Planar Hall Torque

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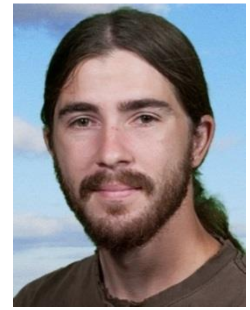
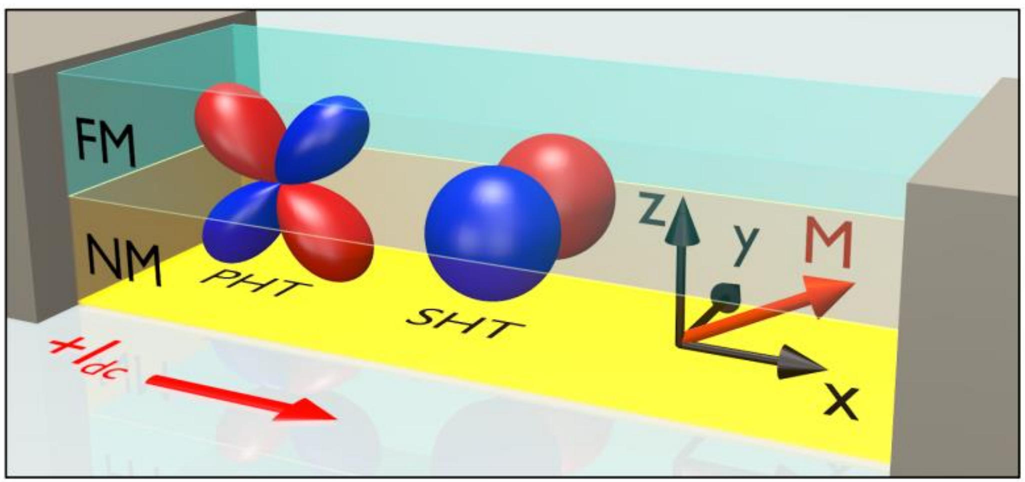
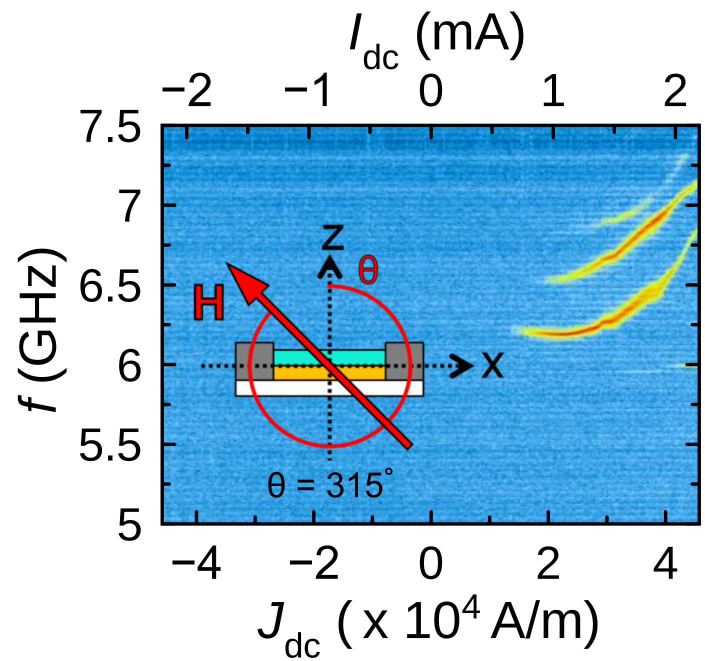


Chris Safranski

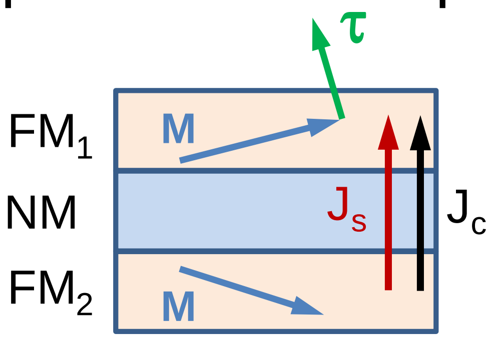
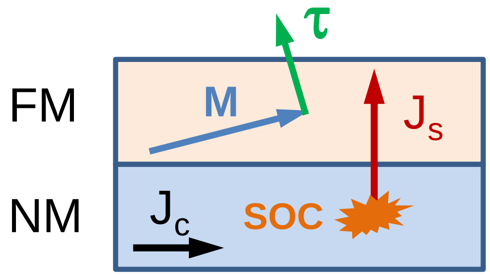
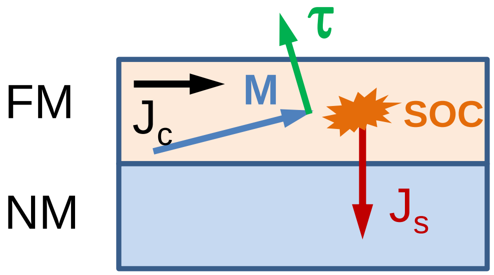
Eric Montoya



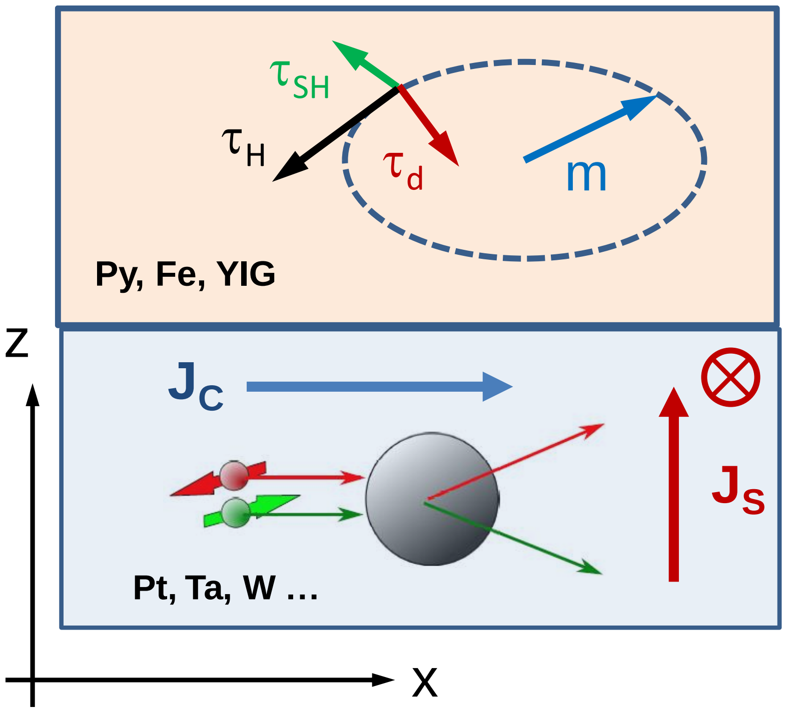


*C. Safranski, E. Montoya, IK, Nature Nanotechnology **14**, 27 (2019)*

Spin torques

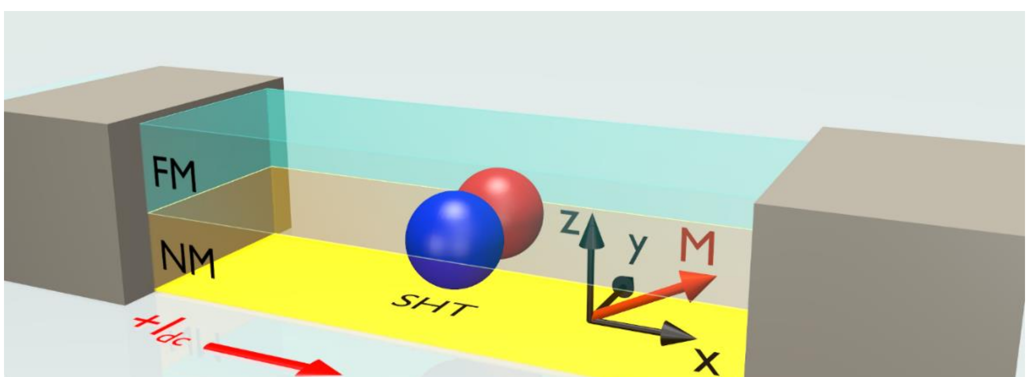
Spin transfer torque	Spin Hall torque	Planar Hall torque
		
*Katine et al., PRL **84**, 3149 (2000)* *Grollier et al., APL **78**, 3663 (2001)*	*Ando et al., PRL **101**, 036601 (2008)* *Liu et al., PRL **109**, 096602 (2012)*	*Safranski et al., Nature Nanotech. **14**, 27 (2019)*
Spin current origin: spin filtering	Spin current origin: spin-orbit coupling in non-magnetic metal	Spin current origin: spin-orbit coupling in ferromagnetic metal
Corresponding transport effect: giant magneto-resistance	Corresponding transport effect: spin Hall magneto-resistance	Corresponding transport effect: anisotropic magneto-resistance
*Baibich et al., PRL **61**, 2472 (1988)* *Binasch et al., PRB **39**, 4828 (1989)*	*Weiler et al., PRL **108,** 106602 (2012)* *Huang et al. PRL **109**, 107204 (2012)*	*W. Thomson, Proc. Royal Soc. **8**, 546 (1857)*

Spin Hall torque



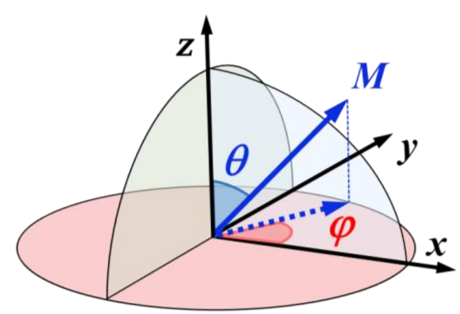
Spin Hall torque is damping-like

- Depends on the direction of magnetization
- Modifies effective damping of the ferromagnet

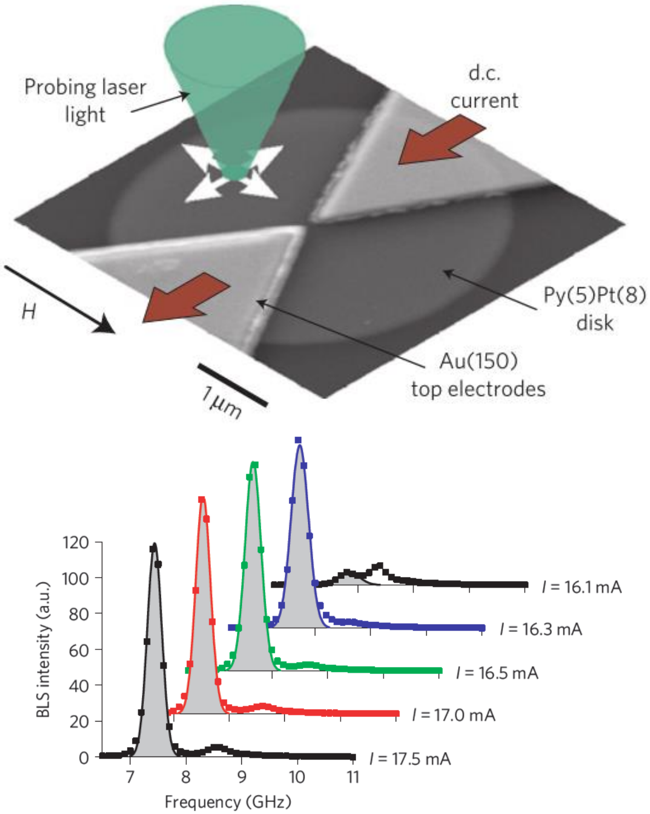


Red – negative damping
Blue – positive damping

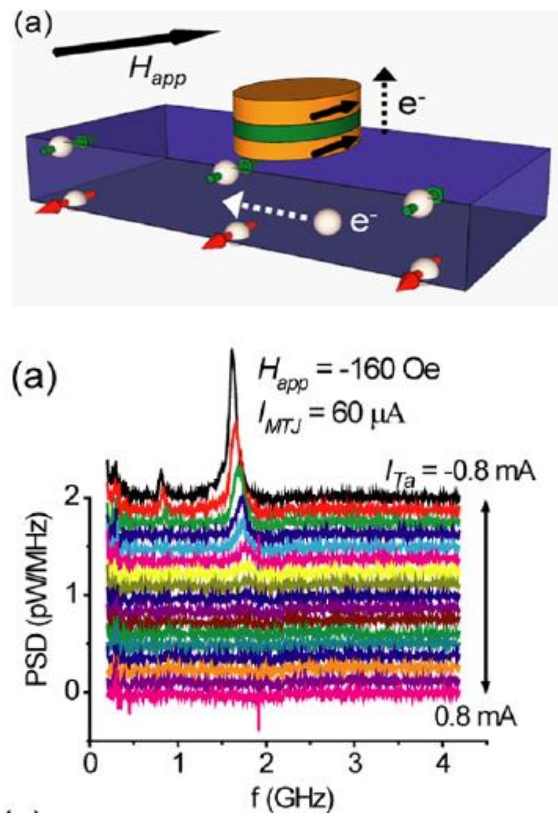
Angular dependence of current-induced damping: $\sin(\theta)\sin(\varphi)$



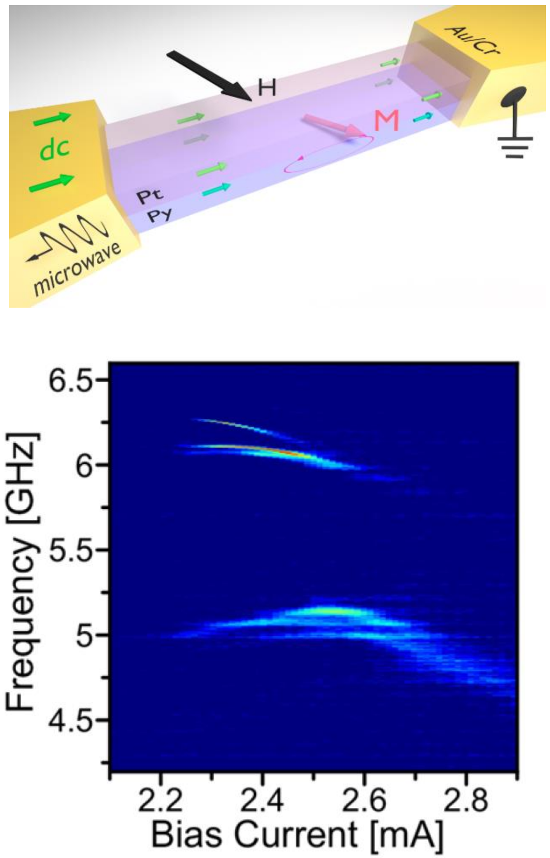
Spin Hall oscillators



Demidov et al. Nat. Mater. (2012)



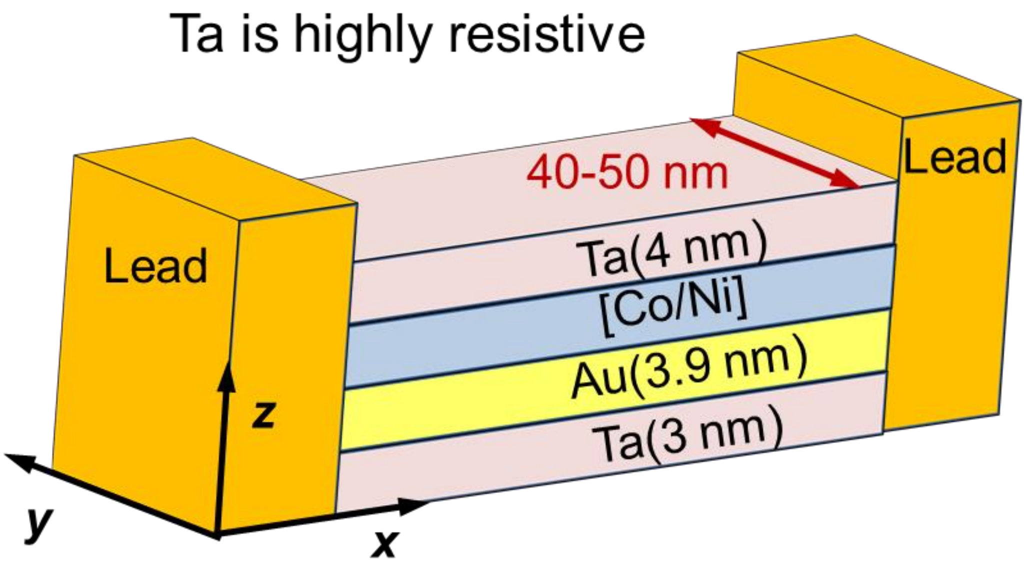
Liu et al. PRL (2012)

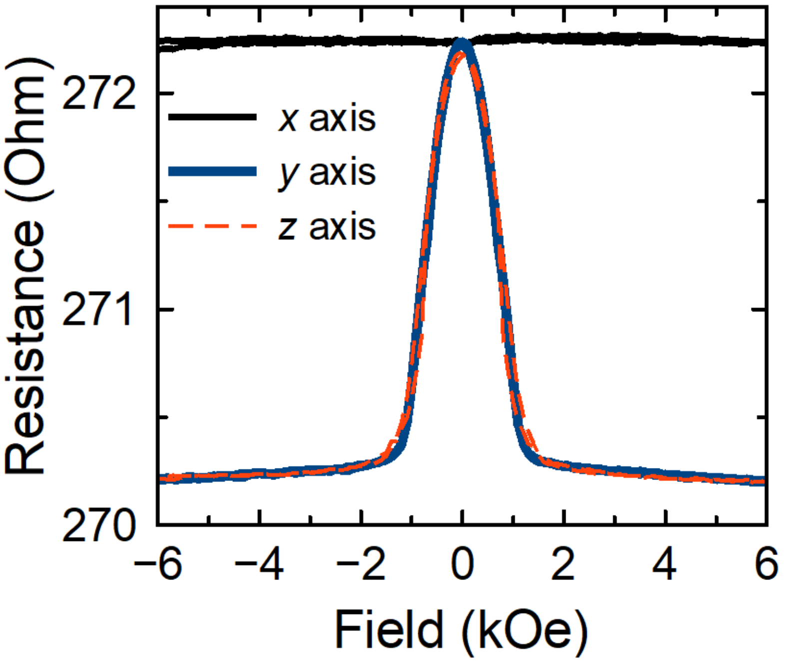


Duan et al. Nat. Commun. (2014)

- Several types of spin Hall oscillators were demonstrated
- Can be phase locked [*Awad et al. Nat. Phys. 13, 292 (2017)*]
- Auto-oscillations stop upon reversal of magnetization

Nanowires for studies of angular dependence of SOT





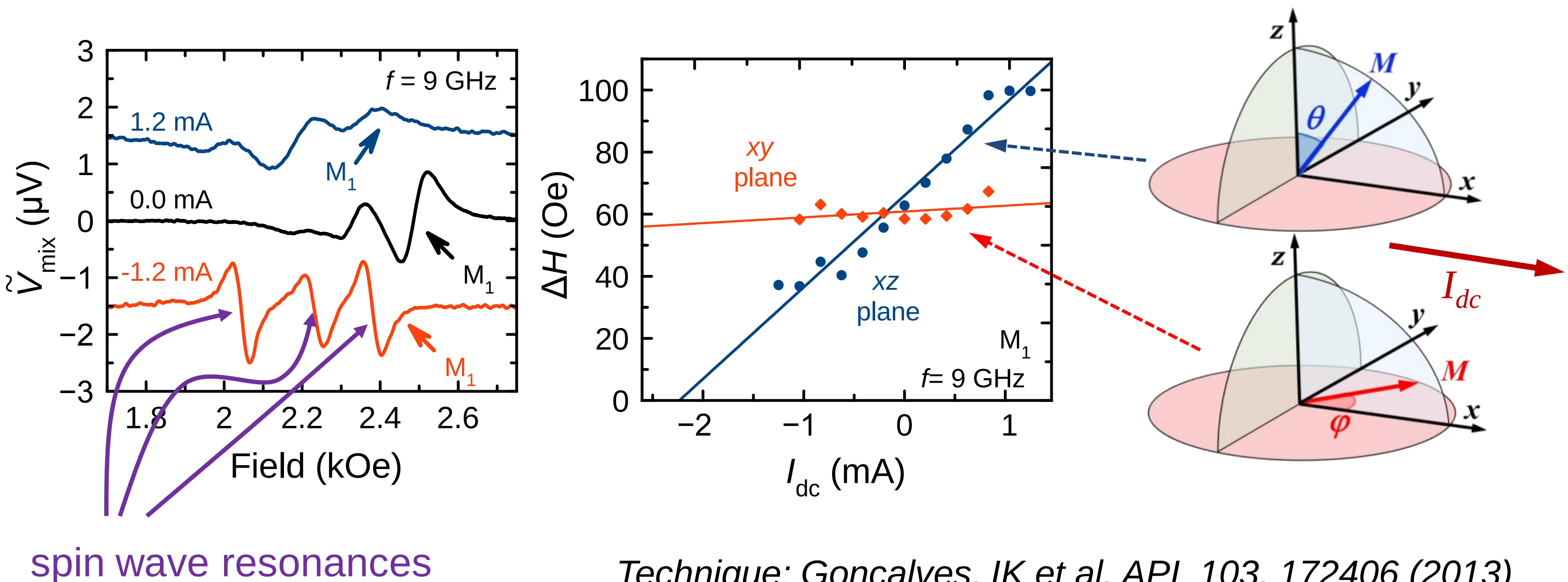
[Co/Ni] = Co/Ni/Co/Ni/Co (5.1 nm)

- [Co/Ni] multilayer ferromagnet (FM) chosen for perpendicular anisotropy
- The FM can be easily saturated along any direction

Spin wave resonance spectroscopy

Electrical detection of spin wave resonances in nanowire

- linewidth (damping) is linear in direct current I_{dc}
- maximum variation of damping with I_{dc} is in the xz plane at θ=45°
- small variation of damping with I_{dc} in the xy plane



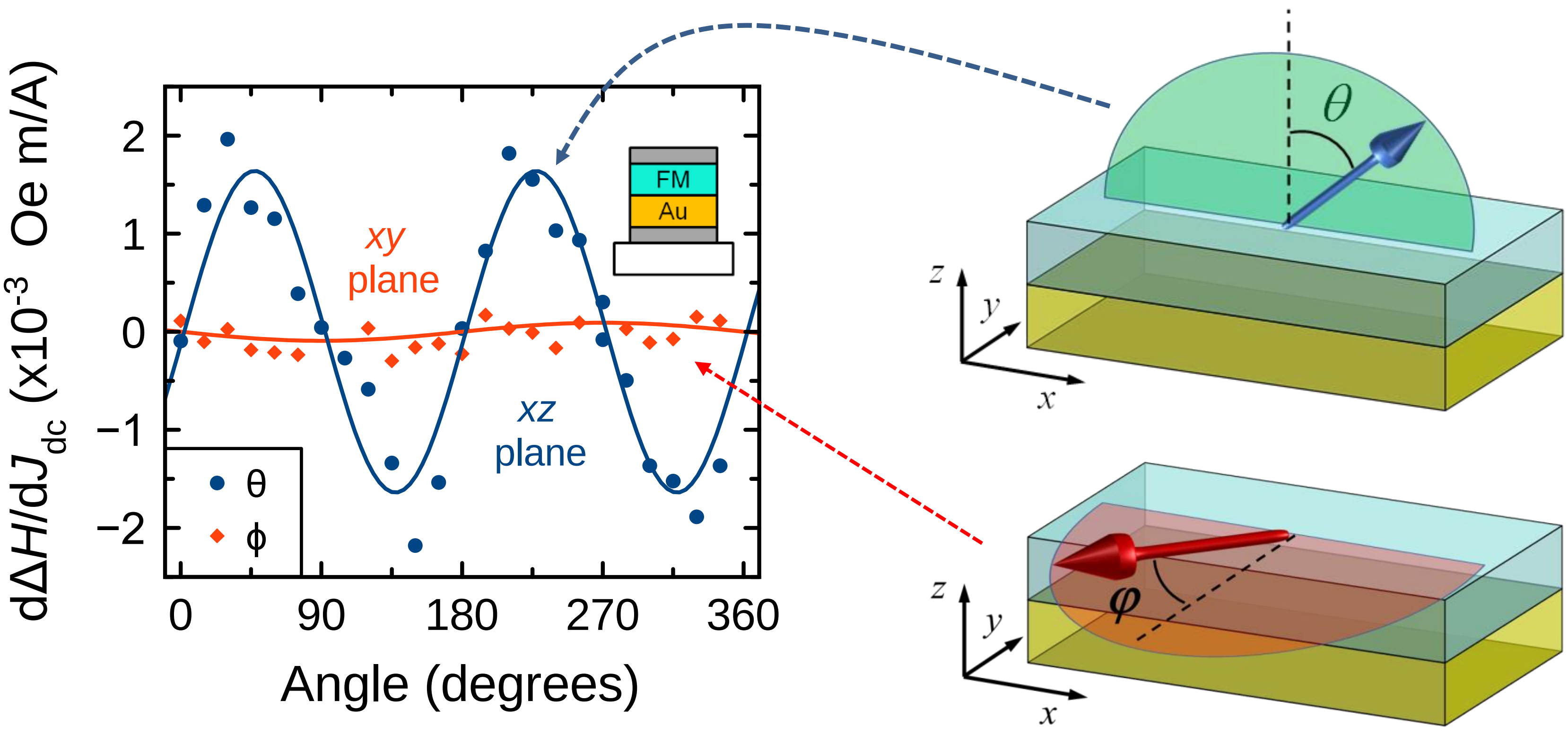
Technique: Goncalves, IK et al. APL 103, 172406 (2013)

Angular dependence of damping-like torque

- Slope of the linewidth ΔH vs I_{dc} is proportional to the damping-like torque efficiency

- Slope ~ sin(θ)cos(θ) in the *xz* plane

- Slope is small and ~ sin(φ) in the *xy* plane

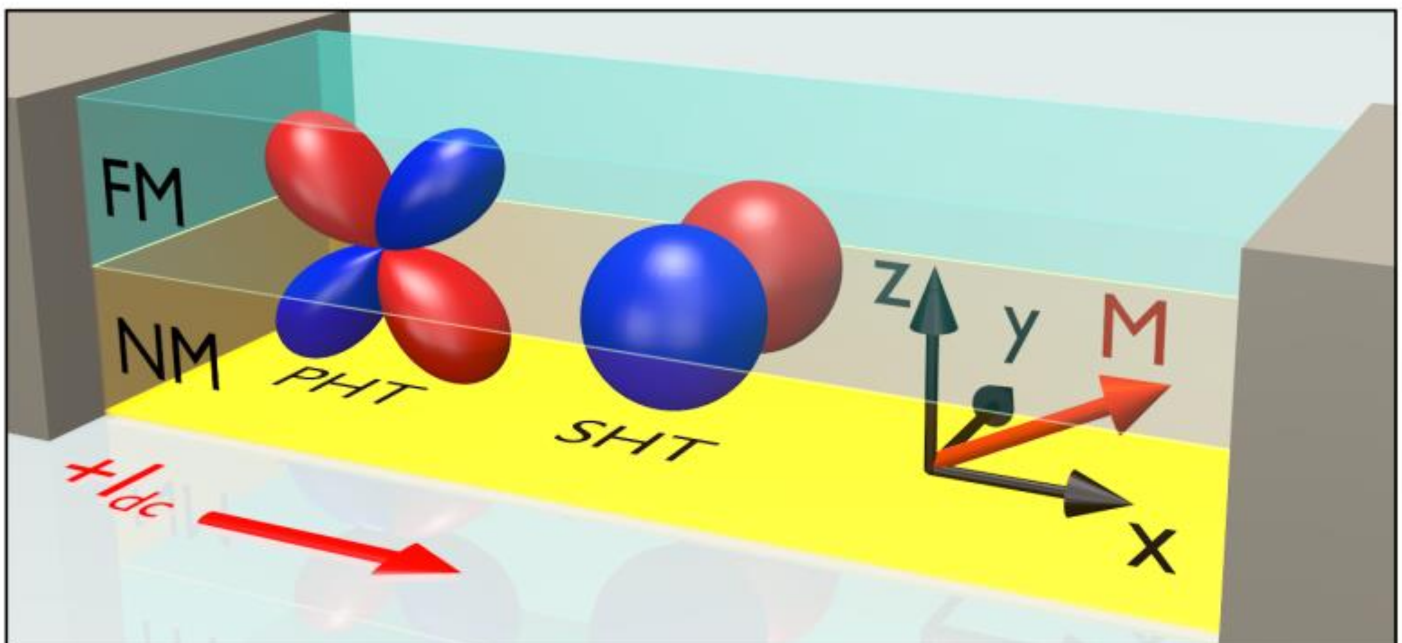


Biaxial antidamping torque

Detailed measurements reveal the antidamping torque is biaxial in the *xz* plane:

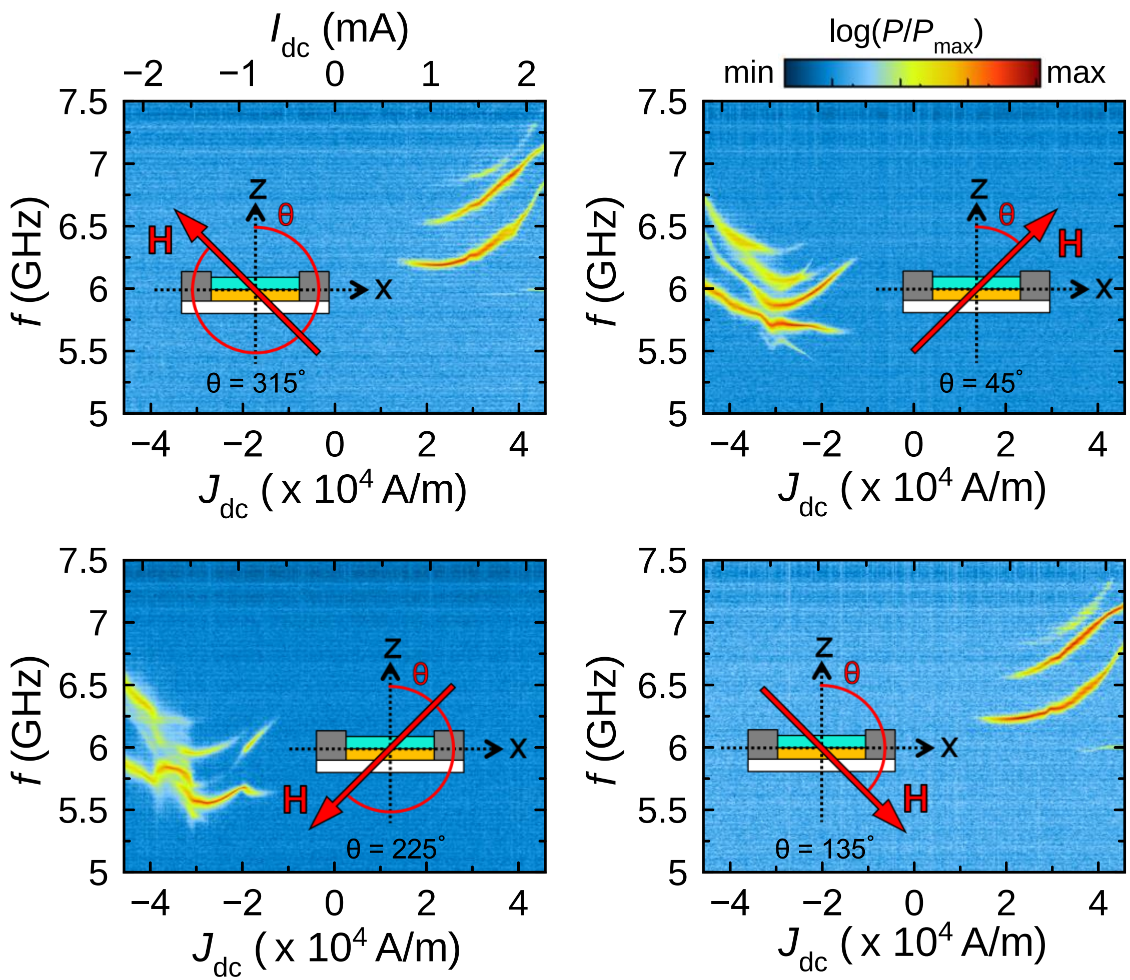
- current-induced damping ~ $I_{dc}\ \sin(\theta)\cos(\theta)\cos(\varphi)$

- maximized for magnetization near 45° to the normal



Microwave emission driven by biaxial torque

- Spontaneous current-driven microwave emission is observed when magnetization is in the *xz* plane
- Lowest critical current for magnetization at 45° to sample normal
- Emission is unaltered upon reversal of magnetization

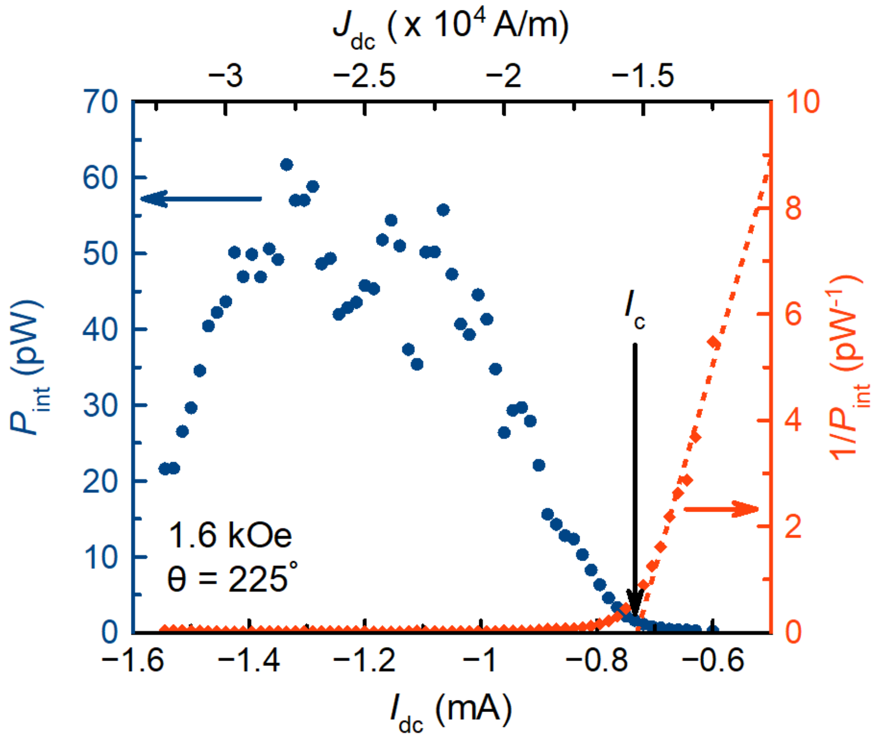


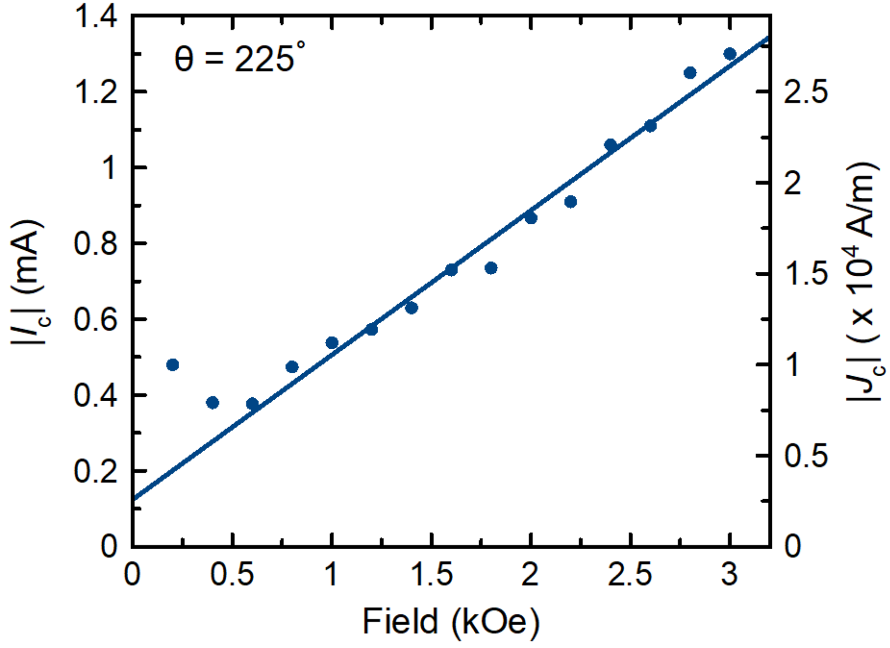
J_{dc} – sheet current density

Consistent with antidamping $\sim I_{dc}\sin(\theta)\cos(\theta)\cos(\varphi)$

Enhanced microwave power

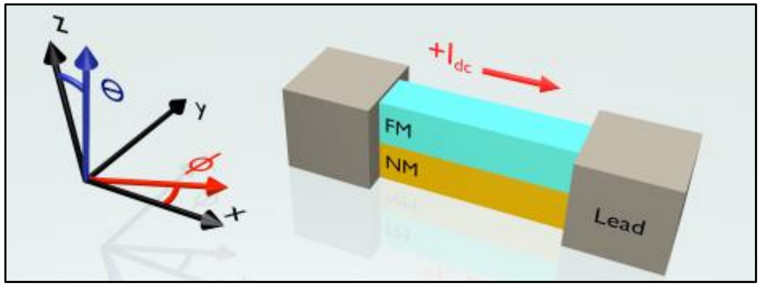
- Higher microwave power than spin Hall oscillators
  - At 45°, conversion of magnetic oscillations into resistance oscillations by AMR is maximum
  - At 45°, both torque efficiency and AMR oscillations are maximized



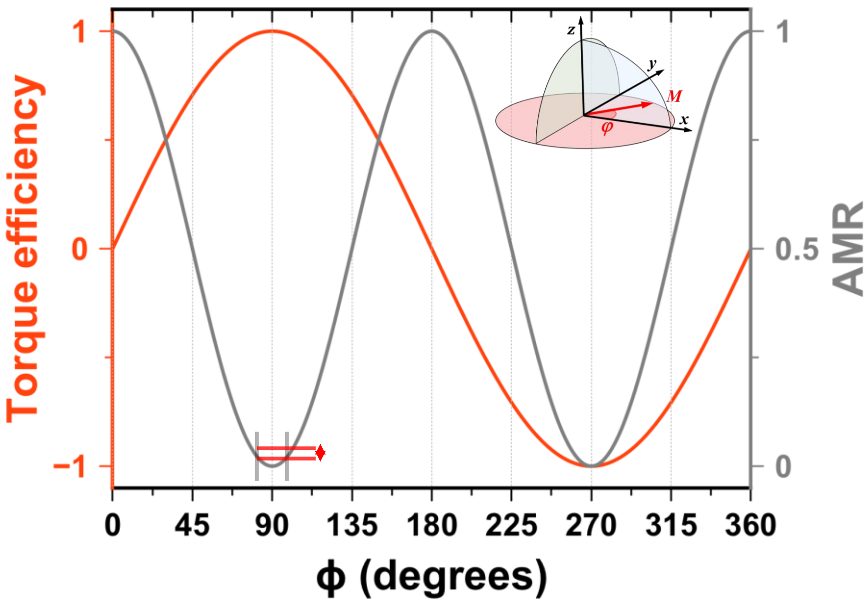


Enhanced microwave power: mechanism

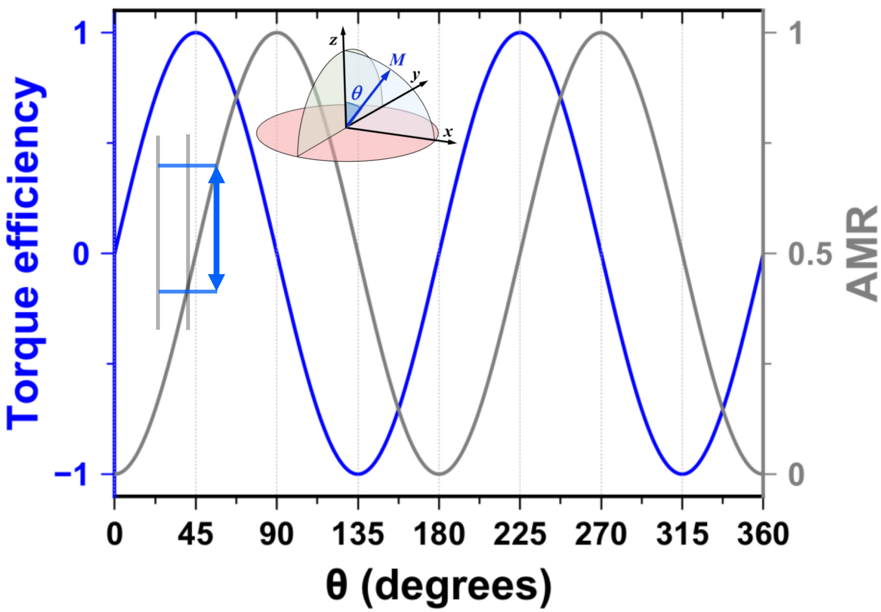
- Magnetic oscillations converted to resistance oscillations
- **AMR** $\sim(\vec{m}\cdot\vec{E})^2 \sim(\vec{m}\cdot\vec{x})^2$



xy plane



xz plane

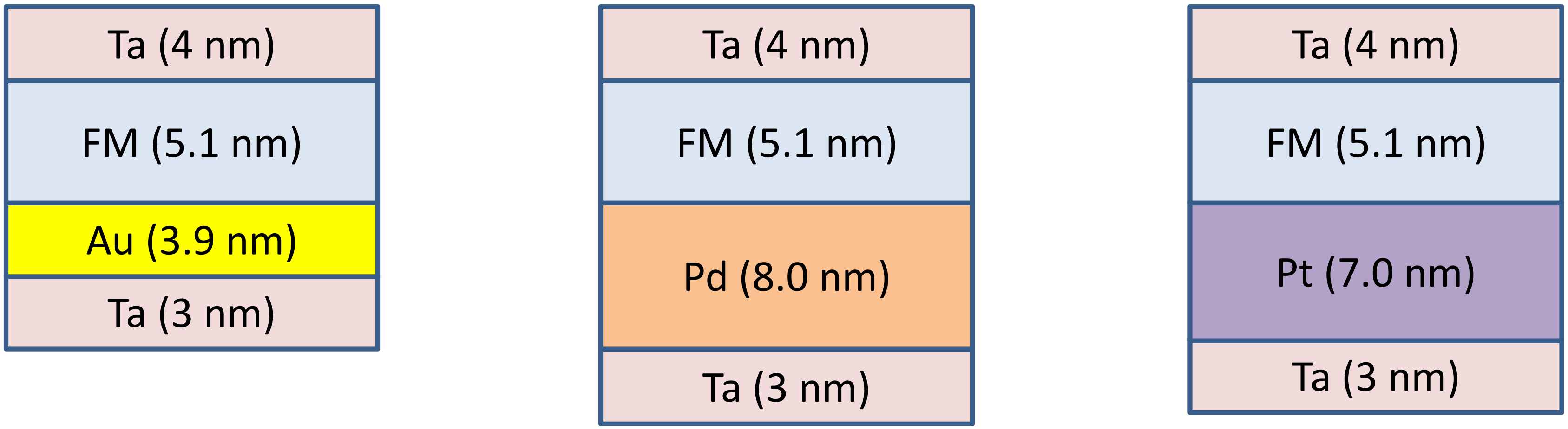


Spin Hall torque efficiency is maximum when AMR oscillations are minimized

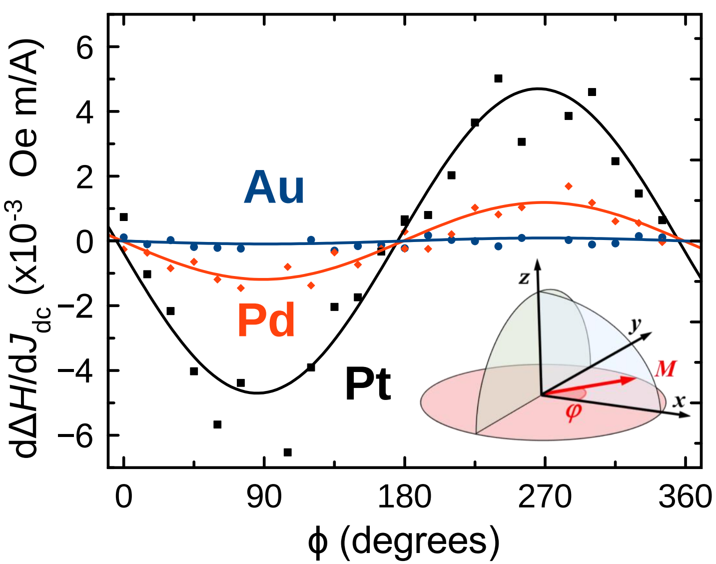
Biaxial antidamping torque efficiency and AMR oscillations are maximized at 45°

Origin of torque: NM material dependence ?

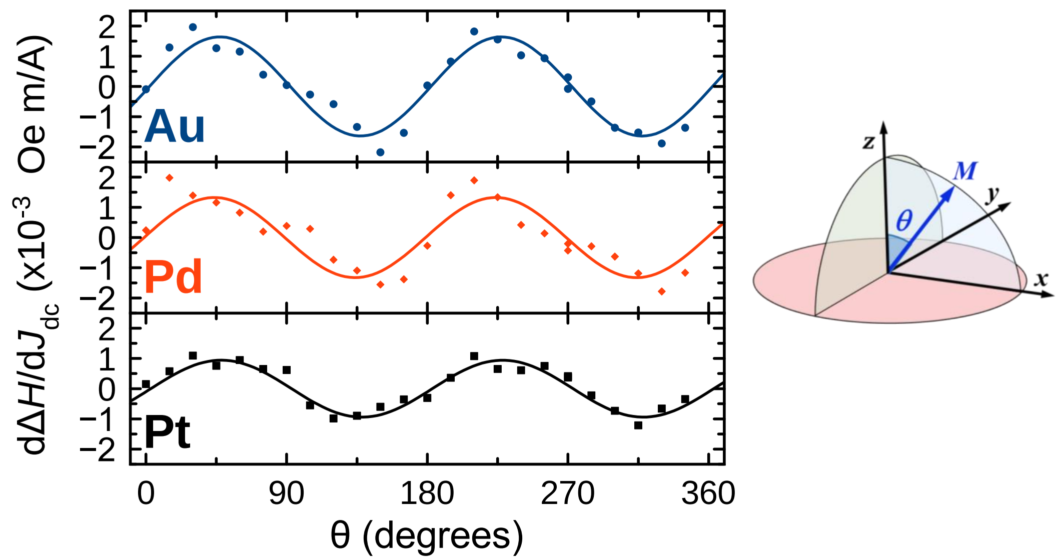
Three samples with identical resistances of Au, Pd and Pt layers



_xy_-plane, spin Hall torque



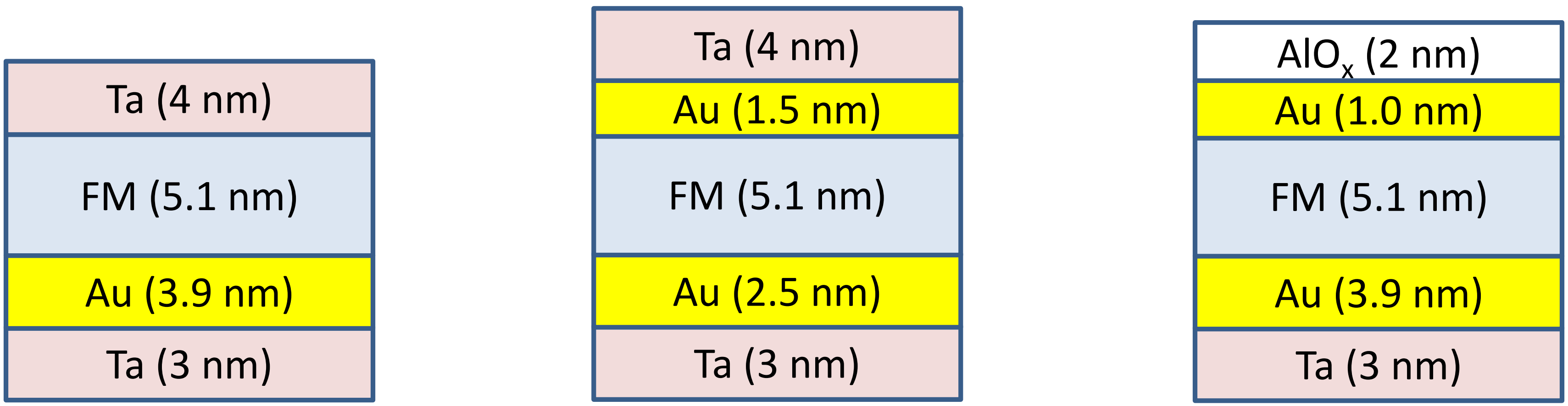
_xz_-plane, new biaxial torque



Origin of torque: FM/NM interface dependence ?

Measured biaxial antidamping torque is not purely interfacial

[1] [2] [3]

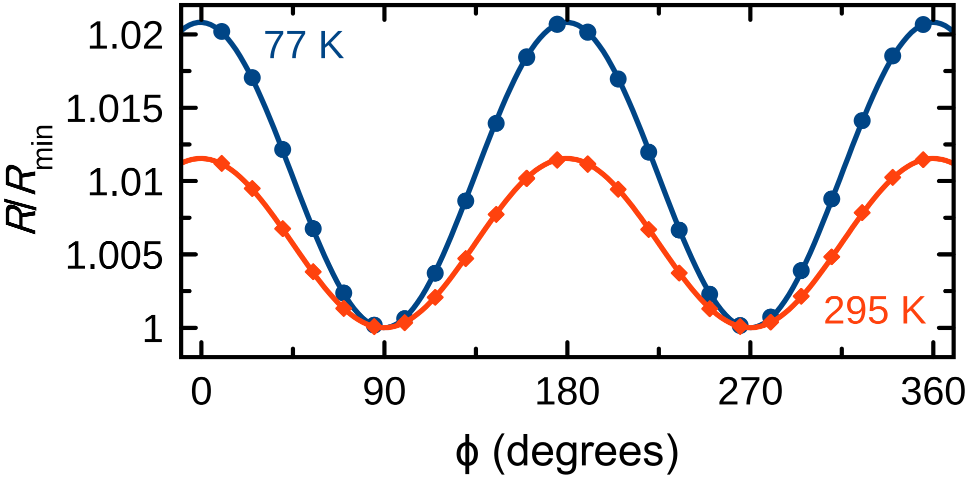


Large biaxial antidamping | No biaxial antidamping | Large biaxial antidamping

Samples [2] and [3] have the same Au/FM/Au interfaces but radically different biaxial antidamping torques

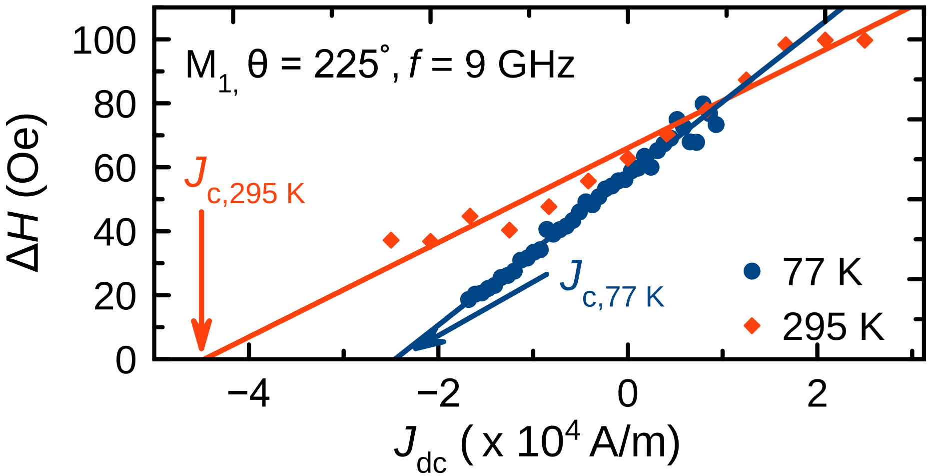
Relation to anisotropic magneto-resistance ?

Both AMR and antidamping torque increase with decreasing temperature



$$\frac{AMR_{77\ K}}{AMR_{295\ K}} = 1.8$$

$$\frac{J_{c,295K}}{J_{c,77\ K}} = 1.8$$



Antidamping torque magnitude is proportional to AMR

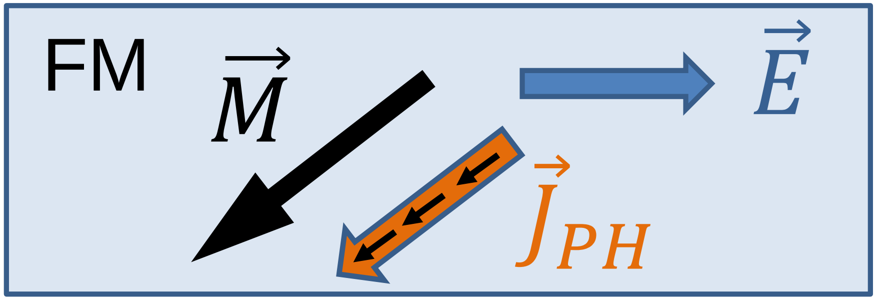
Planar Hall current

Spin-orbit interaction gives rise to magnetization-dependent spin-polarized electrical current in a ferromagnetic conductor:

- flows in the direction of magnetization
- polarized in the direction of magnetization
- magnitude depends on the direction of magnetization
- gives rise to anisotropic magneto-resistance (AMR) and planar Hall effect

$$\vec{J}_{PH} \sim (\vec{E} \cdot \vec{m})\vec{m}$$

$$\vec{p} \sim \vec{m}$$



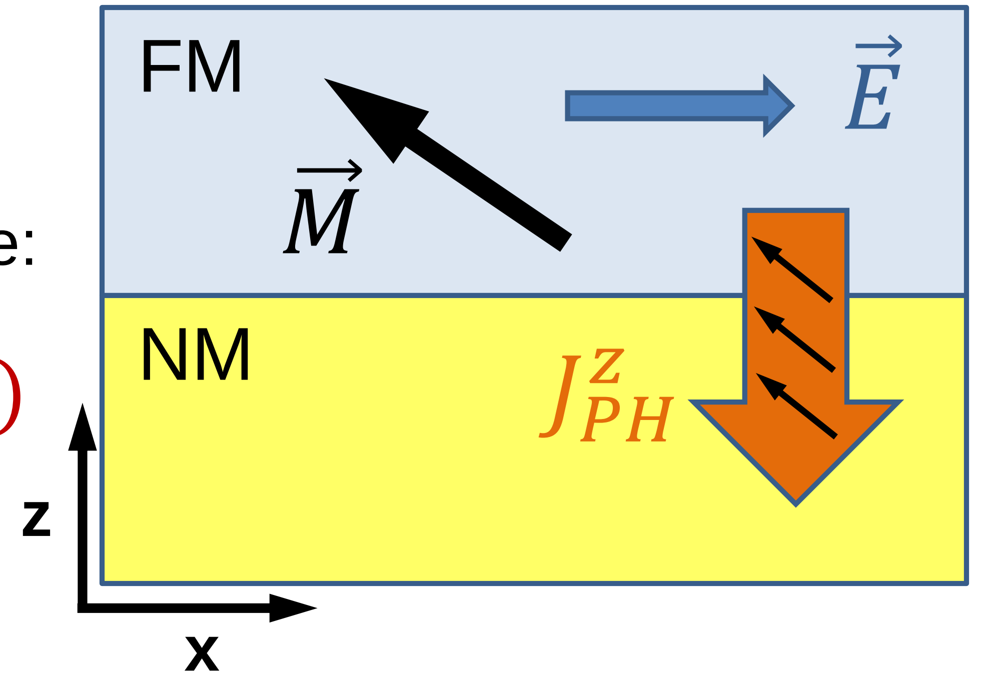
Taniguchi et al. Phys. Rev. Appl. ***3****, 044001 (2015)*

Kokado et al. J. Phys. Soc. Japan ***81****, 024705 (2012)*

Spin transfer by planar Hall current

In a FM/NM bilayer, spin-polarized planar Hall current carried across FM/NM interface:

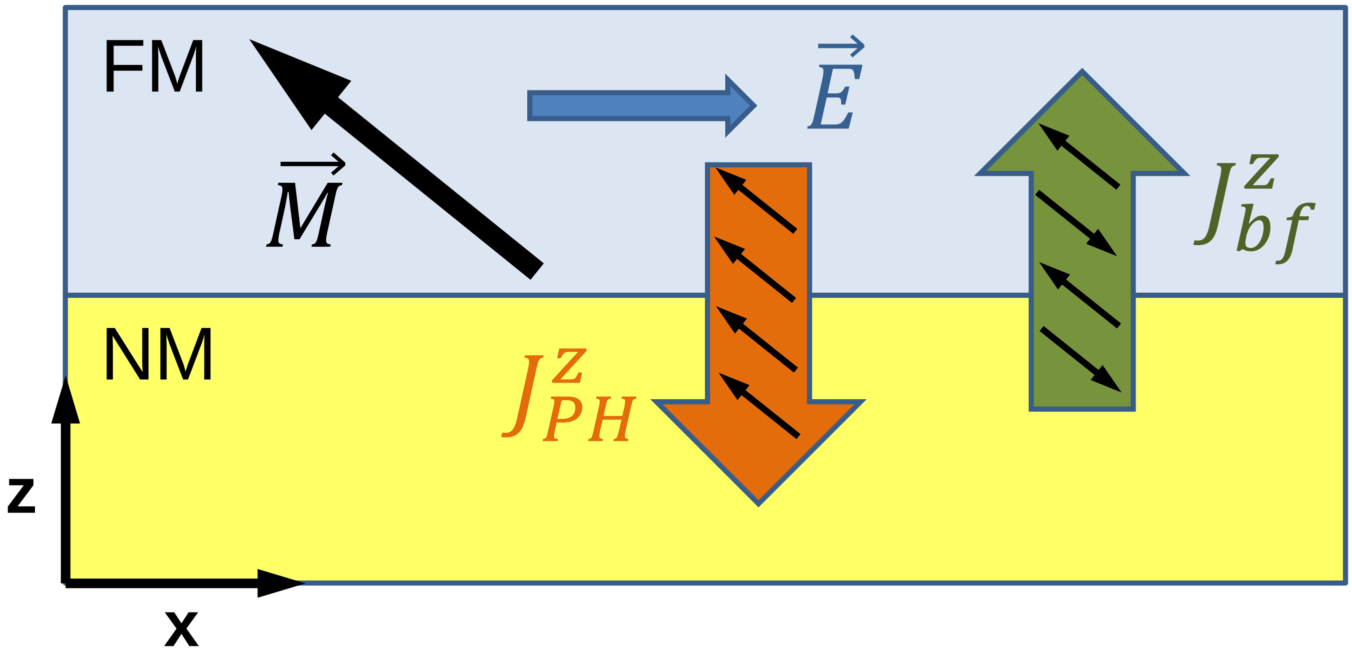
$$\left(\vec{J}_{PH} \cdot \hat{z}\right) \sim \left(\vec{E} \cdot \vec{m}\right)\left(\hat{z} \cdot \vec{m}\right)$$



$$\left(\vec{J}_{PH} \cdot \hat{z}\right) \sim E \sin(\theta) \cos(\theta) \cos(\varphi)$$

Angular dependence of the component of J_{PH} flowing across the FM/NM interface is identical to that of the measured biaxial antidumping torque

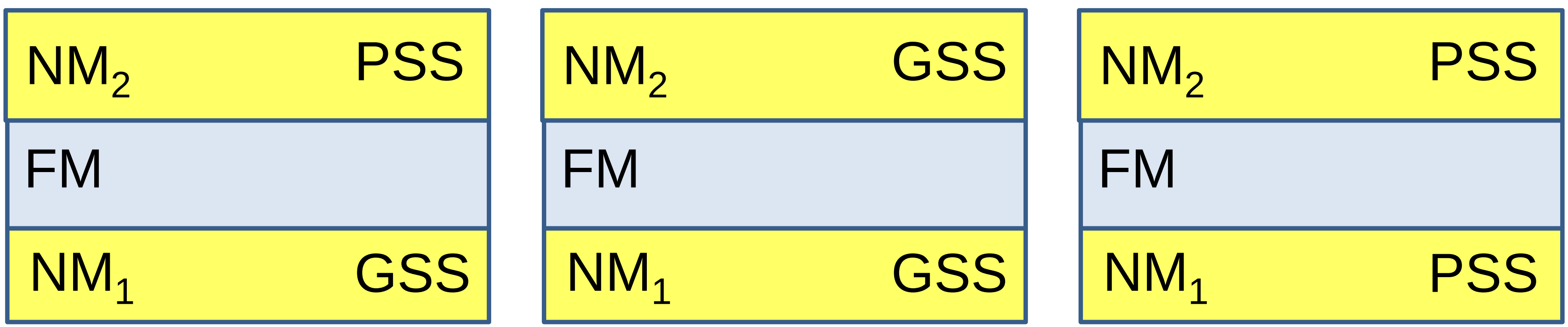
Planar Hall torque



- In steady state, no net charge current flow across the FM/NM
- A backflow charge current J_{bf} must flow from NM to FM
- To maximize net spin transfer across the NM/FM interface, J_{bf} must be unpolarized (NM must be a good spin sink)

Dependence of planar Hall torque on NM layers

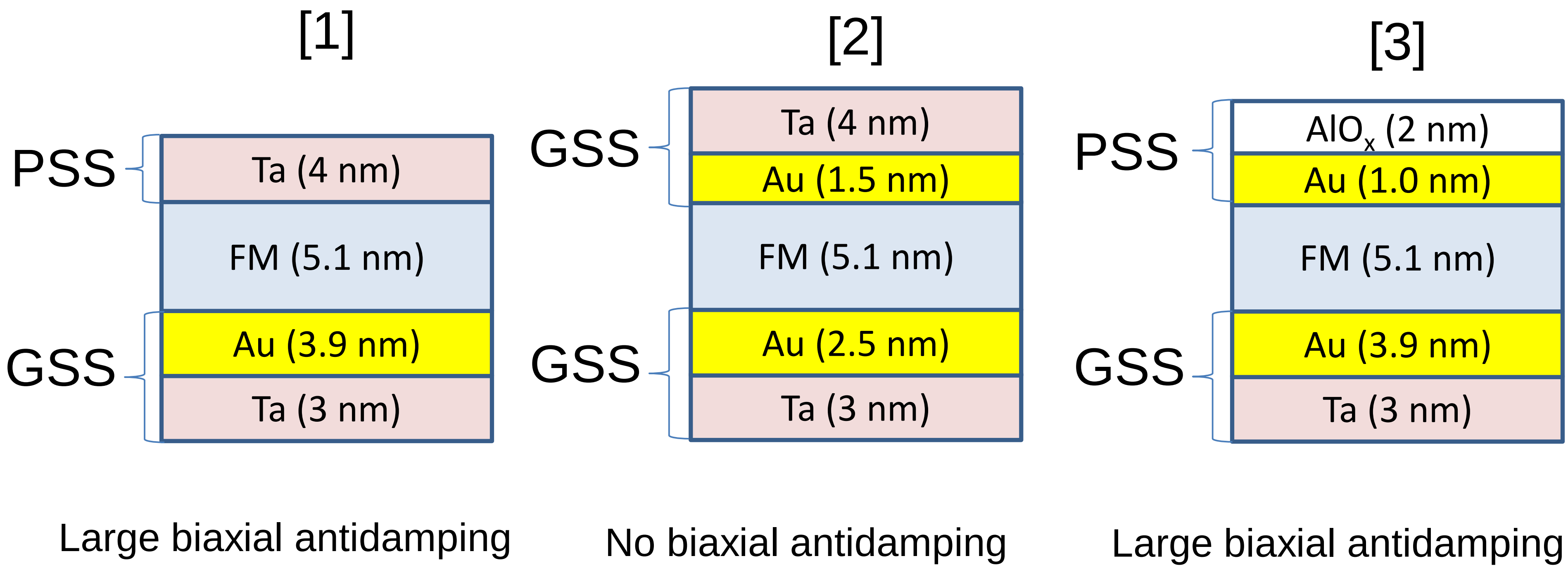
- To maximize planar Hall torque in $NM_1/FM/NM_2$, one NM layer must be a good spin sink (GSS), while the other a poor spin sink (PSS)
- Otherwise net spin transfer to FM is zero



Large PHT | Negligible PHT | Negligible PHT

Dependence of PHT on NM spin scattering

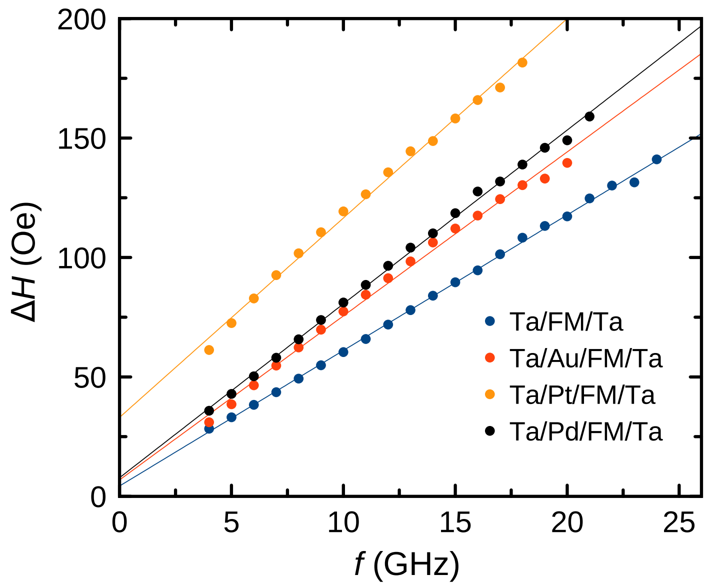
Magnitude of the biaxial antidamping torque in samples with different capping layers are explained by the NM layer spin sinking



- Spin pumping measurements are used find is NM is a GSS or PSS
- Spin flipping in NM can happen anywhere in the layer, so the effect is not purely interfacial, explains nonlocality

Spin pumping measurements

- Broadband FMR measurements on films
- Determined damping enhancement by spin pumping to determine which NM layers are good spin sinks



Sample	$4\pi M_{eff}$ (Oe)	g	α (10^{-3})	$\Delta H(0)$ (Oe)
Ta(3.0)/FM/Ta(4.0)	7160	2.17	17.2	4
Ta(3.0)/Au(3.9)/FM/Ta(4.0)	3010	2.17	20.9	7
Ta(3.0)/Au(2.5)/FM/Au(1.5)/Ta(4.0)	3220	2.14	21.7	4
Ta(3.0)/Pt(7.0)/FM/Ta(4.0)	1480	2.17	25.3	33
Ta(3.0)/Pd(8.0)/FM/Ta(4.0)	4060	2.18	22.2	8
Ta(3.0)/Au(3.9)/FM/Au(1.0)/AlO_x(2.0)	2760	2.14	20.6	20

Good spin sinks (GSS): Au/Ta, Pd/Ta, Pt/Ta

Poor spin sinks (PSS): Ta, AlO_x, Au/AlO_x

Recent quantitative theory of PHT

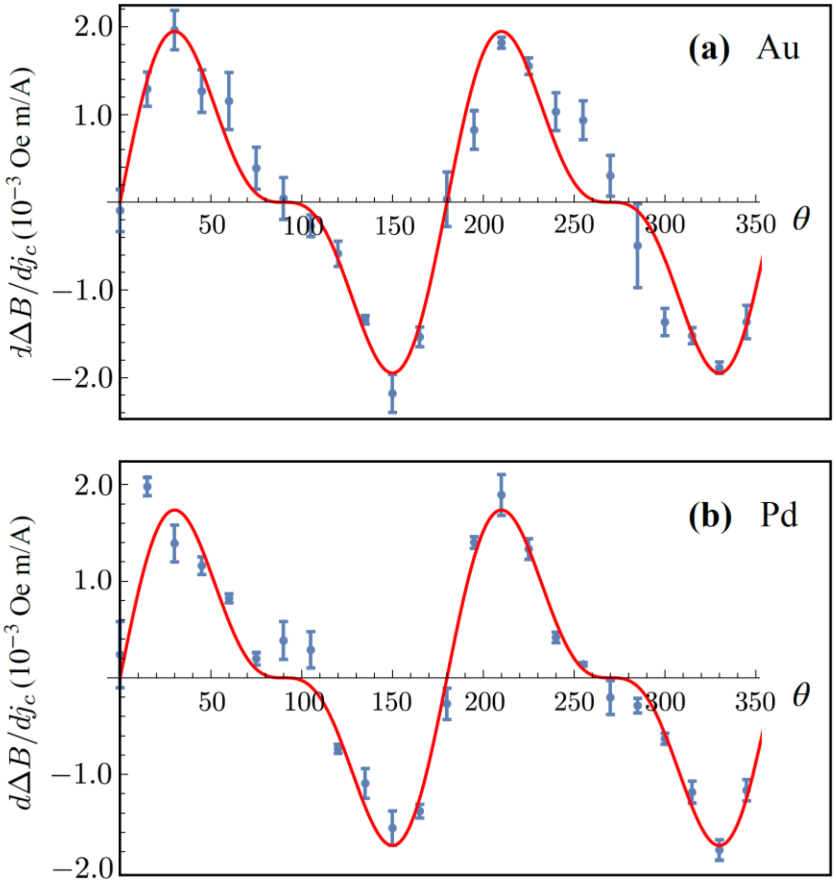
- Recently a quantitative theory of PHT has been developed

  H. Ochoa, R. Zarzuela,Y. Tserkovnyak, JMMM ***538****, 168262 (2021)*

- It predicts an additional term in the angular dependence of PHT current-induced damping:

$$\sim\sigma_{AMR}\left[\sin(2\theta)+\frac{1}{2}\sin(4\theta)\right]\cos(\varphi)$$

- Our data are better fit with this $\sin(4\theta)\cos(\varphi)$ term
  - without additional fitting parameters



Summary

- Strong antidamping torque with unusual biaxial symmetry is found in NM/FM bilayers
- The torque is strong enough to enable operation of spin torque oscillators with better efficiency than in SHOs
- The origin of the new torque is spin-polarized planar Hall current in the ferromagnetic layer. Thus the torque has the same origin as anisotropic magneto-resistance.

*C. Safranski, E. Montoya, IK, Nature Nanotechnology **14**, 27 (2019)*

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