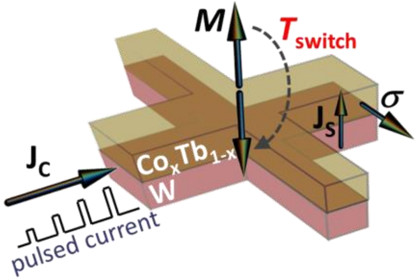
INSTITUT JEAN LAMOUR

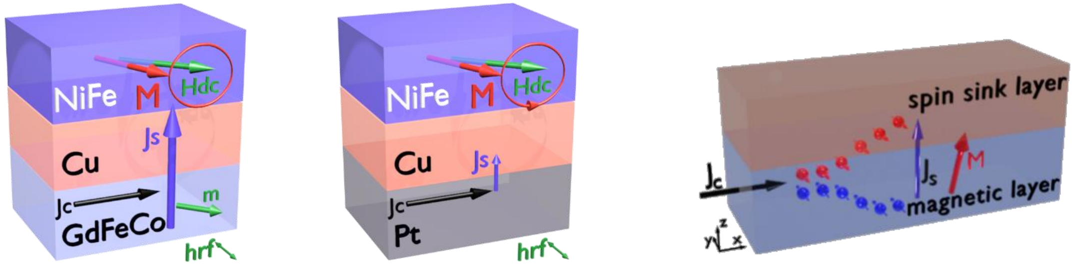
www.ijl.univ-lorraine.fr

https://spin.ijl.cnrs.fr/

Ferrimagnetic spintronics and self-torque



T. H. Pham, JCRS *et al.*, *Phys. Rev. Appl. 9, 064032 (2018)*



D. Cespedes-Berrocal, H. Damas, *et al.*, *Adv. Mat. 33, 2007047 (2021)*

H. Damas, A. Anadon *et al.*, *Physica Status Solidi RRL (2022)* doi.org/10.1002/pssr.202200035

J. Carlos Rojas-Sánchez

Juan-carlos.rojas-sanchez@univ-lorraine.fr

@carlos_rojas101

May/18/2022

SPICE SPIN PHENOMENA INTERDISCIPLINARY CENTER

SPIN+X SFB/TRR 173 Kaiserslautern • Mainz

Visiting scholar at New York University (NYU)

03/28/2022 – 07/27/2022

Andrew Kent
Professor Of Physics;
Director of the Center for Quantum Phenomena
NYU

H2020-MSCA-RISE
ULTIMATE-I

https://spin.ijl.cnrs.fr/projects/eu-ultimate-i/

PhD position to start 10/2022:
https://spin.ijl.cnrs.fr/jobs-phd/

Post-doc position at NYU:
https://as.nyu.edu/physics/information/jobs.html#2

Institut Jean Lamour

Clean Room (Minalor)

TUBE (Daum)

Spintronic and Nanomagnetism Team offices

28000 m^2

Magnetotransport and Squid setups

KEY FIGURES 2020

Staff:

166 permanent researchers

70 post-doctoral researchers

171 PhD students

103 support staff

Scientific activity:

360 peer-reviewed articles

54 new research contracts

30 PhD thesis defenses

International:

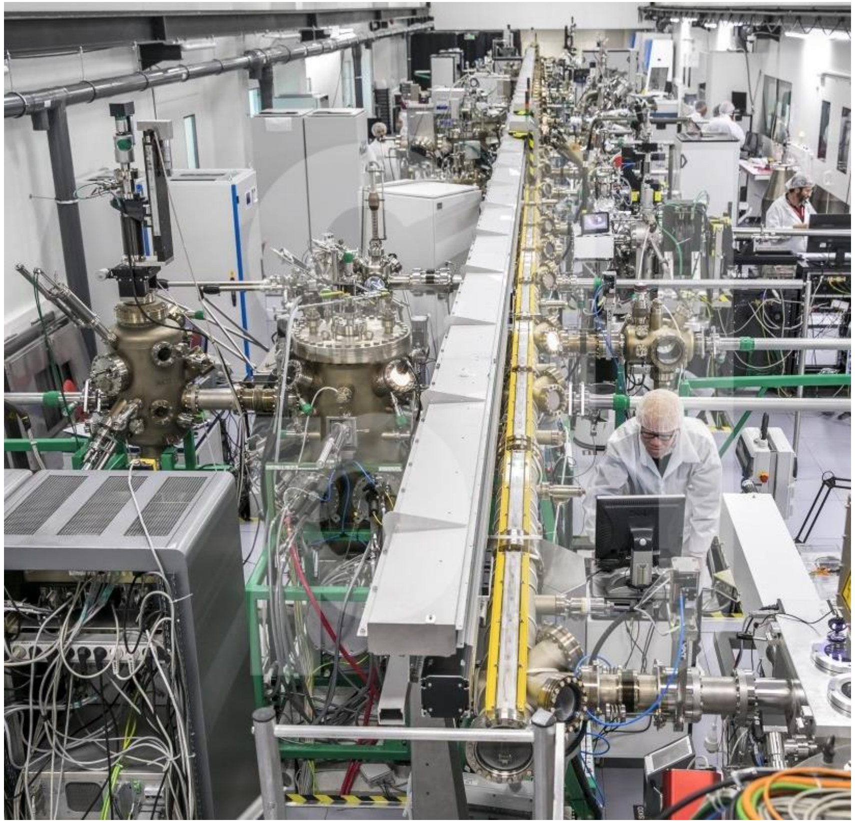
51 nationalities

200 collaborative actions

30 partner countries

Institut Jean Lamour

Unique plateforme: Tube Daum



70 m UHV
40 m to fundamental research
30 m to technology transfer

Growth

MBE PVD PLD ALD	Rare-erath, metals, semiconductors, oxydes, insulators, superconductors, molecular materials

Analysis

Structural	RHEED, STM, AFM
Chemical/ spectrocopies	XPS, AES, SARPES
Physics	Magnetic (Kerr), Optic (elippsometry), Transport (STM MFM)

IJL's MiNaLor skill center

Platform for Micro and Nanotechnologies

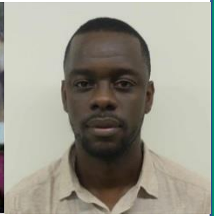
3 Engineers

260 m² of cleanroom

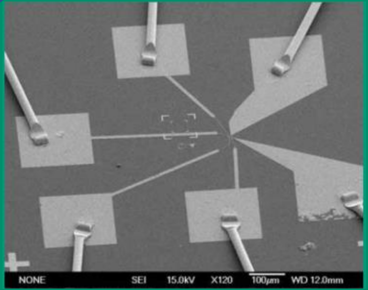
15 equipments

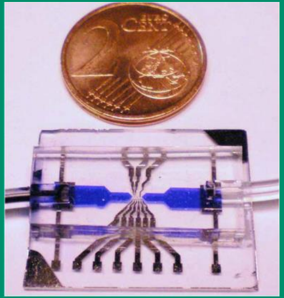
Laurent Badie

Gwladys Legaigne

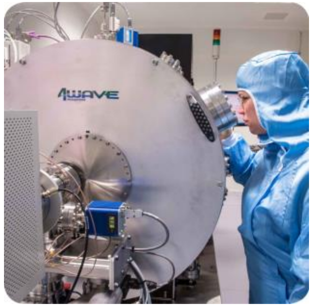


Demba Ba



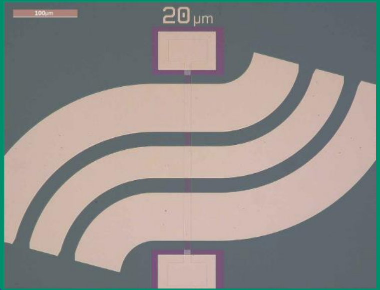


lithography
Optical and
e-beam



Thin film deposition and etching

Sophie Bravetti



- > Nanostructures
- > Lab on chip
- > Micro and nano-antennas
- > Piezoelectric and magnetic sensors

INSTITUT JEAN LAMOUR

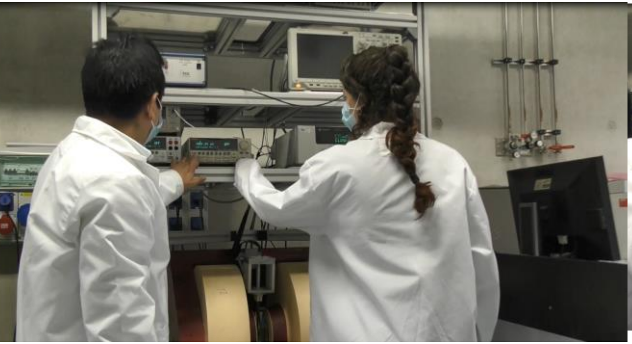
SPIN group

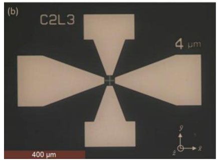
https://spin.ijl.cnrs.fr/

5 main research topics :

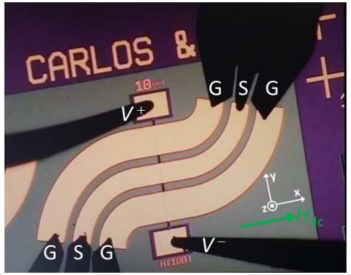
- Materials growth :
  - Heusler Compounds (S. Andrieu)
  - Oxydes (O. Copie & K. Dumesnil)
- Spin transport :
  - Spin-Orbitronics (C. Rojas-Sánchez)
  - Spin-Caloritronics (C. Rojas-Sánchez)
  - Spin precession MTJ (D. Lacour)
- Magnetization Dynamics :
  - Oscillators (S. Petit-Watelot)
  - Picosecond Dynamics (J. Gorchon)
  - Ultra-fast Dynamic (G. Malinowski)
  - All Optical Switching (S. Mangin)
- Nanomagnetism :
  - Spin-Ice (F. Montaigne)
- Applications
  - Magnetic SAW Sensors (M. Hehn)
  - Magnetic Printing (T. Hauet)

Spin-orbitronics measurements

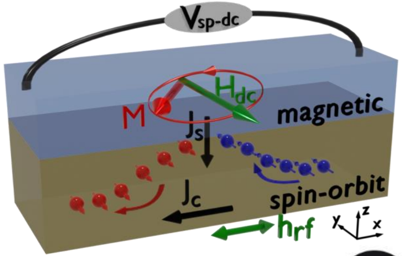




Heloïse DAMAS, Eva DIAZ, Wei YANG
PhD students



Alberto ANADON-B.
Post-doc



UNIVERSITÉ DE LORRAINE

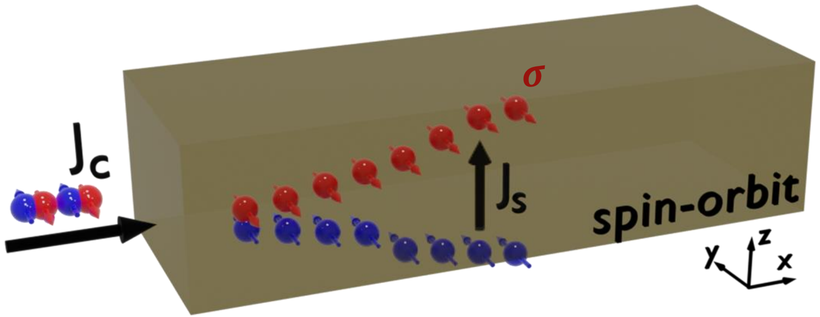
Ultra Thin magneto Thermal Sensoring
H2020-MSCA-RISE
ULTIMATE-I

Charge to spin current conversion

➔ Spin Hall effect (SHE) 3D systems

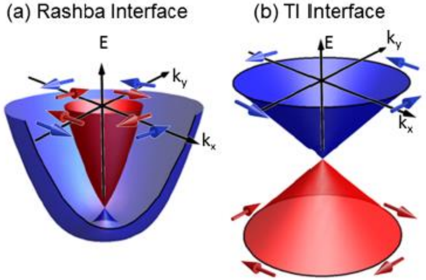
M. I. Dyakonov and V. I. Perel, (1971)
J. E. Hirsch (1999)

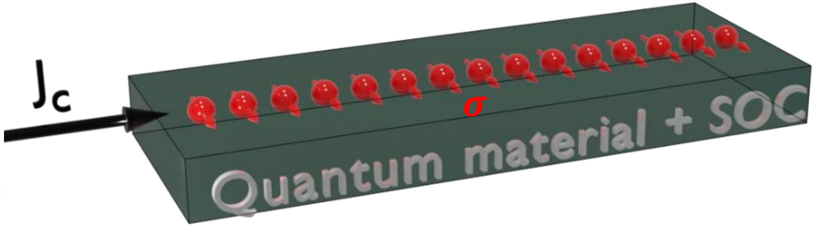
Charge to spin current



➔ Edelstein effect (EE) 2D systems with helical spin texture Rashba interfaces, TIs

Bychkov and Rashba, (1984)
Edelstein (1990)

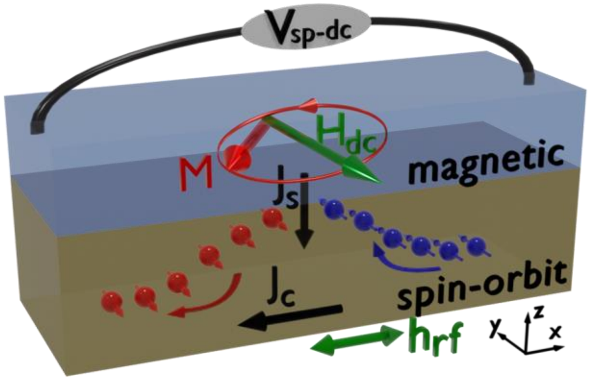




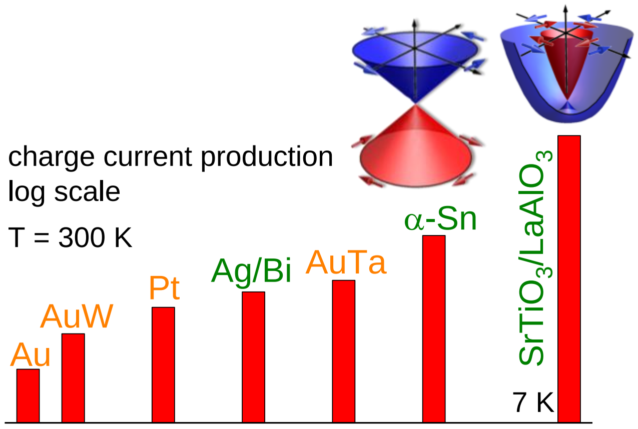
Juan-carlos.rojas-sanchez@univ-lorraine.fr @carlos_rojas101

IEE vs ISHE : advantage of 2D systems

Spin pumping voltage at ferromagnetic resonance



Tserkovnyak et al. PRL 88, 117601 (2002)
Silsbee et al. PRB 19, 4382 (1979)
Azevedo et al. JAP (2005), Saitoh et al. APL (2006)
K. Ando et al. JAP 108 , 113925 (2010)



Spin-Orbit in 2D system is more efficient than in 3D (SHE) for spin-charge conversion and spintronic devices

JCRS & A Fert ***PRAppl*** **2019**

Ag/Bi interface @ 300 K J.-C. Rojas-Sánchez *et al.*, *Nat. Comm.* 4, 2944 (2013)

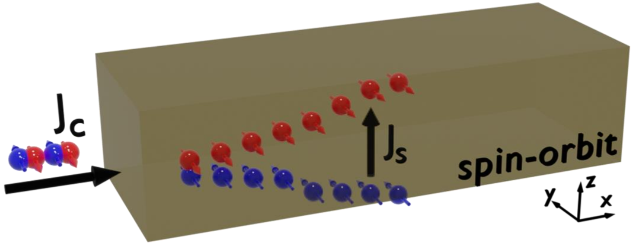
α-Sn topological insulator @ 300 K *PRL* 116, 096602 (2016), arXiv (2015)

STO/LAO Oxides Rashba interfaces @ 7 K E. Lesne *et al.*, *Nat. Mater.* 15, 261 (2016)

Examples of spin-orbit effect in bulk: Spin Hall Effect (SHE) and spin-orbit torque (SOT)

SHE and ISHE (bulk effects)

M. I. Dyakonov and V. I. Perel, (1971)
J. E. Hirsch (1999)



➔ Efficiency of conversion:

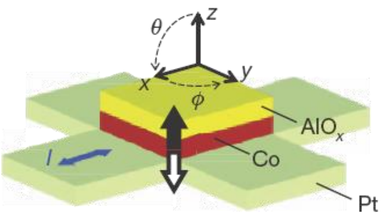
Spin hall angle $\theta_{SHE} = \frac{\textit{spin current density}}{\textit{charge current density}}$

(dimensionless)

Some reviews:
Hoffmann IEEE TM (2014);
Niimi & Otani RPP (2015
Sinova et al. PRM (2015)
Manchon et al. PRM (2019)

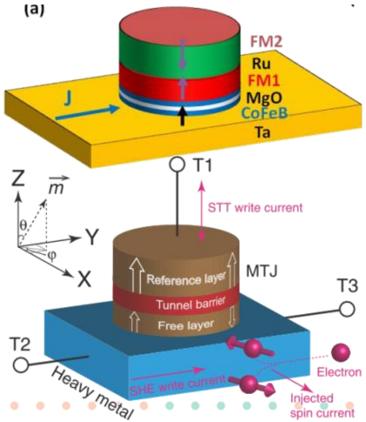
Applications

SOT or electrical switching



I. M. Miron *et al.*, Nature 476, 789 (2011)
Liu et al. Science 333, 555 (2012)
Pt/$(Co/Ni)_3$/AlOx
J.C R-S et al. APL 108, 082406 (2016)
W/$Co_{1-x}Tb_x$/AlOx
T.H. Pham, JC R-S et al. (PRAppl 2018)
Je, JC R-S et al. APL (2018)

Ultrafast 3-terminal SOT MRAM



M. Cubukcu *et al.*, APL (2015)
Switching very fast < 1 ns

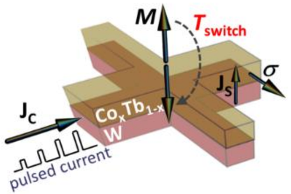
via photoswitcher 6ps:
Kaushal, JCRS, Gorchon *et al.*
Nat Elect. (2020)

Z. Wang, W. S. Zhao *et al.*, J. Phys. D: 48, 065001 (2015)

Outline

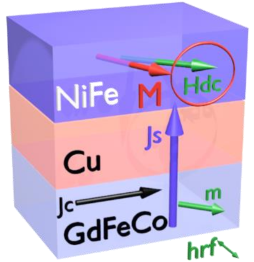
Ferrimagnetic alloys & spintronics

T. H. Pham, JCRS *et al*. Phys. Rev. Applied 11, 054049 (2018)



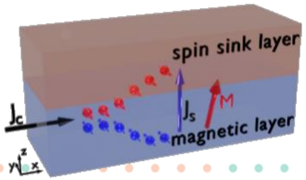
Spin Hall effect (SHE) & Spin Anomalous Hall effect (SAHE)

Héloïse Damas *et al.* PSS RLL (2022) invited https://doi.org/10.1002/pssr.202200035
David Céspedes-Berrocal, H. Damas, *et al.* Advanced Materials (2021)

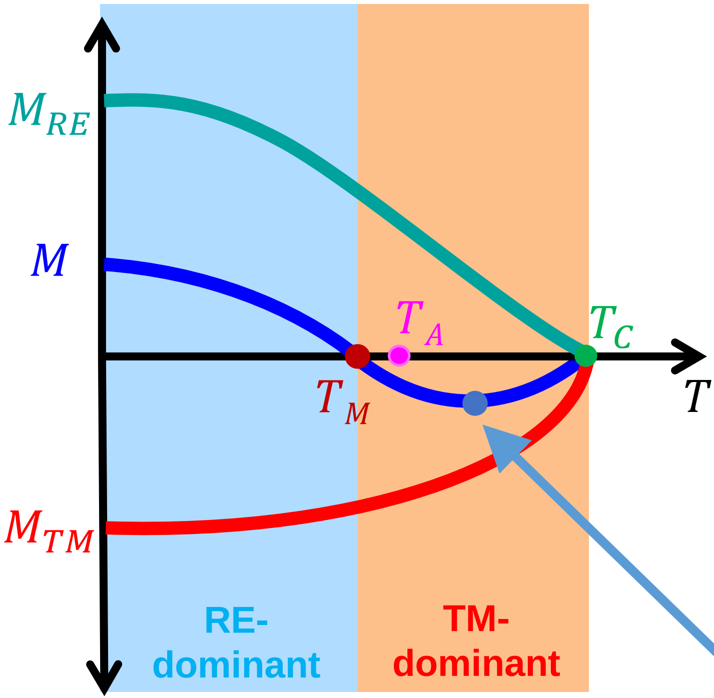


Self-spin-orbit-torques : GdFeCo/Cu

David Céspedes-Berrocal, H. Damas, A. Fert, JCRS *et al.* Advanced Materials (2021)
https://doi.org/10.1002/adma.202007047



Temperatures in RE-TM ferrimagnetic alloys



RE: rare earth

TM: transition metal

$$\vec{M}(T) = \vec{M}_{RE}(T) + \vec{M}_{TM}(T)$$

$$\vec{M}_{RE} = \gamma_{RE}\vec{L}_{RE}$$

$$\vec{M}_{TM} = \gamma_{TM}\vec{L}_{TM}$$

$$\vec{A}(T) = \frac{\vec{M}_{RE}}{\gamma_{RE}}(T) + \frac{\vec{M}_{TM}}{\gamma_{TM}}(T)$$

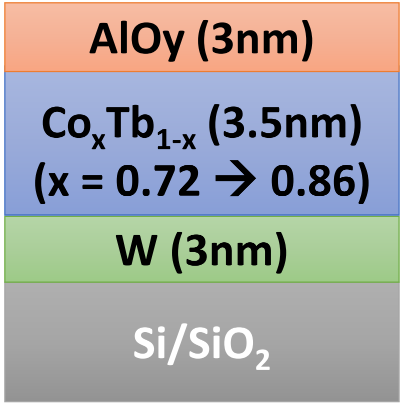
3 different temperatures:

T_M, T_A, T_C

Recently: Characteristic temperature $\partial M/\partial T = 0$

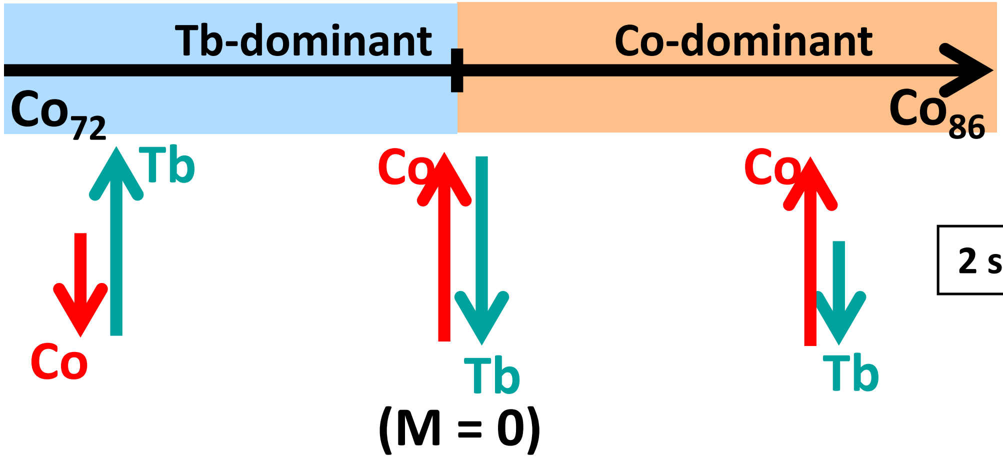
U. Ritzmann *et al.*, *Phys. Rev. B 95, 054411 (2017)*

Co_xTb_{1-x} ferrimagnetic



grown by sputtering

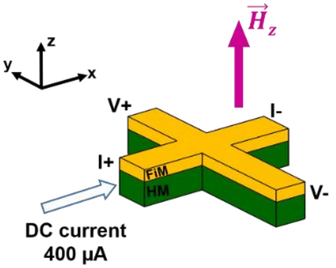
CoTb « easy » to integrate with any system (3D, 2D) while keeping its magnetization M out of plane



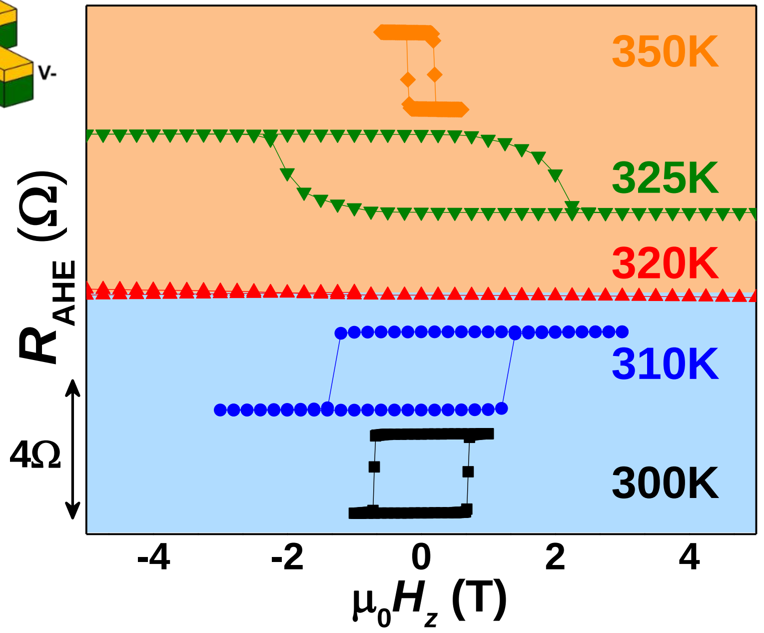
2 sub-lattices

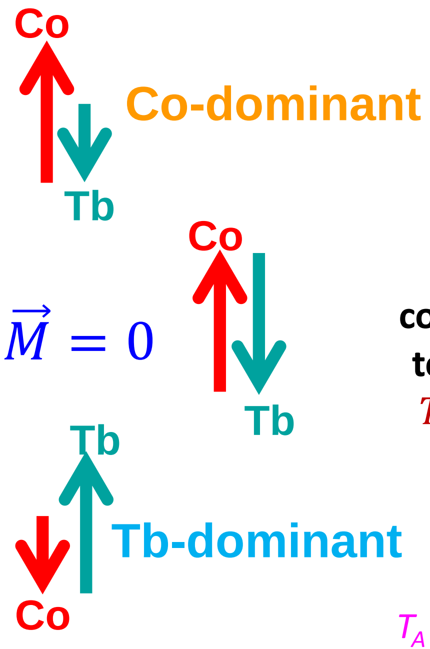
Magnetization compensation @ x_M

Magnetic characteristic : *T* dependence



W(3nm)/$Co_{0.76}Tb_{0.24}$(3.5nm)/AlO_y





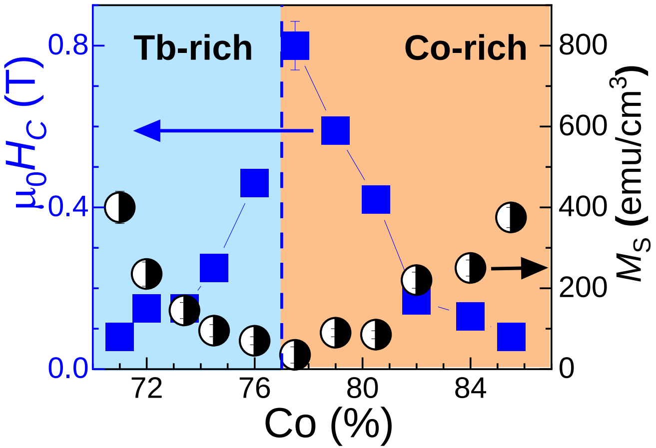
Magnetic compensation temperature
$T_M = 320K$

T. H. Pham, JCRS *et al., Phys. Rev. Appl. 9, 064032 (2018)*

T_A determination by DWP :
Kim et. *al*. Nat Elect. (2020)
Talk by Kyung-Jin Lee

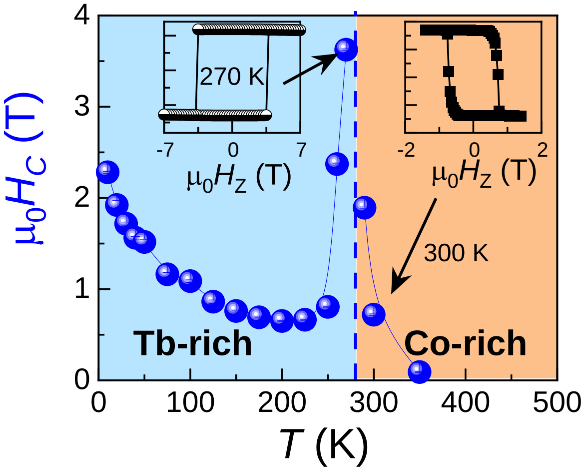
W/Co_xTb_{1-x}/Al: *T* and Co_x dependence

SQUID results @ 300 K
(as-grown films)



M = 0 at compensation $x_M \approx 0.77$

AHE results @ x=0.78
(Hall bars)



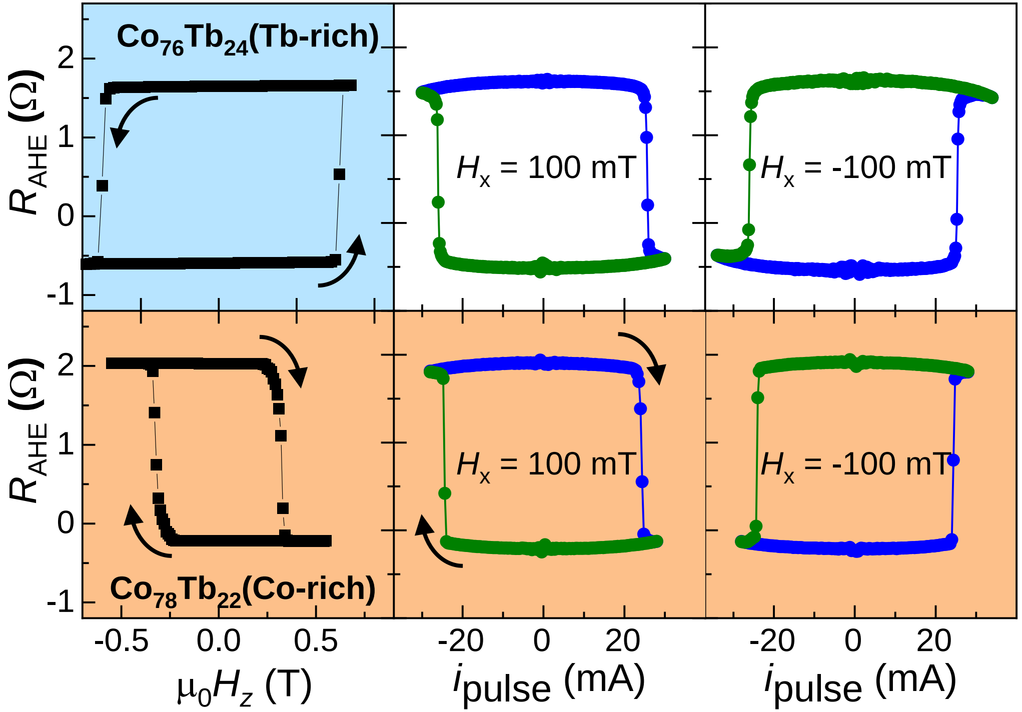
The R_{AHE} loop changes sign when crossing the compensation temperature

Co_xTb_{1-x} alloys allow us to
tune the net magnetic moment by varying the **Co concentration** or **temperature**

W/Co_xTb_{1-x}/Al: Spin-orbit torque

300K

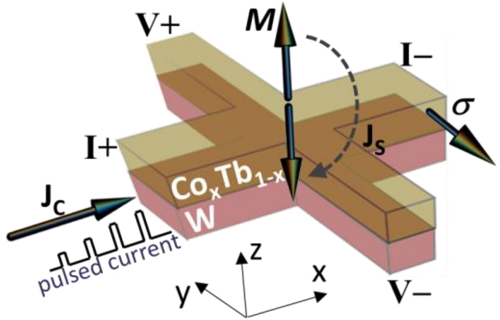
Field-induced switching **Current-induced switching**



i_{dc}=400 μA

100 μs current pulse
V_{AHE} simultaneously measured

"unexpected" SOT-switching polarity for Tb-rich samples

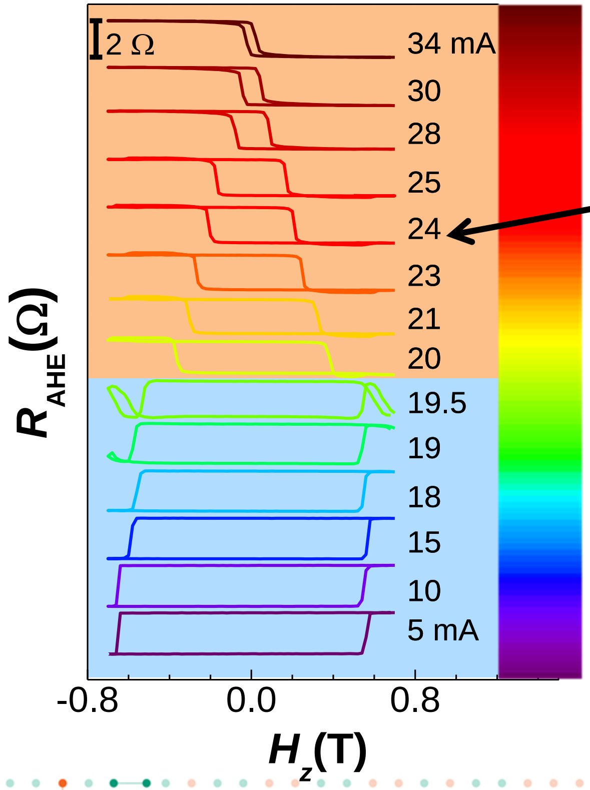


- 100 % M switching
- Even with H_x= 2 mT

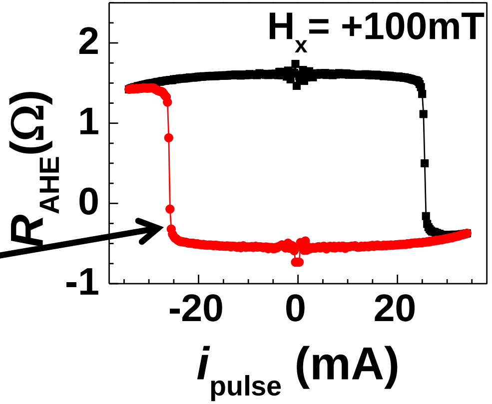
Strong thermal contribution

300K

W(3nm)/$Co_{0.76}Tb_{0.24}$(3.5nm)/AlO_x



i_{switch}



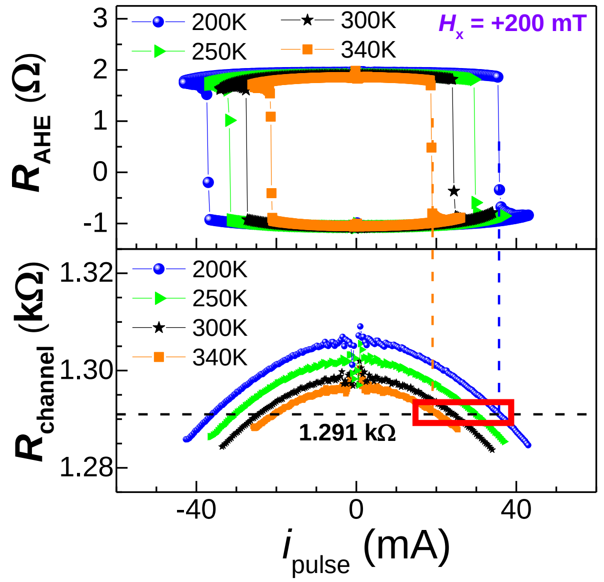
"unexpected" switching polarity because during pulses, sample temperature is higher than compensation temperature

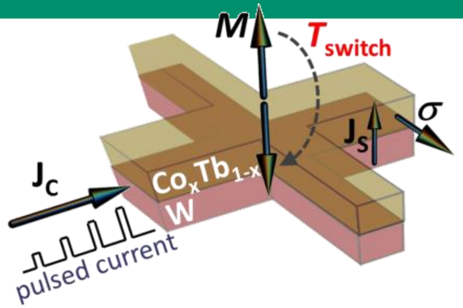
Cryostat temperature $T_{Cryostat}$ < **Compensation temperatures** T_M, T_A < **Sample temperature** T < **Curie temperature** T_C

T. H. Pham *et al.*, *Phys. Rev. Appl. 9, 064032 (2018)*

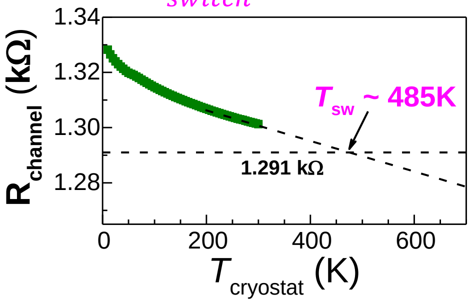
Switching temperature (T_{switch})

W(3nm)/$Co_{0.79}Tb_{0.21}$(3.5nm)/AlO_y





$T_{switch} \approx 485K$



T. H. Pham, JCRS *et al.*, *Phys. Rev. Appl. 9, 064032 (2018)*

Acknowledgement to collaborators

Thai Ha Pham, **Soong-gung Je**, P. Vallobra, T. Fache, D. Lacour, G. Malinoswki, **M. Hehn**, S. Mangin
IJL, Nancy, France

Soong-gung Je, O. Boulle, G. Gaudin, M.C. Cyrille
Spintec, CEA-Grenoble, France

PHYSICAL REVIEW APPLIED **9**, 064032 (2018)

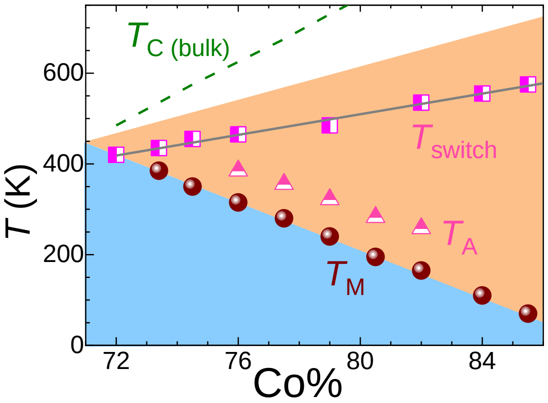
Thermal Contribution to the Spin-Orbit Torque in Metallic-Ferrimagnetic Systems

S.G. Je, JCRS *et al.*, *Appl. Phys. Lett 112, 062401 (2018)*

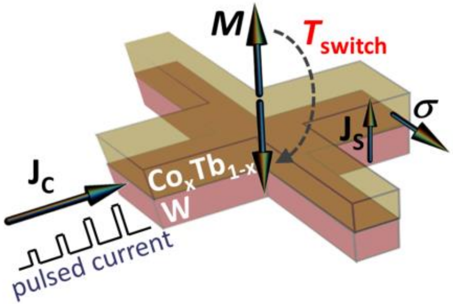
T. H. Pham, JCRS *et al.*, *Phys. Rev. Appl. 9, 064032 (2018)*

Summary First part

W(3nm)/Co_xTb1-x(3.5nm)/AlO_y



- ✓ W/Co_xTb_{1-x}/AlO_y (0.71 ≤ x ≤ 0.86)
- ✓ SOT switching: obtained at different composition and temperature.
- ✓ Important role of temperature: T_{switch}
- ✓ $T_{switch} \propto T_C$
- ✓ $J_{sw} \sim 1 - 3 \times 10^{11} A/m^2$, $min\, H_x = 2\, mT$
- ✓ **Heating is an advantage ➔ Allows to strongly reduce H_x.** Not for Pt/ Co_xTb_{1-x} (checked)

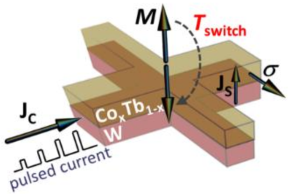


T. H. Pham, JCRS *et al., Phys. Rev. Appl. 9, 064032 (2018)*

Outline

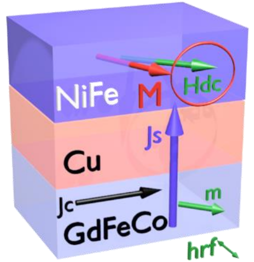
Ferrimagnetic alloys & spintronics

T. H. Pham, JCRS *et al*. Phys. Rev. Applied 11, 054049 (2018)



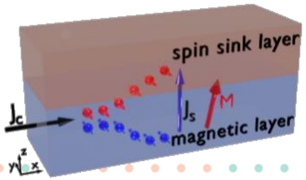
Spin Hall effect (SHE) & Spin Anomalous Hall effect (SAHE)

Héloïse Damas *et al.* PSS RLL (2022) invited https://doi.org/10.1002/pssr.202200035
David Céspedes-Berrocal, H. Damas, *et al.* Advanced Materials (2021)

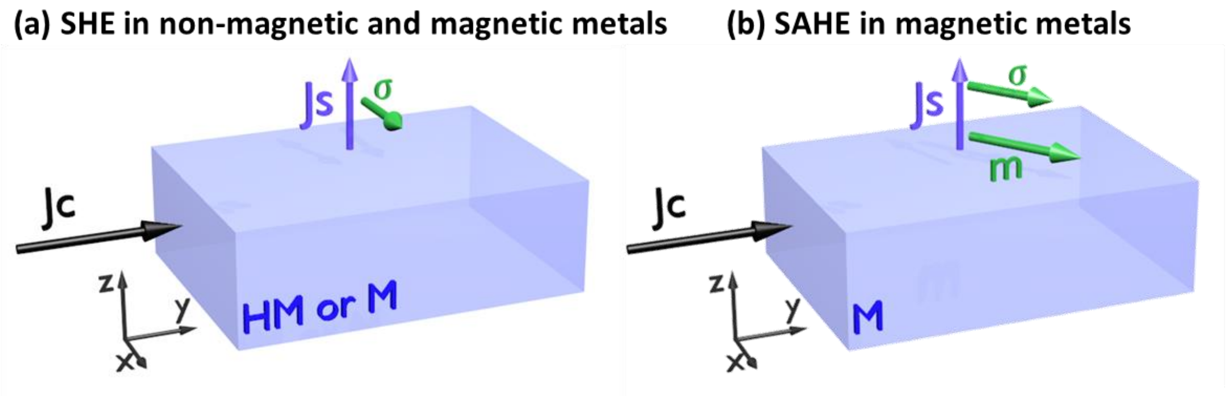


Self-spin-orbit-torques : GdFeCo/Cu

David Céspedes-Berrocal, H. Damas, A. Fert, JCRS *et al.* Advanced Materials (2021)
https://doi.org/10.1002/adma.202007047



Spin Anomalous Hall Effect (SAHE)



Spin current Js along z has a spin polarization **σ** perpendicular to both, Js and Jc

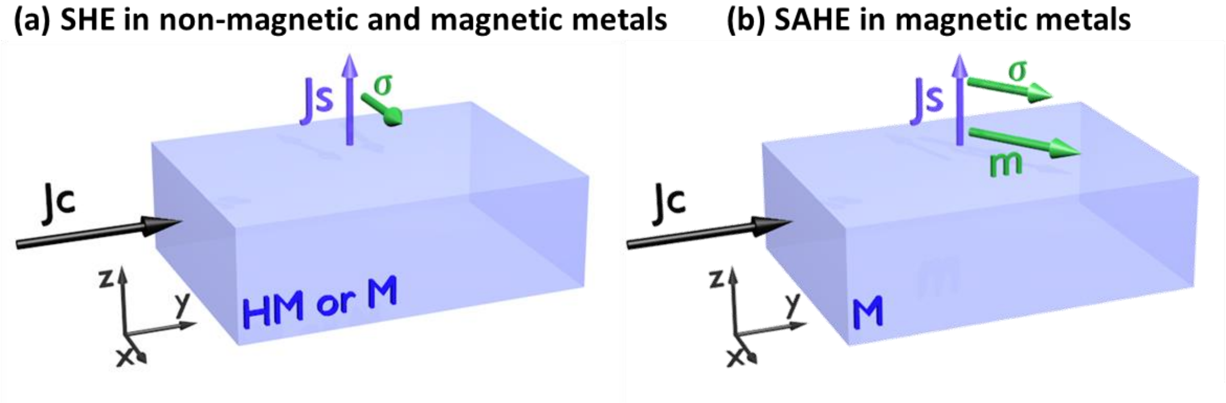
$$\mathbf{J}_s \propto \theta_{\mathrm{SHE}}(\mathbf{J}_\mathbf{c} \times \sigma)$$

Spin current Js along z has a spin polarization **σ** parallel (or antiparallel) to magnetization **m**

$$\mathbf{J}_s \propto \theta_{\mathrm{SAHE}}(\mathbf{J}_\mathbf{c} \times \mathbf{m}) \cdot \mathbf{z}$$

T. Taniguchi, J. Grollier, and M. D. Stiles
"Spin-Transfer Torques Generated by the Anomalous Hall Effect and Anisotropic Magnetoresistance"
Phys Rev Appl. **3**, 044001 (2015).

SAHE-like & SHE-like symmetries in Magnetic materials



Spin current Js along z has a spin polarization σ perpendicular to both, Js and Jc

Spin current Js along z has a spin polarization σ parallel (or antiparallel) to magnetization **m**

More recent papers enhanced theory:
Amin *et al.* PRB **99**, 220405 (2019)
Amin *et al.* PRL **121**, 1136805 (2018)
Amin *et al.* PRB **94**, 104420 (2016)
…
K-W Kim & Kyung-Jin Lee PRL **125**, 207205 (2020)

Spin-currents generation **Js**:
- **SHE-like** (Spin Hall Effect) **σ ⊥ m & Jc**
- **SAHE-like** (Spin Anomalous Hall Effect) **σ || m**

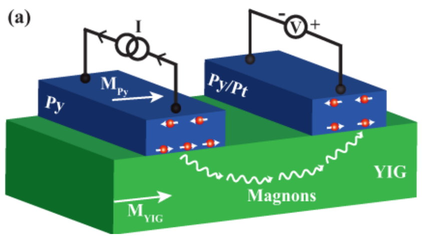
David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Mat. (2021)

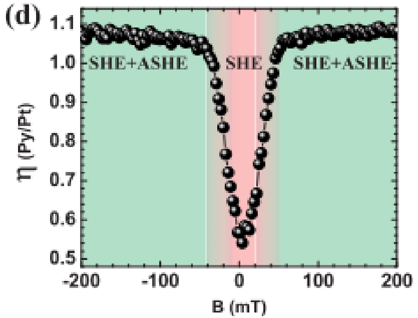
Spin Anomalous Hall Effect (SAHE) in NiFe and CoFeB

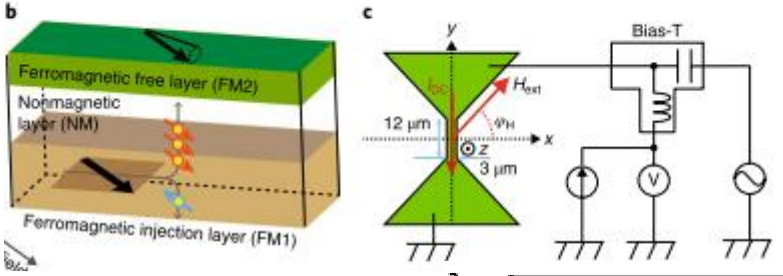
NiFe

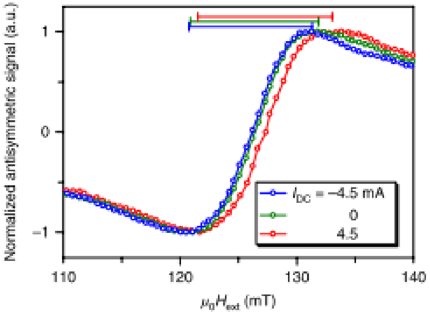
CoFeB

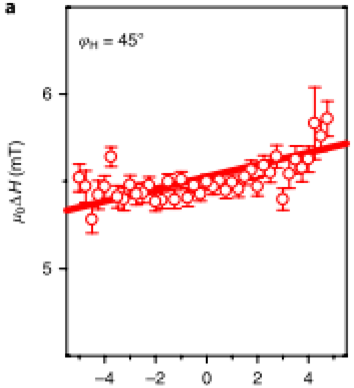
DAS, SCHOEMAKER, VAN WEES, AND VERA-MARUN











Also by ISHE-SP-FMR
Tsukahara et al. PRB **98**, 235317 (2014)

& by Kerr ASOT: Wenrui Wang et al. Nat. Nano **14**, 819 (2019)

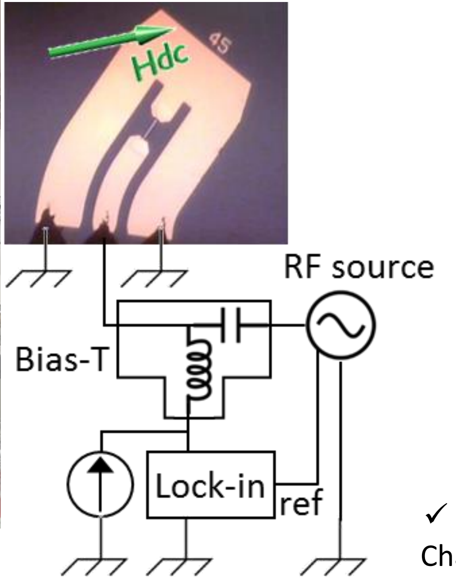
$(\theta_{SAHE} + \theta_{SHE})_{NiFe} \approx \theta_{SHE-Pt}$

$\theta_{SAHE-CoFeB} = 0.14$

K. S. Das, W. Y. Schoemaker, B. J. Van Wees, and I. J. Vera-Marun *Phys. Rev. B* **96**, 1 (2017).

S. Iihama, T. Taniguchi, K. Yakushiji, A. Fukushima, Y. Shiota, S. Tsunegi, R. Hiramatsu, S. Yuasa, Y. Suzuki, and H. Kubota *Nat. Electron.* **1**, 120 (2018)

Spin-torque Ferromagnetic Resonance (ST-FMR) based setup



L. Liu et al. " *Phys. Rev. Lett.* **106**, 036601 (2011).
D. Fang et al. Nat. Nanotechnology **6**, 413 (2011)
K. Kondou et al. *Appl. Phys. Express* **5**, 1 (2012).
…

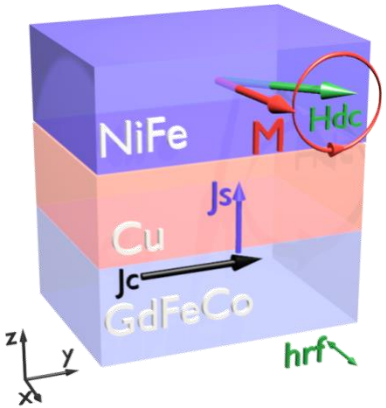
✓ E. Liu *et al.* Phys. Rev. Appl. **12**, 044074 (2019)
Strain-Enhanced Charge-to-Spin Conversion in Multilayers Grown on Flexible Mica Substrate

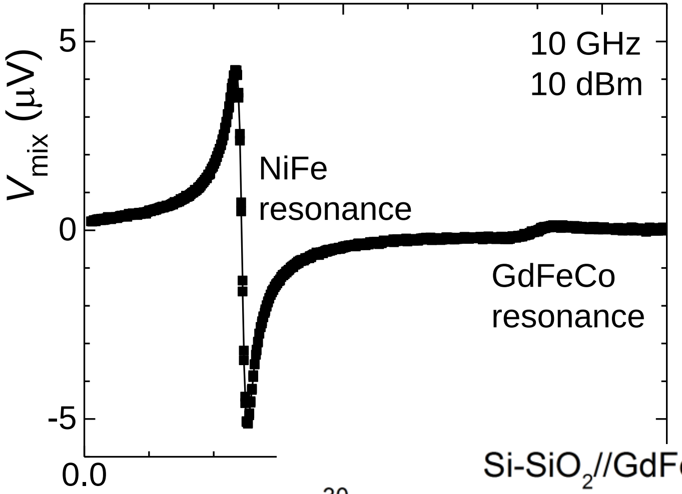
✓ C. Guillemard, *et al*. Appl. Phys. Lett. **113**, 262404 (2018).
Charge-spin current conversion in high quality epitaxial Fe/Pt systems : Isotropic spin Hall angle along different in-plane crystalline directions

✓ H. Saglam *et al*. Phys. Rev. B 98, 094407 (2018)
Independence of SOT from exchange bias anisotropy in NiFe/IrMn

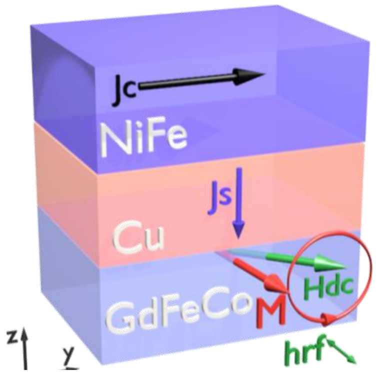
ST-FMR in //GdFeCo/Cu/NiFe

NiFe resonance



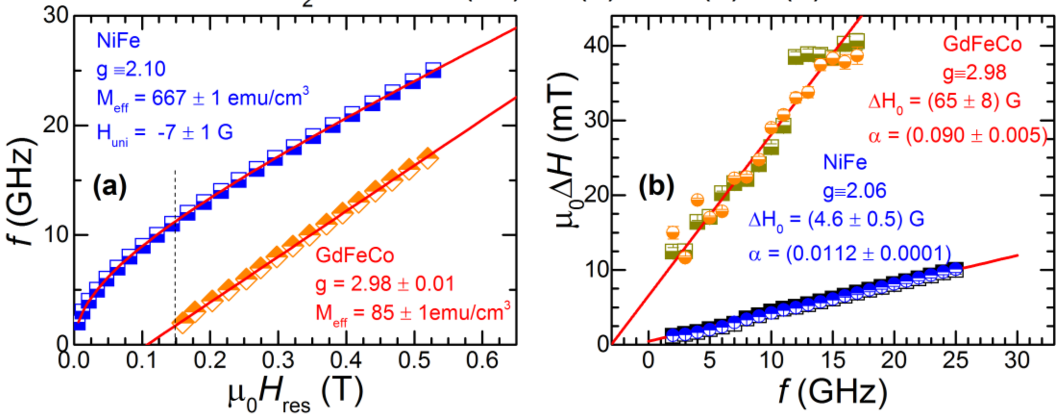


GdFeCo resonance



Si-SiO_2//GdFeCo(10)/Cu(6)/NiFe(4)/Al(3)

David Céspedes-Berrocal

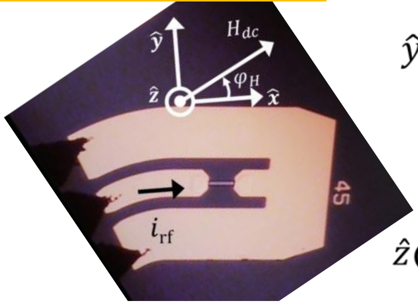


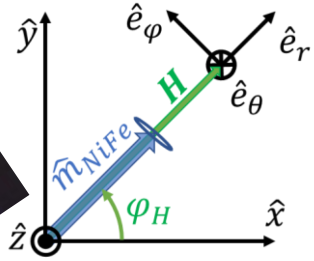
Longitudinal voltage by ST-FMR

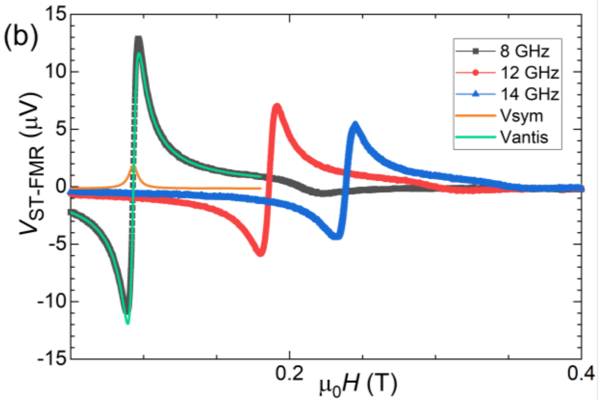
$$V_{dc} = -\frac{\Delta R_{AMR}^{NiFe}}{2}\sin(2\varphi_H) I_{rf}\left(\chi'_{\varphi\theta}\delta h_\theta + \chi'_{\varphi\varphi}\,\delta h_\varphi\right),$$

$$\delta h_\theta = h_{DL}^{SHE}\cos(\varphi_H)$$

$$\delta h_\varphi = \cos(\varphi_H)(h_{Oe} - h_{FL}^{SHE})$$







ΔR_{AMR}^{NiFe} is the anisotropic magnetoresistance amplitude,

$\chi'_{\varphi\theta}$ and $\chi'_{\varphi\varphi}$: real part of $\varphi\theta$ and $\varphi\varphi$ components of the susceptibility matrix of NiFe.

✓ ➔ V_{sym} : contribution from SHE-like

Heloïse DAMAS

https://doi.org/10.1002/pssr.202200035

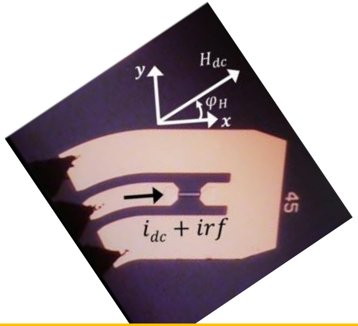
Héloïse Damas et al. PSS RLL 2022

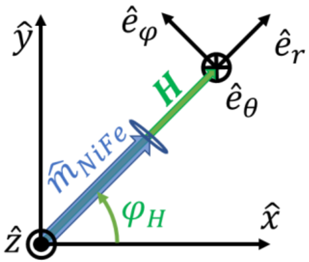
Modulation of Damping: adding i_{dc}

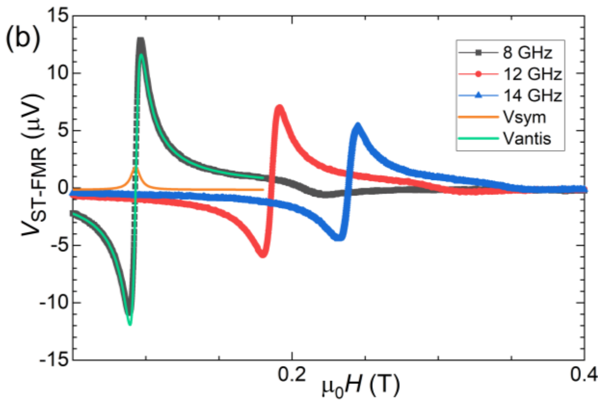
➔ Change in dynamical susceptibility matrix which in turns is related to the effective field along which the magnetization lies

➔ Spin polarizations with a projection along this effective field induce a change in the susceptibility

$$V_{dc} = -\frac{\Delta R_{AMR}^{NiFe}}{2}\sin(2\varphi_H) I_{rf}\left(\chi'_{\varphi\theta}\delta h_\theta + \chi'_{\varphi\varphi}\,\delta h_\varphi\right),$$







$$\frac{\partial \Delta H_{NiFe}}{\partial i_{dc}} = -\frac{f}{\gamma_{NiFe}} \frac{2}{\left(2H_{res}^{NiFe} + M_{eff}^{NiFe}\right)} \frac{S_{GdFeCo}}{W t_{GdFeCo}} \frac{\hbar}{2e} \sin(\varphi_H) \frac{\theta_{DL}^{SAHE} + \theta_{DL}^{SHE}}{\mu_0 M_s^{NiFe} t_{NiFe}}$$

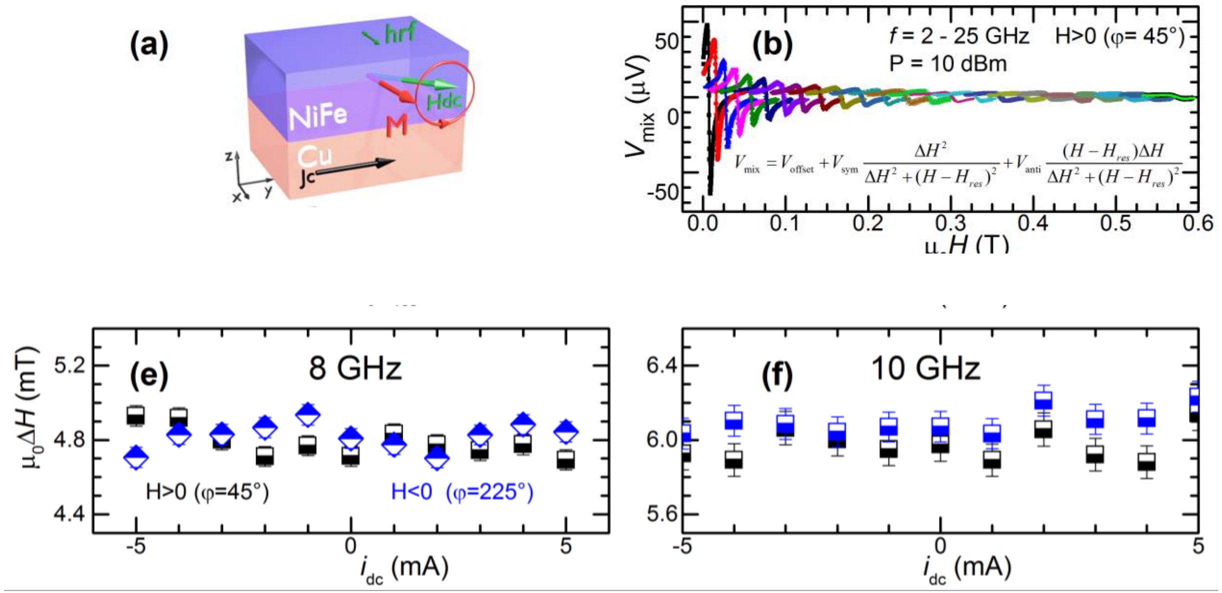
David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Materials (2021)

Héloïse Damas et al. PSS RLL (2022)

✓ ➔ ΔH_{NiFe} : contribution from both $\theta_{DL}^{SAHE} + \theta_{DL}^{SHE}$

Control system: Cu/NiFe

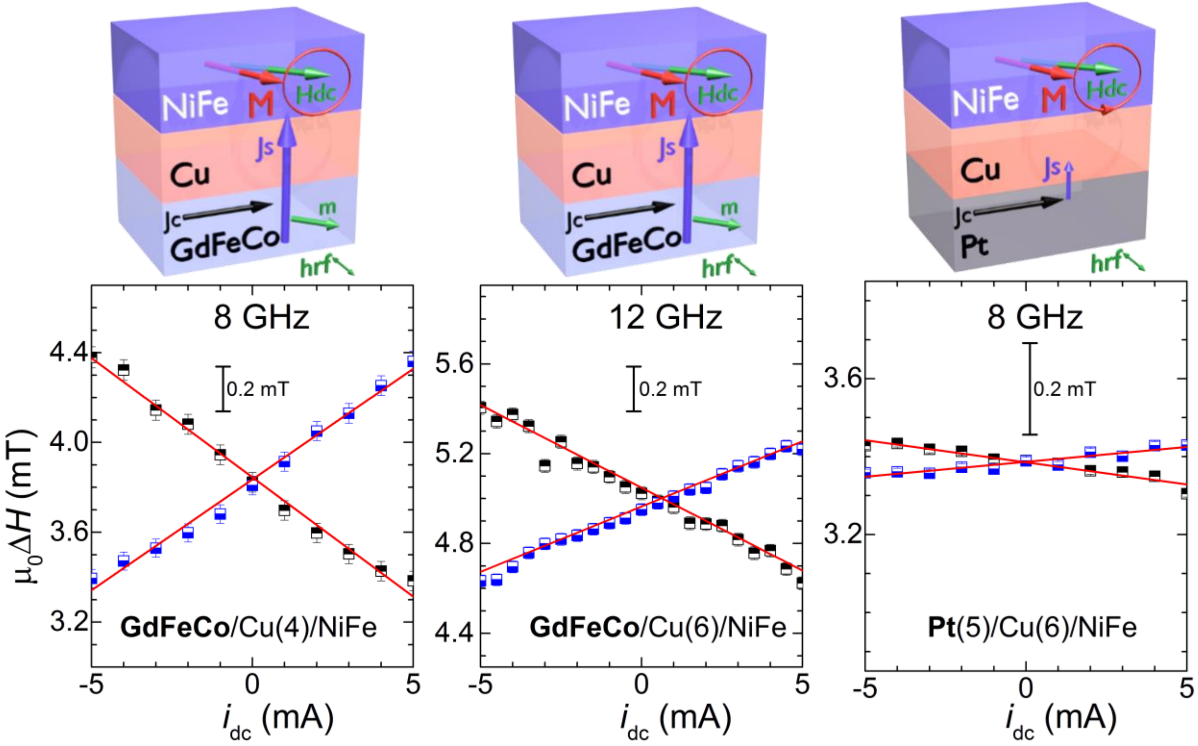
Cu/NiFe



➔No modulation of ΔH in NiFe/Cu

David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Mat. (2021)

Comparison of the spin current production by the eff-(SAHE+SHE) of GdFeCo and the SHE of Pt



$\theta_{SHE+SAHE-\ GdFeCo} \approx 0.8$ $\theta_{SHE+SAHE-\ GdFeCo} \approx 0.7$ $\theta_{SHE-\ Pt} \approx 0.03$

- Clearly Modulation of NiFe linewidth ΔH with a i_{dc} bias
- Reproducibility

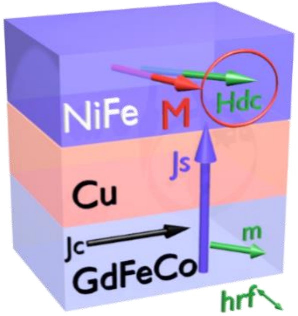
S. Petit et al. Phys. Rev. Lett. **98**, 077203 (2007)
S. Petit et al. Phys. Rev. B **78**, 184420 (2008)
L. Liu et al. " *Phys. Rev. Lett.* **106**, 036601 (2011)
S. Iihama, et al. *Nat. Electron.* **1**, 120 (2018)

GdFeCo/Cu is ~25x more efficient than Pt/Cu

The highest charge-spin current conversion efficiency reported so far (similar method)

David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Mat. (2021)

Contributions in GdFeCo



NiFe (0.005 to 0.053)
Tsukahara et al. PRB **98**, 235317 (2014)
Das *et al. Phys. Rev. B* **96**, 1 (2017)
Wang et al. Nat. Nano **14**, 819 (2019)

CoFeB (0.14) Iihama *et al.* *Nat. Electron.* **1**, 120 (2018)

L10-FePt (0.25)

- → **Overall Effective $\theta_{SHE+SAHE\text{-} GdFeCo} \approx 0.75$ (SAHE-like + SHE-like)**
- → **All come from bulk? Interface contribution?**
- → **Rashba interface? Gd & GdO_x exhibit Rashba splitting**

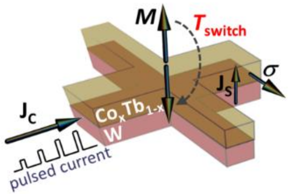
The highest charge-spin current conversion efficiency reported so far (similar method)

David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Mat. (2021)

Outline

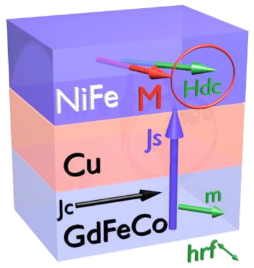
Ferrimagnetic alloys & spintronics

T. H. Pham, JCRS *et al*. Phys. Rev. Applied 11, 054049 (2018)



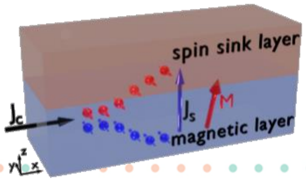
Spin Hall effect (SHE) & Spin Anomalous Hall effect (SAHE)

Héloïse Damas *et al.* PSS RLL (2022) invited https://doi.org/10.1002/pssr.202200035
David Céspedes-Berrocal, H. Damas, *et al.* Advanced Materials (2021)



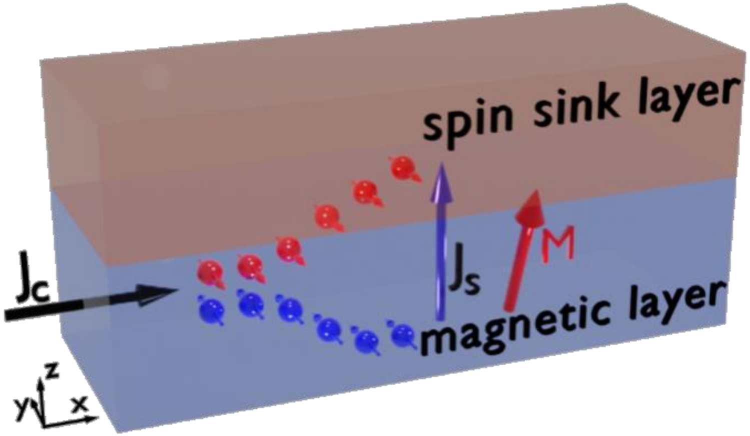
Self-spin-orbit-torques : GdFeCo/Cu

David Céspedes-Berrocal, H. Damas, A. Fert, JCRS *et al.* Advanced Materials (2021)
https://doi.org/10.1002/adma.202007047



Ways to exploit self-induced SOT

David Céspedes-Berrocal, Heloise Damas, A. Fert, JCRS *et al.* Adv. Mat. (2021)



Spin-sink ($t \geq l_{sf}$)

Spin-currents generation Js from bulk and/or interfaces:

- **SHE-like $\sigma \perp m \perp J_c$ self-torque only if absorbed outside**

- **SAHE-like σ || m not self-torque**

Similar conclusions in NM/FM/NM with NM a good spin-sink
C. Safranski, E. A. Montoya, and I. N. Krivorotov., *Nat. Nanotech.* (2019)

Some examples of self-torques

$L1_0$ FePt

Liang Liu et al. PRB **101**, 220402 (R) (2020) — s//TiN(5)/FePt/? (switching)
Meng Tang et al. Adv. Materials **32**, 2002607 (2020) — MgO//FePt(4-20)/? (switching)

CoTb

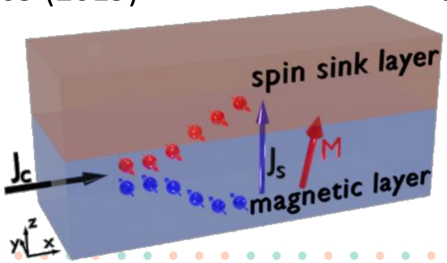
R. Q. Zhang et al. PRB **101**, 214418 (2020) — Si-SiO_2//SiN(3)/CoTb(4-15)/SiN(3) (switching)
Jae Wook Lee et al. PRAppl. **13**, 044030 (2020) — Si-Si_3N_4//Co_xTb_{1-x}(15)/SiN_x(15) (DL and FL by 2w)
Z Zheng et al. Nat. Comm. **12**, 4555 (2021) — //Al/$Co_{0.87-\delta}Tb_{0.13+\delta}$(15)/Al (2w & switching)

GdFeCo/Al

Sachin Krishnia et al. PRAppl. **16**, 024040 (2021) — Si-SiO_2//GdFeCo(*t*)/Al(5) (DL and FL by 2w & XMCD-PEEM)

NiFe

Wenrui Wang et al. Nat. Nano **14**, 819 (2019) — Si-SiO_2//AlO_x(3)/NiFe(40)/AlO_x(3) (SOT by Kerr)
Mohammad Haidar et al. Nat. Commun. **10**, 2362 (2019) — Al_2O_3//NiFe(15)/SiO_2(15) (ST-FMR in nano-constriction)
O. Gladii et al. PRB **100**, 174409 (2019) — Si-SiO_2//X/NiFe/X (T-dependence SP-FMR)



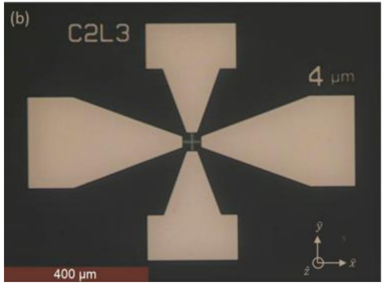
✓ ➔ fulfill the condition of having a good spin sink

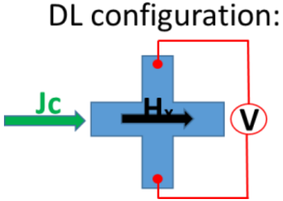
2nd harmonic technique in GdFeCo/Cu : only SHE-symmetry

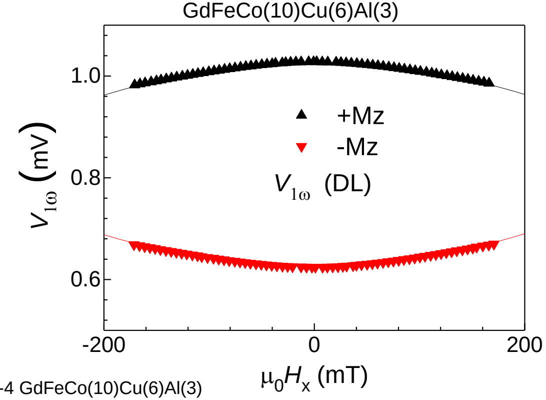
J. Kim, et al. Nat. Mat. **12**, 248 (2012).
K. Garello, et al. Nat. Nano **8**, 587 (2013).
M. Hayashi et al. *Phys. Rev. B* **89**, 144425 (2014).
C. O. Avci et al. *Phys. Rev. B* **89**, 214419 (2014).
K. Ueda et al. *Appl. Phys. Lett.* 108, 232405 (2016)

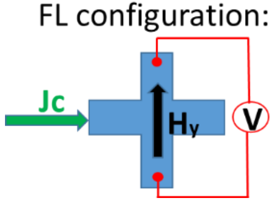
- In the limit of low field & PHE<< AHE:

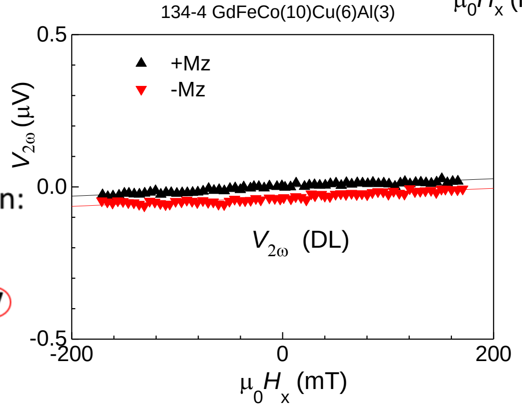
$$H_{FL(DL)} = \left(-2\frac{dV_{2\omega}}{dH_{x(y)}}\right) / \left(\frac{d^2V_{\omega}}{dH^2_{x(y)}}\right)$$

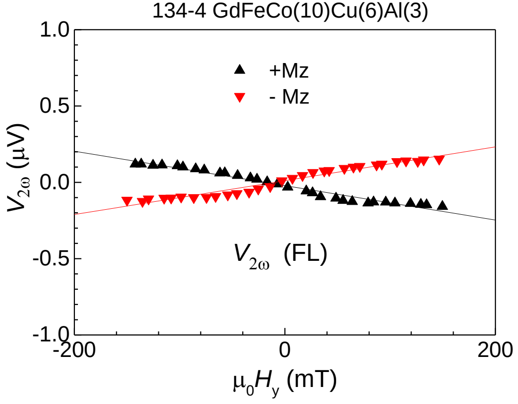








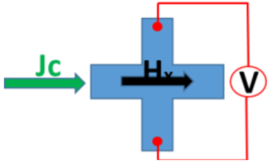




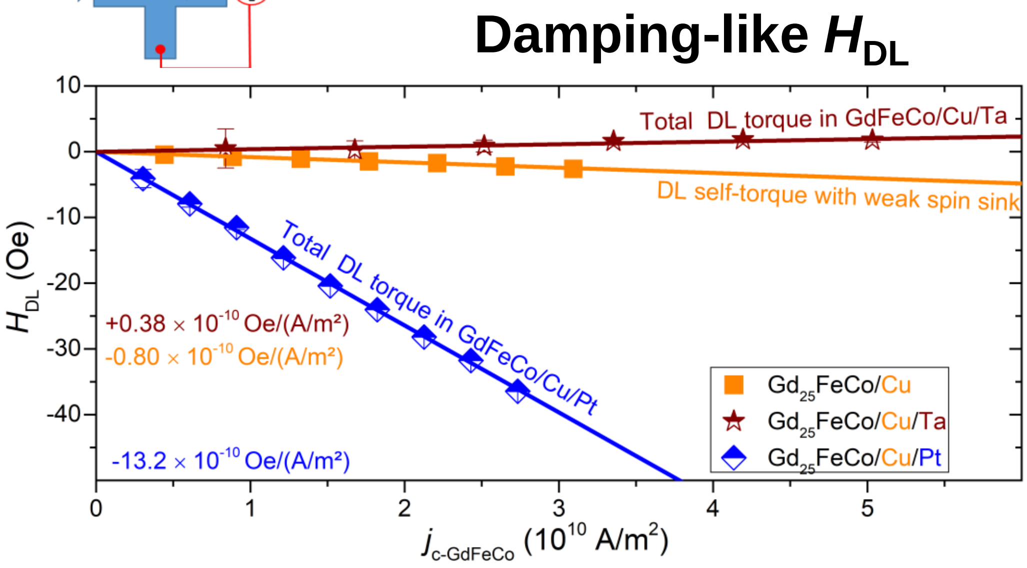
David Céspedes-Berrocal, Heloise Damas, SPW, A. Fert, JCRS *et al.* Adv. Mat. (2021)

DL in GdFeCo/Cu and GdFeCo/Cu/Pt (Ta)

DL configuration:



Damping-like torque from SHE-like spin current emission by (interface + bulk) contributions

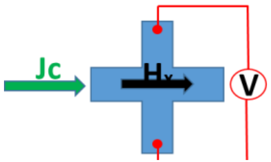


- Small DL with only Cu (spin current is not absorbed but reflected)
- Large DL torque in trilayers with:
- Addition of self (GdFeCo) + SHE of Pt
- Substraction of self (GdFeCo) and SHE of Ta

David Céspedes-Berrocal, Heloise Damas, SPW, A. Fert, JCRS *et al.* Adv. Mat. (2021)

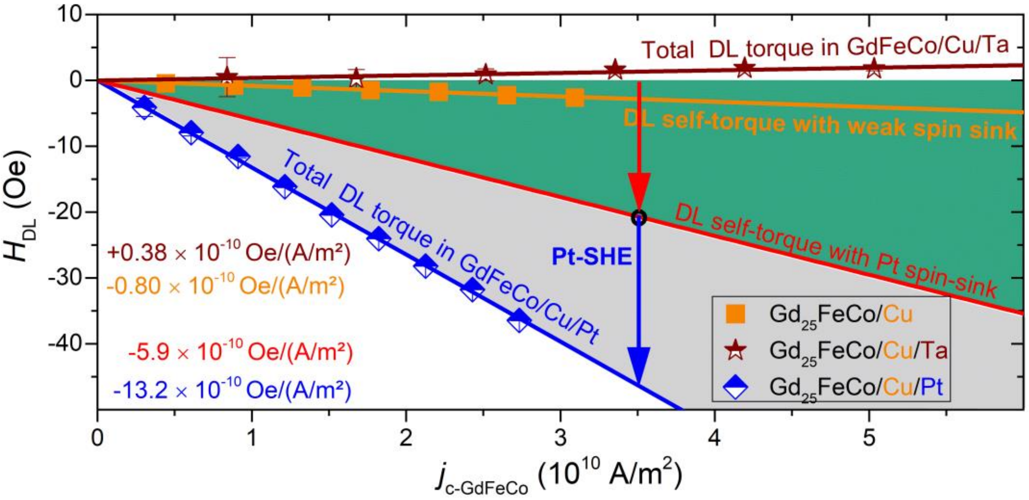
DL in GdFeCo/Cu and GdFeCo/Cu/Pt (Ta)

DL configuration:



Damping-like torque from SHE-like spin current emission by (interface + bulk) contributions

Damping-like H_{DL}



The self-induced spin currents emitted by GdFeCo are efficiently absorbed by the "spin sinks" Pt:

$H_{DL}(GdFeCo/Cu/Pt) = H_{DL}(self) + H_{DL}(Pt\text{-}SHE)$

$$\frac{H_{DL}(Pt-SHE)}{j_c(GdFeCo)} = -\frac{\hbar}{2e}\frac{\theta^{Pt}_{SHE}}{\mu_0 M_s t_F}\frac{j_c(Pt)}{j_c(GdFeCo)}$$

$\theta_{SHE\text{-}Pt} \approx 0.03$

$H_{DL}(GdFeCo/Cu/Pt)/j_c(GdFeCo) = -13.2 \times 10^{-10}$ Oe m²/A

$H_{DL}(Pt\text{-}SHE)/j_c(GdFeCo) = -7.3 \times 10^{-10}$ Oe m²/A

$H_{DL}(self)/j_c(GdFeCo) = -5.9 \times 10^{-10}$ Oe m²/A

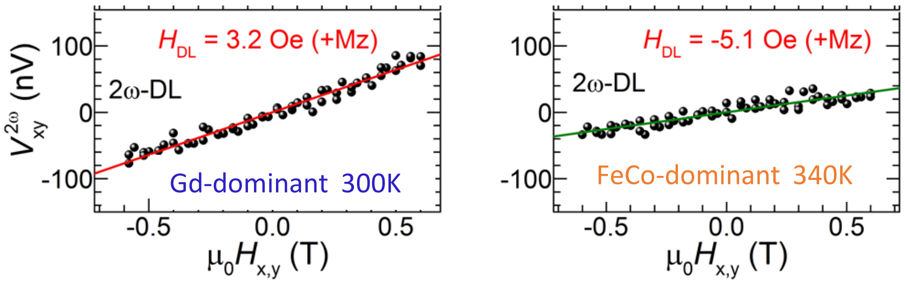
Only SHE-like contribution

David Céspedes-Berrocal, Heloise Damas, SPW, A. Fert, JCRS *et al.* Adv. Mat. (2021)

Signatures for external SOT vs. self-torque : h_{DL}

Self-SOT H_{DL}

GdFeCo(10)/Cu(2)/AlOx



$$h_{DL} \propto (\sigma \times m)$$

We have anticipated:

- $h_{DL(FL)}$ changes sign at T_M and again at T_A (**L** & **M** are || between T_M and T_A)
- ➔SOT-switching polarity keep the same sign according to h_{DL} ??

D. Céspedes-Berrocal, H. Damas *et al.* Adv. Mat. (2021)

External SOT H_{DL}

≠

Mishra et al., PRL (2017) (Pt/CoGd)

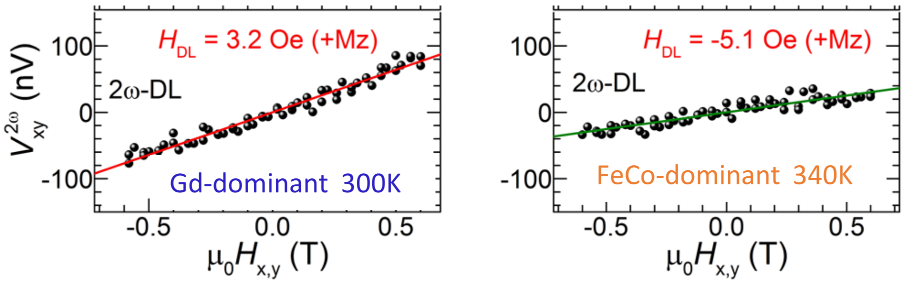
Kawakami et al., Jap. Journal of App. Phy. (2019) (Ta/GdFeCo)

Roschewsky et al., APL (2016) (Ta/GdFeCo)

Signatures for external SOT vs. self-torque : h_{DL}

Self-SOT H_{DL}

GdFeCo(10)/Cu(2)/AlOx



$$h_{DL} \propto (\sigma \times m)$$

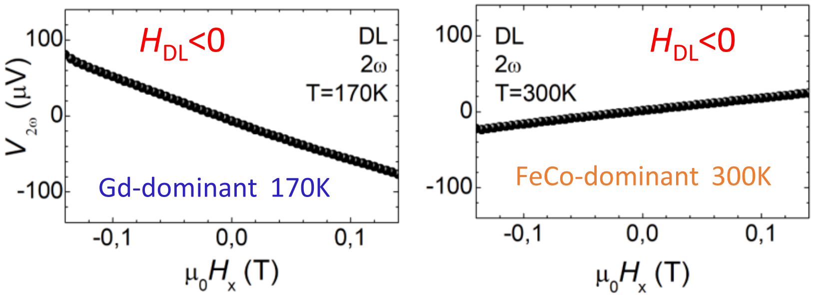
We have anticipated:

- $h_{DL(FL)}$ changes sign at T_M and again at T_A (**L** & **M** are || between T_M and T_A)
- ➔SOT-switching polarity keep the same sign according to h_{DL} ??

D. Céspedes-Berrocal, H. Damas *et al.* Adv. Mat. (2021)

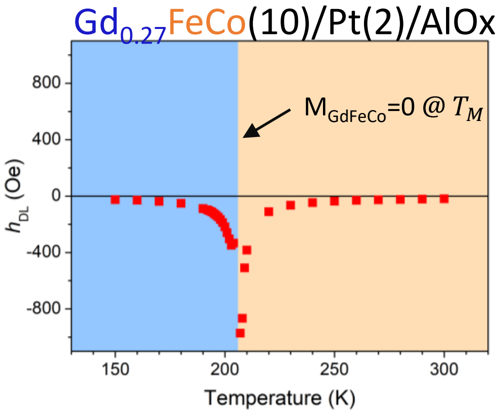
External SOT H_{DL}

GdFeCo(10)/Pt(2)/AlOx

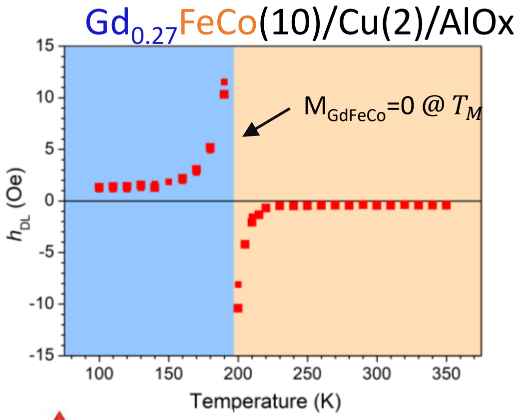


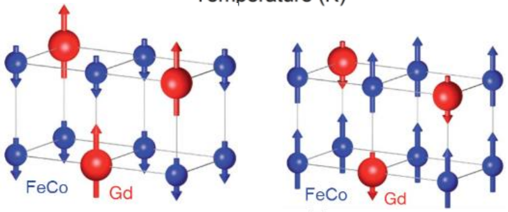
Signatures for external SOT vs. self-torque : h_{DL}

External SOT H_{DL}



Self-SOT H_{DL}





$$h_{DL} \propto (\sigma \times m)$$

We have anticipated:

- $h_{DL(FL)}$ changes sign at T_M and again at T_A (**L** & **M** are || between T_M and T_A)
- ➔SOT-switching polarity keep the same sign according to h_{DL} ??

D. Céspedes-Berrocal, H. Damas *et al.* Adv. Mat. (2021)

Roschewsky et al. *Appl. Phys. Lett.* ***109****, 112403 (2016)*
Finley & Liu Phys. Rev. Appl. ***6****, 054001 (2016)*
Mishra et al., PRL (2017)
Kawakami et al., Jap. Journal of App. Phy. (2019)
Je et al., APL (2018) in our W/CoTb (unpublished by 2f)

Reviews:
Finley & Liu APL (2020)
Barker & Atxitia JPSP (2021)
Kim et al. Nat. Mat. (2022)

More recently in FeTb: Q. Liu et al. Appl. Phys. Rev **9**, 021402 (2022)

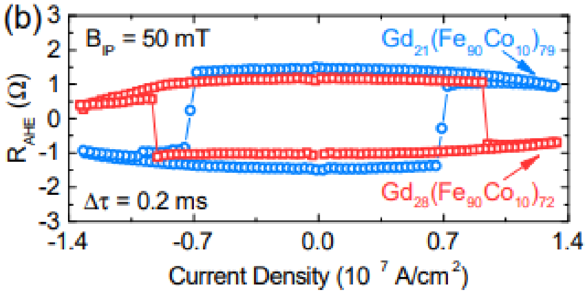
Heloise Damas et al., Unpublished

External SOT vs. self-torque : *SOT polarity ?*

Heloïse DAMAS

External SOT H_{DL}

Switching in Ta/GdFeCo



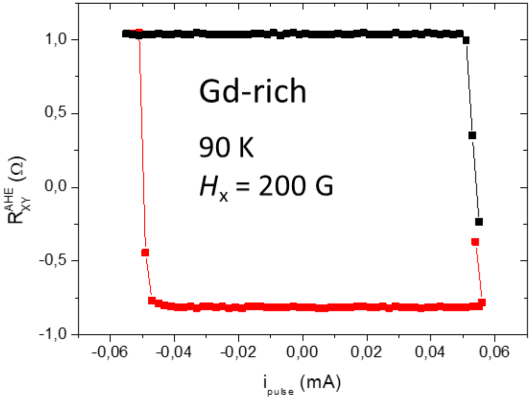
Inversion of the cycle polarity with the compensation point

Roschewsky et al. *Appl. Phys. Lett.* ***109****, 112403 (2016)*

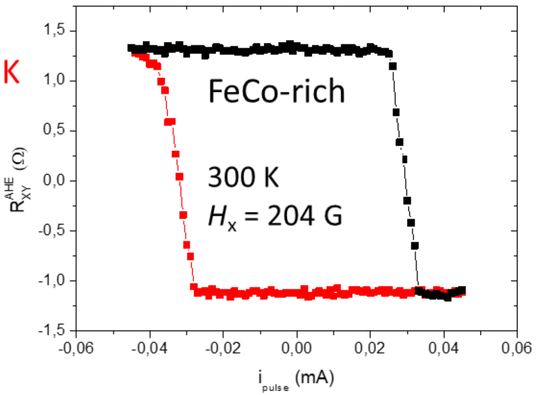
Reviews external SOT in FiM:
Finley & Liu APL (2020)
Barker & Atxitia JPSP (2021)
Kim et al. Nat. Mat. (2022)

Self-SOT H_{DL}

GdFeCo(10)/Cu(3)/spin-sink/AlOx



T_{MC}~140 K



We verified:

- $H_{DL(FL)}$ changes at T_M (and again at T_A)
- SOT-switching polarity keep the same sign according to H_{DL} (in progress)

Heloise Damas et al., Unpublished

International Spintronics Workshop
Spin Argentina 2022 6-11 Nov

https://fisica.cab.cnea.gov.ar/spin2022/

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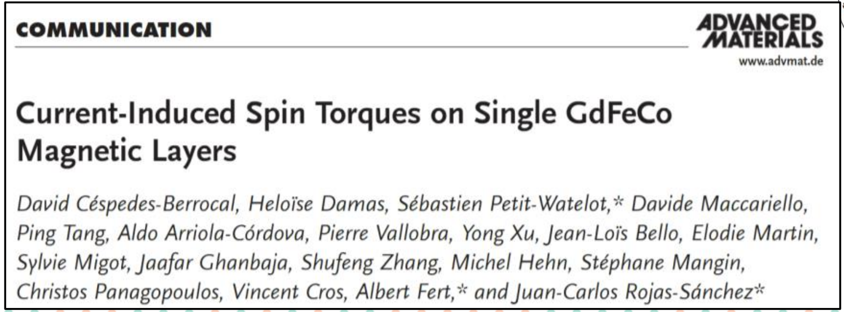

COMMUNICATION — ADVANCED MATERIALS — www.advmat.de

Current-Induced Spin Torques on Single GdFeCo Magnetic Layers

David Céspedes-Berrocal, Heloïse Damas, Sébastien Petit-Watelot, Davide Maccariello, Ping Tang, Aldo Arriola-Córdova, Pierre Vallobra, Yong Xu, Jean-Loïs Bello, Elodie Martin, Sylvie Migot, Jaafar Ghanbaja, Shufeng Zhang, Michel Hehn, Stéphane Mangin, Christos Panagopoulos, Vincent Cros, Albert Fert,* and Juan-Carlos Rojas-Sánchez**

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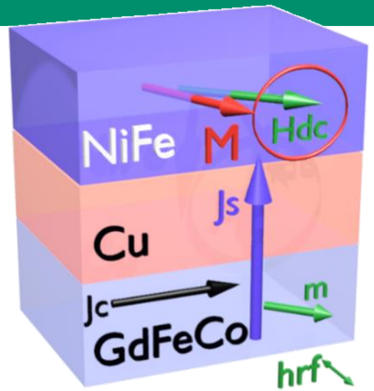
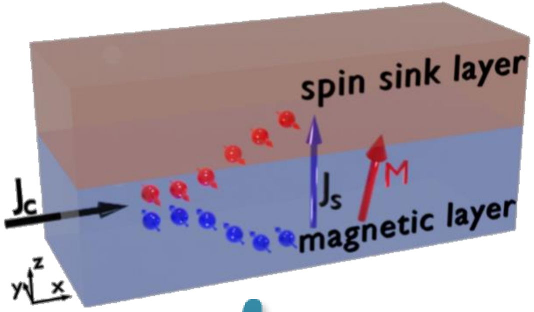
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR — ANR

Summary second part



- ✓ Giant **effective** overall SAHE+SHE angle
  ~0.75 in GdFeCo (Gd-rich) *vs.* **~0.03 in Pt**
- ✓ SAHE-like (**0.59**) and SHE-like (**0.16**)
- ✓ **Large DL self-torque** induced by GdFeCo layer on its own magnetization if right conditions for no spin current reflection
- ✓ **Perspectives:** switching without external heavy metal (self-torque), DMI production, skyrmions motion.



Current-induced spin torques on single GdFeCo magnetic layers
Advanced Materials (2021) https://doi.org/10.1002/adma.202007047

Ferrimagnet GdFeCo Characterization for Spin-Orbitronics: Large Field-Like and Damping-Like Torques
PSS RLL (2022) invited https://doi.org/10.1002/pssr.202200035

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Thank you!