SPIN CALORICS AND SPIN TRANSFER IN MAGNETIC NANOSTRUCTURES

G. Reiss¹, D. Meier¹, A. Böhnke¹, H.W. Schumacher², S. Serrano-Guisan³, M. Walter⁴, J.C. Leutenantsmeyer⁴, M. Münzenberg⁵

¹Bielefeld University, Physics Department, P.O. Box 100131, 33501 Bielefeld, Germany
²Physikalisch Technische Bundesanstalt, 38159 Braunschweig, Germany
³International Iberian Nanotechnology Laboratory, 4715-330 Braga, Portugal
⁴I. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany
⁵Institut für Physik, Ernst-Moritz-Arndt Universität Greifswald, Germany

Collaborations:

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FAQ’s: Where is Bielefeld?
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 $M_S$
There are many ways to transfer spins / angular momentum:

- Charge & angular momentum by a spin polarized current
- Angular momentum by Stoner-like spin flips
- Charge & angular momentum but perpendicular by strong spin-orbit interaction
- Angular momentum by a temperature grad.
... 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, ..)
Spincalorics – Seebeck and Inverse Spin Hall Effect

Spintransport by a T-gradient

Spin separation in Spin Hall Effect

Spin Seebeck Effect

Longitudinal

Transverse (???)
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:**

\[ \vec{E}_{ISHE} \propto \vec{J}_S \times \vec{\sigma} \]

\[ \vec{\sigma} : \text{Spin polarization of charge carriers} \]
Nernst effects only in conducting materials
Overview of Spin-Seebeck- and competing Nernst-Effects:

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<tr>
<th>Hx</th>
<th>NiFe</th>
<th>Pt</th>
<th>Gradx T</th>
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<th>NiFe2O4</th>
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- **Overview of Spin-Seebeck- and competing Nernst-Effects:**

- **Spincalorics – Spin Seebeck and Competing Effects**

- **Put together by:**

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

$E_{\text{ISHE}} \propto J_s \times \sigma$


TSSE still under discussion ..
Other Spin-Seebeck-Effects:

On insulating LaY$_2$Fe$_5$O$_{12}$ 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$_2$O$_4$

Measured in Prof. Saitoh’s lab, Tohoku University, Sendai, Japan (T. Kuschel, D. Meier)
NiFe$_2$O$_4$ from A. Gupta, Alabama University, Tuscaloosa, USA
Spincalorics – LSSE in NiFe$_2$O$_4$

- Measured @Bielefeld lab,
- CVD-NiFe$_2$O$_4$ from A. Gupta, Alabama
- PVD-NiFe$_2$O$_4$ from Bielefeld-lab

.. reproducible signals

but

watch Nernst effects!

a, b, d, e: LSSE in NiFe$_2$O$_4$ for various values of $\Delta T$ and angle $\alpha$ between $\Delta T$ and $\mathbf{H}$

c, f: LSSE amplitude as function of $\Delta T$ and $\alpha$
Spincalorics – LSSE in NiFe$_2$O$_4$

a, b, d: LSSE in NiFe$_2$O$_4$ films for various values of ΔT and T$_0$

c: LSSE amplitude vs ΔT for various T$_0$

→ use semiconducting properties of NiFe$_2$O$_4$ and variable base temperature

LSSE on Pt-stripe and Anomalous Nernst signal on bare NiFe$_2$O$_4$
NiFe$_2$O$_4$ has semiconducting-type temperature dependence of the conductivity

→ compare LSSE at variable base temperature with conductivity

→ Conductivity drops by 6 orders of magnitude,

→ $V_{\text{Sat}}$ of (??) LSSE drops only by 1 ½ orders

→ $V_{\text{Sat}}$ due to LSSE

→ directly measured Nernst effect agrees with these data
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 \( \nabla T_z \):
\[
\vec{E}_{ANE} = N_{ANE} \nabla T \times \vec{M}.
\]

Expect: PNE for \( \nabla T_x \):
\[
V_y \propto |M|^{2} \sin(\varphi) \cos(\varphi) |\nabla T| \propto M_x \cdot M_y |\nabla T|
\]

? TSSE
Easy axis at 15°

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

„TSSE“-signal for various values of $\alpha$ as a function of the external field $H$

→ only symmetric effects

Gives only PNE (Planar Nernst Effect)
Symmetric part: Planar Nernst Effect

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

T₀ = 300K, ΔT variable
Pt stripe on hot side of the sample, thick Au tips as voltage probes (1mm)

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

**Spincalorics – TSSE in Permalloy?**

![Graphs showing heat flow directions on Nernst effects in Py/Pt bilayers](image)

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. Reiss1

PRL 111, 187201 (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. Back1
Magnetic Tunnel Junctions with CoFeB (in plane or perpendicular) and other materials
(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

(a) MTJ stack composition. HL, TC and BC: heater line, electrical top and contact
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f) simulated temperature profile across the MgO barrier

and

enlarged view of the MTJ
Seebeck coefficient $S$ for tunnel junctions:

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

$\partial_E f(E, \mu, T)$: 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: $S \neq$ conductivity $g = \frac{e^2}{h} \int T(E)(-\partial_E f(E, \mu, T))dE$
Spincalorics in MTJs
Spincalorics in MTJs

Tunneling Magnetothermopower in Magnetic Tunnel Junction Nanopillars

N. Liebing, S. Serrano-Guisan, K. Rott, G. Reiss, J. Langer, B. Ocker, and H. W. Schumacher

Seebeck effect in magnetic tunnel junctions

Marvin Walter, Jakob Walowski, Vladyslav Zbarsky, Markus Münzenberg, Markus Schäfers, Daniel Ebke, Günter Reiss, Andy Thomas, Patrick Peretzki, Michael Seibt, Jagadeesh S. Moodera, Michael Czerner, Michael Bachmann, and Christian Heiliger
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: \( \sigma \) 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: \( \sigma \) changes from P to AP configuration!

Reports: \( I_{TP}=0 \) ??

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

Onsager’s relations valid for TMTP..
Spincalorics in MTJs

Gap in one spin direction should increase not only TMR but also (large asymmetry of DOS at $E_F$)

\[
S = \frac{\int T(E)(E - \mu)(-\partial_E f(E, \mu, T))dE}{e T \int T(E)(-\partial_E f(E, \mu, T))dE}
\]

→ Co$_2$FeSi

replace by highly spin polarized Heusler alloy

a) TMS reaches 90 ... 96 % comparable to TMR (b)

c) Dependence of TMS ratio on applied laser power.

... ongoing experimental and theoretical work
Resistance vs Magnetic Field for:

A CoFeB / MgO / CoFeB pseudo-spinvalve MTJ and a Co$_2$FeAl / MgO / CoFeB structure Heusler MTJ

„Normal“ in plane tunnel junctions
Push high current pulses through tunnel junction

Spin Transfer in MTJs

Landau-Lifshitz-Gilbert-Slonczewski equation

\[
\frac{dm}{dt} = -\gamma(m \times H_{eff}) + \alpha (m \times \frac{dm}{dt}) - T_{J\text{(hot)}} m \times (m \times \hat{m}_p),
\]

friction torque (damping)

STT – Spin Transfer Torque (antidamping)

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

MTJ Stack

Cap / Wiring
2-4 nm CoFeB free layer or
0.8-2 nm MgO tunnel barrier
2-3 nm CoFeB fixed layer
0.9 nm Ru
2-4 nm CoFe
5-20 nm Base layer
Substrate

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

Spintransfer in perpendicular MTJs

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).

MgO thickness down to 3 monolayers
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: \(2 \cdot 10^5 \text{ A/cm}^2\) (!!)

Parameter space for thermal spin-transfer torque

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: \(2 \cdot 10^5 \text{ A/cm}^2\) (!!)

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 \(10^4 \text{ A/cm}^2\) !!!!
Free layer:
- Low Magnetization
- Small or high damping
- High anisotropy
- Easy to switch
- High spin polarization

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
New Materials

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

Goal: $10 \times 10 \text{ nm}^2 = 0.001 \text{ µm}^2$

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

TMR loops of **multilayers** CoPt ...
\((\text{Co}_{0.6}/\text{Pt}_{1.8})_4/\text{Co}_{0.7}/\text{Mg}_{0.5}/\text{MgO}_{2.1}/(\text{Co}_{0.7}/\text{Pt}_{1.8})_2/\ldots\) at 300 K

Major loop of **alloys** ...
\((\text{CoFe})_{79}\text{Tb}_{21}30\text{nm}/\text{CoFeB}1\text{nm}/\text{Mg}0.5\text{nm}/\text{MgO}2.1\text{nm}/\text{CoFeB}1\text{nm}/(\text{CoFe})_{79}\text{Tb}_{21}10\text{nm}/\ldots\) at 360 K

Both show similar good temperature dependence

But:
Large damping
So far low TMR

.. candidate systems:
The Heusler-class Mn$_{3-x}$Ga and Mn$_{2-x}$Co$_{1-y}$Ga

- D0$_{\text{22}}$ + β-Mn
- tetragonal D0$_{\text{22}}$
- L1$_0$ + D0$_{\text{22}}$
- L1$_0$

Composition:
- Mn$_3$Ga, x=0.15, a,b=3.9Å, c=7.1Å
- Mn$_2$Ga, x≈1.2, a,b=3.9Å, c=3.65Å
First results on Mn$_{2.6}$Ga: Very strong perpendicular anisotropy, low magnetization

Could work down to 5nm feature size!

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

J.-M. Schmalhorst
A. Thomas
T. Kuschel
D. Meier
Ch. Klewe

.. and you for listening!

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