Vector measurements of the current induced effective fields in Ta|CoFeB|MgO heterostructures

Masamitsu Hayashi, Junyeon Kim, Jaivardhan Sinha, Seiji Mitani

National Institute for Materials Science

Tetsuhiro Suzuki

Renesas Electronics

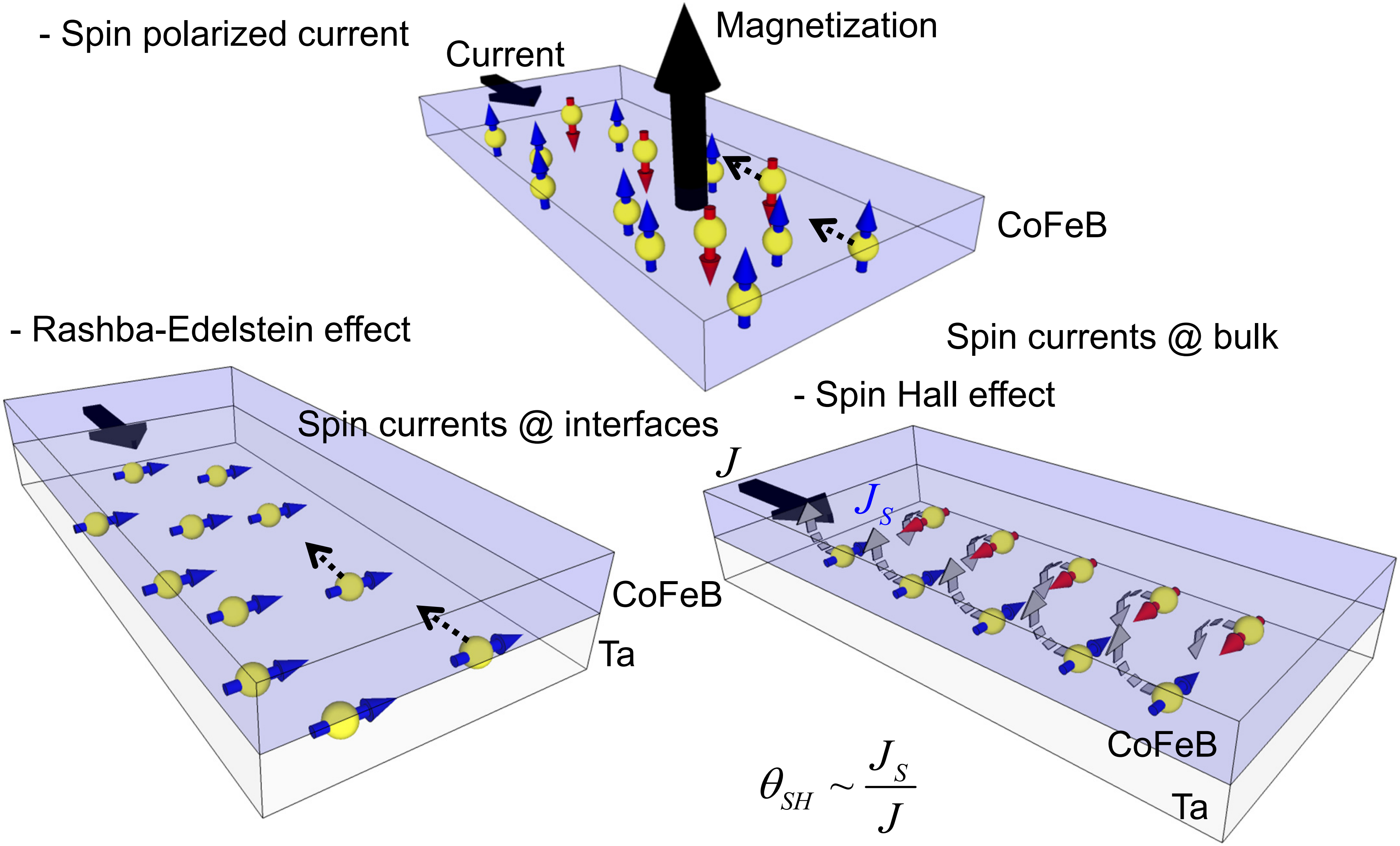
Michihiko Yamanouchi, Shunsuke Fukami, and Hideo Ohno

Tohoku University

Acknowledgement: JSPS FIRST program

Email: hayashi.masamitsu@nims.go.jp

Spin current generation



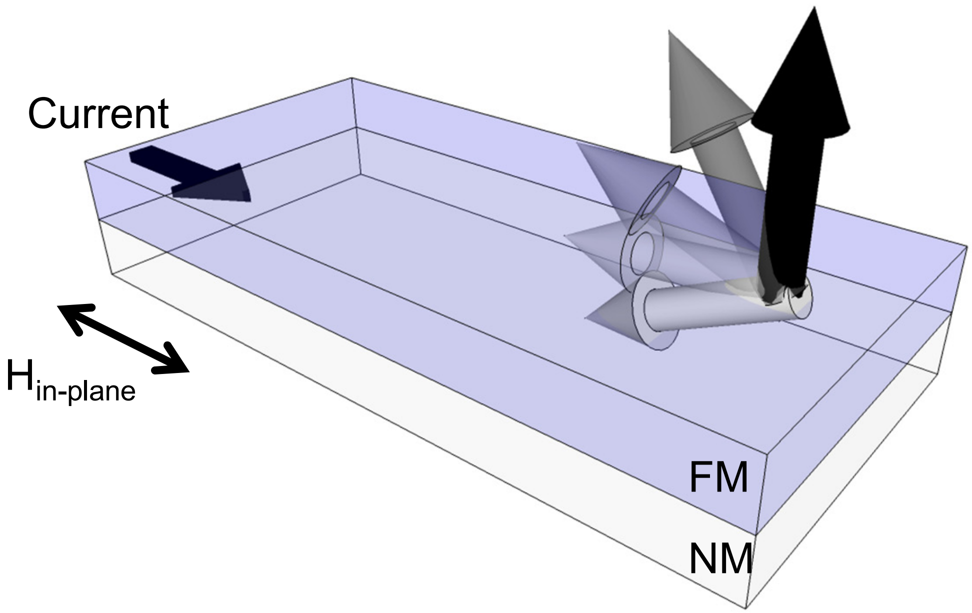
$$\theta_{SH} \sim \frac{J_S}{J}$$

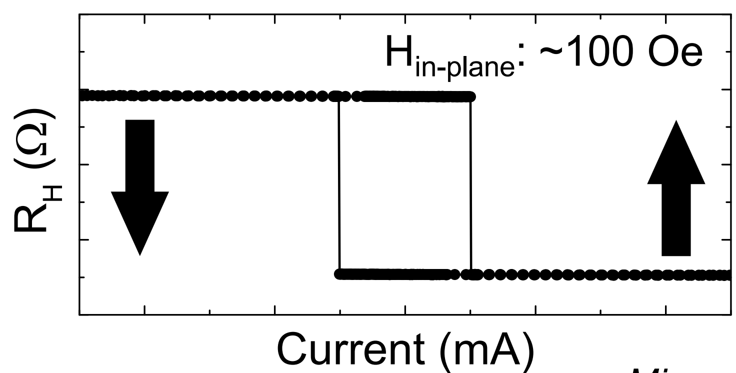
Pt θ_{SH}: ~0.02 to ~0.07

Ta θ_{SH}: ~-0.002 to ~-0.15

Morota et al., PRB ***83****, 174405 (2011)*
Liu et al., arXiv:1111.3702
Liu et al., Science ***336****, 555 (2012)*

Magnetic switching with in-plane current & in-plane field





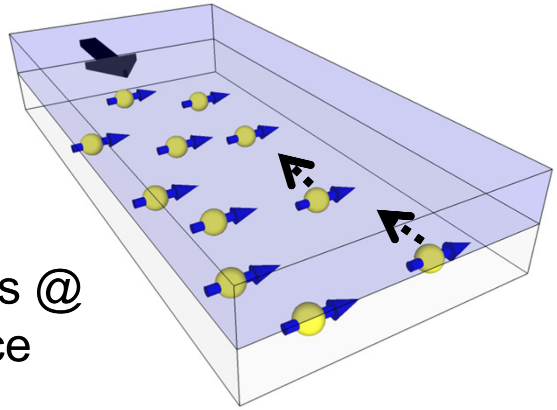
Miron et al., Nature ***476****, 189 (2011)*

Liu et al., Science ***336****, 555 (2012)*

- In-plane current and in-plane field can set the magnetization direction perpendicular to the plane

Current induced domain nucleation

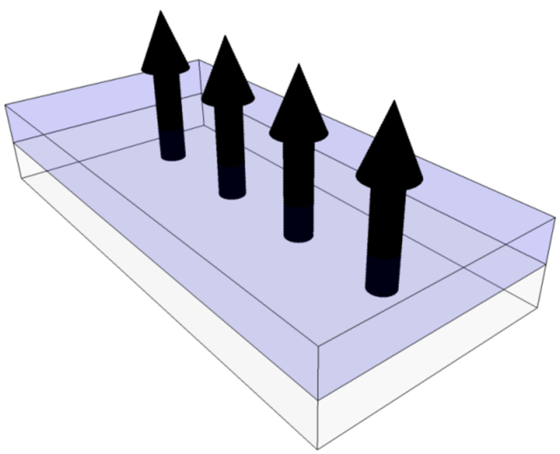
- Rashba-Edelstein effect



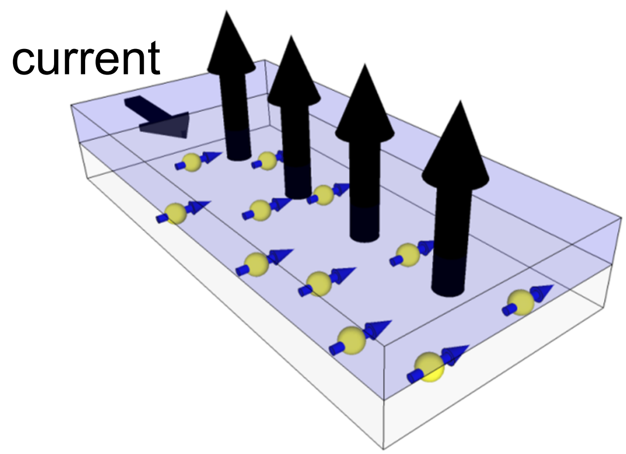
Spin currents @ interface

Miron et al., Nature Mater. ***9****, 230 (2010)*

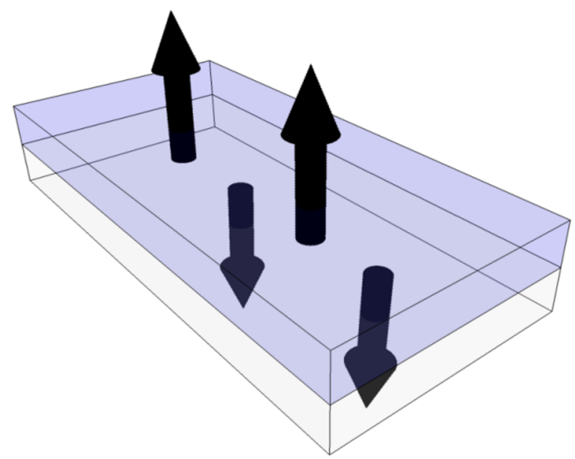
1. Start from uniform magnetization



2. Apply in-plane current



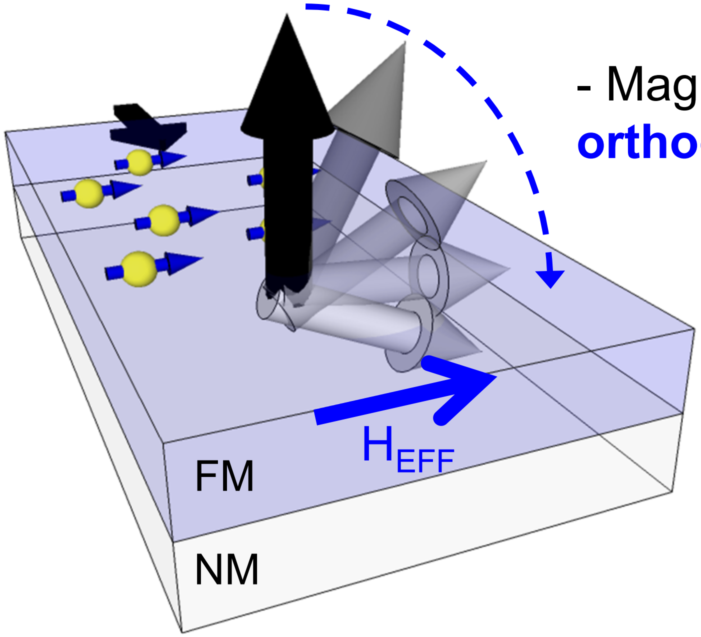
3. Turn off current



→ Random nucleation of reversed domains

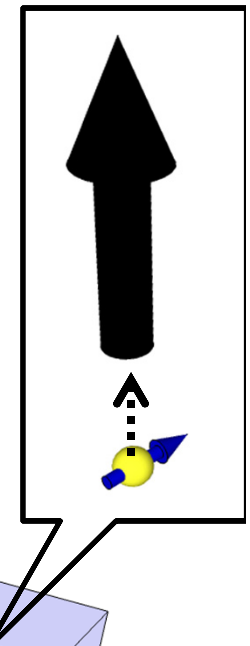
Spin current acting on magnetization

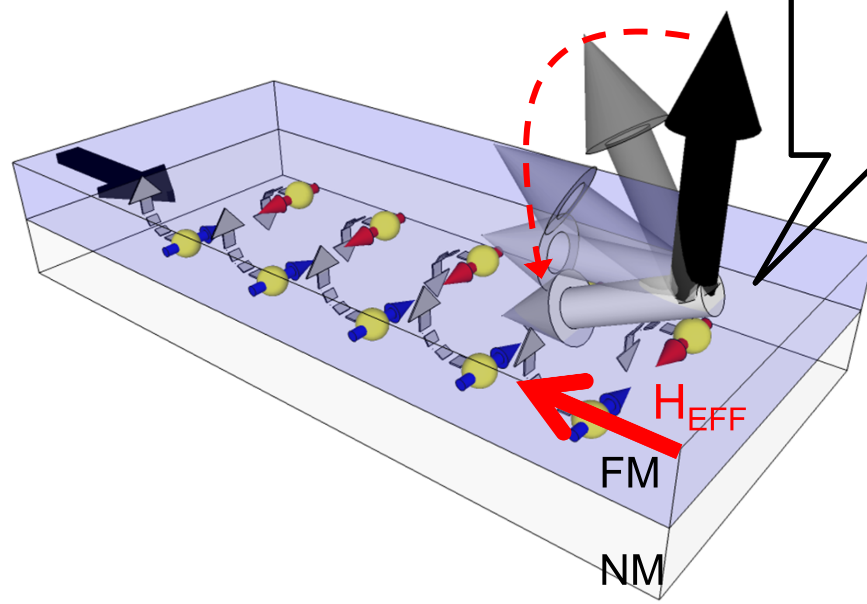
- Rashba + Exchange interaction



- Magnetization tilts toward the direction **orthogonal to the current flow**

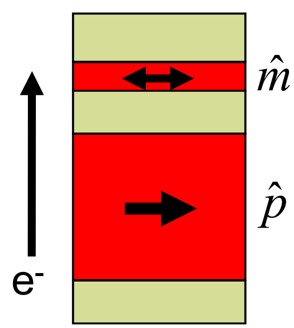
- Spin Hall + spin torque
- Magnetization tilts toward the direction **along the current flow**





- Spin transfer torque

$$\sim \hat{m} \times (\hat{m} \times \hat{p})$$



- Tilting direction of the moments gives information on the spin currents!

Current induced effective fields

- Apply magnetic field to assist/counteract the current effect
  → Estimate e***ffective magnetic field*** generated by the spin currents

- 3 Pt|0.6 Co|3 AlO_X

- Transverse field: ~3000~10000 Oe @ J~10^8 A/cm^2

  Miron et al., Nature Mater. ***9****, 230 (2010)*
  Pi et al., APL ***97****, 162507(2010)*

- Longitudinal field: ~800 Oe @ J~10^8 A/cm^2

  Miron et al., Nature ***476****, 189 (2011)*

- 1 Ta|1 CoFeB|2 MgO|1 Ta

- Transverse field: ~1900 Oe @ J~10^8 A/cm^2

  Suzuki et al., APL ***98****, 142505 (2011)*

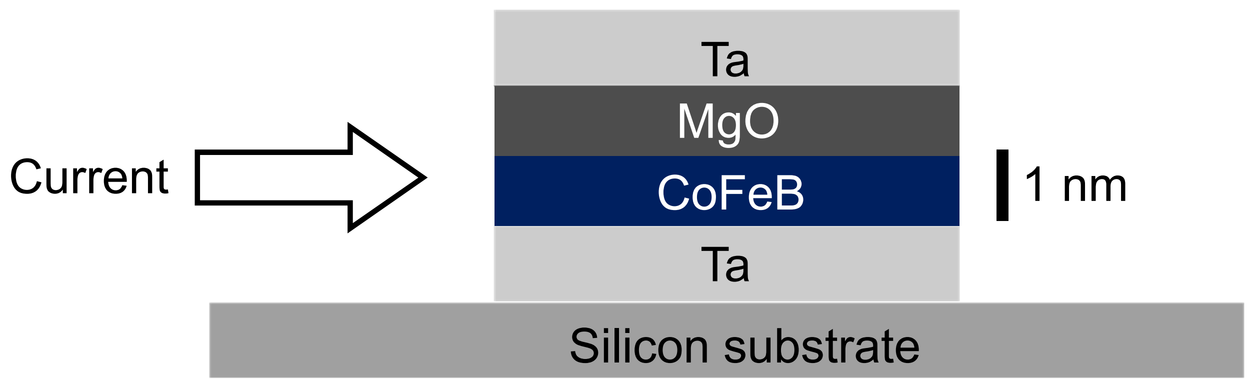
- No transverse, non-zero longitudinal

  Liu et al., Science ***336****, 555 (2012)*

Motivation

Quantitative determination of the current induced effective field in Ta|CoFeB|MgO

- Film stack: Sub|Ta|CoFeB|MgO|Ta

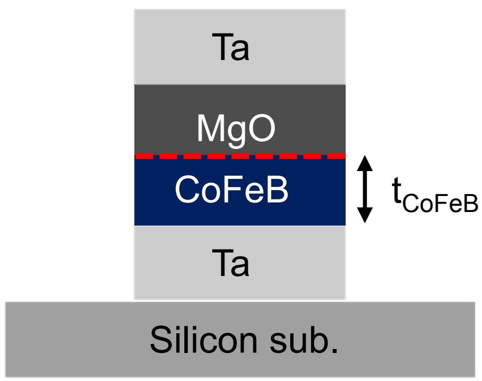


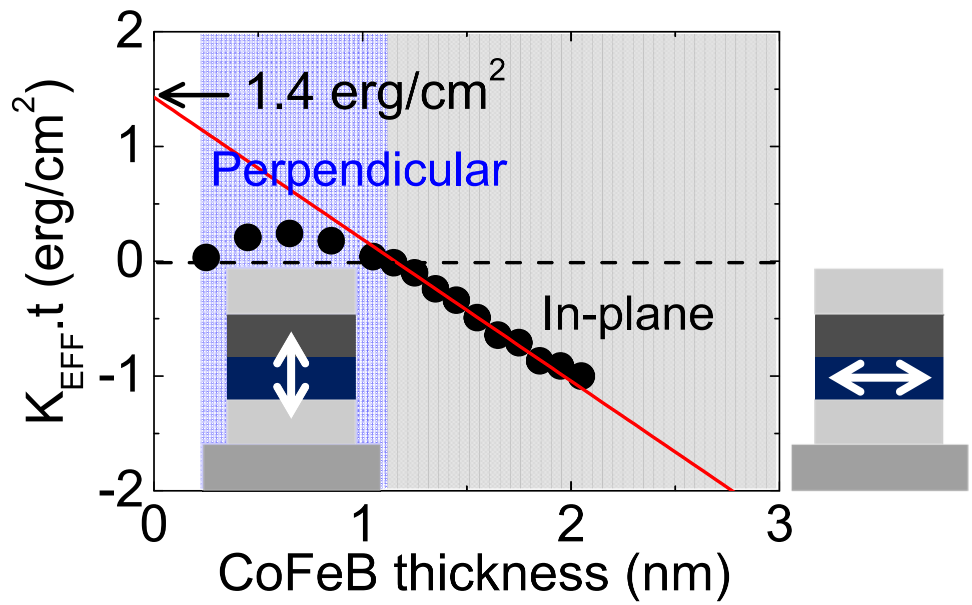
Perpendicular magnetic anisotropy in CoFeB|MgO

- CoFeB|MgO interface gives the perpendicular magnetic anisotropy

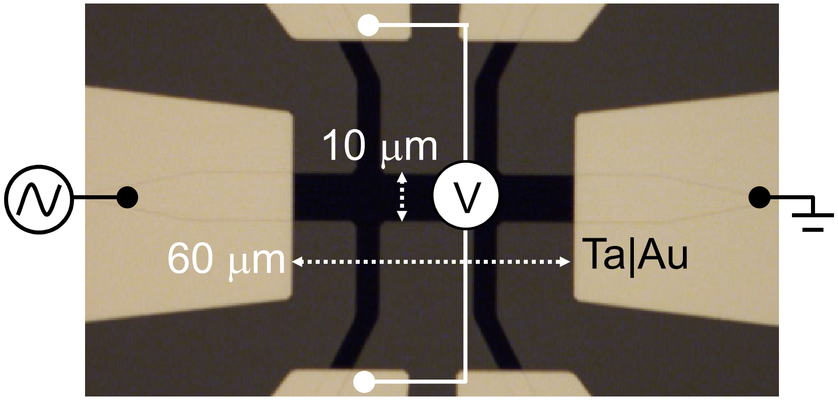
Ikeda et al., Nature Mater. ***9****, 721 (2010)*

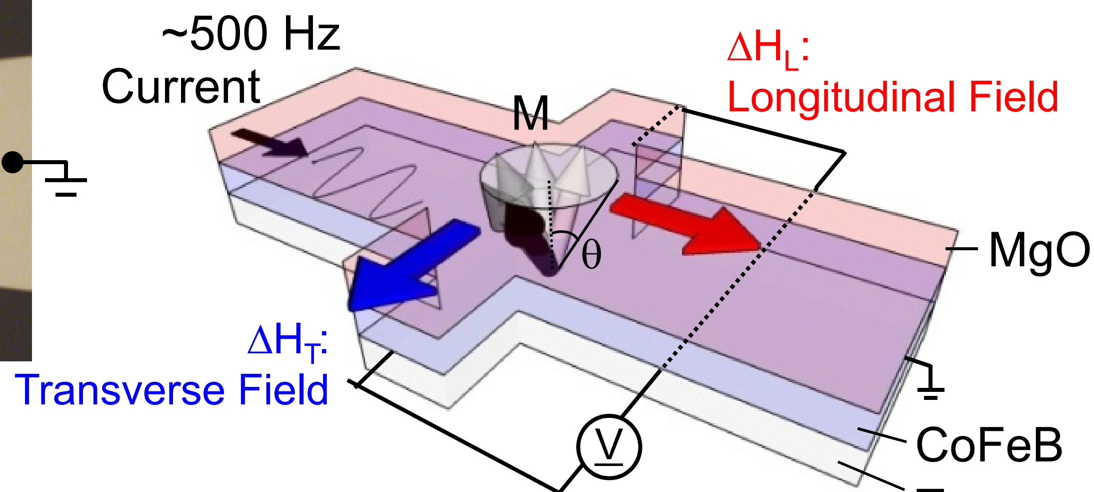
- Film stack: Sub|Ta|CoFeB|MgO|Ta





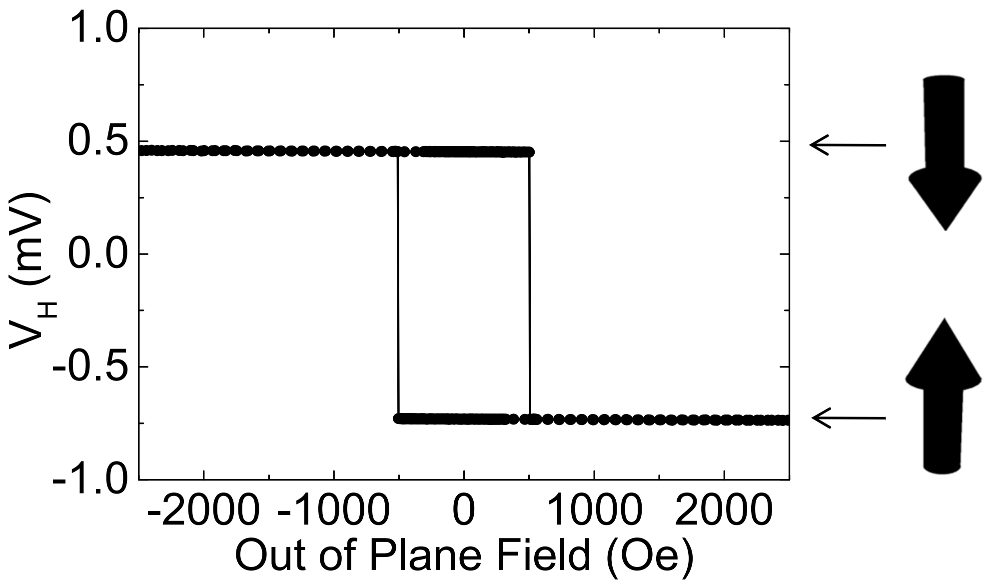
Experimental setup





$$V_H = R_H I$$

- Extraordinary Hall effect

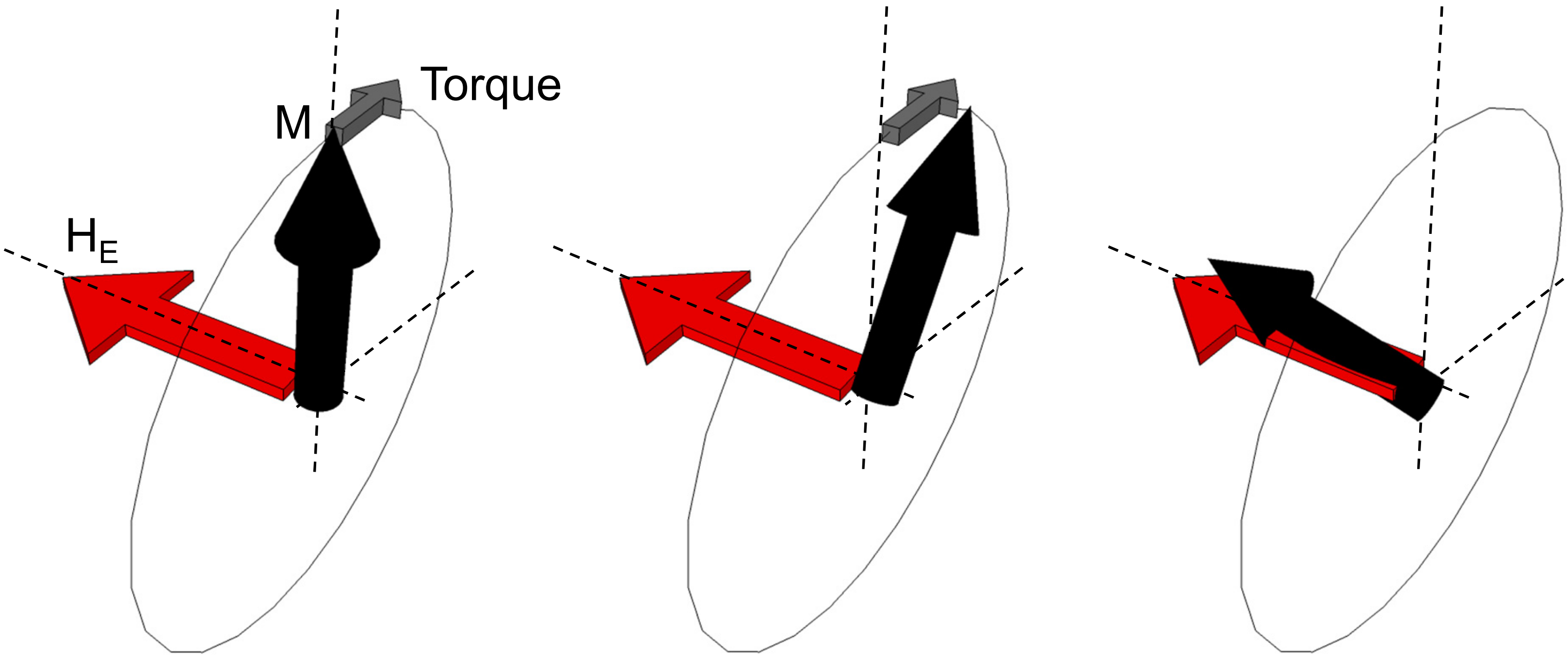


$$V_H = R_H I$$

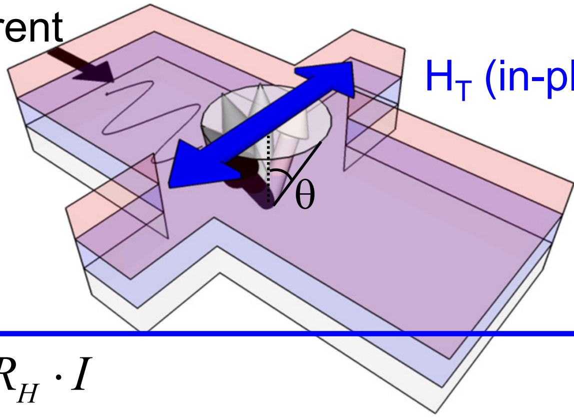
$$R_H(H) = \Delta R_H \cos\theta$$

Effective field and Torque

$$\frac{\partial \hat{m}}{\partial t} = -\gamma \hat{m} \times \left(\vec{H}_E \right) + \alpha \hat{m} \times \frac{\partial \hat{m}}{\partial t}$$



Current induced effective fields: AC measurements



- Measure first and second harmonic Hall voltage

Pi *et al.*, APL **97**, 162507(2010)

$$V_H = R_H \cdot I$$

$$I = \Delta I \sin \omega t \qquad R_H(H) = \Delta R_H \cos\theta$$

$$\theta = \theta(H_T + \Delta H_T \sin\omega t) \sim \theta(H_T) + \frac{\partial\theta}{\partial H_T}\Delta H_T \sin\omega t$$

$$R_H(H) = \Delta R_H \cos\theta \sim \Delta R_H \left(\cos\theta_0 - \sin\theta_0 \cdot \frac{\partial\theta}{\partial H_T}\Delta H_T \sin\omega t \right)$$

$$V_H \sim \Delta R_H \Delta I \left(\cos\theta_0 \sin\omega t - \frac{\partial \cos\theta_0}{\partial H_T}\frac{1}{2}\Delta H_T \cos 2\omega t \right)$$

$$\theta_0 \sim \frac{H_T}{2K_u / M_S - 4\pi M_S + H_Z} \equiv \frac{H_T}{D}$$

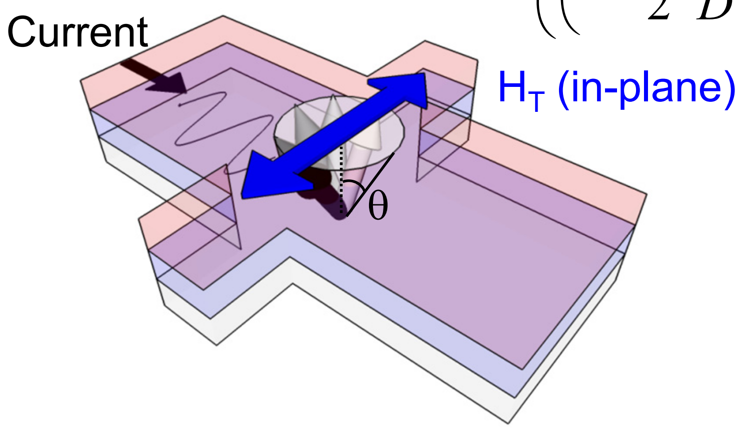
$$V_H \sim \Delta R_H \Delta I \left(\left(1 - \frac{1}{2}\frac{H_T{}^2}{D^2} \right) \sin\omega t + \left(\frac{H_T}{D^2} \right) \frac{1}{2}\Delta H_T \cos 2\omega t \right) \qquad (\theta << 1)$$

Current induced effective fields: AC measurements

$\Delta I \sin \omega t$

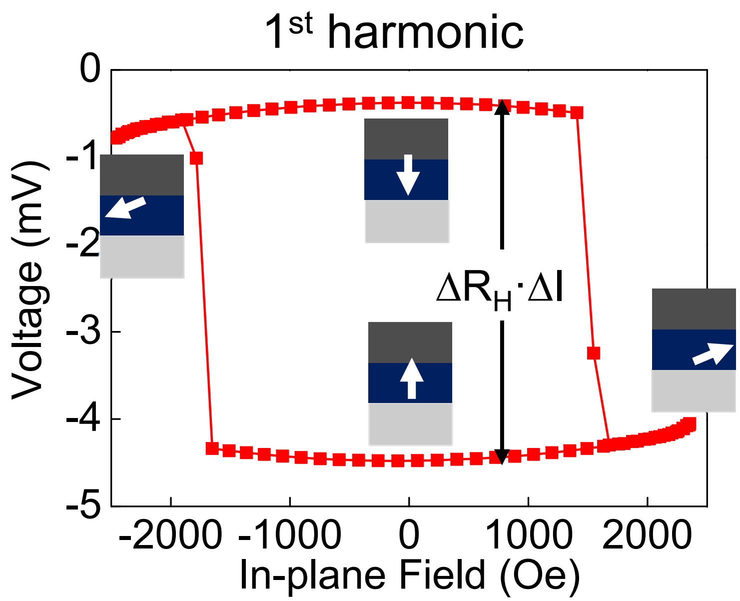
$$V_H \sim \Delta R_H \Delta I \left(\left(1 - \frac{1}{2}\frac{H_T{}^2}{D^2} \right) \sin \omega t + \left(\frac{H_T}{D^2} \right) \frac{1}{2} \Delta H_T \cos 2\omega t \right)$$

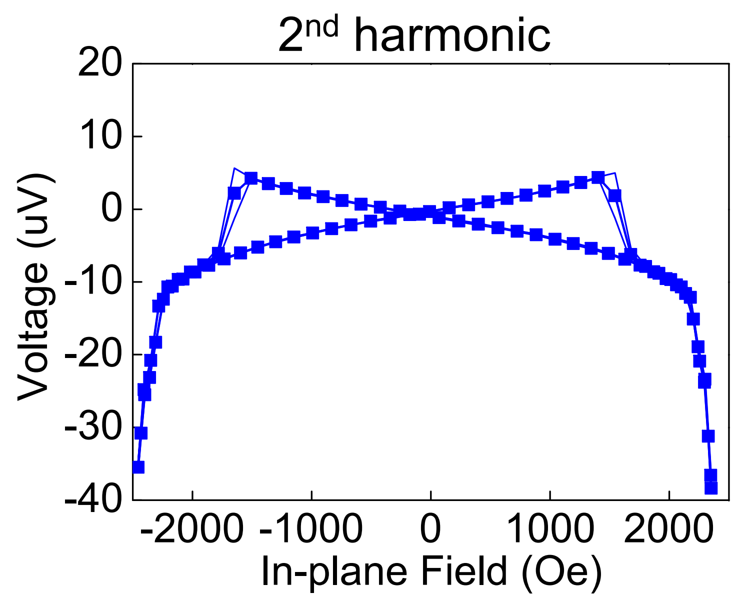
$$D = D(K, M_S)$$

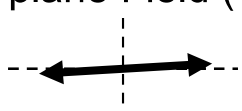


$$\frac{\partial^2 V_H{}^{1st}}{\partial H_T{}^2} \sim -\frac{\Delta R_H \Delta I}{D^2} \qquad \frac{\partial V_H{}^{2nd}}{\partial H_T} \sim -\frac{\Delta R_H \Delta I}{D^2}\frac{\Delta H_T}{2}$$

$$\Delta H_T = -2 \left(\frac{\partial V_H{}^{2nd}}{\partial H_T} \right) \Big/ \left(\frac{\partial^2 V_H{}^{1st}}{\partial H_T{}^2} \right) \qquad (\theta << 1)$$

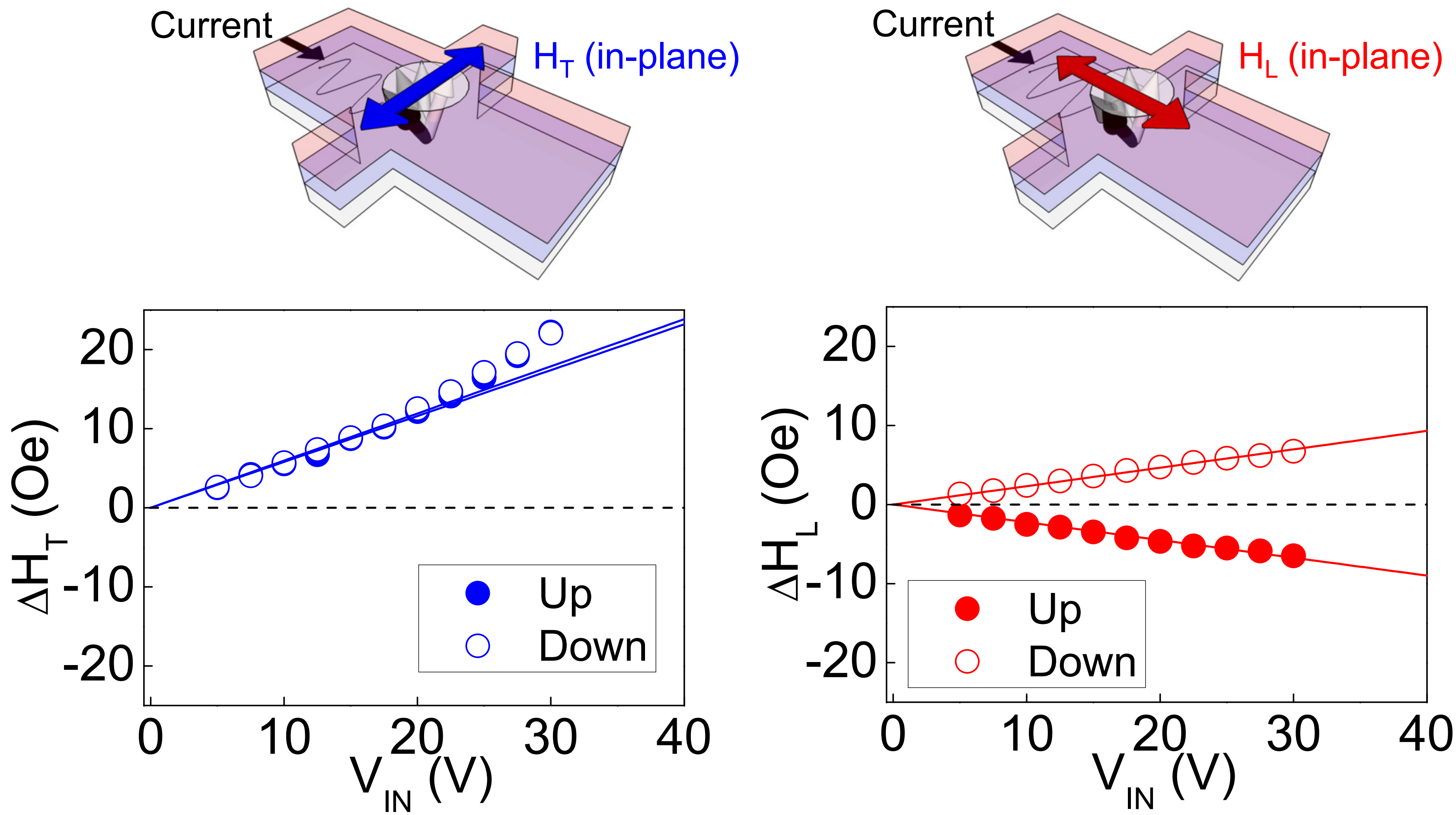






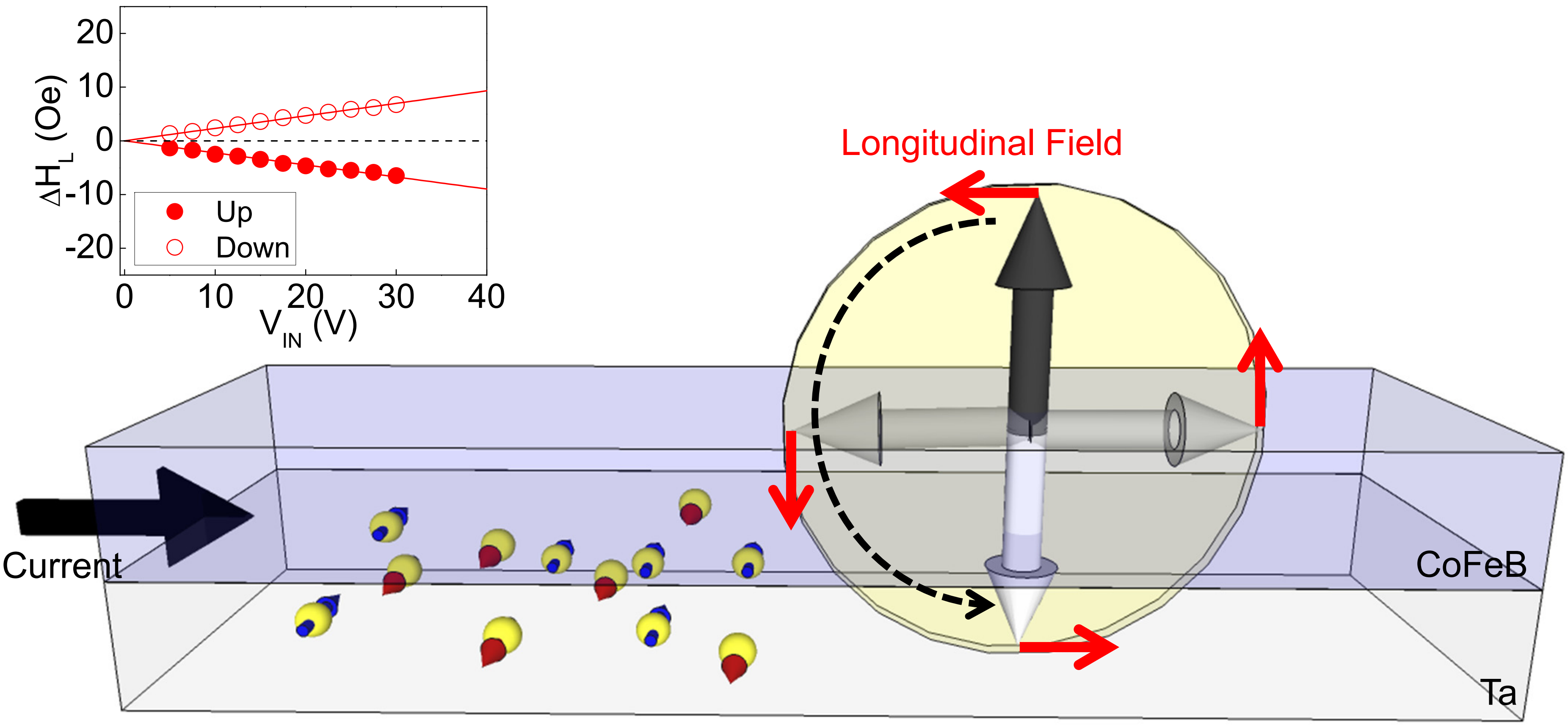
ΔH_T~60 Oe

Current induced effective fields

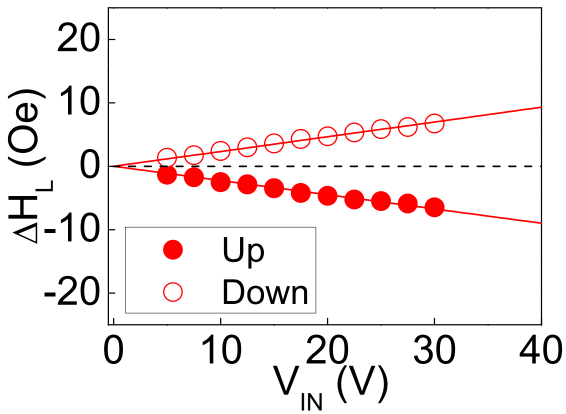


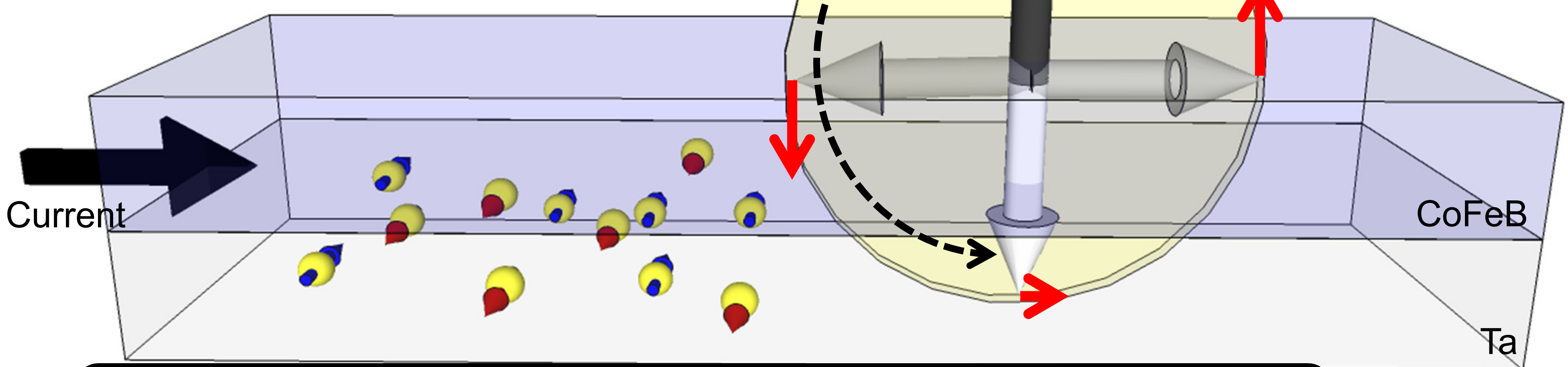
- Effective field scales with excitation amplitude
- It depends on the magnetization direction for the longitudinal field

The Longitudinal Field



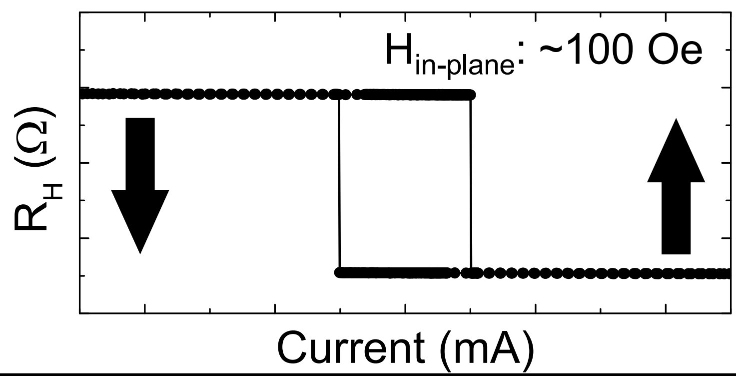
The Longitudinal Field



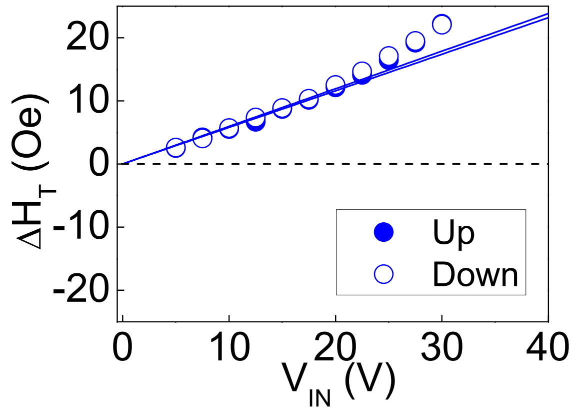


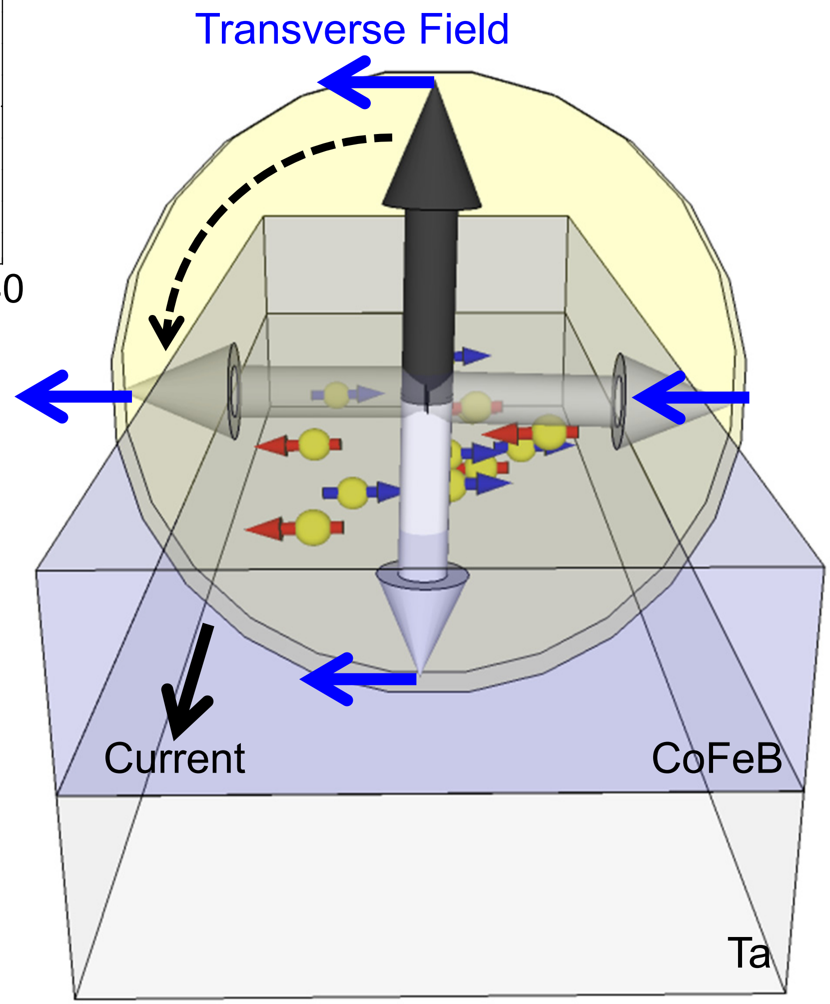
Explains magnetization switching with in-plane current and in-plane field

*Miron et al., Nature **476**, 190 (2011)*
*Liu et al., Science **336**, 555 (2012)*

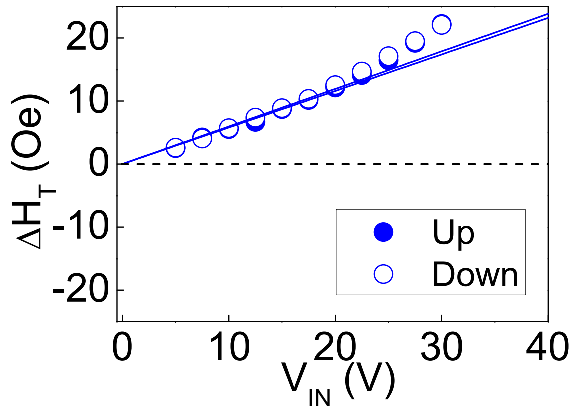


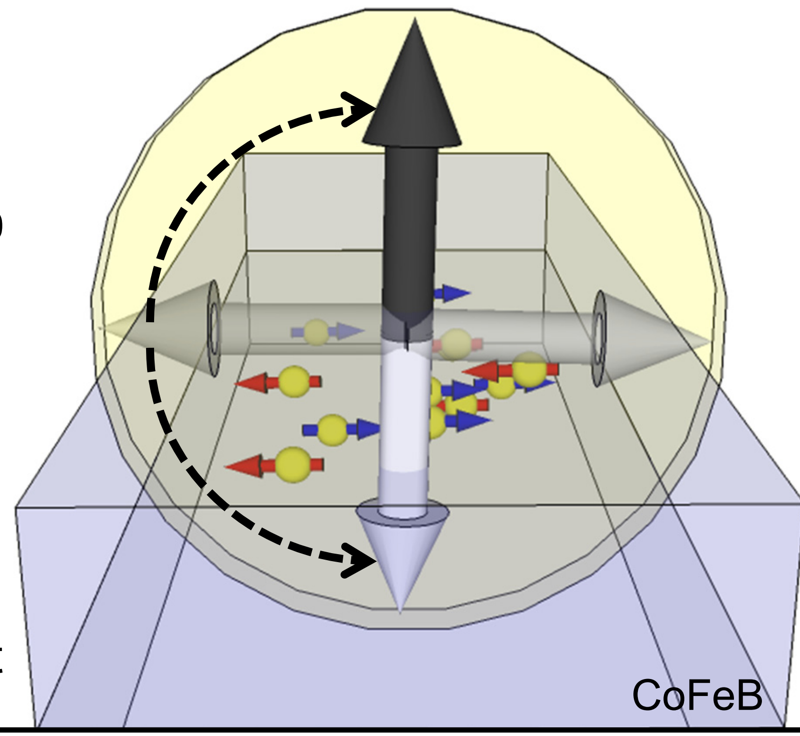
The Transverse Field





The Transverse Field

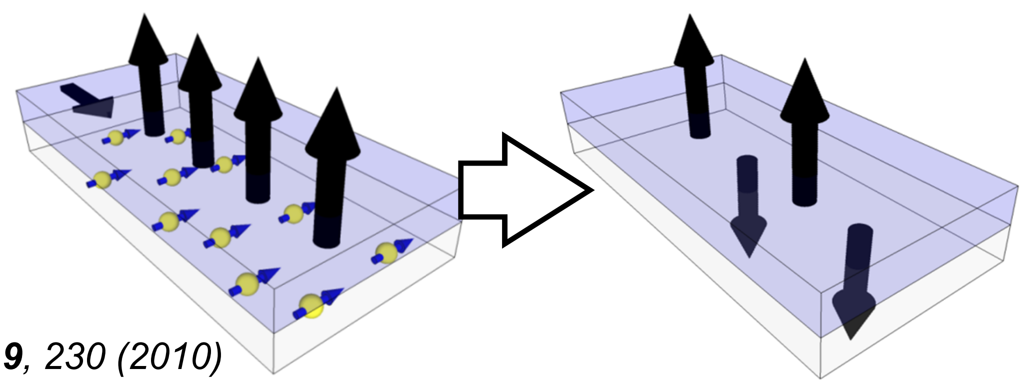




Turn off current

Explains random nucleation of reversed domains with the application of in-plane current

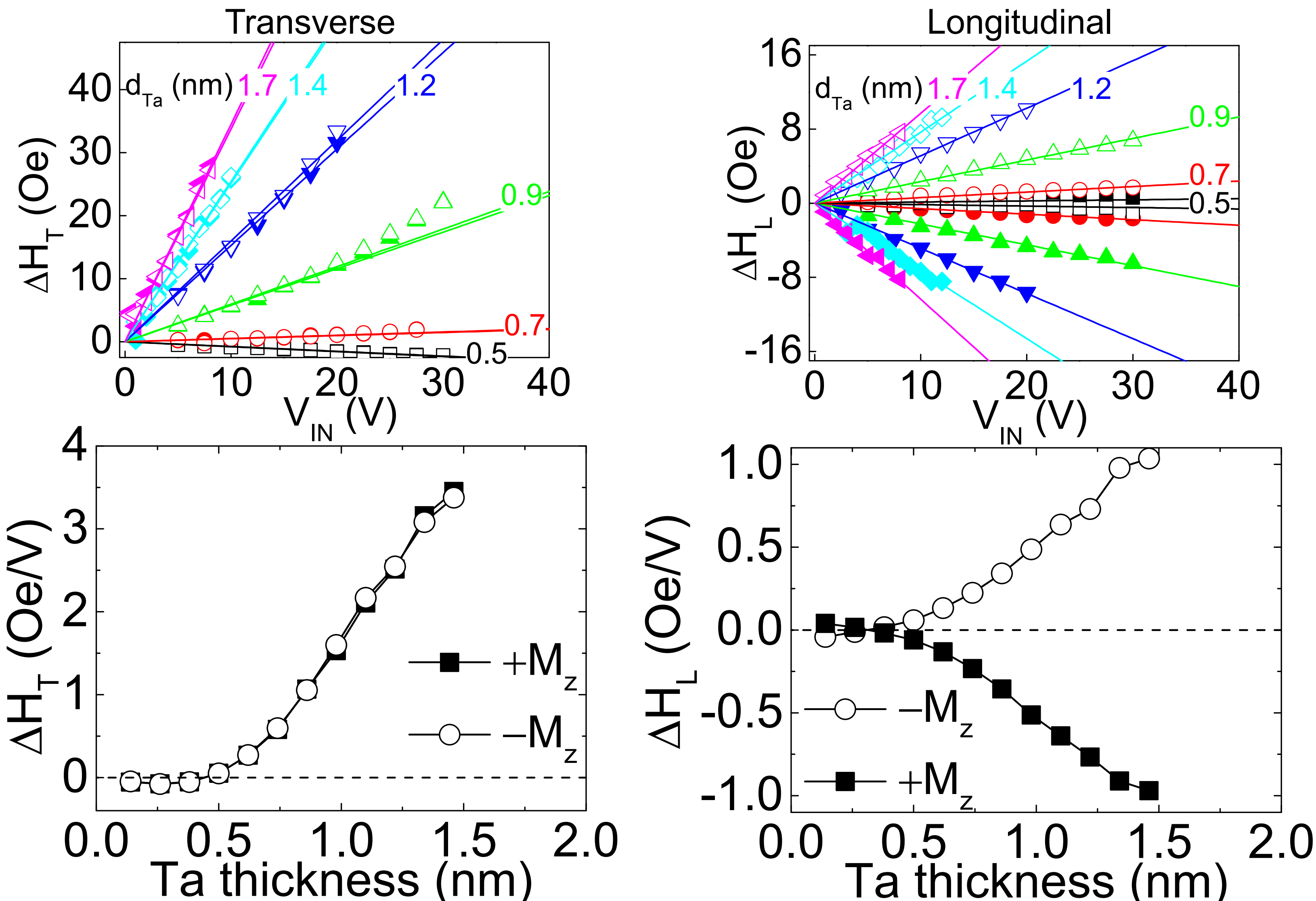
Miron et al., Nature Mater. ***9****, 230 (2010)*



Film stack dependence of the effective field

- **d Ta** | 1 CoFeB | 2 MgO | 1 Ta

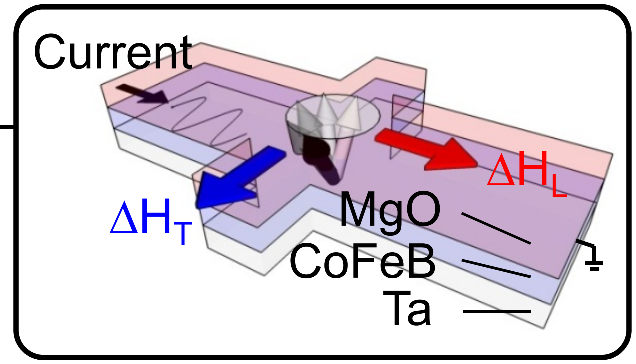
J. Kim et al., Nature Mater. ***12****, 240 (2013)*

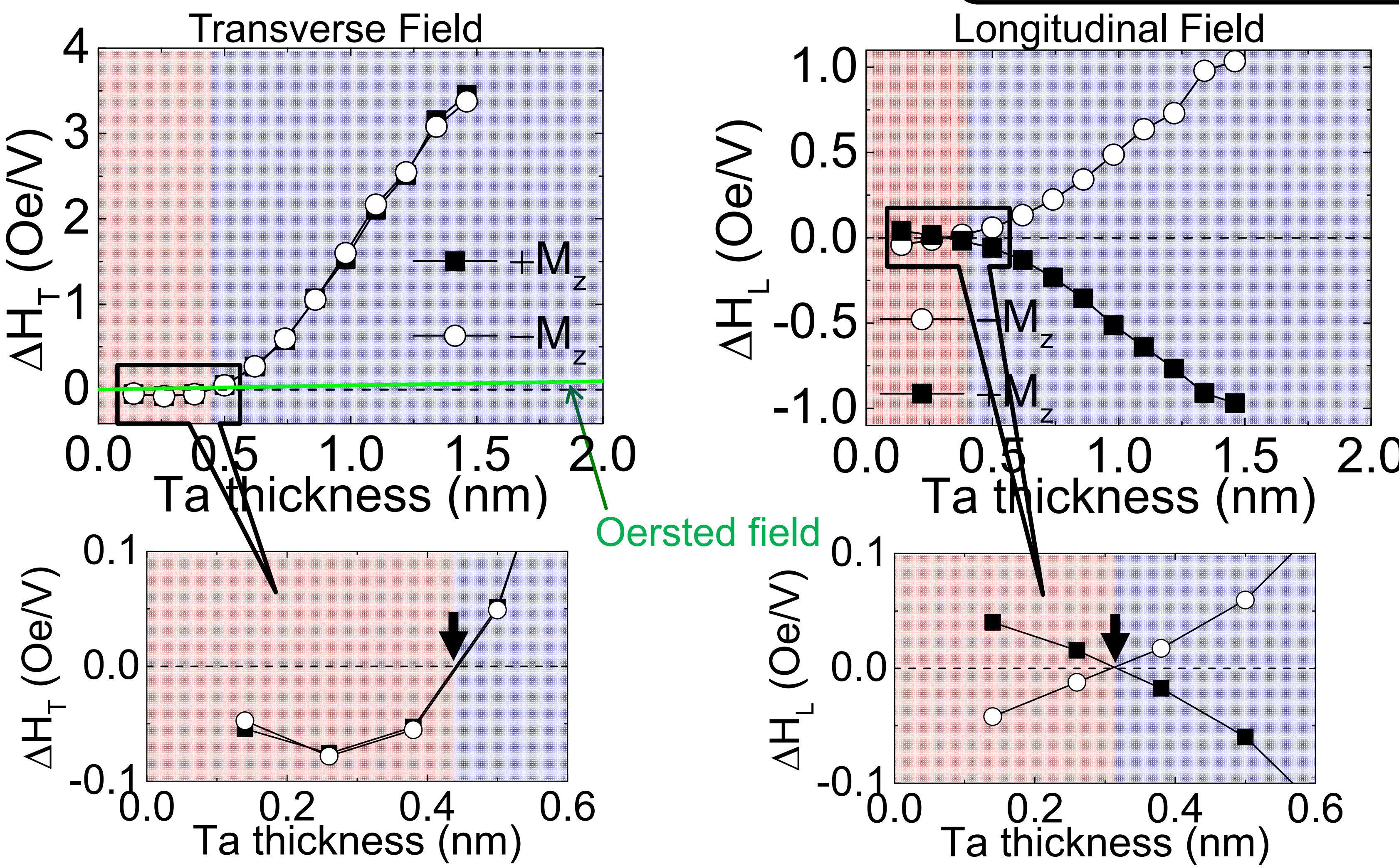


- Effective field changes significantly with the Ta layer thickness!

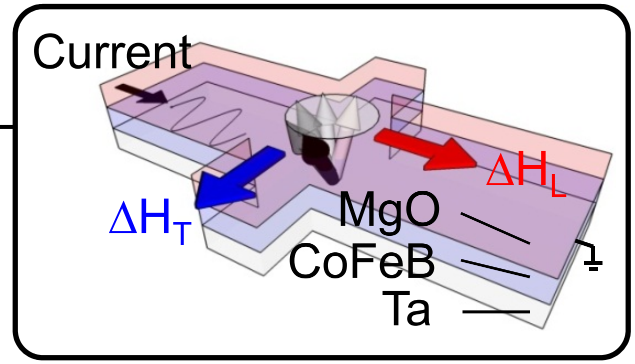
Current induced effective fields

- Effective field larger than the Oersted field
- Sign changes when the Ta layer thickness is reduced

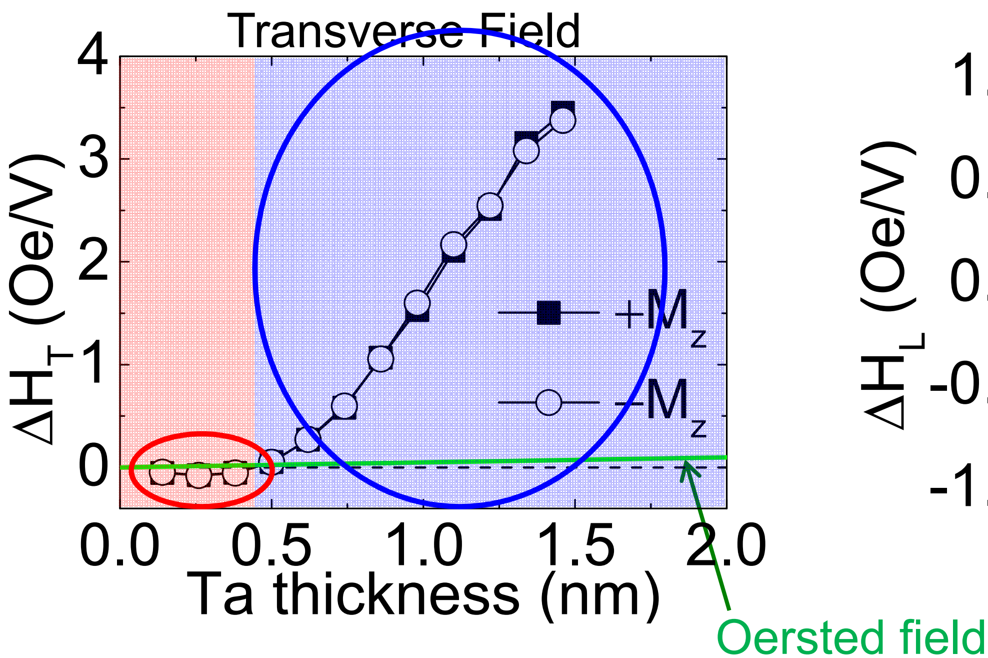


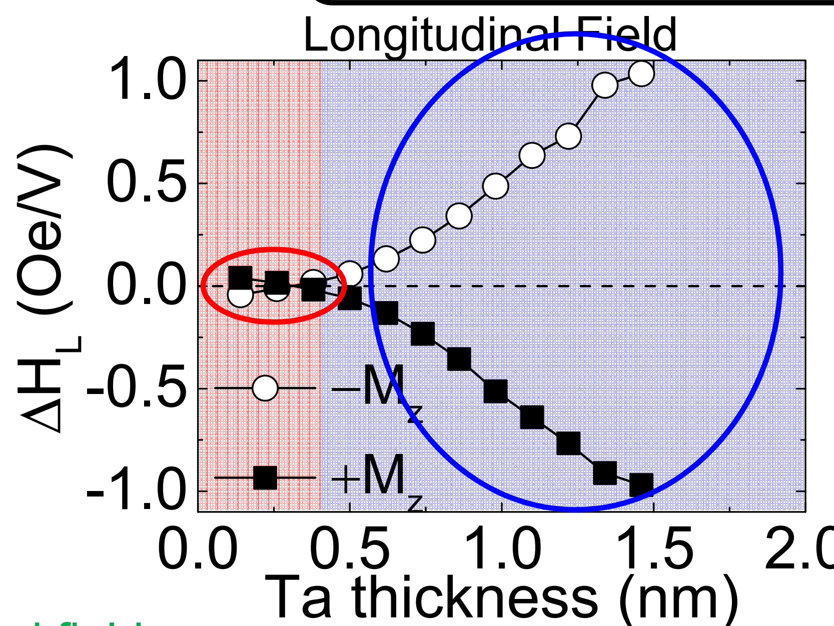


Current induced effective fields



- Effective field larger than the Oersted field
- Sign changes when the Ta layer thickness is reduced





Thin Ta:

- Little change with the Ta thickness

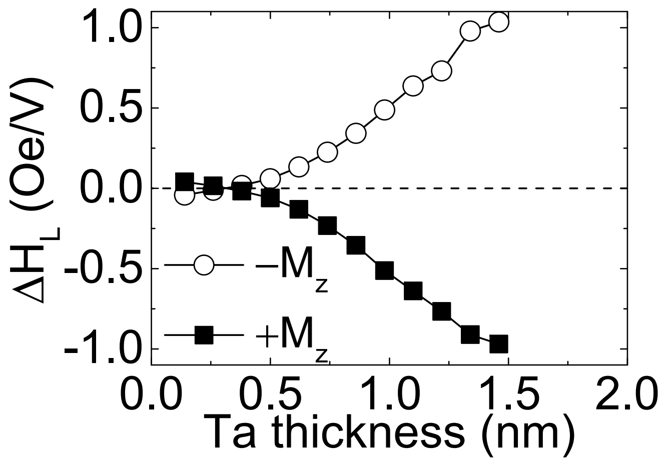
→ Rashba or other interface related effects?

Thick Ta regime:

- $\Delta H_{T(L)}$ scales with Ta layer thickness

→ Contributions from the spin Hall effect?

Spin Hall effect



$$\Delta H = \frac{\hbar}{2eM_S t_{FM}} J_S \left(\hat{m} \times \hat{p} \right)$$

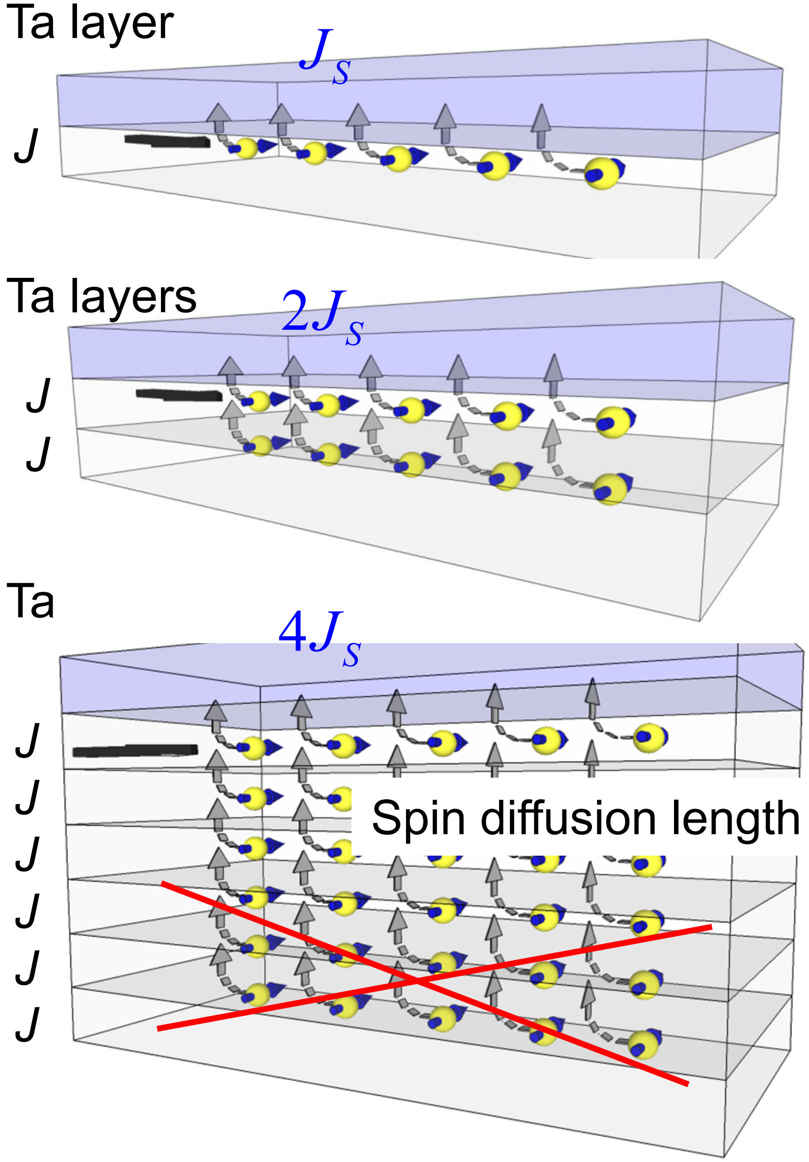
*Liu et al. PRL **109**, 096602 (2012)*

– J_S and thus ΔH saturates with Ta thickness

$$J_S = J\theta_{SH} = J_S(\infty)\left(1 - \mathrm{sech}\left(\frac{d}{\lambda_{SD}}\right)\right)$$

Constant current density *J*

- 1 Ta layer
- 2 Ta layers
- 6 Ta



Cf. Analogue to spin transfer torque

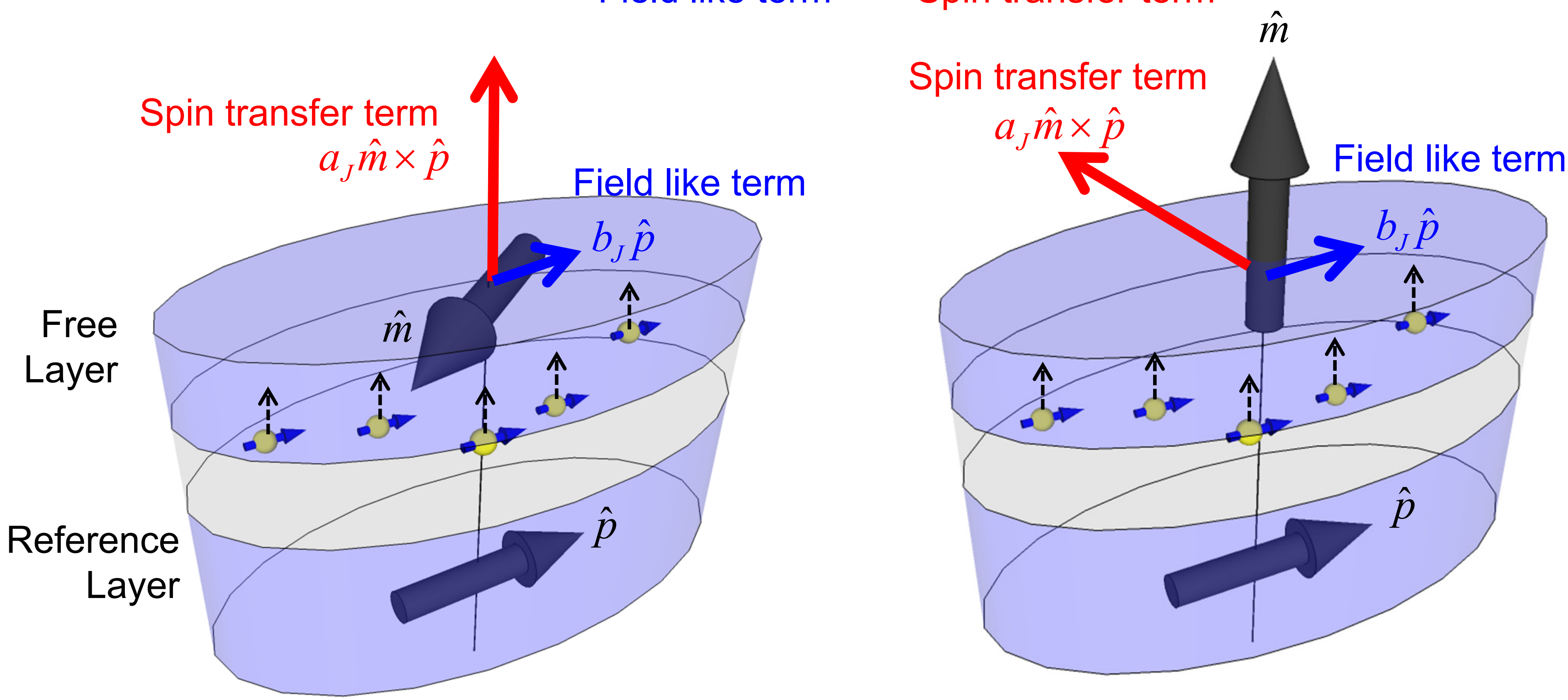
- Current induced effective field

$$\frac{\partial \hat{m}}{\partial t} = -\gamma \hat{m}\times \vec{H}_E - \underbrace{\hat{m}\times \Delta\vec{H}_T}_{\text{Transverse}} - \underbrace{\vec{m}\times\left(\vec{m}\times \Delta\vec{H}_L\right)}_{\text{Longitudinal}} + \alpha \hat{m}\times \frac{\partial \hat{m}}{\partial t}$$

- Spin transfer torque

Zhang et al., PRL 88, 236601 (2002)

$$\frac{\partial \hat{m}}{\partial t} = -\gamma \hat{m}\times\left(\vec{H}_E\right) + \alpha \hat{m}\times \frac{\partial \hat{m}}{\partial t} \underbrace{- \gamma b_J \hat{m}\times \hat{p}}_{\text{Field like term}} \underbrace{- a_J \hat{m}\times\left(\hat{m}\times \hat{p}\right)}_{\text{Spin transfer term}}$$

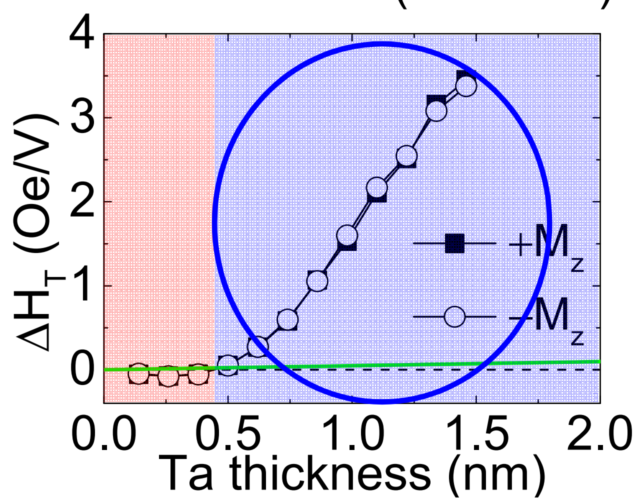


Ratio of the Longitudinal/Transverse Fields

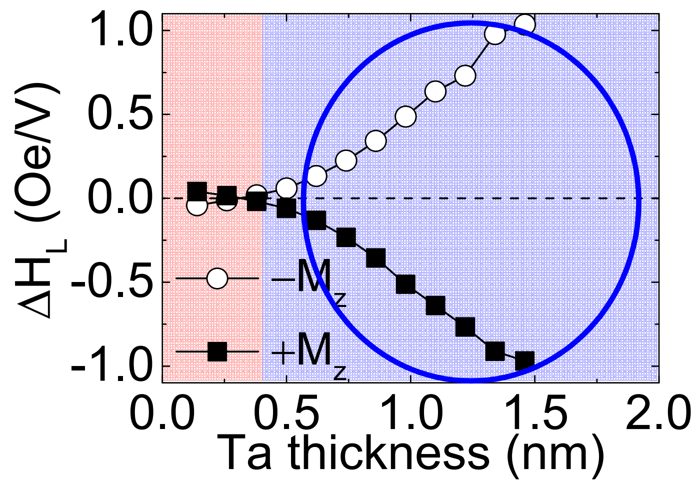
- d Ta | 1 CoFeB | 2 MgO | 1 Ta

J. Kim et al., Nature Mater. ***12****, 240 (2013)*

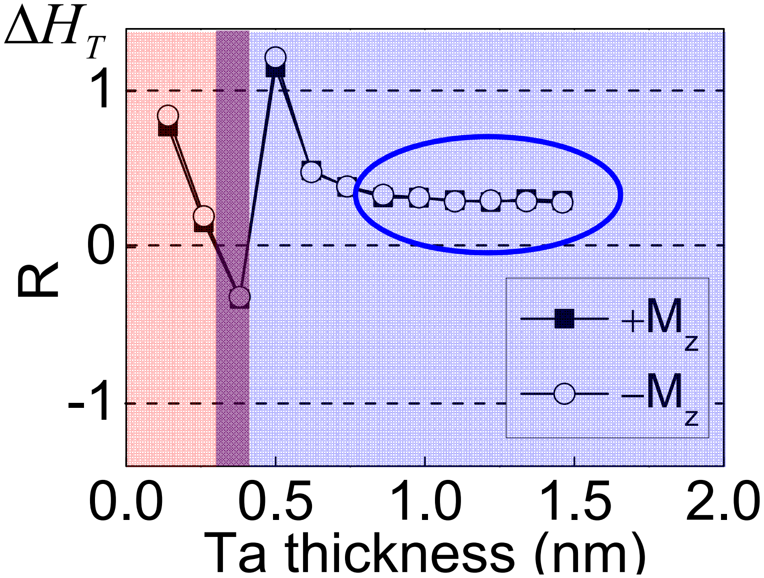
Transverse Field (Field like)



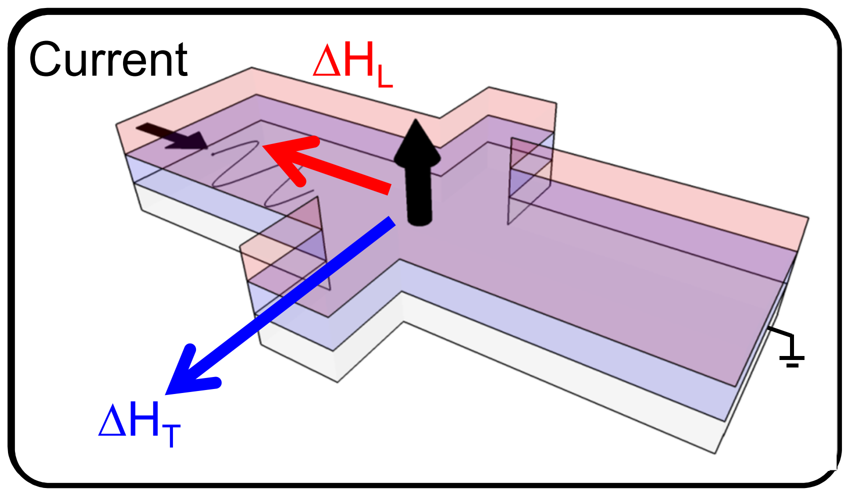
Longitudinal Field (Spin transfer)



$$R = \frac{\Delta H_L}{\Delta H_T}$$



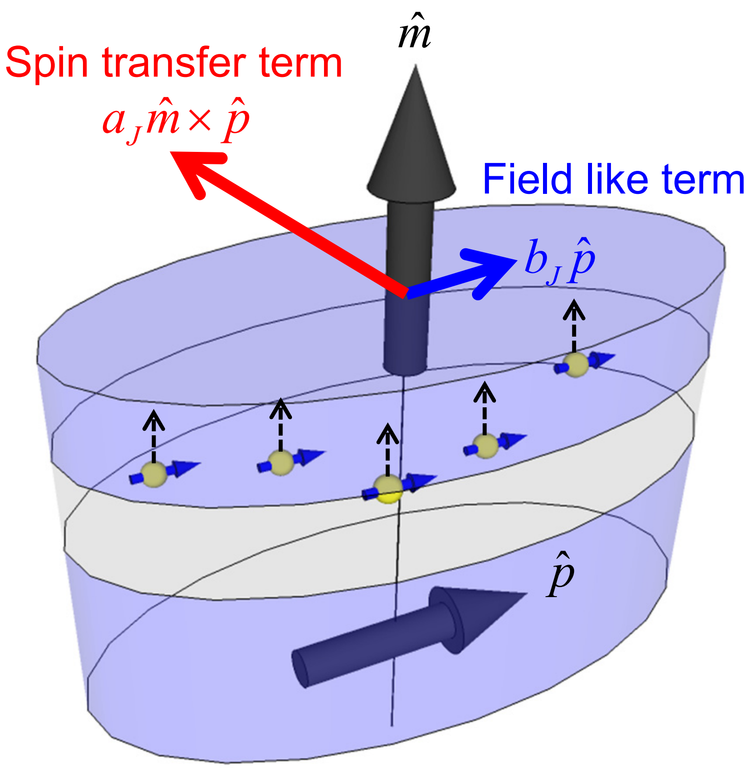
- The transverse field three times larger than the longitudinal field

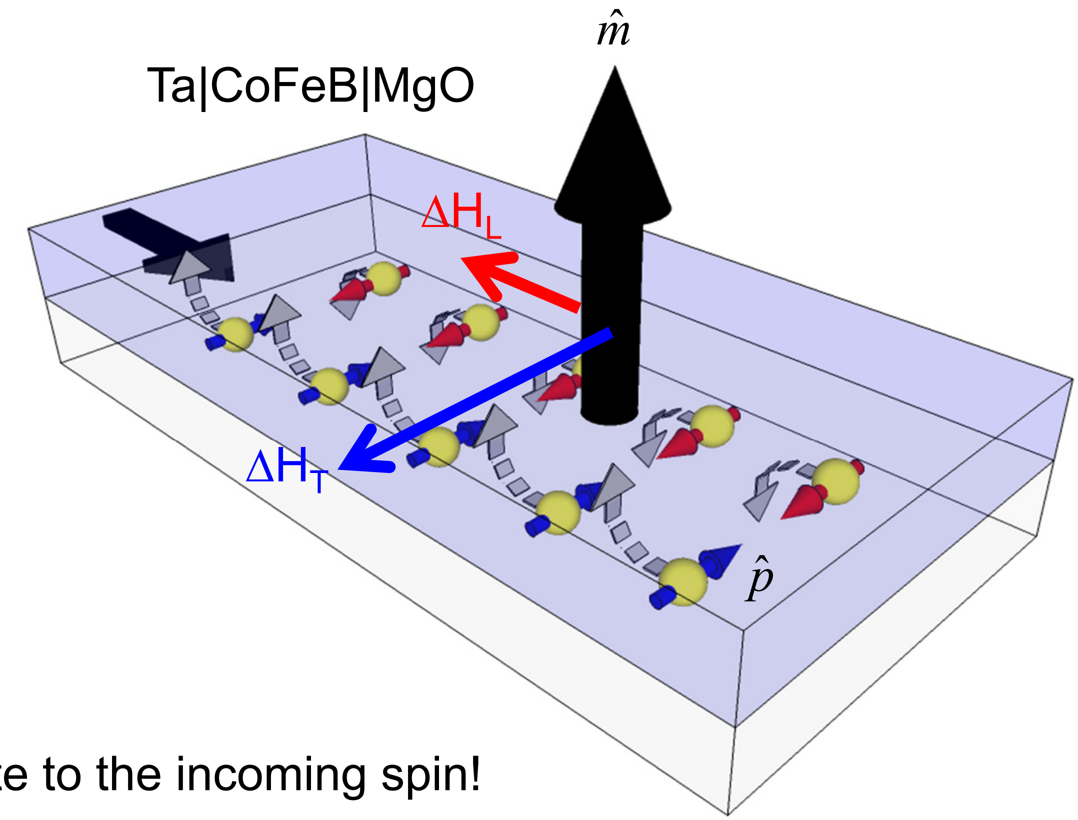


Spin Hall spin torque

Spin valves and MTJs

- Field like term is smaller (~10x) than the spin transfer term
- Both terms assist magnetization switching





Spin Hall spin torque

- Field like term opposite to the incoming spin!
- Field like term is larger (~3x) than the spin transfer term

Summary

- Current induced effective field vector measurements in Ta|CoFeB|MgO

- Effective field increases with Ta thickness

- Sign changes at low Ta thickness

- Transverse field is larger than the longitudinal field for thick Ta regime, i.e. large field-like term

- Field like term points opposite to the incoming spin for spin Hall spin torque