Spin Seebeck effect

[1]Institute for Materials Research, Tohoku University, Japan
[2]CREST, Japan Science and Technology Agency, Japan
[3]ASRC, Japan Atomic Energy Agency, Japan

Ken-ichi Uchida[1,2] *and Eiji Saitoh*[1-3]

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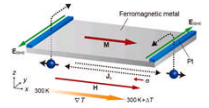
Methods for generating charge and spin currents

	Electro-magnetically	thermally	Optically
electric voltage	• electromagnetic induction • Lorentz force	thermoelectric effect (Seebeck effect)	photoelectric effect
spin voltage	• spin pumping • spin Hall effect • non-local method	??	circularly-polarized light excitation

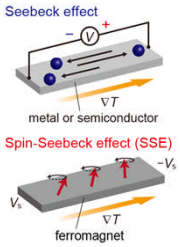
K. Uchida *et al*., Nature (2008).

Spin Seebeck effect



Seebeck and spin Seebeck effects

	Seebeck effect	SSE
metal	○	○ Uchida *et al*. (2008)
semi-conductor	○	○ Jaworski *et al*. (2010)
Insulator	×	○ Uchida *et al*. (2010)



The spin Seebeck effect (SSE) appears
both in a magnetic conductors and insulators.

Spin Seebeck effects (SSEs)

Experiments: This talk & Today's panel session (a.m.)

K. Uchida *et al*., Nature (2008). [SSE in metals]
K. Uchida *et al*., Nat. Mater. (2010). [SSE in insulators]
K. Uchida *et al*., Appl. Phys. Lett. (2010). [SSE in insulators]
C. M. Jaworski *et al*., Nat. Mater. (2010). [SSE in semiconductors]
C. M. Jaworski *et al*., Phys. Rev. Lett. (2011). [SSE in semiconductors]
A. Slachter *et al.* Nature Physics (2010). [Thermal spin-current injection by spin-dependent Seebeck effect]

Theory: Today's panel session (p.m.)

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). [Linear-response theory]
J. Ohe *et al*. Phys. Rev. B (in press). [Numerical calculation]

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- **Review of previous study**
  Spin Seebeck effect in metals and insulators
- **Acoustic spin Seebeck effect**
- **Acoustic spin pumping**
- **Conclusion**

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- **Review of previous study**
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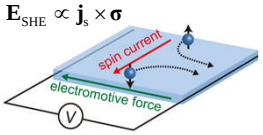
- **Acoustic spin pumping**
- **Conclusion**

Inverse spin-Hall effect and spin pumping

Inverse spin-Hall effect (ISHE)

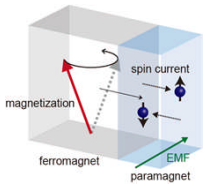
Electric detection of spin voltage

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



- E. Saitoh *et al.*, Appl. Phys. Lett. (2006).
- S.O. Valenzuela *et al.*, Nature (2006).
- T. Kimura *et al.*, Phys. Rev. Lett. (2007).
- T. Seki *et al.*, Nature Mater. (2008).

Spin pumping



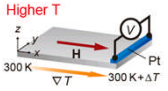
When the magnetization motion is maintained, a spin current is pumped out of the ferromagnet.

- R. H. Silsbee *et al.*, Phys. Rev. B (1979).
- Y. Tserkovnyak *et al.*, Phys. Rev. Lett. (2002).

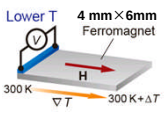
Detection of SSE in ferromagnetic metal (*F*)/Pt system

***F*(20 nm)/Pt(10 nm) system**
(*F* = $Ni_{81}Fe_{19}$, Ni, Fe)

Higher T

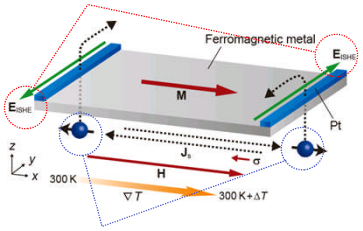


Lower T **4 mm×6mm** Ferromagnet



fabricated on a sapphire (Al_2O_3) substrate

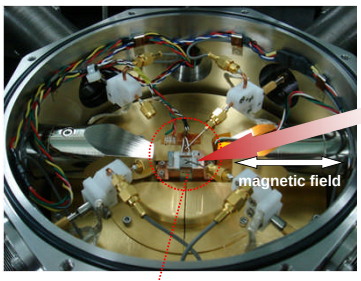
Electromotive force of opposite sign



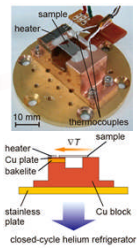
Spin voltage of opposite sign

K. Uchida *et al.*, Nature (2008).

Measurement system

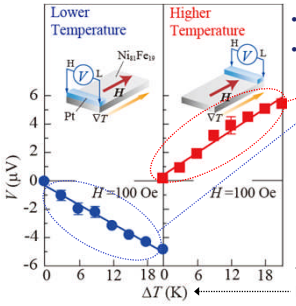


∇*T*-generation system



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

Δ*T* dependence of *V* ($Ni_{81}Fe_{19}$, 300 K)

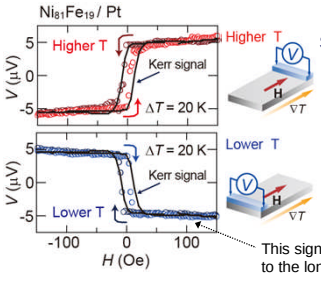


- The sign of *V* is proportional to Δ*T*.
- The sign of *V* is reversed between the lower/higher temperature ends.

ISHE voltage induced by the spin-Seebeck effect

Temperature difference between the end of the sample

Magnetic field *H* dependence of *V* ($Ni_{81}Fe_{19}$, 300 K)



Sign reversal of *V* by reversing *H*
+
Hysteresis loops

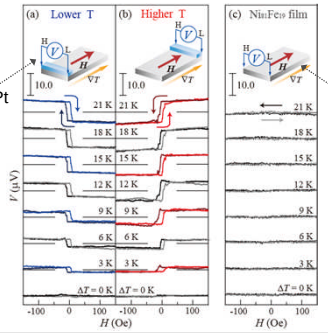
The origin of the *V* signal is a spin current.

This sign reversal of *V* corresponds to the longitudinal Kerr loops.

H-angle dependence of *V* and other supplementary experiments are consistent with the ISHE symmetry.

Δ*T* and *H* dependences of *V* ($Ni_{81}Fe_{19}$, 300 K)

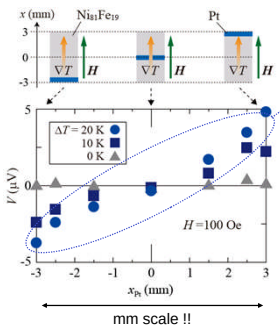
$Ni_{81}Fe_{19}$/Pt system



plain $Ni_{81}Fe_{19}$ film

K. Uchida *et al.*, Nature (2008).

Pt-wire-position x_{Pt} dependence of V ($Ni_{81}Fe_{19}$, 300 K)



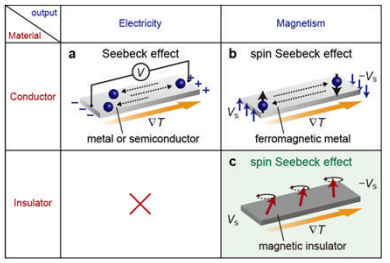
mm scale !!

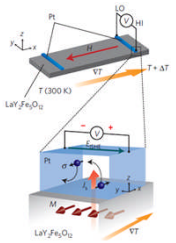
V varies almost linearly along the ∇T direction
+
$V = 0$ at $x_{Pt} = 0$

The spin-diffusion equation cannot reproduce this ***long-range*** spin-voltage distribution.

$$\nabla^2(\tilde{\mu}_\uparrow - \tilde{\mu}_\downarrow) = \frac{1}{\lambda^2}(\tilde{\mu}_\uparrow - \tilde{\mu}_\downarrow)$$

Seebeck and spin Seebeck effects



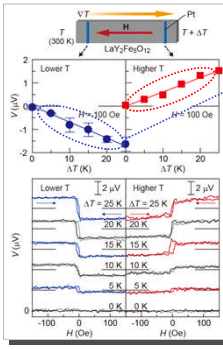


$$\mathbf{E}_{SHE} \propto \mathbf{j}_s \times \boldsymbol{\sigma}$$

The spin Seebeck effect appears even in a magnetic insulator.

K. Uchida *et al.*, Nature Mater. (2010).

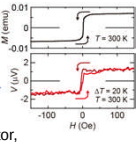
H dependence of *V* ($LaY_2Fe_5O_{12}$, 300 K)



Sign reversal of *V* by reversing *H*

ISHE voltage induced by the spin-Seebeck effect

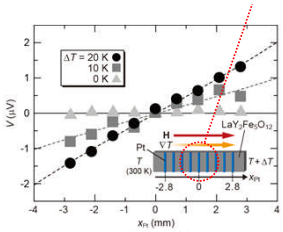
The reversal of *V* corresponds to the magnetization reversal.



Since $LaY_2Fe_5O_{12}$ is an insulator, the conventional Seebeck and the Nernst-Ettingshausen effects are irrelevant.

Pt-wire-position x_{Pt} dependence of *V* ($LaY_2Fe_5O_{12}$, 300 K)

Nine Pt wire were fabricated on a single $LaY_2Fe_5O_{12}$ sample.



Pt-wire position

When a finite ΔT is applied, *V* clearly increases for $x_{Pt}>0$ but decreases for $x_{Pt}<0$.

similar to the behavior of the SSE observed in ferromagnetic metals.

The long-range spatial distribution of the spin voltage bears witness to the extremely weak damping of the magnetization dynamics in *YIG*.

Proposed theories

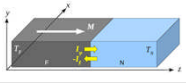
In magnetic insulators,

Conduction electron excitation is prevented by a huge charge gap.

Collective excitation of local spins (magnon) easily occurs under 300 K.

- Spin pumping + two temperature model — J. Xiao, G.E.W. Bauer *et al.*
- Nonequilibrium (Keldysh) Green's function — H. Adachi, S. Maekawa *et al.*
- Numerical simulation using LLG equation — J. Ohe, S. Maekawa *et al.*

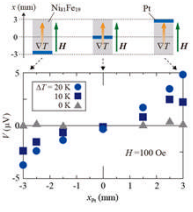
Collective motion of local spins (magnons), the s-d interaction at the F/Pt interface, and the fluctuation-dissipation theorem are important.



The SSE-induced spin current is proportional to the difference between the effective magnon temperature in YIG and electron temperature in Pt.

Unsolved issues on SSE

What causes the long-range nature of the spin Seebeck effect *in metals*?



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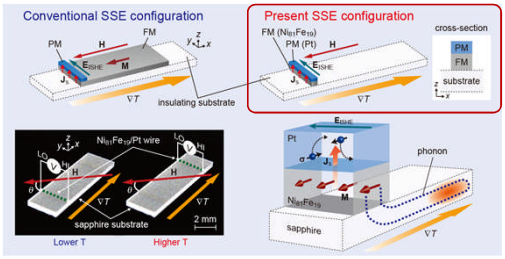
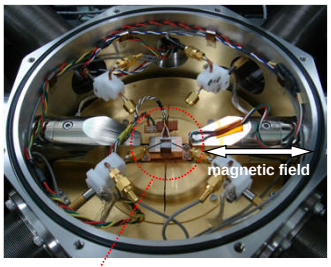
Experimental setup for acoustic SSE

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

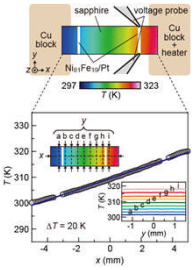


The $Ni_{81}Fe_{19}$/Pt wire is completely isolated both electrically and magnetically.

Measurement system and temperature gradient

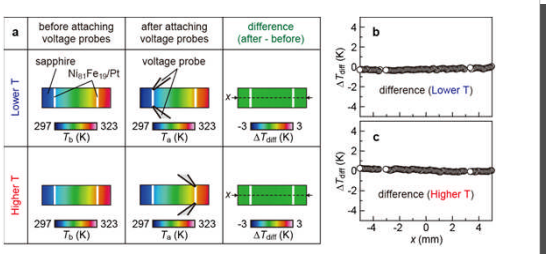


Electric voltage between the ends of the Pt wire was measured with applying the magnetic field and temperature gradient.



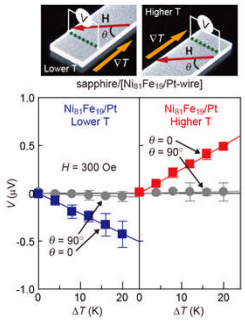
A uniform temperature gradient is confirmed using an infrared camera.

Influence of voltage-probe contact



The temperature of the sapphire/[$Ni_{81}Fe_{19}$/Pt-wire] sample does not change at every position by attaching the voltage probes.

ΔT dependence of V ($Ni_{81}Fe_{19}$/Pt wire, 300 K)

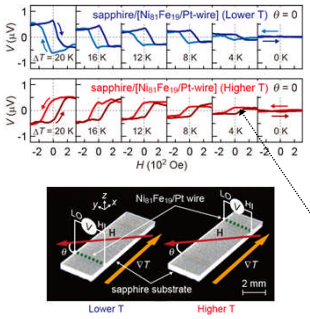


- The V magnitude is proportional to ΔT.
- The V signal disappears when **H** $\perp \nabla T$.
- The sign of V is reversed between the lower/higher temperature regions.

The $Ni_{81}Fe_{19}$/Pt wire picks up its own position on the substrate.

K. Uchida *et al.*, arXiv:1103.6120 (2011).

H dependence of V ($Ni_{81}Fe_{19}$/Pt wire, 300 K)

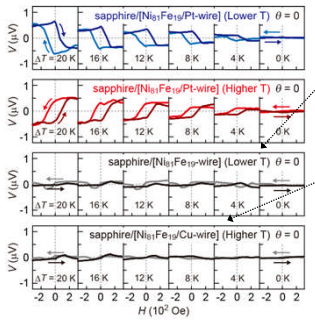


Sign reversal of V by reversing H
+
Hysteresis loops

ISHE voltage induced by the spin-Seebeck effect

These sign reversals of V corresponds to the magnetization reversal of the $Ni_{81}Fe_{19}$ layer.

H dependence of *V* ($Ni_{81}Fe_{19}$/Pt wire, 300 K)



The *V* signal disappears both

in the sapphire/[$Ni_{81}Fe_{19}$-wire] sample in which the Pt layer is missing

and

in the sapphire/[$Ni_{81}Fe_{19}$/Cu-wire] sample in which the Pt layer is replaced by a Cu film.

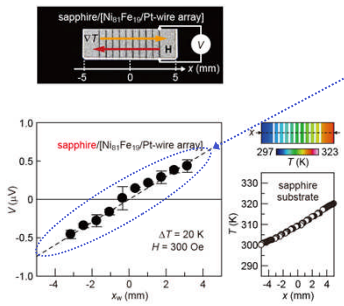
The *V* signal is generated in the Pt layer.

Wire-position x_w dependence of *V* (sapphire substrate)

Ten $Ni_{81}Fe_{19}$/Pt wires were attached to a single sapphire substrate.

The wires are separated from each other far enough to cut electric and magnetostatic coupling between them.

Wire-position x_w dependence of *V* (sapphire substrate)



V varies almost linearly along the ∇T direction

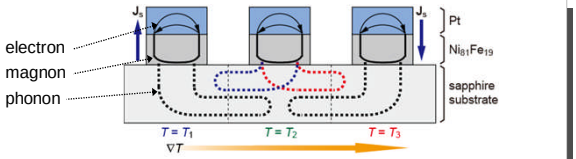
+

$V = 0$ at $x_w = 0$

The SSE appears even in the ***isolated*** $Ni_{81}Fe_{19}$/Pt wire on the insulating substrate.

The $Ni_{81}Fe_{19}$/Pt wires know their positions.

Model calculation by Adachi *et al.*



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

θ_{SH}: spin Hall angle, w: wire width
σ_c: electrical conductivity
R: magnetic coupling strength at the interface
B: entropy-related quantity

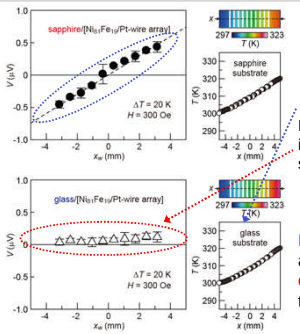
phonon life time in substrate

The SSE signal should depend on the substrate species.

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

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

Wire-position x_w dependence of *V* (glass substrate)



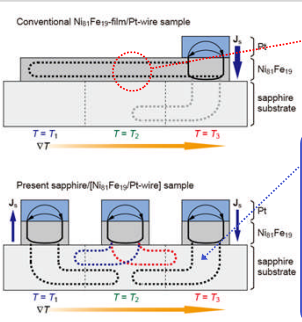
$V = \left(\frac{\theta_{SH}}{\sigma_c}\right)\left(\frac{k_B e}{w\hbar^3}\right)\tau_{ph}\lambda_{eff}^2 RB\Delta T$

In the glass substrate, the uniform ∇T is generated.

Nevertheless, the *V* signal disappears in the glass/[$Ni_{81}Fe_{19}$/Pt-wire array] sample.

Phonon propagation in the substrate and acoustic-impedance-matching condition between the substrate and the $Ni_{81}Fe_{19}$ layer are important.

What causes long-range feature of SSE in metals?



The phonon-mediated process through the $Ni_{81}Fe_{19}$ film can explain the long-range spin voltage in the $Ni_{81}Fe_{19}$.

The path of phonons is limited to the substrate.

The SSE signal in the conventional $Ni_{81}Fe_{19}$/Pt system is one order of magnitude greater than that observed in the present sample.

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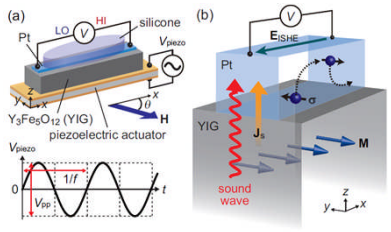
K. Uchida *et al.*, arXiv:1103.6120 (2011).

Sample system



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

Sample size:

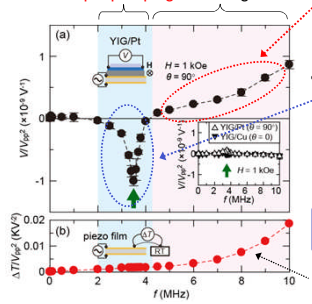
$Y_3Fe_5O_{12}$ slab:
6 mm × 2 mm × 1 mm

Pt film:
6 mm × 0.5 mm × 15 nm

- By applying AC voltage with the frequency f (<10 MHz) to the piezo actuator, longitudinal sound waves are injected into the YIG slab.
- The sound-wave-driven spin current is detected by using the ISHE.

Comparison between f dependences of V and heating effect

Acoustic spin pumping SSE signal

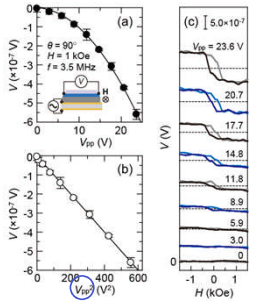


- When f > 5 MHz, the SSE signal appears due to the heating of the piezoelectric actuator.
- Around f = 3.5 MHz, the V dip of negative sign appears, although the heating is negligible small.

The V dip is irrelevant to the conventional SSE.

Temperature rise of the actuator

V_{pp} dependence of V ($Y_3Fe_5O_{12}$, 300 K)



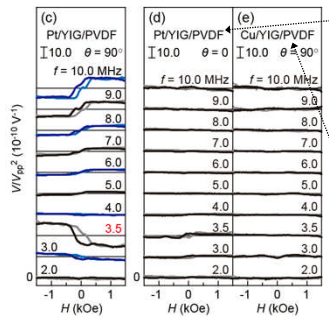
- The magnitude of the V dip is proportional to V_{pp}^2, i.e., sound-wave intensity injected in the YIG.
- The sign of V is reversed by reversing H.

ISHE voltage induced by the acoustic spin pumping

K. Uchida *et al.*, arXiv:1103.6120 (2011).

Electrical power applied to the piezoelectric actuator

H dependence of V for various values of f

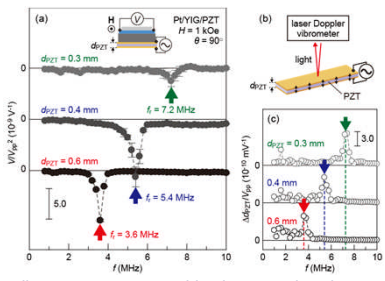


The V signal disappears when $\mathbf{H} \perp \nabla T$.

consistent with the ISHE symmetry:
$\mathbf{E}_{SHE} \propto \mathbf{j}_s \times \boldsymbol{\sigma}$

The V signal disappears when the Pt layer is replaced by Cu.

f dependence of V for various PZT thicknesses



The V-dip structure generated by the acoustic spin pumping is due to the elastic resonance of the piezoelectric actuator.

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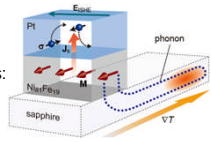
Conclusion

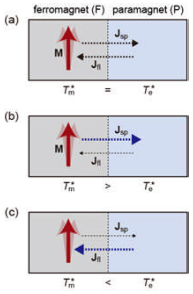
- We observed the spin Seebeck effect (SSE) in ferromagnetic metals and ferrimagnetic insulators by means of the inverse spin-Hall effect in Pt.
- We revealed that the long-range nature of the SSE in ferromagnetic metals is due to *phonons*;

Electrons can recognize temperature information at remote locations through the magnon-phonon coupling.

- By using the Pt/YIG/piezoelectric-actuator systems, we demonstrated the direct generation of spin currents from sound waves: the *acoustic spin pumping*.



Essence of spin Seebeck effect



[1] When an effective magnon temperautre in a ferromagnet deviates from an electron temperature in an attachd paramagnet, spin currents are generated at the interface.

[2] There are various processes to disturb the magnon temperature in equilibrium,

e.g., magnon-mediated process
phonon-mediated process
sound-wave-driven process