
## Spin Caloritronics

*Gerrit E.W. Bauer*

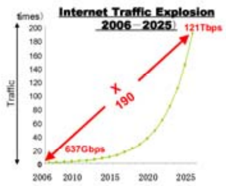
*Institute for Materials Research, Sendai &*
*Kavli Institute of NanoScience Delft*

Arne Brataas, Yaroslav Tserkovnyak, Moosa Hatami, Jiang Xiao, Sadamichi Maekawa, Saburo Takahashi, Eiji Saitoh, Ken-ichi Uchida, Ke Xia, Xingtao Jia

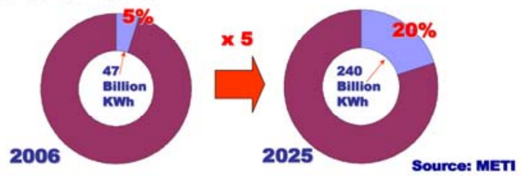
## Contents

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

## ICT Energy Consumption

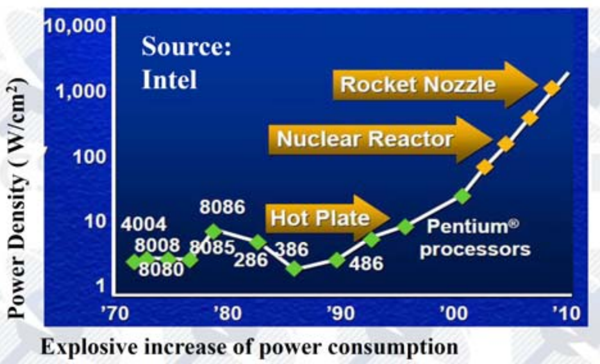



| | Network | Data Center | PC | Display |
|---|---|---|---|---|
| 2006 | 8B kWh | 21.4BkWh | 1.6BkWh | 15.6BkWh |
| | 17 % | 46 % | 3.6 % | 33.4 % |
| 2025 | 103BkWh | 52.7BkWh | 4.1BkWh | 81.6BkWh |
| | 43 % | 22 % | 1.7 % | 34 % |
| Ratio | X 13 | X 2.5 | X 2.5 | X 5.2 |



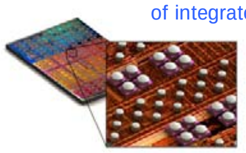

Source: Ministry of Economy, Trade, and Industry of Japan

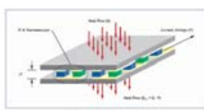
## Heat management




## Electronics solutions

Peltier spot cooling
of integrated circuits





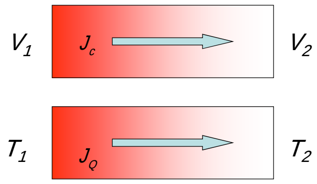
~~m~~heat scavenging/harvesting

## Contents

Thomas Johann Seebeck (1770-1831)

- Motivation
- Thermoelectrics and Onsager reciprocity
- Spin caloritronics
  - spin-dependent Seebeck effect
  - spin Seebeck effect

## Metals



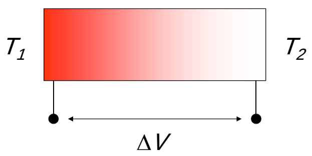

$$G = \left(\frac{J_c}{\Delta V}\right)_{\Delta T=0}$$

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

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

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

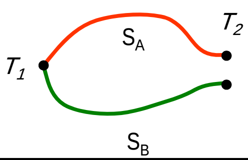
## Thermoelectric power




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

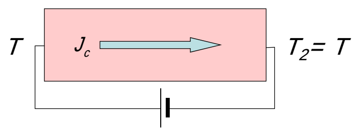
Seebeck coefficient

Thermocouple:




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

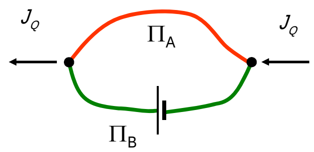
## Peltier effect




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

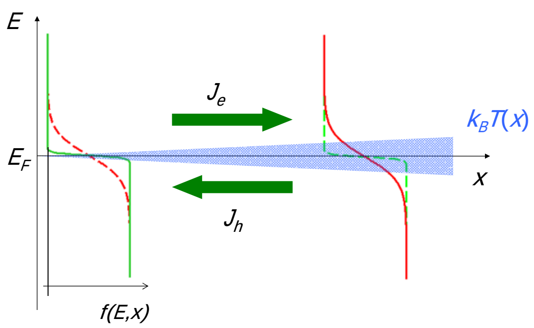
Peltier coefficient

Thermoelectric heat pump:

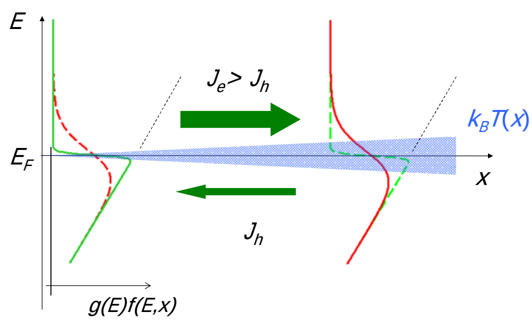



$$\Pi_{AB} = \Pi_A - \Pi_B$$

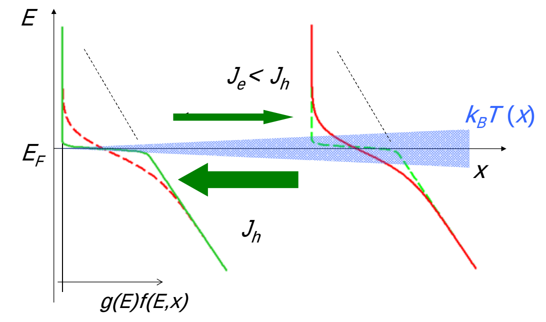
## Heat transport in metals




## Heat and charge transport (electron like)

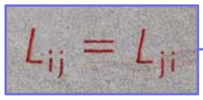


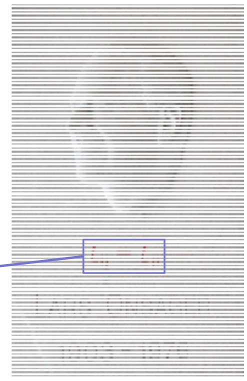
## Heat and charge transport (hole like)




## 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)

$i$ = {mass, charge, energy, volume, (angular) momentum, ...}

$X_i$ generalized forces

$J_i$ generalized currents

$J_m = \sum_n L_{mn} X_n$ linear response

If: $\dot{S} = \sum_i X_i J_i$ entropy creation rate

Then: $L_{ij} = L_{ji}$ **Onsager relations**

When time reversal symmetry is broken: $L_{ij}(\mathbf{m}, \mathbf{H}_{ext}) = \varepsilon_i \varepsilon_j L_{ji}(-\mathbf{m}, -\mathbf{H}_{ext})$

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

## 1st Law of Thermodynamics

$$dU_n = dQ_n + dW_n = T_n dS_n + \mu_n dN_n$$

$$dS_n = \frac{dU_n}{T_n} - \frac{\mu_n}{T_n} dN_n$$

$$dU_1 = -dU_2 \equiv dU; \quad dN_1 = -dN_2 \equiv dN$$

$$J_U = -\frac{dU}{dt}; \quad J_N = -\frac{dN}{dt}$$

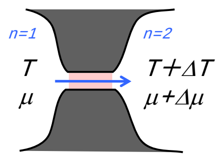
$$dS = dS_1 + dS_2;\ T_1 = T;\ T_2 = T + \Delta T;\ \mu_2 = \mu + \Delta\mu$$

$$\frac{dS}{dt} = \left(\frac{1}{T+\Delta T} - \frac{1}{T}\right) J_U + \left(\frac{\mu}{T} - \frac{\mu + \Delta\mu}{T + \Delta T}\right) J_N$$

$$T\frac{dS}{dt} \approx (J_U - \mu J_N)\left(-\frac{\Delta T}{T}\right) - J_N \Delta\mu$$

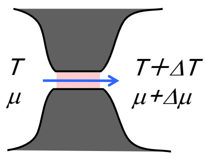
$$= J_Q\left(-\frac{\Delta T}{T}\right) + J_N(-\Delta\mu) = \sum_i J_i X_i \geq 0$$

conjugate currents and forces identified!




## Onsager-Kelvin relation

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




$$L_{12} = L_{21}$$

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

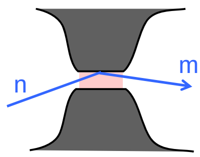
$R = 1/G$ electrical resistance
$\kappa$ thermal conductance
$S$ Seebeck coefficient
$\Pi = ST$ Peltier coefficient

## Landauer-Büttiker formalism (Butcher, 1990)

$t_{nm}$ transmission coefficient

$g(E) = \sum_{nm}^{\varepsilon_n, \varepsilon_m = E} |t_{nm}|^2$ total transmission probability

$f(E)$ Fermi-Dirac function

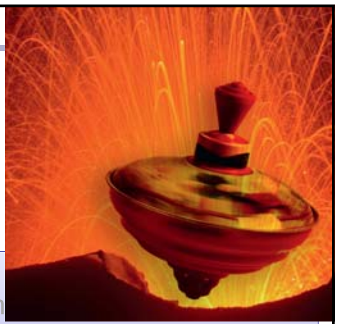



$$G = -\frac{2e^2}{h}\int dE \left(\frac{\partial f}{\partial E}\right) g(E) \to \frac{2e^2}{h} g(E_F)$$

$$GS = \frac{2e^2}{h}\frac{k_B}{e}\int dE \left(\frac{\partial f}{\partial E}\right) g(E) \frac{E - E_F}{k_B T} \to -eL_0 T \frac{2e^2}{h} \left.\frac{\partial g(E)}{\partial E}\right|_{E_F}$$

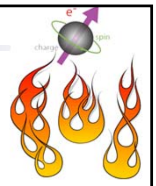
$$\frac{\kappa}{T} = S^2 G + \frac{2e^2}{h}\left(\frac{k_B}{e}\right)^2 \int dE \left(\frac{\partial f}{\partial E}\right) g(E) \left(\frac{E - E_F}{k_B T}\right)^2 \to \left(S^2 + L_0 T\right) G$$

## Contents



- Motivation
- Thermoelectrics an
- Spin caloritronics
  - spin-dependent Seebeck effect (single particle)
  - spin Seebeck effect (collective)

## Spin caloritronics





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

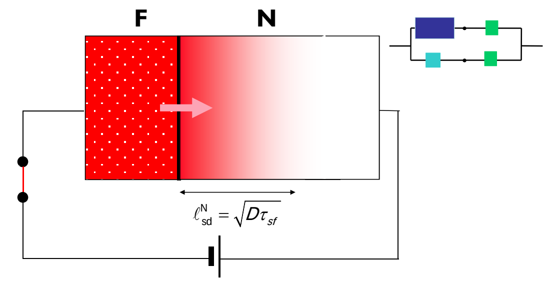

| name | alternative name | subject |
|---|---|---|
| electronics | | control of charge transport |
| spintronics | spin electronics | control of spin & charge transport |
| *calori*metry | | measuring heat |
| caloritronics | heattronics, thermotronics | controlling heat transport |
| spin caloritronics | spin caloric transport | control of spin, charge & heat transport |

## Spin caloritronics/caloric transport

- **Spin-dependent (magneto) thermoelectrics**
  - o 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-accumulation and spin-current

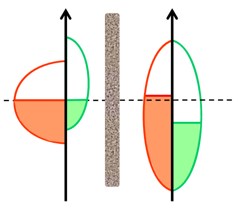


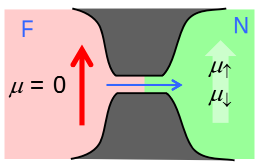

$\ell_{sd}^{N}$ spin diffusion length

$D$ diffusion constant

$\tau_{sf}$ spin-flip relaxation time

## Spin dependent conductance






$$\begin{pmatrix} J_\uparrow \\ J_\downarrow \end{pmatrix} = -\frac{1}{e^2}\begin{pmatrix} G_\uparrow & 0 \\ 0 & G_\downarrow \end{pmatrix}\begin{pmatrix} \mu_\uparrow \\ \mu_\downarrow \end{pmatrix}$$

$$\begin{pmatrix} J_c \\ J_s \end{pmatrix} = -\frac{G}{e^2}\begin{pmatrix} 1 & P \\ P & 1 \end{pmatrix}\begin{pmatrix} \mu_c \\ \mu_s \end{pmatrix}$$

$$g^{\uparrow(\downarrow)}(E) = \sum_{nm}^{\varepsilon_n,\varepsilon_m=E} \left|t_{nm}^{\uparrow(\downarrow)}\right|^2$$

$\mu_c = \frac{\mu_\uparrow + \mu_\downarrow}{2}$ (charge) chemical potential

$\mu_s = \mu_\uparrow - \mu_\downarrow$ spin accumulation

$G_c = G_\uparrow + G_\downarrow$ (charge) conductance

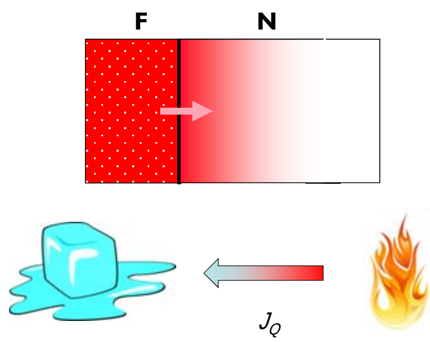
(conductance)

$P = \frac{G_\uparrow + G_\downarrow}{G_\uparrow - G_\downarrow}$ spin polarization

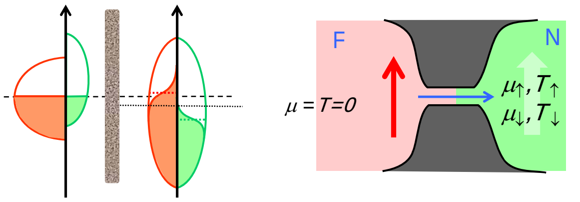
$J_c = J_\uparrow + J_\downarrow$ charge current

$J_s = J_\uparrow - J_\downarrow$ spin current

## Thermal spin-injection



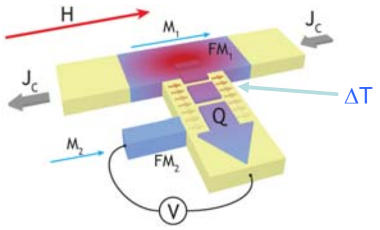
## Spin dependent thermoelectrics



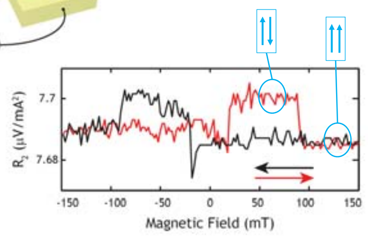

With $T_\uparrow = T_\downarrow$:

$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = -G \begin{pmatrix} 1 & P & ST_0 \\ P & 1 & P'ST \\ ST_0 & P'ST_0 & L_0T_0^2 \end{pmatrix} \begin{pmatrix} -\Delta\mu_c \\ -\Delta\mu_s \\ \Delta T / T_0 \end{pmatrix} \qquad P' = \left.\frac{\partial_E PG}{\partial_E G}\right|_{E_F}$$

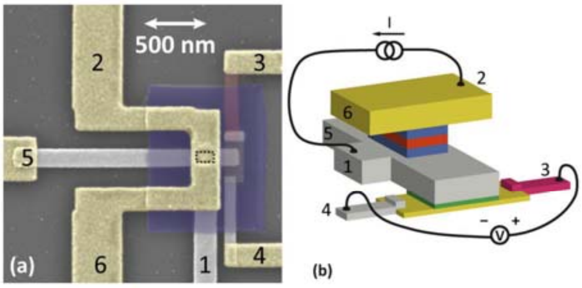
## Spin-dependent Seebeck effect




Slachter *et al.* (2010)




## Spin caloritronic cooler

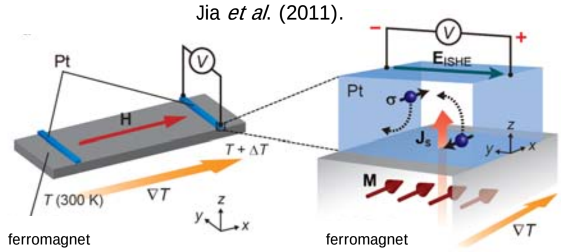



Flipse *et al.* (2011)

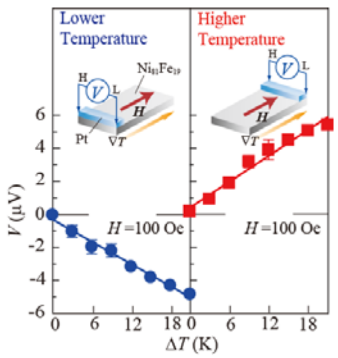
## Spin Seebeck effect

Experiments: Uchida *et al.* (2008/**2010**/2011), Jaworski *et al.* (2010/2011)

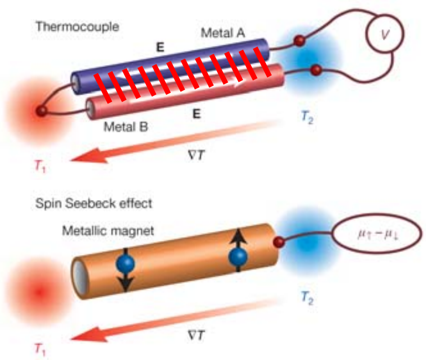
Theory: **Xiao *et al.* (2010)**, Adachi *et al.* (2010), Jia *et al.* (2011).



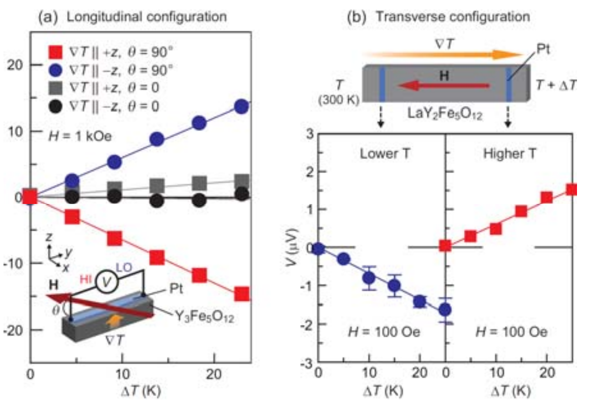

## Spin Seebeck effect in Permalloy



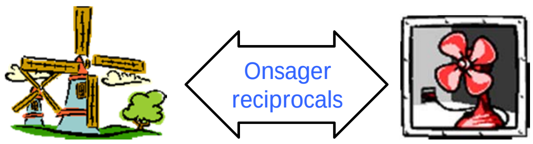

## Spin Seebeck effect [Uchida *et al.* (2008)]



## Spin Seebeck effect in YIG



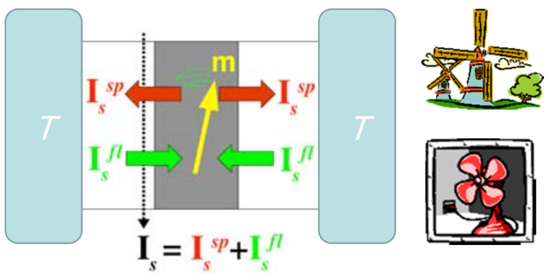

## Spin torque and spin pumping




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

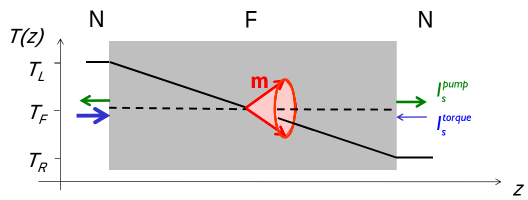
Magnetization motion causes spin currents (spin pumping, Tserkovnyak, 2002).

## Magnetic Johnson-Nyquist noise



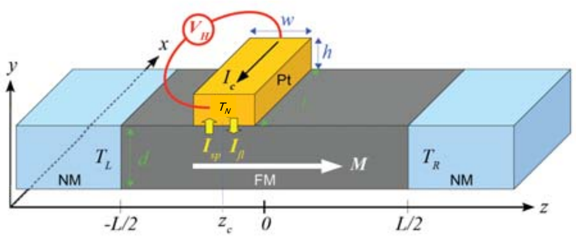

Foros *et al.*, 2005
Xiao *et al.*, 2009

## Macro-spin model




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

## SSE and issues beyond the simplest model



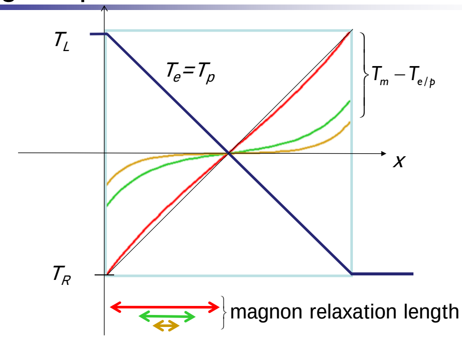

Mixing conductance

Linear position dependence.

$$\langle I_s\rangle(z) = \frac{\gamma\hbar k_B g_r^{\uparrow\downarrow}}{2\pi M_s V_F}\left(T_F - T_N(z)\right)$$

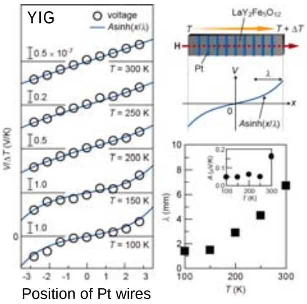
Volume of the magnet

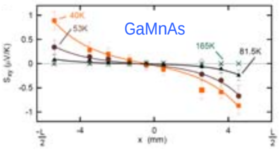
## Magnon-phonon relaxation




Saunders and Walton (1977) $V_H = \xi \frac{\sinh\frac{z_c}{\lambda}}{\sinh\frac{L}{2\lambda}}\Delta T$

## Spatial dependence of sSe

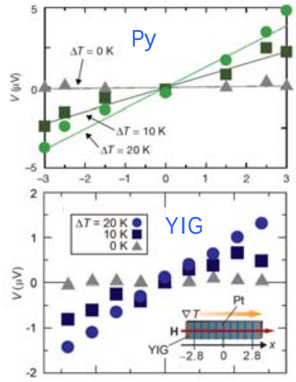


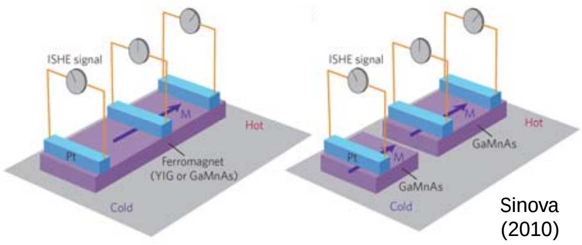

Jaworski *et al.* (2010)

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

## Why are these so similar?



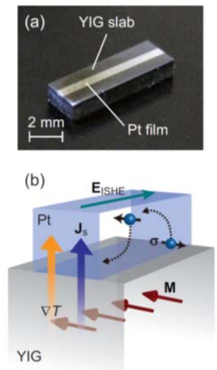

## Think globally but act locally

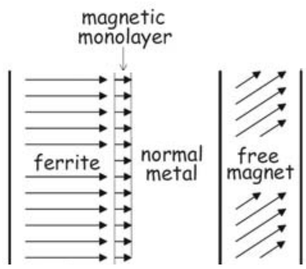



Sinova (2010)

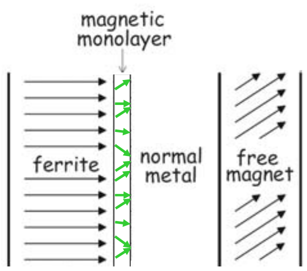
Role of the phonons in substrate (Adachi *et al.*, 2010,2011)

## Longitudinal SSE and Slonczewski proposal

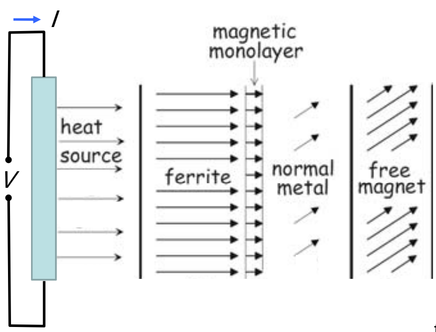



## John Slonczewski (2010)

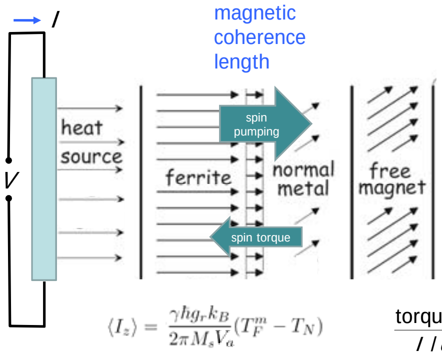



## John Slonczewski (2010)




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

## J. Xiao *et al.* (2010)




$$\langle I_z \rangle = \frac{\gamma \hbar g_r k_B}{2\pi M_s V_a}(T_F^m - T_N)$$

$$\frac{\text{torque}/\hbar}{I/e} = \frac{eV}{\hbar\omega}$$

## 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.