Spin caloritronics: Spin caloritronics: spin-dependent thermoelectrics and beyond

Gerrit E.W. Bauer

Institute for Materials Research, Sendai & Kavli Institute of NanoScience Delft

Spin caloritronics
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Thermodynamic analysis of interfacial transport and of the Thermodynamic analysis of interfacial transport and of the
Thermoelectric system
Thermoelectric system


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Spin caloritronics

Why?
Why?

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

Not: magnetocalorics (adiabatic demagnetization)

Contents

- Why?
- Heat
- Spin
- Spin and Heat

Applied (metal) spintronics

Physics of spin caloritronics

- Spin-dependent (magneto) thermoelectrics
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Not: magnetocalorics (adiabatic demagnetization)
Applied thermoelectrics

Peltier spot cooling of integrated circuits

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Energy waste in Gcal/year

Toshiba Review 63, 7 (2008)

Creative use of waste heat

Thermoelectric conversion of waste heat

Thermoelectric conversion of waste heat

heat scavenging/harvesting

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Contents

• Why?
• Heat
• Spin
• Spin and Heat

Metals

\[ V_1 \rightarrow J_1 \rightarrow V_2 \]

\[ G = \left( \frac{J}{\Delta V} \right)_{T, \sigma} \]

\[ T_1 \rightarrow J_0 \rightarrow T_2 \]

\[ K_e = -\left( \frac{J_0}{\Delta T} \right)_{J, \sigma} \]

Wiedemann-Franz Law:

\[ \lim_{T \to 0} \frac{K}{T} = L T \]

Lorenz number:

\[ L_e = \frac{\pi^2}{3} \left( \frac{k_B}{e} \right)^2 \]
Thermoelectric power

$T_2 - T_1 \Delta V = (S_a - S_b) \Delta T$

Thermocouple:

Peltier effect

$T \rightarrow T_f \Pi \rightarrow \frac{J_o (J_f)}{J_{fT}}$

Thermoelectric heat pump:

$L_{ij} = L_{ji}$

Contents

• Why?
• Heat
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Electron spin

|up⟩  | down⟩

Spin-accumulation and spin-current

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

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

Current-induced spin-transfer torque

\[ \mathbf{f} = i_z^s = g^{\uparrow \downarrow} (\mu_0^\uparrow - \mu_0^\downarrow) / 2 \]

- \( g^{\uparrow \downarrow} \): Spin-mixing conductance
- \( \mu_0^\uparrow \) and \( \mu_0^\downarrow \): Spin accumulation

Berger (1996), Slonczewski (1996)

Spin transfer torque

Spin torque and spin pumping

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

Magnetization motion causes spin currents (spin pumping, Tserkovnyak, 2002).
Thermal spin-injection by metals

\[
\begin{bmatrix}
    J_x \\
    J_y \\
    J_z
\end{bmatrix} =
G
\begin{bmatrix}
    1 & P & ST \\
    P & 1 & PST \\
    ST & PST & LT^2
\end{bmatrix}
\begin{bmatrix}
    \Delta V \\
    -\Delta \mu_x \\
    -\Delta T / T
\end{bmatrix}
\]

\[
P' = \frac{\partial P_G}{\partial T} I_r
\]

Spin-dependent Seebeck effect

\[
J_x = \sum \frac{\partial P}{\partial T} I_r
\]

\[
J_y = \sum \frac{\partial P}{\partial T} I_r
\]

\[
J_z = \sum \frac{\partial P}{\partial T} I_r
\]

Spin-dependent Peltier effect

\[
\Delta T = \sum \frac{\partial P}{\partial T} I_r
\]

Mark Johnson and R. H. Silsbee (1987)

Single particle spin caloritronics (expt.)

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<th>Experiment</th>
<th>Reference</th>
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<tr>
<td>Spin-dependent Seebeck effect</td>
<td>Slachter et al.</td>
<td>2010</td>
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<tr>
<td>Magneto-Seebeck tunneling</td>
<td>Walter et al.</td>
<td></td>
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<tr>
<td>Tunneling anisotropic magnetothermopower in GaMnAs/GaAs</td>
<td>Naydenova et al.</td>
<td>2011</td>
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<tr>
<td>Thermal spin injection into Silicon</td>
<td>Le Breton et al.</td>
<td>2011</td>
</tr>
<tr>
<td>Spin-dependent Peltier effect</td>
<td>Flipse et al.</td>
<td>2012</td>
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Onsager reciprocity holds between spin-dependent Seebeck and Peltier effects.
Collective effects in insulators

- Magnetic (electric) insulator

- NM

- Magnetic and Johnson-Nyquist noise

- Foros et al. (2005)
- Xiao et al. (2009)

- Origin of spin Seebeck effect

- Independent particle vs. collective spin current

- Independent spins
- Collective excitations

- V_{SHE} = A J_s
- J_s = J_s^{pump} - J_s^{J-N noise}
- = A' g^{1/2} (T_F^M - T_N^c)

- (Longitudinal) spin Seebeck effect

- Uchida et al. (2010/2011)

- Collective spin caloritronics (expt.)
Potential applications of spin caloritronics

- Heat management and enhanced logics by magnetic tunnel junction
- Spin Seebeck planar thermoelectric generator
- Spin Seebeck position sensitive heat detector
- Highly efficient thermal magnetization reversal
- Spin caloritronic nanomachines

Magnetic tunnel junctions

\[ TMR = \frac{R_{m} - R_{p}}{R_{p}} \leq 1000\% \]

Thermopower of magnetic tunnel junctions

- Large thermopower (> 1 mV/K)
- Switchable thermopower (TMS > 200 %)
- Low heat conductance, large ZT
- Thermal switching?

Thermopile

Planar spin Seebeck generator

\[ \Delta V = \text{const}. J \rho L \approx 1 \text{V} \]

Position sensitive heat detector

Image reconstruction

Uchida et al. (2011)
**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.