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Cooling and heating with electron spins: Observation of the spin Peltier effect

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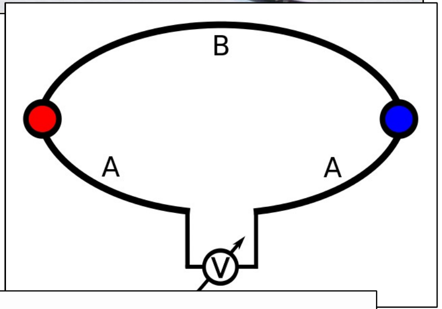
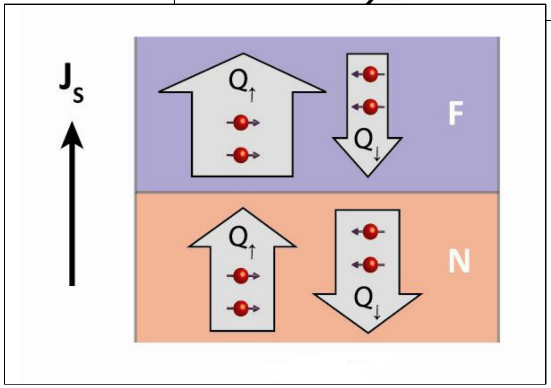
Outline

- Motivation
- Peltier effect
- Spin Peltier effect
  - at interfaces
  - in multilayer stacks
- Measurement
- Conclusions

Motivation





Peltier effect:

Thermoelectric effect
Local refrigeration/heating

Applications:
Thermal stabilization in CCDs, sensors, diode lasers ...

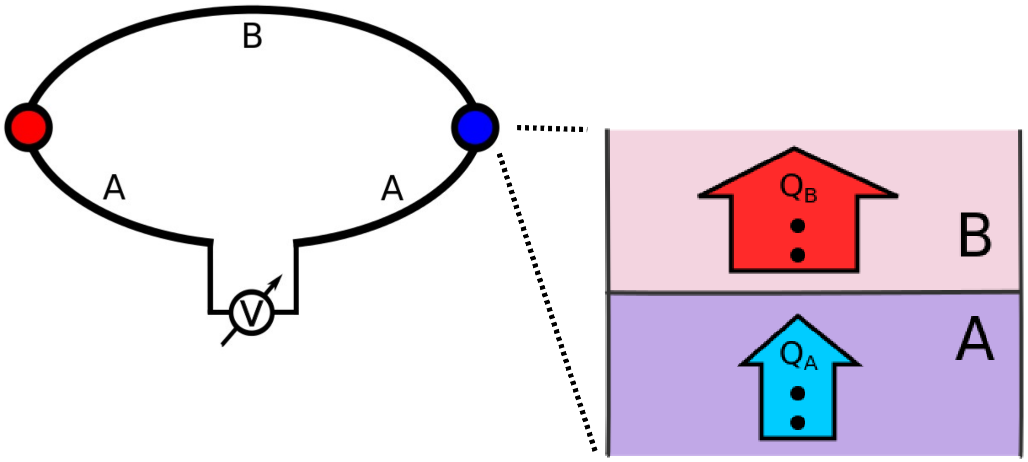
Spin Peltier effect:

Indicated by Gravier *et al.* (2006)
Theoretical description by Hatami *et al.* (2009)
Not yet directly measured

Potential application:

Downscaling of computer components yields problem of heat dissipation,
Spin Peltier effect offers magnetically switchable cooling of devices on the nm-scale

Peltier effect



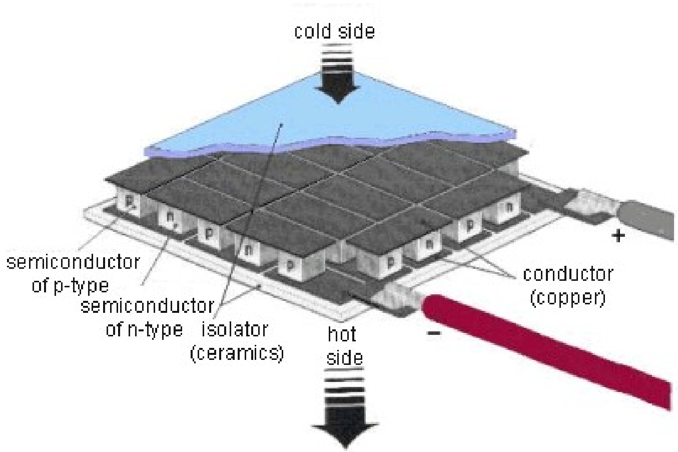
Thermoelectric effect
Jean Peltier, 1834:

Conversion of current into temperature difference at a junction

$$\Delta Q = (\Pi_B - \Pi_A) I$$

$$\Pi_i = \text{Peltier coefficient}$$

$$\Delta Q \propto \Delta T$$

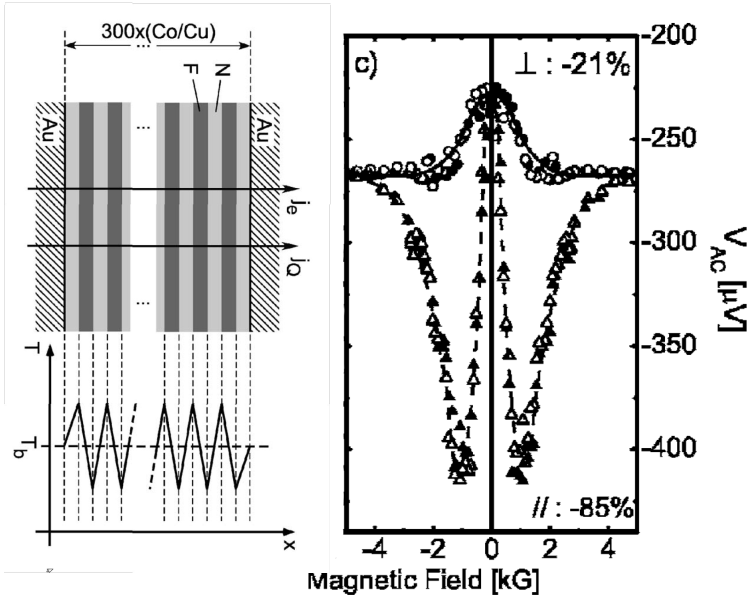


Characteristics:

No moving parts, no refrigerant
Reliable, low maintenance
Low efficiency

$$\Delta T_{\text{max}} \approx 70\text{K}$$

Spin Peltier effect I



Pioneering experiment:

Gravier *et al.*, PRB 73, 052410 (2006)

- Field dependent magnetothermogalvanic voltage in Co/Cu multilayers
- Explanation:
  Spin dependent Peltier coefficients

Theoretical work:

Hatami *et al.*, PRB 79, 174426 (2009)

Schematic explanation:

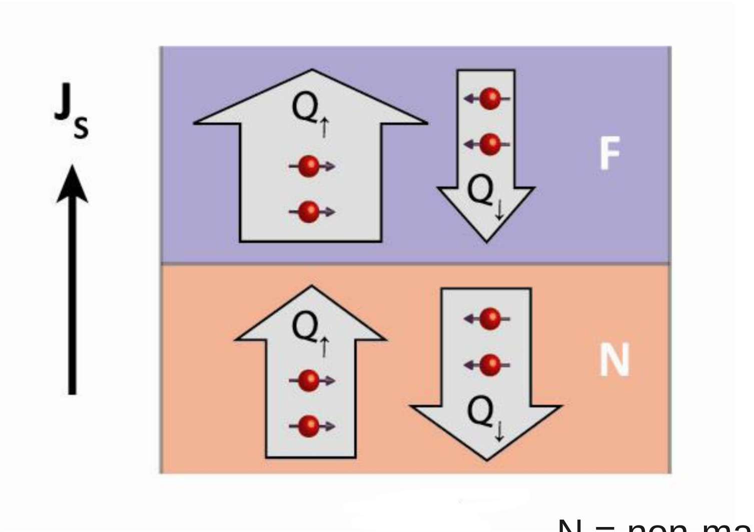
Spin channels transport heat independently

$$\text{N} : \Pi_\uparrow = \Pi_\downarrow$$

$$\text{F} : \Pi_S = \Pi_\uparrow - \Pi_\downarrow \neq 0$$

$$Q_\Pi = \Pi_\uparrow J_\uparrow + \Pi_\downarrow J_\downarrow$$

→ net heat current in F



N = non-magnetic
F = ferromagnetic

Spin Peltier effect II

N : $J_\uparrow = -J_\downarrow$

F : $J_S = J_\uparrow - J_\downarrow \neq 0$

- F: Non-zero spin current polarization
- Minority spin accumulation at interface

$$\mu_S^0 = \mu_\uparrow^0 - \mu_\downarrow^0$$

- Conservation of angular momentum:
  Spin flip processes (→ Joule heating)

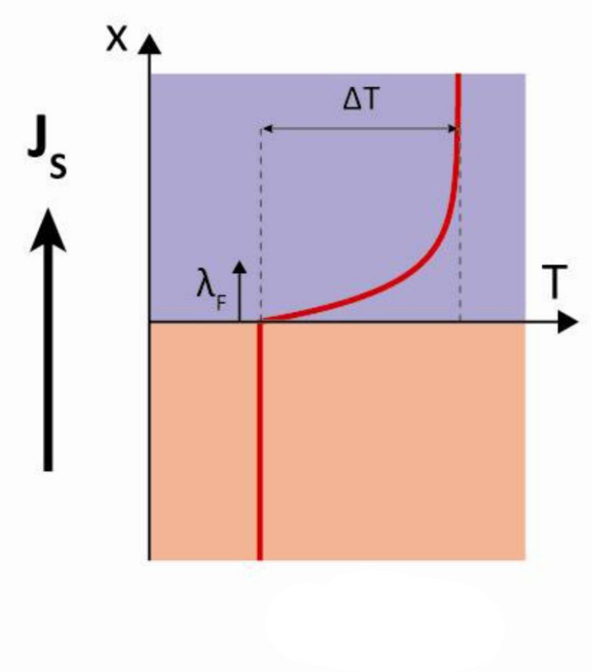
$$\mu_S = \mu_S^0 \, e^{-x/\lambda_F}$$

- Peltier heat current drops
  within several λ_F (λ_F= spin relaxation length)

$$Q_\Pi = \Pi_\uparrow J_\uparrow + \Pi_\downarrow J_\downarrow \Rightarrow \dot{Q} \neq 0$$

- Heat transfer from interface into F
- Temperature drop

$$\Delta T_{\text{Peltier}} = \frac{\sigma}{4\kappa}(1 - P_\sigma^2)\Pi_S \mu_S^0$$

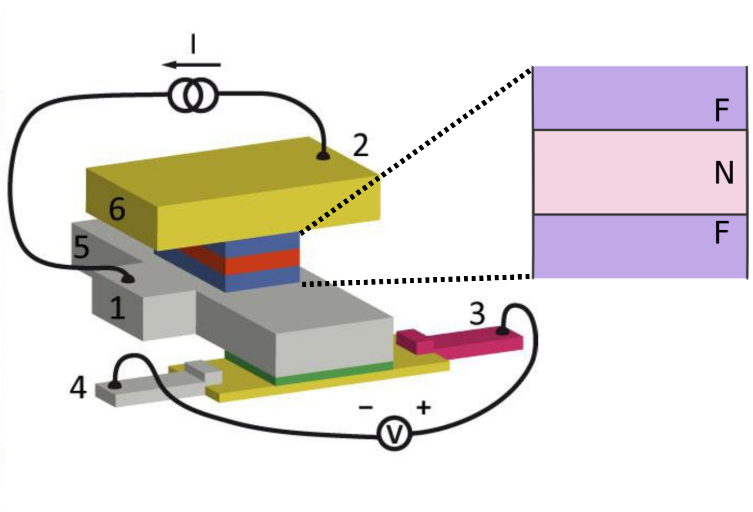


$P_\sigma = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$ conductivity polarization

κ thermal conductivity

$\sigma = \sigma_\uparrow + \sigma_\downarrow$ conductivity

Experimental setup

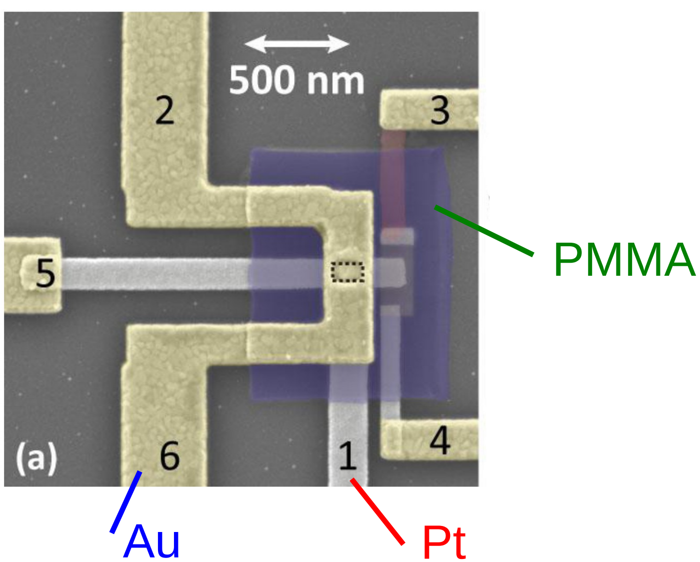


Layered stack:

spin valve pillar structure $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}$

thickness N << λ_F

T_0 on top fixed



Measurement:

Current I_{12} through stack

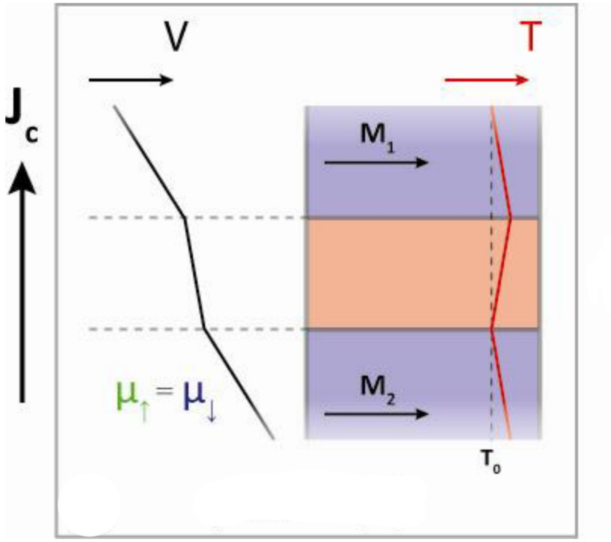
Thermocouple voltage $V_{3,4} = R_1 I + R_2 I^2 + \ldots$

AC lock-in technique separates
1st and 2nd harmonic response:

$$\Delta T_{\text{Peltier}} \propto I$$

$$\Delta T_{\text{Joule}} \propto I^2$$

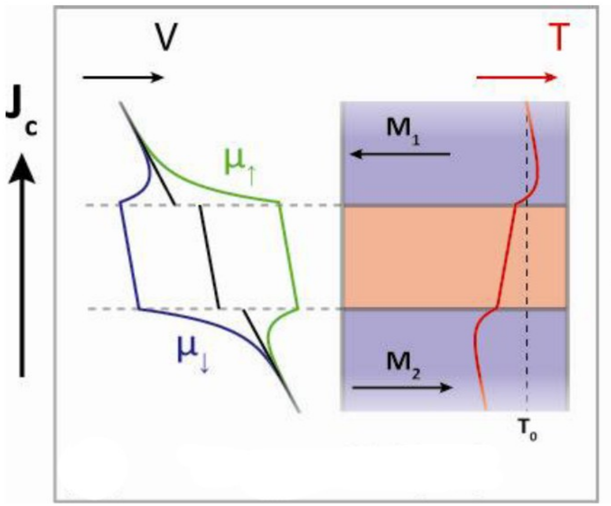
Spin Peltier effect in a stack I



Two configurations:

Parallel: $M_1 || M_2$

- Spin currents
  $J_{S1} = J_{S2}$
- No spin accumulation
  $\mu_S = 0$
- Joule heating and charge Peltier effect



Antiparallel: $M_1 \upharpoonleft\downharpoonright M_2$

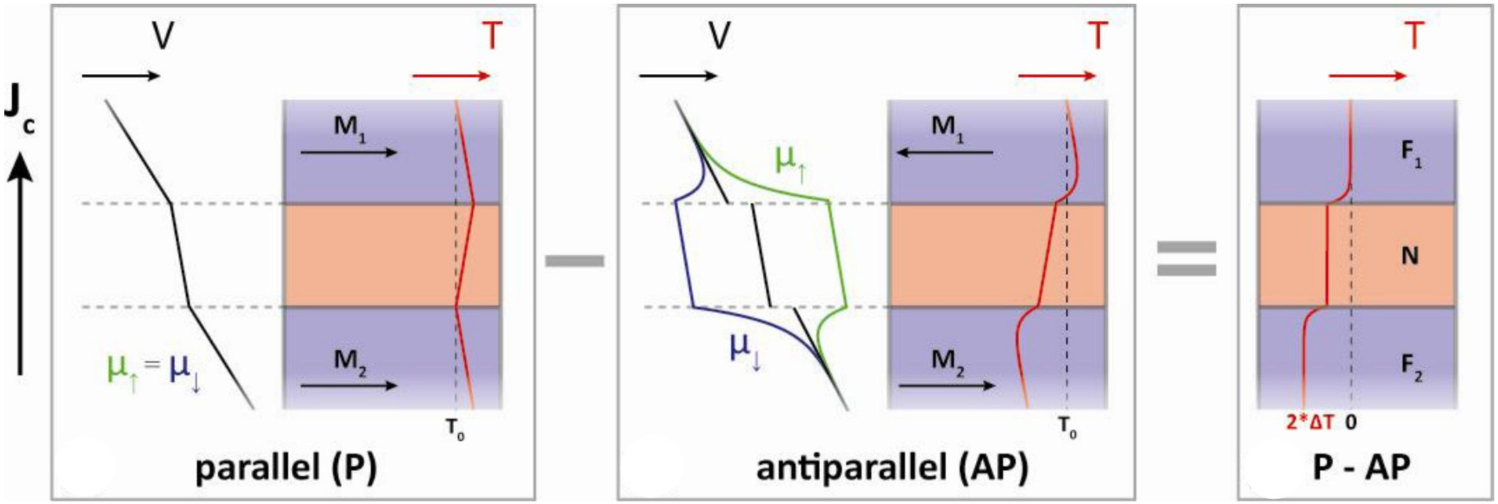
- Spin currents
  $J_{S1} = -J_{S2}$
- Spin accumulation at interfaces
  $\mu_S \neq 0$
- Spin Peltier effect
- Additional ΔT

↑ : spin majority electrons
↓ : spin minority electrons

Spin Peltier effect in a stack II

B-field sweep: $M_1 || M_2 \Rightarrow M_1 \upharpoonleft\downharpoonright M_2$

Extract spin Peltier part,
causes temperature change $\Delta T = 2\Delta T_{\text{Peltier}}$

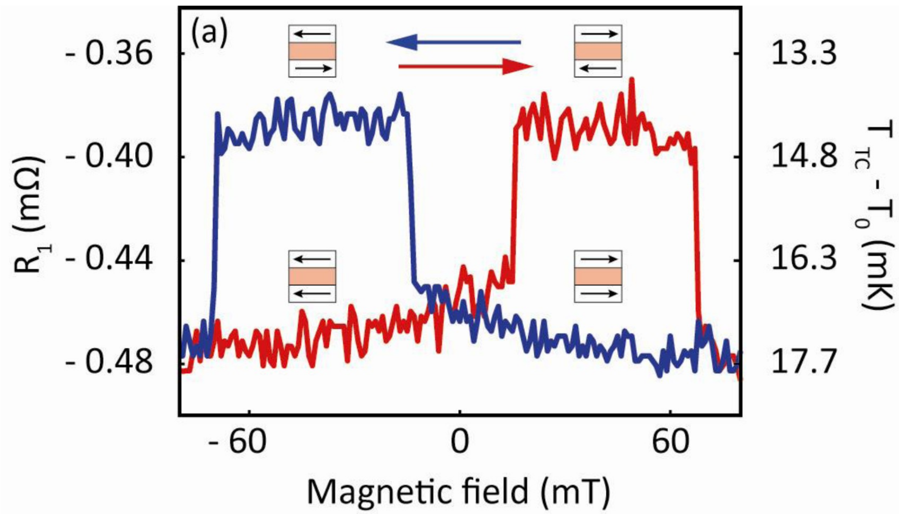


$$\nabla T_{\text{Peltier}} = -\frac{\sigma}{\kappa}\left(\underbrace{\Pi \nabla \mu_C}_{\text{charge}} + \underbrace{\frac{1}{4}(1-P_\sigma^2)\Pi_S \nabla \mu_S}_{\text{spin}}\right)$$

Extracted spin Peltier contribution

Measurements

$$V_{3,4} = \underbrace{R_1 I}_{\text{Peltier}} + \underbrace{R_2 I^2}_{\text{Joule}} + \ldots$$



1st harmonic response R_1

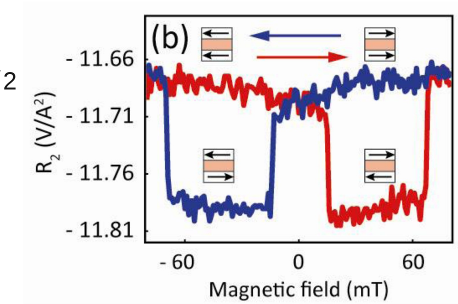
T = 300K

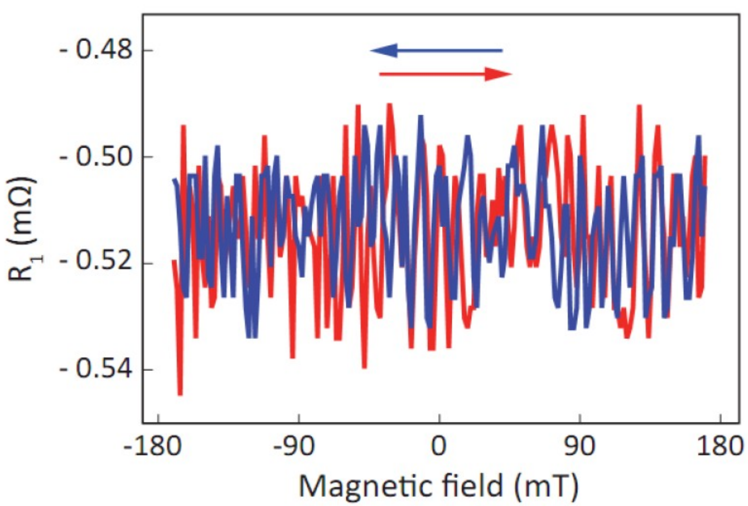
$\Delta T \approx 3\text{mK}$

$\Pi_S \approx -0.9\text{mV}$

2nd harmonic response R_2

Joule heating due to spin relaxation





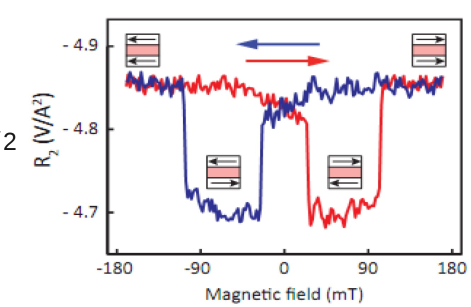
1st harmonic response R_1

T = 77K

No signal since $\Pi = S \cdot T$

$\Pi_S \propto T^2$

2nd harmonic response R_2



→ Measured effect at 300K is spin Peltier effect

Conclusions and outlook

- Introduction spin Peltier effect
- Direct experimental evidence of cooling/heating via spin currents
- Reached temperature difference $\Delta T \approx 3\,\text{mK}$
- Magnetically controllable heat current by employing the spin dependence of Peltier coefficient
- Non-metallic materials may enhance effect e.g. ferromagnetic oxides