SWISS CONTRIBUTION

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NANOSPIN

Temperature dependency of Spin Hall Effect in Ta/CoFeB systems

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Presentation outline

1. Spin Hall effect (SHE) - short introduction

2. Sample structure (Ta/CoFeB) and characterization
   a. Structural properties and resistivity
   b. Magnetic properties and Dead Layer

3. Spin Hall effect: harmonic voltage measurement

4. SHE in Ta/CoFeB with perpendicular anisotropy

Short summary I

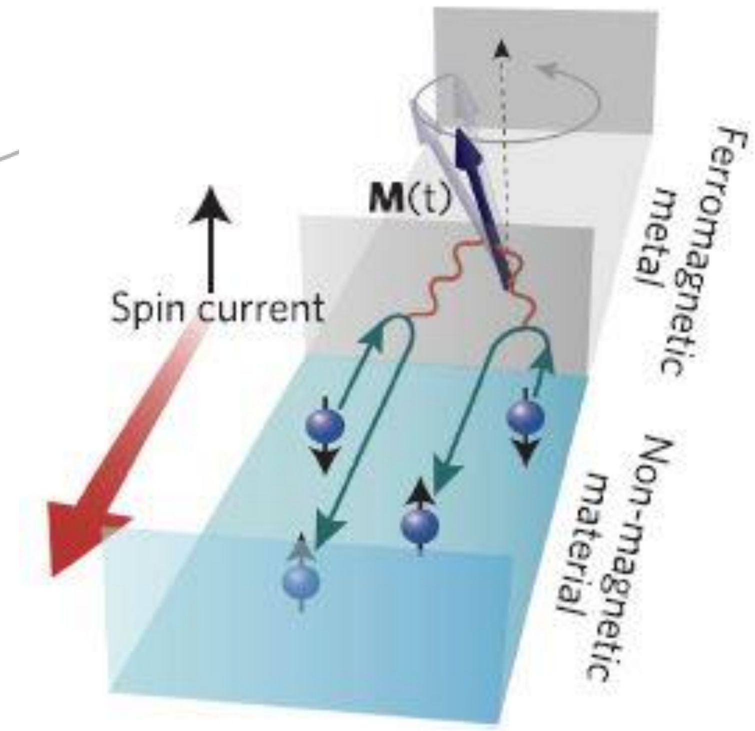
5. Sample structure and SHE in W/CoFeB with perpendicular anisotropy

Short summary II

6. SHE in structures with in-plane anisotropy

Short summary III

Spin Hall effect



K. Ando, et al.,
J. Appl. Phys. 109, 103913 (2011)

- Spin polarized current in a nonmagnetic metal due to spin-orbit interacions
- High spin Hall angle in Ta, W, Pt, CuIr, BiSe

Topological insulators

SHE induced by iridium impurities in copper

Key parameters:

Spin Hall angle θ_{SH} is a spin current density to charge current ratio:

$$\theta_{SH} = \left(\frac{\hbar J_s / 2e}{J_e} \right)$$

Spin diffusion length λ is the mean distance that electrons diffuse between spin-flipping collisions.

Spin Hall effect

L. Liu et al. *Science* 336, 555 (2012)
Ta 8 nm/CoFeB 4 nm: θ_{SH} = 0.15; ρ = 190 [μΩ·cm]
Ta 4 nm/CoFeB 1 nm: θ_{SH} = 0.12

Q. Hao Phys. Rev. B 91, 224413 (2015)
Ta 4 nm/ CoFeB 1 nm: θ_{SH} = 0.11; ρ = 200 [μΩ·cm]

C. Zhang et al. Appl. Phys. Lett. 103, 262407 (2013)
Ta 2.5 nm/ CoFeB 1 nm: θ_{SH} = 0.03; ρ = [μΩ·cm

Allen et al. Phys. Rev. B 91, 144412 (2015)
Ta 1-8 nm/ CoFeB 4 nm: θ_{SH} = 0.11; ρ = 185 [μΩ·cm]

Avci et al. Phys. Rev. B 89, 214419 (2014)
Ta 1-8 nm/ CoFeB 4 nm: θ_{SH} = 0.08; ρ = 185 [μΩ·cm]

Spin diffusion lenght: λTa =1.2 nm ~ 2.5 nm
Kwon et al. APL 107, 022401 (2015); Allen et al. PRB **91**, 144412 (2015)

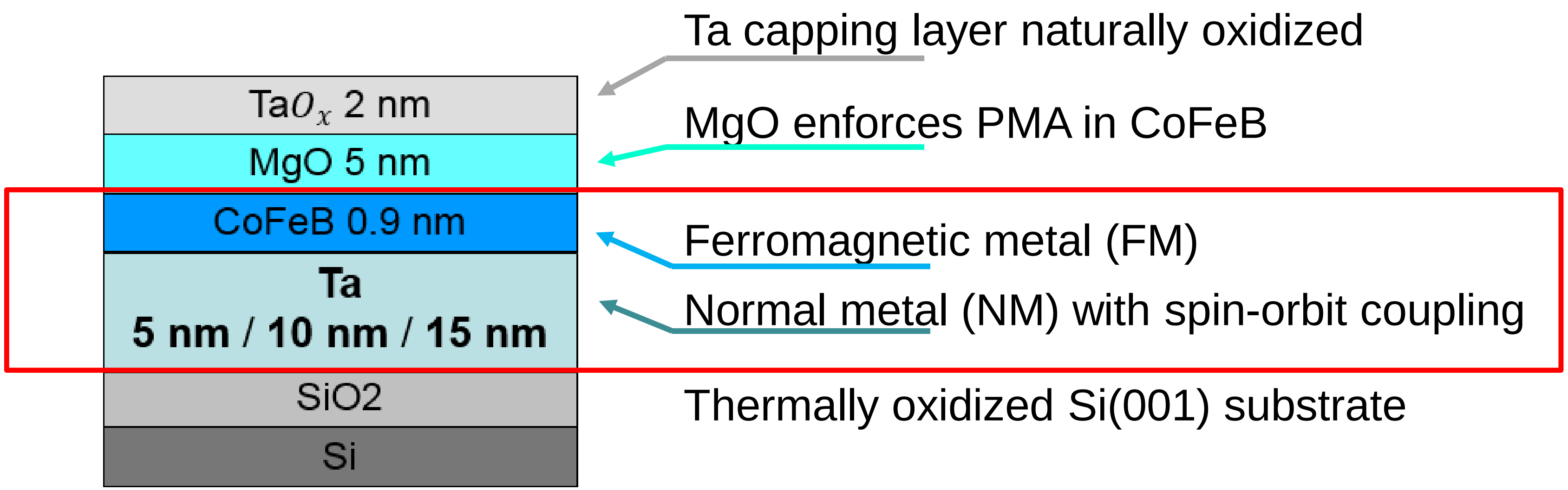
Aim:
- Explain literatures discrepancy
- Investigate an influence of the microstructure
- Examine the interface between normal metal and ferromagnet

Samples structure

Annealed in 330˚C for 20min:

d Ta / 0.91 CoFeB / 5 MgO / TaO_x

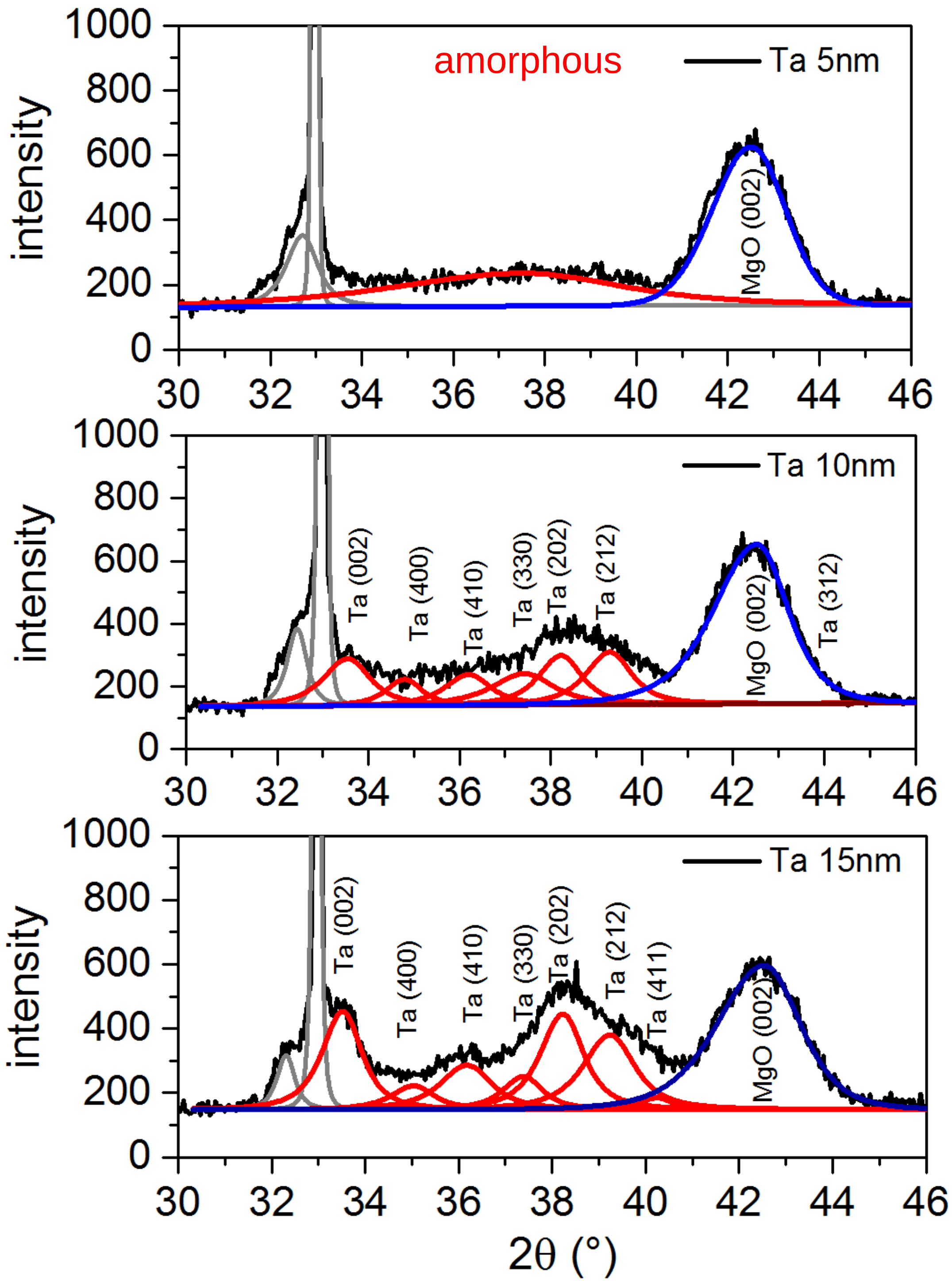
d Ta = 5 nm, 10 nm, 15 nm



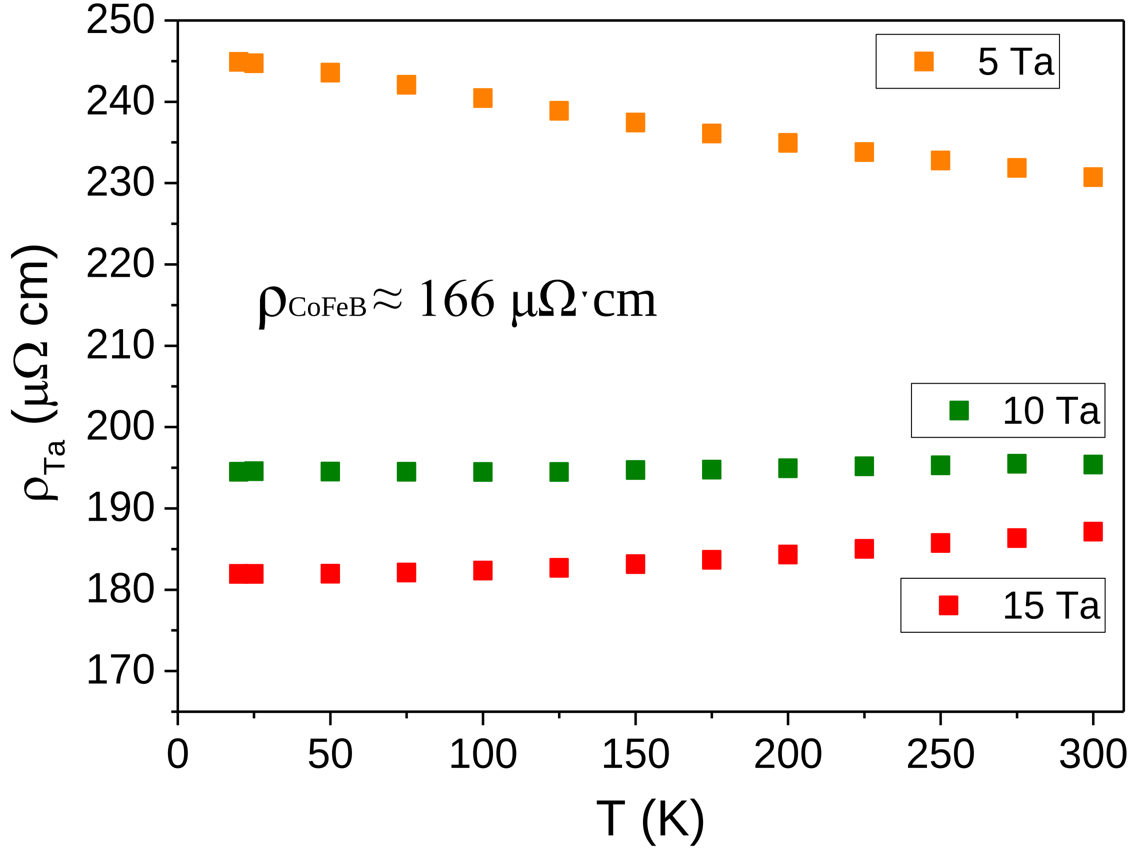
Deposited using sputtering method in Singulus Timaris PVD Cluster Tool System

PMA – perpendicular magnetic anisotropy

Structural properties and resistivity



d Ta/ 0.9 CoFeB/ 5 MgO/ TaO_x (AN)
d = 5 nm, 10 nm, 15 nm



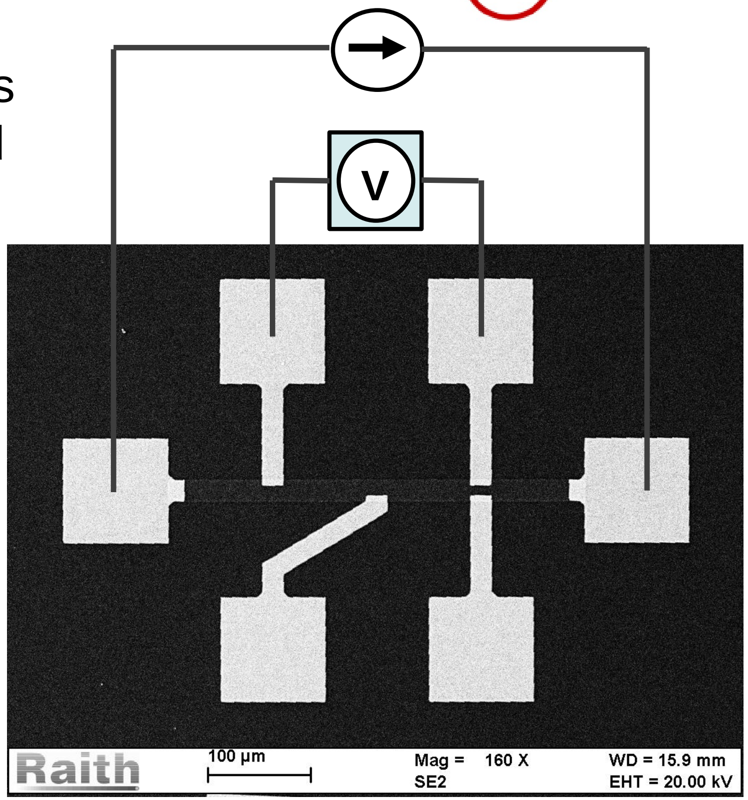
Absence of α-tantalum phase

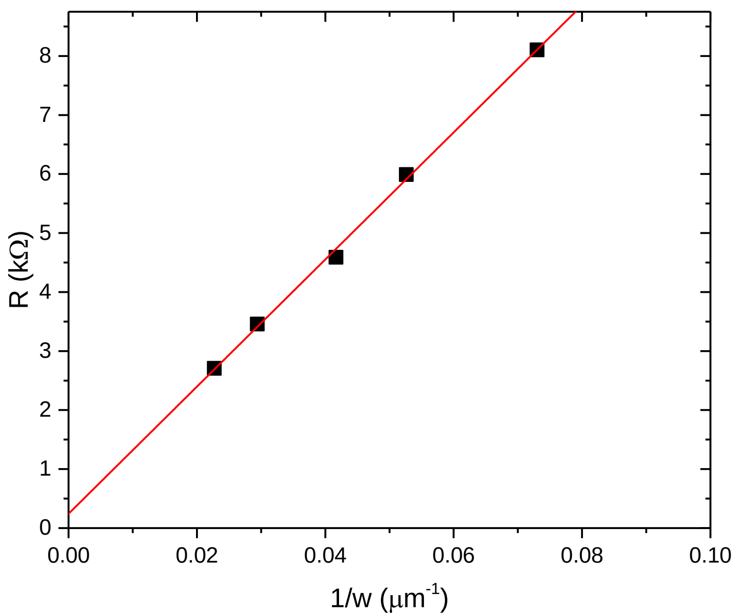
- High resistivity (100–200μΩcm) β-tantalum
- Amorphous films (>200 μΩcm)

[Stella et al. Appl. Phys. **42,** 135417 (2009)]

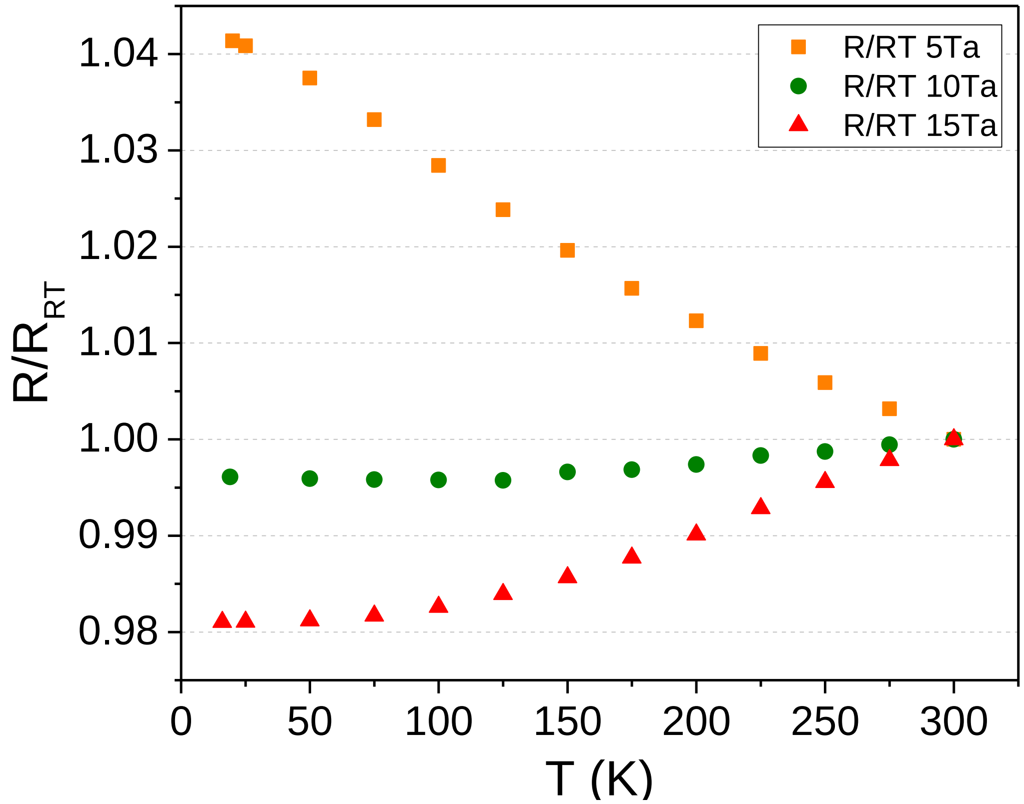
Structural properties and resistivity

4-points method





d Ta/ 0.9 CoFeB/ 5 MgO/ TaO_x (AN)
d = 5 nm, 10 nm, 15 nm

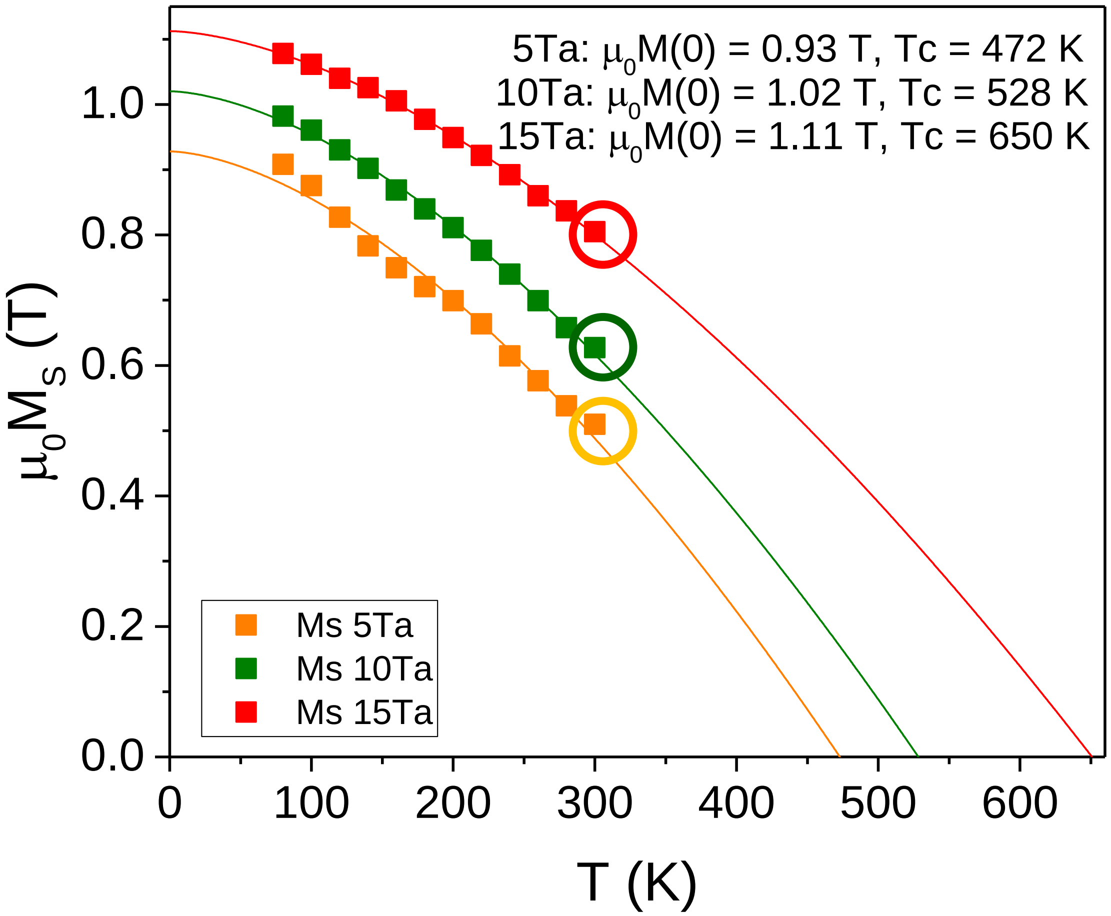


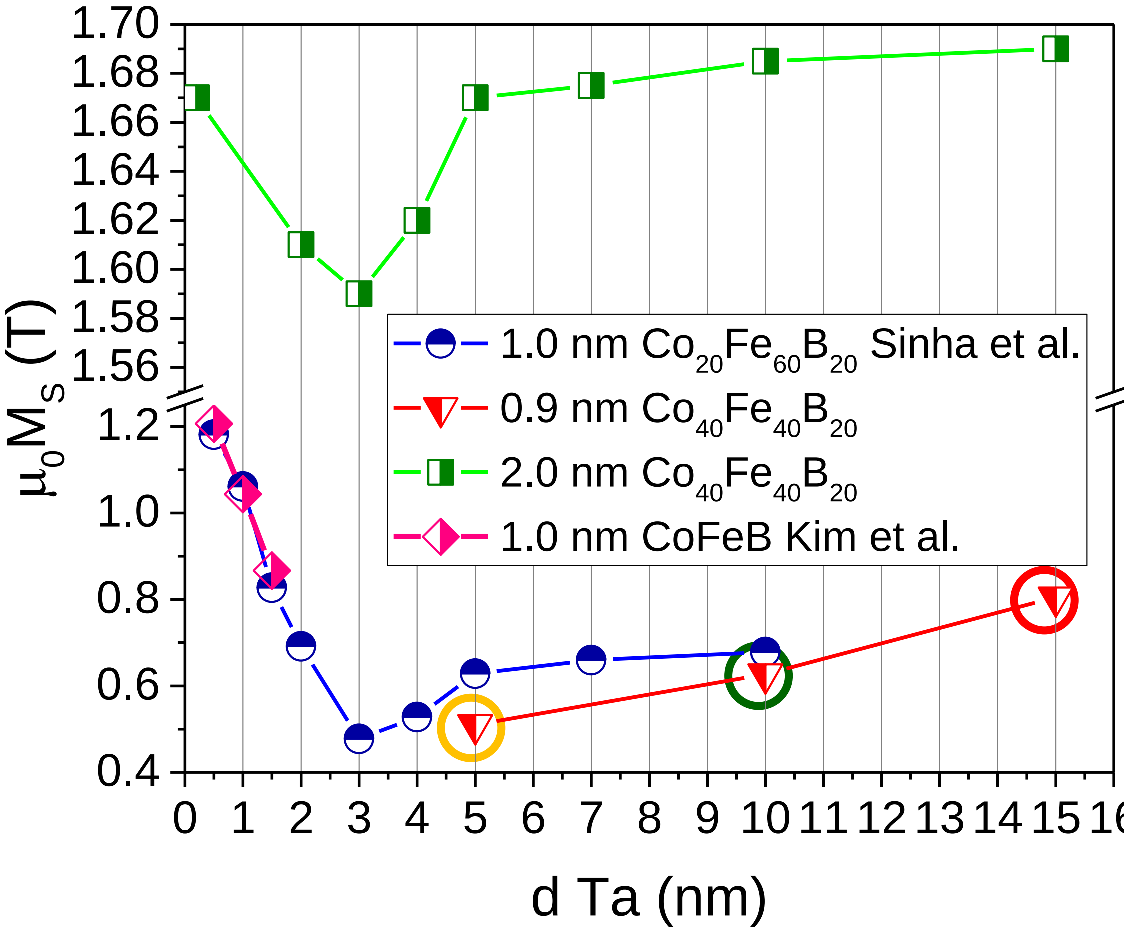
Absence of α-tantalum phase

- High resistivity (100–200µΩcm) β-tantalum
- Amorphous films (>200 µΩcm)

[Stella et al. Appl. Phys. **42,** 135417 (2009)]

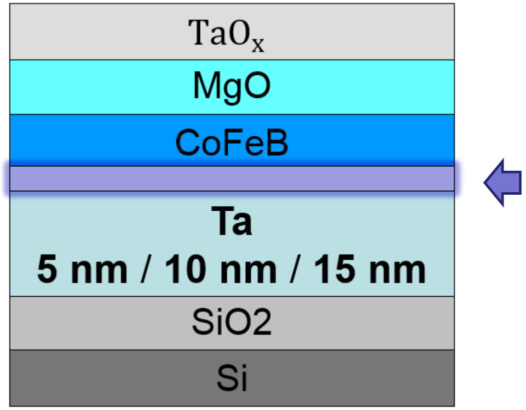
Magnetic properties





Bloch law: $\mu_0M_S= M_0(1-(T/Tc)^{3/2})$

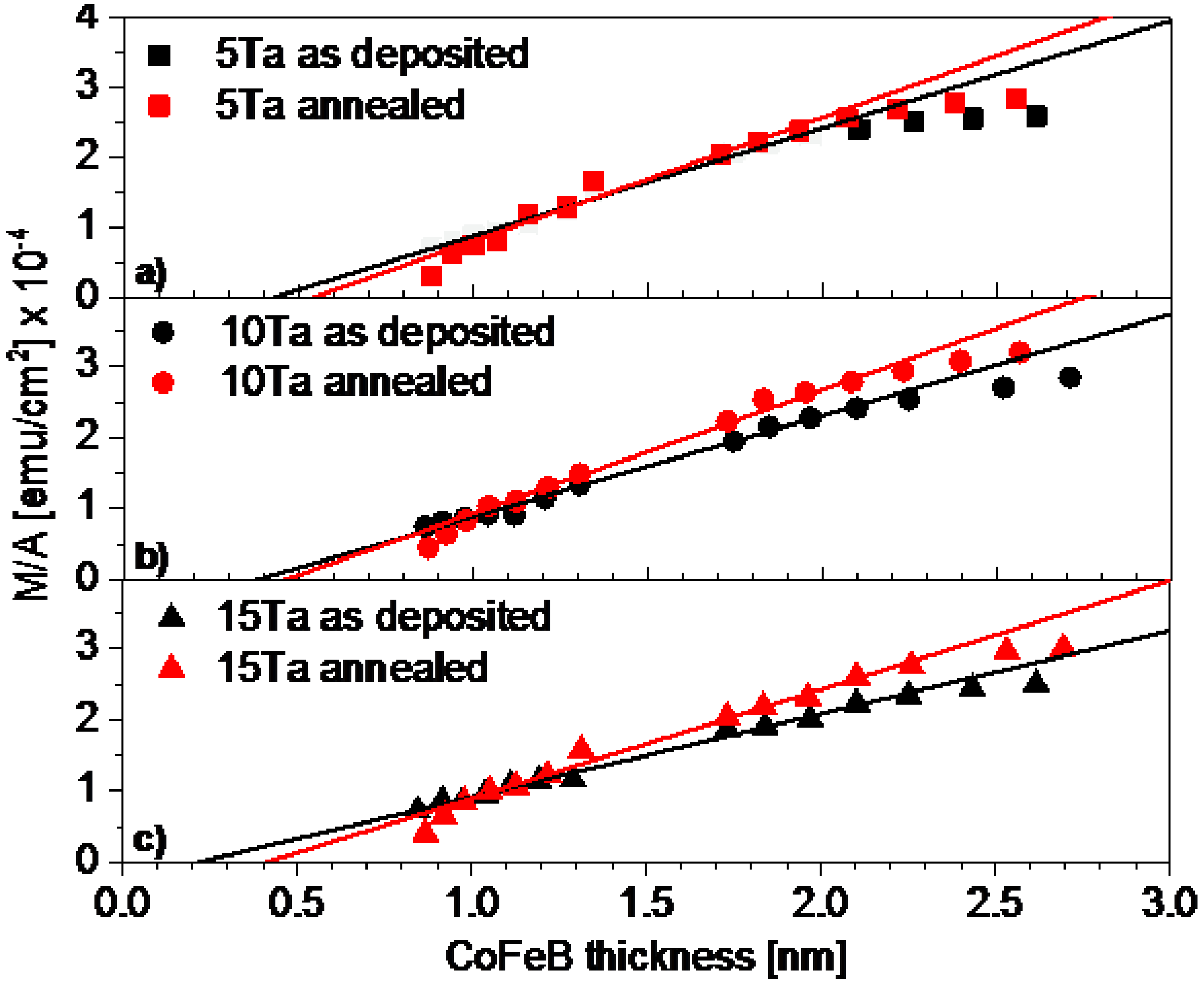
J. Sinha et al. Appl. Phys. Lett. **102**, 242405 (2013) J. Kim et al. PRB **89**, 174424 (2014)



Additional interfacial layer

Magnetic dead layer for T = 300 K

	5 nm Ta	10 nm Ta	15 nm Ta
AD [nm]	0.43 (±0.03)	0.39 (±0.04)	0.22 (±0.03)
AN [nm]	0.52 (±0.05)	0.50 (±0.04)	0.40 (±0.03)



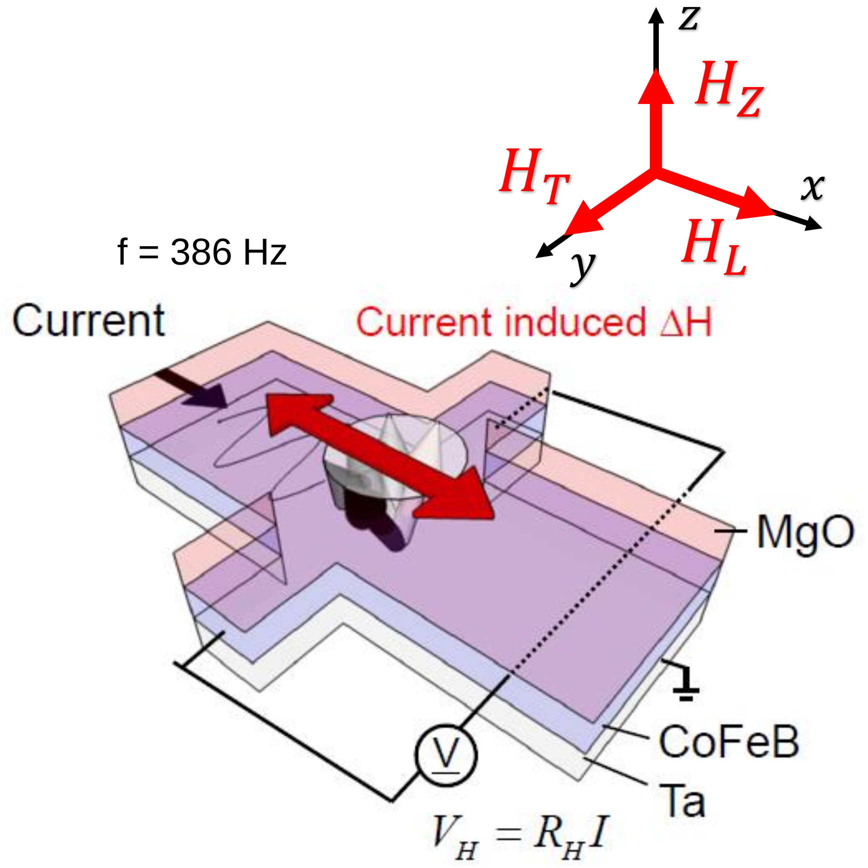
Nominal CoFeB thickness t_{CoFeB} = 0.9 nm, PMA after annealing

Harmonic Hall voltage measurement

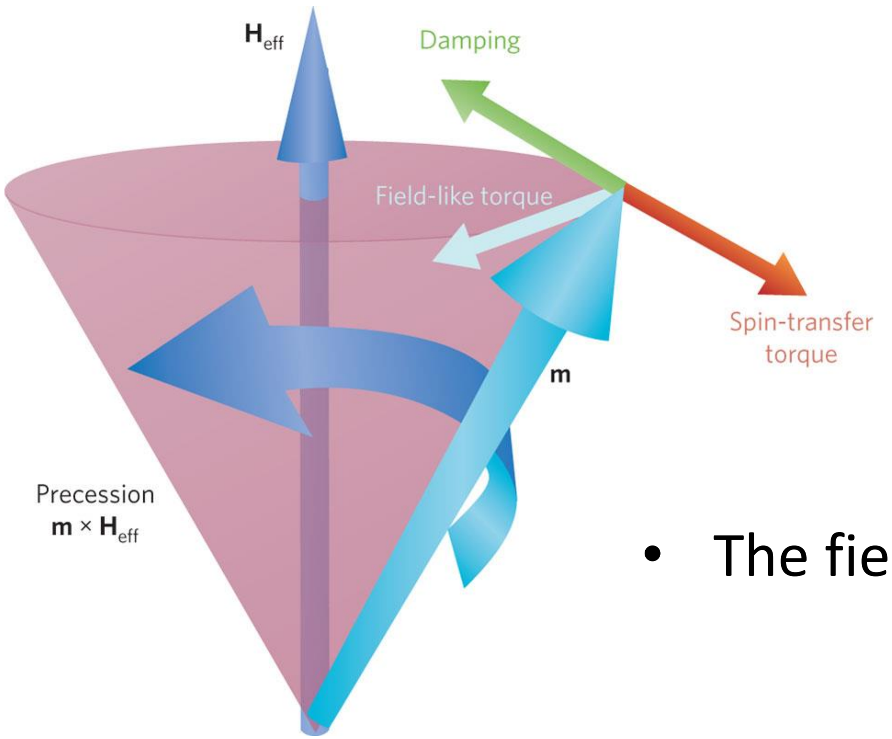
Lock-in amplifier detection:
modulation of the input signal

Longitudinal and transverse effective fields:

$$\Delta H_{L,T} = -2\frac{\partial V_{2\omega}/\partial H_{L,T}}{\partial^2 V_{\omega}/\partial H_{L,T}^2} \qquad \Delta R_P/\Delta R_A \ll 1$$



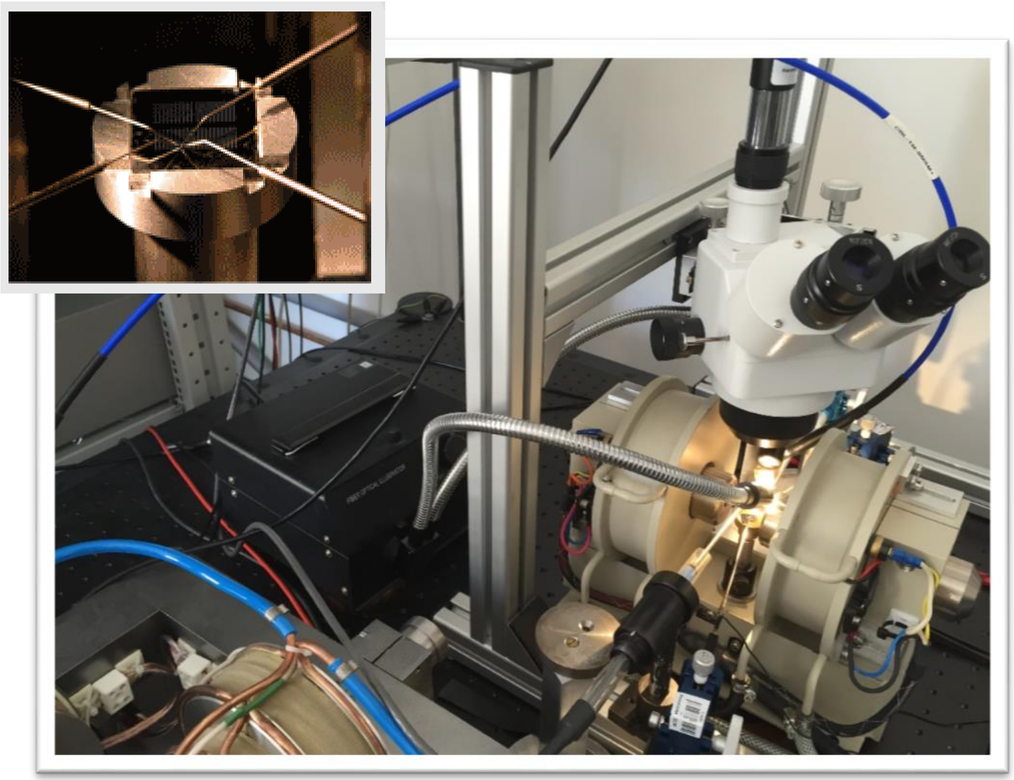
J. Kim et al. PRB **89**, 174424 (2014)

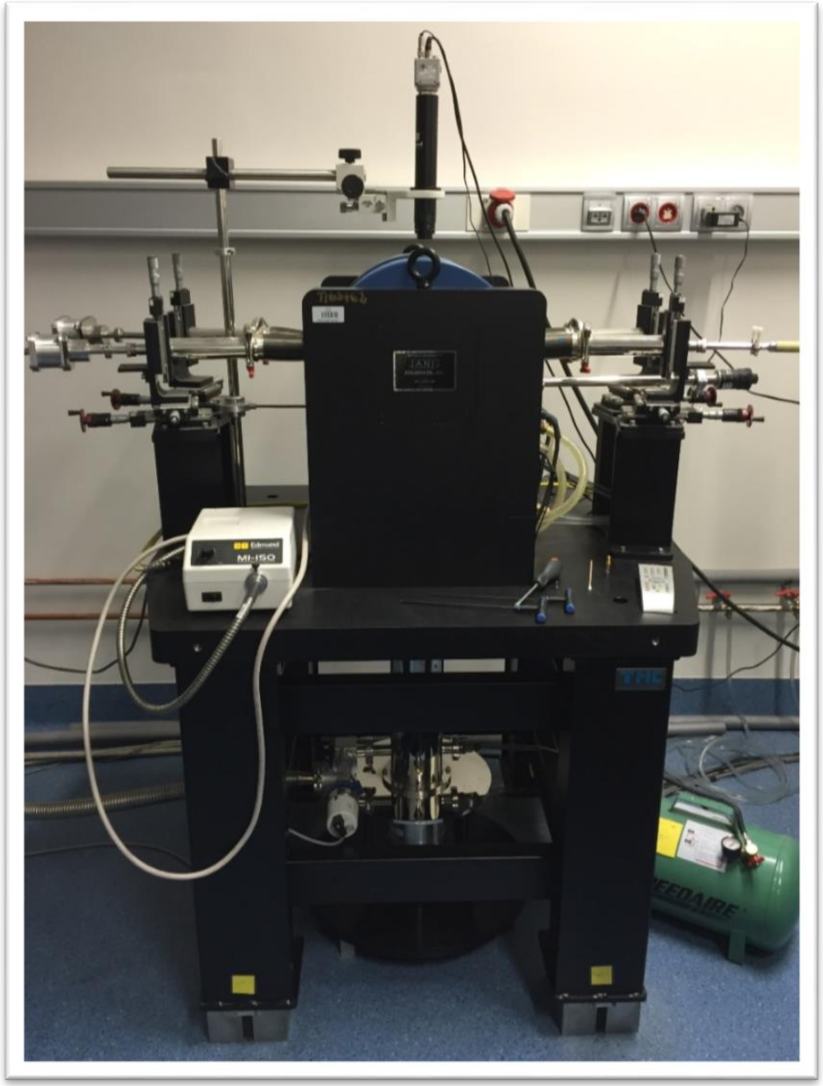


- The field-like and antidamping-like spin torques

J. Sinova et al. Rev. Mod. Phys. 87, 4 (2015)

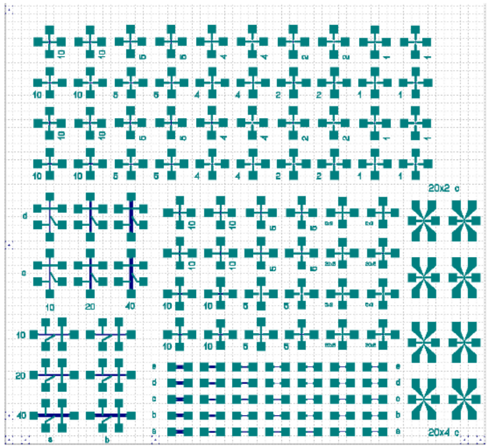
Harmonic Hall voltage measurements

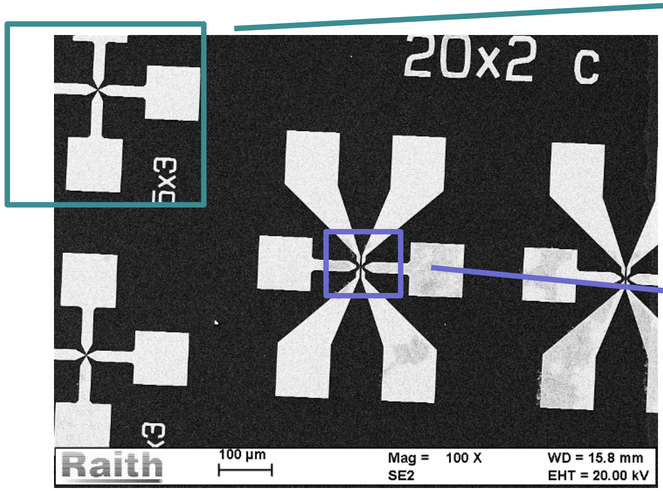


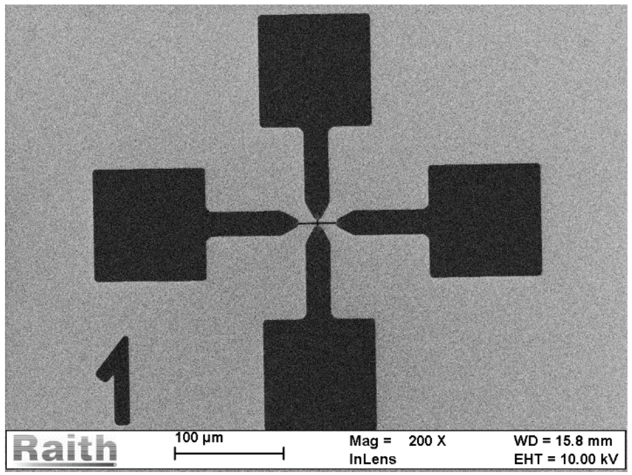


Academic Centre for Materials and Nanotechnology

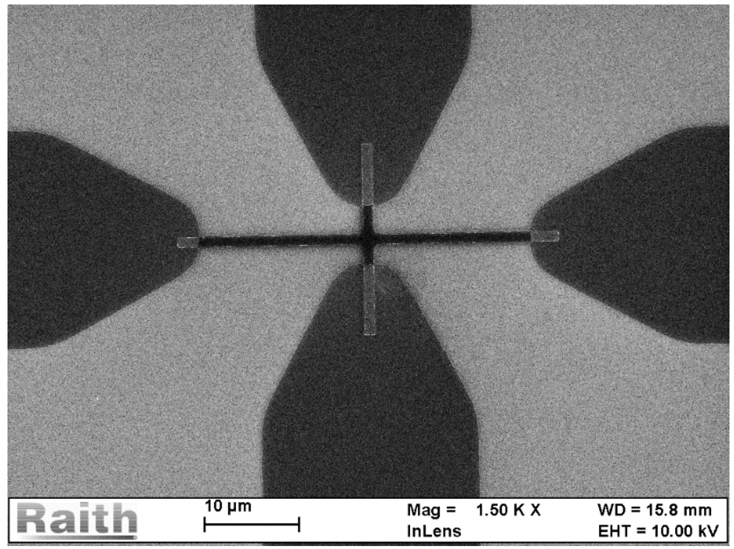
Hall μ-bars

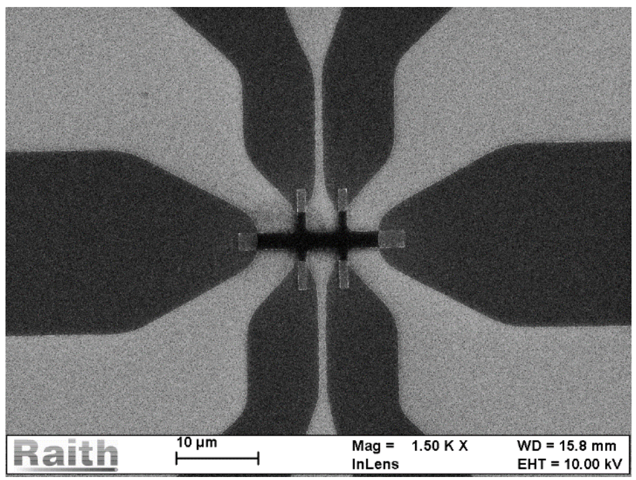




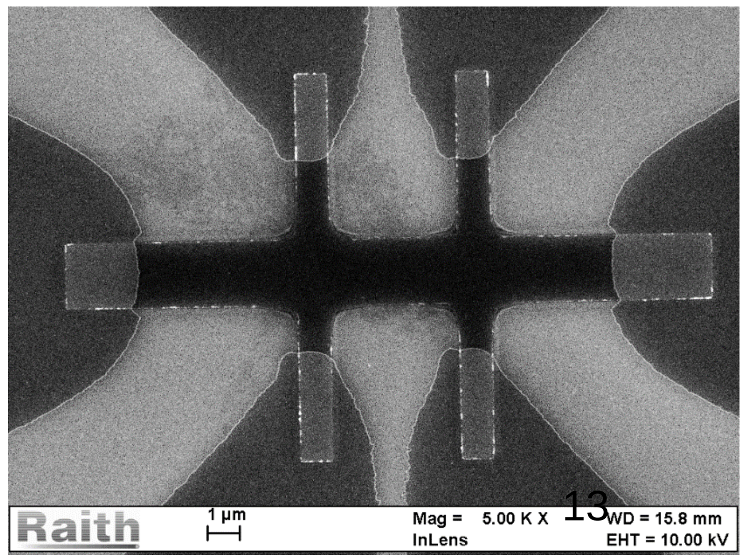


70 μm x 1 μm



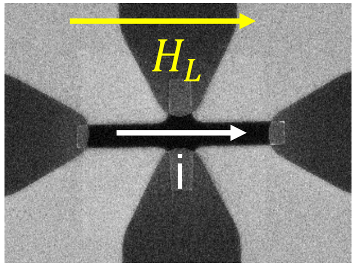


20 μm x 2 μm

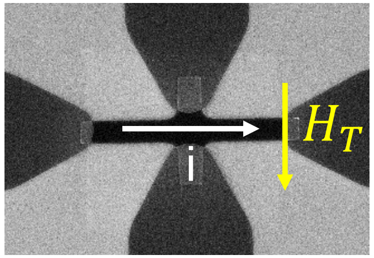


Harmonic Hall voltage measurements

Longitudinal in-plane field

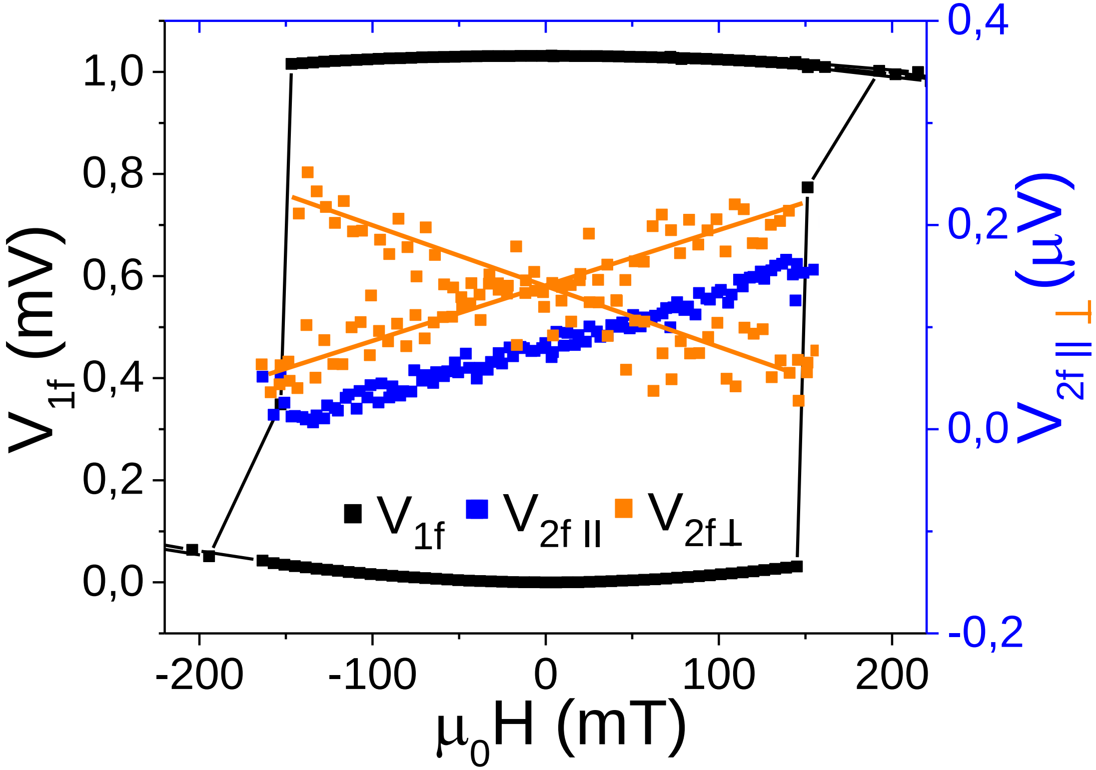


Transverse in-plane field



$$\Delta R_P / \Delta R_A < 1\%$$

$$\Delta H_{L,T} = -2 \frac{\partial V_{2\omega} / \partial H_{L,T}}{\partial^2 V_{\omega} / \partial H_{L,T}^2}$$



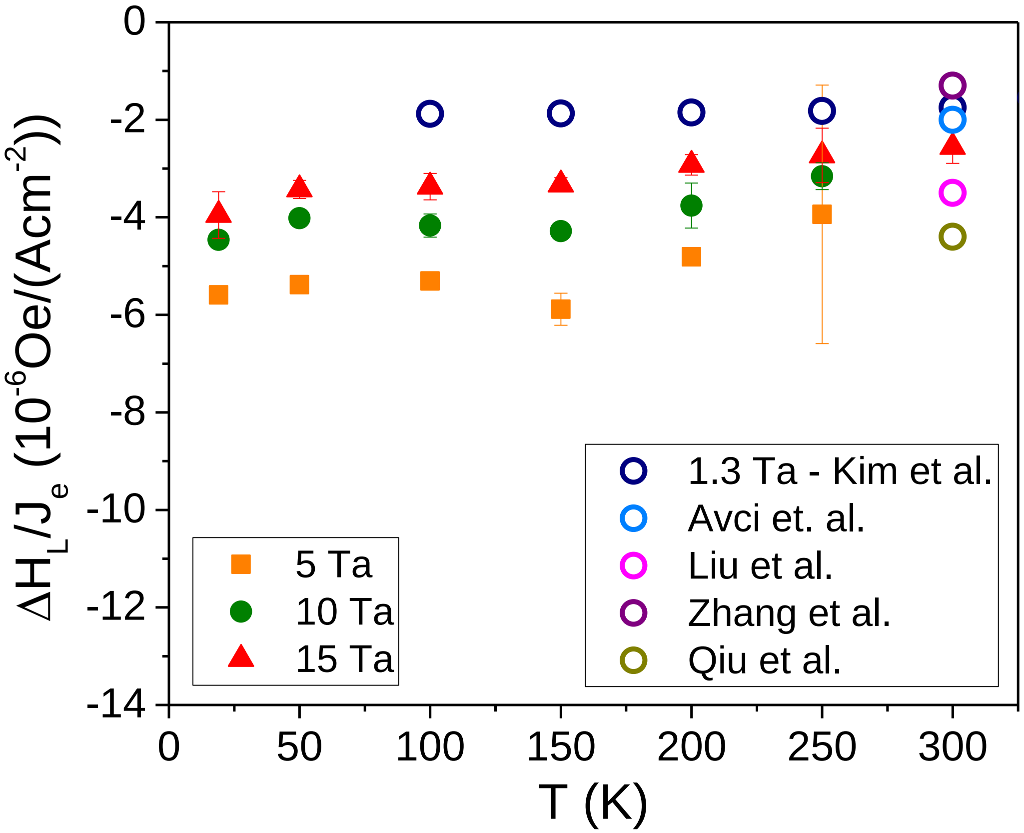
ΔH_T refers to field-like torque

ΔH_L reffers to an antidamping-like torque

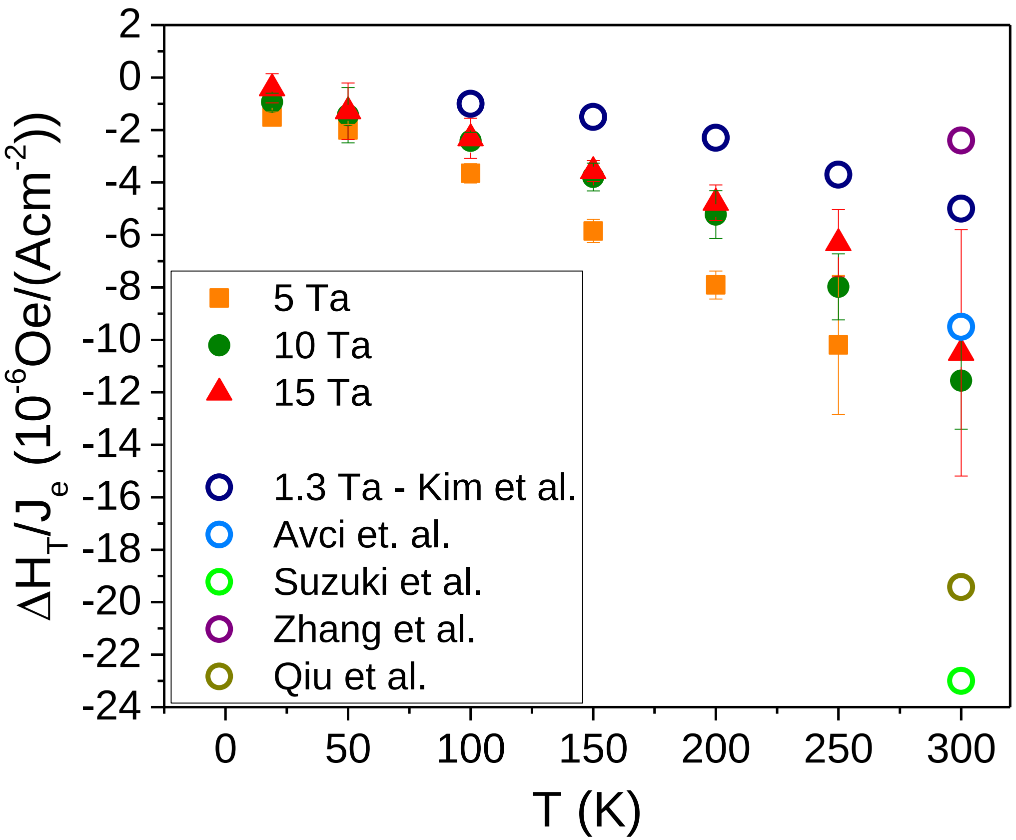
ΔR_P - Planar Hall Resistance ΔR_A - Anomalous Hall Resistance

SOT-induced effective fields

Longitudinal SOT-induced effective field



Transverse SOT-induced effective field



J. Kim et al. PRB **89**, 174424 (2014) Ta(1.3 nm)/$Co_{20}Fe_{60}B_{20}$ (1 nm)

C. Avci et al. PRB **89**, 214419 (2014) Ta(3 nm)/$Co_{60}Fe_{20}B_{20}$ (0.9 nm)

L. Liu et al. Ta(6 nm)/CoFeB(1 nm)

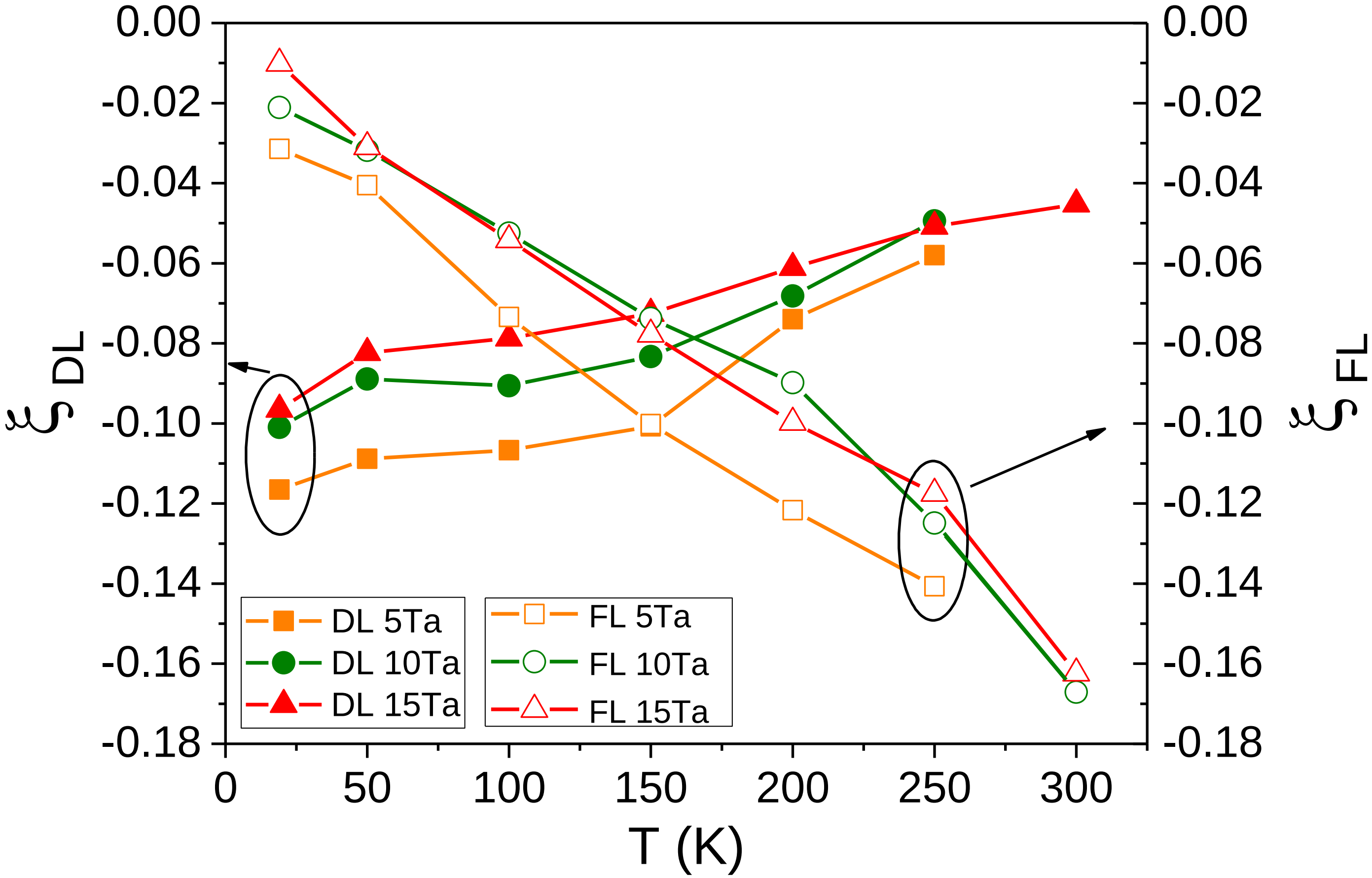
T. Suzuki et al. Appl. Phys. Lett. **98**, 142505 (2011) Ta(1 nm)/$Co_{40}Fe_{40}B_{20}$ (1 nm)

C. Zhang et al. Appl. Phys. Lett. **103**, 262407 (2013) Ta(2.5 nm)/CoFeB(1 nm)

X. Qiu et al. Scientific Reports 4 : 4491 (2014) Ta(2 nm)/$Co_{40}Fe_{40}B_{20}$ (0.8 nm)

Spin Hall torque efficiencies

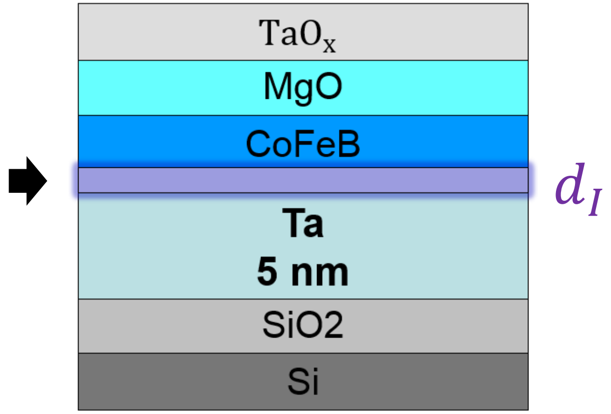
$$\xi_{DL/FL} = \Delta H_{L,T} \cdot 2e\mu_0 M_S t_{CoFeB} \Big/ J_e^{Ta} \cdot \hbar$$



From room temperature down to 150 K field-like torque is dominating.

Spin diffusion lenght: **λTa = 2.5 nm**

Allen et al. PRB **91**, 144412 (2015)



Field-like torque efficiency:

$$\xi_{FL} = -\theta_{SH}\left(1 - \frac{1}{\cosh(\frac{d}{\lambda_N})}\right)\frac{g_i}{(1+g_r)^2+g_i^2},$$

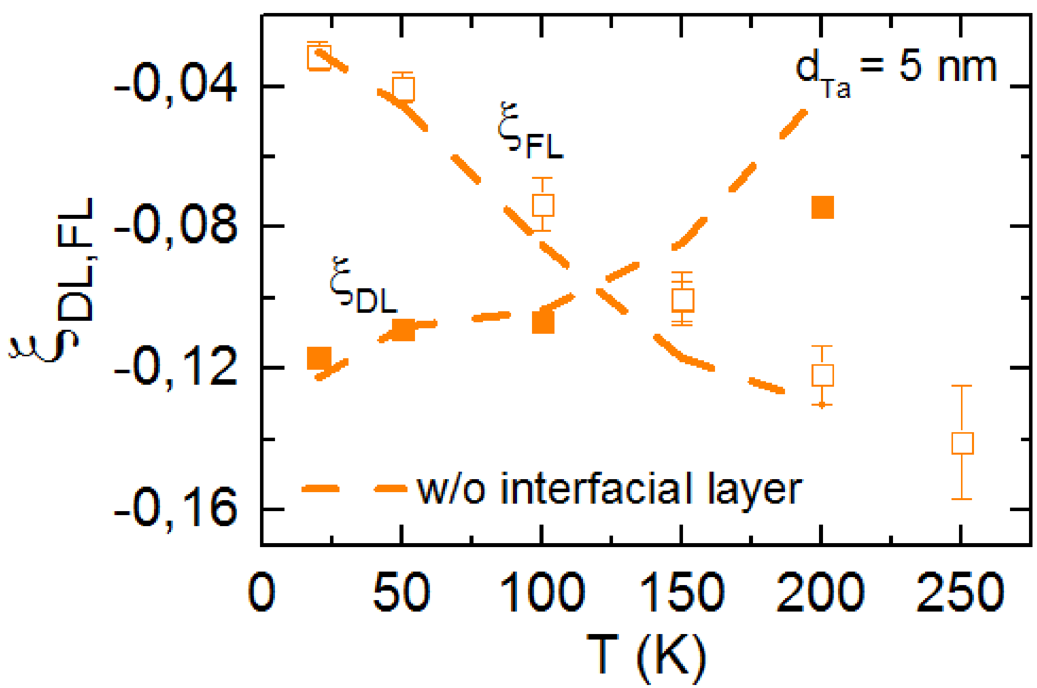
Damping-like torque efficiency:

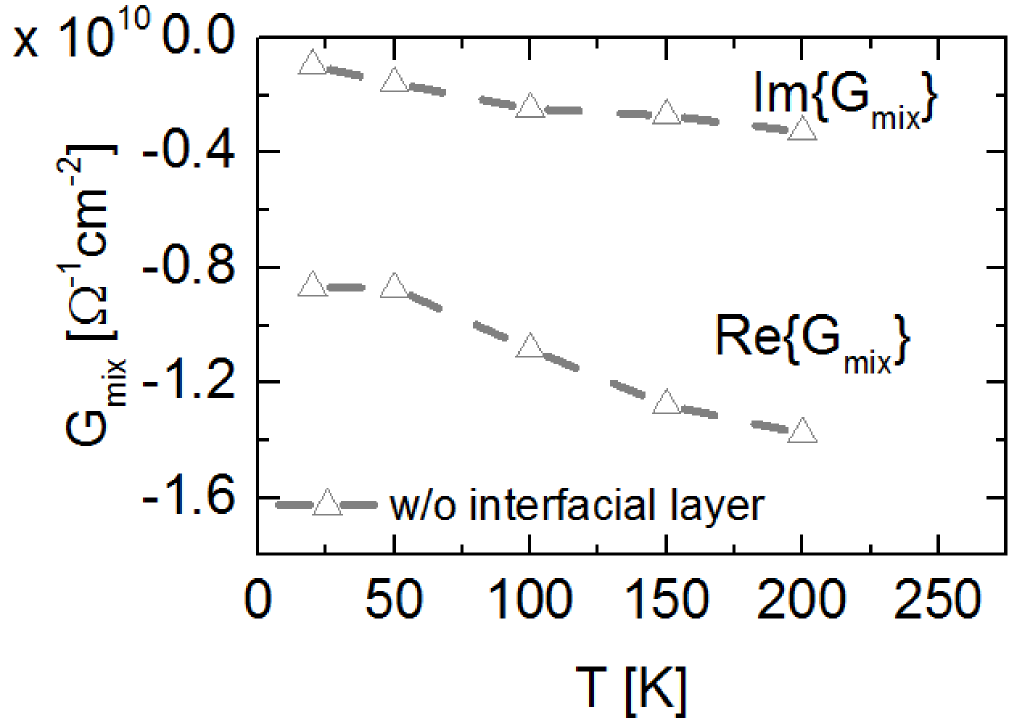
$$\xi_{DL} = -\theta_{SH}\left(1 - \frac{1}{\cosh(\frac{d}{\lambda_N})}\right)\frac{(1+g_r)g_r+g_i^2}{(1+g_r)^2+g_i^2},$$

Mixing conductance:

$$g_{r,i} = G_{r,i}\rho_N\lambda_N \coth(d/\lambda_N)$$

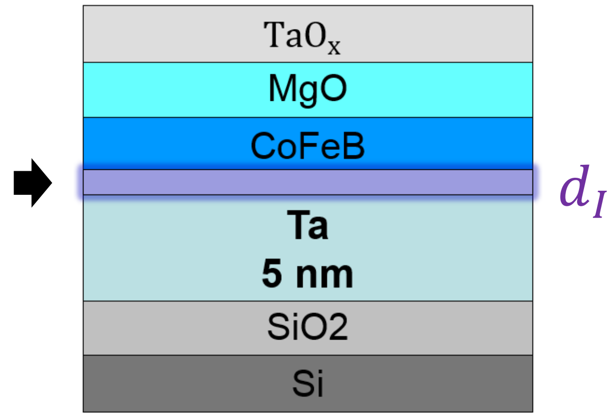
Y-T. Chen et al. Phys. Rev. B 87, 144411 (2013)





Spin diffusion lenght: **λTa = 2.5 nm**

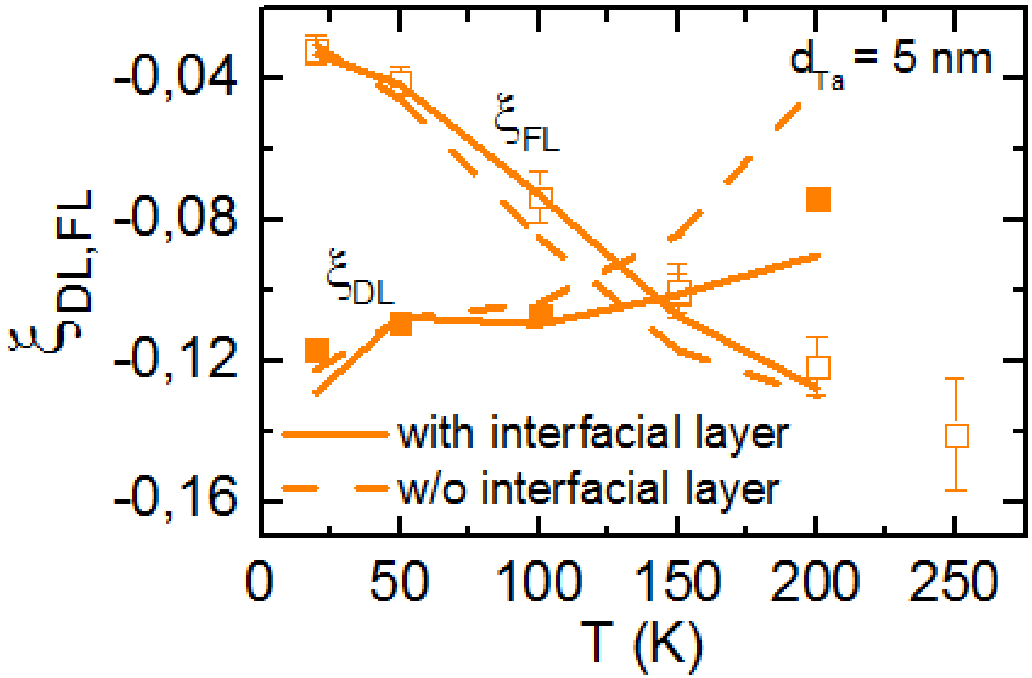
Allen et al. PRB **91**, 144412 (2015)

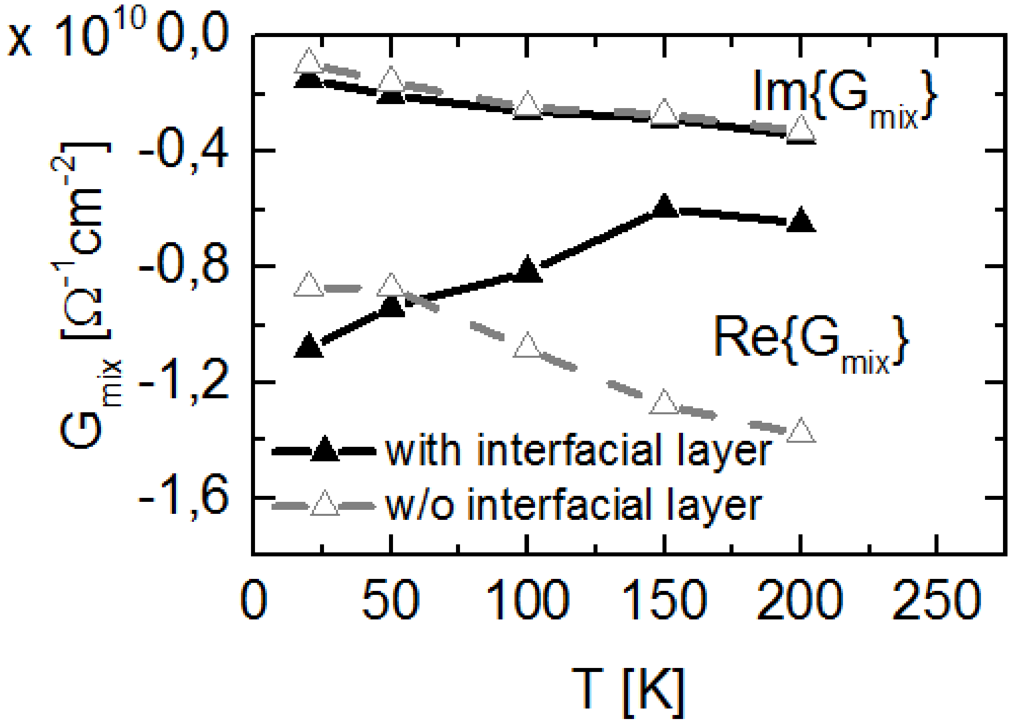


$$\xi_{DL} = -\theta_{SH}\frac{\tanh(\frac{d_N}{2\lambda_N})\text{csch}(\frac{d_I}{\lambda_I})}{\coth(\frac{d_N}{\lambda_N})\coth(\frac{d_I}{\lambda_I}) + \frac{\rho_I\lambda_I}{\rho_N\lambda_N}}\frac{g_r(1+g_r)+g_i^2}{(1+g_r)^2+g_i^2}m_z\,,$$

$$\xi_{FL} = -\theta_{SH}\frac{\tanh(\frac{d_N}{2\lambda_N})\text{csch}(\frac{d_I}{\lambda_I})}{\coth(\frac{d_N}{\lambda_N})\coth(\frac{d_I}{\lambda_I}) + \frac{\rho_I\lambda_I}{\rho_N\lambda_N}}\frac{g_i}{(1+g_r)^2+g_i^2}\,,$$

$$g_{r,i} = 2G_{r,i}\frac{\coth(\frac{d_N}{\lambda_N})\coth(\frac{d_I}{\lambda_I}) + \frac{\rho_I\lambda_I}{\rho_N\lambda_N}}{\frac{1}{\rho_I\lambda_I}\coth(\frac{d_N}{\lambda_N}) + \frac{1}{\rho_N\lambda_N}\coth(\frac{d_I}{\lambda_I})}$$





SHE in Ta/CoFeB: summary

AGH

❖ Significant changes in the structure of Ta

Amorphous 5 nm Ta with high resistivity (240 μΩ·cm), disoriented β-phase structure for 10 nm and 15 nm Ta

❖ Characteristic change of the dead layer (DL) thickness in function of the Ta thickness

Maximum DL/ minimum M_S for 5 nm Ta

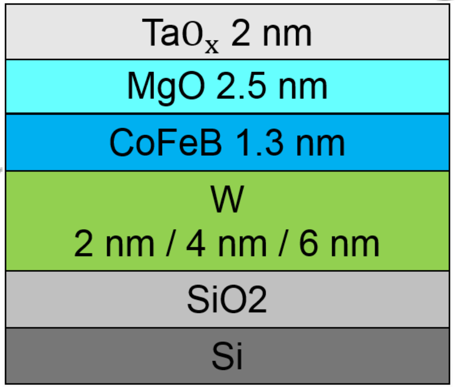
❖ Both Spin Hall torque efficiencies higher for sample with 5 nm of Ta

Domination of antidamping torque below 150 K

❖ Still remain open questions

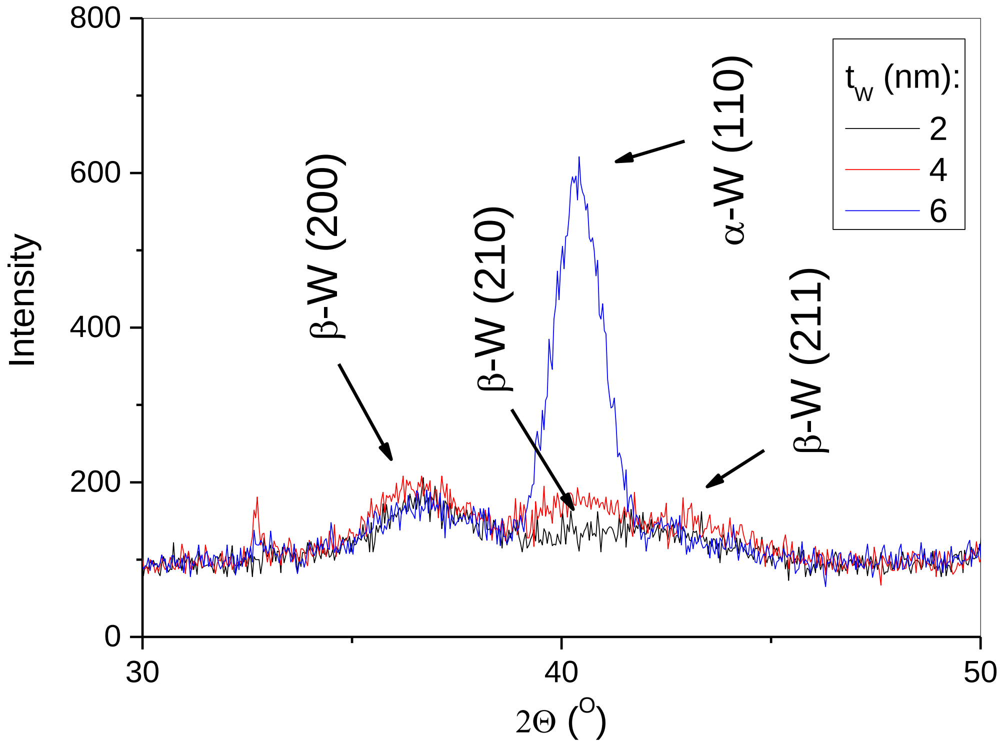
Spin diffusion lenght in Ta and in the interface

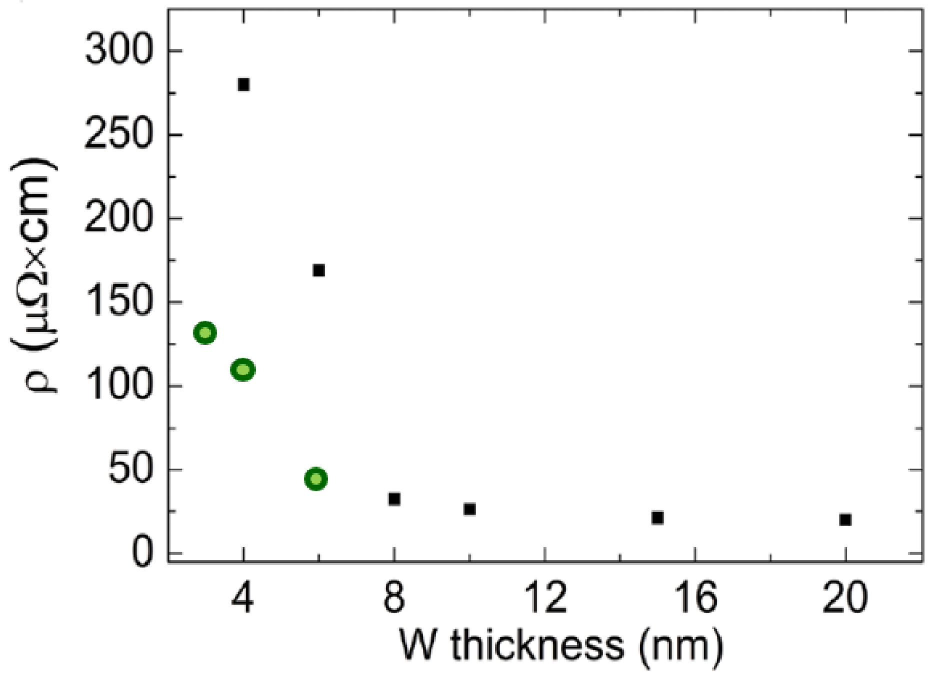
Spin Hall torque efficiencies in W



W(t_W)/$Co_{12}Fe_{68}B_{20}$ (1.3)/MgO(2.5)/Ta(4)
t_W= 2, 4, and 6 nm

t_W (nm)	2	4	6
ρ_W (μOhm*cm)	128	105	36

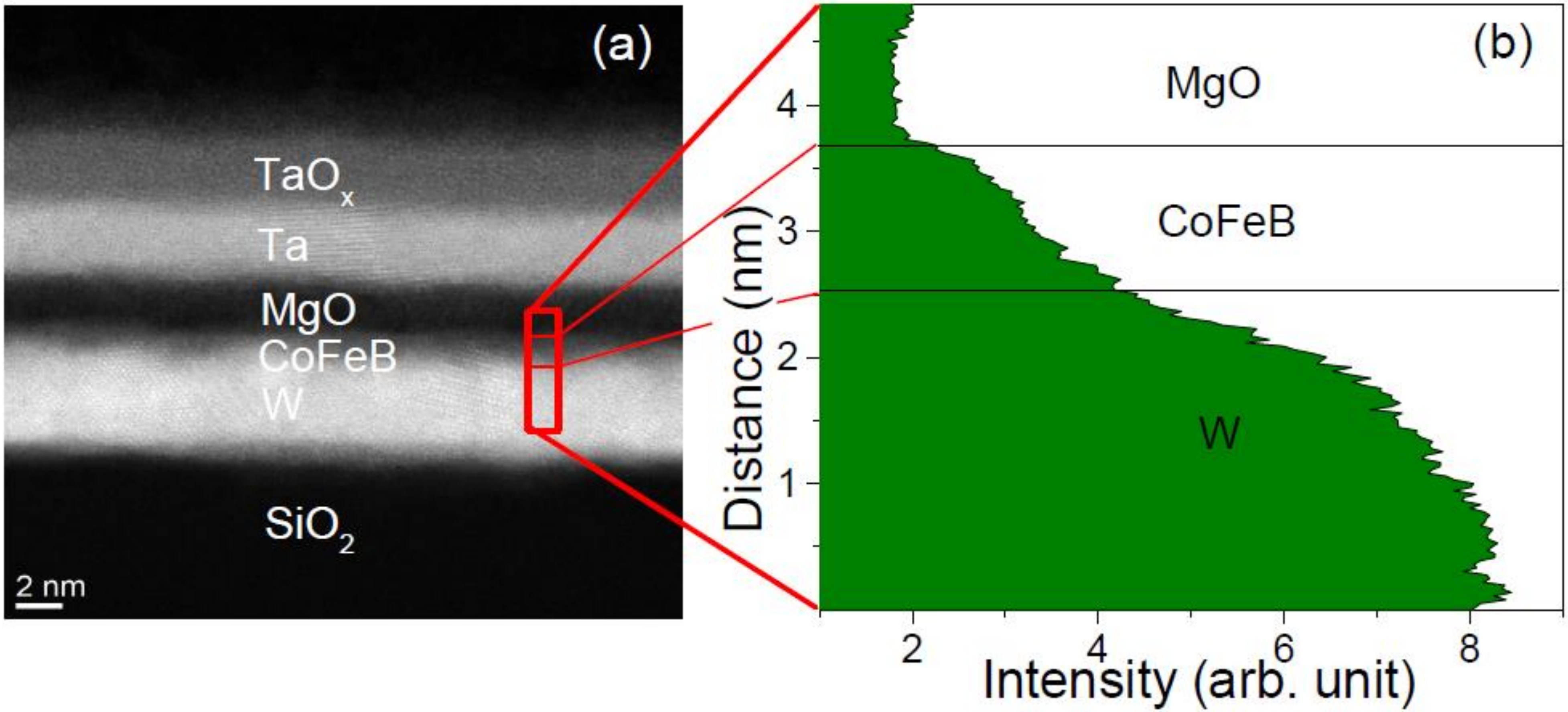




W. Skowroński, M. Cecot, J. Kanak, S. Zietek, T. Stobiecki, L. Yao, S. van Dijken, T. Nozaki, K. Yakushiji, and S. Yuasa *arxiv* **arXiv:1604.05204v1** (2016)

C.-F. Pai et al. Appl. Phys. Lett. 101, 122404 (2012)

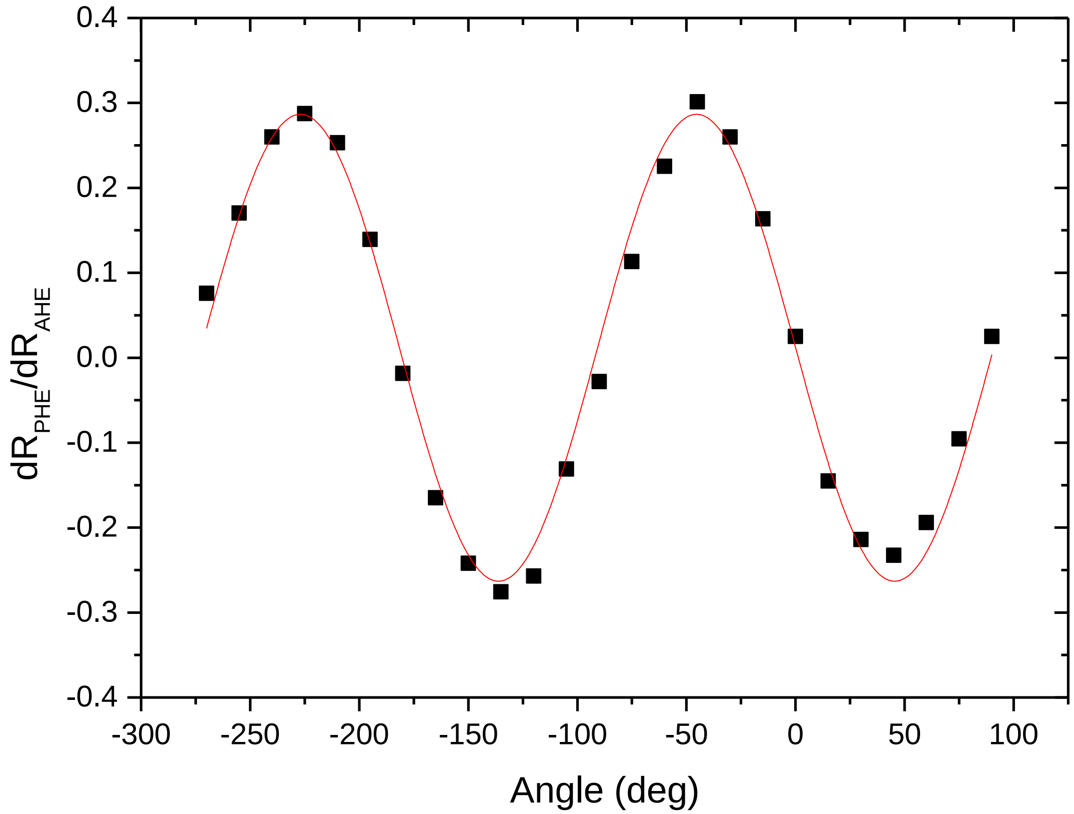
Z-contrast TEM image of fabricated multilayer stack (a) and line scan profile along vertical axis (b), indicating chemical intermixing at the interface between CoFeB and W.

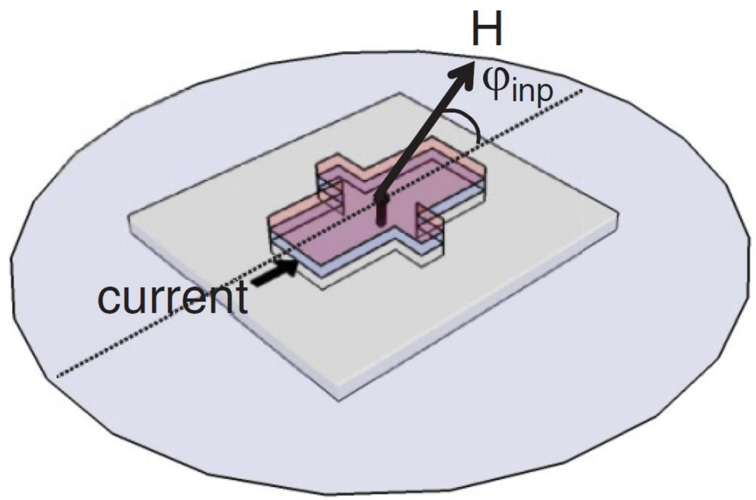


W. Skowroński, M. Cecot, J. Kanak, S. Zietek, T. Stobiecki, L. Yao, S. van Dijken, T. Nozaki, K. Yakushiji, and S. Yuasa *arxiv* **arXiv:1604.05204v1** (2016)

- Strong interdiffusion of W into CoFeB

Planar Hall effect in W





$$\Delta R_P / \Delta R_A = 30\ \%$$

Effective fields:

$$\Delta H_L = -2\frac{(B_L \pm 2\xi B_T)}{1 - 4\xi^2},$$

$$\Delta H_T = -2\frac{(B_T \pm 2\xi B_L)}{1 - 4\xi^2},$$

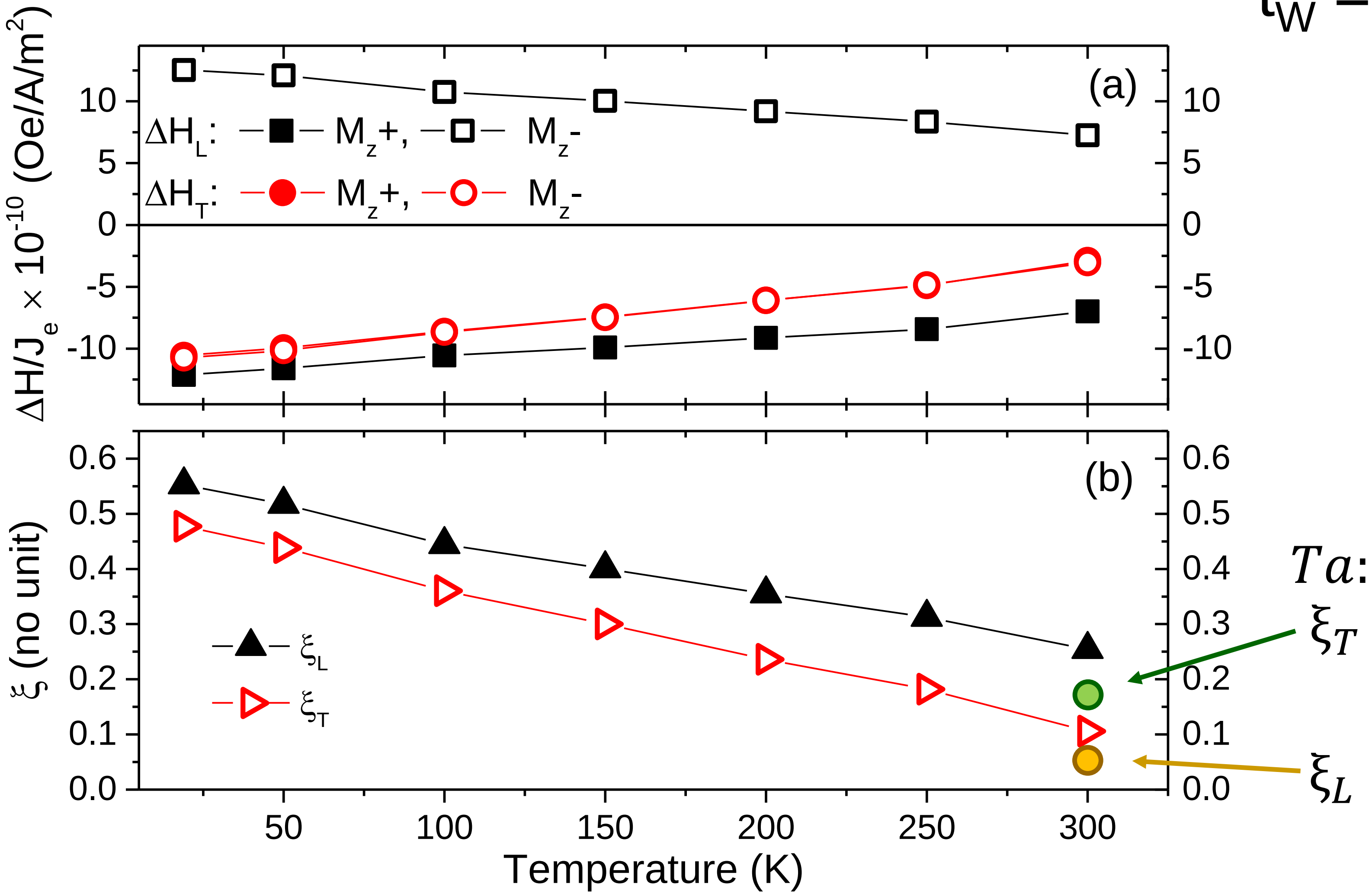
$$\xi \equiv \frac{\Delta R_P}{\Delta R_A}$$

For Ta $\Delta R_P / \Delta R_A < 5\%$

Kim et al. PRB 89, 174424 (2014)
Cho et al. Sci. Rep. 5, 14668 (2015)

Spin Hall torque efficiencies in W

$t_W = 2$ nm



W. Skowroński, M. Cecot, J. Kanak, S. Zietek, T. Stobiecki, L. Yao, S. van Dijken, T. Nozaki, K. Yakushiji, and S. Yuasa *arxiv* **arXiv:1604.05204v1** (2016)

θ_H = 0.33 in Pai et al. APL 104,082407 (2014)

SHE in W/CoFeB: summary

- Significant changes in the structure of W

High resistive β-phase structure for 2 nm and 4 nm of W (above 100 μΩ·cm) and α-phase for thicker layer (36 μΩ·cm)

- Strong interdiffusion of W into CoFeB

The lack of sharp interface

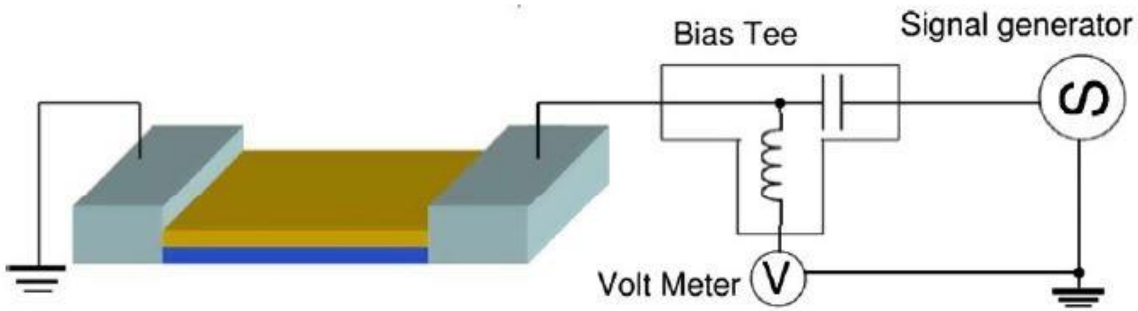
- Both Spin Hall torque efficiencies have the same temperature dependence

Domination of antidamping torque

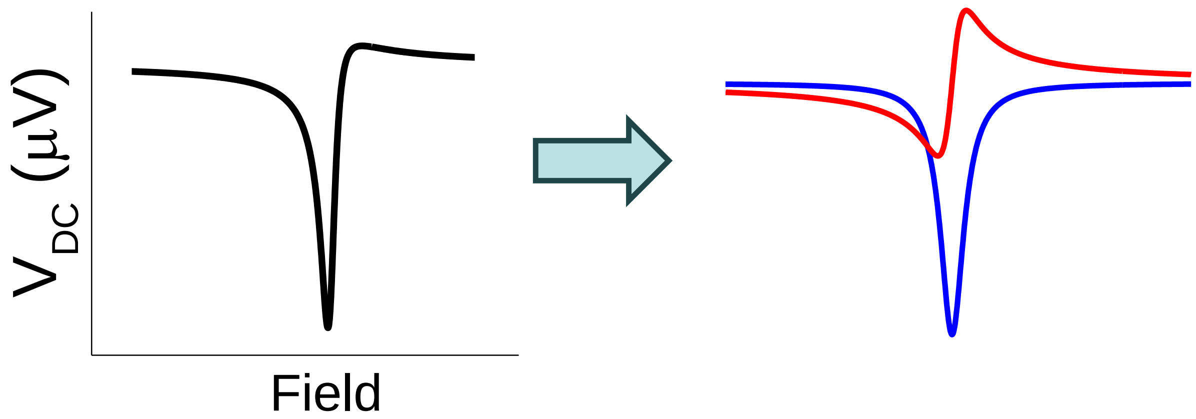
SHE: second measurement method

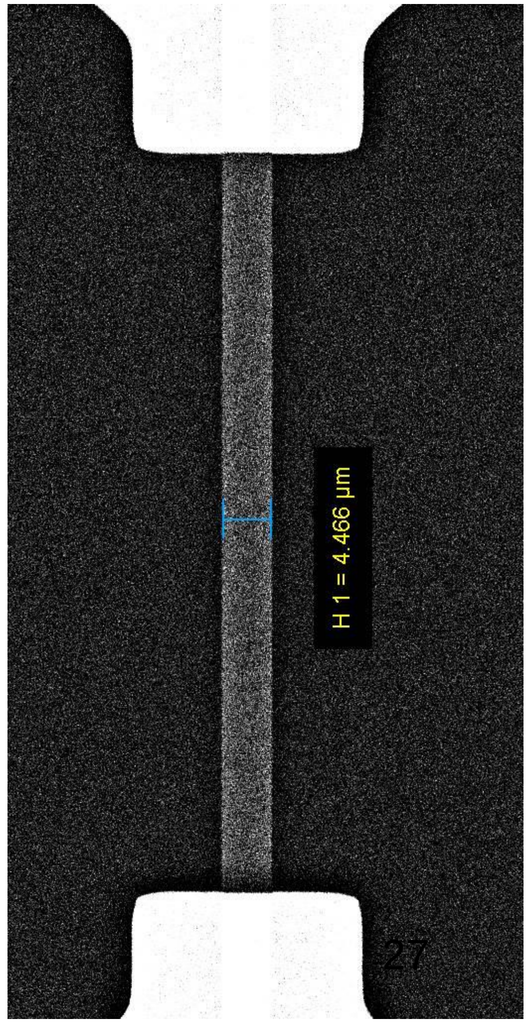
$$\theta_{SH} = \frac{J_s}{J_c} = \frac{S}{A} \times \frac{e\mu_0 M_s t d}{\hbar} \times \sqrt{1 + \left(\frac{M_{eff}}{H_0}\right)}$$

- Spin Diode Effect



Liu et al. PRL 106, 036601 (2011)





A direct voltage signal measured along the stripe comes from the RF current mixed with the oscillating resistance

ST-FMR (Spin Diode Effect)

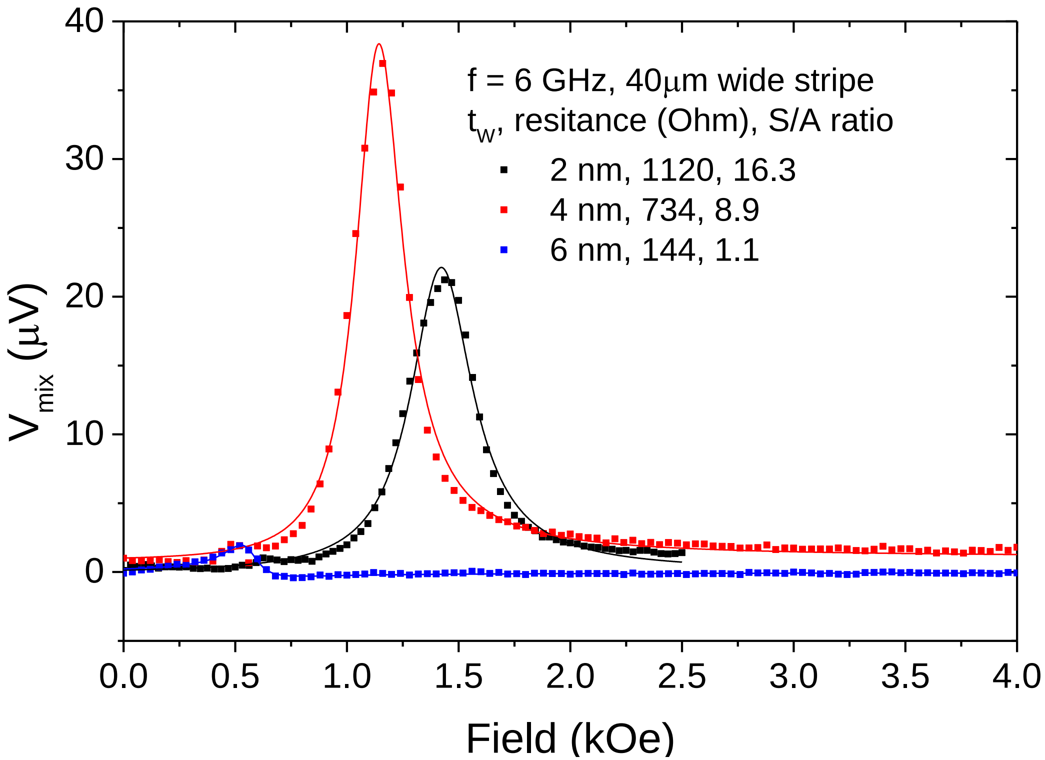
As-deposited:

d W / 1.5 CoFeB / 5 MgO / 4 Ta

d W = 2 nm, 4 nm, 6 nm

$$\theta_{SH} = \frac{J_s}{J_c} = \frac{S}{A} \times \frac{e\mu_0 M_s t d}{\hbar} \times \sqrt{1 + \left(\frac{M_{eff}}{H_0}\right)}$$

Liu et al. PRL 106, 036601 (2011)



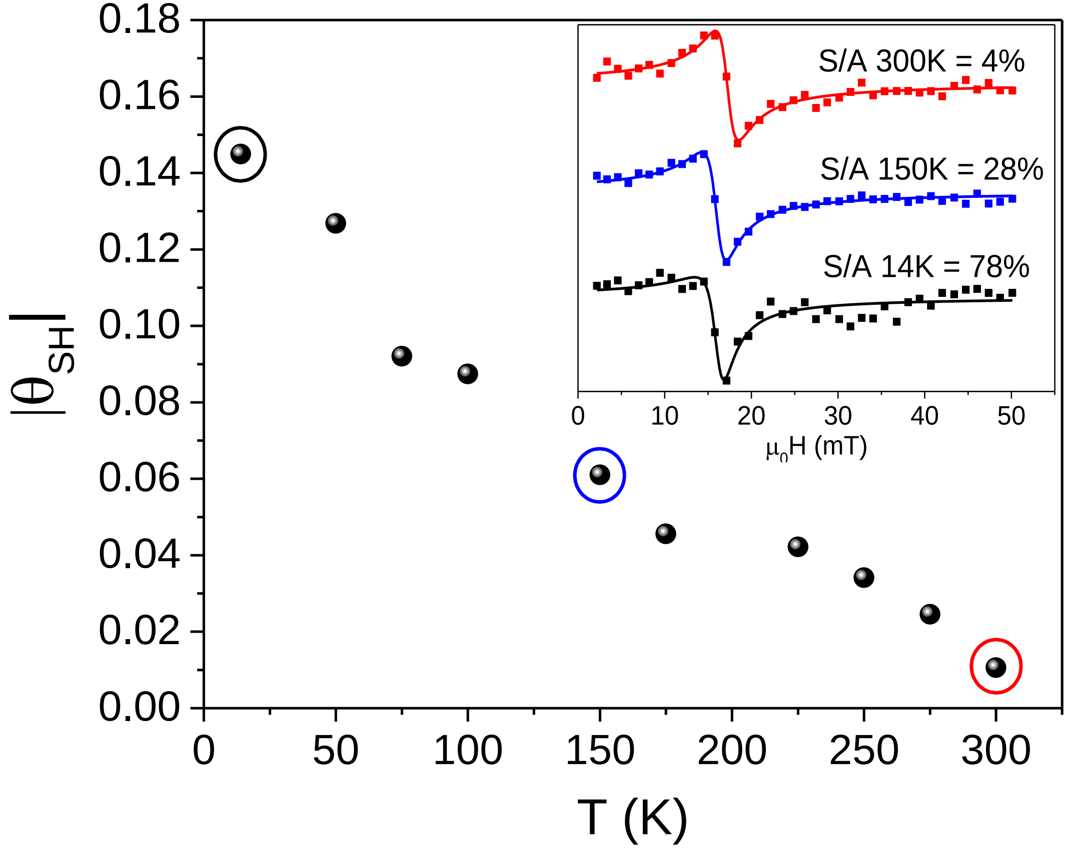
	f (GHz)	4.00	5.00	6.00	Resistivity (μOhm*cm)
d (nm)	**2**	0.13	0.13	0.16	**128**
	4	0.22	0.21	0.21	**110**
	6	0.05	0.06	0.05	**41**

AMR ~ 0.3 %

ST-FMR (Spin Diode Effect)

As-deposited:
d Ta / 2.5 CoFeB / 5 MgO / Al_2O_3
d Ta = 5 nm, 10 nm, 15 nm

Temperature dependence for
5 Ta / 2.5 CoFeB / 5 MgO / Al_2O_3



$$\theta_{SH} = \frac{J_s}{J_c} = \frac{S}{A} \times \frac{e\mu_0 M_s t d}{\hbar} \times \sqrt{1 + \left(\frac{M_{eff}}{H_0}\right)}$$

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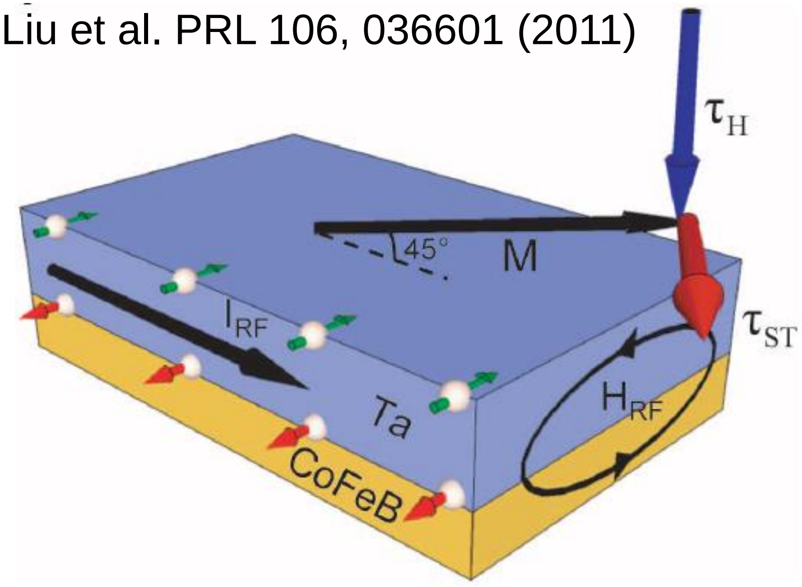


AMR ~ 0.1 %
effective damping α ≈ 0.006

SHE in samples with in-plane magnetization: summary

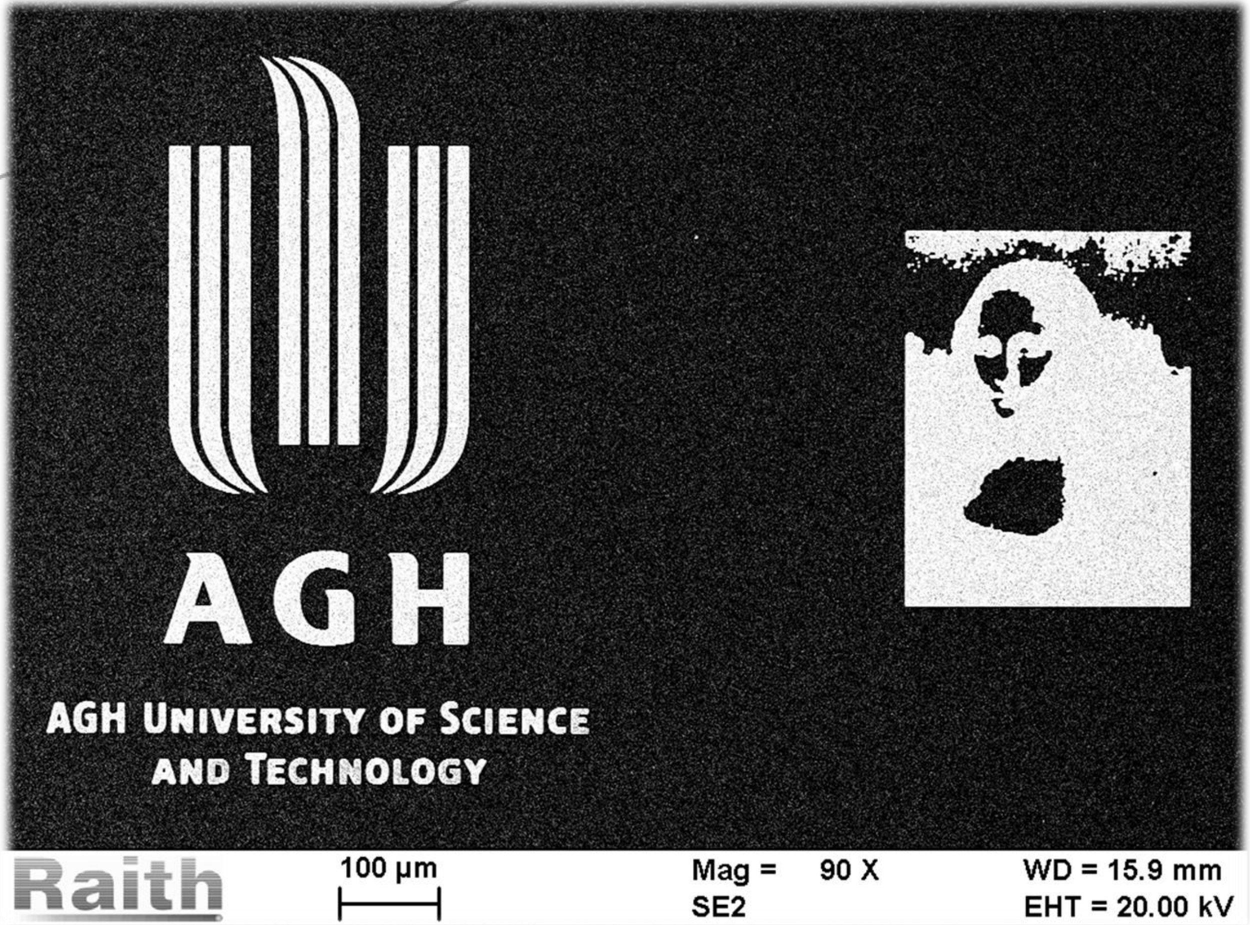
- Lack of compliance for Ta compared to other methods

- For W a better agreement with harmonic Hall voltage measurements

Hall angle for t_W = 2 nm is 0.13 in spin diode measurements and 0.25 in harmonic method

- An influence of the several factors on shape of the line

Field-like component, Oersted field from the electrodes and bottom metal layer



Thank you for your kind attention!

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