Spin Caloritronics

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• Motivation: energy crises
• Thermoelectrics and Onsager reciprocity
• Spin caloritronics
  • spin-dependent Seebeck effect
  • spin Seebeck effect

ICT Energy Consumption

Heat management

Electronics solutions

Heat scavenging/harvesting

Source: Ministry of Economy, Trade, and Industry of Japan
Motivation
Thermoelectrics and Onsager reciprocity
Spin caloritronics
- spin-dependent Seebeck effect
- spin Seebeck effect

Contents

Metals

\[ V_1 \rightarrow J_1 \rightarrow V_2 \quad G = \left( \frac{J}{\Delta V} \right)_{\Delta T = 0} \]

\[ T_1 \rightarrow J_\sigma \rightarrow T_2 \quad \kappa = \left( \frac{J}{\Delta T} \right)_{\Delta T = 0} \]

Wiedemann-Franz Law:
\[ \lim_{T \to 0} \frac{\kappa}{\rho T} = L \frac{e}{k_B} \]
Lorenz number:
\[ L_e = \frac{\pi^2}{3} \left( \frac{k_B}{e} \right)^2 \]

Thermoelectric power

\[ S = \left( \frac{\Delta V}{\Delta T} \right)_{\Delta T = 0} \]

Seebeck coefficient

Thermocouple:
\[ \Delta V = (S_A - S_B) \Delta T \]

Peltier effect

\[ \Pi = \left( \frac{J}{T} \right)_{\Delta T = 0} \]

Peltier coefficient

Thermoelectric heat pump:
\[ \Pi_A - \Pi_B = \Pi_A - \Pi_A - \Pi_B \]

Heat transport in metals

\[ E \]
\[ J_e \]
\[ J_h \]
\[ k_B T(x) \]

Heat and charge transport (electron like)

\[ E \]
\[ J_e > J_h \]
\[ k_B T(x) \]
\[ g(E) f(E,x) \]
Heat and charge transport (hole like)

\[ E_f \quad J_e < J_h \quad k_B T (x) \quad g(E)(E,x) \]

Lars Onsager Memorial at NTNU Trondheim

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

Onsager symmetry (1931)

- \( i = \{ \text{mass, charge, energy, volume, (angular) momentum, ...} \} \)
- \( X_i \) generalized forces
- \( J_i \) generalized currents
- \( J_n = \sum L_{nn} X_n \) linear response

If: \( S = \sum X_i J_i \) entropy creation rate

Then: \( L_{ij} = L_{ji} \) Onsager relations

When time reversal symmetry is broken:

\( \epsilon_i = \begin{cases} 1 & \text{when variable } i \text{ even (charge)} \\ -1 & \text{odd (spin)} \end{cases} \)

Onsager-Kelvin relation

\[
\begin{align*}
\begin{bmatrix} J_x \\ J_o \end{bmatrix} &= \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} \Delta \mu \\ \Delta T \end{bmatrix} \\
L_{12} &= L_{21}
\end{align*}
\]

\[
\begin{bmatrix} -L(T) \\ J_o \end{bmatrix} = \begin{bmatrix} R & S \\ \Pi & \kappa \end{bmatrix} \begin{bmatrix} \Delta V \\ -\Delta T \end{bmatrix}
\]

Onsager-Kelvin relation

- \( R = 1/G \) electrical resistance
- \( \kappa = S/G \) thermal conductance
- \( \Pi = ST \) Peltier coefficient

Landauer-Büttiker formalism (Butcher, 1990)

- \( t_{nm} \) transmission coefficient
- \( g(E) = \sum_{n=1}^{\infty} |t_{nm}|^2 \) total transmission probability
- \( f(E) \) Fermi-Dirac function

\[
G = \frac{2e^2}{h} \int dE \frac{\partial f}{\partial E} g(E) \rightarrow 2e^2 \int \frac{f(E)}{E} g(E) \rightarrow -eL T \frac{2e^2}{h} \frac{\partial f}{\partial E} g(E)
\]

\[
\kappa \frac{T}{\Pi} = S^2 G \frac{2e^2}{h} \left( \frac{k_B T}{k_B} \right)^2 \int dE \frac{\partial f}{\partial E} g(E) \left( \frac{E - E_f}{k_B T} \right)^2 \rightarrow (S^2 + L T) G
\]
Spin caloritronics

Thermodynamic analysis of interfacial transport and of the Thermomagnetoelectric system
Mark Johnson and R. H. Silsbee

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Spin caloritronics/caloric transport

- Spin-dependent (magneto) thermoelectrics
  - Spin-dependent Seebeck and Peltier effects
- Spin Seebeck/Peltier effect
- Thermal spin transfer torques
  - Spin, planar and anomalous Nernst, Ettingshausen, and Righi-LeDuc effects
  - Heat-driven magnetization dynamics
  - Magnonic heat & spin transport
  - Nanoscale magnetic heat engines
  - Spin-dependent heat conductance (spin heat valve)
  - General spin-dependent irreversible thermodynamics

Not: magnetocalorics (adiabatic demagnetization)

Spin dependent conductance

\[
\begin{align*}
\langle j_{x} \rangle &= \frac{1}{e^2} \begin{pmatrix} G \ 0 \\ 0 \ G \end{pmatrix} \begin{pmatrix} \mu_c \\ \mu_s \end{pmatrix} \\
\langle j_{z} \rangle &= \frac{G}{e^2} \begin{pmatrix} P \ 1 \\ 1 \ P \end{pmatrix} \begin{pmatrix} \mu_c \\ \mu_s \end{pmatrix} \\
\langle j_{\uparrow} \rangle &= \sum_{m} \langle j_{\uparrow m} \rangle \\
g^{(1)}(E) &= \sum_{m} \langle j_{\uparrow m} \rangle
\end{align*}
\]

\[
\mu_c = 0
\]

Spin accumulation and spin-current

\[
\tau_{sf} = \sqrt{D \tau_{sf}}
\]

- Spin diffusion length
- D: diffusion constant
- \( \tau_{sf} \): spin-flip relaxation time

Thermal spin-injection

\[
J_{\uparrow} = J_{\uparrow \uparrow} + J_{\downarrow \downarrow}
\]

\[
J_{\uparrow} = J_{\uparrow \uparrow} - J_{\downarrow \downarrow}
\]

\[
J_{0}
\]
Spin dependent thermoelectrics

\[ \mu = T = 0 \]

With \( T_\uparrow = T_\downarrow \):

\[
\begin{pmatrix}
J_x \\
J_y \\
J_z
\end{pmatrix} = -G
\begin{pmatrix}
1 & \rho & S T_0 \\
\rho & 1 & P S T \\
S T_0 & P S T_0 & L T_0^2
\end{pmatrix}
\begin{pmatrix}
-\Delta \mu_\uparrow \\
-\Delta \mu_\downarrow \\
\Delta T / T_0
\end{pmatrix}
\]

\[ p^r = \frac{\partial F}{\partial \mu} \]

Spin-dependent Seebeck effect

\( \Delta T \)

Slachter et al. (2010)

Spin caloritronic cooler

Flipse et al. (2011)

Spin Seebeck effect

Theory: Xiao et al. (2010), Adachi et al. (2010), Jia et al. (2011).

Spin Seebeck effect in Permalloy

Spin Seebeck effect [Uchida et al. (2008)]
Spin Seebeck effect in YIG

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

Spin torque and spin pumping

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

Magnetic Johnson-Nyquist noise

Foros et al., 2005
Xiao et al., 2009

Macro-spin model

For magnetization fluctuations transport spin and heat currents.
- F does not need to conduct electrons.

SSE and issues beyond the simplest model

Magnetic Johnson-Nyquist noise

Mixing conductance

Linear position dependence.

Volume of the magnet

Saunders and Walton (1977)

Magnon-phonon relaxation

Saunders and Walton (1977)
Spatial dependence of sSe

Uchida et al. (2010); Adachi et al. (2010).

Why are these so similar?

Think globally but act locally

Role of the phonons in substrate (Adachi et al., 2010, 2011)

Longitudinal SSE and Slonczewski proposal

John Slonczewski (2010)

Torque generation efficiency: \[ \frac{\text{torque}}{\text{current}} = \frac{eV}{F} \]
Conclusions

• Spin, charge, and heat transport are coupled in magnetic nanostructures -> spin caloritronics.
• In magnetic metals the spin-dependence of the conductance causes spin-dependent thermoelectric effects.
• The collective dynamics in magnetic insulators cause completely new phenomena such as the spin Seebeck effect.
• Spin caloritronics provides new strategies for waste heat scavenging and heat management in nanostructures.