Spin dependent thermoelectrics

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FOM

Thermal spin transport in metal systems

- Introduction into thermoelectrics
- Spin caloritronics: spin+charge+heat
- Thermally driven spin injection from a ferromagnet into a non-magnetic metal, A. Slachter et al., Nature Physics 6, 879 (2010) arXiv:1004.1566
- F.L. Bakker et al.,Phys. Rev. Lett. 105, 136601 (2010)
- Spin Peltier effect (first experiments)
- Thermal valve
- Outlook

Recent developments

* Observation of the spin Seebeck effect
K. Uchida et al., Nature 455, 788 (2008)
(macroscopic Py film with Pt contacts)

* Transmission of electrical signals by spin wave interconversion in a magnetic insulator,
Y. Kajiwara et al., Nature 464, 262 (2010)
(macroscopic YIG film with Pt contacts)

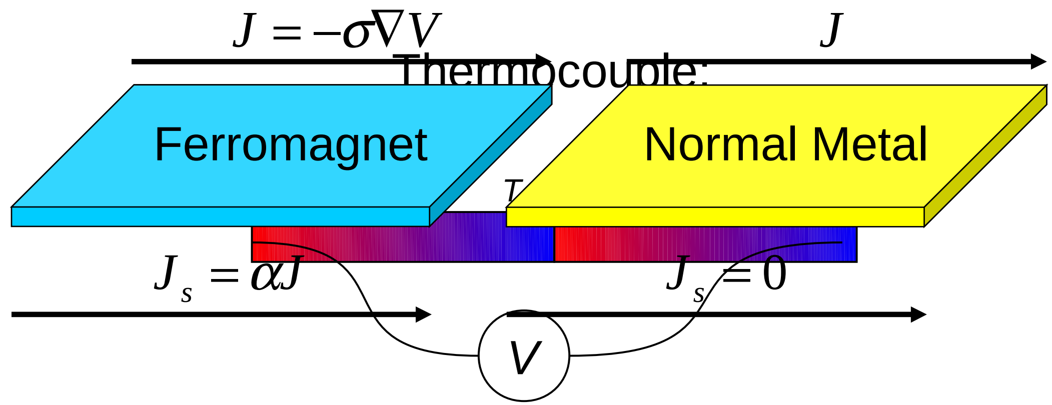
* Dynamax EU project, projectleader G.E.W. Bauer
* Macalo EU project, projectleader A. Brataas

Introduction

- Thermoelectricity:

$$\begin{pmatrix} J \\ Q \end{pmatrix} = -\begin{pmatrix} \sigma & -\sigma S \\ -\sigma\Pi & k \end{pmatrix}\begin{pmatrix} \nabla V \\ \nabla T \end{pmatrix}$$

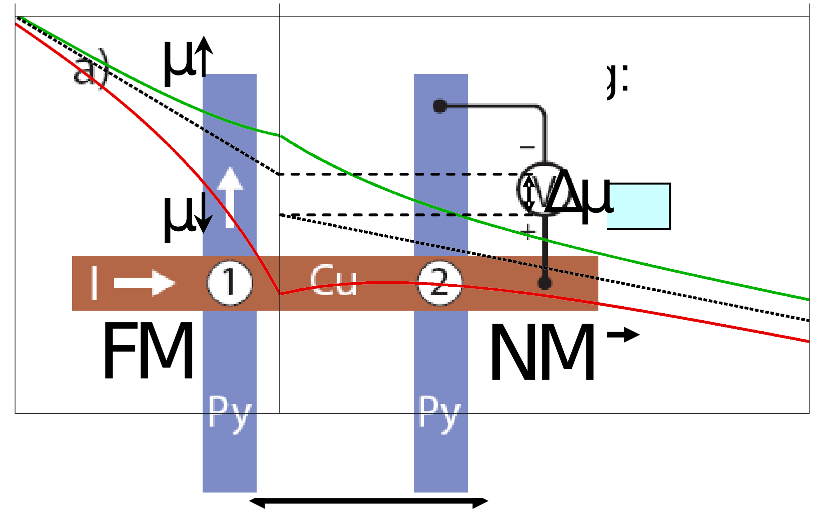
$$\nabla J = 0 \qquad \nabla Q = \frac{J^2}{\sigma}$$



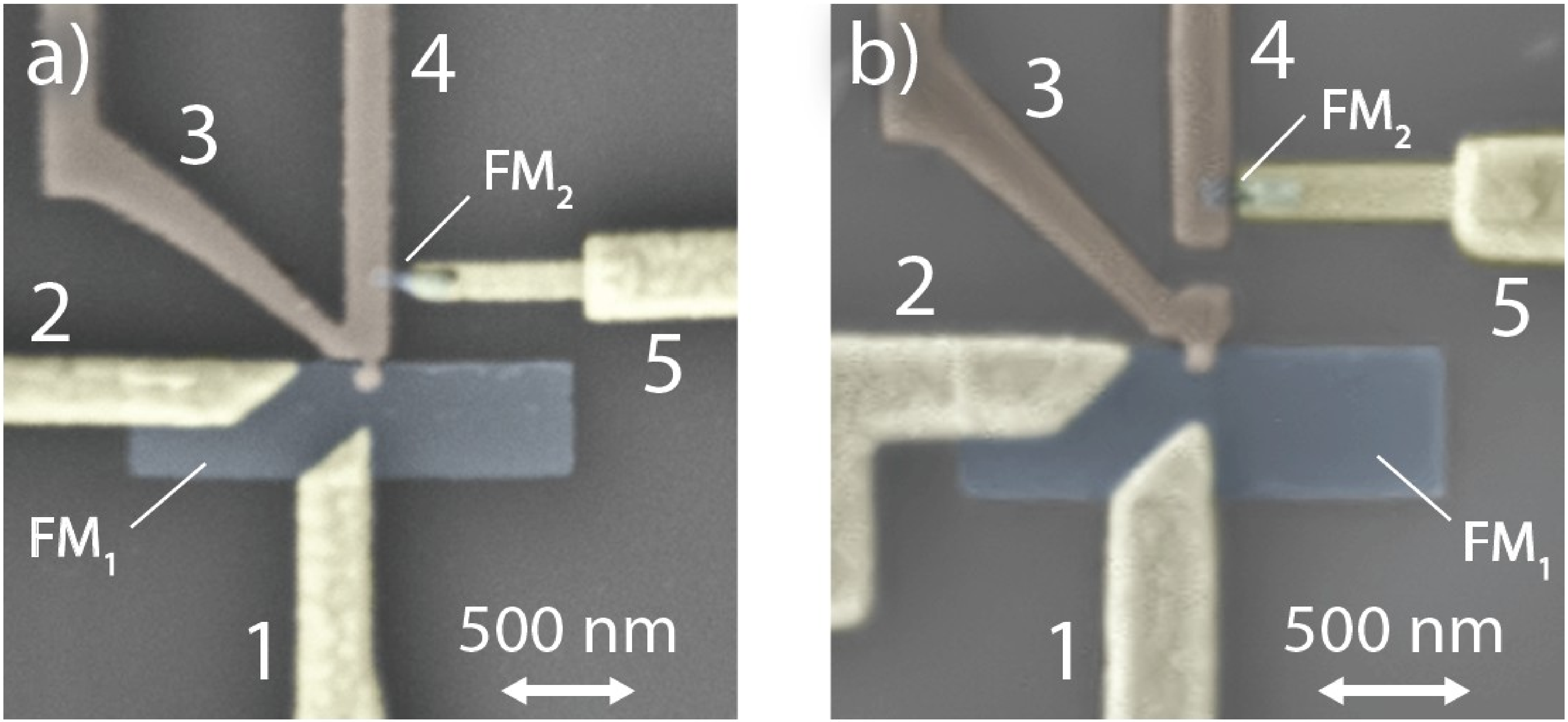
- Spin Transport:

$$J_{\uparrow,\downarrow} = -\sigma_{\uparrow,\downarrow}\nabla V_{\uparrow,\downarrow}$$

$$\nabla J = 0 \qquad \nabla J_s = \frac{1}{2}\left(1-\alpha^2\right)\frac{\left(V_\uparrow - V_\downarrow\right)}{\lambda^2}$$



Coupled Seebeck and Peltier effects



Current from 1 to 3, voltage measured between 4 and 5

Measure 1st, 2nd and 3rd harmonic

$$V = R_1 I + R_2 I^2 + ...$$

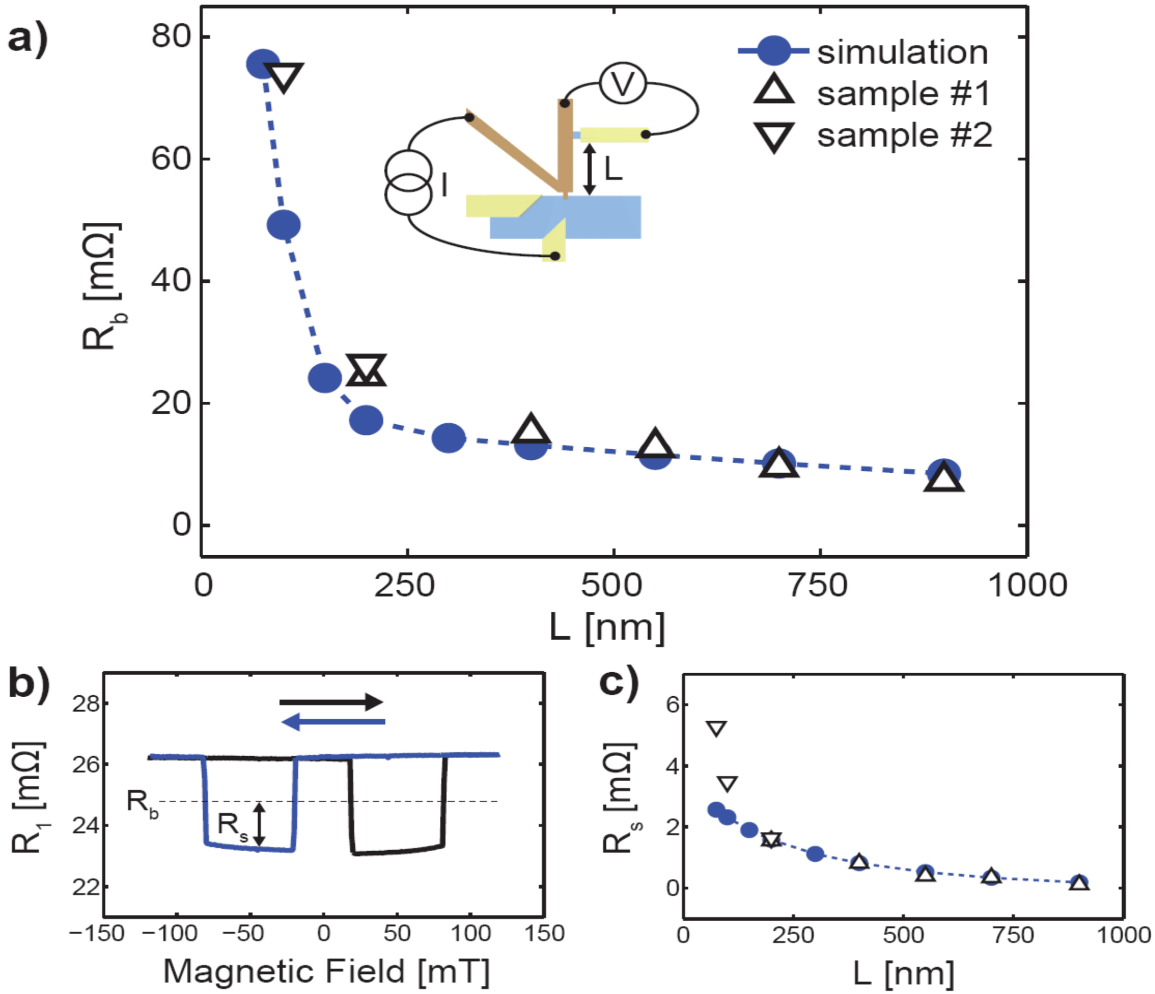
Spin valve signal in R_1

Background in R_1 : Ohmic voltage drop

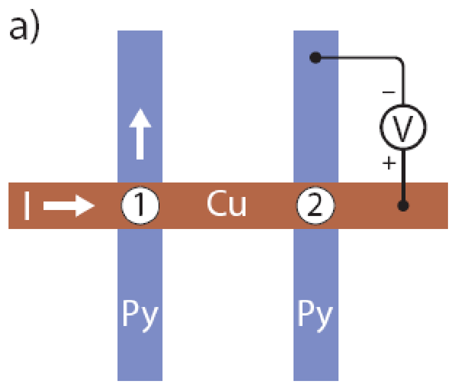
But also: Peltier cooling/heating of injector circuit, Seebeck effect in detector circuit

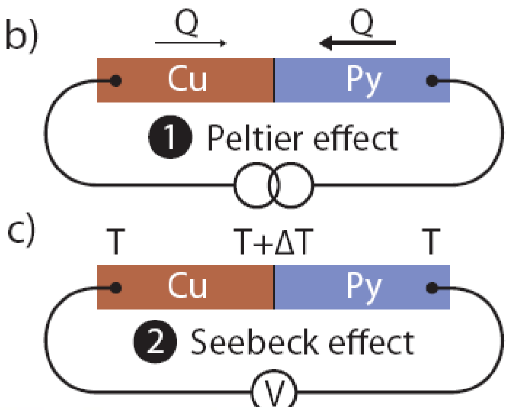
Background in R_2 : Joule heating of injector circuit, Seebeck effect in detector circuit

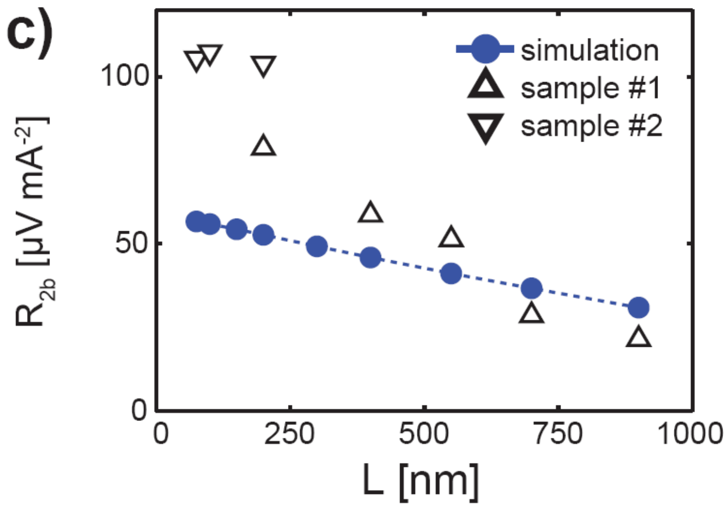
Non-local spin valve: spin signal+background

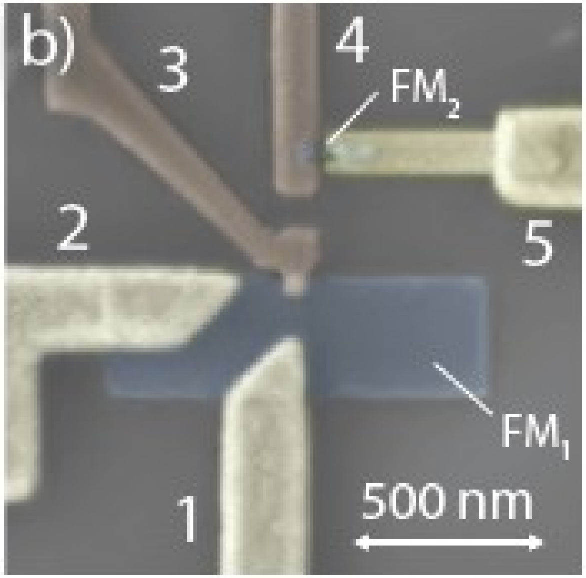


Background in non-local devices due to combined Peltier/Seebeck effects.









Introduction spin-heat coupling

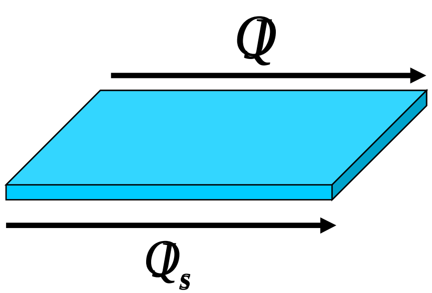
- Thermal Spin Transport:

$$\begin{pmatrix} J_\uparrow \\ J_\downarrow \\ Q_\uparrow \\ Q_\downarrow \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & -\sigma_\uparrow S_\uparrow & 0 \\ 0 & \sigma_\downarrow & 0 & -\sigma_\downarrow S_\downarrow \\ -\sigma_\uparrow \Pi_\uparrow & 0 & k_\uparrow & 0 \\ 0 & -\sigma_\downarrow \Pi_\downarrow & 0 & k_\downarrow \end{pmatrix} \begin{pmatrix} \nabla V_\uparrow \\ \nabla V_\downarrow \\ \nabla T_\uparrow \\ \nabla T_\downarrow \end{pmatrix}$$

$$\nabla J = 0 \qquad \nabla Q = \frac{J^2}{\sigma}$$

$$\nabla J_s = \frac{1}{2}\left(1-\alpha^2\right)\frac{\left(V_\uparrow - V_\downarrow\right)}{\lambda^2}$$

$$\nabla Q_s = \frac{1}{2}\left(1-\alpha_k{}^2\right)\frac{\left(T_\uparrow - T_\downarrow\right)}{\lambda_T{}^2}$$



Spin ‘Temperature’?

$$\begin{aligned} \alpha_T &= \alpha \\ \lambda_T &= \lambda \end{aligned} \quad ?$$

Thermal driven spin injection

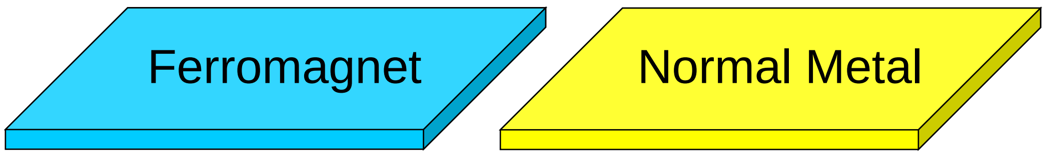
Thermally driven spin injection from a ferromagnet into a non-magnetic metal

A. Slachter,* F. L. Bakker, J. -P. Adam, and B. J. van Wees
Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, The Netherlands

arXiv:1004.1566

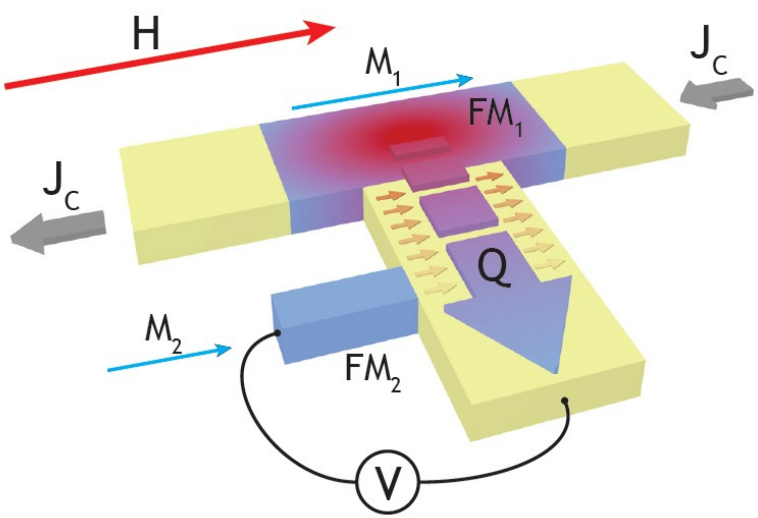
Thermally Driven Spin Injection

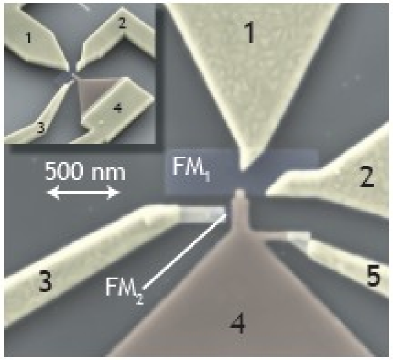
$Q = -\kappa \nabla T$ $\qquad$ Q

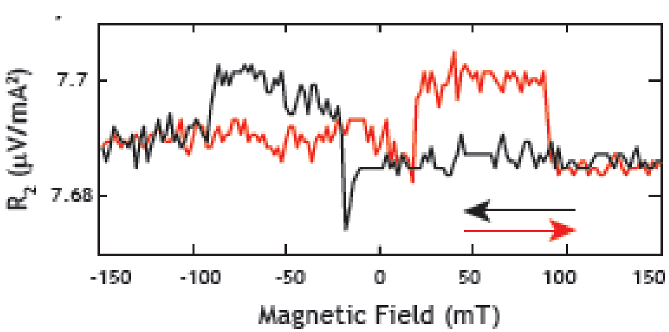


$J_s = \sigma(1-\alpha^2) S_S \nabla T$ $\qquad$ $J_s = 0$

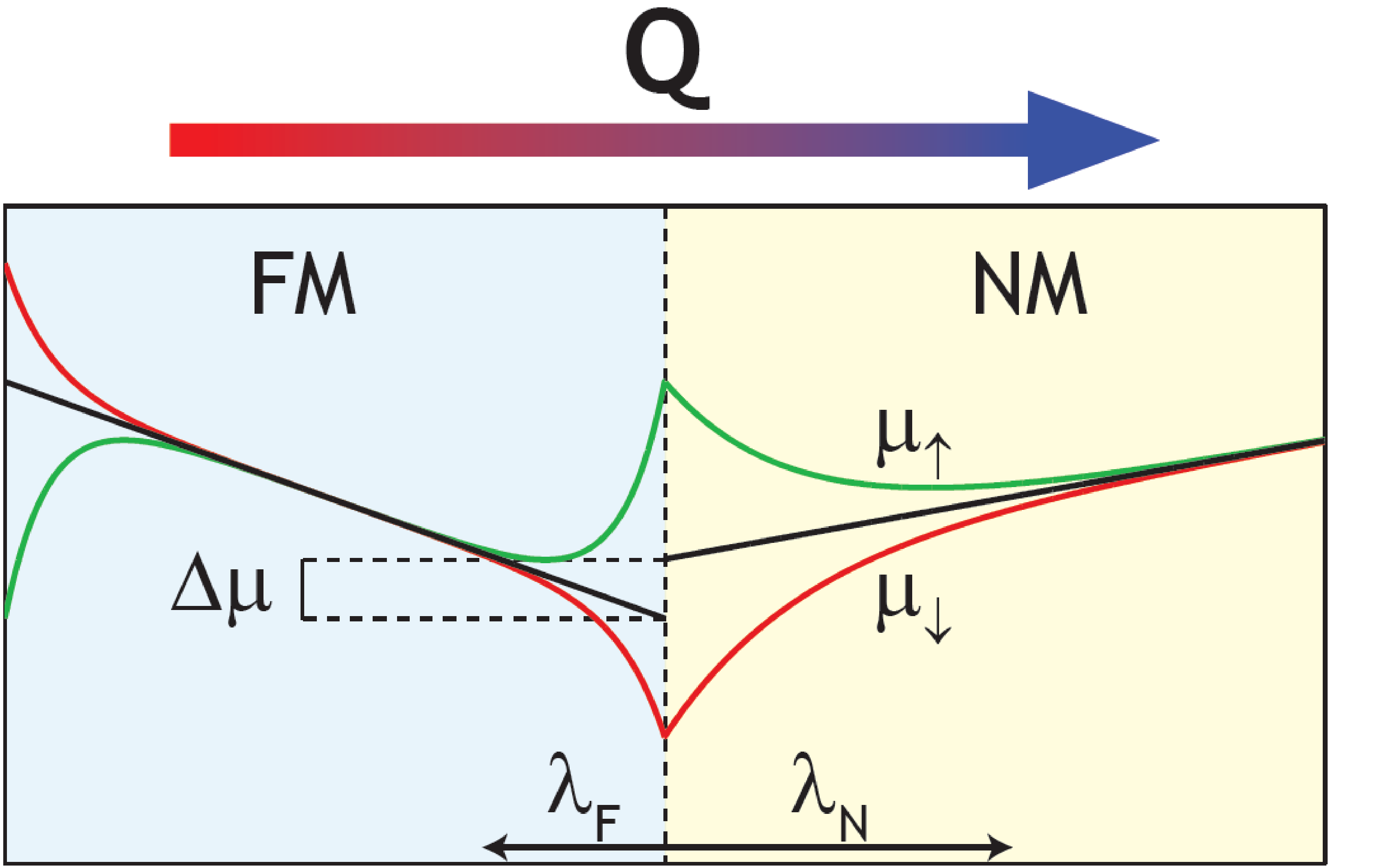
$$\begin{pmatrix} J_\uparrow \\ J_\downarrow \\ Q_\uparrow \\ Q_\downarrow \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & -\sigma_\uparrow S_\uparrow & 0 \\ 0 & \sigma_\downarrow & 0 & -\sigma_\downarrow S_\downarrow \\ -\sigma_\uparrow \Pi_\uparrow & 0 & k_\uparrow & 0 \\ 0 & -\sigma_\downarrow \Pi_\downarrow & 0 & k_\downarrow \end{pmatrix} \begin{pmatrix} \nabla V_\uparrow \\ \nabla V_\downarrow \\ \nabla T_\uparrow \\ \nabla T_\downarrow \end{pmatrix}$$



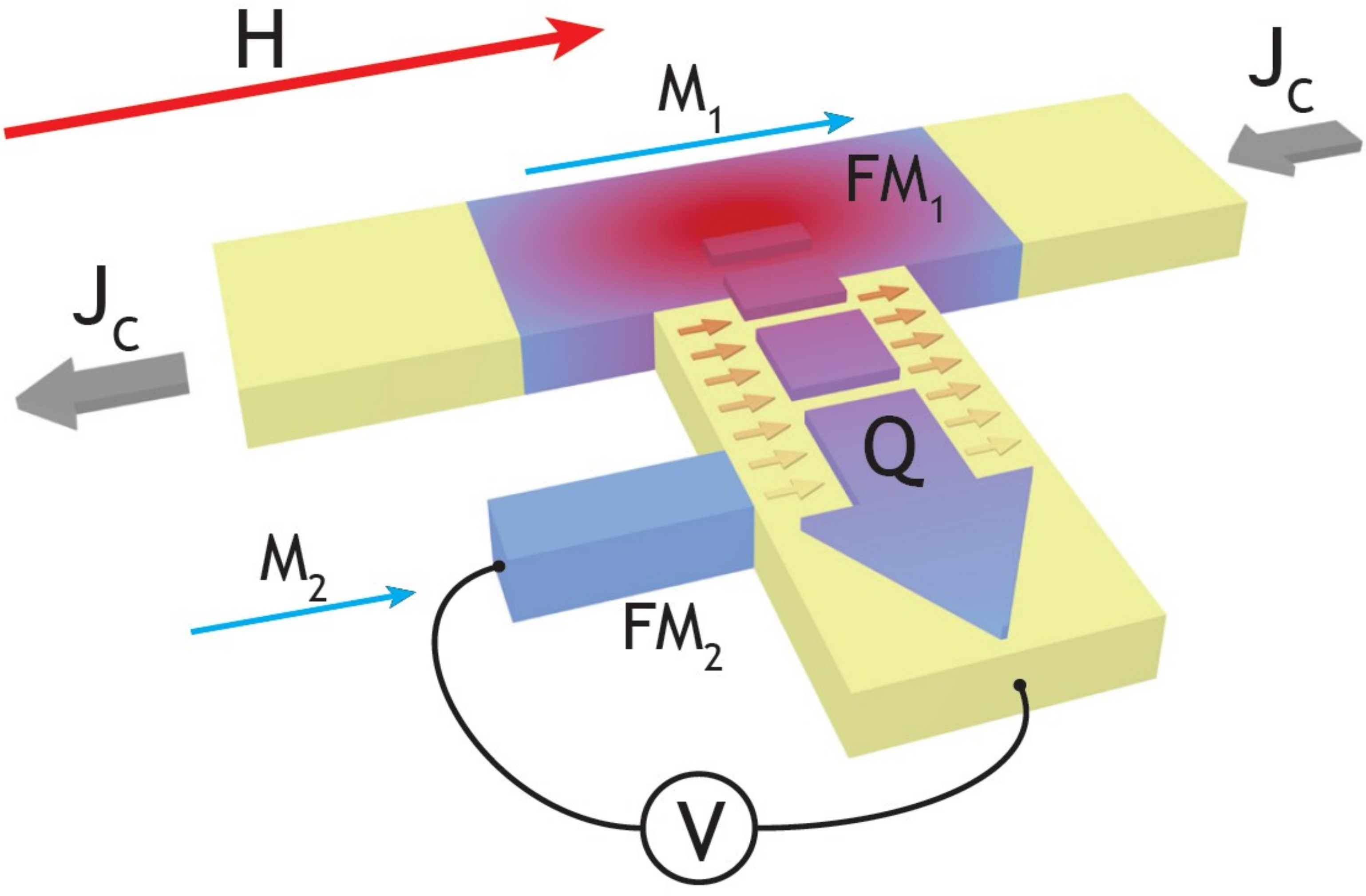




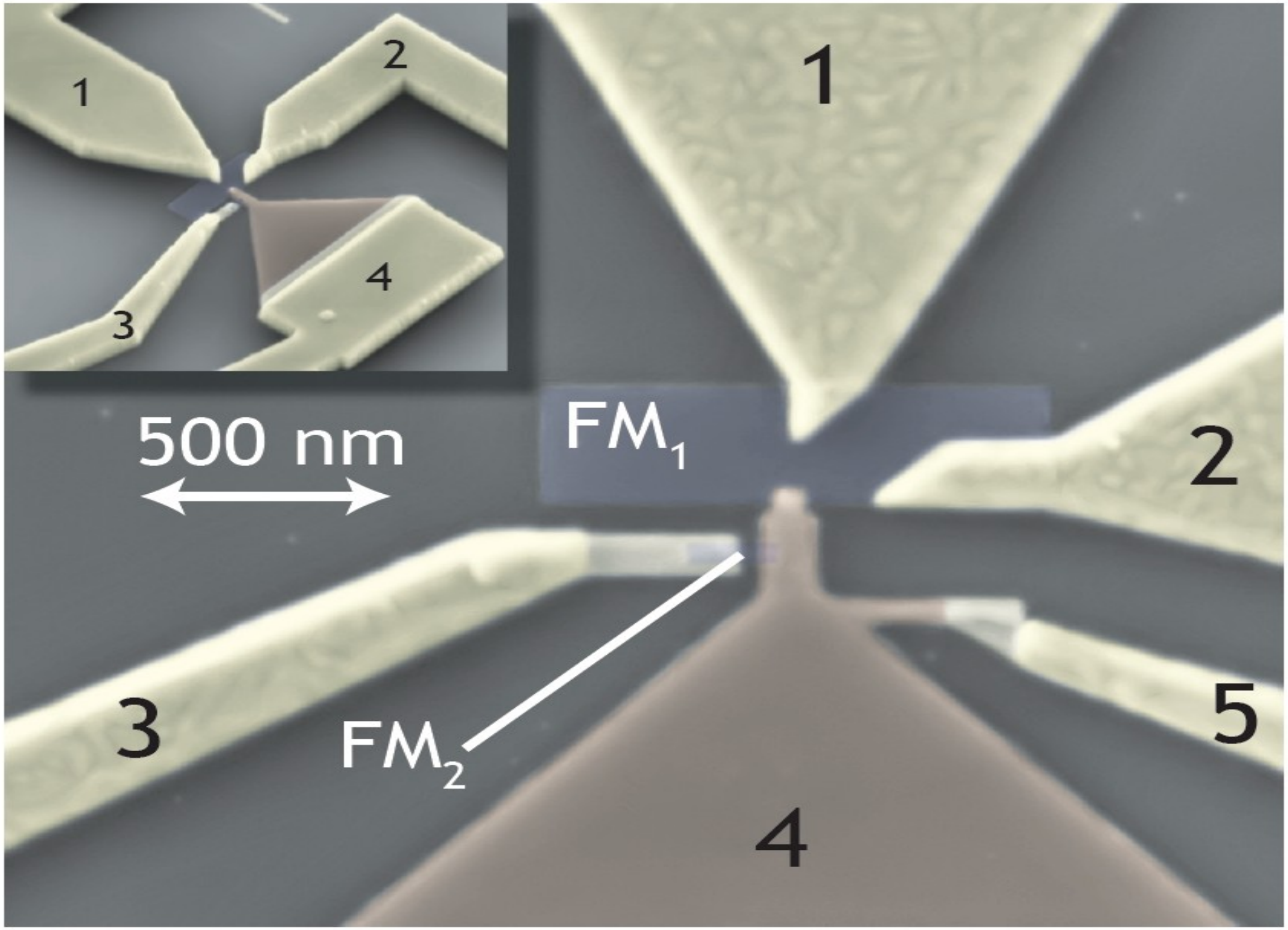
Thermal spin injection



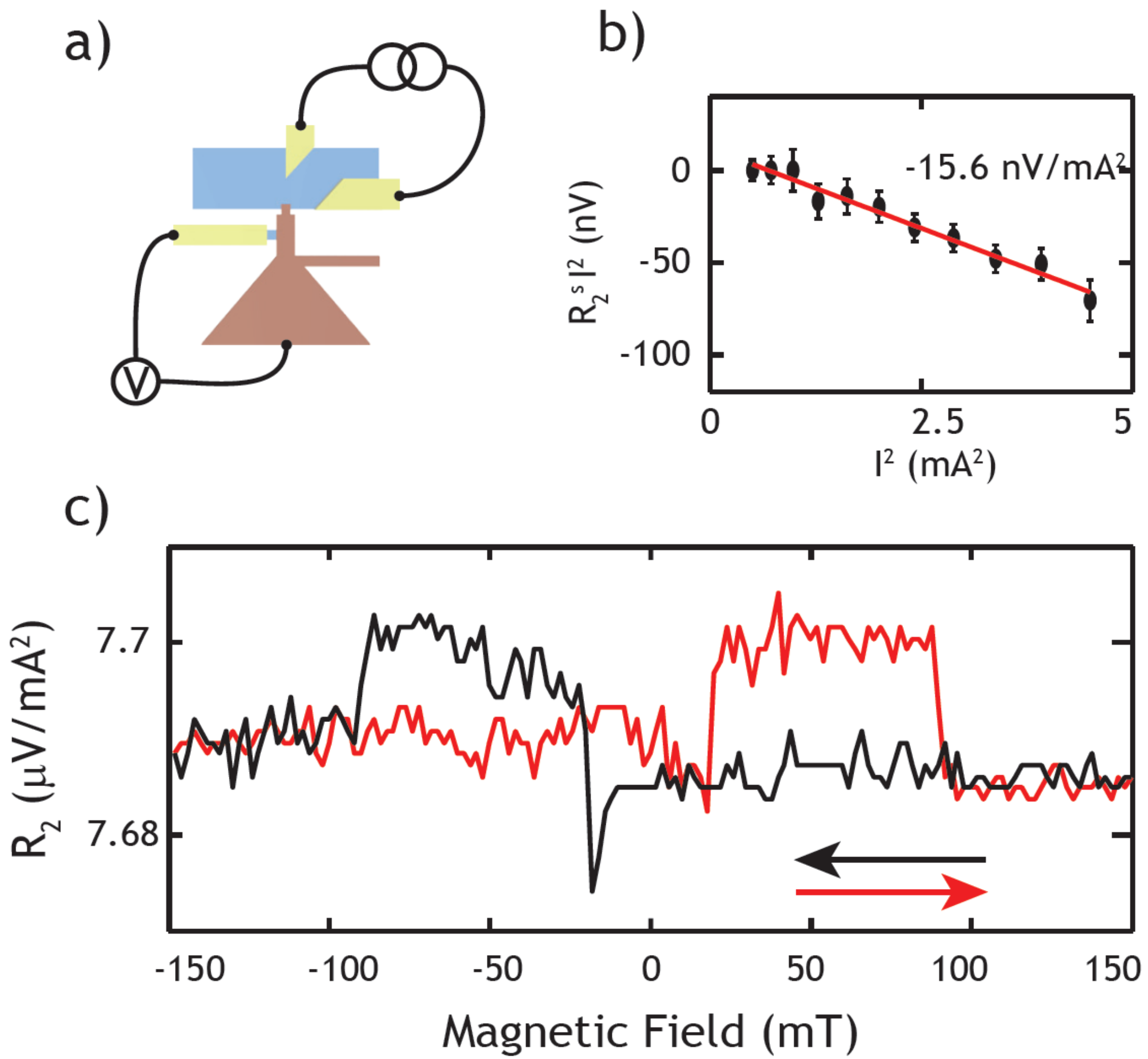
Experimental set up



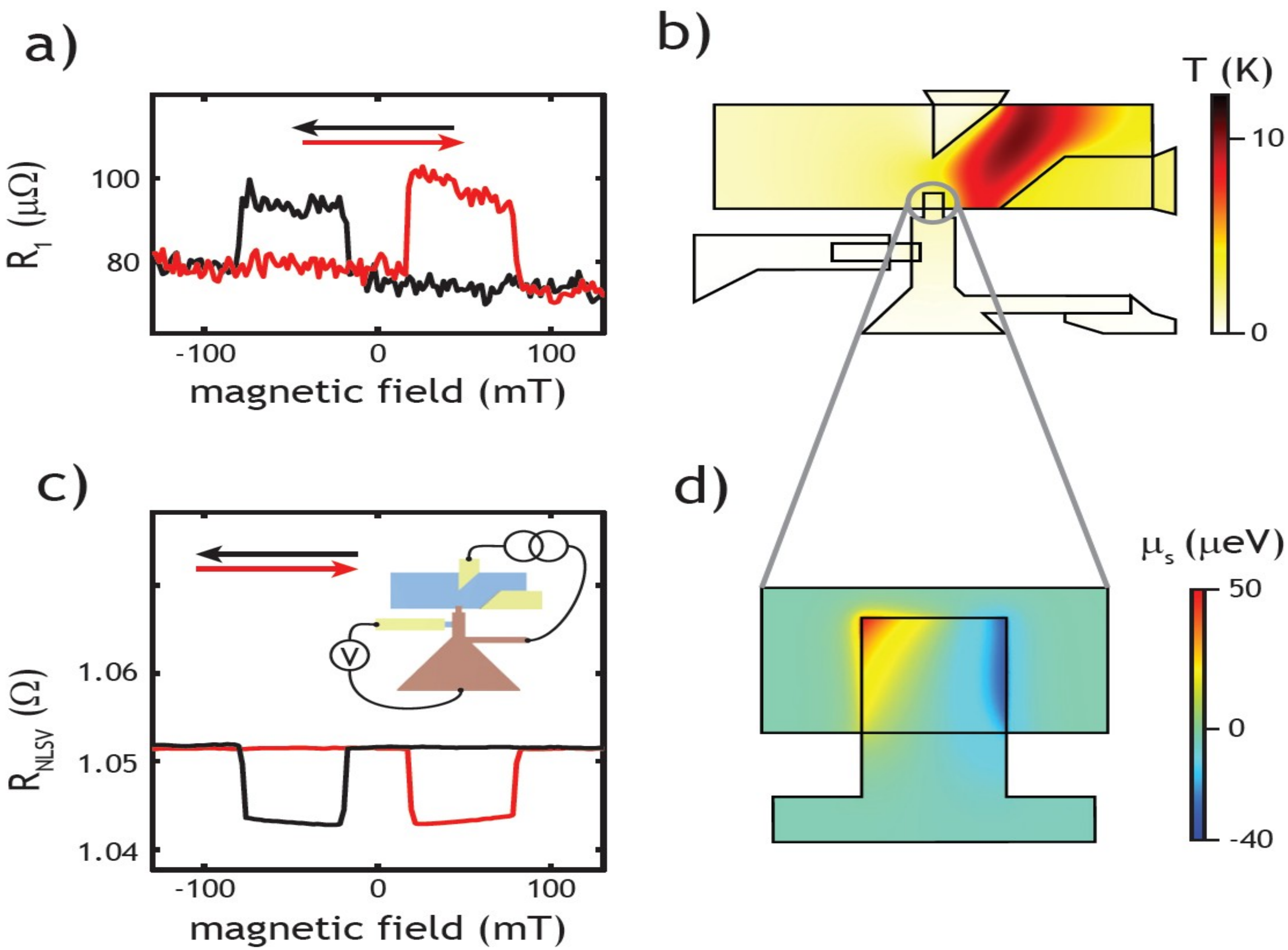
SEM picture of device



Observation of thermal spin injection



Modelling



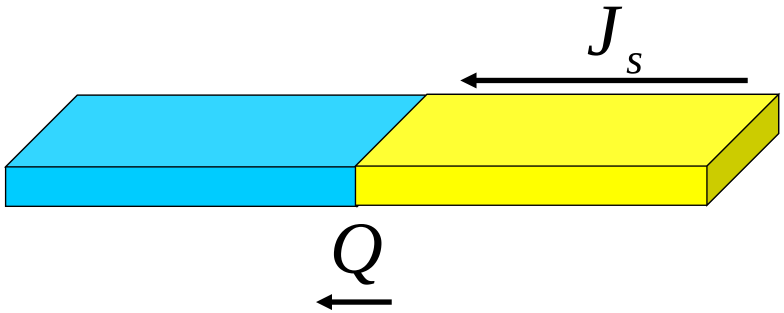
a)
b)
c)
d)
100
80
-100
0
100
magnetic field (mT)
R1 (μΩ)
T (K)
10
0
1.06
1.05
1.04
-100
0
100
magnetic field (mT)
RNLSV (Ω)
V
μs (μeV)
50
0
-40

Spin Current induced Thermal Transport

Thermally driven spin injection: $Q \overset{\text{FM-NM}}{\Longrightarrow} J_s$

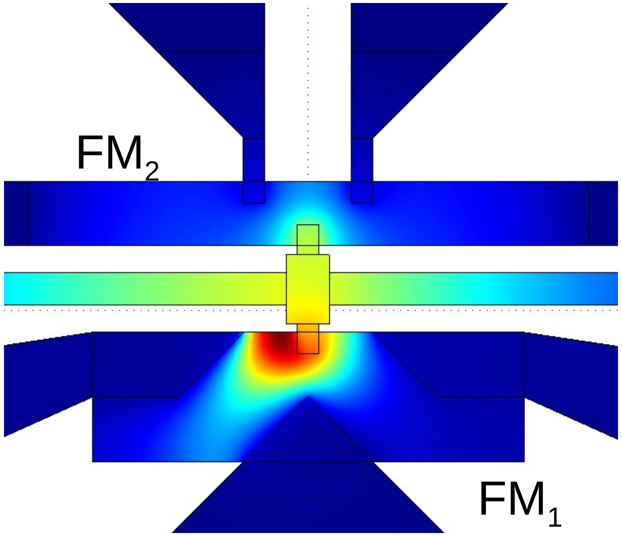
$$\begin{pmatrix} J_\uparrow \\ J_\downarrow \\ Q_\uparrow \\ Q_\downarrow \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & -\sigma_\uparrow S_\uparrow & 0 \\ 0 & \sigma_\downarrow & 0 & -\sigma_\downarrow S_\downarrow \\ -\sigma_\uparrow \Pi_\uparrow & 0 & k_\uparrow & 0 \\ 0 & -\sigma_\downarrow \Pi_\downarrow & 0 & k_\downarrow \end{pmatrix} \begin{pmatrix} \nabla V_\uparrow \\ \nabla V_\downarrow \\ \nabla T_\uparrow \\ \nabla T_\downarrow \end{pmatrix}$$

Does the Onsager also work? $J_s \overset{\text{FM-NM}}{\Rightarrow} Q$



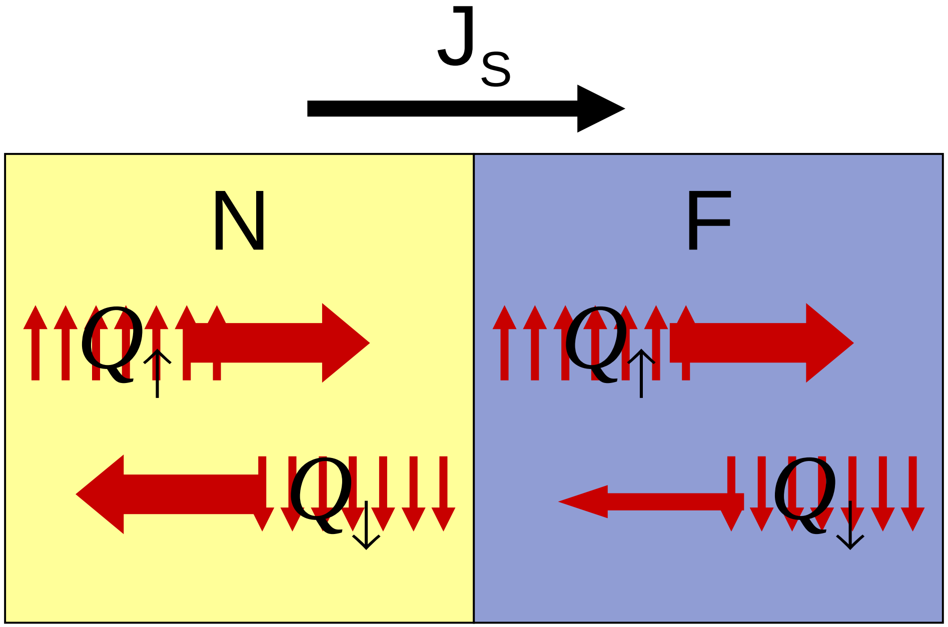
$$Q \propto \left(\Pi_\uparrow - \Pi_\downarrow\right) J_s$$

$\Delta S_{Py\text{-}NiCr} = 50\ \mu V/K$



$$R_{SV} = 30\mu\Omega$$

Spin Peltier



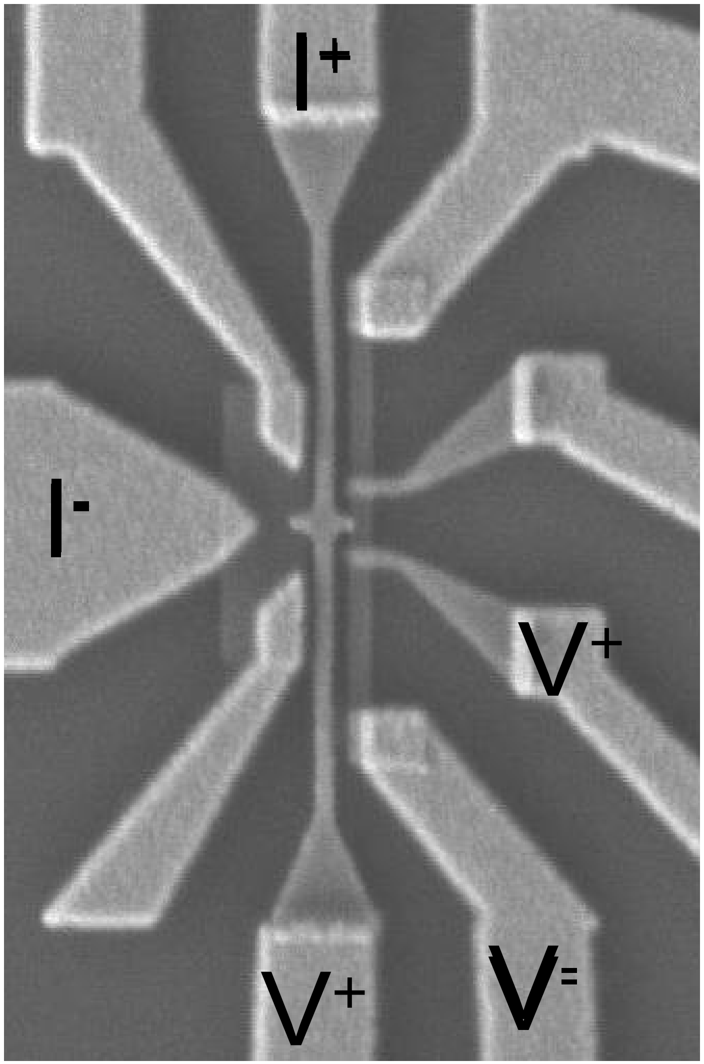
$$Q_{\uparrow,\downarrow} = \Pi \, J_{\uparrow,\downarrow}$$

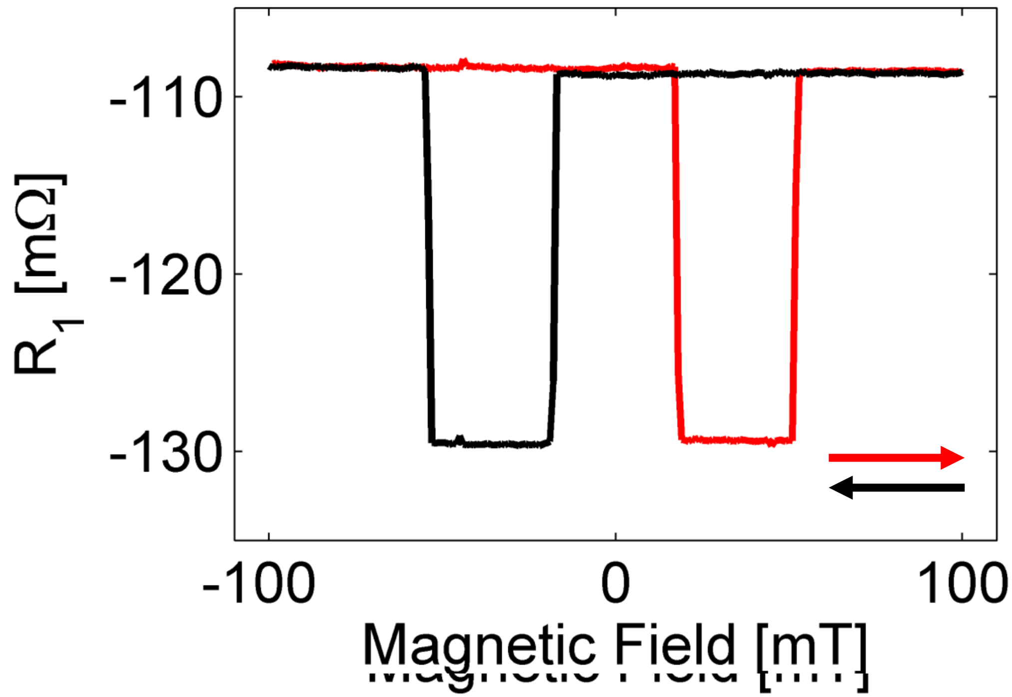
Peltier coefficient

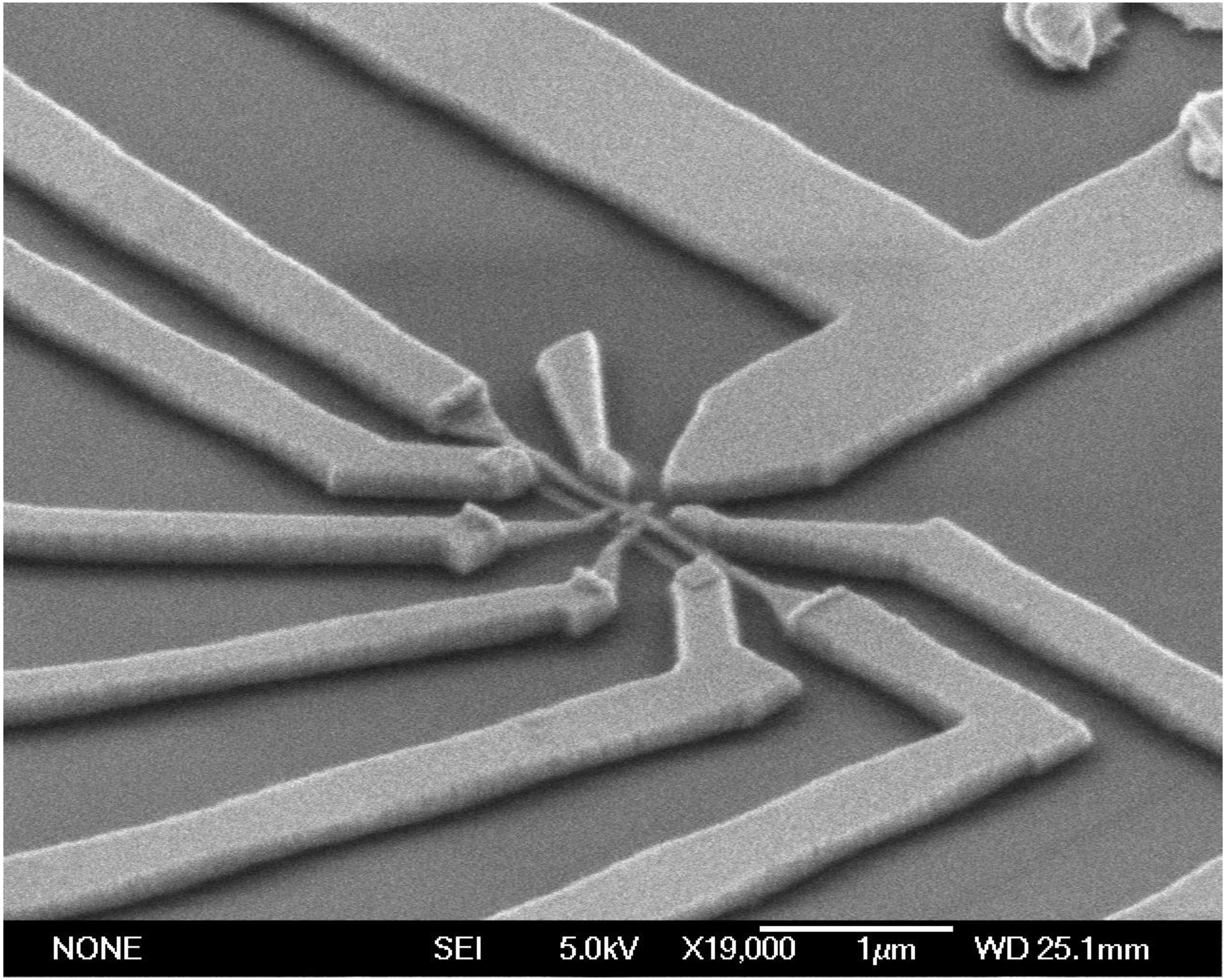
$$Q_{\uparrow,\downarrow} = \Pi_{\uparrow,\downarrow} \, J_{\uparrow,\downarrow}$$

with $\Pi_\uparrow \neq \Pi_\downarrow$

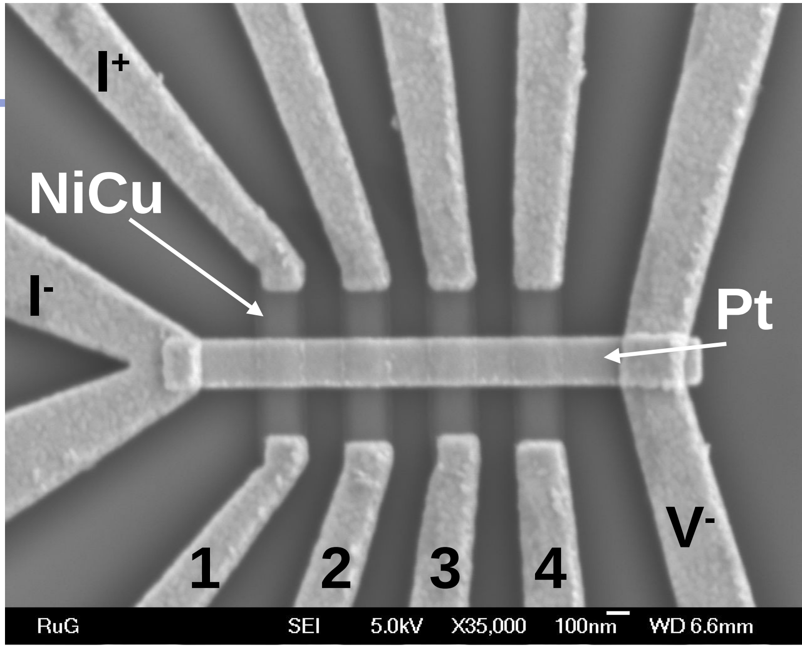
Device geometry for Spin Peltier

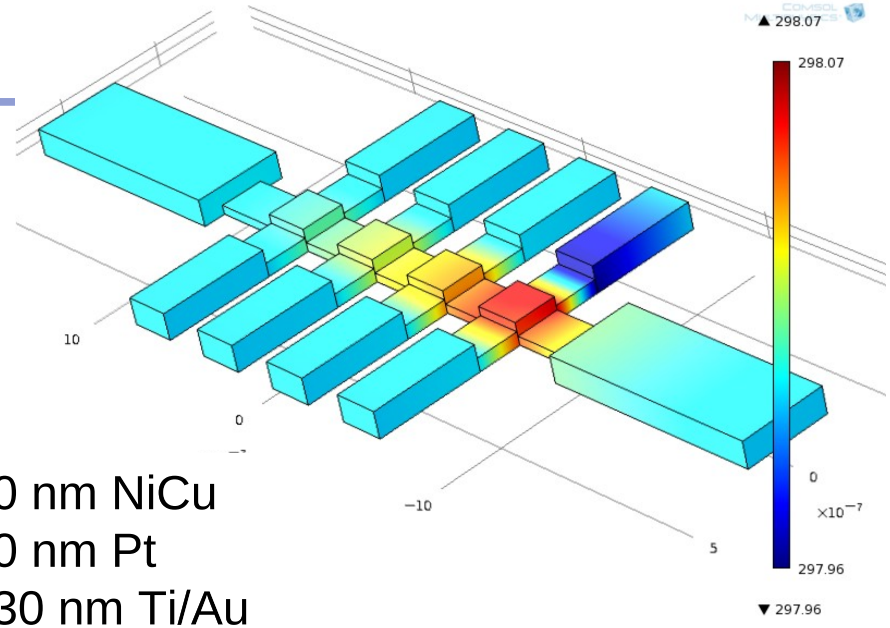




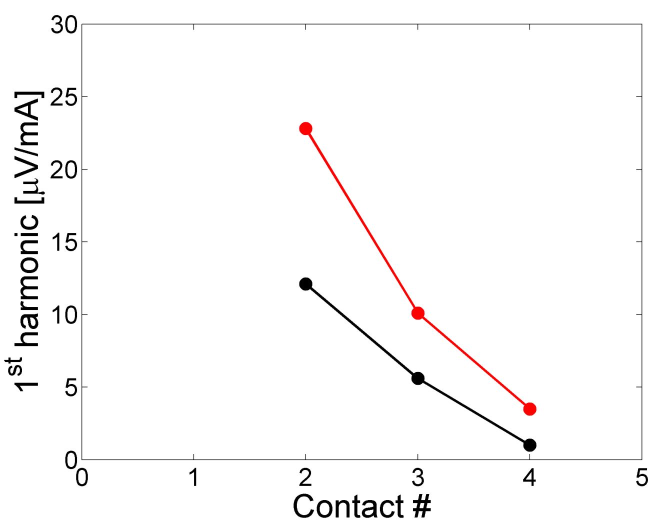

NONE
SEI
5.0kV
X19,000
1μm
WD 25.1mm

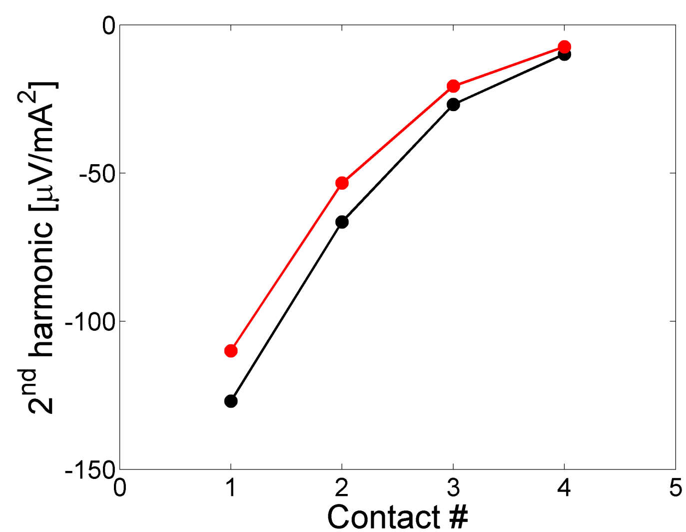
NiCu (Constantan) test device



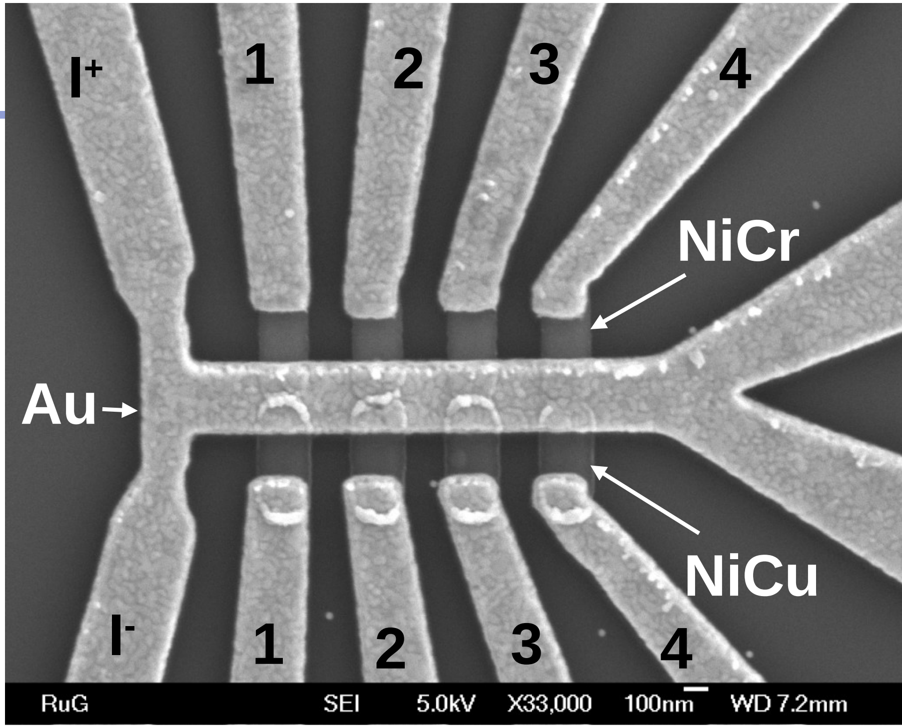


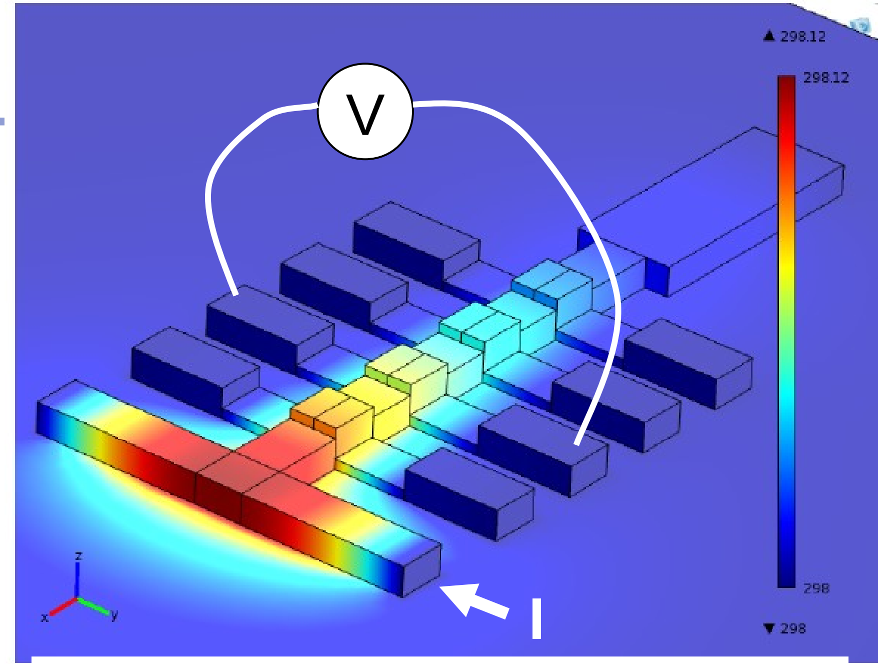
40 nm NiCu
60 nm Pt
130 nm Ti/Au





Nanoscale thermometer (thermocouple)

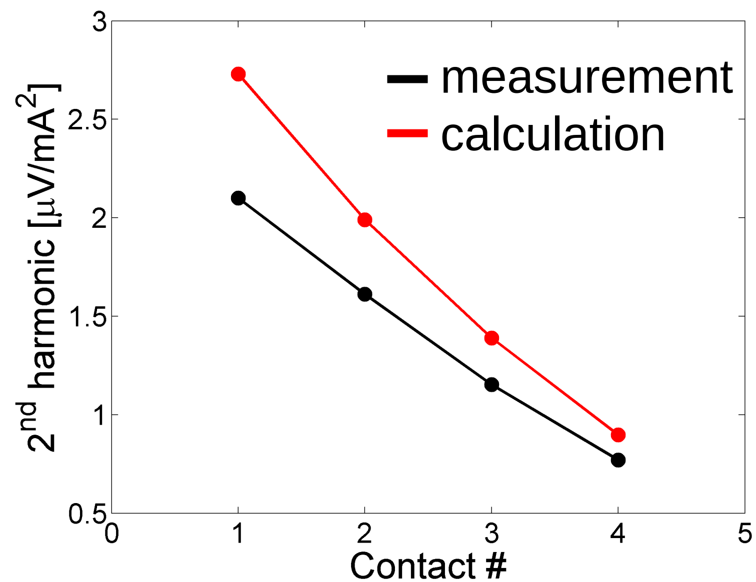




50 nm NiCu
50 nm NiCr
120 nm Ti/Au

S_{NiCu} = -40 μV K^{-1}
S_{NiCr} = 20 μV K^{-1}
S_{Au} = 1.5 μV K^{-1}

Sensitivity: 50 nV / mK

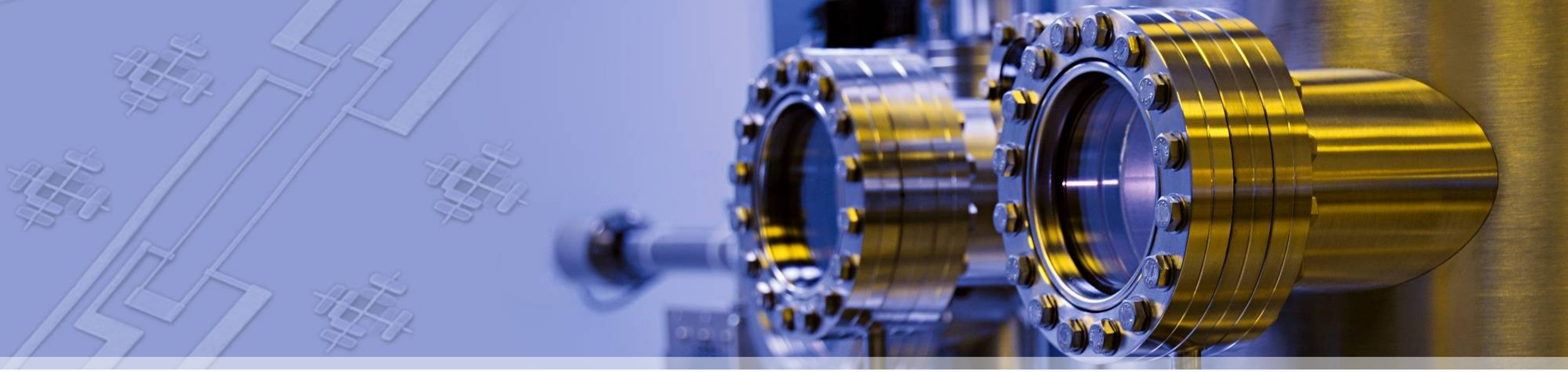


Conclusion

- Signals in lateral spin valves and other magneto-electronic devices are often dominated by thermo-electric effects
  - Calibration of Peltier/Joule heating
  - Thermal spin injection due to spin dependence of the Seebeck coefficient

- There is a very rich variety of thermoelectric spin effects yet to be explored for which the non local geometry is ideal

* Application to ferromagnetic insulators (YIG)



Thank you for your attention

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