Modelling and Simulation

a physicist's point of view

Part 2

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Who's Afraid of YIG?

Barnett Newman, Who's Afraid of Red, Yellow and Blue III, 1967-68

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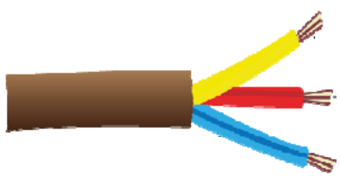
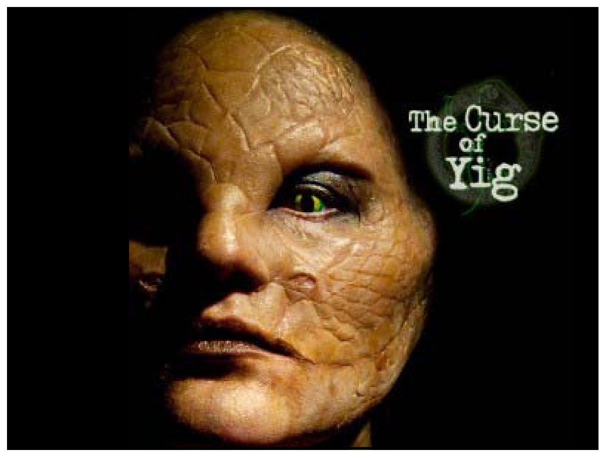
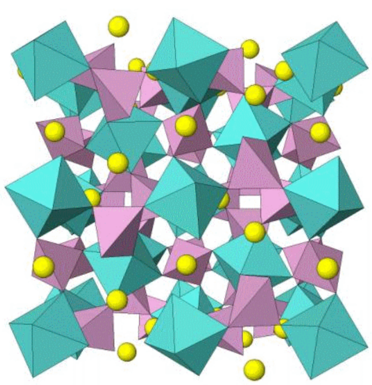


- YIG electronic and magnetic structure
- Spin Hall magnetoresistance of YIG|Pt
- Spin Seebeck effect in YIG vs. GdIG



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



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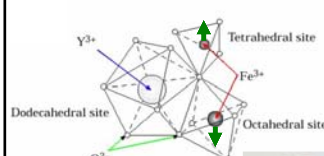
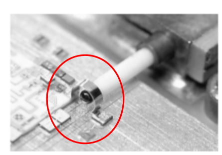
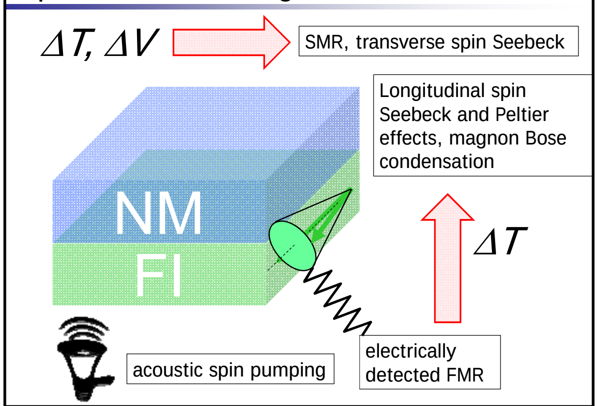




- 80 atoms & 20 moments/unit cell
- ferrimagnetic insulator
- Curie temperature 550 K
- man-made near perfection with Gilbert damping $\alpha \sim 10^{-5}$

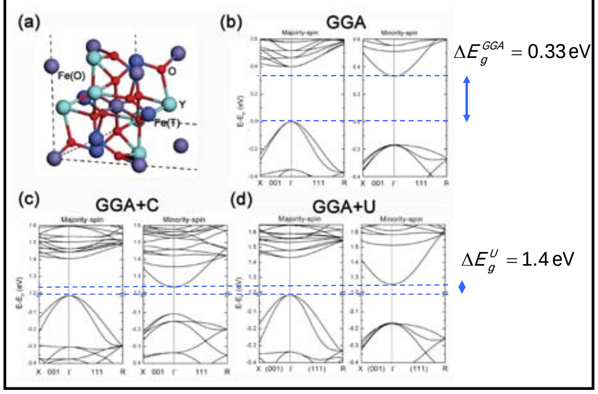
Tabuchi et al. (2014)

Spintronics with magnetic insulators

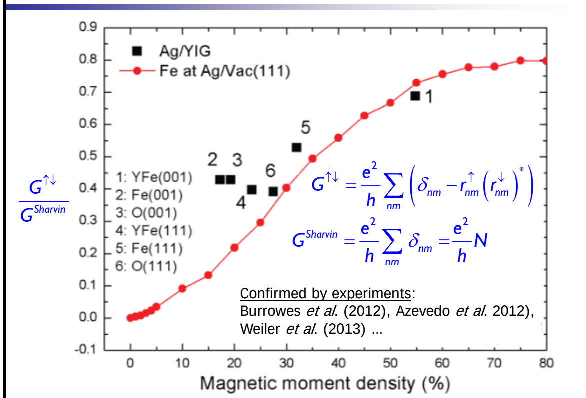


YIG band structure

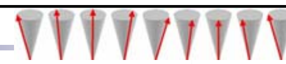
Jia *et al.*, EPL (2011)

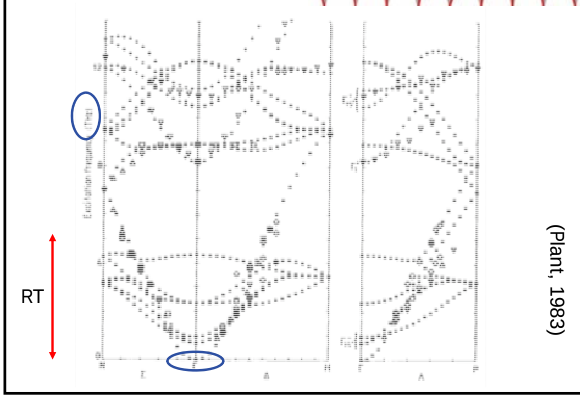


Mixing conductance of YIG|Ag (Jia *et al.*, 2011)



Spin waves in YIG





Lars Onsager Memorial at NTNU Trondheim

The Nobel Prize in Chemistry 1968:
"for the discovery of the reciprocal relations bearing his name, which are fundamental for the thermodynamics of irreversible processes"

Onsager symmetry (1931)

i = {mass, charge, energy, volume, (angular) momentum, ...}

X_i generalized forces

J_i generalized currents

$J_m = \sum_n L_{mn} X_n$ linear response

If: $\dot{S} = \sum_i X_i J_i$ entropy creation rate

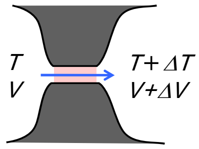
then: $L_{ij} = L_{ji}$ **Onsager relations**

When time reversal symmetry is broken: $L_{ij}\left(\mathbf{m}, \mathbf{H}_{ext}\right) = \varepsilon_i \varepsilon_j L_{ji}\left(-\mathbf{m}, -\mathbf{H}_{ext}\right)$

$\varepsilon_i = \begin{cases} 1 \\ -1 \end{cases}$ when variable *i* even (charge) / odd (spin)

Thermoelectrics

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



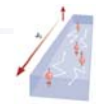
$L_{12} = L_{21}$ Onsager reciprocity

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

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

Onsager-Thomson (Kelvin) relation

Spin-dependent thermoelectrics



$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = G \begin{pmatrix} 1 & P & ST \\ P & 1 & P'ST \\ ST & P'ST & L_0T^2 \end{pmatrix} \begin{pmatrix} (V_\downarrow + V_\uparrow)/2 \\ (V_\downarrow - V_\uparrow)/2 \\ -\Delta T/T \end{pmatrix} \qquad P' = \left.\frac{\partial_E PG}{\partial_E G}\right|_{E_F}$$

spin-dependent Peltier effect

spin-dependent Seebeck effect

Johnson and Silsbee (1987)
Hatami *et al.* (2009)
Slachter *et al.* (2010)
Flipse *et al.* (2012)

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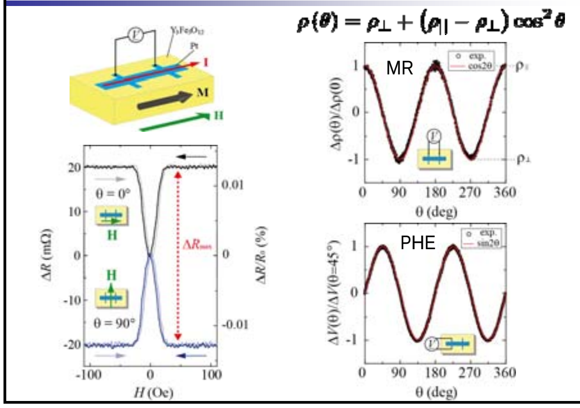
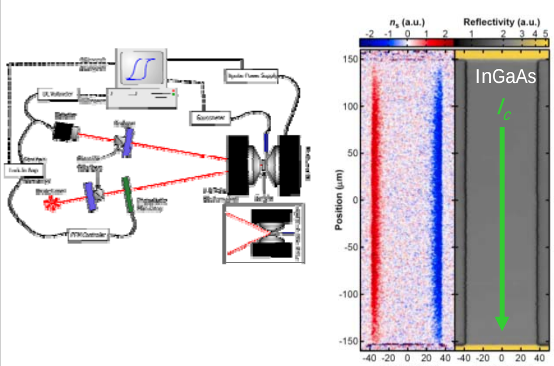
- YIG electronic and magnetic structure
- Spin Hall magnetoresistance of YIG|Pt
- Spin Seebeck effect in YIG vs. GdIG
- Strong coupling with microwaves

SMR (Nakayama *et al.*, 2013)

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



Kato *et al.* (2004)

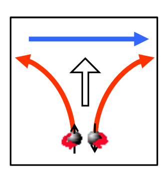


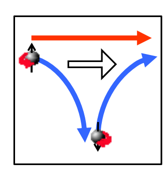
Spin current tensor, spin Hall angle

$$\vec{J}_s = \left(\mathbf{J}_s^x, \mathbf{J}_s^y, \mathbf{J}_s^z\right) = \begin{pmatrix} \mathbf{J}_{s,x} \\ \mathbf{J}_{s,y} \\ \mathbf{J}_{s,z} \end{pmatrix}$$

$\mathbf{J}_s^x$ polarization of current || x

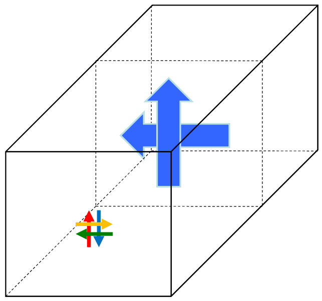
$\mathbf{J}_{s,x}$ current direction of polarization || x





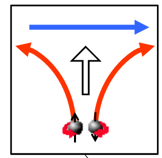
$$\mathbf{J}_{s,\beta} = \theta_{SH}\hat{\beta} \times \mathbf{J}_c \qquad \mathbf{J}_c = \theta_{SH}\sum_\alpha \mathbf{J}_s^\alpha \times \hat{\alpha}$$

3D spin Hall effect

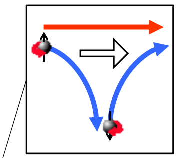


Onsager reciprocity in the spin Hall effect

spin Hall effect

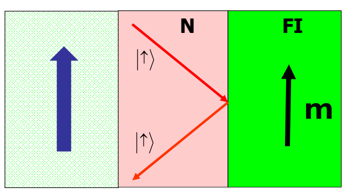


inverse spin Hall effect

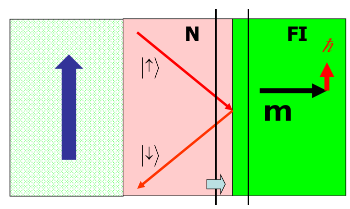


$$\begin{pmatrix} \mathbf{j}_c \\ \mathbf{j}_s^x \\ \mathbf{j}_s^y \\ \mathbf{j}_s^z \end{pmatrix} = \sigma_N \begin{pmatrix} 1 & \theta_{SH}\hat{x}\times & \theta_{SH}\hat{y}\times & \theta_{SH}\hat{z}\times \\ \theta_{SH}\hat{x}\times & 1 & 0 & 0 \\ \theta_{SH}\hat{y}\times & 0 & 1 & 0 \\ \theta_{SH}\hat{z}\times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

Heterostructure



Exchange spin transfer torque



Absorbed spin current = spin-transfer torque

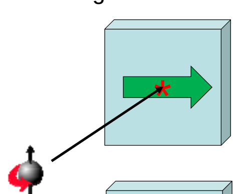
$$\mathbf{L} = \mathbf{I}_S^N = \frac{\hbar}{2}\frac{\mathrm{Re}\,G^{\uparrow\downarrow}}{e^2}\left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right) \approx Area \times k_F^2 \times \left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right)$$

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

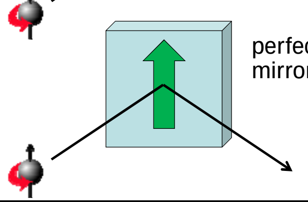
spin-mixing conductance

A switchable mirror for spins

Ferromagnetic insulator

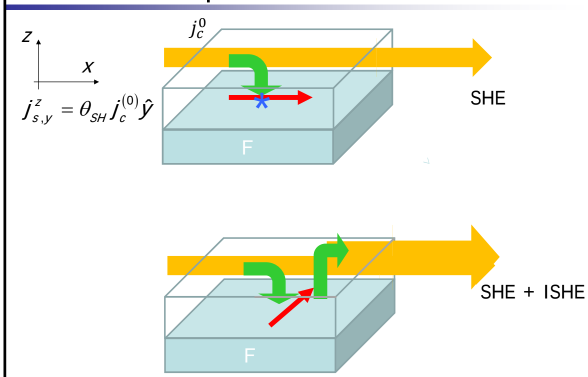


efficient absorber



perfect mirror

Detection of spin current mirror



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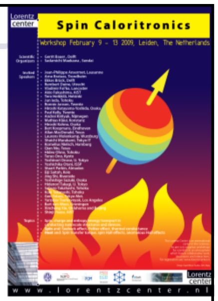

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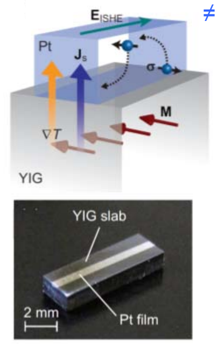
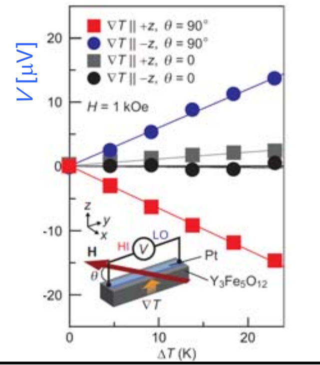
(Longitudinal) spin Seebeck effect

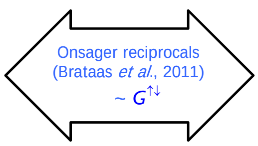
$\neq$ spin-dependent Seebeck effect!





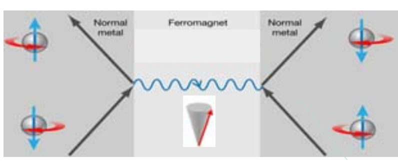
Uchida *et al.* (2010/2011)

Spin torque and spin pumping

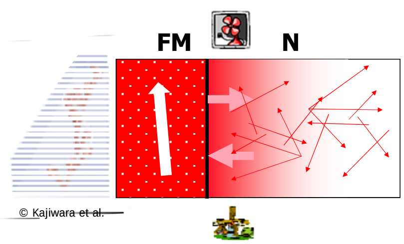


Spin currents cause magnetization motion (spin transfer torque, Slonczewski, 1996).

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

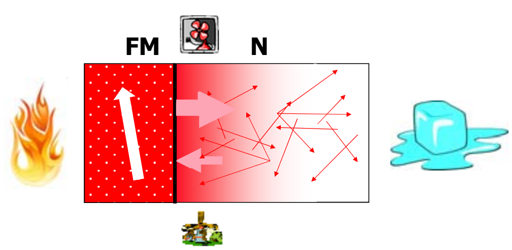


Noise-induced spin currents



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

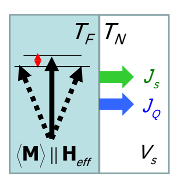
Noise-induced spin currents



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

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

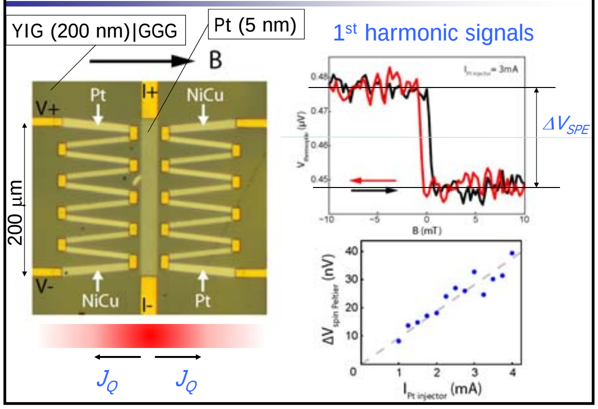
$$\begin{pmatrix} \dot{M}_z \\ J_s \\ J_Q \end{pmatrix} = \begin{pmatrix} L_{mm} & L_{ms} & L_{mQ} \\ L_{sm} & L_{ss} & L_{sQ} \\ L_{Qm} & L_{Qs} & L_{QQ} \end{pmatrix} \begin{pmatrix} \delta H_{\text{eff}} \\ V_s / 2 \\ -\Delta T / T \end{pmatrix}$$

heat conductance

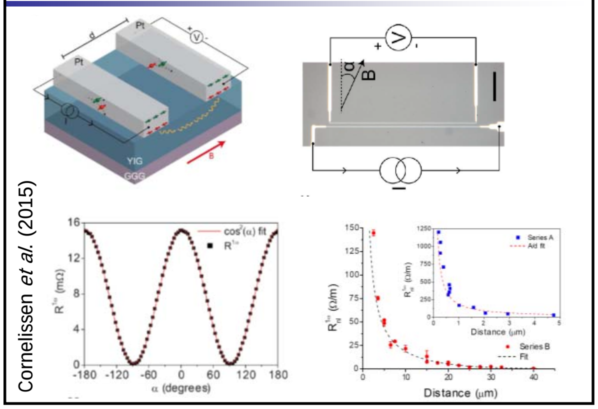
magnon Peltier effect

spin Peltier effect

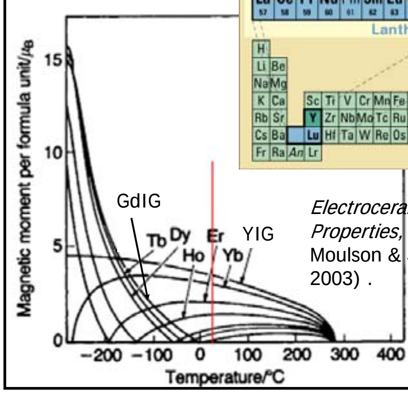
Spin Peltier effect (Flipse et al., 2014)

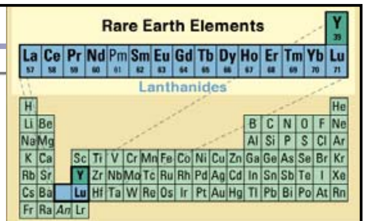


Magnon transport (also Kajiwara *et al.* (2010))



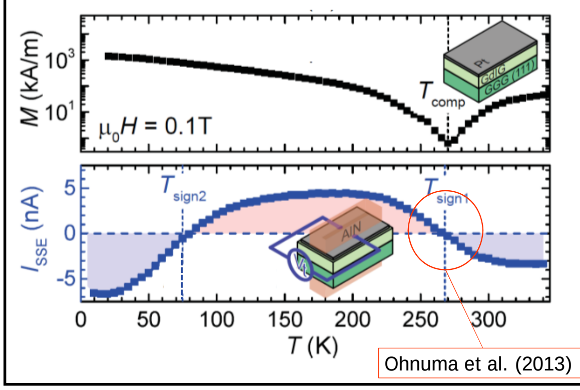
RE-IG





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

Geprägs *et al.* (2015)



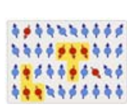
Spin Seebeck effect and spin correlation

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

Equal time and position spin correlation function

Spin-spin correlation power spectra:

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

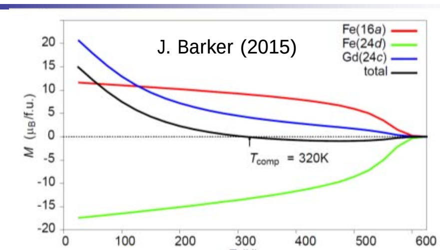


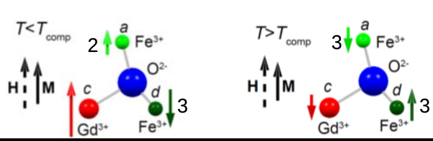
Atomistic spin simulations:

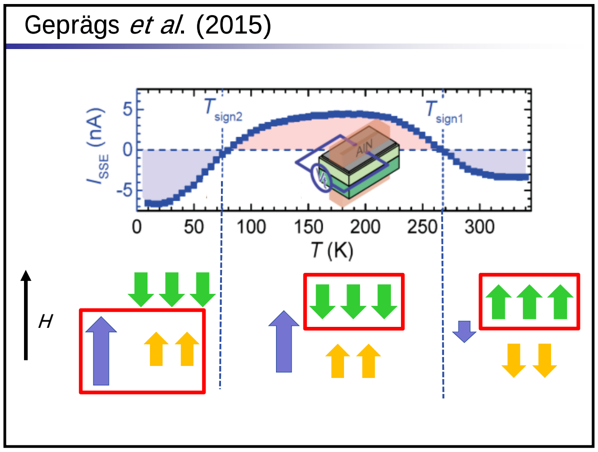
$$\dot{\mathbf{S}}_i = -\gamma \mathbf{S}_i \times \mathbf{B}_i^{eff} + \alpha_i \mathbf{S}_i \times \dot{\mathbf{S}}_i \qquad \mathbf{B}_i^{eff} = -\frac{\partial E_i}{\partial \mathbf{S}_i} + \mathbf{b}_i(t)$$

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

Rare Earth Iron Garnets → GdIG







Geprägs et al. (2015)
T sign2
T sign1
I SSE (nA)
5
0
-5
0
50
100
150
200
250
300
T (K)
AlN
H