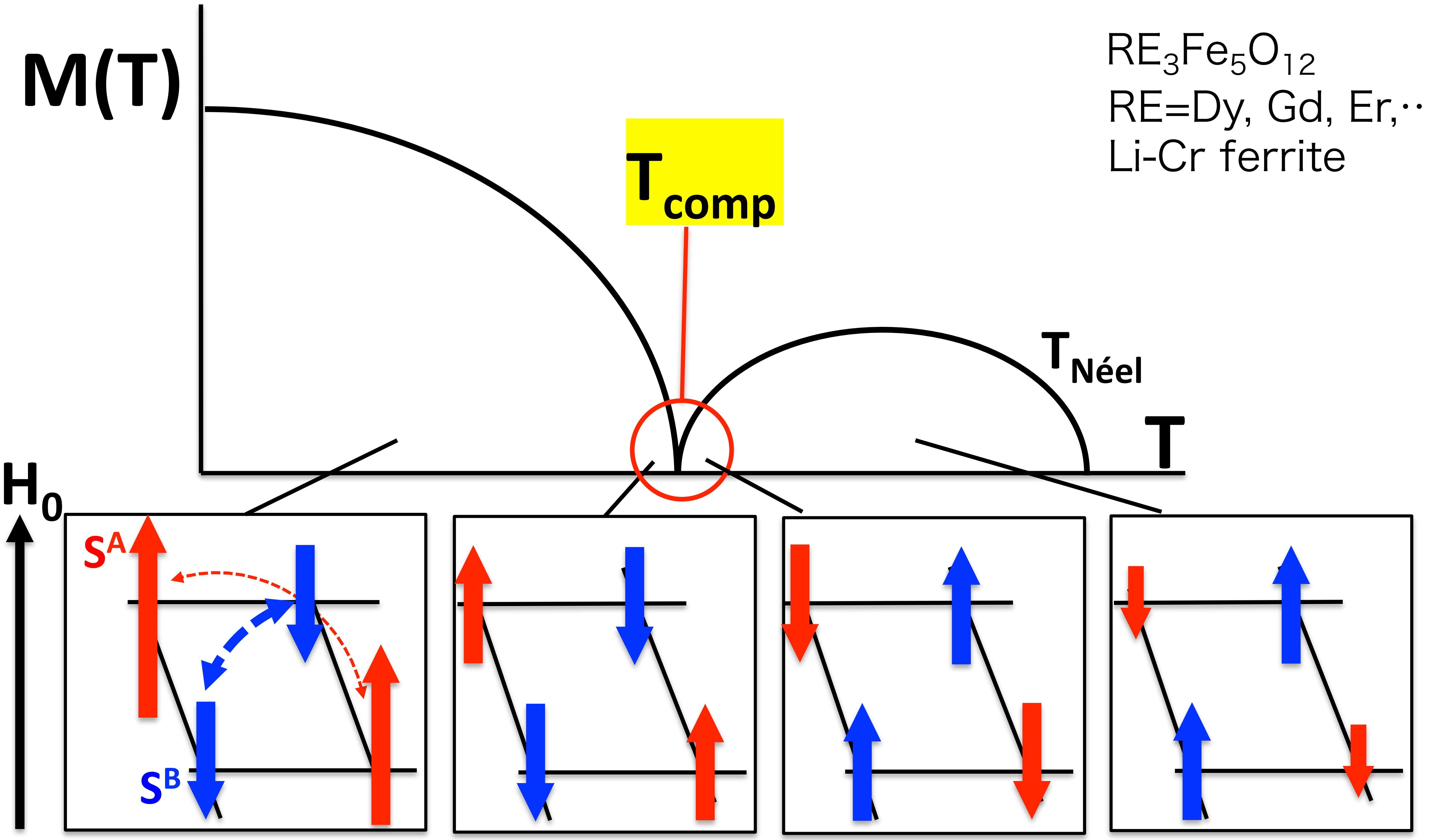
Two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

Nat. Commun. (2016)



Two sign changes

Magnetization compensation effect

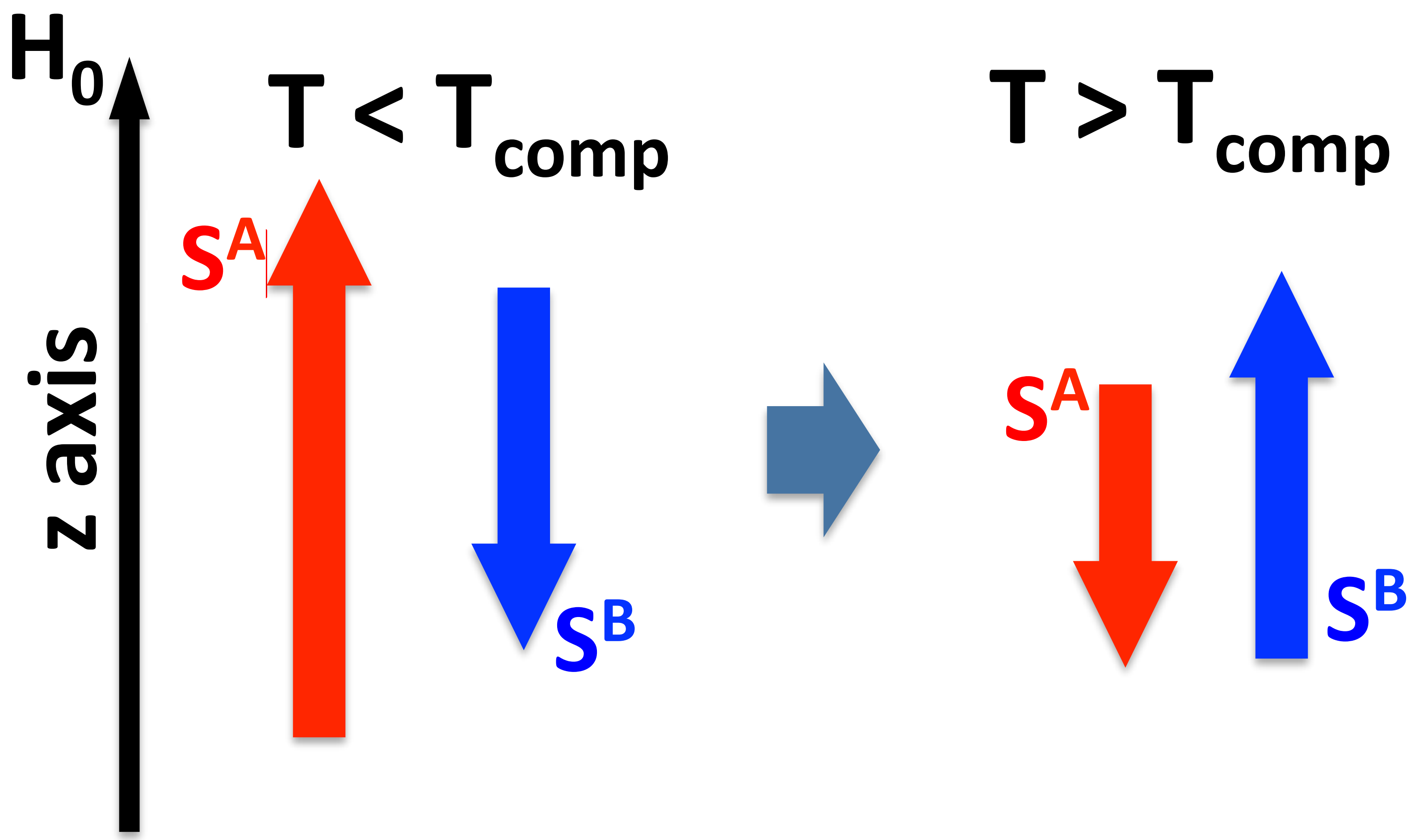


Origin of the 1st sign change

PRB **87** 014423 (2013)

S^A : Gd

S^B : Fe

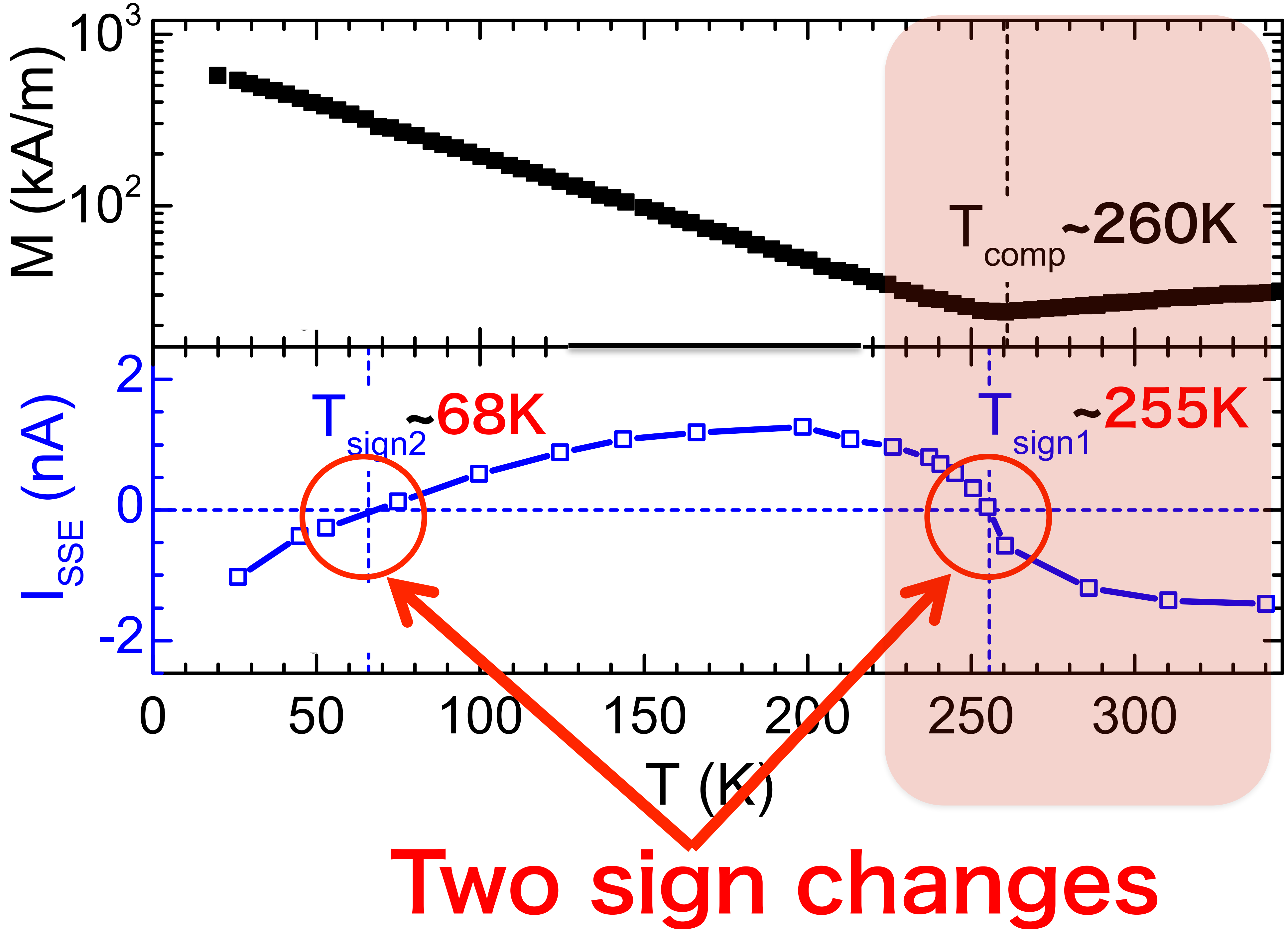


Magnetization compensation effect causes sign change at T_{sign1}.

$T_{sign1} = T_{comp}$

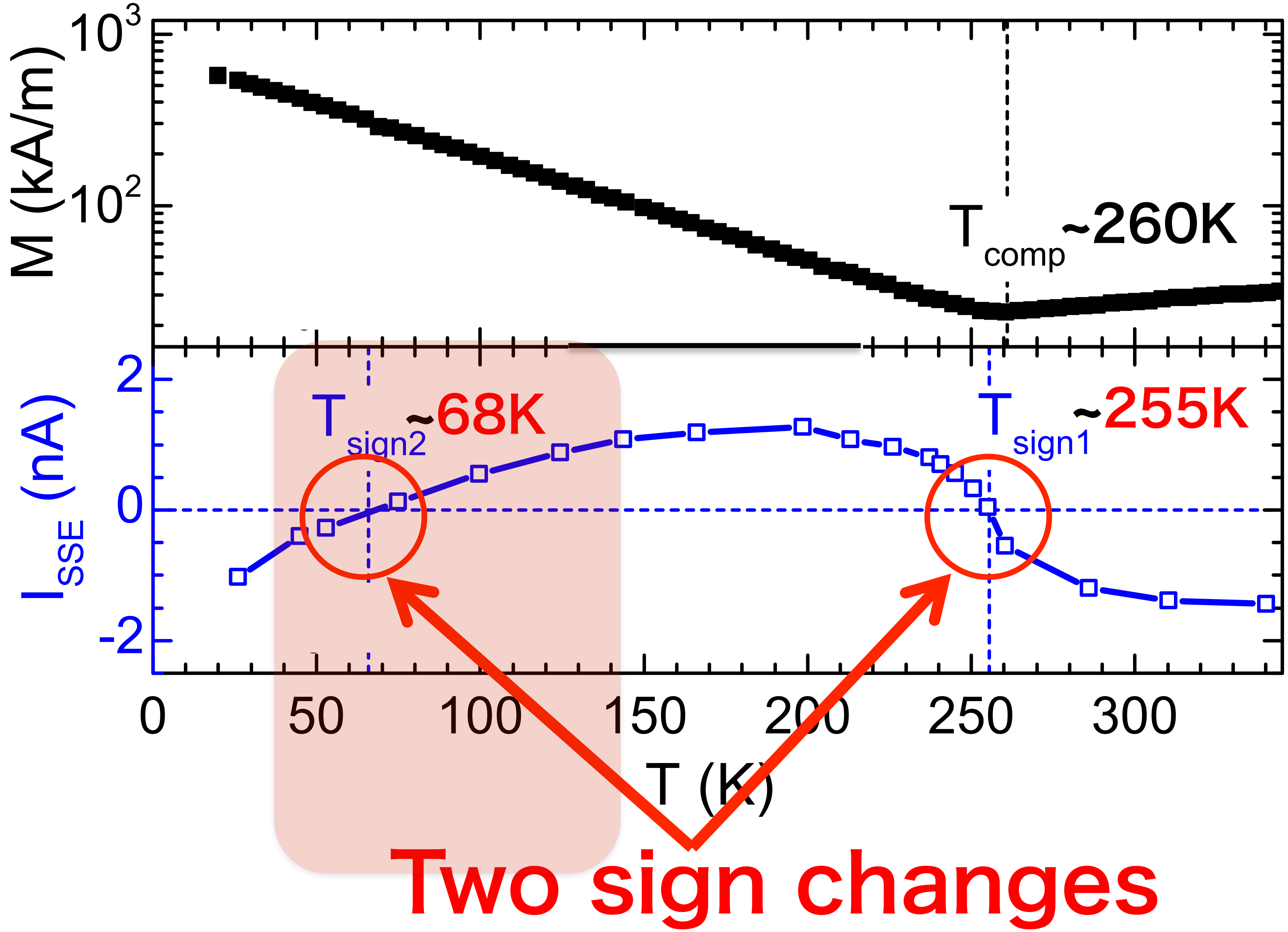
Two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

Nat. Commun. (2016)

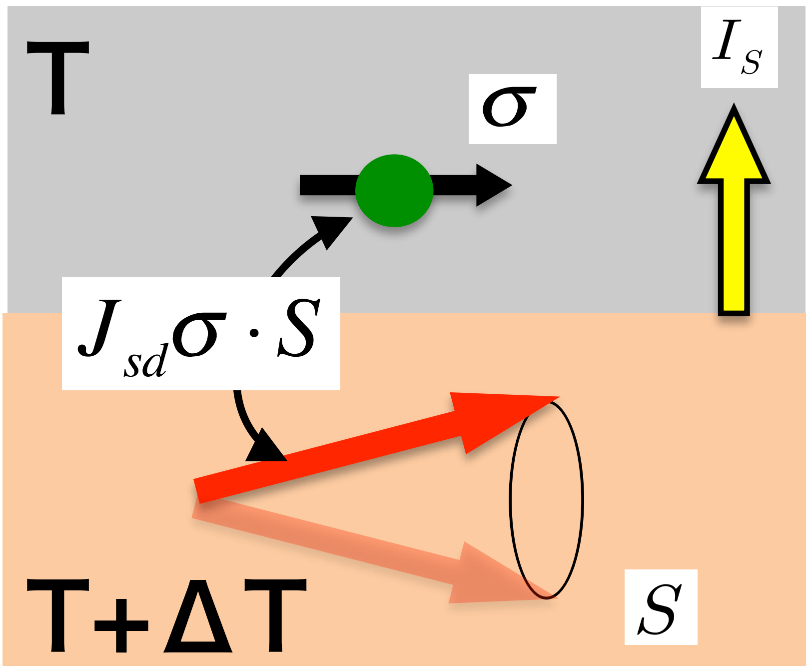


Two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

Nat. Commun. (2016)



Spin Seebeck effect in metal/ferromagnets

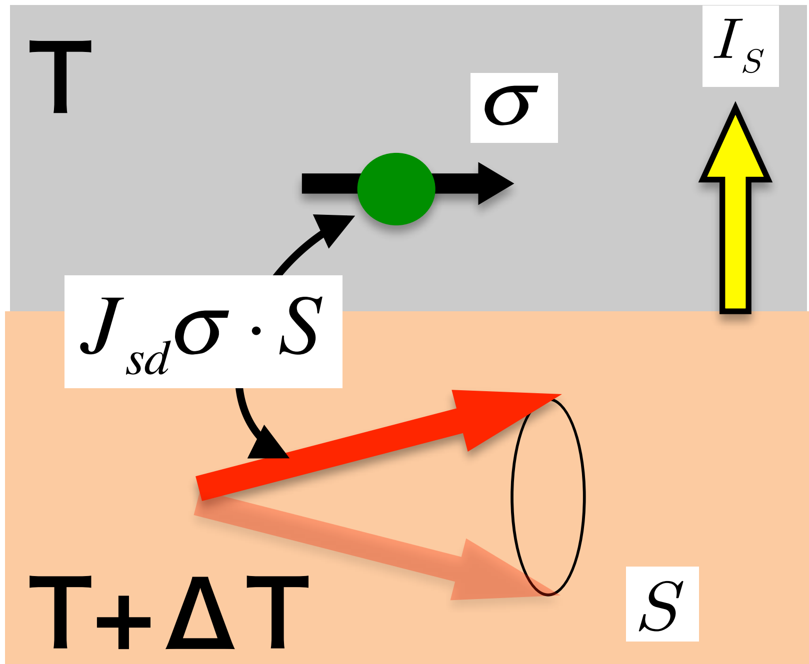


$$I_S^{FM} = \Delta T \int_\omega \tilde{J}_{sd}(\omega) D(\omega) \frac{\partial f(\omega)}{\partial T}$$

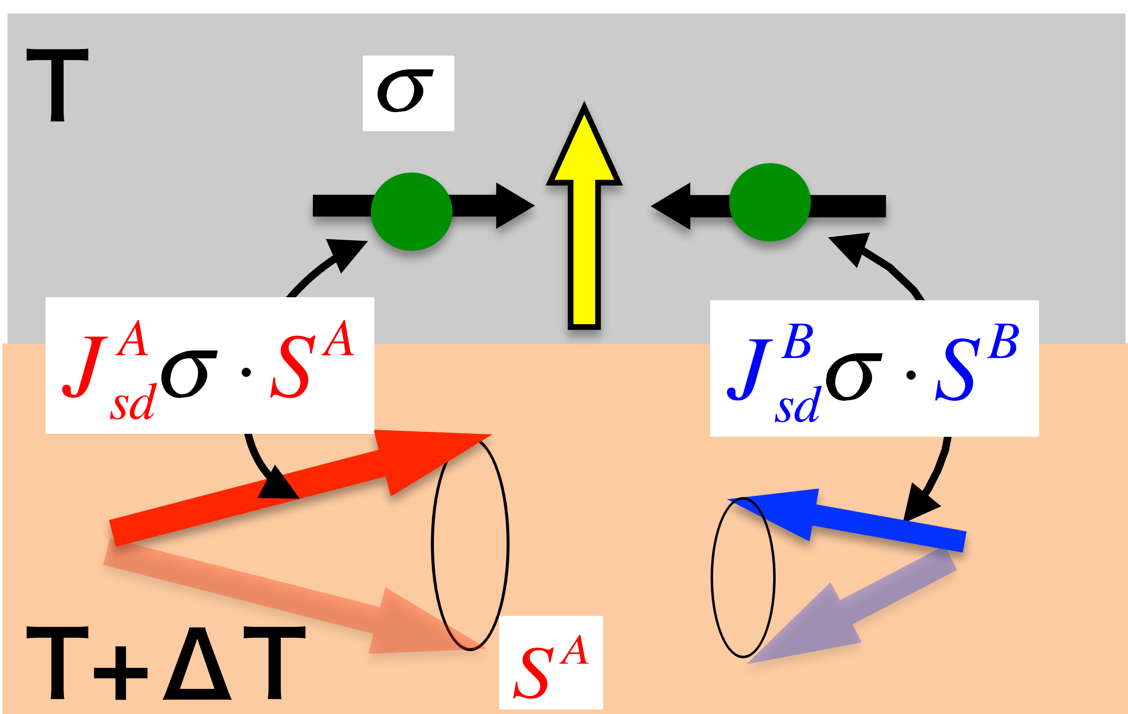
Effective exchange at interface

Number of magnons

Spin Seebeck effect in metal/*ferrimagnets*



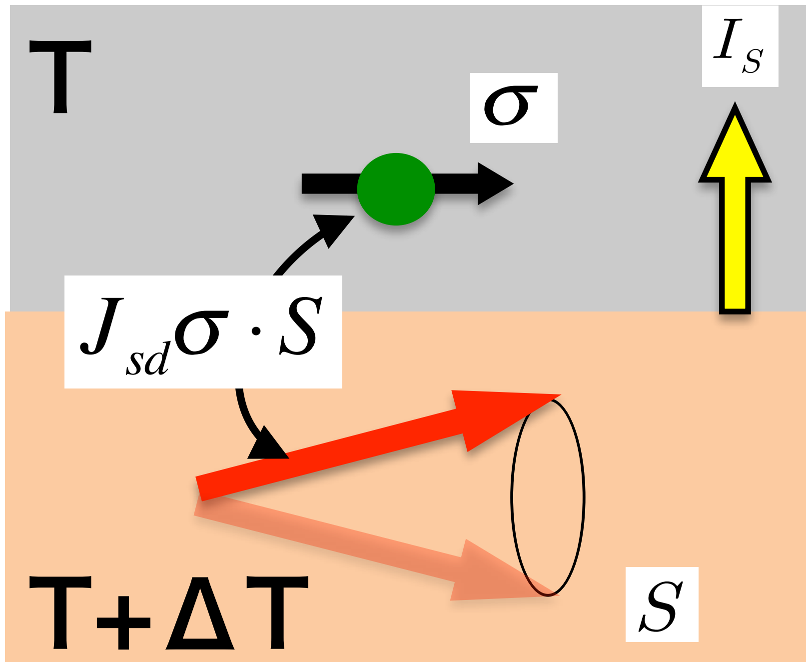
$$I_S^{FM} = \Delta T \int_\omega \tilde{J}_{sd}(\omega) D(\omega) \frac{\partial f(\omega)}{\partial T}$$



Two sub-lattice spins

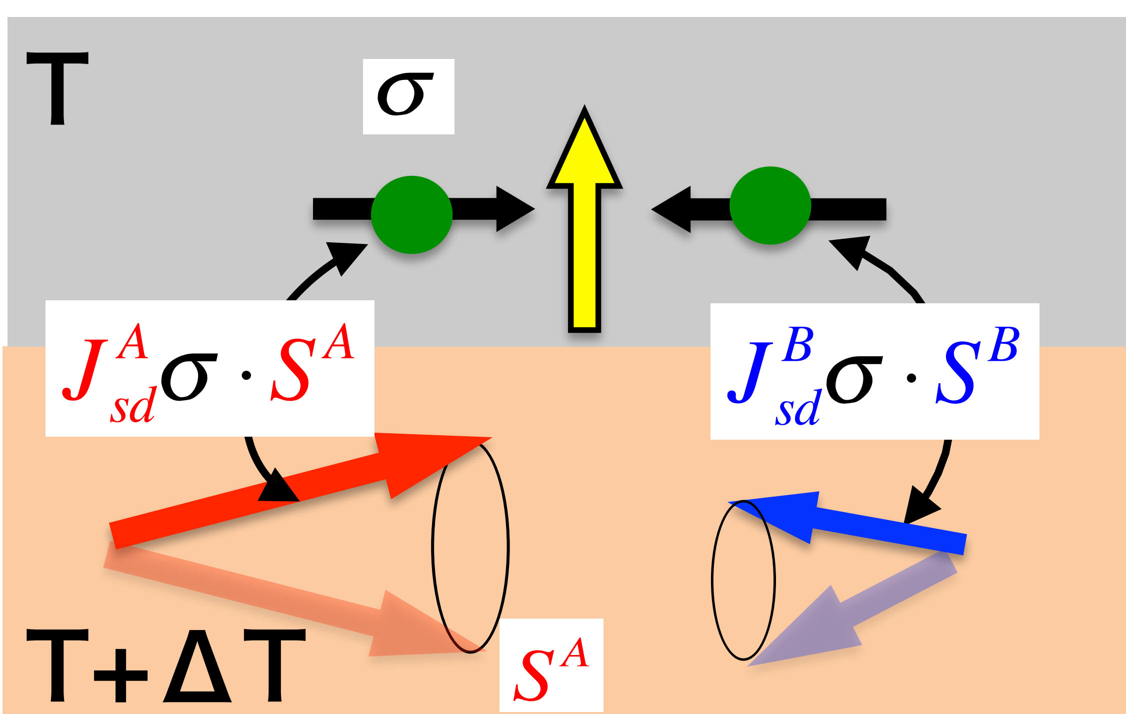
J^A_{sd} & J^B_{sd}

Spin Seebeck effect in metal/*ferrimagnets*



$$I_S^{FM} = \Delta T \int_\omega \tilde{J}_{sd}(\omega)\, D(\omega)\, \frac{\partial f(\omega)}{\partial T}$$

Mode decoupling



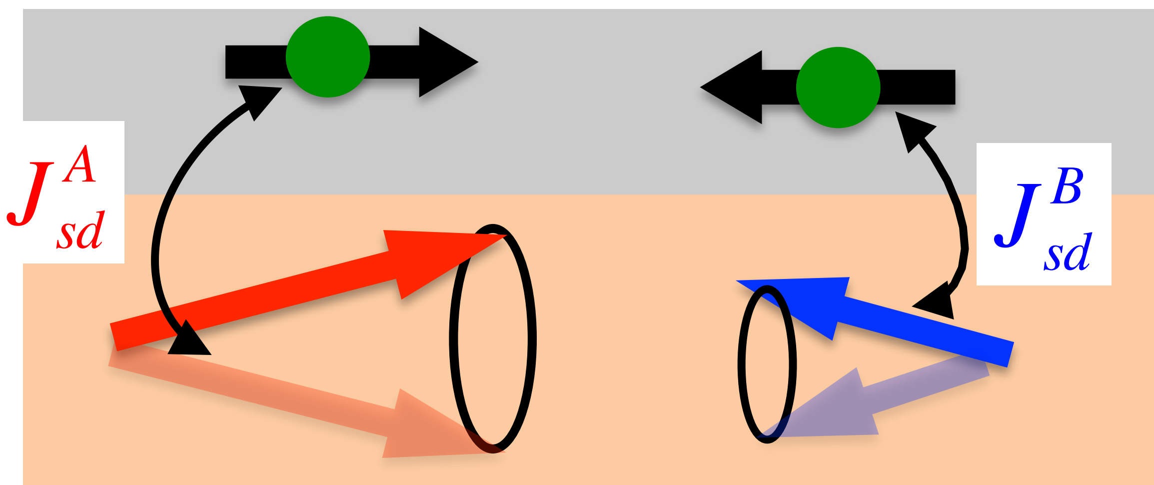
$$I_S^{Ferri} = I_S^{\alpha} - I_S^{\beta}$$

$$I_S^{\alpha} = \Delta T \int_\omega \tilde{J}_{sd}^{\alpha}(\omega)\, D^{\alpha}(\omega)\, \frac{\partial f(\omega)}{\partial T}$$

$$I_S^{\beta} = \Delta T \int_\omega \tilde{J}_{sd}^{\beta}(\omega)\, D^{\beta}(\omega)\, \frac{\partial f(\omega)}{\partial T}$$

Competition of two modes of magnons

$$I_S^{Ferri} = I_S^{\alpha} - I_S^{\beta}$$



$$I_S^{\alpha} = \Delta T \int_{\omega} \tilde{J}_{sd}^{\alpha}(\omega) \times \left[D^{\alpha}(\omega) \frac{\partial f(\omega)}{\partial T} \right]$$

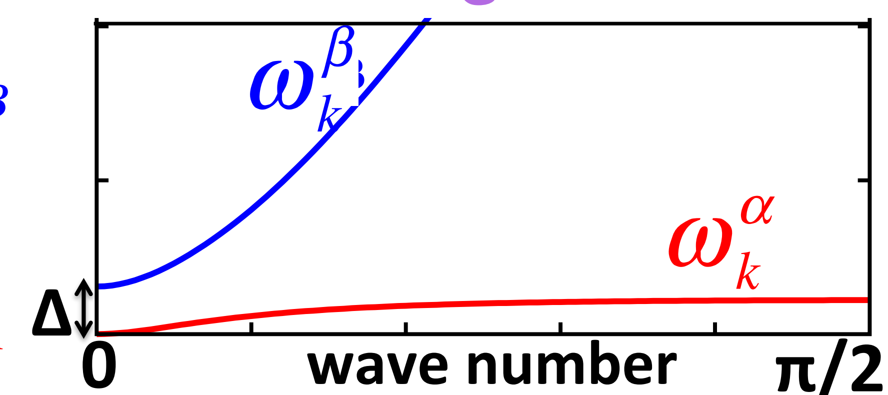
$$I_S^{\beta} = \Delta T \int_{\omega} \tilde{J}_{sd}^{\beta}(\omega) \times \left[D^{\beta}(\omega) \frac{\partial f(\omega)}{\partial T} \right]$$

Number of magnons

Effective exchange at interface

$$\tilde{J}_{sd}^{\alpha}(\omega) \sim \left(J_{sd}^{A}\right)^2 S^{A} + \left(\Delta / k_B T_N\right)\left(J_{sd}^{B}\right)^2 S^{B}$$

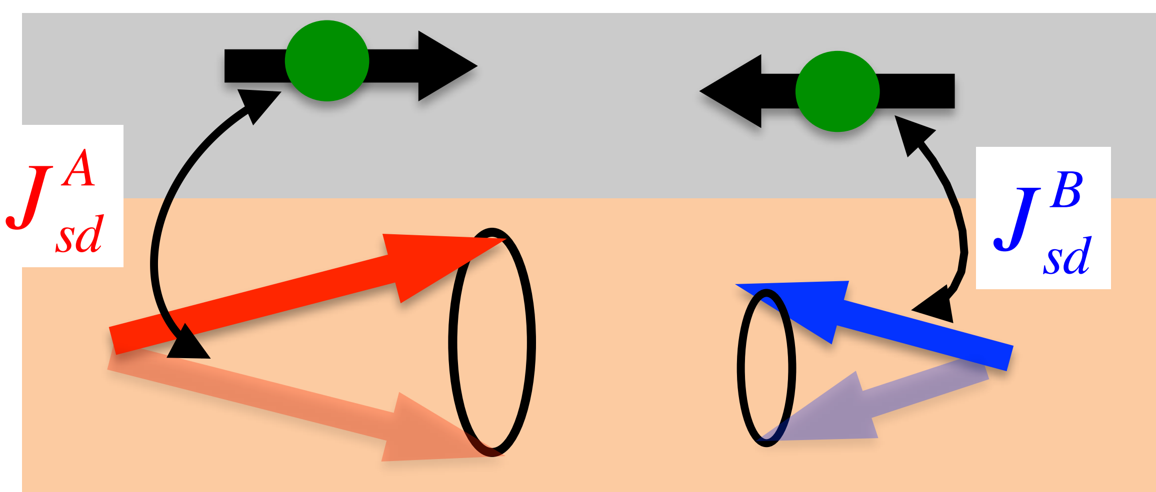
$$\tilde{J}_{sd}^{\beta}(\omega) \sim \left(J_{sd}^{B}\right)^2 S^{B} + \left(\Delta / k_B T_N\right)\left(J_{sd}^{A}\right)^2 S^{A}$$



$$\Delta = zJ_{AB}\left(S^{A} - S^{B}\right)$$

Competition of two modes of magnons

$$I_S^{Ferri} = I_S^{\alpha} - I_S^{\beta}$$



$$I_S^{\alpha} = \Delta T \int_{\omega} \boxed{\tilde{J}_{sd}^{\alpha}(\omega)} \times \boxed{\left[D^{\alpha}(\omega) \frac{\partial f(\omega)}{\partial T} \right]}$$

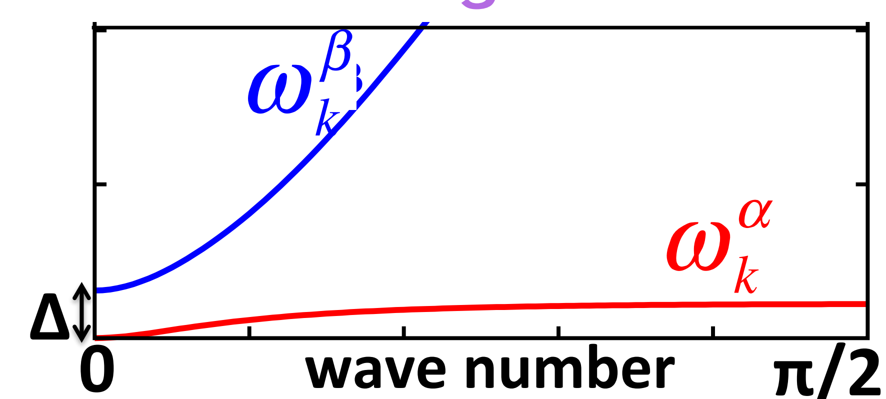
$$I_S^{\beta} = \Delta T \int_{\omega} \boxed{\tilde{J}_{sd}^{\beta}(\omega)} \times \boxed{\left[D^{\beta}(\omega) \frac{\partial f(\omega)}{\partial T} \right]}$$

Number of magnons

Effective exchange at interface (dominant)

$$\tilde{J}_{sd}^{\alpha}(\omega) \sim \left(J_{sd}^{A}\right)^2 S^{A}$$

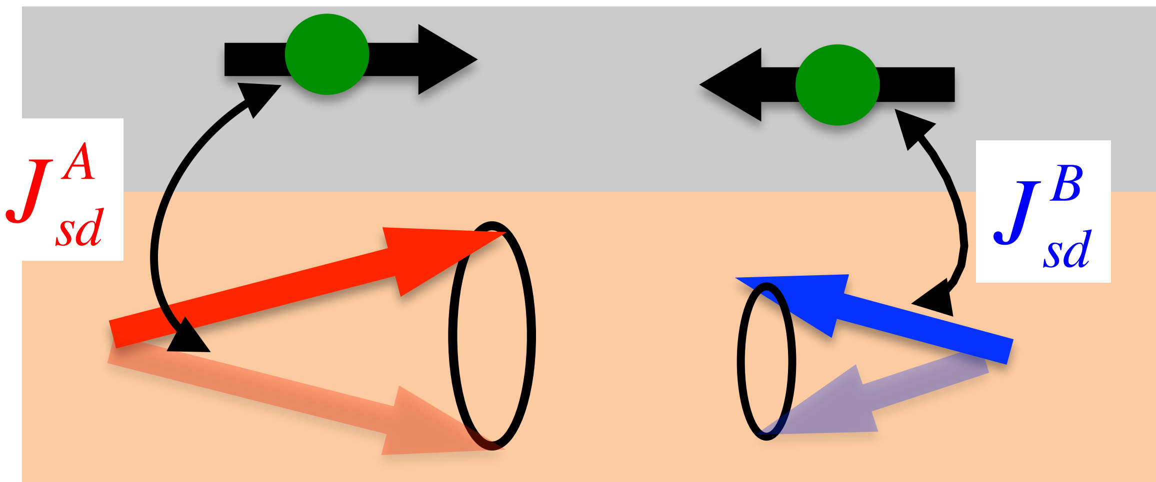
$$\tilde{J}_{sd}^{\beta}(\omega) \sim \left(J_{sd}^{B}\right)^2 S^{B}$$



$$\Delta = zJ_{AB}\left(S^{A} - S^{B}\right)$$

Competition of two modes of magnons

$$I_S^{Ferri} = I_S^{\alpha} - I_S^{\beta}$$



$$I_S^{\alpha} = \Delta T \int_{\omega} \tilde{J}_{sd}^{\alpha}(\omega) \times \left[D^{\alpha}(\omega) \frac{\partial f(\omega)}{\partial T} \right]$$

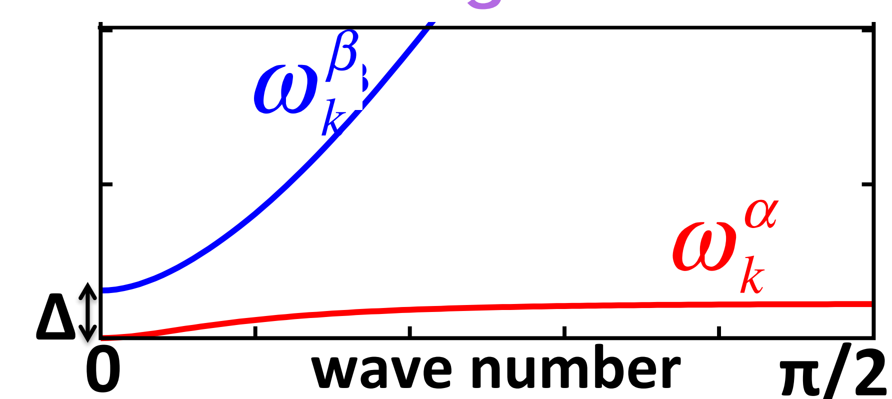
$$I_S^{\beta} = \Delta T \int_{\omega} \tilde{J}_{sd}^{\beta}(\omega) \times \left[D^{\beta}(\omega) \frac{\partial f(\omega)}{\partial T} \right]$$

Number of magnons

Effective exchange at interface (dominant)

$$\tilde{J}_{sd}^{\alpha}(\omega) \sim \left(J_{sd}^{A}\right)^2 S^{A}$$

$$\tilde{J}_{sd}^{\beta}(\omega) \sim \left(J_{sd}^{B}\right)^2 S^{B}$$



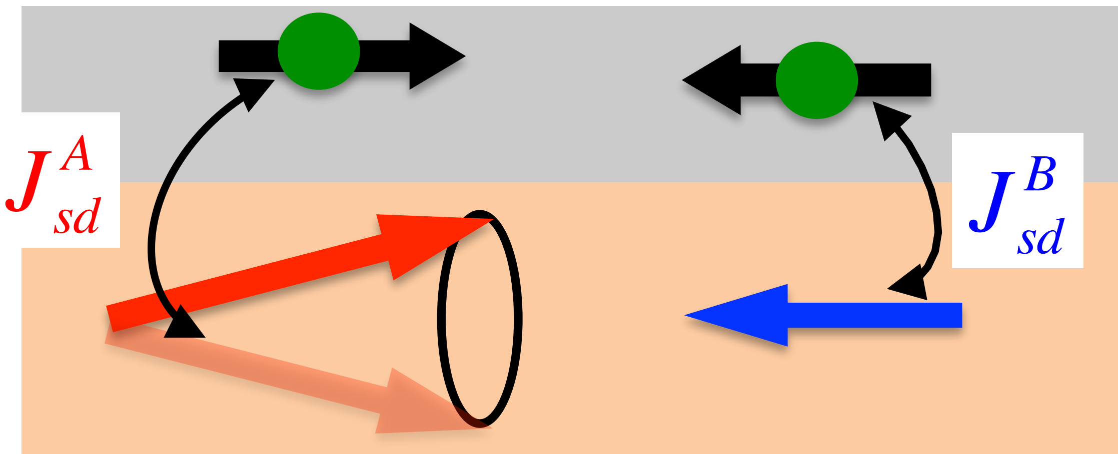
$$\Delta = zJ_{AB}\left(S^{A} - S^{B}\right)$$

(spin A is Gd) $J_{sd}^{A} << J_{sd}^{B}$ ➡ $\tilde{J}_{sd}^{\alpha}(\omega) << \tilde{J}_{sd}^{\beta}(\omega)$

$\omega_{k=0}^{\beta} = \Delta, \omega_{k=0}^{\alpha} \sim 0$ ➡ $D^{\alpha}(\omega)\frac{\partial f}{\partial T} >> D^{\beta}(\omega)\frac{\partial f}{\partial T}$

Origin of the 2nd sign change

$$\Delta > k_B T$$



$$D^{\beta}(\omega)\frac{\partial f}{\partial T} \sim 0 \Rightarrow I_S^{\beta} = 0$$

$$I_S = I_S^{\alpha}$$

Spin current from mode alpha is dominant.

$$\Delta < k_B T$$

$$J_{sd}^{A} \ll J_{sd}^{B} \Rightarrow I_S^{\alpha} \ll I_S^{\beta}$$

$$I_S = -I_S^{\beta}$$

Spin current from mode beta is dominant.

Origin of the 2nd sign change

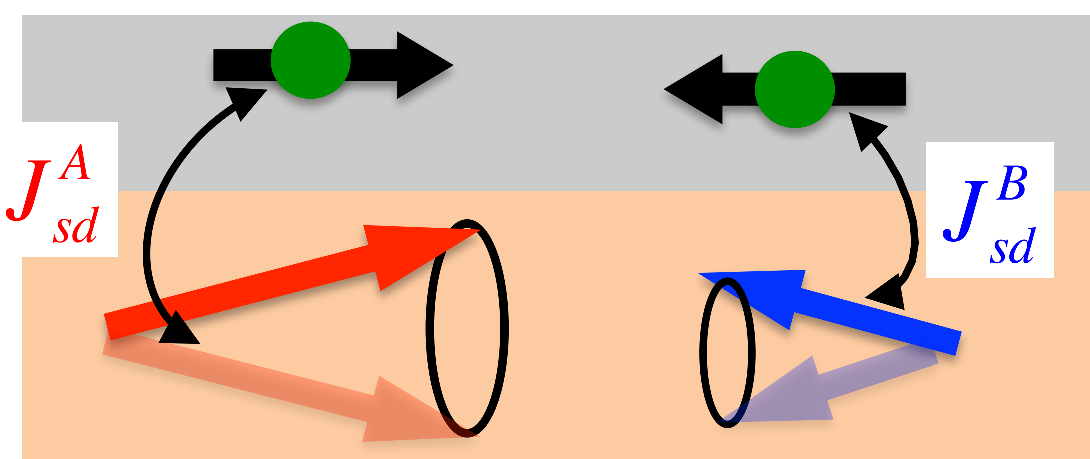
$\Delta > k_B T$

$D^{\beta}(\omega)\frac{\partial f}{\partial T} \sim 0 \Rightarrow I_S^{\beta} = 0$

$I_S = I_S^{\alpha}$

Spin current from mode alpha is dominant.

$\Delta < k_B T$



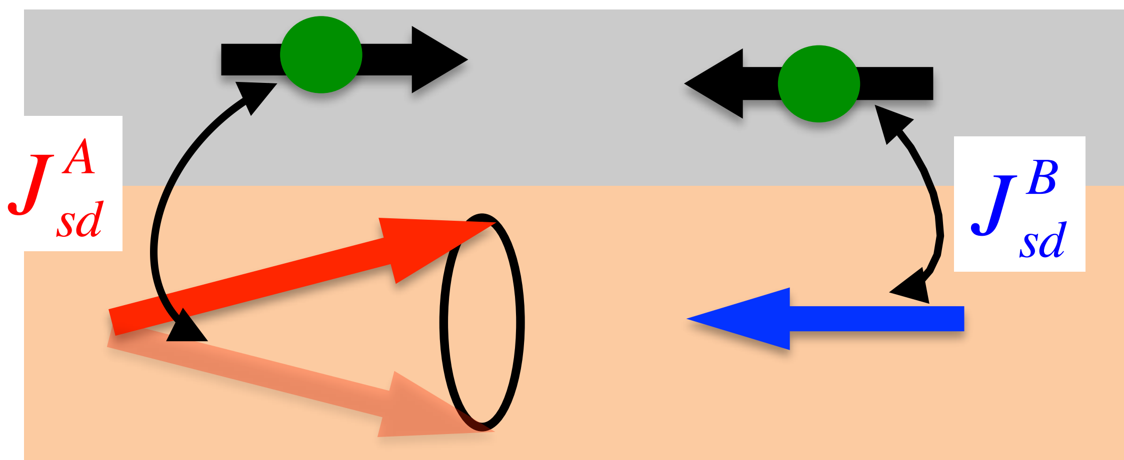
$J_{sd}^{A} \ll J_{sd}^{B} \Rightarrow I_S^{\alpha} \ll I_S^{\beta}$

$I_S = -I_S^{\beta}$

Spin current from mode beta is dominant.

Origin of the 2nd sign change

$\Delta > k_B T$

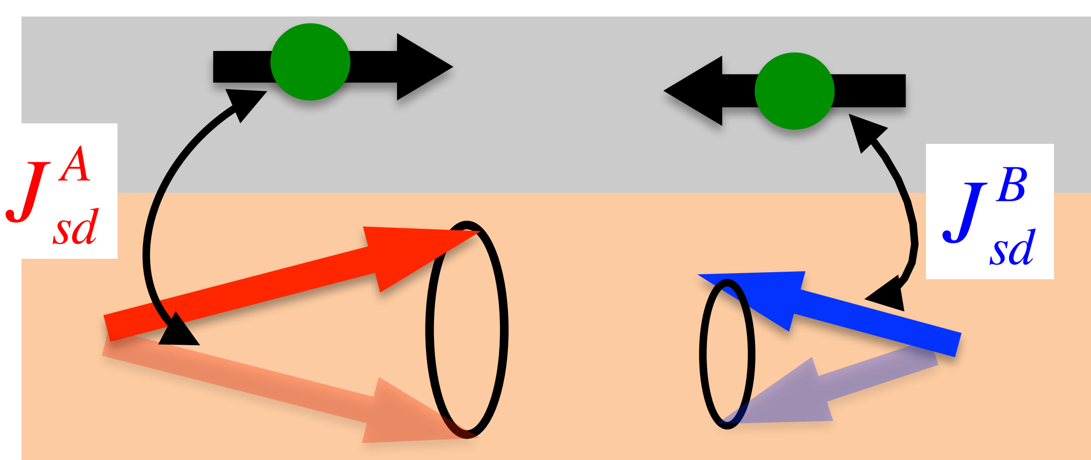


$$D^{\beta}(\omega)\frac{\partial f}{\partial T} \sim 0 \Rightarrow I_S^{\beta} = 0$$

$$I_S = I_S^{\alpha}$$

Spin current from mode alpha is dominant.

$\Delta < k_B T$



$$J_{sd}^{A} \ll J_{sd}^{B} \Rightarrow I_S^{\alpha} \ll I_S^{\beta}$$

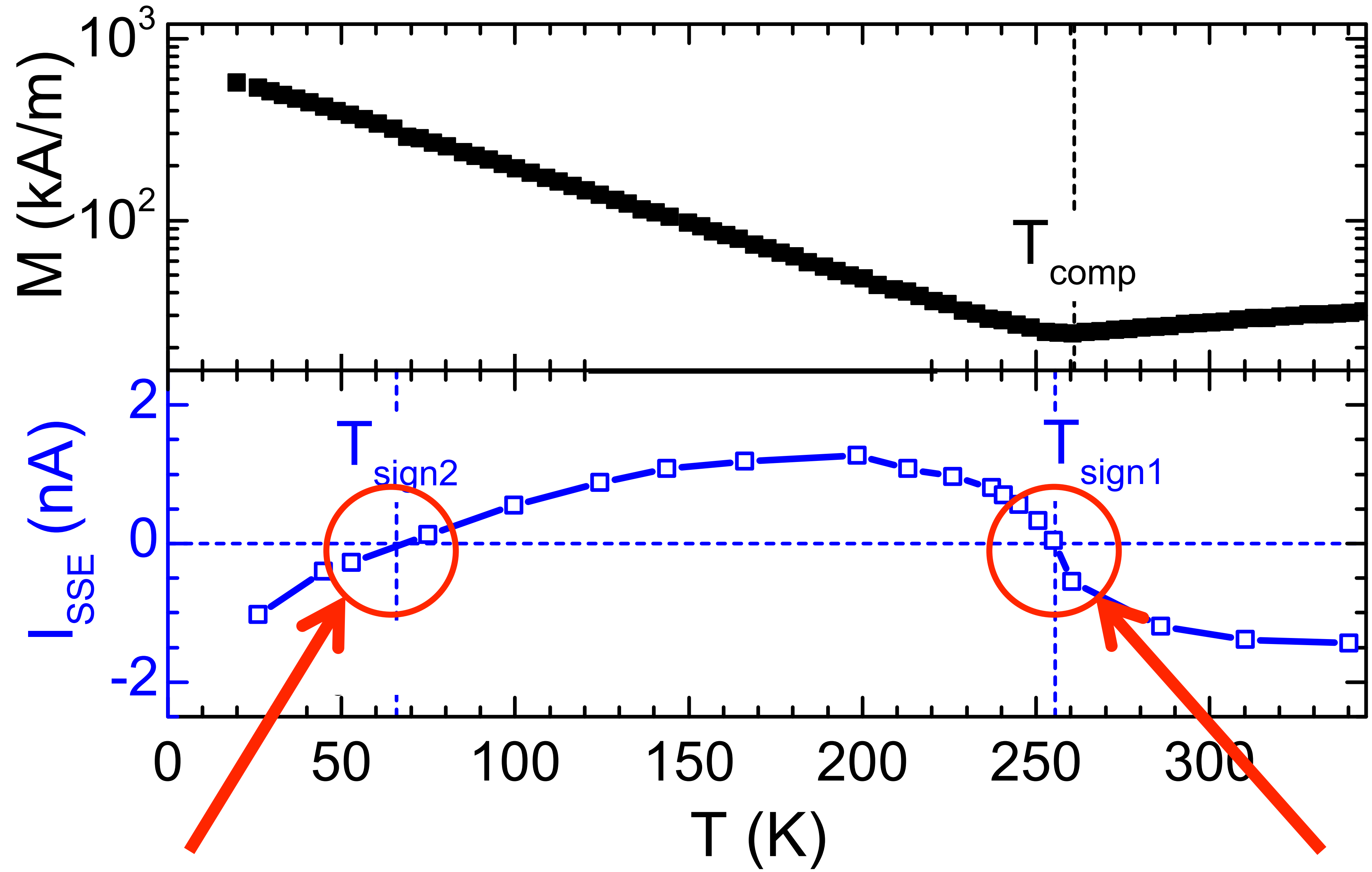
$$I_S = -I_S^{\beta}$$

Spin current from mode beta is dominant.

Competition of magnons causes 2nd sign change.

Origins of two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

Nat. Commun. 2016

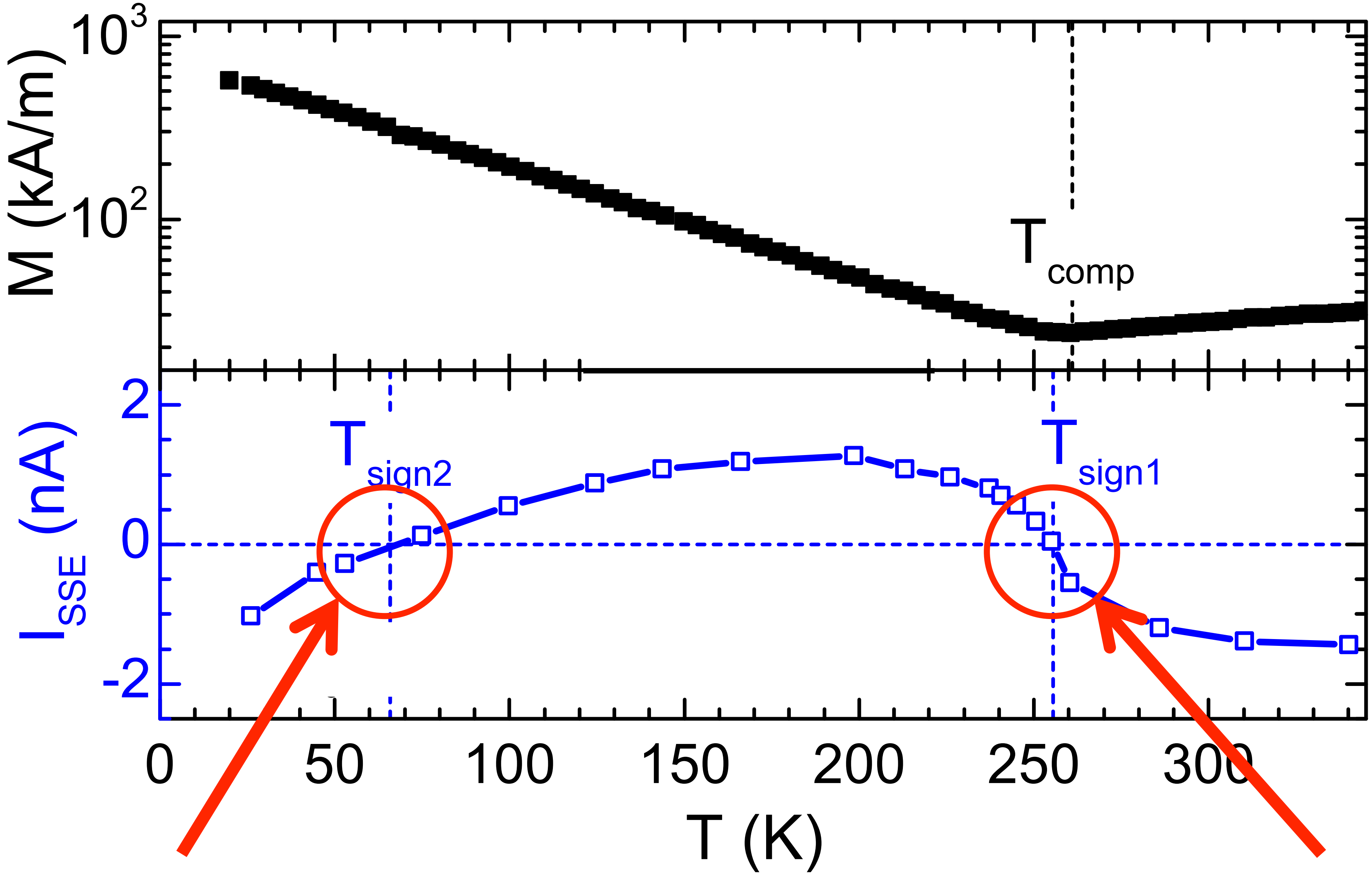


2nd sign change

1st sign change

Origins of two sign changes of spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt

Nat. Commun. 2016



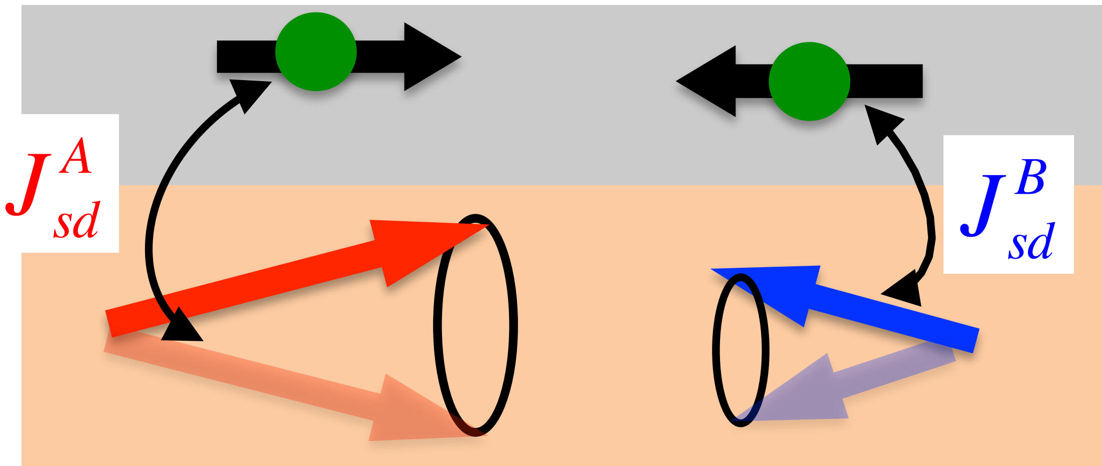
Competition of magnons

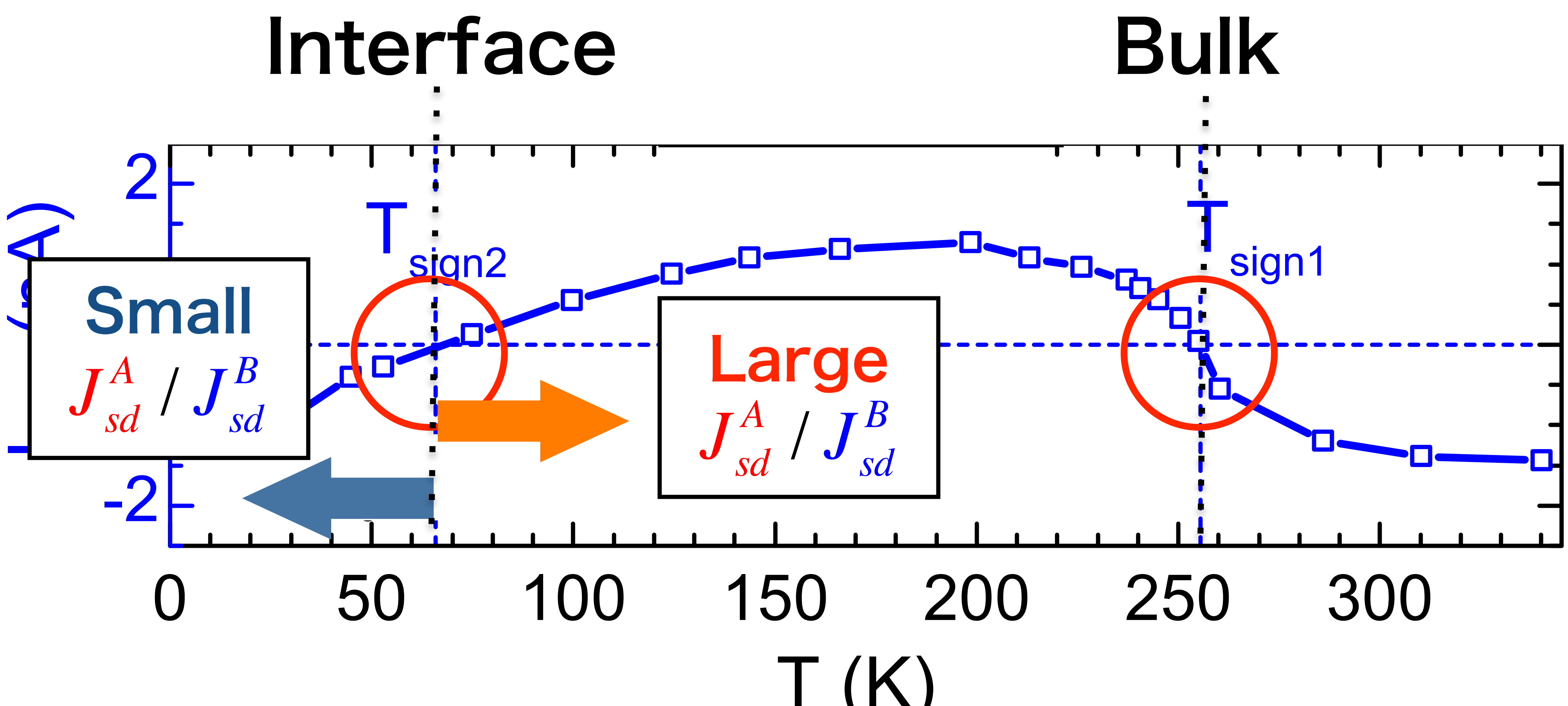
Compensation effect

T_{sign2} and interfacial interaction

$$\tilde{J}^{\alpha}_{sd}(\omega) \sim \left(J^{A}_{sd}\right)^2 S^{A}$$

$$\tilde{J}^{\beta}_{sd}(\omega) \sim \left(J^{B}_{sd}\right)^2 S^{B}$$

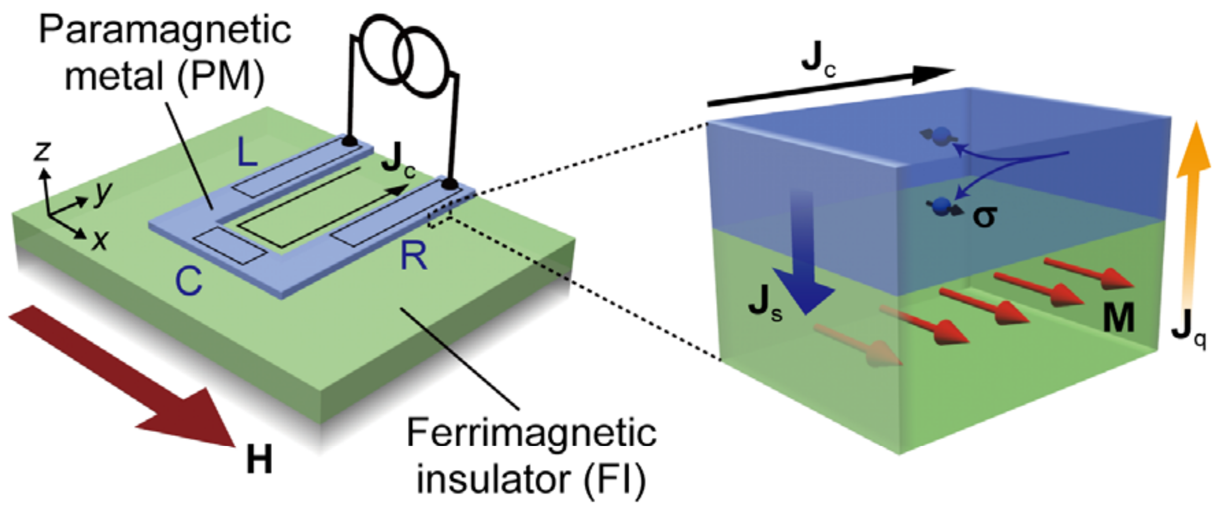


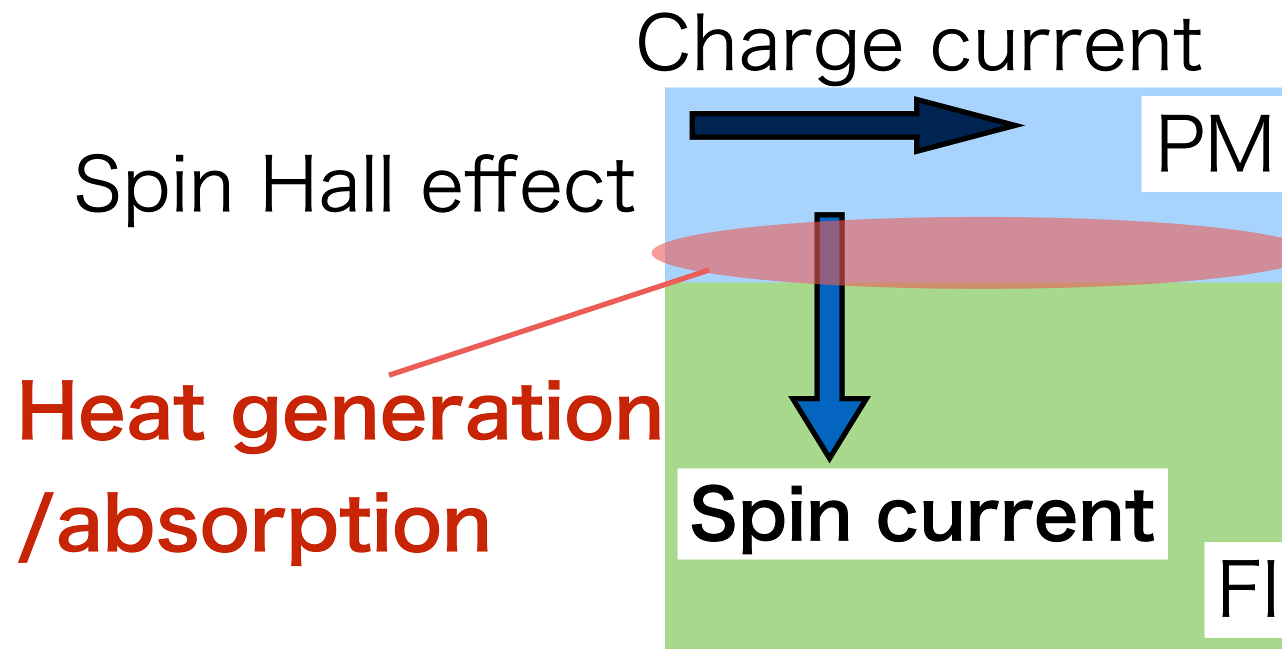


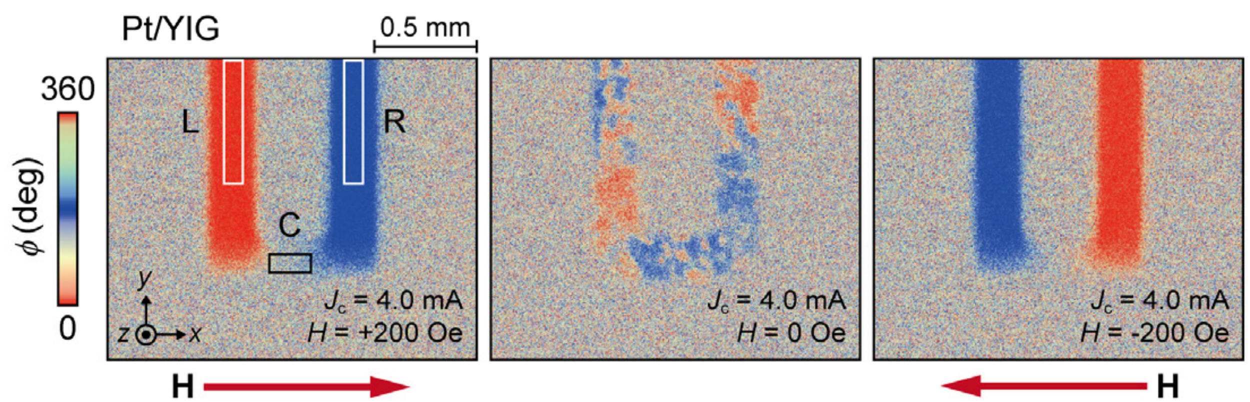
$$T_{sign2} \rightarrow J^{A}_{sd} / J^{B}_{sd}$$

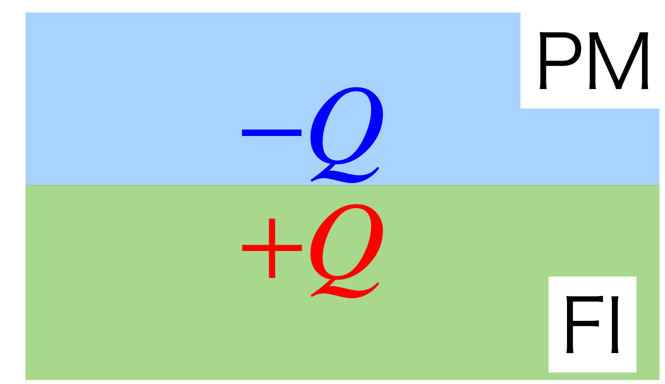
Spin Peltier effect

Spin Peltier effect









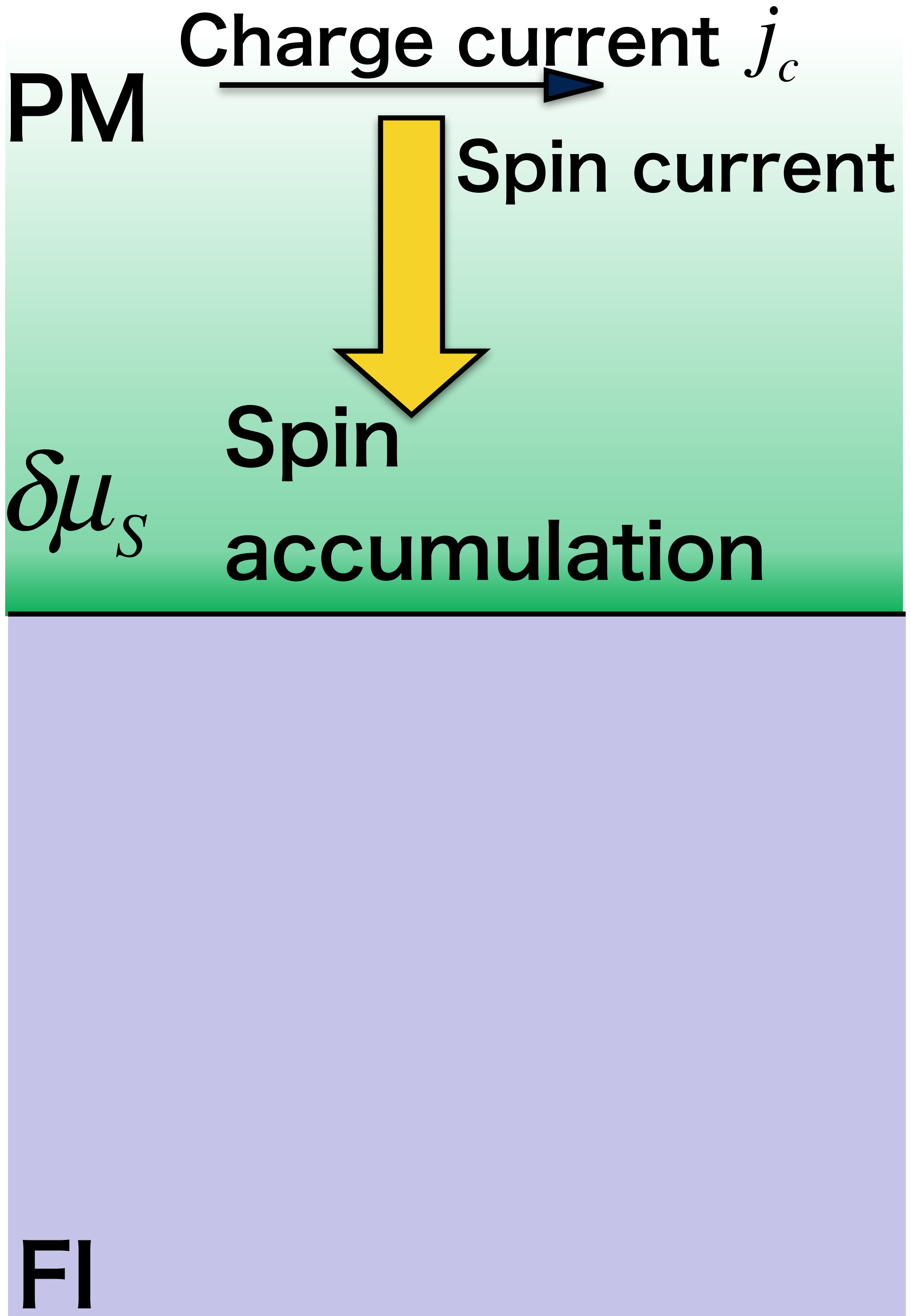
Daimon

Flipse et al., PRL (2014)
Daimon et al., Nat. Commun. (2016)
Uchida et al., PRB (2017)
Daimon et al., PRB (2017)

ΔT : 0.5mK (2.0mA)

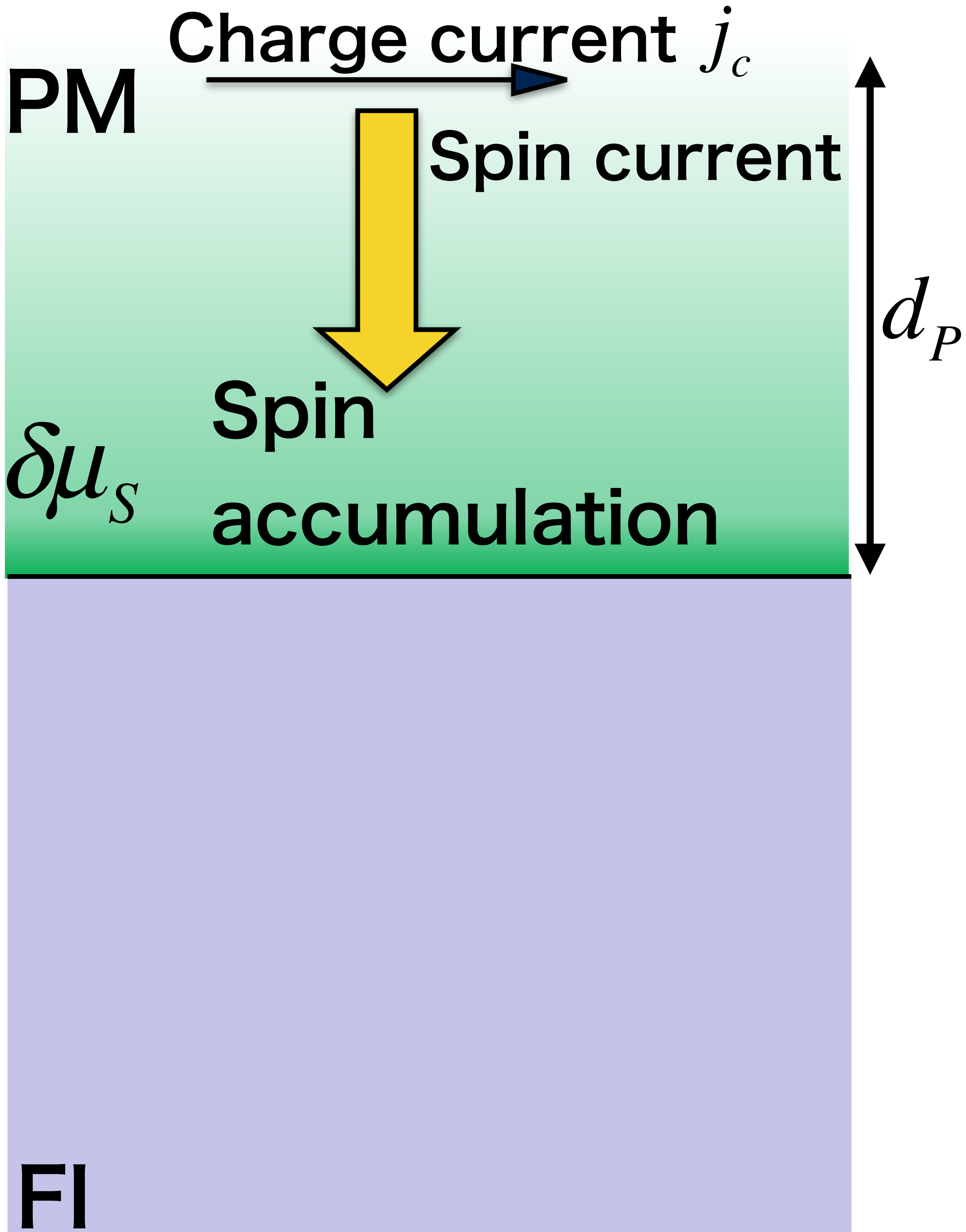
Heat generation and absorption due to spin current

Outline of our theory



Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Outline of our theory



Spin accumulation $\delta\mu_S := \mu_\uparrow - \mu_\downarrow$

From the spin diffusion equation in PM,

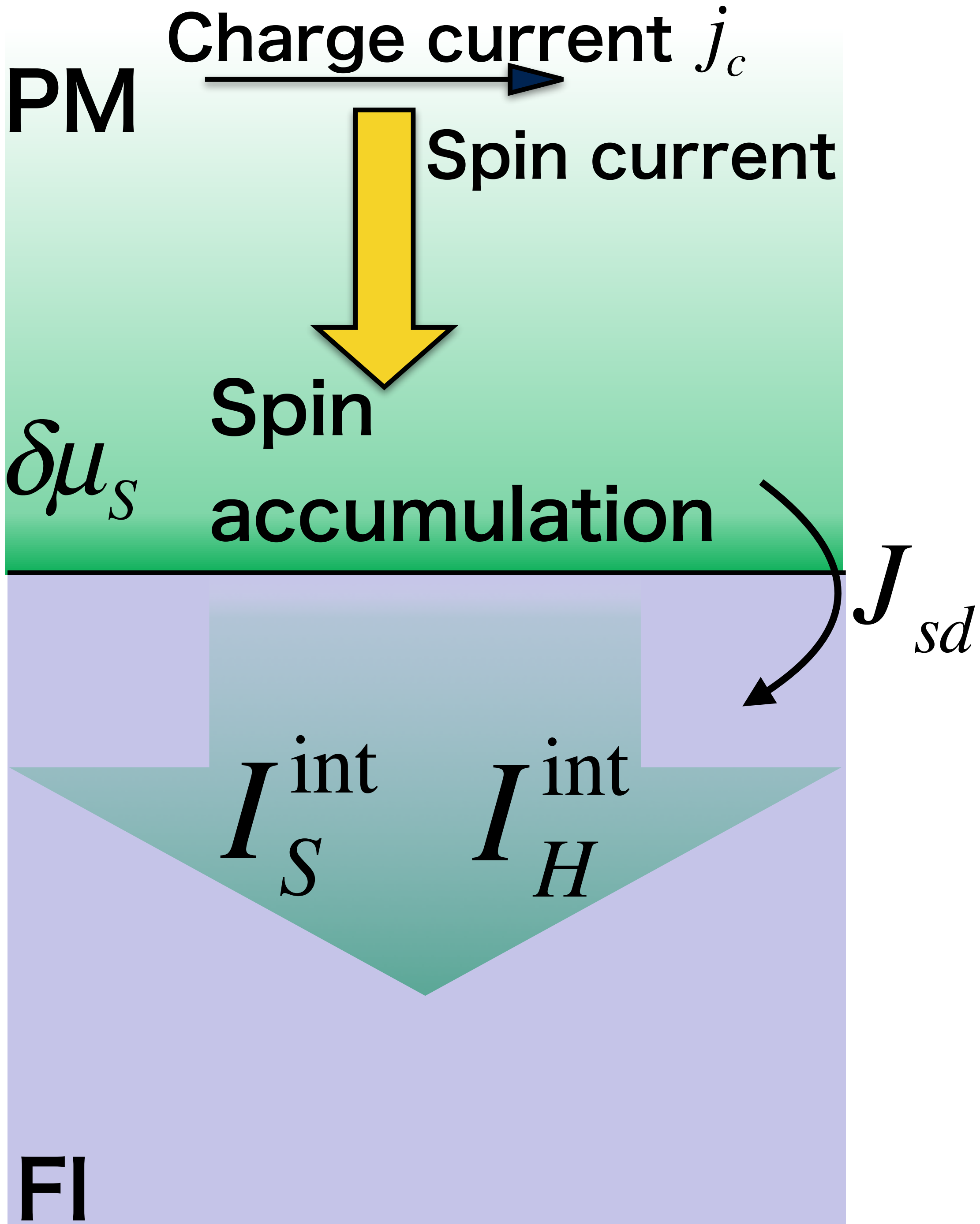
$$\delta\mu_S = 2e\alpha_{SH}\lambda_P\rho_P j_c \tanh\left(d_P / 2\lambda_P\right)$$

Spin Hall angle	Relaxation length

S. Zhang 2000

Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Outline of our theory



Spin accumulation $\delta\mu_S := \mu_\uparrow - \mu_\downarrow$

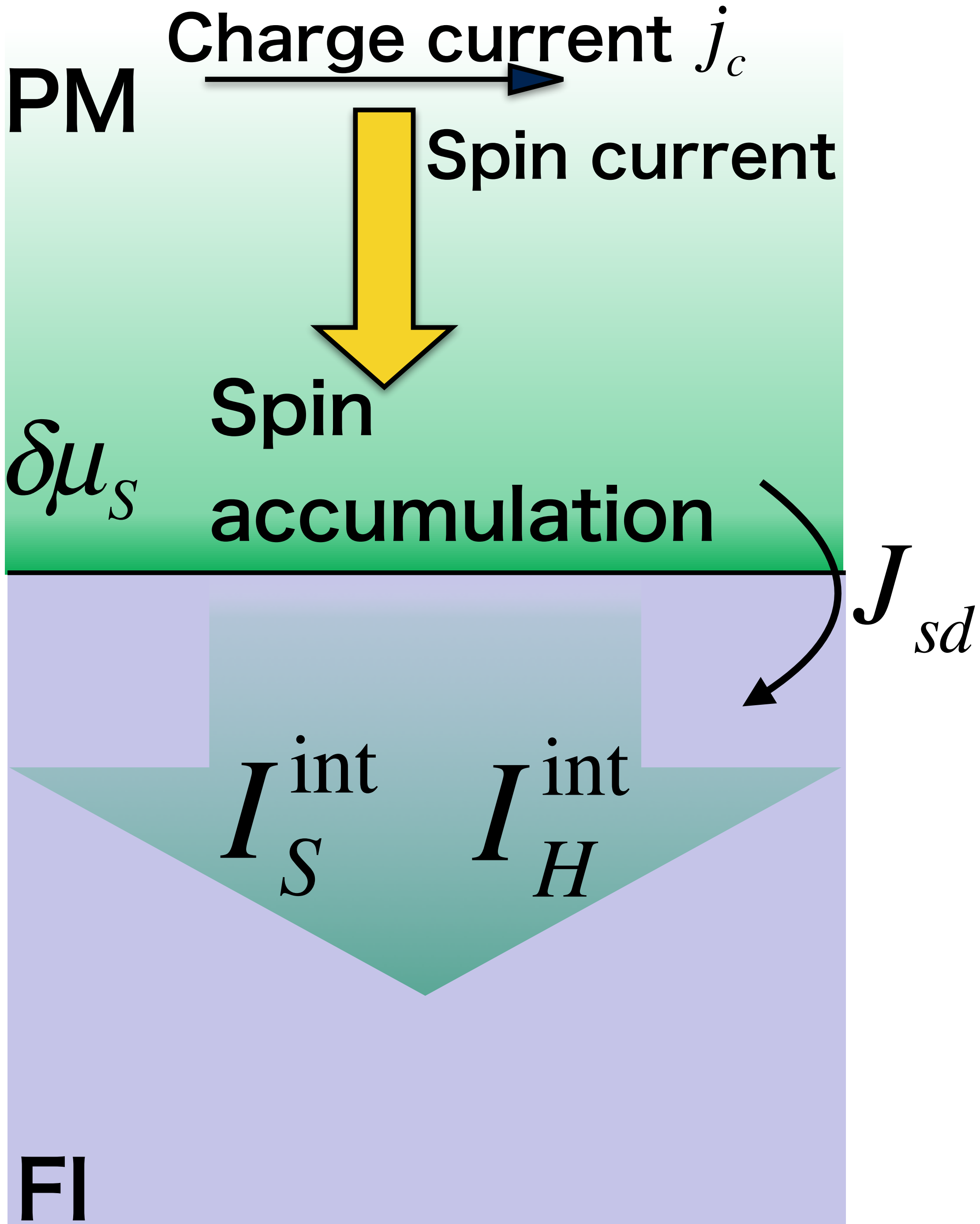
From the spin diffusion equation in PM,

$$\delta\mu_S = 2e\alpha_{SH}\lambda_P\rho_P j_c \tanh\left(d_P / 2\lambda_P\right)$$

S. Zhang 2000

Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Outline of our theory



Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Spin accumulation $\delta\mu_S := \mu_\uparrow - \mu_\downarrow$

From the spin diffusion equation in PM,

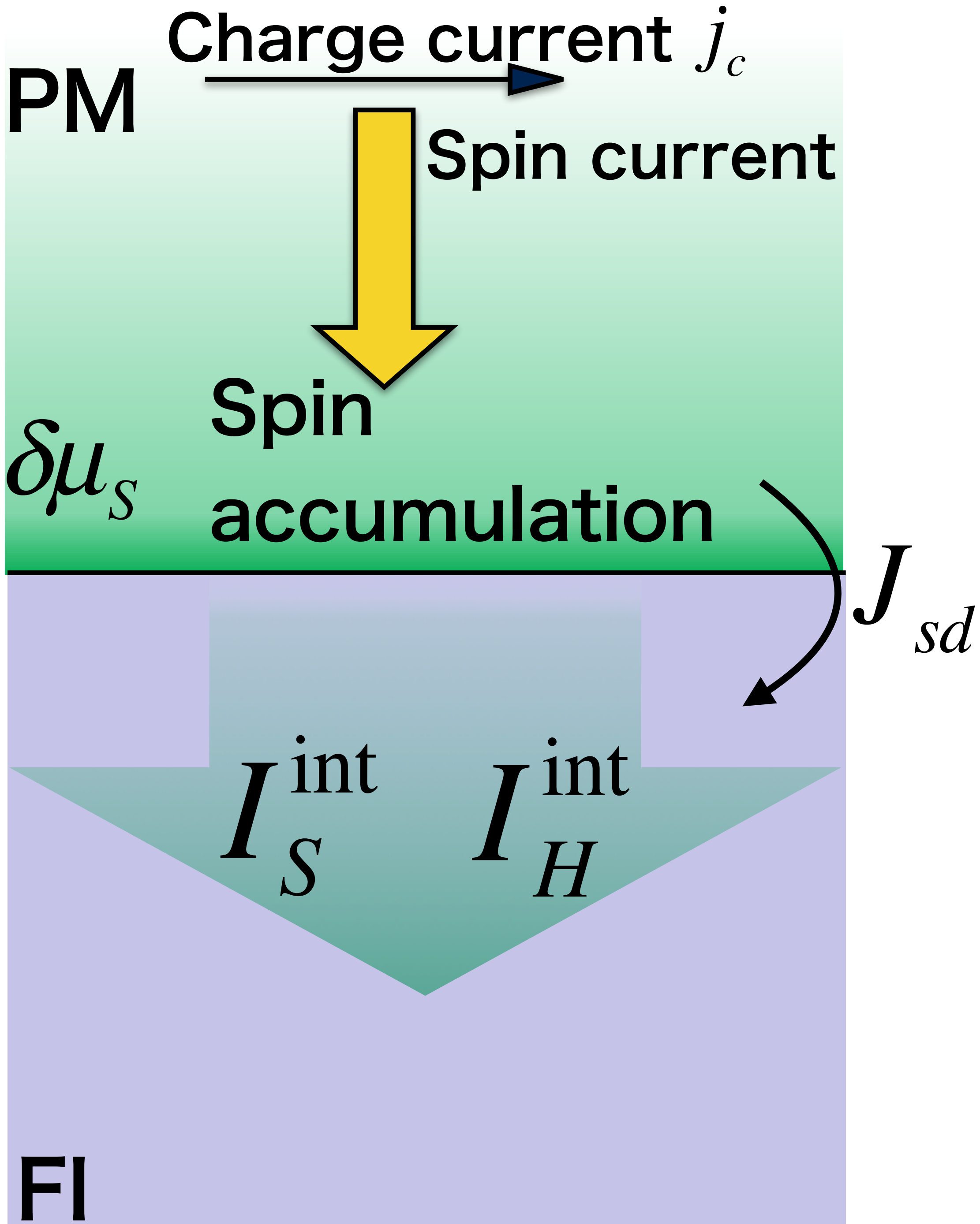
$$\delta\mu_S = 2e\alpha_{SH}\lambda_P\rho_P j_c \tanh\left(d_P / 2\lambda_P\right)$$

S. Zhang 2000

	$\delta\mu_S$	$\Delta T\ (= T_N - T_F)$
Spin $I_S^{\rm int}$	Spin injection	SSE
Heat $I_H^{\rm int}$	SPE	Heat Transport

Heat current injection due to spin accumulation

Outline of our theory



Spin accumulation $\delta\mu_S := \mu_\uparrow - \mu_\downarrow$

From the spin diffusion equation in PM,

$$\delta\mu_S = 2e\alpha_{SH}\lambda_P\rho_P j_c \tanh\left(d_P / 2\lambda_P\right)$$

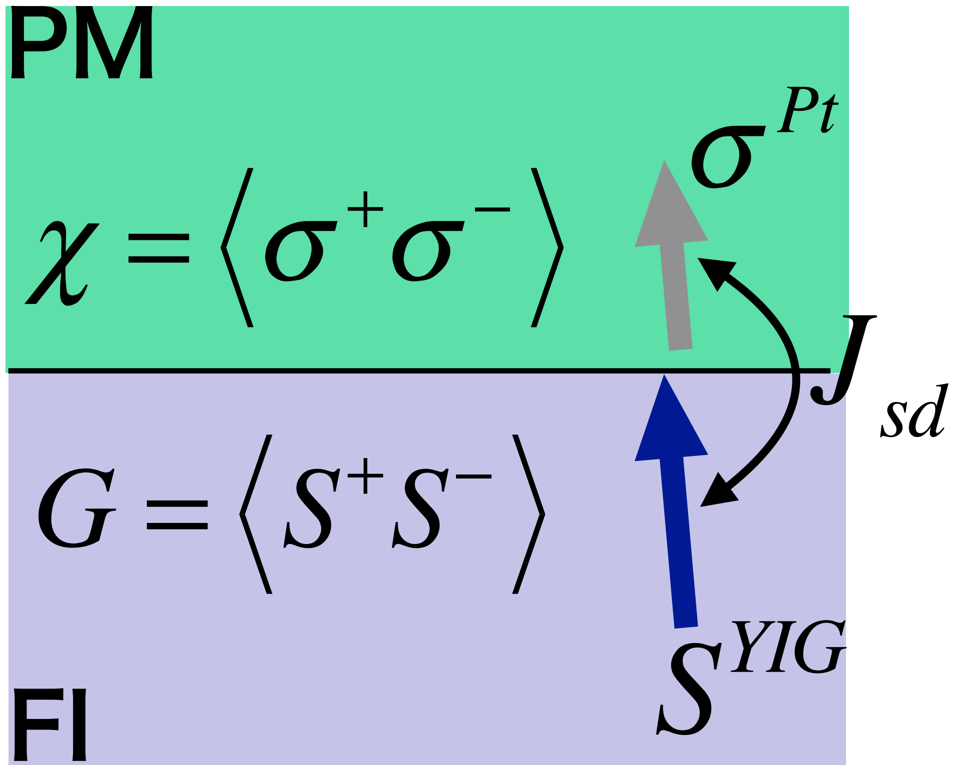
S. Zhang 2000

	$\delta\mu_S$	$\Delta T \ (= T_N - T_F)$
Spin I_S^{int}	**Spin injection**	**SSE**
Heat I_H^{int}	**SPE**	**Heat Transport**

Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Onsager's reciprocal relation

Spin current injection into FI



Spin injection into FI

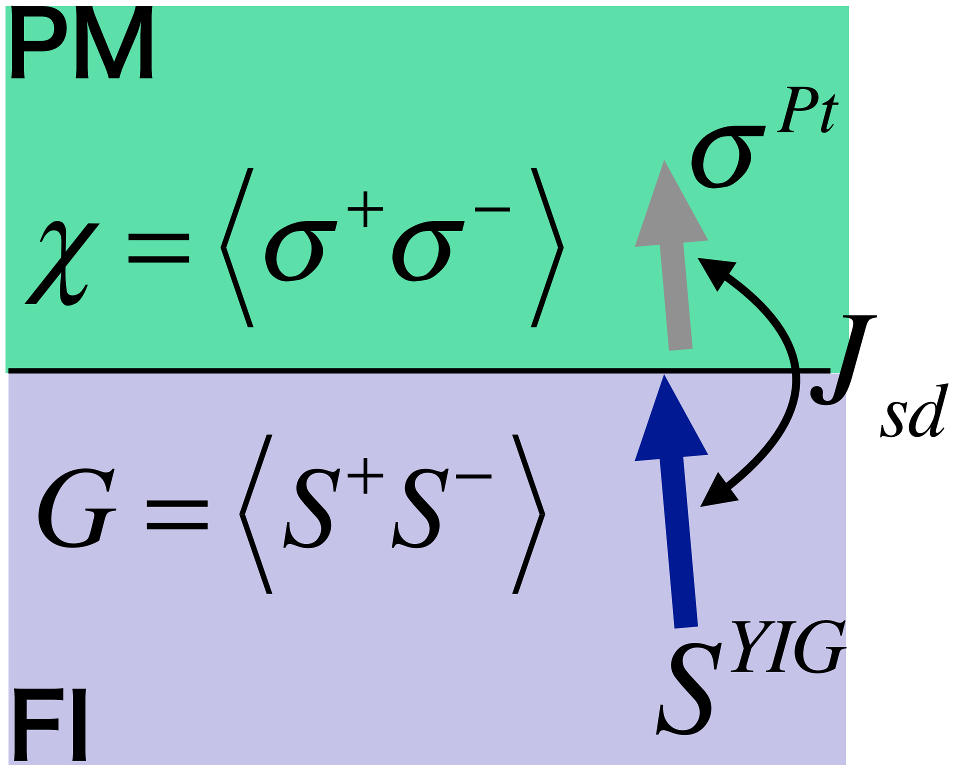
$$I_S^{\mathrm{int}} = -\sum_i \langle \partial_t \sigma_i^z \rangle$$

König & Martinek 2003

Adachi 2011

Ohnuma 2013, 2014, 2017

Spin current injection into FI



Spin injection into FI

$$I_S^{\mathrm{int}} = -\sum_i \langle \partial_t \sigma_i^z \rangle$$

König & Martinek 2003
Adachi 2011
Ohnuma 2013, 2014, 2017

$$\boxed{H = J_{sd} \sum_i \sigma_i \cdot S_i}$$

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\, \chi_{q\omega}^R \, \mathrm{Im}\, G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Spin current = Interfacial Exchange × **DOS of PM** × **DOS of FI** × **Diff. of distribution**

Spin injection and spin Seebeck effect

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Spin current = Interfacial Exchange × DOS of PM × DOS of FI × Diff. of distribution

Spin injection

Spin Seebeck effect

Spin injection and spin Seebeck effect

$$I_S^{\text{int}} = J_{sd}^2 \int_{kq\omega} \operatorname{Im}\chi_{q\omega}^R \operatorname{Im}G_{k\omega}^R \left(f_\omega^P - f_\omega^F\right)$$

Spin current = Interfacial Exchange × DOS of PM × DOS of FI × Diff. of distribution

Spin injection

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar\partial\omega}\delta\mu_S$$

Spin accumulation

Spin Seebeck effect

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T}\Delta T$$

$$\Delta T \coloneqq T_{PM} - T_{FI}$$

Temperature difference

Spin injection and spin Seebeck effect

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F\right)$$

Spin current = Interfacial Exchange × DOS of PM × DOS of FI × Diff. of distribution

Spin injection

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \frac{\partial f_\omega^{BE}}{\hbar\,\partial\omega}\delta\mu_S$$

Spin accumulation

Spin Seebeck effect

$$I_S^{SSE} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \frac{\partial f_\omega^{BE}}{\partial T}\Delta T$$

Temperature difference

Heat-current injection into FI

Spin current

$$I_S^{\mathrm{int}} = -\sum_i \left\langle \partial_t \sigma_i^z \right\rangle$$

Time derivative of spin in PM

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Interfacial exchange	DOS in PM	DOS in FI	Diff. of distribution

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar \partial \omega} \delta\mu_S$$

Spin injection

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T} \Delta T$$

SSE

Heat-current injection into FI

Spin current

$$I_S^{\mathrm{int}} = -\sum_i \langle \partial_t \sigma_i^z \rangle$$

Time derivative of spin in PM

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Interfacial exchange	DOS in PM	DOS in FI	Diff. of distribution

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar \partial \omega} \delta\mu_S$$

Spin injection

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T} \Delta T$$

SSE

Heat current

$$I_H^{\mathrm{int}} = \sum_i \langle \partial_t H_F \rangle$$

Time derivative of Hamiltonian of FI

Maki & Griffine (1965)

$$H_F = J \sum_{ij} S_i \cdot S_j - g\mu_B H_0 \sum_i S_i^z$$

Heat-current injection into FI

Spin current

$$I_S^{\text{int}} = -\sum_i \langle \partial_t \sigma_i^z \rangle$$

Time derivative of spin in PM

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_S^{\text{int}} = J_{sd}^2 \int_{kq\omega} \operatorname{Im} \chi_{q\omega}^R \operatorname{Im} G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Interfacial exchange	DOS in PM	DOS in FI	Diff. of distribution

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar \partial \omega} \delta\mu_s$$ Spin injection

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T} \Delta T$$ SSE

Heat current

$$I_H^{\text{int}} = \sum_i \langle \partial_t H_F \rangle$$

Time derivative of Hamiltonian of FI

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_H^{\text{int}} = J_{sd}^2 \int_{kq\omega} \hbar\omega \operatorname{Im} \chi_{q\omega}^R \operatorname{Im} G_{k\omega}^R \left(f_\omega^P - f_\omega^F \right)$$

Interfacial exchange	$\langle H \rangle$	DOS in PM	DOS in FI	Diff. of distribution

Heat transport driven by spin accumulation

Spin current

$$I_S^{\mathrm{int}} = -\sum_i \langle \partial_t \sigma_i^z \rangle$$

Time derivative of spin in PM

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_S^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F\right)$$

Interfacial exchange | DOS in PM | DOS in FI | Diff. of distribution

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar \partial \omega} \delta\mu_s$$ Spin injection

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T} \Delta T$$ SSE

Heat current

$$I_H^{\mathrm{int}} = \sum_i \langle \partial_t H_F \rangle$$

Time derivative of Hamiltonian of FI

$$H = J_{sd} \sum_i \sigma_i \cdot S_i$$

$$I_H^{\mathrm{int}} = J_{sd}^2 \int_{kq\omega} \hbar\omega \,\mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(f_\omega^P - f_\omega^F\right)$$

Interfacial exchange $\langle H \rangle$ | DOS in PM | DOS in FI | Diff. of distribution

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\hbar \partial \omega} \delta\mu_s$$ SPE

$$f_\omega^P - f_\omega^F = \frac{\partial f_\omega^{BE}}{\partial T} \Delta T$$ Heat transport

Reciprocal relation of SSE and SPE

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ -\Delta T / T \end{pmatrix}$$

$L_{11} = J_{sd}^2 \int_{kq\omega} \frac{1}{\hbar} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\, G_{k\omega}^R \frac{\partial f_\omega^{BE}}{\partial \omega}$	$L_{12} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\, G_{k\omega}^R \left(-T \frac{\partial f_\omega^{BE}}{\partial T} \right)$
$L_{21} = J_{sd}^2 \int_{kq\omega} \omega \, \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\, G_{k\omega}^R \frac{\partial f_\omega^{BE}}{\partial \omega}$	$L_{22} = J_{sd}^2 \int_{kq\omega} \hbar\omega \, \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\, G_{k\omega}^R \left(-T \frac{\partial f_\omega^{BE}}{\partial T} \right)$

Reciprocal relation of SSE and SPE

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & \boxed{L_{12}} \\ \boxed{L_{21}} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ -\Delta T / T \end{pmatrix}$$

Spin Seebeck effect

$$L_{12} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \left(-T \frac{\partial f_\omega^{BE}}{\partial T} \right)$$

Spin Peltier effect

$$L_{21} = J_{sd}^2 \int_{kq\omega} \omega \,\mathrm{Im}\,\chi_{q\omega}^R \,\mathrm{Im}\,G_{k\omega}^R \frac{\partial f_\omega^{BE}}{\partial \omega}$$

Reciprocal relation of SSE and SPE

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & \boxed{L_{12}} \\ \boxed{L_{21}} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_s \\ -\Delta T / T \end{pmatrix}$$

Spin Seebeck effect

$$L_{12} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\,G_{k\omega}^R \left(\boxed{-T \frac{\partial f_\omega^{BE}}{\partial T}} \right)$$

Spin Peltier effect

$$L_{21} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\,G_{k\omega}^R \, \boxed{\omega \frac{\partial f_\omega^{BE}}{\partial \omega}}$$

$$\frac{\partial f_\omega^{BE}}{\partial T} = \frac{\hbar\omega}{k_B T^2} \frac{1}{4\sinh^2\left(\hbar\omega / 2k_B T\right)}$$

$$\boxed{\omega \frac{\partial f_\omega^{BE}}{\partial \omega} = -T \frac{\partial f_\omega^{BE}}{\partial T}}$$

$$\frac{\partial f_\omega^{BE}}{\partial \omega} = -\frac{\hbar}{k_B T} \frac{1}{4\sinh^2\left(\hbar\omega / 2k_B T\right)}$$

Reciprocal relation of SSE and SPE

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & \boxed{L_{12}} \\ \boxed{L_{21}} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ -\Delta T / T \end{pmatrix}$$

Spin Seebeck effect

$$L_{12} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\,G_{k\omega}^R \left(-T \frac{\partial f_\omega^{BE}}{\partial T} \right)$$

Spin Peltier effect

$$L_{21} = J_{sd}^2 \int_{kq\omega} \mathrm{Im}\,\chi_{q\omega}^R \, \mathrm{Im}\,G_{k\omega}^R \left(-T \frac{\partial f_\omega^{BE}}{\partial T} \right)$$

Onsager's reciprocal relation

$$L_{12} = L_{21}$$

Kelvin's relation of thermal spin effects

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ -\Delta T / T \end{pmatrix}$$

Spin Seebeck coefficient	Spin Peltier coefficient
$I_S^{\mathrm{int}} = -S_{SSE}\Delta T$	$I_H^{\mathrm{int}} = \Pi_{SPE}\delta\mu_S$
$S_{SSE} = L_{12} / T$	$\Pi_{SPE} = L_{21}$

Kelvin's relation of thermal spin effects

$$\begin{pmatrix} I_S^{\mathrm{int}} \\ I_H^{\mathrm{int}} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ -\Delta T / T \end{pmatrix}$$

Spin Seebeck coefficient	Spin Peltier coefficient
$I_S^{\mathrm{int}} = -S_{SSE}\Delta T$	$I_H^{\mathrm{int}} = \Pi_{SPE}\delta\mu_S$
$S_{SSE} = L_{12} / T$	$\Pi_{SPE} = L_{21}$

$$L_{12} = L_{21}$$

(cf: Kelvin's relation
For thermoelectric effect

$$\Pi = TS$$

$$\Pi_{SPE} = TS_{SSE}$$

Kelvin's relation for thermal spin effects

Heat generation from spin current

$$E^{YIG} = \int_{k\omega} \hbar\omega \, \mathrm{Im}\, \delta G^{<}_{k\omega}$$

Heat = Energy of magnon × Number of magnon

$$\mathrm{Im}\, \delta G^{<}_{k\omega} = \mathrm{Im}\, G^{R,YIG}_{k\omega} \times \delta f^{YIG}_{\omega}$$

DOS × Distribution Function

Rate equation

$$\frac{\delta G^{<}_{k\omega}}{\tau_{k\omega}} = I_S^{\mathrm{int}}(\omega)$$

$$\tau_{k\omega} = \frac{1}{\alpha\omega}$$

α : Gilbert damping constant

$$E^{YIG} = \frac{I_S}{2\alpha} \propto \delta\mu_S^{Pt}$$

Heat = Damping of magnon Spin Accumulation

Temperature change

$$E^{YIG} = \frac{I_S}{2\alpha}$$

$$\sim \frac{\delta\mu_S^{Pt}}{\alpha} \times N_{\mathrm{int}} \left[\delta\alpha \left(\frac{k_B T}{\hbar\omega_M} \right)^{3/2} \gamma_{SPE/SP} \right]$$

$\delta\mu_S^{Pt} = 2.3 \times 10^{-6} [eV]$ Daimon 2016

$N_{\mathrm{int}} = 1 \times 10^{11}$

$\delta\alpha = 3.6 \times 10^{-3}$

$\alpha = 10^{-5}$

$\frac{k_B T}{\hbar\omega_M} = 0.53$

@300K

$$\gamma_{SPE/SP} = \frac{\int_0^1 dy \int_{x_0}^{x_M} dx \frac{\sqrt{y}}{(1+y)^2 + \left(x k_B T \tau_{sf} / \hbar\right)^2} \frac{x\sqrt{x - x_0}}{4\sinh^2(x/2)}}{\int_0^1 dy \frac{\sqrt{y}}{(1+y)^2 + \left(\omega_0 \tau_{sf}\right)^2}} \sim 1$$

$$x_0 = \frac{\hbar\gamma H_0}{k_B T}, \qquad x_M = \frac{\hbar\omega_M}{k_B T}$$

Pt / YIG @300K

$$E^{YIG} \sim 4 \times 10^{-14} [J]$$

ΔT in YIG/Pt

$$\Delta T^{YIG} = \frac{E^{YIG}}{C_v^{YIG}} \sim 1[mK]$$

(cf: **0.5mK** (Daimon 2016)

$$C_v^{YIG} = 5.5 \times 10^{-10} [J/K]$$

Summary

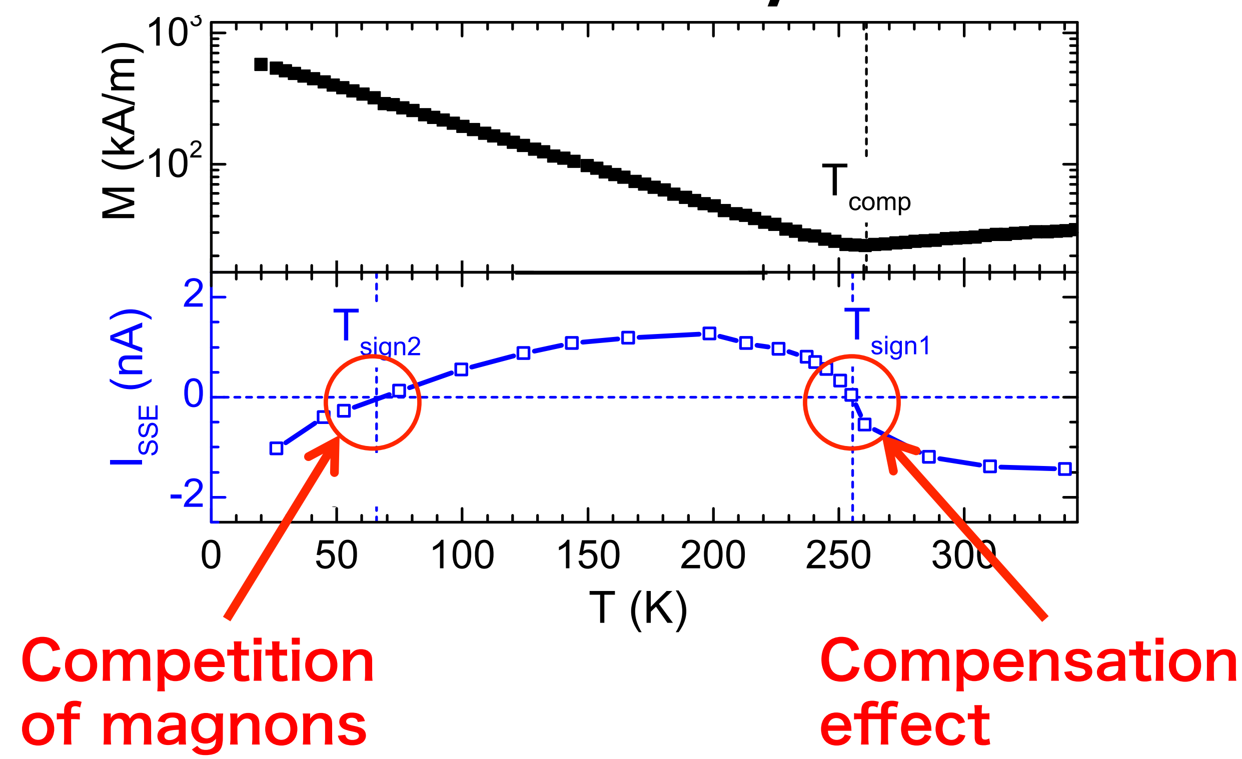
Summary

Spin Seebeck effect

$$I_S^{Ferri} = I_S^{\alpha} - I_S^{\beta}$$

$$T_{sign2} \Rightarrow J_{sd}^{A} / J_{sd}^{B}$$

Gd3Fe5O12/Pt

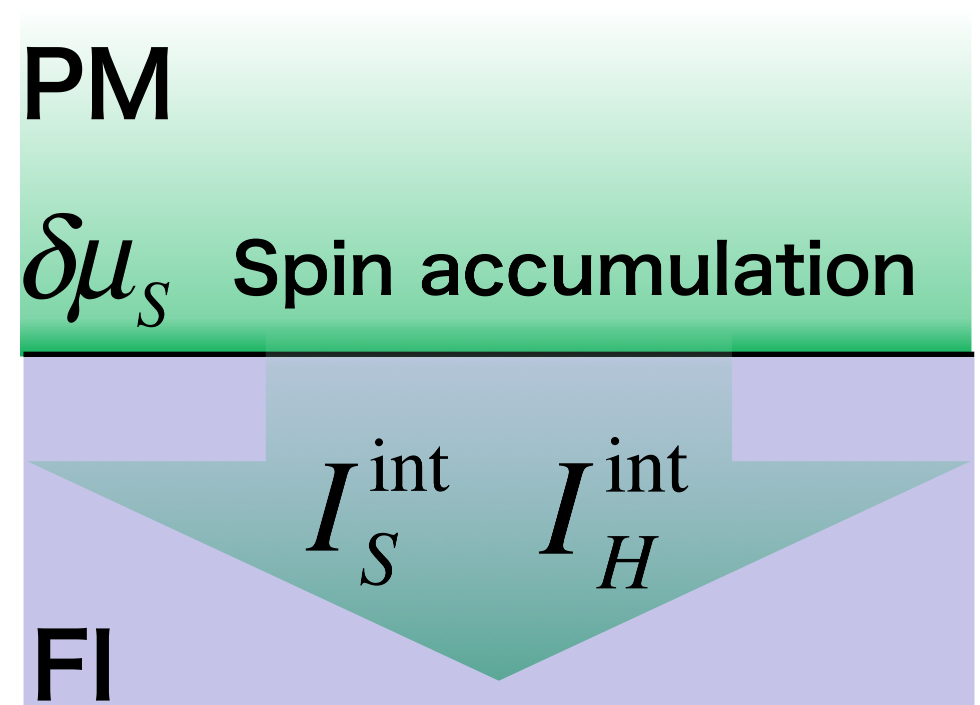


Spin Peltier effect

$$I_S^{\mathrm{int}} \propto \delta\mu_S$$

$$I_Q^{\mathrm{int}} \propto \delta\mu_S$$

$$\Delta T^{YIG} \sim 1[mK]$$



Note

Seebeck & Peltier effects in bulk materials

Charge current

$$j_e = q\langle \partial_t N_e \rangle$$

Heat current

$$j_h = \langle \partial_t H \rangle$$

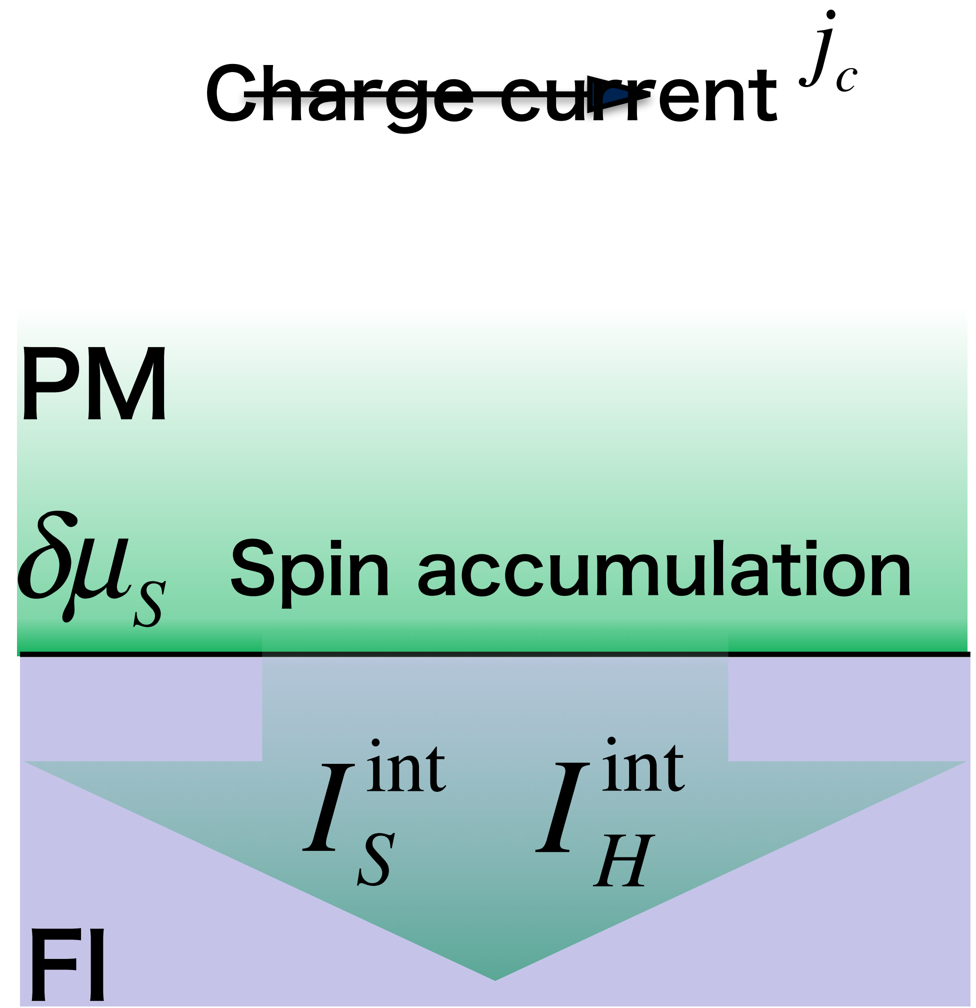
$$\begin{pmatrix} j_e \\ j_h \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} E \\ -\nabla T / T \end{pmatrix}$$

Linear response theory of Seebeck & Peltier effects

$$L_{12} = TS^{SSE} = \lim \frac{1}{\omega} \int_0^\infty \langle [j_q(t), j_e] \rangle e^{-i\omega t}$$

$$L_{21} = \Pi^{SSE} = \lim \frac{1}{\omega} \int_0^\infty \langle [j_h(t), j_e] \rangle e^{-i\omega t}$$

Luttinger 1964



Y. Ohnuma et al.,
Phys. Rev. B **96**, 134412 (2017)

Achievements

Publications (7 papers)

[1] Theory of the spin Peltier effect
Y. Ohnuma, M. Matsuo, and S. Maekawa, Phys. Rev. B **96**, 134412 (2017).

[2] Theory of spin hydrodynamic generation
M. Matsuo, Y. Ohnuma, and S. Maekawa, Phys. Rev. B, **96**, 020401(R) (2017).

[3] Spin transport in half-metallic ferromagnets
Y. Ohnuma, M. Matsuo, and S. Maekawa, Phys. Rev. B, **94**, 184405 (2016).

[4] Origin of the spin Seebeck effect in compensated ferrimagnets
S. Geprägs and Y. Ohnuma et al., Nat. Commun., **7**, 10452 (2016).

[5] Magnon instability driven by heat current in magnetic bilayers
Y. Ohnuma et al., Phys. Rev. B, **92**, 224404 (2015).

[6] Enhanced dc spin pumping into a fluctuating ferromagnet near Tc
Y. Ohnuma et al., Phys. Rev. B, **89**, 174417 (2014).

[7] Spin Seebeck effect in antiferromagnets and compensated ferrimagnets
Y. Ohnuma et al., Phys. Rev. B, **87**, 014423 (2013).