- In this version, unpublished data that do not belong to us are deleted.

IEEE 7th International Symposium on Metallic Multilayers

Spin current coupled with charge and heat currents

Institute for Materials Research (IMR)

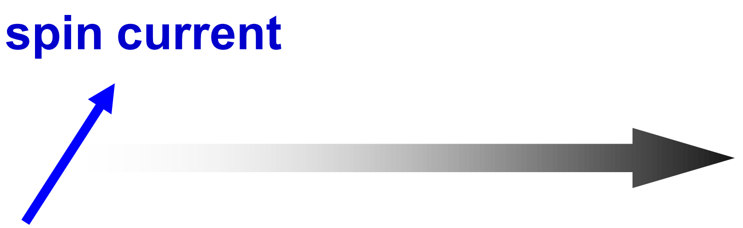
Tohoku University, Japan

and

Japan Atomic Energy Agency, Japan

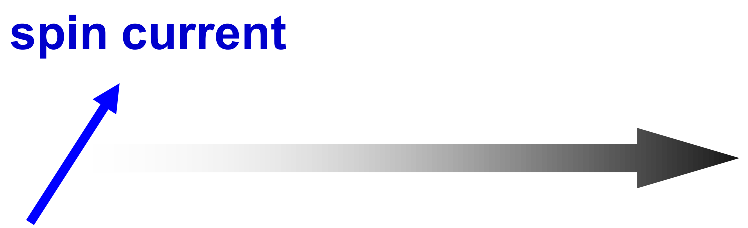
Eiji SAITOH

My talk today: spin current physics



contents:

- Introduction - spin current- (for nonspecialists)
- Inverse spin-Hall effect and spin-Hall effect
- Spin pumping and spin torque
- Spin Seebeck effect

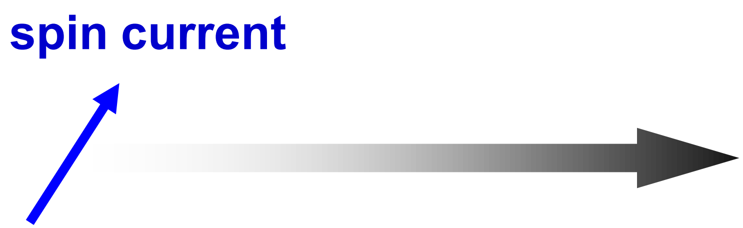


contents:

- Introduction - *What is spin current?* -
- Inverse spin-Hall effect and spin-Hall effect
- Spin pumping and spin torque
- Spin Seebeck effect

Spin current (SC):

is a flow of spin angular momentum:



an electron has charge and spin

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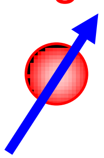
electron

charge



spin

Charge Current (electric current)

electric charge

(+ or -)

: a **leading role** in *electronics*

Spin Current

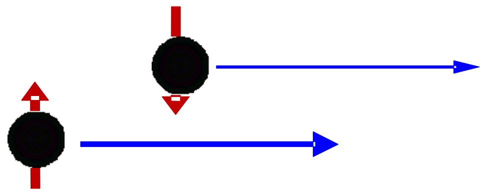
: a **leading role** in *spintronics*

spin

: a flow of spin-angular momentum of electrons

There is a variety of charge currents including….

- Paramagnetic charge current
  (incoherent mode , conduction electron)



- Topological current

- Super charge current (collective mode)

$$j \sim \nabla \Theta$$

an electron has charge and spin

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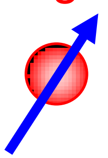
electron

charge



spin

Charge Current (electric current)

electric charge

(+ or -)

: a **leading role** in *electronics*

Spin Current

: a **leading role** in *spintronics*

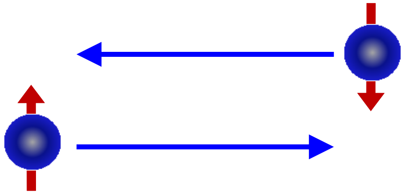
spin

: a flow of spin-angular momentum of electrons

There is a variety of spin currents including….

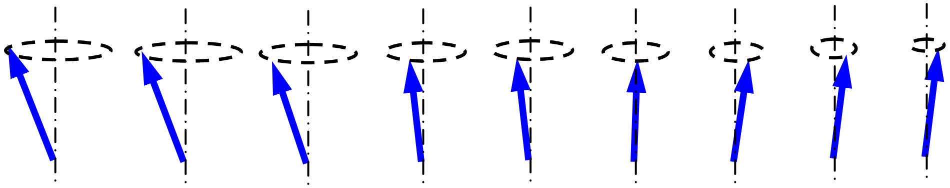
A spin current is carried by

- Conduction electron (incoherent mode)

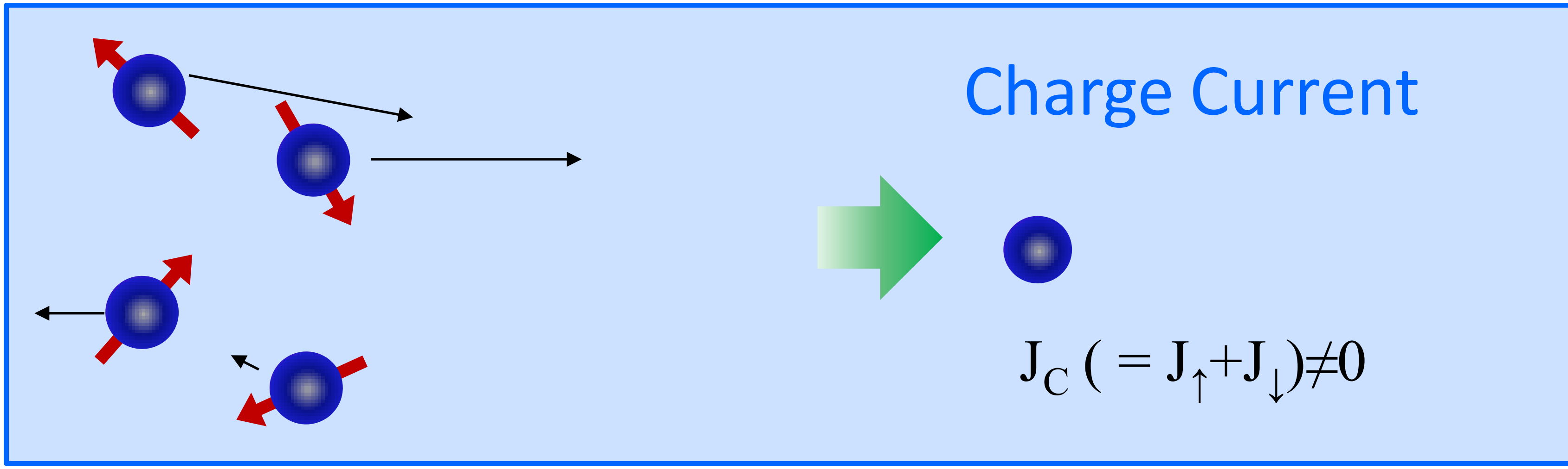


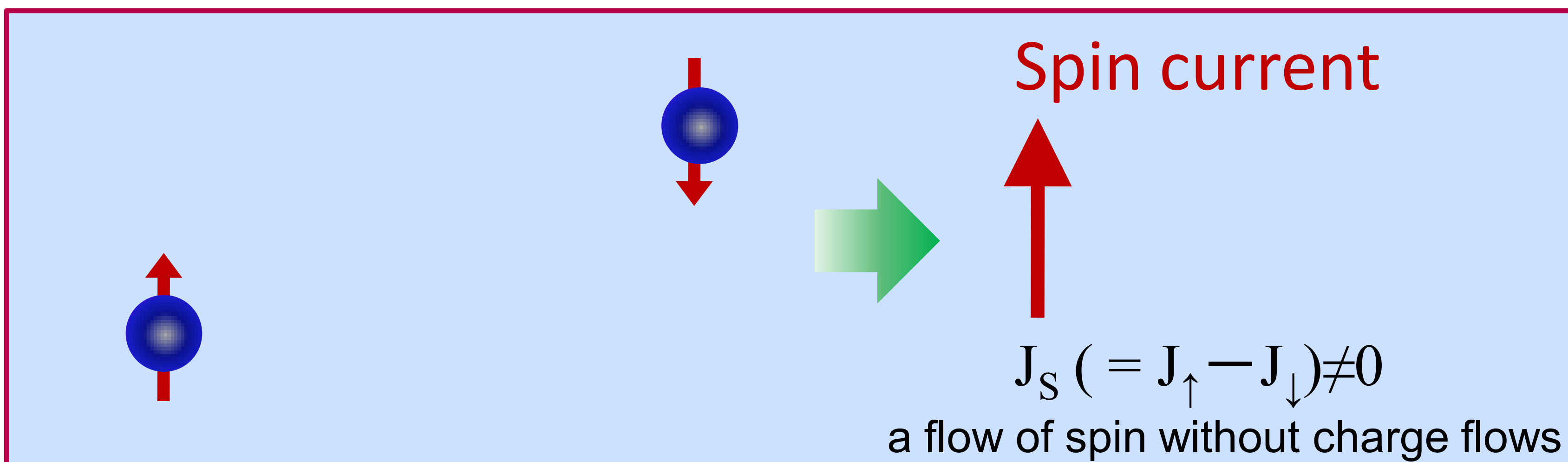
- Edge state in topological insulators

- Spin waves (collective mode)



A form of charge and Spin current carried by conduction electron





Spin current has wonderful properties…

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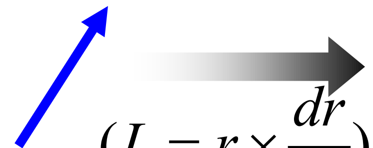
- time reversible

Charge Current

$$v = \frac{dr}{dt}$$

Spin Current



$$(L = r \times \frac{dr}{dt}) \otimes (v = \frac{dr}{dt})$$

- electric capacity is zero → no wiring delay
- magnetization manipulation ***without*** magnetic fields

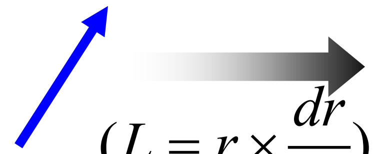
Spin current has wonderful properties…

- time reversible

Charge Current

$$v = \frac{dr}{dt}$$

Spin Current



$$(L = r \times \frac{dr}{dt}) \otimes (v = \frac{dr}{dt})$$

- electric capacity is zero → no wiring delay
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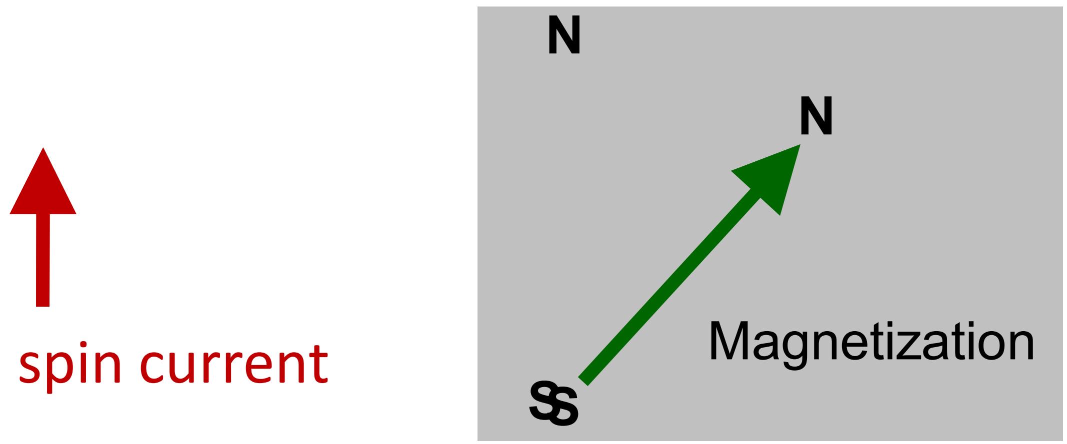
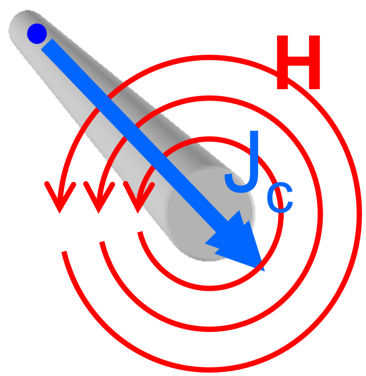
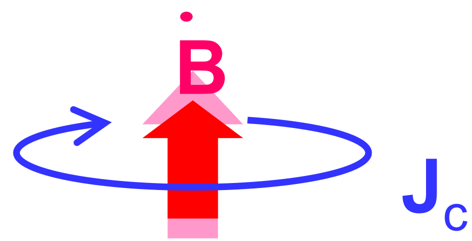


There are *no* spin currents in electronics and electromagnetism



Ampere's

$$\mathrm{rot}\mathbf{H} = \dot{\mathrm{L}} \quad . \quad \mathbf{j}_c$$

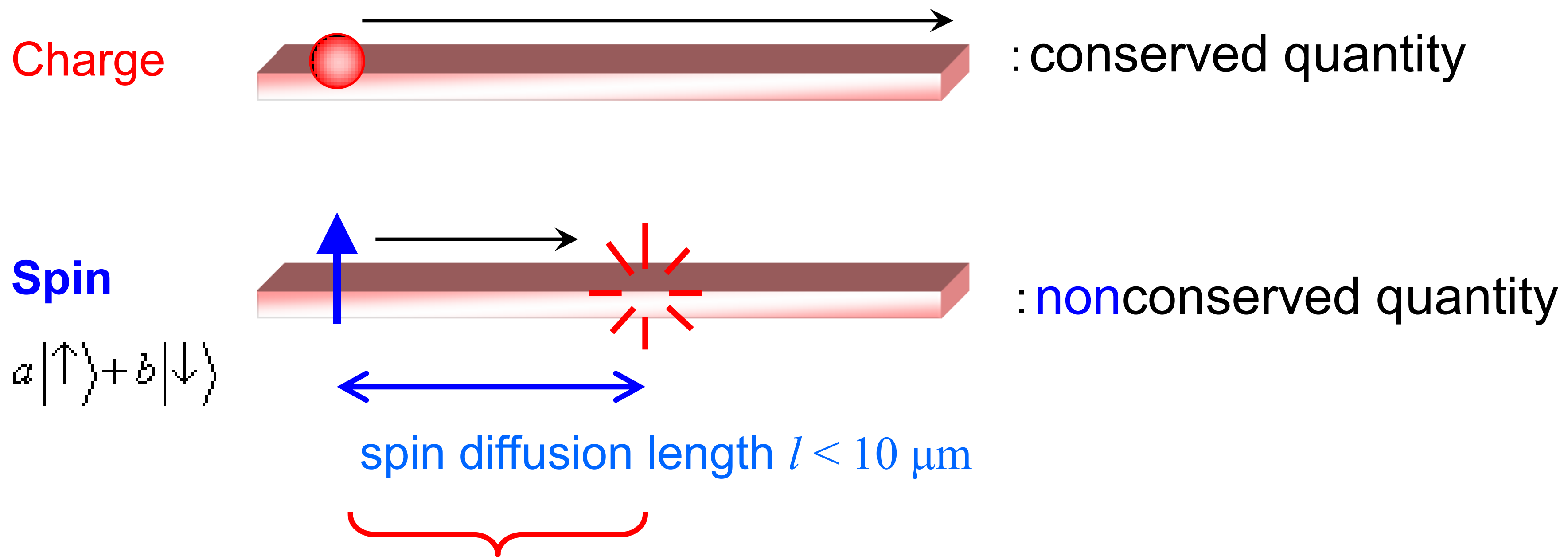


Faraday's

$$\mathrm{rot}\mathbf{E} = -\dot{\mathrm{L}}$$

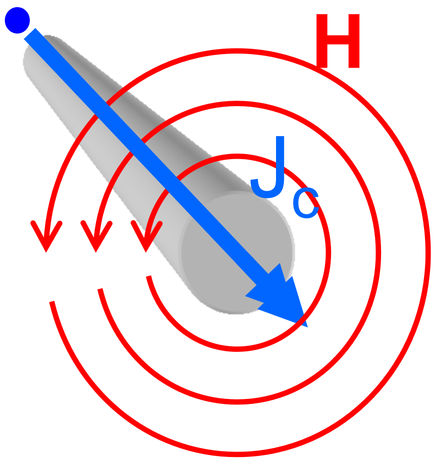
Spin is not conserved…..

charge current vs spin current



an electron loses spin memory after running l

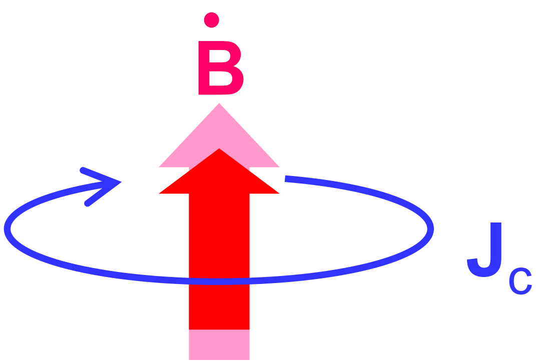
Maxwell's and constituent equations in electromagnetism



Ampere's

$$\mathrm{rot}\mathbf{H} = \dot{\mathbf{D}} + \mathbf{j}_c$$

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



Faraday's

$$\mathrm{rot}\mathbf{E} = -\dot{\mathbf{B}}$$

… temporal variation of *B* generates j_c

$$\mathrm{div}\mathbf{D} = \rho$$
$$\mathrm{div}\mathbf{B} = 0$$
$$\mathrm{rot}\mathbf{E} = -\dot{\mathbf{B}}$$
$$\mathrm{rot}\mathbf{H} = \dot{\mathbf{D}} + \mathbf{j}_c$$
$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$$
$$\mathbf{B} = \mu_0\mathbf{H} + \mathbf{M}$$
$$\mathbf{j}_c = \mathbf{j}_{ce} + \sigma\mathbf{E}$$

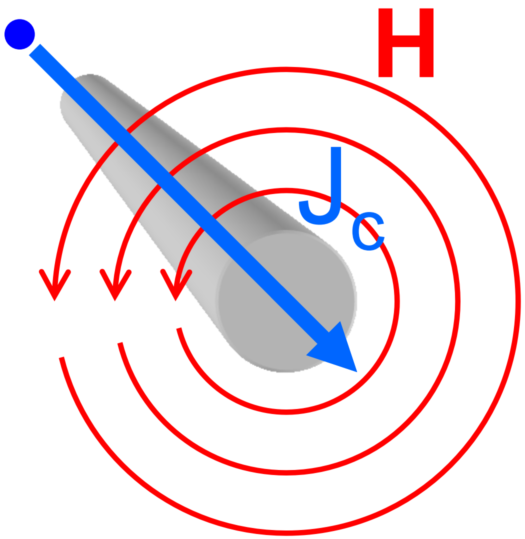
no spin current terms

Aim of Study 1

- We have investigated the ***interaction between SC and electromagnetic field*** using a pure SC.

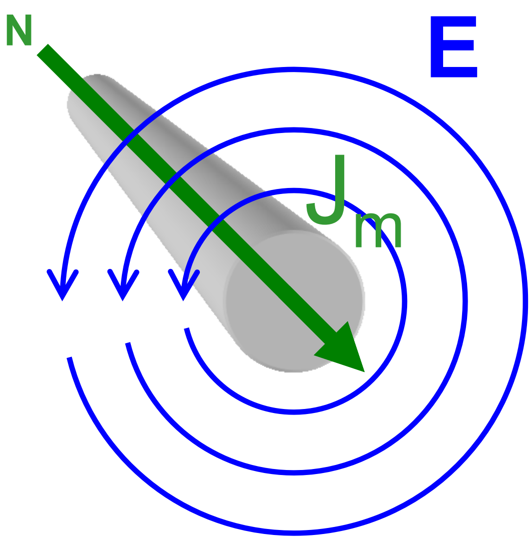
Starting point of our consideration
- electromagnetic duality -

- Charge current
- hypothetical monopole current



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

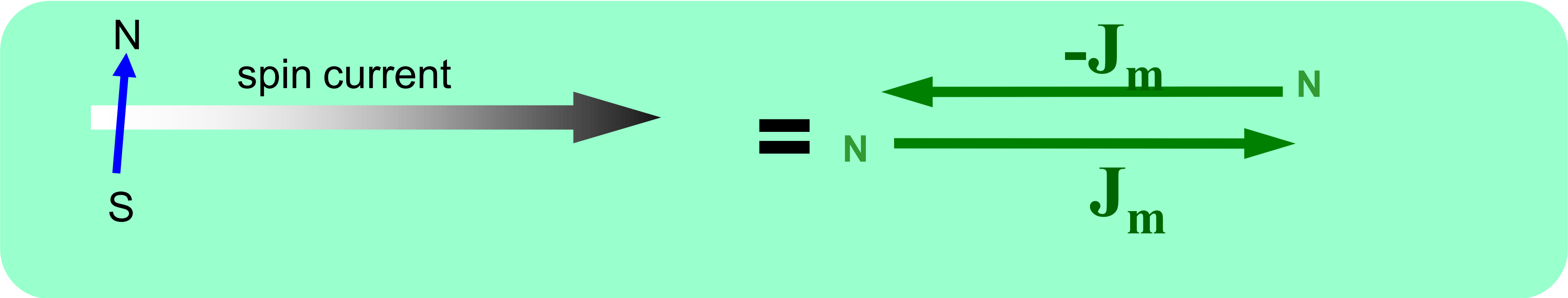
Ampere's law

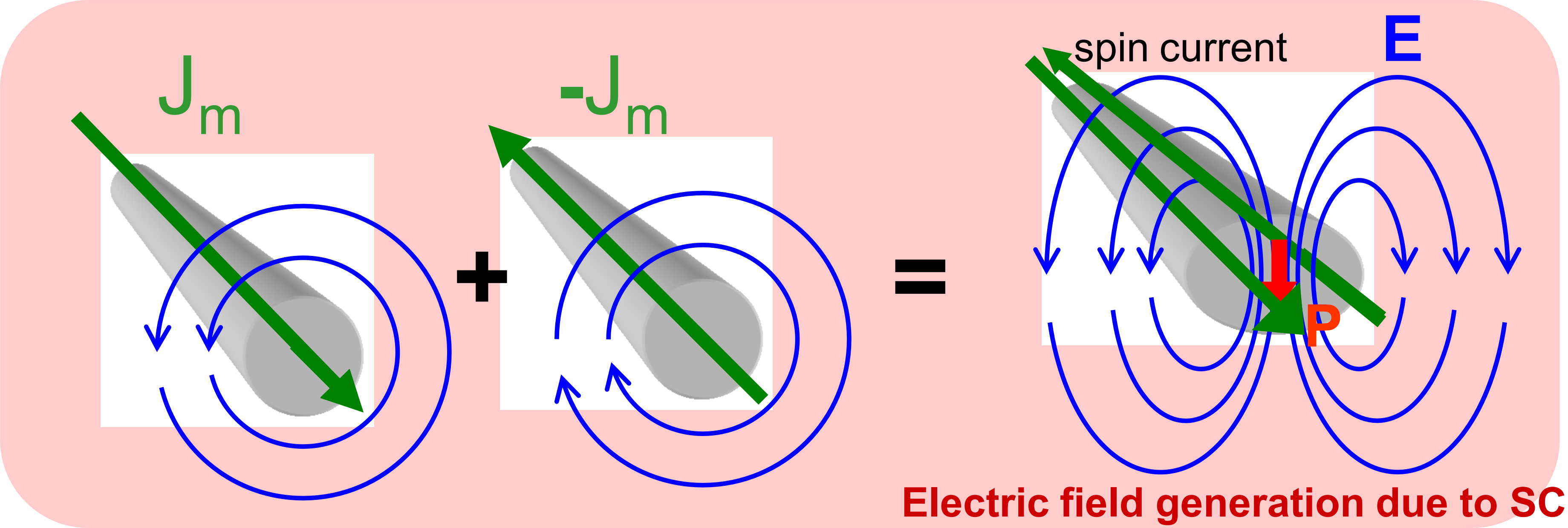


$$\mathrm{rot}\,\mathbf{E} = -\mathbf{J}_m$$

Dirac

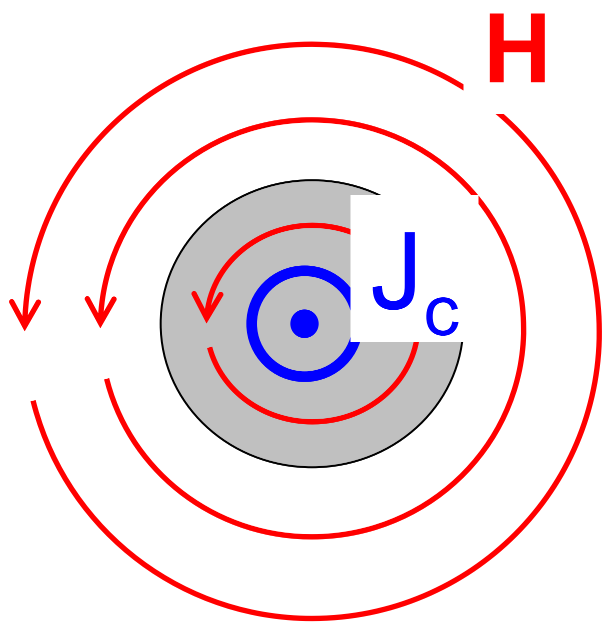
spin current = a pair of magnetic monopole currents with opposite signs





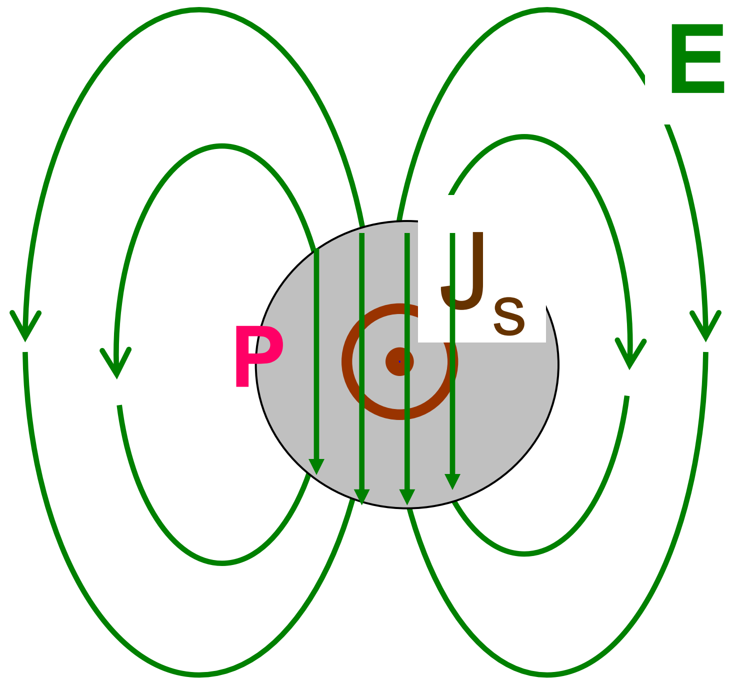
spin current is expected to generate an electric field

- Ampere's law



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

- Spin current analogy



… a spin current generates ***E***

··from quantum mechanical point of view

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

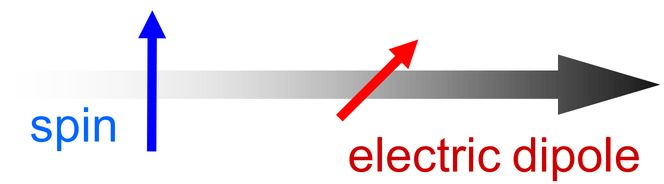
Dipole Term

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

density　　Darwin term

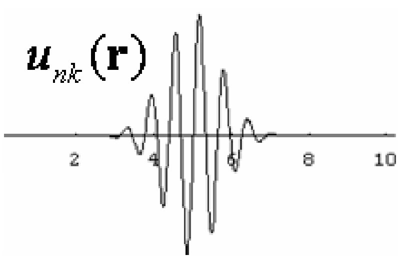
due to the SO interaction acting on spins which contains ∇

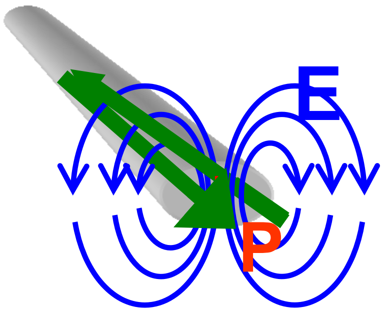
spin motion generates electric dipole
due to spin-orbit interaction



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

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

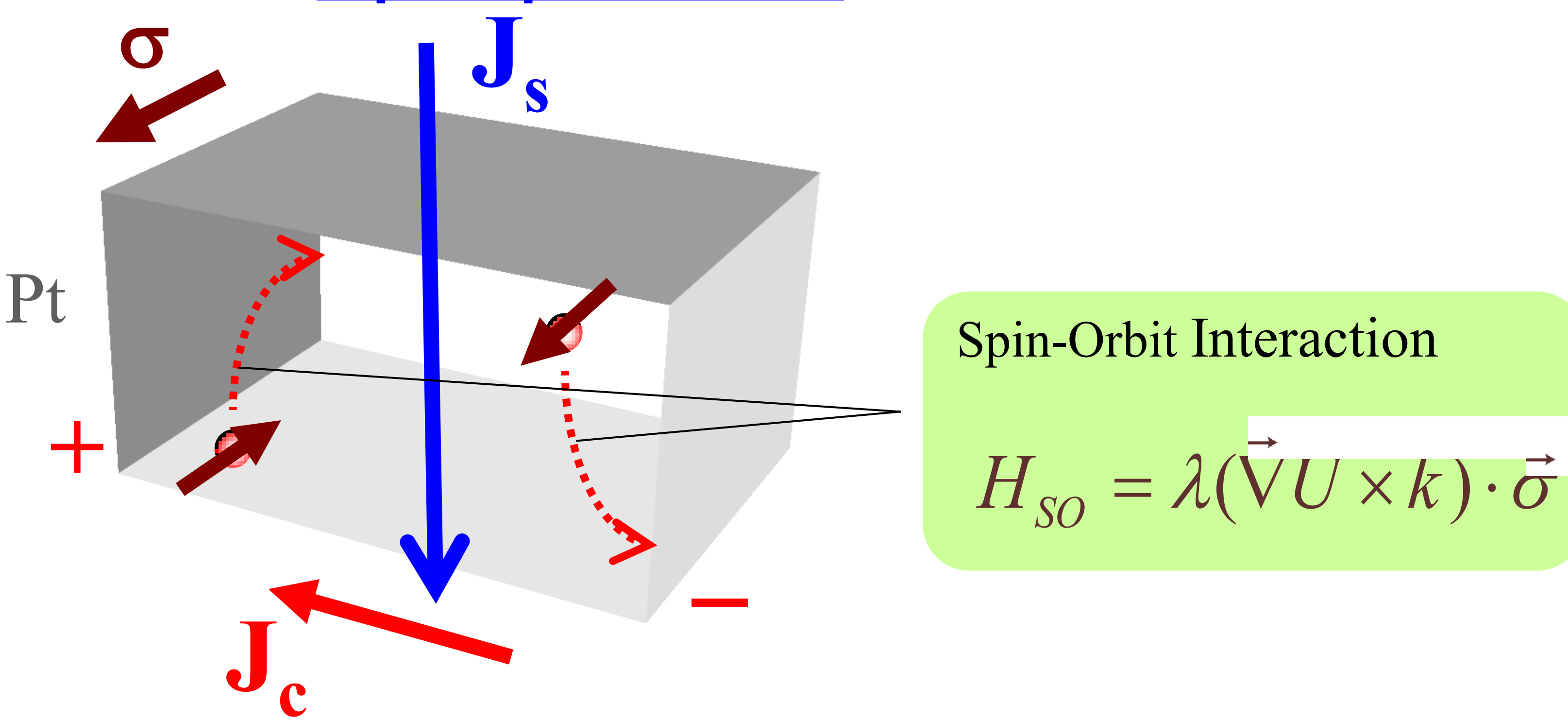




can be argued from another point of view

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

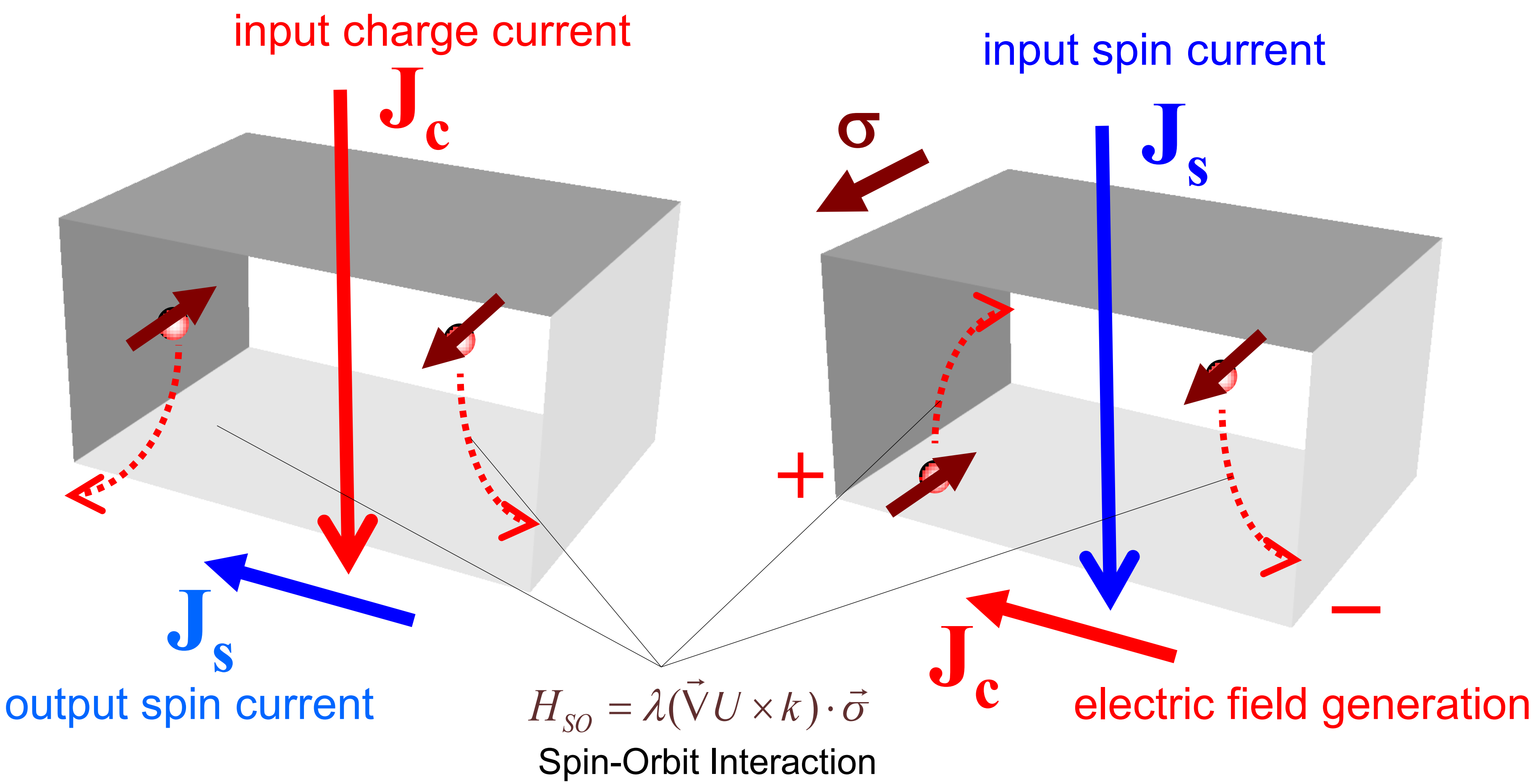
input spin current



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

Spin-Hall effect family

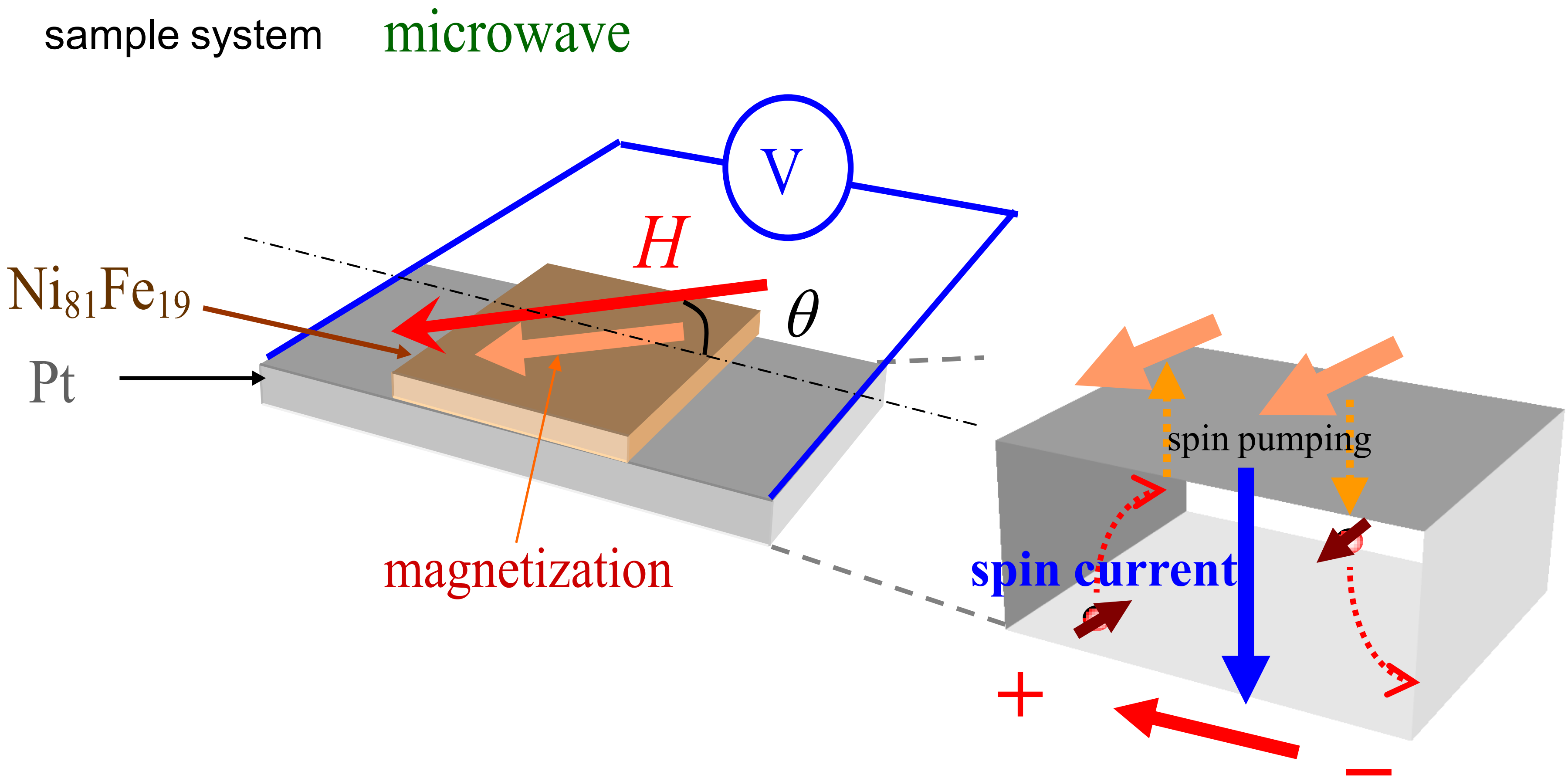
- Spin Hall effect (SHE)
- **Inverse Spin Hall effect (ISHE)**



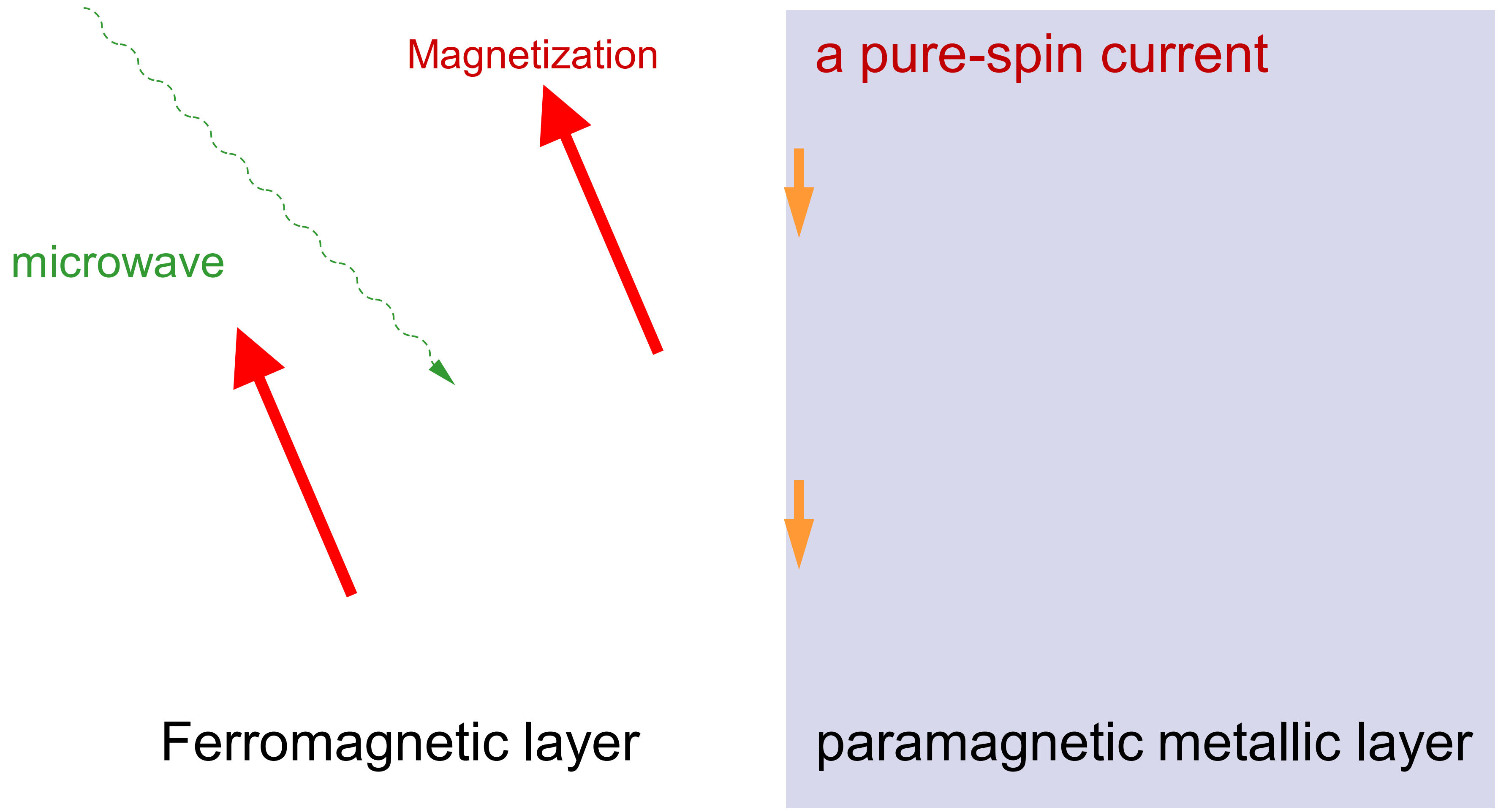
Contents

Experiment 1

- spin-current induced electric voltage (ISHE) in Pt is measured



Spin Pumping operated by FMR

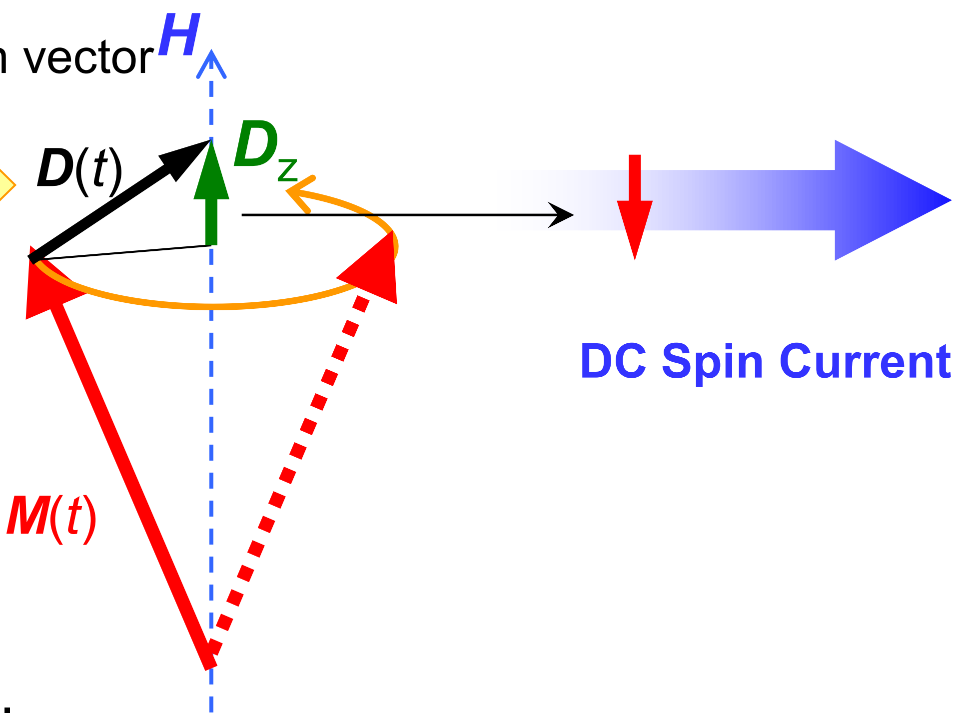


DC spin pumping operated by FMR

- spin dumping and spin pumping

D: Magnetization reaxation vector

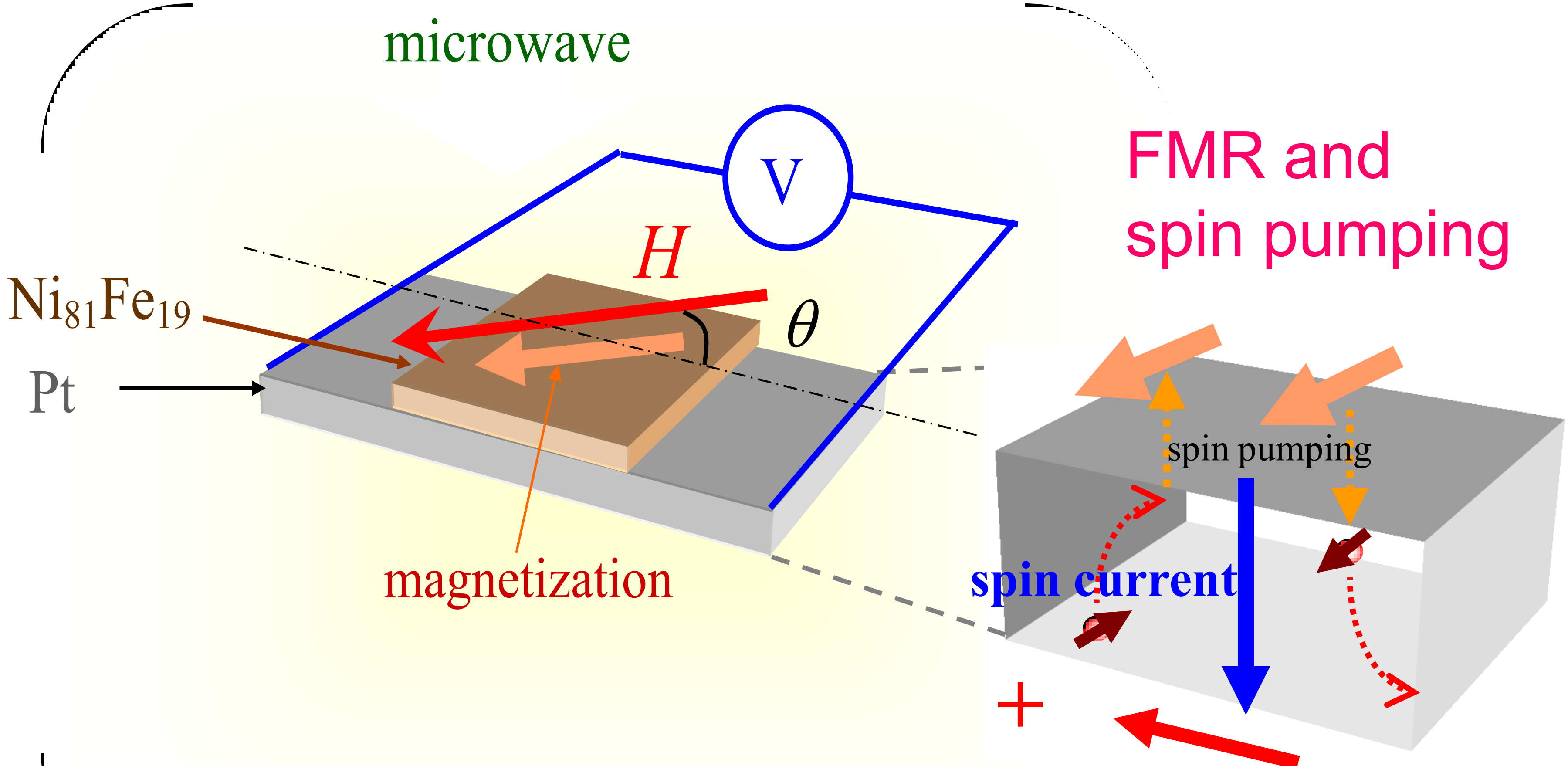
$$\mathbf{D}(t) = \alpha \mathbf{M}(t) \times \frac{d\mathbf{M}(t)}{dt}$$



Tserkovnyak et al. PRL(2002).
Mikukami *et al.* JJAP(2001).
Heinrich *et al.* PRL(1987).

$$j_{\mathrm{sDC}} \propto |\mathbf{M}| - \sqrt{|\mathbf{M}|^2 - M_{xy}{}^2} \approx \frac{1}{2} M_{xy}{}^2$$

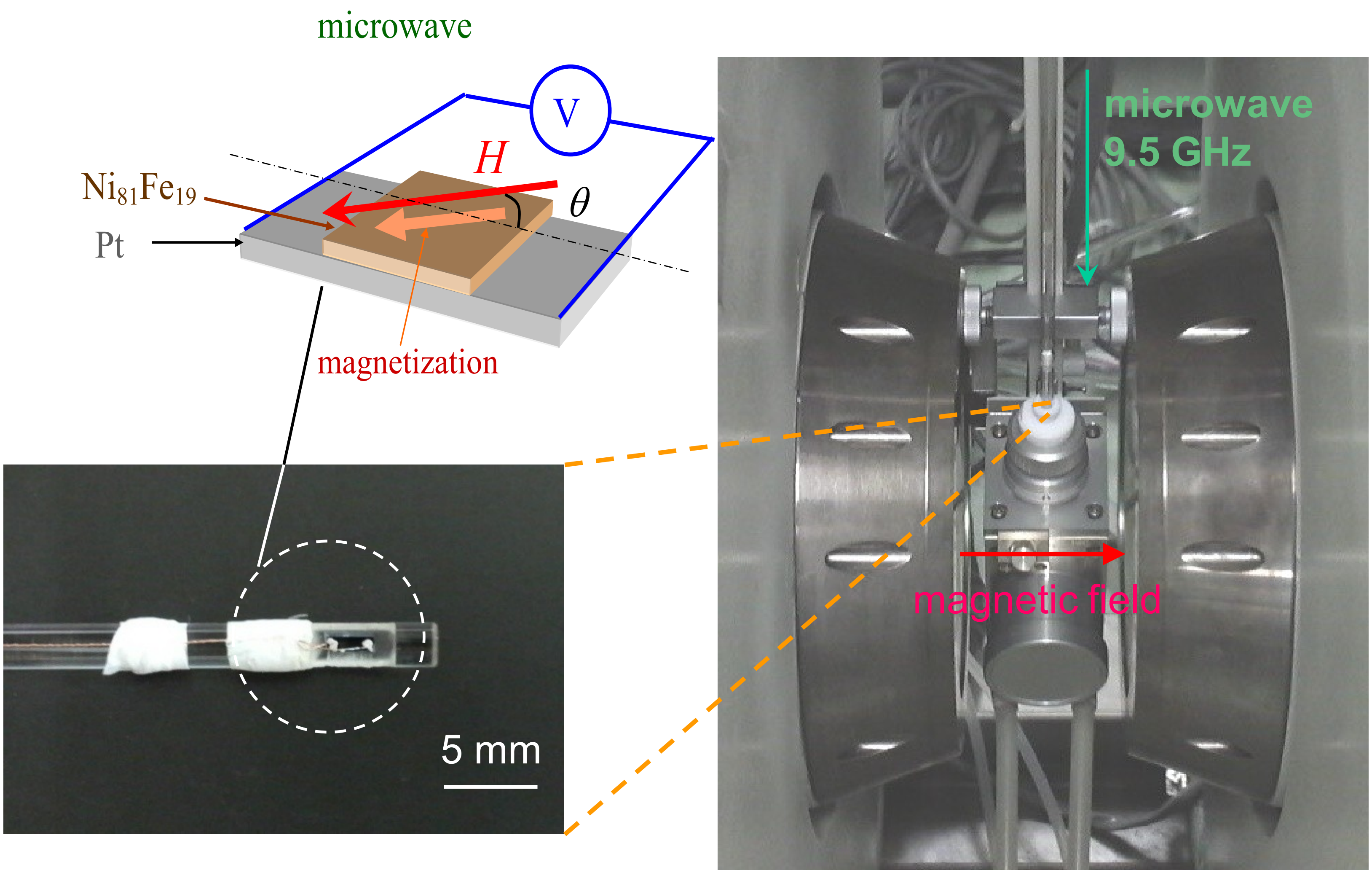
sample system



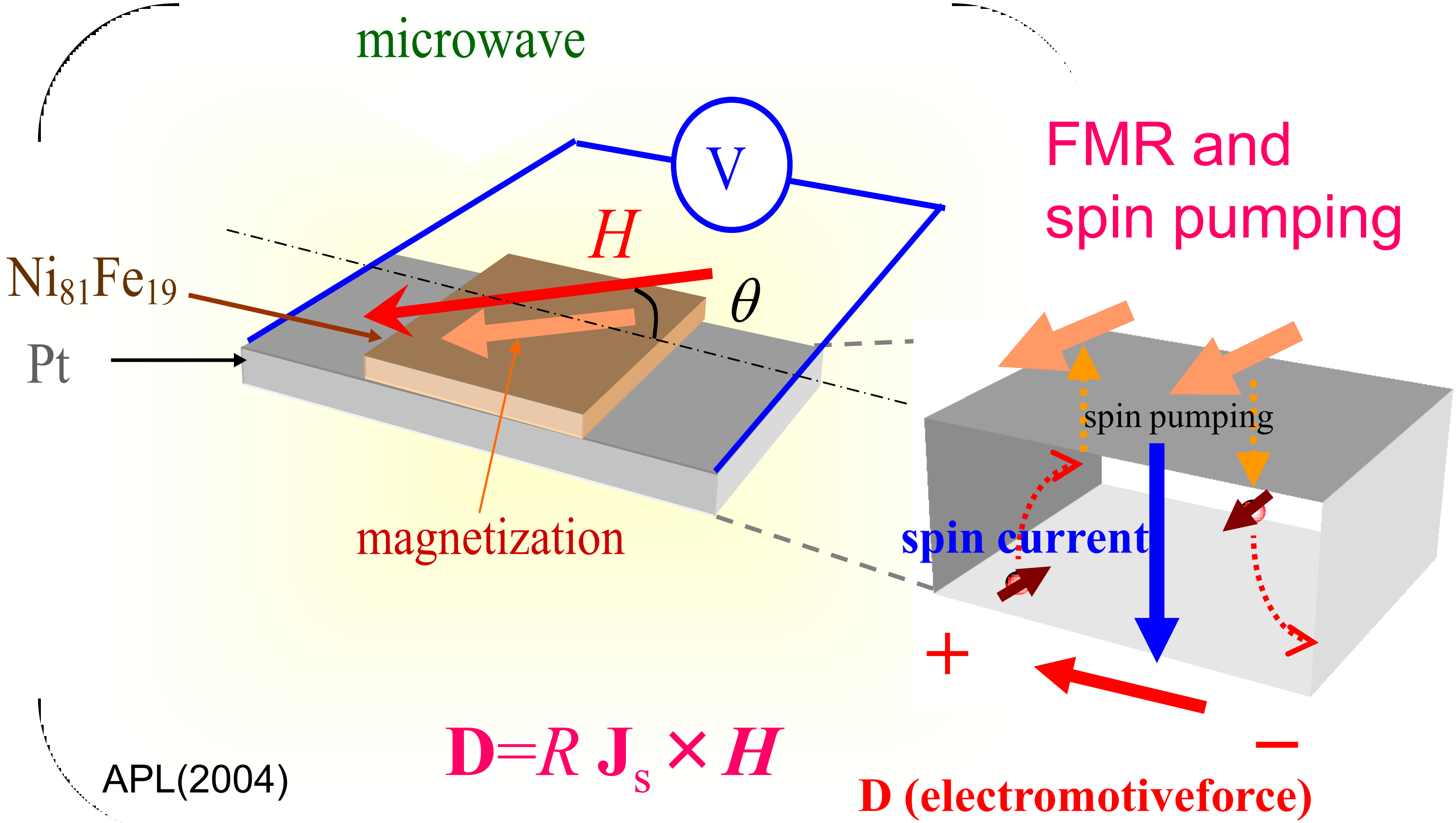
$$\mathbf{D} = R\,\mathbf{J}_s \times \boldsymbol{H}$$

D (electromotiveforce)

measurement setup



sample system



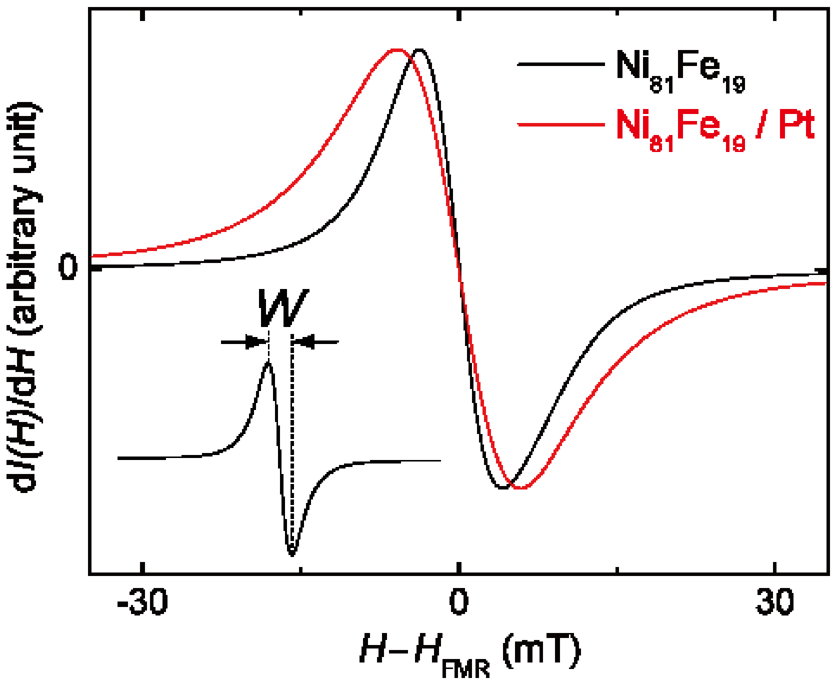
$$\mathbf{D} = R\,\mathbf{J}_s \times \boldsymbol{H}$$

APL(2004)

Spectral width modulation by attaching Pt

Landau-Lifshitz-Gilbert equation

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} +$$ [redacted] ← **damping**



$$\alpha = \frac{\sqrt{3}\gamma}{2\omega_0} W$$

ω_0 : resonance frequency

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

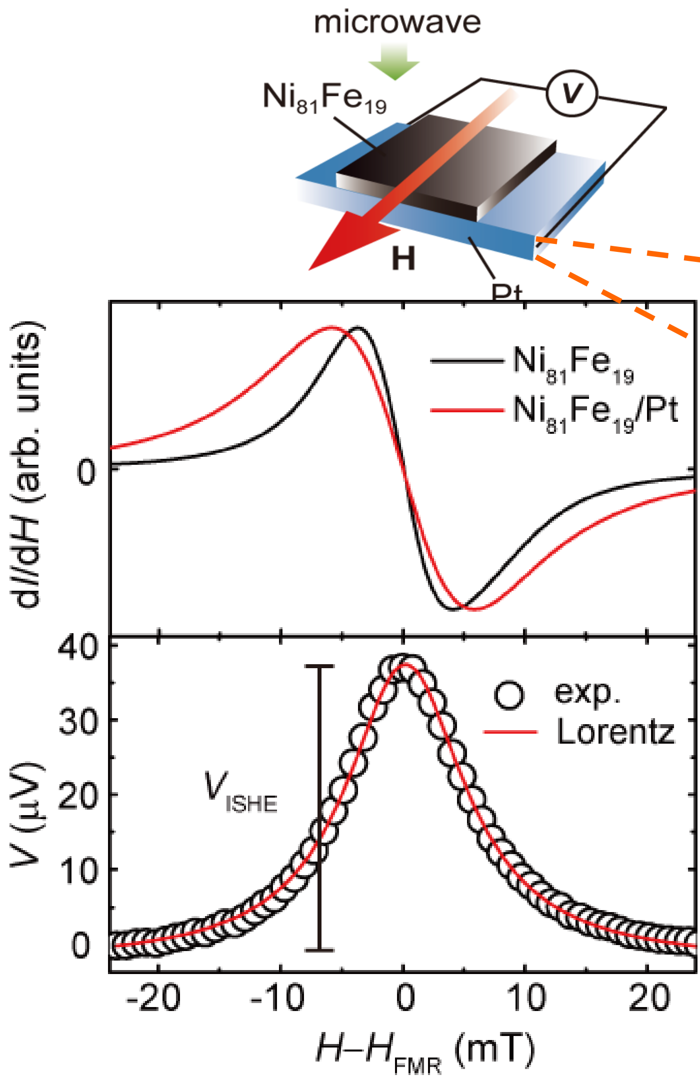
α in enhanced

dissipation of spin angular momentum

evidence for the spin pumping to the Pt layer

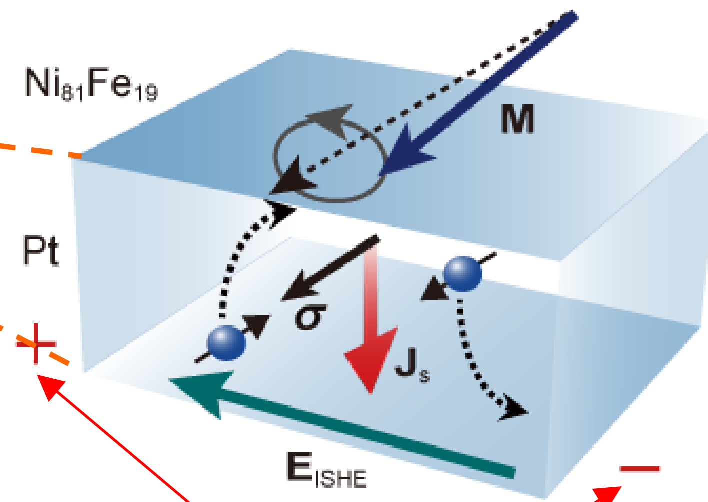
Inverse spin-Hall effect induced by spin pumping

$Ni_{81}Fe_{19}$ (10 nm) / Pt (10 nm) thin film



APL(2004)

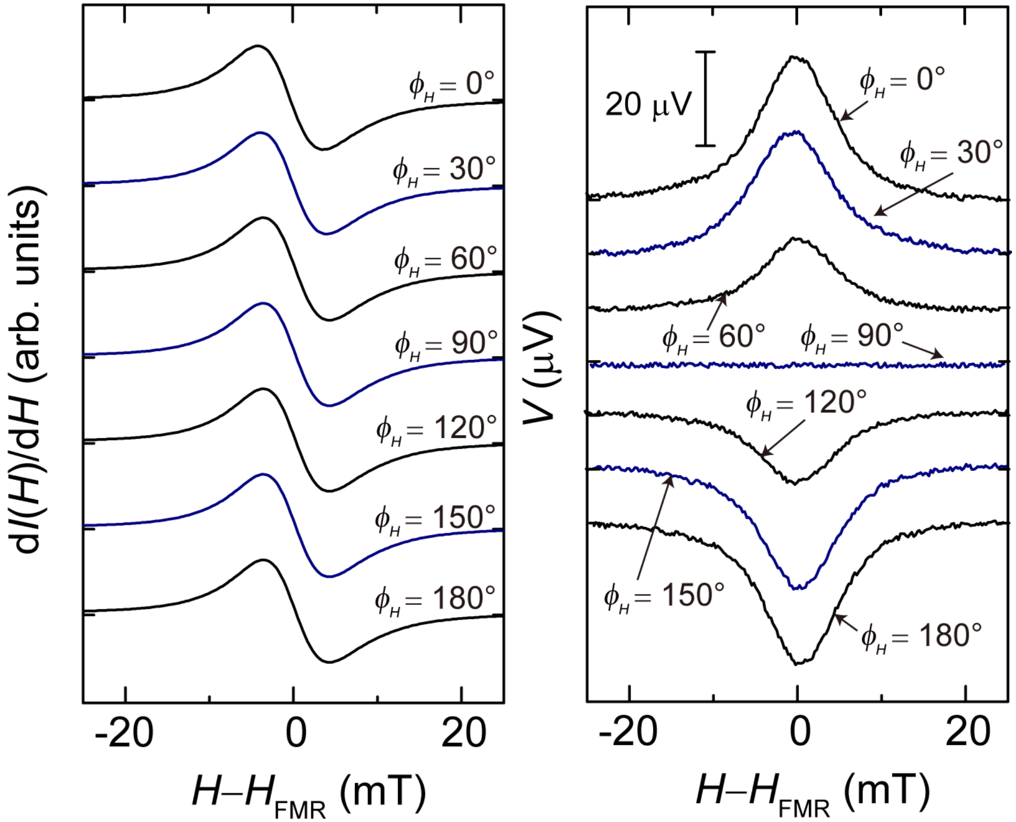
Spin pumping operated by FMR injects spin currents into the Pt layer

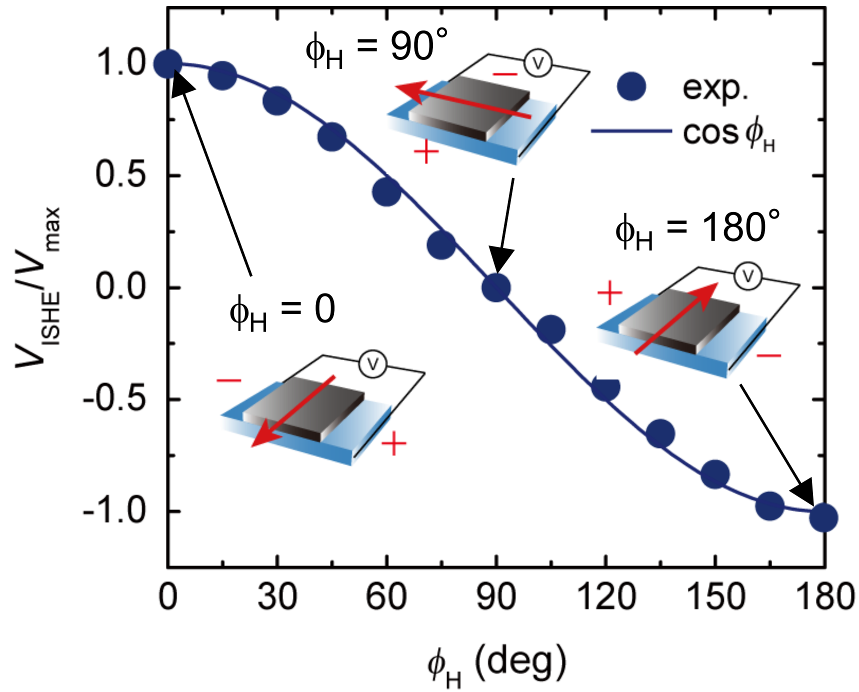


Electromotive force induced by ISHE

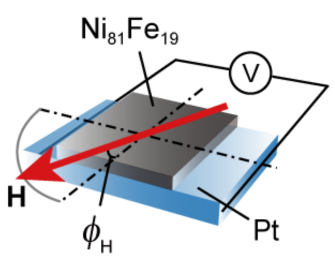
Electromotive force signal appears around H_{FMR}

In-plane magnetic field angle dependence of ISHE signal





$$V_{\mathrm{ISHE}} \propto \cos \phi_H$$



ISHE

$$\boldsymbol{E}_{\mathrm{ISHE}} \propto \boldsymbol{J}_s \times \boldsymbol{\sigma}$$

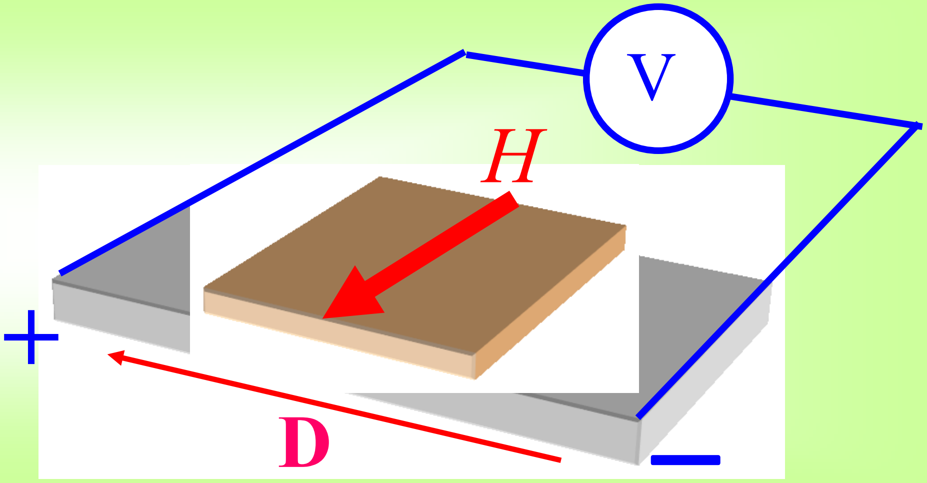
consistent with ISHE and direct-current spin pumping model

Field-direction dependence

- *when Θ*=90° ....

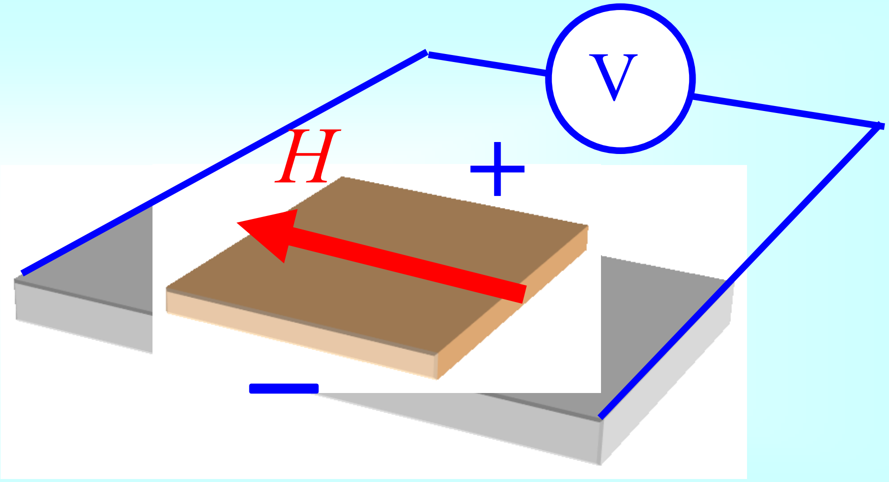
$$V = V_{MAX}$$

$$\mathbf{E} \parallel \mathbf{J}_s \times \boldsymbol{\sigma}$$

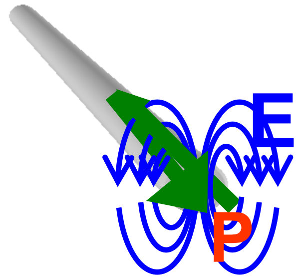


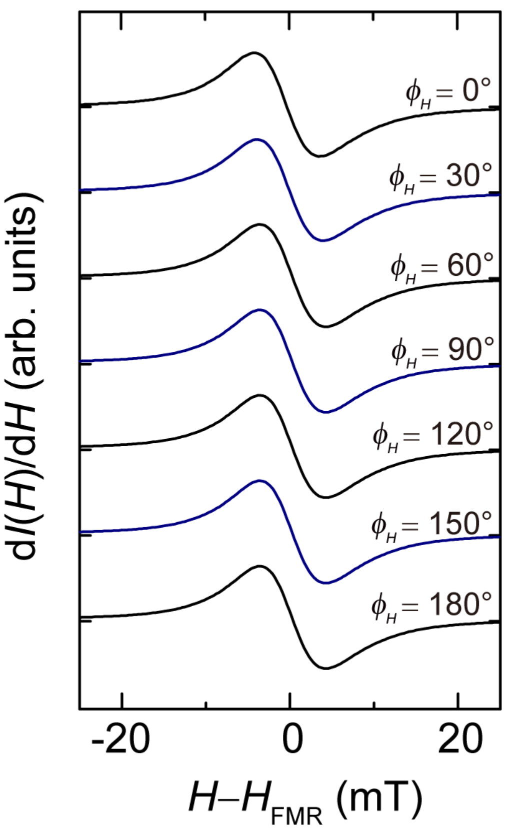
- *when Θ*=0 ....

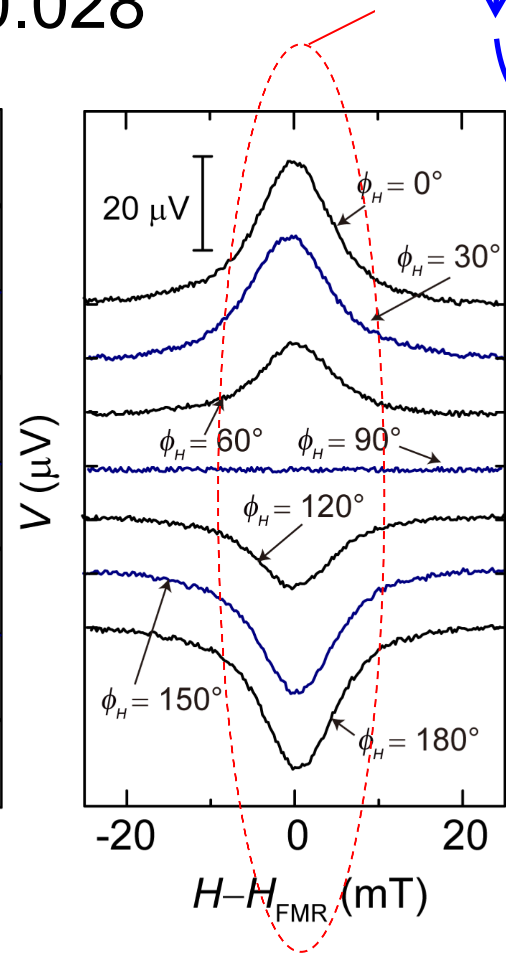
$$V = 0$$

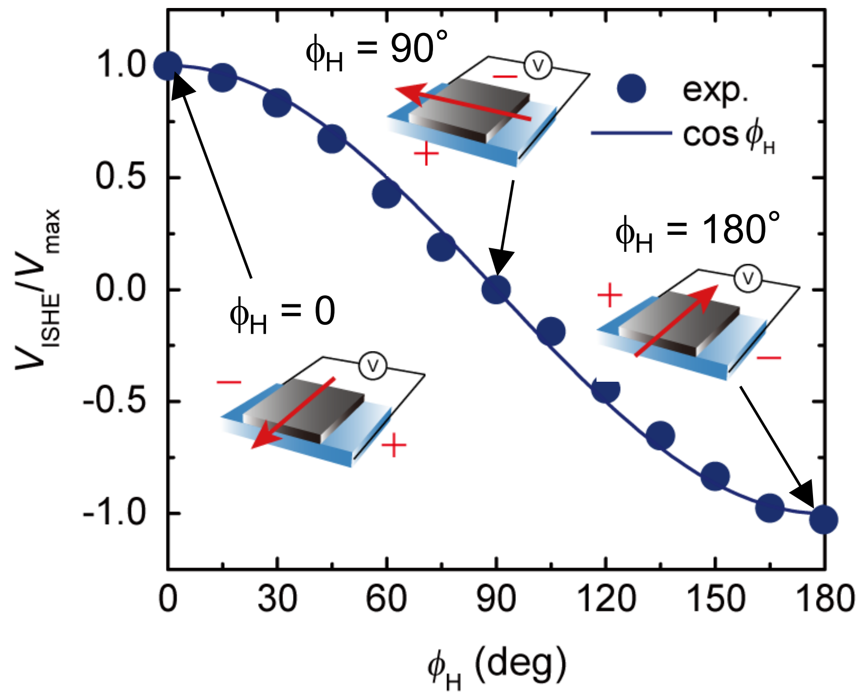


$\Theta_{\mathrm{spinHall;\,Pt}} = 0.028$

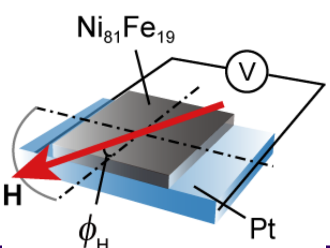








$$V_{\mathrm{ISHE}} \propto \cos \phi_H$$

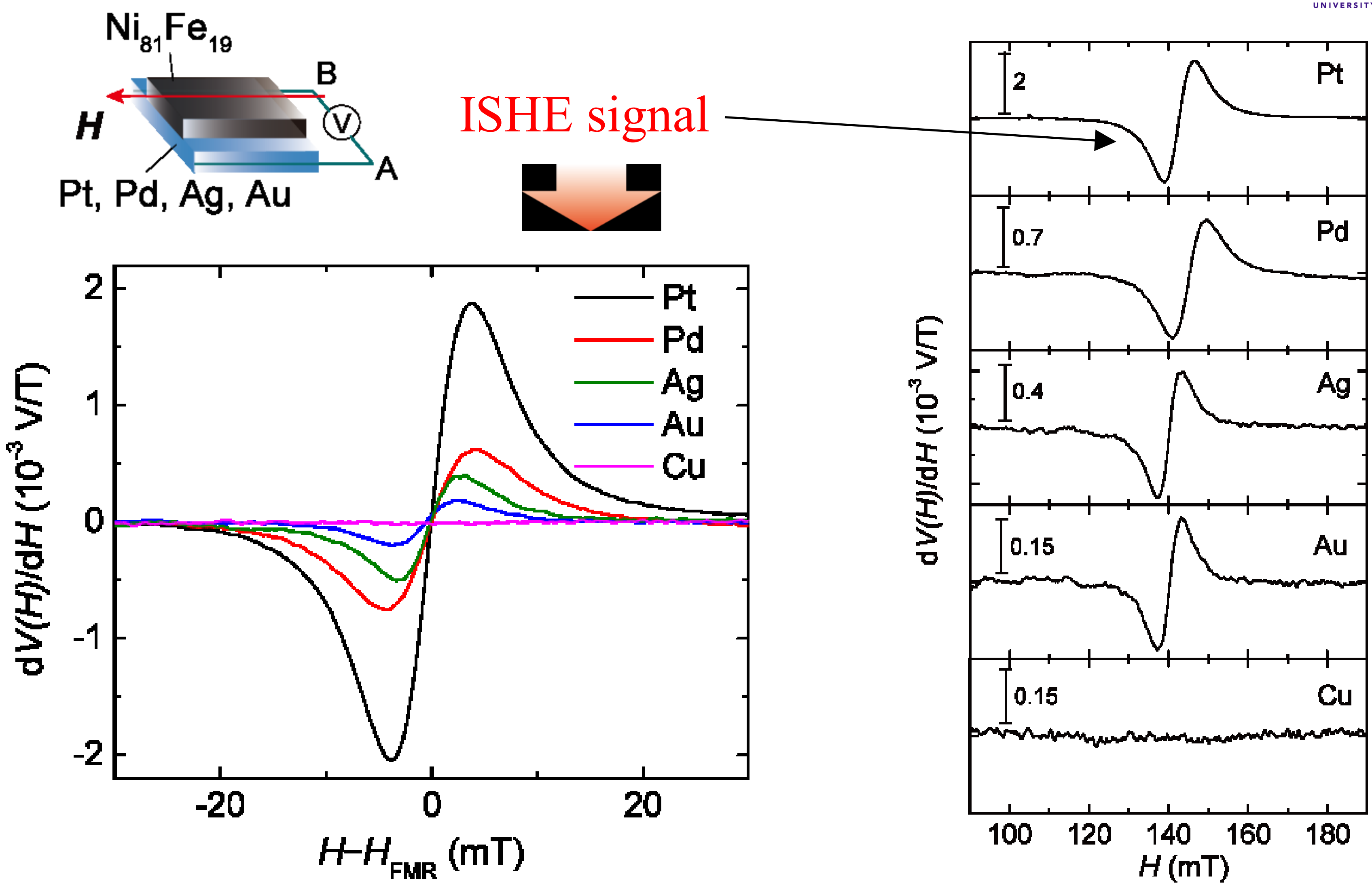


ISHE

$$\boldsymbol{E}_{\mathrm{ISHE}} \propto \boldsymbol{J}_s \times \boldsymbol{\sigma}$$

consistent with ISHE and direct-current spin pumping model

Rough Material dependence of ISHE

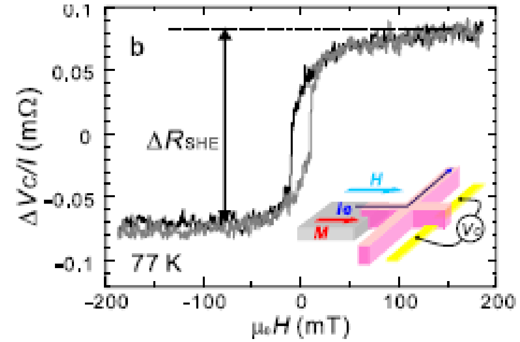


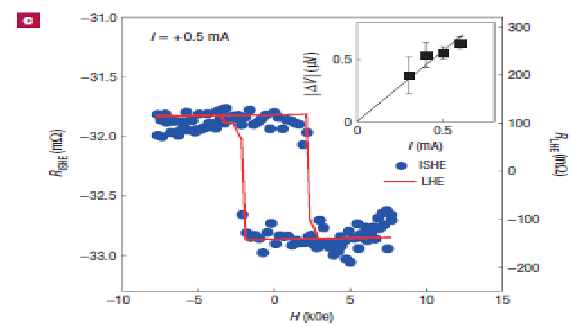
Valenzuela *et al.* Nature (2006).
in Al non local

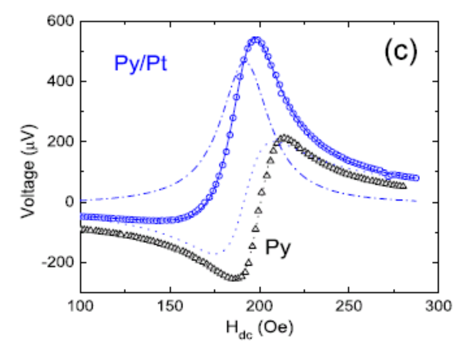
Kimura *et al.* PLR (2007).
in Pt non local

Seki *et al.*, Nature Mat. (2008).
in Au non local

Mosendz et al. PRL (2010)
in Pt Spin pumping







Spin-charge coupling in a $Ni_{81}Fe_{19}$/Pt film

Spin Dynamics

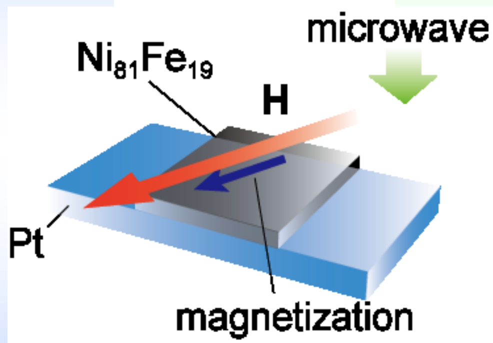
Spin Pumping

α **enhancement**

?

J_s

Spin current



J_s

Conduction Electron

Inverse SHE

$J_s \rightarrow J_c$

output

charge-current

Spin Hall effect

(SHE)

$J_c \rightarrow J_s$

input

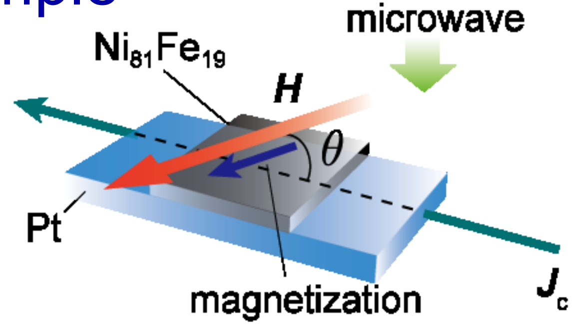
charge-current

Contents

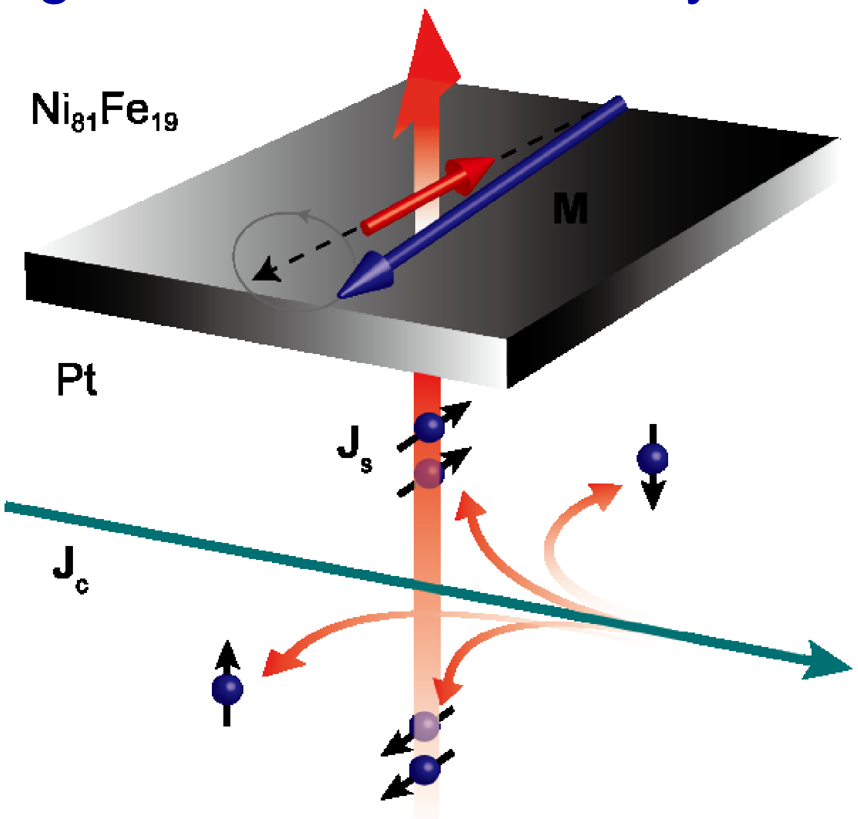
Experimental 2

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

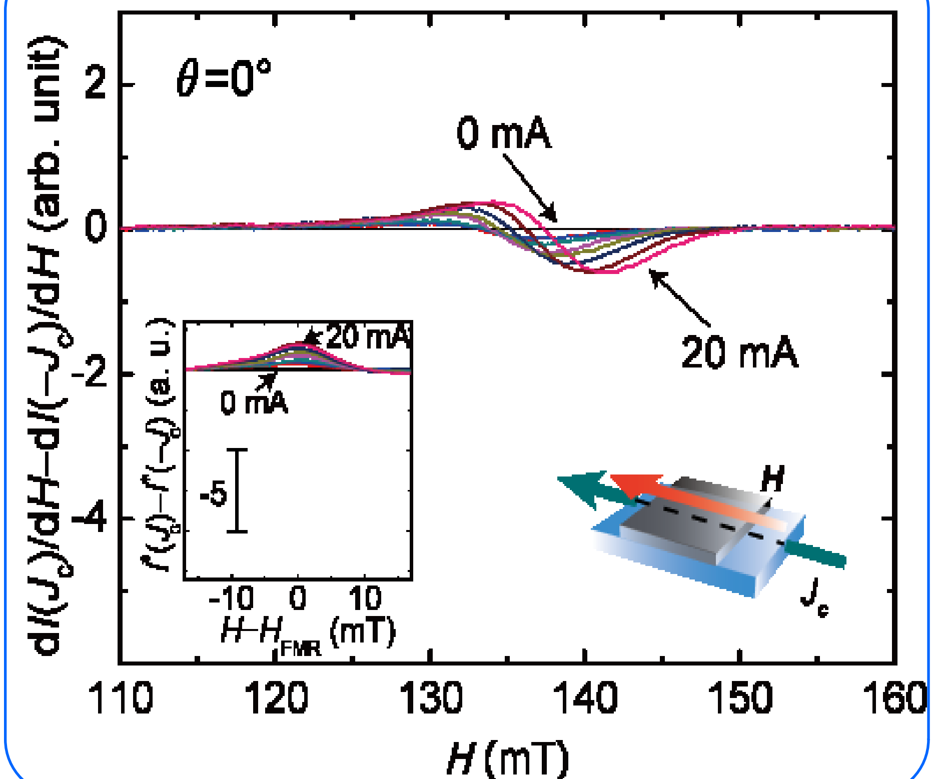
Asymmetry component of FMR

$$\frac{dI(J_C)}{dH} - \frac{dI(-J_C)}{dH}$$

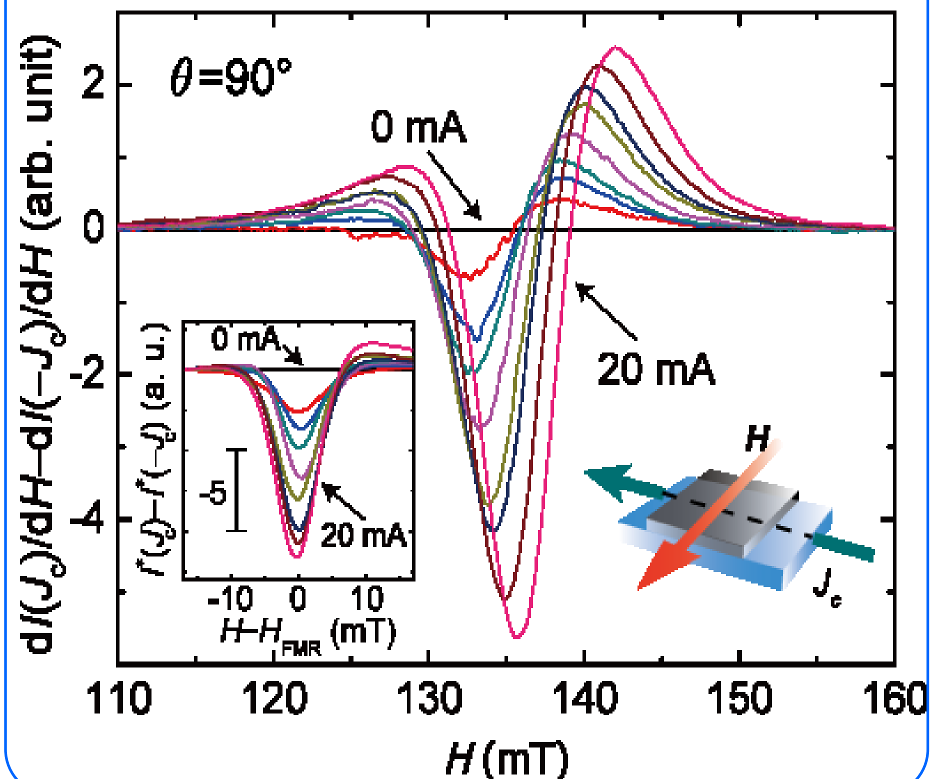
I: FMR absorption intensity

J_c: Electric current applied to the Pt layer

$\theta = 0$



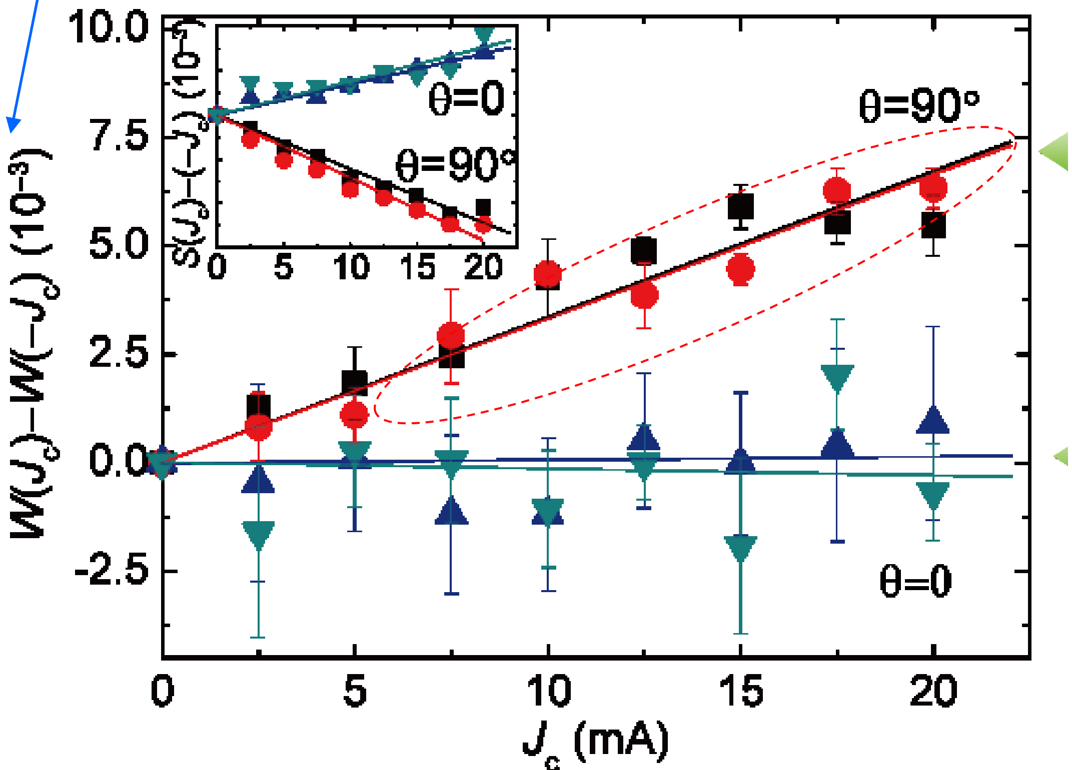
$\theta = 90°$

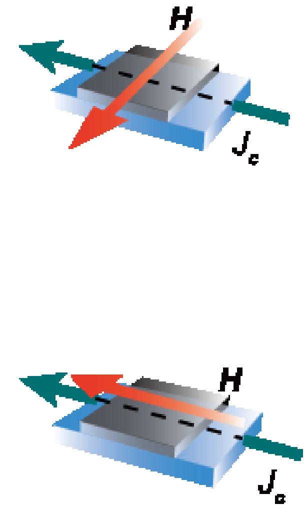


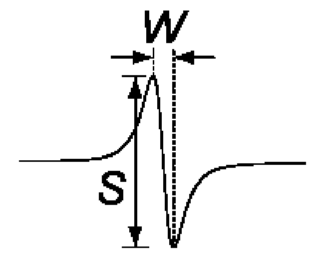
Ando & Saitoh *et al.* PRL (2008).

Current (J_c) induced modulation of spectral width

W (spectral width)～ spin relaxatic







W : width

S : intensity

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

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

Current induced modulation of **α** !

Measurement in $Ni_{81}Fe_{19}$ and $Ni_{81}Fe_{19}$/Cu films

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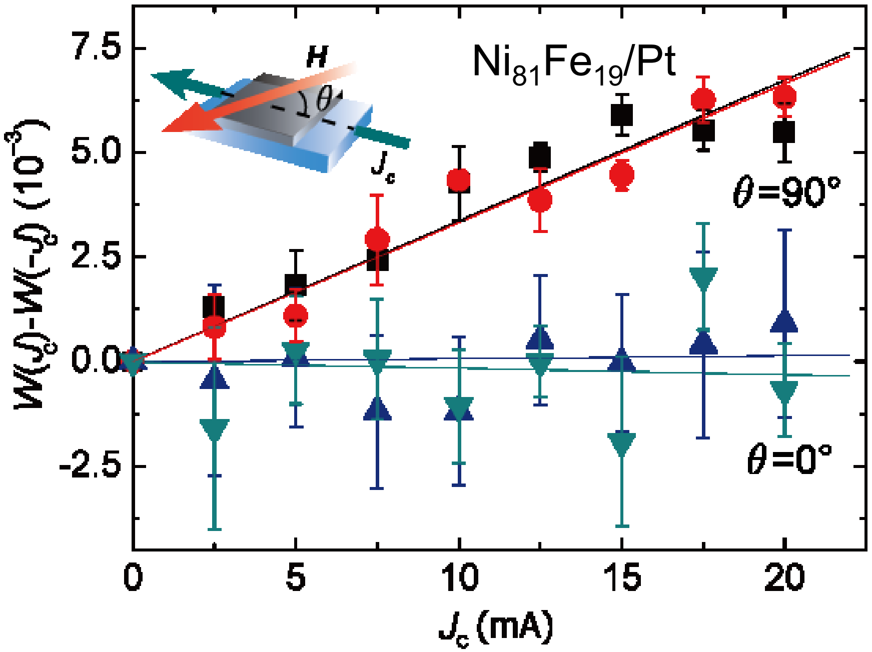
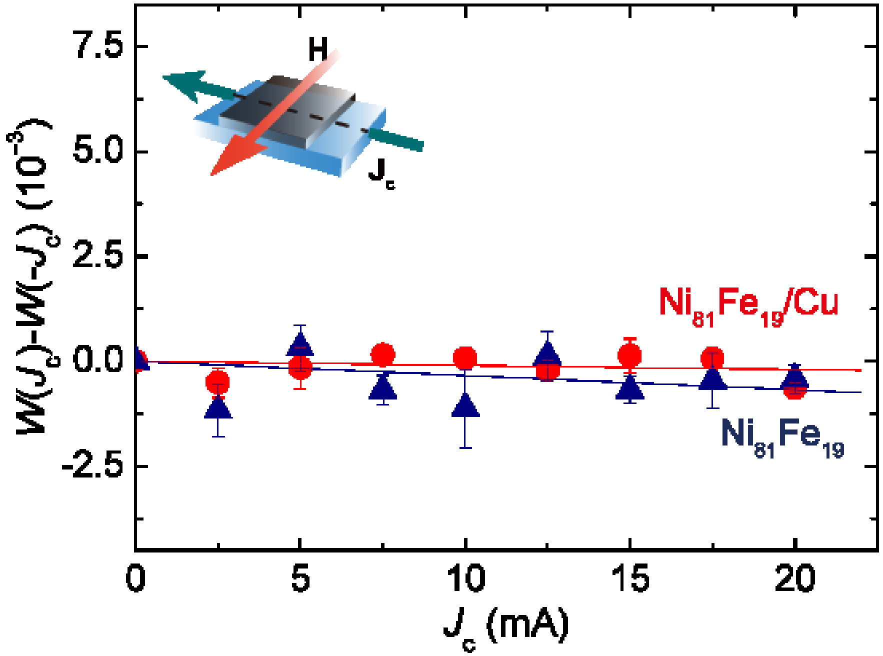
$Ni_{81}Fe_{19}$/Pt

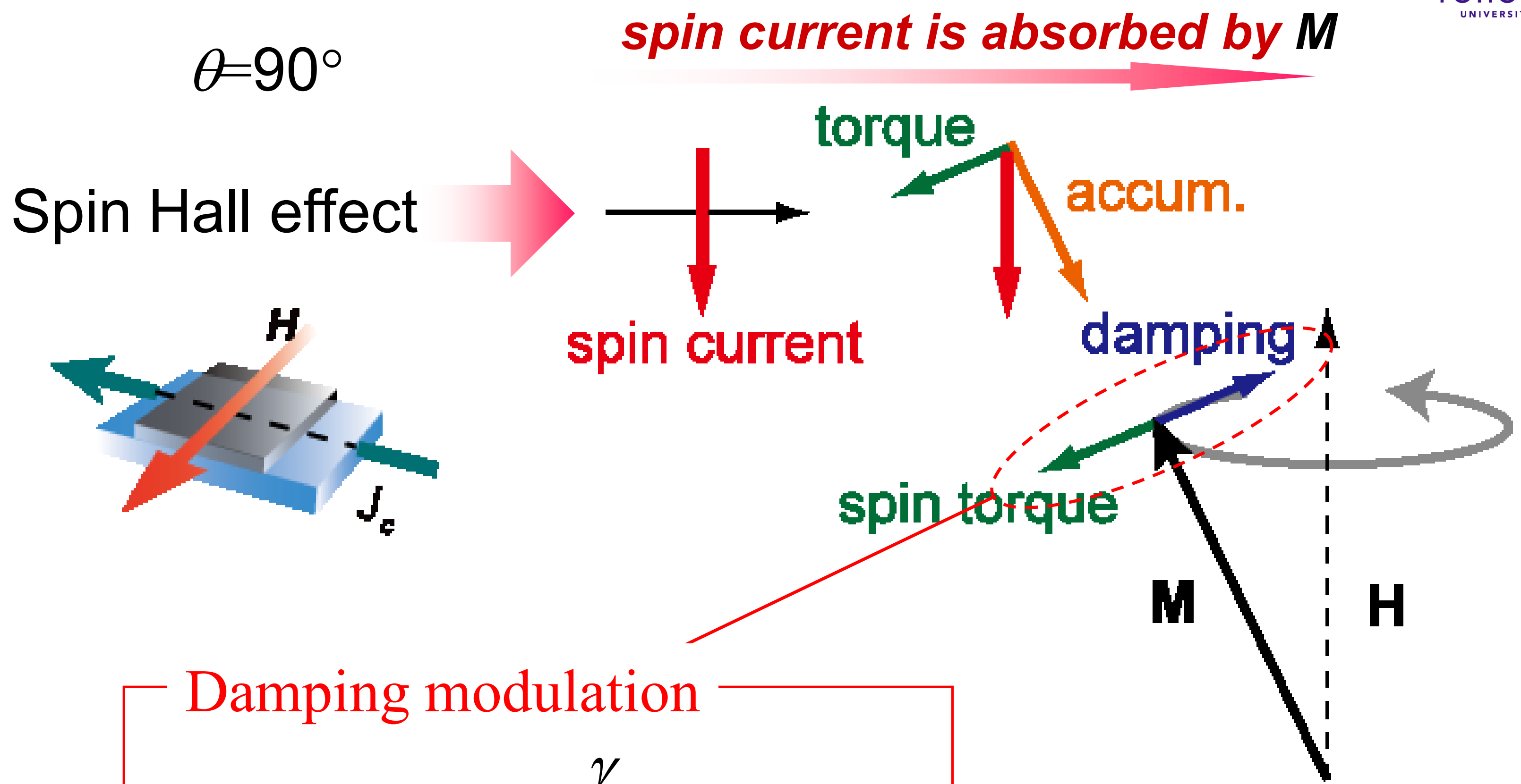


$Ni_{81}Fe_{19}$/Cu and $Ni_{81}Fe_{19}$



inhomogeneity of an Oersted magnetic field **is irrelevant!**

Damping modulation via spin torque



Damping modulation

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

Takahashi & Maekawa *et al.*

Spin-charge coupling in a $Ni_{81}Fe_{19}$/Pt film

Spin Dynamics

Spin Pumping

α **enhancement**

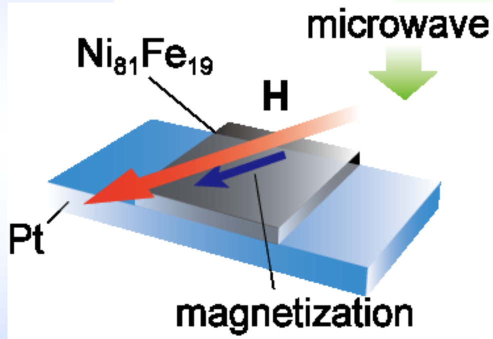
Spin Torque

Modulation of α

J_s

Spin current

J_s



Conduction Electron

Inverse SHE

$J_s \rightarrow J_c$

output

charge-current

Spin Hall effect

(SHE)

$J_c \rightarrow J_s$

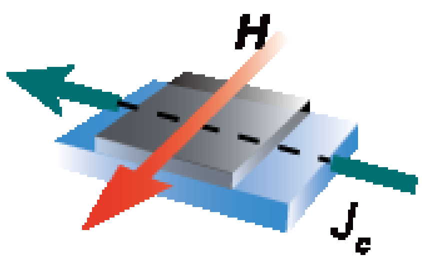
input

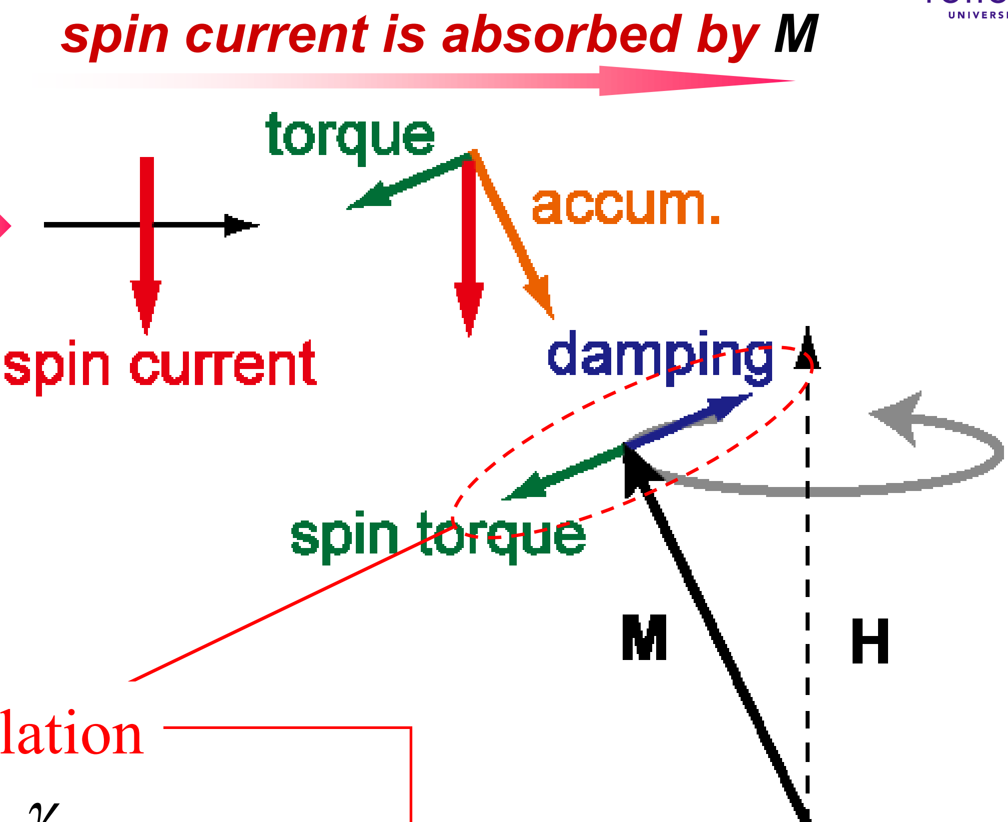
charge-current

Damping modulation via spin torque

θ=90°

Spin Hall effect





Damping modulation

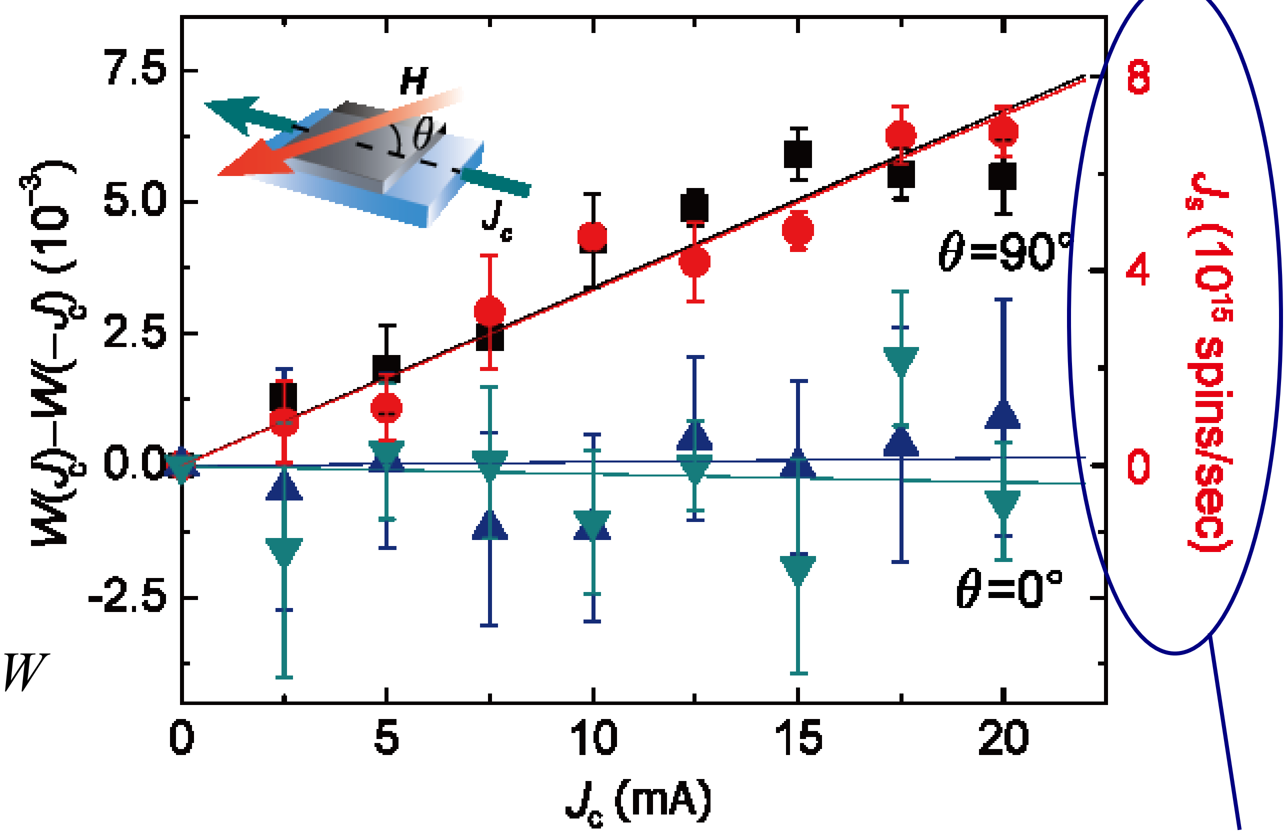
$$\Delta\alpha_{SHE} = \frac{\gamma}{\omega M_S V_F} J_S$$

Takahashi & Maekawa *et al.*

M_s: saturation magnetization
V_F: volume of the F layer
ω: FMR frequency
γ: gyromagnetic ratio

Spin-Current Meter

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

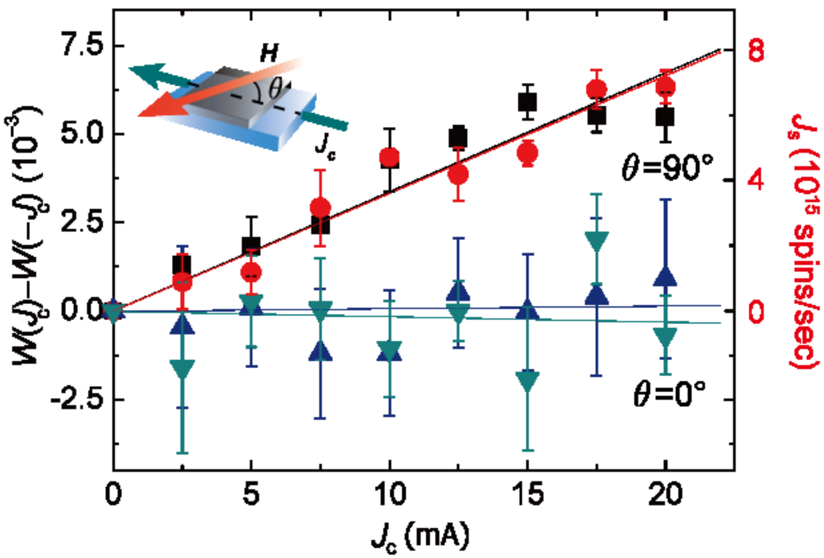


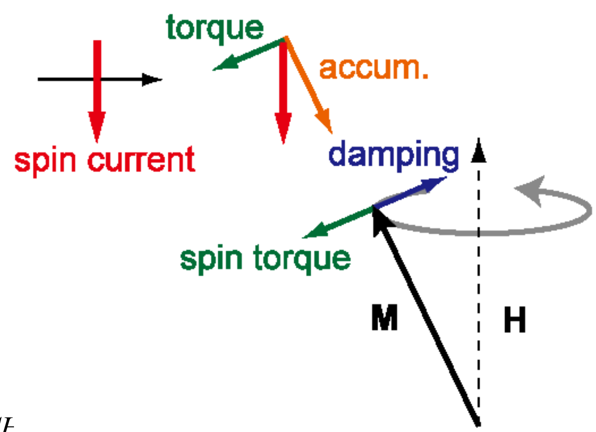
$$\alpha = \frac{\sqrt{3}\gamma}{2\omega_0}W$$

can be used as a spin current meter

Ando & Saitoh *et al.* PRL (2008).

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





$\Delta\alpha_{SH}$

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

It is *possible*! by using a magnetic insulator.

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 (~μeV)
- magnetization damping is very small ($\alpha \sim 6.7\times10^{-5}$)

α : damping constant

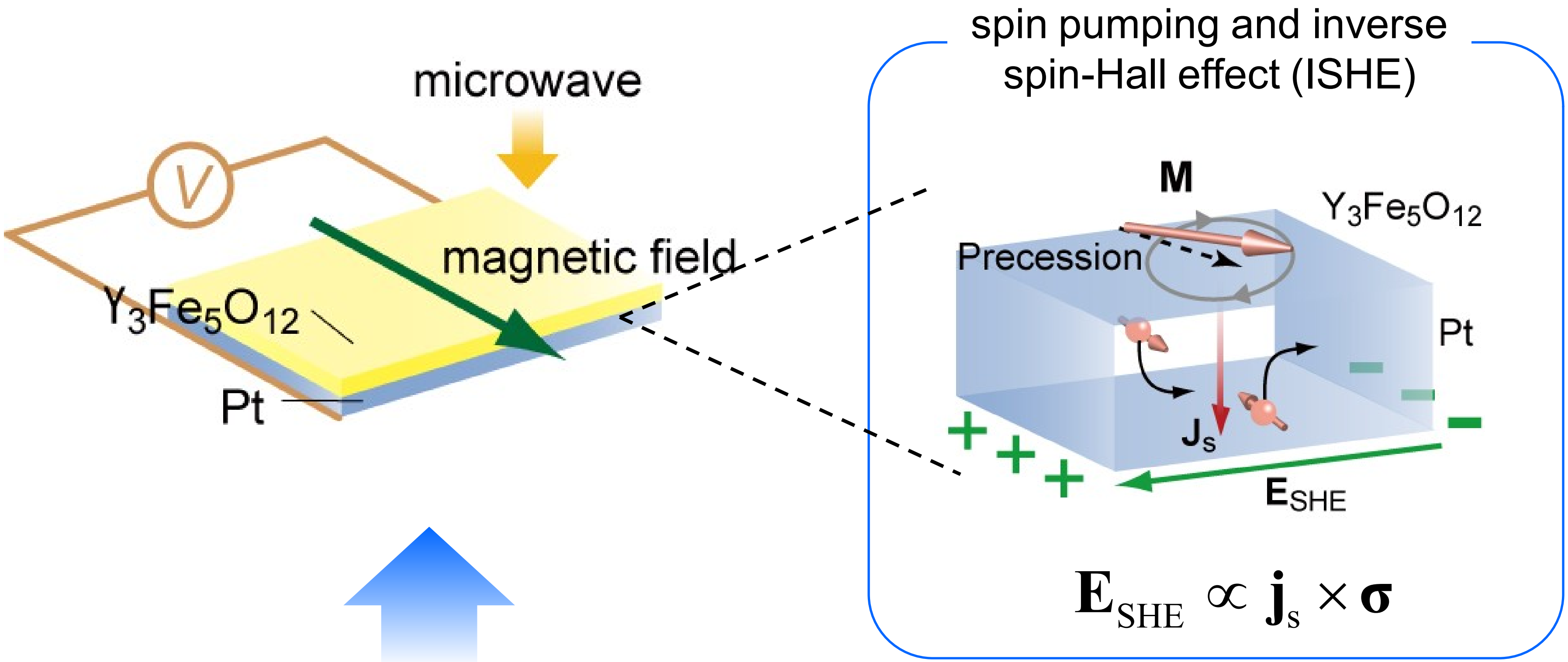
→ Spin wave propagates over several tens centimeters.

(T. Schneider, *et al. Appl. Phys. Lett.* **92,** 022505 (2008).)

If spin exchange (spin pumping & spin injection) is possible in this system, we can combine the spin wave (SW) as well as a SW-spin current in this insulator with SHEs.

Let's try!

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

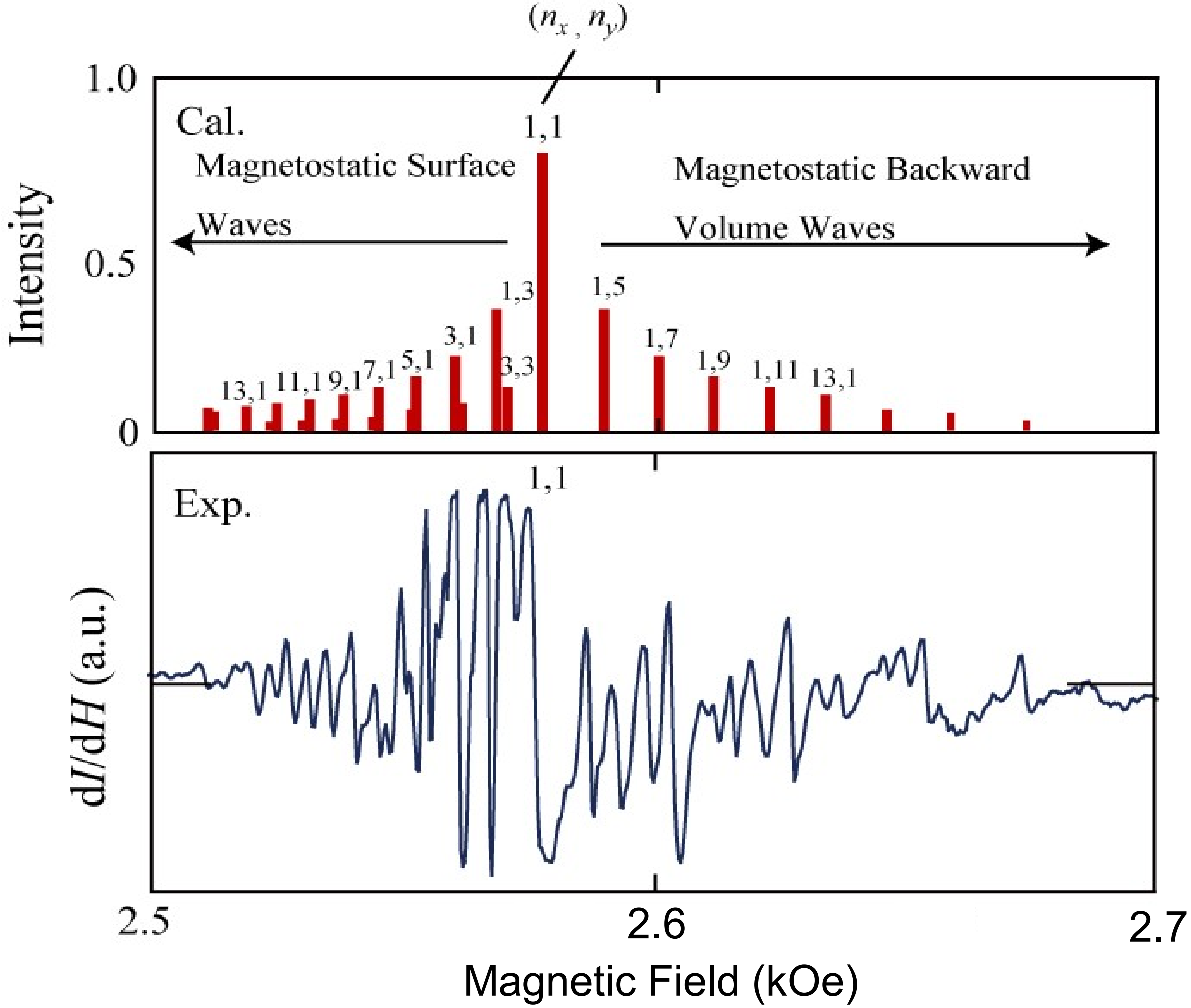


$$\mathbf{E}_{\mathrm{SHE}} \propto \mathbf{j}_s \times \boldsymbol{\sigma}$$

detection of spin current induced by spin pumping

Spin-wave resonance in $Y_3Fe_5O_{12}$

Microwave absorption spectrum



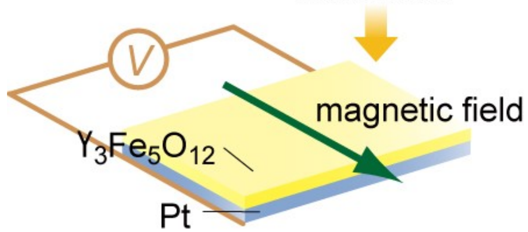
Mode calculation

Observed SWR spectrum

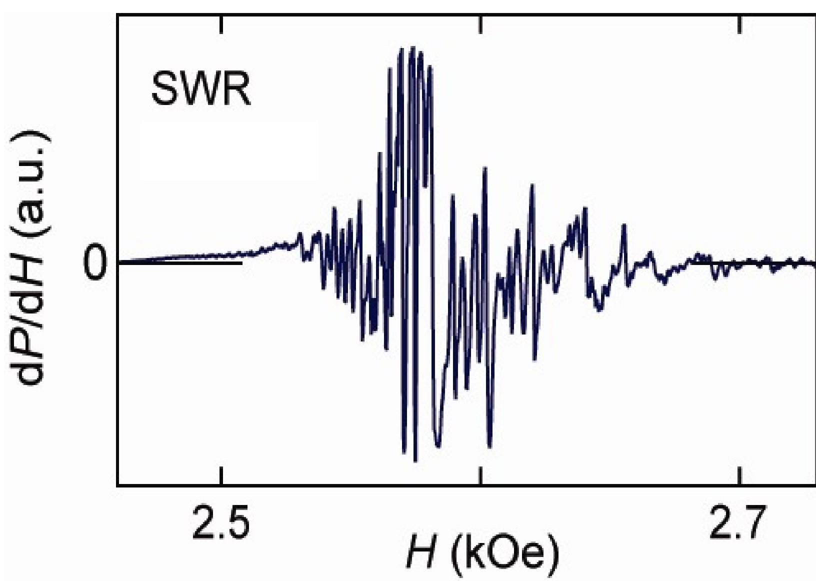
Multi peaks are assigned with MSW-SW

Inverse spin-Hall effect (voltage appears!)

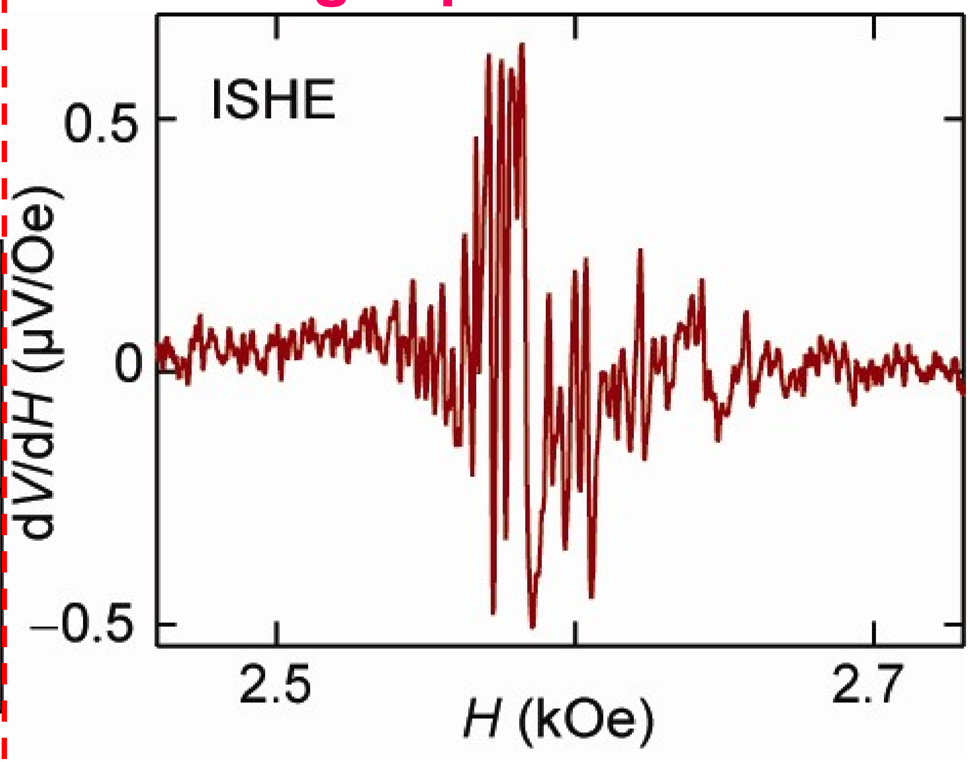
Inverse spin-Hall effect in $Y_3Fe_5O_{12}$(1.2 μm)/Pt(10 nm) system



Spin-wave resonance spectrum



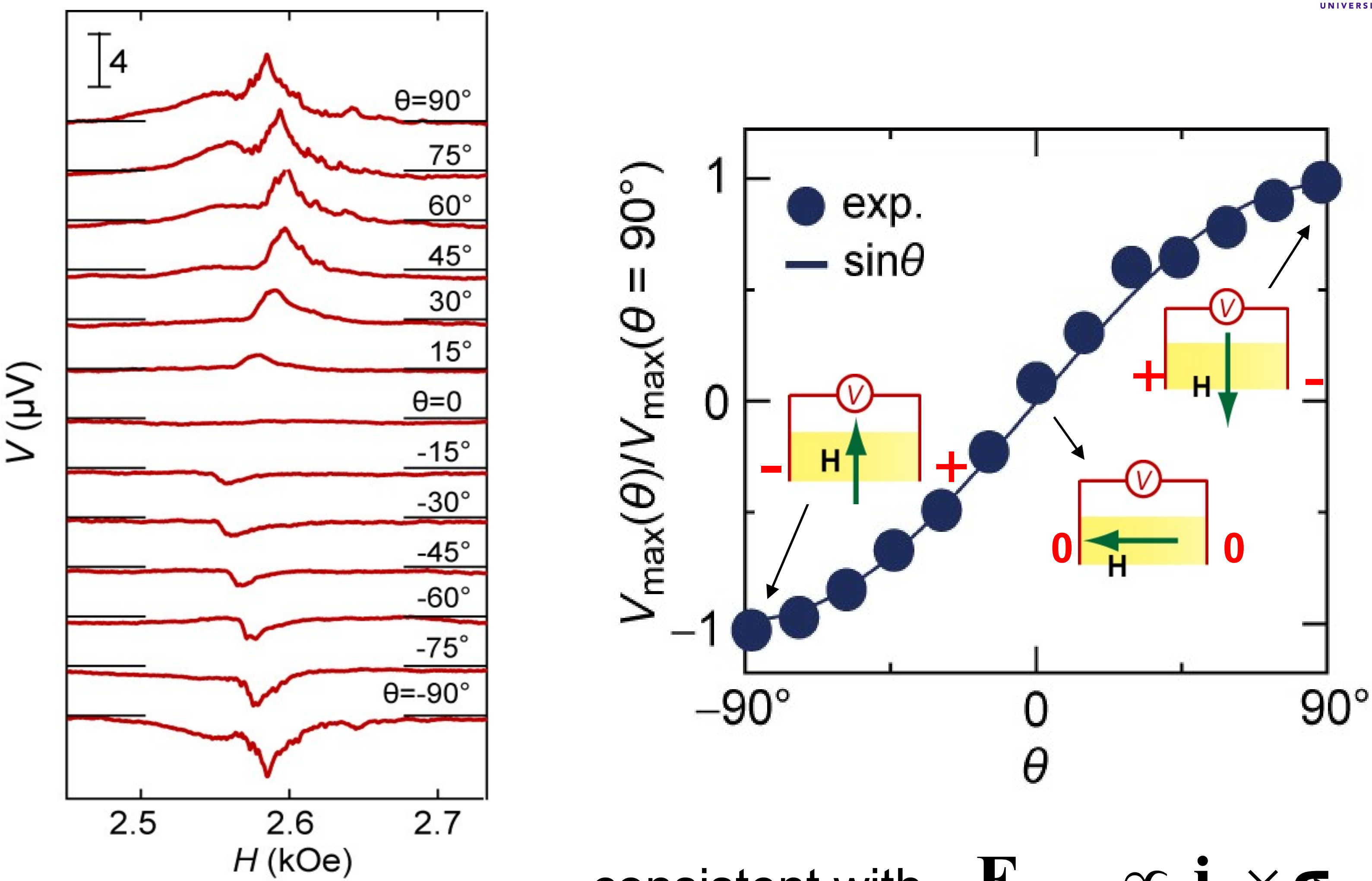
Voltage spectrum



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

Spin pumping appears at $Y_3Fe_5O_{12}$/Pt junction !

Magnetic-field angle dependence of ISHE



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

spin mixing at $Y_3Fe_5O_{12}$/Pt juction was estimated・・・

Spin current induced in Pt

$$j_s^z(x) = -\frac{\hbar}{4e}\frac{\cdots}{\lambda_N}\frac{\cdots}{1+\Gamma^2} e \cdots = \frac{\hbar}{4e}\frac{\cdots}{\lambda_N}\frac{\cdots}{1+\Gamma^2}\left(\frac{\cdots}{M_z^2}\right) e^{-x/\lambda_N},$$

$$\Gamma = (\tau_{ex}/\tau_{sf})(\lambda_N/a_{eff}) \qquad g_{\uparrow\downarrow} \cdots \frac{1}{\cdots}\frac{\sigma}{\lambda_N}\frac{A_N}{}\frac{h}{2e^2}$$

Electric voltage induced by ISHE

$$V \approx \alpha_{SHE}\frac{\hbar}{4e}\left(\frac{\cdots}{d_N}\right)\frac{\tanh(d_N/\lambda_N)\tanh(d_N/2\lambda_N)}{1+\Gamma^2\tanh^2(d_N/\lambda_N)}\left(\frac{M_+M_-}{M_z^2}\right)$$

On resonance $\left(\frac{M_+M_-}{M_z^2}\right) = \frac{2\delta M_z}{M_z} = \frac{(\gamma h_{ac})^2}{(\omega-\gamma H)^2+(\alpha\omega)^2},$

From spin-pumping data…

$$V = 4.8\mu V \quad d_N = 10\text{nm},\ w_N = 3\text{mm},\ \lambda_N = 7\text{nm}, \quad \alpha = 6.7\times 10^{-5},$$

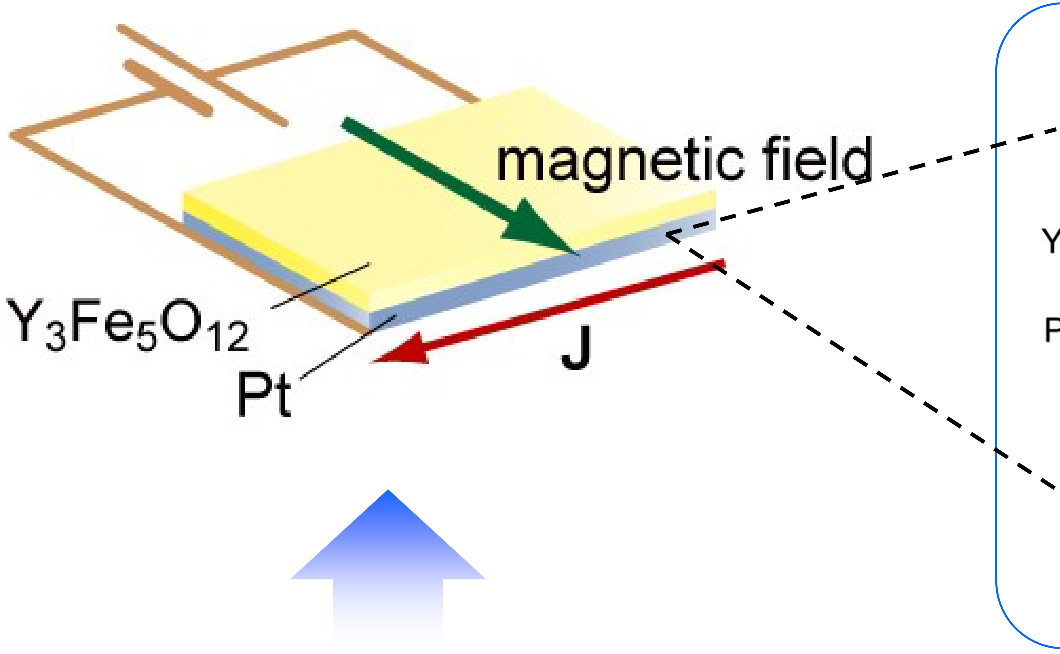
$$f = 9.4\times 10^9\,\text{s}^{-1},\ \gamma = 1.76\times 10^7\,\text{Oe}^{-1}\text{s}^{-1},\ \ \alpha_{SHE} = 0.0037,\ \ a_S \sim 1.24\text{nm},$$

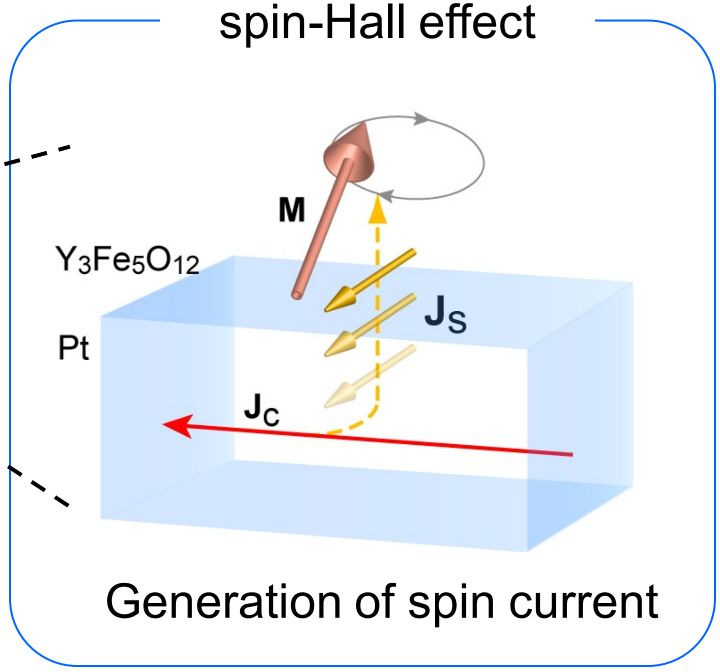
Mixing conductance： $g_{\uparrow\downarrow}/A_N = 3\times 10^{12}\,\text{cm}^{-2}$

Spin pumping appears at the interface to YIG. Then, what about the spin injection?

Let's try! - spin transfer into YIG-

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



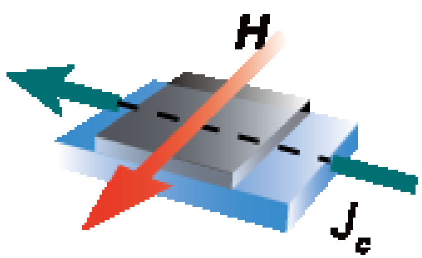


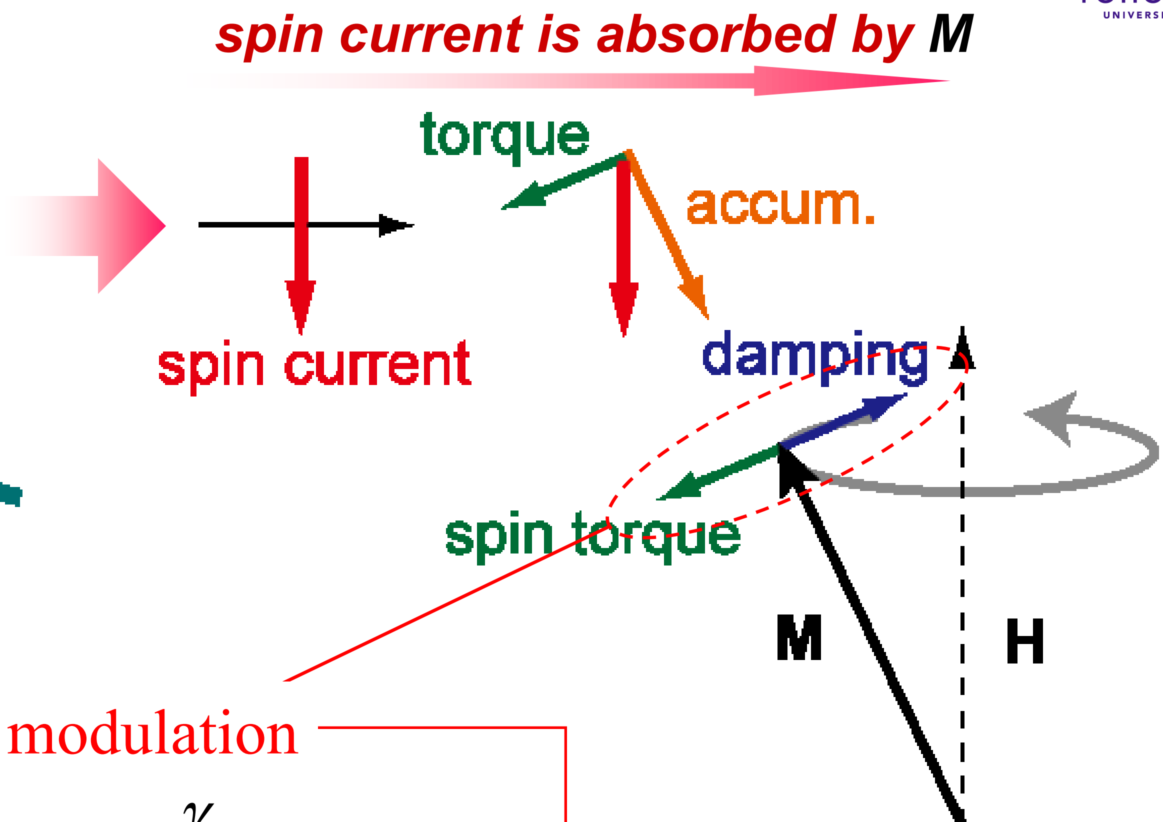
detection of microwave oscillation

Damping modulation via spin torque

θ=90°

Spin Hall effect





Damping modulation

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

Takahashi & Maekawa *et al.*

M_s: saturation magnetization
V_F: volume of the F layer
ω: FMR frequency
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Yttrium Iron Garnet (YIG) : $Y_3Fe_5O_{12}$

ferrimagnetic insulator (CT-type insulator)

- charge excitation gap is large (2.7 eV).
- very small spin excitation gap (~μeV)
- magnetization damping is very small ($\alpha \sim 6.7\times10{-5}$)

α : damping constant

→ Spin wave propagates over several tens centimeters.

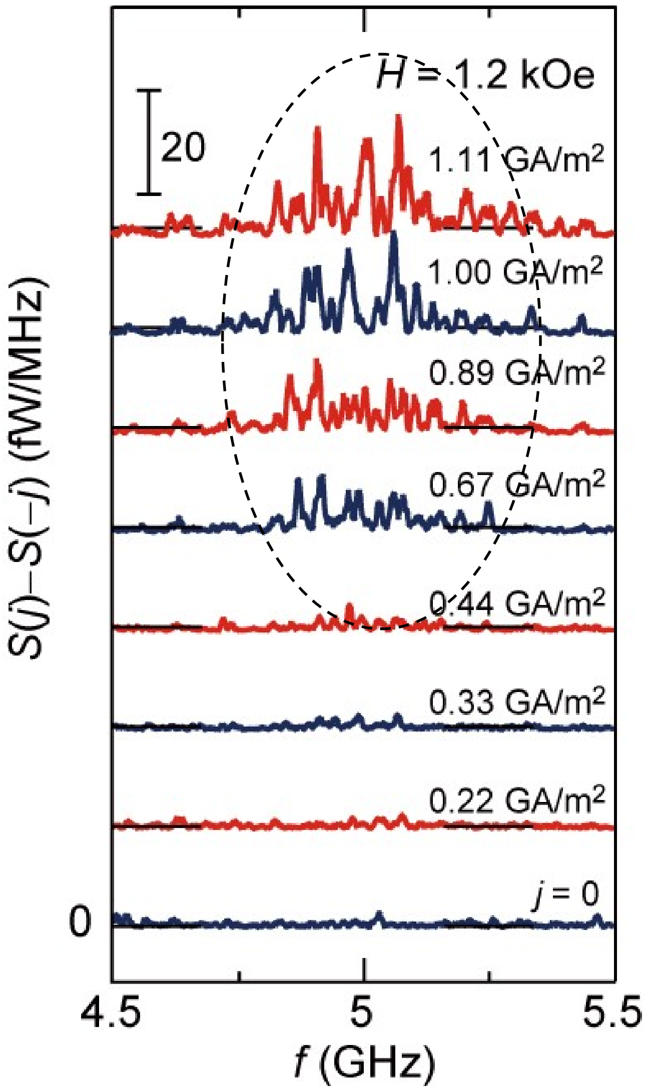
(T. Schneider, *et al. Appl. Phys. Lett.* **92,** 022505 (2008).)

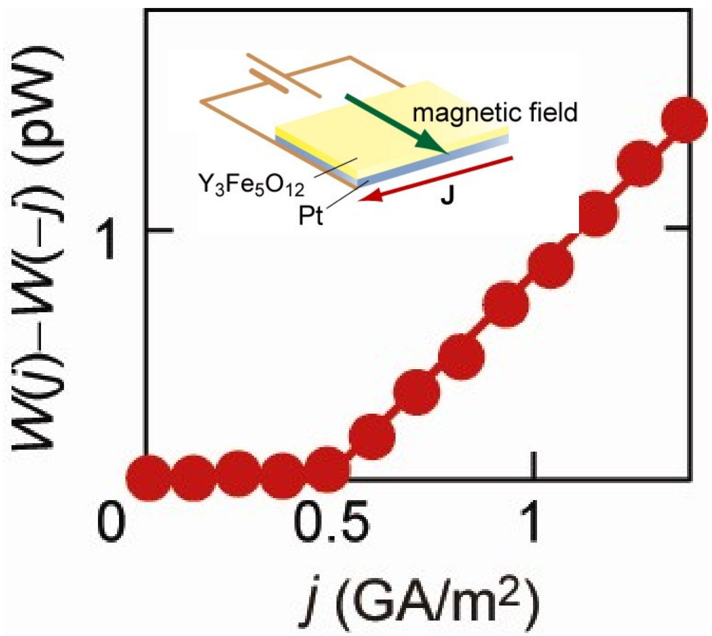
Since the original magnetization relaxation in YIG is very small, this relaxation may be negated by the spin torque, which may induce the self oscillation of the magnetization…

Microwave emission spectra

microwave emission spectra

(measured with Takanashi's group)

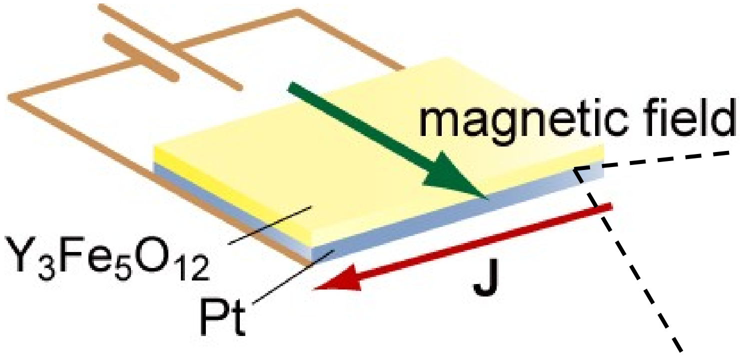


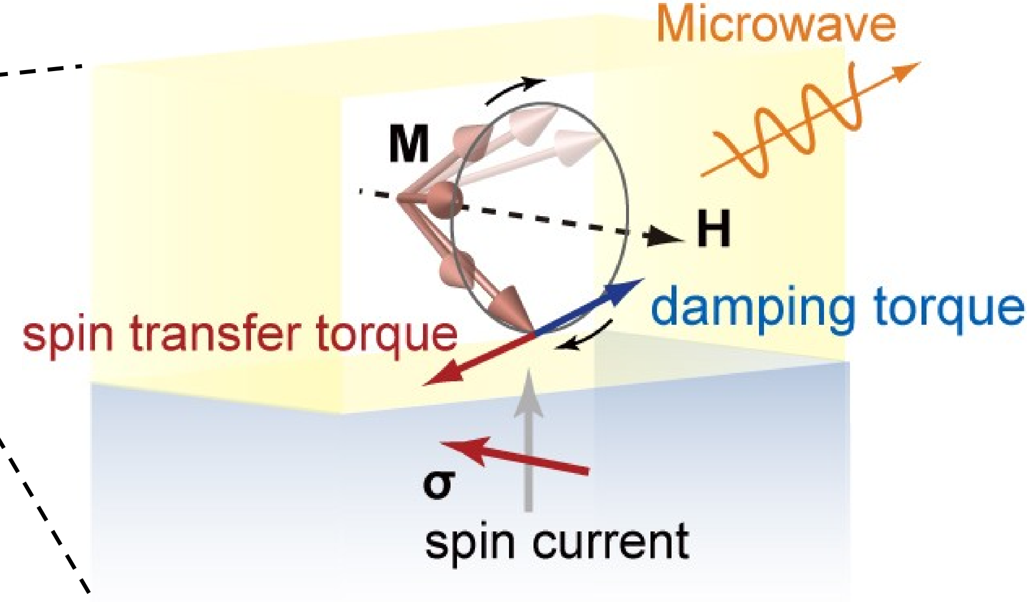


There is a threshold in the current dependence of the emission intensity

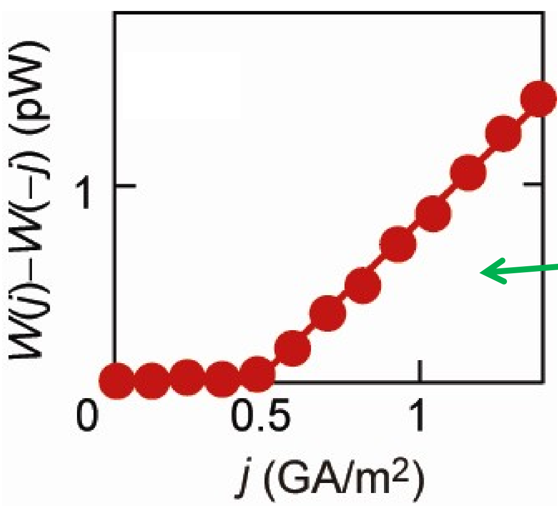
Kajiwara & Saitoh *et al.* Nature (2010)

spin-transfer torque





Current density dependence of microwave



this show that, at 0.5 GA/m^2 ,magnetization relaxation becomes zero and self oscillations of **M** is induced

Magnetic field dependence

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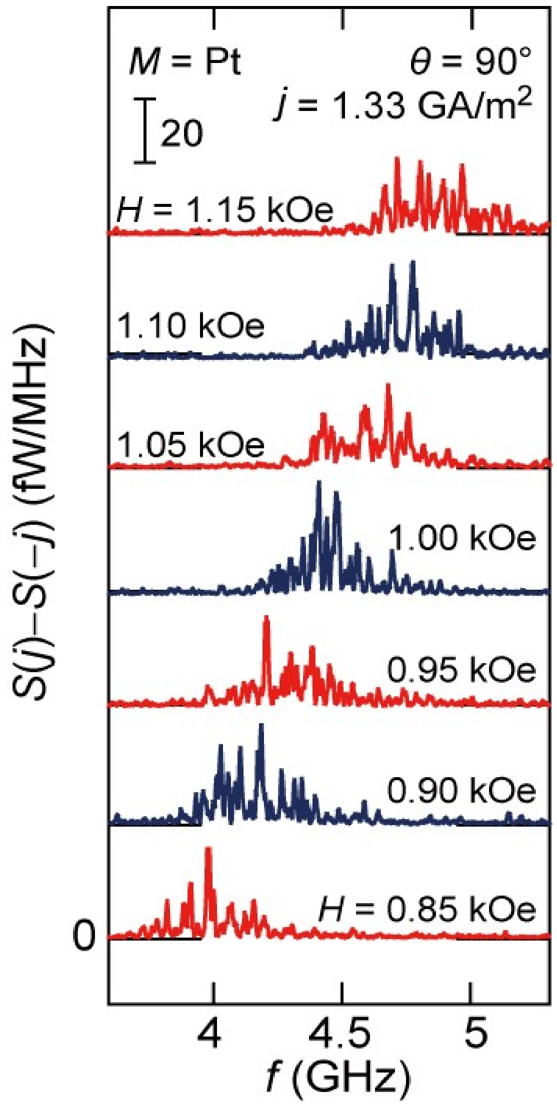

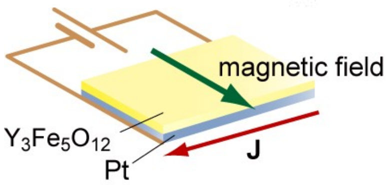

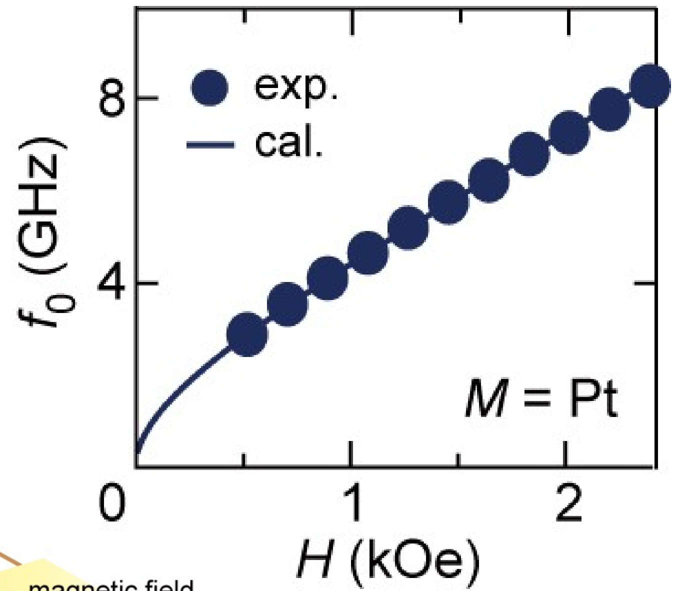

By changing the field, the emission frequency is shifted according the Kittel's equition

We have shown the spin-current exchange at YIG/Pt junction

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

ferrimagnetic insulator (CT-type insulator)

- charge excitation gap is large (2.7 eV).
- very small spin excitation gap (~μeV)
- magnetization damping is very small ($\alpha \sim 6.7 \times 10^{-5}$)

α : damping constant

→ Spin wave propagates over several tens centimeters.

(T. Schneider, *et al. Appl. Phys. Lett.* **92,** 022505 (2008).)

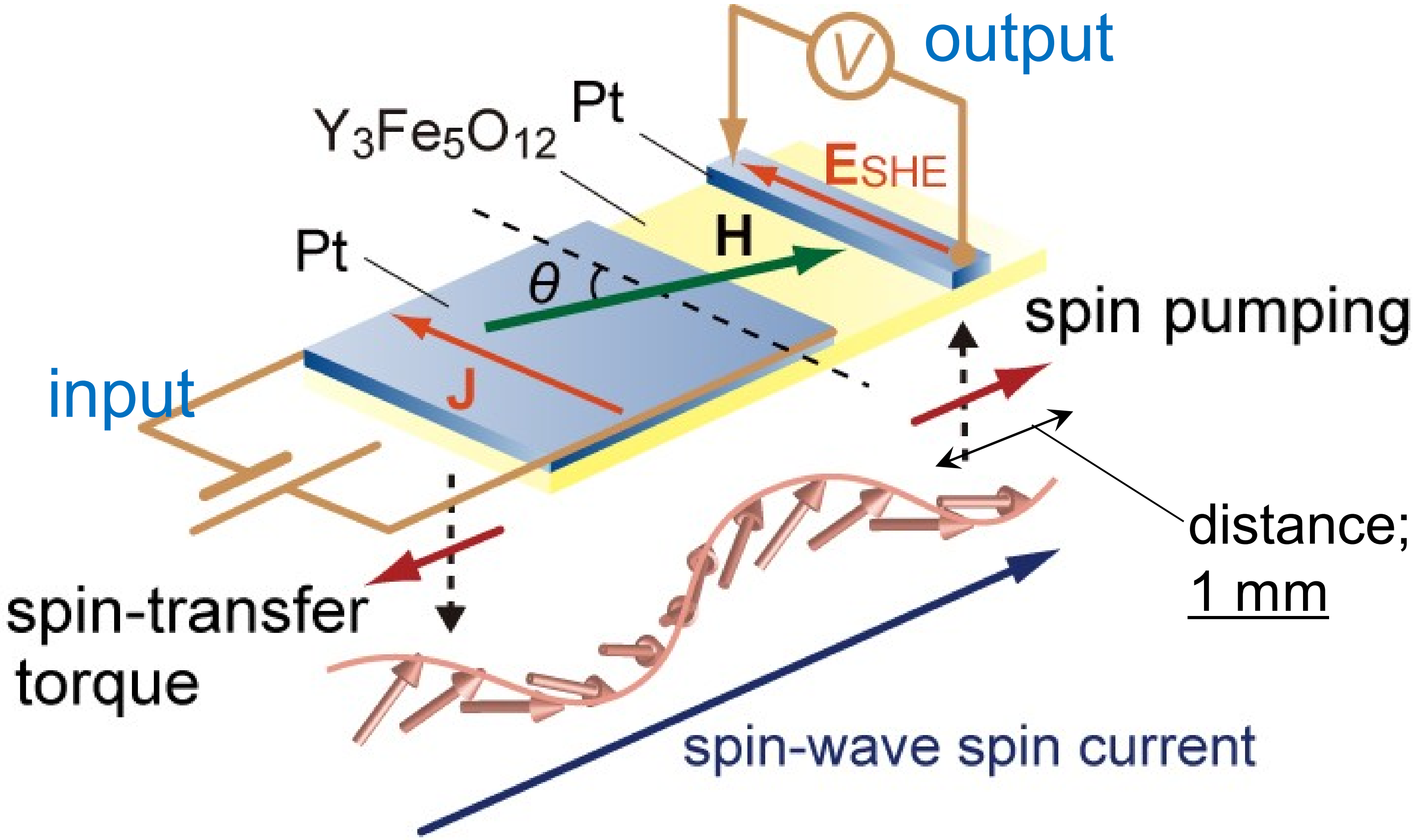
In YIG:

Spin-wave spin current has ***VERY LONG decay length***!

by using SHE, we can combine this long-range spin current with spintronics

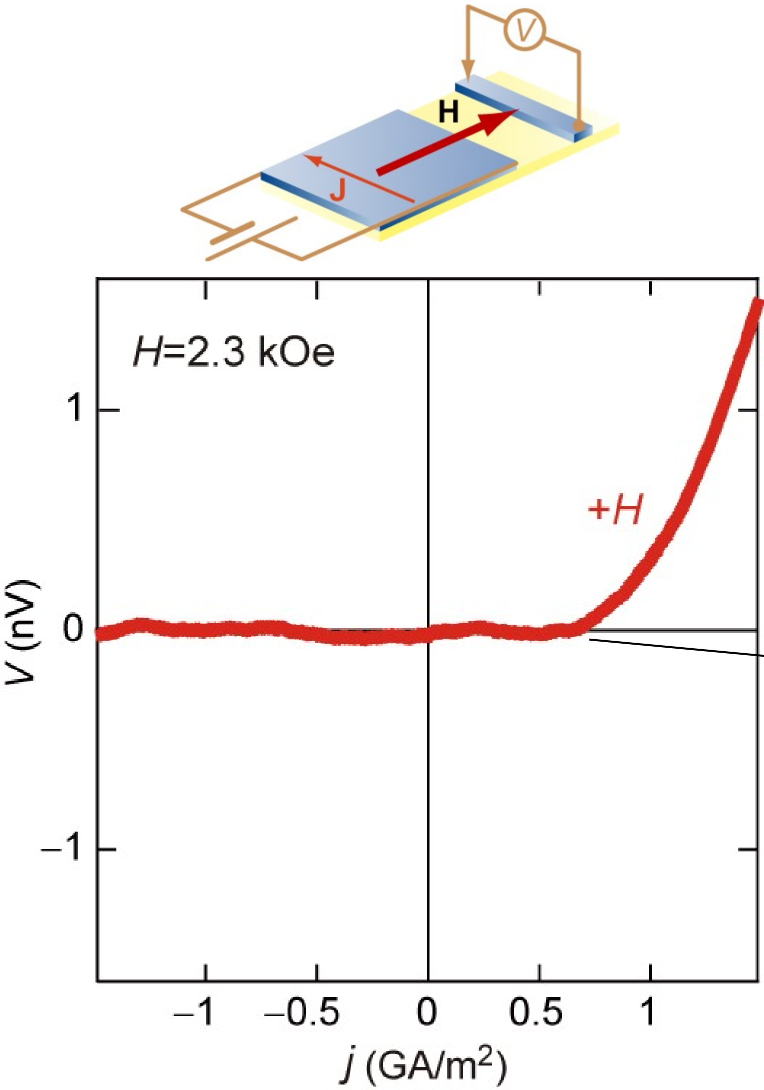
spin pumping and torque are used at the same time…

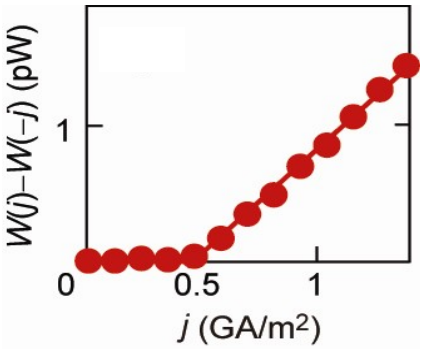
: we can send DC signal in insulators via SC interconversion



Non-local I-V curve

H is perpendicular to electric current

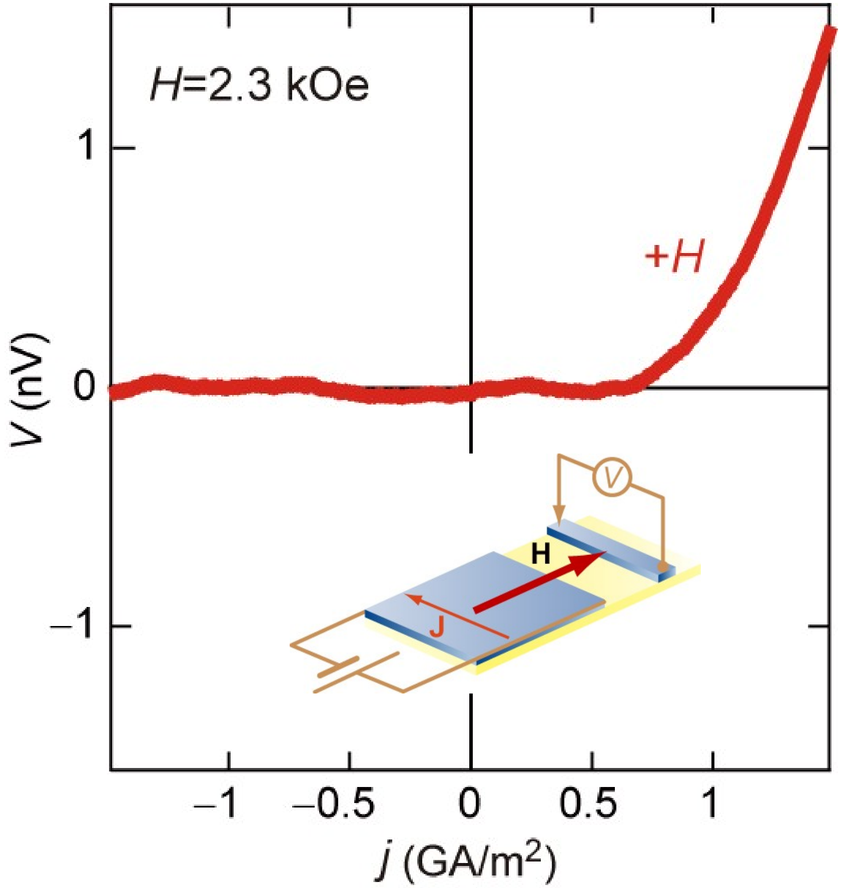


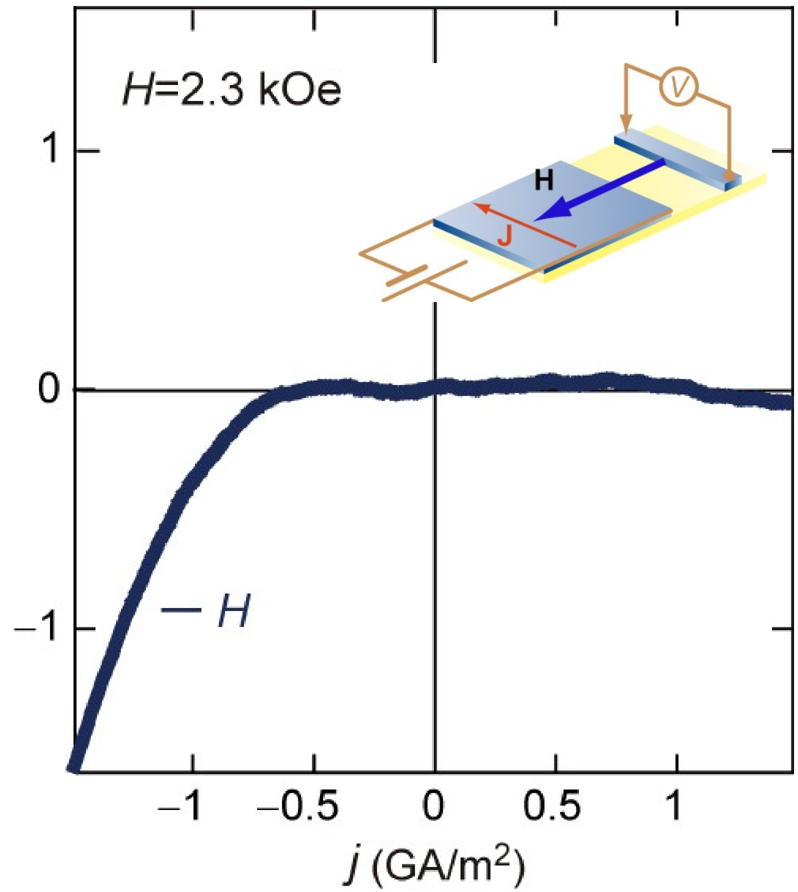


coincides with the threshold of the current induced magnetization oscillation in the same system, showing that the spin-wave interconversion induced by the SHE.

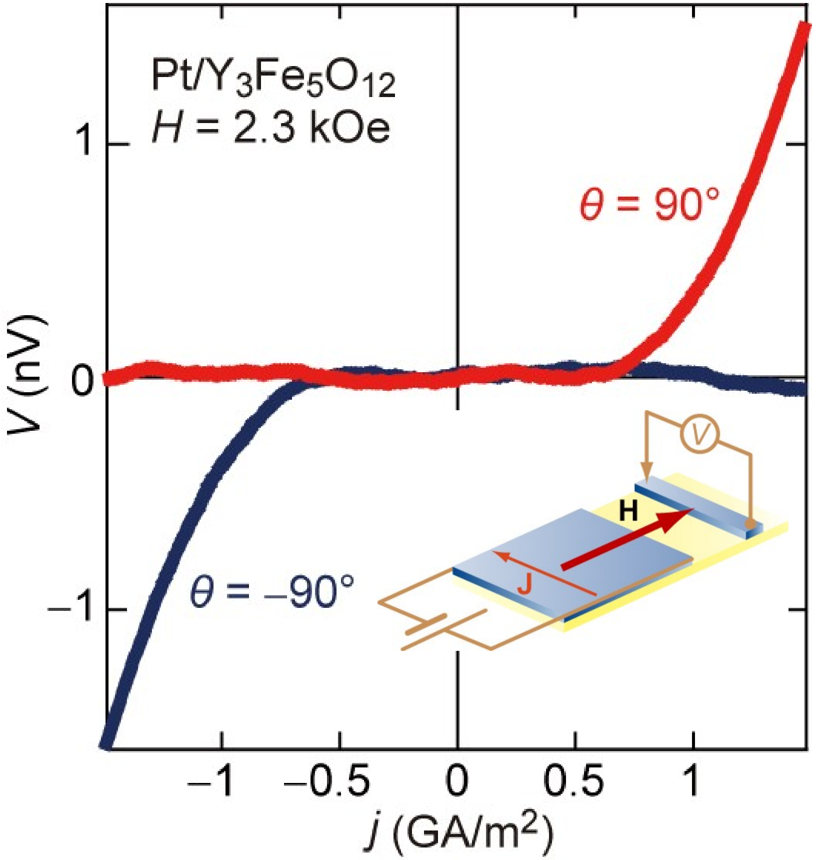
Non-local I-V curve

Magnetic field reversal

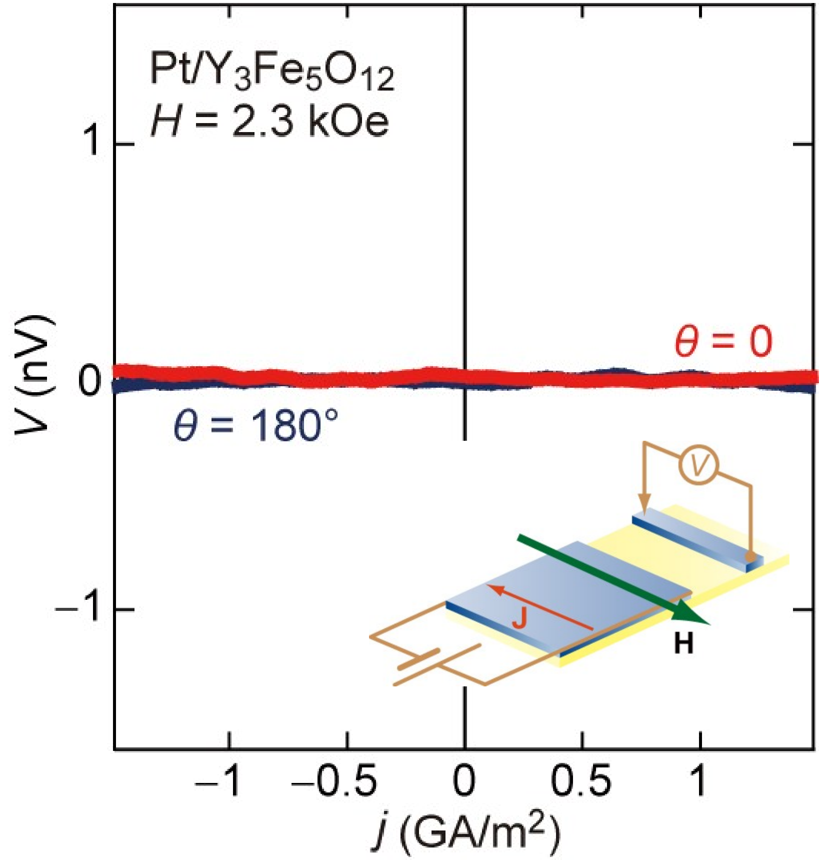




Magnetic field is perpendicular to electric current.



Magnetic field is parallel to electric current.



SHE/ISHE are not activated

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

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

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

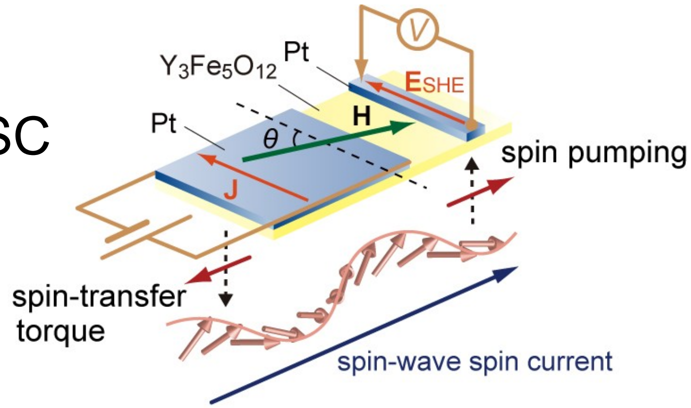
ferrimagnetic insulator (CT-type insulator)

- charge excitation gap is large (2.7 eV).
- spin excitation gap is very small (~μeV)
- magnetization damping is very small ($\alpha \sim 6.7\times10{-}5$)

α : damping constant

YIG: insulator for charge but conductor for SC

SC is combined with SHE



Ferrimagnetic insulator with weak magnetic anisotropy

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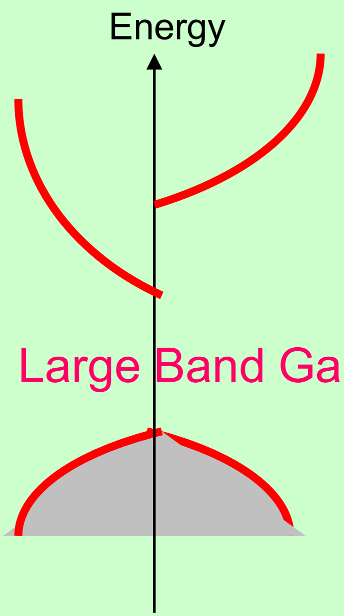
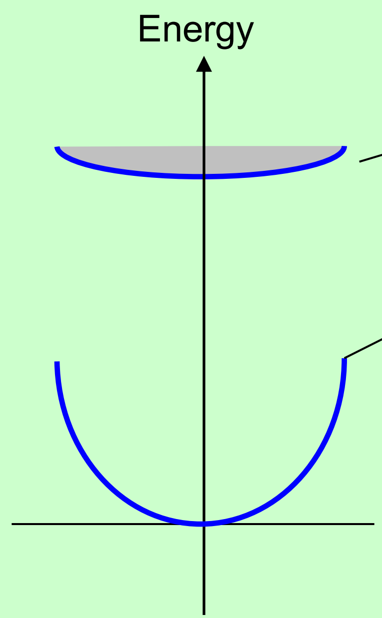
Charge sector



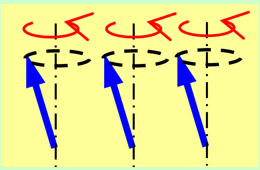
Mott Gap（CT Gap）

Spin sector



Individual Mode
（Stoner Excitation）

Collective mode
（spin wave）

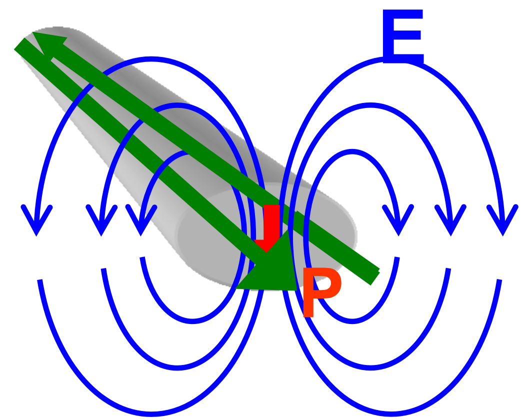


Almost
Zero Gap

Insulator for Charge but Conductor for Spin current

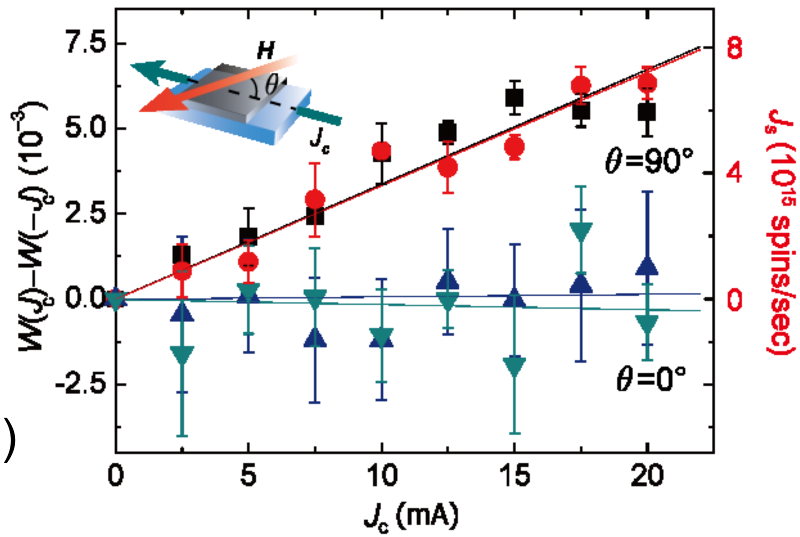
ways for measuring spin currents are found:

- Inverse spin-Hall effect (ISHE)



…. allows sensitive electric detection
of spin current (SC)

- magnetization relaxation modu



…. allows quantitative measurement
of spin current (SC)

Contents

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- Introduction - *What is spin current?* -
- Inverse spin-Hall effect and spin-Hall effect
- Spin pumping and spin torque
- Spin Seebeck effect

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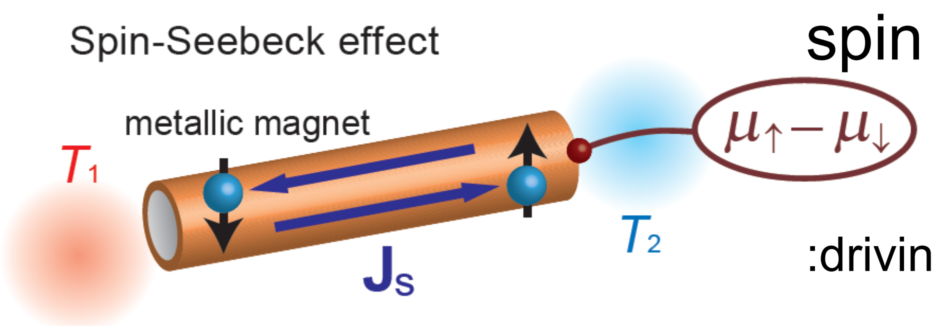

spin voltage

:driving potential for spin

Spin Voltage $(\mu_\uparrow - \mu_\downarrow)$

: potential for driving a spin current

NOT necessary equal to the spin accumulation (spin polarization) but includes thermo-dynamic component etc. besides the accumulation component

$$\delta\mu_{\uparrow(\downarrow)} = \left(\frac{\partial\mu_{\uparrow(\downarrow)}}{\partial n_{\uparrow(\downarrow)}}\right)\delta n_{\uparrow(\downarrow)} + \left(\frac{\partial\mu_{\uparrow(\downarrow)}}{\partial T}\right)\delta T + e\delta\phi$$

Accumulation Term
(responsible for spin polarization :
not important in macroscopic scale)

Entropy Term
(thermo-dynamic contribution
: small but subsists even in a macroscopic scale)

Spin voltage induced from ∇ *T*

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Spin-dependndt electrochemical potential: $\mu_\sigma(T, n_\sigma, \phi) = \mu_\sigma^c(T, n_\sigma) + e\phi$

$\left[\begin{array}{ll} \mu_\sigma^c & \text{: chemical potential} \\ \phi & \text{: electrostatic potential} \end{array}\right]$

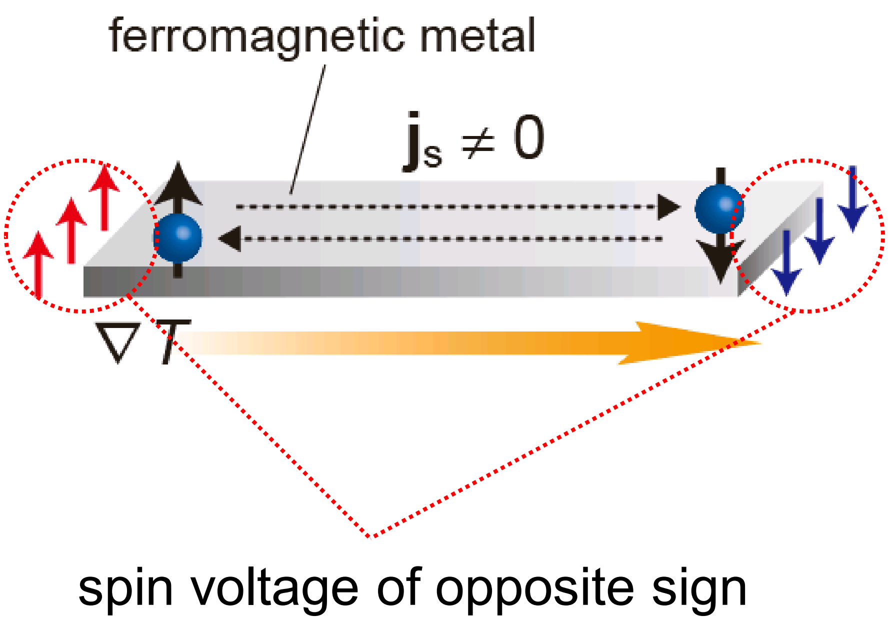
derivative expansion

$$\nabla \mu_\sigma = \left(\frac{\partial \mu_\sigma^c}{\partial T}\right)_{n_\sigma} \nabla T + \left(\frac{\partial \mu_\sigma^c}{\partial n_\sigma}\right)_T \nabla n_\sigma + e\nabla\phi$$

entropy contribution

accumulation

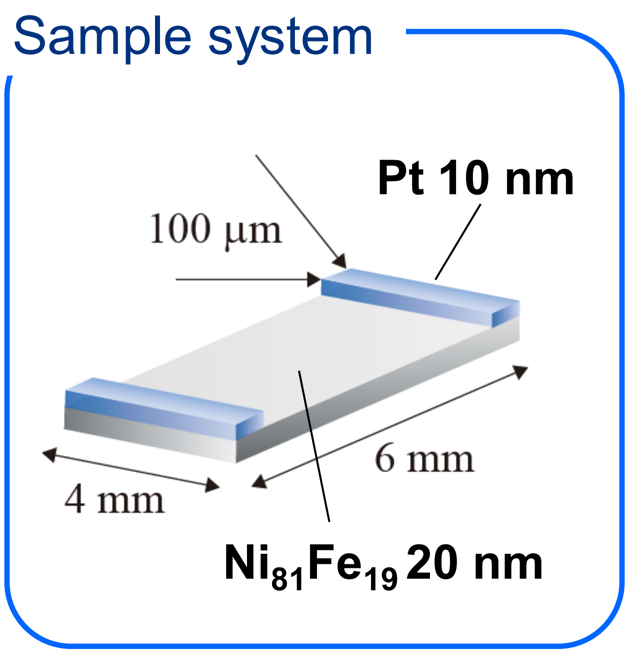
decay within the spin-diffusion-length scale

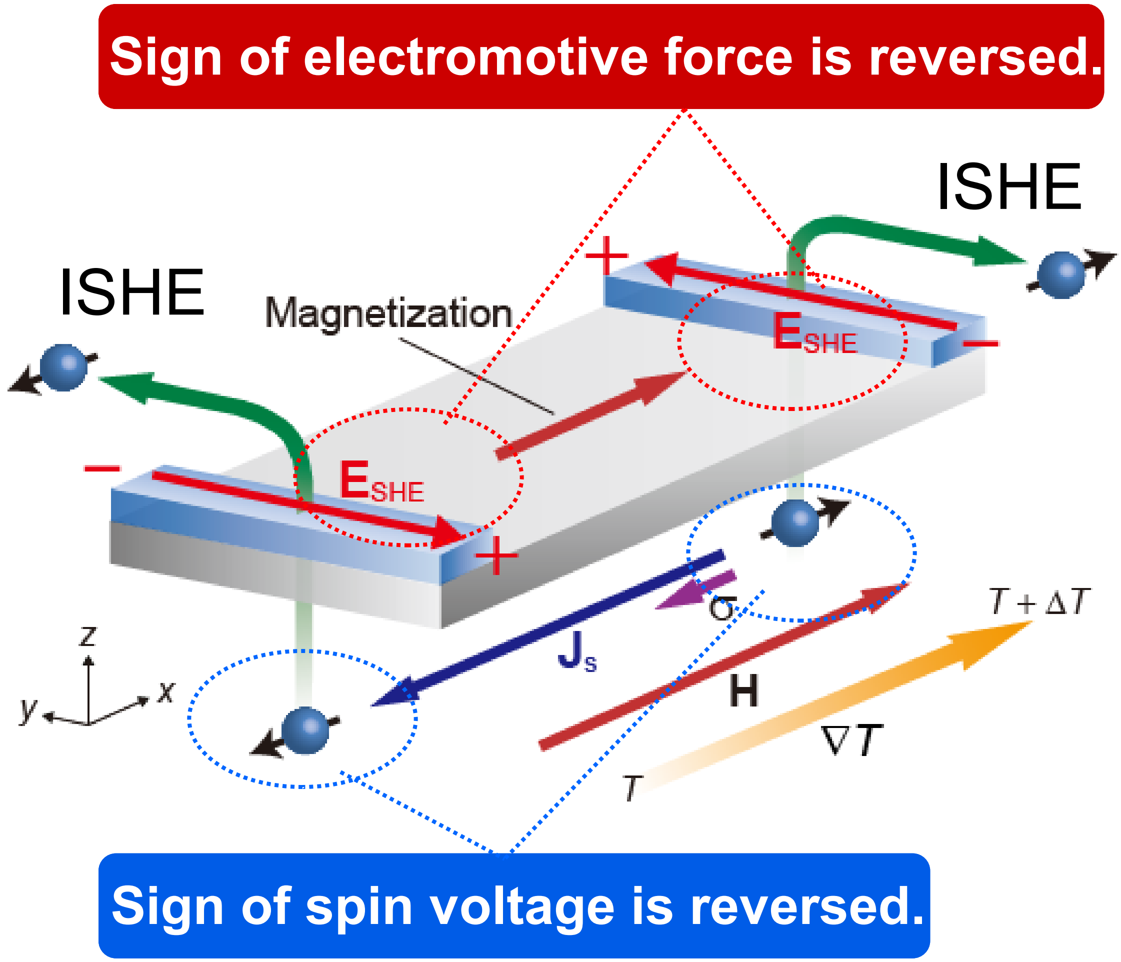


$$\mu_\uparrow - \mu_\downarrow = \left[\left(\frac{\partial \mu_\uparrow^c}{\partial T}\right)_{n_\uparrow} - \left(\frac{\partial \mu_\downarrow^c}{\partial T}\right)_{n_\downarrow}\right] \nabla T \cdot x$$

spin voltage induced from ∇ *T*

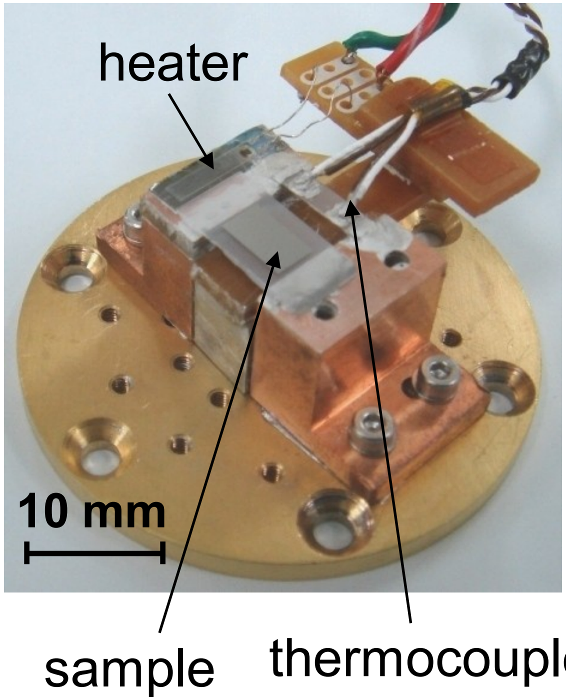
SSE detection mechanism

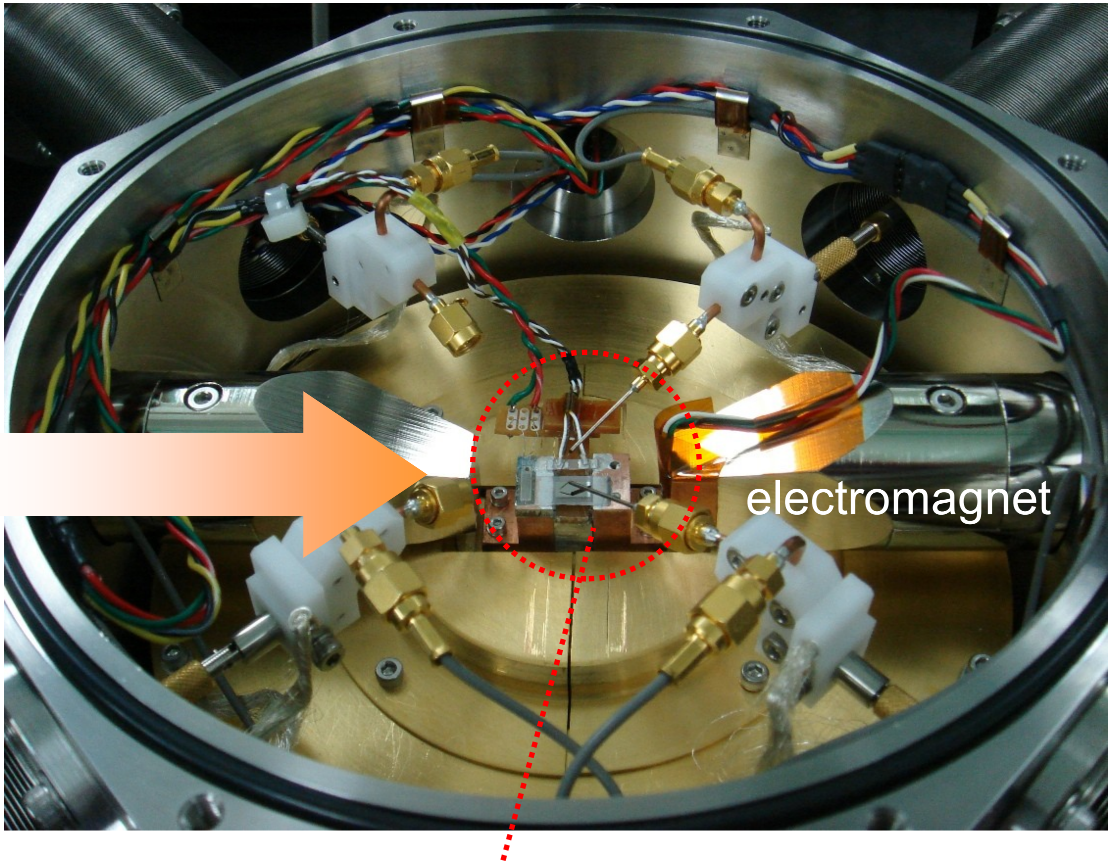




SSE measurement setup

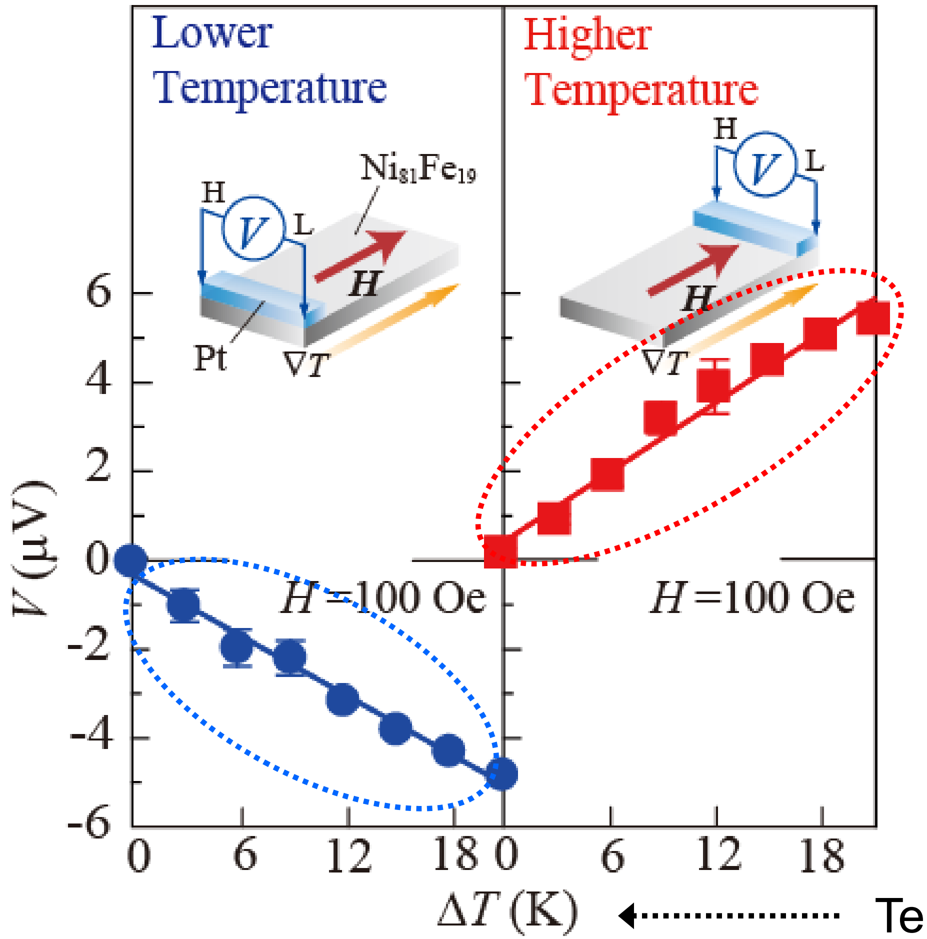
Temperature-gradient generator





Electric voltage V between the ends of the Pt wire is measured at 300 K.

ΔT dependence of V



Temperature differ.

The magnitude of *V* is proportional to ∇*T*.

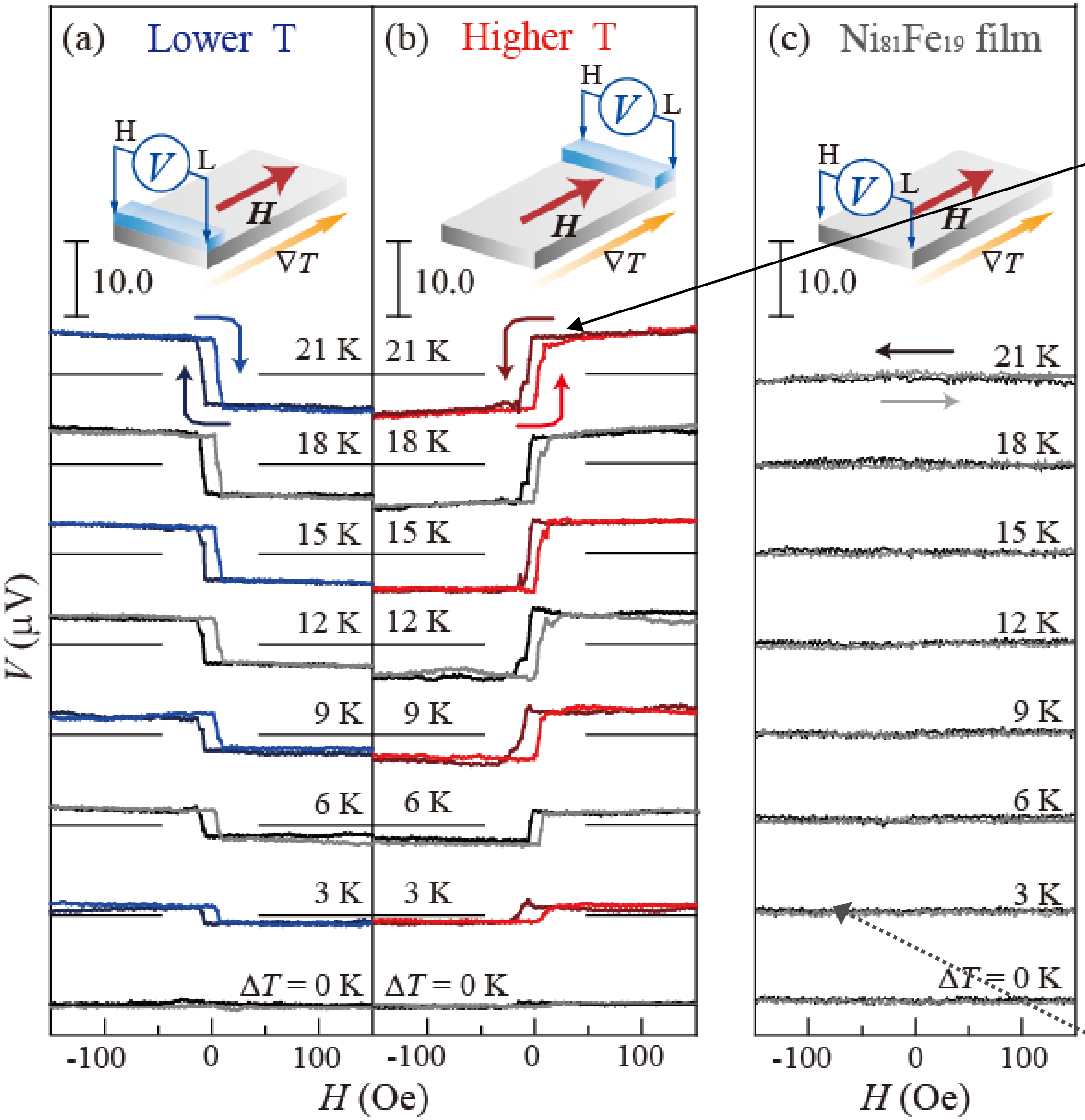
The sign of V is reversed between the lower and the higher temperature ends.

ISHE voltage induced by the spin-Seebeck effect

Nature (2008).

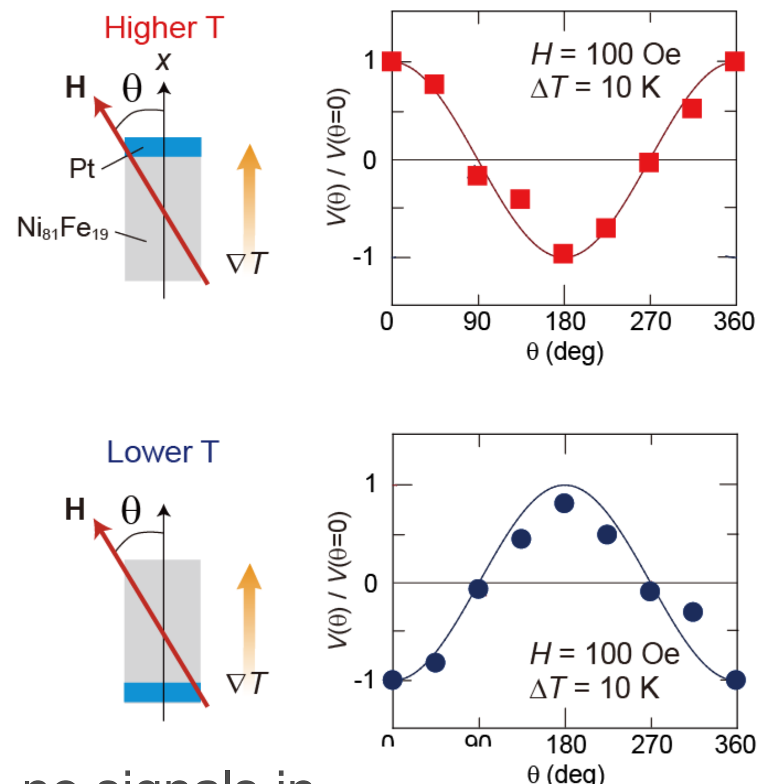
Magnetic-field dependence of *V*

Nature (2008).



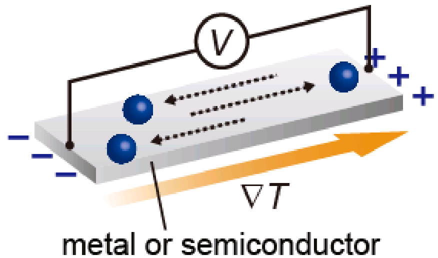
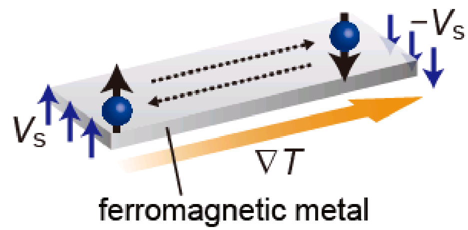
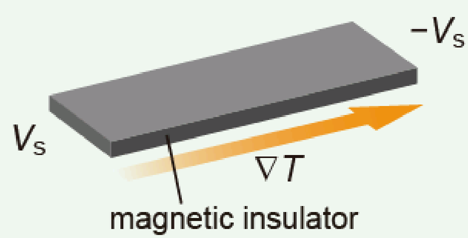
hysteresis loop

Nature (2008).



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

huge difference
between conventional and spin Seebeck effects

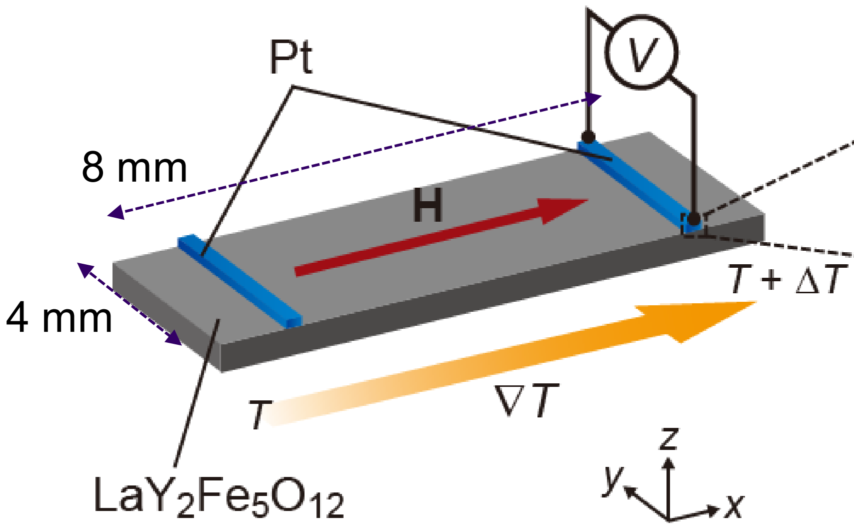
Material \ output	Electricity	Magnetism
Conductor	Seebeck effect 	spin Seebeck effect 
Insulator	×	spin Seebeck effect 

The spin Seebeck effect appears both in insulators and conductors

Electric detection of the spin Seebeck effect in insulator

TOHOKU UNIVERSITY

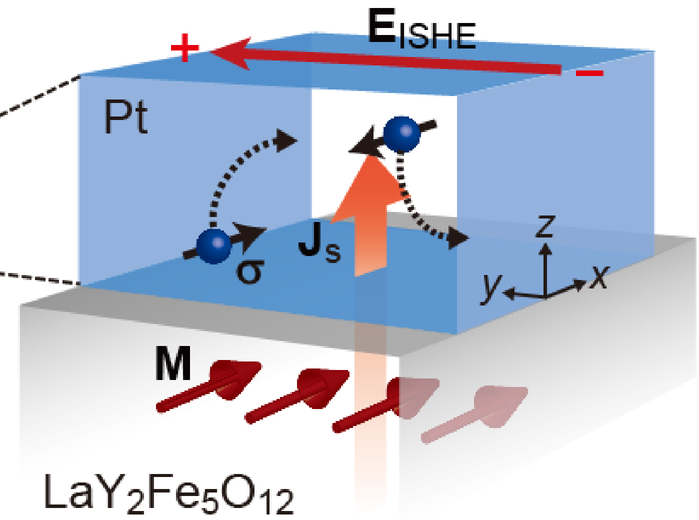
Sample system



(YIG, ferrimagnetic insulator)

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

Inverse spin-Hall effect (ISHE)



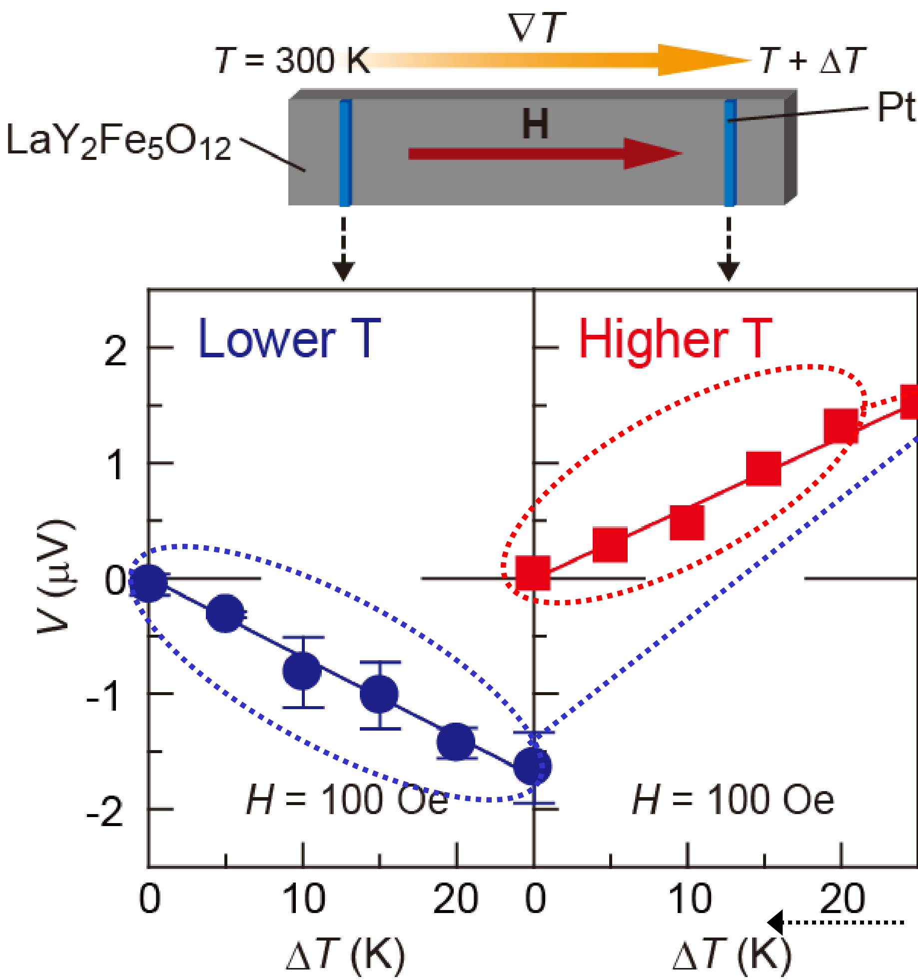
Electric detection of spin currents

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

Unpublished

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

TOHOKU UNIVERSITY



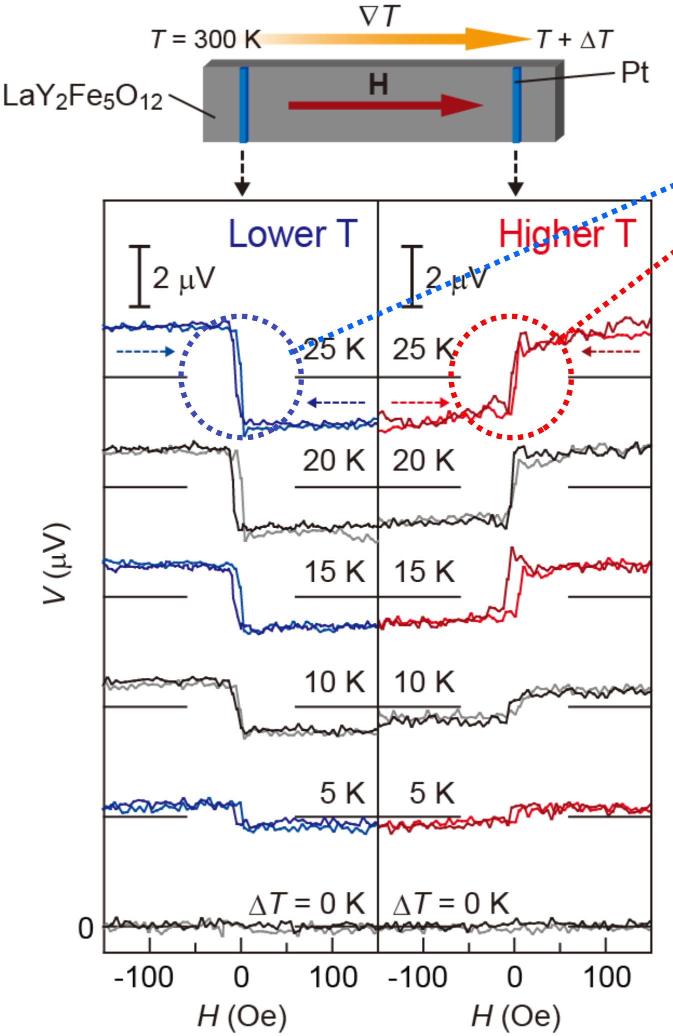
Temperature difference

- The sign of V is proportional to ΔT.
- The sign of V is reversed between the lower/higher temperature ends.

same as in the $Ni_{81}Fe_{19}$/ Pt system.

Unpublished

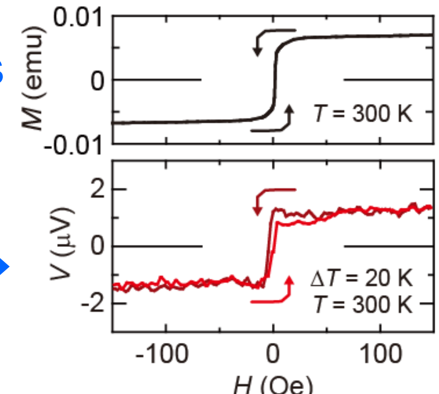
H dependence of V ($LaY_2Fe_5O_{12}$, 300 K)



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, the conventional Seebeck and the Nernst-Ettingshausen effects are irrelevant.

Unpublished

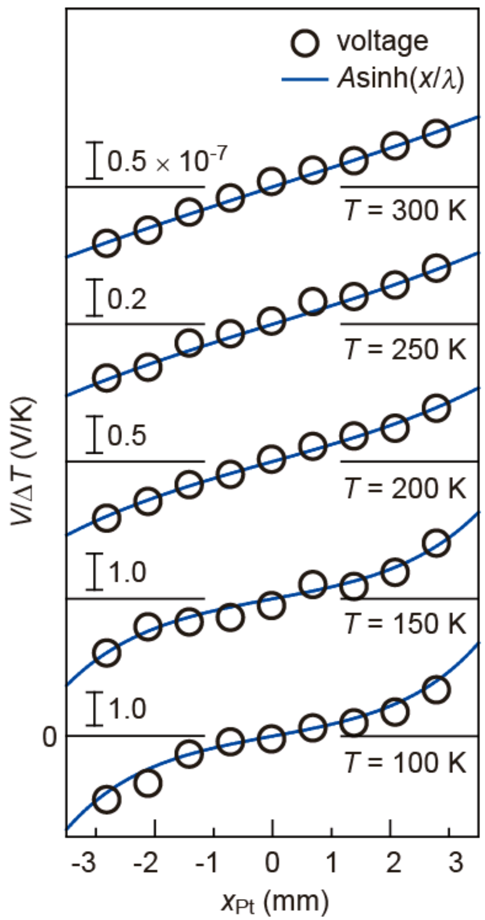
- possibility of artifacts is eliminated:

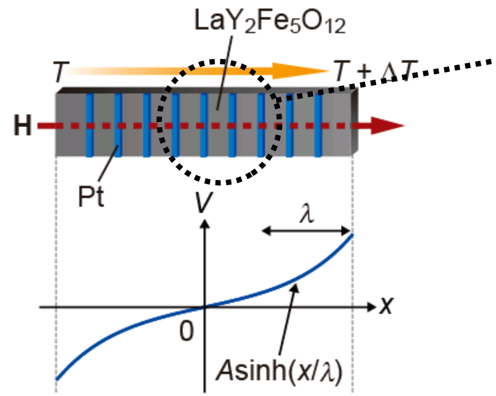
~~*back-flow currents, AMR, AHE,*~~
~~*Seebeck effect, Nernst effects ......*~~

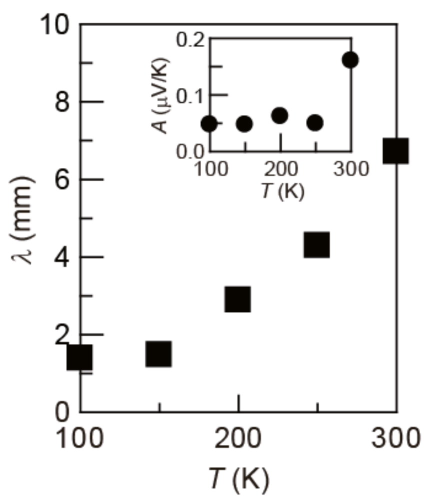
↑

YIG is a good ***insulator*** !!

spatial distribution is very *T* dependent







Position of Pt wires

Nine Pt wire were fabricated on the identical $LaY_2Fe_5O_{12}$ (YIG).

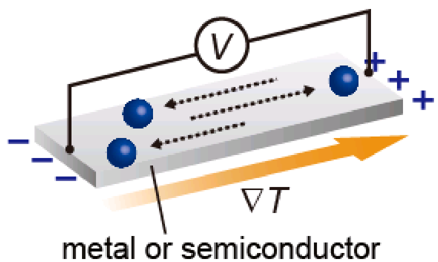
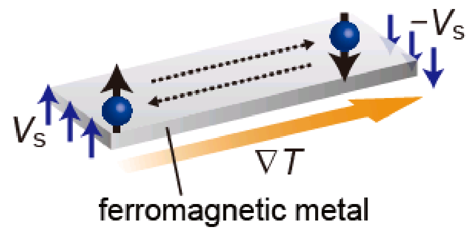
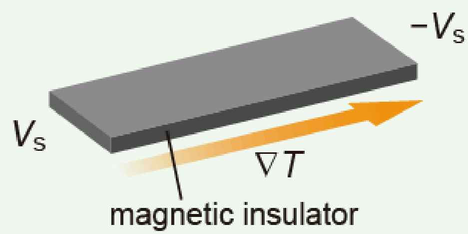
V varies x_{Pt} in a hyperbolic sine distribution

The fitting results using *A*sinh(*x*/*λ*) show that the decay length *λ*

- varies in the range from 2 to 6 mm
- decreases with decreasing *T*

λ is clearly different from the spin-diffusion length

Critical difference between spin and charge Seebeck effects

<table>
<tr><td>output / Material</td><td>Electricity</td><td>Magnetism</td></tr>
<tr><td>Conductor</td><td>Seebeck effect

</td><td>spin Seebeck effect

</td></tr>
<tr><td>Insulator</td><td>×</td><td>spin Seebeck effect

</td></tr>
</table>

The spin Seebeck effect appears both in insulators and metals

J. Xiao and G.E.W. Bauer's theory

Spin currents at the YIG/Pt interface is attributed to the spin pumping

$$\langle I_z \rangle \simeq \frac{\gamma \hbar g_r k_B}{2\pi M_s V_a}(T_F^m - T_N)$$

proportional to the difference between magnon temperature T_m and phonon temperature T_p

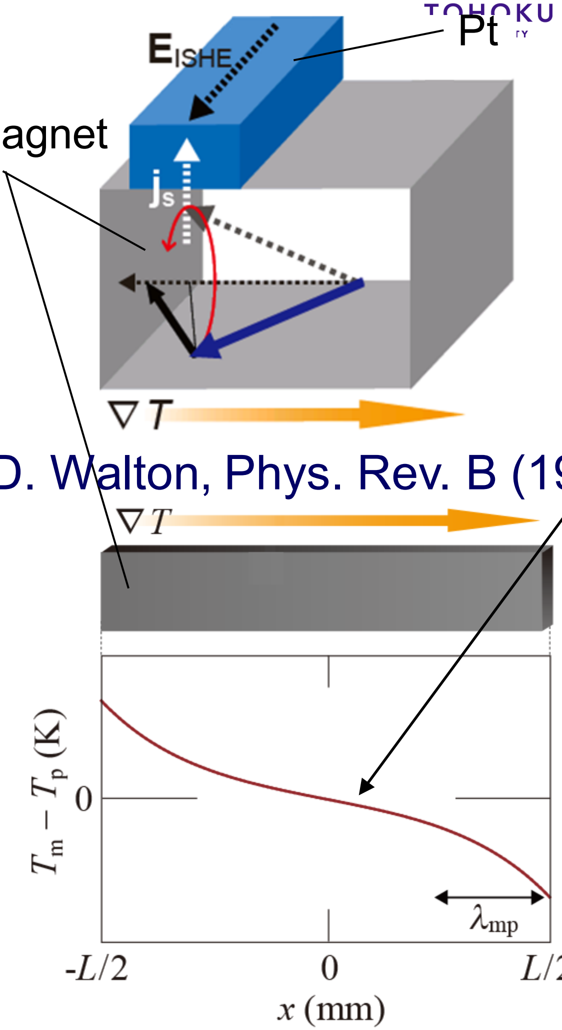
D. J. Sanders and D. Walton, Phys. Rev. B (1977)

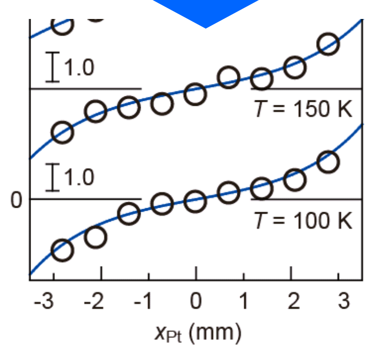
Spatial distribution of $T_m - T_p$:

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

The decay length λ reaches several millimeters in YIG.

consisten with the experiment.





Xiao et al. PRB (2010)

Final slide:

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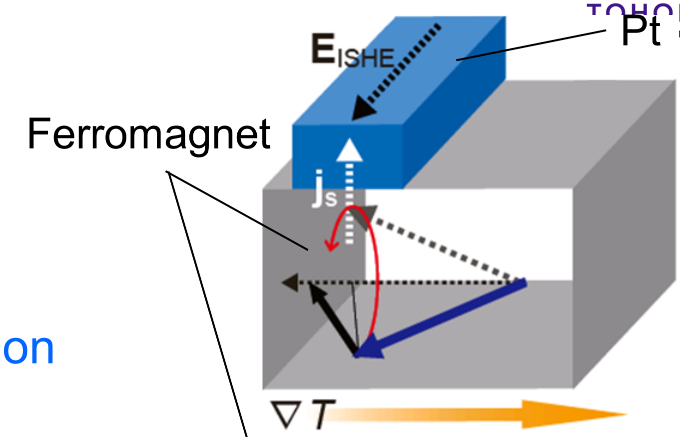

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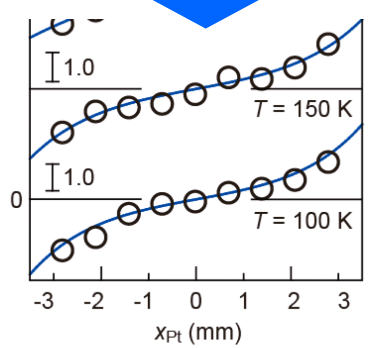
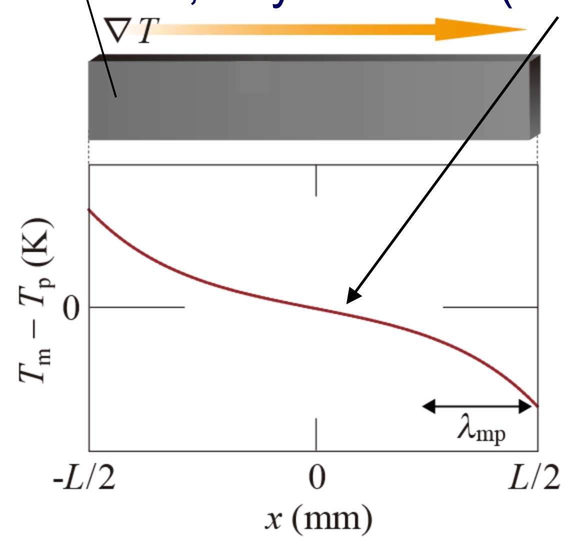




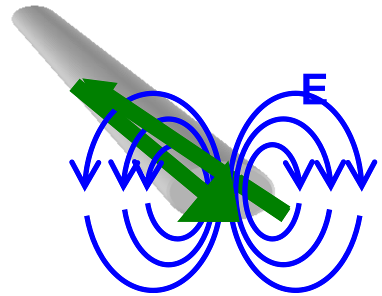
Xiao et al. PRB (2010)

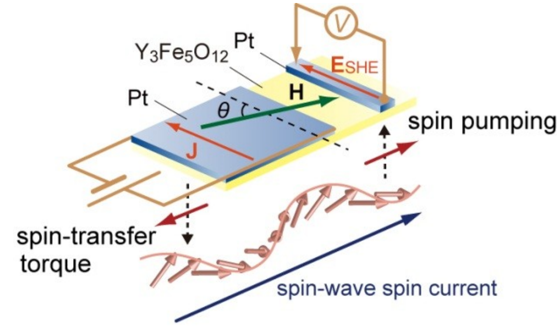
Friday P9 by Prof.G. Bauer

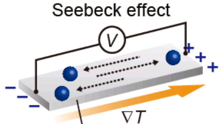
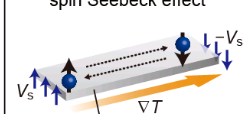
Summary

- insulators may be useful in spintronics

- We have found methods for sensitive measurement of a spin current in solids using ISHE.
- Spin transfer and spin torque were found to appear in magnetic insulators.
- Using ISHE, we found the spin-Seebeck effect both in insulator and metal systems.





Material \ output	Electricity	Magnetism
Conductor	Seebeck effect 	spin Seebeck effect 
Insulator	×	spin Seebeck effect