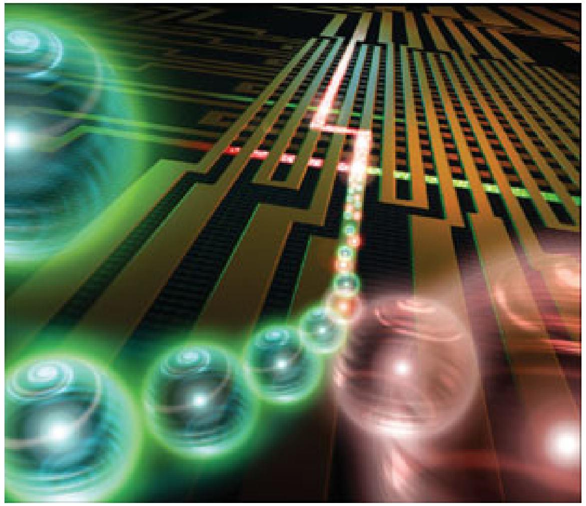
Master thesis

Spin Seebeck effect

Bertrand Lacoste

Under supervision of Pr. Jan Aarts
and daily supervision of Drs. M. Shahbaz Anwar

Spintronics

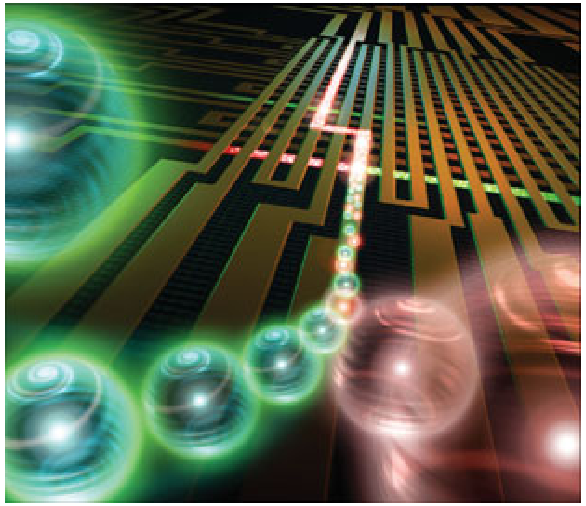


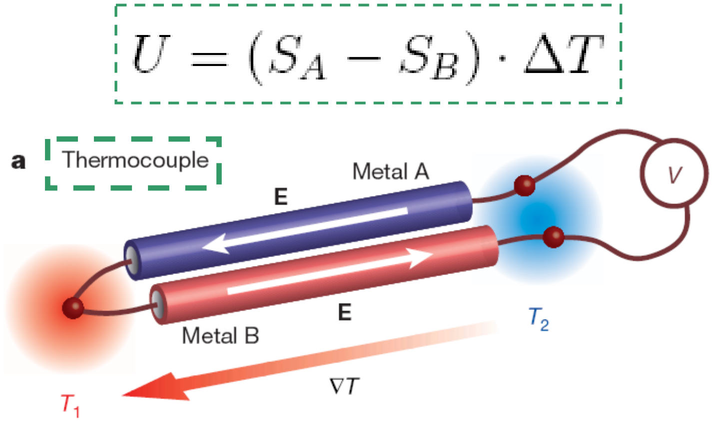
- Hard drive
- MRAM

- … spin-Transistor

- … … … …Quantum computer

Spintronics + calorimetrics





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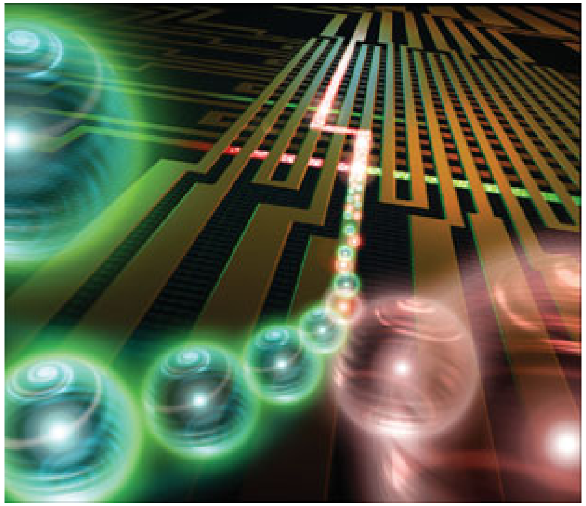
Spintronics + calorimetrics



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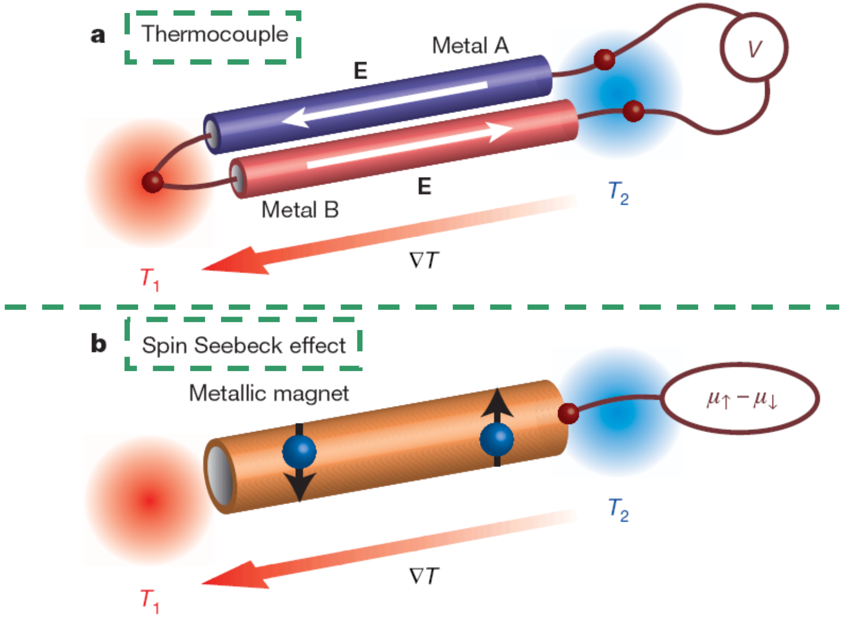
$$U = (S_A - S_B) \cdot \Delta T$$



$$U_s = S_s \, \Delta T$$

Outline

- Theory of spin-dependent thermoelectric transport
- Description of the results of Uchida et al. (Nature, 2008)
- Setup and experiment
- Results
- Possible explanations
- A new discovery ?

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} j_q \\ j_c \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c / 2e \end{pmatrix}$$

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} \\ 0 \end{pmatrix} = \begin{pmatrix} & \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c / 2e \end{pmatrix}$$

$$j_c = 0 \longrightarrow S = -\frac{\Delta V}{\Delta T}$$

Thermoelectric transport

Seebeck effect : Thermoelectric equation

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Mott's law :

$$S = -eL_0 T \frac{D'(\epsilon_F)}{D(\epsilon_F)}$$

$$j_c = 0 \longrightarrow S = -\frac{\Delta V}{\Delta T}$$

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} j_q \\ j_c \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c / 2e \end{pmatrix}$$

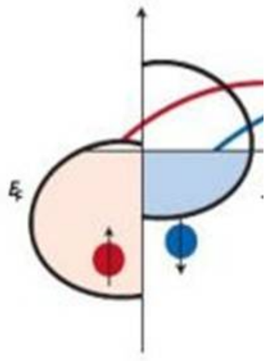
$$j_c = 0 \longrightarrow S = -\frac{\Delta V}{\Delta T}$$

Mott's law : $S = -eL_0 T \frac{D'(\epsilon_F)}{D(\epsilon_F)}$

Two-fluid model : Stoner model :

$$\epsilon_\uparrow(k) = \epsilon_0(k) - I\frac{n_\uparrow}{n}$$

$$\epsilon_\downarrow(k) = \epsilon_0(k) - I\frac{n_\downarrow}{n}$$



Thermoelectric transport

Seebeck effect : Thermoelectric equation

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Mott's law : $S = -eL_0 T \frac{D'(\epsilon_F)}{D(\epsilon_F)}$

$$j_c = 0 \rightarrow S = -\frac{\Delta V}{\Delta T}$$

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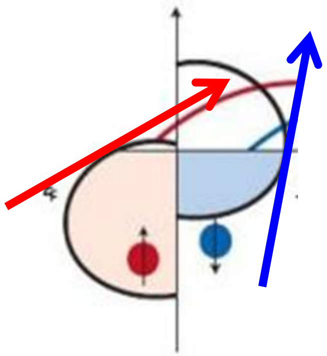

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} j_q \\ j_c \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c / 2e \end{pmatrix}$$

Mott's law :

$$S = -eL_0 T \frac{D'(\epsilon_F)}{D(\epsilon_F)}$$

$$j_c = 0 \longrightarrow S = -\frac{\Delta V}{\Delta T}$$

Two-fluid model :

$$\begin{pmatrix} j_q \\ j_c \\ j_s \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST & P'ST \\ S & 1 & P \\ P'S & P & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c / 2e \\ \nabla \mu_s / 2e \end{pmatrix}$$

$$P = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \qquad S = \frac{\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \qquad P' = \frac{\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow}{\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow} = \frac{\partial_\epsilon \sigma_\uparrow - \partial_\epsilon \sigma_\downarrow}{\partial_\epsilon \sigma_\uparrow + \partial_\epsilon \sigma_\downarrow}$$

Gravier et al., PRB **73**, 024419, 2006

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} j_q \\ j_c \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c/2e \end{pmatrix}$$

Mott's law : S $= -eL_0 T \frac{D'(\epsilon_F)}{D(\epsilon_F)}$

$j_c = 0$ → $S = -\frac{\Delta V}{\Delta T}$

Two-fluid model :

$$\begin{pmatrix} \\ 0 \\ j_s \end{pmatrix} = \begin{pmatrix} & & \\ S & 1 & P \\ P'S & P & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c/2e \\ \nabla \mu_s/2e \end{pmatrix}$$

$j_c = 0$

Thermoelectric transport

Seebeck effect : Thermoelectric equation

$$\begin{pmatrix} j_q \\ j_c \end{pmatrix} = \sigma \begin{pmatrix} \frac{\kappa}{\sigma} & ST \\ S & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c/2e \end{pmatrix}$$

Mott's law :

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Two-fluid model :

$$\begin{pmatrix} \\ 0 \\ j_s \end{pmatrix} = \begin{pmatrix} & & \\ S & 1 & P \\ P'S & P & 1 \end{pmatrix} \begin{pmatrix} -\nabla T \\ \nabla \tilde{\mu}_c/2e \\ \nabla \mu_s/2e \end{pmatrix}$$

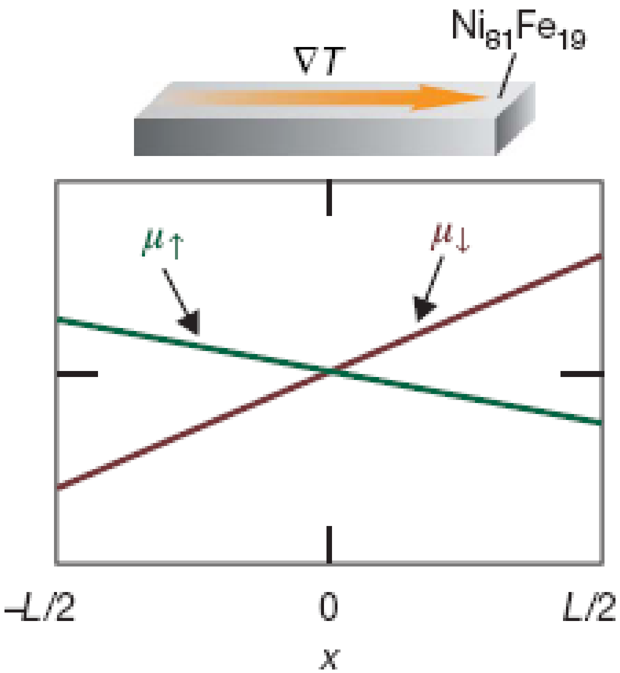
$$j_c = 0 \rightarrow$$

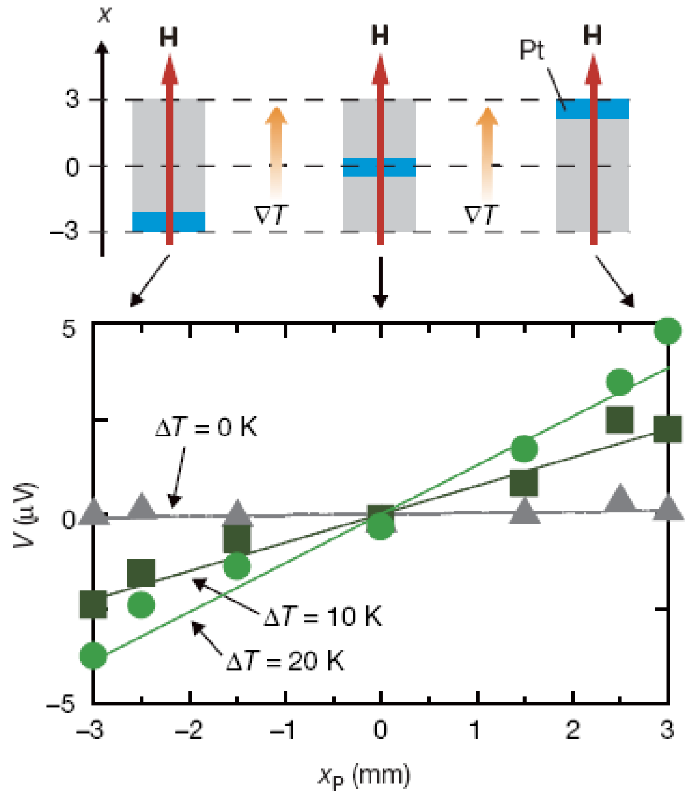
$$\nabla \mu_s/2e = \frac{-1}{P}[-S\nabla T + \nabla \tilde{\mu}_c/2e]$$

$$j_s = \sigma \left[(P' - \frac{1}{P})(-S\nabla T) + (P - \frac{1}{P})\nabla \tilde{\mu}_c/2e \right]$$

Spin Seebeck effect

Uchida et al., Nature, Oct 2008 :

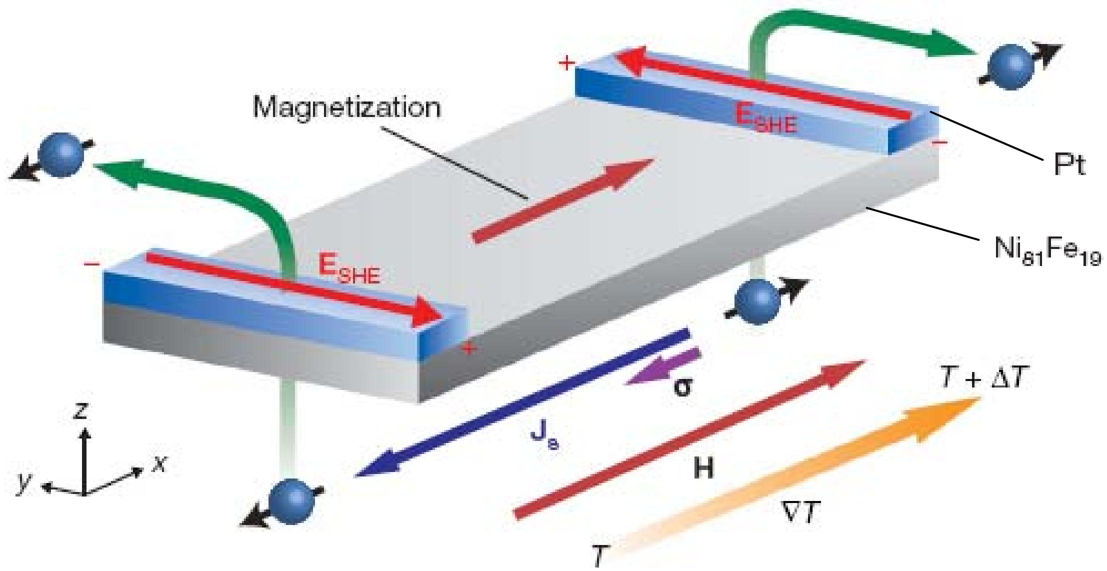




$$\mu_{\uparrow} - \mu_{\downarrow} = eS_S(\nabla T)x$$

Two principles in the experiment:

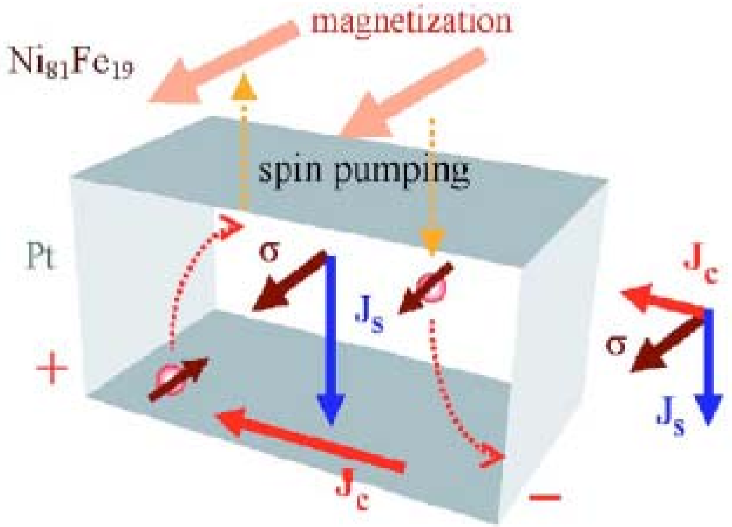
- spin-Seebeck effect: generation of a spin voltage in the magnet
- inverse spin-Hall effect (ISHE): transformation of a spin current into a charge current.



$$L_{Pt} = 4\text{mm}$$
$$w_{Pt} = 100\mu\text{m}$$
$$d_{Pt} = 10\text{nm}$$

$$L_{Py} = 6\text{mm}$$
$$w_{Py} = 4\text{mm}$$
$$d_{Py} = 20\text{nm}$$

Inverse spin-Hall effect :

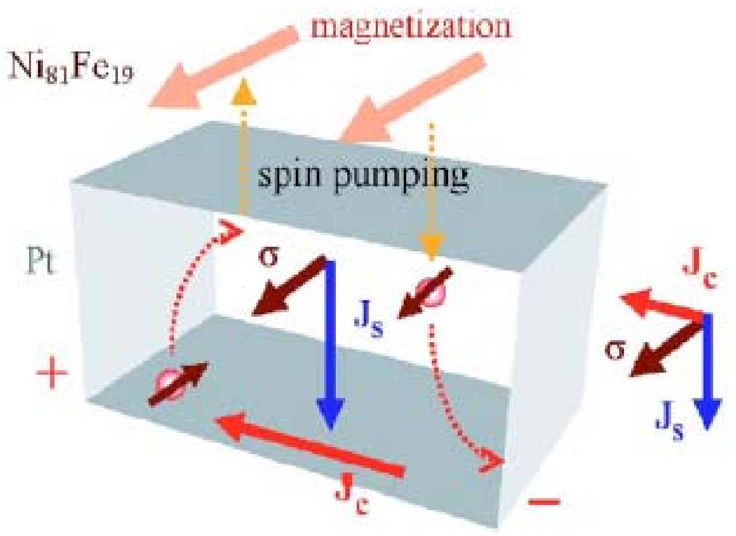


$$\mathbf{J}_c = D_{ISHE} \mathbf{J}_s \times \boldsymbol{\sigma}.$$

Effect due to spin-orbit coupling

Needs spin injection in Pt !

Inverse spin-Hall effect :

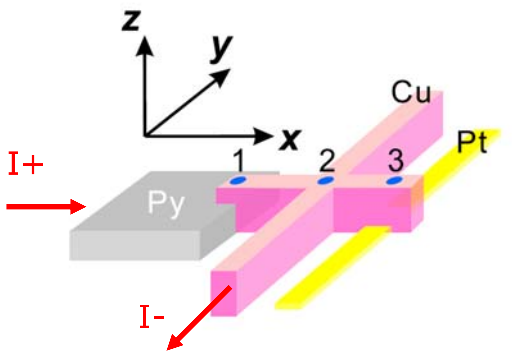


$$\mathbf{J}_c = D_{ISHE}\mathbf{J}_s \times \boldsymbol{\sigma}.$$

Effect due to spin-orbit coupling

Needs spin injection in Pt !

$$V \approx \theta_{Pt}\eta_{NiFe-Pt}(L_{Pt}/d_{Pt})S_S \Delta T/2$$



Hall angle ~ D_{ISHE} : $\theta_{Pt} = 0.0037$

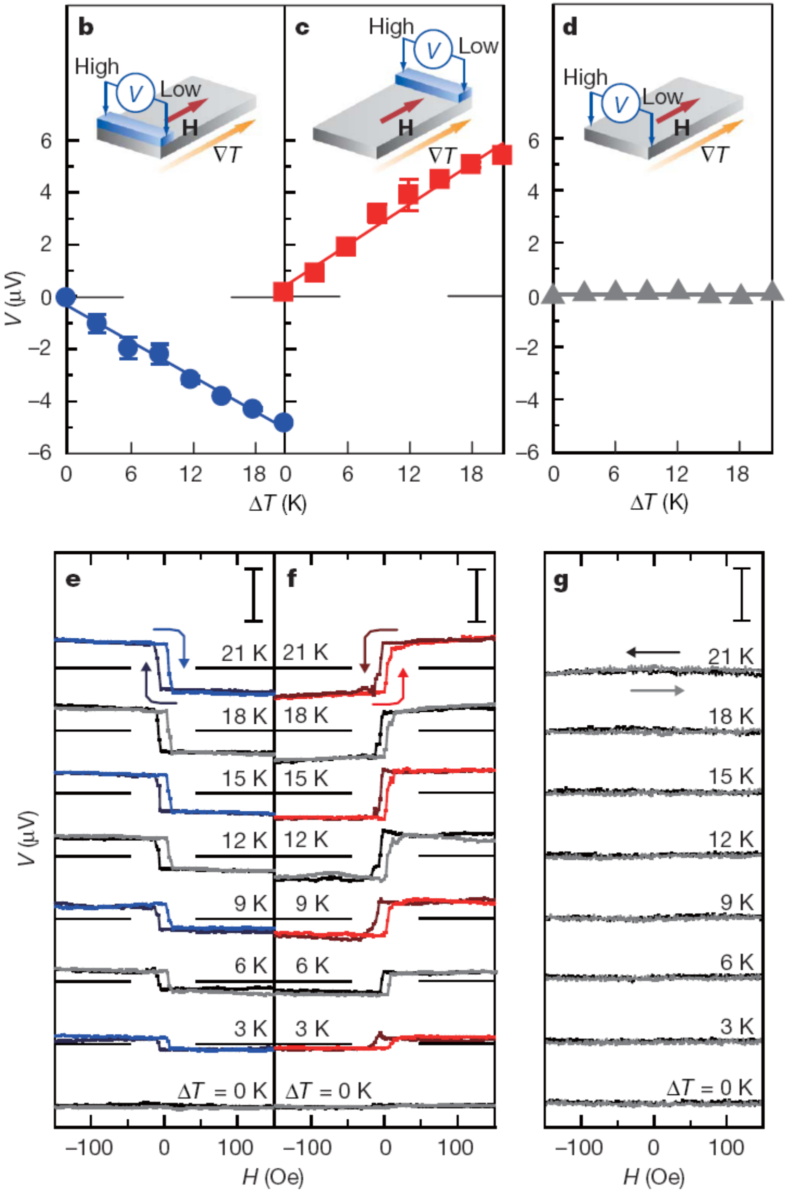
$\eta_{NiFe-Pt} \approx 0.2$

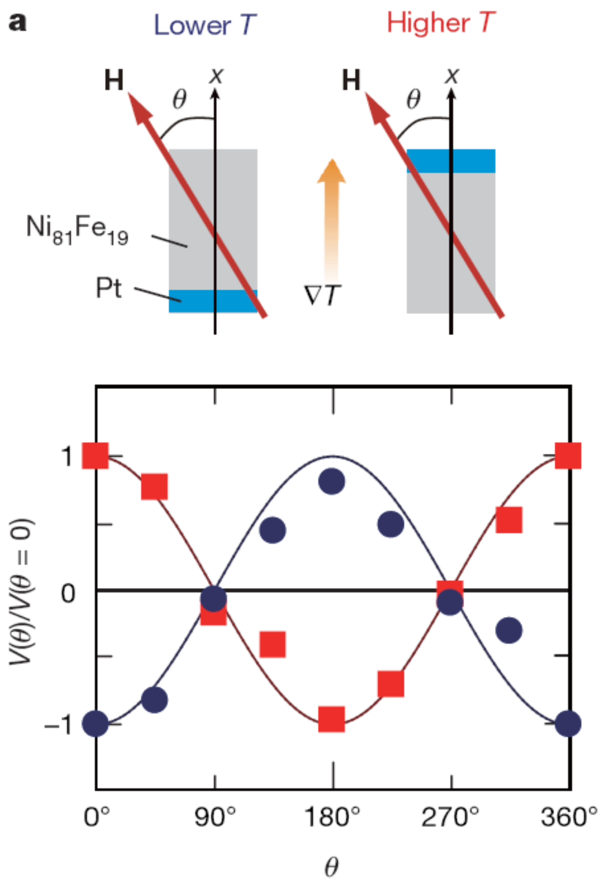
$L_{Pt}/d_{Pt} \approx 4 \times 10^5$

Kimura et al., PRL **98**, 2007 :

Field effect :

$$\mathbf{J}_c = D_{ISHE} \mathbf{J}_s \times \boldsymbol{\sigma}.$$





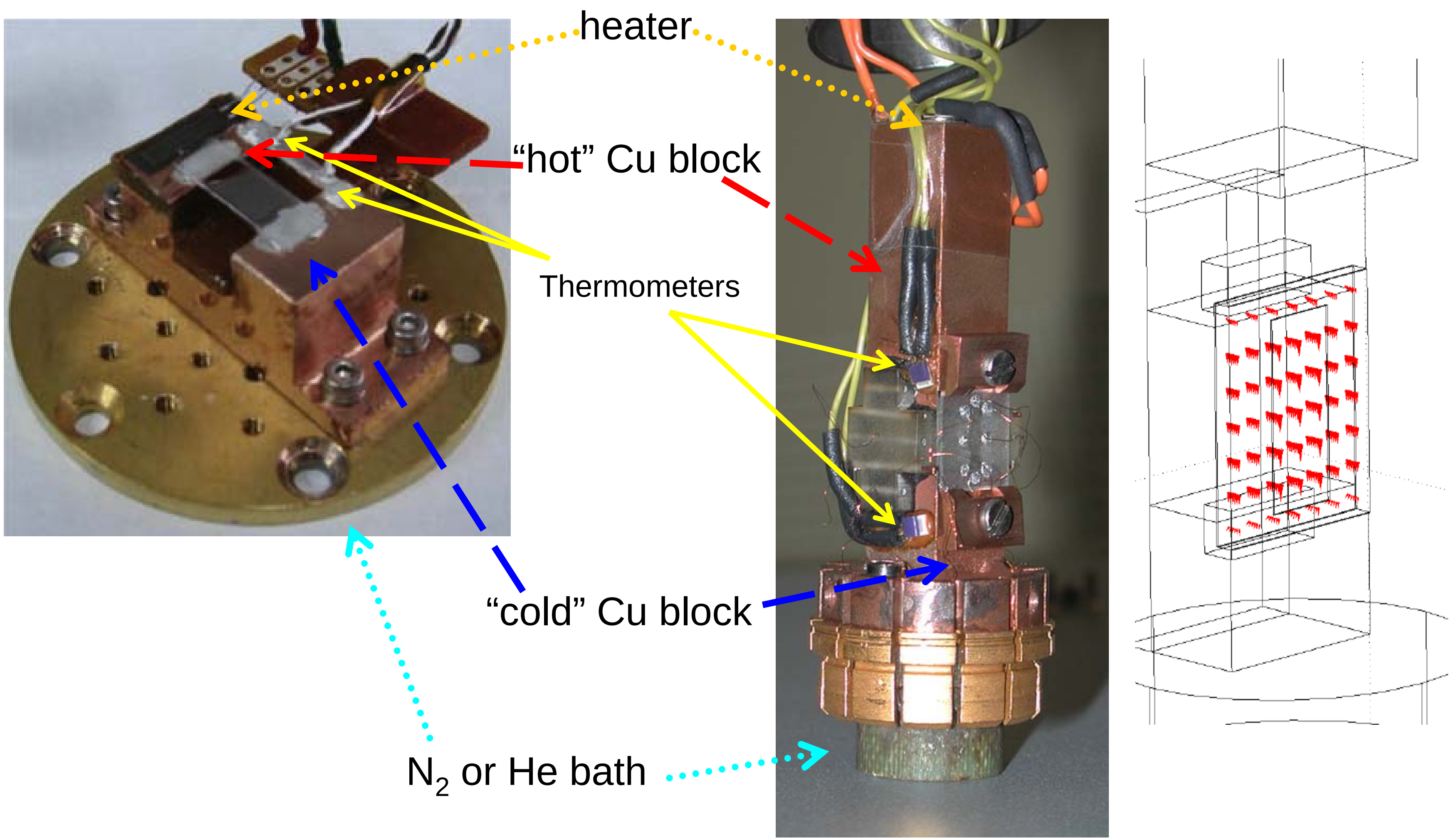
Uchida et al., Nature, Oct 2008 :

Experiment :

Comparison

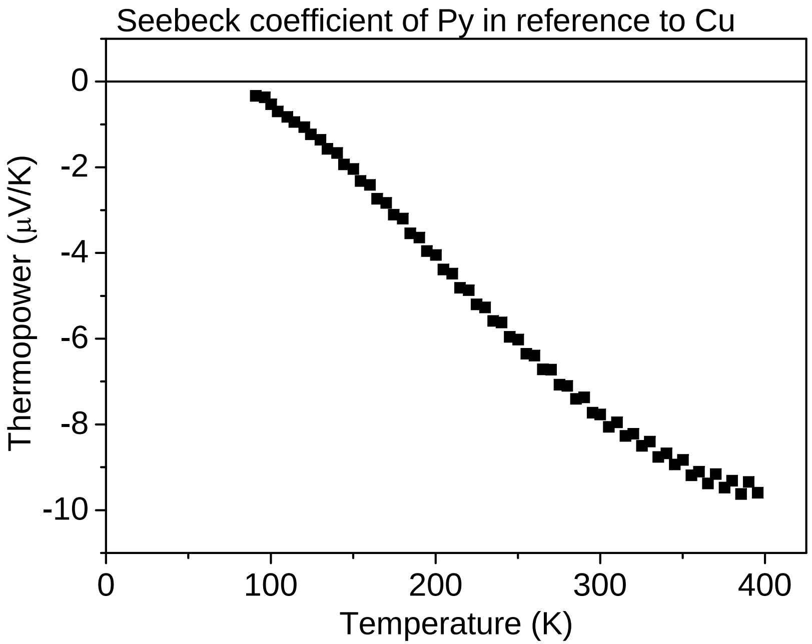
Made in Japan

Made in Holland



Experiment :

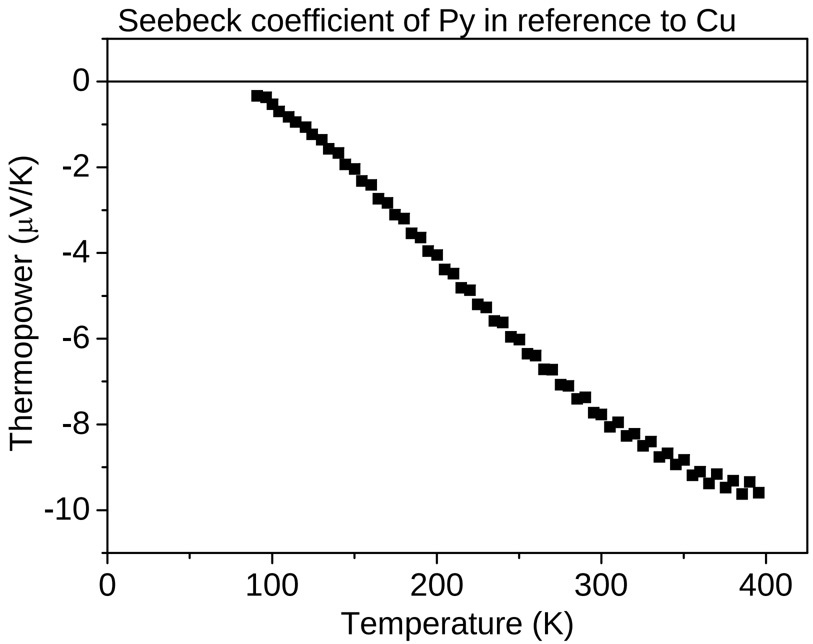
Normal Seebeck coefficient



10x10 Py film, 20nm thick on Al_2O_3

Experiment :

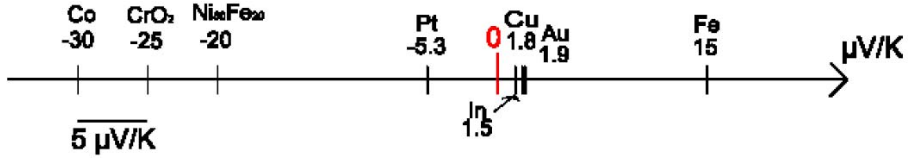
Normal Seebeck coefficient



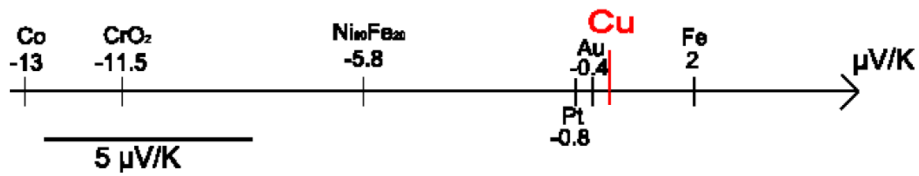
10x10 Py film, 20nm thick on Al_2O_3

Absolute thermopower at 300K

In literature :



Our measurements :

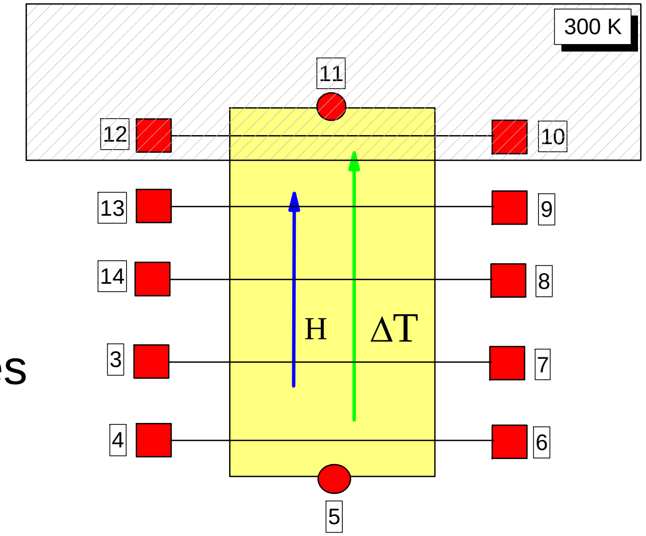


Results : exp #1

4x8 mm Py strip

5x0.1 mm Pt wires

2 mm spacing between wires

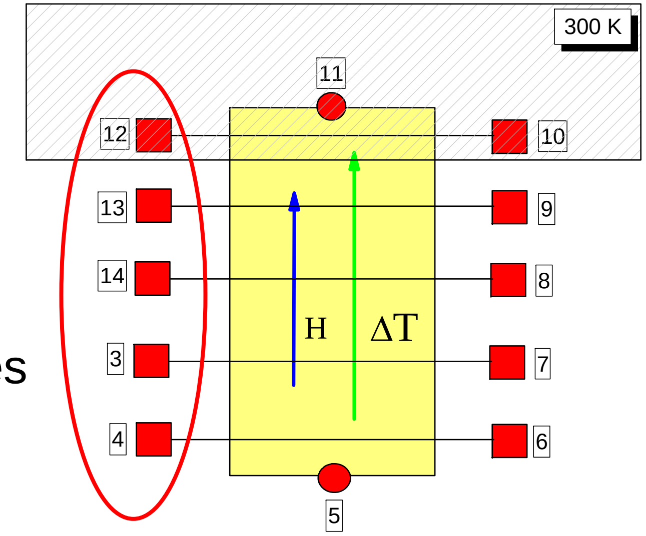


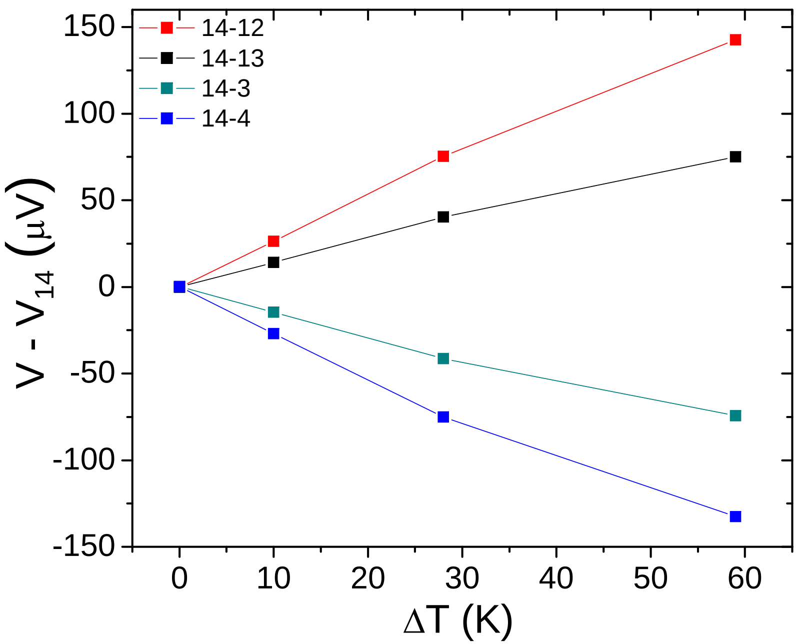
Results : exp #1

4x8 mm Py strip

5x0.1 mm Pt wires

2 mm spacing between wires



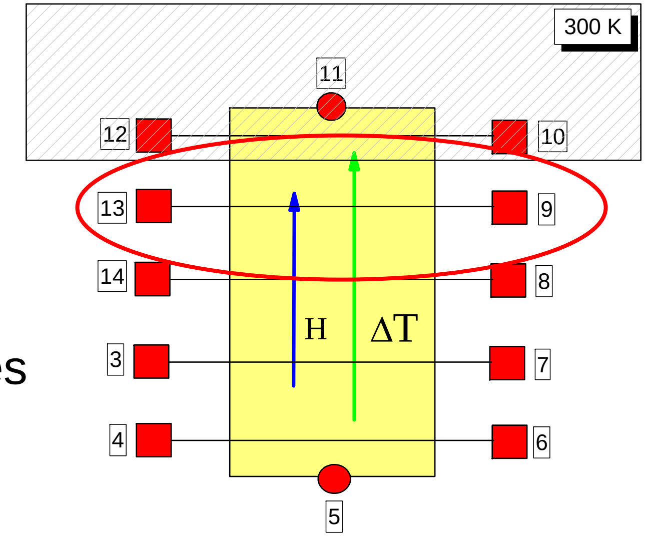


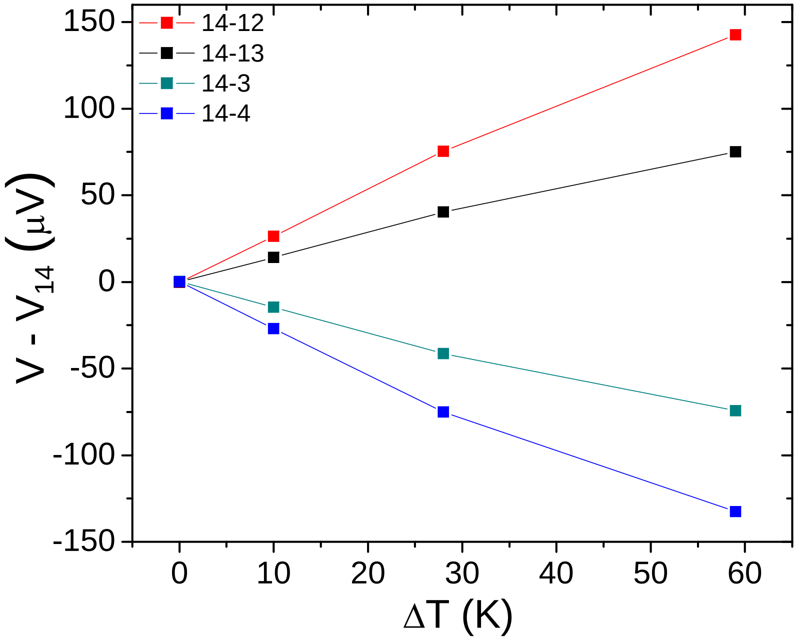
Results : exp #1

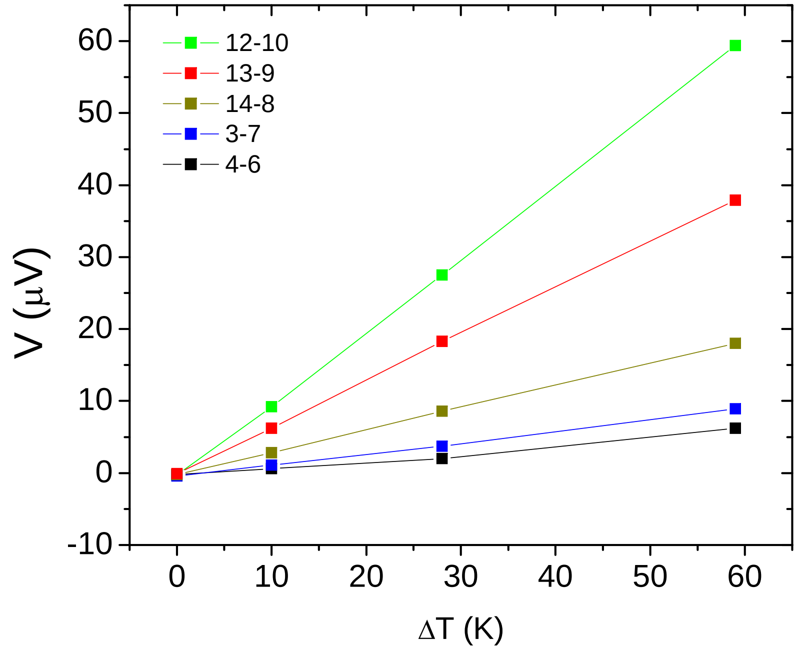
4x8 mm Py strip

5x0.1 mm Pt wires

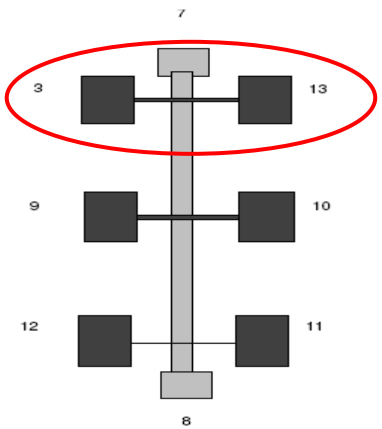
2 mm spacing between wires



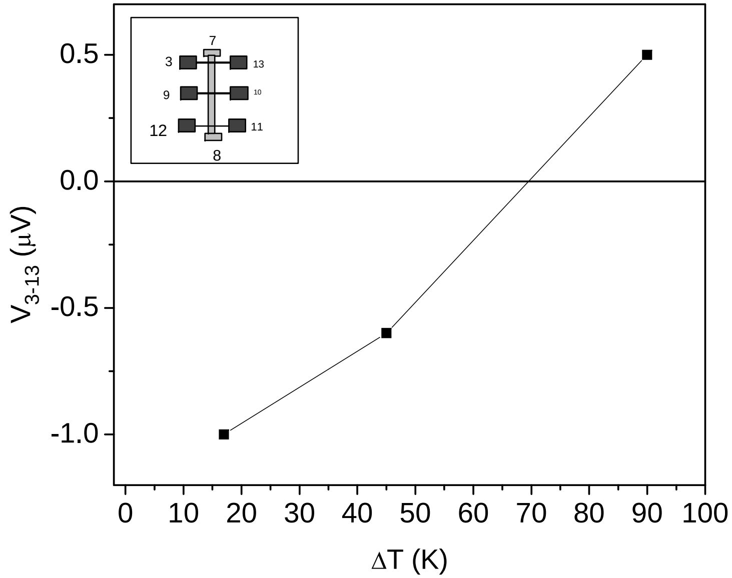




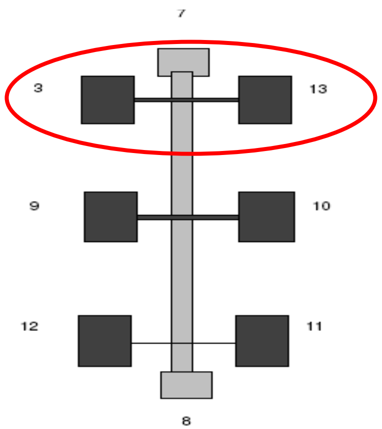
Results : exp #2



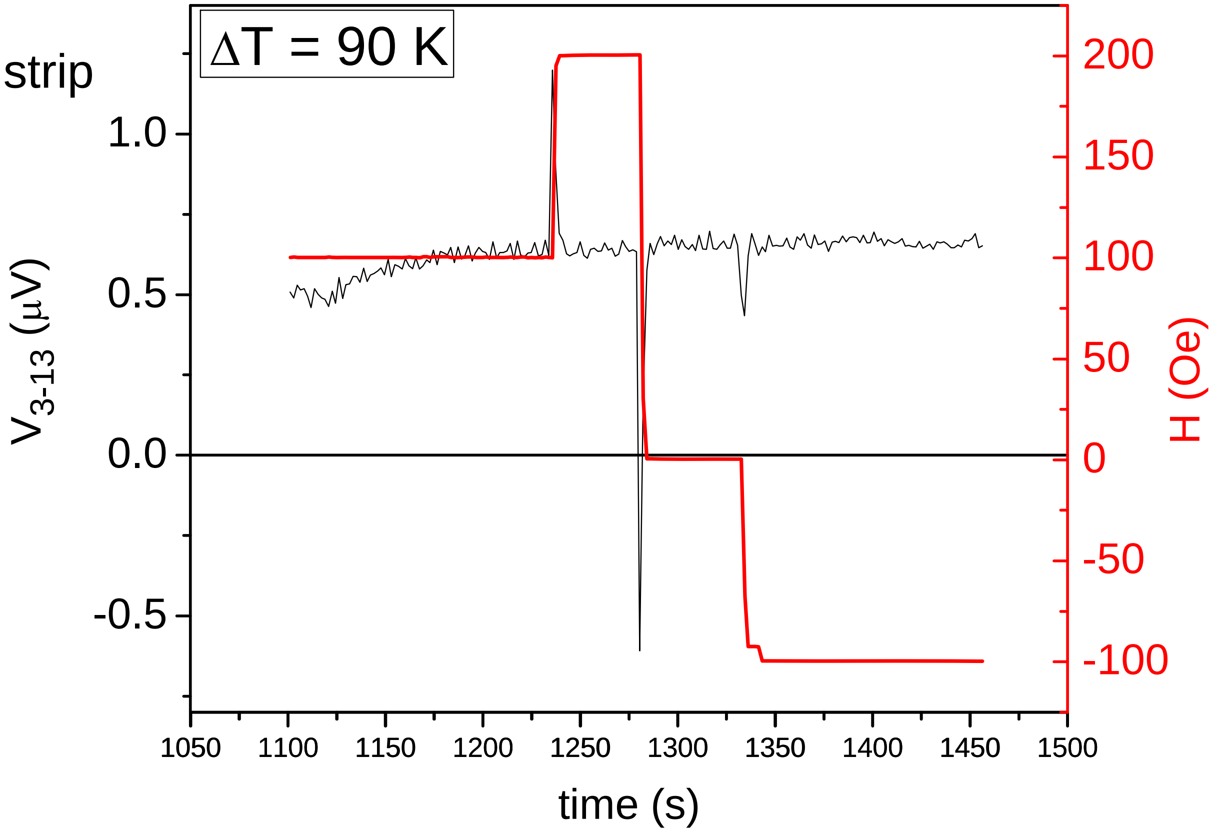
0.4x6 mm Py strip



Results : exp #2



0.4x6 mm Py strip

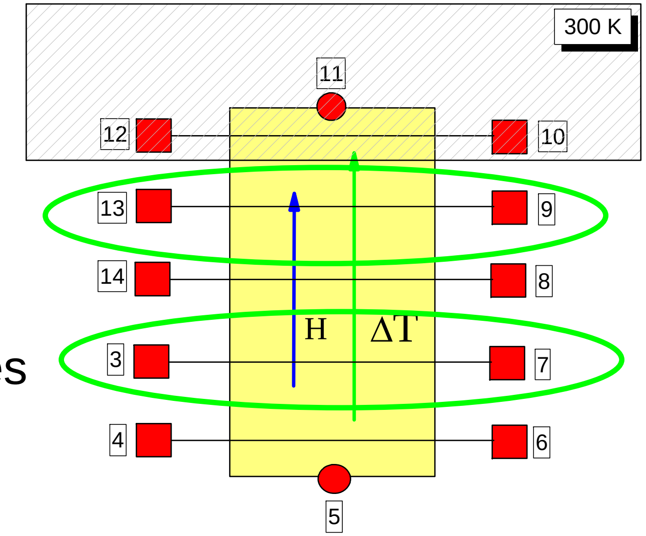


Results : exp #1

4x8 mm Py strip

5x0.1 mm Pt wires

2 mm spacing between wires

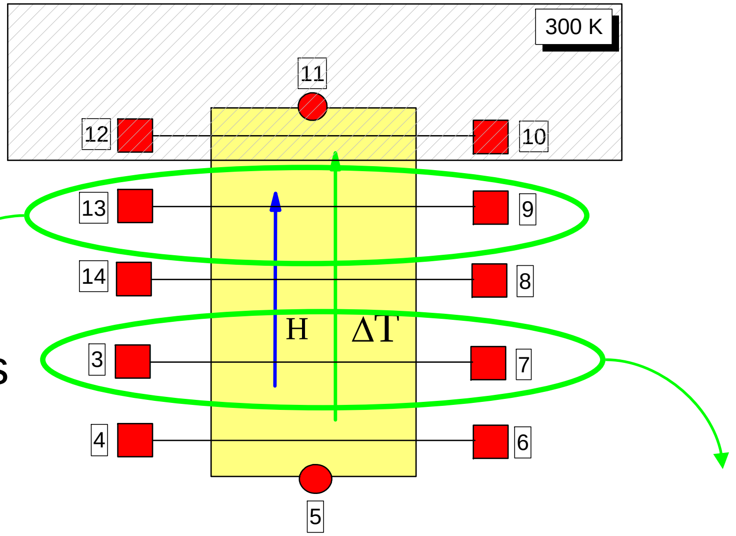


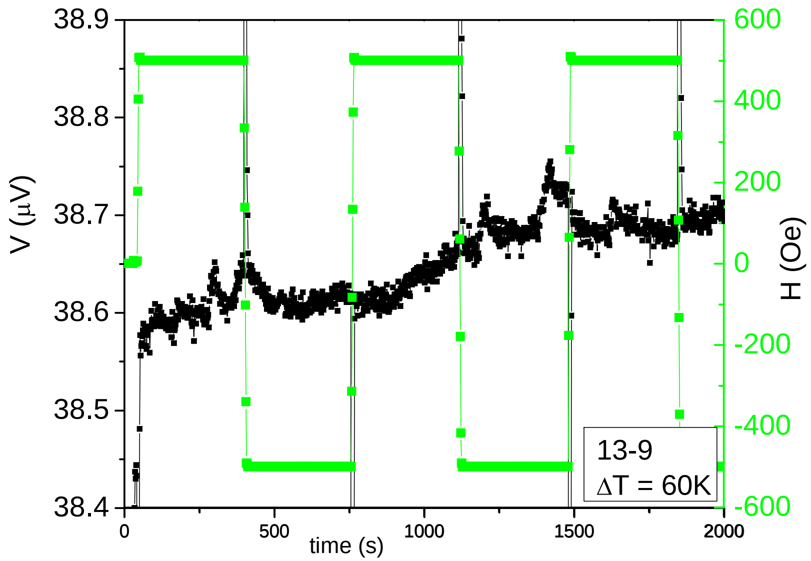
Results : exp #1

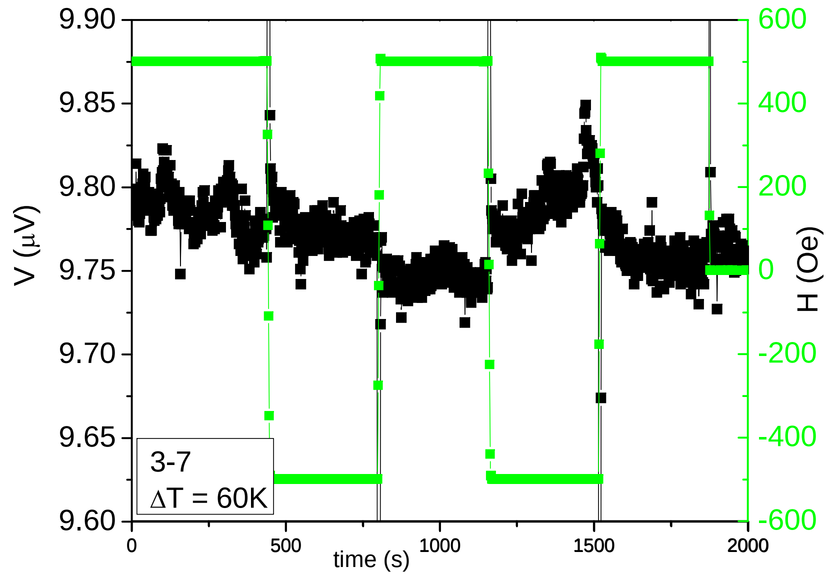
4x8 mm Py strip

5x0.1 mm Pt wires

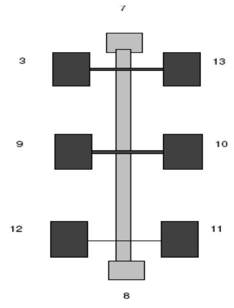
2 mm spacing between wires

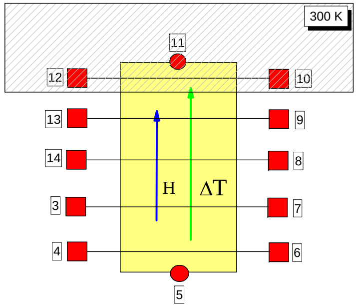


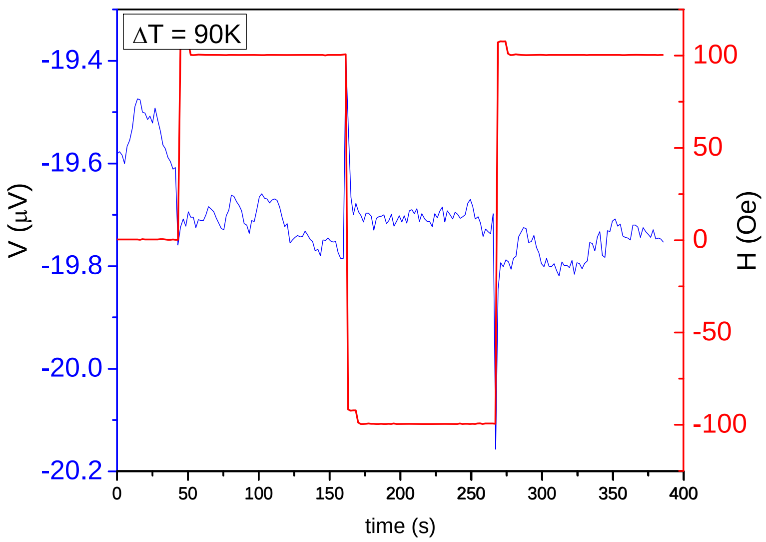


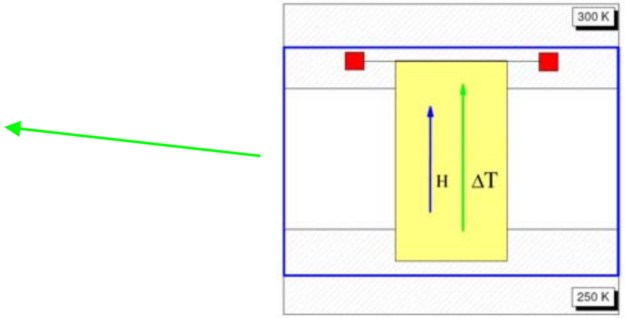


- narrow Py strip, three Pt wires on top.
- wide Py strip, three Pt wires on top.
- wide Py strip, five Pt wires under it.
- wide Py strip, five Pt wires on top.
- wide Py strip, single Pt wires under it.





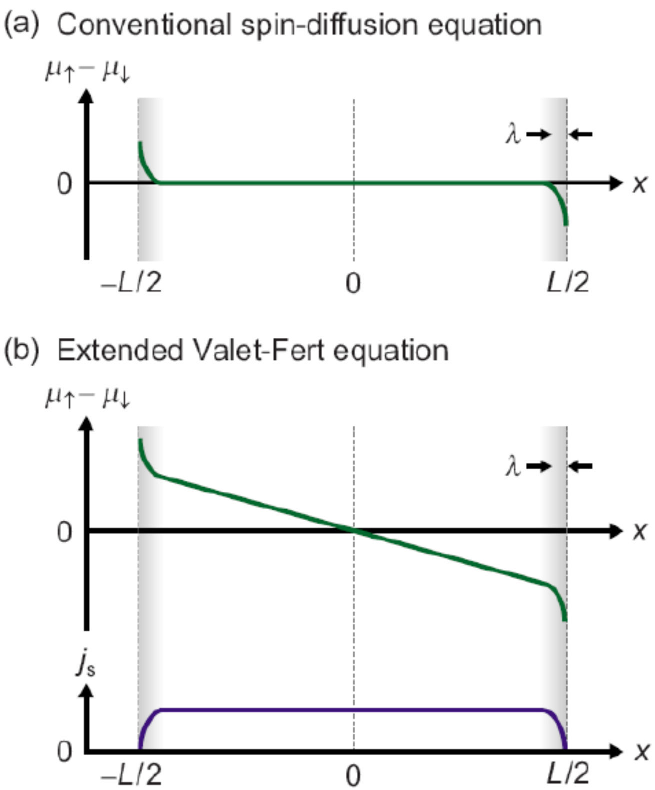




Partial conclusion

- Unable to reproduce the previous experiment
- Questions about spin injection in Pt
- Questions about the theoretical model

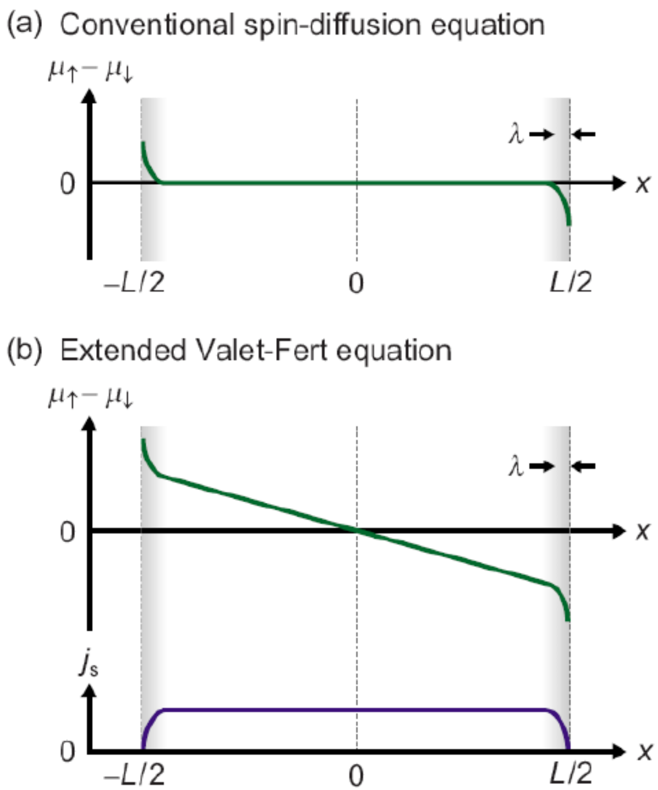
Can we doubt Uchida's experiment?



$$\mu_\uparrow - \mu_\downarrow = e\lambda(S_\uparrow - S_\downarrow)\frac{\sinh(x/\lambda)}{\cosh(L/2\lambda)}\nabla T.$$

$$\mu_\uparrow - \mu_\downarrow = eS_S(\nabla T)x$$

Can we doubt Uchida's experiment?



$$\mu_\uparrow - \mu_\downarrow = e\lambda(S_\uparrow - S_\downarrow)\frac{\sinh(x/\lambda)}{\cosh(L/2\lambda)}\nabla T.$$

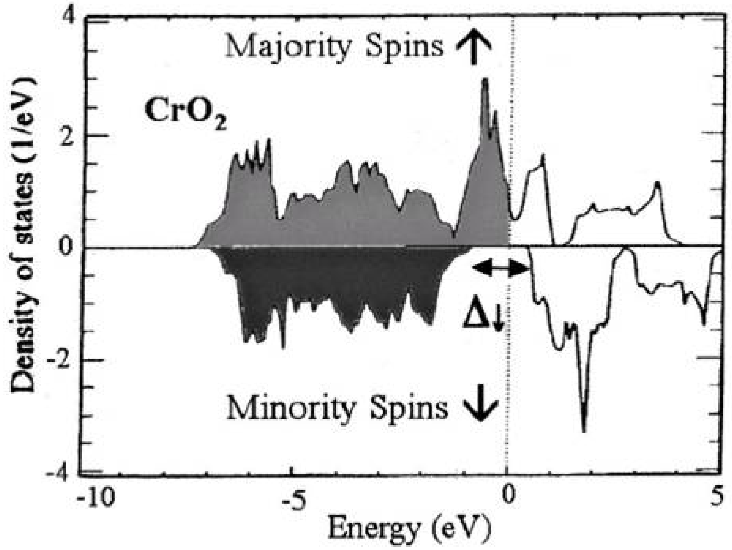
$$\mu_\uparrow - \mu_\downarrow = eS_S(\nabla T)x$$

Hatami et al., Solid State Communications, 2010

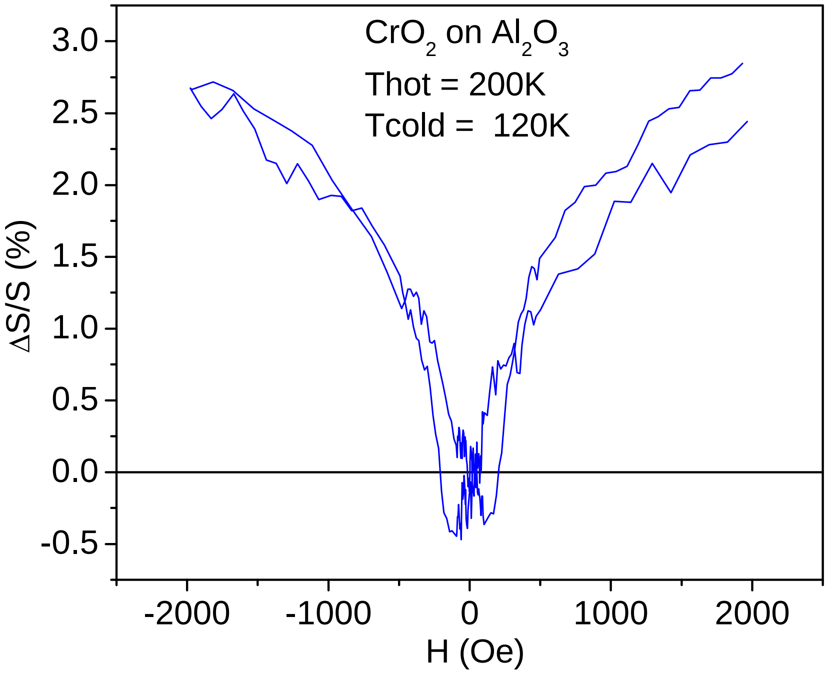
Anisotropic magneto-thermopower

Half-metal : Chromium dioxide

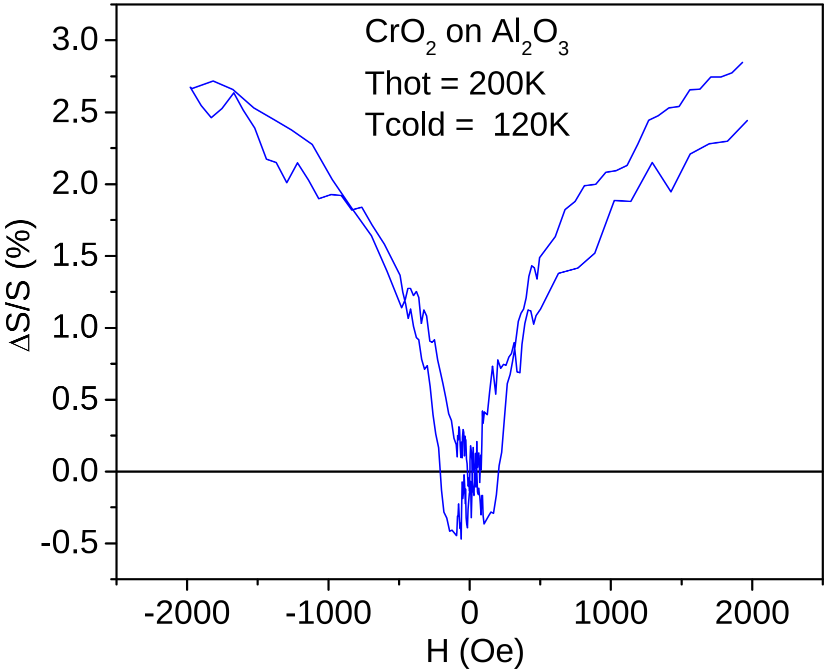
P = 1

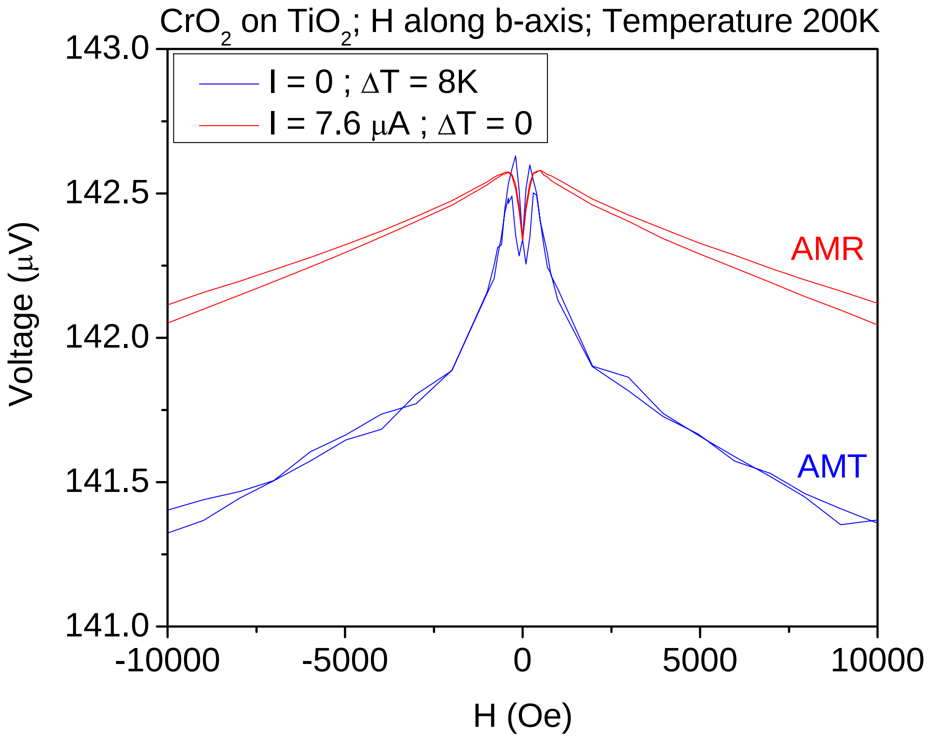


Anisotropic magneto-thermopower

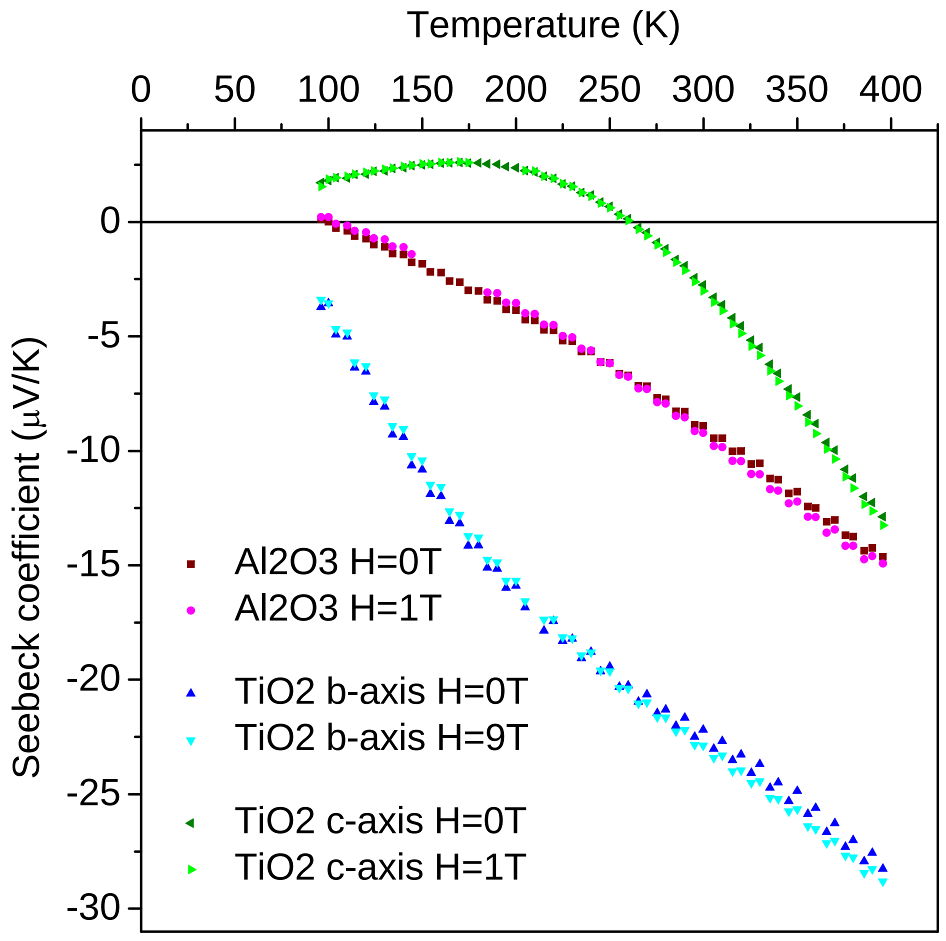


Anisotropic magneto-thermopower





Anisotropic magneto-thermopower



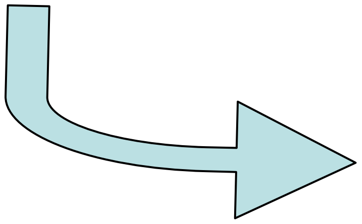
Conclusion

- Unable to reproduce Uchida’s experiment
- Difficult to prove who is right
- An interesting feature in CrO_2

Do you want more answers ?

Then ask questions

Field effect :

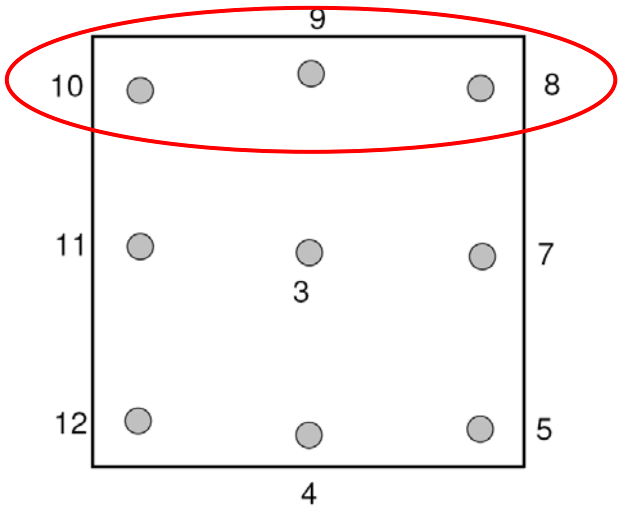


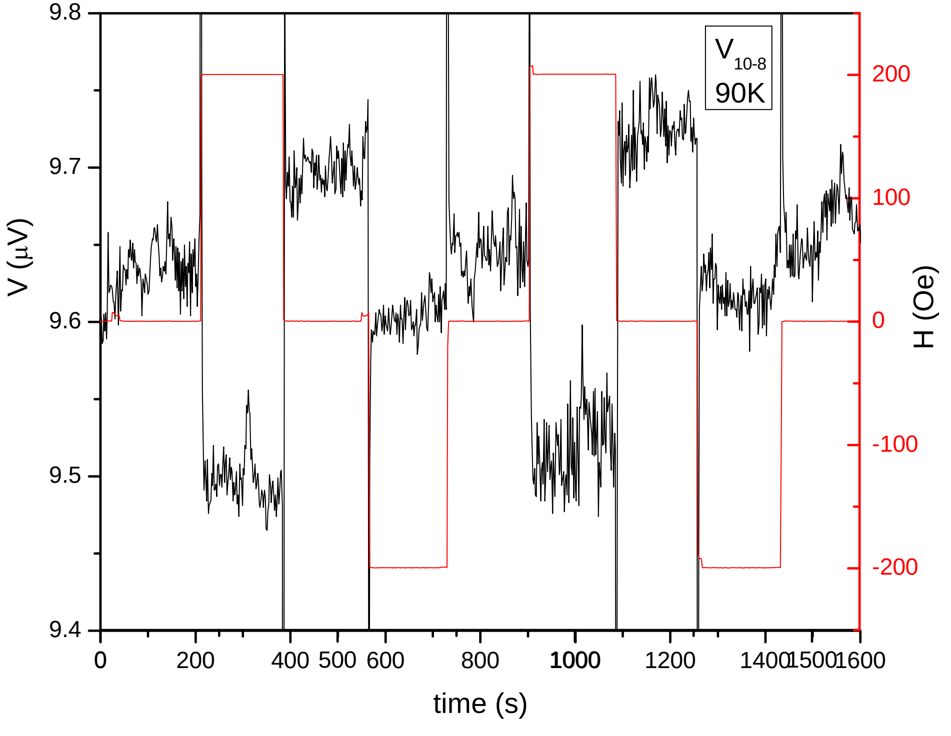
But not spin Hall voltage

High temperature difference

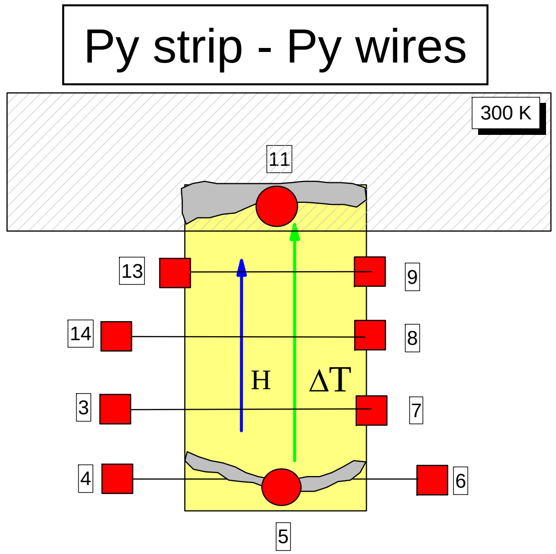
No Pt

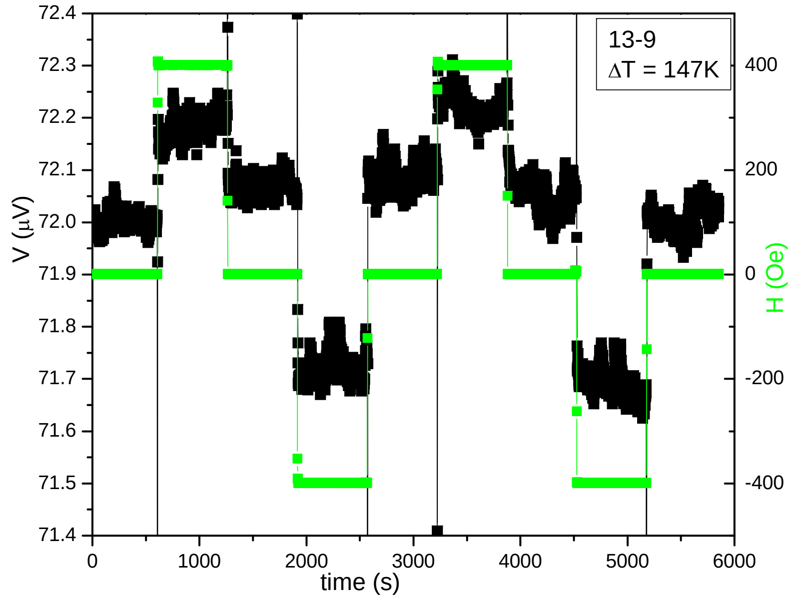
10 nm thick Py film

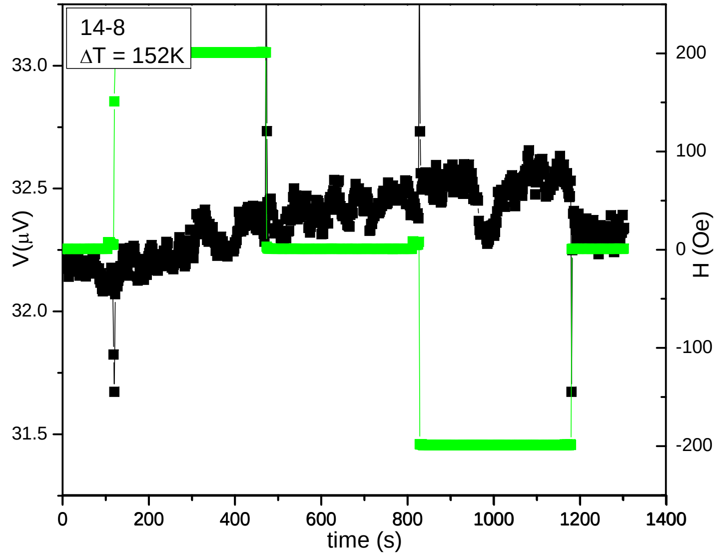


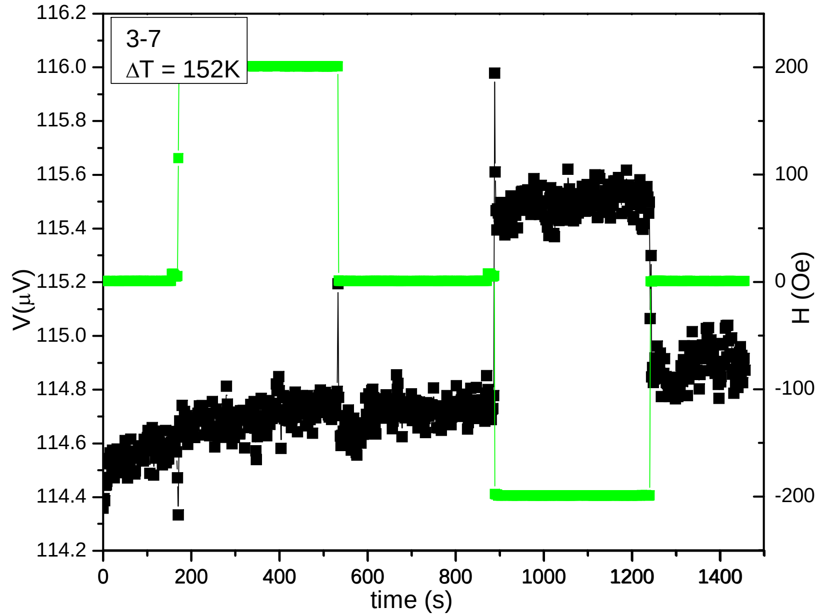


Field effect :

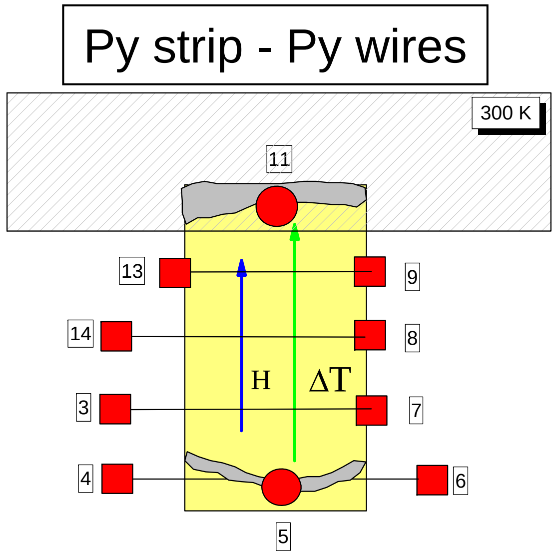


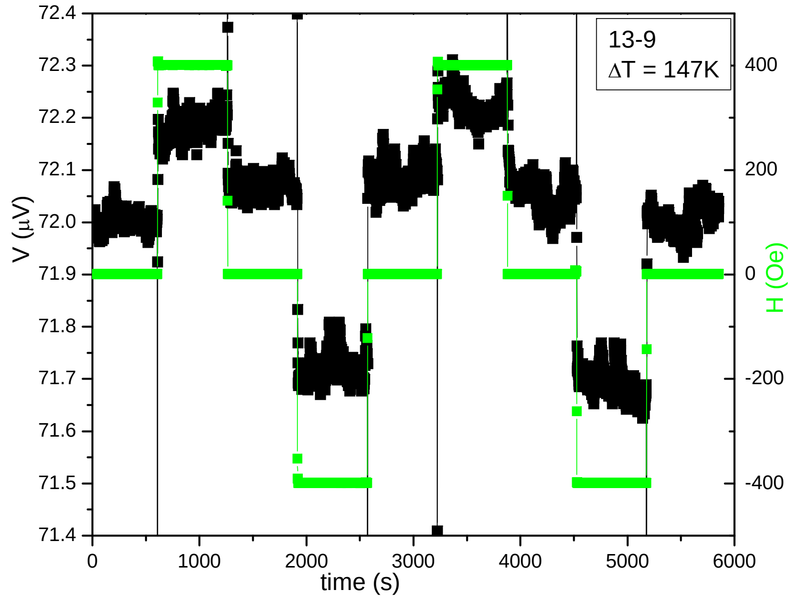


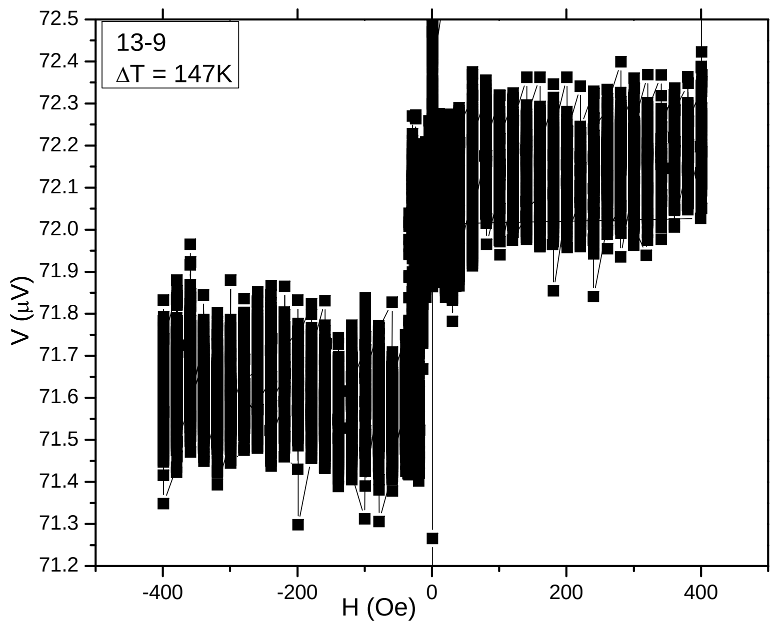


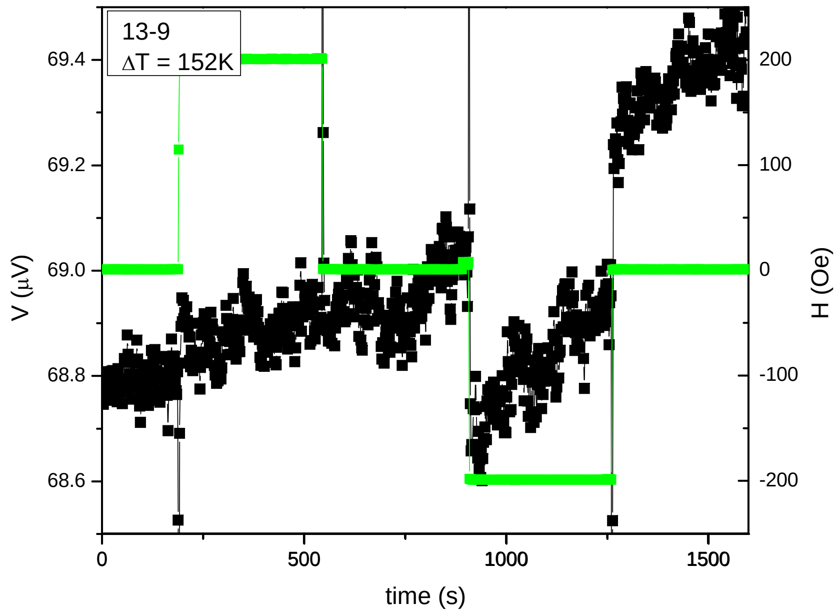


Field effect :



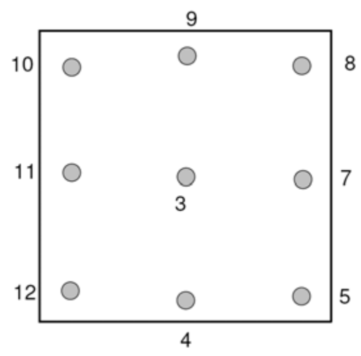


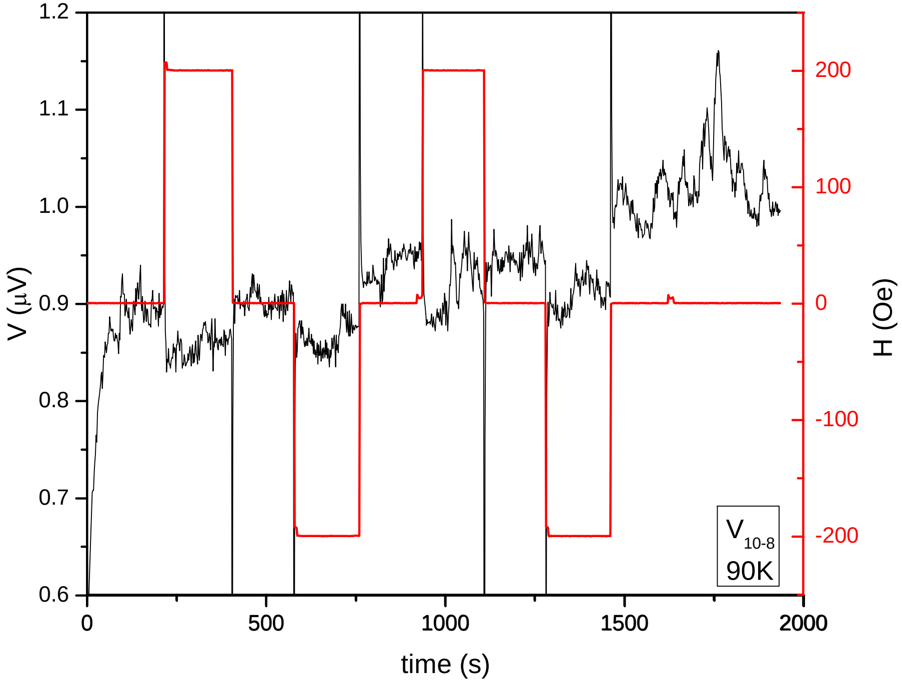


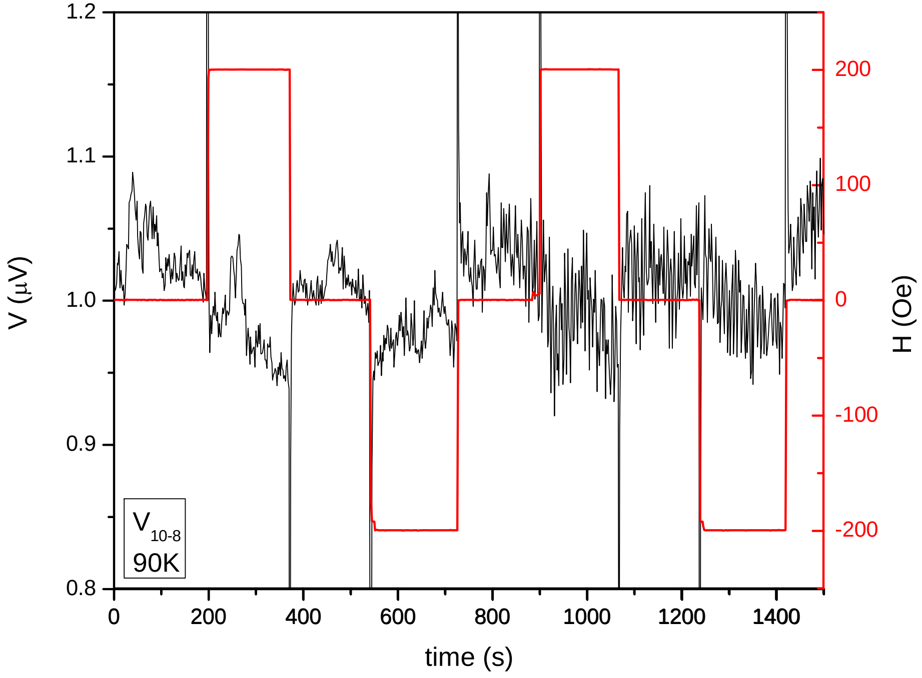


Field effect :

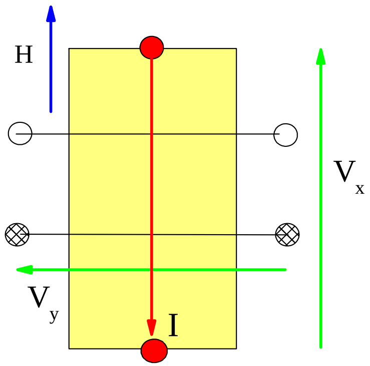
20 nm thick Au film on MoGe







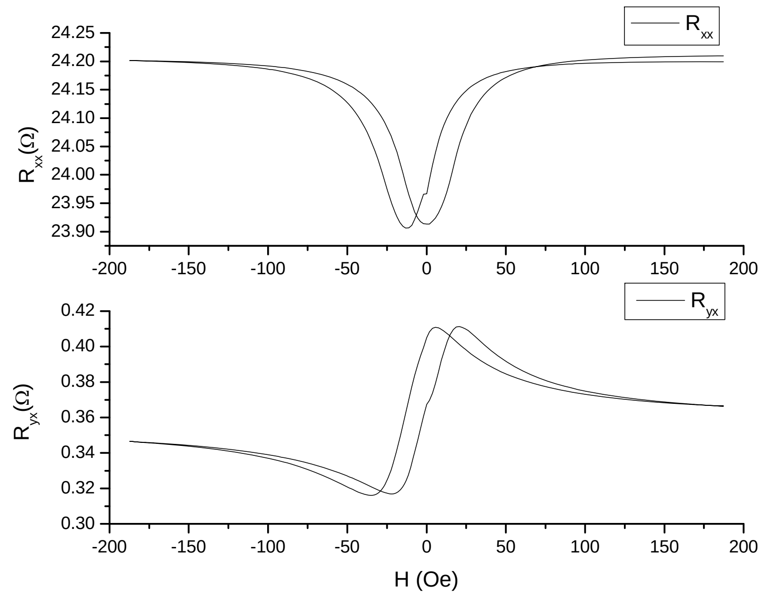
Planar Hall effect and AMR

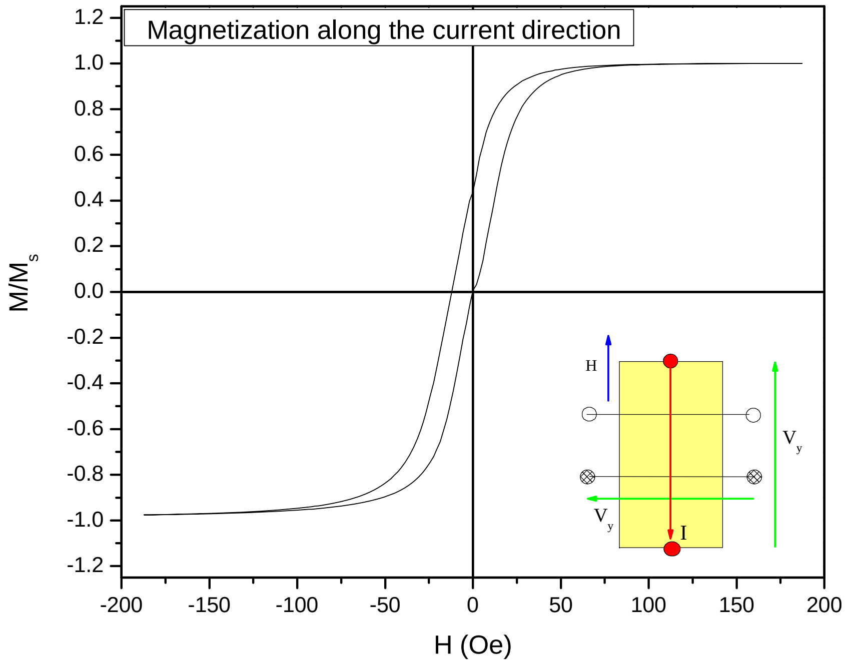


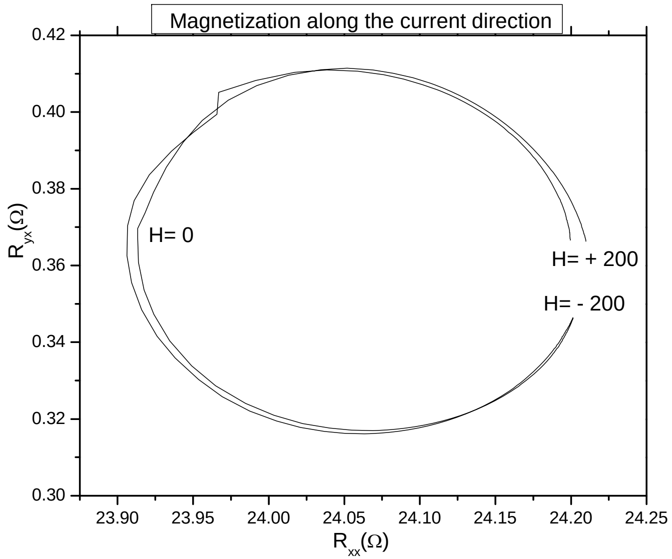
T = 4K

Anisotropic magnetoresistance for single domain :

$$E_x = \left[\frac{\rho_\parallel + \rho_\perp}{2} + \frac{\rho_\parallel - \rho_\perp}{2}\cos 2\theta_M\right] J_x$$
$$E_y = \left[\frac{\rho_\parallel - \rho_\perp}{2}\sin 2\theta_M\right] J_x$$

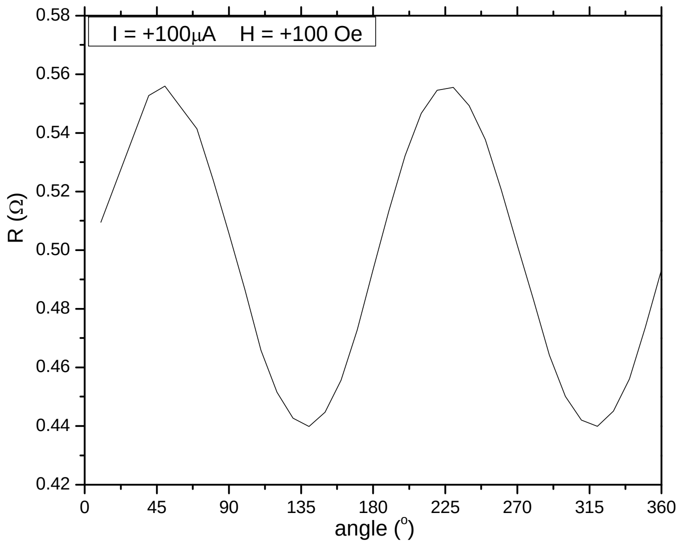


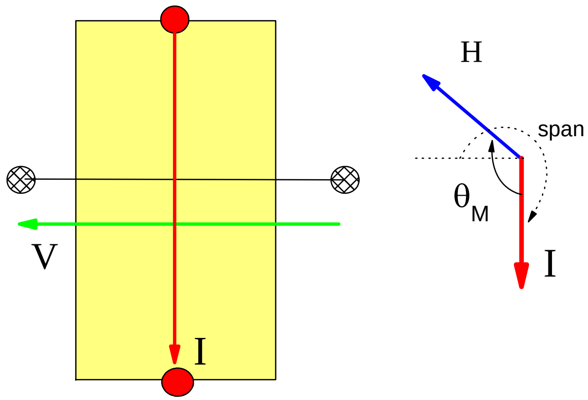


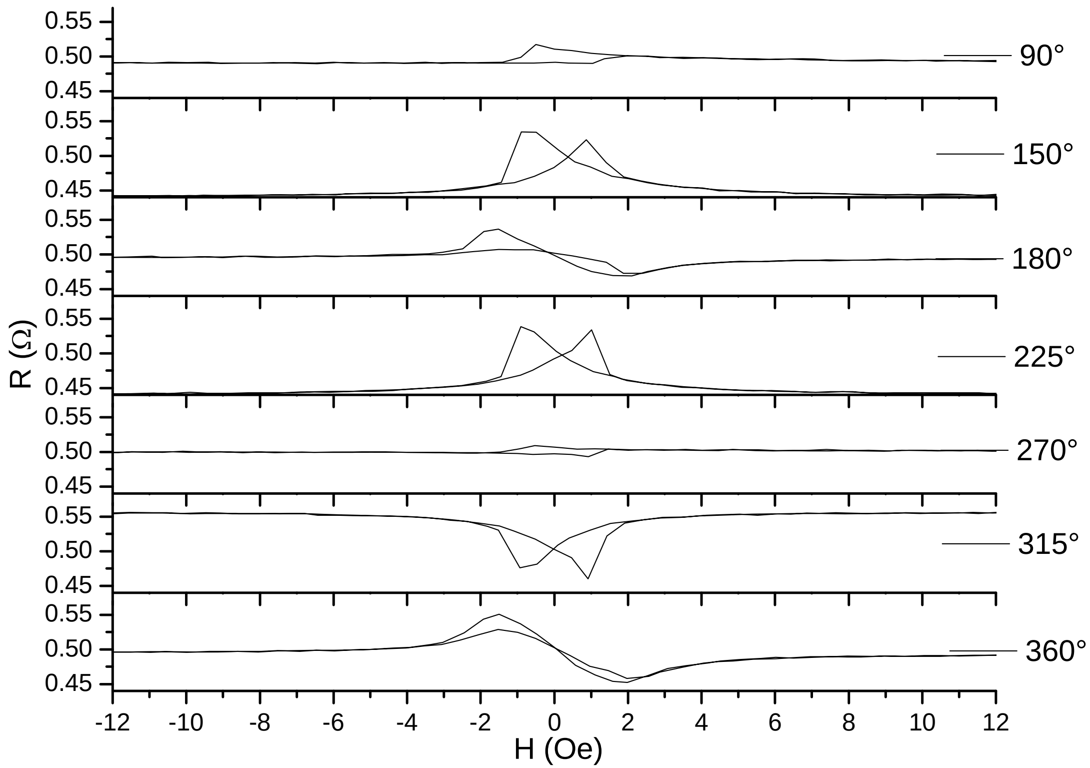


Planar Hall effect and AMR

Room temperature





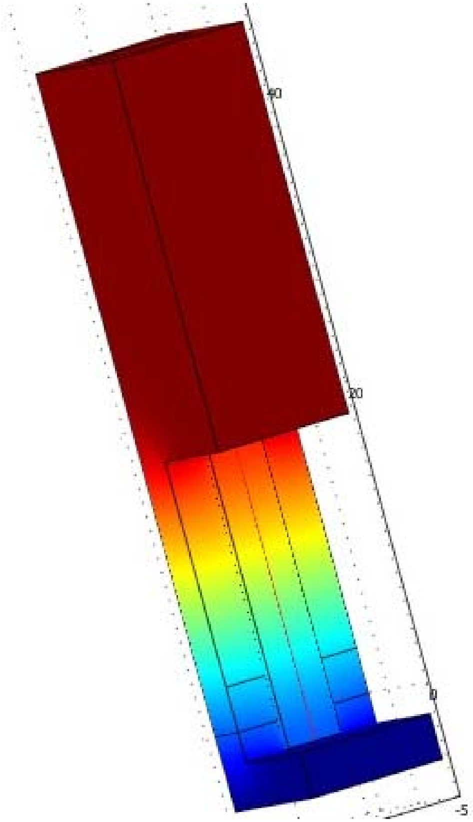


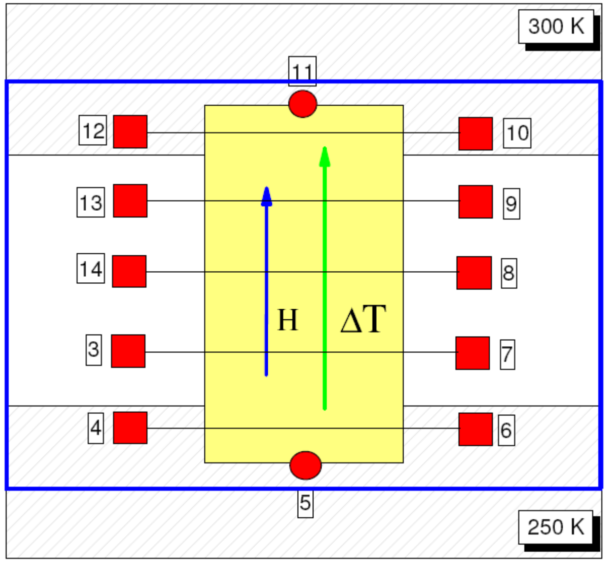
Anisotropic magnetoresistance for single domain :

$$E_x = \left[\frac{\rho_\parallel + \rho_\perp}{2} + \frac{\rho_\parallel - \rho_\perp}{2}\cos 2\theta_M\right] J_x$$

$$E_y = \left[\frac{\rho_\parallel - \rho_\perp}{2}\sin 2\theta_M\right] J_x$$

Experiment



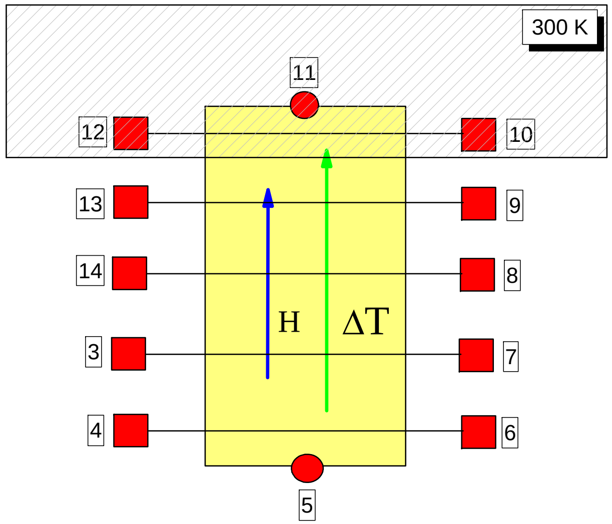


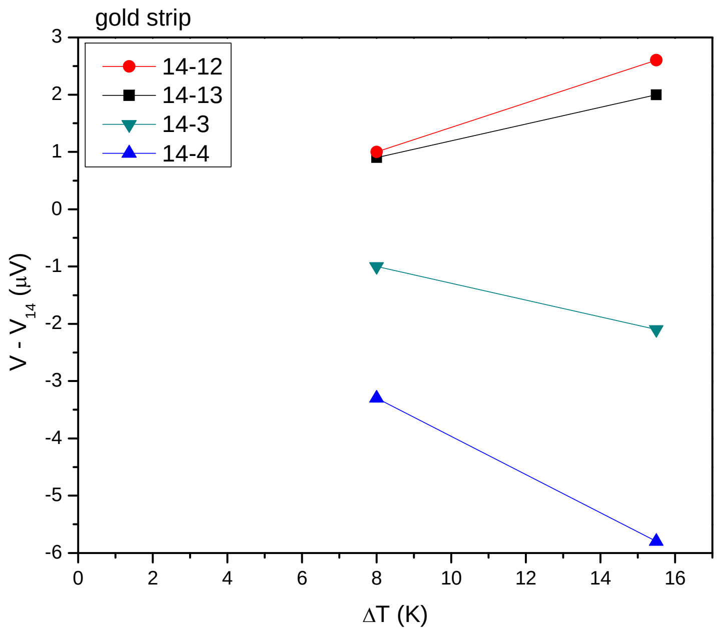
4x8 mm Py strip

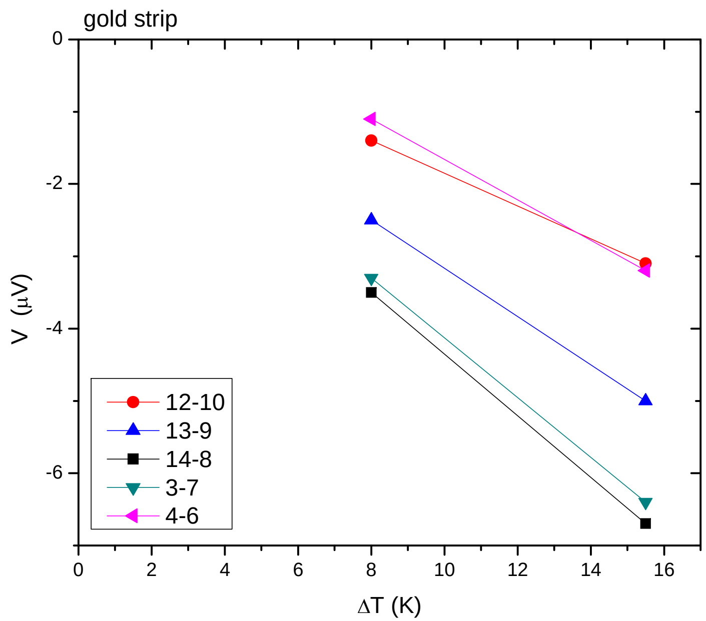
5x0.1 mm Pt wires

2 mm spacing between wires

Au strip - Pt wires







Py strip - Py wires