Spin caloritronics: spin-dependent thermoelectrics and beyond

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ACTIVITIES/OUTREACH

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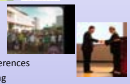


Awards
- Student Travel Grants to attend conferences
- Best Student Presentation at Intermag
- Achievement Award

Distinguished Lecturers 2012
- Shinji Yuasa, "Magnetoresistance and spin torque in magnetic tunnel junctions"
- George C. Hadjipanayis, "Science and Technology of Modern Permanent Magnet Materials"
- Gerrit Bauer, "Spin Caloritronics"
- Masahiro Yamaguchi, "Soft Magnetic Thin Film Applications at Radio Frequencies"

Spin caloritronics

Thermodynamic analysis of interfacial transport and of the thermomagnetoelectric system
M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987)

name	alternative name	subject
electronics		control of charge transport
spintronics	spin electronics	control of spin & charge transport
calorimetry		measuring heat
caloritronics	heattronics, thermotronics	controlling heat transport
spin caloritronics	spin caloric transport	control of spin, charge & heat transport

Spin caloritronics: G.E.W. Bauer, E. Saitoh & B.J. van Wees, In: Nature Materials Insights "Spintronics", Nature Materials **11**, 391 (2012).

Contents

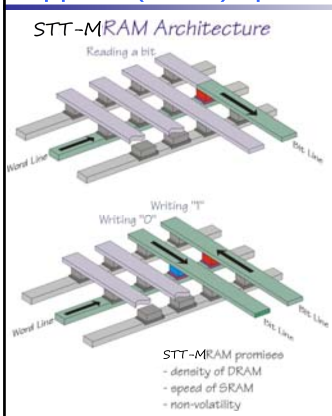
- **Why?**
- **Heat**
- **Spin**
- **Spin and Heat**

Physics of spin caloritronics

- Spin-dependent (magneto) thermoelectrics
  - o Spin-dependent Seebeck and Peltier effects
  - o 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)

Applied (metal) spintronics

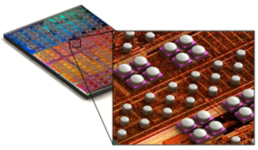


hynix
TOSHIBA

SAMSUNG
GRANDIS

Applied thermoelectrics

Peltier spot cooling of integrated circuits



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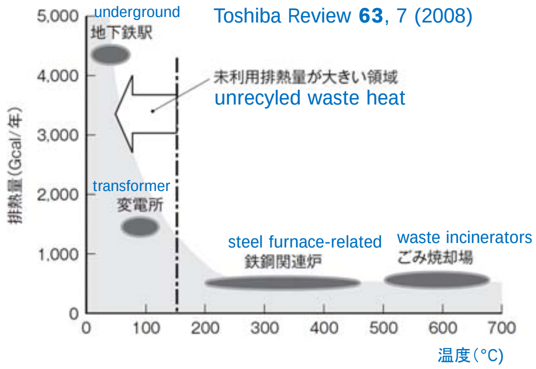
Energy waste in Gcal/year

Toshiba Review **63**, 7 (2008)



Creative use of waste heat

Thermoelectric conversion of waste heat

~~m~~heat scavenging/harvesting

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Contents

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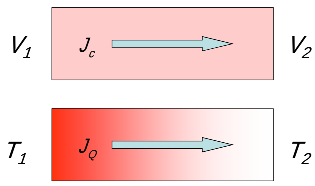
Thomas Johann Seebeck (1770-1831)

Metals



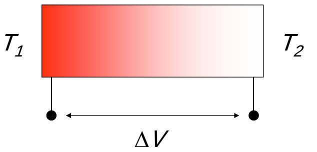
$$G = \left(\frac{J_c}{\Delta V}\right)_{\Delta T=0}$$

$$K_e = -\left(\frac{J_Q}{\Delta T}\right)_{J_c=0}$$

Wiedemann-Franz Law: $\lim_{T\to 0} \frac{K_e}{G} = L_0 T$

Lorenz number: $L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$

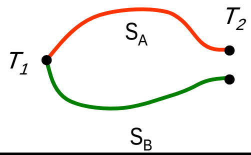
Thermoelectric power



$$S = \left(\frac{\Delta V}{\Delta T}\right)_{J_c=0}$$

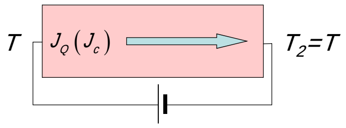
Seebeck coefficient

Thermocouple:



$$\Delta V = (S_B - S_A)\Delta T$$

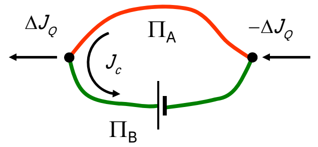
Peltier effect



$$\Pi = \left(\frac{J_Q}{J_c}\right)_{\Delta T=0}$$

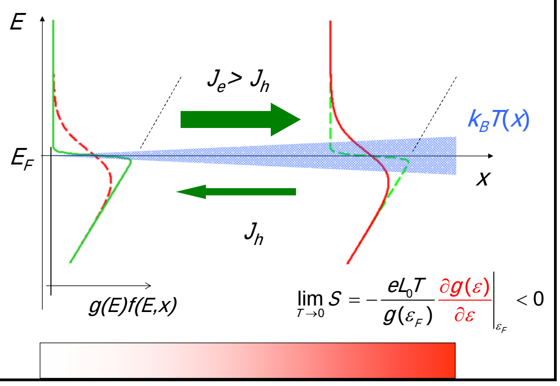
Peltier coefficient

Thermoelectric heat pump:



$$\Delta J_Q = (\Pi_A - \Pi_B) J_c$$

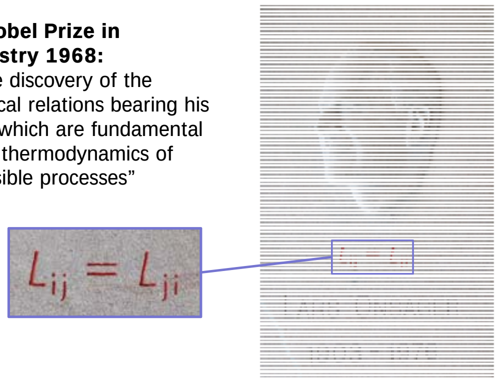
Heat and charge transport (electron like)



$$\lim_{T\to 0} S = -\frac{eL_0 T}{g(\varepsilon_F)} \left.\frac{\partial g(\varepsilon)}{\partial \varepsilon}\right|_{\varepsilon_F} < 0$$

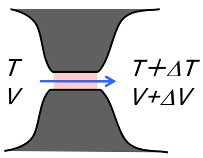
Lars Onsager Memorial at NTNU Trondheim

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"



Thermoelectrics

$$\begin{pmatrix} J_c \\ J_Q \end{pmatrix} = \begin{pmatrix} L_{11} & L_{21} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} \Delta V \\ -\frac{\Delta T}{T} \end{pmatrix}$$



$L_{12} = L_{21}$ Onsager reciprocity

$$\begin{pmatrix} \Delta V \\ J_Q \end{pmatrix} = \begin{pmatrix} R & S \\ \Pi & K \end{pmatrix} \begin{pmatrix} J_c \\ -\Delta T \end{pmatrix}$$

$R = 1/G$ electrical resistance
K thermal conductance
S Seebeck coefficient
$\Pi = ST$ Peltier coefficient

Onsager-Thomson (Kelvin) relation

$$ZT = \frac{S^2 T}{RK} < \infty$$ thermoelectric figure of merit

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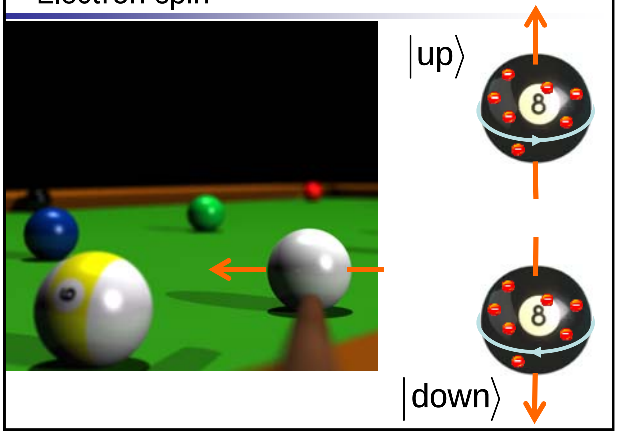
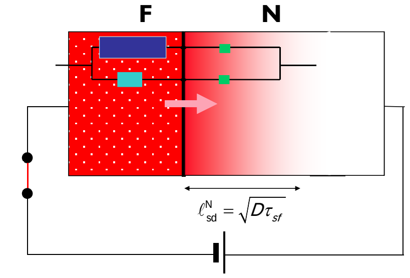
Electron spin

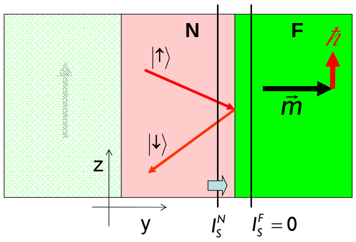


Spin-accumulation and spin-current



ℓ_{sd}^{N} Spin-flip diffusion length
D diffusion constant
τ_{sf} spin-flip relaxation time

Current-induced spin-transfer torque



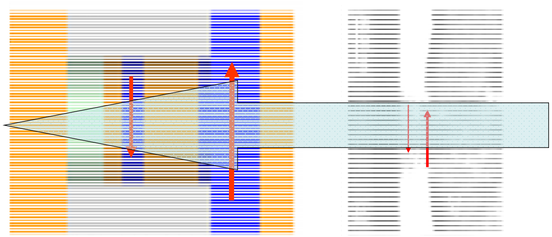
$\vec{T} = \vec{I}_S^N = g^{\uparrow\downarrow}\left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right)/2$

$g^{\uparrow\downarrow}$ spin-mixing conductance

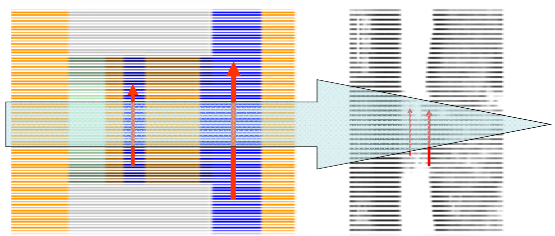
$\mu_N^{\uparrow} - \mu_N^{\downarrow}$ spin accumulation

Berger (1996)
Slonczewski (1996)

Spin transfer torque

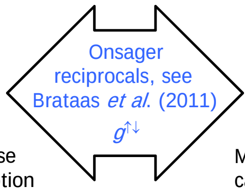


Spin transfer torque



Spin torque and spin pumping

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



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

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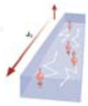
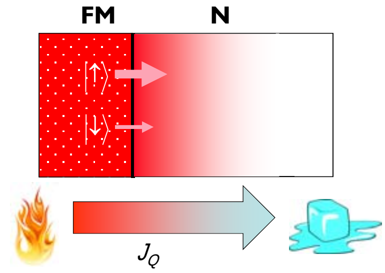
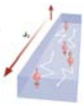
Thermal spin-injection by metals





Thermal spin-injection by metals



$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = G \begin{pmatrix} 1 & P & ST \\ P & 1 & P'ST \\ ST & P'ST & L_0T^2 \end{pmatrix}\begin{pmatrix} \Delta V \\ -\Delta\mu_s \\ -\Delta T/T \end{pmatrix} \qquad P' = \left.\frac{\partial_E PG}{\partial_E G}\right|_{E_F}$$

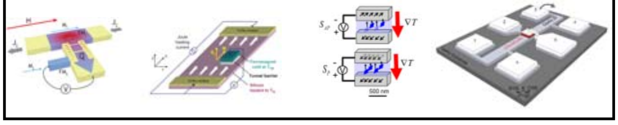
spin-dependent Peltier effect

spin-dependent Seebeck effect

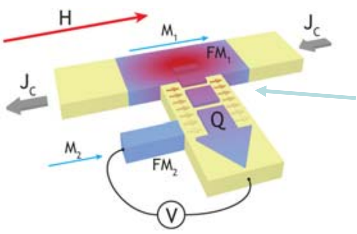
Mark Johnson and R. H. Silsbee (1987)

Single particle spin caloritronics (expt.)

Experiment	Reference	Year
Spin-dependent Seebeck effect	Slachter *et al.*	2010
Magneto-Seebeck tunneling	Walter *et al.* Liebing *et al.* Lin *et al.*	2011
Tunneling anisotropic magneto-thermopower in GaMnAs/GaAs	Naydenova *et al.*	2011
Thermal spin injection into Silicon	Le Breton *et al.*	2011
Spin-dependent Peltier effect	Flipse *et al.*	2012

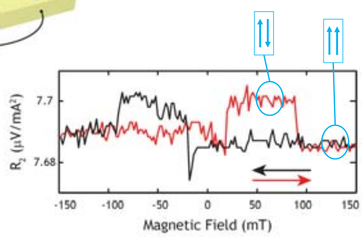


Spin-dependent Seebeck effect



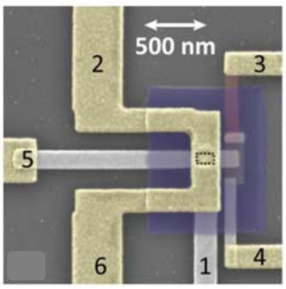
≠ spin Seebeck effect!

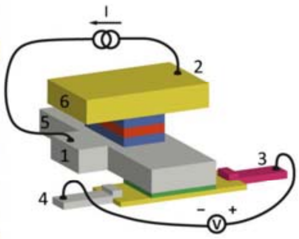
ΔT



Slachter *et al.* (2010)

Spin-dependent Peltier effect

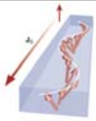


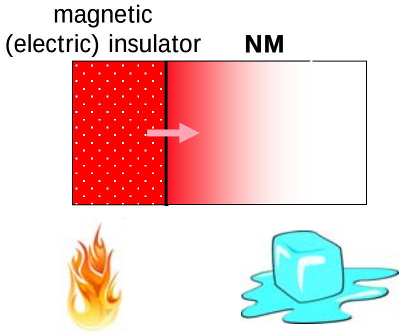


Flipse *et al.* (2012)

Onsager reciprocity holds between spin-dependent Seebeck and Peltier effects.

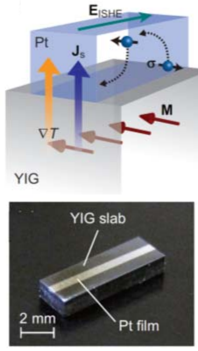
Collective effects in insulators

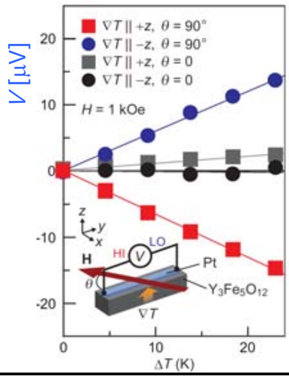




(Longitudinal) spin Seebeck effect

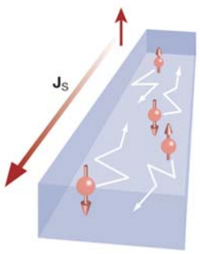
≠ spin-dependent Seebeck effect!



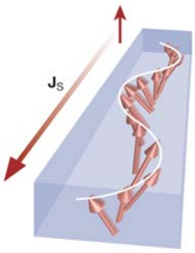


Uchida *et al.* (2010/2011)

Independent particle vs. collective spin current



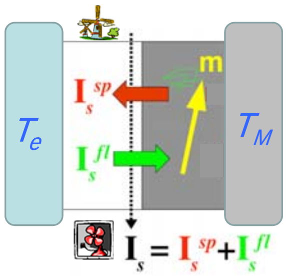
Independent spins



Collective excitations

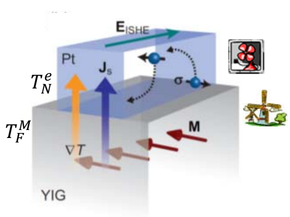
© Kajiwara *et al.* (2010)

Magnetic and Johnson-Nyquist noise



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

Origin of spin Seebeck effect



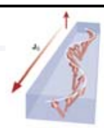
$$V_{ISHE} = AJ_s$$

$$J_s = J_s^{\text{pump}} - J_s^{\text{J-N noise}}$$

$$= A' g^{\uparrow\downarrow} \left(T_F^M - T_N^e \right)$$

Xiao *et al.* (2010)
Adachi *et al.* (2010)

Collective spin caloritronics (expt.)



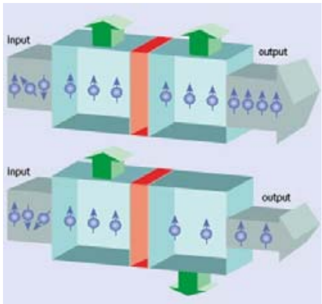
Experiment	Reference	Year
Spin Seebeck effect	Uchida *et al.* Jaworski *et al.*	2008,2010 2010
Magnon-drag thermopower	Costache et al.	2011
Thermal spin torque in spin valves	Yu *et al.*	2010
Magnon cooling	Saitoh *c.s.*	Unpublished.
Heat current-induced domain wall motion	Parkin *c.s.*	Unpublished.

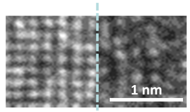
Potential applications of spin caloritronics

- 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

Fe (↑) | MgO | Fe (↑/↓)

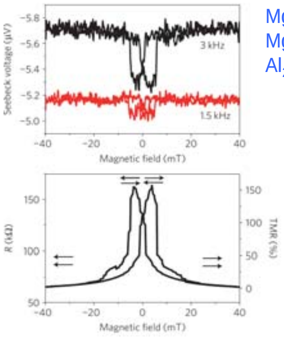




MgO CoFeB

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P} \leq 1000\%$$

Thermopower of magnetic tunnel junctions

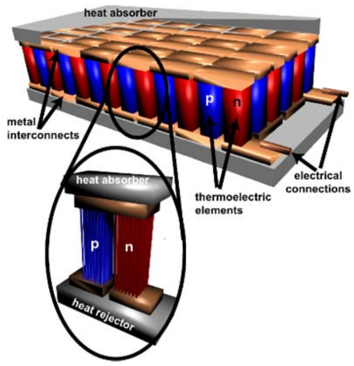


Walter *et al.* (2011)

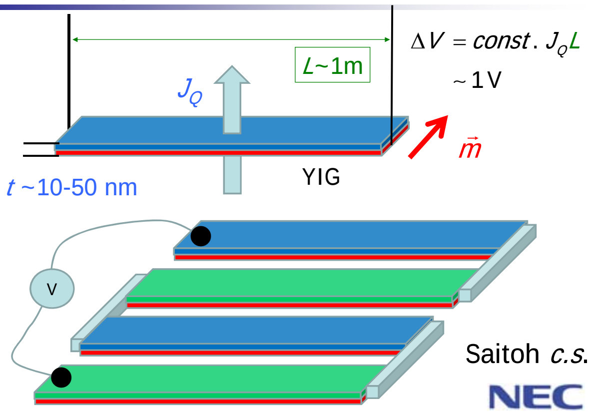
MgO (optical): Walter *et al.* (2011)
MgO (electrical): Liebing *et al.* (2011)
Al_2O_3 (optical): Lin *et al.* (2011)

- large thermopower (> 1 mV/K)
- switchable thermopower (TMS > 200 %)
- low heat conductance, large ZT?
- thermal switching?

Thermopile



Planar spin Seebeck generator



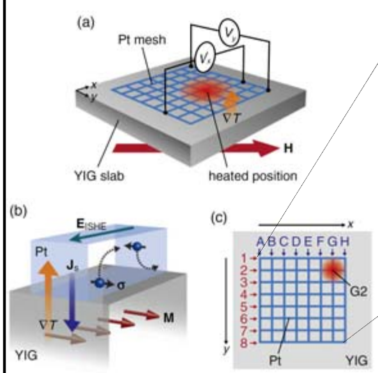
$\Delta V = const.\ J_Q L$

$\sim 1\,\mathrm{V}$

Saitoh *c.s.*

NEC

Position sensitive heat detector



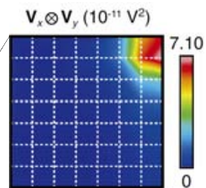
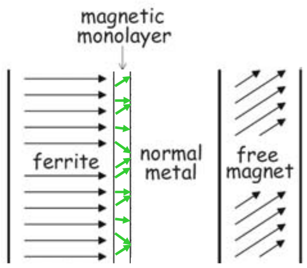


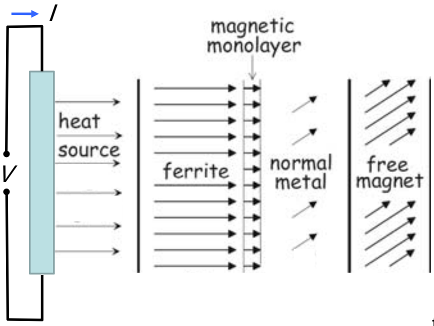
Image reconstruction

Uchida *et al.* (2011)

John Slonczewski (2010)

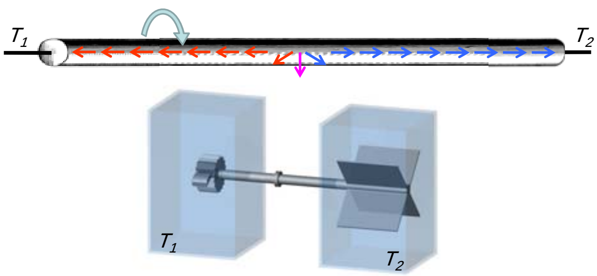


John Slonczewski (2010)



Torque generation efficiency: $\frac{\text{torque}/\hbar}{\text{current}/e} = \frac{eV}{F}$

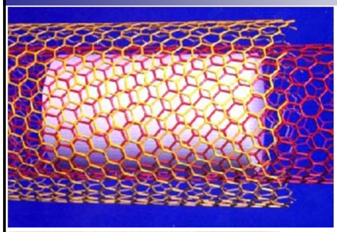
Magnetic nanoscale heat engines



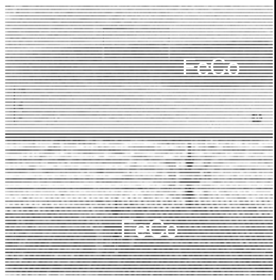
Brownian motor: Continuum version of Feynman's ratchet & pawl

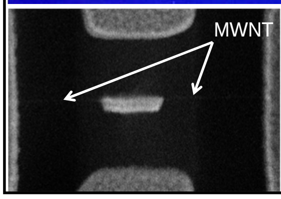
Heat pump: Kovalev *et al.* (2010,2011)
Motor: Bauer *et al.* (2010)

Magnetic wire in MW carbon nanotubes



Elias *et al.* (2005)





Fennimore *et al.* (2003)

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.