Spin Seebeck effect

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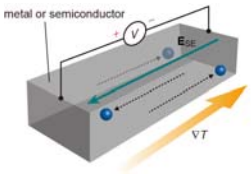
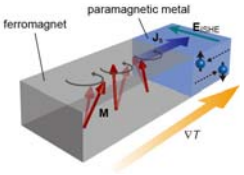
Spin Seebeck effect:
generation of **spin voltage** as a result of **heat flows**

Seebeck effect



Electric-voltage generation as a result of a temperature gradient

Spin Seebeck effect (SSE)



Spin-voltage generation as a result of a temperature gradient

Spin voltage generates a spin current into an attached conductor.

contents:

- スピン流とは
- スピン流の重要な現象を幾つか紹介
  - 逆スピンホール効果
  - スピンポンピング
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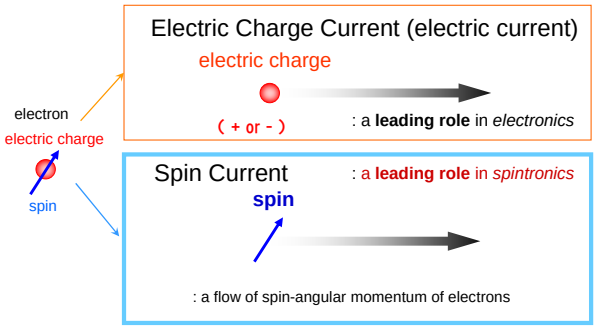
an electron has charge and spin



Spin currents

Spin current type	Carrier of spin current	intensity
Conduction electron Spin current	conduction electrons	$j_S = j_\uparrow - j_\downarrow$
Spin wave Spin current f_k f_{-k} magnons	Spin Waves (magnons)	$j_S \sim f_k - f_{-k}$ f: Magnon-distributon function

Spin is not conserved.....

charge current vs spin current

Charge : conserved quantity

Spin $a|\uparrow\rangle + b|\downarrow\rangle$: nonconserved quantity

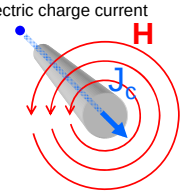
spin diffusion length $l < 10\ \mu$m

an electron loses spin memory after running l

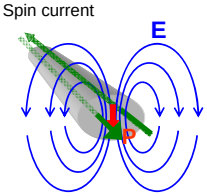
spin current is expected to generate an electric field

- Ampere's law
- Spin current → E

Electric charge current



Spin current

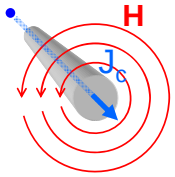


Saitoh APL(2006) Nature(2010)

… an electric current generates ***H*** … a spin current generates ***E***

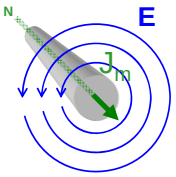
Starting point of our consideration - electromagnetic duality -

- Charge current
- hypothetical monopole current



$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{J}_c$$

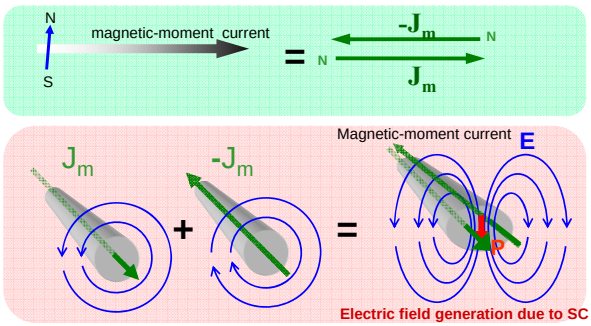
Ampere's law



$$\mathrm{rot}\,\mathbf{E} = -\mathbf{J}_m$$

Dirac

- magnetic-moment flow= a pair of magnetic monopole currents with opposite signs



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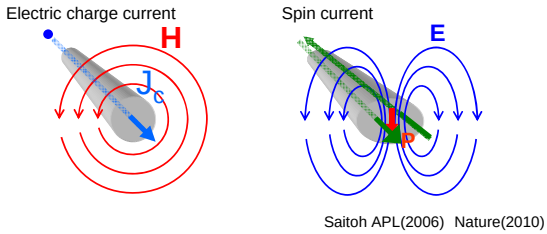


Saitoh APL(2006) Nature(2010)

… an electric current generates ***H***

… a spin current generates ***E***

‥from quantum mechanical point of view

- e/m^2-order correction of Dirac eq.

Dipole Term

$$j^0 = \nabla \bullet \Gamma\{\nabla(u^\dagger(x)u(x)) + iu^\dagger(x)(\nabla - \overleftarrow{\nabla}) \times \boldsymbol{\sigma} u^\dagger(x)\}$$

density — Darwin term

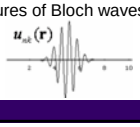
due to the SO interaction acting on spins which contains ∇

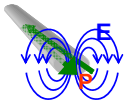
spin motion generates electric dipole
due to spin-orbit interaction

spin — electric dipole

…. should be **enhanced** in **solids** due to fine structures of Bloch waves

Bloch wave $\varphi(\mathbf{r}) = u_{nk}(\mathbf{r})e^{i\mathbf{kr}}$

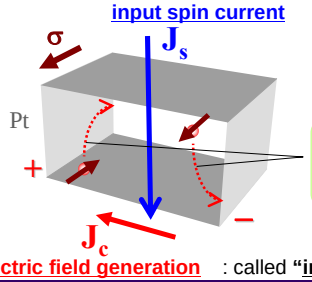




can be argued from another point of view

A two-particle model for electric polarization generation from spin current

input spin current



Spin-Orbit Interaction

$$H_{SO} = \lambda(\vec{\nabla}U \times \vec{k}) \cdot \vec{\sigma}$$

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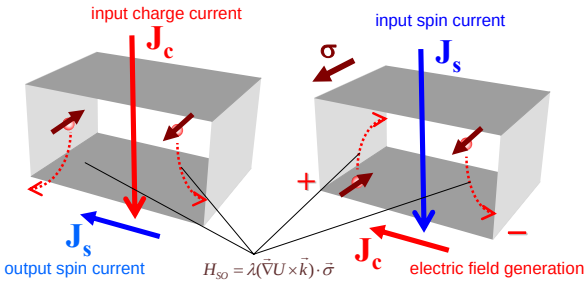
electric field generation : called **"inverse spin-Hall effect"**

Spin-Hall effect family

- Spin Hall effect (SHE)
- **Inverse Spin Hall effect (ISHE)**



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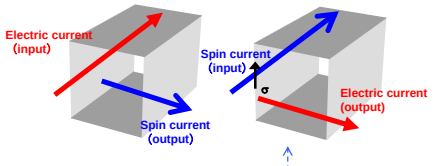
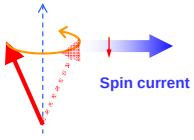
Fundamental spin-current phenomena

- **Spin Hall effect (electric→spin current)**
- **inverse spin-Hall effect (spin→electric current)**

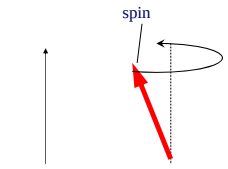


- Spin pump



Spin Dynamics

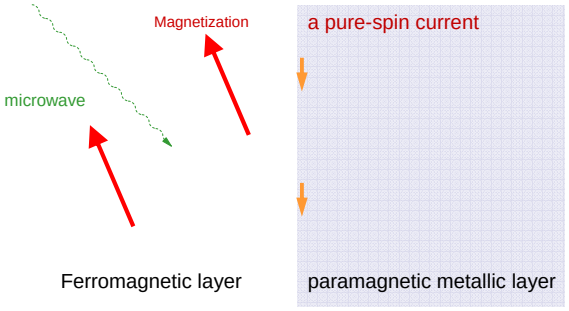
- Spin rotates only in an anti-clockwise fashion



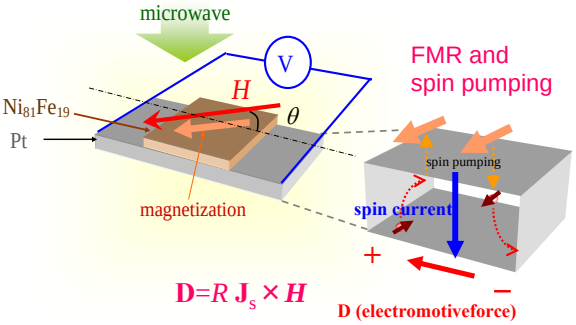
Spinning tops

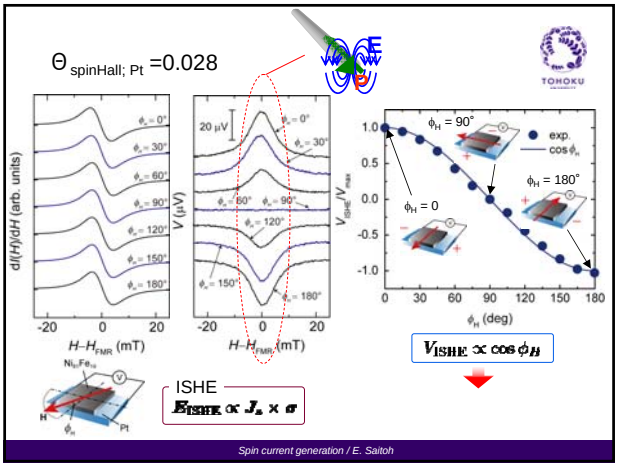
Spins carry angular momentum and thus exhibit precession motion.

Spin Pumping operated by FMR

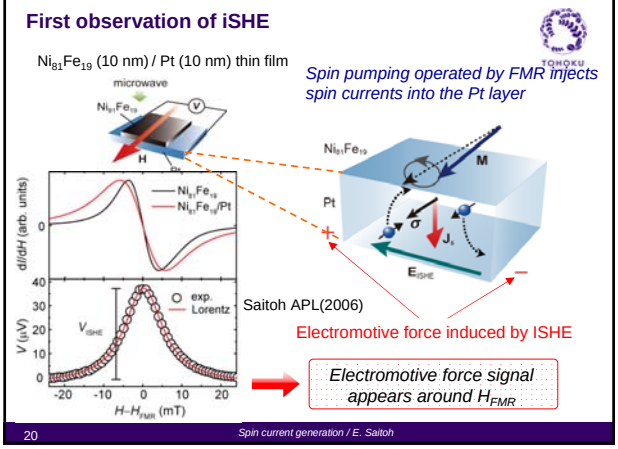


First observation of iSHE induced by SP





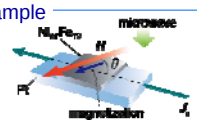
First observation of iSHE



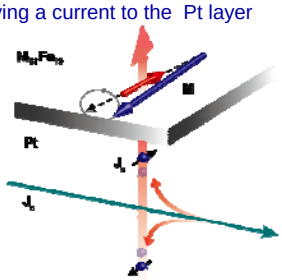
Experimental 2

FMR measurement with applying a current to the Pt layer

sample



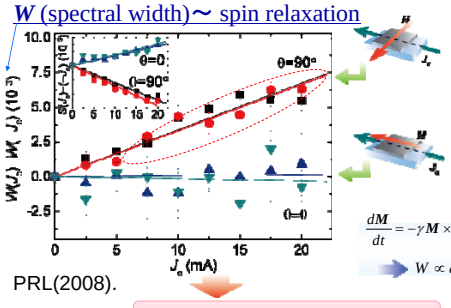
$Ni_{81}Fe_{19}$ 10 nm / Pt 10 nm



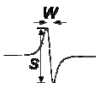
Spin-Hall effect:
charge current → spin current

Current (J_c) induced modulation of spectral width

W (spectral width)～ spin relaxation



PRL(2008).



W : width
S : intensity

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \frac{\alpha}{M_S} \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

$$W \propto \alpha \quad S \propto \frac{1}{\alpha}$$

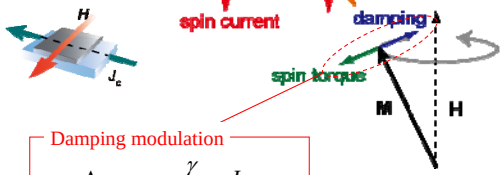
Current induced modulation of α !

Damping modulation via spin torque

θ=90°

spin current is absorbed by M

Spin Hall effect → spin current → torque, accum. → damping, spin torque

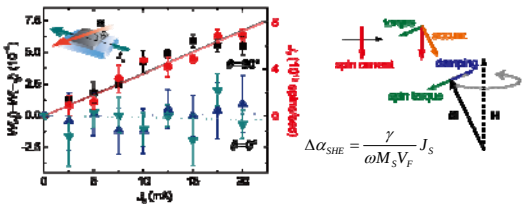


Damping modulation

$$\Delta\alpha_{SHE} = \frac{\gamma}{\omega M_S V_F} J_S$$

Takahashi & Maekawa *et al.*

- We have shown that electric manipulation of spin relaxation is possible using SHE.

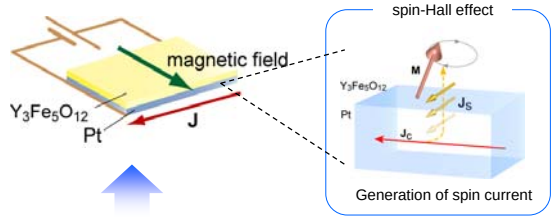


$$\Delta\alpha_{SHE} = \frac{\gamma}{\omega M_S V_F} J_S$$

- Then, is it possible to zero this spin relaxation?

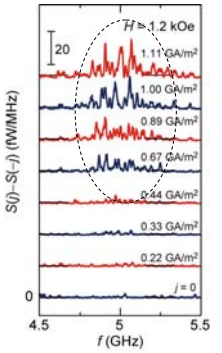
Let's try! - spin transfer into YIG-

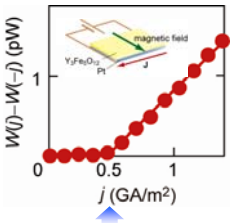
sample system:
$Y_3Fe_5O_{12}$(1.2 μm) / Pt(10nm)



detection of microwave oscillation

microwave emission spectra

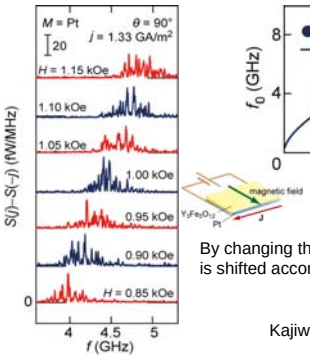


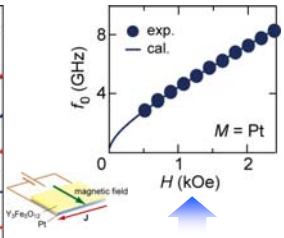


There is a threshold in the current dependence of the emission intensity

Kajiwara & Saitoh *et al.* Nature (2008)

Magnetic field dependence





By changing the field, the emission frequency is shifted according the Kittel's equition

Kajiwara & Saitoh *et al.* Nature (2008)

we can send electric voltage in YIG **by the SW interconversion** induced by SHE ....

Yttrium Iron Garnet (YIG) : $Y_3Fe_5O_{12}$

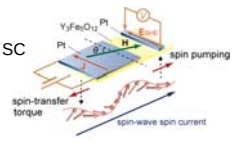
ferrimagnetic insulator (CT-type insulator)

- charge excitation gap is large (2.7 eV).
- spin excitation gap is very small (~ μ eV)
- magnetization damping is very small (α ~ 6.7×10−5)

α : damping constant

YIG: insulator for charge but conductor for SC

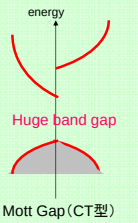
SC is combined with SHE



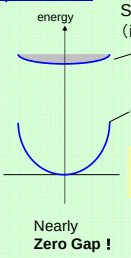
Insulator for Charge *but* Conductor for Spin

- Ferrimagnet with tiny anisotropy

Charge sector



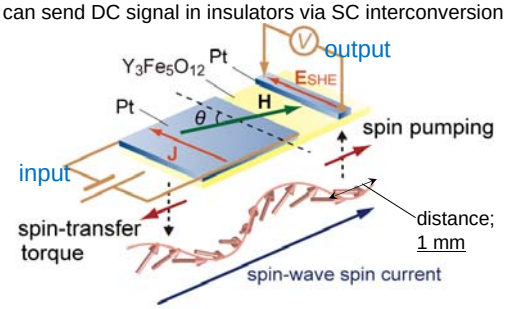
Spin sector



Coherent (spin wave) spin current

spin pumping and torque are used at the same time…

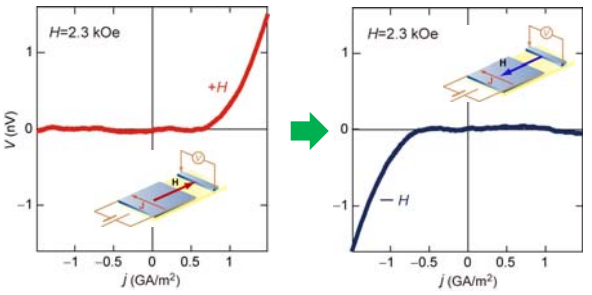
: we can send DC signal in insulators via SC interconversion



Kajiwara & Saitoh *et al.* Nature (2008)

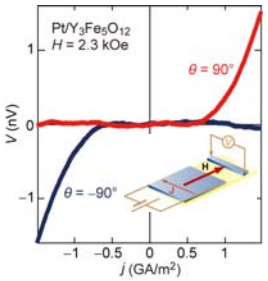
Non-local I-V curve

Magnetic field reversal

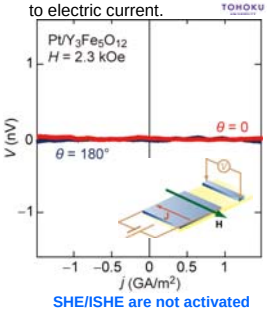


Kajiwara & Saitoh *et al.* Nature (2008)

Magnetic field is perpendicular to electric current.



Magnetic field is parallel to electric current.



SHE/ISHE are not activated

$$\mathbf{E}_{SHE} \propto \mathbf{j}_s \times \boldsymbol{\sigma}$$

Kajiwara & Saitoh *et al.* Nature (2008)

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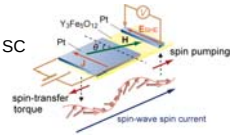

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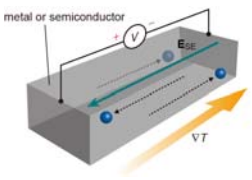
Spin Seebeck effect:

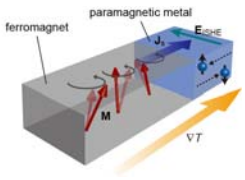
generation of **spin voltage** as a result of **heat flows**

Seebeck effect



Electric-voltage generation as a result of a temperature gradient

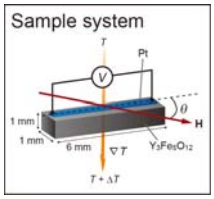
Spin Seebeck effect (SSE)



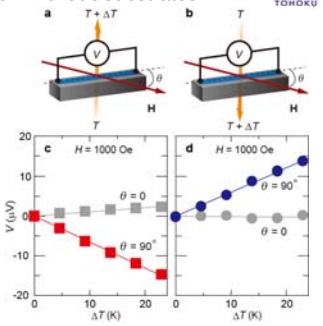
Spin-voltage generation as a result of a temperature gradient

Spin voltage generates a spin current into an attached conductor.

Most fundamental configuration of SSE;
"Longitudinal" configuration ***without*** substrates



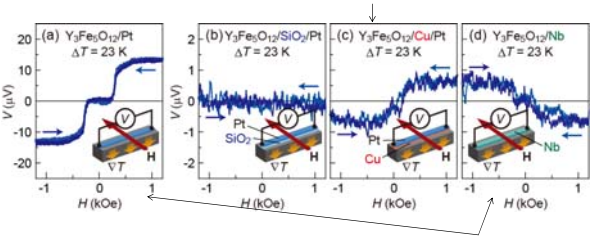
bulk YIG crystal



Uchida & Saitoh et al. APL (2010)

This is due **NOT** to proximity effect in Pt near the YIG/Pt interface…

The SSE signal disappears in the YIG/SiO_2 (10 nm)/Pt system, but the finite signal appears in the YIG/Cu (10 nm)/Pt system.



The sign of SSE signal is reversed in the YIG/Nb (10 nm)/Pt, where Nb exhibits opposite ISHE sign.

Spin Seebeck effects (SSEs)

Experiments:

Uchida & Saitoh *et al.*, Nature (2008). [SSE in metals]
S. Bosu *et al.*, Nature (2008).
and so on ……
Uchida & Saitoh *et al.*, Nat. Mater. (2010). [SSE in insulators]
Uchida & Saitoh *et al.*, APL (2010).
C. M. Jaworski *et al.*, Nat. Mater. (2010). [SSE in semiconductors]
C. M. Jaworski *et al.*, ArXiv (2011).
and so on ……

A. Slachter *et al.* Nature Physics (2010).
[Thermal spin-current injection by spin-dependent Seebeck effect]

Theory

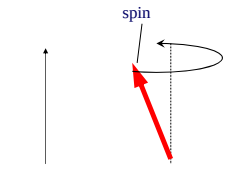
J. Xiao *et al.*, Phys. Rev. B (2010) [Scattering theory]
H. Adachi *et al.*, Appl. Phys. Lett. (2010). [Linear-response theory]
H. Adachi *et al.* Phys. Rev. B (in press).
J. Ohe *et al.* Phys. Rev. B (in press). [Numerical calculation]
……

contents:

- スピン流とは
- スピン流の重要な現象を幾つか紹介
  - 逆スピンホール効果
  - スピンポンピング
- スピンゼーベック効果
- スピンゼーベック効果の理解
- スピン流熱輸送

Spin Dynamics

- Spin rotates only in an anti-clockwise fashion



A spin exhibits precession motion due to its angular momentum

Spinning tops

Spins carry angular momentum and thus exhibit precession motion.

Equation of motion of spin

Torque due to H

$$\frac{d\vec{M}}{dt} = -\frac{i}{\hbar}[\vec{M}, H] \longrightarrow \frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff}$$

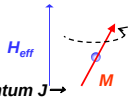
$$[M_x, M_y] = iM_z$$
$$[M_y, M_z] = iM_x$$
$$[M_z, M_x] = iM_y$$

Gyromagnetic constant

$$\gamma = \frac{g\mu_B}{\hbar}$$

$$\begin{cases} H = -\vec{M} \cdot \vec{H}_{eff} \\ \vec{H}_{eff} = -\dfrac{\delta E}{\delta \vec{M}} \end{cases}$$

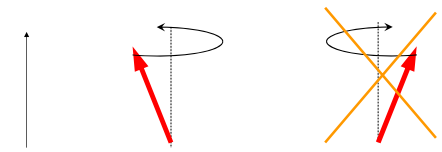
$$\vec{M} = -\gamma \vec{J}$$



same as a classical EOM of angular momentum J

Crucial property of spin（non reciprocity）

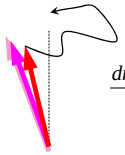
- Spin precesses *one way*



Magnetic field　Spin precession

awareness of the issues

- stochastic LLG equation （thermal fluctuation is included）



comes from commutation relation of spin

Random field

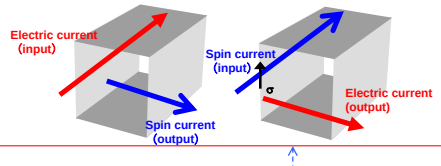
$$\frac{d\vec{m}(t)}{dt} = -\gamma \vec{m}(t) \times (\vec{H} + \vec{h}_{random}) - \alpha \vec{m}(t) \times \frac{d\vec{m}(t)}{dt}$$

$$\langle h_i(t) \rangle = 0$$
$$\langle h_i(t) h_j(t') \rangle = \frac{2\alpha k_B T}{\gamma M_s V} \delta_{ij} \delta(t - t')$$

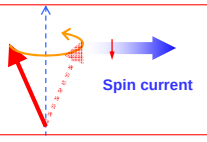
motion of *M(t)* is random, but anti clockwise as the expected value **!**
（<M(t)×dM(t)/dt>≠0）
: a manifestation of non reciprocity of spin

Fundamental spin-current phenomena

- **Spin Hall effect**
  （electric→spin current）
- **inverse spin-Hall effect**
  （spin→electric current）

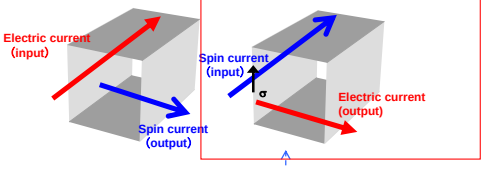


- Spin pump

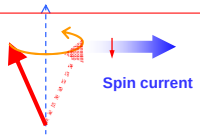


Fundamental spin-current phenomena

- Spin Hall effect (electric→spin current)
- inverse spin-Hall effect (spin→electric current)



- Spin pump



A calculation result using Keldysh
- common mechanism for SSE-
co by Bauer, Xiao, Adachi, Ohe, Saitoh, Maekawa

$$I_{\rm spin} = -2J'^2 {\rm Re} \int_{\mathbf{q},\mathbf{k}} \int_\omega \left[\underbrace{\chi_N^R(\mathbf{k},\omega) X_F^K(\mathbf{q},\omega)}_{I_{\rm pump} \propto -\coth(\frac{\omega}{2T_{F1}})} + \underbrace{\chi_N^K(\mathbf{k},\omega) X_F^A(\mathbf{q},\omega)}_{I_{\rm back} \propto \coth(\frac{\omega}{2T_{N1}})} \right]$$

$$\propto \int_{\mathbf{q},\mathbf{k}} \int_\omega {\rm Im}\chi_N^{\rm R}(\mathbf{k},\omega) {\rm Im} X_F^{\rm R}(\mathbf{q},\omega) \left[\coth(\frac{\hbar\omega}{2k_{\rm B}T_{N1}}) - \coth(\frac{\hbar\omega}{2k_{\rm B}T_{F1}}) \right]$$

$T_{\rm spin} - T_{\rm electron\ env.}$

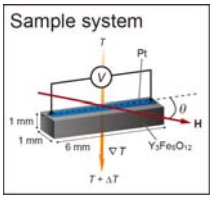
$$\vec{M}(t) \times \frac{d\vec{M}(t)}{dt}$$

$$< \vec{m}(t) >= 0$$

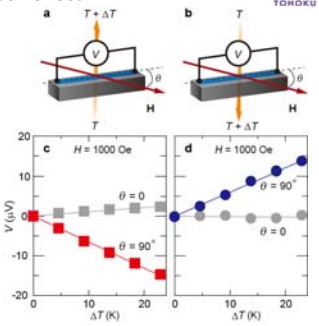
$$< \vec{m}(t) \times \frac{d\vec{m}(t)}{dt} >\neq 0$$

Back from electron system in metal

another configuration (simplest structure);
"Longitudinal" spin-Seebeck effect



bulk YIG crystal



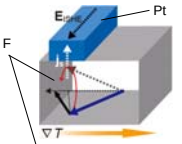
Uchida & Saitoh *et al.* Nature (2009) Nature Mat. (2010) Nature Mat.(2011)

Two proposed mechanisms for T_F-T_N ?

1. Phonon Drag (metal & insulator)

Maekawa Q2-1

see Uchida Saioh *et al.* Nature mat (2011)



2. Long Magnon thermalization length

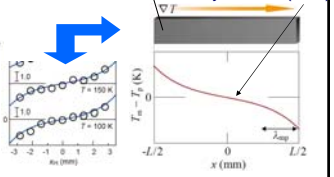
Xiao et al. PRB (2010)

Spatial distribution of T_m–T_p:

$$\Delta T_{mp}(z) = \eta \frac{\sinh\frac{z}{\lambda}}{\sinh\frac{L}{2\lambda}} \Delta T$$

The decay length λ reaches several millimeters in YIG.

D. J. Sanders and D. Walton, Phys. Rev. B (1977)

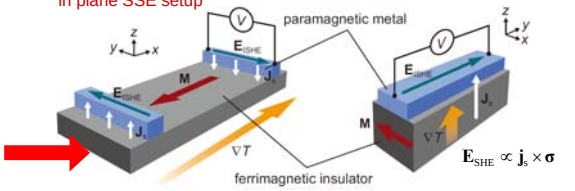


➡ can induce T_F-T_N and SSE

Longitudinal spin Seebeck effect

(Conventional)
in plane SSE setup

Longitudinal SSE setup

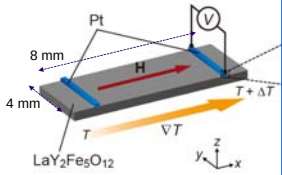


The spin currents flowing *perpendicular to* a temperature gradient are measured.

The spin currents flowing ***parallel to*** a temperature gradient are measured.

more complicated configuration : IPC
IPC-SSE in YIG

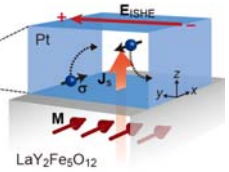
Sample system



(YIG, ferrimagnetic insulator)

A ferromagnetic metal layer is replaced by a ferrimagnetic insulator $LaY_2Fe_5O_{12}$.

Inverse spin-Hall effect (ISHE)

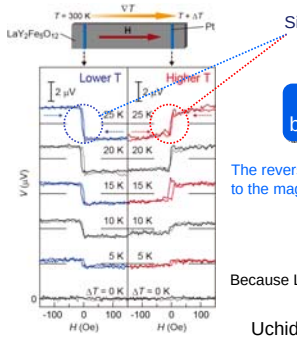


Electric detection of spin currents

$\mathbf{E}_{SHE} \propto \mathbf{j}_s \times \boldsymbol{\sigma}$

Uchida & Saitoh et al. Nature Mat (2010)

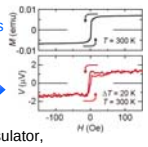
H dependence of *V* ($LaY_2Fe_5O_{12}$, 300 K)



Sign reversal of *V* by reversing *H*

ISHE voltage induced by the spin-Seebeck effect

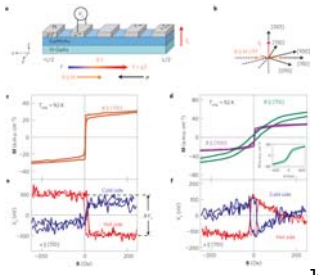
The reversal of *V* corresponds to the magnetization reversal.



Because $LaY_2Fe_5O_{12}$ is an insulator,

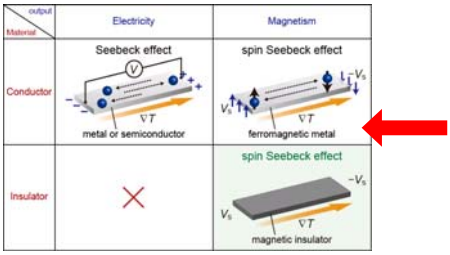
Uchida & Saitoh et al. Nature Mat (2010)

Jaworski *et al*. (SSE in GaMnAs)



Jaworski & Heremans *et al.* (OSU)
Nature Mat. (2010)

Critical difference
between spin and charge Seebeck effects

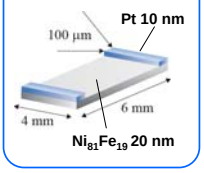


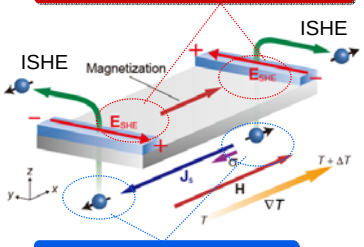
The spin Seebeck effect appears both in insulators and metals

SSE detection mechanism

Sign of electromotive force is reversed.

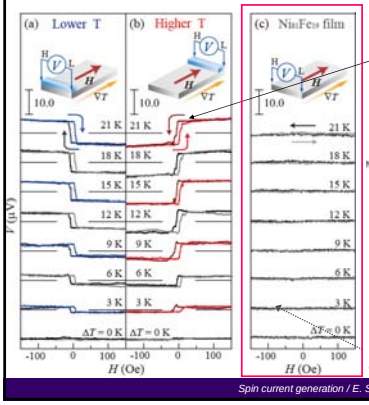
Sample system





Sign of spin voltage is reversed.

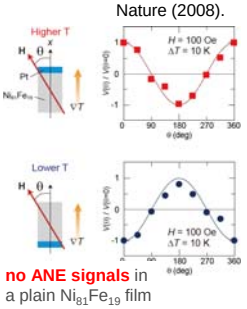
Magnetic-field dependence of *V*



Nature (2008).

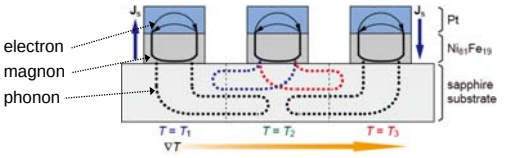
hysteresis loop

Nature (2008).



no ANE signals in a plain $Ni_{81}Fe_{19}$ film

Model calculation by Adachi et al.



ISHE voltage: $V = \left(\frac{\theta_{SH}}{\sigma_c}\right)\left(\frac{k_B e}{w\hbar^3}\right)\tau_{ph}^2 \tau_{eff}^2 RB\Delta T$

phonon life time in substrate

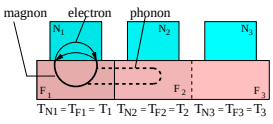
proportional to acoustic-impedance (Z) matching condition between $Ni_{81}Fe_{19}$ and substrate.

$$T_{S-F} = \frac{4Z_S Z_F}{(Z_S + Z_F)^2} \leq 1$$

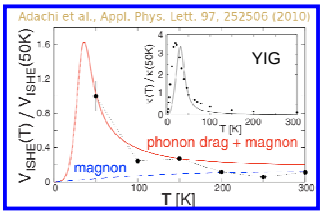
The SSE signal should depend on the substrate species.
YES! OBSERVED

Phonon-drag SSE (Adachi, APL 2010)

Localized spin in ferromagnet is excited by ***phonon*** heat current



$$J_s^{ph-drag} \propto \tau_{ph}\left(T_{mag} - T_{elec}\right)$$

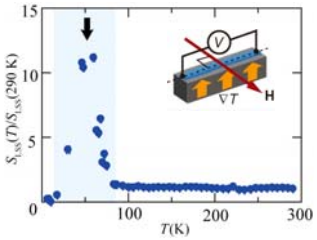


At low T (< 100K), phonon lifetime (tau$_{ph}$) gets longer due to the rapid suppression of the umklapp scattering.

→ *Phonon-drag gives low-T enhancement of SSE!*

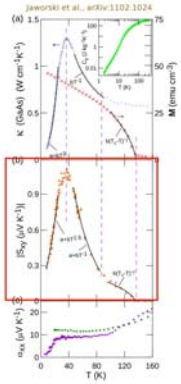
Very recent experimet

YIG



T. Ota *et al.*, (submitted).

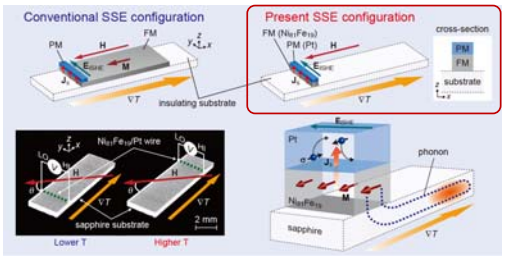
GaMnAs



Pronounced peak consistent with our prediction!

Experimental setup for acoustic SSE

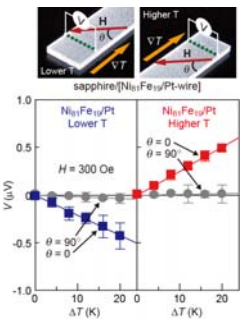
Sample: A Ni$_{81}$Fe$_{19}$/Pt bilayer wire placed on a single-crystal sapphire substrate, where only *phonons* can pass through the substrate.



The Ni$_{81}$Fe$_{19}$/Pt wire is completely isolated both electrically and magnetically.
Uchida Saitoh et al. Nature Mat (2011)

ΔT dependence of V (Ni$_{81}$Fe$_{19}$/Pt wire, 300 K)

Nature mat (2011)



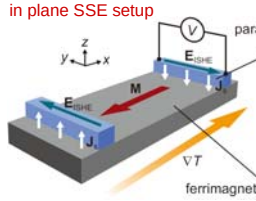
- **The V magnitude is proportional to ΔT.**
- **The V signal disappears when H $\perp \nabla T$.**
- **The sign of V is reversed between the lower/higher temperature regions.**

The Ni$_{81}$Fe$_{19}$/Pt wire picks up its own position on the

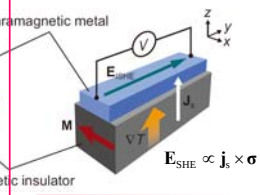
Uchida Saitoh et al. Nature Mat (2011)

Longitudinal spin Seebeck effect

(Conventional)
in plane SSE setup



Longitudinal SSE setup



$$\mathbf{E}_{\mathrm{SHE}} \propto \mathbf{j}_{\mathrm{s}} \times \boldsymbol{\sigma}$$

The spin currents flowing *perpendicular to* a temperature gradient are measured.

The spin currents flowing ***parallel to*** a temperature gradient are measured.