Spin Currents and Spin Caloritronics

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Barcelona, Spain

Cargèse
March 6th 2013

Image credit: NPG

Spin currents and spin caloritronics

Outline

Spin caloritronics: *Thermoelectricity meets spintronics*

– Nonequilibrium phenomena involving charge, energy and spin transport. Usually in magnetic structures

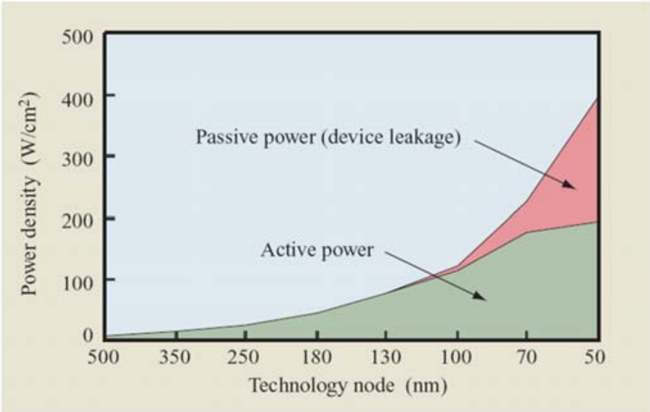
Area of research	Topic
Electronics	Transport/manipulation of charge
Spin elec***tronics*** or Spintronics	Transport/manipulation of charge and spin
Calorimetry	Study and measure the heat of chemical reactions or physical changes
Spin Caloritronics	Transport/manipulation of charge, spin and heat

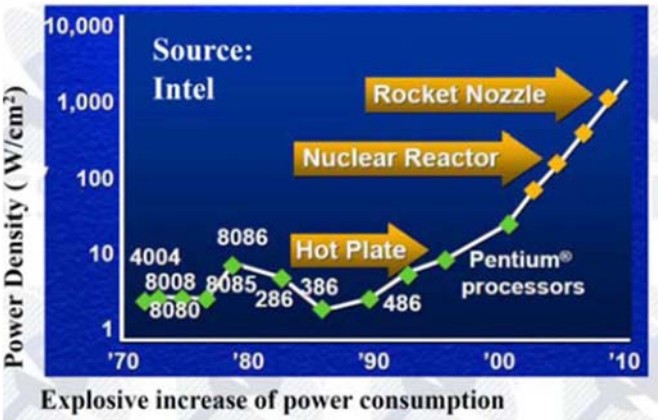
M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987)

Reviews: Bauer, MacDonald, Maekawa, Solid State Commun. (2010); Bauer in *Spin Current* (Oxford University Press, 2012)

Spin currents and spin caloritronics
Outline

Spin caloritronics: *Why is important?*





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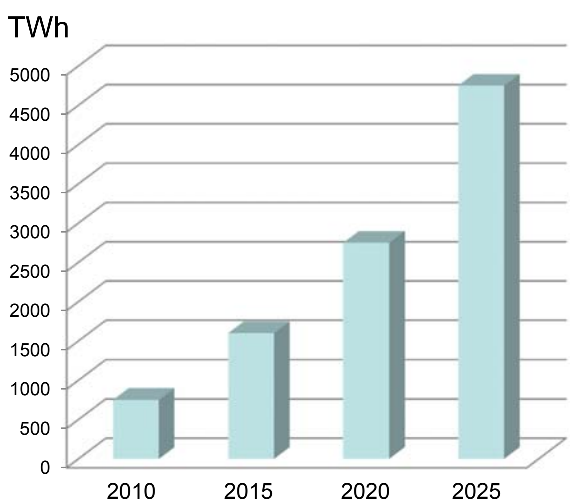
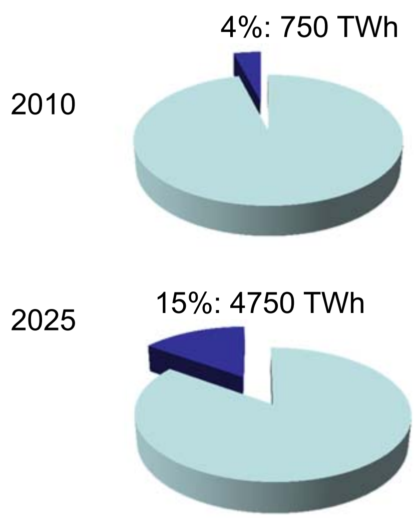
Spin currents and spin caloritronics
Outline

ICT Consumption Forecast



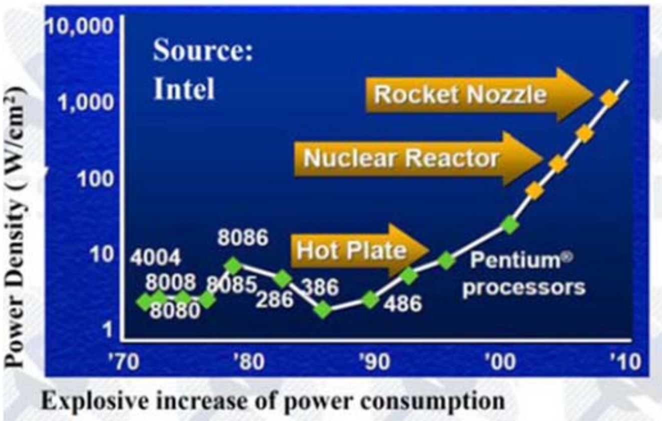


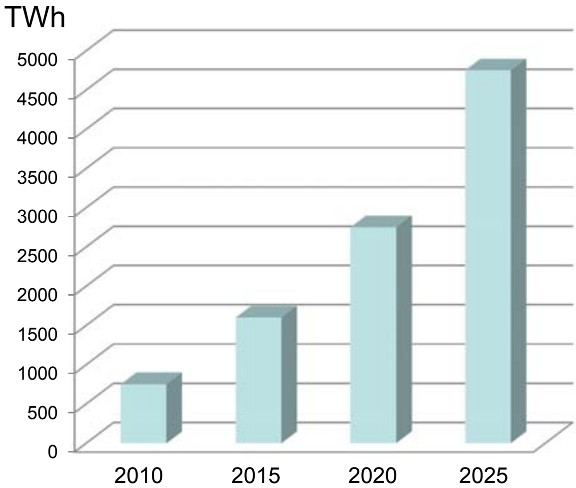
Goal: To find creative ways of using wasted heat

Spin currents and spin caloritronics

Outline

Spin caloritronics: *Why is important?*





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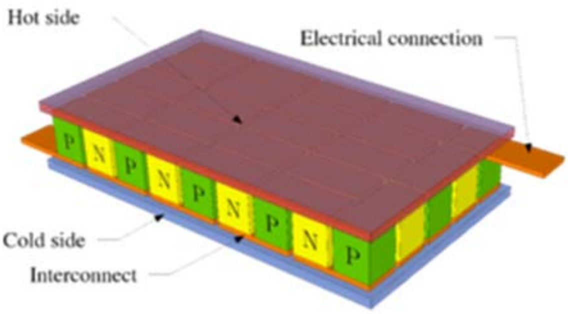
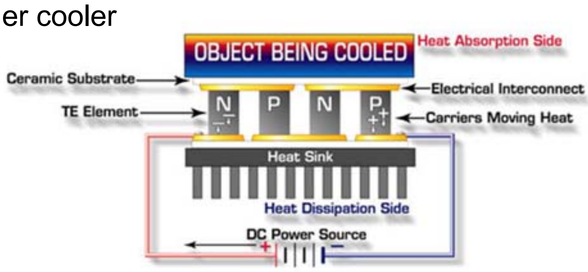
Spin currents and spin caloritronics

Outline

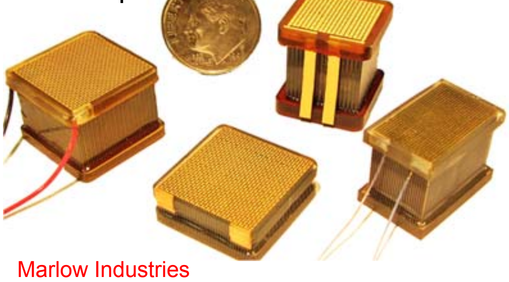
Thermoelectricity, energy harvesting, cooling

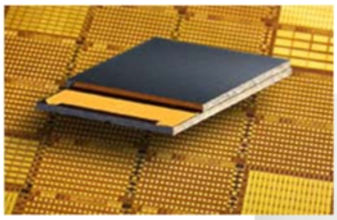


Peltier cooler



Thermopile





Marlow Industries

Spin currents and spin caloritronics

Outline

Spin caloritronics

- Thermoelectricity
  - Seebeck effect
  - Peltier effect
  - Onsager reciprocity relation
- Spin Currents: independent electron, collective
- Thermoelectricity + Spins
- Observed spin caloritronic effects: spin-dependent Seebeck effect, spin Peltier effect, thermal GMR, thermal GMR, thermal torques, magnon drag, spin Seebeck effect.

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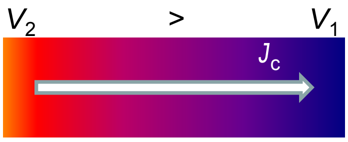
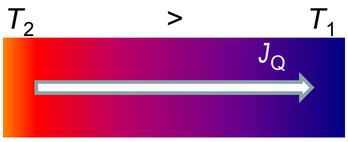
Thermoelectricity

Electrical vs thermal transport



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



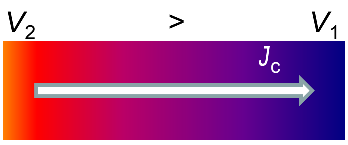
$$\kappa = \left(\frac{J_Q}{\Delta T}\right)_{J_c=0}$$ Thermal Conductivity

Wiedemann-Franz Law

$$\frac{\kappa}{\sigma} = LT \qquad L = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = 2.4\times10^{-8}\,\mathrm{W\Omega K^{-2}}$$

Thermoelectricity

Electrical vs thermal transport



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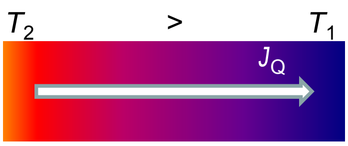

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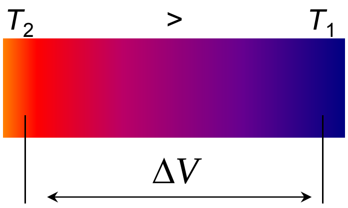
European School on Magnetism 2013, Cargèse, Corsica *Spin Currents and Spin Caloritronics*

Thermoelectricity

Seebeck effect

Conversion of temperature differences directly into electricity

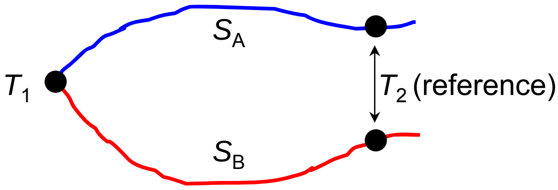


$$S = \left(\frac{\Delta V}{\Delta T}\right)_{J_c=0}$$

Seebeck coefficient

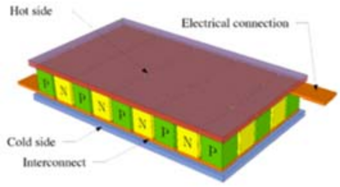
Thomas J. Seebeck
(1770-1831)

Thermocouple



$$\Delta V = \int_{T_1}^{T_2} [S_B(T) - S_A(T)]dT$$

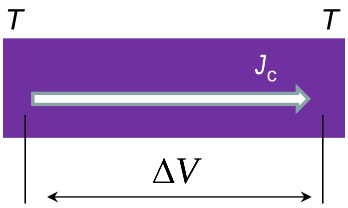
$$\Delta V \approx (S_B - S_A)\Delta T$$



Thermoelectricity

Peltier effect

Conversion of charge current into heat flow

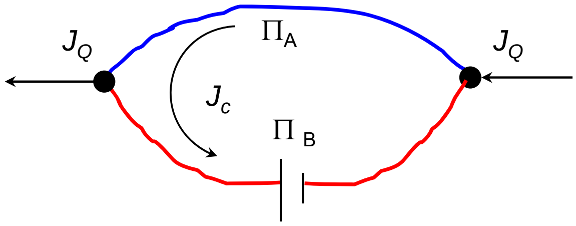


$$\Pi = \left(\frac{J_Q}{J_c}\right)_{\Delta T=0}$$

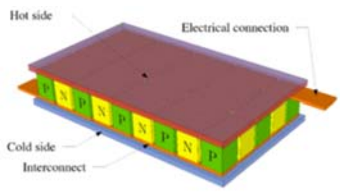
Seebeck coefficient

Jean C. A. Peltier
(1785-1845)

Heat pump: cooler / heater

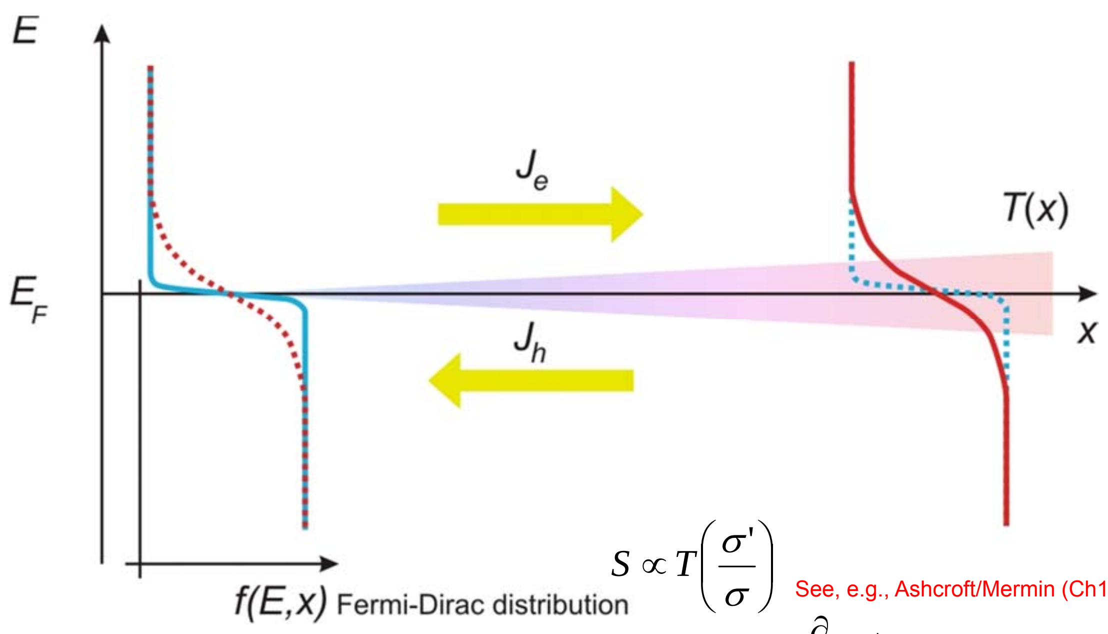


$$J_Q \approx (\Pi_B - \Pi_A)J_c$$



Thermoelectricity

Metal



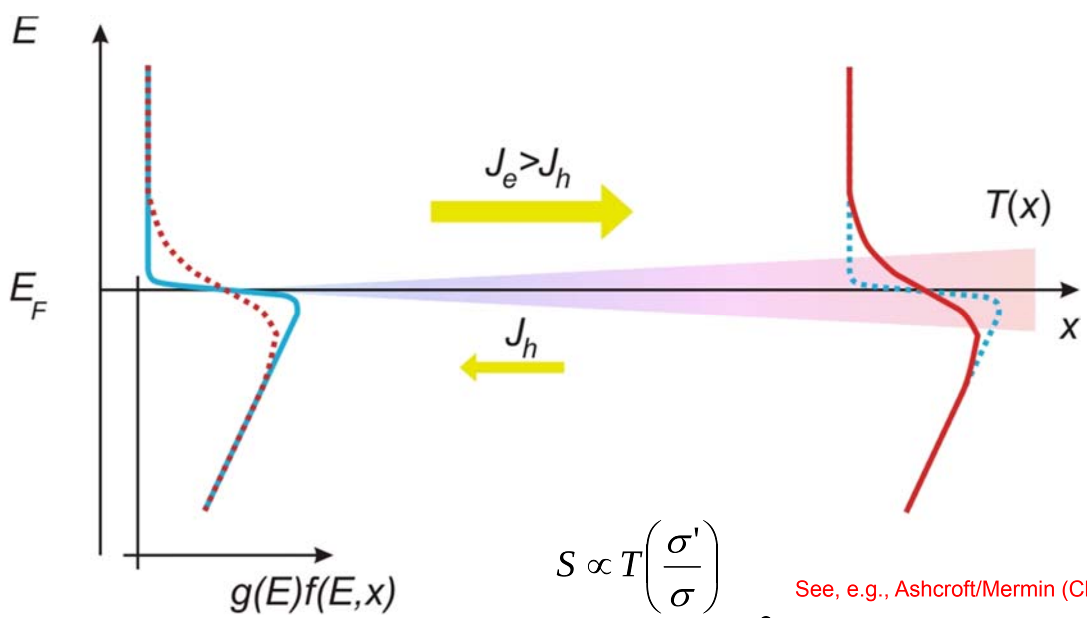
$$S \propto T\left(\frac{\sigma'}{\sigma}\right)$$

See, e.g., Ashcroft/Mermin (Ch13)

$$\sigma' = \frac{\partial}{\partial E}\sigma\Big|_{E=E_F}$$

Thermoelectricity

Heat and charge transport (electron like)



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G. Bauer *et al.* Nat. Mater. (2012)

Thermoelectricity

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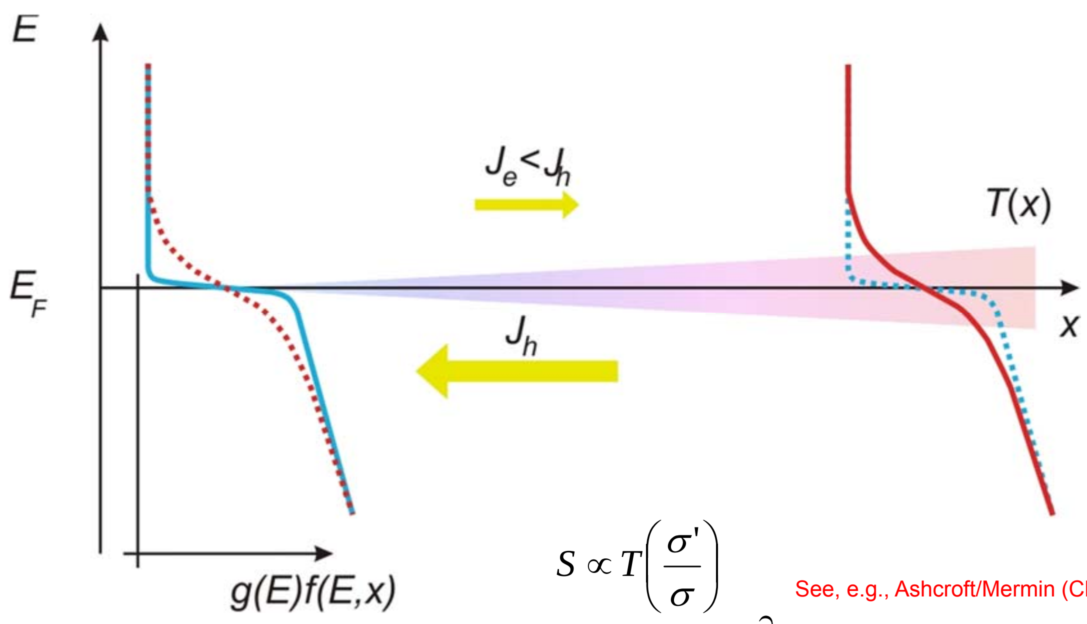

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G. Bauer *et al.* Nat. Mater. (2012)

Thermoelectricity

Onsager reciprocity

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"

Lars Onsager
(1906-1976)

F_n	Generalized force
J_n	Generalized current
If $J_i = \sum_j L_{ij} F_j$	Linear response
and $\frac{dS}{dt} = \sum_j F_j J_j$	entropy change rate

then $L_{ij} = L_{ji}$

$$\begin{pmatrix} J_c \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & S \\ \Pi & \kappa/\sigma \end{pmatrix} \begin{pmatrix} \Delta V \\ -\Delta T \end{pmatrix}$$

First law of thermodynamics: identify F_n, J_n

F_n : ΔV, $-\Delta T/T$

then $\Pi = ST$ (Thomson relation)

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Spin currents vs. charge currents

Charge

$\vec{j}_e = \frac{d}{dt}(q\vec{r})$ $\vec{j}_e = q\vec{v}$

Moving charge, kinetic energy and dissipation

Spín

$\vec{j}_s = \frac{d}{dt}(\sigma\vec{r})$ $\vec{j}_s = \sigma\vec{v} + \dot{\sigma}\vec{r}$

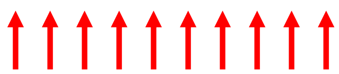
Spin currents are even under time reversal

Electrons do not need to move

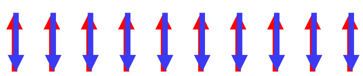
Nonvolatile memory

Possibility to reduce dissipation

Spins in motion (independent electron)



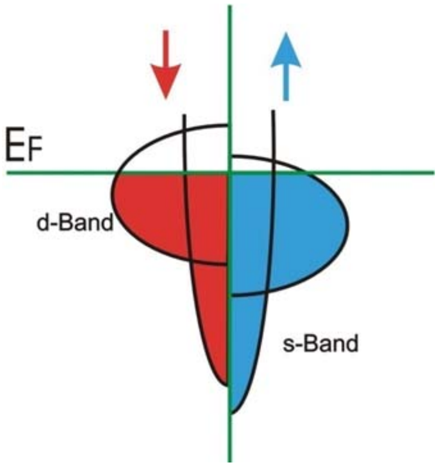
Spin dynamics (collective)



J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006).

Spin generation and spin injection

- Two spin channel model (Mott 1930)
  - Metallic ferromagnets. Spin-up and spin-down are two independent families of carriers



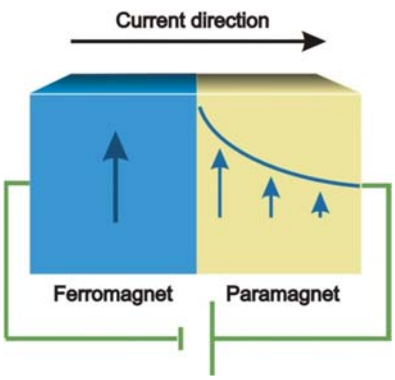
Spin splitting
- Different density of states at the Fermi level for spin up and down carriers
- Different mobility for spin up and down carriers

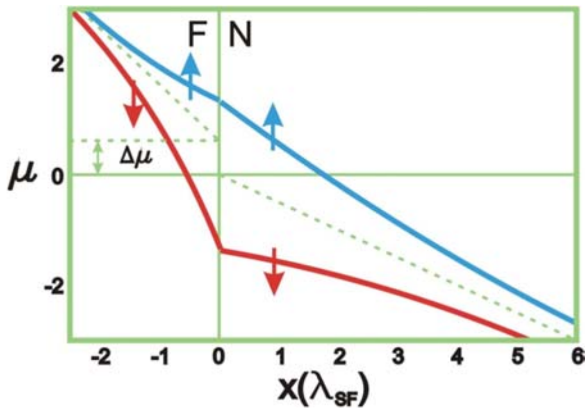
$$P = \frac{N_M - N_m}{N_M + N_m} \qquad -1 \leq P \leq 1$$

I.I. Mazin, PRL **83**, 1427-1430 (1999)

Spin currents and spin accumulation

- Spin polarized current in a nonmagnetic metal
- Spin accumulation decays exponentially
- Characteristic length. Spin diffusion/relaxation length λ_{sf}





$$\nabla^2 \left(\mu^{\uparrow} - \mu^{\downarrow}\right) = \frac{1}{\lambda_{sf}} \left(\mu^{\uparrow} - \mu^{\downarrow}\right)$$

Johnson and Silsbee PRB **35**, 4959 (1987)
van Son et al., PRL **58**, 2271 (1987)

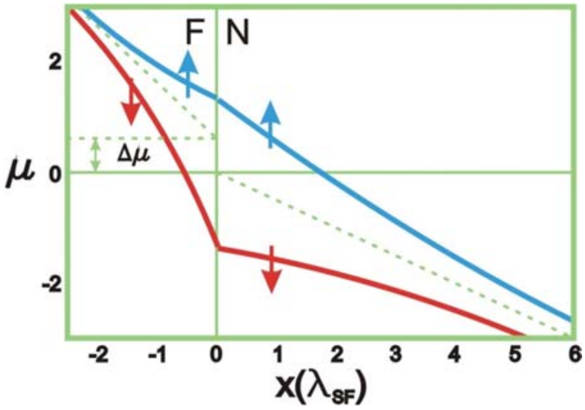
Spin dependent transport

In general the spin conductivities, $\sigma^\uparrow$, $\sigma^\downarrow$ are not equal

$$\begin{pmatrix} J^\uparrow \\ J^\downarrow \end{pmatrix} = \begin{pmatrix} \sigma^\uparrow & 0 \\ 0 & \sigma^\downarrow \end{pmatrix} \begin{pmatrix} \Delta\mu^\uparrow / e \\ \Delta\mu^\downarrow / e \end{pmatrix}$$

thus

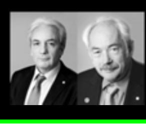
$$\begin{pmatrix} J_c \\ J_s \end{pmatrix} = \sigma \begin{pmatrix} 1 & P \\ P & 1 \end{pmatrix} \begin{pmatrix} \Delta\mu_c / e \\ \Delta\mu_s / e \end{pmatrix}$$

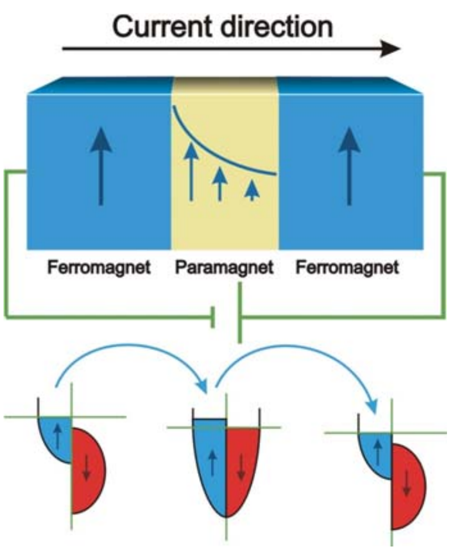


where

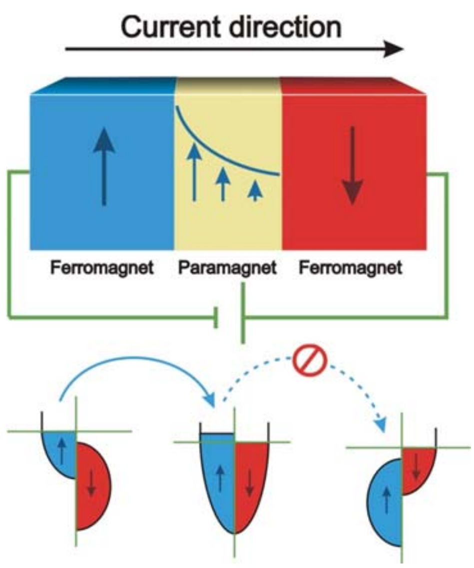
$J_c = J^\uparrow + J^\downarrow$	Charge current	$\mu_c = \dfrac{\mu^\uparrow + \mu^\downarrow}{2}$	Charge chemical potential
$J_s = J^\uparrow - J^\downarrow$	Spin current	$\mu_s = \mu^\uparrow - \mu^\downarrow$	Spin accumulation
$P = \dfrac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$	Spin polarization	$\sigma = \sigma^\uparrow + \sigma^\downarrow$	Charge conductance

Two terminal spin electronics (GMR)





Parallel Magnetization, ↑↑
High conductance

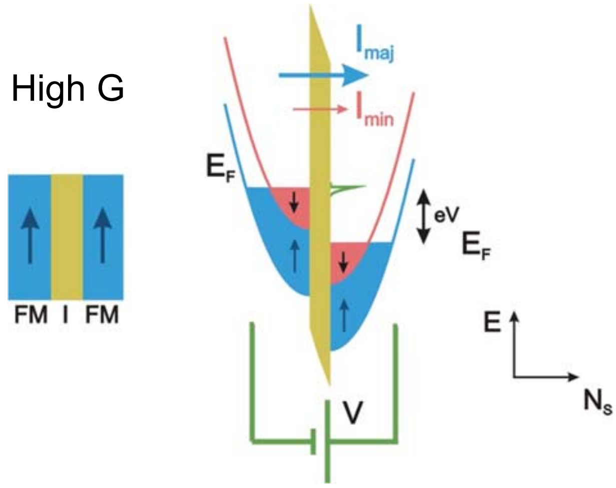


Antiparallel Magnetization, ↑↓
Low conductance

Fert, Grünberg. Nobel Prize 2007

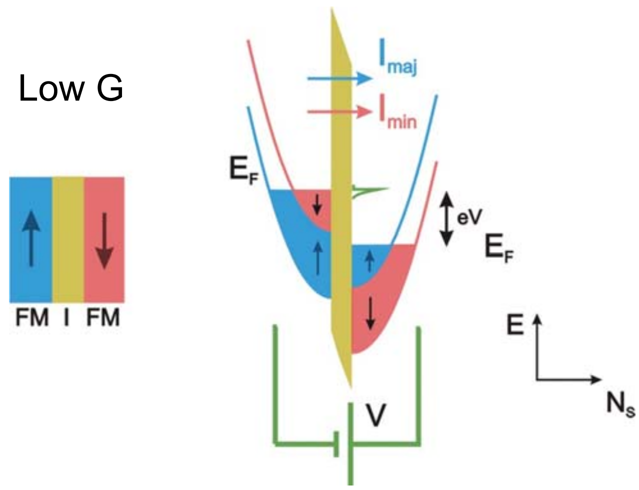
European School on Magnetism 2013, Cargèse, Corsica
Spin Currents and Spin Caloritronics

Two terminal spin electronics (TMR)



$$G_P \approx N_M^L N_M^R + N_m^L N_m^R$$

↑ ↓



$$G_{AP} \approx N_M^L N_m^R + N_m^L N_M^R$$

↑ ↓

Two terminal spin electronics

- Magnetic Tunnel Junctions (MTJ).

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_L P_R}{1 - P_L P_R}$$

$$G_P \approx N_M^L N_M^R + N_m^L N_m^R \qquad G_{AP} \approx N_M^L N_m^R + N_m^L N_M^R$$

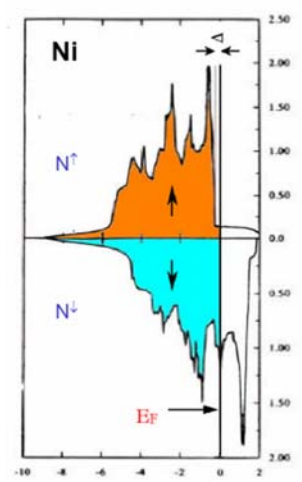
$$P_{L,R} = \frac{N_M^{L,R} - N_m^{L,R}}{N_M^{L,R} + N_m^{L,R}}$$

Julliére, Phys. Lett. **54A**, 225 (1975)

Spin dependent tunneling. Density of states

How is P defined ?

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_L P_R}{1 - P_L P_R}$$



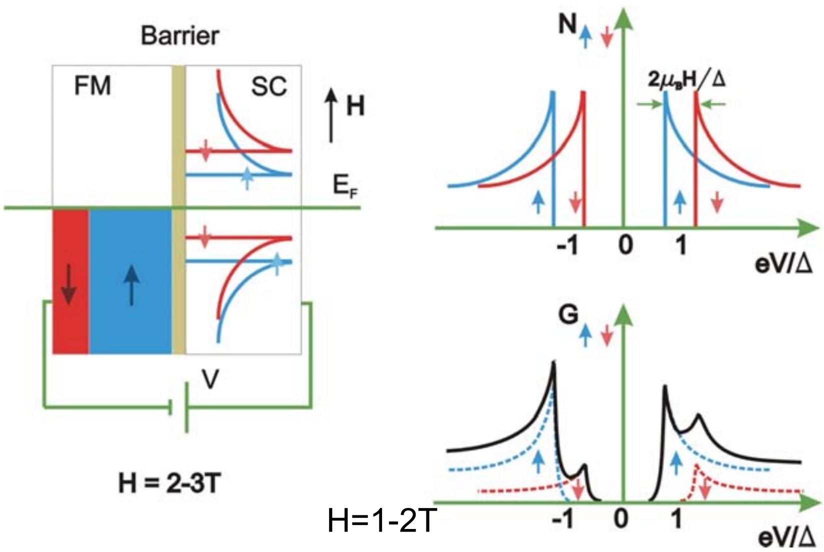
- Julliere: *P* equals the spin polarization of the electrons at the Fermi level
- From energy band calculations *P* < 0 for Ni and *P* > 0 for Fe
- Experimentally TMR > 0 for Ni-I-Fe and bias dependent
- Tunneling probability has to be taken into account (tunneling matrix)
- Current and tunneling mediated by free-like electrons
- Interface. Symmetry states

Stearns, J. Magn. Magn. Mat. **5**, 167 (1977)

Polarization measurement

Meservey-Tedrow

- Meservey-Tedrow technique. Superconductor with Zeeman split density of states as a spin detector
  - *P* is obtained at high field, low temperatures and zero bias



H=1-2T

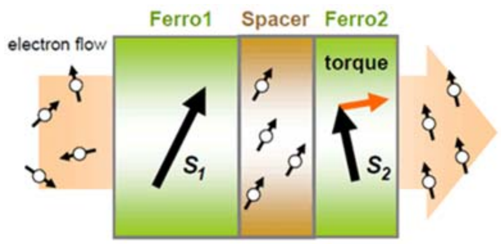
Partially polarized materials:
Fe, Co, Ni
(*P* ~ 25-45 %)

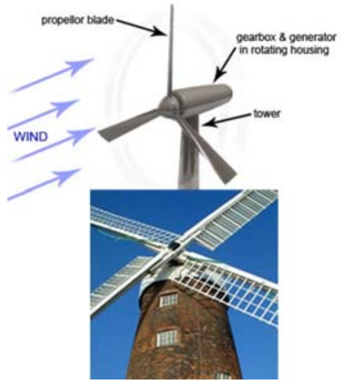
Meservey and Tedrow, Phys. Rep. **238**, 173 (1994)

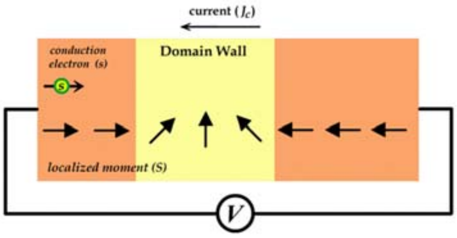
Spin Torque vs spin pumping

Onsager reciprocity

Michel Viret talk (yesterday)

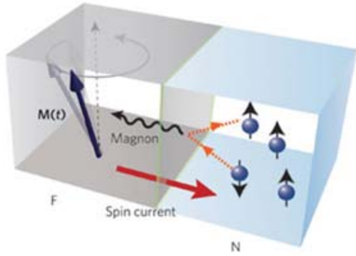






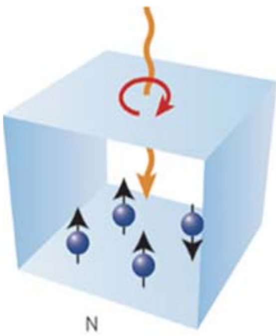
S. Maekawa (Tohoku and JAEA)

Spin pumping

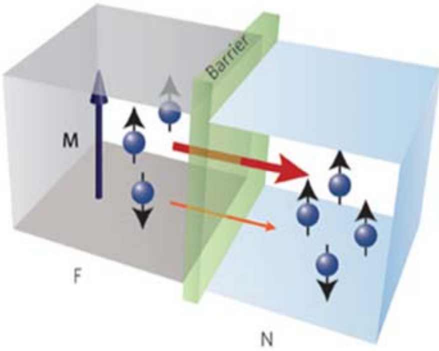


Spin current generation and accumulation

Optical Orientation



Spin Injection



Spin Pumping

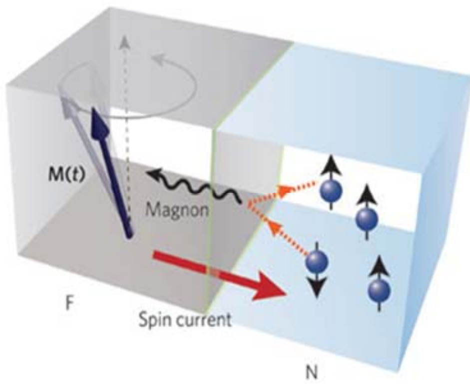
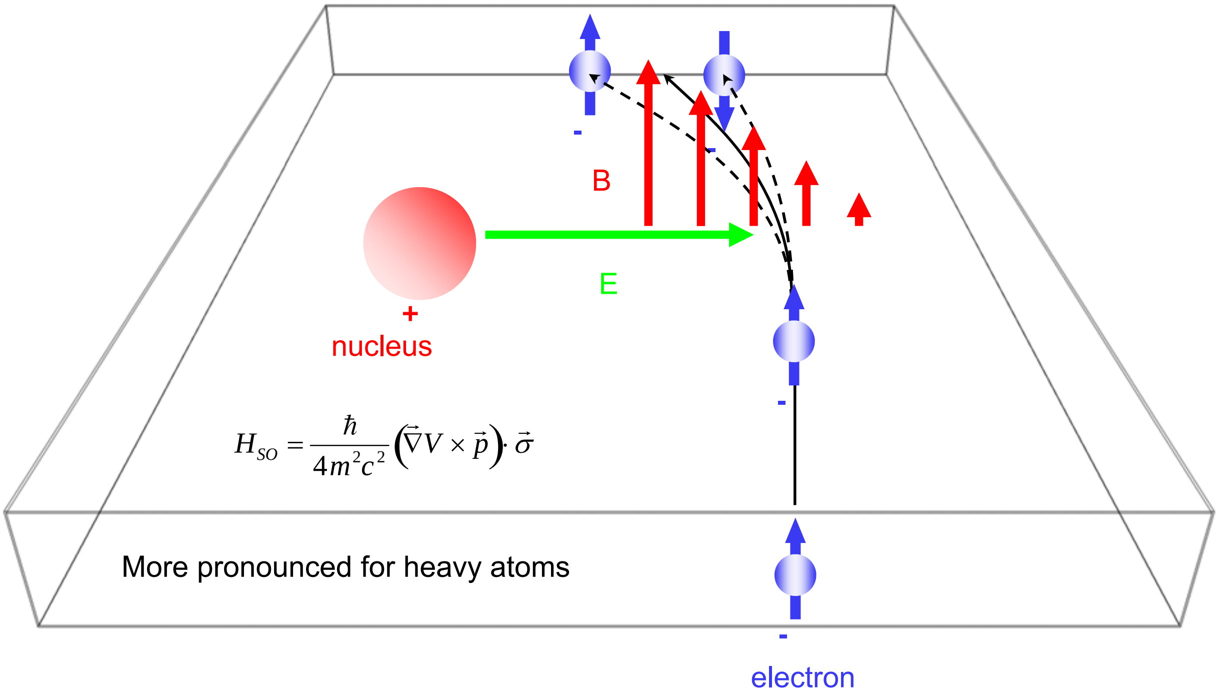


Figure from Zutic and Dery Nat. Mater (2011)

Spin Hall effect

Skew Scattering



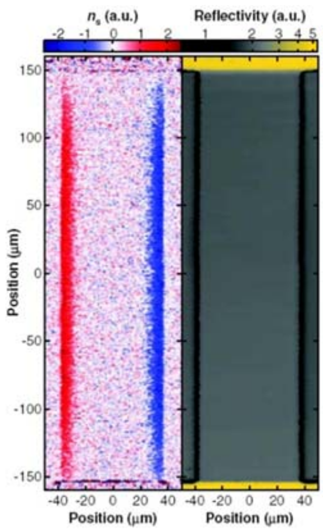
$$H_{SO} = \frac{\hbar}{4m^2c^2}\left(\vec{\nabla}V \times \vec{p}\right)\cdot\vec{\sigma}$$

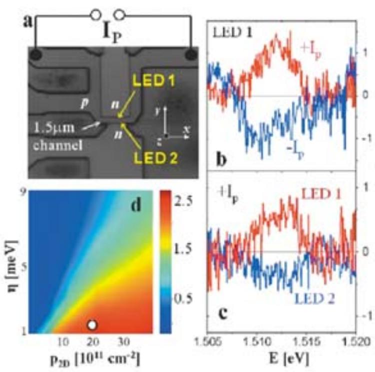
Axel Hoffmann, Argonne National Laboratory, US.

Spin Hall Effect

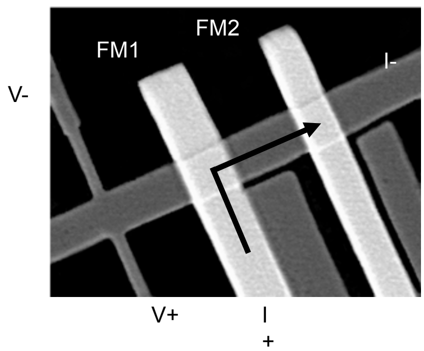
Pure spin currents

(Direct) spin Hall effect





Inverse spin Hall effect
(follows for Onsager reciprocity)



Valenzuela and Tinkham Nature (2006)

Y.K. Kato *et al.* Science (2004); J. Wunderlich, PRL (2005).

V. Sih *et al.* Nature Physics (2005).

Spin currents and spin caloritronics

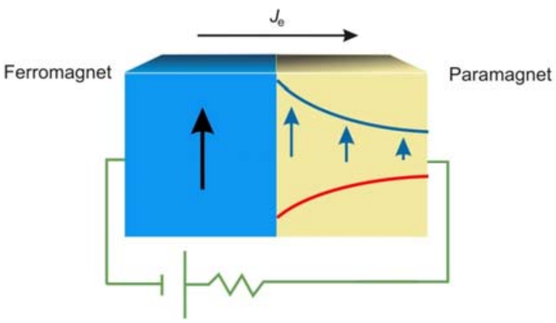
Outline

Spin caloritronics

- Thermoelectricity
  - Seebeck effect
  - Peltier effect
  - Onsager reciprocity relation
- Spin Currents: independent electron, collective
- Thermoelectricity + Spins
- Observed spin caloritronic effects: spin-dependent Seebeck effect, spin Peltier effect, thermal GMR, thermal GMR, thermal torques, magnon drag, spin Seebeck effect.

Spin currents and spin caloritronics

Thermal spin injection

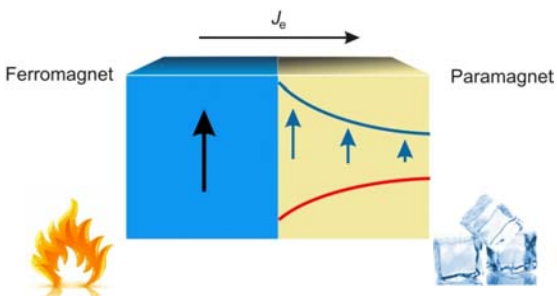


$$\begin{pmatrix} J_c \\ J_s \end{pmatrix} = \sigma \begin{pmatrix} 1 & P \\ P & 1 \end{pmatrix} \begin{pmatrix} \Delta\mu_c / e \\ \Delta\mu_s / e \end{pmatrix}$$

$$\begin{pmatrix} J_c \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & S \\ \Pi & \kappa / \sigma \end{pmatrix} \begin{pmatrix} \Delta V \\ -\Delta T \end{pmatrix}$$

$$S \propto T \left(\frac{\sigma'}{\sigma} \right) \quad \sigma' = \frac{\partial}{\partial E} \sigma \Big|_{E=E_F}$$

$\Pi = ST$ (Thomson relation)



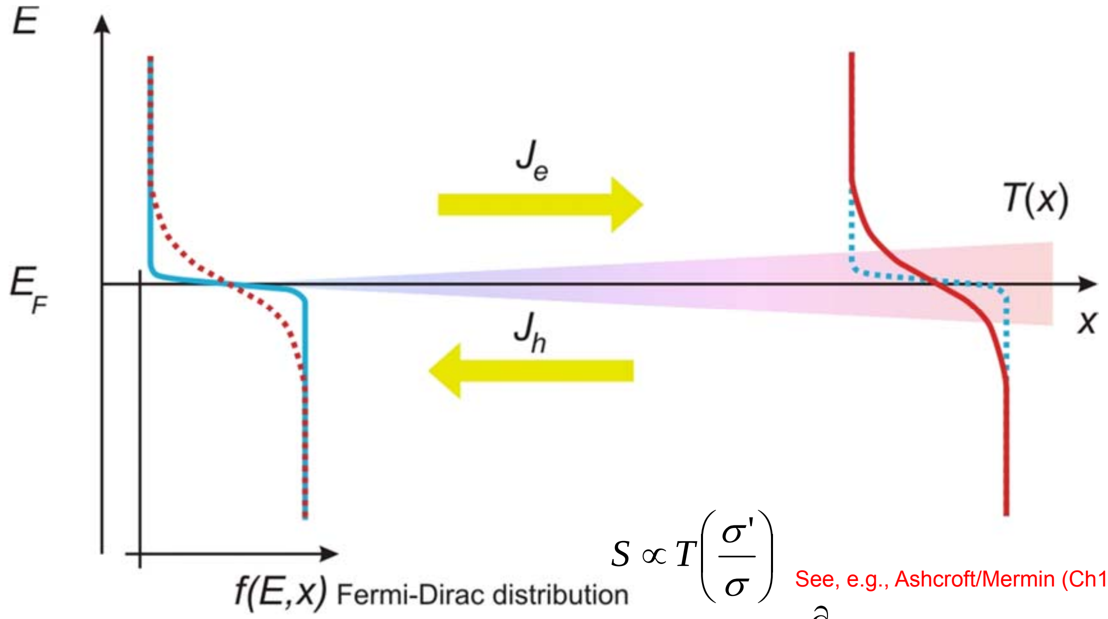
$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & P & S \\ P & 1 & P'S \\ ST & P'ST & \kappa / \sigma \end{pmatrix} \begin{pmatrix} \Delta\mu_c / e \\ \Delta\mu_s / e \\ -\Delta T \end{pmatrix}$$

$$P = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad P' = \frac{\partial_\varepsilon \sigma^{\uparrow} - \partial_\varepsilon \sigma^{\downarrow}}{\partial_\varepsilon \sigma^{\uparrow} + \partial_\varepsilon \sigma^{\downarrow}} \Bigg|_{\varepsilon_F}$$

M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987)

Thermoelectricity

Metal



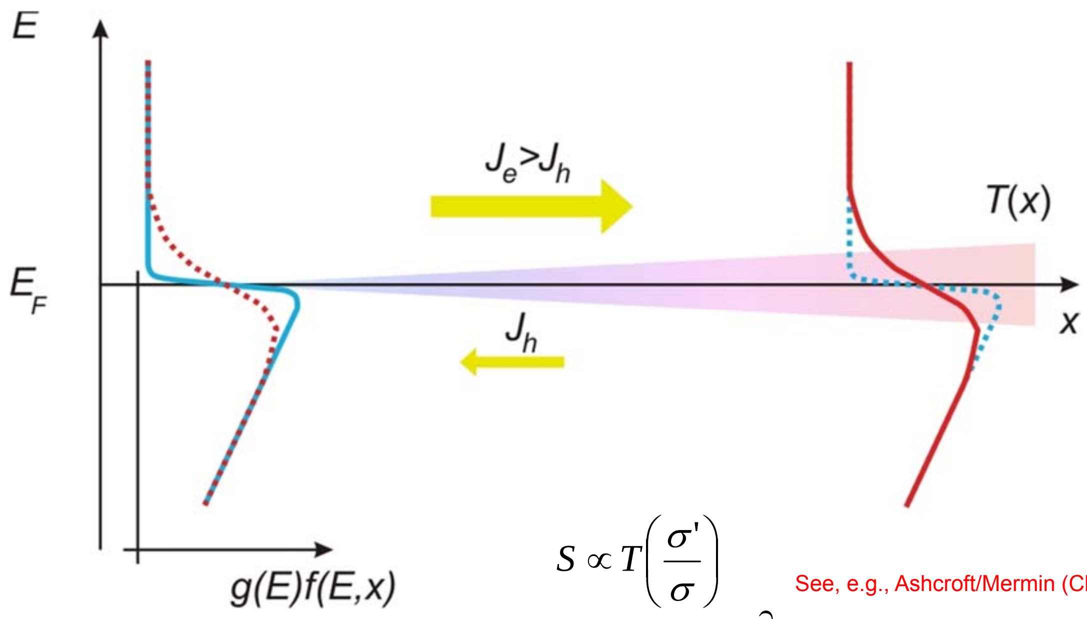
$$S \propto T\left(\frac{\sigma'}{\sigma}\right)$$

See, e.g., Ashcroft/Mermin (Ch13)

$$\sigma' = \frac{\partial}{\partial E}\sigma\Big|_{E=E_F}$$

Thermoelectricity

Heat and charge transport (electron like)



$$S \propto T\left(\frac{\sigma'}{\sigma}\right)$$

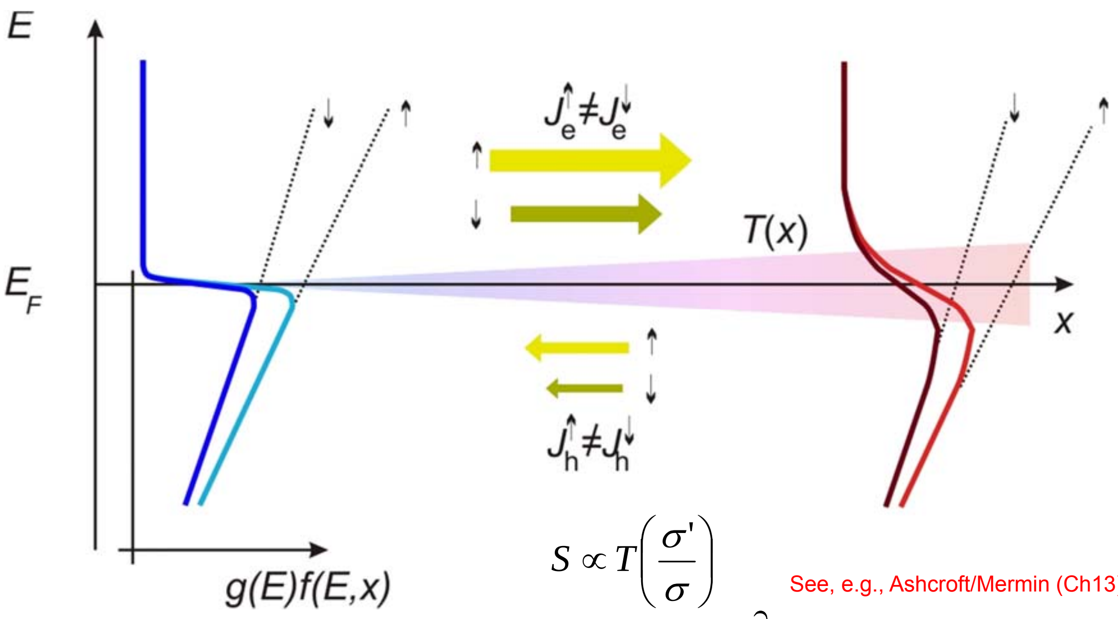
See, e.g., Ashcroft/Mermin (Ch13)

$$\sigma' = \frac{\partial}{\partial E}\sigma\Big|_{E=E_F}$$

G. Bauer *et al.* Nat. Mater. (2012)

Thermoelectricity + Spin

Heat , spin and charge transport (electron like)



$$S \propto T\left(\frac{\sigma'}{\sigma}\right)$$

See, e.g., Ashcroft/Mermin (Ch13)

$$\sigma' = \frac{\partial}{\partial E}\sigma\Big|_{E=E_F}$$

G. Bauer *et al.* Nat. Mater. (2012)

Spin currents and spin caloritronics

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Spin caloritronics

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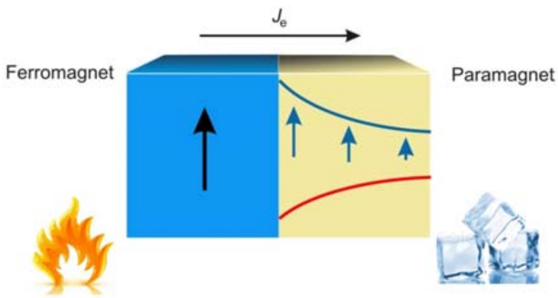
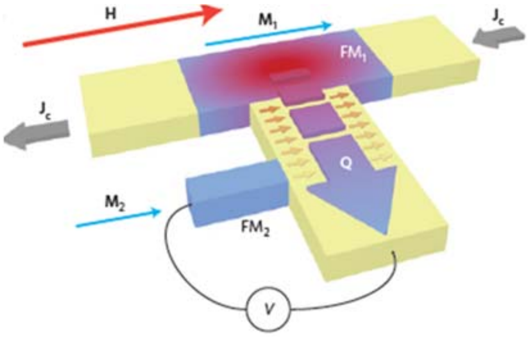
Spin-dependent Seebeck effect



$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & P & S \\ P & 1 & P'S \\ ST & P'ST & \kappa/\sigma \end{pmatrix} \begin{pmatrix} \Delta\mu_c / e \\ \Delta\mu_s / e \\ -\Delta T \end{pmatrix}$$



Slachter *et al.* Nature Phys. (2010)

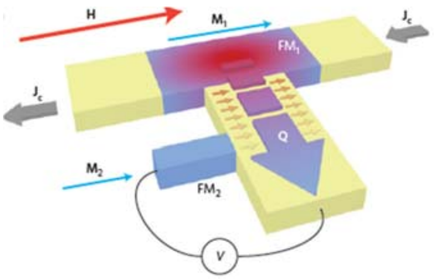
Ferromagnetic injector: Permalloy (NiFe)

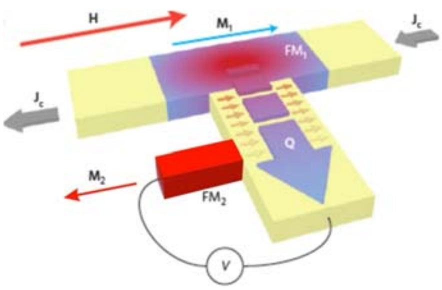
Paramagnetic material: Cu

S_{Py} = -20 uW/K

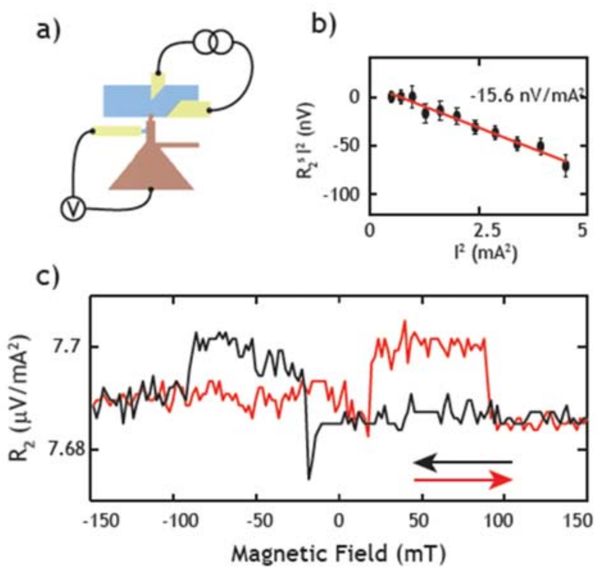
S_{Cu} = 1.6 uW/K

Spin-dependent Seebeck effect

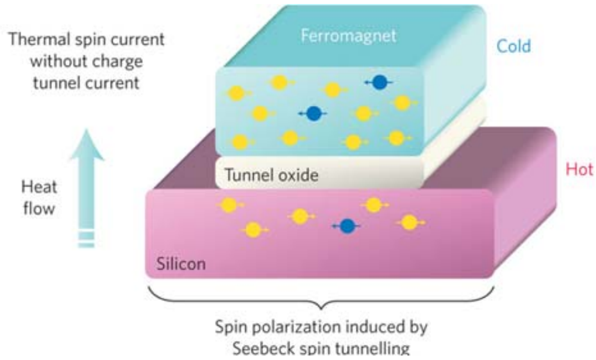


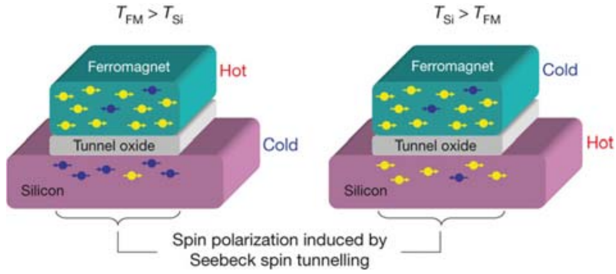


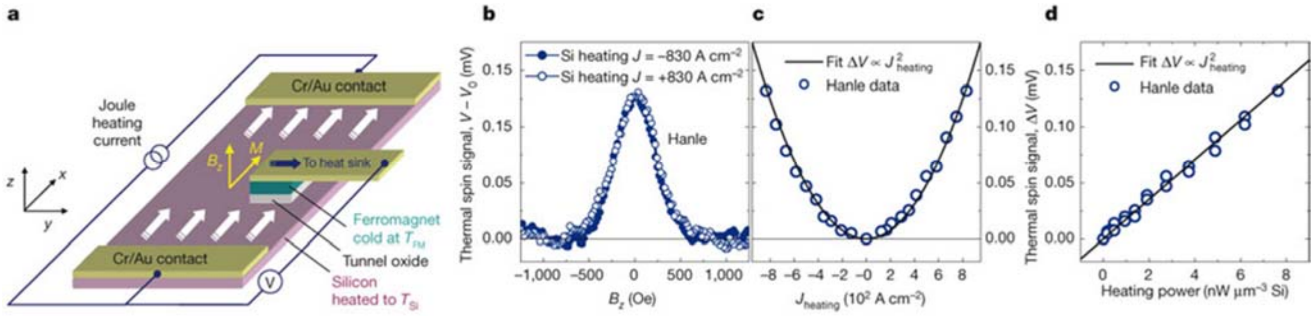
Slachter *et al.* Nature Phys. (2010)



Spin-dependent Seebeck tunneling

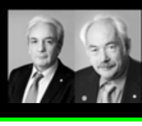


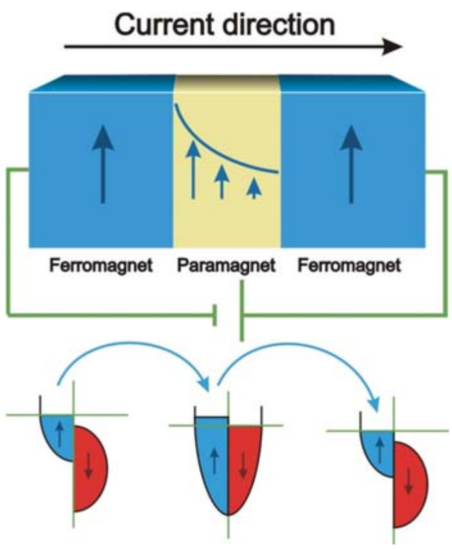


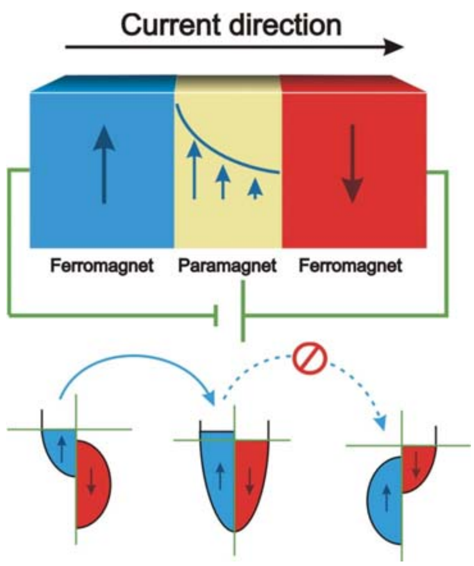


Le Breton *et al.* Nature (2011)

Two terminal spin electronics (GMR)







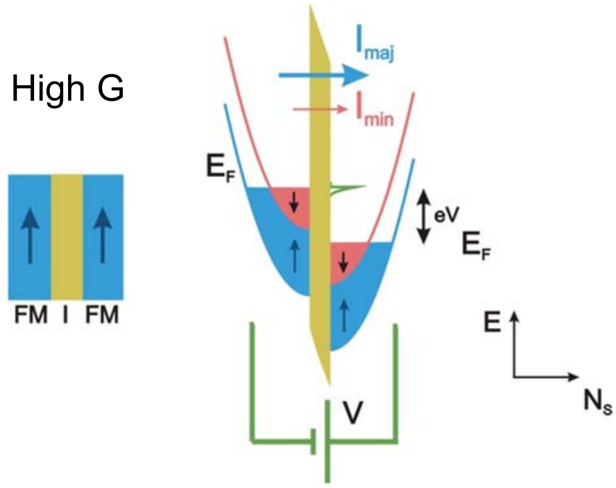
Parallel Magnetization, ↑↑
High conductance

Antiparallel Magnetization, ↑↓
Low conductance

Fert, Grünberg. Nobel Prize 2007

Two terminal spin electronics (TMR)

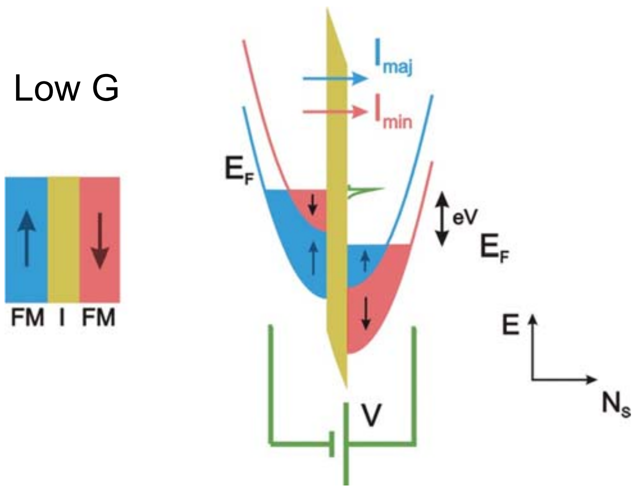
High G



$$G_P \approx N_M^L N_M^R + N_m^L N_m^R$$

↑ ↓

Low G

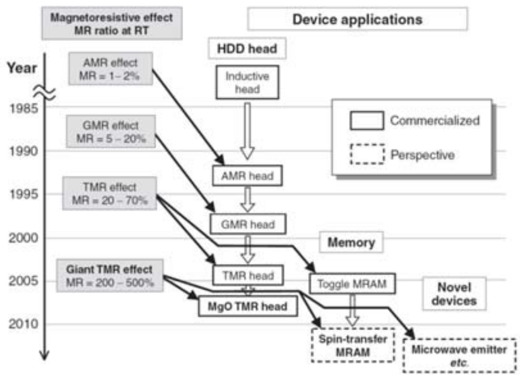


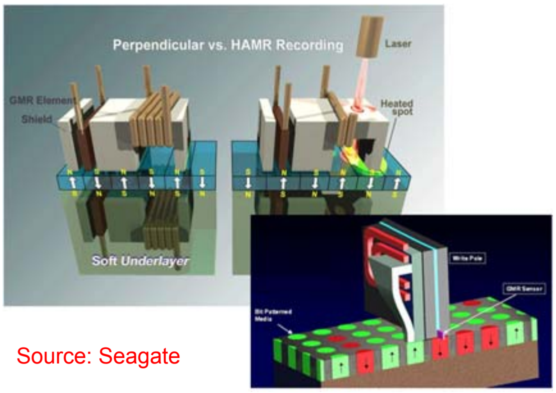
$$G_{AP} \approx N_M^L N_m^R + N_m^L N_M^R$$

↑ ↓

Spin valves

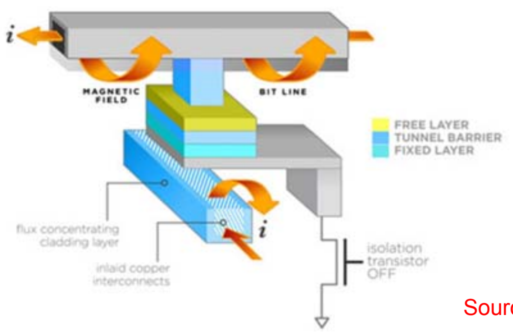
Magnetic Access Random Memory (MRAM) Current developments



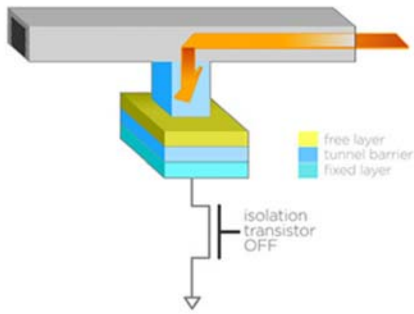


Source: Seagate

Toggle RAM (commercialized)



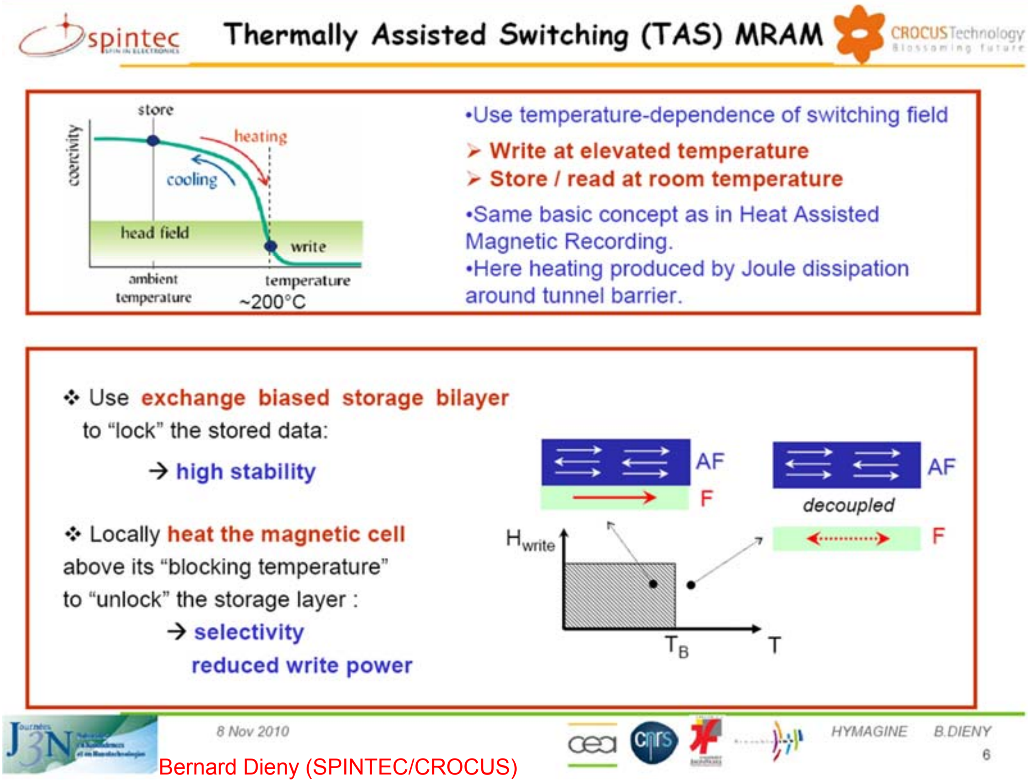
Spin Transfer Torque RAM (under development)



Source: Everspin

Spin valves

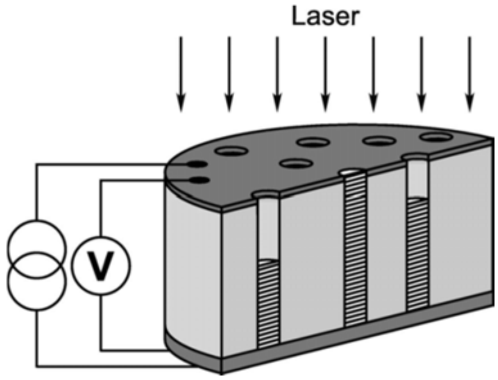
Magnetic Access Random Memory (MRAM) Current developments

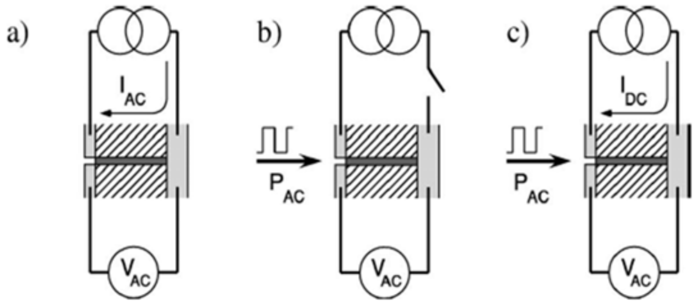


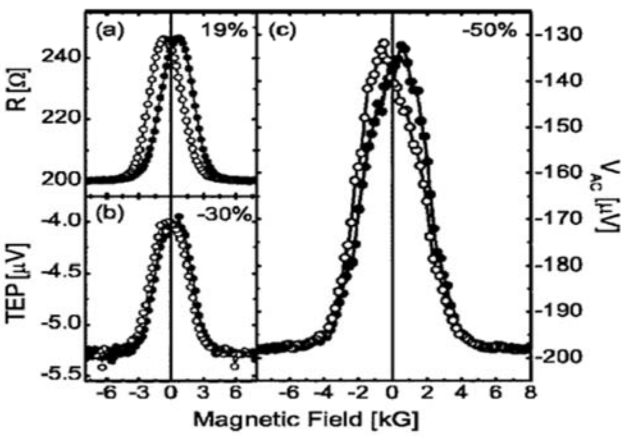
Spin-dependent thermoelectric effects in spin valves (2006)

J. Shi, K. Pettit, *et al.* Phys. Rev. B (1996)
McCann, E. & Fal'ko, Appl. Phys. Lett. (2002).

thermoelectric power and thermal conductivity on granular and multilayer GMR systems



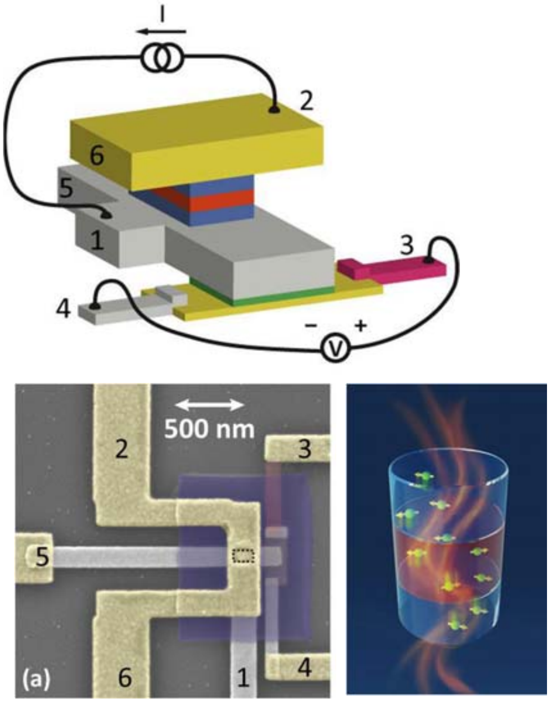


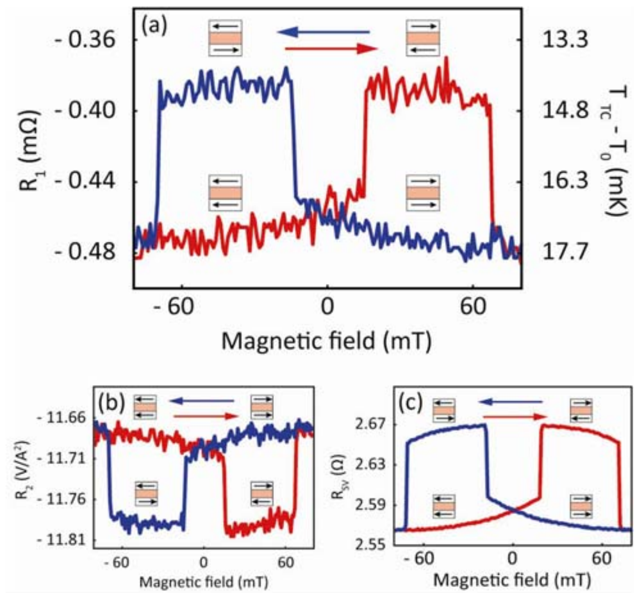


L. Gravier, S. Serrano-Guisan, *et al.*, Phys. Rev. B (2006)

Spin-dependent heat and charge transport perpendicular to the plane of magnetic Co/Cu multilayers. Peltier effect.

Spin-dependent Peltier effect



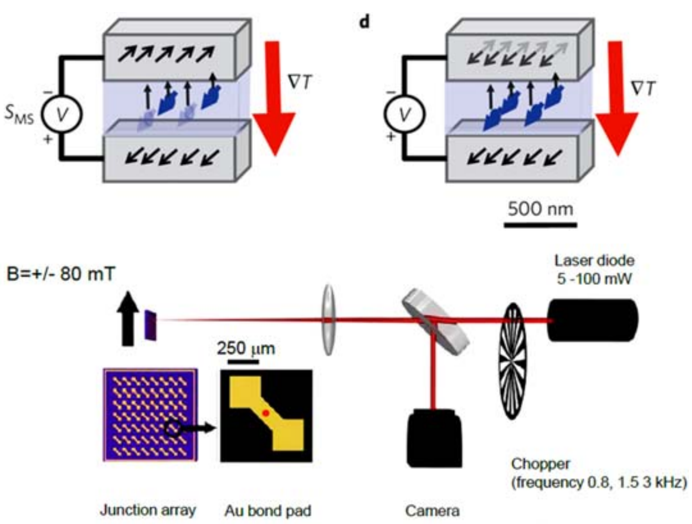


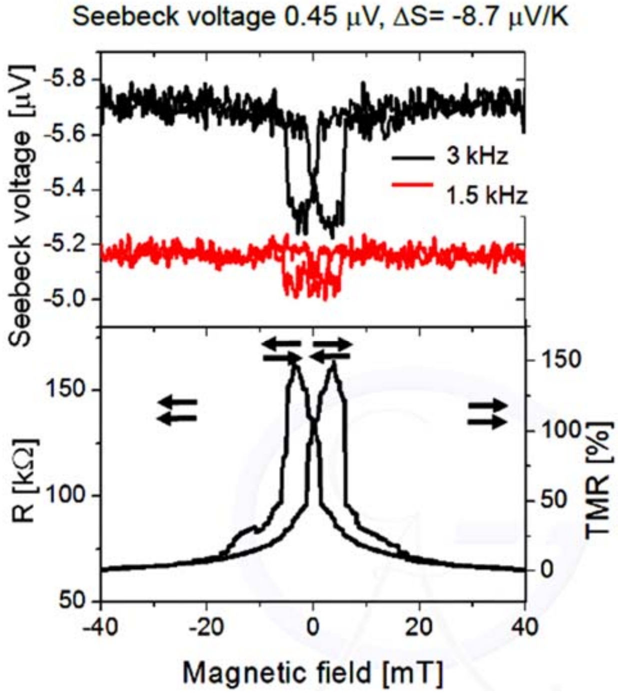
Flipse *et al.* Nature Nanotechnol. (2012)

Magneto Seebeck effect tunnel junctions

Magneto Seebeck effect -8.8%

$$S_{MS} = \frac{S_P - S_{AP}}{\min(S_P, S_{AP})}$$





Walter *et al.* Nature Mater. (2011)

Spin currents vs. charge currents

Charge

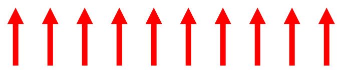
$$\vec{j}_e = \frac{d}{dt}(q\vec{r}) \qquad \vec{j}_e = q\vec{v}$$

Moving charge, kinetic energy and dissipation

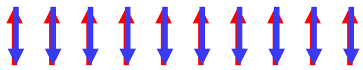
Spín

$$\vec{j}_s = \frac{d}{dt}(\sigma\vec{r}) \qquad \vec{j}_s = \sigma\vec{v} + \dot{\sigma}\vec{r}$$

Spins in motion (independent electron)



Spin dynamics (collective)



Spin currents are even under time reversal

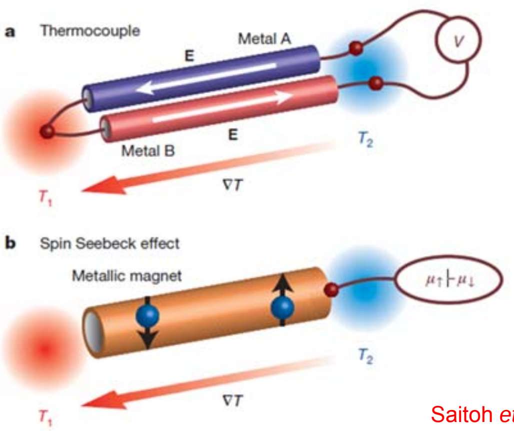
Electrons do not need to move

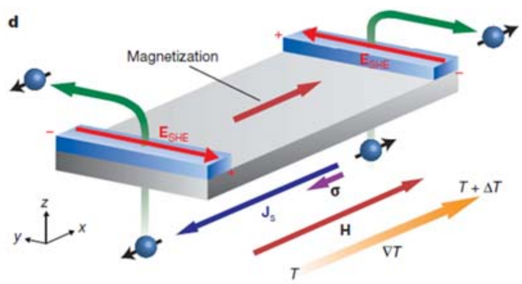
Nonvolatile memory

Possibility to reduce dissipation

J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006).

Spin Seebeck effect



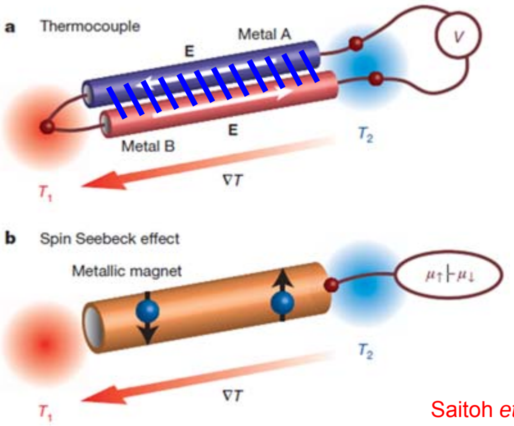


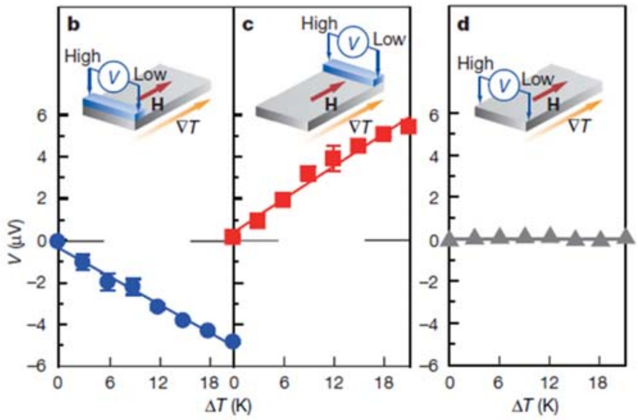
Saitoh *et al.* Nature (2008)

Original idea: two spin channels acting as the two distinct materials in a thermocouple. A temperature gradient should result in a spin voltage proportional to the temperature difference Which can be detected by inverse spin Hall effect in Pt

Reviews: Bauer, MacDonald, Maekawa, Solid State Commun. (2010); Bauer in *Spin Current* (Oxford University Press, 2012)

Spin Seebeck effect





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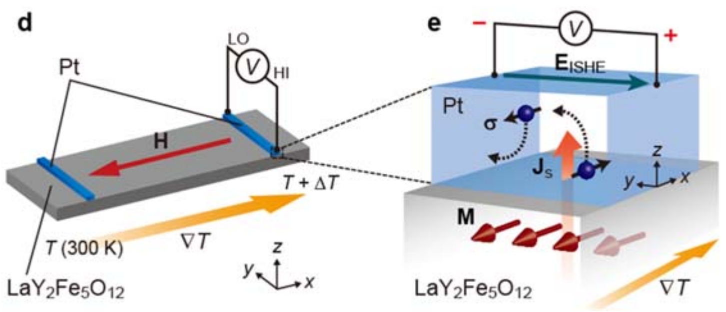
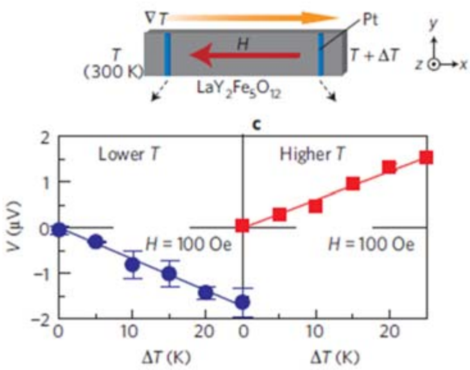
Spin Seebeck effect

Basic mechanism

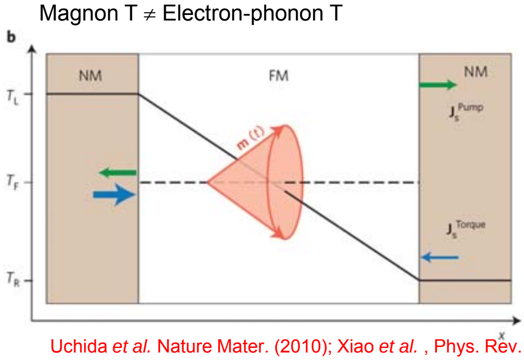
Spin Seebeck in insulators





Uchida *et al.* Nature Mater. (2010)

Magnon T ≠ Electron-phonon T



Spin pumping (SP) vs. Johnson-Nyquist noise

$$V_{ISHE} \propto J_S$$

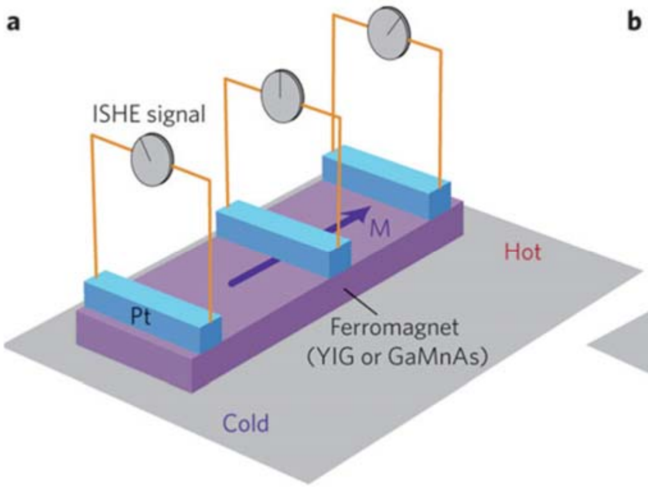
$$J_S = J_S^{SP} - J_S^{J-N} = C(T_F^M - T_N^e)$$

Uchida *et al.* Nature Mater. (2010); Xiao *et al.* , Phys. Rev. B (2010); Bauer *et al.* Nature Mater. (2012)

Spin Seebeck effect

Basic mechanism

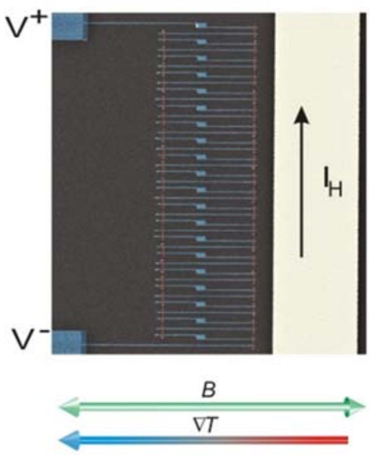
Spin Seebeck in semiconductors

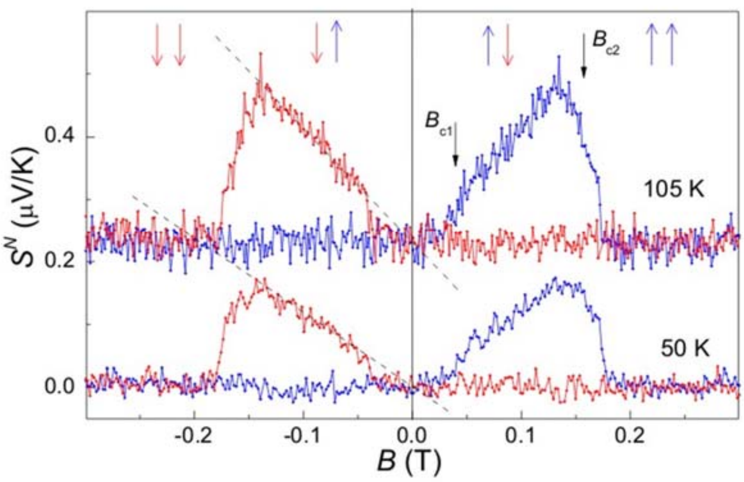


Jaworski *et al.* Nature Mater. (2010); Sinova Nature Mater. (2010)

Thermopile

Thermopower





$S^N = (V^+ - V^-) / \Delta T$

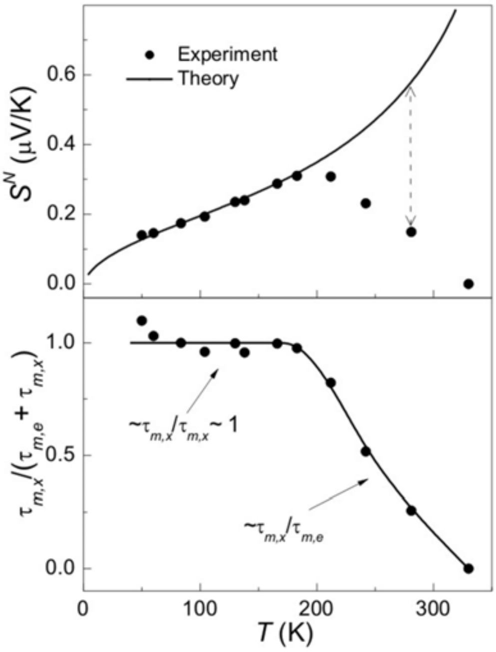
Signal only observed in the antiparallel configuration

Linear in *B* extrapolates to zero at *B* = 0

M.V. Costache, G. Bridoux, I. Neumann and SOV, Nature Mater. (2012)

Thermopile

Thermopower modeling



$S^{MD} \propto P_{m,e}/(P_{m,x}+P_{m,e}) \propto \tau_{m,x}/(\tau_{m,x}+\tau_{m,e})$

$P_{m,e}$: Probability magnon-electron interaction

$P_{m,x}+P_{m,e}$ Probability magnon interaction

Phonons: Ziman in *Electrons and phonons* (OUP, 1960)

$$S^{MD}(B,T)=\frac{1}{n'_c e}\frac{k_B^{5/2}T^{3/2}F(y)}{6\pi^2 D^{3/2}}\left(\frac{\tau_{m,x}}{\tau_{m,x}+\tau_{m,e}}\right)$$

$y=(g\mu_B B_{int}/k_B T) \qquad n'_c = n_c/\alpha$

$F(y)$ Quenching function

Grannemann and Berger , Phys. Rev. B (1976)

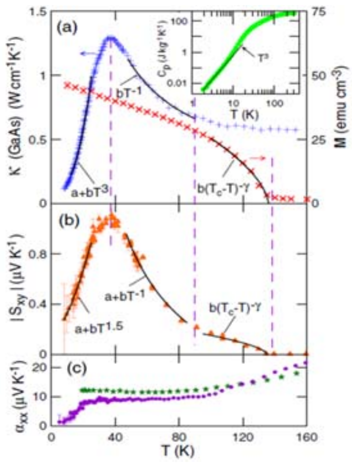
For low *T*: $\tau_{m,x}/(\tau_{m,x}+\tau_{m,e}) \approx 1$

$$S^N = V/\Delta T = N[S^{MD}(T,-B)-S^{MD}(T,+B)].$$

Spin Seebeck effect

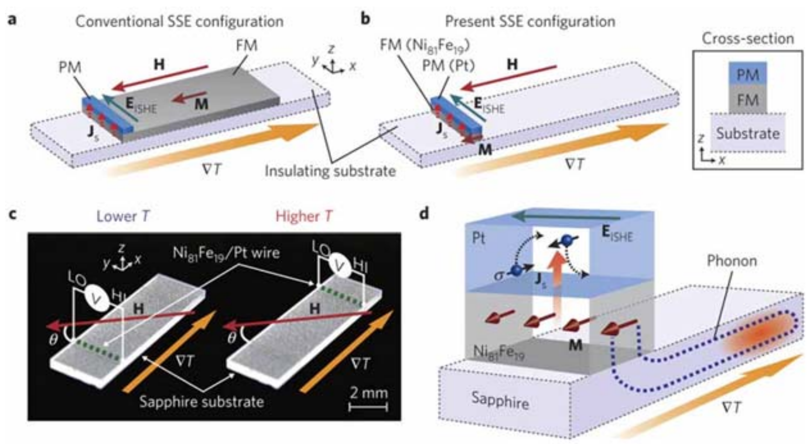
Basic mechanism

Magnons and phonons

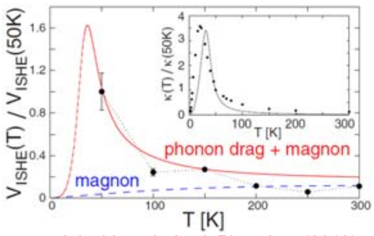


Jaworski *et al.*, Phys. Rev. Lett (2011)

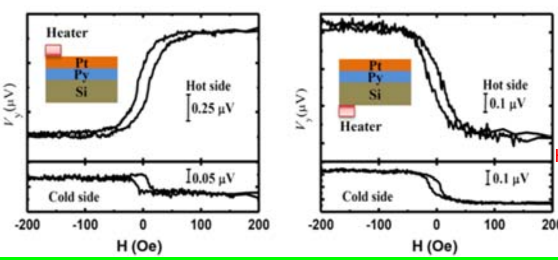
Acoustic spin pumping



Uchida *et al.* Nature Mater. (2011)



Adachi *et al.*, Appl. Phys. Lett (2010)

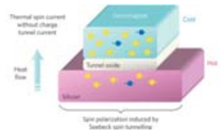


Anomalous Nernst effect

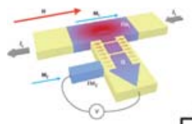
Huang *et al.*, Phys. Rev. Lett (2011)

Spin caloritronics

Spin caloritronics: interaction between spin and heat transport

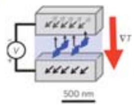


Spin-dependent conductivities: Cause spin-dependent thermoelectric effects

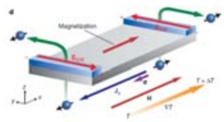


Collective spin dynamics: Associated to new thermomagnetic phenomena such as de spin Seebeck effect (strikingly in insulators)

Thermomagnetic effects: new means to control heat flow and harvest energy

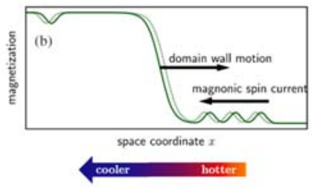


Need to know: Electron-phonon, electron-magnon, phonon-magnon … interactions. Independent determination of the time scales of these interactions



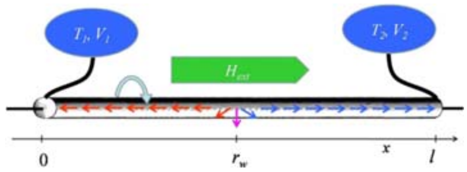
Look at: Resistivity effects, thermoelectric effects: e.g. magnetoresistance, phonon- and magnon-drag

Be careful with: artifacts and mimicking effects, e.g. AMR, phonon drag…



Domain wall motion by magnonic spin currents

Heat engines and motors



Hinzke , Nowak, Phys. Rev. Lett. (2011)

Bauer *et al.*, Phys. Rev. B (2010)