at Hvar (October 1-7, 2017)

Spin Seebeck and Spin Peltier Effects

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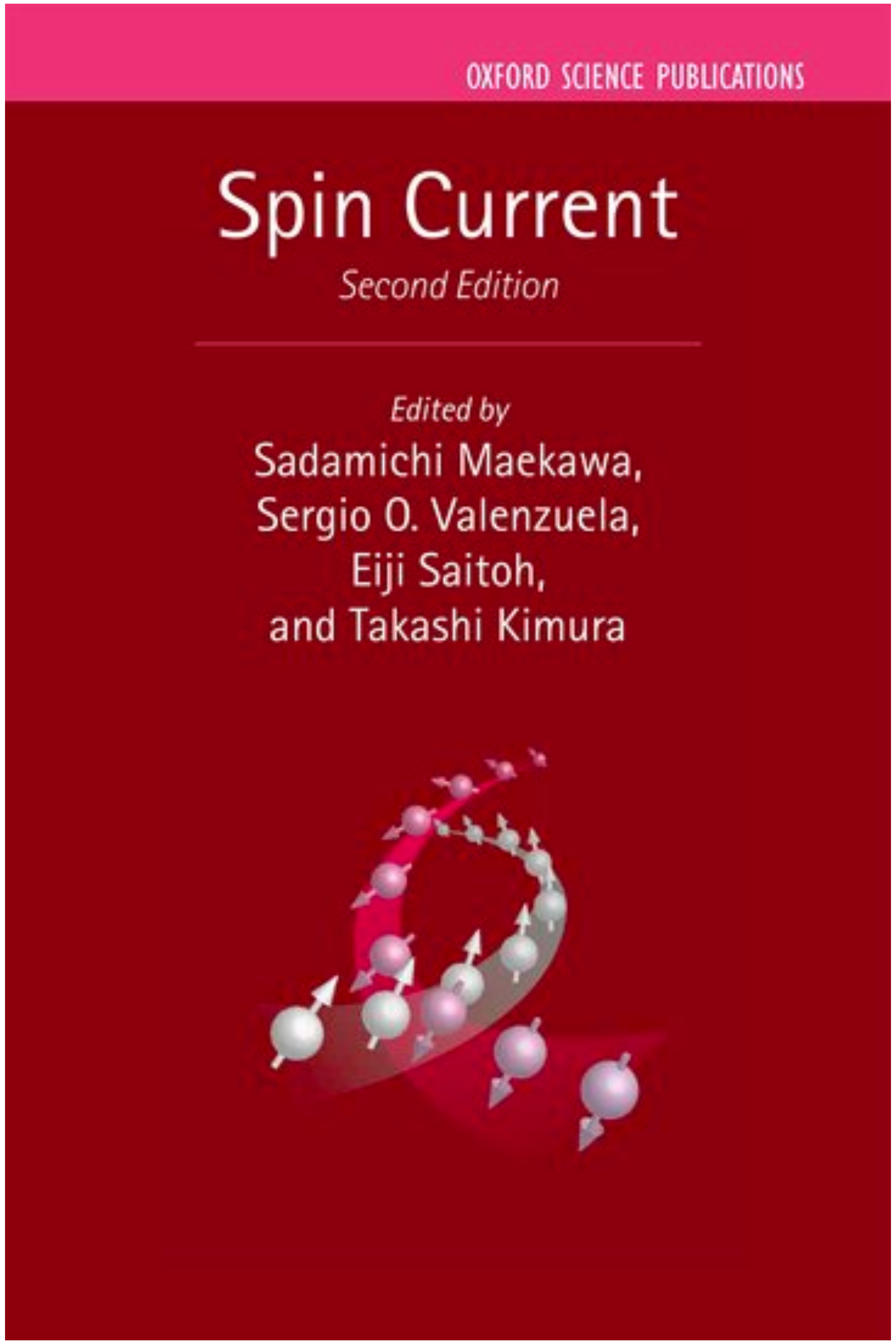
References:

∗S. Maekawa(ed.)"Concepts in Spin Electronics" (Oxford University Press, 2006),

***S. Maekawa et al. (eds.) "Spin Current" (Oxford University Press, 2017),**



Second Edition:
Published in September 2017

*** "Spin Current"(First Edition) : (Oxford University Press, 2012),**

Outline

Spin Seebeck Effect and Spin Peltier Effect:

i) Spin Seebeck Effect:

Review Article,
[K.Uchida, H.Adachi, T.Kikkawa, A.Kirihara, M.Ishida, S.Yorozu, S.Maekawa and E.Saitoh, Proc. IEEE 104, 1946 (2016)].

ii) Spin Peltier Effect:

Y. Ohnuma , M.Matsuo and S.Maekawa: to be published in Phys. Rev. B (2017).

Co-Workers:

Theory:

Y. Ohnuma (ASRC, JAEA),
H. Adachi (ASRC, JAEA→ Okayama U.),
M. Matsuo (ASRC, JAEA).

Experiment:

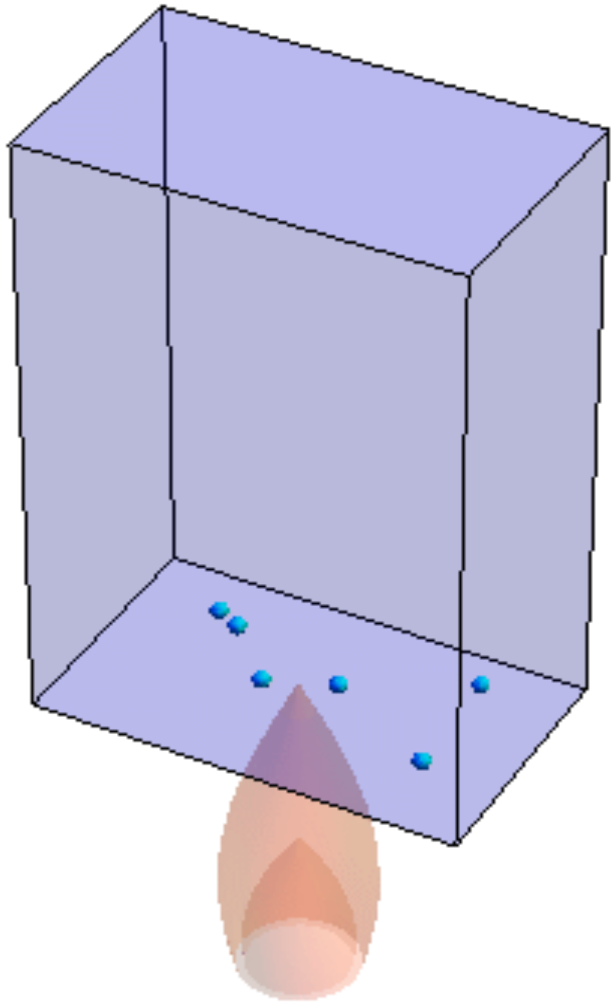
E. Saitoh(Tohoku U.) and members in his group,
K. Uchida (Tohoku U.→ NIMS, Tsukuba) ,

Heat vs. Electricity

	To get Electricity	To get Heat
Charge	Seebeck effect	Peltier effect
Spin	Spin Seebeck effect Uchida 2008	Spin Peltier effect Flipse 2014 Daimon 2016

Seebeck effect, spin Seebeck effect

Boiling of water



Boiling of electrons
(Seebeck effect)

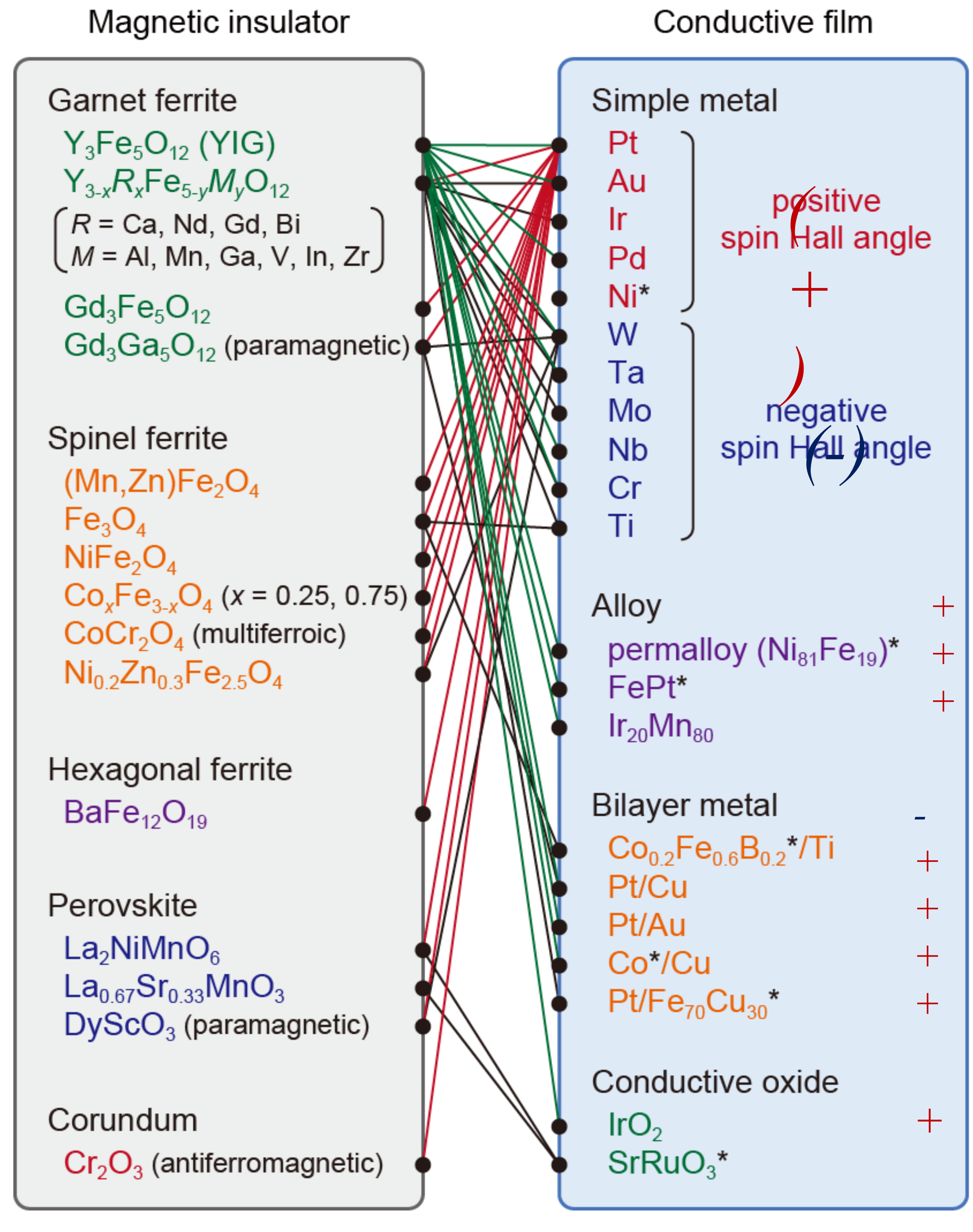
Boiling of spin current
(spin Seebeck effect)

Combination of magnetic insulators and conductive films used for measuring SSE

SSE is a universal phenomenon in magnetic materials

Model system:

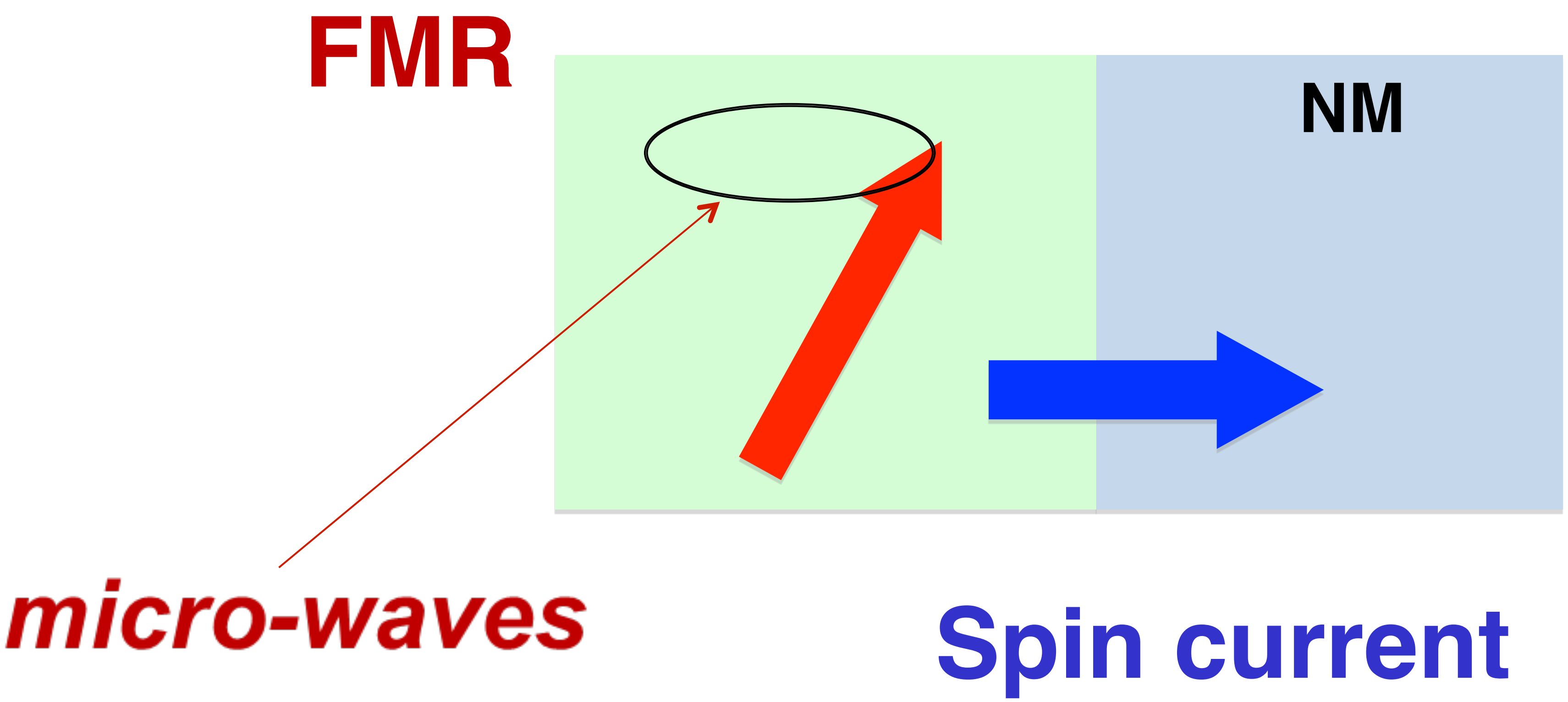
Pt/$Y_3Fe_5O_{12}$ (YIG) junction



K. Uchida, H. Adahci, T. Kikkawa, A. Kirihara, M. Ishida, S. Yorozu, S. Maekawa, and E. Saitoh, "Thermoelectric generation based on spin Seebeck effects" (IEEE Proc., ***104****, 1946 (2016)).*

Spin pumping

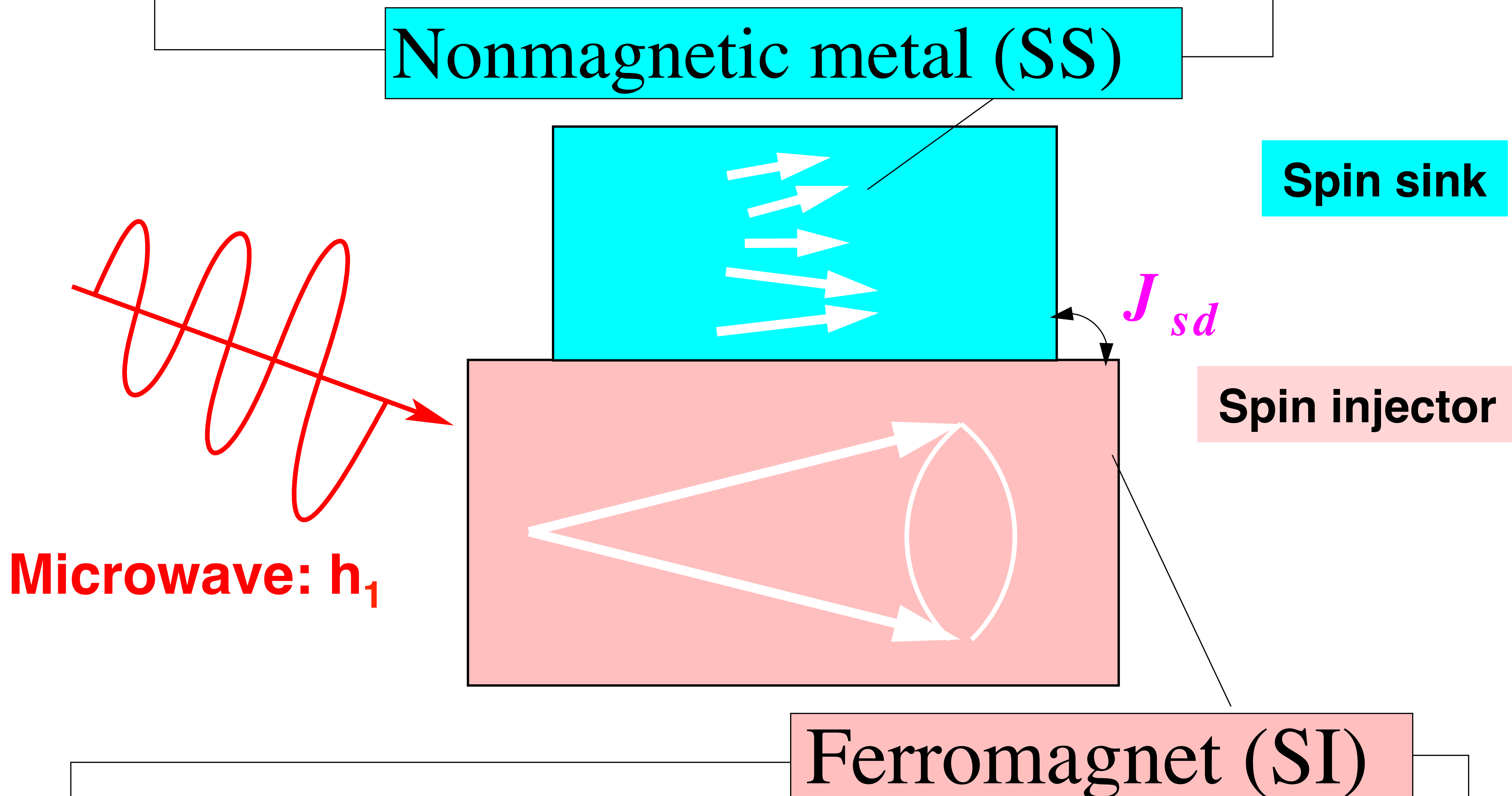
(spin current generation by FMR)



Spin current generation by FMR

Bloch eq. (s: spin accumulation)

$$\frac{d}{dt}s = J_{sd}\, m \times s + (D_N \nabla^2 - \Gamma)(s - s_0 m)$$



$$\frac{d}{dt}m = J_{sd}\, s \times m + \gamma (H_0 + h_1) \times m + \alpha\, m \times \frac{d}{dt}m$$

Landau-Lifshitz-Gilbert eq. (m: localized moment)

Linear response (busy slide, but important) !!

Bloch eq.: $\partial_t \boldsymbol{s} = J_{sd}\boldsymbol{m}\times\boldsymbol{s} + (D_N\nabla^2 - \Gamma)(\boldsymbol{s} - s_0\boldsymbol{m})$ $\quad (s_0 = \chi_N J_{sd})$

LLG eq.: $\partial_t \boldsymbol{m} = J_{sd}\boldsymbol{s}\times\boldsymbol{m} + \gamma(\boldsymbol{H}_0 + \boldsymbol{h}_1)\times\boldsymbol{m} + \alpha\boldsymbol{m}\times\partial_t\boldsymbol{m}$

1) Define the spin current injected into N by $J_s^{in} = (1/A_{contact})\langle ds^z/dt \rangle$.

From Bloch equation: $J_s^{in} \equiv \langle \partial_t s^z \rangle = \dfrac{J_{sd}}{A_{contact}} \mathrm{Im}\int d\omega \langle s^+(\omega) m^-(-\omega) \rangle$

2) Linearize above two equations with respect to s^x, s^y, m^x, m^y.

$$s^+(\omega) = J_{sd}\chi_N(\omega)G_F(\omega)\gamma h_1^+(\omega)$$
$$m^-(\omega) = G_F(\omega)\gamma h_1^-(\omega)$$

$\chi_N(\omega)$: spin susceptibility of N

$G_F(\omega)$: spin susceptibility of F

3) Substitute 2) into 1) and obtain the following result:

$$J_s^{in} = -\frac{J_{sd}^2}{A_{contact}} \int d\omega\, \mathrm{Im}\,\chi_N(\omega) |G_F(\omega)|^2 \langle \gamma h_1^+(\omega)\gamma h_1^-(-\omega) \rangle$$

This is the general expression valid for any types of spin pumping!

Model for spin injection by thermal magnons

H. Adachi et al.: Phys.Rev. B83, 094410 (2011)).

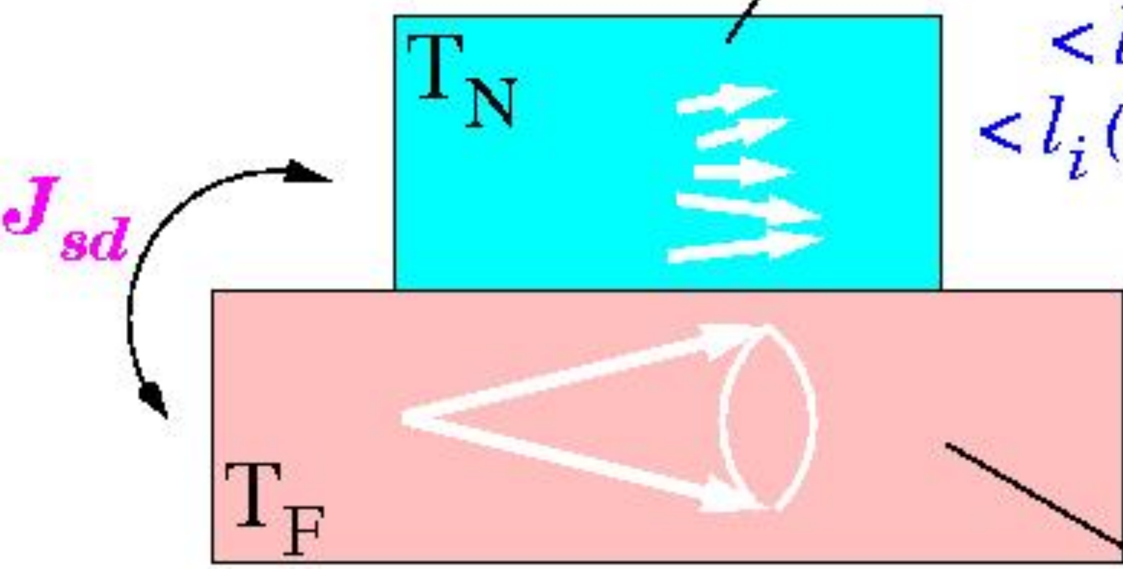
Nonmagnetic metal (N)

$$\frac{d}{dt}s = J_{sd}\, m \times s + (D_N \nabla^2 - \Gamma)(s - s_0 m) + l$$

$$\langle l_i(r) \rangle = 0$$

$$\langle l_i(r,t)\, l_j(r',t') \rangle = 2k_B T_N(r)\, \chi_N \Gamma\, \delta_{ij}\, \delta(r-r')\,\delta(t-t')$$

(Fluctuation-Dissipation theorem)



Ferromagnet (F)

$$\frac{d}{dt}m = -J_{sd}\, s \times m + \gamma (H_{eff} + h) \times m + \alpha\, m \times \frac{d}{dt}m$$

$$\langle h_i(r) \rangle = 0$$

$$\langle h_i(r,t)\, h_j(r',t') \rangle = \frac{2k_B T_F(r)\, \alpha}{\gamma M_s}\, \delta_{ij}\, \delta(r-r')\,\delta(t-t')$$

(c.f., J. Xiao et al.: Phys. Rev. B81, 214418 (2010))

(Local) spin injection by thermal magnons

(H. Adachi et al.: Phys.Rev. B83, 094410 (201

Spin diffusion eq.: $\partial_t \boldsymbol{s} = J_{sd}\boldsymbol{m}\times\boldsymbol{s} + (D_N\nabla^2 - \Gamma)(\boldsymbol{s} - s_0\boldsymbol{m}) + \boldsymbol{l}$ $\quad (s_0 = \chi_N S_0 J_{sd})$

LLG eq.: $\partial_t \boldsymbol{m} = J_{sd}\boldsymbol{s}\times\boldsymbol{m} + \gamma(\boldsymbol{H}_{eff} + \boldsymbol{h})\times\boldsymbol{m} + \alpha\boldsymbol{m}\times\partial_t\boldsymbol{m}$

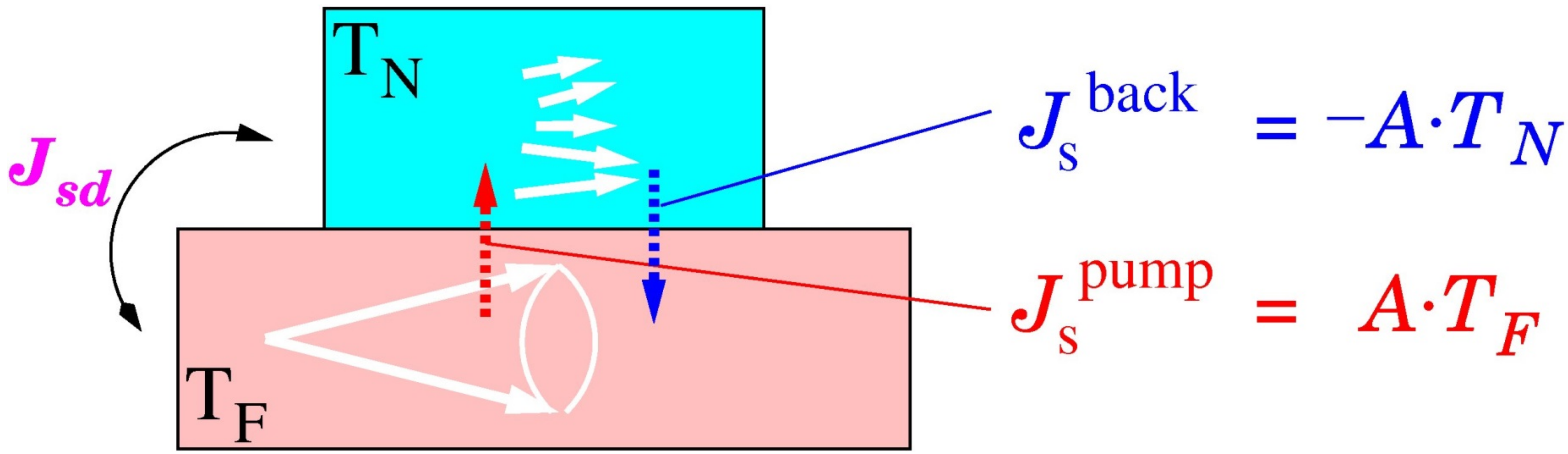
Injected spin current: $J_s^{\,in} \equiv <\partial_t s^z> = J_{sd}\,\mathrm{Im}\int d\omega < s^+(\omega) m^-(-\omega) >$

$$s^+(\omega) = \Gamma s_0 G_F^{\,*}(-\omega)\gamma h^+(\omega) + \chi_N^{\,*}(-\omega) l^+(\omega)$$
$$m^-(\omega) = G_F(\omega)\gamma h^-(\omega) + J_{sd} G_F(\omega)\chi_N(\omega) l^-(\omega)$$
$$(a^{\pm} \equiv a^x \pm i a^y)$$

$$J_s^{\,in} = J_{sd}\int d\omega \frac{1}{\omega}\mathrm{Im}\,\chi_N(\omega)\,\mathrm{Im}\,G_F(\omega)\left[\Gamma s_0 < \gamma h^+(\omega)\gamma h^-(-\omega) > -\alpha J_{sd} < l^+(\omega) l^-(-\omega) >\right]$$

↑ J_s^{pump} ↑ J_s^{back}

$$\therefore J_s^{\,in} = J_s^{\,pump} - J_s^{\,back}$$



Local non-equilibrium

$$\therefore J_s^{in} = A(T_F - T_N)$$

$$\left(\quad A \propto J_{sd}^{\,2} \int d\omega \frac{1}{\omega} \mathrm{Im}\,\chi_N(\omega)\,\mathrm{Im}\,G_F(\omega) \quad \right)$$

To get the non-equiliburium condition, we need heat flow!

Outline

Spin Seebeck Effect and Spin Peltier Effect:

i) Spin Seebeck Effect:

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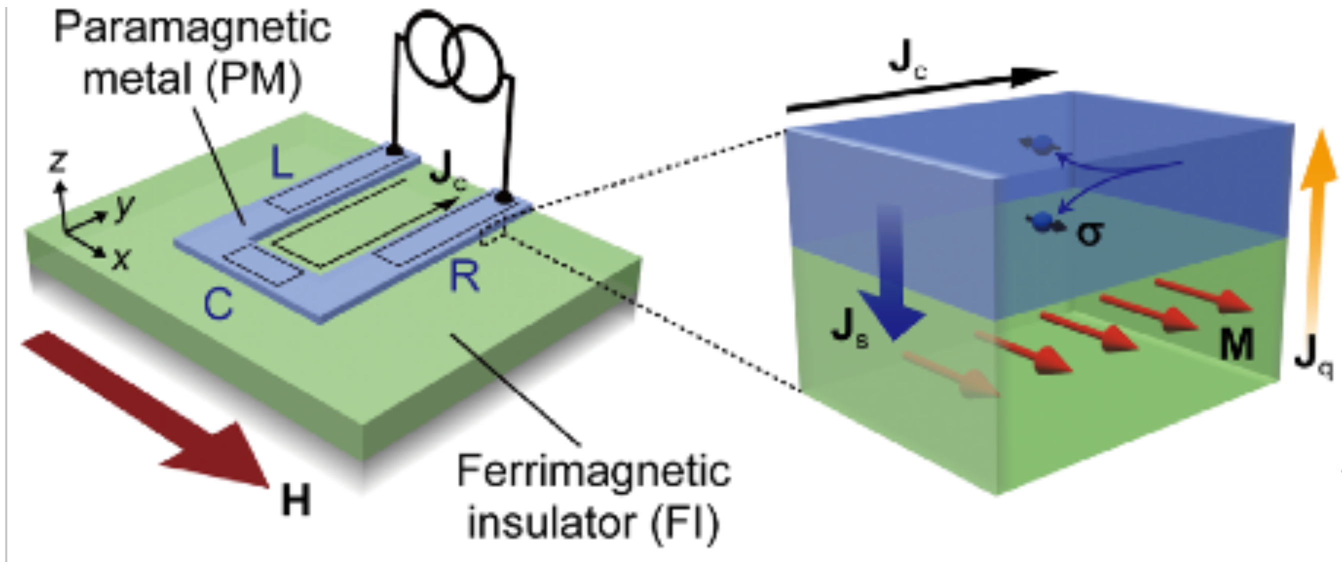
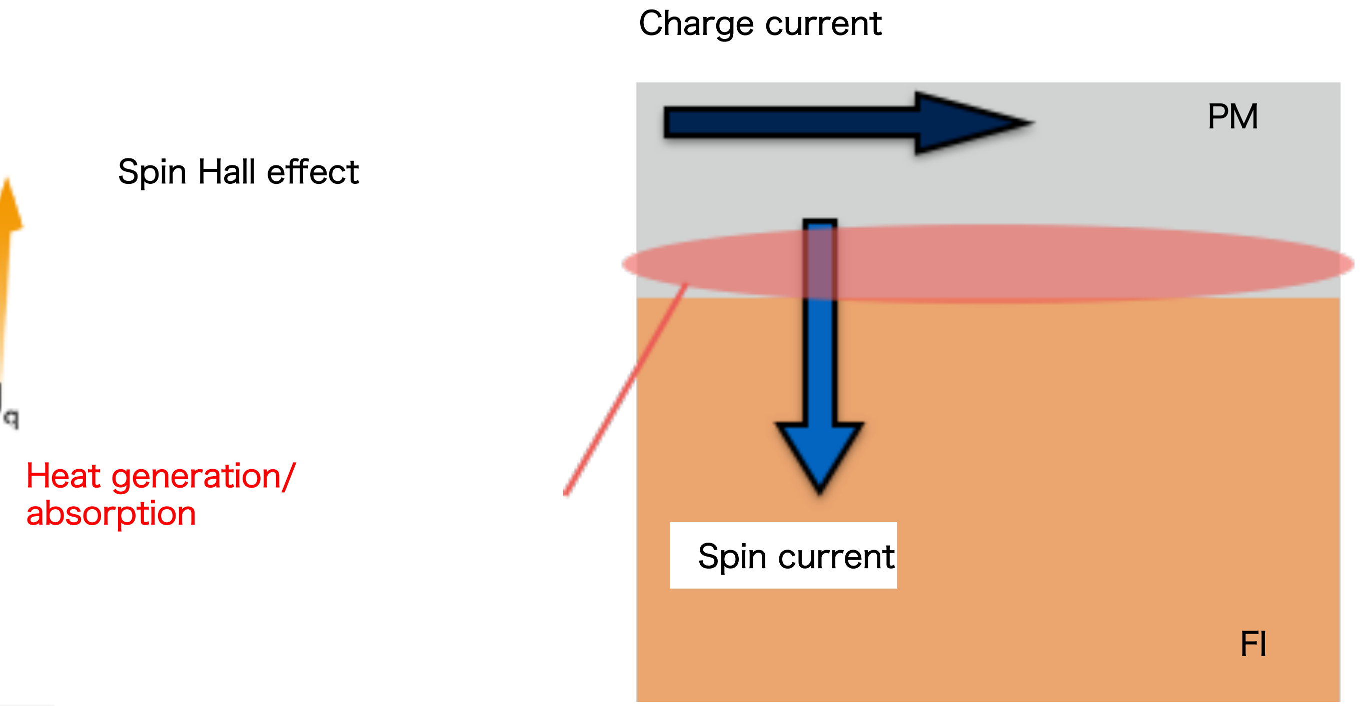
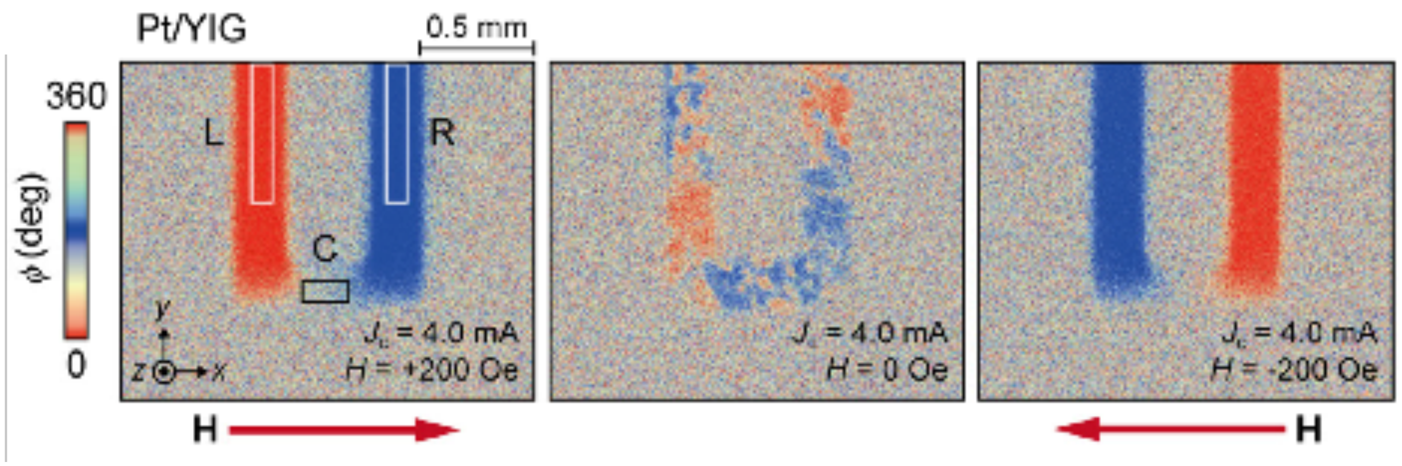
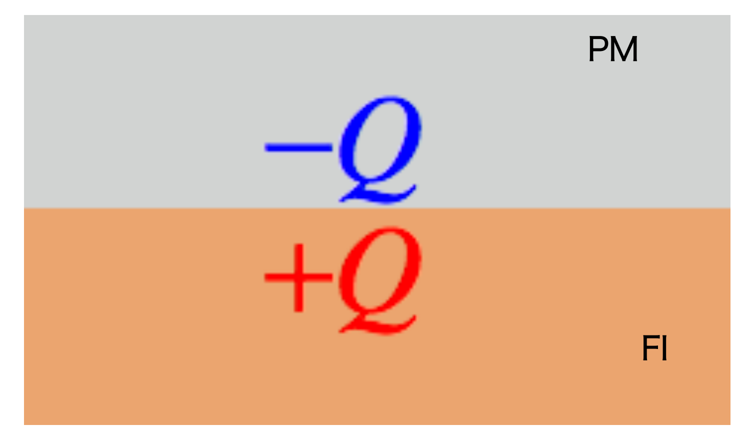
Spin Peltier Effect







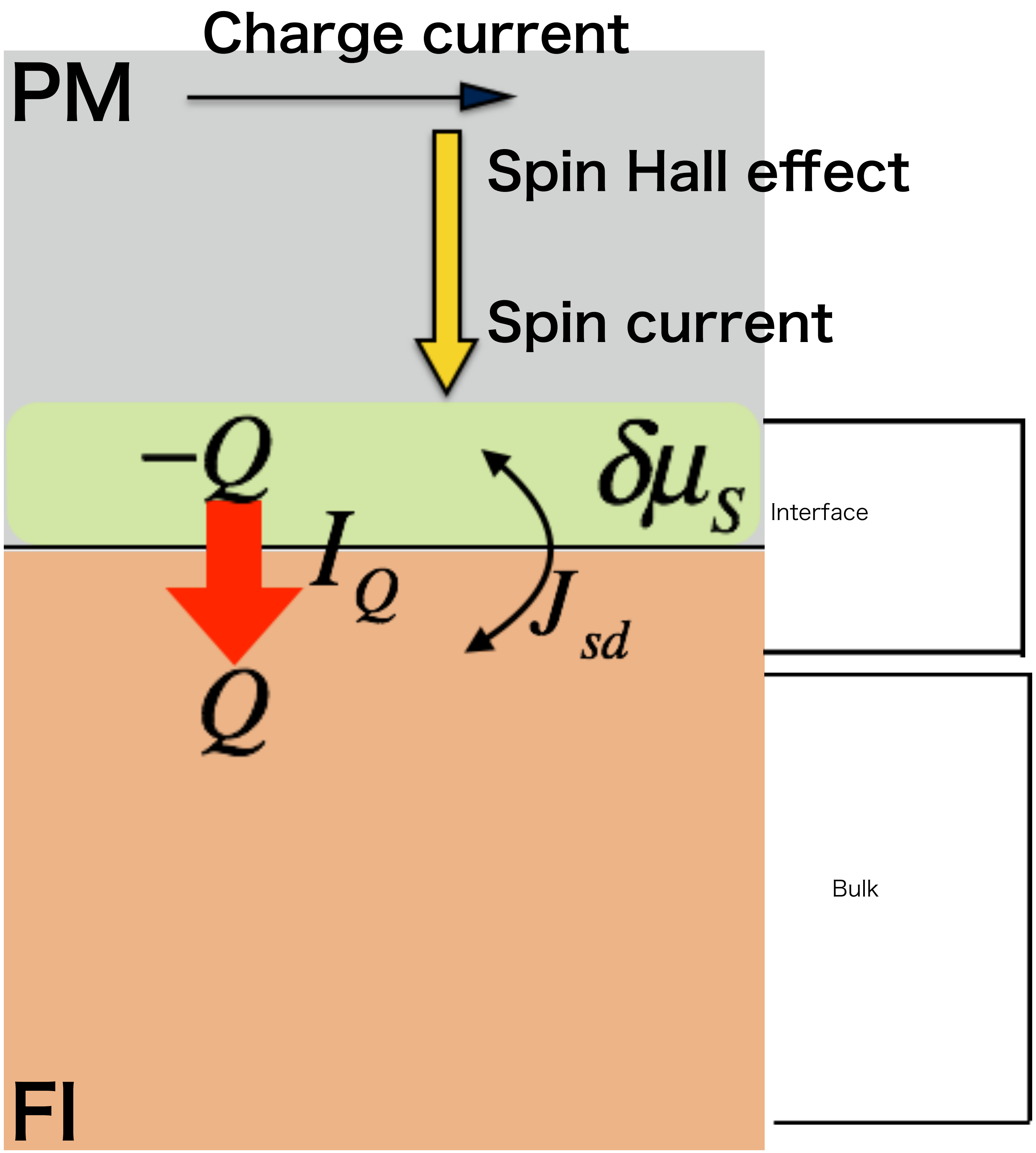
Daimon Nat. Common. (2016)
Flipse PRL (2014)



Daimon (2016)

Generation & absorption of heat driven by spin current

Theoretical model for spin Peltier effect



Spin accumulation
-> magnon current
-> heat current

Heat current

$$I_Q \propto \delta\mu_s$$

Temperature gradient

Kadanoff Baym equations
Of magnon and phonon

Spin current driven by spin accumulation

Spin accumulation at the interface (S. Zhang 2000)

$$\delta\mu_S = e\alpha_{SH}\lambda_{PM}\tanh\left(d_{PM}/\lambda_{PM}\right)E$$

Spin accumulation = Spin Hall angle × Spin diffusion length × Geometrical factor × Electric field

Heat current injection into FI

$$I_Q = \langle \partial_t H_{FI} \rangle$$ …following Maki & Griffin (1965)

$$H^{\mathrm{int}} = J_{sd}\sum_i \sigma_i^{PM}\cdot S_i^{FI}$$

$$I_Q = \delta\mu_S \times \Pi_{SPE}$$

Π_{SPE} : **Spin Peltier coefficient**

$$\Pi_{SPE} = \int_{kq\omega}\left[J_{sd}^2 \times \hbar\omega \times \mathrm{Im}\,\chi_{q\omega}^{Pt} \times \mathrm{Im}\,G_{k\omega}^{FI} \times \frac{\partial f}{\hbar\partial\omega}\right]$$

Exchange interaction × Energy × Spectral function in PM × Spectral function in FI × Distribution function

Spin & heat injection

Spin diffusion eq.: $\partial_t \mathbf{s} = \left(J_{sd}\mathbf{m} + \mathbf{b}\right) \times \mathbf{s} + (D_N \nabla^2 - \Gamma)(s - s_0 \mathbf{m}) + \boldsymbol{l}$

LLG eq.: $\partial_t \mathbf{m} = J_{sd}\mathbf{s} \times \mathbf{m} + \gamma(\mathbf{H}_{eff} + \mathbf{h}) \times \mathbf{m} + \alpha \mathbf{m} \times \partial_t \mathbf{m}$

$\mathbf{b} = \delta\mu_S \mathbf{z}$

$(s_0 = \chi_N S_0 J_{sd})$

1) Define the spin and heat current injected into N.

From Bloch equation: $J_{Spin}{}^{in} \equiv < \partial_t s^z > = J_{sd} \, \mathrm{Im} \int d\omega < s^+(\omega) m^-(-\omega) >$

H. Adachi et al.: Phys.Rev. B 83, 094410 (2011).

From Heisenberg eqaution: $J_{Heat}{}^{in} \equiv < \partial_t H > = J_{sd} \, \mathrm{Im} \int d\omega \hbar\omega < s^+(\omega) m^-(-\omega) >$

2) Linearize above two equations with respect to s and m.

$$s^+(\omega) = \Gamma s_0 G_F^*(\omega) \gamma h^+(\omega) + \chi_N^*(\omega + \delta\mu_S) l^+(\omega)$$

$$m^-(\omega) = G_F(\omega) \gamma h^-(\omega) + J_{sd} G_F(\omega) \chi_N(\omega + \delta\mu_S) l^-(\omega)$$

3) Substitute 2) into 1) and obtain the following results:

$$J_{Spin}{}^{in} = J_{sd} \int d\omega \, \mathrm{Im}\, \chi_N(\omega + \delta\mu_S) \, \mathrm{Im}\, G_F(\omega) \left[\Gamma s_0 \frac{< \gamma h^+(\omega) \gamma h^-(-\omega) >}{\omega} - \alpha J_{sd} \frac{< l^+(\omega) l^-(-\omega) >}{\omega + \delta\mu_S} \right]$$

↑ $J_s{}^{pump}$ ↑ $J_s{}^{back}$

$$J_{Heat}{}^{in} = J_{sd} \int d\omega \hbar\omega \, \mathrm{Im}\, \chi_N(\omega + \delta\mu_S) \, \mathrm{Im}\, G_F(\omega) \left[\Gamma s_0 \frac{< \gamma h^+(\omega) \gamma h^-(-\omega) >}{\omega} - \alpha J_{sd} \frac{< l^+(\omega) l^-(-\omega) >}{\omega + \delta\mu_S} \right]$$

↑ $J_H{}^{pump}$ ↑ $J_H{}^{back}$

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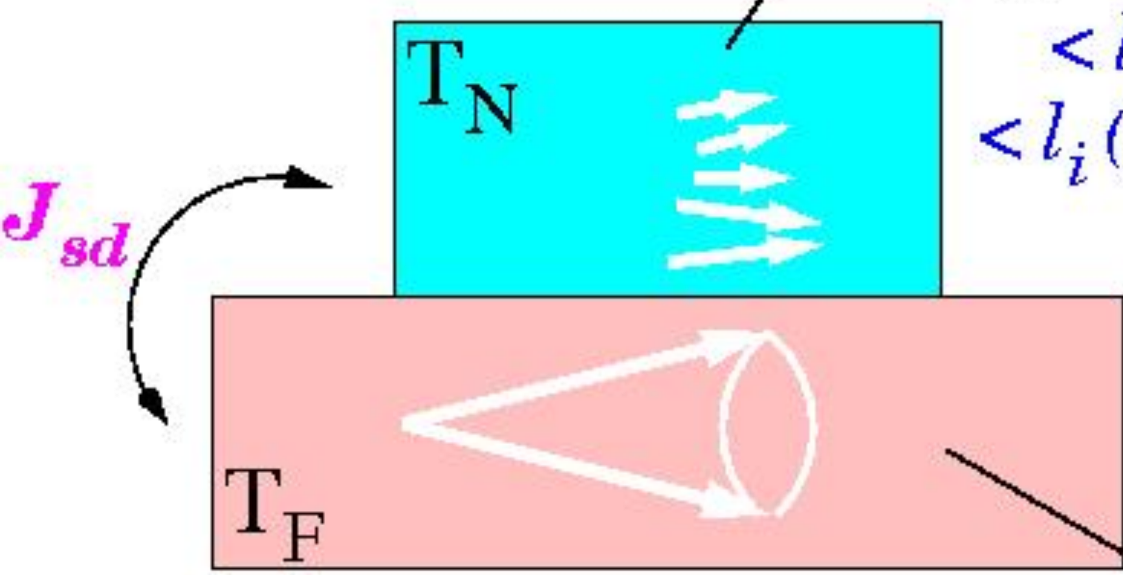
(Fluctuation-Dissipation theorem)



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$$\frac{d}{dt}m = -J_{sd}\, s \times m + \gamma (H_{eff} + h) \times m + \alpha\, m \times \frac{d}{dt}m$$

$$< h_i(r) > = 0$$

$$< h_i(r,t)\, h_j(r',t') > = \frac{2k_B T_F(r)\, \alpha}{\gamma M_s}\, \delta_{ij}\, \delta(r-r')\, \delta(t-t')$$

(c.f., J. Xiao et al.: Phys. Rev. B81, 214418 (2010))

Expression of spin & heat current

4) Substitute the correlation of noises into 3) :

$$J_{Spin}{}^{in} = J_{eff}^2 \int d\omega \, \mathrm{Im}\, \chi_N(\omega + \delta\mu_S)\, \mathrm{Im}\, G_F(\omega) \left(\frac{T_N + \Delta T}{\omega} - \frac{T_N}{\omega + \delta\mu_S} \right)$$

$$J_{Heat}{}^{in} = J_{eff}^2 \int d\omega \hbar\omega \, \mathrm{Im}\, \chi_N(\omega + \delta\mu_S)\, \mathrm{Im}\, G_F(\omega) \left(\frac{T_N + \Delta T}{\omega} - \frac{T_N}{\omega + \delta\mu_S} \right)$$

$$J_{eff}^2 \coloneqq 2 J_{sd}^2 \chi_N \alpha \Gamma k_B$$

$$\Delta T \coloneqq T_F - T_N$$

5) Obtain the linear response theory as follows:

$$J_{Spin}{}^{in} = J_{eff}^2 \int_{-\infty}^{\infty} d\omega X(\omega) \left[\omega \Delta T + T_N \delta\mu_S \right]$$

$$J_{Heat}{}^{in} = J_{eff}^2 \int_{-\infty}^{\infty} d\omega \hbar\omega X(\omega) \left[\omega \Delta T + T_N \delta\mu_S \right]$$

$$X(\omega) \coloneqq \frac{\mathrm{Im}\, \chi_N(\omega + \delta\mu_S)}{\omega + \delta\mu_S} \frac{\mathrm{Im}\, G_F(\omega)}{\omega} \sim \frac{\chi_N^2}{1 + (\omega / \Gamma)^2} \frac{1}{(\omega - \omega_0)^2 + (\alpha\omega)^2}$$

Spin Seebeck effect and spin Peltier effect

6) From the fluctuation dissipation theorem, 3) reduce as follows:

$$\begin{pmatrix} J_{Spin}{}^{in} \\ J_{Heat}{}^{in} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} \delta\mu_S \\ \Delta T / T \end{pmatrix}$$

$$L_{12} = 2J_{sd}^2 \alpha \Gamma k_B T_F \int d\omega \omega \frac{\mathrm{Im}\,\chi_N(\omega + \delta\mu_S)}{\omega + \delta\mu_S} \frac{\mathrm{Im}\,G_F(\omega)}{\omega}$$

$$= L_{21}$$

Onsager's reciprocal relation

"Kelvin relation" for interconversion of heat and spin currents

$$J_{Spin}{}^{in} = S_{SSE} \Delta T$$

$$J_{Heat}{}^{in} = \Pi_{SPE} \delta\mu_S$$

$$\Pi_{SPE} = T S_{SSE}$$

Generation of heat by spin current

$$Q^{FI} = \int_{k\omega} \hbar\omega \, \delta G^{<,FI}_{k\omega}$$

Heat = Energy of magnon × Number density of magnons

$$\delta G^{<,FI}_{k\omega} = \mathrm{Im}\, G^{R,FI}_{k\omega} \times \delta f^{(2),FI}_{k\omega}$$

Spectral function × Distribution function

Rate equation of magnons

$$\int_{k\omega} \frac{\hbar\omega \, \delta G^{<,FI}_{k\omega}}{\tau_{mag}} = I_Q$$

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

α : Gilbert damping constant

$$Q^{FI} = \left\langle \tau_{mag} \times I_Q \right\rangle_{k\omega} \propto \delta\mu_S$$

Heat = Relaxation time × Heat current

$$\left\langle \tau_{mag} I_Q \right\rangle_{k\omega} \coloneqq \int_{k\omega} \tau_{mag} I_Q(k,\omega)$$

$$I_Q = \int_{k\omega} I_Q(k,\omega)$$

$$= J_{sd}^2 \int_{k\omega} \omega \, \mathrm{Im}\, \chi^{R,Pt}_{q\omega} \, \mathrm{Im}\, G^{R,FI}_{k\omega} \frac{\partial f}{\partial \omega}$$

Estimation of temperature change

Pt/YIG system

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

$\delta\mu_S^{Pt} = 2.3\times10^{-7}[eV]$ Daimon 2016

$N_{\text{int}} = 1\times10^{11}$

$\delta\alpha = 3.6\times10^{-3}$

$\alpha = 10^{-5}$

$\frac{k_B T}{\hbar\omega_M} = 0.53$ @300K

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

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

$$\sim 4\times10^{-13}[J]$$

Estimation of ΔT

$$\Delta T = \frac{Q^{YIG}}{C_v^{YIG}} \sim 20mK$$

(cf: 0.5mK [Daimon 2016])

$$C_v^{YIG} = 5.5\times10^{-10}[J/K]$$

Onsager's relation

Spin current

$$I_S := \left\langle \partial_t \sigma^z \right\rangle$$

Heat current

$$I_Q = \left\langle \partial_t H_{FI} \right\rangle$$

Transport coefficients

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

Spin Seebeck coefficient

$$S_{SSE} := L_{12} / T \qquad L_{12} = \int_{kq\omega} \left[J_{sd}^2 \operatorname{Im} \chi_{q\omega}^{PM} \operatorname{Im} G_{k\omega}^{FI} \left(-T \frac{\partial f}{\partial T} \right) \right]$$

Spin Peltier coefficient

$$\Pi_{SPE} := L_{21} \qquad L_{21} = \int_{kq\omega} \left[J_{sd}^2 \omega \operatorname{Im} \chi_{q\omega}^{PM} \operatorname{Im} G_{k\omega}^{FI} \frac{\partial f}{\partial \omega} \right] = L_{21}$$

Onsager's relation

$$\frac{\partial f}{\partial \omega} = -\frac{T}{\omega} \frac{\partial f}{\partial T}$$

Kelvin relation for spin and heat current in PM/FM

$$\Pi_{SPE} = T S_{SSE}$$

In conclusion:

Heat vs. Electricity

	To get Electricity	To get Heat
Charge	**Seebeck effect**	**Peltier effect**
Spin	**Spin Seebeck effect** Uchida 2008	**Spin Peltier effect** Flipse 2014 Daimon 2016