Magneto-Seebeck effect in magnetic tunnel junctions

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Department of Physics, Universität Bielefeld, Germany
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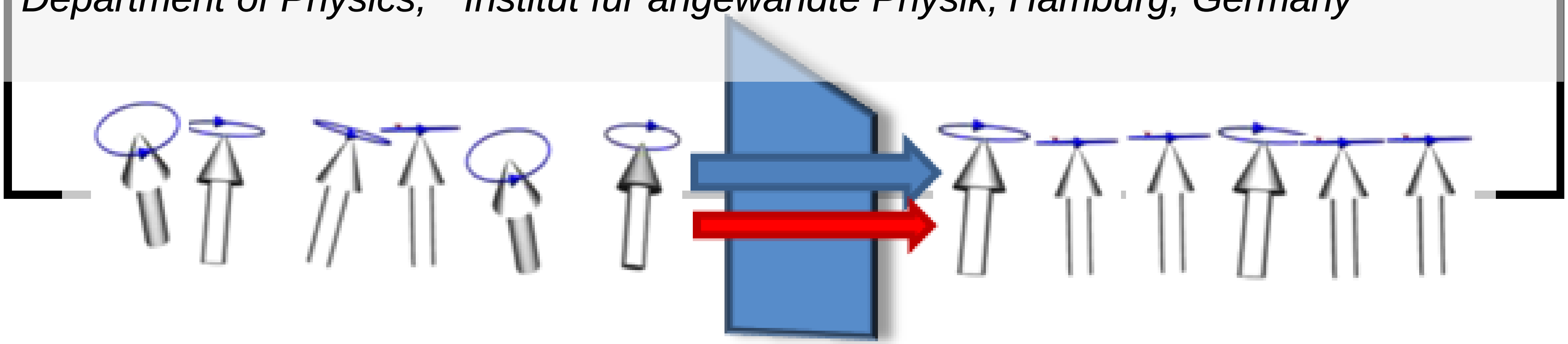
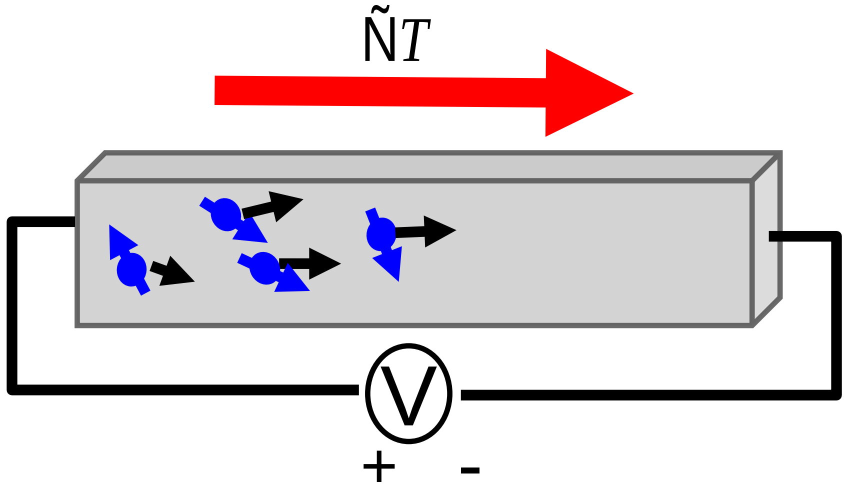
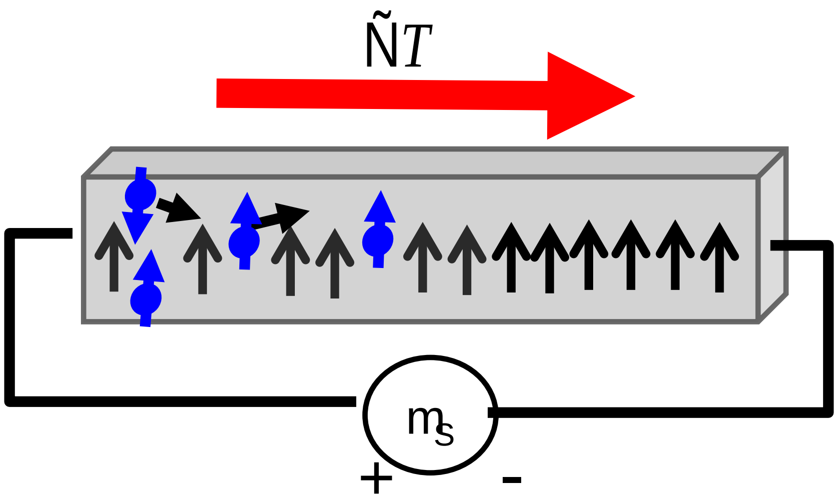


Charge and spin-dependent Seebeck effect



$\Delta V = S \Delta T$

„charge accumulation“



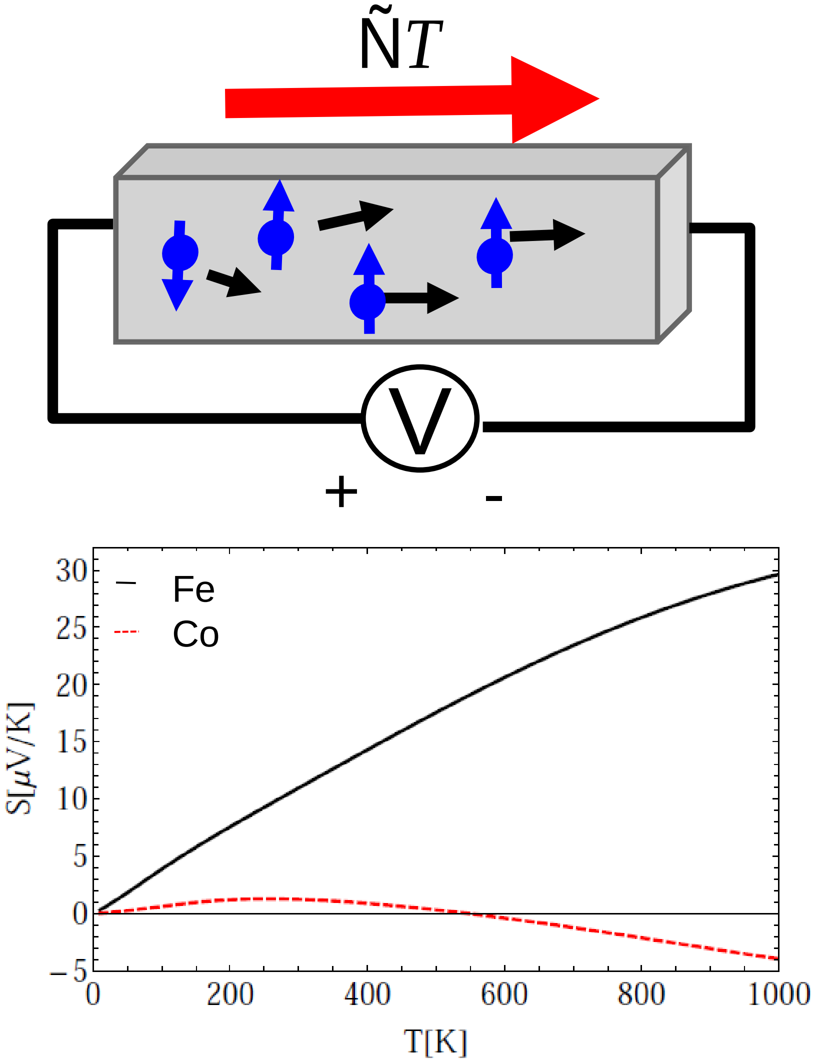
$\Delta \mu_s = S_s \Delta T$

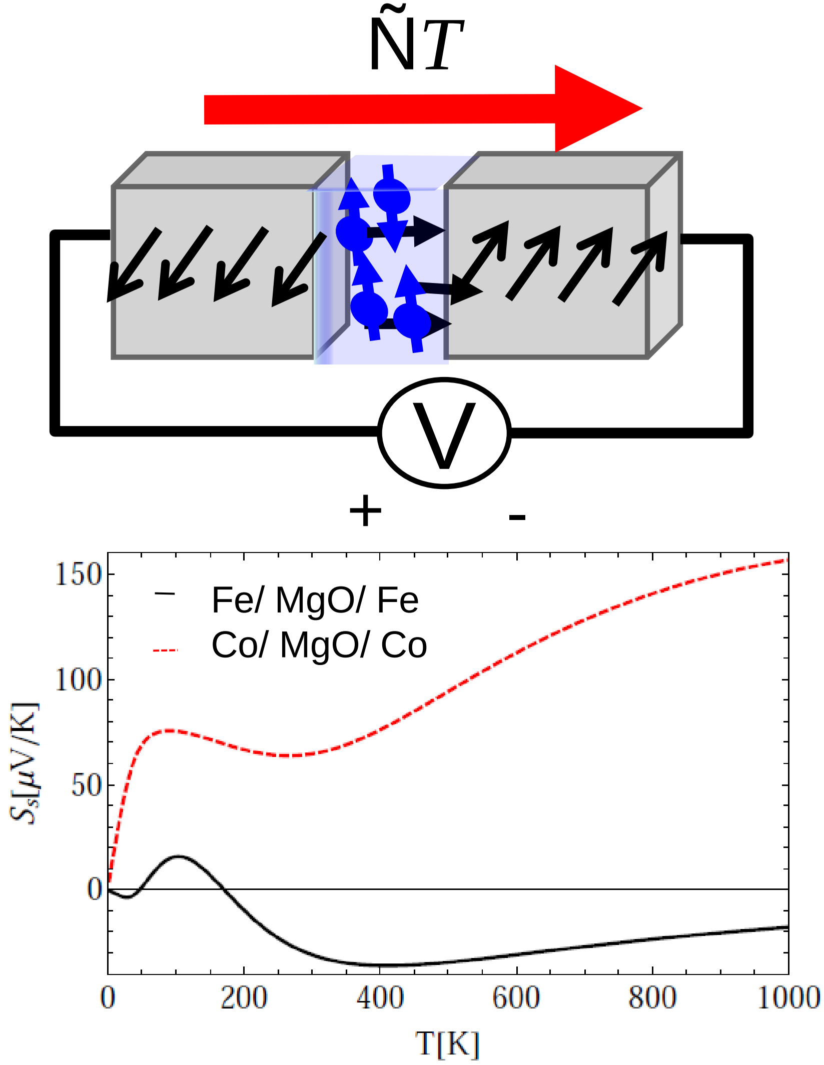
„spin accumulation“

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

Experiment: L. Gravier Phys. Rev. B 73, 024419 (2006).
K. Uchida Nature 455, 778 (2008).
A. Slachter Nature Phys. 6, 879 (2010).
G.E.W. Bauer, Spin Caloritronics, Solid State Comm. 150, 459 (2010).

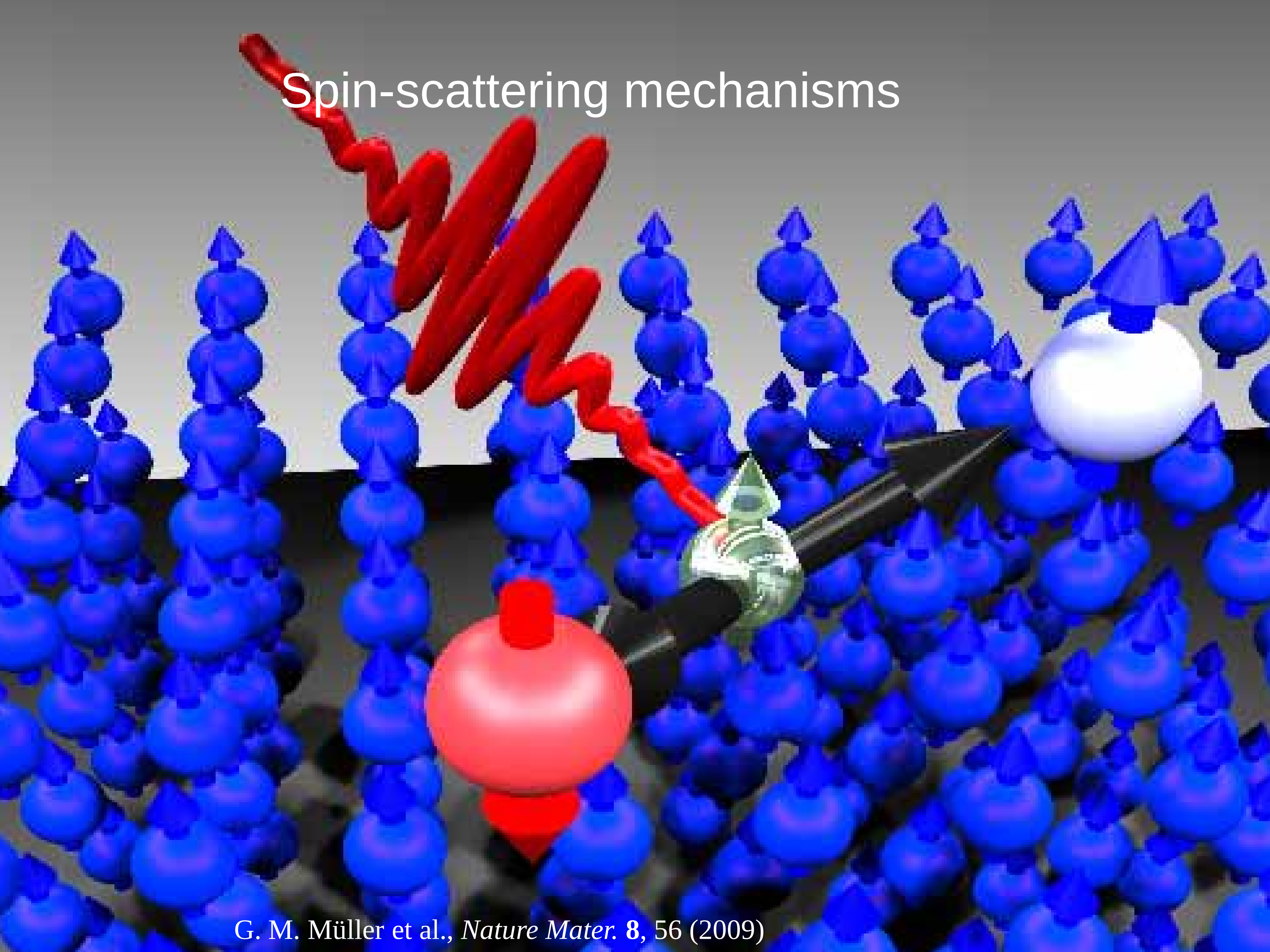
… in bulk and tunnel junctions





M. Czerner et al. Phys. Rev. B 83, 132405 (2011)

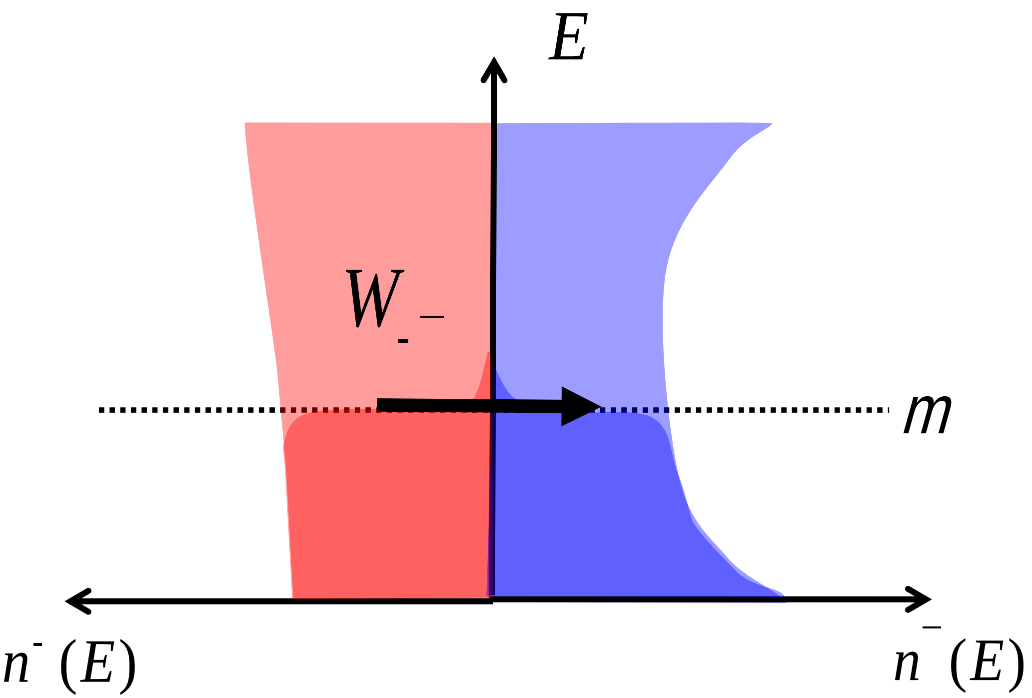
Spin-scattering mechanisms



G. M. Müller et al., *Nature Mater.* **8**, 56 (2009)

Spin-scattering mechanisms

Elliott-Yafet process: femtosecond demagnetization and FMR



$$W_{-\,-} \sim n_e^{-}(E_F)\, c^2 n_h^{-}(E_F)$$

Spin mixing:

$c \sim V_{SO} / \mathrm{D}E_{exch}$ Spin-orbit interaction

Spin polarization:

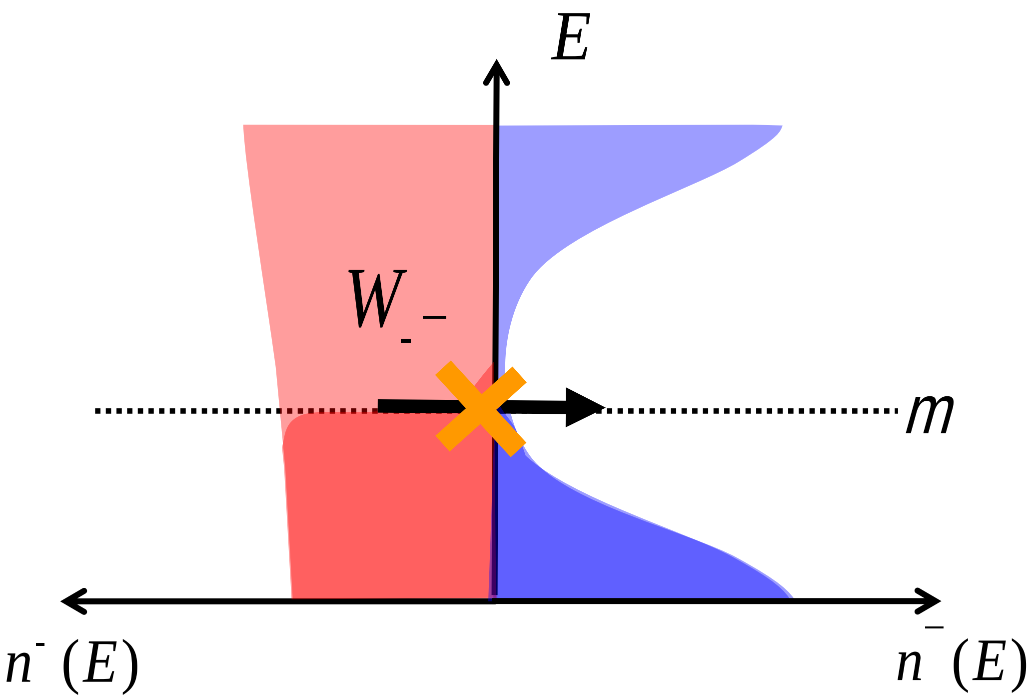
$$P_0 = \frac{n_e^{-} - n_e^{-}}{n_e^{-} + n_e^{-}}$$

R. J. Elliott, *Phys. Rev.* **96** (1954).

Fs pump-probe: G. M. Müller et al., *Nature Mater.* **8**, 56 (2009)

Spin-scattering mechanisms

Elliott-Yafet process: femtosecond demagnetization and FMR



$$W_{-–} \sim n_e^{-}(E_F)\, c^2 n_h^{–}(E_F)$$

Spin mixing:

$c \sim V_{SO} / \mathrm{D}E_{exch}$ Spin-orbit interaction

Spin polarization P dependent relaxation

$$P_0 = \frac{n_e^{-} - n_e^{–}}{n_e^{-} + n_e^{–}}$$

For P ® 1 :

- Spin-flip processes are prohibited
- Electron and spin system are isolated

R. J. Elliott, *Phys. Rev.* **96** (1954).
Fs pump-probe: G. M. Müller et al., *Nature Mater.* **8**, 56 (2009)

Spin-scattering mechanisms

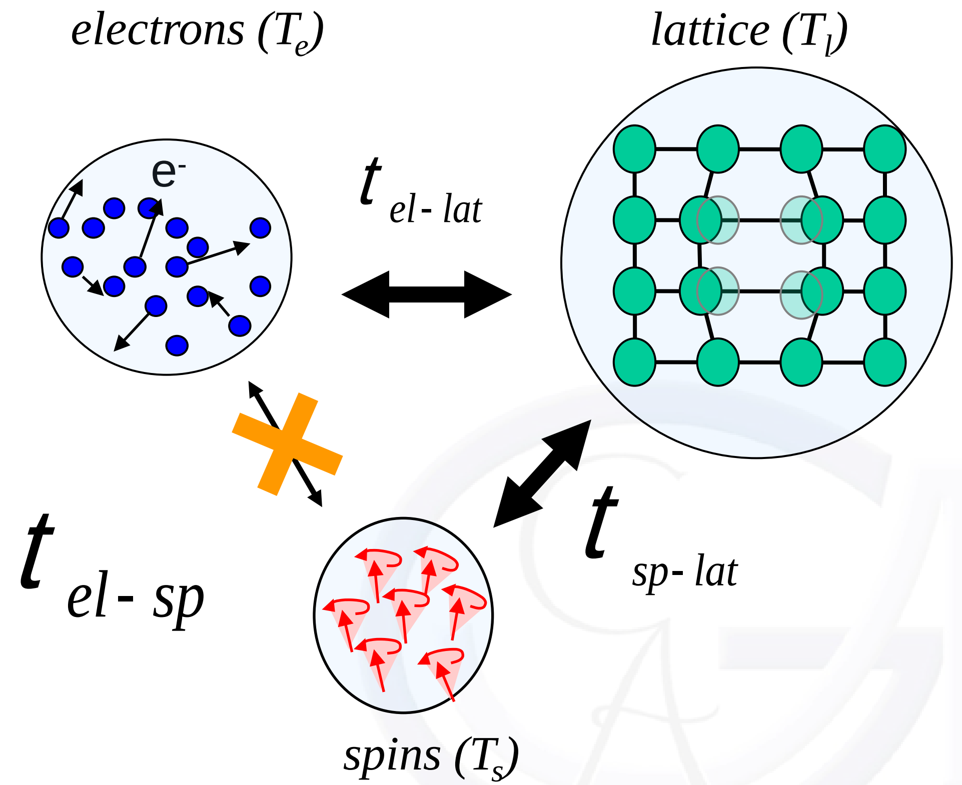
Test of the effect of the coupling parameter:

- $g_{el\text{-}sp}$

- 2nd: suppression of the spin scattering

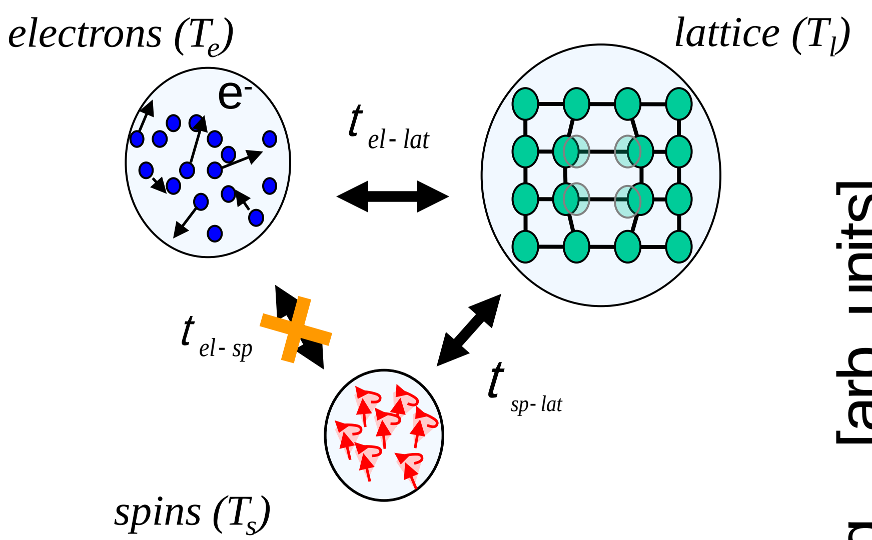
Coupling parameters

- $g_{el\text{-}lat} > g_{sp\ \text{-}lat} > g_{el\text{-}sp}$



Spin relaxation in half metals

Three temperature model: half metal



- Spin-flip processes are prohibited
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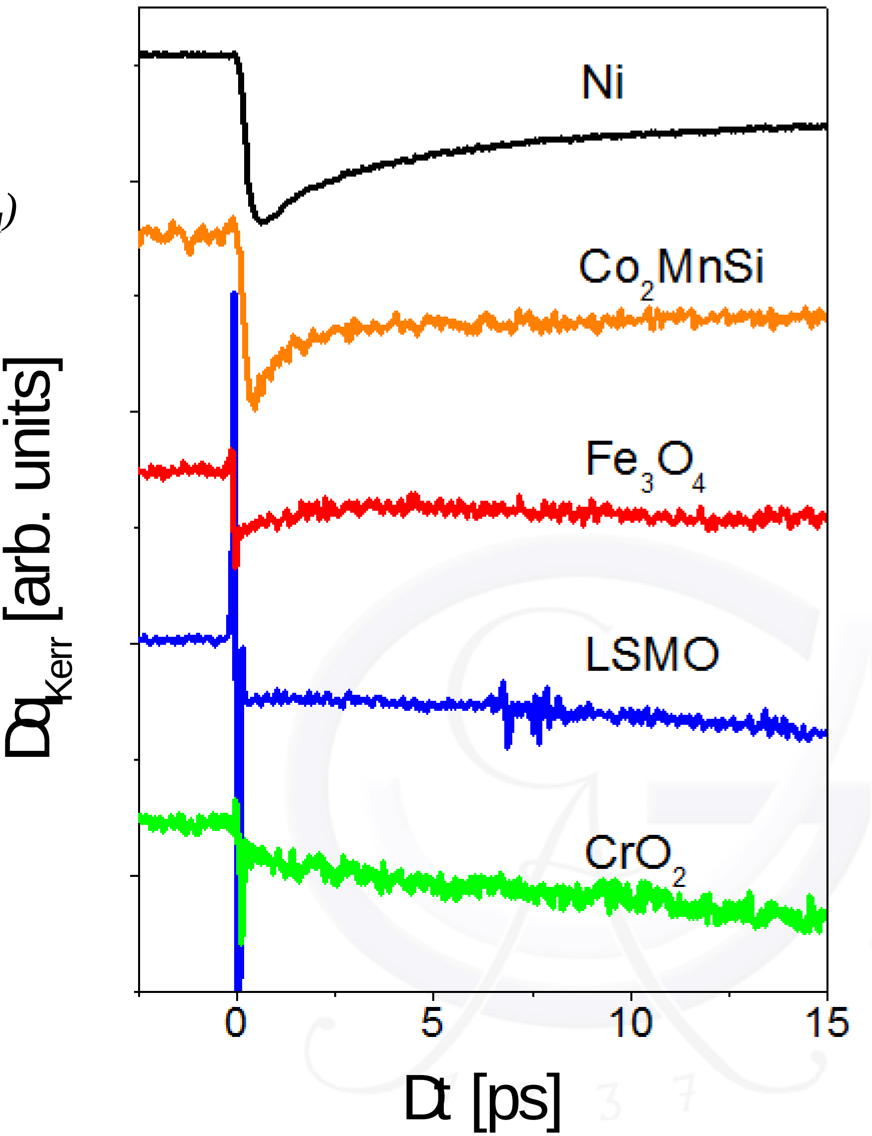
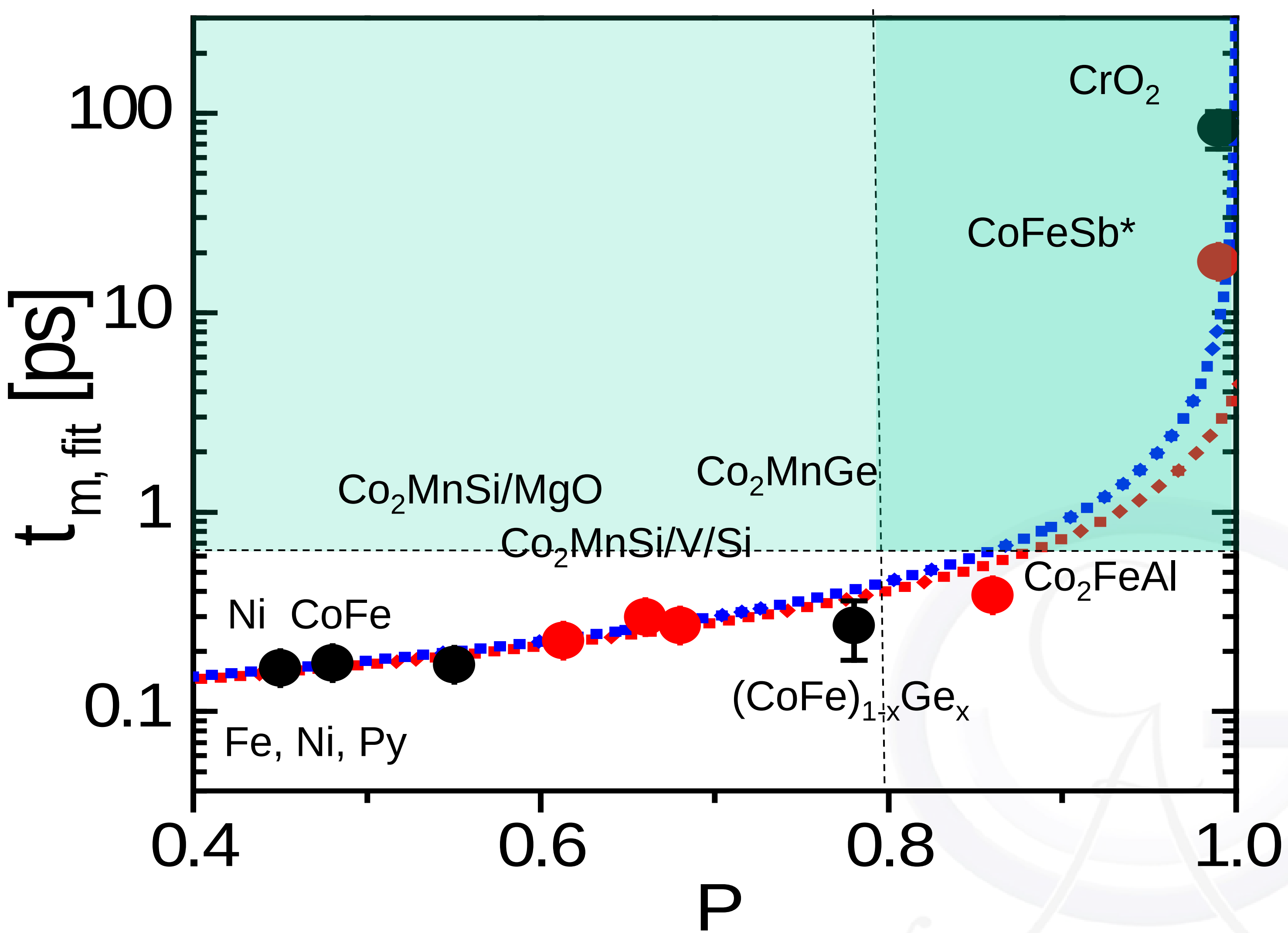


G. M. Müller et al., *Nature Mater. 8*, 56 (2009)

Spin relaxation in half metals



Collaboration with: Bielefeld University and Hitachi GST

Magneto-Seebeck effect?

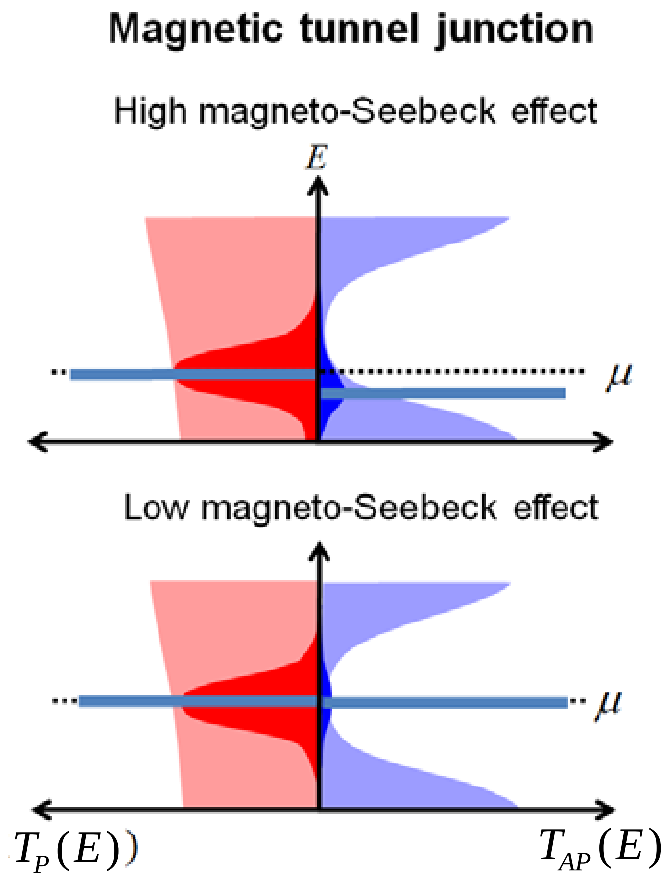
- “Conventional” Seebeck effect: Voltage generation due to a temperature gradient in the material:

$$DV = SDT$$

- In a magnetic tunnel junction depence on magnetization orientation:

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

“Magneto-Seebeck effect”



People who do the work

Benjamin Lenk

Jakob Walowski

Andreas Mann (now EPFL),
Henning Ulrichs (now U Münster),
Fabian Garbs

Marvin Walter

…. + Valdislav Zbarsky

Bachelor students:

Martin Lüttich, Christian Leutenantsmeyer, Jelena Panke, Nils Abeling, Mirco Marahrens, Anissa Zeghuzi

Deutsche Forschungsgemeinschaft DFG

Priority program SpinCaT

einzelnes Atom SFB 602 kondensierte Materie
mikroskopisch makroskopisch
1nm 1µm

Outline

- Introduction into coherent tunneling
- Magneto-Seebeck experiment:
    - Experimental setup
    - Simulations of the temperature gradients
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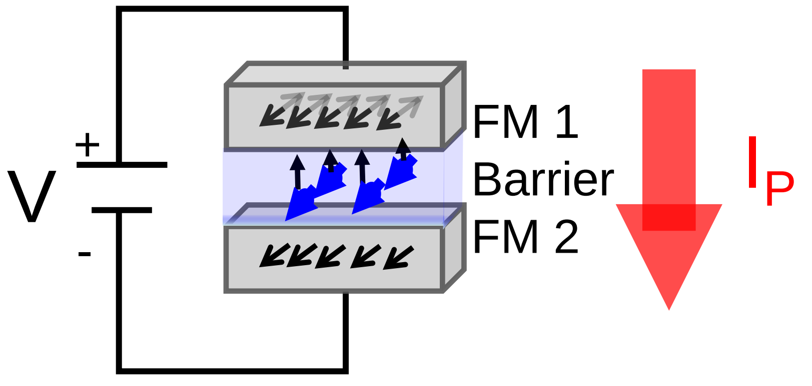
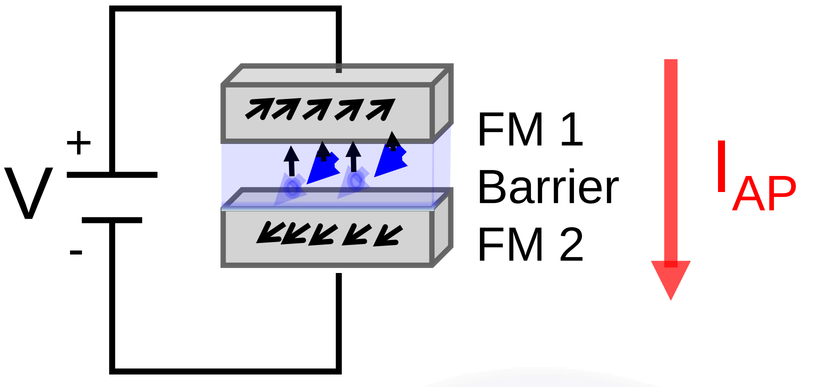
Giant tunneling magnetoresistance

Parallel magnetization



Antiparallel magnetization

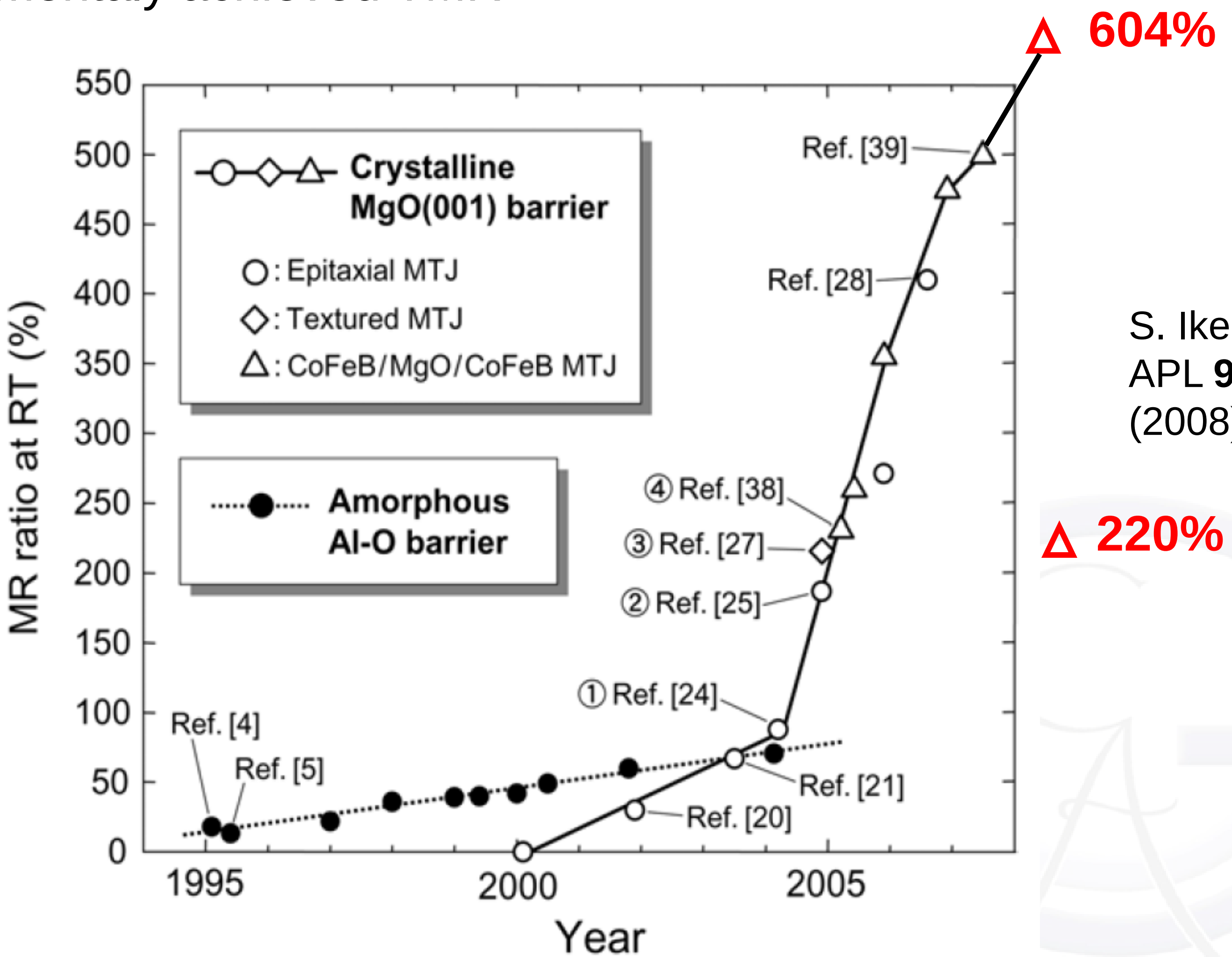


Resistance change is tunneling magnetoresistance (TMR):

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P}$$

Giant tunneling magnetoresistance

Experimentaly achieved TMR

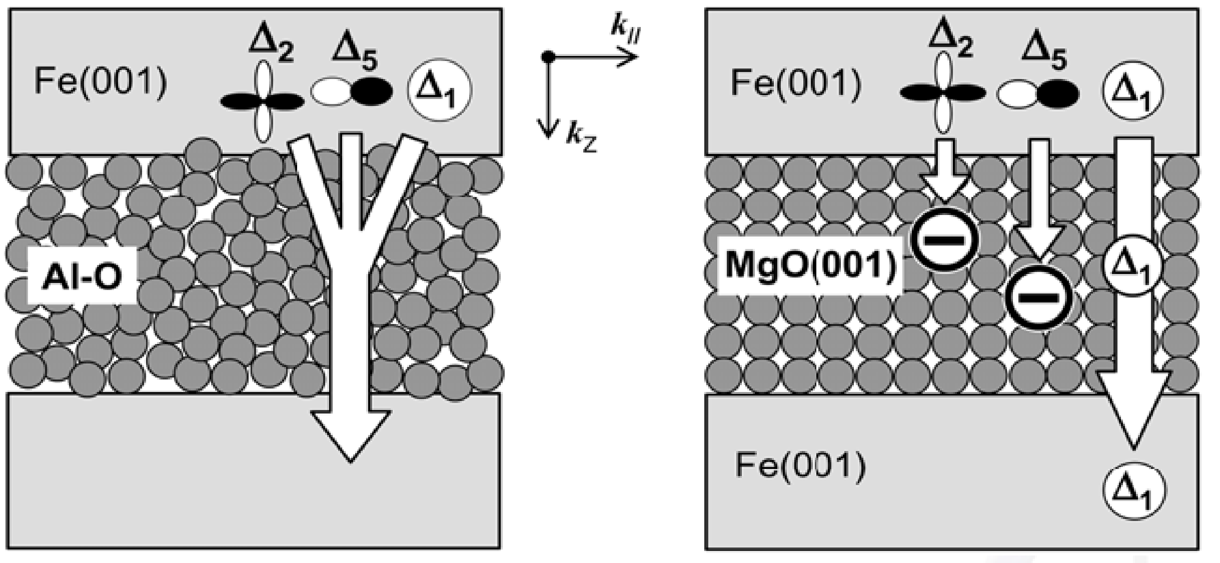


S. Ikeda et al. APL **93**,082508 (2008)

S. Yuasa und D. D. Djayaprawira, J. Phys. D: Appl. Phys. **40**, R337-R354 (2007)

Giant tunneling magnetoresistance

Difference between Al_2O_3 and MgO barriers

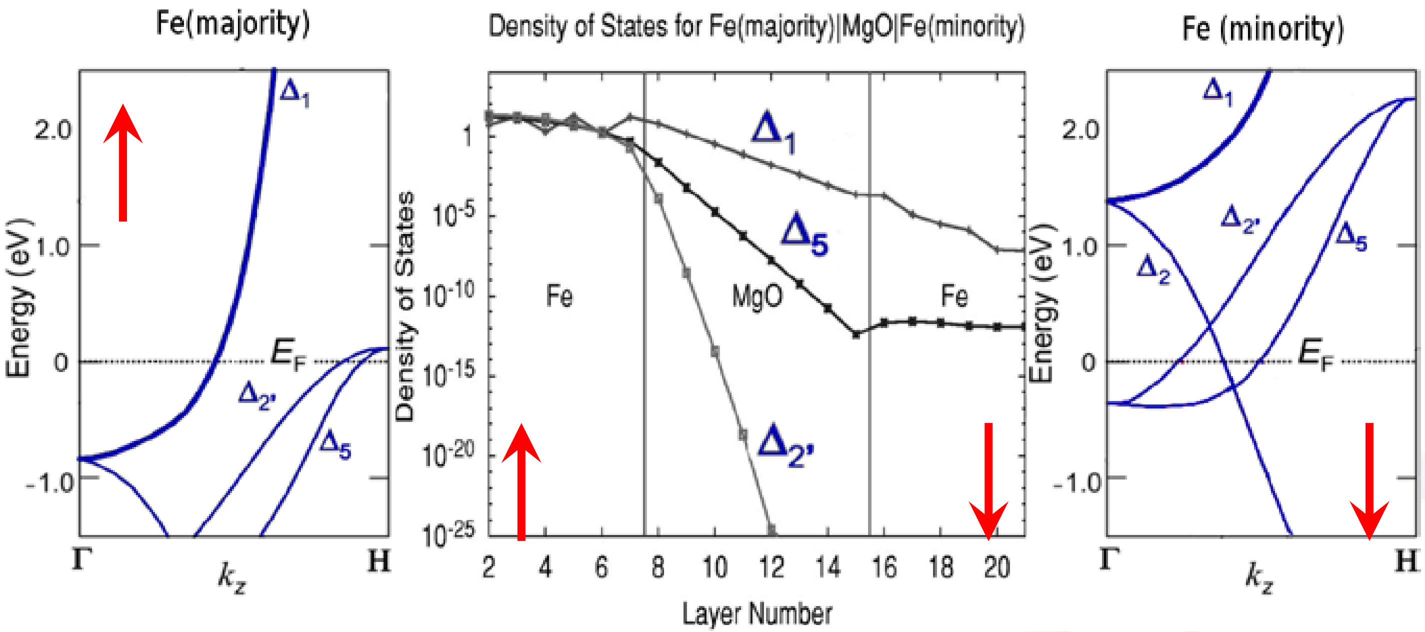


- Transmission probability is the same for different electronic bands
- Transmission probability changes for different electronic bands

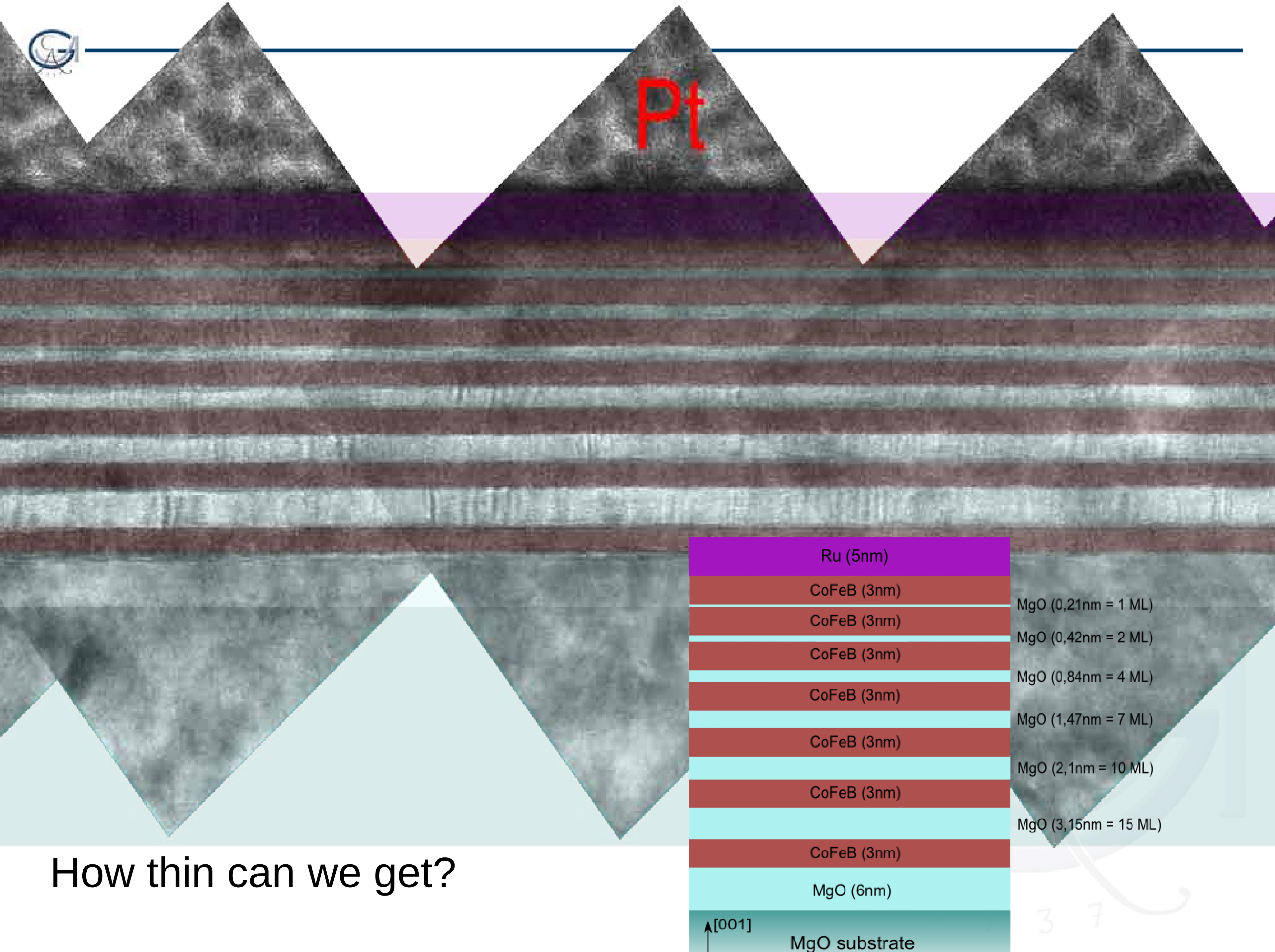
S. Yuasa und D. D. Djayaprawira, J. Phys. D: Appl. Phys. **40**, R337-R354 (2007)

Giant tunneling magnetoresistance

Fe|MgO|Fe coherent tunneling

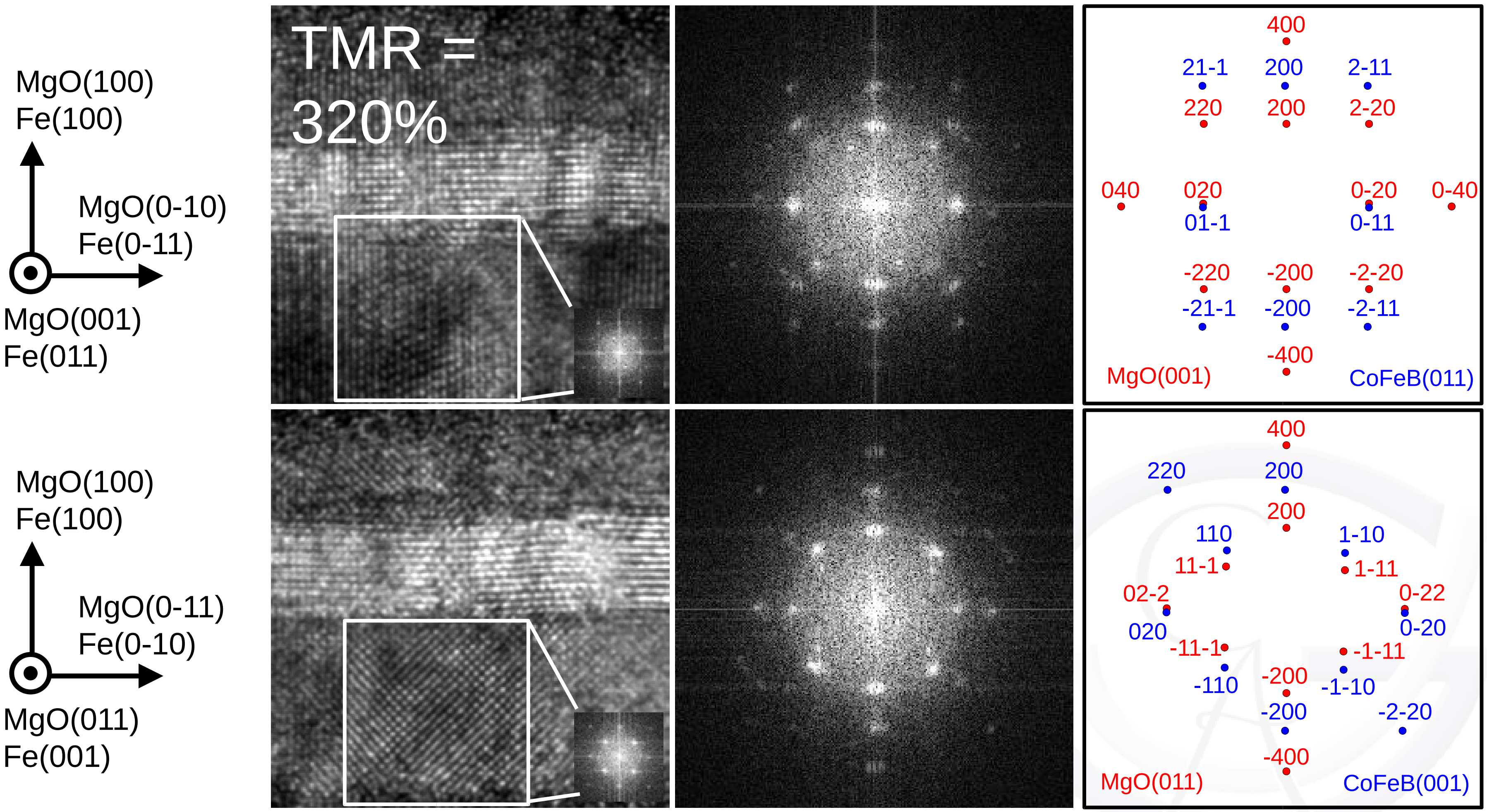


	Fe|MgO|Fe	Co|MgO|Co	FeCo|MgO|FeCo
Heiliger *et al.*	6000-8800%	900-2000%	
Mathon, Umerski	1200%		
Butler *et al.*	6000%	13000%	34000%



How thin can we get?

Atomic structure – columnar growth

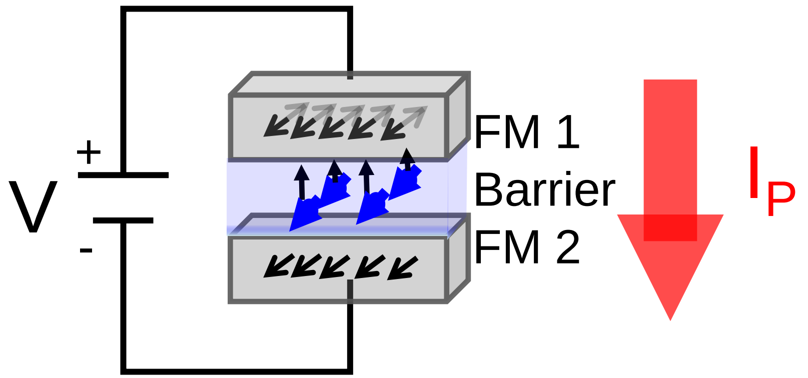


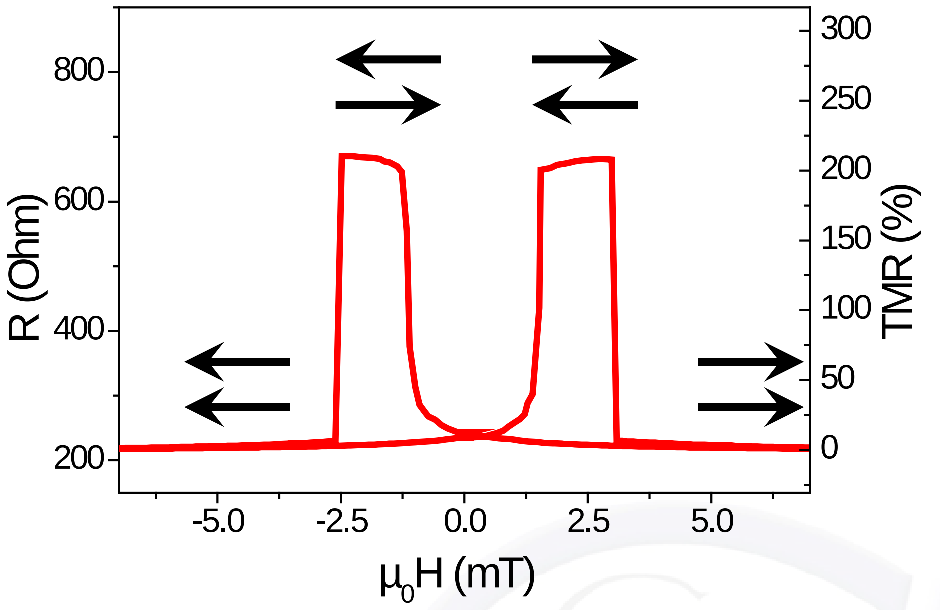
Sample annealed 400°C

In collaboration with: M. Seibt U Göttingen
A. Thomas, G. Reiss U Bielefeld

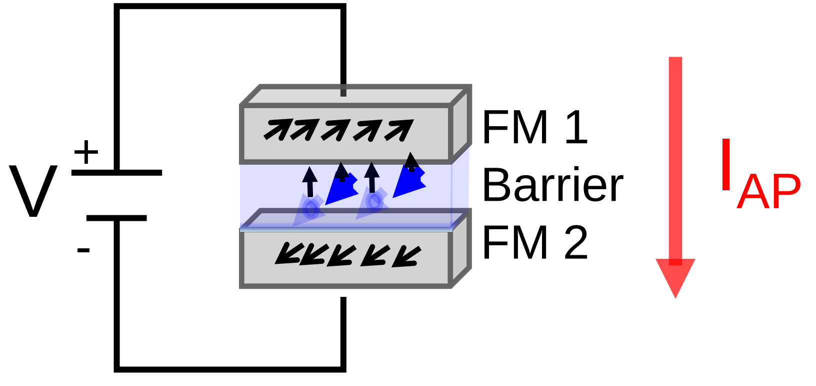
Giant tunneling magnetoresistance

Parallel magnetization





Antiparallel magnetization



CoFeB/ MgO/ CoFeB junctions are half metallic with highest TMR (~600% at RT)

$$TMR = \frac{R_{AP} - R_P}{R_P}$$

Appl. Phys. Lett. **95**, 232119 (2009)

J. Appl. Phys. **105**, 073701 (2009)

Outline

- Introduction into coherent tunneling
- Magneto-Seebeck experiment:
  - Experimental setup
  - Simulations of the temperature gradients
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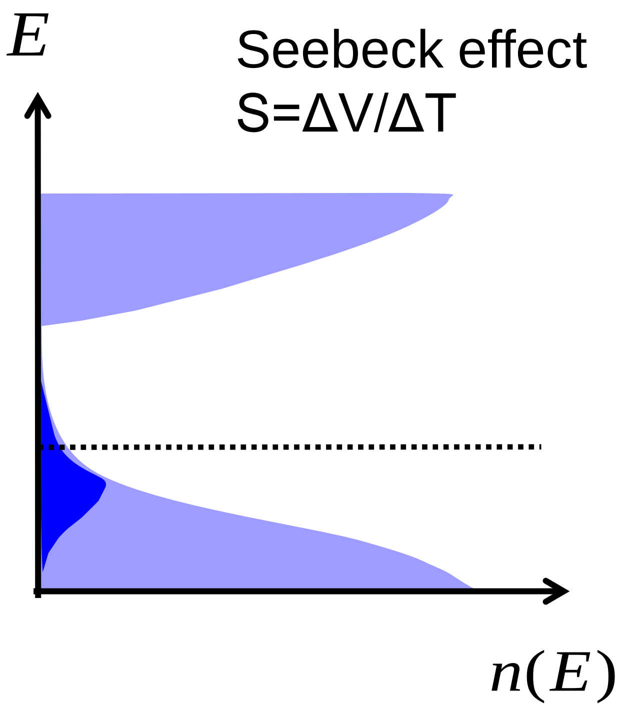
Magneto-Seebeck effect

Semiconductor

Seebeck effect
S=ΔV/ΔT



Semiconductors have a large Seebeck effect

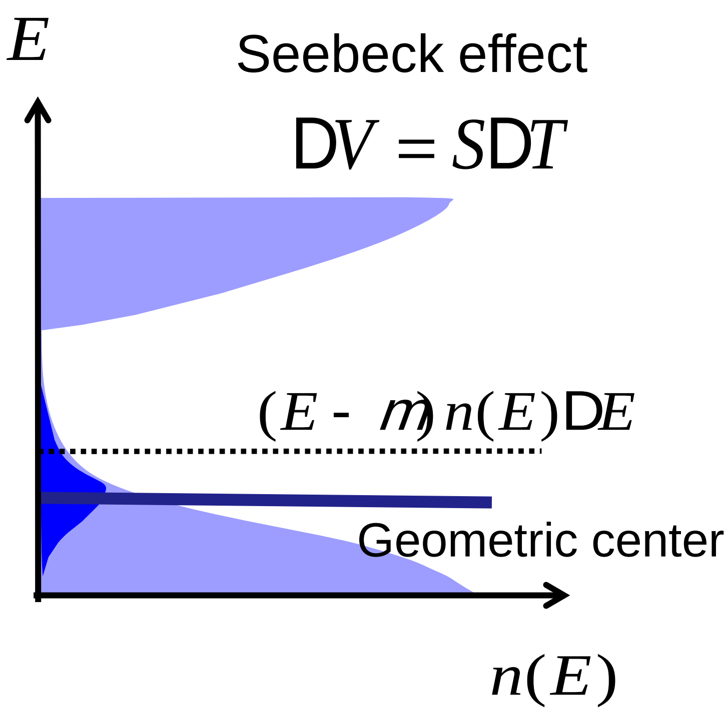
Orgin is the
- Large asymmetrie of the electrons at around the Fermi energy

Conduction
- Determined by the density of states n(E)

$$g = \frac{e^2}{h} \int T(E)(-\partial_E f(E,\mu,T))dE$$

Magneto-Seebeck effect

Semiconductor



Semiconductors have a large Seebeck effect

Orgin is the
- Large asymmetrie of the electrons at around the Fermi energy

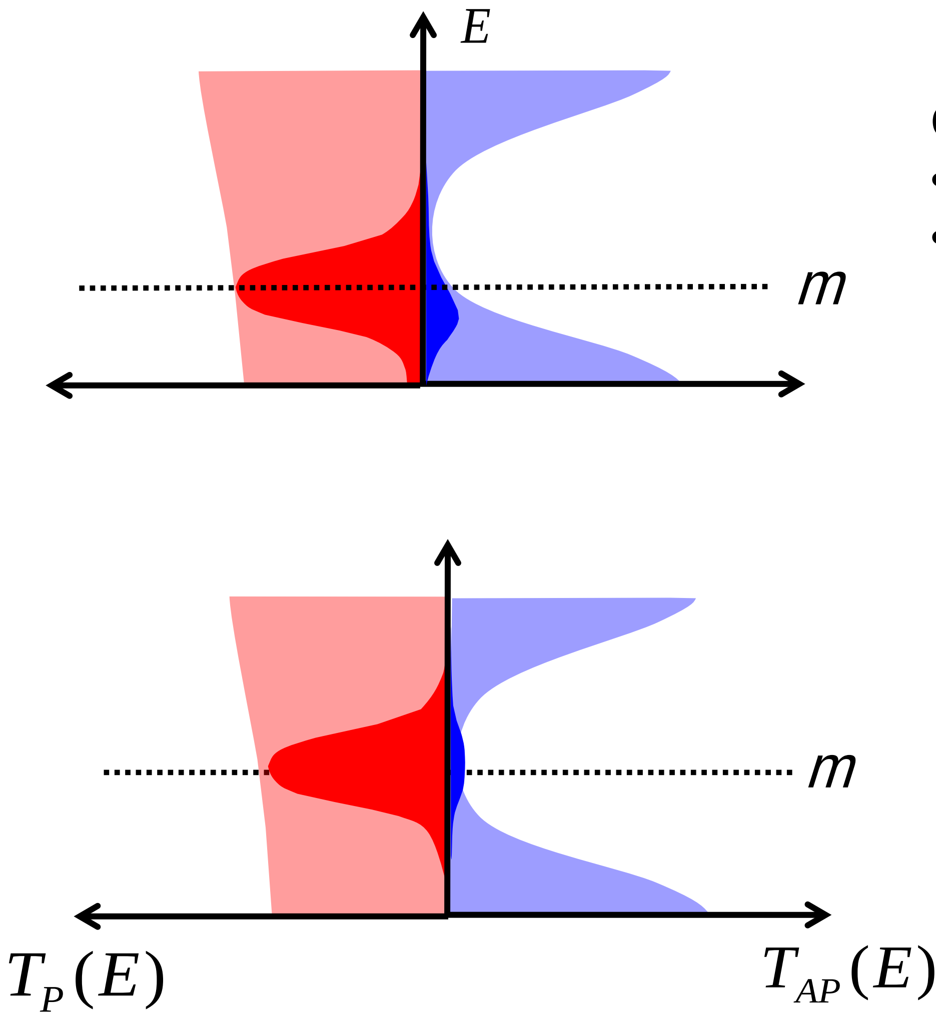
Conduction
- Determined by the density of states n(E)

Seebeck coefficient S
- Determined by density of states
- weigthed by (E-μ)
- times derivative $\frac{df(E)}{dE}$

$$S = -\frac{\int T(E)(E-\mu)(-\partial_E f(E,\mu,T))dE}{eT\int T(E)(-\partial_E f(E,\mu,T))dE}$$

Magneto-Seebeck effect

Tunnel junction



For tunnel junctions:

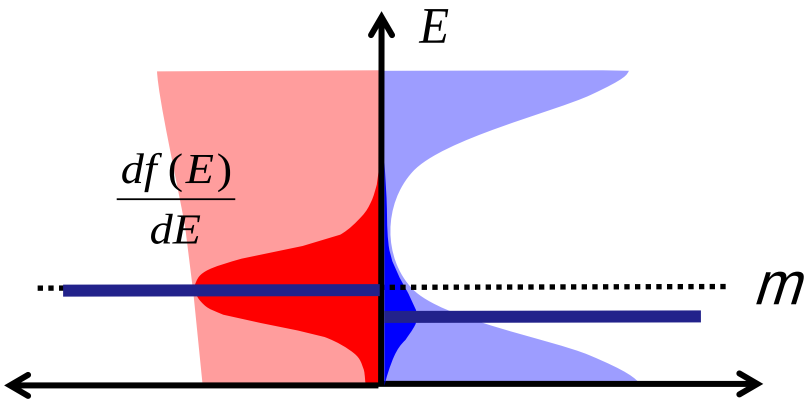
Conduction

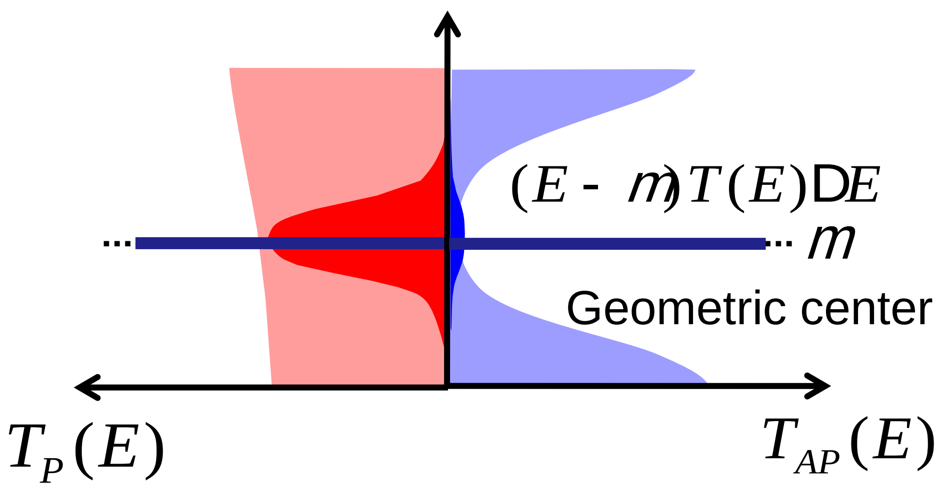
- Determined by the transmission T(E)
- High TMR

M. Walter et al. Nature. Mater. 10, 742 (2011).

Magneto-Seebeck effect

Tunnel junction





For tunnel junctions:

Conduction
- Determined by the transmission T(E)

Seebeck coefficient
- Determined transmission T(E)
- weigthed by (E-m)
- times derivative $\frac{df(E)}{dE}$

Definition of the magneto-Seebeck effect

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

M. Walter et al. Nature. Mater. 10, 742 (2011).

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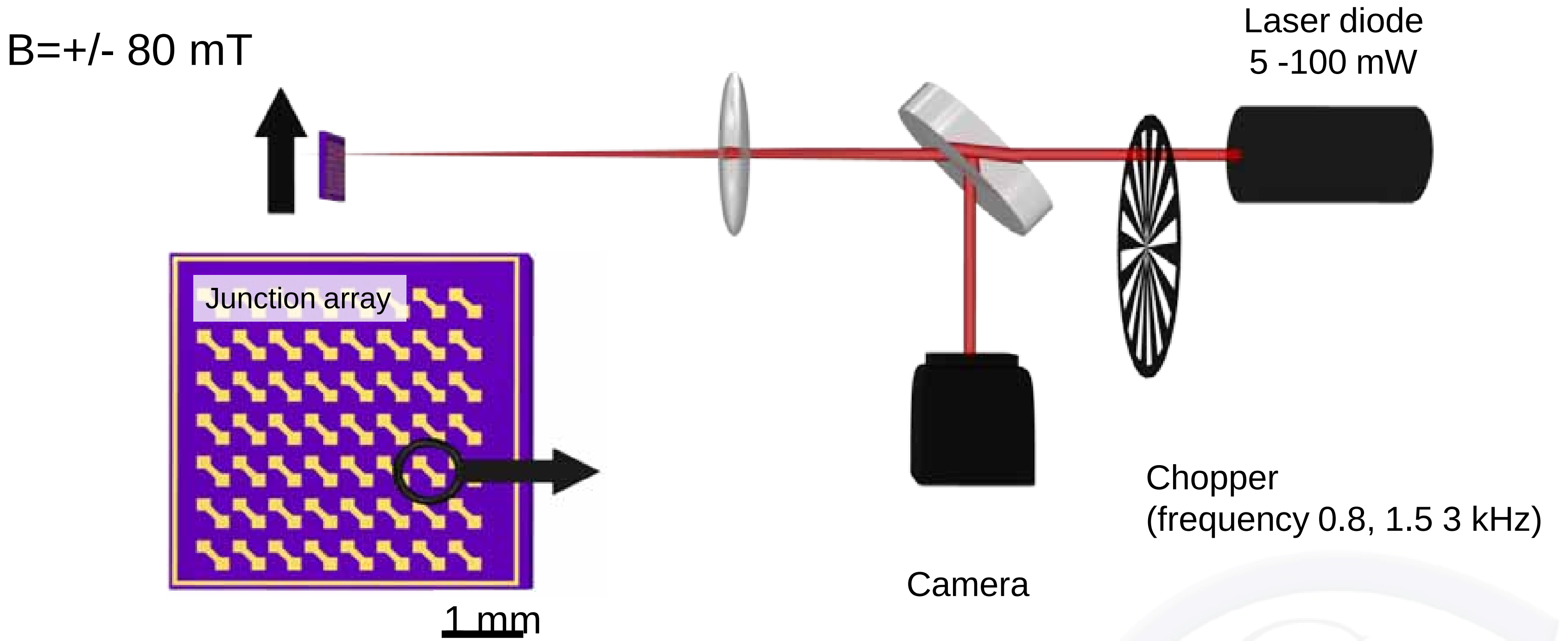
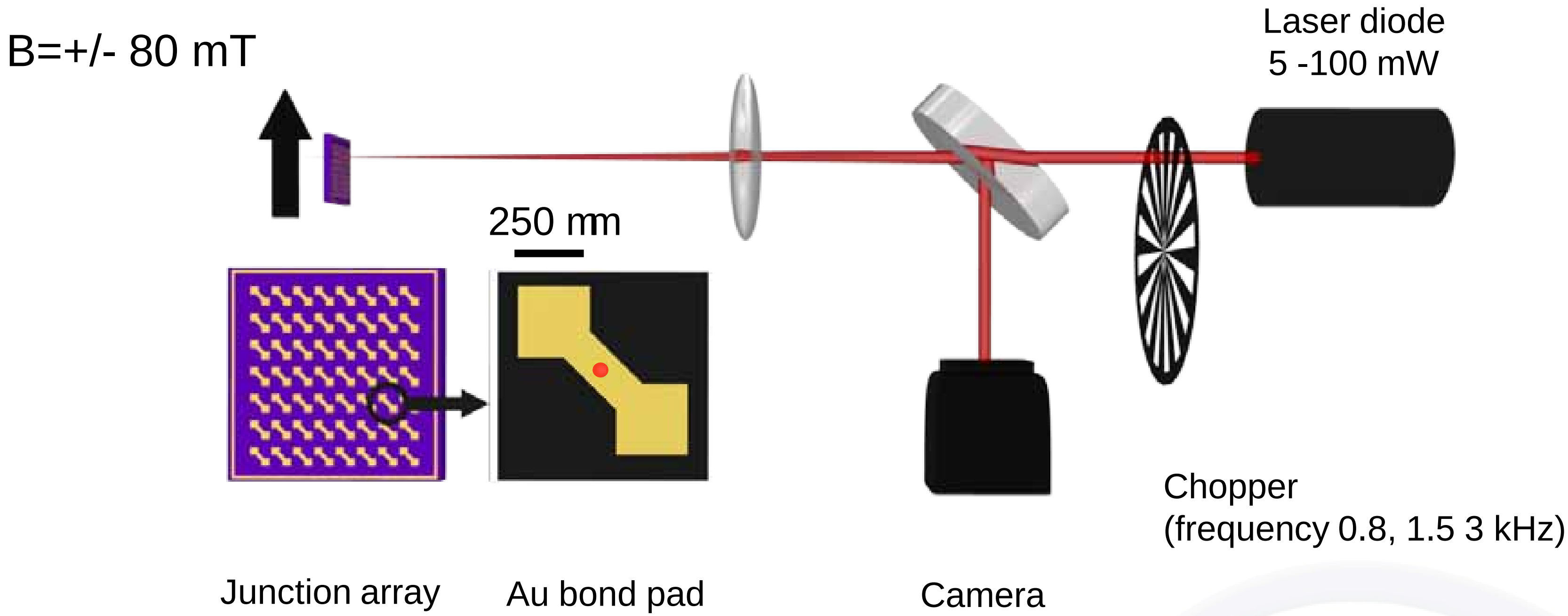
Experimental setup



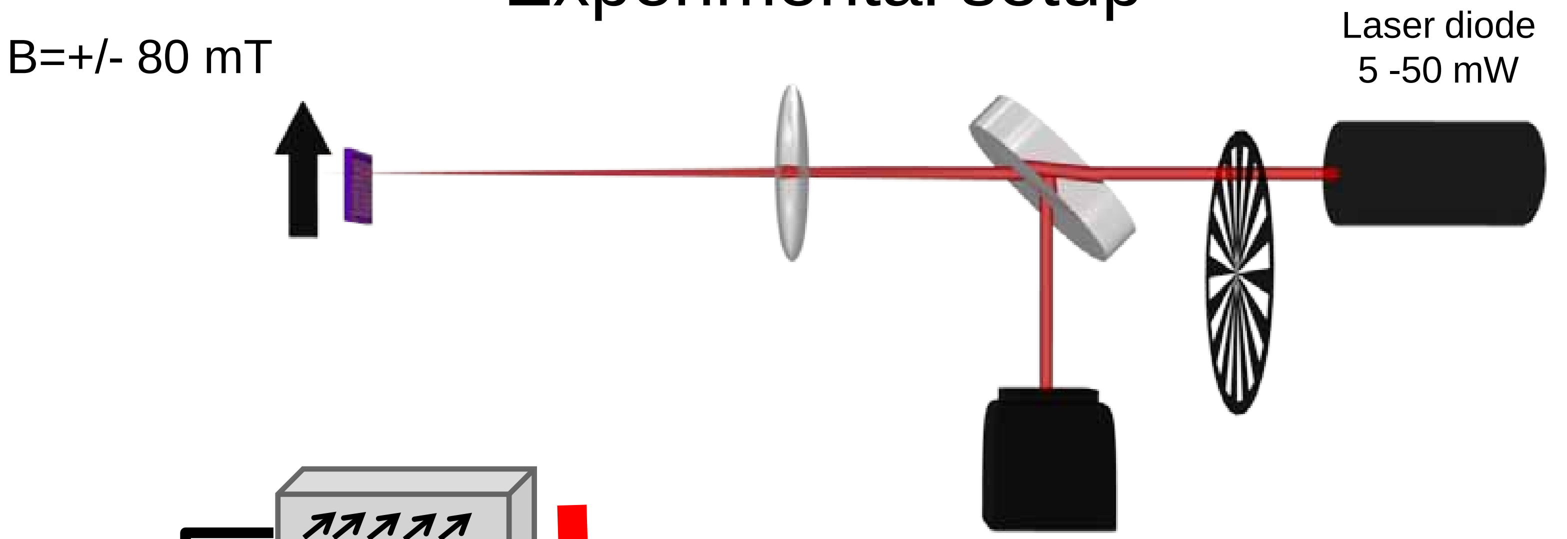
- Toptica stabilized laser diode (784 nm)
- Most experiments: 30 mW laser power
- Modulation 800 Hz, 1.5 kHz, and 3 kHz

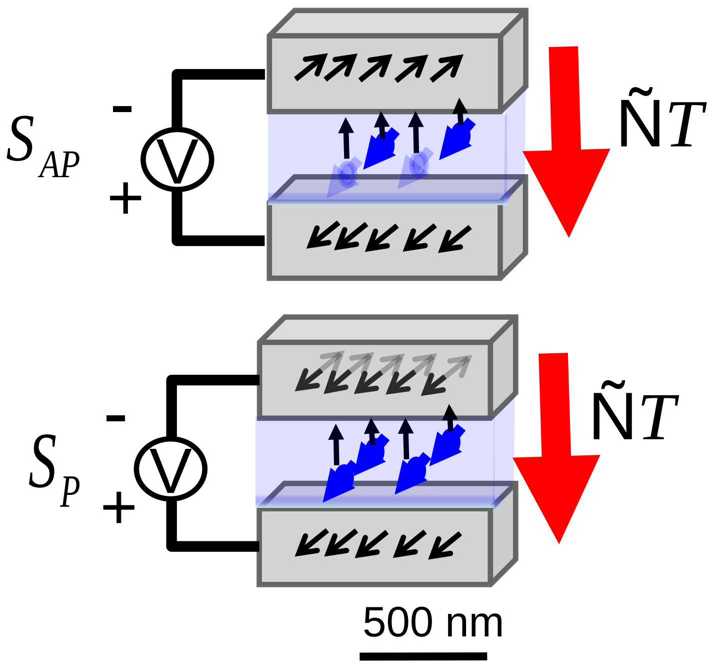
Experimental setup



- Focus15-20 µm diameter
- High input impedance (100 GΩ) (LT1113 Linear Technology)
- Resistance change < 1 nV

Experimental setup





Seebeck effect:

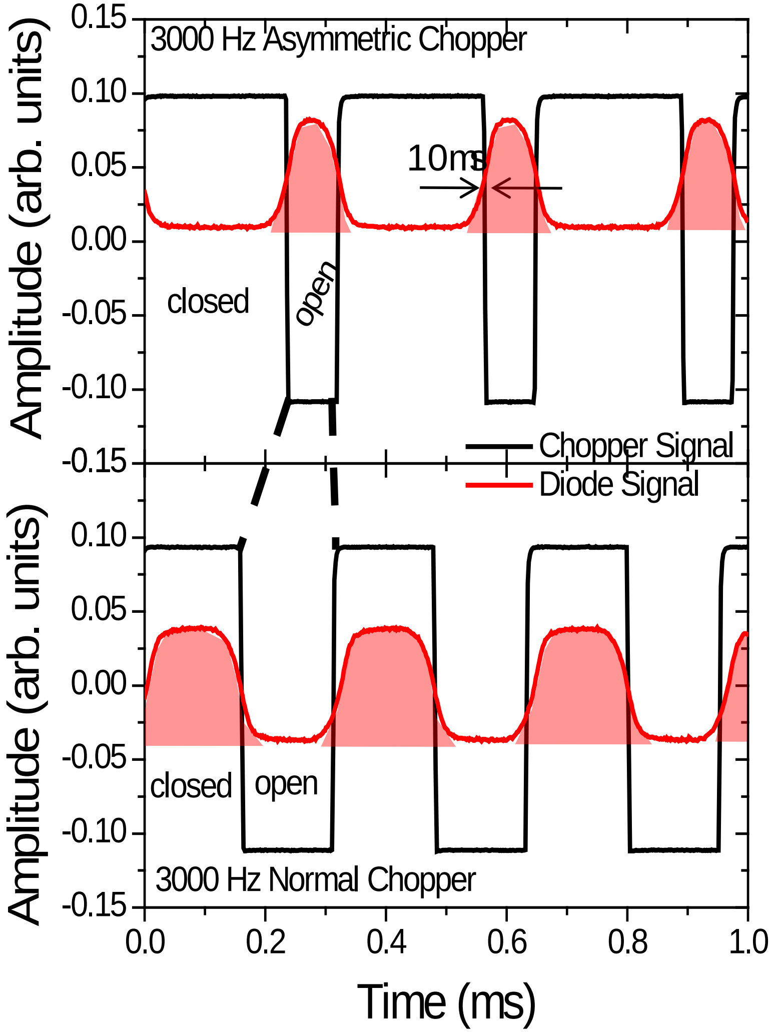
$$\mathrm{D}V_{P,AP} = S_{P,AP}\mathrm{D}T$$

Magneto -Seebeck effect:

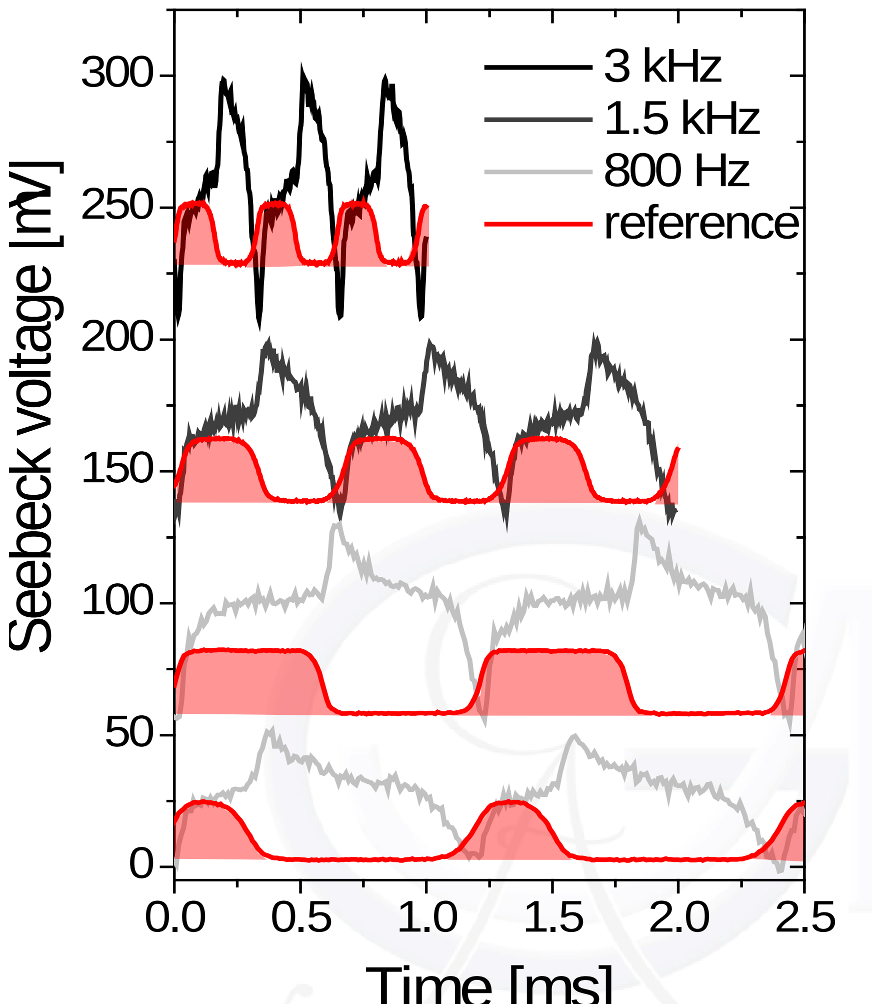
$$S_{\mathrm{MS}} = \frac{S_{\mathrm{P}} - S_{\mathrm{AP}}}{\min(S_{\mathrm{P}}, S_{\mathrm{AP}})}$$

Experimental setup

Modulation chopper and laser intensity



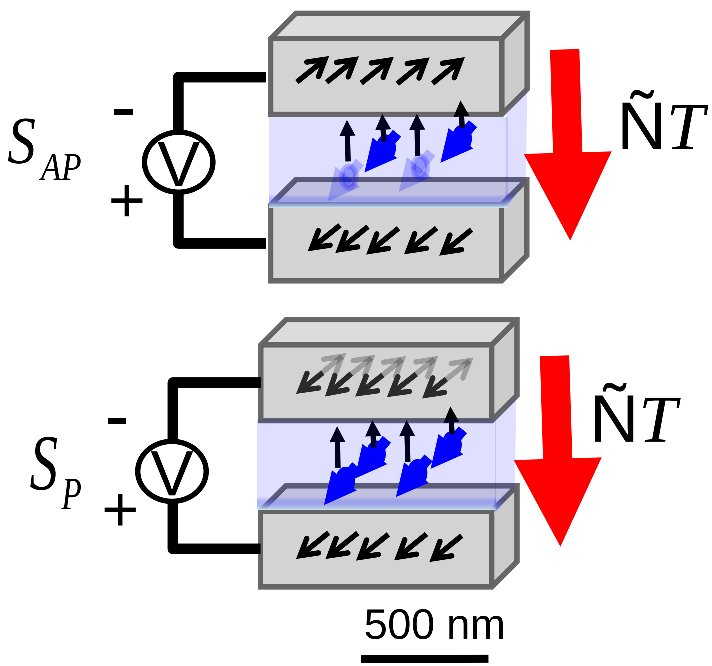
Seebeck voltage



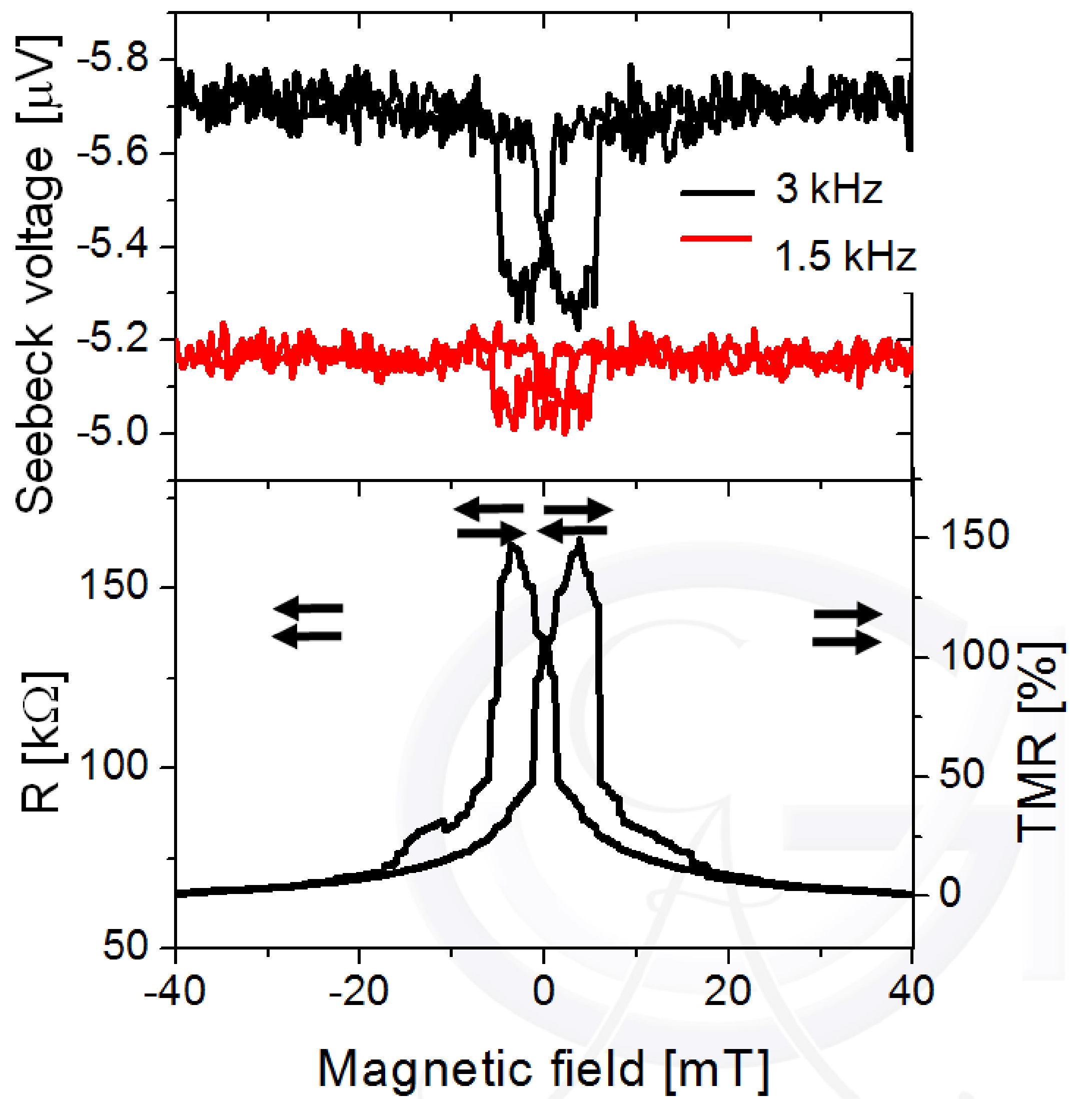
Magneto-Seebeck effect

Magneto-Seebeck effect: -8.8%

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



Seebeck voltage 0.45 mV, DS= -8.7 mV/K



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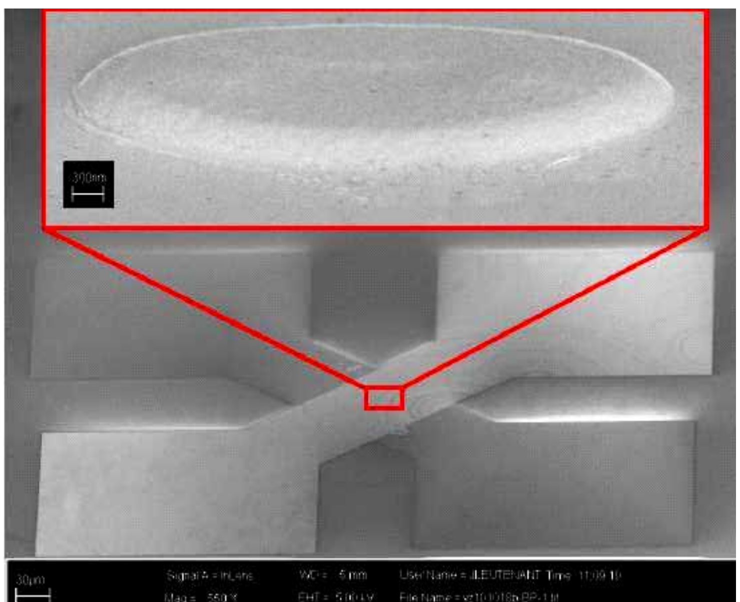
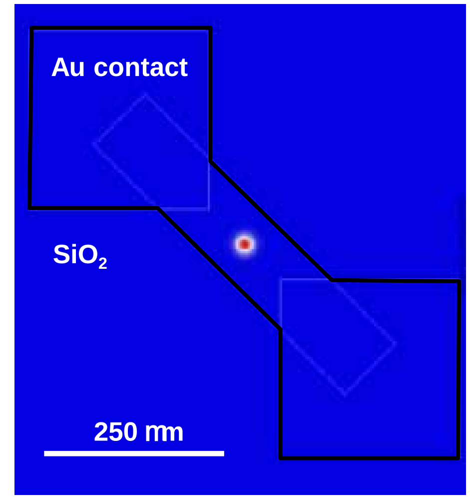
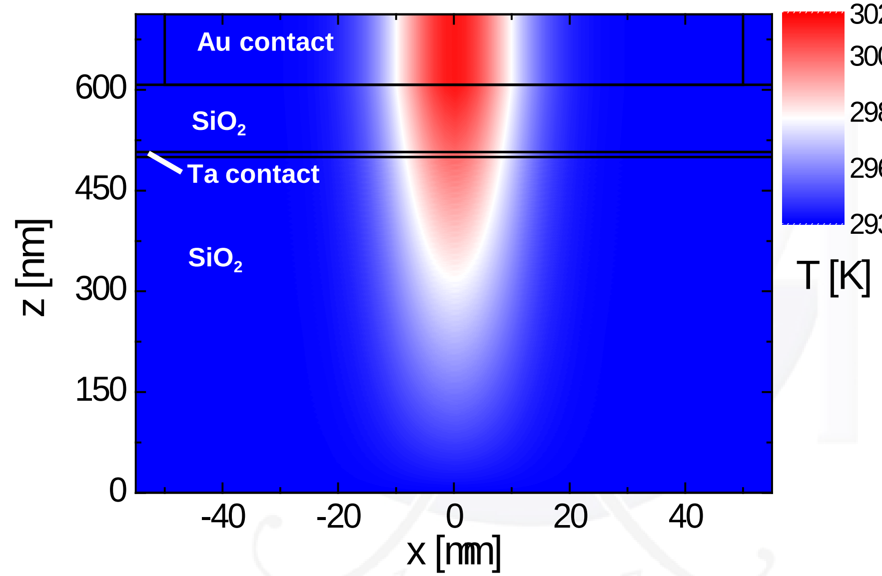
COMSOL finite element modeling

- COMSOL uses finite elements methods
- Solving of heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

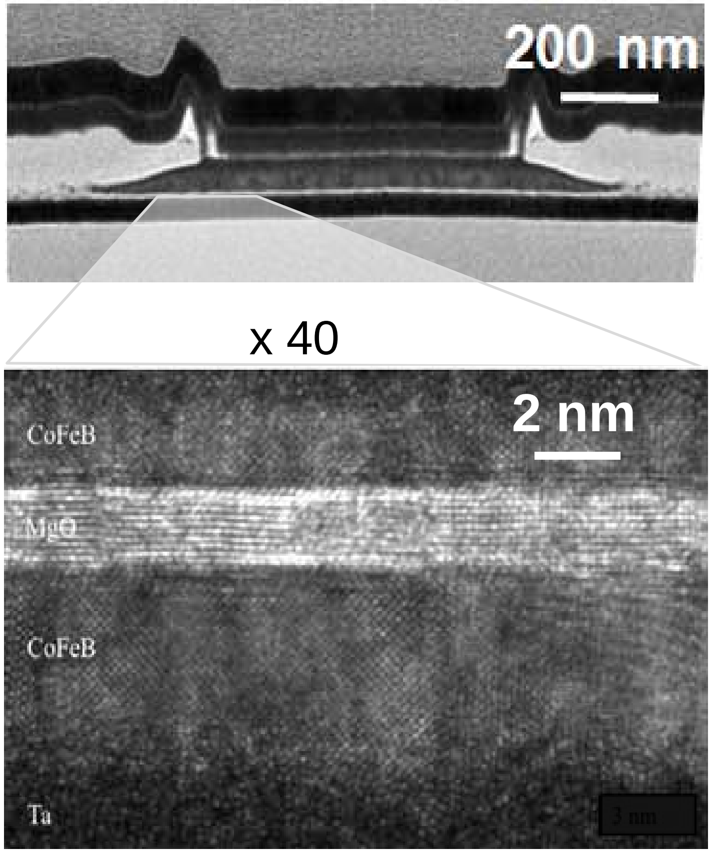




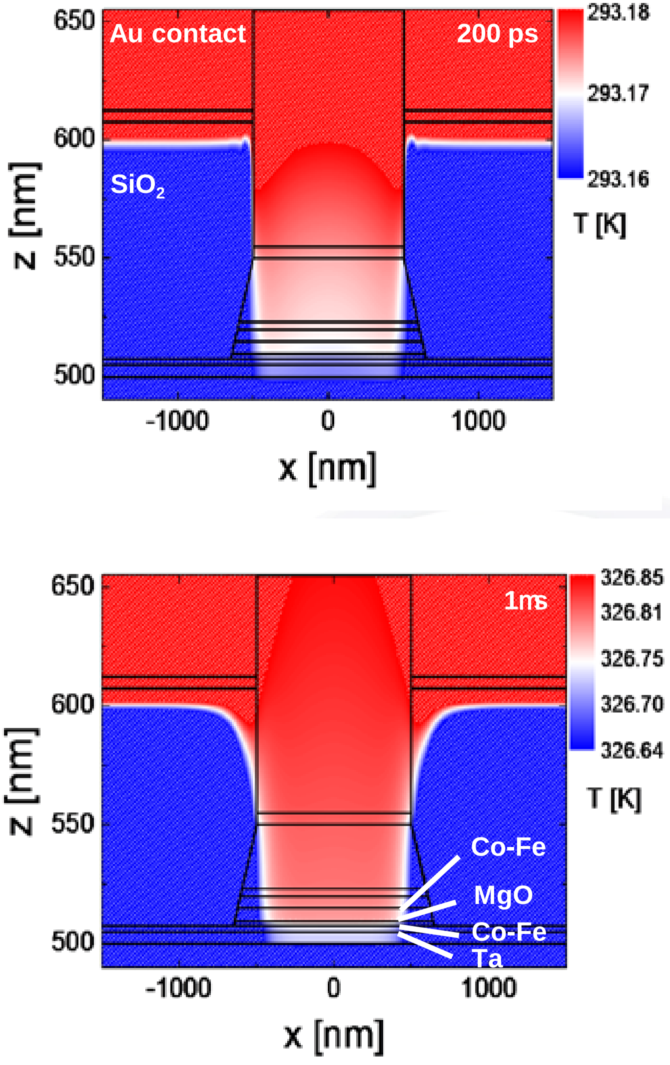


COMSOL finite element modeling

Device structure by HRTEM



Temperature gradients: 1 to 50 mK



COMSOL finite element modeling

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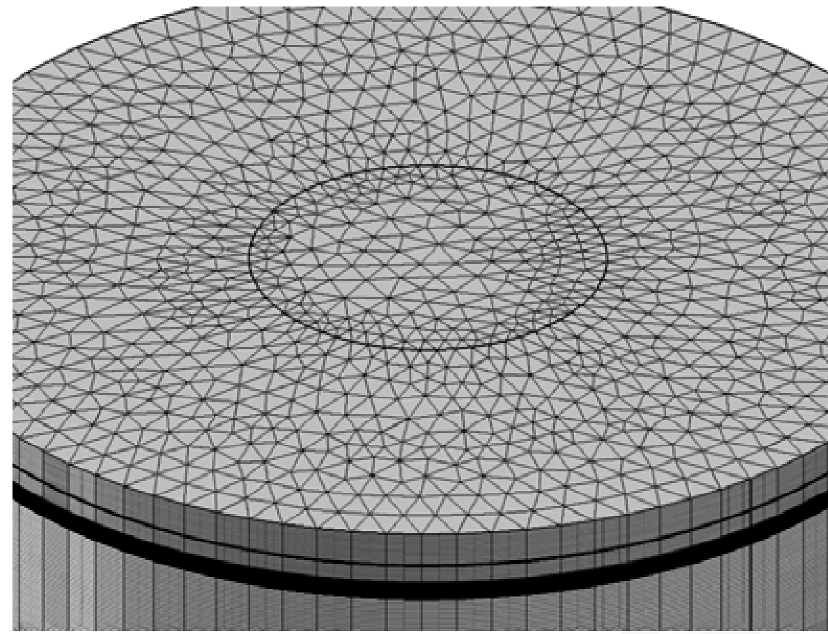
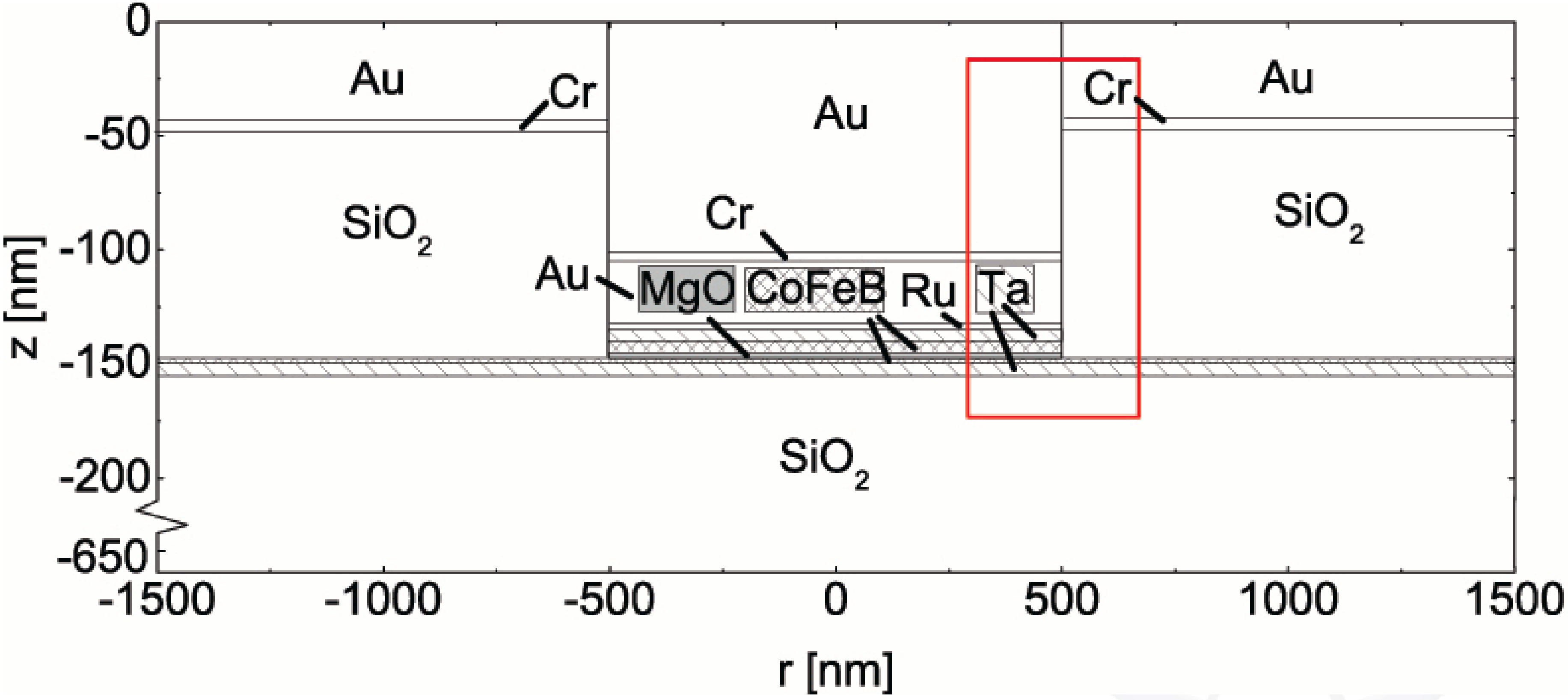
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

- 3d or 2d cylindrical model



Material	κ [W/(m·K)]
Ta	57
Ru	117
Au	320
Cr	94
MgO	4 (48)
SiO_2	1.4
$Co_{20}Fe_{60}B_{20}$	87

COMSOL finite element modeling

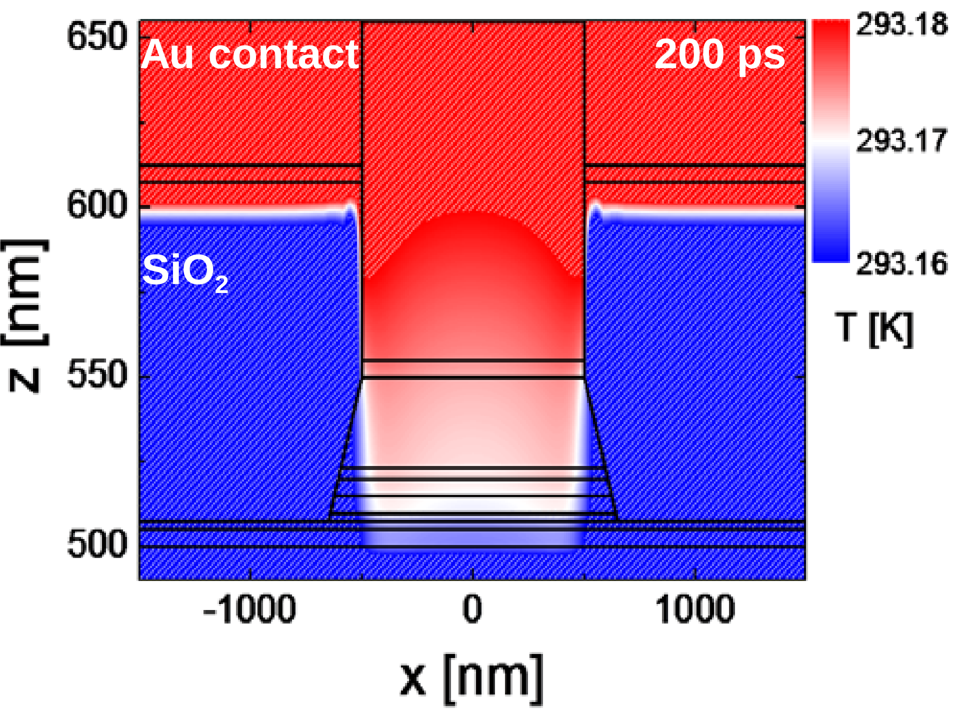


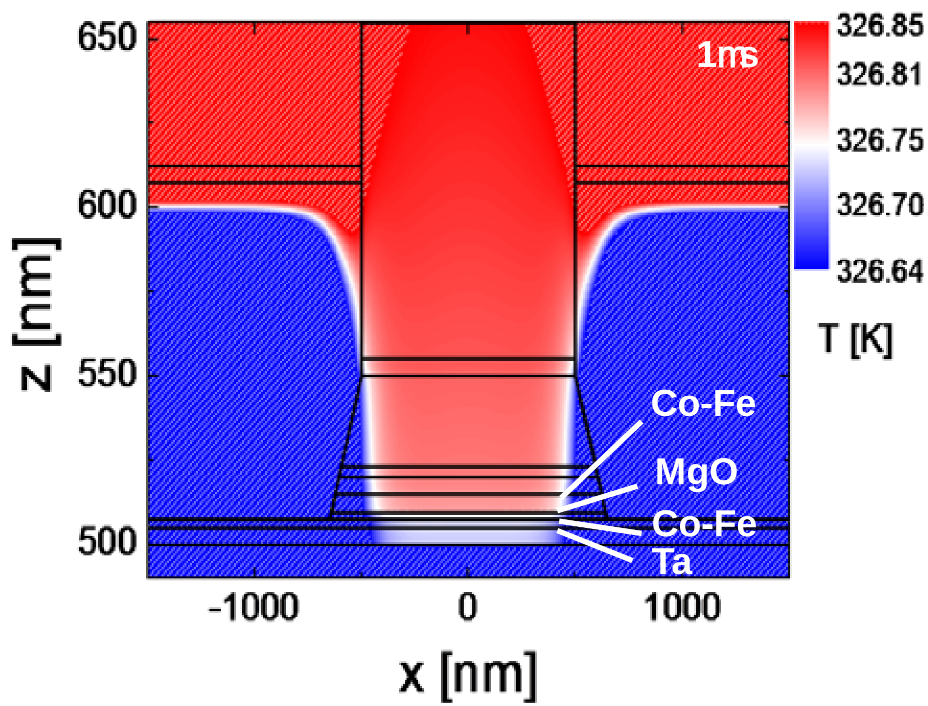
COMSOL finite element modeling

Cross section of the finite element model

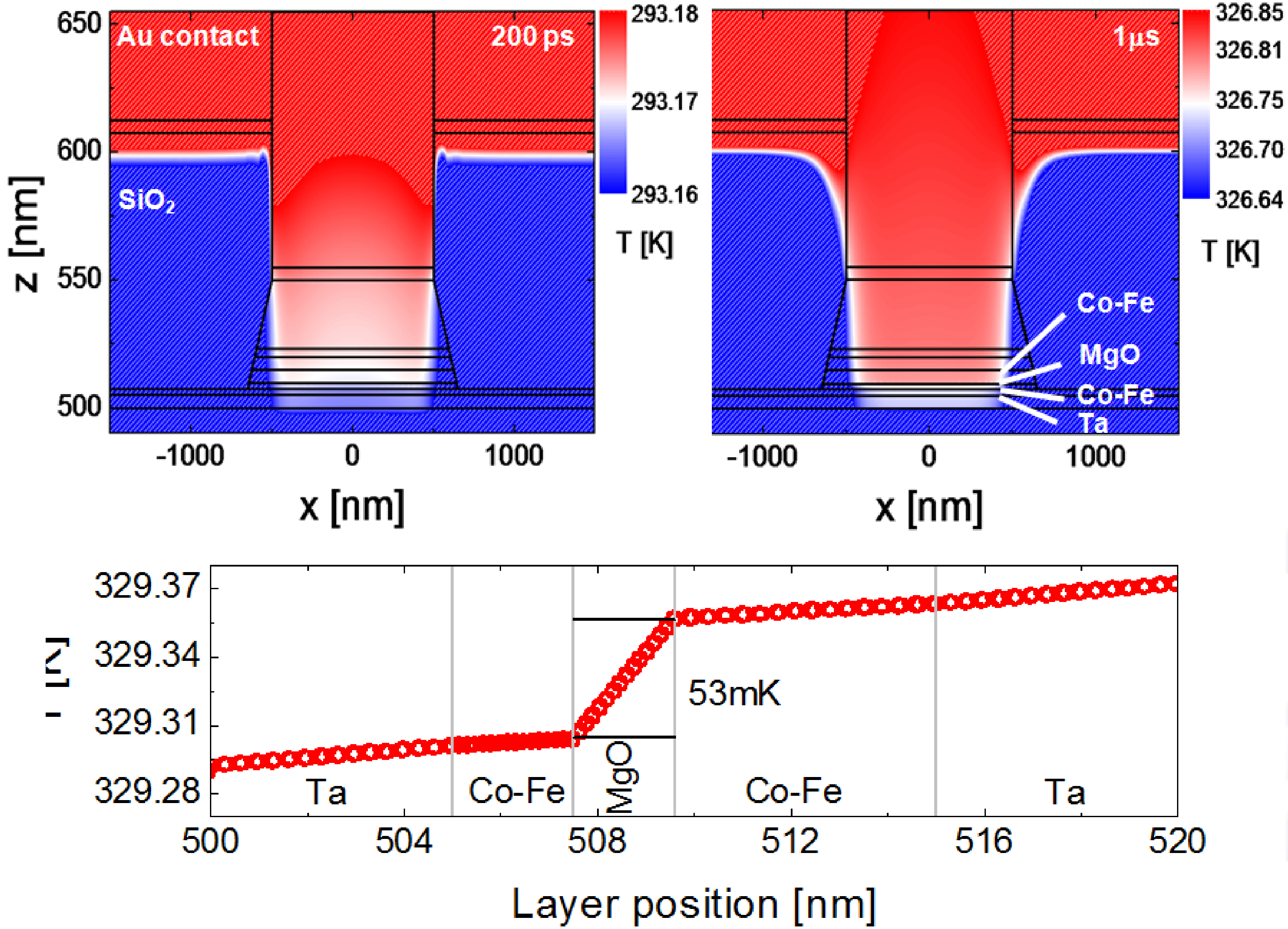
Temperature gradients: 1 to 50 mK

$$S = \Delta V / \Delta T$$





COMSOL finite element modeling



M. Walter et al. Nature. Mater. 10, 742 (2011).

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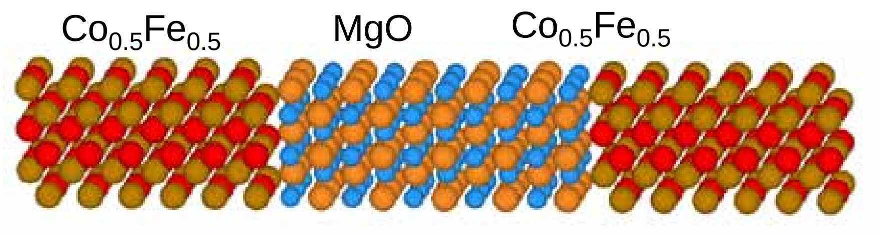
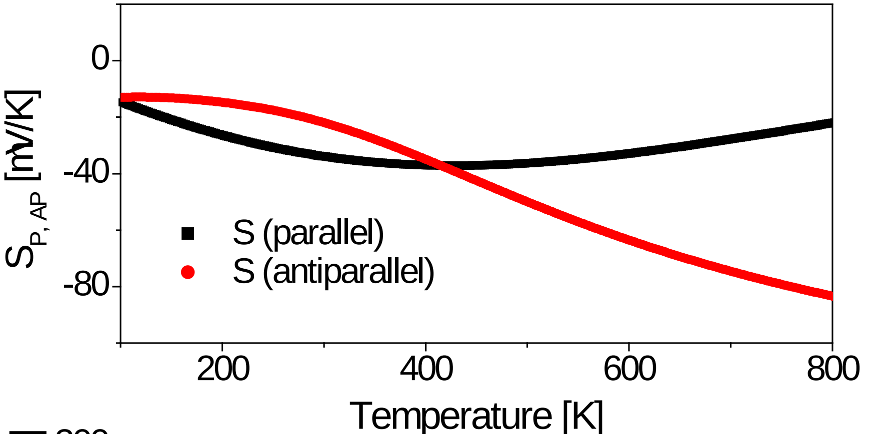
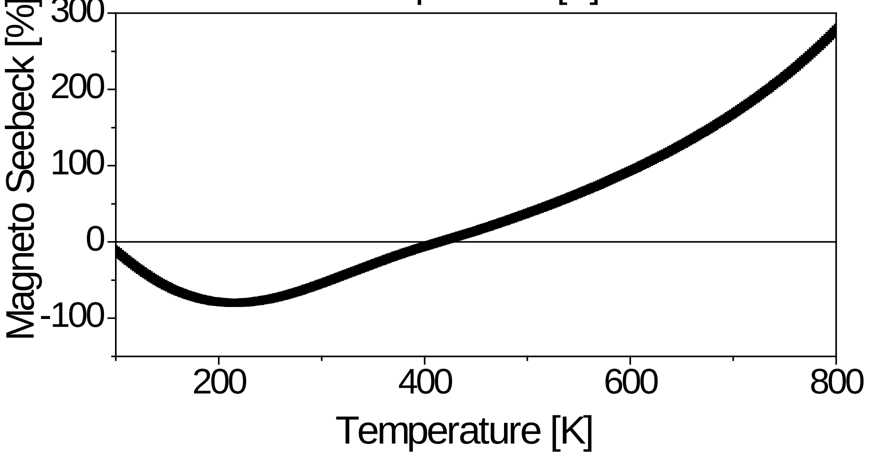
Magneto-Seebeck effect







Calculations by C. Heiliger U Gießen

For tunnel junctions:

Conduction

$$g = \frac{e^2}{h} \int T(E)(-\partial_E f(E, \mu, T)) dE$$

Seebeck coefficient

$$S = -\frac{\int T(E)(E-\mu)(-\partial_E f(E, \mu, T)) dE}{eT \int T(E)(-\partial_E f(E, \mu, T)) dE}$$

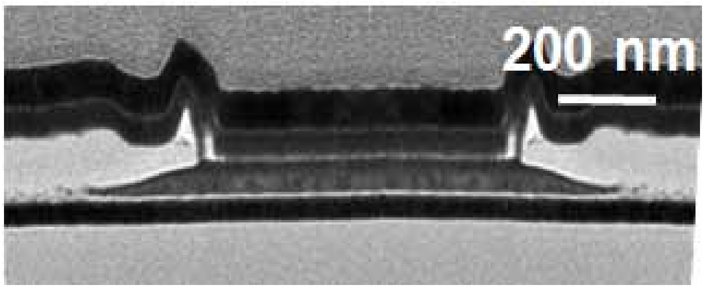
Definition of the magneto-Seebeck effect

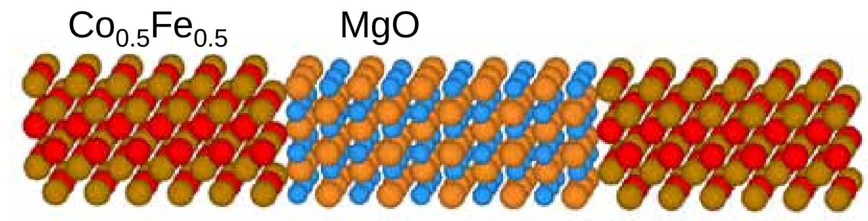
$$S_{\mathrm{MS}} = \frac{S_{\mathrm{P}} - S_{\mathrm{AP}}}{\min(S_{\mathrm{P}}, S_{\mathrm{AP}})}$$

Magneto-Seebeck effect

Device structure by HRTEM

Seebeck voltage 0.45 mV, DS= -8.7 mV/K

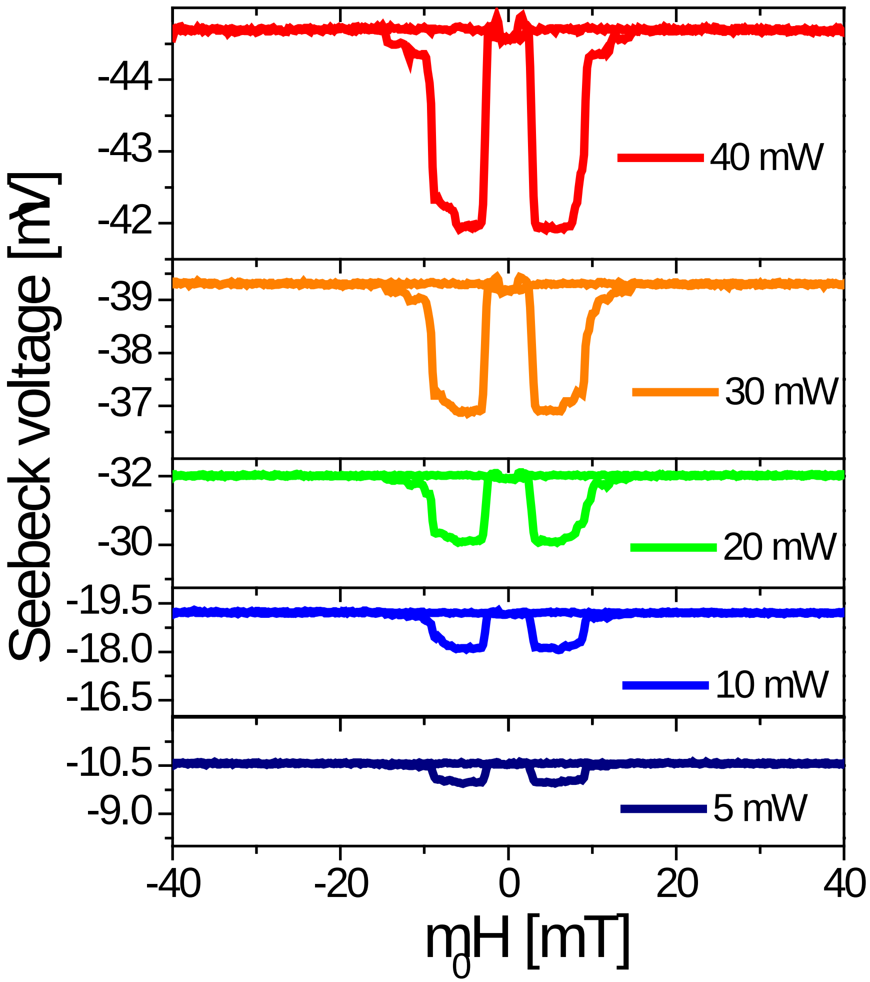




	S_P [μV/K]	S_{AP} [μV/K]	$S_P - S_{AP}$ [μV/K]	S_{MS} [%]
CoFe	-19.7	-32.4	12.7	64.1
FeCo	45.9	-50.0	95.9	209.0
CFFC	9.4	-44.6	54.0	573.2
$Co_{0.5}Fe_{0.5}$	-34.0	-21.9	-12.1	-55.2
Experimental value	-107.9 (-1300)	-99.2 (-1195)	-8.7 (-105)	-8.8 (-8.8)

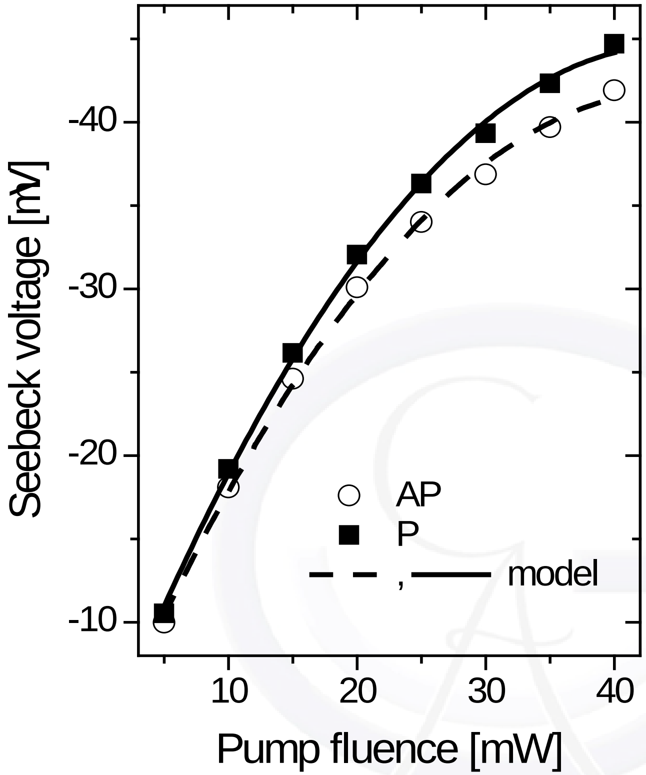
M. Walter et al. Nature. Mater. 10, 742 (2011).

Magneto-Seebeck effect



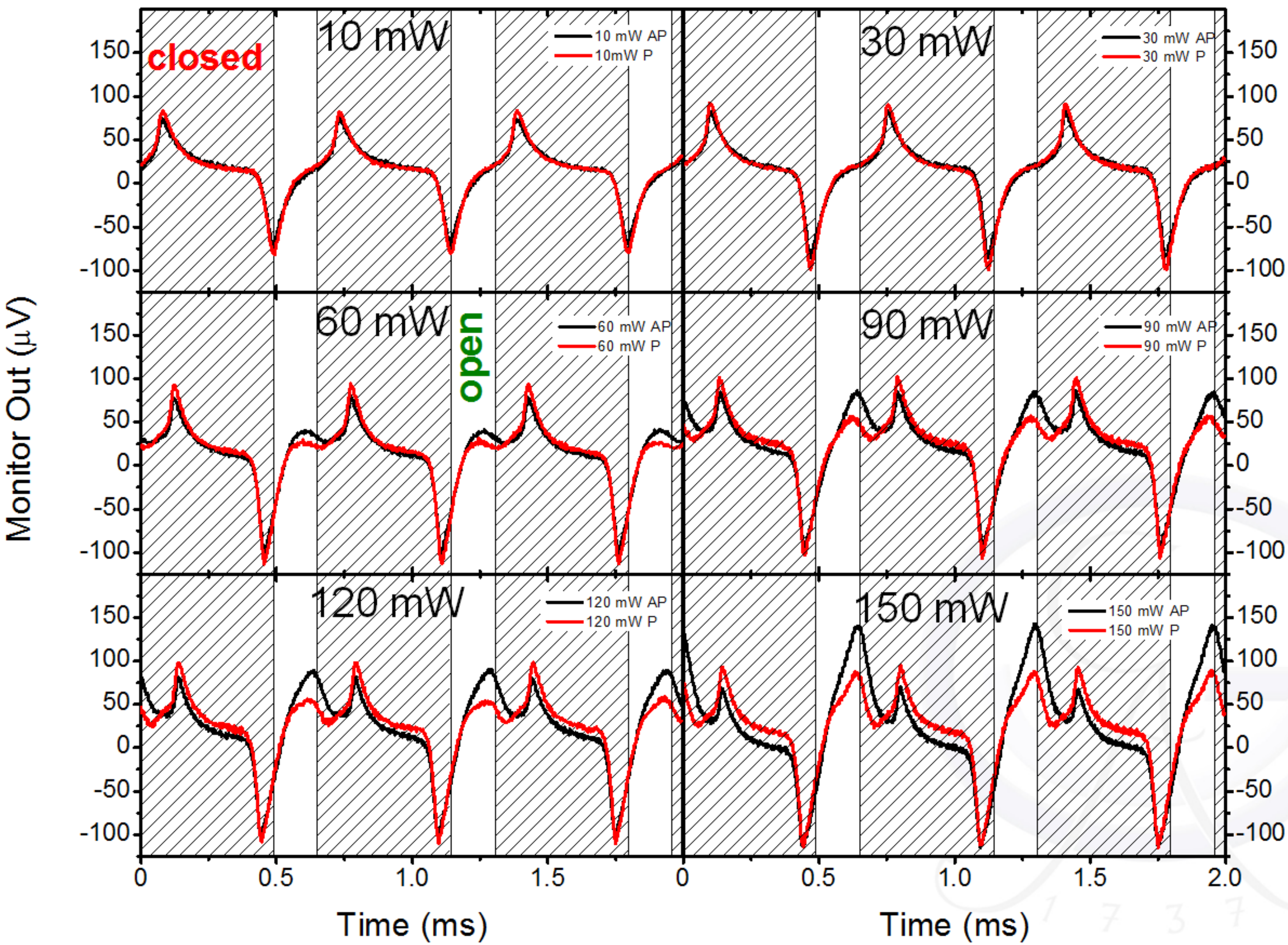
Higher T and gradient expected for higher laser powers

- nonlinear behavior $\Delta V = S(T)\Delta T$

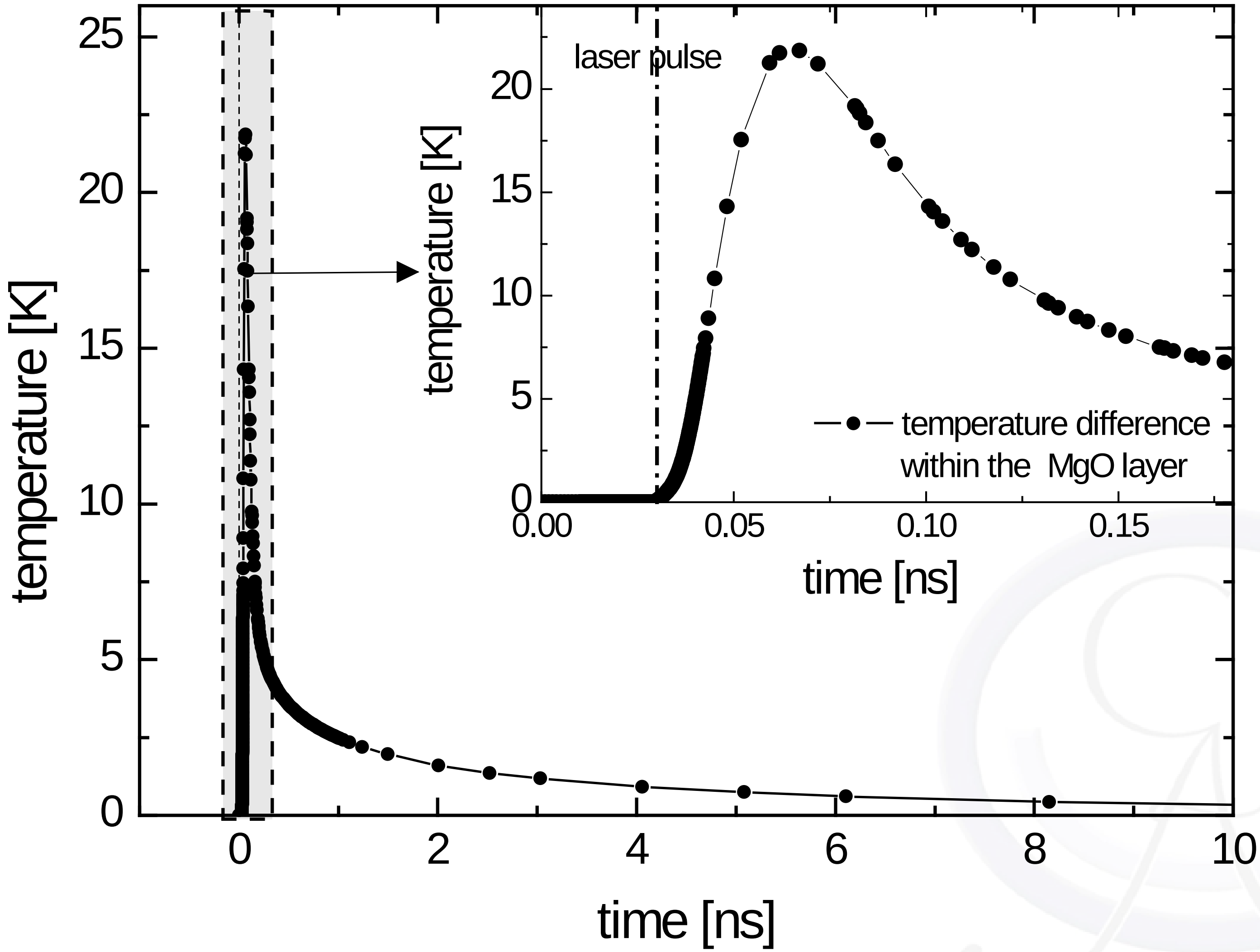


M. Walter et al. Nature. Mater. 10, 742 (2011).

High fluence data: femtosecond laser



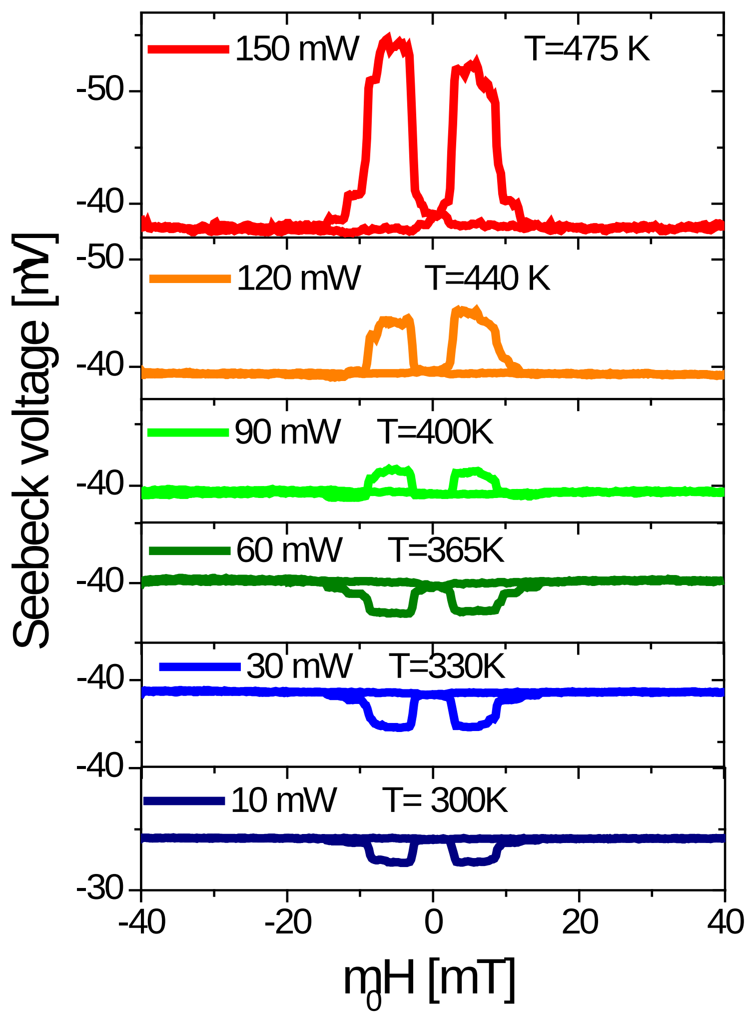
High fluence data: femtosecond laser

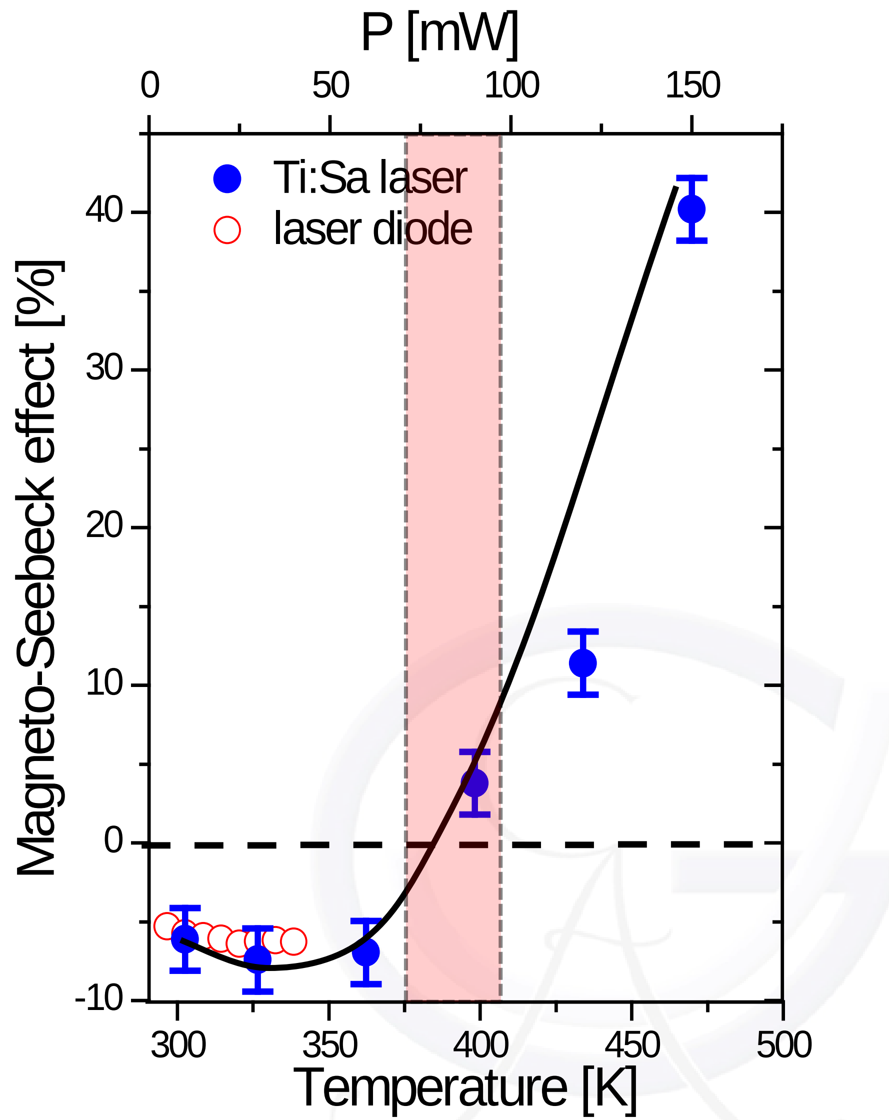


•Large temperature gradinets are achievable: 10K per nanometer

Magneto-Seebeck effect

Sign change as predicted:





M. Walter et al. Nature. Mater. 10, 742 (2011).

Summary

- Magneto-Seebeck experiment:
  - Experimental verification
  - Simulations of the temperature gradients
  - Switching of Seebeck coefficients demonstrated
- Ab initio calculations
  - Typical features are reproduced by the experiment

Increasing temporal resolution

Seebeck voltage autocorrelation:

- Femtosecond laser excitation (40 fs temporal resolution)
- Delay t in between the pulses
- Probes non-linearity of the Seebeck voltage
- ~80 ps time scale is the expected timescale when the maximum temperature difference is reached (from simulation)