Phonon-Drag on Spin Seebeck Effect

Sadamichi Maekawa
Advanced Science Research Center,
Japan Atomic Energy Agency at Tokai
and CREST-JST.
Seebeck effect vs. Spin Seebeck effect:

Electric voltage

$$\delta V = S \delta T$$

(Inverse Spin Hall effect)

$$\delta V_{\text{spin}} = S_{\text{spin}} \delta T$$

Spin accumulation

( Spin voltage)

c.f., G. Bauer’s talk
Seebeck effect:
Entropy flow vs. charge current,

Spin Seebeck effect:
Entropy flow vs. spin current.

→ Inverse spin Hall effect

c.f., S. Maekawa et a.: “Physics of Transition metal oxides” (Springer, 2004)
**Spin wave Spin Current:**

* *Linear response theory*

* Spin Seebeck effect:
  - in (Ga,Mn)As (C.M.Jaworski et al.: Nature Materials (2010)).
* in Fe-Ni/Pt hybrid wires (K. Uchida et al.: Nature Materials (2011)).

**Theory:**

**Experiment:**
E. Saitoh, K. Uchida, Y. Kajiwara, K. Ando (Tohoku University),
J. Heremans and his colleagues (Ohio State University).

**Acknowledgements:**
G. Bauer (Tohoku/Delft), J. Xiao (Fudan), B. Hillebrants
(Kaiserlautern),
R. Ibarra (Zaragoza), S. Rezende (Recife).
Dissipative spin currents:

- **Conduction-electron spin current**

\[
\begin{align*}
  j &= j_\uparrow + j_\downarrow \\
  j_{\text{spin}} &= j_\uparrow - j_\downarrow
\end{align*}
\]

- **Spin-wave spin current**


*Insulating magnets are good spin current conductors!!*
Spin Seebeck effect is a general phenomenon in ferromagnets:

Ferromagnetic metals Py. Fe, Co Ni etc.
Ferromagnetic insulators YIG, Ferrites.
Ferromagnetic semiconductors (Ga,Mn)As: Michigan State U. + UCSB

“Spin waves are common in ferromagnets”

**Propagating spin wave**

\[ j_s = \sum_q n_q v_q = \sum_q n_q v_q + n_{-q} v_{-q} \]
\[ v_q = 2Dq \]

\( n : \text{Magnon number} \)

\( n_q = n_{-q} : \text{Standing wave} \)

\( n_q \neq n_{-q} : \text{Propagating wave (spin-wave spin current)} \)

**Spin current is a non-equilibrium quantity!**
Model for spin injection by thermal magnons

\[ \frac{d}{dt} s = J_{sd} m \times s + (D_N \nabla^2 - \Gamma) (s - s_0 m) + I \]

\[ <l_i(r)> = 0 \]

\[ <l_i(r,t) l_j(r',t')> = 2k_B T(r) \chi_N \Gamma \delta_{ij} \delta(r-r')\delta(t-t') \]

\[ \frac{d}{dt} m = -J_{sd} s \times m + \gamma (H_{eff} + h) \times m + \alpha m \times \frac{d}{dt} m \]

\[ <h_i(r)> = 0 \]

\[ <h_i(r,t) h_j(r',t')> = \frac{2k_B T(r) \alpha}{\gamma M_s} \delta_{ij} \delta(r-r')\delta(t-t') \]

(c.f., J. Xiao and G. Bauer)
Linear response of LOCAL spin injection by heat

Bloch eq.: \[ \partial_t s = J_{sd} m \times s + (D_N \nabla^2 - \Gamma)(s - s_0 m) + l \] (\(s_0 = \chi_N S_0 J_{sd}\))

LLG eq.: \[ \partial_t m = J_{sd} s \times m + \gamma(H_{\text{eff}} + h) \times m + \alpha m \times \partial_t m \]

Injected spin current: \[ J_s^{in} \equiv \langle \partial_t s^z \rangle = J_{sd} \text{Im} \int d\omega < s^+(\omega)m^-(-\omega) > \]

\[ s^+(\omega) = \Gamma s_0 X_F^*(-\omega) \chi_N^*(-\omega) \gamma h^+(\omega) + \chi_N^*(-\omega)l^+(\omega) \]

\[ m^- (\omega) = X_F(\omega) \gamma h^- (\omega) + J_{sd} X_F(\omega) \chi_N (\omega)l^- (\omega) \quad (a^\pm \equiv a^x \pm ia^y) \]

\[ J_s^{in} = J_{sd} \int d\omega \frac{1}{\omega} \text{Im} \chi_N(\omega) \text{Im} X_F(\omega) [\Gamma s_0 < \gamma h^+(\omega) \gamma h^-(-\omega) > - \alpha J_{sd} < l^+(\omega)l^-(-\omega) > ] \]

\[ J_s^{in} = J_s^{pump} - J_s^{back} = A(T_F - T_N) \]

SSE is a competition between pumping flow (noise in F) and back flow (noise in N)
Local spin injection by magnons

\[ J_{s}^{\text{back}} = -A \cdot T_N \]

\[ J_{s}^{\text{pump}} = A \cdot T_F \]

\[ J_{s}^{\text{in}} = A(T_F - T_N) \]

\[ (A \propto J_{sd}^2 \int d\omega \frac{1}{\omega} \text{Im} \chi_N(\omega) \text{Im} X_F(\omega)) \]

\[ J_{s}^{\text{in}} \equiv < \partial_t s^z > = J_{sd} \text{Im} \int d\omega < s^+(\omega)m^-(\omega) > \]

\[ \rightarrow \quad (\text{Field theoretical calculation of Green's function}) \]
No temp-diff. between Pt and YIG in the experiment ➔ need to consider the effect of **temp-gradient** in YIG

Consider the following model

**Static condition:**

Local equilibrium

\[
\begin{align*}
T_{N1} &= T_{F1} = T_1 \\
T_{N2} &= T_{F2} = T_2 \\
T_{N3} &= T_{F3} = T_3
\end{align*}
\]
Interpretation by magnon effective temp.

\[ T_{N1} = T_{F1} = T_1 \quad T_{N2} = T_{F2} = T_2 \quad T_{N3} = T_{F3} = T_3 \]

\[ J_s^{\text{in}} = A(T_F - T_N) \]

Magnon at higher (lower) temp. feels lower (higher) temp. → Spin wave dynamics for spin Seebeck effect.
**T-dependence of \( J_s^{\text{ph-drag}} \):**

\[ J_s^{\text{ph-drag}} \propto \tau_{ph} \Delta T \]

\( J_s^{\text{ph-drag}} \) shows low-temp. enhancement due to the rapid suppression of umklapp scatt.

( \leftarrow \text{Similar phenomenon known in thermoelectrics} )

---

**Phonon: additional ingredient!**
Phonon-drag contribution to SSE

Phonon drag process;
Magnons dragged by nonequilibrium phonons → spin injection

Phonon drag gives low-T enhancement of SSE due to the rapid suppression of umklapp scatt.
Fitting of the data by our theory

\[ J_s^{\text{ph-drag}}(T) = \text{const} \cdot B_1(T)B_2(T)\tau_{ph}(T) \]

\[ \tau_{ph}(T) = \tau_{ph}^{(0)} \left( \frac{1}{1 + (1/a)\exp[-b(T_D/T)]} \right) \left( \frac{1}{1 + (1/c)(T/T_D)} \right) \]

\[ B_1(T) = (T/T_D)^5 \int_0^{T_D/T} \frac{du u^6}{sh^2(u/2)} \]

\[ B_2(T) = (T/T_M)^{9/2} \int_0^{T_M/T} \frac{dv v^{7/2}}{th(v/2)} \]
Spin Seebeck eff. without global spin current

Our interpretation

Phonon drag: Effective at low-T.
GaMnAs: low Curie temp

Observation of the Spin-Seebeck Effect in a Ferromagnetic Semiconductor

C. M. Jaworski¹ J. Yang², S. Maek³, D. D. Awschalom³, J. P. Heremans¹, R. C. Myers²

[Graph and diagrams showing experimental results and interpretations]

electron

magnon

phonon

nonmagnetic substrate

break magnon coherence

T_{N1} = T_{F1} = T_1
T_{N2} = T_{F2} = T_2
T_{N3} = T_{F3} = T_3

Cold Side

Middle

Hot Side

T (K)

S_y^v (μV/K)

V_y (nV)

B (Oe)

x (mm)

Before

Scratch

After
Longitudinal Spin Seebeck Effect:
*(Conventional vs. Longitudinal)*

**Conventional**
*(Transverse)*

- **COLD**
- **Pt**
- **Pt**
- **Pt**
- **YIG**
- **HOT**

- Heat current

**Longitudinal**

- **COLD**
- **Pt**
- **Pt**
- **YIG**
- **HOT**

- spin current injected into Pt

**POSITIVE spin injection @ colder side**

**NEGATIVE spin injection @ colder side**
**Theory of Longitudinal SSE**

**KEY:** Heat current flows through Pt terminal in case of the longitudinal SSE.

Electron-phonon coupling > Phonon-Magnon coupling, Pt is heated by **phonon heat current** greater than YIG.
Summary:

1) Spin-Wave Spin Current,
   “Linear Response Theory of Spin-Wave Spin Current”
   “Magnetic insulator is a good spin current conductor!”

2) Spin Seebeck effect in a variety of systems,
   “Conversion among heat, electric and magnetic energies”

In the same way as Seebeck effect,
Spin Seebeck effect may be applied to a variety of
Energy saving devices!!