Universität Bielefeld

Department of Physics

CENTER FOR SPINELECTRONIC MATERIALS AND DEVICES

SPIN CALORICS AND SPIN TRANSFER IN MAGNETIC NANOSTRUCTURES

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DFG
Priority
Programme
SpinCat

IEEE Magnetics Santa Clara Valley Chapter April 2014

FAQ's: Where is Bielefeld ?

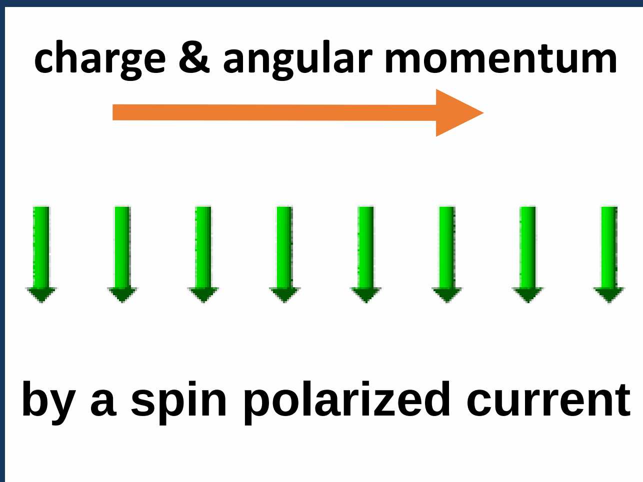
There

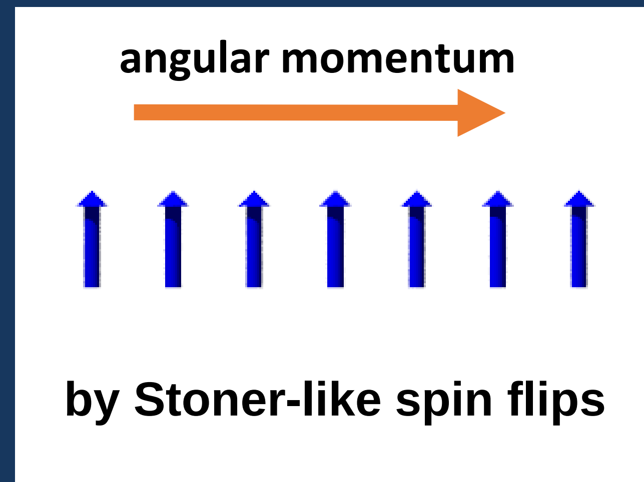
Content

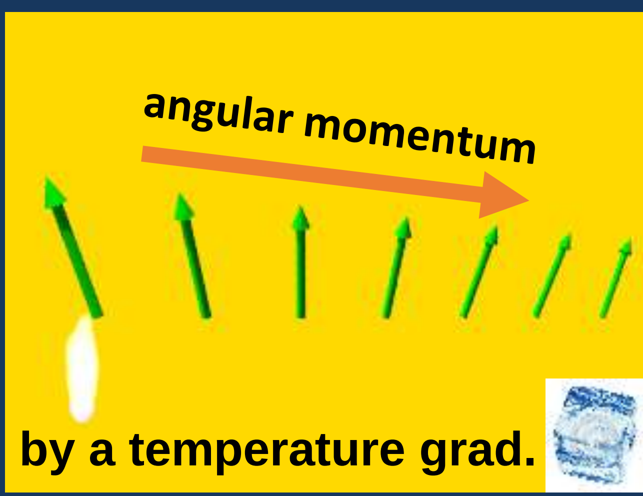
Introduction	Spintransfer
Spincalorics	LSSE in Ni-Ferrite TSSE in Permalloy ??
Spincalorics	in MTJs
Spin Transfer	in MTJs in p-MTJs STT at the limit
New Materials	High K, low M_S

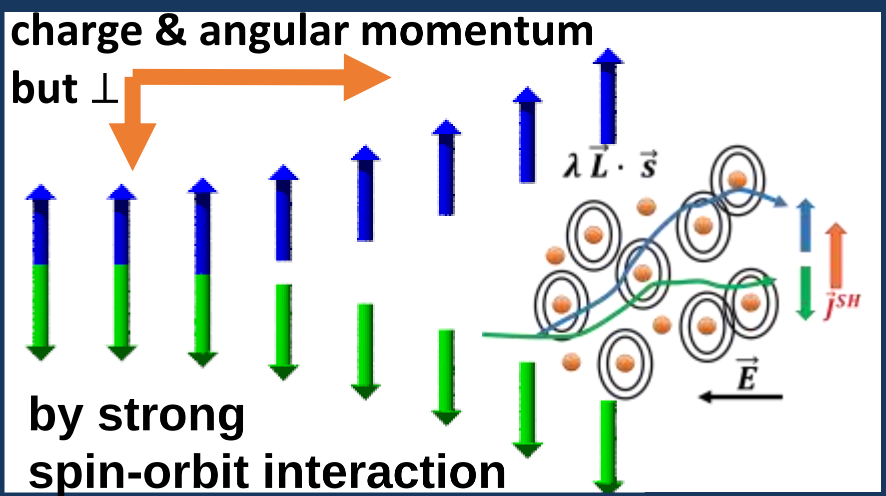
Spintransfer

There are many ways to transfer spins / angular momentum:







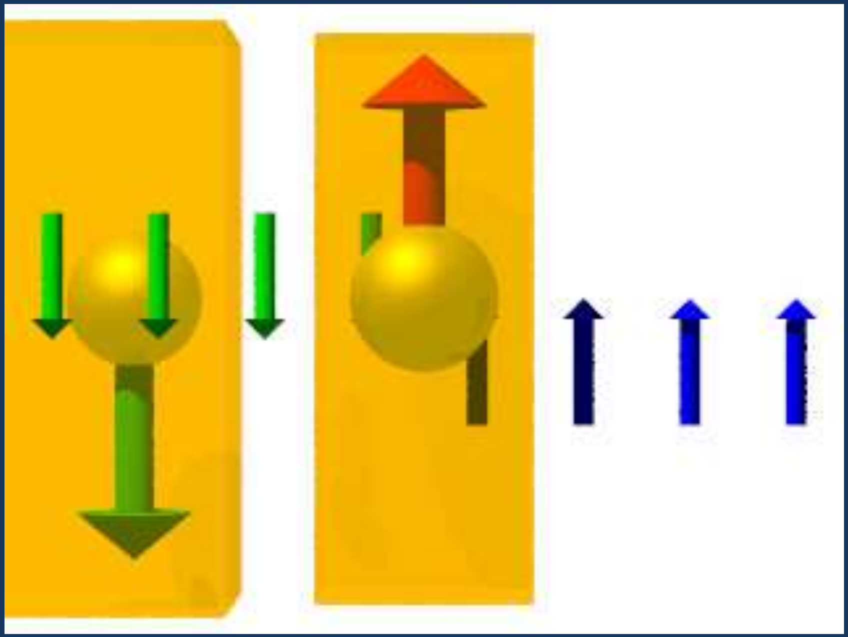


Spintransfer

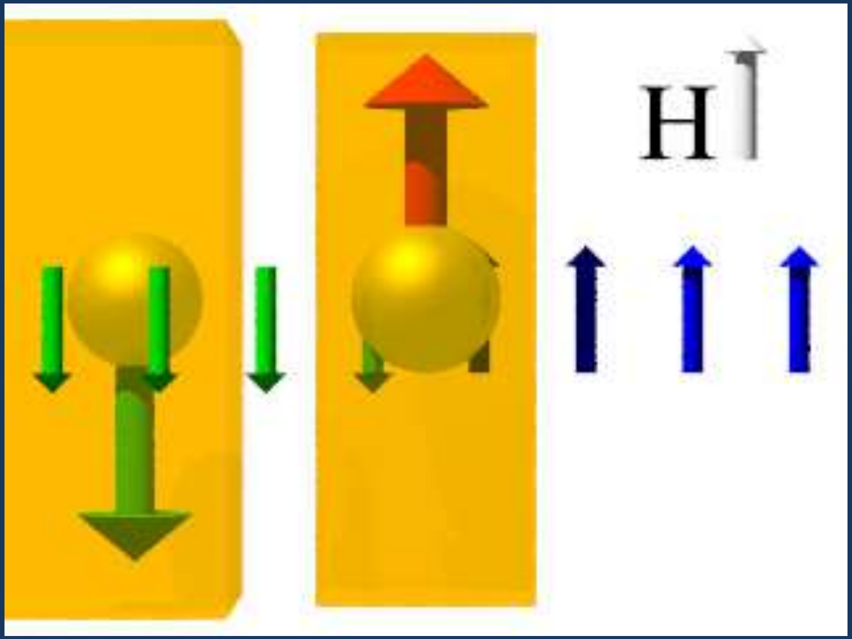
… but why should one like to transfer spins / angular momentum?

→ Because the total angular momentum is conserved

→ Spintransfer gives handle on magnetization



Example 1: Spin-Transfer-Torque Switching (STT) of a magnetic double layer
→ writing information



Example 2: Spin-Transfer-Torque induced magnetization oscillations in a magnetic double layer
→ creating microwave emission

.. and many more (driving magnetic domain walls, enhancing their speed, ..)

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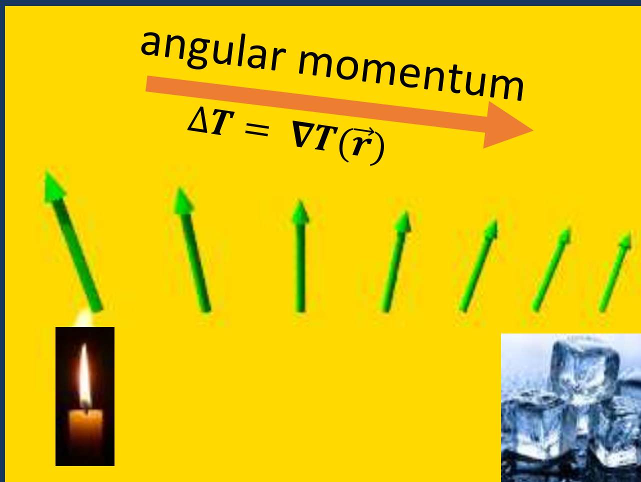
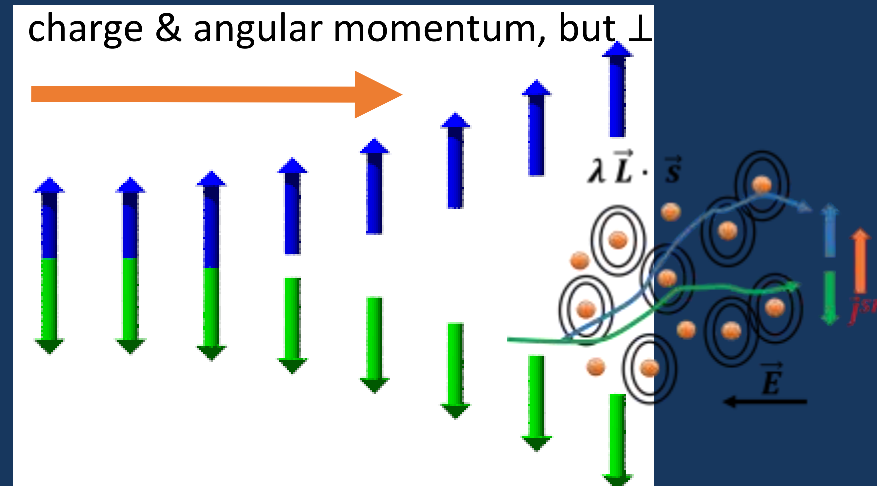
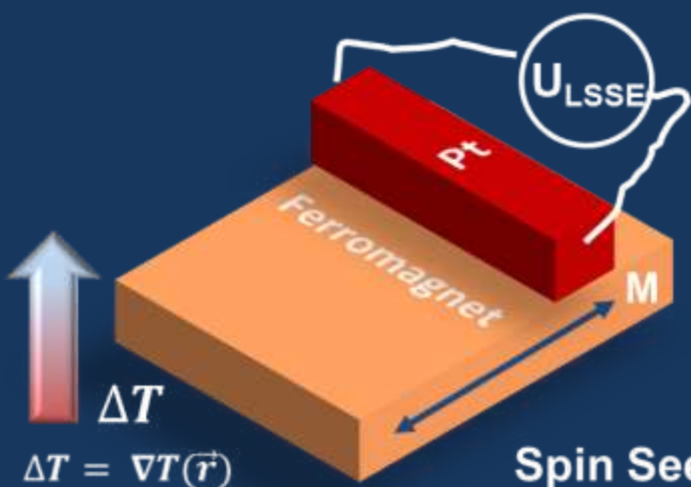
Spincalorics – Seebeck and Inverse Spin Hall Effect



Spintransport by a T-gradient

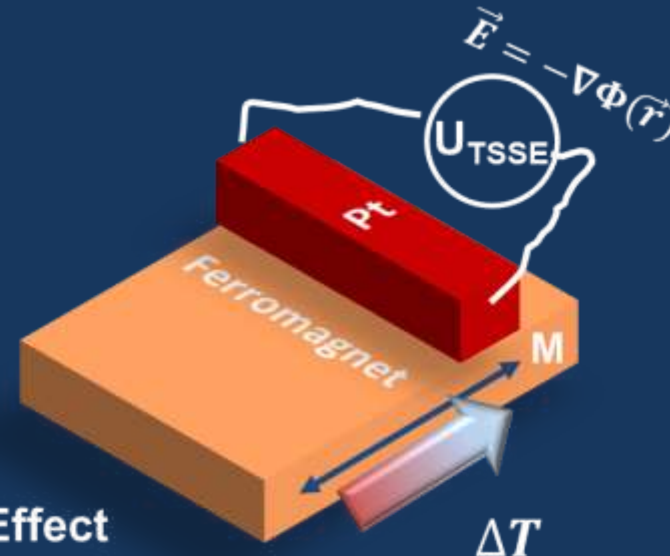


Spin separation in Spin Hall Effect



Longitudinal

Spin Seebeck Effect



Transverse (???)

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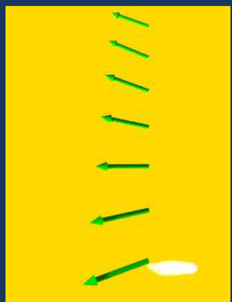
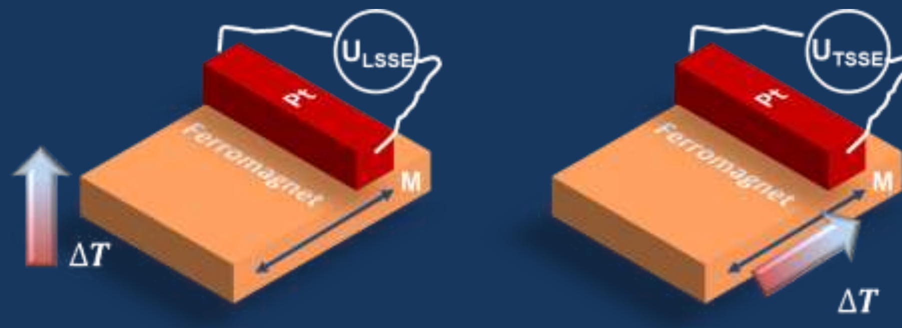
Spincalorics – Seebeck and Inverse Spin Hall Effect

Ingredients for SpinCalorics:



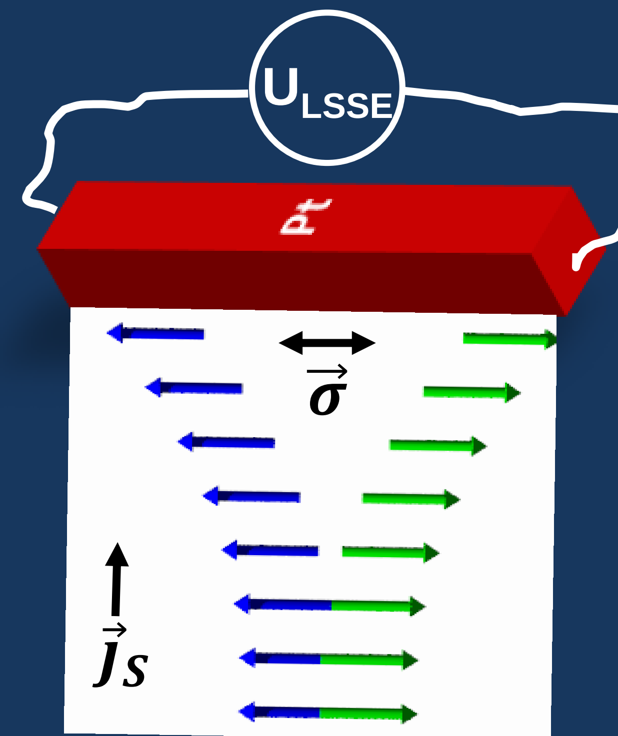


???

Induced Spin Current:

$\vec{j}_S \parallel \nabla T$

$\vec{\sigma} \parallel \vec{M}$

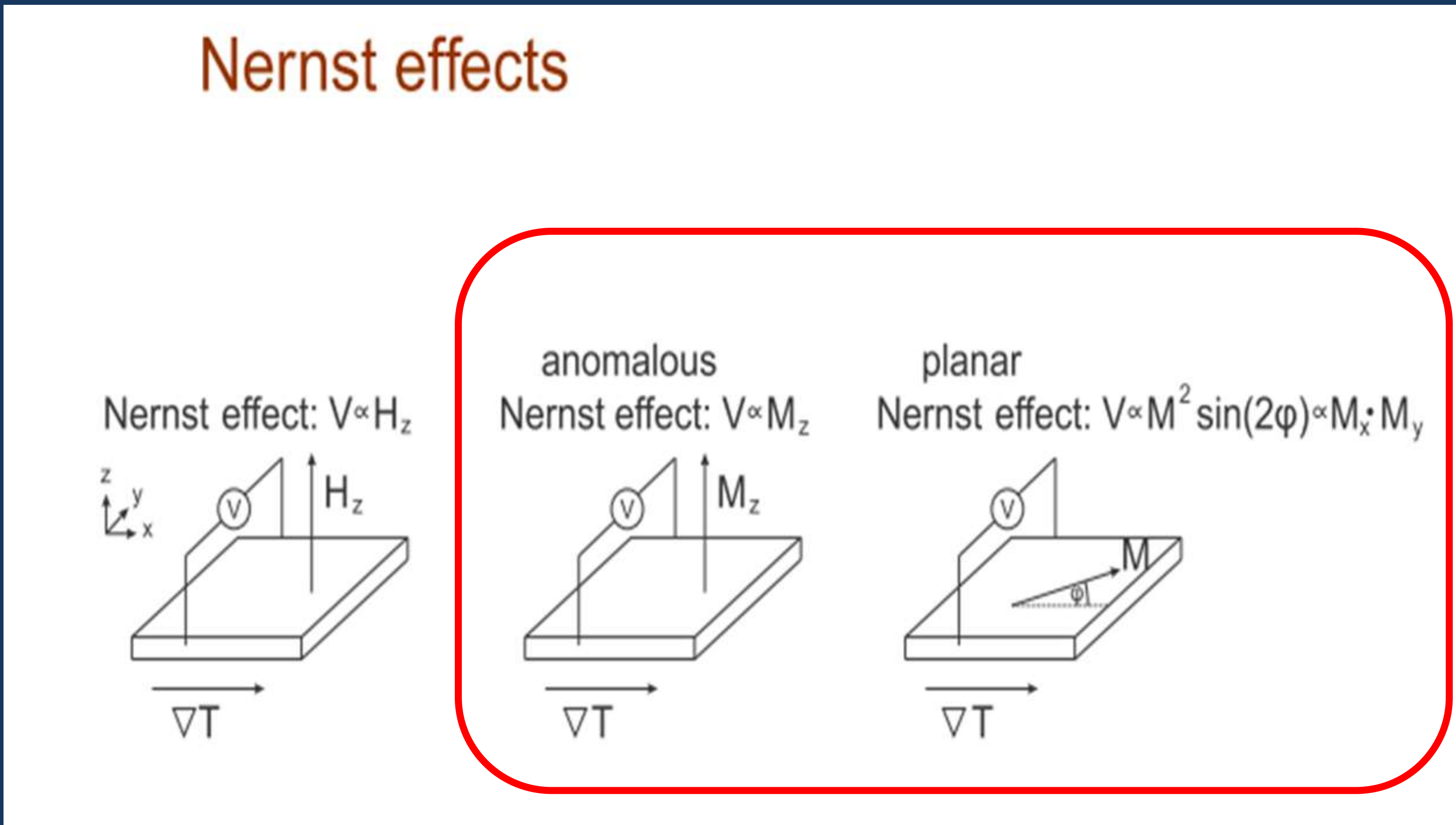


Voltage V induced by the Inverse Spin Hall Effect:

$$\vec{E}_{ISHE} \propto \vec{j}_S \times \vec{\sigma}$$

$\vec{\sigma}$: Spin polarization of charge carriers

Spincalorics – Spin-Seebeck and Competing Effects



$$\vec{E}_{NE} \propto \nabla T \times \vec{H}$$

$$\vec{E}_{\mathrm{ANE}} = \alpha \nabla T \times \vec{m}.$$

Nernst effects only in conducting materials

Overview of Spin-Seebeck- and competing Nernst-Effects:

		Gradx T				Gradz T			
		Nernst $\propto$ Hz	anomalous Nernst $\propto$ Mz	planar Nernst $\propto$ Mx*My	transversal spin-Seebeck $\propto$ sigmax	Nernst $\propto$ Hx	anomalous Nernst $\propto$ Mx	planar Nernst $\propto$ My*Mz	longitudinal spin-Seebeck $\propto$ sigmax
Hx	NiFe								
	Pt								
Hy	NiFe								
	Pt								
Hz	NiFe								
	Pt								
Hx,Hy	NiFe								
	Pt								
Hy,Hz	NiFe								
	Pt								
Hz,Hx	NiFe								
	Pt								
Hx	NiFe2O4								
	Pt								
Hy	NiFe2O4								
	Pt								
Hz	NiFe2O4								
	Pt								
Hx,Hy	NiFe2O4								
	Pt								
Hy,Hz	NiFe2O4								
	Pt								
Hz,Hx	NiFe2O4								
	Pt								

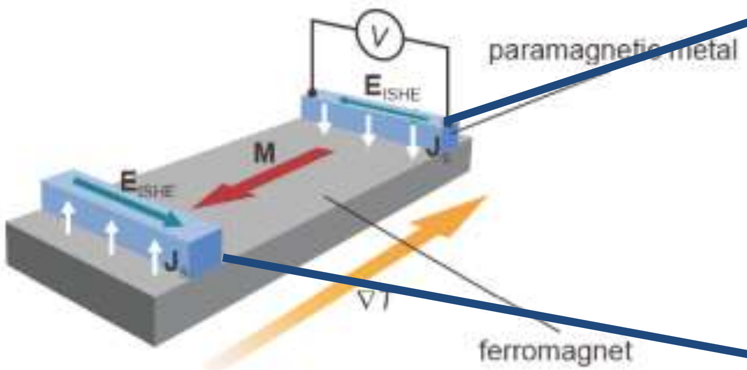
no effect
linear
anisotropy
hysteresis

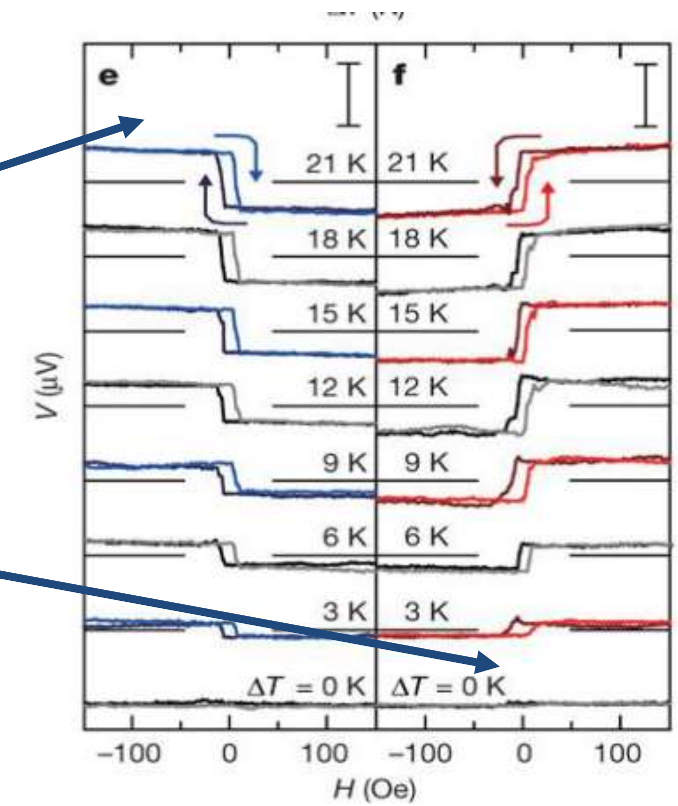
put together by

Timo Kuschel

Spincalorics – Transverse Spin Seebeck

Transverse Spin-Seebeck-Effects was the first to be reported:



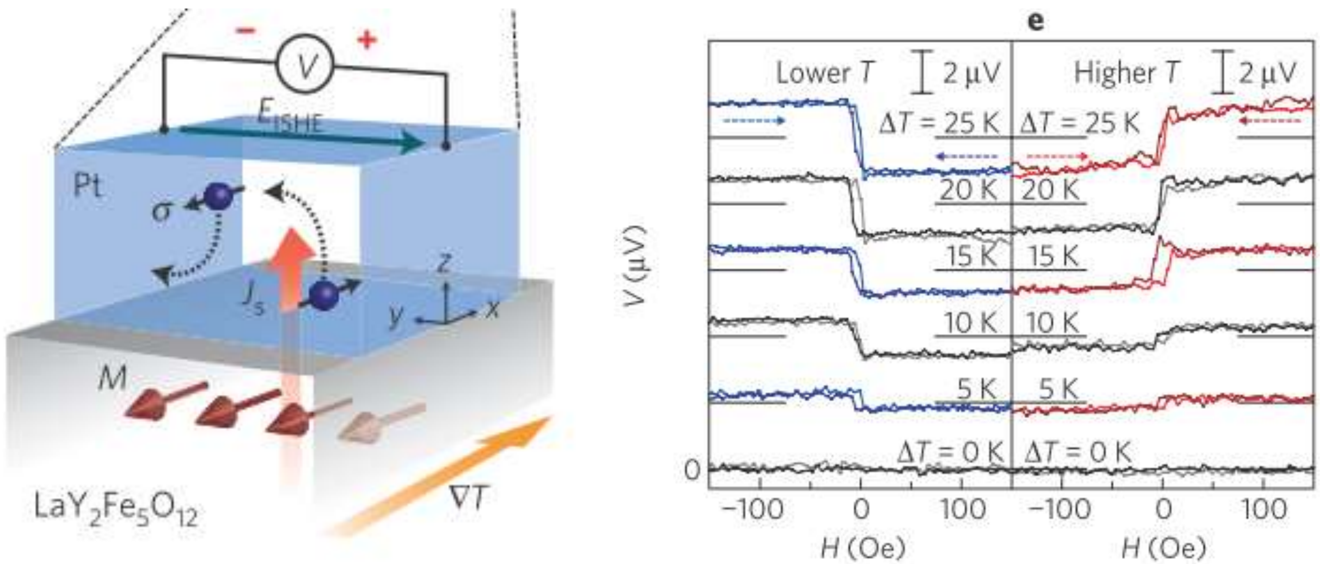


- $E_{ISHE} \propto J_s \times \sigma$
- K. Uchida et al., Nature **455**, 778 (2008)

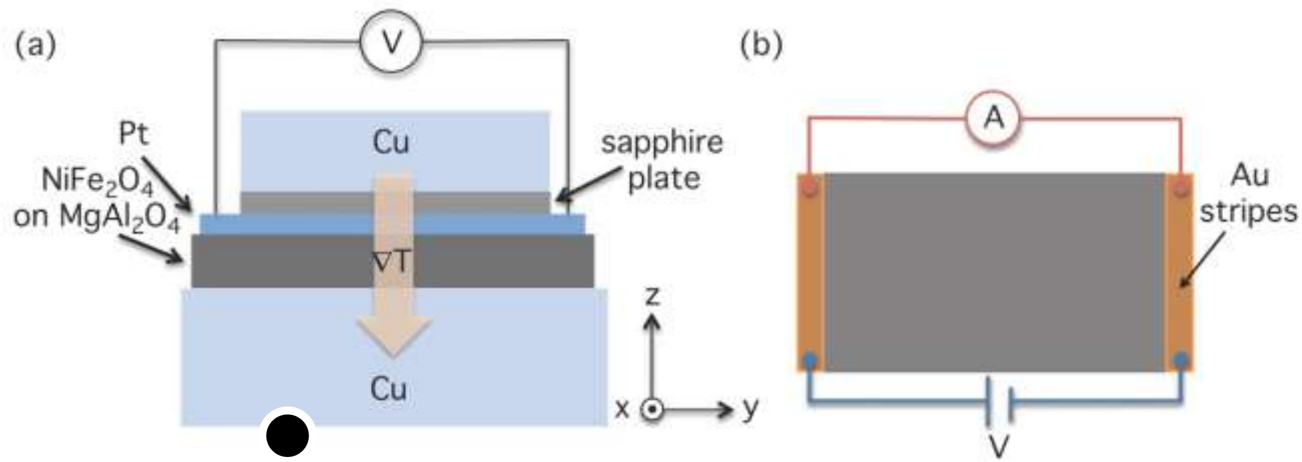
TSSE still under discussion ..

Spincalorics – Longitudinal Spin Seebeck Effect (LSSE)

Other Spin-Seebeck-Effects :



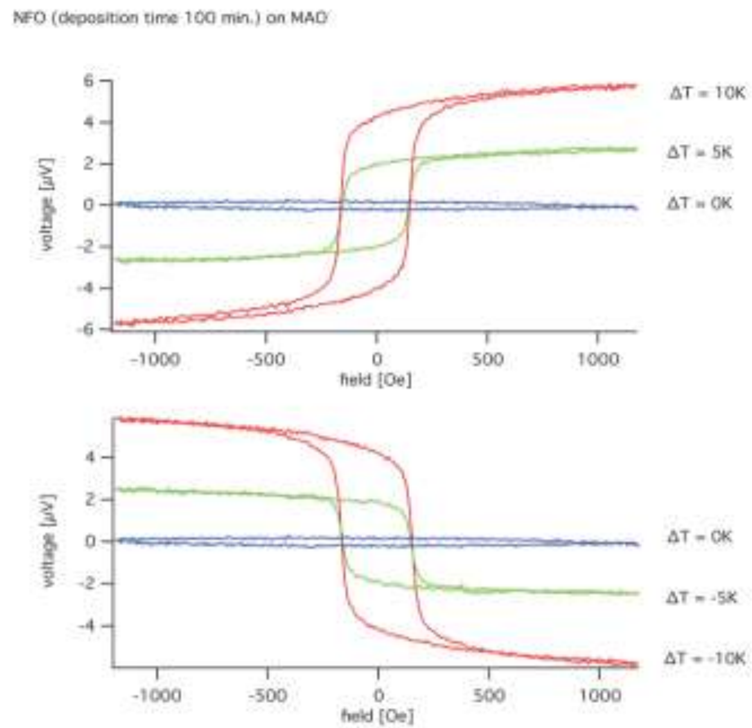
On insulating $LaY_2Fe_5O_{12}$
Uchida et.al., Nat. Mat. Sept. 2010

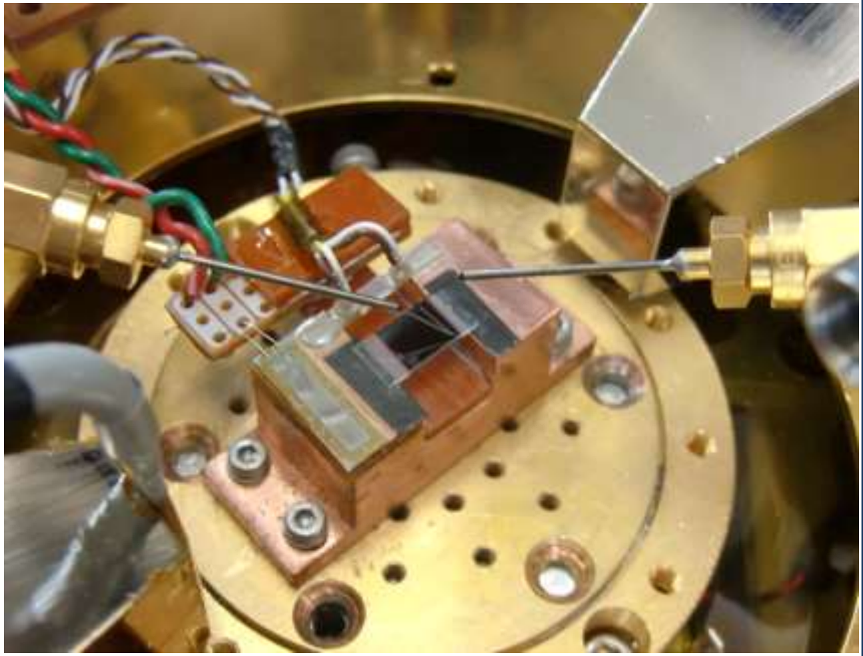


Sample arrangement for LSSE (left) and conductivity (right) @Bielefeld

T_0 : variable base temperature

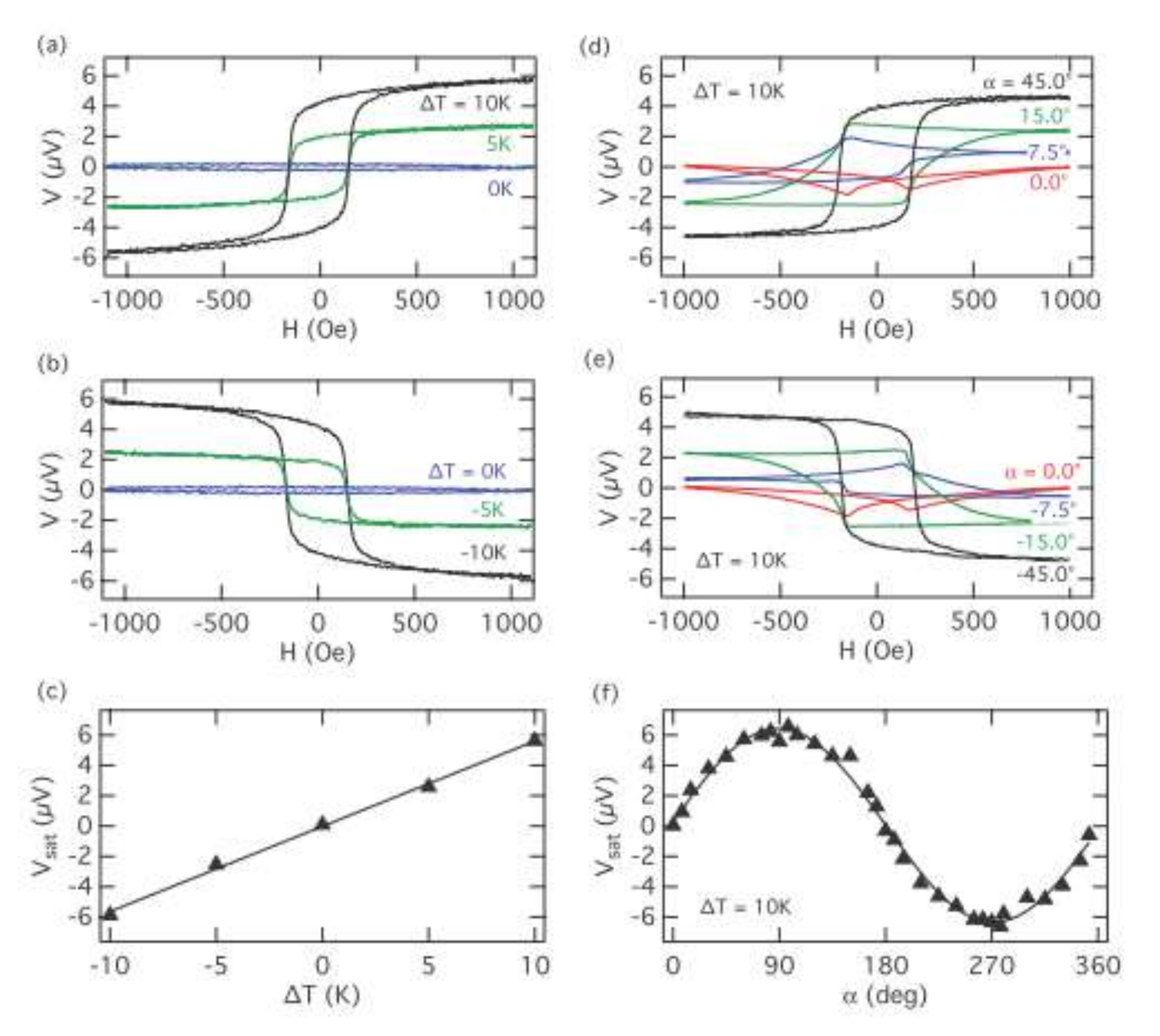
Spincalorics – LSSE in $NiFe_2O_4$





Measured in Prof. Saitoh's lab, Tohoku University, Sendai, Japan (T. Kuschel, D. Meier)
$NiFe_2O_4$ from A. Gupta, Alabama University, Tuscaloosa, USA


Spincalorics – LSSE in $NiFe_2O_4$



Measured @Bielefeld lab,
CVD-$NiFe_2O_4$ from A. Gupta, Alabama
PVD-$NiFe_2O_4$ from Bielefeld-lab

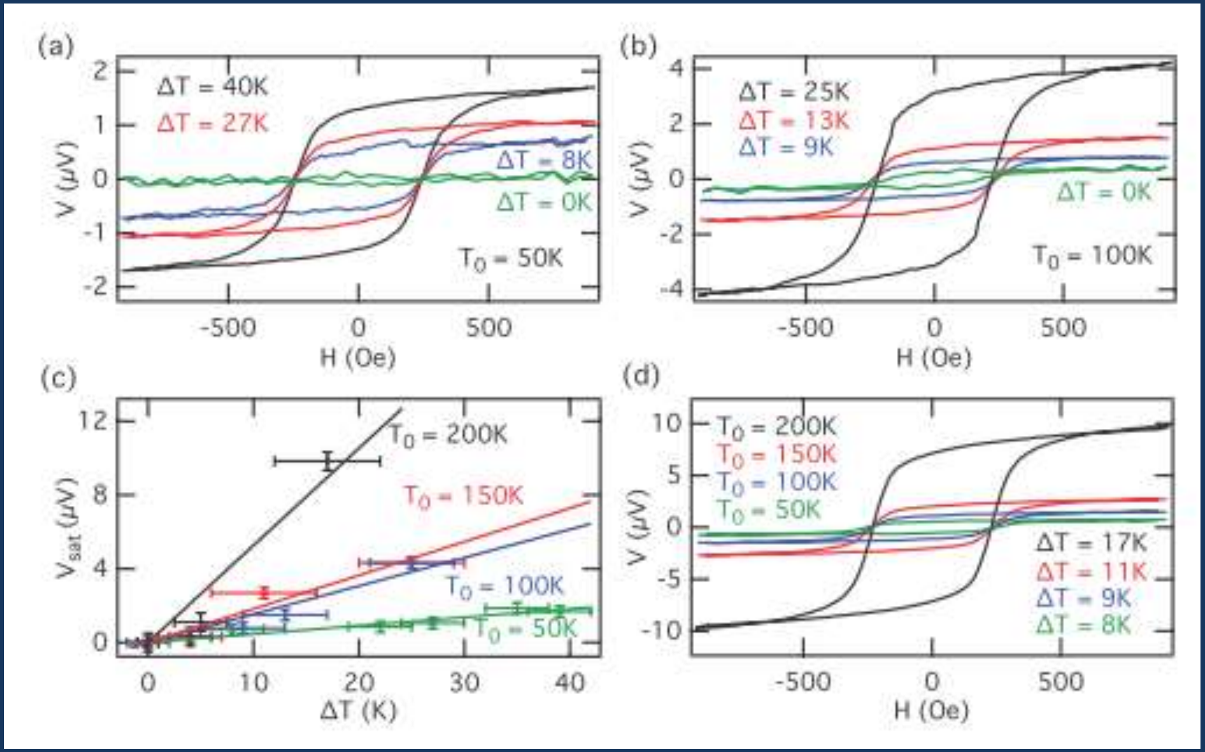
.. reproducible signals

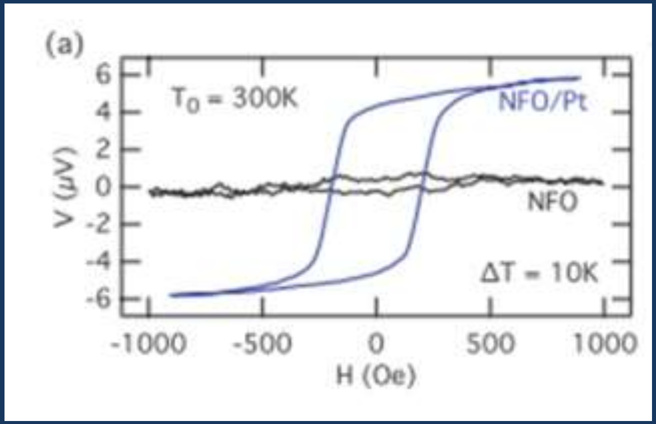
but

watch Nernst effects!

a, b, d, e: LSSE in $NiFe_2O_4$ for various values of ΔT and angle α between ΔT and $\vec{H}$
c, f: LSSE amplitude as function of ΔT and α

Spincalorics – LSSE in $NiFe_2O_4$





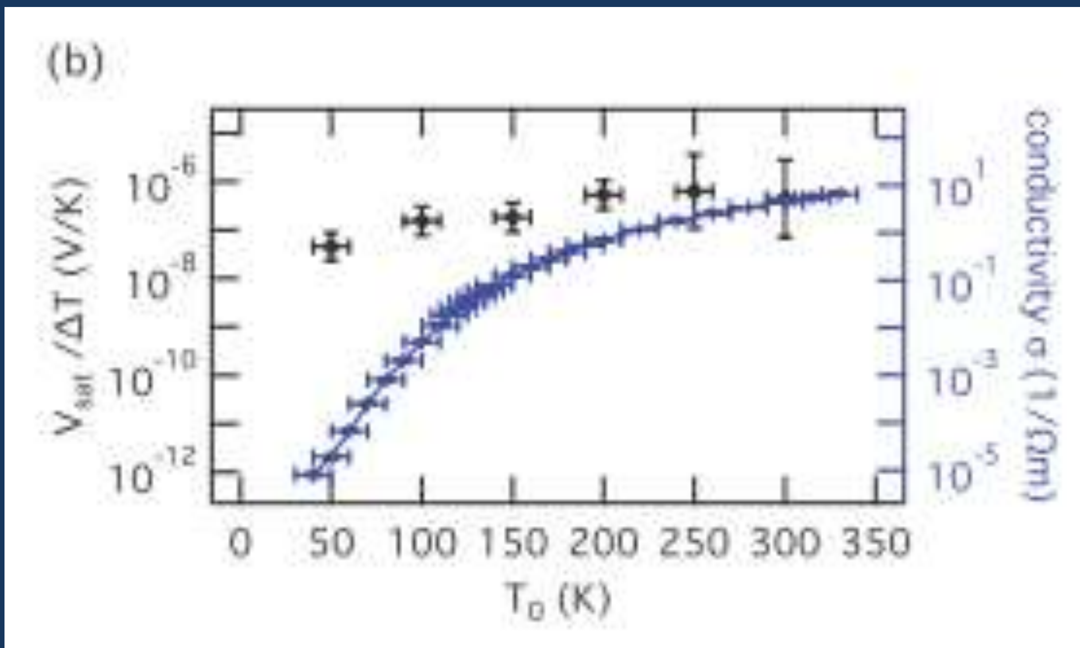
LSSE on Pt-stripe and Anomalous Nernst signal on bare $NiFe_2O_4$

a, b, d: LSSE in $NiFe_2O_4$ films for various values of ΔT and T_0
c: LSSE amplitude vs ΔT for various T_0

→ use semiconducting properties of $NiFe_2O_4$ and variable base temperature

Spincalorics – LSSE in $NiFe_2O_4$

$NiFe_2O_4$ has semiconducting-type temperature dependence of the conductivity
→ compare LSSE at variable base temperature with conductivity



→ Conductivity drops by 6 orders of magnitude,
→ V_{Sat} of (??) LSSE drops only by 1 ½ orders

→ V_{sat} due to LSSE

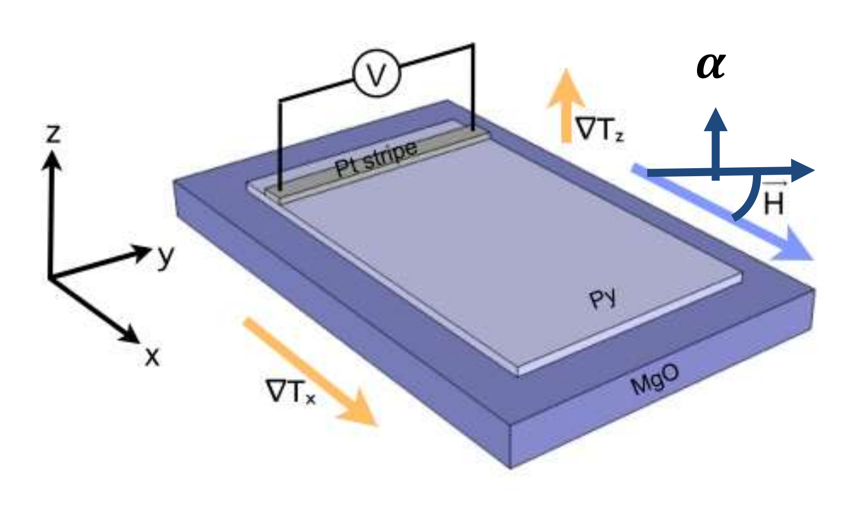
→ directly measured Nernst effect agrees with these data

PHYSICAL REVIEW B **87**, 054421 (2013)

Thermally driven spin and charge currents in thin $NiFe_2O_4$/Pt films

D. Meier,[1,*] T. Kuschel,[1] L. Shen,[2] A. Gupta,[2] T. Kikkawa,[3] K. Uchida,[3,4] E. Saitoh,[3,5,6,7] J.-M. Schmalhorst,[1] and G. Reiss[1]

Spincalorics – TSSE in Permalloy?



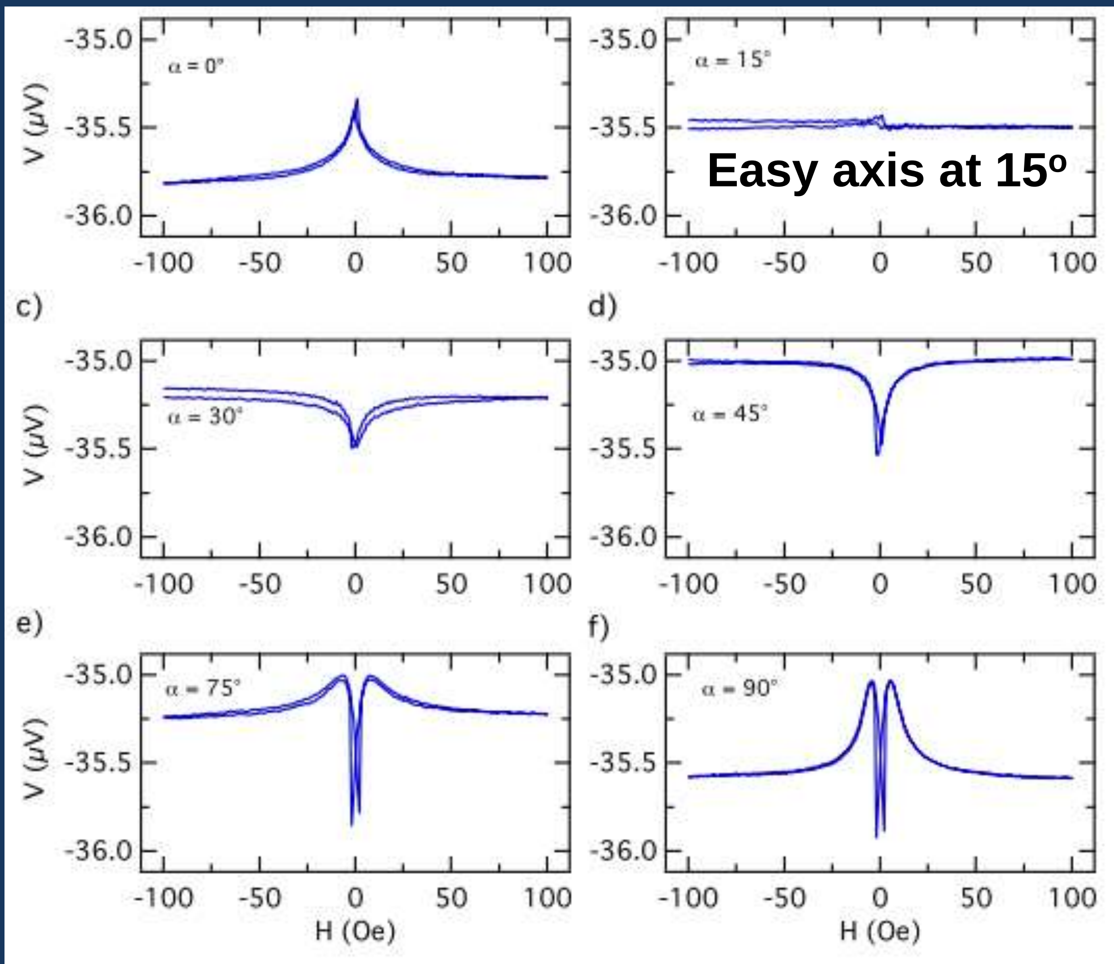
Experimental arrangement (new setup) with
- Two possible temperature gradients
- Wire bonding to Pt
- In vacuum
- At variable base temperature

Expect: ANE for ∇T_z: $\vec{E}_{\mathrm{ANE}} = N_{\mathrm{ANE}} \nabla T \times \vec{M}.$

Expect: PNE for ∇T_x: $V_y \propto |M|^2 \sin(\varphi)\cos(\varphi)|\nabla T| \propto M_x \cdot M_y |\nabla T|$

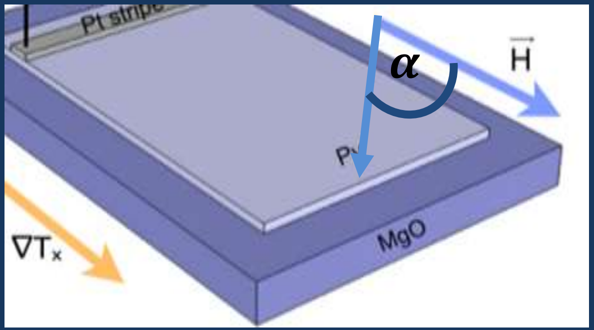
? TSSE

Spincalorics – TSSE in Permalloy ?



„TSSE"-signal for various values of α as a function of the external field H

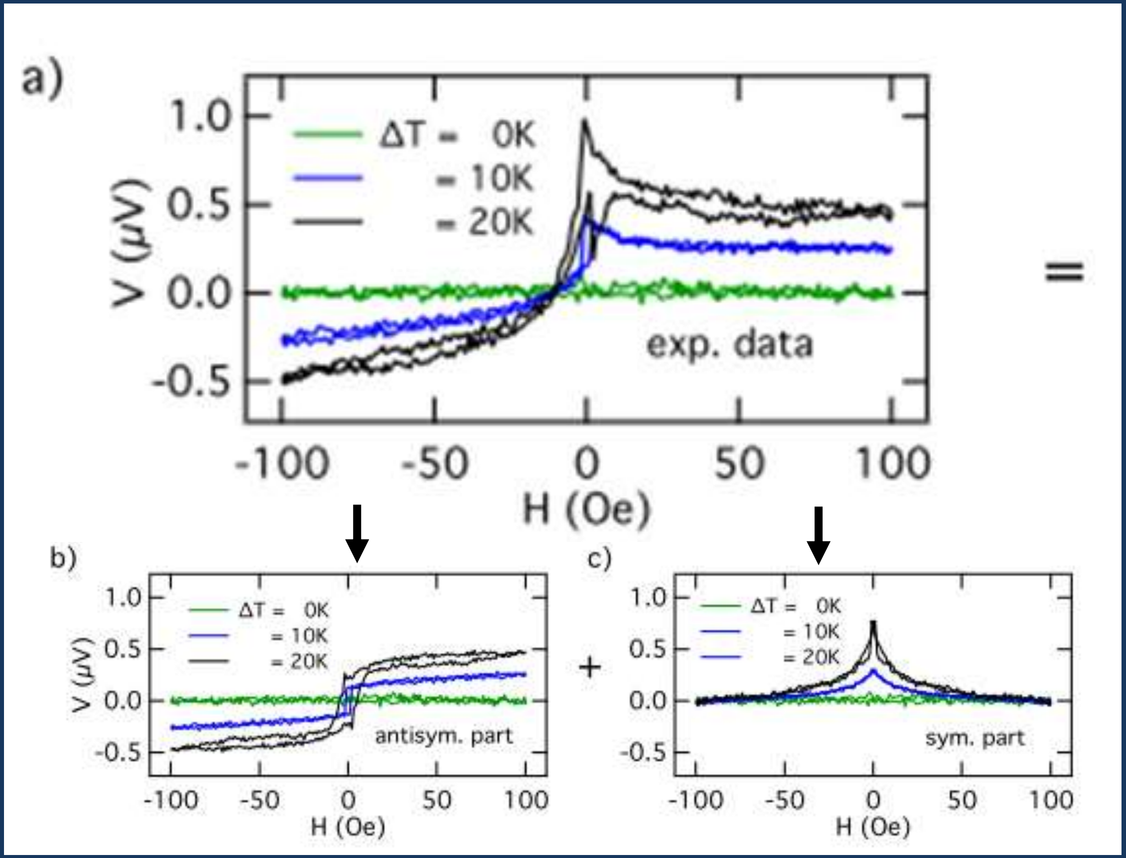
→ only symmetric effects



At T_0 = 300K
Pt-stripe on hot side of the sample.
Field in sample plane.
Thin W-tips as voltage probes

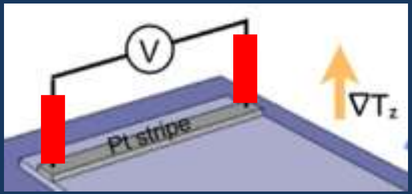
Gives only PNE (Planar Nernst Effect)

Spincalorics – TSSE in Permalloy?



a: „TSSE“ signal on Pt on Py for various ΔT as a function of the external field H measured with thick Au-tips

b, c: antisymmetric and symmetric part of the measured signal



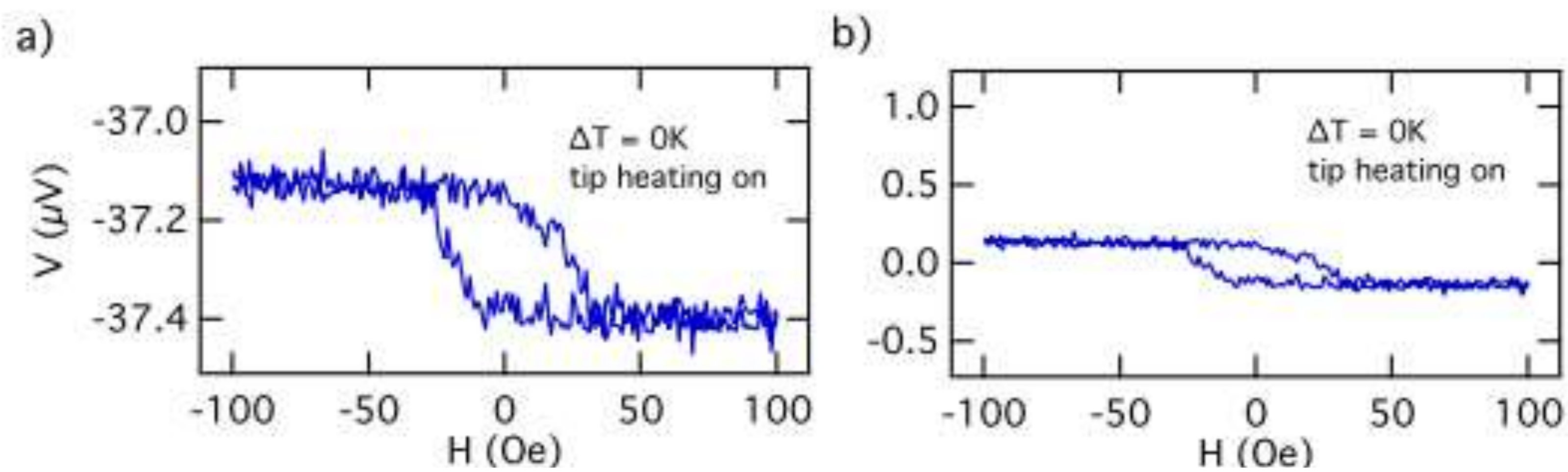
T_0 = 300K, ΔT variable
Pt stripe on hot side of the sample,
thick Au tips as voltage probes (1mm)

Symmetric part: Planar Nernst Effect

Antisymmetric: Anomalous Nernst Effect due to heat transport by Au-tips

Spincalorics – TSSE in Permalloy?

⟶ Heat tips and look at voltage signals in TSSE-geometry!



PHYSICAL REVIEW B **88**, 184425 (2013)

Influence of heat flow directions on Nernst effects in Py/Pt bilayers

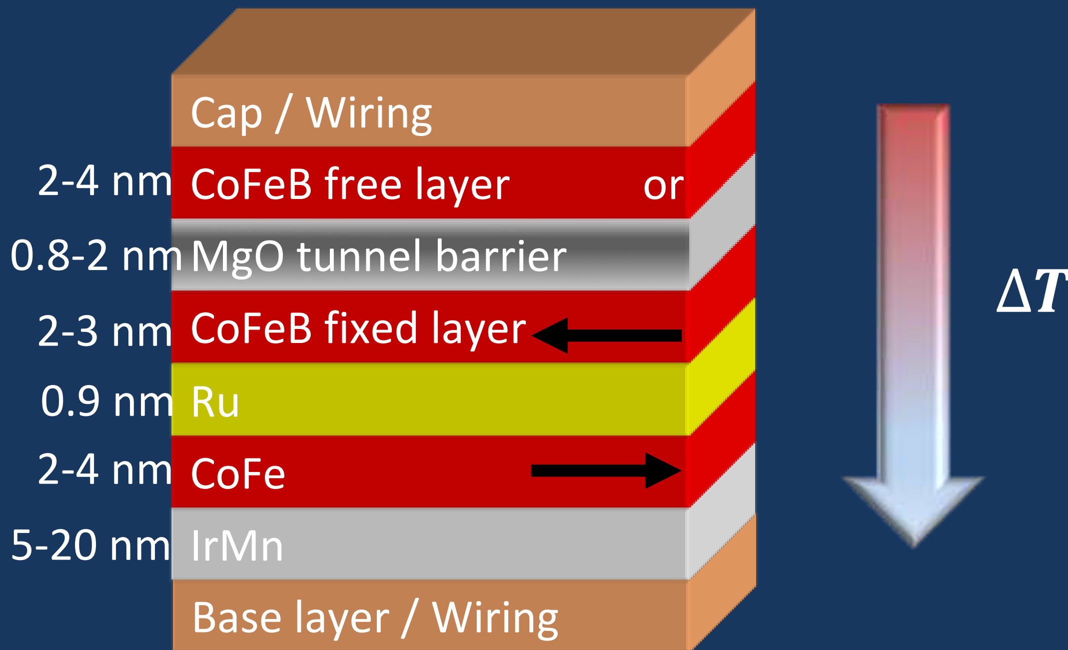
D. Meier,[1,*] D. Reinhardt,[1] M. Schmid,[2] C. H. Back,[2] J.-M. Schmalhorst,[1] T. Kuschel,[1] and G. Reiss[1]

PRL **111,** 187201 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Transverse Spin Seebeck Effect versus Anomalous and Planar Nernst Effects in Permalloy Thin Films

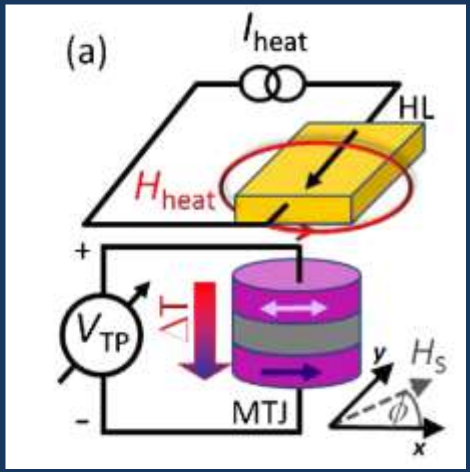
M. Schmid,[1] S. Srichandan,[1] D. Meier,[2] T. Kuschel,[2] J.-M. Schmalhorst,[2] M. Vogel,[1] G. Reiss,[2] C. Strunk,[1] and C. H. Back[1]

Spincalorics in MTJs

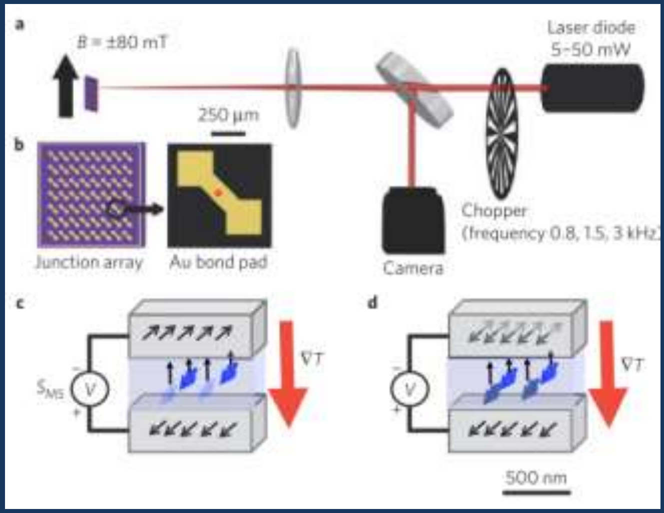


MTJ Stack

Heating by heater line



or laser pulses



Magnetic Tunnel Junctions with CoFeB (in plane or perpendicular) and other materials

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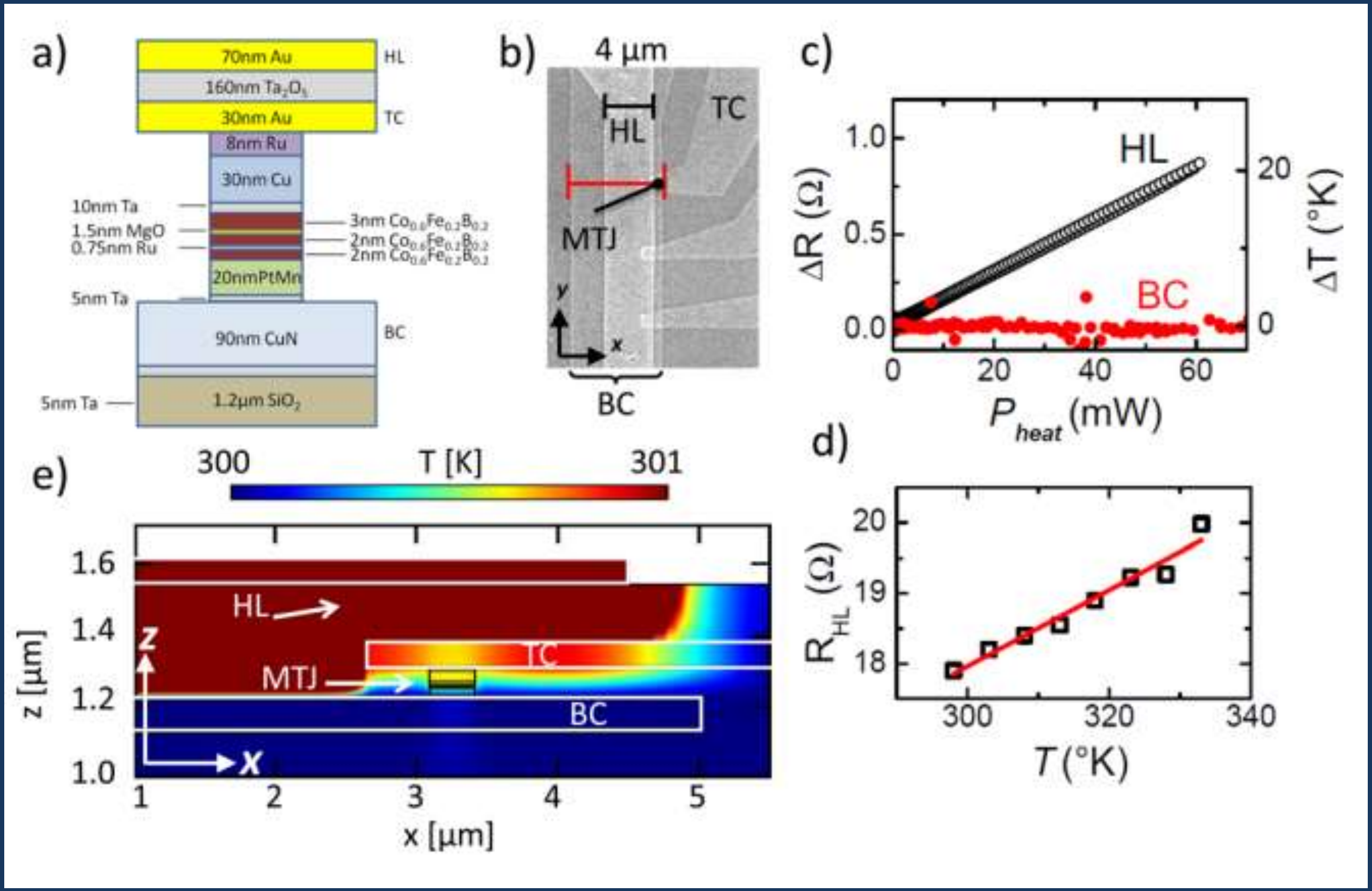
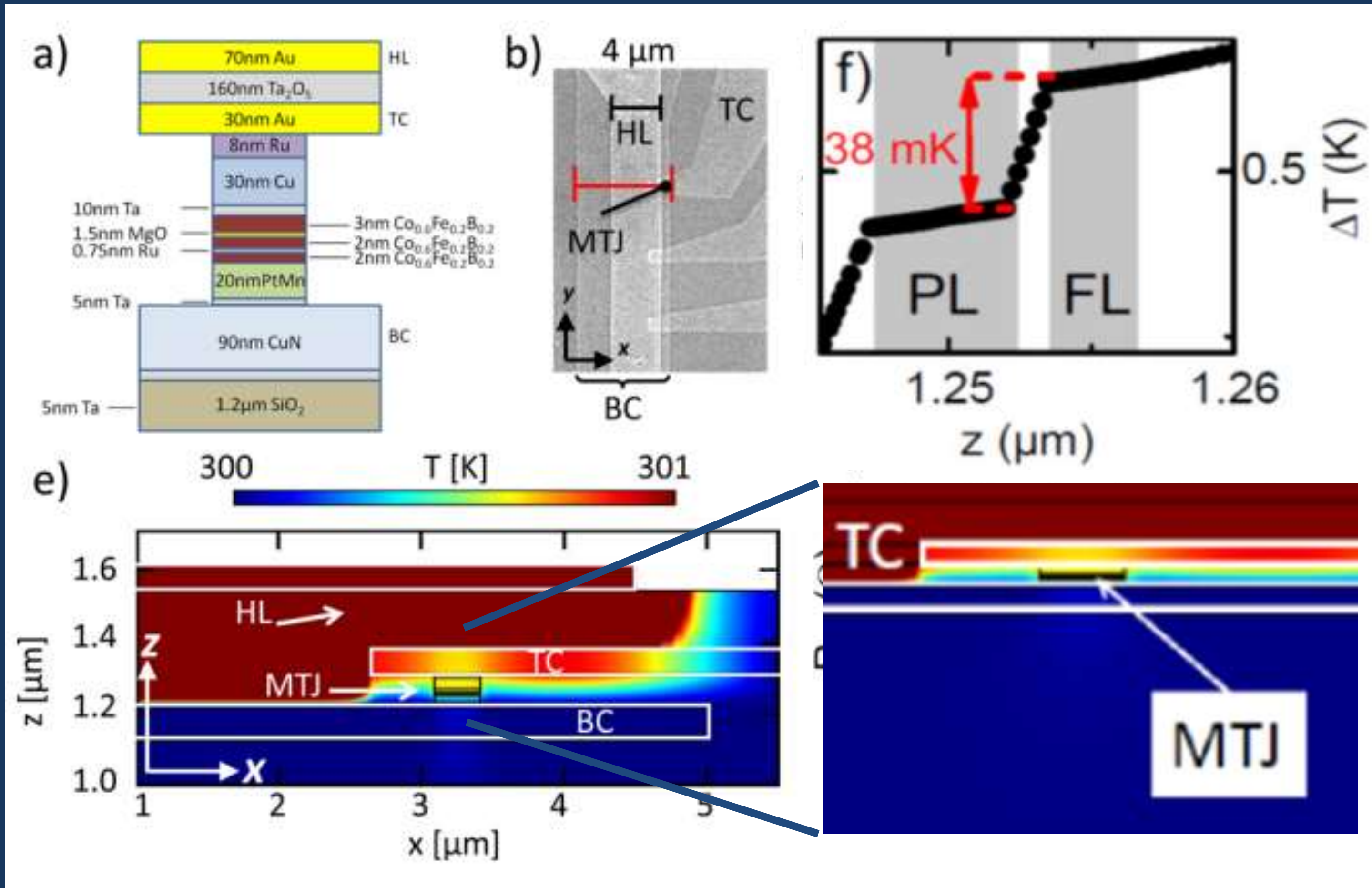
Spincalorics in MTJs



(a) MTJ stack composition. HL, TC and BC: heater line, electrical top and contact
(b) SEM image with HL, BC, and TC (MTJ nanopillar indicated). Red line: cross section for simulations. (c) Resistance increase of HL (open dots) and BC (full dots) vs heating power. Right : temperature increase of HL and BC. (d) Measured temperature dependence of HL resistance. (e) Simulated temperature distribution (2D cross section).

Spincalorics in MTJs



f) simulated temperature profile across the MgO barrier

and

enlarged view of the MTJ

(a) MTJ stack composition. HL, TC and BC: heater line, electrical top and contact
(b) SEM image with HL, BC, and TC (MTJ nanopillar indicated). Red line: cross section for simulations. (c) Resistance increase of HL (open dots) and BC (full dots) vs heating power. Right : temperature increase of HL and BC. (d) Measured temperature dependence of HL resistance. (e) Simulated temperature distribution (2D cross section).

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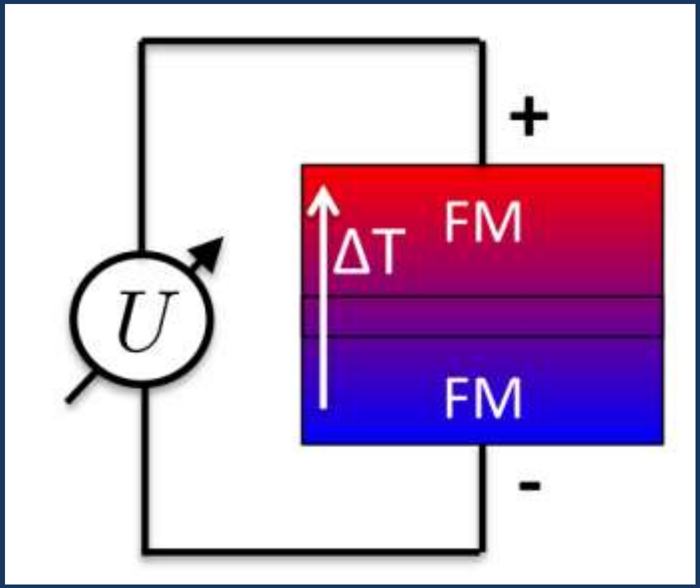
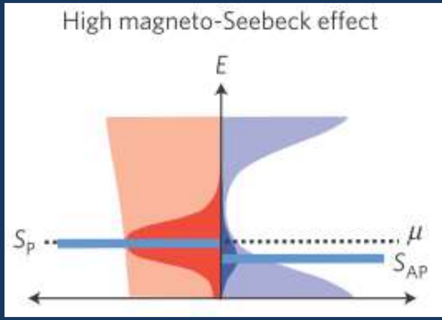
Spincalorics in MTJs



Seebeck coefficient S for tunnel junctions:

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

$\partial_E f(E,\mu,T)$: Derivative of occupation function



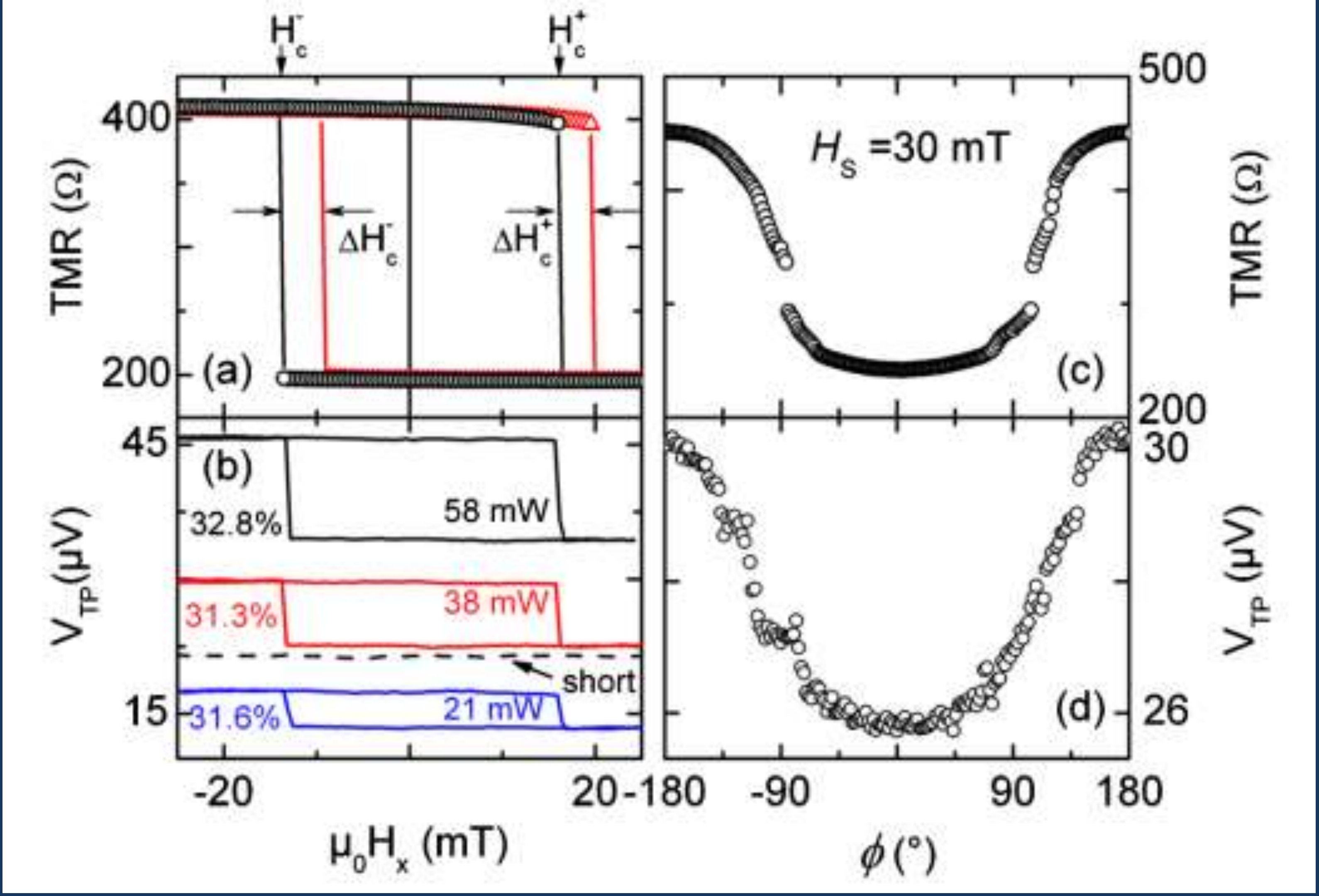
Seebeck coefficient is caused by asymmetric DOS at E_F

$$TMTP\ or\ TMS = \frac{U_{max} - U_{min}}{U_{min}}$$

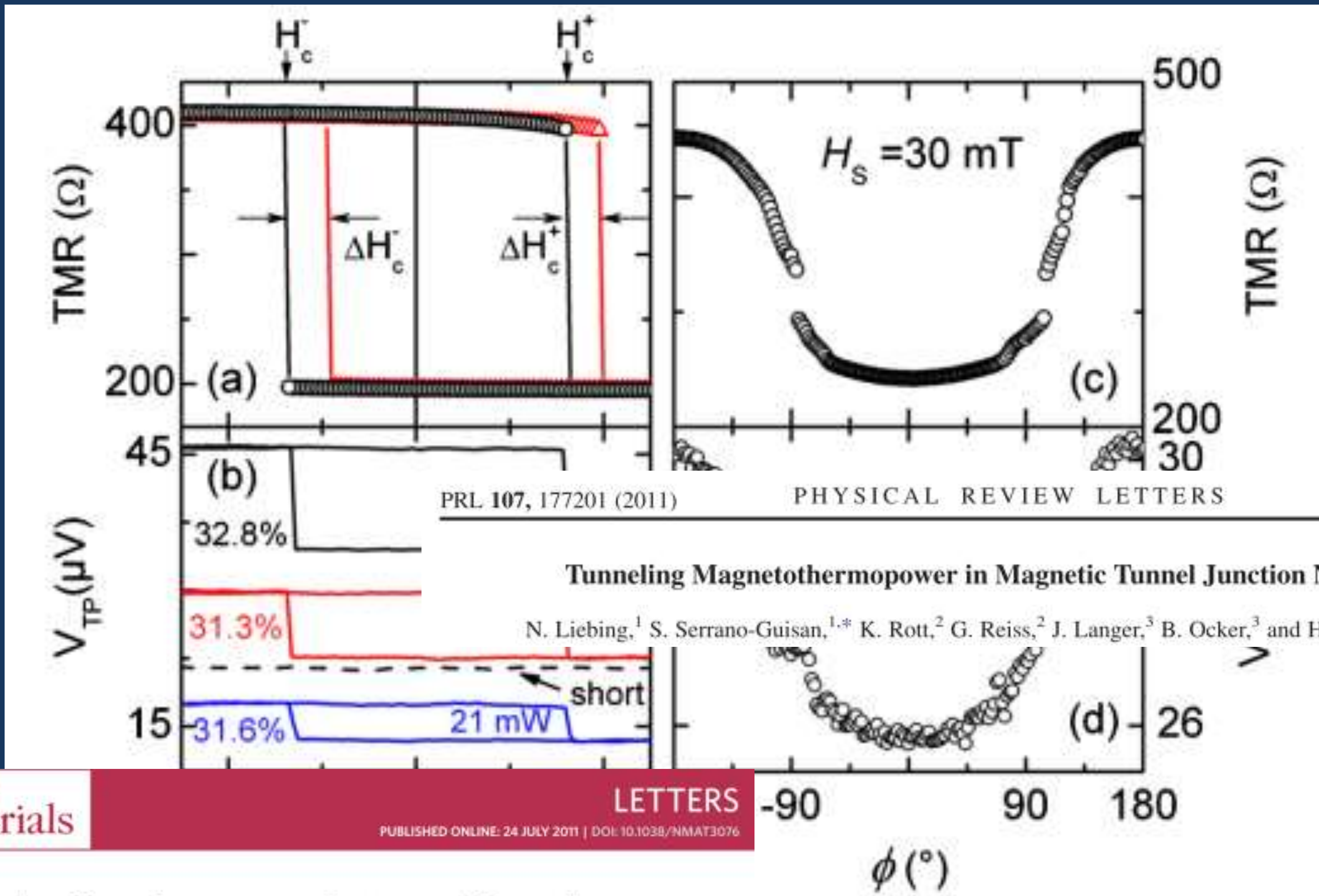
→ Thermovoltage U should depend on magnetization directions

→ Important: S ≠ conductivity $g = \frac{e^2}{h}\int T(E)\left(-\partial_E f(E,\mu,T)\right)dE$

Spincalorics in MTJs



Spincalorics in MTJs



PRL 107, 177201 (2011) PHYSICAL REVIEW LETTERS week 21 OCTO

Tunneling Magnetothermopower in Magnetic Tunnel Junction Nanopillars

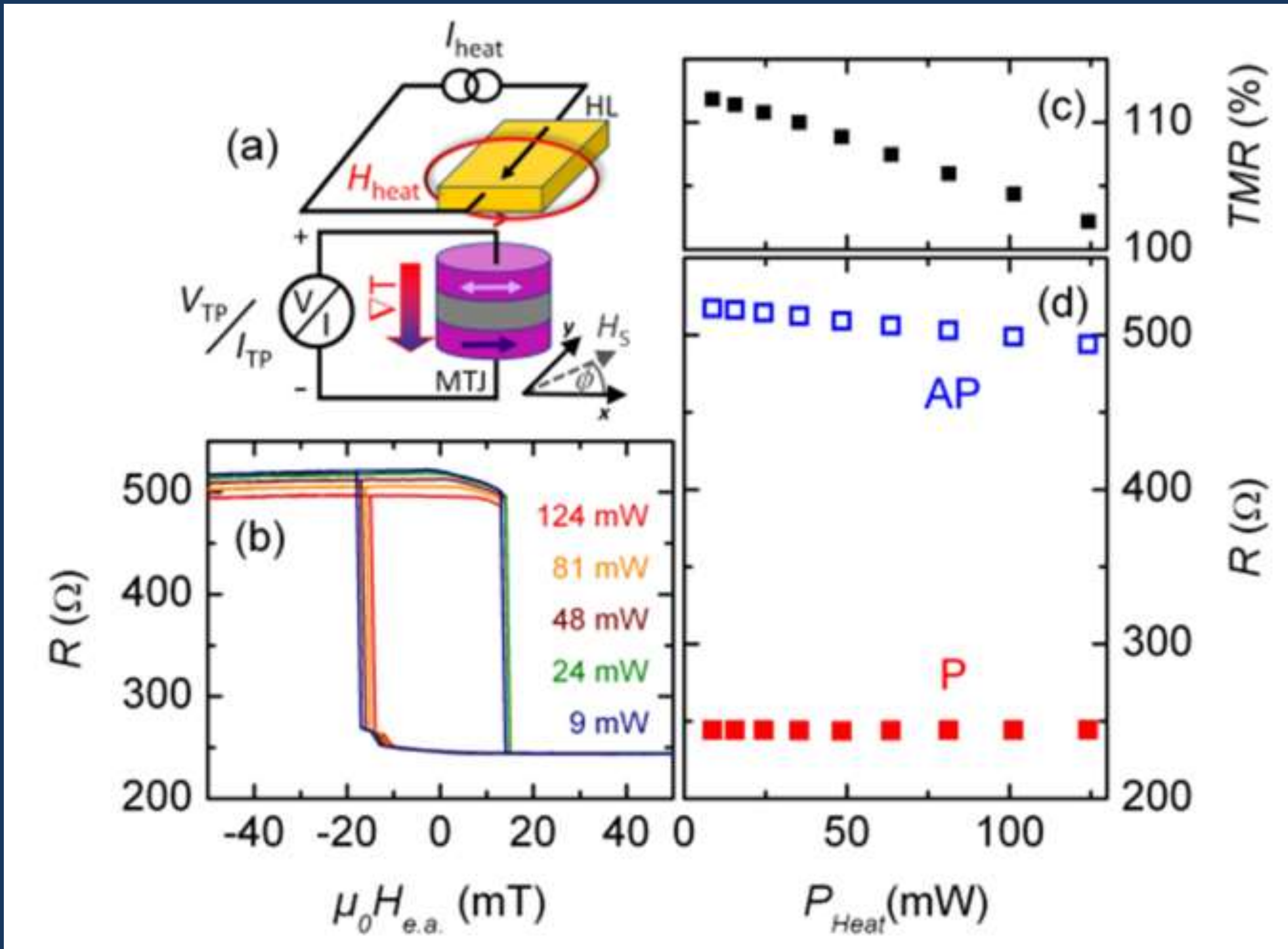
N. Liebing,[1] S. Serrano-Guisan,[1,*] K. Rott,[2] G. Reiss,[2] J. Langer,[3] B. Ocker,[3] and H. W. Schumacher[1]

nature materials
LETTERS
PUBLISHED ONLINE: 24 JULY 2011 | DOI: 10.1038/NMAT3076

Seebeck effect in magnetic tunnel junctions

Marvin Walter[1], Jakob Walowski[1], Vladyslav Zbarsky[1], Markus Münzenberg[1*], Markus Schäfers[2], Daniel Ebke[2], Günter Reiss[2], Andy Thomas[2,3], Patrick Peretzki[4], Michael Seibt[4], Jagadeesh S. Moodera[5], Michael Czerner[6], Michael Bachmann[6] and Christian Heiliger[6]

Spincalorics in MTJs: Thermocurrent



$$I_{Total} = \sigma V_{ext} + \sigma S \nabla T_{MTJ}$$

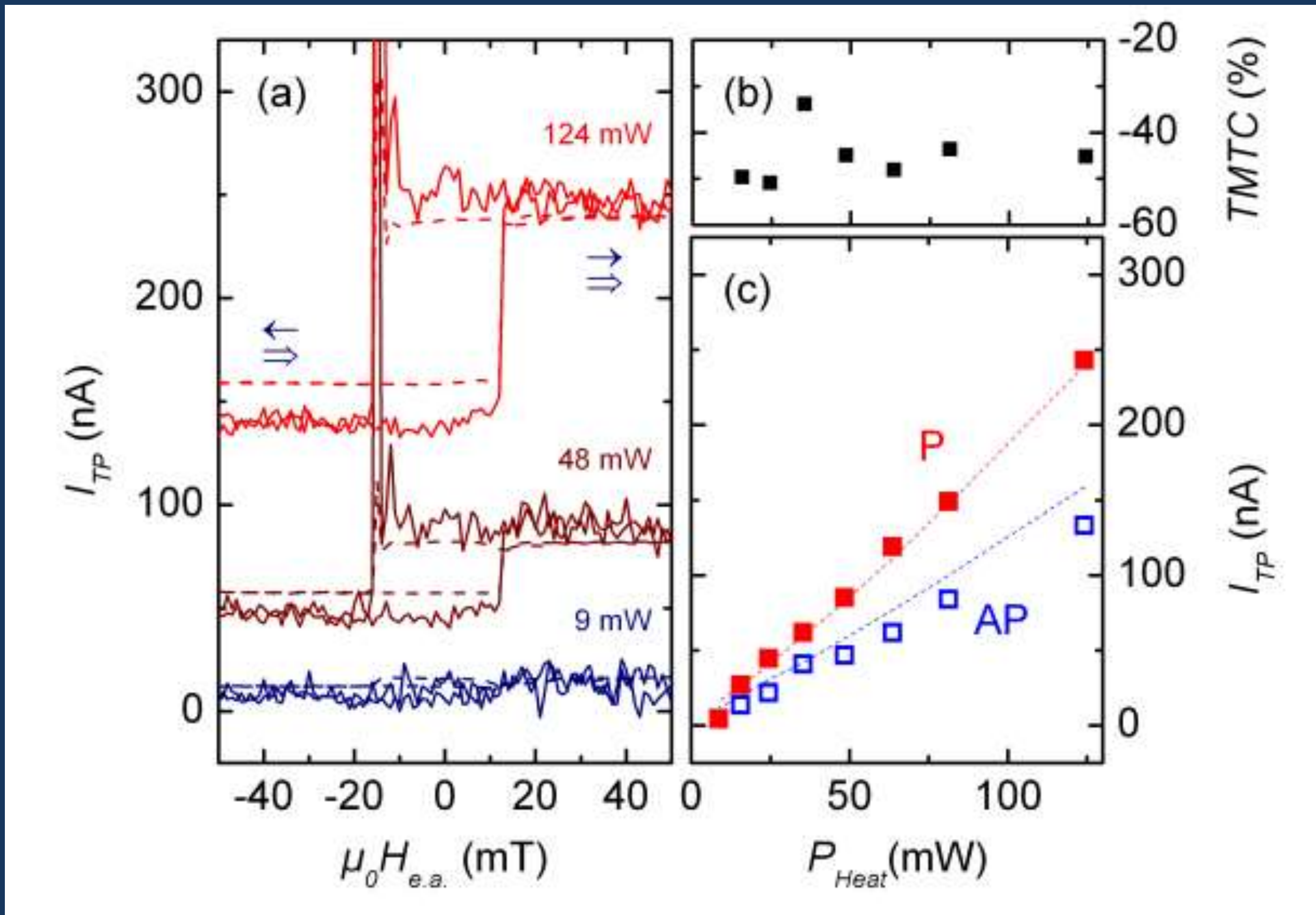
Tunnel-Magneto-Thermocurrent:

$$I_{TP} = \sigma S \nabla T_{MTJ}$$

Note:
σ changes from P to AP configuration !

Reports: I_{TP}=0 ??

Spincalorics in MTJs: Thermocurrent



$$I_{Total} = \sigma V_{ext} + \sigma S \nabla T_{MTJ}$$

Tunnel-Magneto-Thermocurrent:

$$I_{TP} = \sigma S \nabla T_{MTJ}$$

Note:
σ changes from P to AP configuration !

Reports: I_{TP}=0 ??

dashed lines: computed current, solid lines / points: measured values !

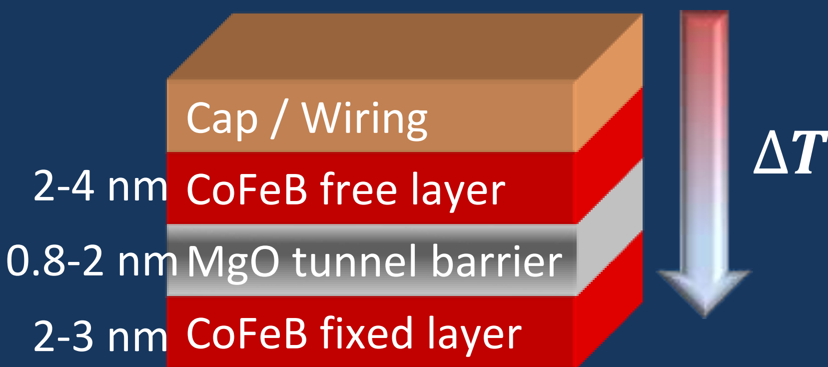
Tunneling magneto thermocurrent in CoFeB/MgO/CoFeB based magnetic tunnel junctions

N. Liebing, S. Serrano-Guisan, P. Krzysteczko, K. Rott, G. Reiss et al.

Citation: Appl. Phys. Lett. **102**, 242413 (2013); doi: 10.1063/1.4811737

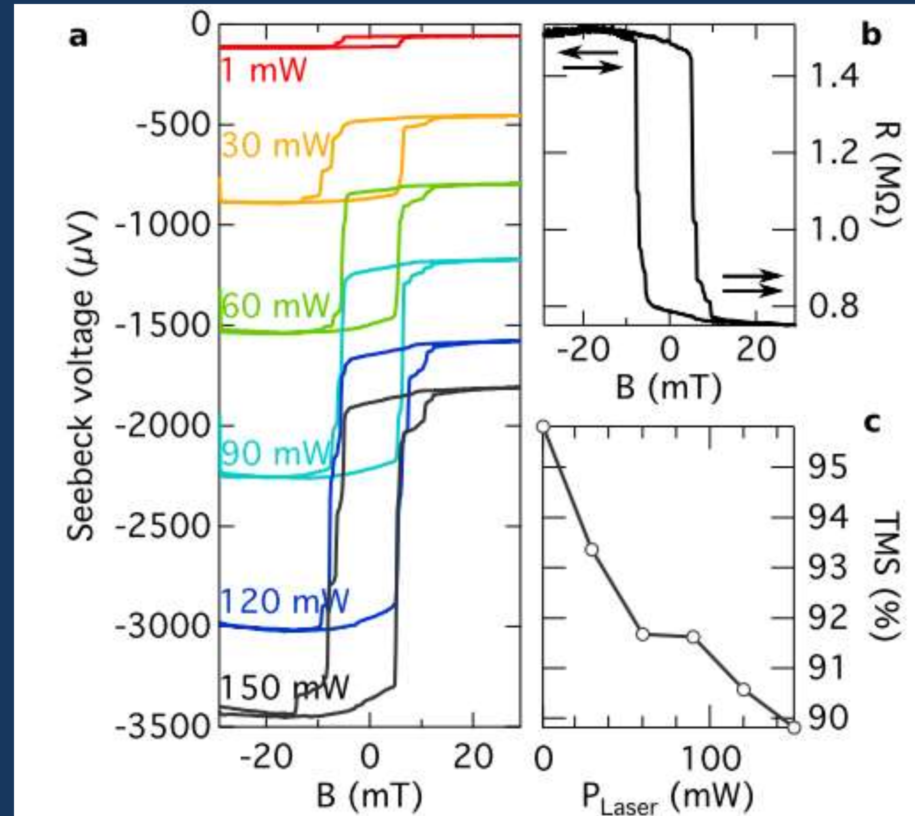
Onsager's relations valid for TMTP ..

Spincalorics in MTJs



replace by highly spin polarized Heusler alloy

→ Co_2FeSi



a) TMS reaches 90 … 96 % comparable to TMR (b)
c) Dependence of TMS ratio on applied laser power.

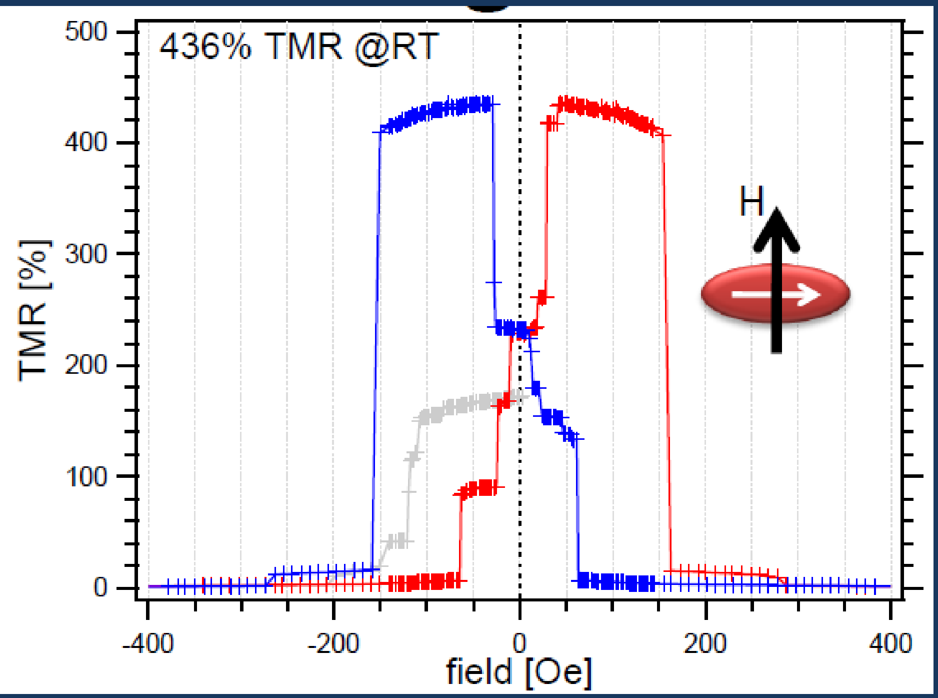
Gap in one spin direction should increase not only TMR but also

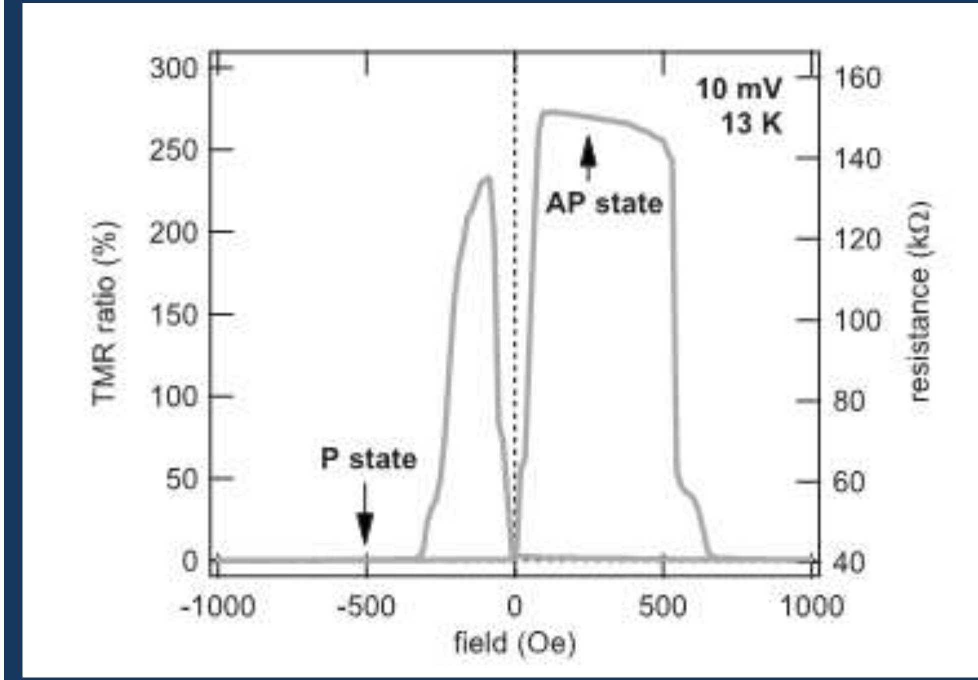
$$S = \frac{\int T(E)(E-\mu)\left(-\partial_E f(E,\mu,T)\right)dE}{e\,T\int T(E)\left(-\partial_E f(E,\mu,T)\right)dE}$$

(large asymmetry of DOS at E_F)

… ongoing experimental and theoretical work

Spin Transfer in MTJs



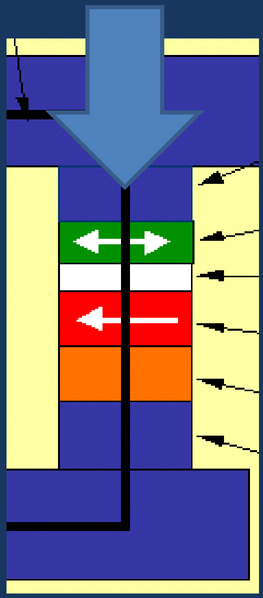


Resistance vs Magnetic Field for:

A CoFeB / MgO / CoFeB pseudo-spinvalve MTJ and a Co_2FeAl / MgO / CoFeB structure Heusler MTJ

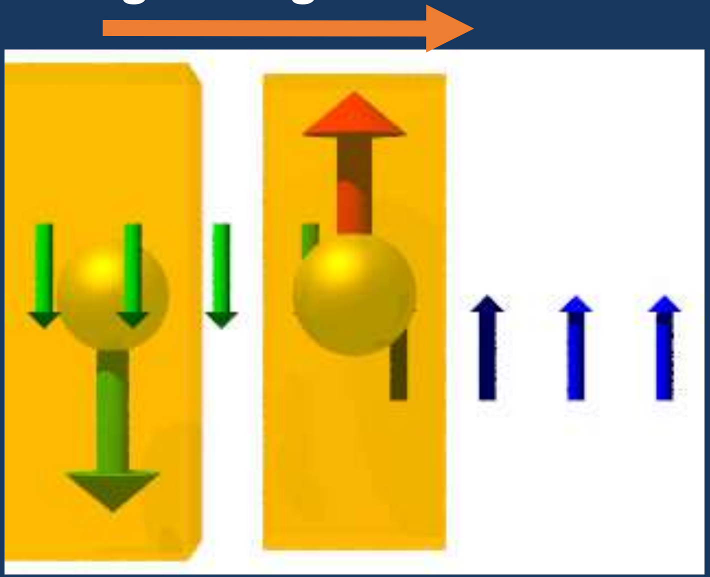
„Normal“ in plane tunnel junctions

Spin Transfer in MTJs



Push high current pulses through tunnel junction

charge & angular momentum



$$\frac{d\mathbf{m}}{dt} = -\gamma(\mathbf{m}\times\mathbf{H}_{\text{eff}}) + \alpha\left(\mathbf{m}\times\frac{d\mathbf{m}}{dt}\right) - T_{J(\text{hot})}\mathbf{m}\times(\mathbf{m}\times\hat{\mathbf{m}}_p),$$

Landau-Lifshitz-Gilbert-Slonczewski equation

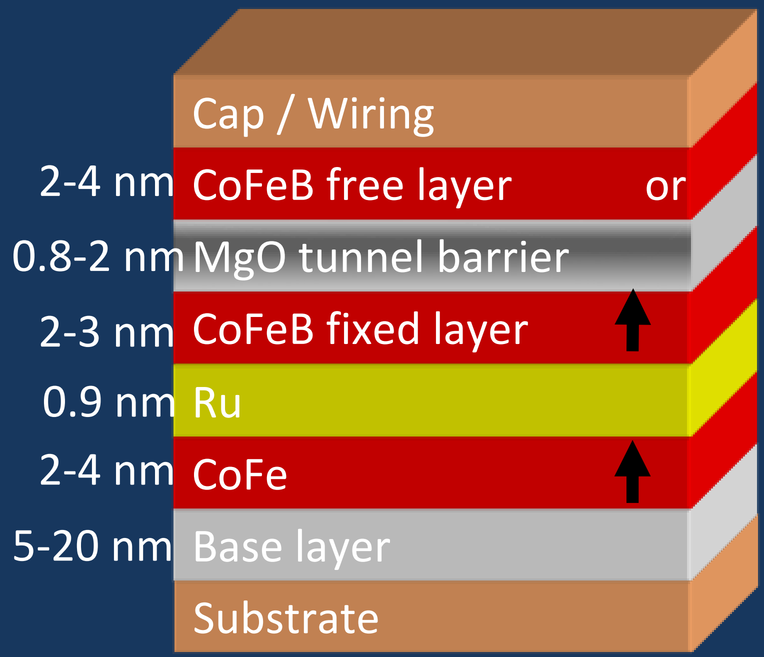
friction torque (damping)

STT – Spin Transfer Torque (antidamping)

→ The spin current switches the device due to transfer of torque

Spintransfer in perpendicular MTJs

The samples:



MTJ Stack

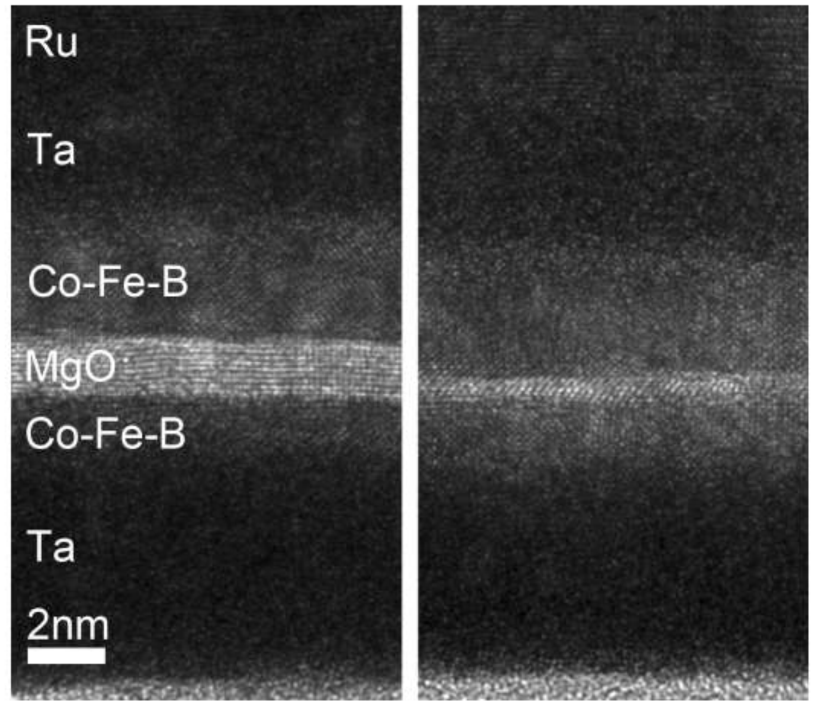
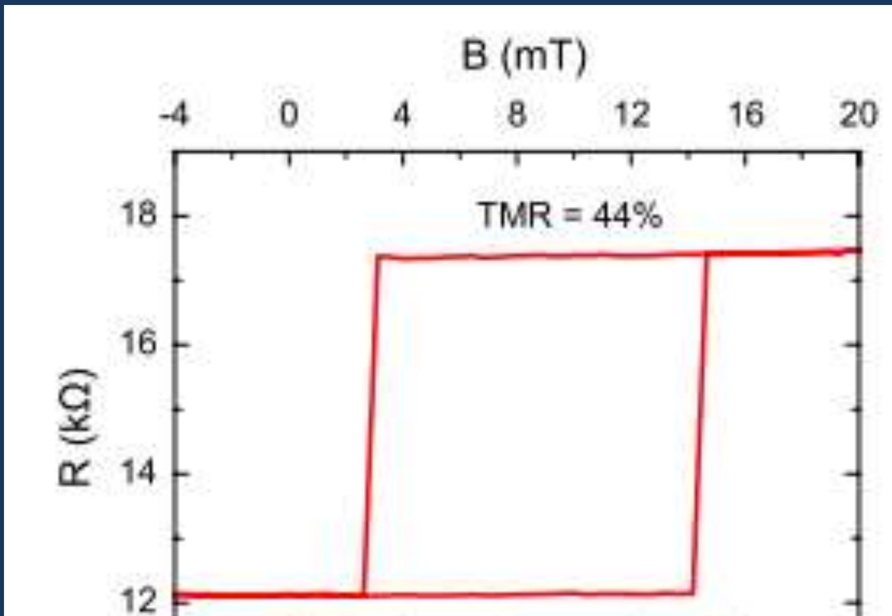


Fig. 1. HRTEM images of a thick 10 ML (left) and a heated 3 ML MgO barrier (right). The IQR values are $(5.6 \pm 1.5)^\circ$ (10 ML) and $(6.7 \pm 0.8)^\circ$ (3 ML).

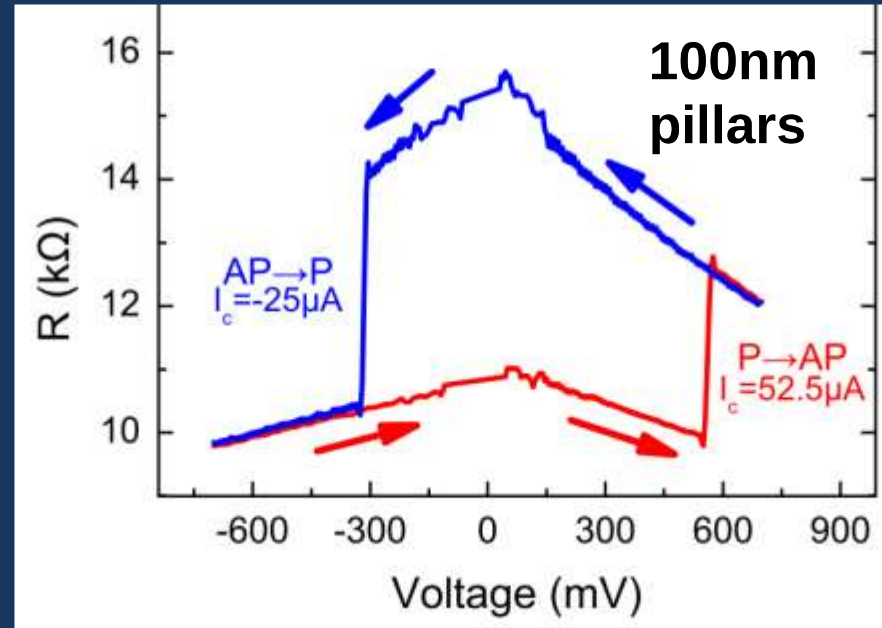
Magnetic Tunnel junctions with CoFeB (in plane or perpendicular) and other materials

MgO thickness down to 3 monolayers

Spintransfer in p-MTJs



Resistance vs. external magnetic field for perpendicular MTJs
1.0nm CoFeB / 4 ML MgO / 1.2nm CoFeB gives around 40-50% TMR



RV-characteristic with an applied field of 8.6 mT

- average critical current density:

$2 \cdot 10^5$ A/cm² (!!)

Parameter space for thermal spin-transfer torque

J. C. Leutenantsmeyer,[1, a)] M. Walter,[1] V. Zbarsky,[1] M. Münzenberg,[1] R. Gareev,[2] K. Rott,[3] A. Thomas,[3] G. Reiss,[3] P. Peretzki,[4] H. Schuhmann,[4] M. Seibt,[4] M. Czerner,[5] and C. Heiliger[5]

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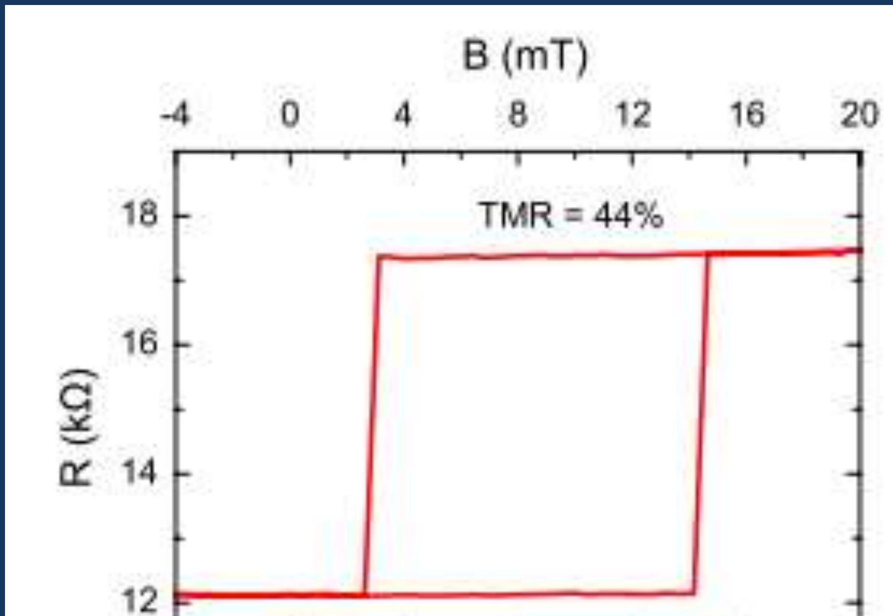
Vol. 3, No. 1 (2013) 1350002 (7 pages)

Universität Bielefeld
Department of Physics
CENTER FOR SPINELECTRONIC MATERIALS AND DEVICES

Spintransfer in p-MTJs



Resistance vs. external magnetic field for perpendicular MTJs
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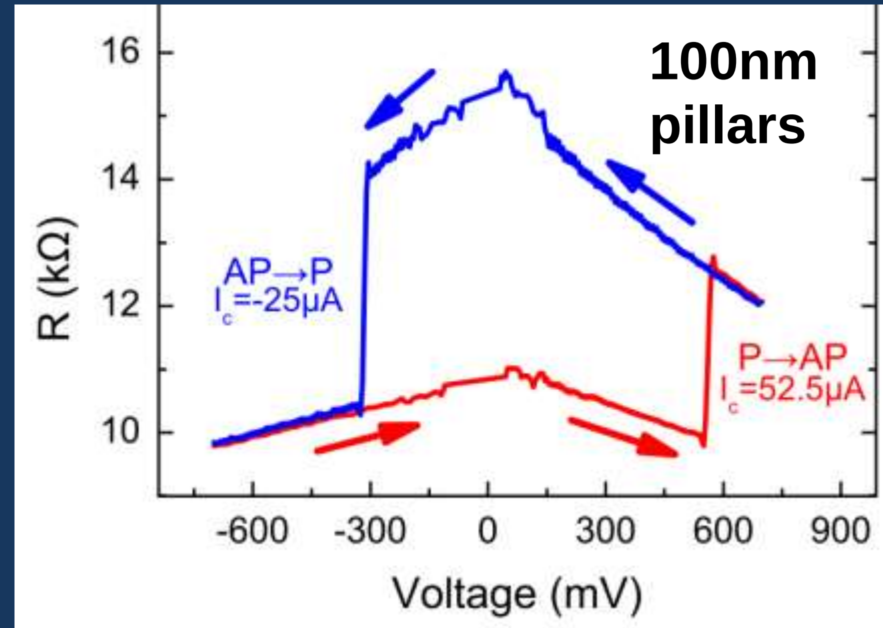


RV-characteristic with an applied field of 8.6 mT

- average critical current density:
  $2 \cdot 10^5$ A/cm² (!!)

Parameter space for thermal …

J…

R…

an…

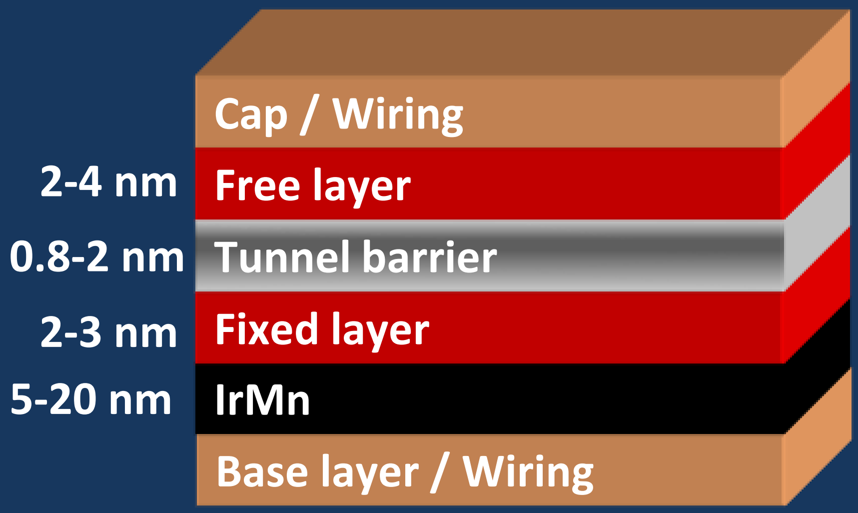
SPIN
Vol. 3, No. 1 (2013) 1350002 (7 pages)

Thermal torque could switch such MTJs if 10K temperature difference across barrier can be realized .. or if J_C is reduced

Latest results:
J_C can be as small as 10^4 A/cm² !!!!

New materials

Free layer:
- Low Magnetization
- Small or high damping
- High anisotropy
- Easy to switch
- High spin polarization



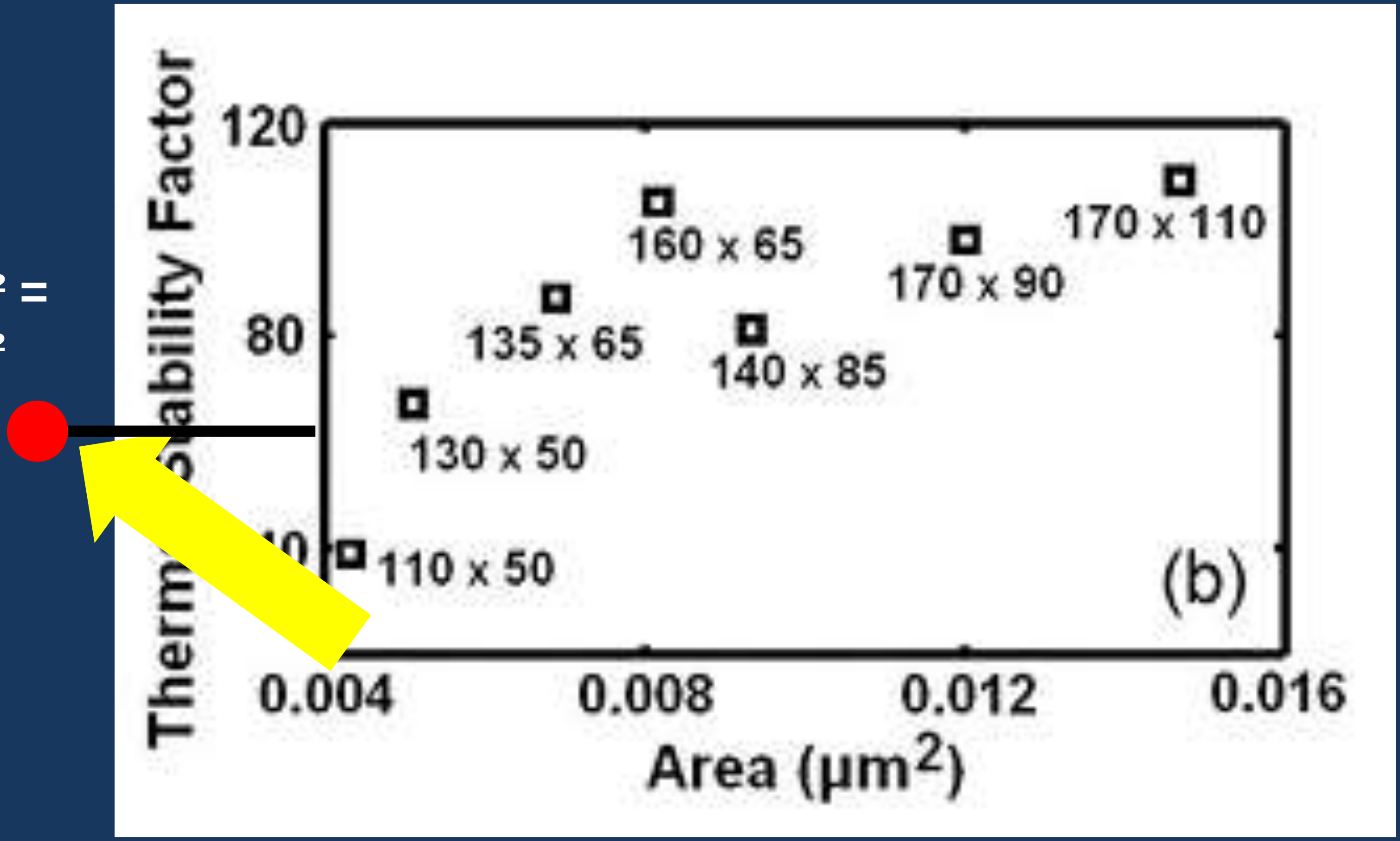
MTJ Stack

Fixed layer
- Moderate magnetization
- Not to switch
- High spin polarization
- Good and affordable exchange bias (perpendicular!)

Tunnel barrier
- Good growth on ferromagnet
- Spin filtering
- Good substrate for ferromagnet

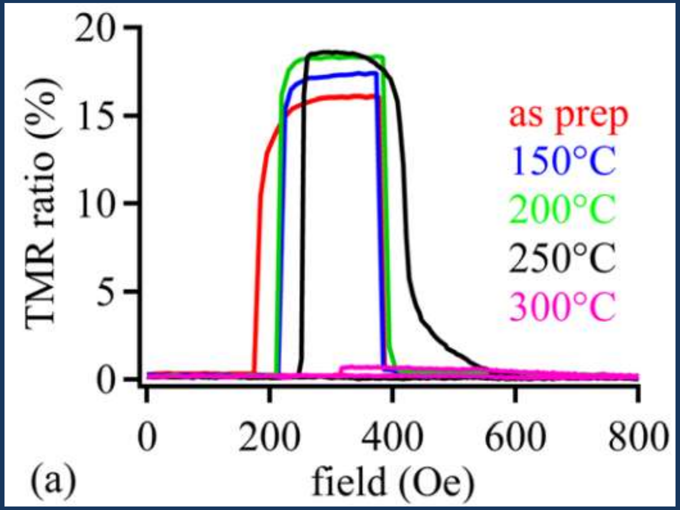
Thermal stability KV / kT > 60 for 10-years data retention: CoFeB on MgO possibly not good enough

Goal:
10 x 10 nm² =
0.001 µm²

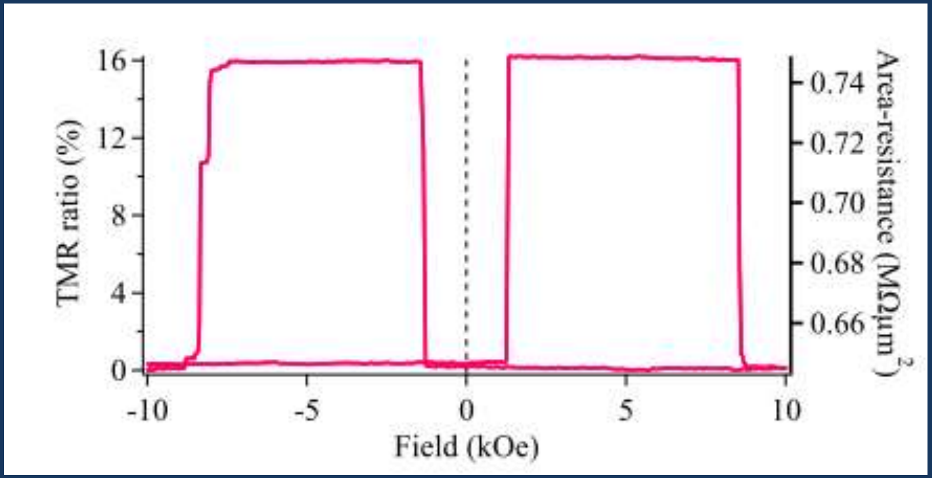


P.K. Amiri et.al, IEEE ELECTRON DEVICE LETTERS, VOL. 32, NO. 1, JANUARY 2011

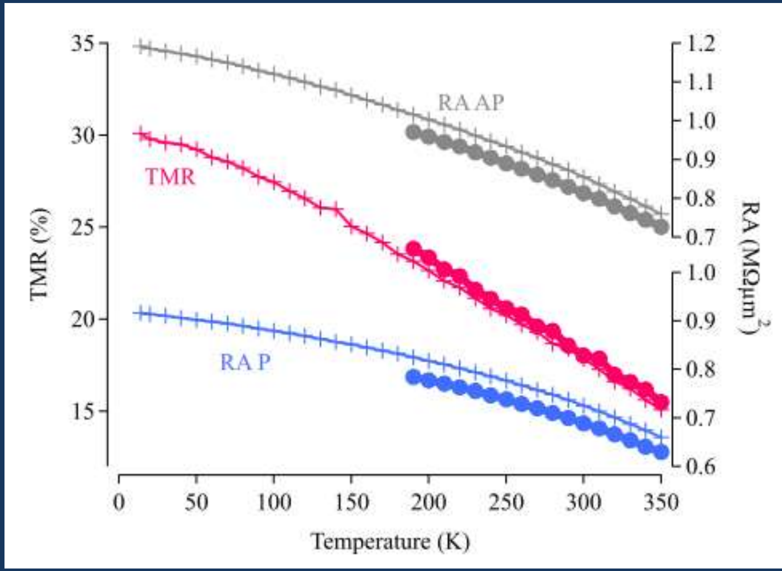
New Materials



TMR loops of <u>multilayers</u> CoPt …/$(Co_{0.6}/Pt_{1.8})_4$ /$Co_{0.7}$/ $Mg_{0.5}$/ $MgO_{2.1}$ / $(Co_{0.7}/Pt_{1.8})_2$ /… at 300 K



Major loop of <u>alloys</u> .../$(CoFe)_{79}Tb_{21}$ 30nm / CoFeB 1nm /Mg 0.5nm /MgO 2.1nm / CoFeB 1nm / $(CoFe)_{79}Tb_{21}$ 10nm /... at 360 K



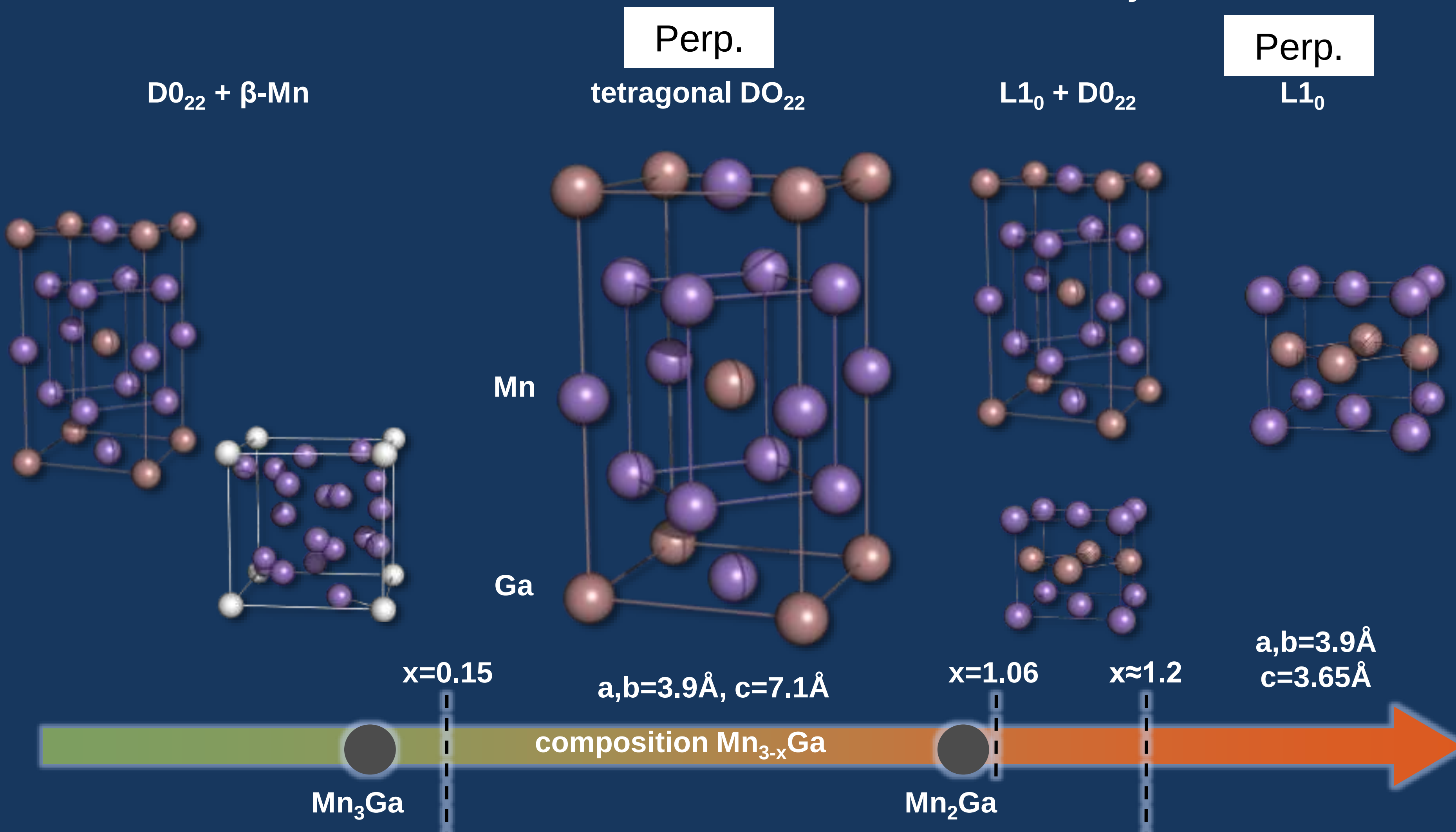
Both show similar good temperature dependence

But:
Large damping
So far low TMR

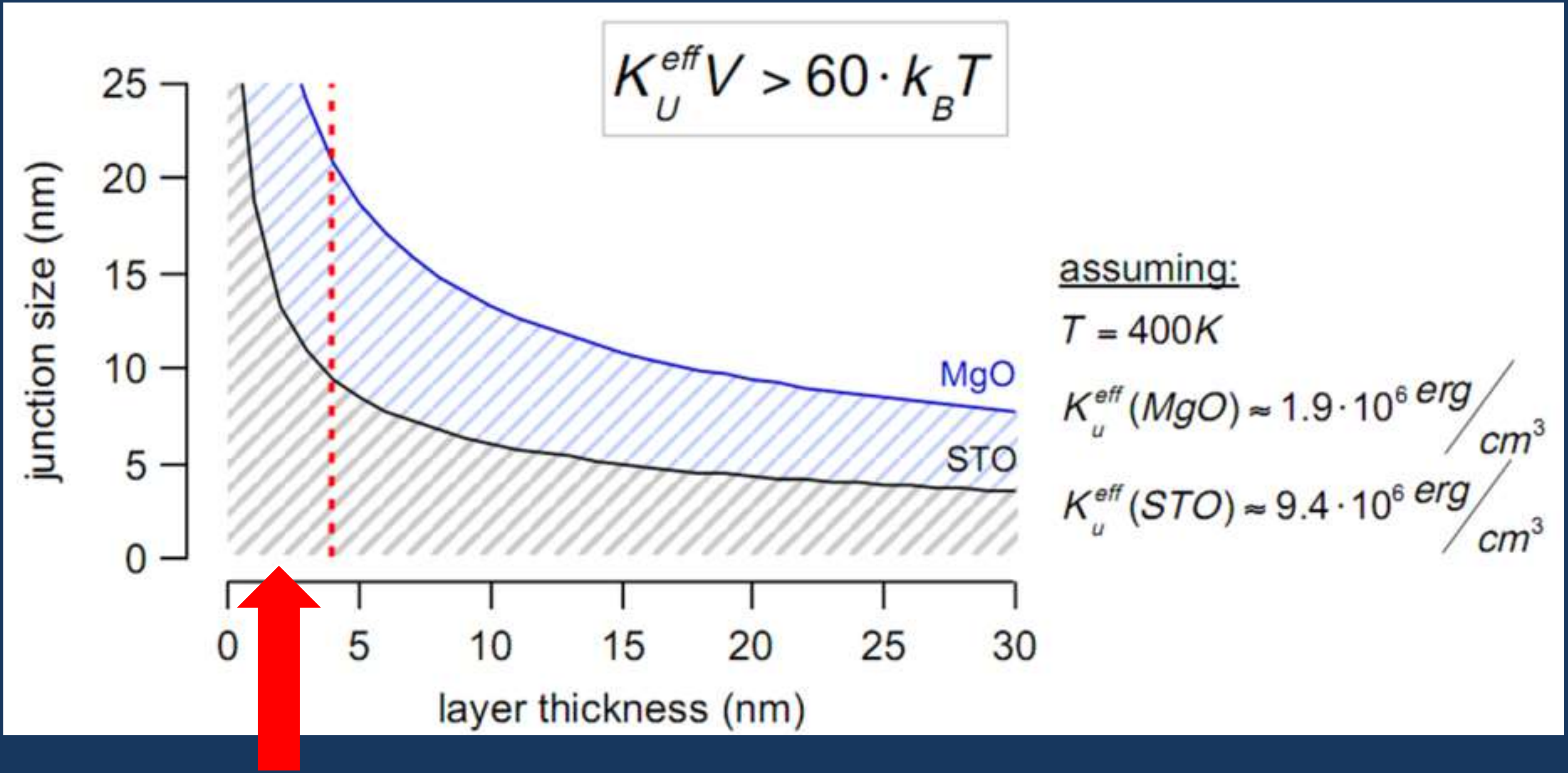
Zoë Kugler, J.-P. Grote, V. Drewello, O. Schebaum, GR, J. Appl. Phys. 111, 07C703 (2012)

.. candidate systems:

The Heusler-class $Mn_{3-x}Ga$ and $Mn_{2-x}Co_{1-y}Ga$



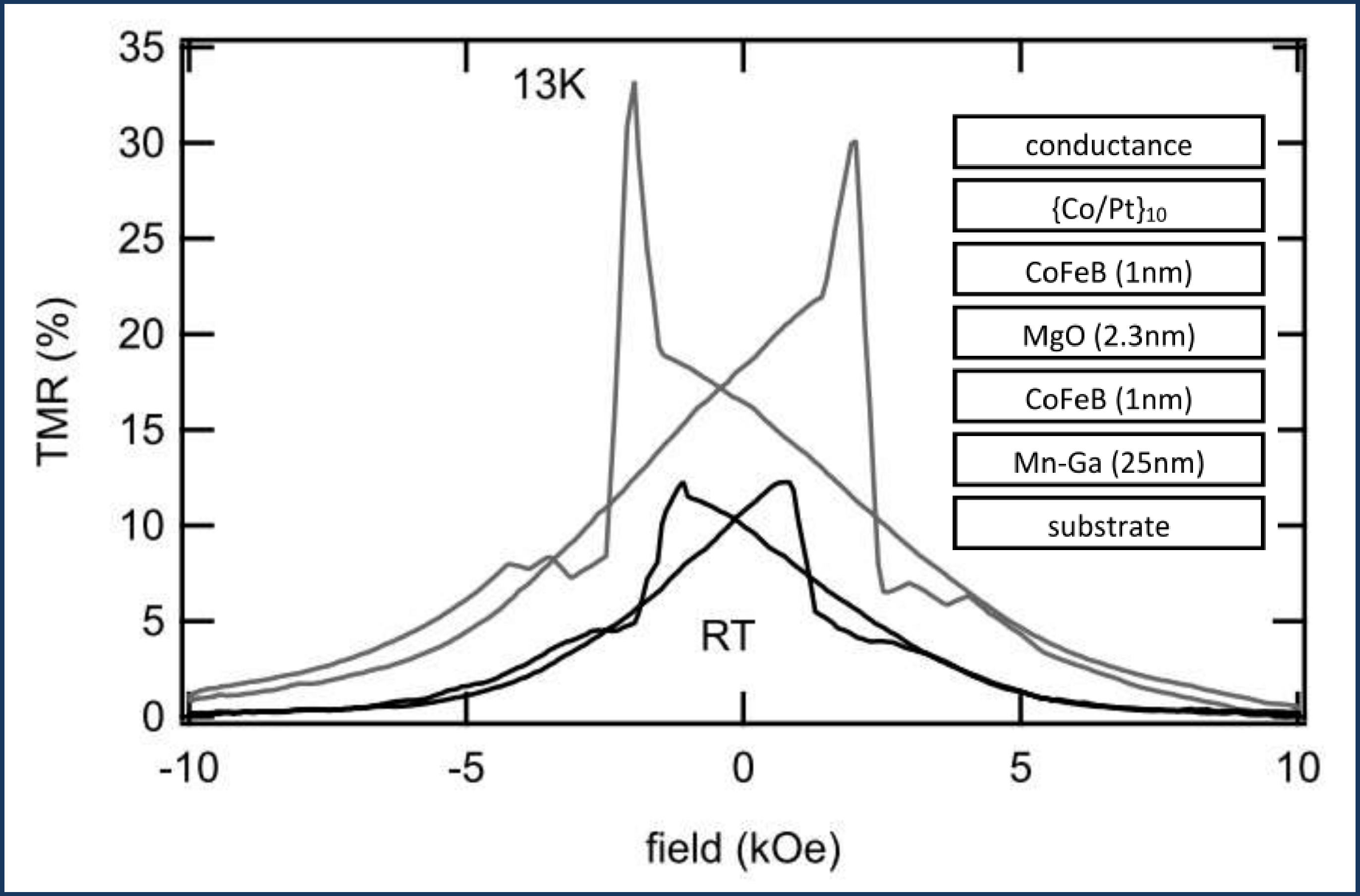
First results on $Mn_{2.6}Ga$: Very strong perpendicular anisotropy, low magnetization



Could work down to 5nm feature size !

M. Glas, C. Sterwerf, J. M. Schmalhorst, D. Ebke, C. Jenkins, E. Arenholz, G. Reiss,
J. Appl. Phys. 114, 183910 (2013)

New Materials



Material gives TMR, but up to now only with CoFeB interlayer and not yet completely antiparallel aligned .. further work on the way

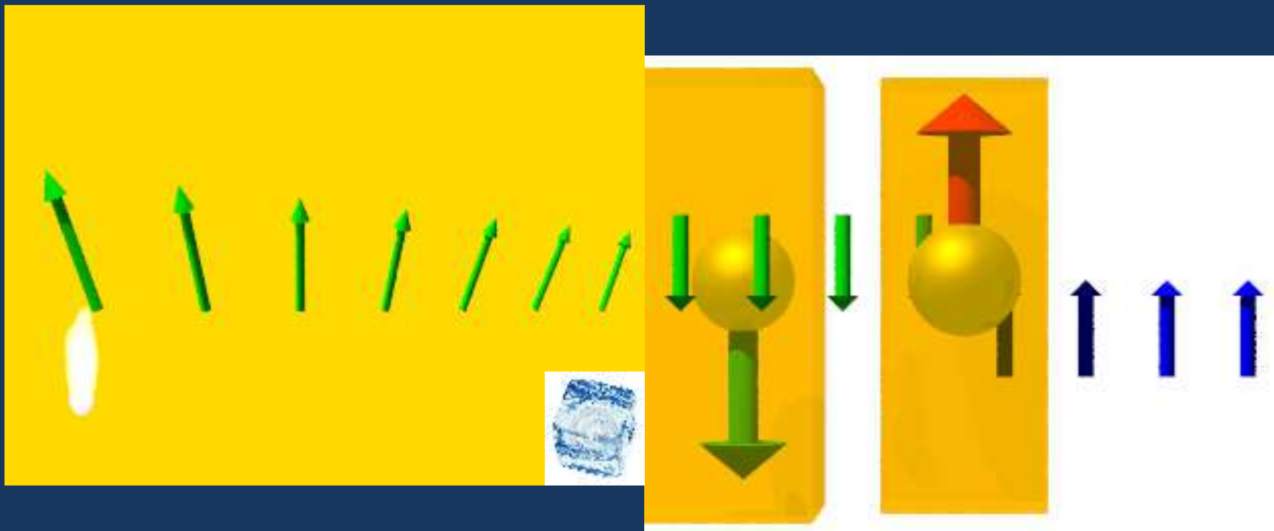
Summary – Take home messages

- Thermally driven spin currents in insulators
  → LSSE (+ ANE, PNE)

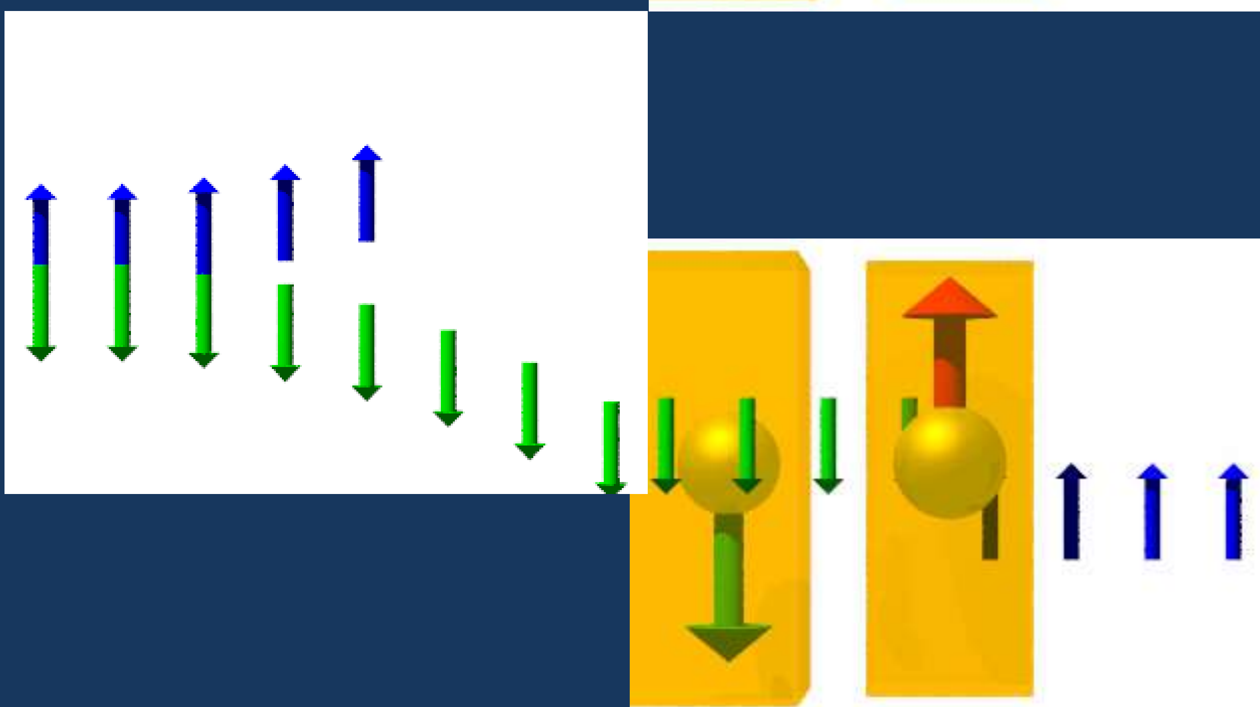
- Thermally driven spin currents in MTJs
  → TMTP, TMS

- Spin transfer and torque in magnetic tunnel junctions
  → STT (+oscillations)

Outlook



Thermal STT switching ?



STT switching by SO-interaction

-- Spin-Orbit-Torque ?

Thanks

All coworkers in Bielefeld



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T. Kuschel
D. Meier
Ch. Klewe

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- European Commission
- Thyssen Krupp Foundation
- Humboldt Foundation

Round Robin Experiment for Spin Seebeck Effects within EMRP-Project: contact H.W. Schumacher

Samples / Lithography: *Center for Spinelectronic Materials and Devices*, http://www.physik.uni-bielefeld.de/experi/d2/research/CSMD.html contact: Speaker