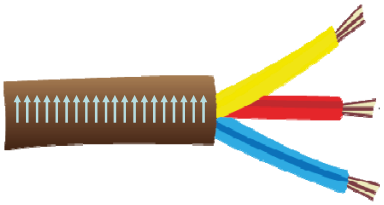
ESM 2015, Gerrit Bauer, Part II

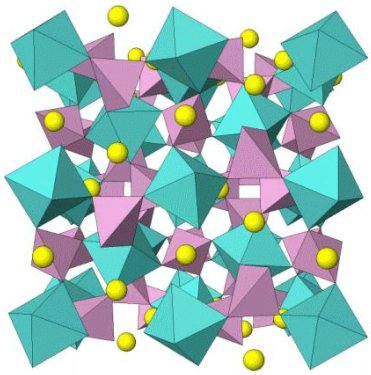


Magnetic Insulators

(with emphasis on YIG)

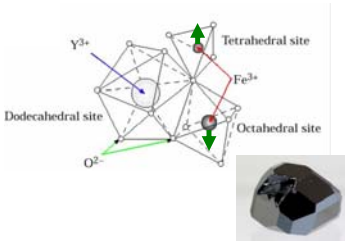
MAGNETISM.eu

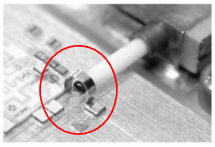
Yttrium Iron Garnet $Y_3^{(3+)}Fe_2^{(3+)}(Fe^{(3+)}O_4^{(2-)})_3$

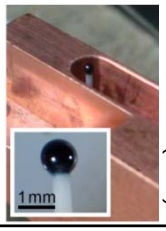


© A.R. Chakhmouradian

Yttrium Iron Garnet $Y_3^{(3+)}Fe_2^{(3+)}(Fe^{(3+)}O_4^{(2-)})_3$





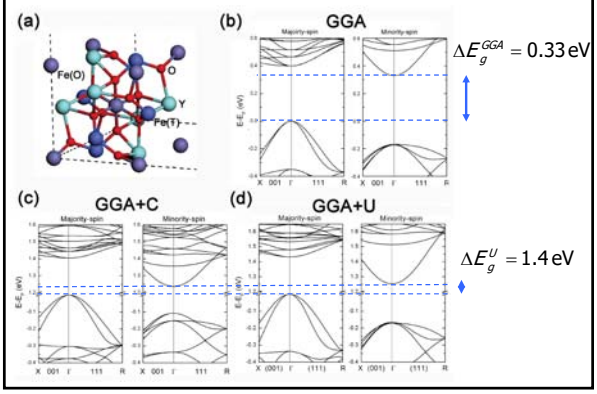


- 80 atoms & 20 moments/unit cell
- ferrimagnetic insulator
- Curie temperature 550 K
- man-made near perfection with Gilbert damping $\alpha \sim 10^{-5}$

Tabuchi et al. (2014)

YIG band structure

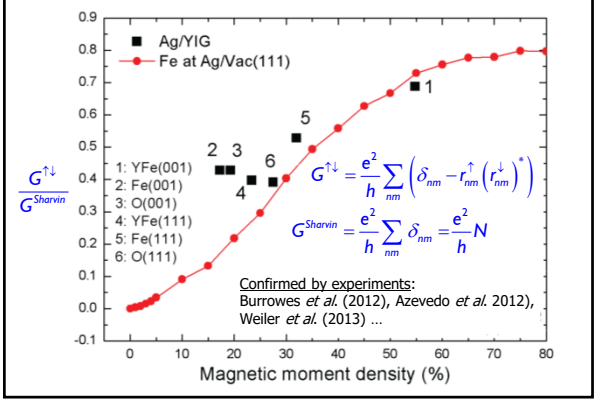
Jia *et al.*, EPL (2011)



$\Delta E_g^{GGA} = 0.33\,\text{eV}$

$\Delta E_g^{U} = 1.4\,\text{eV}$

Mixing conductance of YIG|Ag (Jia *et al.*, 2011)



Confirmed by experiments:
Burrowes *et al.* (2012), Azevedo *et al.* 2012),
Weiler *et al.* (2013) …

Spin waves in insulators

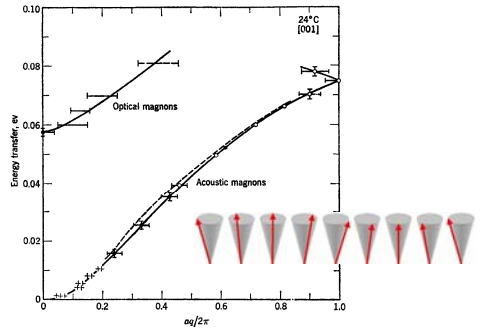
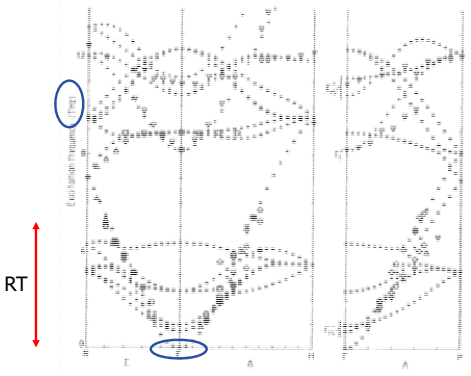


FIG. 1. Acoustical and optical magnon dispersion relations in magnetite, as determined from inelastic neutron scattering by Brockhouse and Watanabe (IAEA Symposium, Chalk River, Ontario, 1962).

Spin waves in YIG



(Plant, 1983)

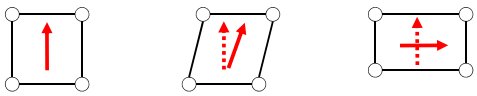
Magnon-phonon coupling

Spin Mechanics 3

Monday, June 22 – Friday, June 26, 2015

[Spin Mechanics 4 in Banff (Ca), Feb. 2017]

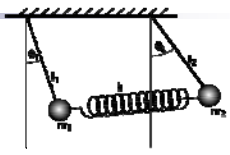
Magnetoelastic coupling



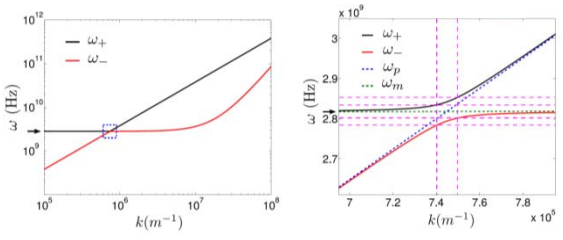
Dynamic effects of magnon-phonon interaction

- thermalization of lattice and spin
- magnon-phonon drift
- magnon-polarons (Kittel, 1958)

Magnon-polarons



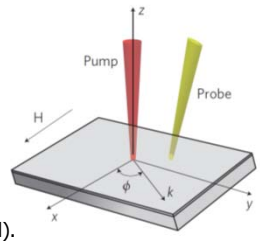
Kamra *et al.* (2015)



Magneto-polaron propagation (Shen, 2015)

Femto-second optical excitation

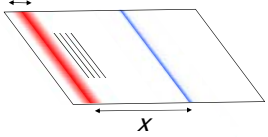
Excitation by – Inverse Faraday effect
– Heat
Detection by – Faraday or Kerr rotation

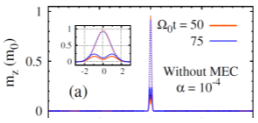


Satoh *et al.* (2012)
Hashimoto *et al.* (unpublished).

Magneto-polaron propagation (Shen, 2015)

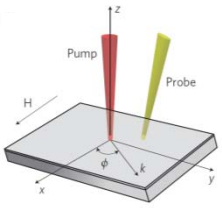
pump
W
probe





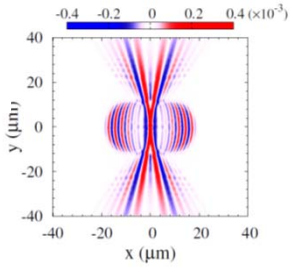
Line source excitation with IFE.

Magneto-polaron propagation (Shen, 2015)

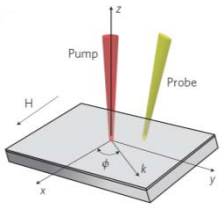


1 μm spot excitation
5 ns coda

inverse Faraday excitation

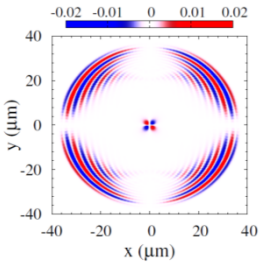


Magneto-polaron propagation (Shen, 2015)

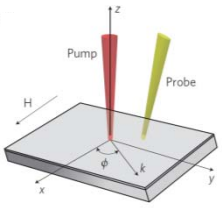


1 μm spot excitation
5 ns coda

pressure wave excitation

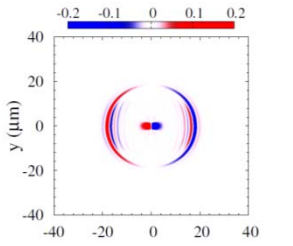


Magneto-polaron propagation (Shen, 2015)



1 μm spot excitation
5 ns coda

Shear deformation excitation



Strong coupling with microwaves

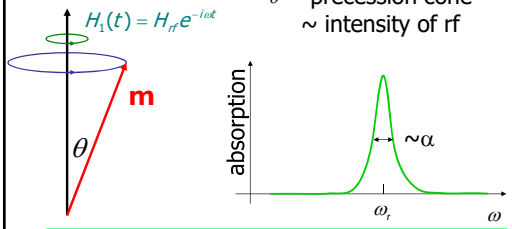
FerroMagnetic Resonance

Landau-Lifshitz-Gilbert equation; Gilbert damping constant α

$$\dot{\mathbf{m}} = \mathbf{m} \times \left(-\gamma \mathbf{B}_{eff} + \alpha \dot{\mathbf{m}}\right)$$

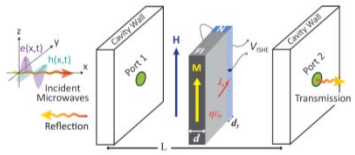
$\hbar\omega_{FMR} = \hbar\gamma B \approx 0.1\ \text{meV} \cdot B[T]$

θ "precession cone" ~ intensity of rf



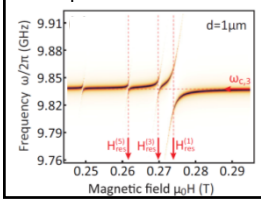
$\alpha_0 \approx 0.01$ in bulk metals, $\sim 10^{-5}$ in best YIG

Thin films in microwave cavities

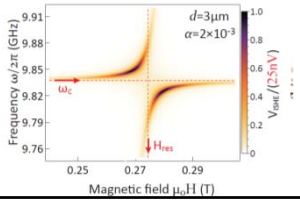


Cao *et al.* (2015)
Bai *et al.* (2015)

spin wave resonance

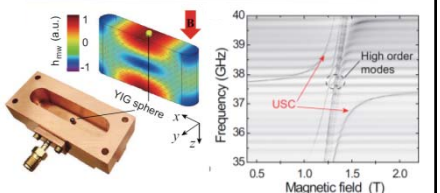


electric readout

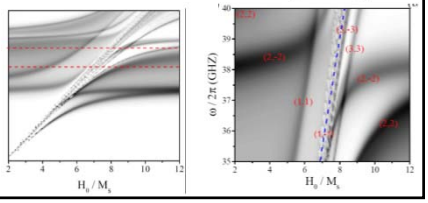


Ultra strong coupling with microwaves

Zhang et al. (2014)



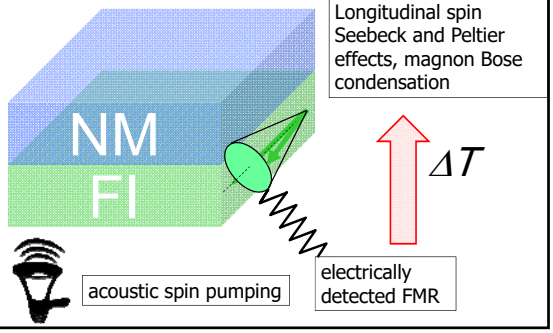
Rameshti et al. (2015) [spherical cavity]



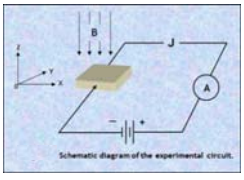
Spintronics with magnetic insulators

$\Delta T, \Delta V$ → SMR, transverse spin Seebeck

Longitudinal spin Seebeck and Peltier effects, magnon Bose condensation

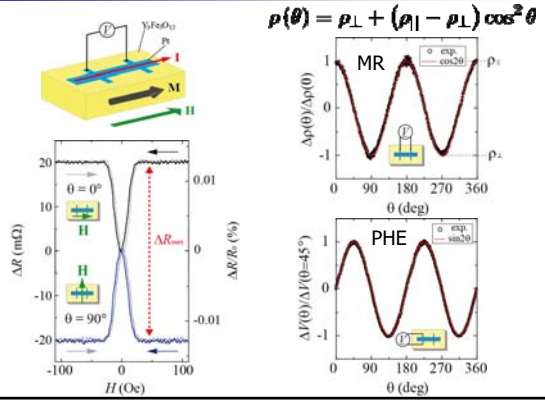


Spin Hall magnetoresistance



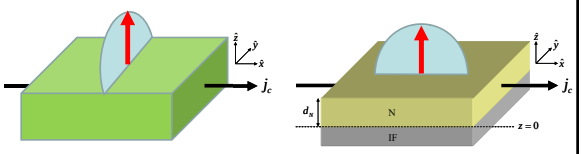
SMR (Nakayama *et al.*, 2013)

$$\rho(\theta) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\theta$$



SMR *vs.* AMR (out of plane magnetization)

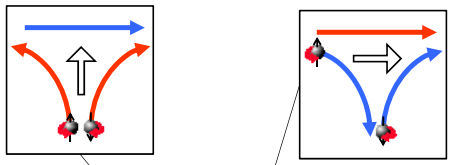
$AMR = 0$ $\qquad$ $SMR = 0$



$$\rho^{AMR} = \rho_\perp + \Delta\rho_A\, m_x^2 \qquad \rho^{SMR} = \rho_0 + \Delta\rho m_y^2$$

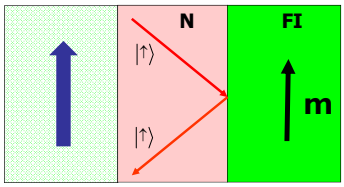
Onsager reciprocity in the spin Hall effect

spin Hall effect $\qquad$ inverse spin Hall effect

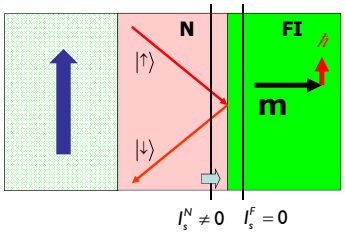


$$\begin{pmatrix} \mathbf{j}_c \\ \mathbf{j}_s^x \\ \mathbf{j}_s^y \\ \mathbf{j}_s^z \end{pmatrix} = \sigma_N \begin{pmatrix} 1 & \theta_{SH}\hat{x}\times & \theta_{SH}\hat{y}\times & \theta_{SH}\hat{z}\times \\ \theta_{SH}\hat{x}\times & 1 & 0 & 0 \\ \theta_{SH}\hat{y}\times & 0 & 1 & 0 \\ \theta_{SH}\hat{z}\times & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ -\nabla V_{sx}/2 \\ -\nabla V_{sy}/2 \\ -\nabla V_{sz}/2 \end{pmatrix}$$

Heterostructure



Exchange spin transfer torque



Absorbed spin current = spin-transfer torque

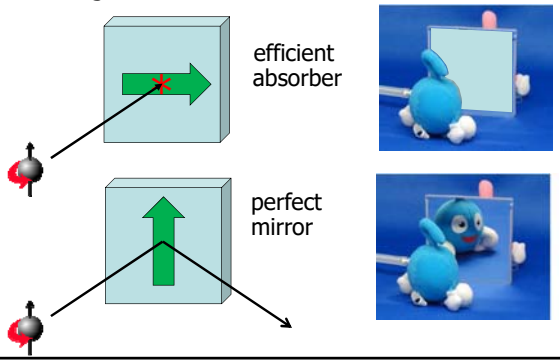
$$\mathbf{L} = \mathbf{I}_S^N = \frac{\hbar}{2}\frac{\mathrm{Re}\,G^{\uparrow\downarrow}}{e^2}\left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right) \approx Area \times k_F^2 \times \left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right)$$

$$G^{\uparrow\downarrow} = \frac{e^2}{h}\sum_{nm}\left(\delta_{nm} - r_{nm}^{\uparrow}\left(r_{nm}^{\downarrow}\right)^*\right)$$

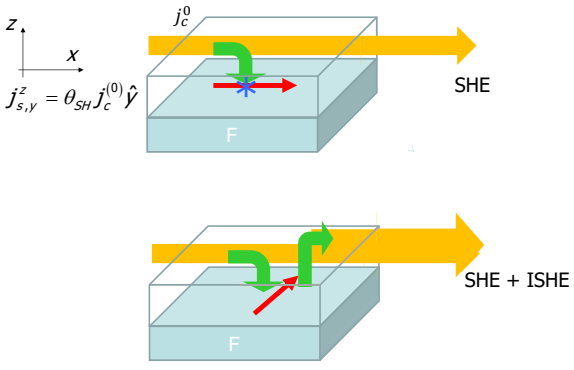
spin-mixing conductance

A switchable mirror for spins

Ferromagnetic insulator



Detection of spin current mirror



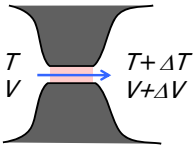
Spin Caloritronics VII, Utrecht,
The Netherlands, 11-15 July 2016

Spin Caloritronics

Thermoelectrics

$$\begin{pmatrix} J_c \\ J_Q \end{pmatrix} = \begin{pmatrix} L_{11} & L_{21} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} \Delta V \\ -\frac{\Delta T}{T} \end{pmatrix}$$

$L_{12} = L_{21}$ Onsager reciprocity

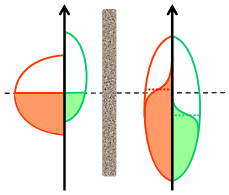


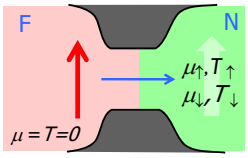
$$\begin{pmatrix} \Delta V \\ J_Q \end{pmatrix} = \begin{pmatrix} R & S \\ \Pi & K \end{pmatrix} \begin{pmatrix} J_c \\ -\Delta T \end{pmatrix}$$

$R = 1/G$	electrical resistance
K	thermal conductance
S	Seebeck coefficient
$\Pi = ST$	Peltier coefficient

Onsager-Thomson (Kelvin) relation

Spin dependent conductance





$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = -G \begin{pmatrix} 1 & P & ST_0 \\ P & 1 & P'ST \\ ST_0 & P'ST_0 & L_0T_0^2 \end{pmatrix} \begin{pmatrix} -\Delta\mu_c / e \\ -\Delta\mu_s / e \\ \Delta T / T_0 \end{pmatrix} \qquad P' = \frac{\partial_E PG}{\partial_E G}\Big|_{E_F}$$

spin-dependent Peltier effect

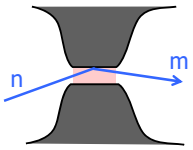
spin-dependent Seebeck effect

Landauer-Büttiker formalism (Butcher, 1990)

t_{nm} transmission amplitude

$g(E) = \sum_{nm}^{\varepsilon_n, \varepsilon_m = E} |t_{nm}|^2$ total transmission probability

$f(E,T)$ Fermi-Dirac function

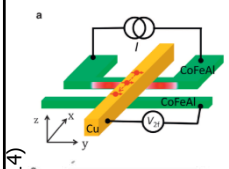


$$G = -\frac{2e^2}{h}\int dE \left(\frac{\partial f}{\partial E}\right) g(E) \to g(E_F)$$

$$GS = \frac{2e^2}{h}\frac{k_B}{e}\int dE \left(\frac{\partial f}{\partial E}\right) g(E)\frac{E - E_F}{k_B T} \to -eL_0 T \left.\frac{\partial G(E)}{\partial E}\right|_{E_F}$$

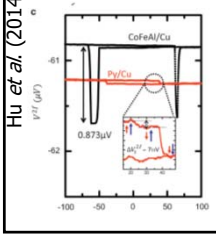
$$\frac{\kappa}{T} = S^2 G + \frac{2e^2}{h}\left(\frac{k_B}{e}\right)^2 \int dE \left(\frac{\partial f}{\partial E}\right) g(E)\left(\frac{E - E_F}{k_B T}\right)^2 \to \left(S^2 + L_0 T\right) G$$

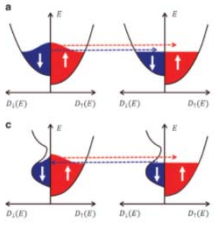
Enhanced spin Seebeck effect



$S_s = -72\frac{\mu V}{K} > S_c = -22\frac{\mu V}{K}$

$|P'| > 1$

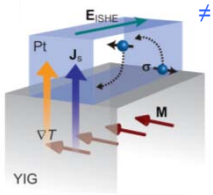




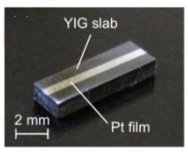
Hu *et al.* (2014)

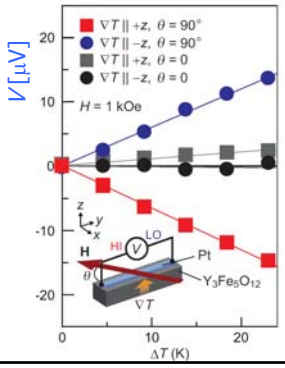
Spin Seebeck effect in YIG

(Longitudinal) spin Seebeck effect



≠ spin-dependent Seebeck effect!





Uchida *et al.* (2010/2011)

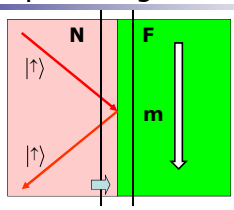
Spin torque and spin pumping

Onsager reciprocals
(Brataas *et al.*, 2011)
$\sim G^{\uparrow\downarrow}$

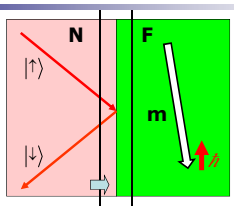
Spin currents cause magnetization motion (spin transfer torque, Slonczewski, 1996).

Magnetization motion causes spin currents (spin pumping, Tserkovnyak, 2002).

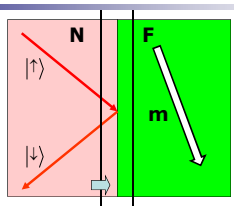
Collinear spin configuration

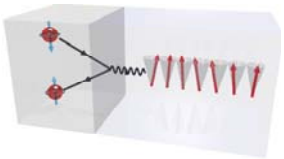


Spin current conversion

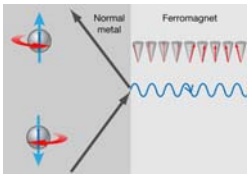


Spin current conversion

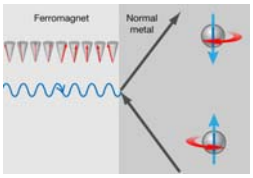




Small angle spin transfer

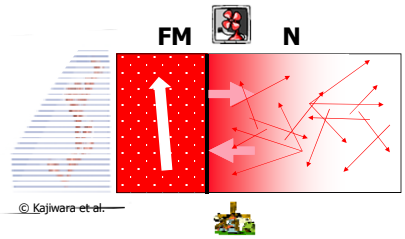


magnon creation



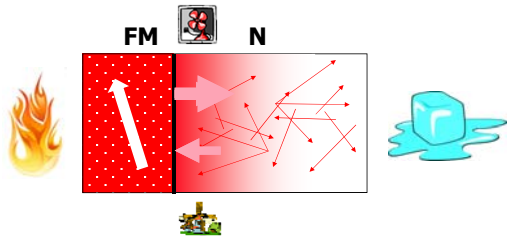
magnon annihilation

Noise-induced spin currents



Foros *et al.* (2005)
Xiao *et al.* (2009)

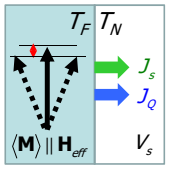
Noise-induced spin currents



$$J_s = J_s^{\text{pump}} - J_s^{\text{J-N noise}} \sim g^{\uparrow\downarrow}\left(T_F^M - T_N^e\right)$$

Xiao *et al.* (2010)
Adachi *et al.* (2011)

Spin Seebeck Onsager matrix



L_{ij} spin-spin correlation functions at the interface

thermal field

spin Seebeck effect

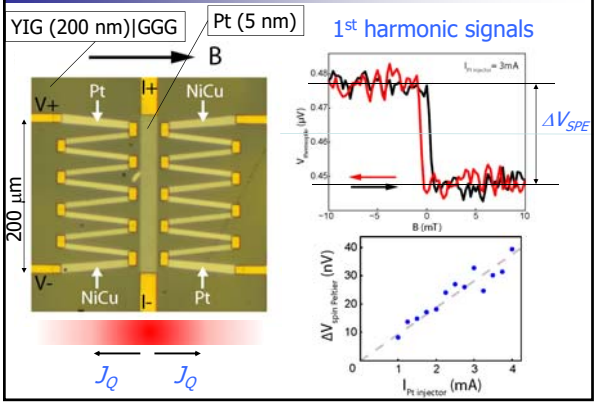
$$\begin{pmatrix} \dot{M}_z \\ J_s \\ J_Q \end{pmatrix} = \begin{pmatrix} L_{mm} & L_{ms} & L_{mQ} \\ L_{sm} & L_{ss} & L_{sQ} \\ L_{Qm} & L_{Qs} & L_{QQ} \end{pmatrix} \begin{pmatrix} \delta H_{\text{eff}} \\ V_s / 2 \\ -\Delta T / T \end{pmatrix}$$

heat conductance

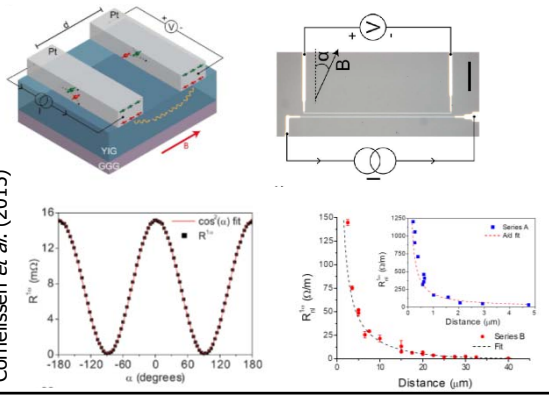
magnon Peltier effect

spin Peltier effect

Spin Peltier effect (Flipse et al., 2014)



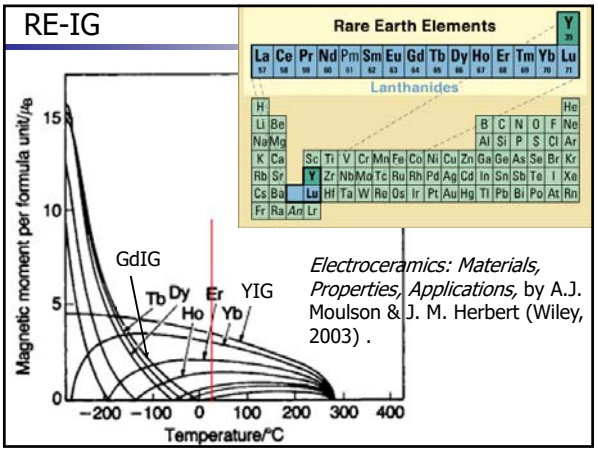
Magnon transport (also Kajiwara *et al.* (2010))



Cornelissen *et al.* (2015)

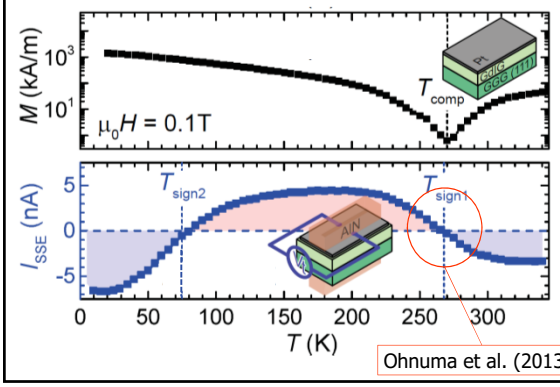
Spin Seebeck effect in GIG

RE-IG



Electroceramics: Materials, Properties, Applications, by A.J. Moulson & J. M. Herbert (Wiley, 2003) .

Geprägs *et al.* (2015)



Spin Seebeck effect and spin correlation

$$\langle J_s \rangle = \frac{M_s V}{\gamma} \int_{\text{interface}} \begin{bmatrix} \alpha' \langle \mathbf{s}(\boldsymbol{\rho},t) \times \dot{\mathbf{s}}(\boldsymbol{\rho},t) \rangle \\ +\gamma \langle \mathbf{s}(\boldsymbol{\rho},t) \times \mathbf{h}'(\boldsymbol{\rho},t) \rangle \end{bmatrix} d\boldsymbol{\rho}$$

Equal time and position spin correlation function

Spin-spin correlation power spectra:

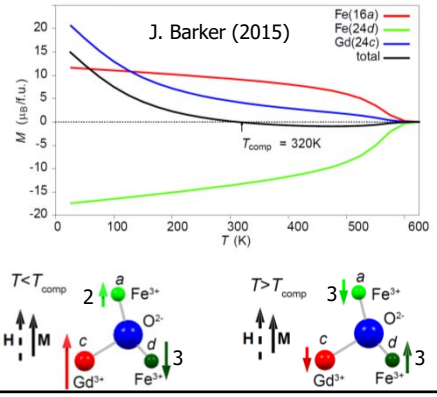
$$S_{ij}(\mathbf{k},\omega) = \mathcal{F}t \langle s_i(\mathbf{r},t) s_j(\mathbf{r}',t') \rangle$$

Atomistic spin simulations:

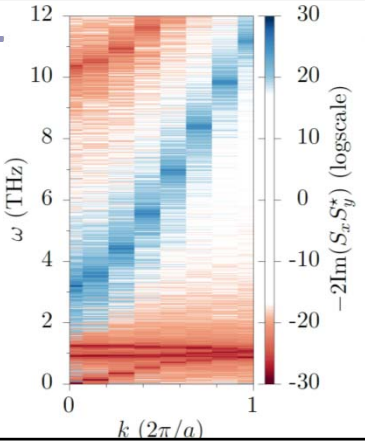
$$\dot{\mathbf{S}}_i = -\gamma \mathbf{S}_i \times \mathbf{B}_i^{eff} + \alpha_i \mathbf{S}_i \times \dot{\mathbf{S}}_i \qquad \mathbf{B}_i^{eff} = -\frac{\partial E_i}{\partial \mathbf{S}_i} + \mathbf{b}_i(t)$$

$$E_i^x = -\sum_{j\neq i}^{N} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \qquad \langle b_k(t) b_l(t') \rangle_i = \frac{2 k_B T \alpha_i}{\gamma M_i} \delta(t-t') \delta_{kl}$$

Rare Earth Iron Garnets → GdIG

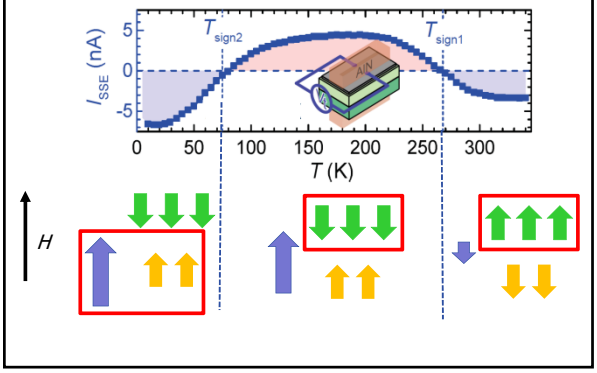


J. Barker (2015)



GdIG spin wave power spectrum and chirality.

Geprägs *et al.* (2015)



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