Introduction to spin torques and spin-orbit torques in metal layers

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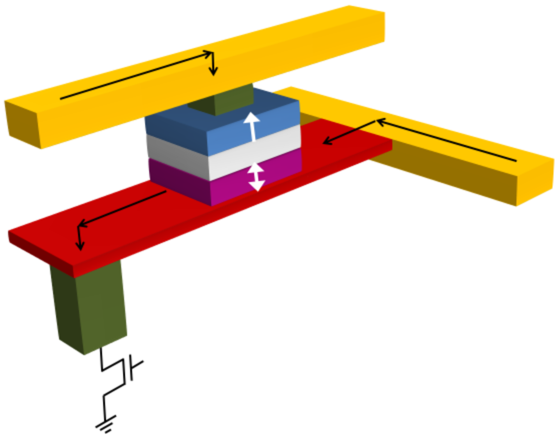
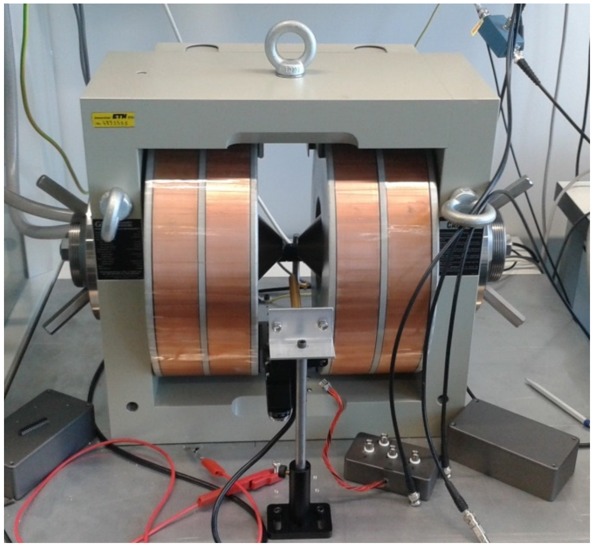
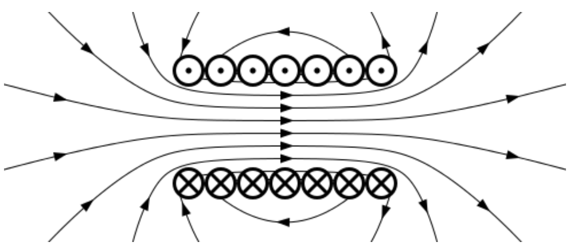


Spinmechanics III, Munich, 22-26/06/2015

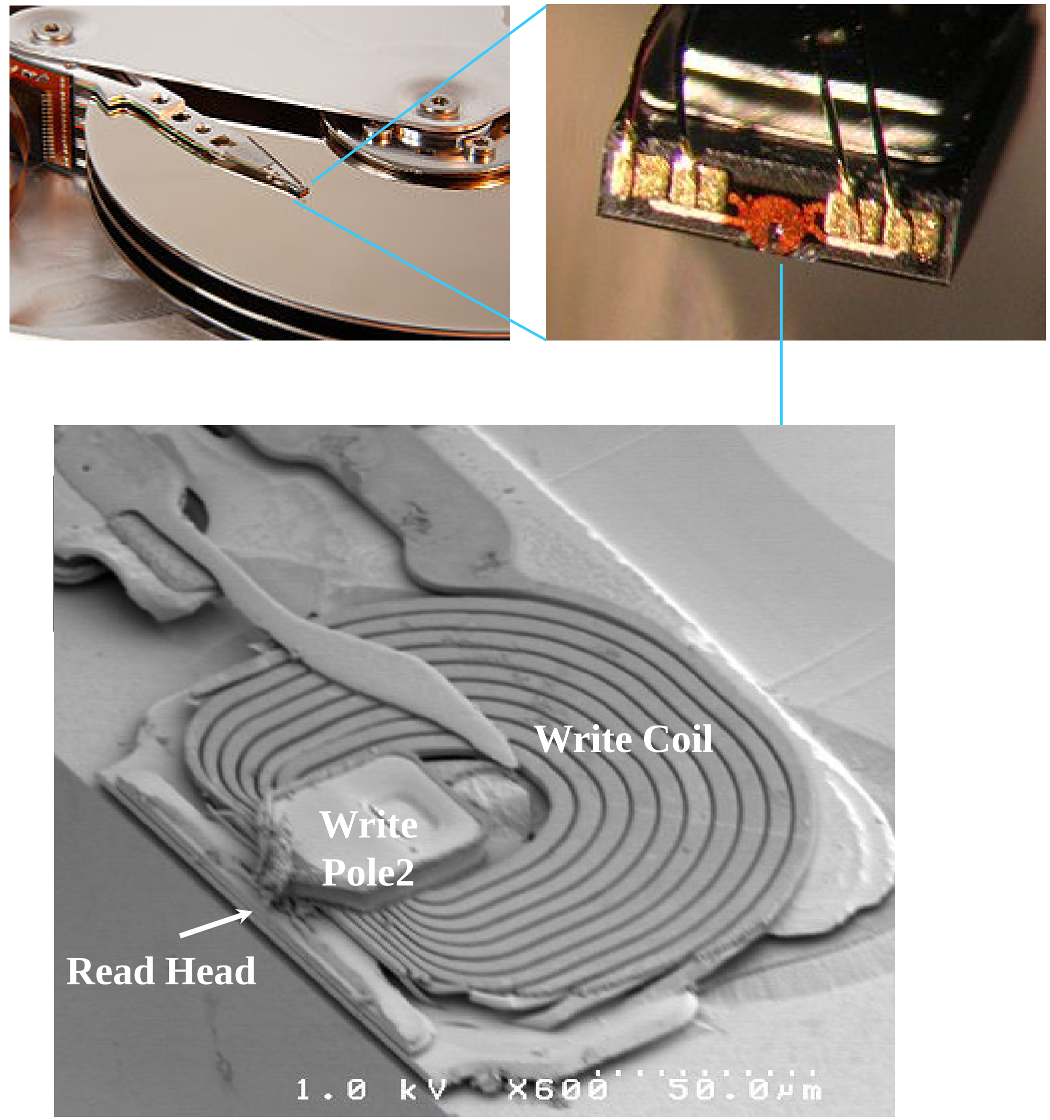
Magnetization reversal – “the art of magnetic writing”



Weight: 350 Kg, Current: 70 A

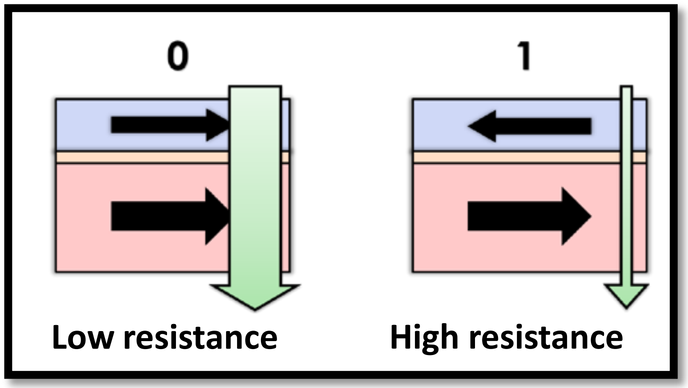


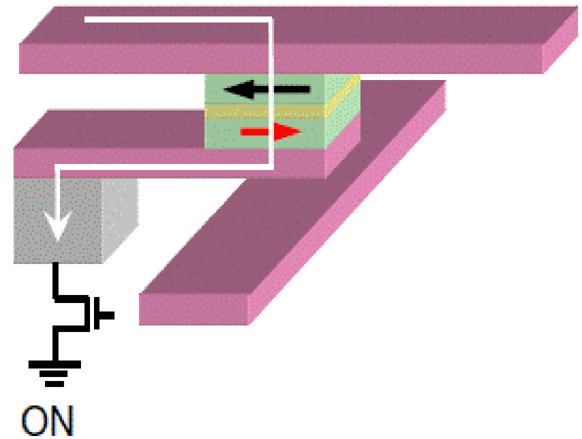
$$B = \mu n I$$

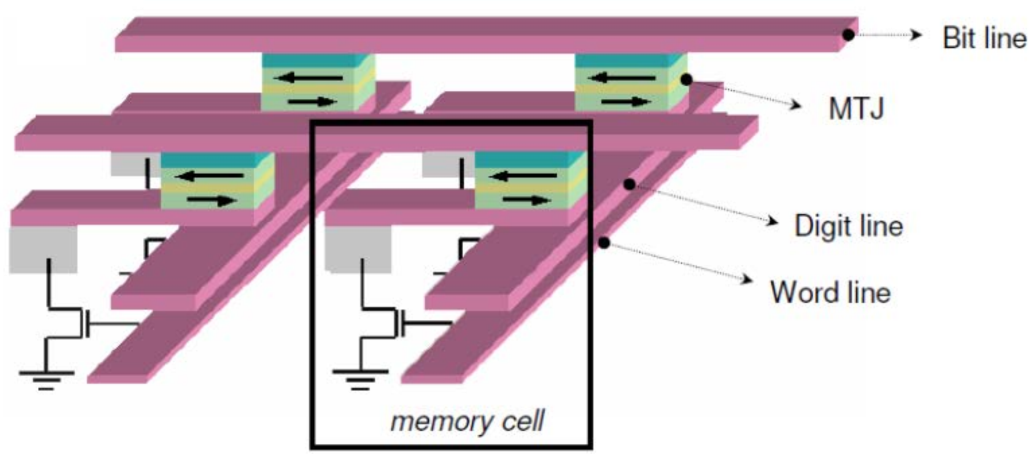


MTJ-based random access memory

Magnetic tunnel junction: two FM electrodes separated by an insulating oxide







"Universal memory"

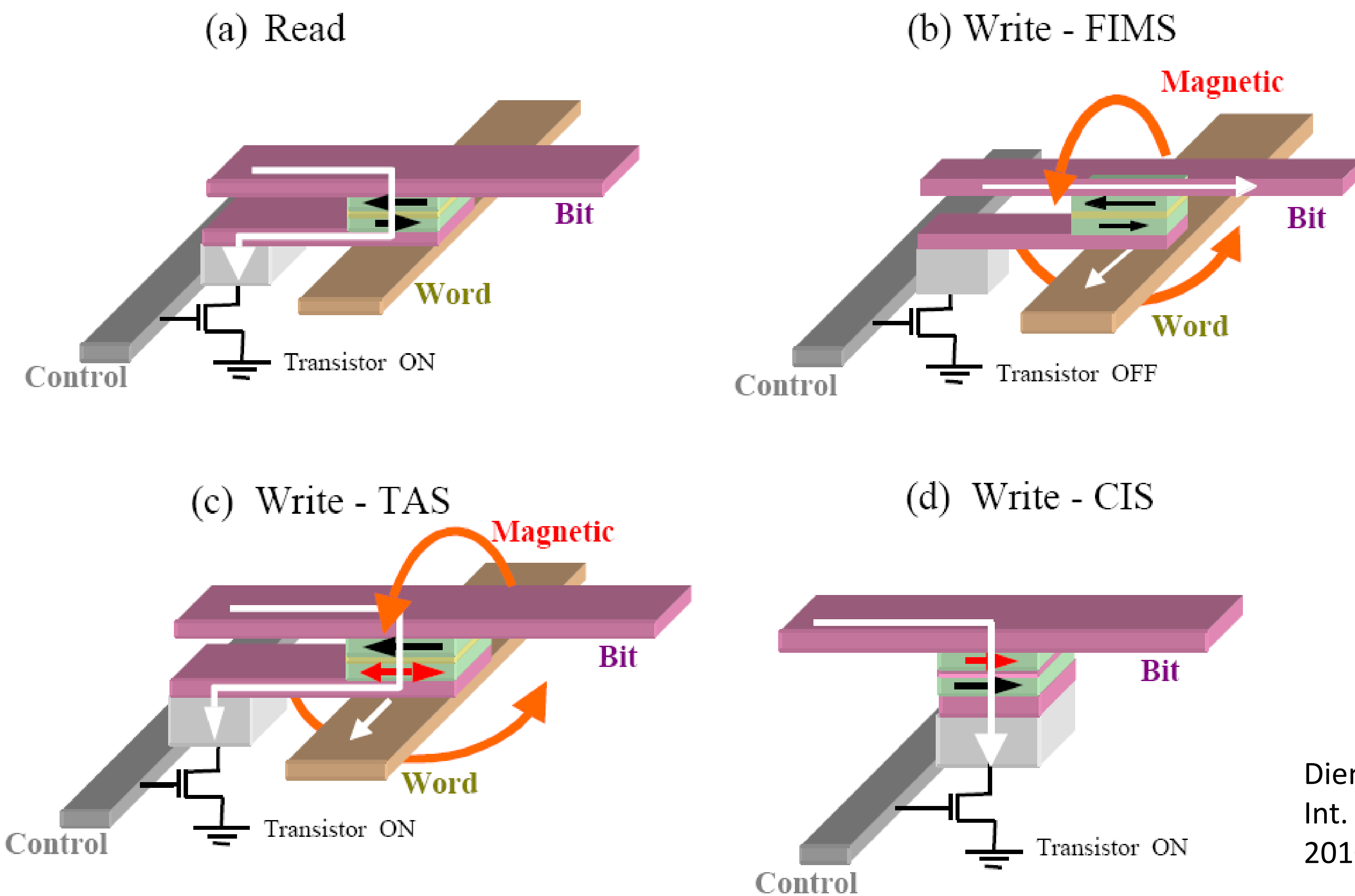
Fast

Dense

Non-volatile

Magnetization reversal in MTJs

Field-induced magnetization switching



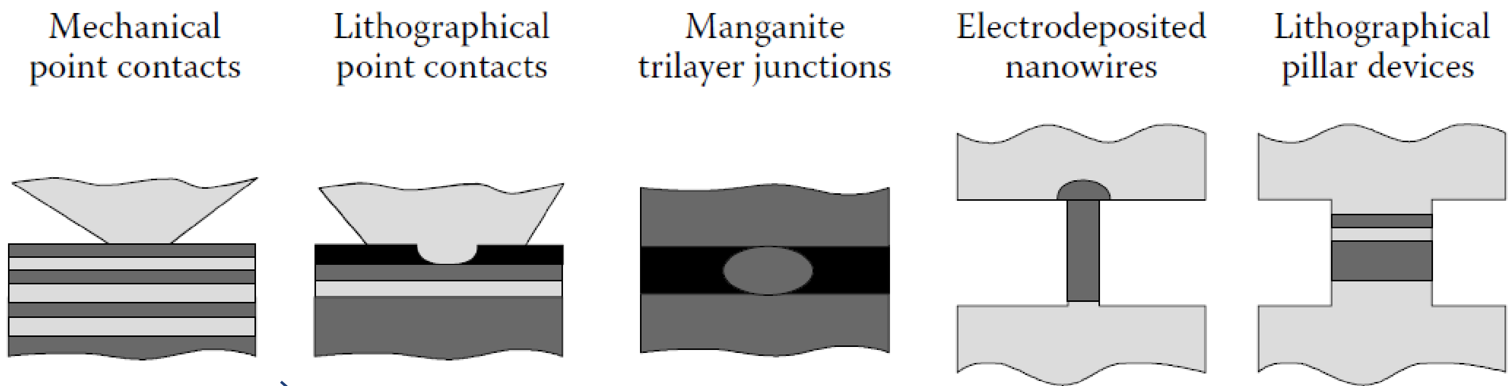
Dieny et al., Int. J. Nanotech. 2010

Thermally-assisted switching

Current-induced switching

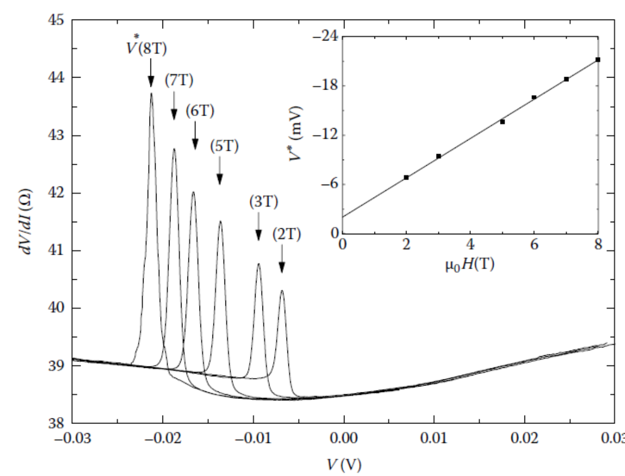
Spin transfer torque: experiments

Theoretical prediction: Berger PRB 1996, Slonczewski, JMMM 1996

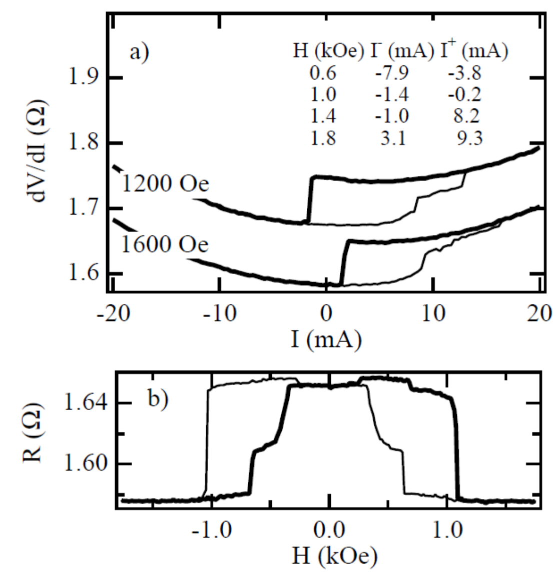


- Multilayer stacks
- GMR detection
- nm–sized contacts

- Large current density
  ~ 10^8 A/cm^2
- Small Oe field
- Good thermal dissipation



Tsoi, et al., PRL 80, 4281, 1998



Katine et al., PRL 84, 3149 (2000)

Outline

- Key concepts in spin transport in FM/NM systems
- Interaction of a spin polarized current with a magnetic layer
- Spin transfer torque (STT): AD and FL components
- STT on domain walls
- Spin pumping
- STT-induced magnetization dynamics

- Spin-orbit coupling and spin-orbit torques (SOT)
- Spin Hall and Rashba effects
- SOT measurements
- Three-terminal SOT magnetic tunnel junctions
- Ultrafast SOT-induced switching
- Conclusions

Spin-dependent conductivity in ferromagnetic metals

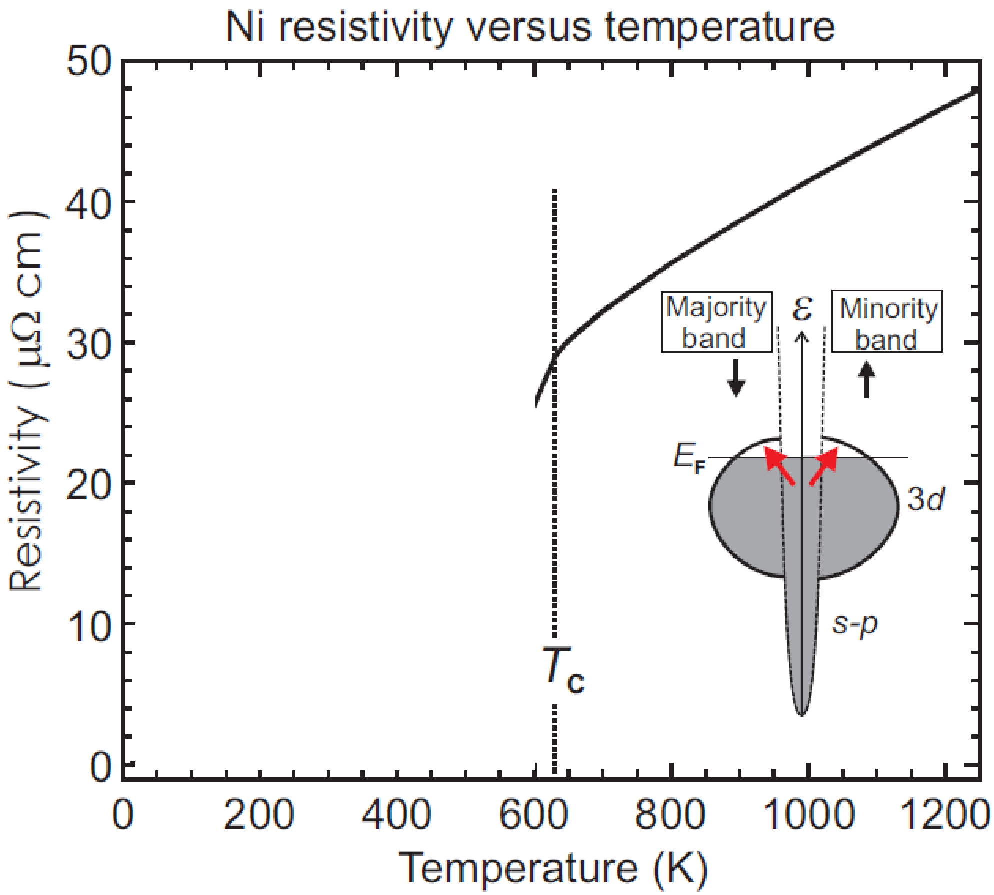
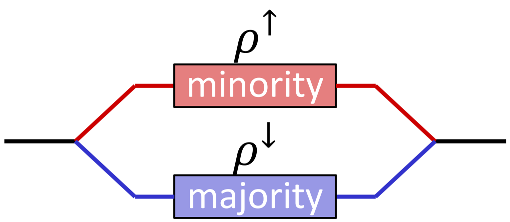


Figure courtesy of J. Stöhr

Mott's two current model

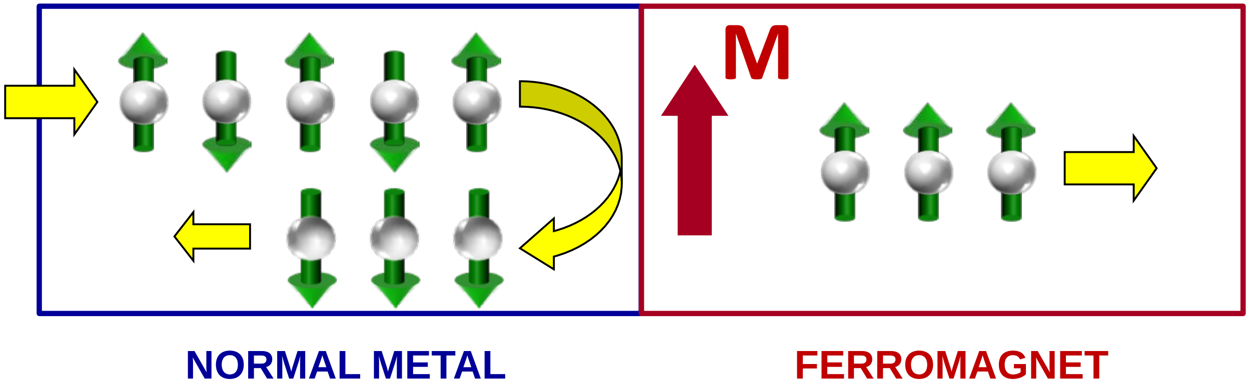


$\rho^{\uparrow} > \rho^{\downarrow}$

- The current flows independently in two spin channels -- **no spin flips** !
- The current below T_C becomes spin-polarized
- Minority band electrons scatter more readily from the s-p band to the d-band due to the availability of hole states in the minority d-band.

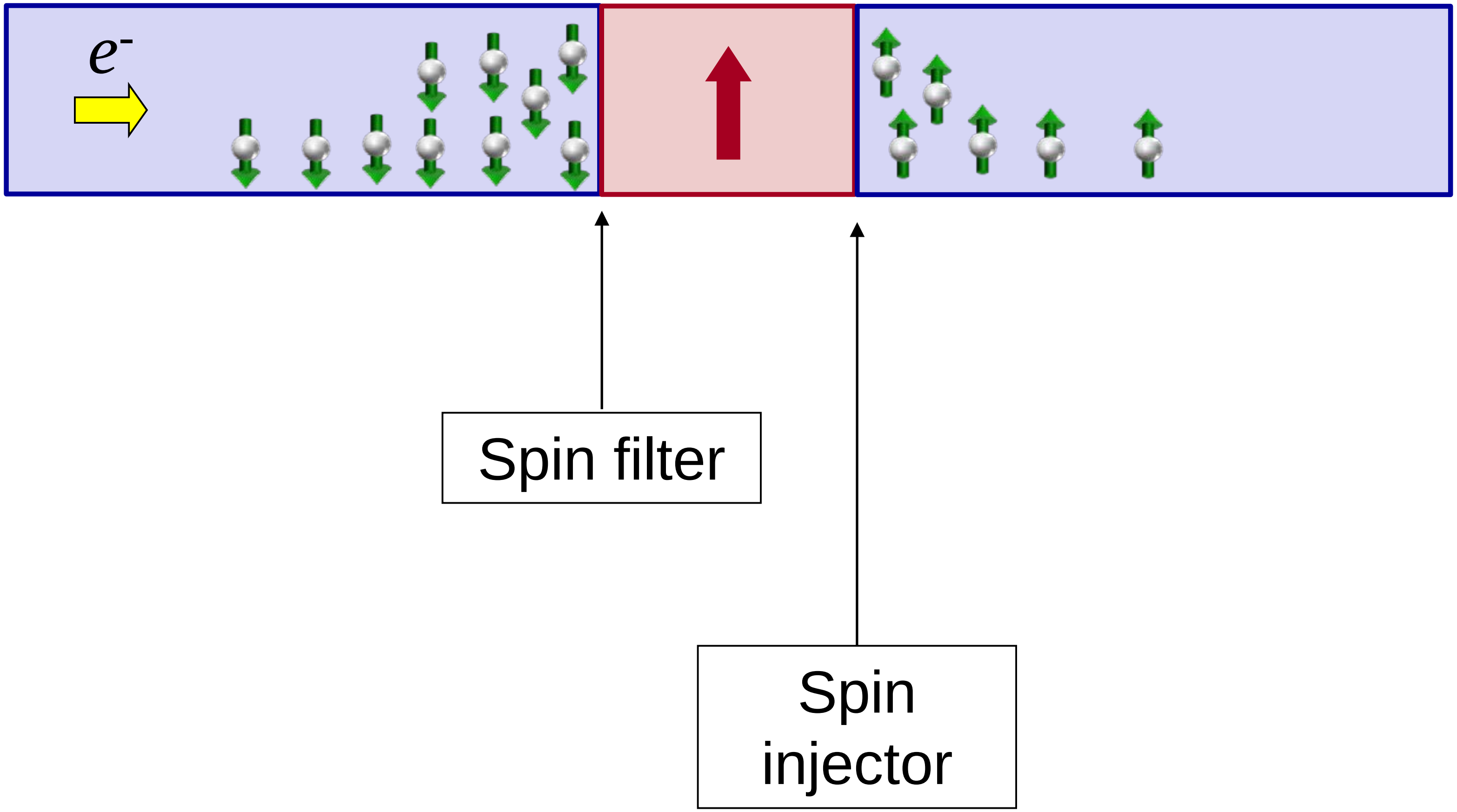
ETH zürich

Interfacial spin-dependent scattering

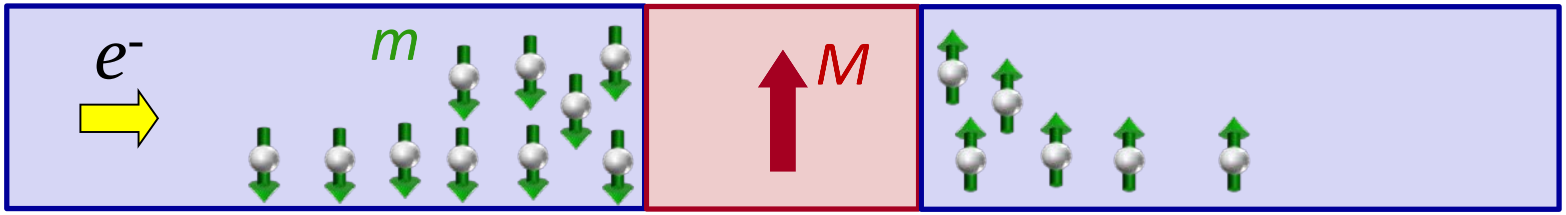


- “Majority” spins are preferentially transmitted.
- ”Minority” spins are preferentially reflected.

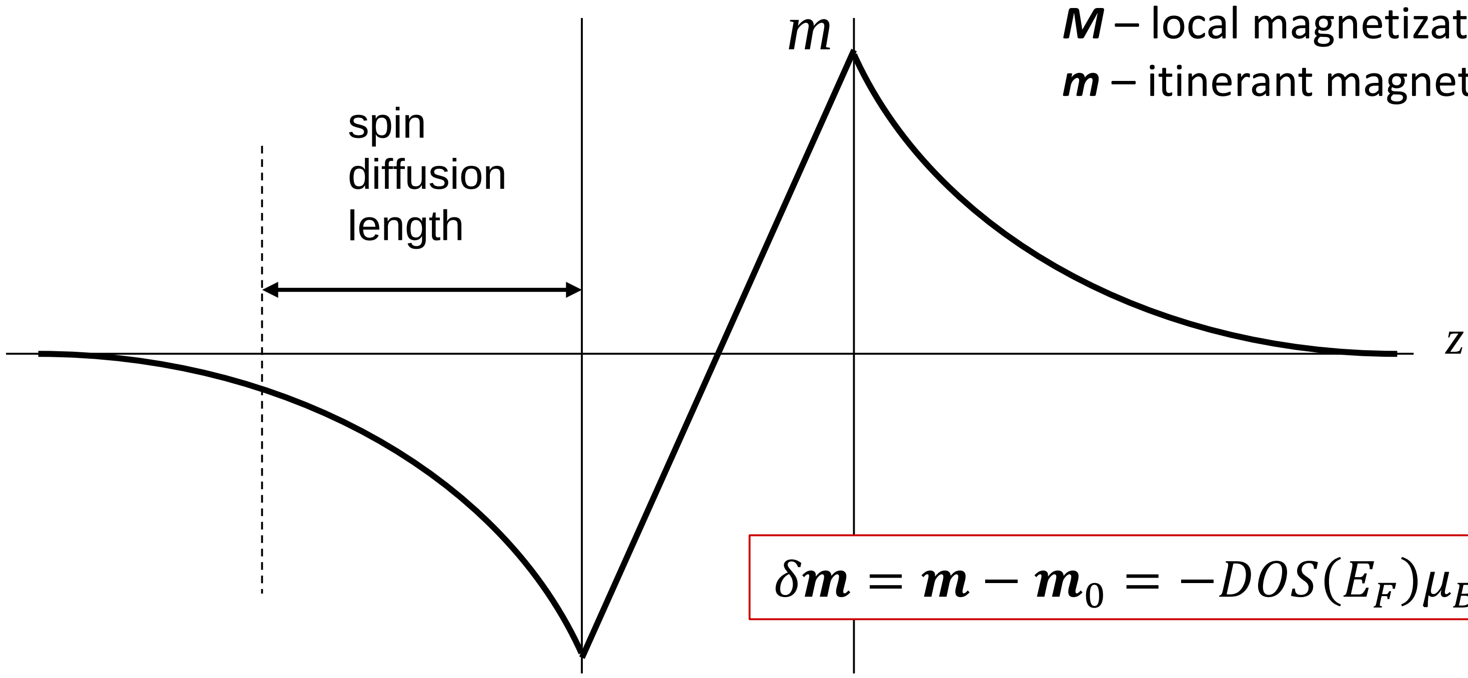
Ferromagnets act as spin filters, even when very thin


e⁻
Spin filter
Spin
injector

Spin accumulation



$$m(z) = m_0 + \delta m$$



$$\delta \boldsymbol{m} = \boldsymbol{m} - \boldsymbol{m}_0 = -DOS(E_F)\mu_B\, \boldsymbol{\mu}_s$$

Notation:

M – local magnetization

m – itinerant magnetization

Due to the conductivity mismatch between ↑ and ↓ spins, non-equilibrium spin polarization "accumulates" near the interfaces of FM and non-magnetic conductors.

Spin current

$$\boldsymbol{Q} = n\frac{\hbar}{2}P\,\boldsymbol{v}\otimes\boldsymbol{\sigma} \quad \left[\frac{\hbar/2}{s\,m^2}\right]$$

$$\boldsymbol{j}_s = neP\,\boldsymbol{v}\otimes\boldsymbol{\sigma} \quad \left[\frac{e}{s\,m^2} = \frac{A}{m^2}\right]$$

n *electron density*

$e = |e|$ *charge*

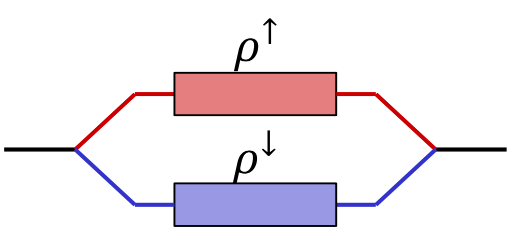
P *spin polarization*

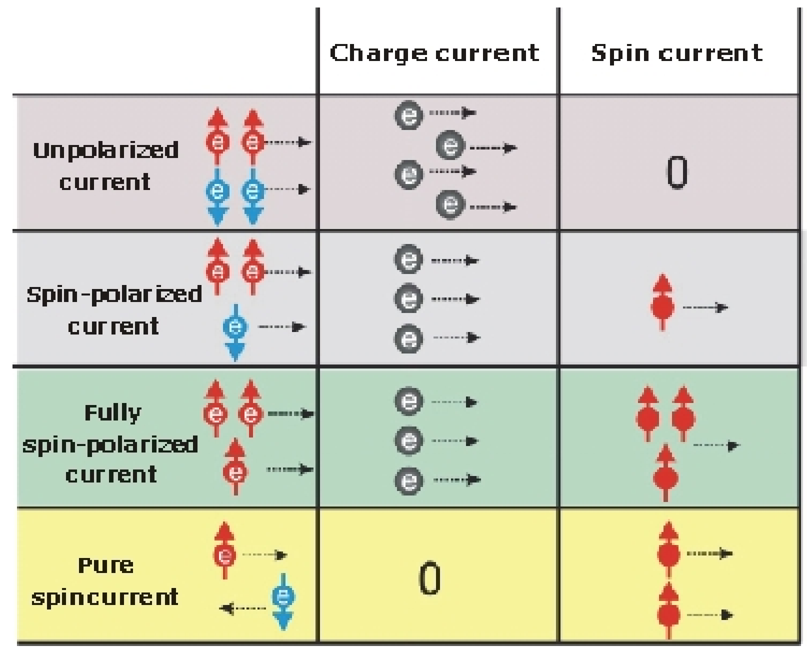
$\boldsymbol{v}$ *velocity*

$\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ *vector of Pauli matrices*

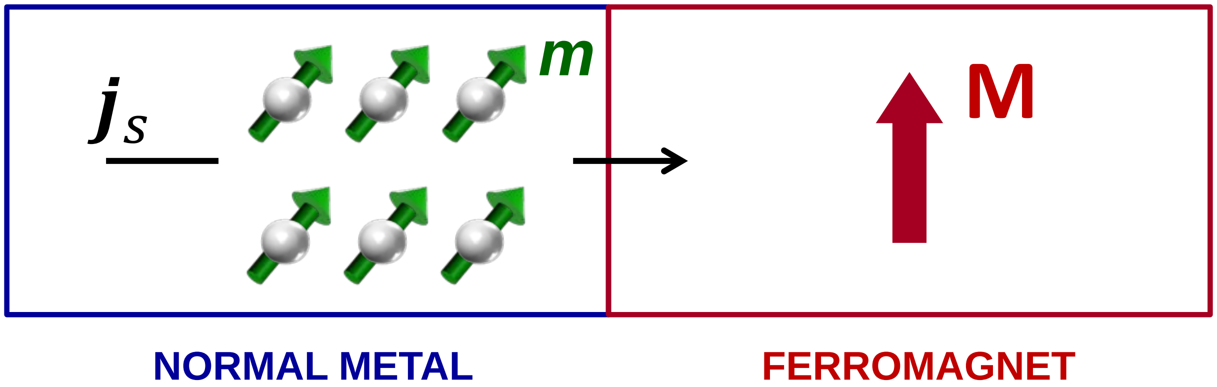
Two-current model:

$$\boldsymbol{j}_s = \boldsymbol{j}_c^{\uparrow} - \boldsymbol{j}_c^{\downarrow}$$





Interaction between spin current and magnetization



A spin current $\boldsymbol{Q}$ (or $\boldsymbol{j}_s$) injected into a material corresponds to a magnetization entering and exiting the material:

$$\boldsymbol{m} = -\frac{\mu_B}{\hbar/2}\frac{\boldsymbol{Q}}{v} = -\frac{\mu_B}{e}\frac{\boldsymbol{j}_s}{v} \qquad \left[\frac{A}{m} = \frac{magnetic\ moment}{volume}\right]$$

The divergence of the spin current corresponds to a change of magnetization:

$$\frac{\partial \boldsymbol{m}}{\partial \boldsymbol{t}} = \frac{\mu_B}{\hbar/2}\nabla \cdot \boldsymbol{Q} = \frac{\mu_B}{e}\nabla \cdot \boldsymbol{j}_s \qquad \left[\frac{A}{m\ s}\right]$$

sd exchange interaction between itinerant and local electrons

$$H_{sd} = -J_{sd}\,\widehat{\boldsymbol{m}} \cdot \widehat{\boldsymbol{M}}$$

J_{sd} exchange coupling constant [energy]

Effective exchange field acting on ***m***: $\boldsymbol{B} = \frac{J_{sd}}{m}\,\widehat{\boldsymbol{M}} \rightarrow$ Torque: $\boldsymbol{T} = J_{sd}\,\widehat{\boldsymbol{m}} \times \widehat{\boldsymbol{M}}$

Effective exchange field acting on ***M***: $\boldsymbol{B} = \frac{J_{sd}}{M}\,\widehat{\boldsymbol{m}} \rightarrow$ Torque: $\boldsymbol{T} = J_{sd}\,\widehat{\boldsymbol{M}} \times \widehat{\boldsymbol{m}}$

Changes of ***m*** and **M** are related by $\frac{d\boldsymbol{m}}{dt} = -\frac{d\boldsymbol{M}}{dt}$ Action = Reaction !

Conservation of angular momentum

Note: This is exact if spin relaxation and spin-orbit coupling are neglected, i.e., assuming weak spin-lattice interactions compared to electron-electron interactions

Spin torques due to the nonequilibrium spin accumulation

$$\boldsymbol{T} = J_{sd}\, \widehat{\boldsymbol{M}} \times \widehat{\boldsymbol{m}}$$

Torque on $\boldsymbol{M}$ due to the *sd* exchange interaction

$$\boldsymbol{m} = \boldsymbol{m}_0 + \delta\boldsymbol{m}$$

$\boldsymbol{m}_0$ equilibrium magnetization of conduction electrons, $\boldsymbol{m}_0 \,||\, \boldsymbol{M}$

$\delta\boldsymbol{m} = -DOS(E_F)\mu_B\, \boldsymbol{\mu}_s$ nonequilibrium magnetization

Assuming $|\boldsymbol{M}| = const.$, the only component of $\boldsymbol{m}$ that gives a torque is $\delta\boldsymbol{m}_\perp$

$$\delta\boldsymbol{m}_\perp = a_j\, \boldsymbol{M} \times \boldsymbol{m} + b_j\, (\boldsymbol{M} \times \boldsymbol{m}) \times \boldsymbol{M}$$

a_j , b_j parameters that depend on the current, magnetization, NM/FM geometry and materials

$$\boxed{\boldsymbol{T} \sim \boldsymbol{M} \times \delta\boldsymbol{m}_\perp = a_j\, \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{m}) + b_j \boldsymbol{M} \times \boldsymbol{m}}$$

"In-plane torque"	"Out-of-plane torque"
"Spin transfer torque"	"Perpendicular torque "
"Slonczewski torque"	"Effective field"
"Antidamping torque"	"Field-like torque"

S. Zhang, P.M. Levy, and A. Fert, PRL 88 236601 (2002); A. Shpiro et al., PRB 67, 104430 (2003).

Antidamping and field-like spin torques

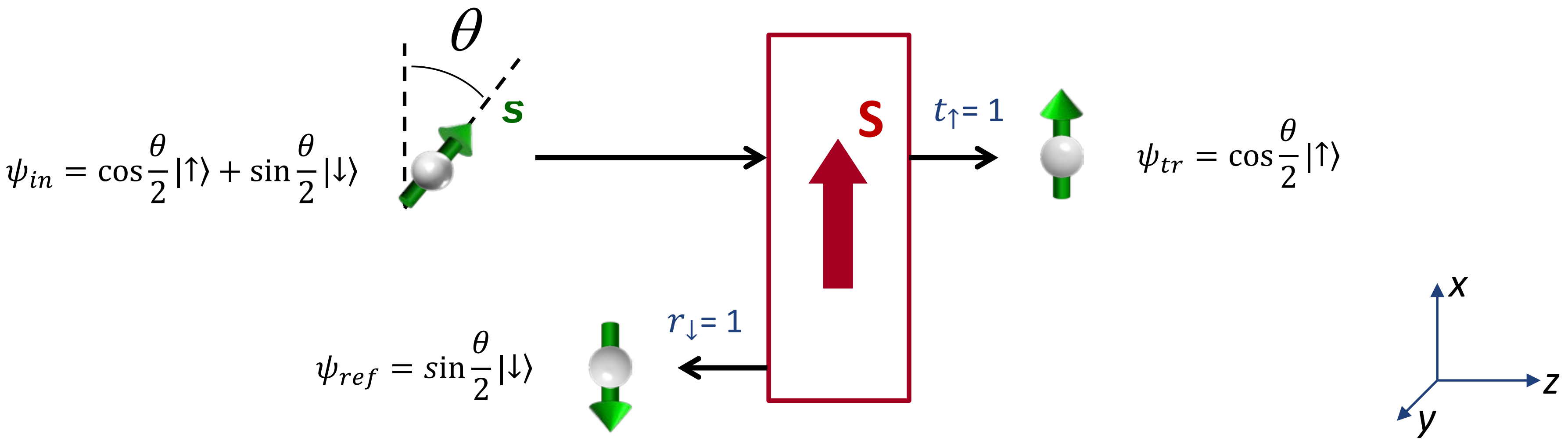
AD torque

Absorption of the transverse part of the spin current
Rotates ***M*** towards the direction of ***m***

FL torque

Precession of ***M*** about the exchange field created by ***m***

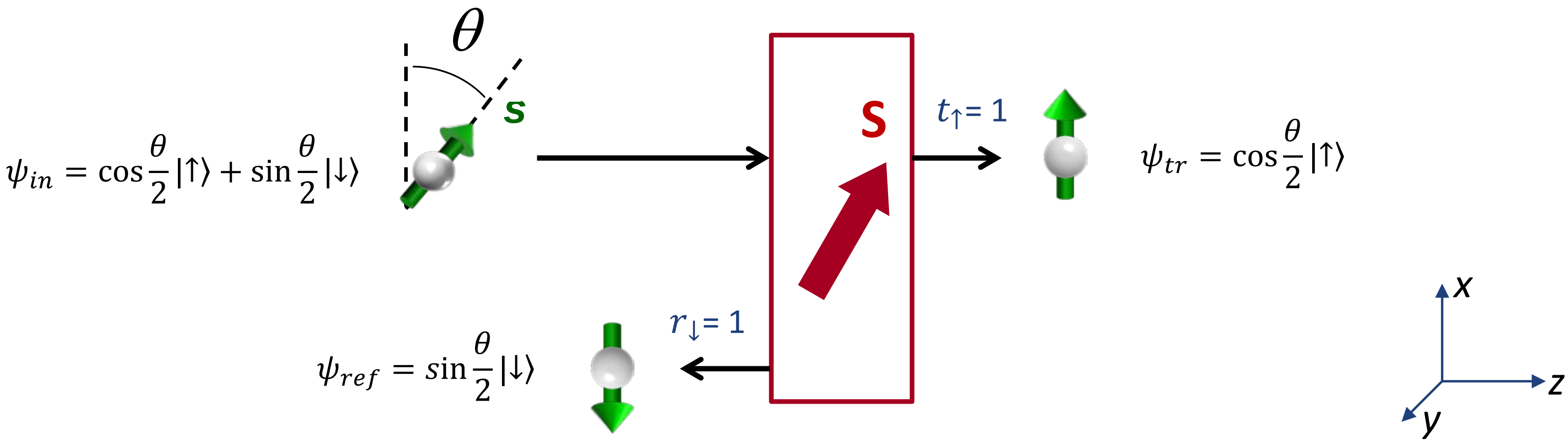
Antidamping torque: elementary model



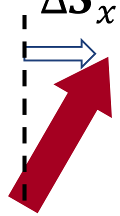
Initial state	Final state		$\Delta s = s_f - s_i$
$\langle s_x^{in}\rangle = \frac{\hbar}{2}\sin\theta$	$\langle s_x^{tr}\rangle = 0$	$\langle s_x^{ref}\rangle = 0$	$\Delta s_x = -\frac{\hbar}{2}\sin\theta$
$\langle s_z^{in}\rangle = \frac{\hbar}{2}\cos\theta$	$\langle s_z^{tr}\rangle = \frac{\hbar}{2}\cos^2\frac{\theta}{2}$	$\langle s_z^{ref}\rangle = -\frac{\hbar}{2}\sin^2\frac{\theta}{2}$	$\Delta s_z = 0$

Conservation of angular momentum: $\Delta \boldsymbol{s} + \Delta \boldsymbol{S} = 0 \;\Rightarrow\; \Delta S_x = +\frac{\hbar}{2}\sin\theta$

Antidamping torque: elementary model



$$\Delta \boldsymbol{S}_x = +\frac{\hbar}{2}\sin\theta\,\hat{\boldsymbol{x}} = \frac{\hbar}{2}\,\boldsymbol{S}\times\underbrace{(\boldsymbol{S}\times\boldsymbol{s})}_{sin\theta}$$

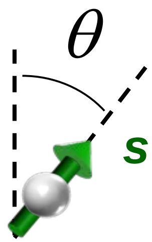


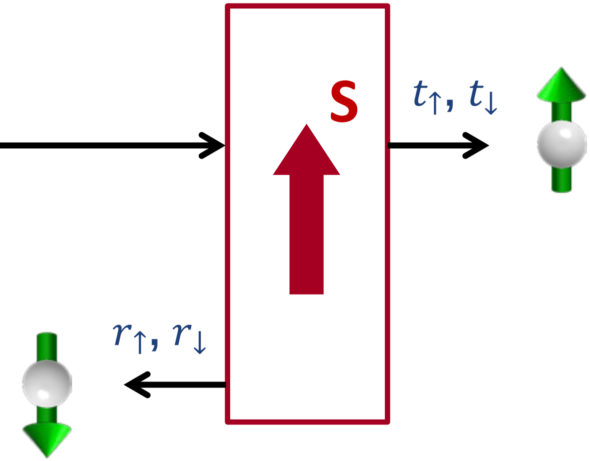
Change of total moment of magnetic layer: $\Delta\boldsymbol{M}\,V = \frac{\hbar}{2}|\gamma|\,\widehat{\boldsymbol{M}}\times(\widehat{\boldsymbol{M}}\times\widehat{\boldsymbol{m}})$ …per incident electron

For a continuous current: $\frac{d\boldsymbol{M}}{dt} = \frac{\hbar}{2}\frac{|\gamma|}{V}\,\widehat{\boldsymbol{M}}\times(\widehat{\boldsymbol{M}}\times\widehat{\boldsymbol{m}})\,\frac{I}{e} = \boxed{\frac{I\hbar|\gamma|}{2eM_s^2V}\,\boldsymbol{M}\times(\boldsymbol{M}\times\widehat{\boldsymbol{m}})}$

Anatomy of spin-transfer torque: 1D toy model

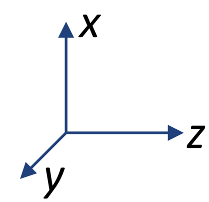
$$\psi_{in} = \frac{e^{ikz}}{\sqrt{V}}\left[\cos\frac{\theta}{2}|\uparrow\rangle + \sin\frac{\theta}{2}|\downarrow\rangle\right]$$





$$\psi_{tr} = \frac{e^{ikz}}{\sqrt{V}}\left[t_{\uparrow}\cos\frac{\theta}{2}|\uparrow\rangle + t_{\downarrow}\sin\frac{\theta}{2}|\downarrow\rangle\right]$$

$$\psi_{ref} = \frac{e^{ikz}}{\sqrt{V}}\left[r_{\uparrow}\cos\frac{\theta}{2}|\uparrow\rangle + r_{\downarrow}\sin\frac{\theta}{2}|\downarrow\rangle\right]$$



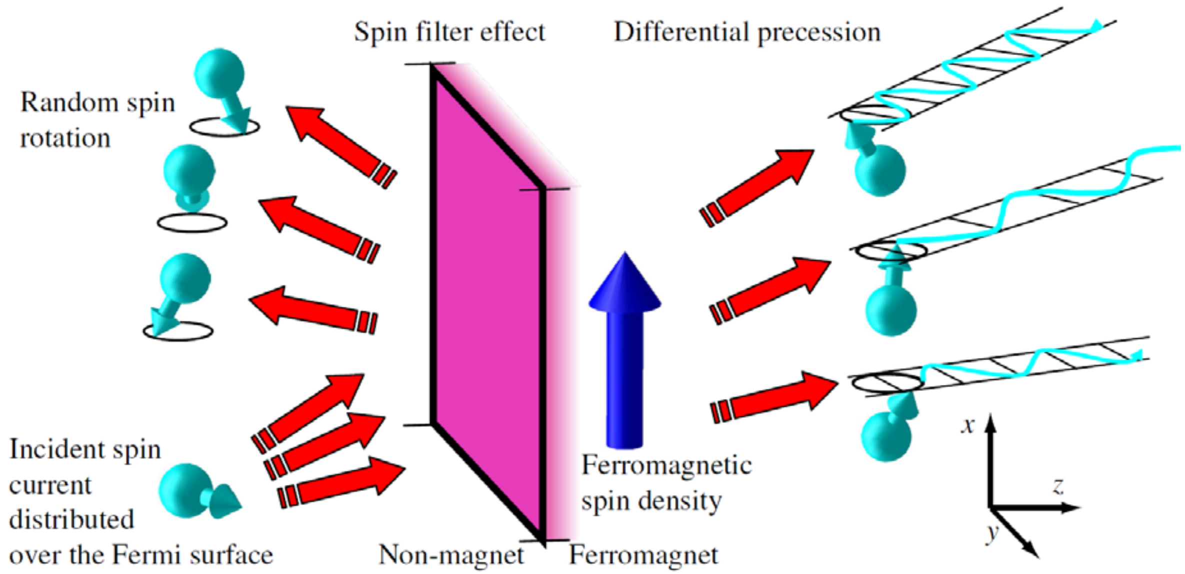
$$\boldsymbol{Q} = \frac{\hbar^2}{2m}\mathrm{Im}\{\psi^*\boldsymbol{\sigma}\otimes\nabla\psi\} \quad\rightarrow\quad \boldsymbol{Q}_{in} = \frac{\hbar^2 k}{2mV}[\sin\theta\,\hat{\boldsymbol{z}} + \cos\theta\,\hat{\boldsymbol{x}}], \qquad etc.$$

$$\boldsymbol{T}_{st} = \left(\boldsymbol{Q}^{in} + \boldsymbol{Q}^{ref} - \boldsymbol{Q}^{tr}\right)\cdot \mathrm{A} \;=\; \frac{A}{V}\frac{\hbar^2 k}{2m}\sin\theta\left[\underbrace{(1 - Re\{t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\})\hat{\boldsymbol{z}}}_{In-plane\ torque} + \underbrace{Im\{t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\}\hat{\boldsymbol{y}}}_{Out-of-plane\ torque}\right]$$

- $\boldsymbol{T}_{st} \perp \hat{\boldsymbol{x}}$ - The torque is perpendicular to the magnetization
- $\boldsymbol{T}_{st} = 0$ if $t_\uparrow = t_\downarrow, r_\uparrow = r_\downarrow$ (no spin filter effect)
- $\boldsymbol{T}_{st} = 0$ if $\theta = 0, \pi$
- The in-plane and out-of-plane torque components depend on the real and imaginary values of the reflection and transmission coefficients

Ralph & Stiles,
JMMM 320, 1190 (2008)

Anatomy of spin-transfer torque: general case



M. D. Stiles and J. Miltat, Topics in App. Phys. 101, 225 (2006).

1. **Spin filter effect**: spin-dependent reflection and transmission at NM/FM interface, reduces the transverse spin components of reflected and transmitted electrons.
2. **The spin rotates upon reflection**: $r_\uparrow r_\downarrow^* = |r_\uparrow r_\downarrow^*| \mathrm{e}^{\mathrm{i}\Delta\phi}$. The relative phase $\Delta\phi$ of the reflected transverse components varies significantly over the Fermi surface. The reflected transverse spin averages out when summing over the electron distribution (classical dephasing).
3. **Spatial precession of the transmitted spins in the FM**. Spin-up and spin-down components have the same total energy E_F , but different kinetic energy $\Rightarrow k_\uparrow \neq k_\downarrow$, leading to a space-dependent phase difference $\mathrm{e}^{\mathrm{i}(k_\uparrow - k_\downarrow)z}$ as the electron penetrates into the FM. The precession frequency is different for electrons from different portions of the Fermi surface, hence complete cancellation of the transverse spin occurs after propagation into the FM by a few lattice constants.

Anatomy of spin-transfer torque: general case

- If the cancellation of the transverse component of $\boldsymbol{Q}^{ref}$ and $\boldsymbol{Q}^{tr}$ is complete, $\boldsymbol{Q}_{\perp}^{in}$ is absorbed at or near the interface, leading to

$$\boldsymbol{T}_{st} = \left(\boldsymbol{Q}^{in} + \boldsymbol{Q}^{ref} - \boldsymbol{Q}^{tr}\right) \cdot \mathrm{A}\hat{\boldsymbol{z}} \approx \boldsymbol{Q}_{\perp}^{in} \cdot \mathrm{A}\hat{\boldsymbol{z}} = \boldsymbol{T}_{AD}$$

The torque is AD-like and proportional to the transverse part of the incident spin current.

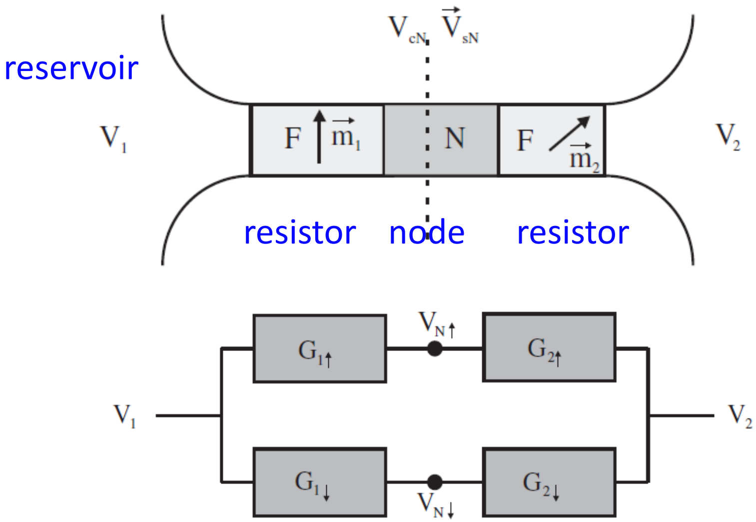
- If the transverse component of $\boldsymbol{Q}^{ref}$ and $\boldsymbol{Q}^{tr}$ does not average out, as is the case in very thin FM layers, a small amount of precession of the reflected and transmitted spins leads to a finite FL torque and

$$\boldsymbol{T}_{st} = \boldsymbol{T}_{AD} + \boldsymbol{T}_{FL}$$

- The relative importance of the spin transfer mechanisms 1-3 depends on materials pair and crystal structure.
- In metallic spin valves (CPP geometry), $\boldsymbol{T}_{FL}$ is typically less than 5% of $\boldsymbol{T}_{AD}$.
- In MTJs, averaging is not so effective due to k-selection, $\boldsymbol{T}_{FL}$ can be ~30% of $\boldsymbol{T}_{AD}$.

K. Xia et al., PRB 65, 220401 (2002); M. D. Stiles and A. Zangwill, PRB 66, 014407 (2002).

Magnetoelectronic circuit theory



- Generalization of the two-channel series resistor model to multilayer structures and noncollinear magnetization
- Similar to drift-diffusion theory but neglects the spatial dependence of the chemical potential within the layers (nodes).
- Practical for treating interface effects and complex device structures.

A. Brataas, Yu. V. Nazarov, and G. E. W. Bauer, PRL 84, 2481 (2000).
A. Braatas, G.E.W. Bauer, and P.J. Kelly, Phys. Rep. 427, 157 (2006).

$$\boldsymbol{j}_s = \underbrace{(j_\uparrow - j_\downarrow)\widehat{\boldsymbol{M}}}_{\text{Bare spin current determined by spin dep. conductivity}} \underbrace{- \frac{2}{e} Re\{G_{\uparrow\downarrow}\} \widehat{\boldsymbol{M}} \times (\widehat{\boldsymbol{M}} \times \boldsymbol{\mu}_s) - \frac{2}{e} Im\{G_{\uparrow\downarrow}\} \widehat{\boldsymbol{M}} \times \boldsymbol{\mu}_s}_{\text{Spin current absorbed by the ferromagnet}}$$

$$G_{\uparrow\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[1 - \sum_{m \in NM} r_\uparrow^{nm} (r_\downarrow^{nm})^*\right]$$

- Spin mixing conductance: relevant for transport at interfaces when the spin accumulation ***m*** and magnetization ***M*** are not collinear

Spin mixing conductance

$$G_\uparrow = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_\uparrow^{nm}|^2$$

$$G_\downarrow = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_\downarrow^{nm}|^2$$

Majority and minority conductances describe electrons going from one material to another

$$G_{\uparrow\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[1 - \sum_{m \in NM} r_\uparrow^{nm} (r_\downarrow^{nm})^* \right]$$

Describes a spin current absorbed by the FM, hence the behavior of the spins in the NM that are perpendicular to the magnetization of the FM

$Re\{G_{\uparrow\downarrow}\}$ Spin current aligned with the transverse part of $\boldsymbol{\mu_s}$ in the NM

$Im\{G_{\uparrow\downarrow}\}$ Spin current perpendicular to both $\boldsymbol{\mu_s}$ and $\boldsymbol{M}$

Both spin current components $Re\{G_{\uparrow\downarrow}\}$ and $Im\{G_{\uparrow\downarrow}\}$ are absorbed in the FM, leading to the spin torque

$$\boldsymbol{\tau}_{ST} = \frac{\hbar}{2e} \boldsymbol{j}_s^{abs} = \frac{\hbar}{e^2} \left[Re\{G_{\uparrow\downarrow}\} \widehat{\boldsymbol{M}} \times \left(\widehat{\boldsymbol{M}} \times \boldsymbol{\mu_s} \right) + Im\{G_{\uparrow\downarrow}\} \widehat{\boldsymbol{M}} \times \boldsymbol{\mu_s} \right]$$

[torque / unit area]

A. Braatas, G.E.W. Bauer, and P.J. Kelly, Phys. Rep. 427, 157 (2006)

Spin mixing conductance

$$G_{\uparrow\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[1 - \sum_{m \in NM} r_{\uparrow}^{nm} (r_{\downarrow}^{nm})^* \right] \qquad \left[\frac{I}{V} = \Omega^{-1} \right]$$

More often $G_{\uparrow\downarrow}$ is given as $\frac{j}{V}$ $[\Omega^{-1} m^{-2}]$; typically $G_{\uparrow\downarrow} = 1 \times 10^{15}\ \Omega^{-1} m^{-2}$ (e.g., Pt/NiFe)

TABLE I. Interface conductances in units of $10^{15}\ \Omega^{-1}\mathrm{m}^{-2}$.

Xia et al., PRB 65, 220401 (2002)

System	Interface	G^{maj}	G^{min}	$\mathrm{Re}G^{mix}$	$\mathrm{Im}G^{mix}$
Cu/Co(111)	Clean	0.42	0.36	0.41	0.009

~ number of conducting channels

~ 0 due to spin filter and dephasing

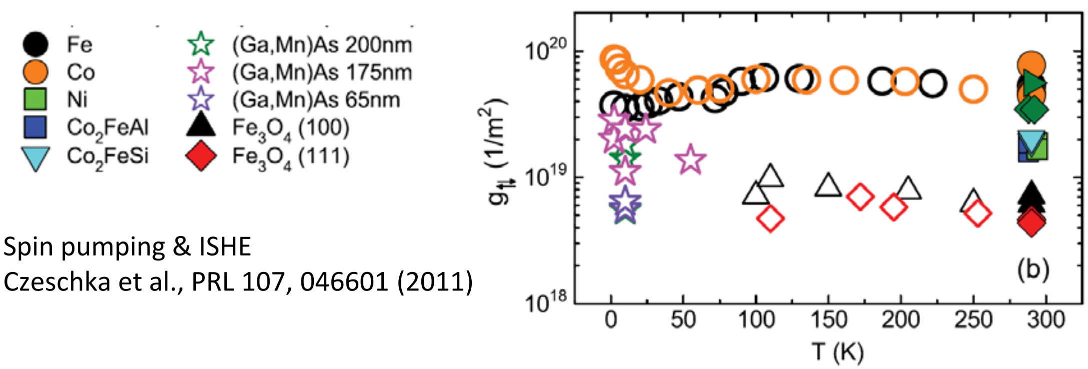
$$\frac{G_{\uparrow\downarrow}}{G_0/2} = \frac{G_{\uparrow\downarrow}}{e^2/h}$$

Quantum of conductance per spin channel

$\sim 1 \times 10^{15}\ \Omega^{-1} m^{-2} \times 25.8\ k\Omega$

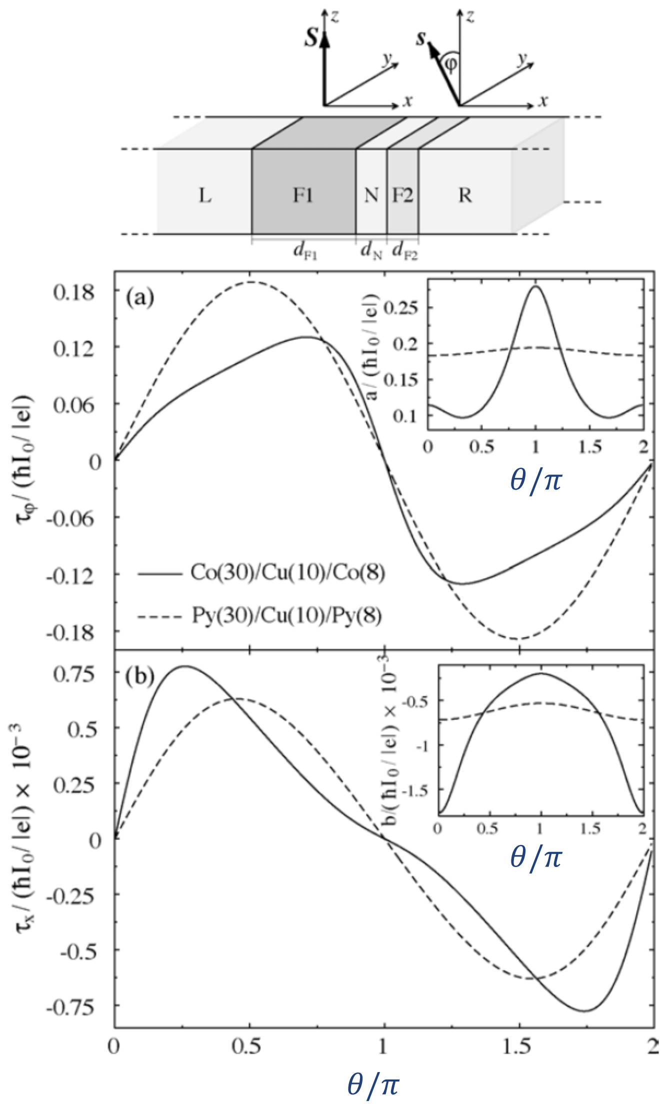
$\approx 3 \times 10^{19}\ m^{-2}$

N.B. # atoms in a monolayer film: $\approx 10^{19}\ m^{-2}$



Spin pumping & ISHE
Czeschka et al., PRL 107, 046601 (2011)

Angular dependence of STT



J. Barnas et al., PRB **72**, 024426 (2005)

A.A. Kovalev et al., PRB **66**, 224424 (2002)

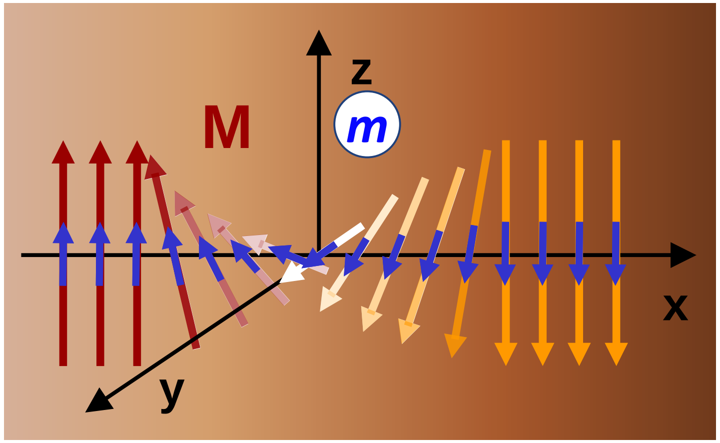
- The spin current and the coefficients a_j and b_j depend on the angle between ***m*** and ***M*** due to the influence of the longitudinal spin accumulation on spin transport

$$\boldsymbol{T_{AD}} = a_j\,(\theta)\,\boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{m})$$

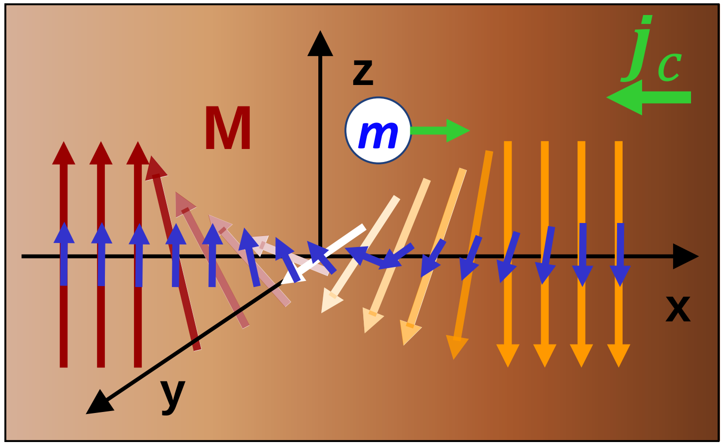
$$\boldsymbol{T_{FL}} = b_j(\theta)\,\boldsymbol{M} \times \boldsymbol{m}$$

Spin torques in nonuniform magnetization textures (DW)

$I = 0$



$I \neq 0$



$$\boldsymbol{Q} = -\frac{\hbar}{2e}\boldsymbol{j}_c \otimes \widehat{\boldsymbol{m}} \approx -\frac{\hbar}{2e}\boldsymbol{j}_c \otimes \widehat{\boldsymbol{M}}$$

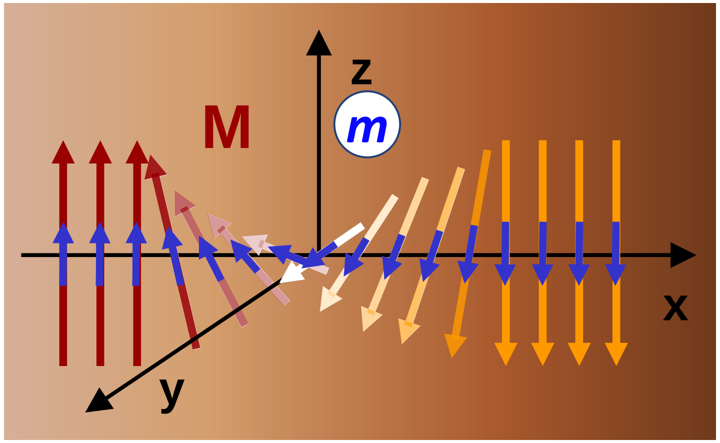
$$\nabla \cdot \boldsymbol{Q} = -\frac{\hbar}{2e} j_c \frac{\partial \widehat{\boldsymbol{M}}}{\partial x}$$

$$\boldsymbol{t}_{st} \approx -\nabla \cdot \boldsymbol{Q}$$

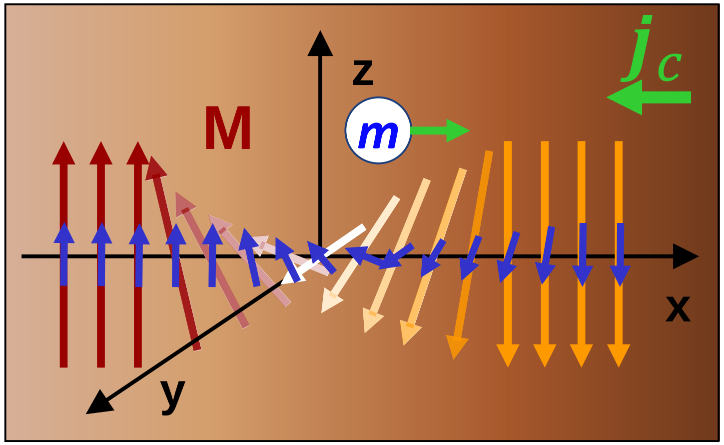
S. Zhang & Z. Li , *Phys. Rev. Lett.* 93, 127204 (2004)

Spin torques in nonuniform magnetization textures (DW)

$I = 0$



$I \neq 0$



$$\delta \boldsymbol{m}_{\perp} \sim \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial x} + \frac{\partial \boldsymbol{M}}{\partial x}$$

$$\boldsymbol{t}_{st} \sim \boldsymbol{M} \times \delta \boldsymbol{m}_{\perp} = -\frac{\mu_B P}{e M_s^3} \boldsymbol{M} \times [\boldsymbol{M} \times (\boldsymbol{j}_c \cdot \boldsymbol{\nabla}) \boldsymbol{M}] - \frac{\mu_B P}{e M_s^2} \beta \boldsymbol{M} \times (\boldsymbol{j}_c \cdot \boldsymbol{\nabla}) \boldsymbol{M}$$

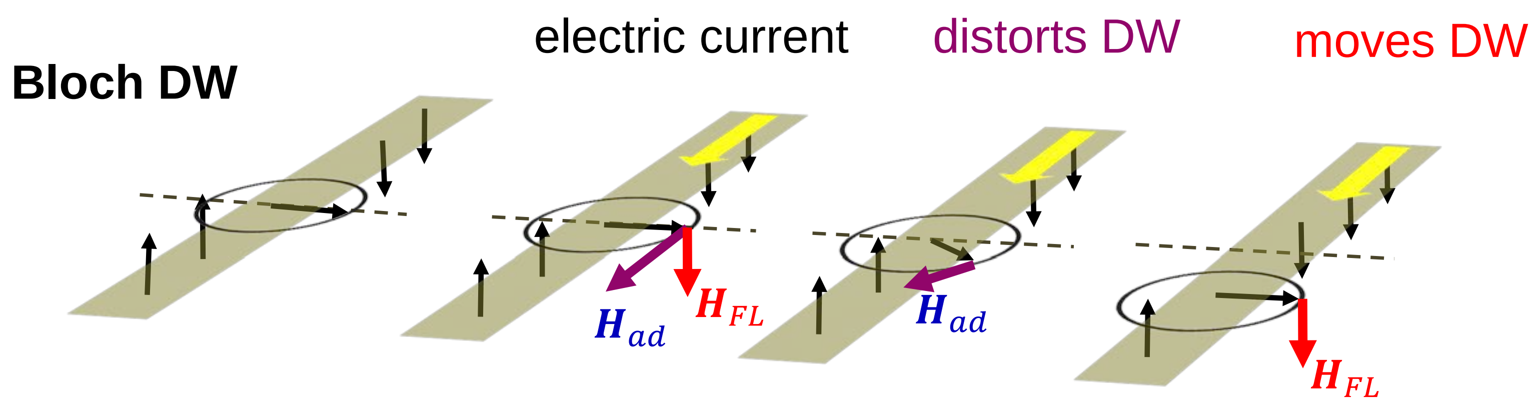
"Adiabatic torque" "Non-adiabatic torque"

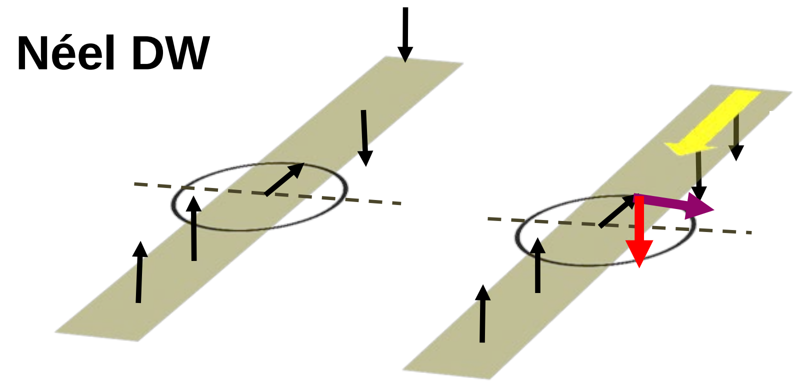
S. Zhang & Z. Li , *Phys. Rev. Lett.* 93, 127204 (2004)

Spin torques in nonuniform magnetization textures (DW)

$$\boldsymbol{t}_{st} = -\frac{\mu_B P}{e M_s^3}\boldsymbol{M}\times[\boldsymbol{M}\times(\boldsymbol{j}_c\cdot\nabla)\boldsymbol{M}] - \frac{\mu_B P}{e M_s^2}\beta\boldsymbol{M}\times(\boldsymbol{j}_c\cdot\nabla)\boldsymbol{M}$$

$$\boldsymbol{H}_{ad}\sim\boldsymbol{M}\times(\boldsymbol{j}_c\cdot\nabla)\boldsymbol{M} \qquad \boldsymbol{H}_{FL}\sim\beta(\boldsymbol{j}_c\cdot\nabla)\boldsymbol{M}$$





- The FL torque induces an effective field along the easy axis of the magnetization
- In the low current (non turbulent) regime, the DW velocity depends on $\boldsymbol{H}_{FL}$

Spin pumping

A spin current moves the magnetization

⇕

Magnetization motion induces a spin current

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} + \boxed{\frac{\alpha}{M} \vec{M} \times \frac{d\vec{M}}{dt}}$$

⇩

Damping term

⇩

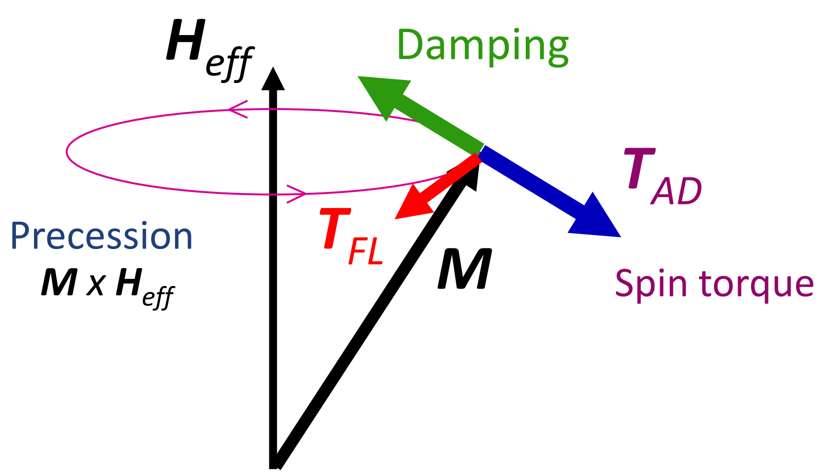
Dissipation of angular momentum

⇩

Transferred to conduction electrons

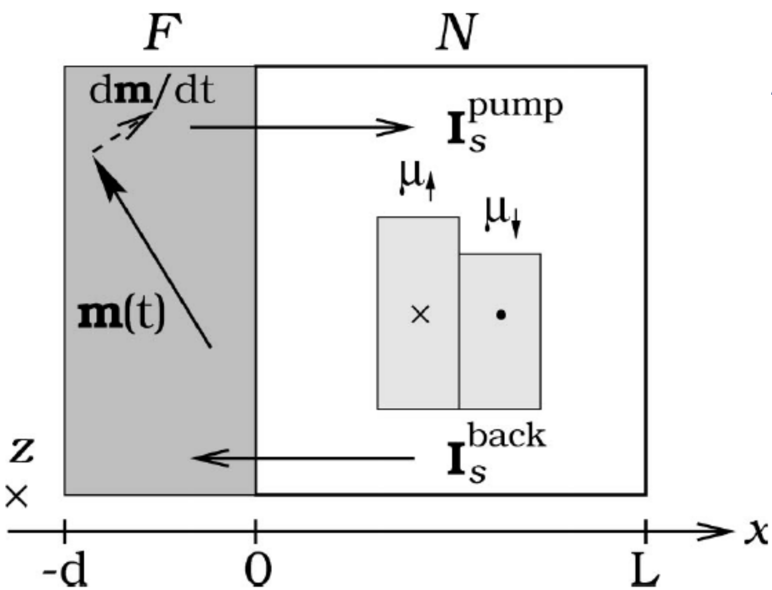
⇩

Generation of **spin current** ($\mu_{\uparrow} \neq \mu_{\downarrow}$)



Y. Tserkovnyak et al., PRL 88, 117601 (2002).
S. Mizukami et al., PRB 66, 104413 (2001); R. Urban et al., PRL 87, 217204 (2001).

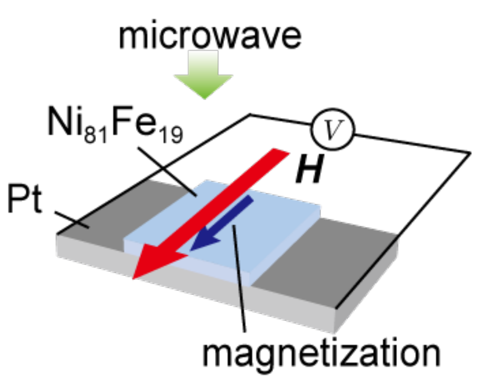
Spin pumping

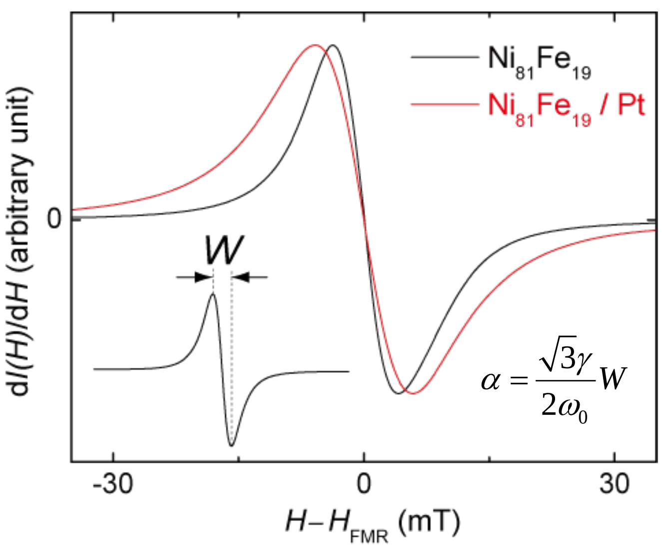


$$j_s = \frac{\hbar}{e}\left[Re\{G_{\uparrow\downarrow}\}\left(\widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{d\boldsymbol{t}}\right) + Im\{G_{\uparrow\downarrow}\}\frac{d\widehat{\boldsymbol{M}}}{d\boldsymbol{t}}\right]$$

- The spin current pumped out of the FM is perpendicular to ***M***
- STT and spin pumping are reciprocal effects, governed by the same conductance parameters

Y. Tserkovnyak et al., PRB 66, 224403 (2002)



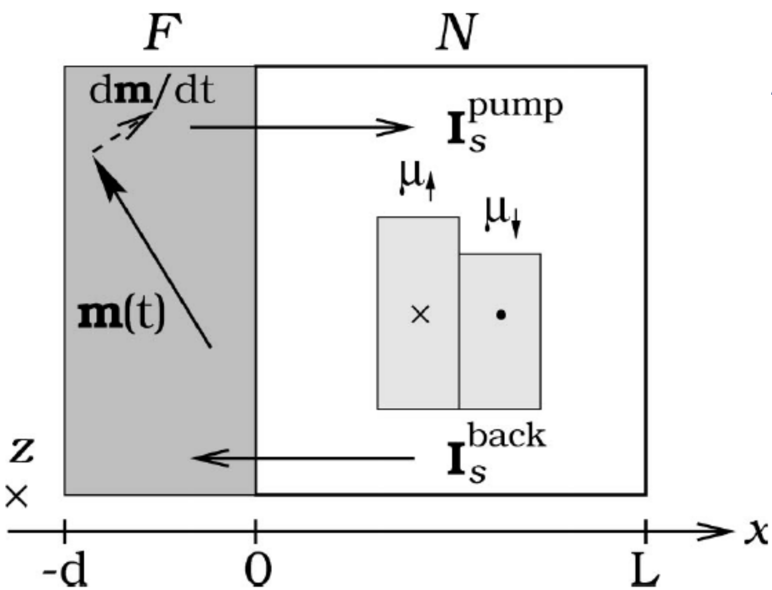


$$\alpha = \alpha_0 + \alpha'$$

$$\alpha' \sim G_{\uparrow\downarrow}$$

Ando et al., PRL 101, 036601 (2008)

Spin pumping



$$\boldsymbol{j}_s = \frac{\hbar}{e}\left[Re\{G_{\uparrow\downarrow}\}\left(\widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{d\boldsymbol{t}}\right) + Im\{G_{\uparrow\downarrow}\}\frac{d\widehat{\boldsymbol{M}}}{d\boldsymbol{t}}\right]$$

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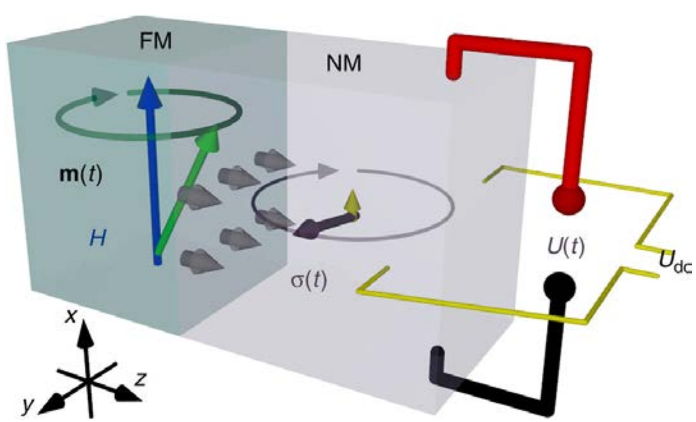
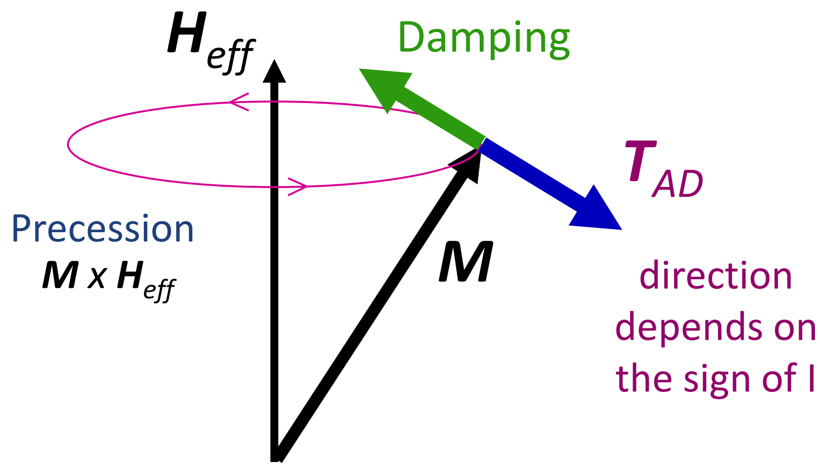
Y. Tserkovnyak et al., PRB 66, 224403 (2002)



$$V_{ISHE} \sim \boldsymbol{j}_s \times \boldsymbol{\sigma}$$

D. Wei et al., Nat. Comm. 5, 3768 (2014)
M. Weiler et al., PRL 113, 157204 (2014)

Spin-transfer driven magnetic dynamics

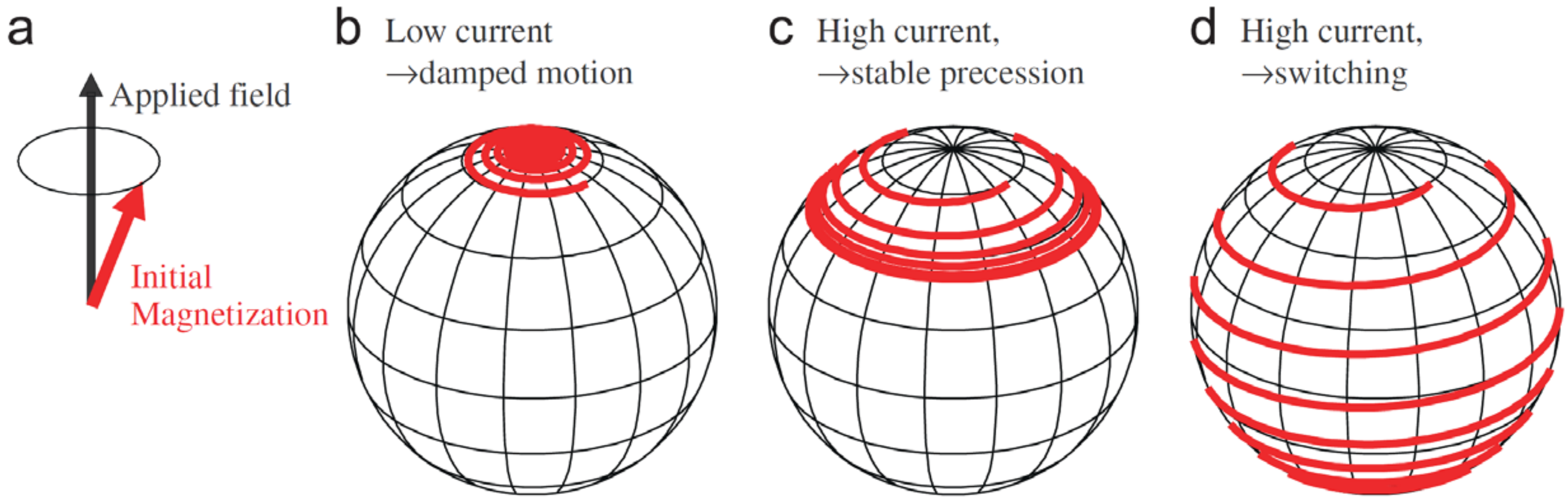


$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M} \vec{M} \times \frac{d\vec{M}}{dt} + \eta(\theta) \frac{\mu_B I}{eV} \hat{M} \times (\hat{M} \times \hat{m})$$

- AD spin torque added to LLG equation for ***M***
- Dynamics of spin accumulation (***m***) much faster than ***M***
- Macrospin approximation or micromagnetic simulations

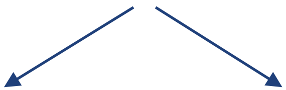
Spin-transfer driven magnetic dynamics

Magnetization in a perpendicular field



$I < I_C$
M spirals back toward z due to damping.

$I > I_C$
The effective damping becomes negative due to STT: precession is amplified and ***M*** spirals away from z.



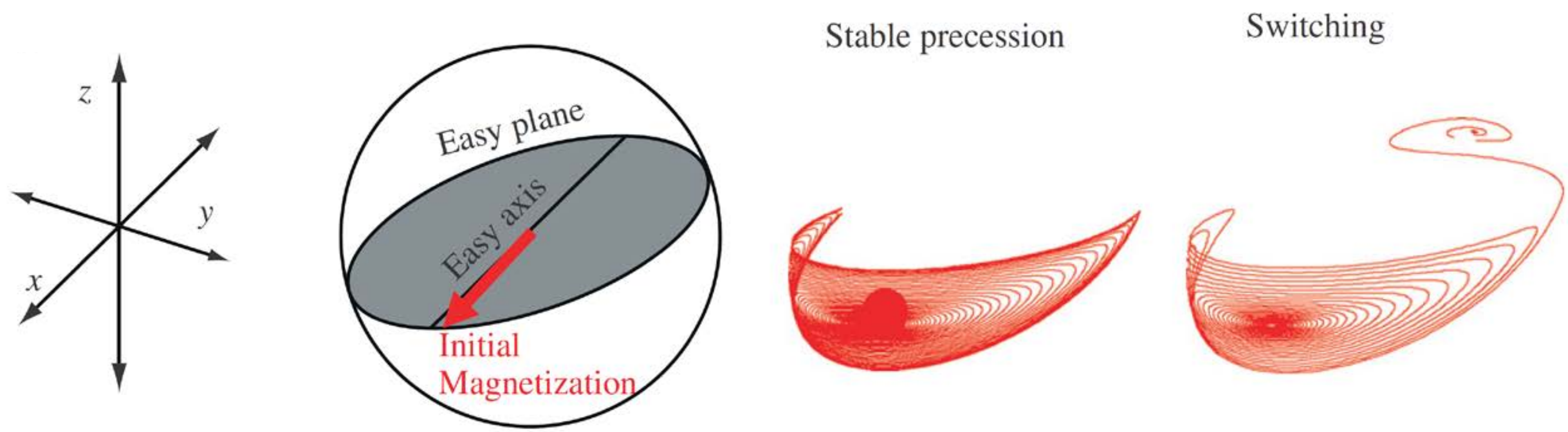
Steady-state precession at large angles

Magnetization reversal

Ralph & Stiles, JMMM 320, 1190 (2008)

Spin-transfer driven magnetic dynamics

Thin film with easy axis along x, hard axis along z



- The critical switching current is reached when the energy lost due to damping is overcomed by the energy gained by STT in each cycle
- Generally, due to the larger amount of spin accumulation in the AP state

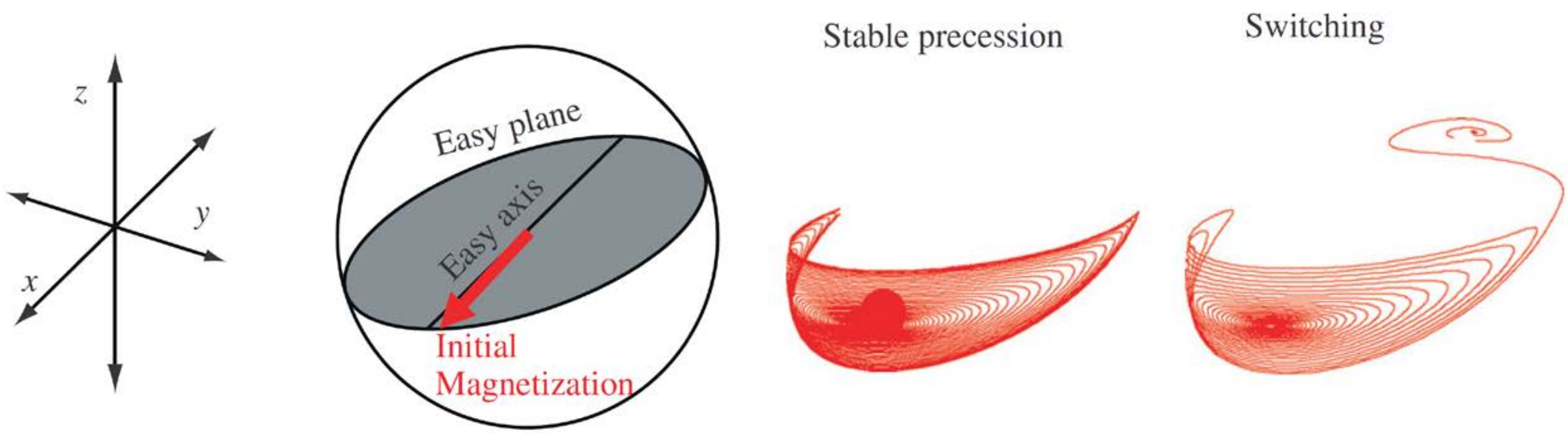
$$\boxed{I_C = \frac{2e}{\hbar}\frac{\alpha}{\eta(\theta_0)} V\, \mu_0 M_s\left(H + H_k + \tfrac{1}{2}M_s\right)}$$

$$\boxed{I_{AP\rightarrow P} \;<\; I_{P\rightarrow AP}}$$

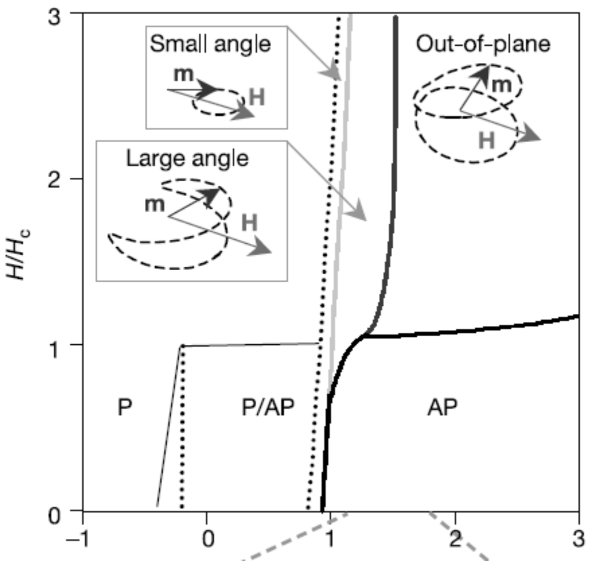
Ralph & Stiles, JMMM 320, 1190 (2008)

Spin-transfer driven magnetic dynamics

Thin film with easy axis along x, hard axis along z



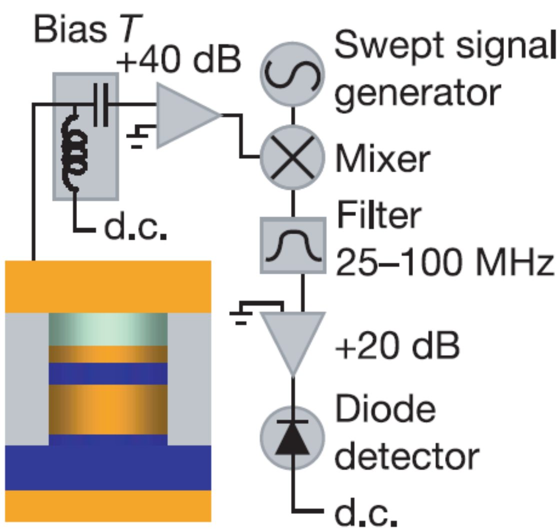
- Different static magnetic states and stationary precessional modes can be reached depending on current and applied field



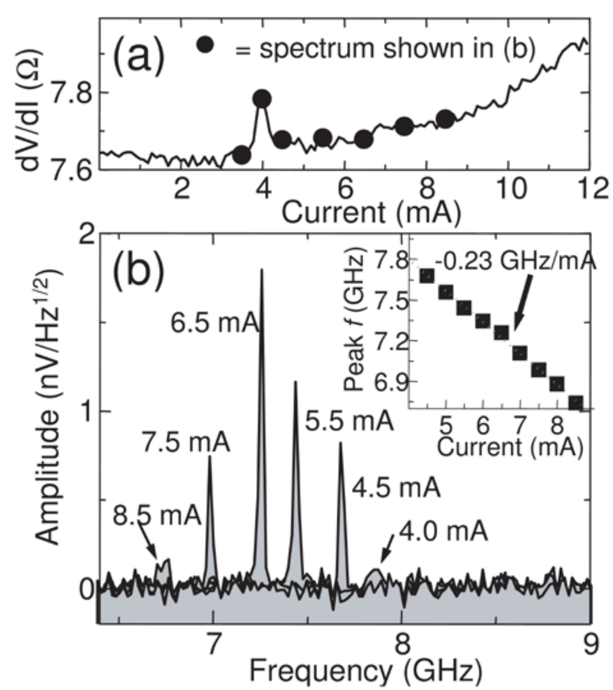
Kiselev et al., Nature 425, 380 (2003)

Spin torque oscillator

DC current → Precession → GMR changes at MW frequency → MW voltage at contacts



Kiselev et al., Nature 425, 380 (2003)



Differential resistance vs *I*

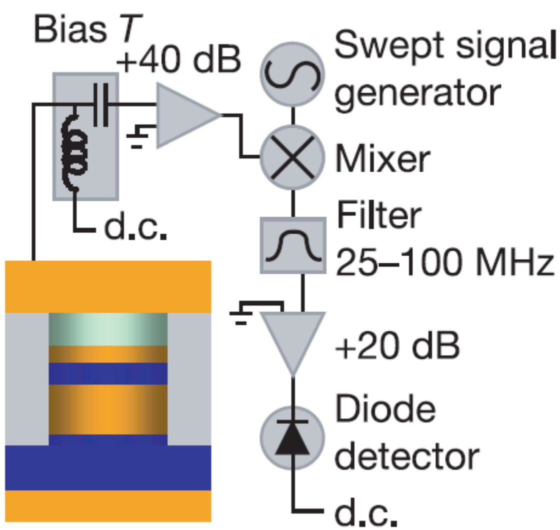
MW voltage *vs I* and *f*

Rippard et al.,
PRL 92, 027201 (2004)

External fields favors P configuration, current favors AP → steady state oscillations

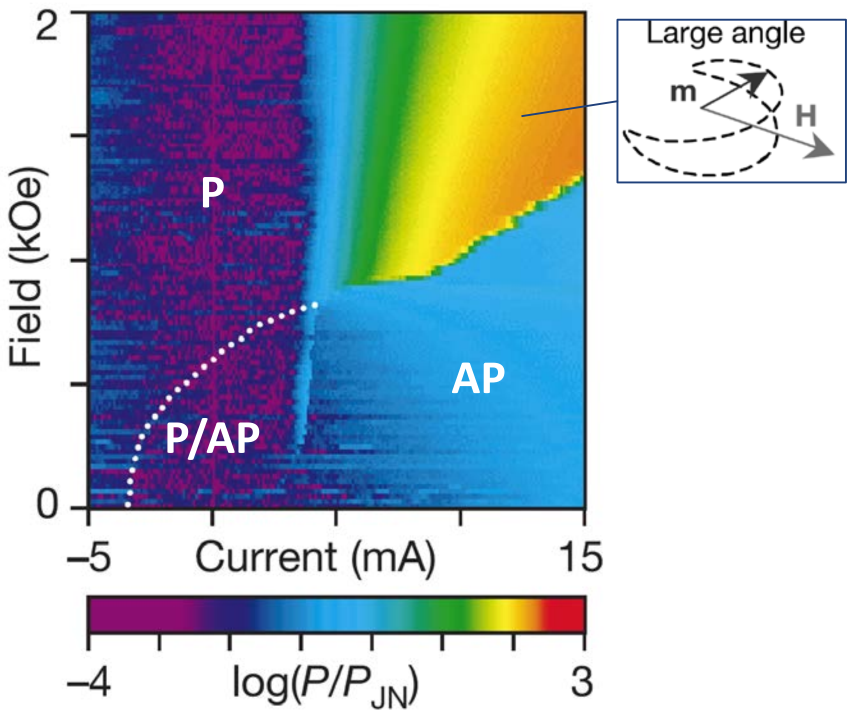
Spin torque oscillator

DC current → Precession → GMR changes at MW frequency → MW voltage at contacts



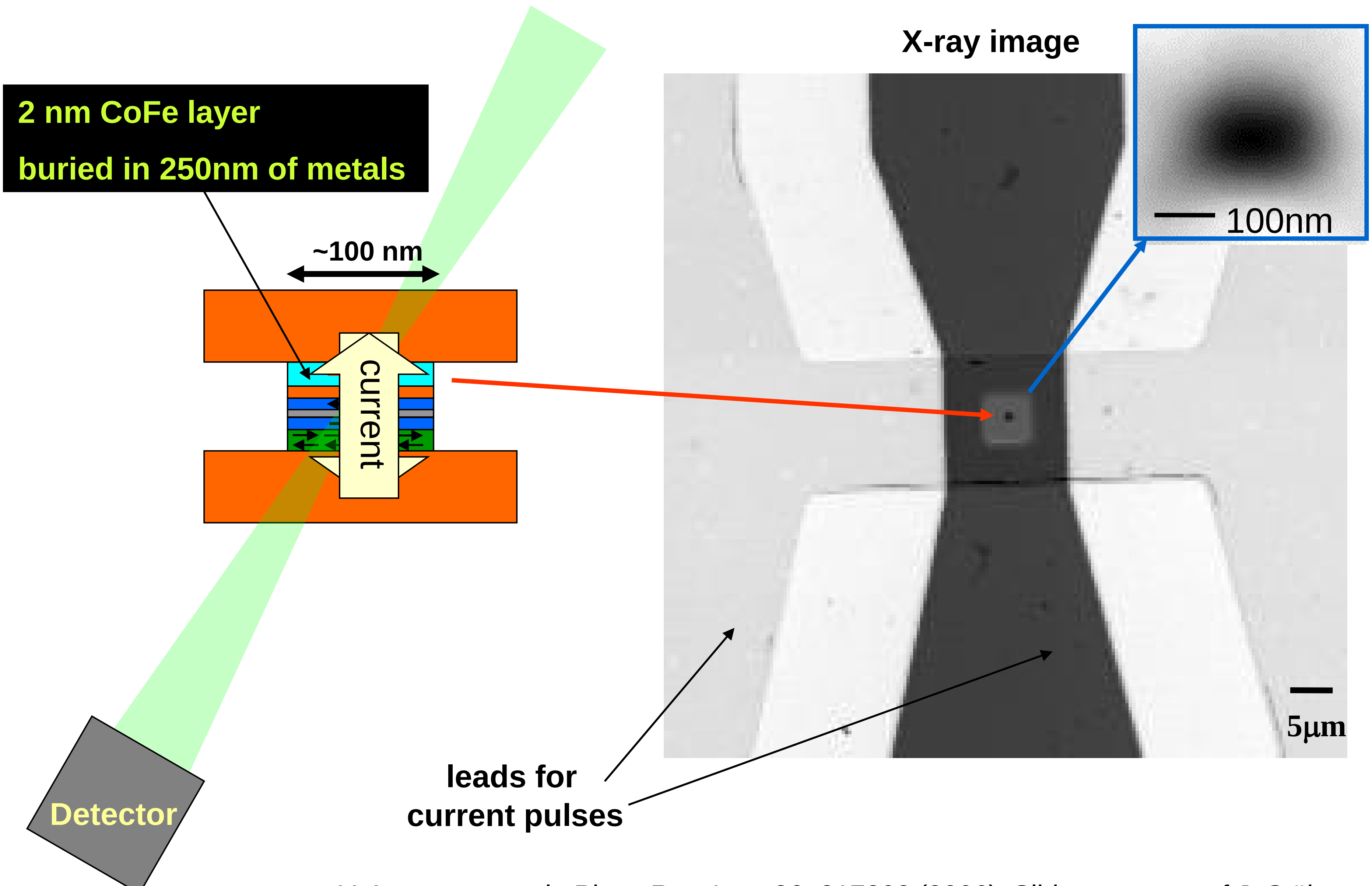
Kiselev et al., Nature 425, 380 (2003)

MW power versus vs I and H applied along the in-plane easy axis.



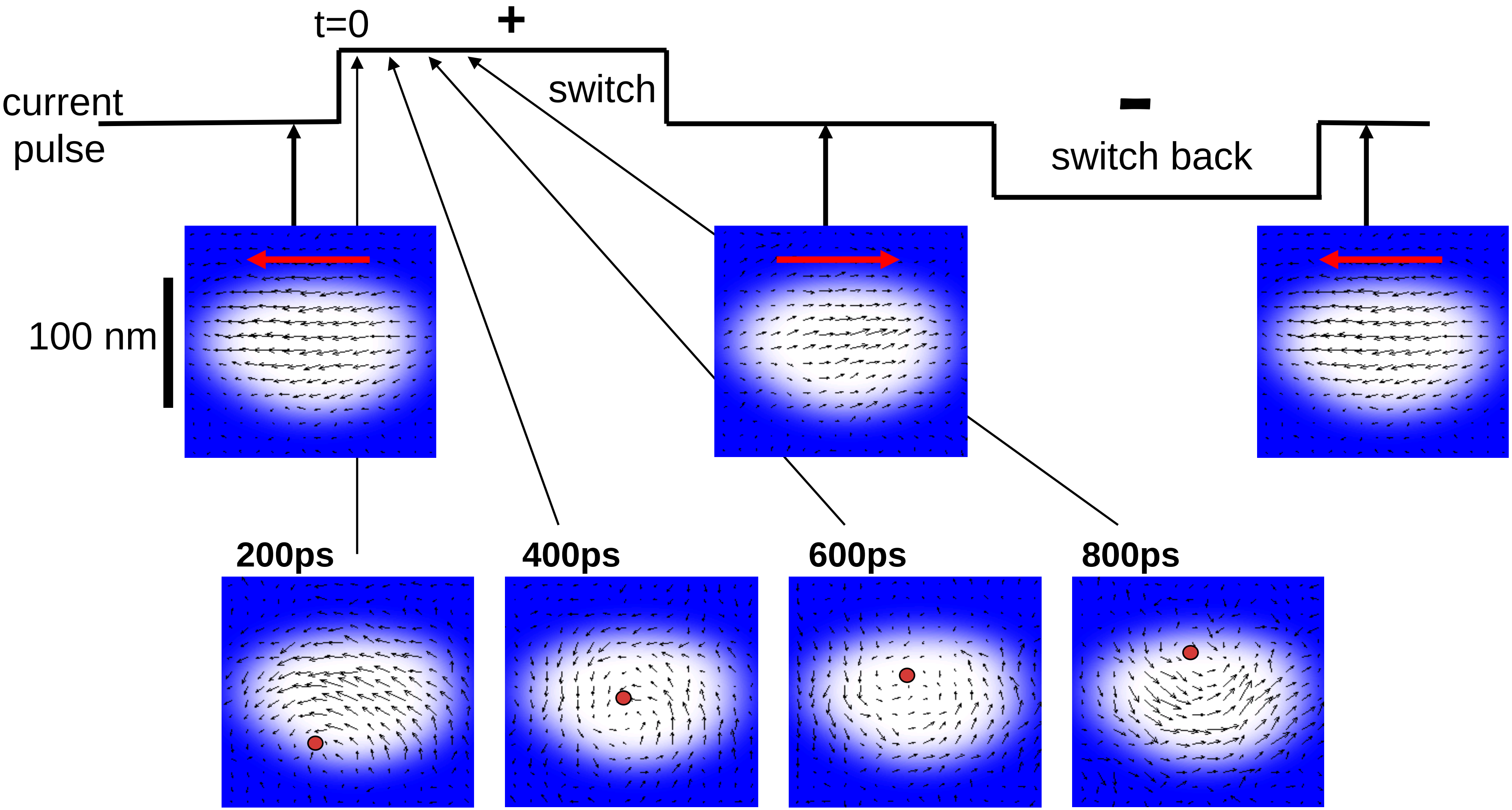
- Nanoscale oscillator or MW source with tunable frequency for on-chip applications
- MW power scales with MR (larger in MTJ)
- Nonlinear coupling between amplitude and frequency leads to *f* fluctuations and broadens the linewidth

Imaging ST-driven switching by time-resolved STXM



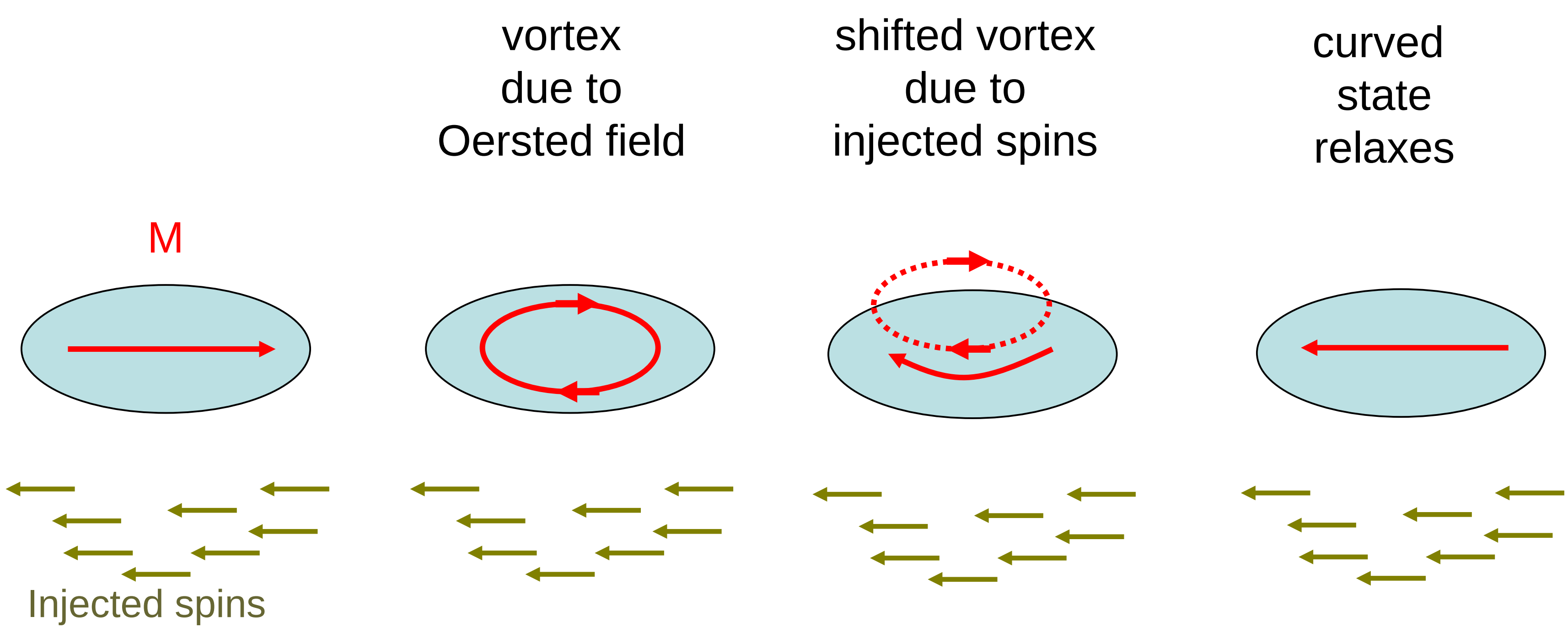
Y. Acremann et al., Phys. Rev. Lett. **96**, 217202 (2006); Slides courtesy of J. Stöhr

ST-driven switching of 180nm x 110nm x 2nm CoFe pillar



Y. Acremann et al., Phys. Rev. Lett. **96**, 217202 (2006)
J. P. Strachan et al., Phys. Rev. Lett. **100**, 247201 (2008)

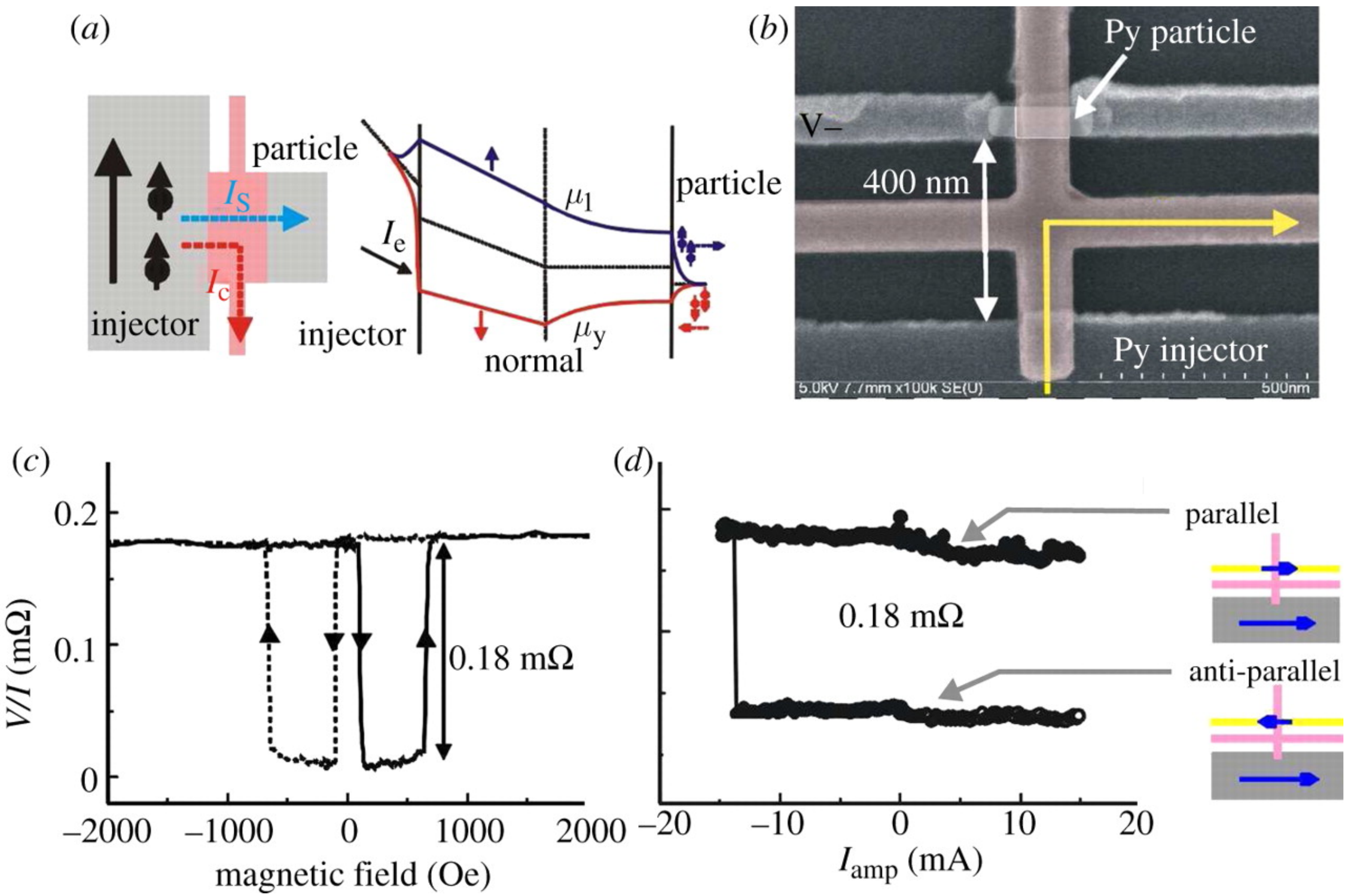
Switching process



- Vortex breaks the symmetry, starts process
- Spin current transfers angular momentum, drives switching
- Switching speed 200 m/s (~ speed of sound)

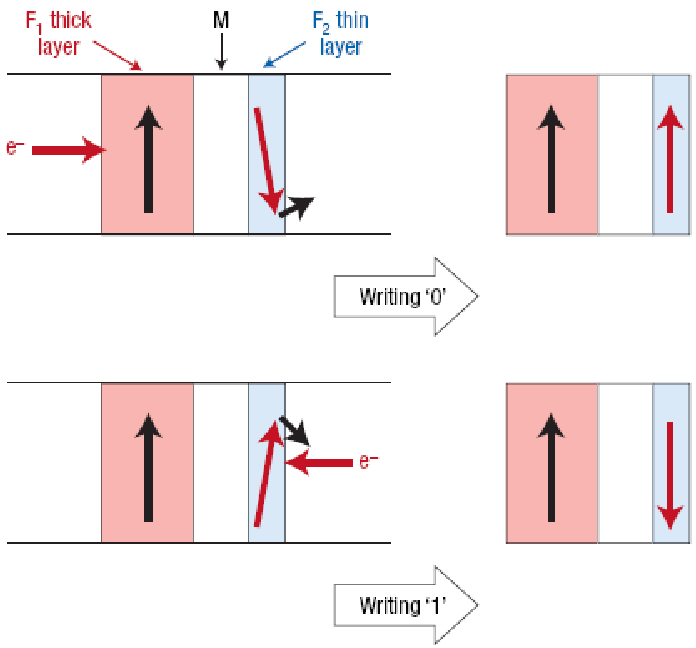
Y. Acremann et al., Phys. Rev. Lett. **96**, 217202 (2006)

Switching by nonlocal spin injection



T. Kimura et al., PRL 96, 037201 (2006); Yang et al., Nat. Phys. 4, 851 (2008)

Summary: STT in FM/NM/FM and textured magnetic layers

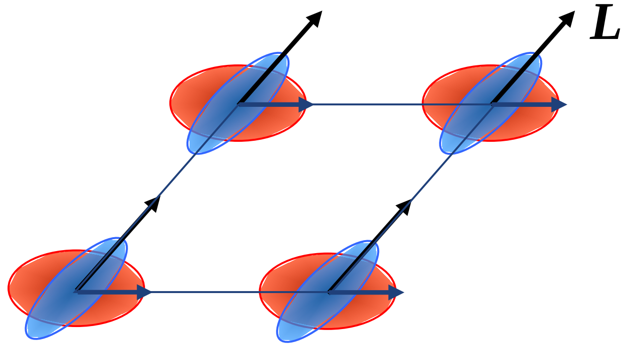


- Spin current generated by the spin- transfer effect from a FM "polarizer" layer or magnetic domain
- Can be used to switch a "free" FM layer, move DWs, or induce sustained oscillations
- It works in metallic spin valves (FM/NM/FM) as well as in magnetic tunnel junctions (FM/oxide/FM)

- Charge and spin transport channels overlap: other device geometries are possible
- Requires at least two FM layers in CPP geometry
- DW motion requires large current density
- $T \sim sin\theta_0 \sim \theta_0$ implies large and unpredictable incubation time to initiate switching

Spin-orbit coupling

Fundamental link between charge and spin



$$\mathcal{H} = \sum_i \left(\frac{\vec{p}_i^2}{2m} + V(\vec{r}_i) \right) + \frac{1}{2} \sum_{i \neq j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|} + \mu_B B \frac{1}{\hbar} \sum_i (\ell_{z,i} + 2\, s_{z,i})$$

$$\mathcal{H}_{\ell s} \;=\; \sum_i \zeta(\vec{r}_i)\, \vec{\ell}_i \vec{s}_i$$

Small... ...but powerful!

	Energy (eV/atom)
Cohesive energy	5.5
Local moment formation	1.0
Alloy formation	0.5
Exchange	0.2
Structural relaxation	0.05
Spin-orbit coupling	0.03-0.08

Effects induced by spin-orbit coupling

- **Magnetocrystalline anisotropy**

$$E(\theta) = K_u \sin^2 \theta$$

- **Antisymmetric exchange**

$$H_{DM} = D_{ij}\left(\mathbf{S_i} \times \mathbf{S_j}\right)$$

- **Magnetic damping**

$$\frac{d\vec{M}}{dt} \sim \frac{\alpha}{M}\vec{M} \times \frac{d\vec{M}}{dt}$$

- **Anisotropic magnetoresistance**

$$R(\theta) = R_{\perp} + \left(R_{//} - R_{\perp}\right)(\hat{\mathbf{j}} \cdot \hat{\mathbf{M}})$$

- **Anomalous Hall effect**

$$R_H = R_0 + R_a(\hat{\mathbf{j}} \times \hat{\mathbf{M}})$$

- **Spin Hall effect**

$$j_i^k = \sigma_{ij}^k E_j$$

- **Rashba effect**

$$H_R = \alpha_R(\sigma_x k_y - \sigma_y k_x)$$

- **Dresselhaus effect**

$$H_D = \beta(\sigma_x k_x - \sigma_y k_y)$$

Effective magnetic fields due to relativistic spin-orbit effects

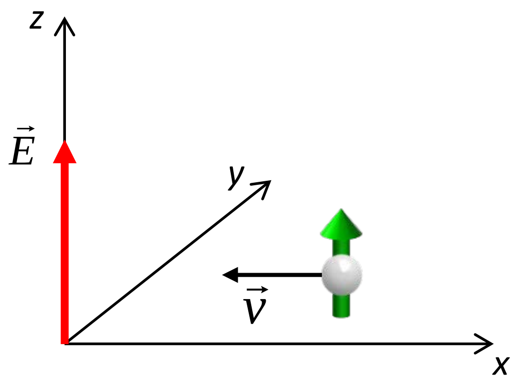
Schrödinger-Pauli Hamiltonian:

$$H = \frac{1}{2m}[\vec{p} + \frac{e}{c}\vec{A}(\vec{r},t)]^2 - e\phi(\vec{r},t) + \frac{e\hbar}{2mc}\vec{\sigma}\cdot\vec{B}(\vec{r},t)$$

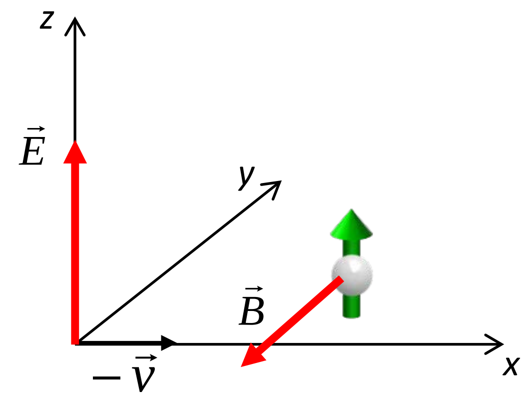
Relativistic effect: **magnetic field due to spin-orbit coupling**

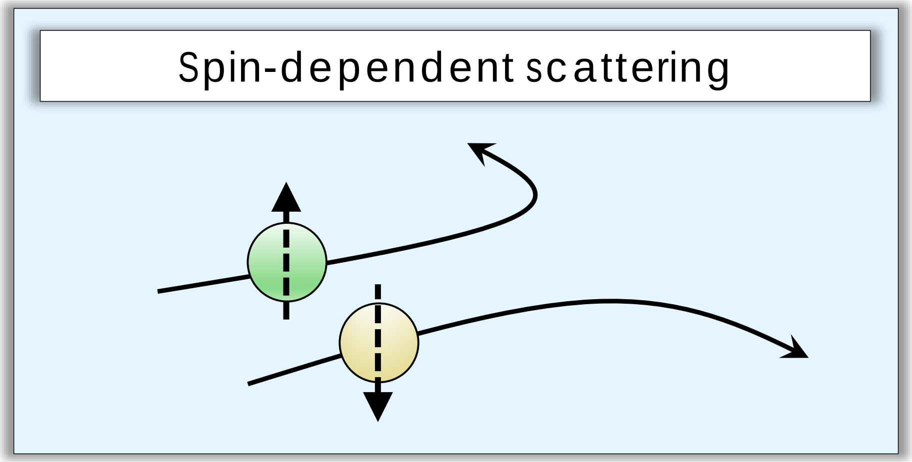
$$\boxed{\vec{B}_{eff}(\vec{k}) = \frac{1}{2c^2}\vec{E}\times\vec{v}}$$

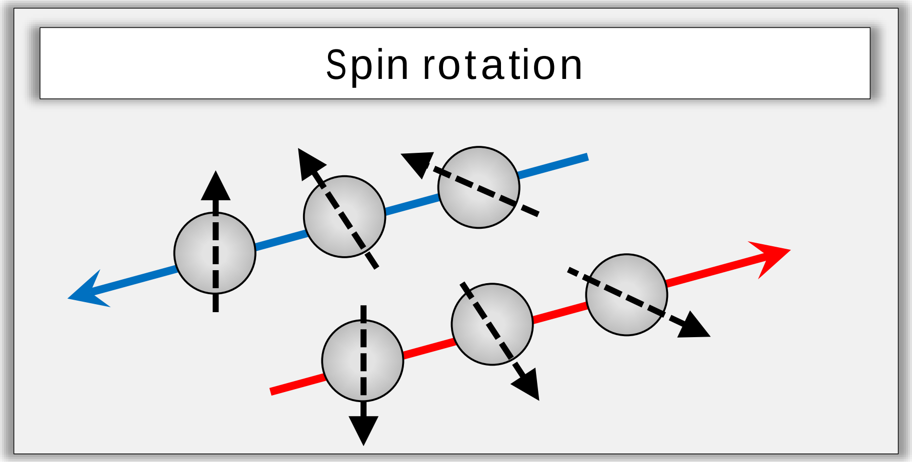
Laboratory reference frame



Electron's rest frame

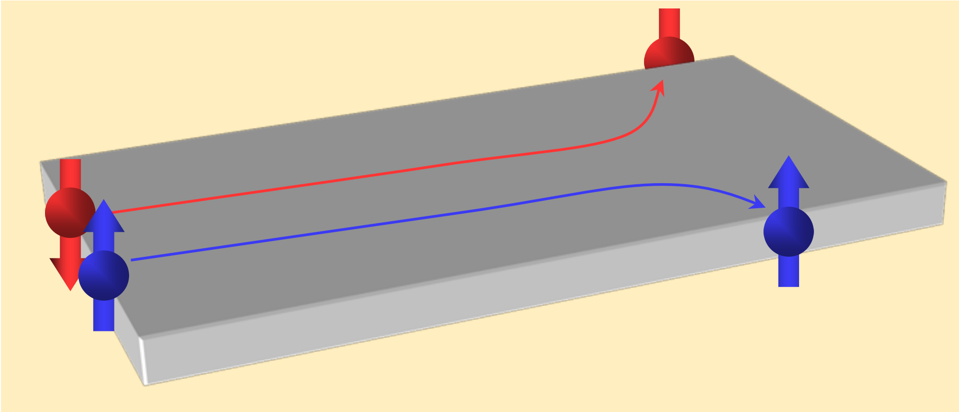



Spin-dependent scattering


Spin rotation

Spin Hall effect

Spin-dependent scattering gives rise to transverse spin imbalance of charge currents

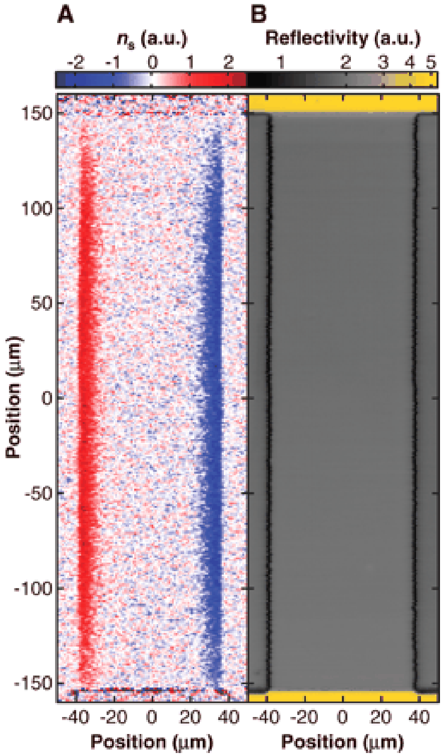


M. I. Dyakonov and V. I. Perel, JETP Lett. **13**, 467 (1971);

J. E. Hirsch, Phys. Rev. Lett. **83**, 1834 (1999)

Reviews: Sinova et al., arXiv:1411.3249

Hoffmann, IEEE Transactions on Magnetics, 2013

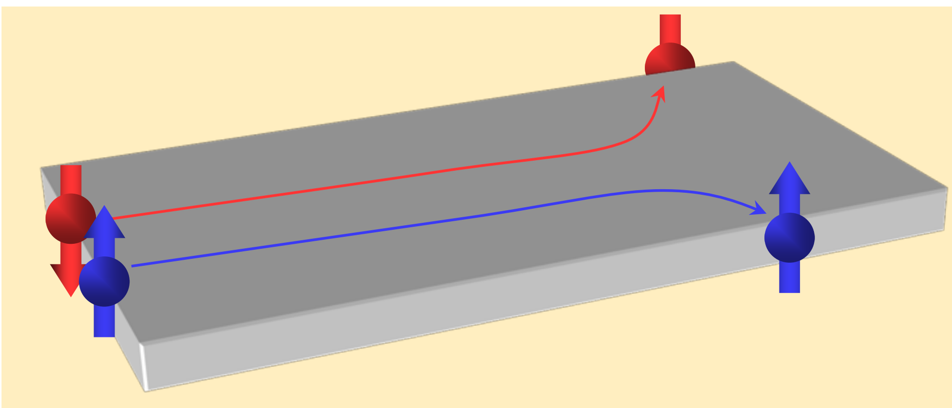


Direct observation in GaAs with optical detection

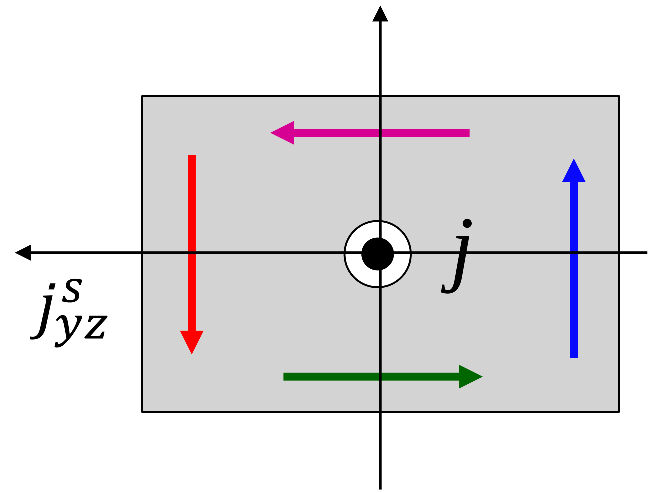
Y. K. Kato *et al.*, Science **306**, 1910 (2004)

Spin Hall effect

Spin-dependent scattering gives rise to transverse spin imbalance of charge currents



$$j^s_{zy} = \theta_{SH}\, j^c_x$$



$$\theta_{SH} = \frac{j_c}{j_s} = \frac{\sigma_{xx}}{\sigma^{SH}_{yx}}$$

M. I. Dyakonov and V. I. Perel, JETP Lett. **13**, 467 (1971);

J. E. Hirsch, Phys. Rev. Lett. **83**, 1834 (1999)

Reviews: Sinova et al., arXiv:1411.3249

Hoffmann, IEEE Transactions on Magnetics, 2013

$\theta_{SH}(\mathrm{Pt}) = 0.0037 \quad \rightarrow \quad 0.08 \quad \rightarrow \quad \geq 0.2$

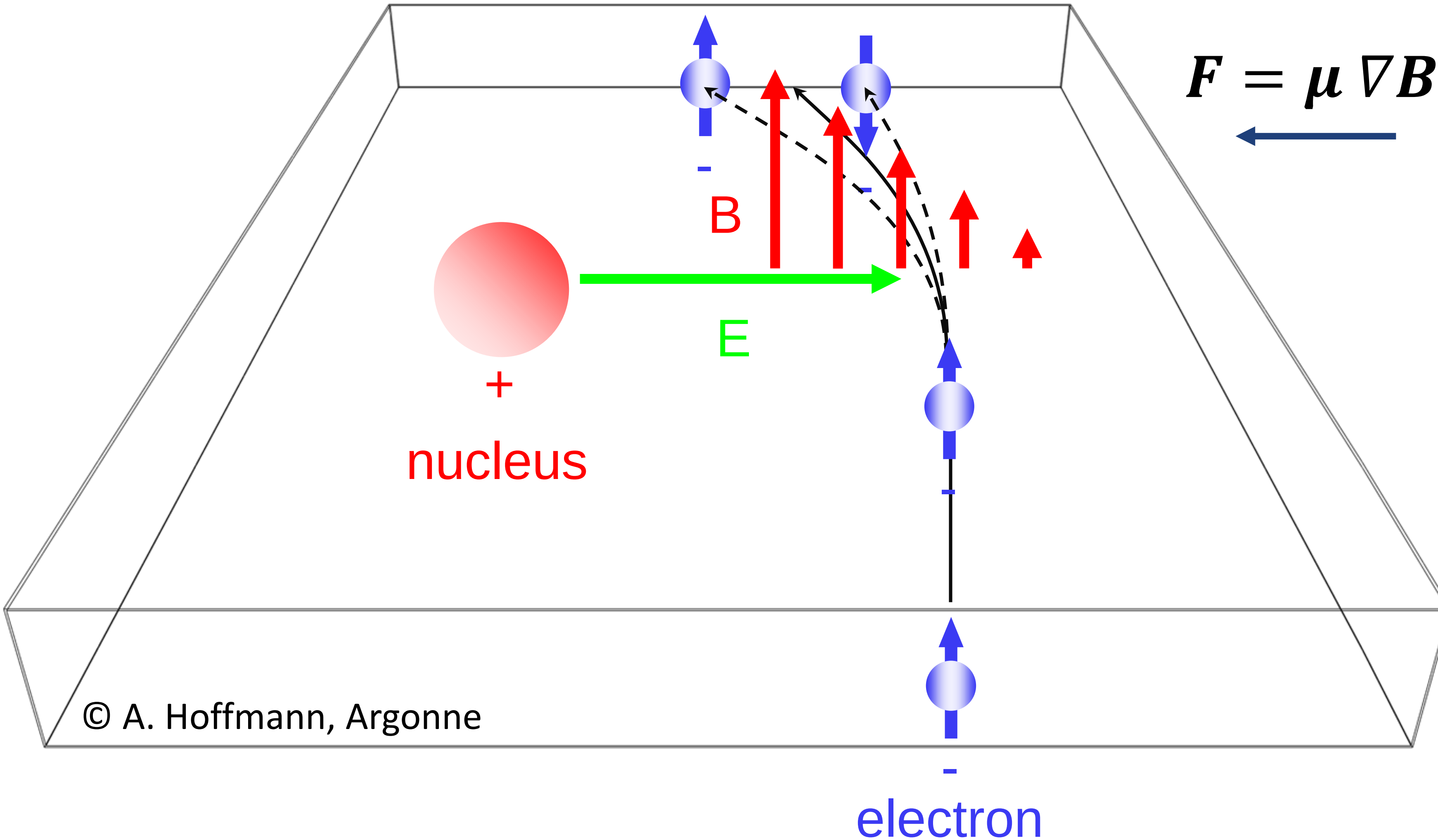
T. Kimura et al., *PRL* 98, 156601 (2007)

E. Saitoh et al., *APL* 88, 182509 (2006)

K. Ando et al., *PRL* 101, 036601 (2008)

M.H. Nguyen et al., *arXiv:1504.02806*

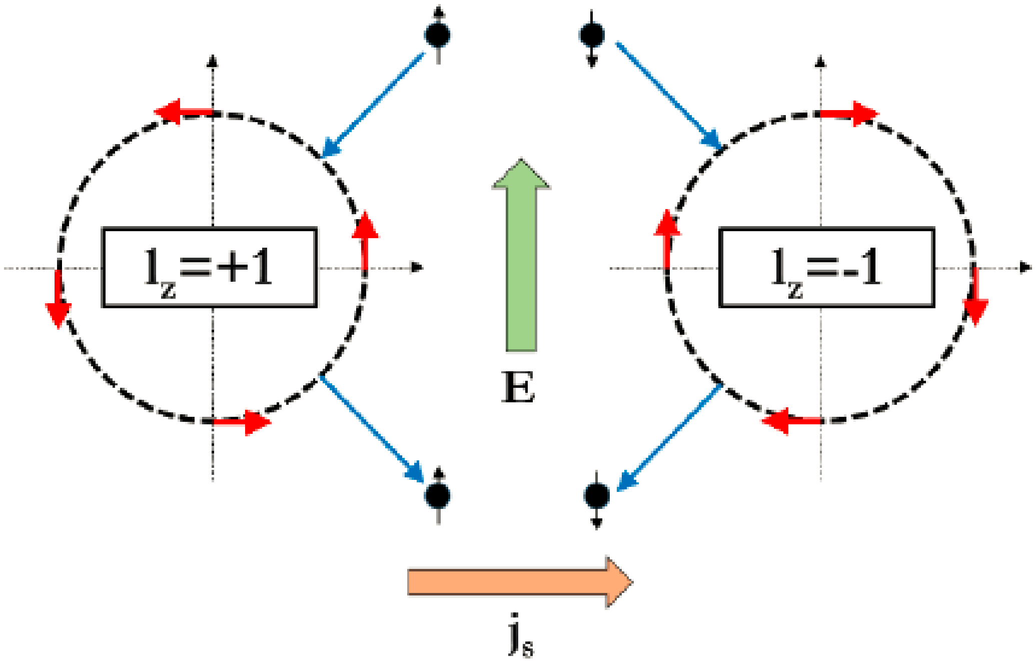
Extrinsic spin Hall effect: skew (Mott) scattering



$$\boldsymbol{F} = \boldsymbol{\mu}\,\nabla \boldsymbol{B}$$

Smit, Physica 24, 39 (1958)

Intrinsic spin Hall effect "in Kindergarten"



PhD thesis
Marc Drouard

- E-field induced hopping of spin up (down) electrons between sd-states with plus (minus) orbital moment according to 3rd Hund's rule
- Electron acquire a finite amount of orbital angular momentum that is spin dependent

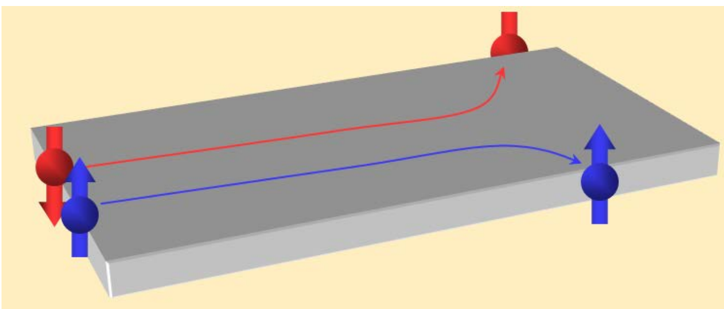
Anomalous velocity

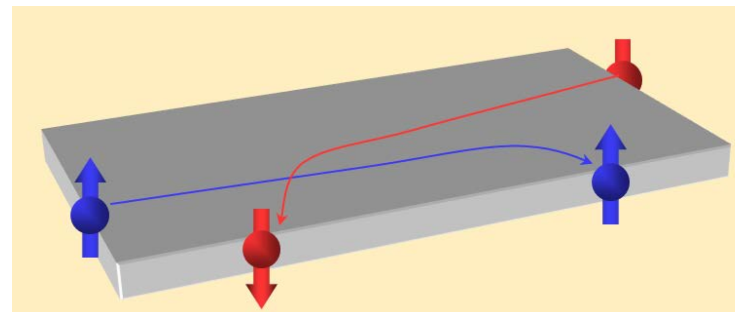
$$\dot{\boldsymbol{x}} = \frac{1}{\hbar}\frac{\partial E_n(\boldsymbol{k})}{\partial \boldsymbol{k}} + \dot{\boldsymbol{k}} \times \boldsymbol{B}_n(\boldsymbol{k})$$

Kontani et al., PRL 100, 096601 (2008); Karplus and Lüttinger, Phys. Rev. 95, 1154 (1954).

Inverse spin Hall effect

SHE		ISHE
Charge Current		Spin Current
⇓	*Spin dependent scattering*	⇓
Transverse spin imbalance		Transverse charge imbalance

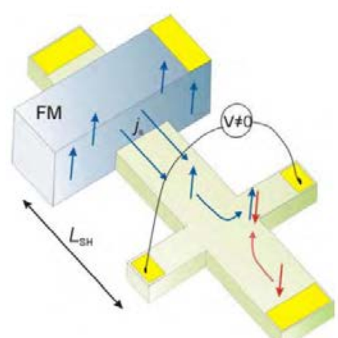


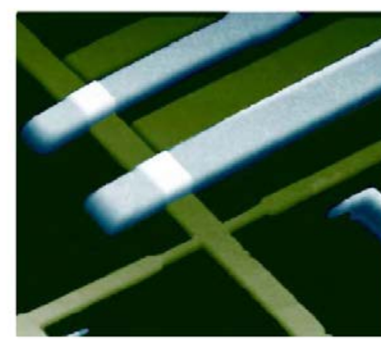


Optical spin excitation: Bakun et al., Sov. Phys. JETP Lett. 40, 1293 (1984)

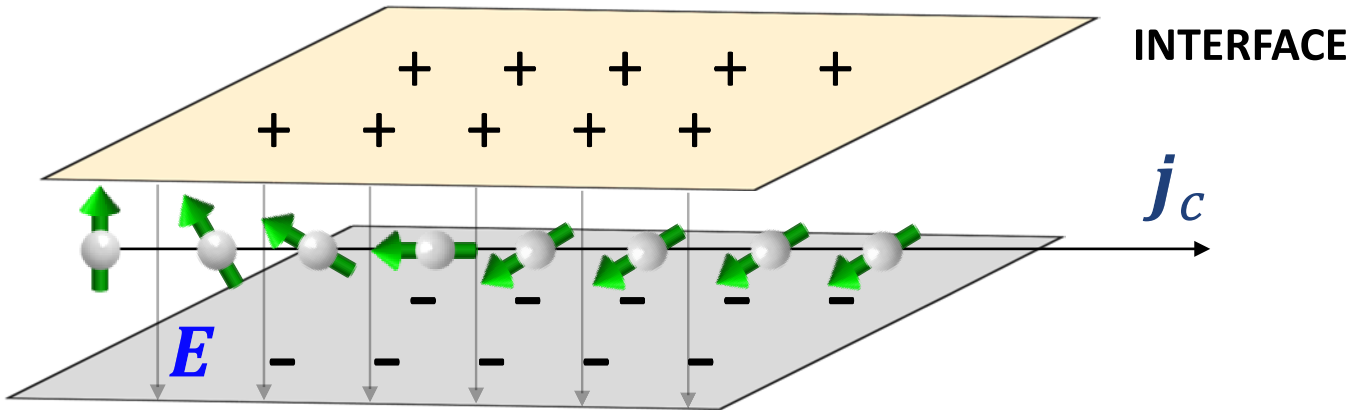
Non local transport: Valenzuela and Tinkham, Nature 442, 176 (2006).

Spin pumping: Saitoh et al., *APL* 88, 182509 (2006)





Effective Rashba magnetic field due to an in-plane current



Conduction electrons moving in an uncompensated $\boldsymbol{E}$ field at interfaces: $\boldsymbol{B} \sim \boldsymbol{v} \times \boldsymbol{E} \sim \boldsymbol{j_c} \times \hat{\boldsymbol{z}}$

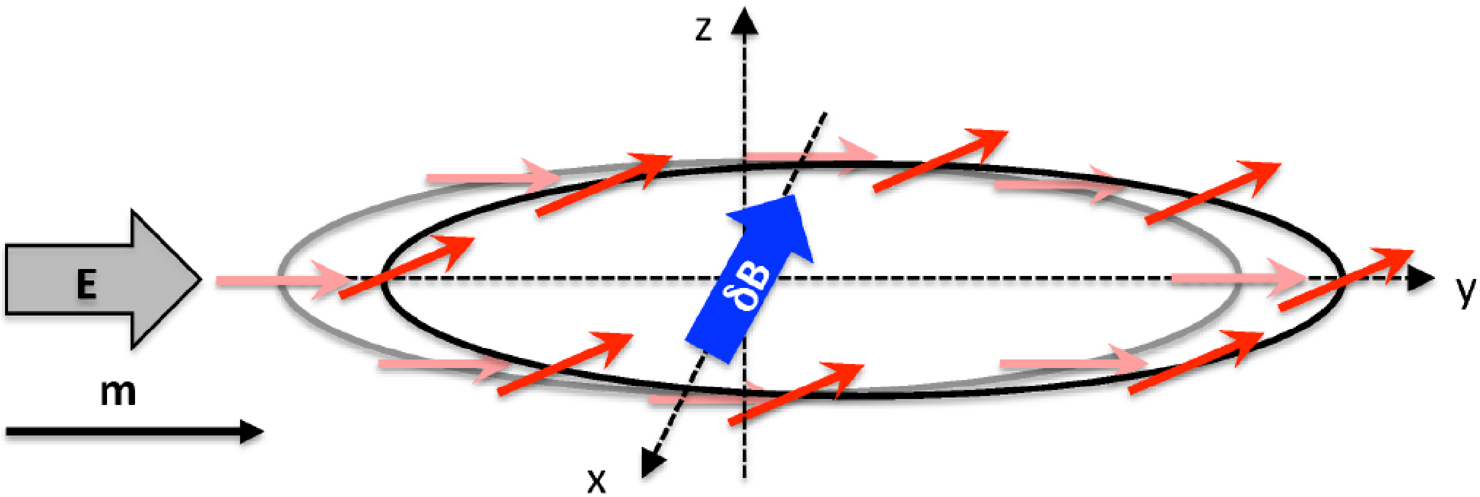
$$\boldsymbol{B}_R = \frac{\alpha_R}{2\mu_B^2}(\boldsymbol{j}_c \times \hat{\boldsymbol{z}})$$

$$\delta m_y = \frac{\mu_B m_e^* \alpha_R}{e\hbar E_F} j_c$$

The Rashba field induces a homogenous spin polarization in-plane, perpendicular to the current.
"Edelstein effect" or "Inverse spin galvanic effect" or "Rashba effect"

Edelstein, Solid State Commun. 1990; Manchon and Zhang, PRB 2008; PG and Miron, Phil. Trans. R. Soc. A 369, 3175 (2011).

Out-of-plane spin polarization due to the Rashba effect



$$\boxed{\delta m_z \sim \frac{\alpha_R}{J_{sd}} j_c}$$

- Displacement of the Fermi surface $\rightarrow$ nonequilibrium spin-orbit field $\delta B \;||\; x$
  - spin precession around δB produces a stationary spin density along z

Kurebayashi et al., Nat. Nanotech. 9, 211 (2014)

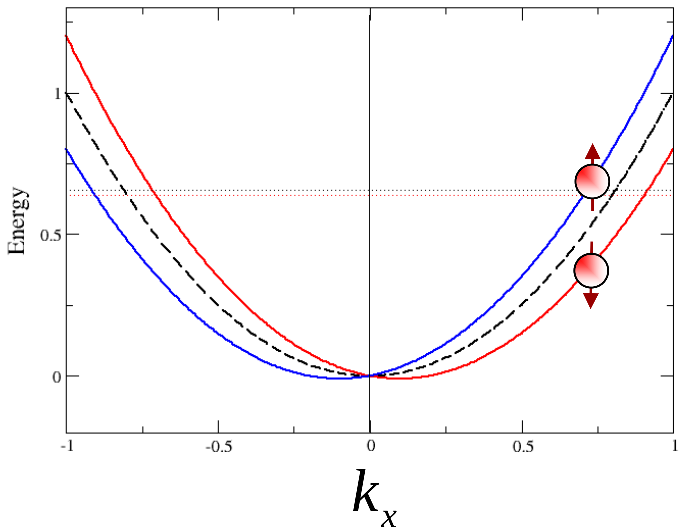
Observation of Rashba-split surface states on metal surfaces

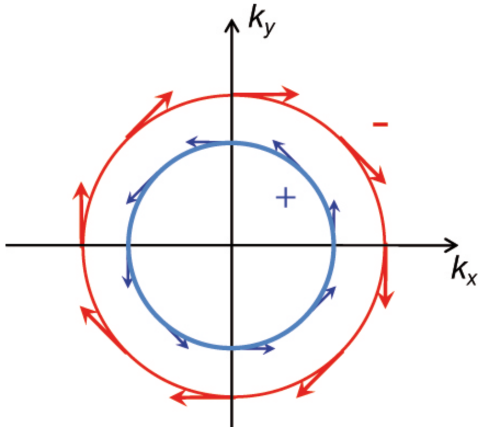
2D electron gas with
structure inversion asymmetry

$$H = -\frac{\hbar^2 k^2}{2m} + \alpha_R(\sigma_x k_y - \sigma_y k_x)$$

Spin-split energy bands
In the absence of local moments

$$E_{+(-)}(k) = \frac{\hbar^2}{2m}k^2 + (-) \cdot \alpha_R k$$

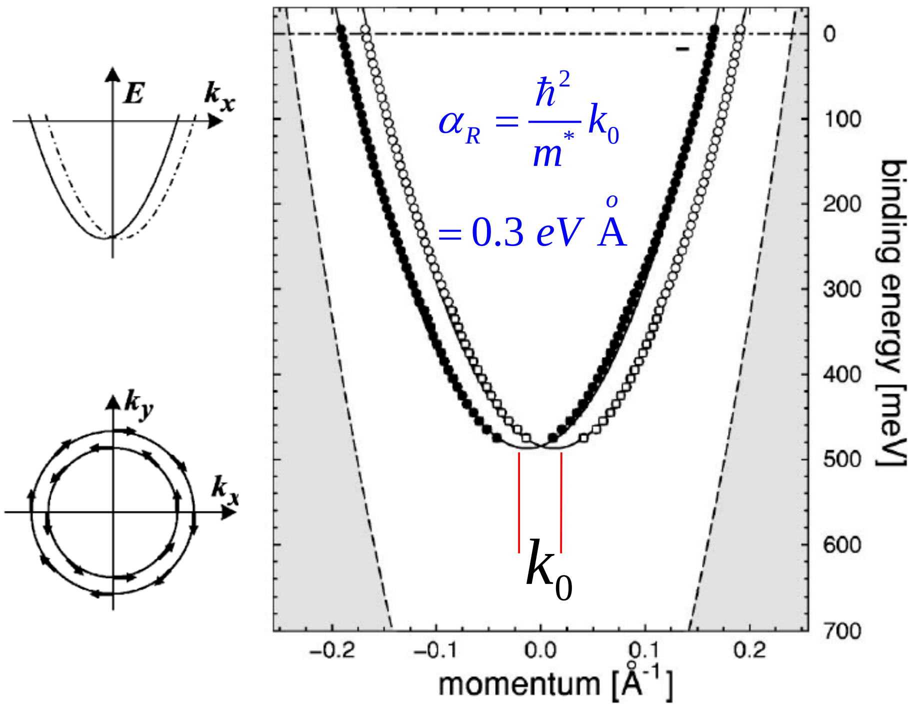




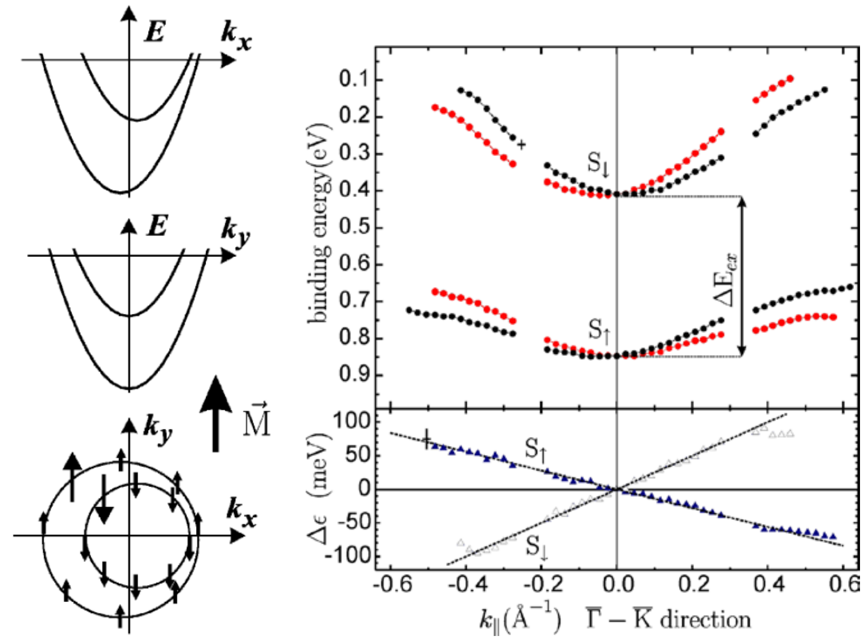
Fermi surface

Observation of Rashba-split surface states on metal surfaces

Au(111)



Gd(0001)



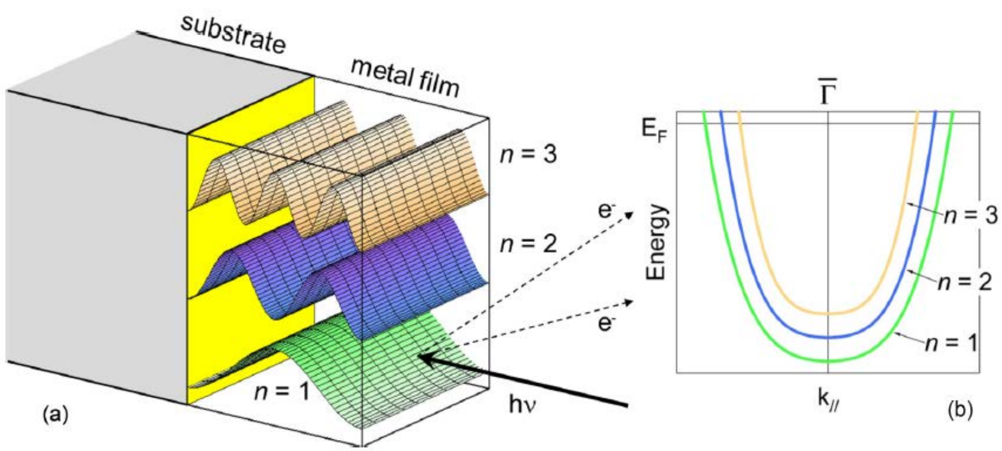
Reinert et al.,

PRB 63, 115415 (2001)

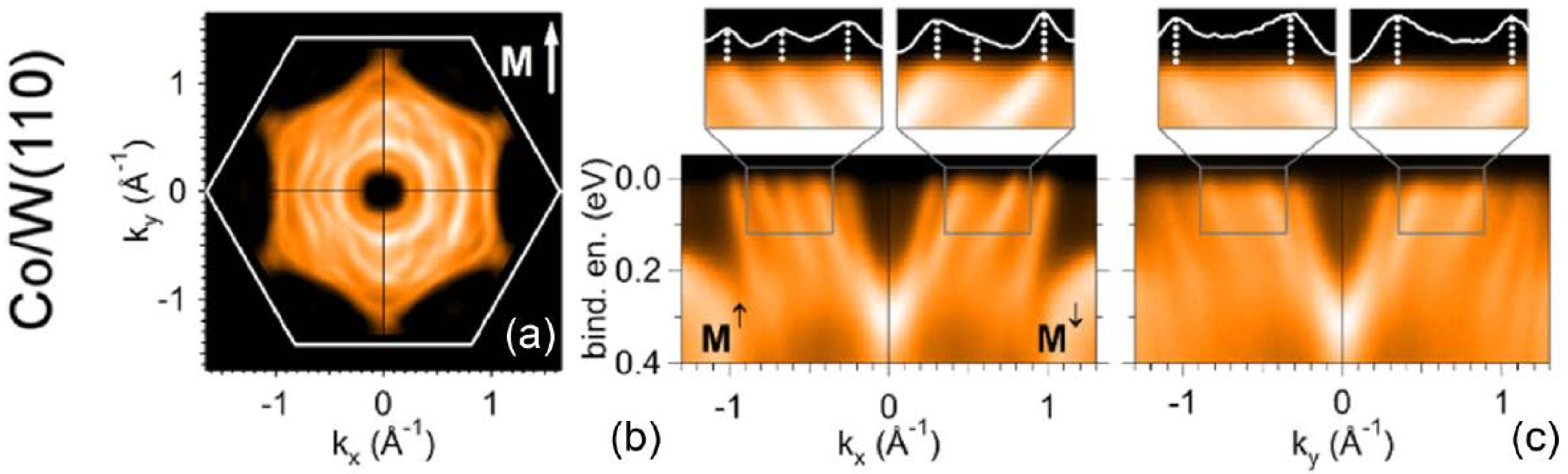
Krupin et al,

PRB 71, 201403(R) (2005)

ETH zürich Rashba-split quantum well states in Co/W(110)

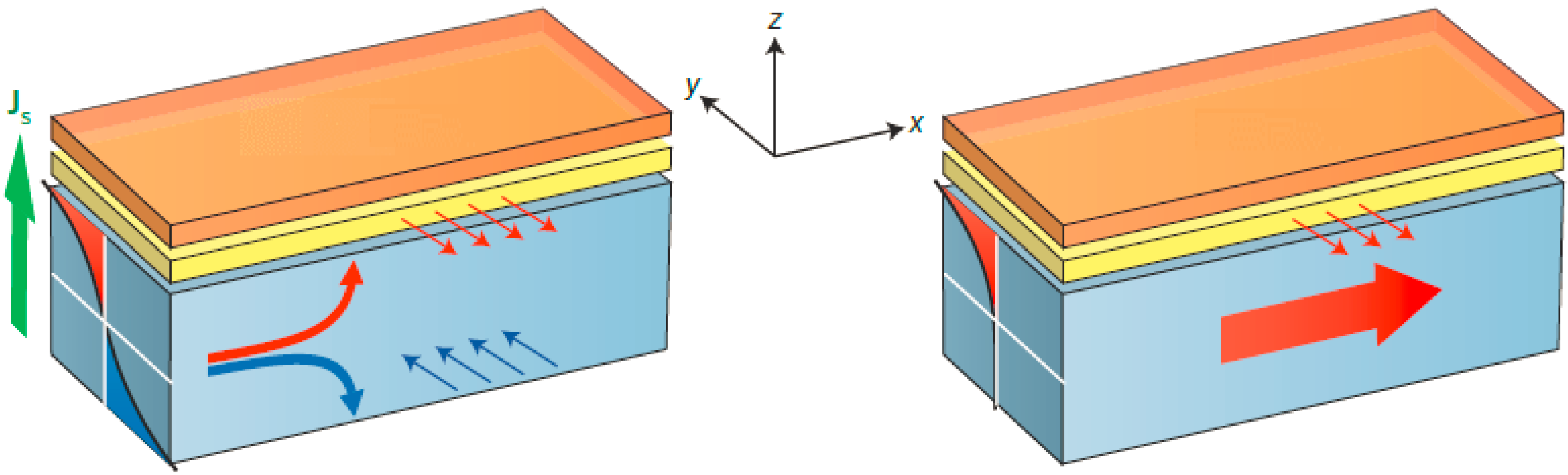


Moras et al.,
PRB 91, 195410 (2015)



QW states of 15 ML-thick Co films on W(110) display both exchange and Rashba splitting

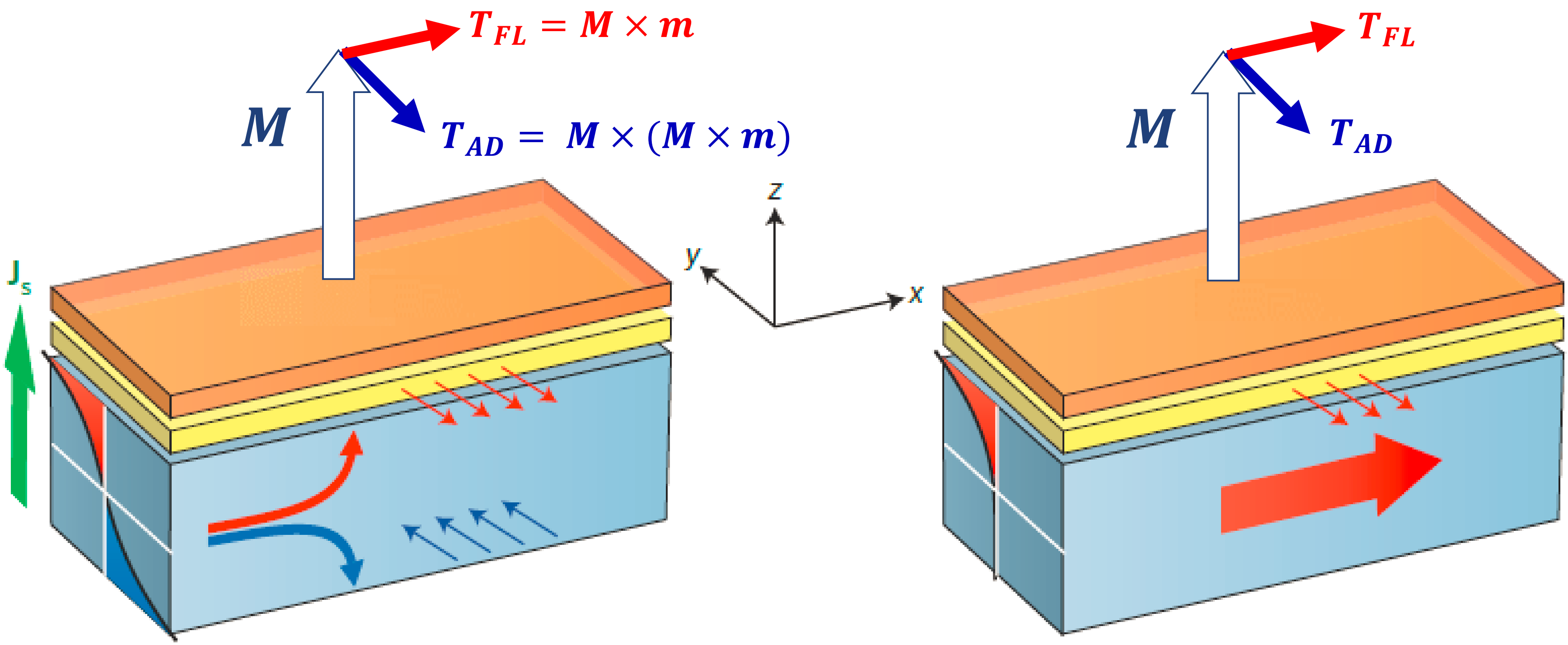
Spin-orbit induced spin accumulation



Spin Hall

Rashba

Spin-orbit torques



Spin Hall

Rashba

Manchon and Zhang, PRB 2009; Garate and Mac Donald, PRB 2009; Matos-Abiague and Fabian, PRB 2009; van der Bijl and Duine, PRB 2012; **Haney et al., PRB 2013; Hang Li et al., arXiv:1501.03292**, …

“You like potato and I like pothato,,

$$\boldsymbol{T_{AD}} = \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{m})$$

“Spin Hall torque”

“Spin transfer torque”

“Slonczewski torque”

$$\boldsymbol{T_{FL}} = \boldsymbol{M} \times \boldsymbol{m}$$

“Spin orbit torque”

“Spin orbit field”

“Rashba torque”

Antidamping and field-like spin-orbit torques (SOT)

Early predictions of current-induced fields in ferromagnets

Dilute magnetic semiconductors:

Bernevig and Vafek, PRB **72**, 033203 (2005)

Yang et al., APL **89**, 132112 (2006)

Chernyshov et al., Nat. Phys. **5**, 656 (2009).

Metal layers:

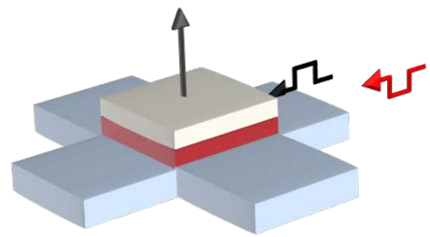
Manchon and Zhang, Phys. Rev. B **78**, 212405 (2008)

Obata and Tatara, PRB **77**, 214429 (2008)

Garate and Mac Donald, PRB **80**, 134403 (2009)

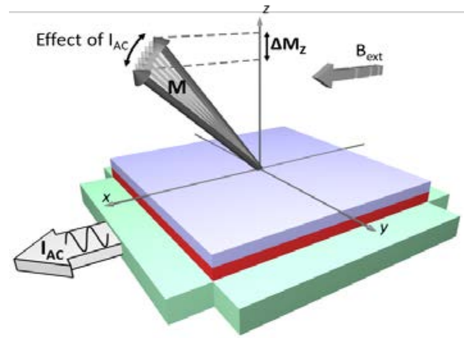
Measurement techniques

Magnetization switching:



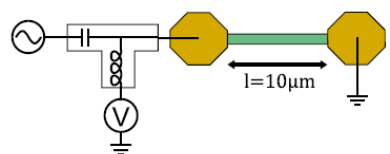
Miron et al.,
Nat. Mater. 2010; Nature 2011

AC Hall voltage and AMR modulation



Pi et al., APL 2010;
Garello et al., Nat. Nanotech. 2013;
Kim et al., Nat. Mater. 2013
…

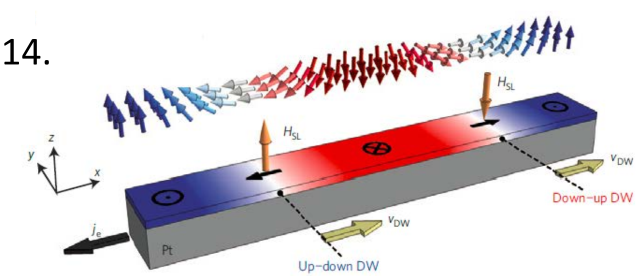
Spin-torque FMR:
(Resonant AC current excitation
AMR readout)



Liu et al., PRL 2011
Fang et al., Nat. Nanotech. 2011

MOKE Fan et al., Nat. Comm. 2014.

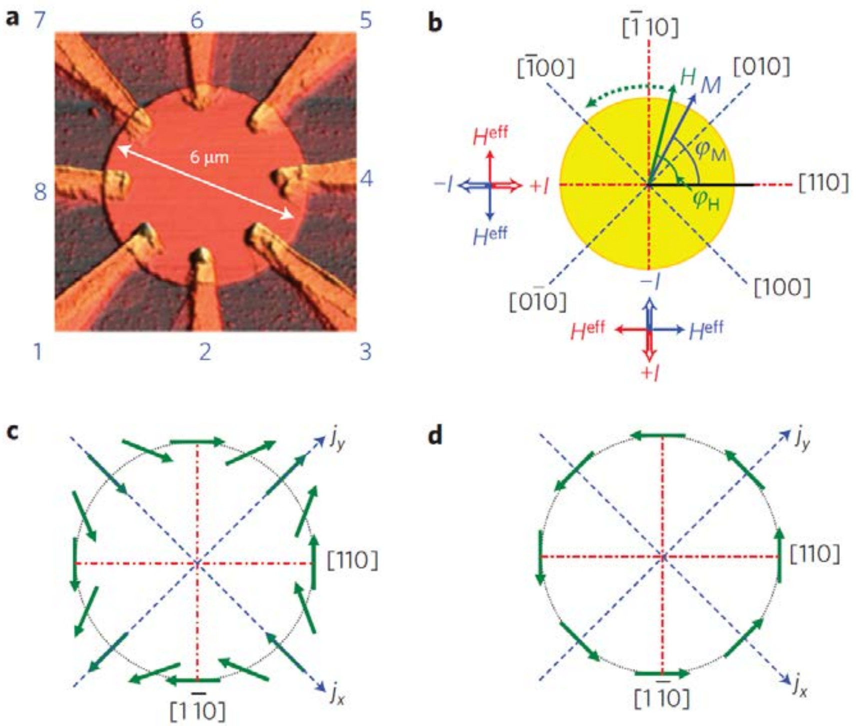
Domain wall motion



Emori et al., Nat. Mater. 2013
Ryu et al., Nat. Nanotech. 2013
Haazen et al., Nat. Mater. 2013

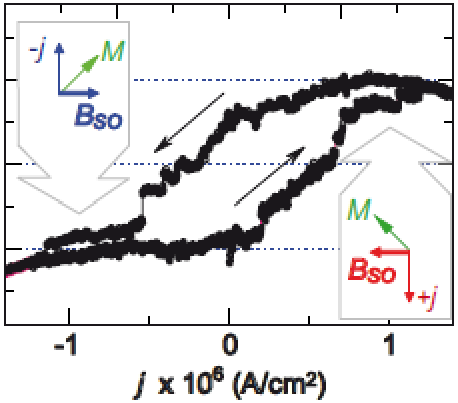
Spin-orbit torques in semiconductors

Ferromagnetic Semiconductor with Zinc-Blende symmetry



$Ga_{1-x}Mn_xAs$ (6 nm)/GaAs(100)

***T* = 40 K**



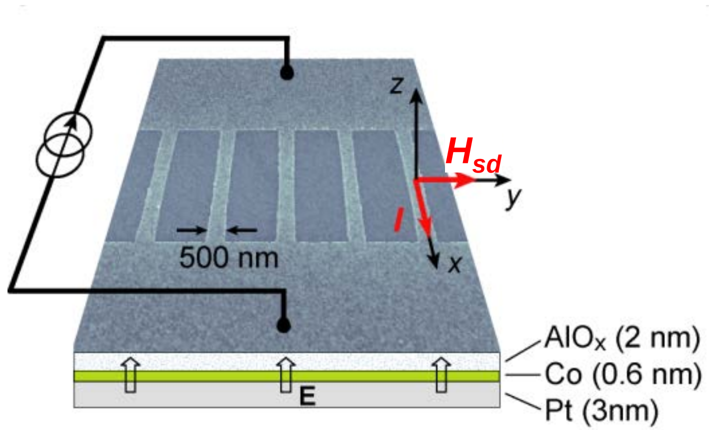
$$\Omega_D \propto k^3$$ Dresselhaus term

$$\Omega_\varepsilon = C\Delta\varepsilon(k_x, -k_y, 0)$$ Strain

$$\Omega_R = \alpha_R(-k_y, k_x, 0)$$ Rashba

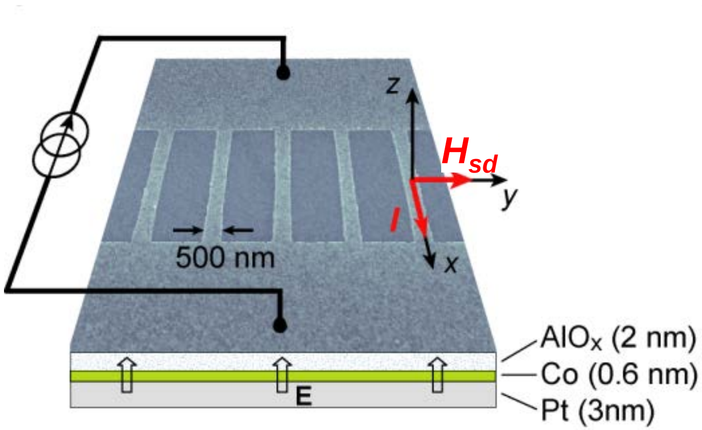
Chernyshov et al., Nature Phys. 5, 656 (2009).

First evidence of field-like spin-orbit torque in metallic FM

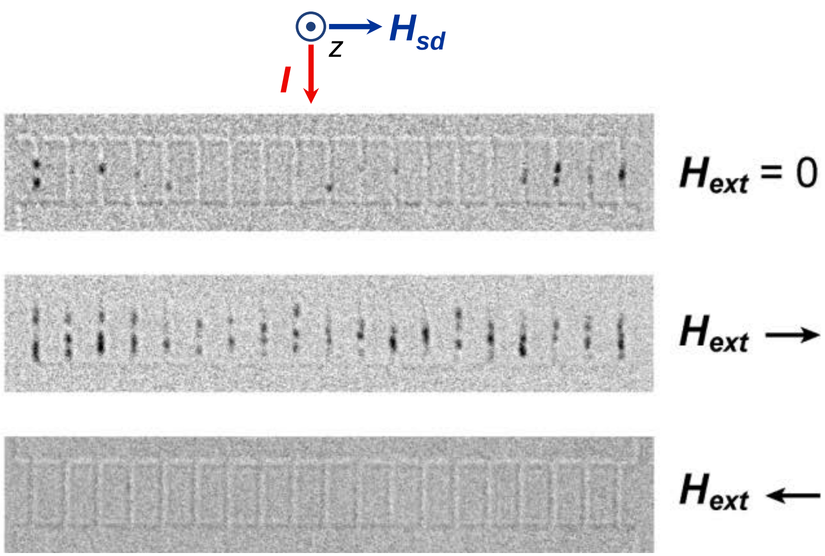


Miron et al., *Nature Mater*. **9**, 230 (2010)

First evidence of field-like spin-orbit torque in metallic FM

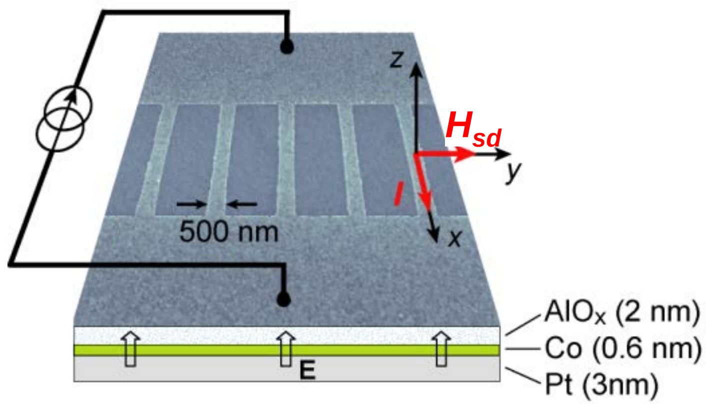


- Pulse amplitude = 7.8 x 10^7 A/cm^2
- Pulse length = 100 ns
- H_{ext} = +/- 475 Oe



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

First evidence of field-like spin-orbit torque in metallic FM



- Pulse amplitude = 7.8 x 10^7 A/cm^2
- Pulse length = 100 ns
- H_{ext} = +/- 475 Oe

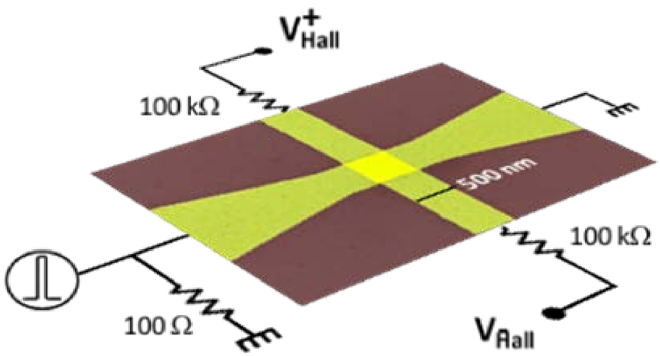
$$\mathbf{B}^{\perp} \sim \mathbf{y}$$ *Transverse field*

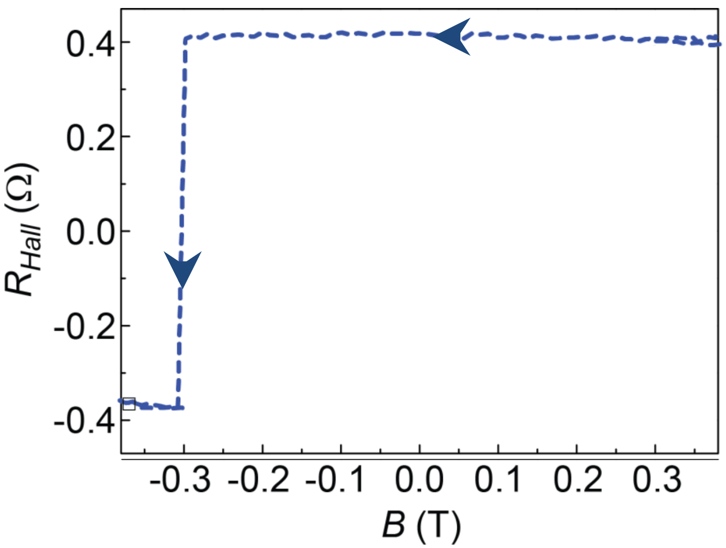
⇩

$$\mathbf{T}^{\perp} \sim (\mathbf{M} \times \mathbf{y})$$ *Field-like torque*

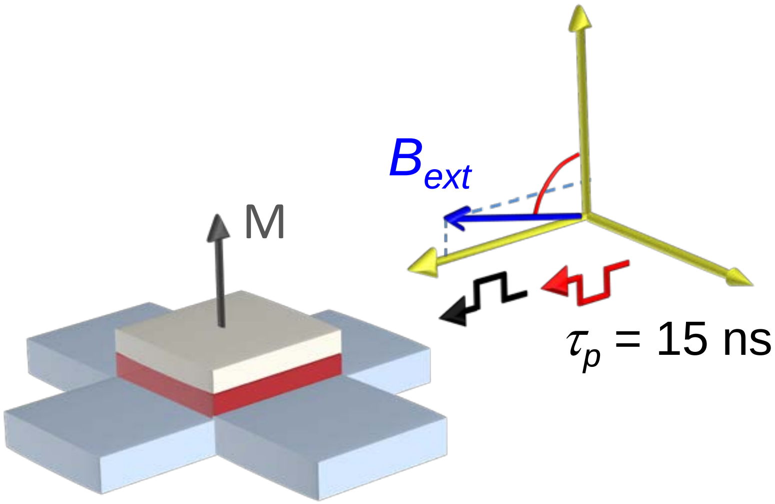
Miron et al., *Nature Mater*. **9**, 230 (2010)

Demonstration of magnetization switching induced by SOT



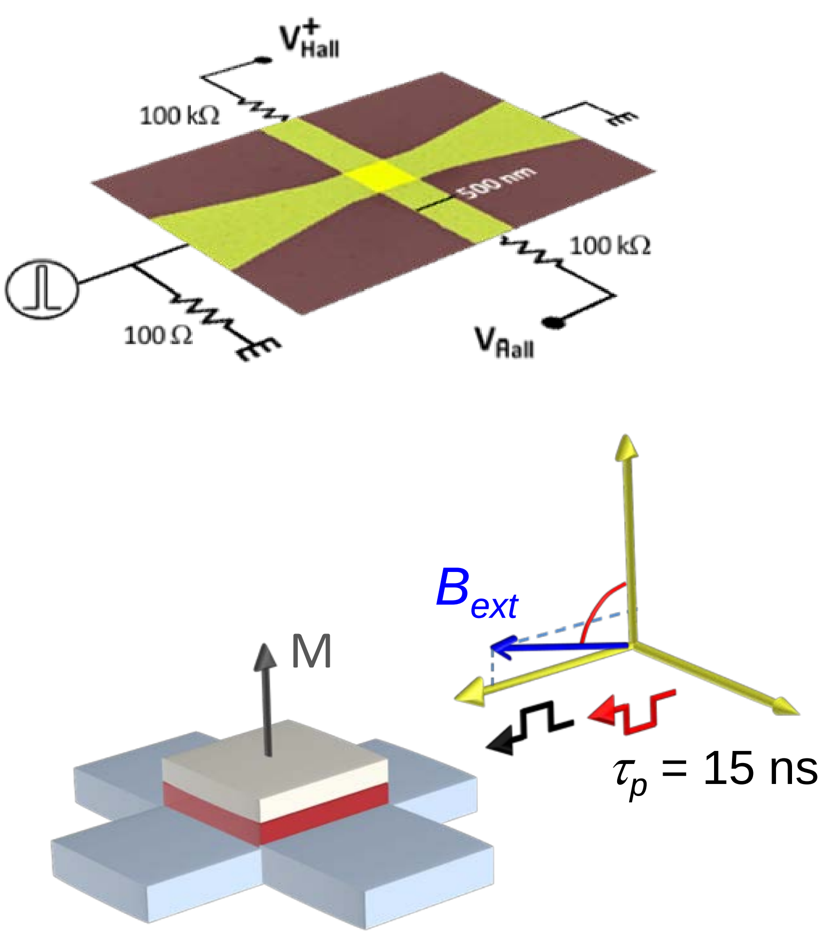


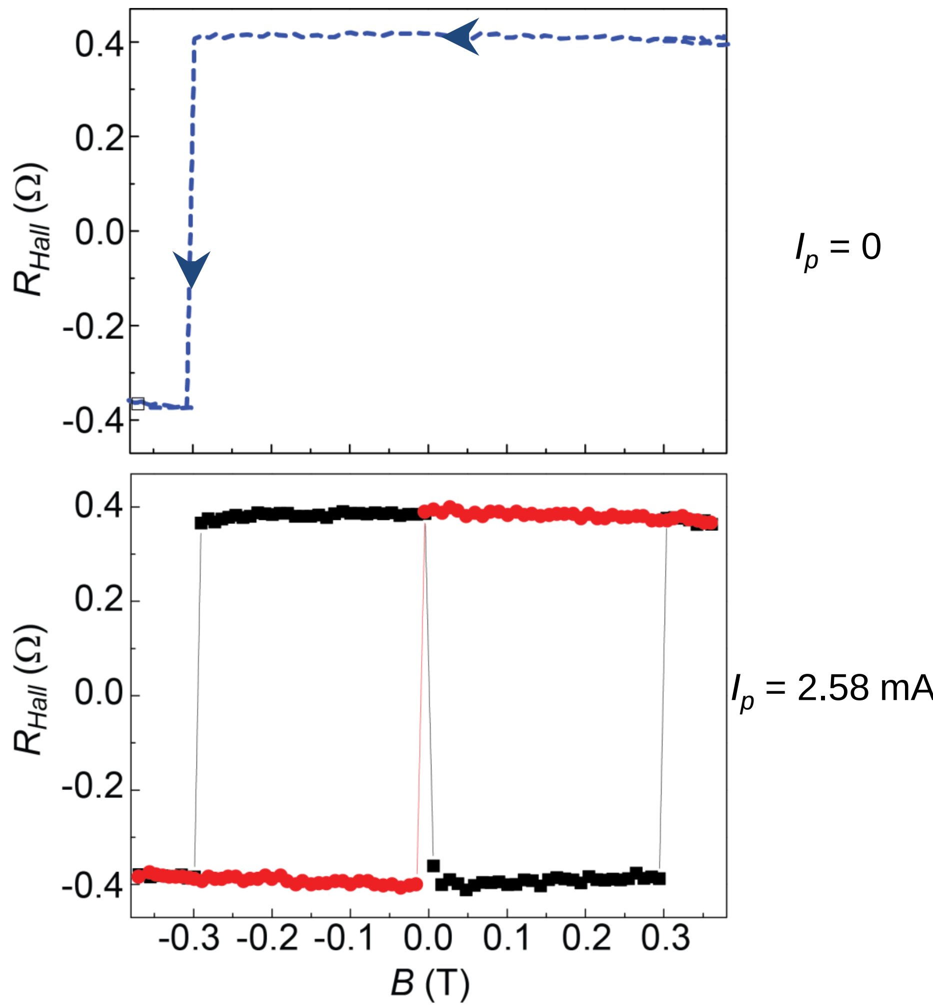
$I_p = 0$



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

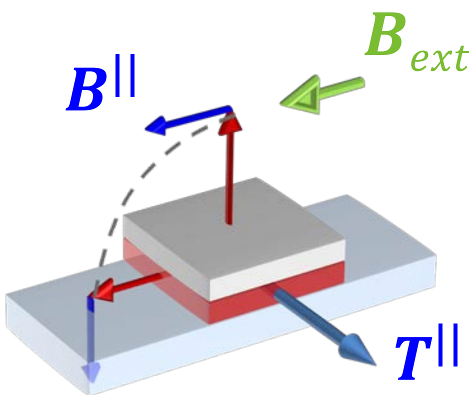
Demonstration of magnetization switching induced by SOT



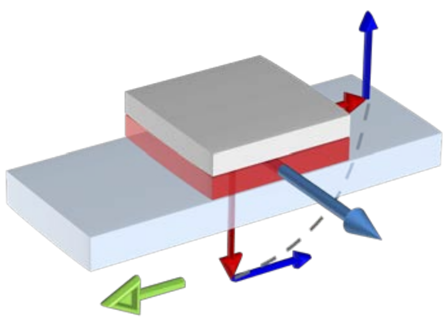


Miron et al., *Nature* 476, 189 (2011)

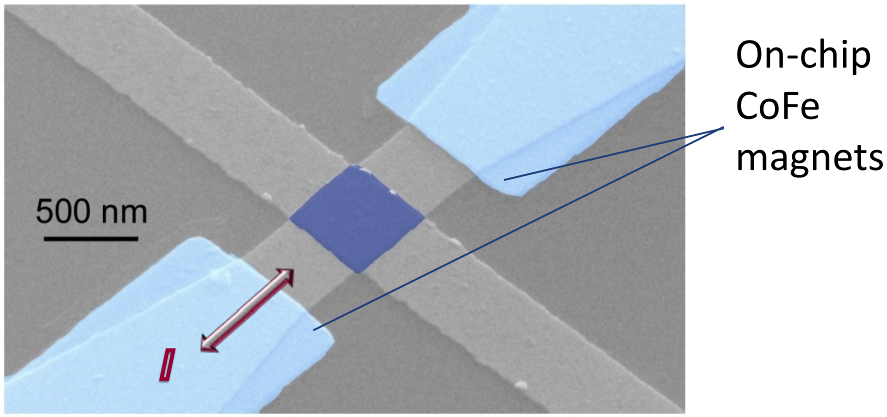
Bipolar magnetization switching induced by the AD spin-orbit torque

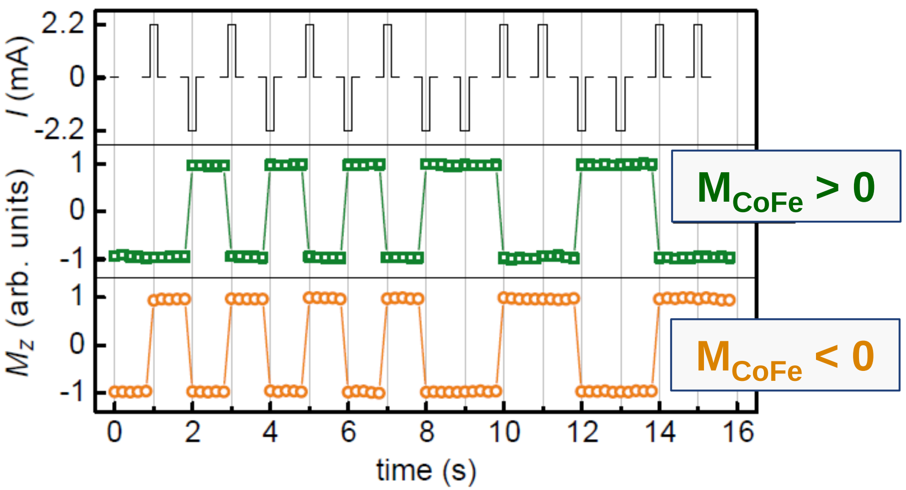


"up" – *unstable*



"down" – *stable*





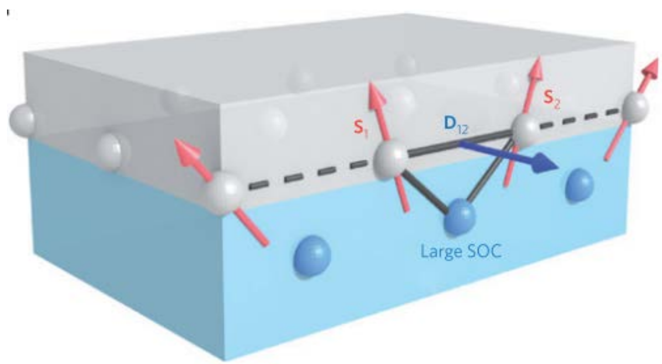
$\mathbf{B}^{\parallel} \sim \mathbf{M} \times \mathbf{y}$ *Longitudinal field*

$\mathbf{T}^{\parallel} \sim \mathbf{M} \times (\mathbf{M} \times \mathbf{y})$ *AD-like torque*

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

ETH zürich

Dzyaloshinskii-Moriya Interaction



$$H_{DM} = D_{ij}\left(\mathbf{S_i} \times \mathbf{S_j}\right)$$

Infinite stripe: $D < Dc = \sqrt{A/K}$

collinear

Infinite stripe: $D > Dc$

spiral

Finite stripe: $D < Dc$

canted

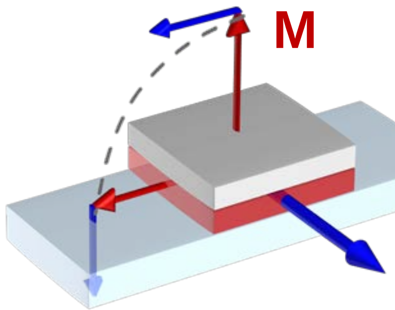
A.I. Liechtenstein *et al.* JMMM **67** (1987) 65, M. Heide *et al*. Spin Orbit Driven Physics at Surfaces
S. Meckler *et al.* Phys. Rev. B **85** (2012) 024420 A. Fert *et al. Nat.* Nanotec. **8** (2013) 152

Origin of antidamping spin-orbit torque

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

doi:10.1038/nature10309

Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection



$\boldsymbol{T_{AD}} \sim \mathbf{M} \times (\mathbf{M} \times \mathbf{y})$

"The symmetry of the switching field is consistent with the spin accumulation induced by the Rashba interaction, as well as with the torque induced by the spin Hall effect in the Pt layer"

"…The switching efficiency increases with the oxidation of the Al layer, suggesting that the Rashba interaction has a key role in the reversal mechanism."

Equivalent spin Hall angle:

$$\theta_{SH}^{eff} = 0.16$$

PRL **109,** 096602 (2012) PHYSICAL REVIEW LETTERS week ending 31 AUGUST 2012

Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect

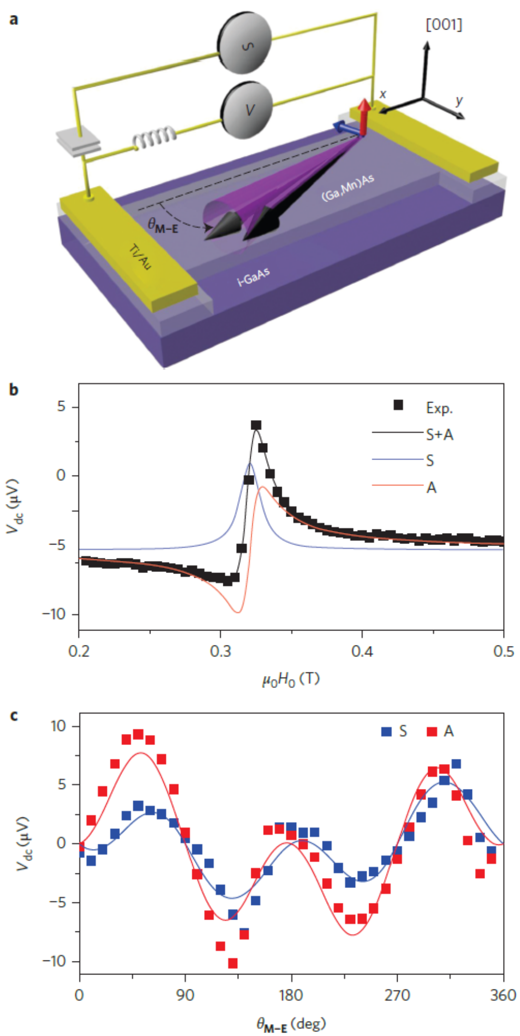
Luqiao Liu,[1] O. J. Lee,[1] T. J. Gudmundsen,[1] D. C. Ralph,[1,2] and R. A. Buhrman[1]

Same system: Pt(2nm)/Co(0.6nm)/AlOx(2nm)

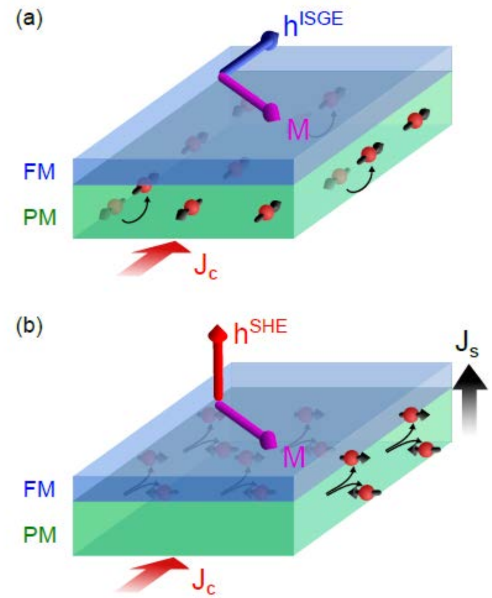
Conclusion: pure "bulk" spin Hall effect; no observation of field-like torque

Disentangling different SOT contributions in semiconductors

Single layer GaMnAs

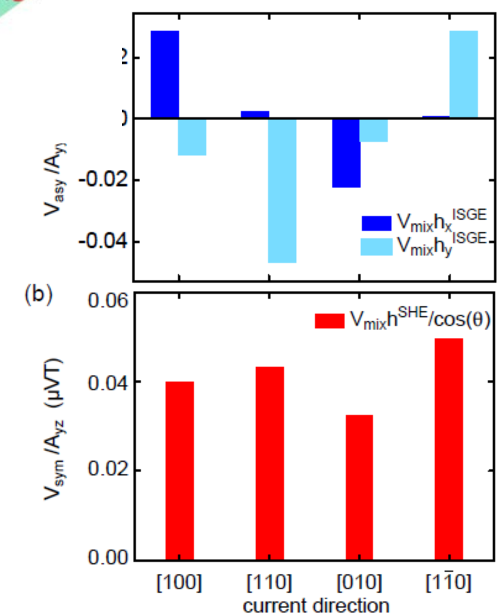


Kurebayashi et al., Nat. Nanotech. 9, 211 (2014)



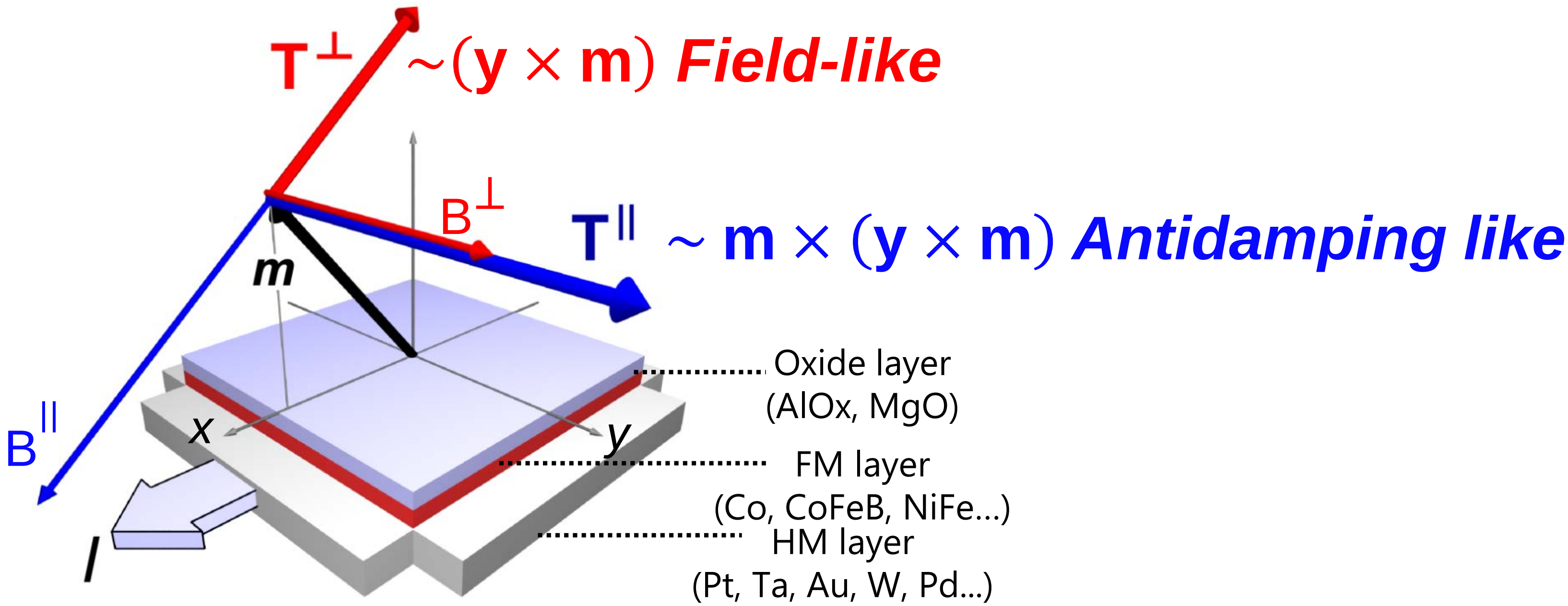
2 nm Fe/GaMnAs

Dresselhaus SOC



Skinner et al., Nat. Comm. 6, 6730 (2015)

FL and AD torques compatible with structure inversion asymmetry



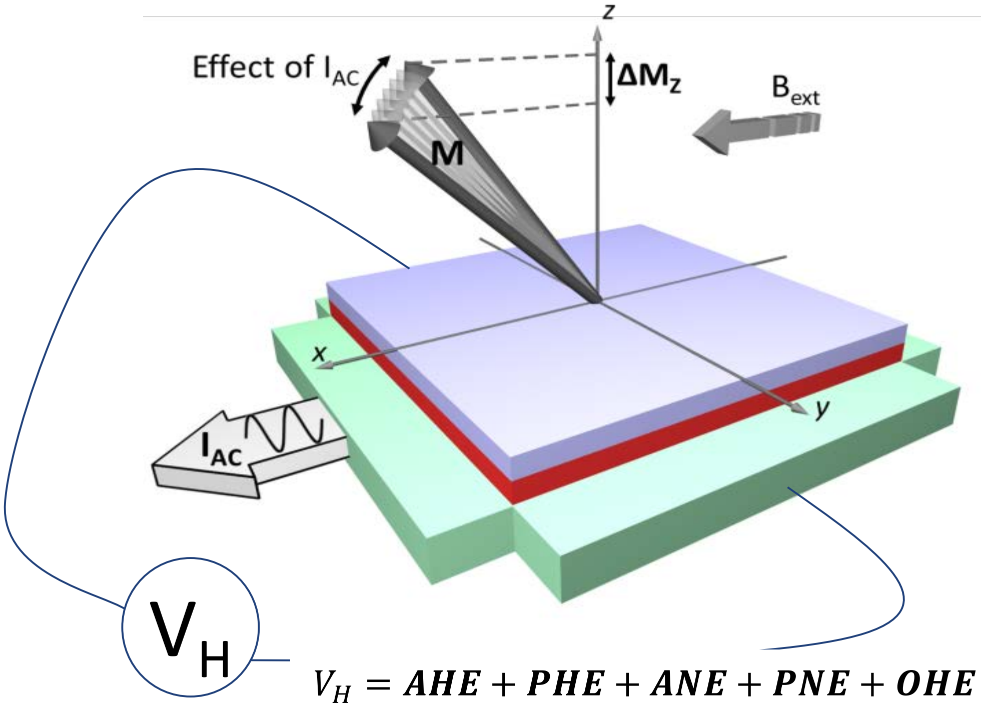
A linear response analysis of the spin accumulation to an *E*-field compatible with the symmetry of the trilayer leads to additional torque terms, depending on the magnetization orientation:

$$\mathbf{T}^{\perp} = (\mathbf{y}\times\mathbf{m})\left[T_0^{\perp} + T_2^{\perp}(\mathbf{z}\times\mathbf{m})^2 + T_4^{\perp}(\mathbf{z}\times\boldsymbol{m})^4\right] + \mathbf{m}\times(\mathbf{z}\times\mathbf{m})(\mathbf{m}\cdot\mathbf{x})\left[T_2^{\perp} + T_4^{\perp}(\mathbf{z}\times\mathbf{m})^2\right]$$

$$\mathbf{T}^{\parallel} = \mathbf{m}\times(\mathbf{y}\times\mathbf{m})\,T_0^{\parallel} + (\mathbf{z}\times\mathbf{m})(\mathbf{m}\cdot\mathbf{x})\left[T_2^{\parallel} + T_4^{\parallel}(\mathbf{z}\times\mathbf{m})^2\right]$$

Garello et al. *Nature Nanotech.* **8,** 587 (2013)

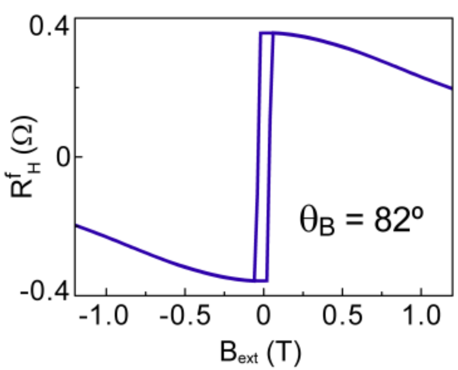
AC harmonic hall voltage measurements



$V_H = \boldsymbol{AHE} + \boldsymbol{PHE} + \boldsymbol{ANE} + \boldsymbol{PNE} + \boldsymbol{OHE}$

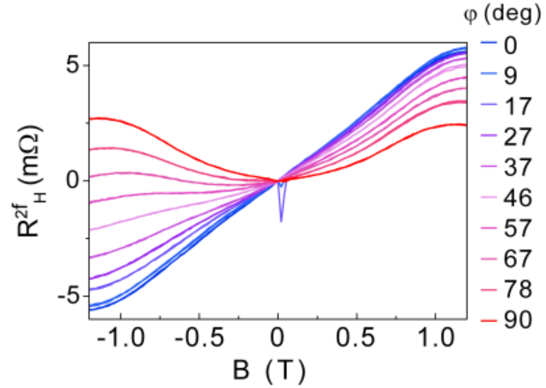
1st harmonic
Hall resistance

M vs B_{ext}



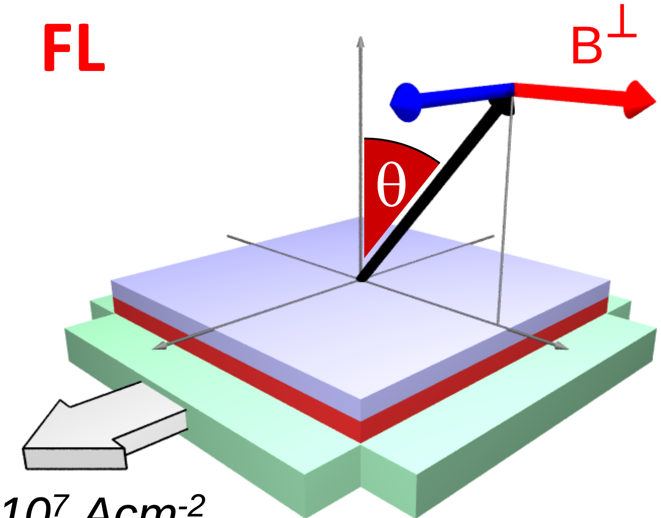
2nd harmonic
Hall resistance

M vs I_{ac}

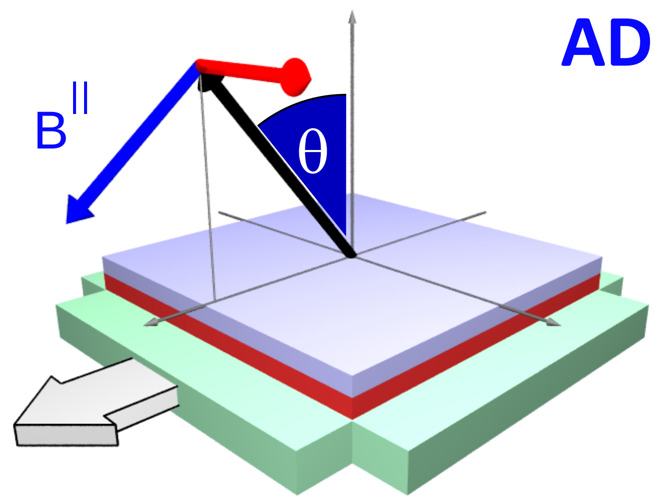


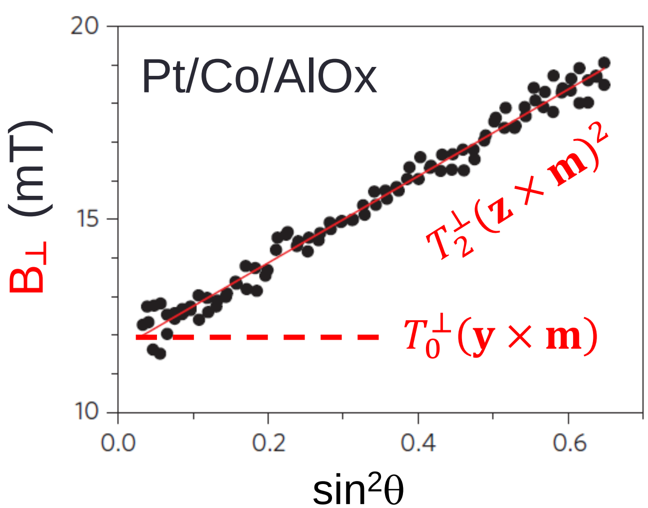
Garello et al. *Nature Nanotech.* **8,** 587 (2013)

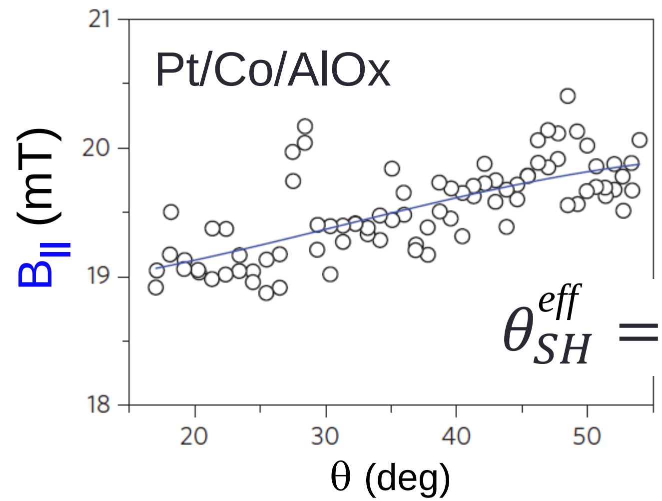
Amplitude and angular dependence of SOTs: Pt/Co



j_{ac}=3x10^7 Acm^{-2}



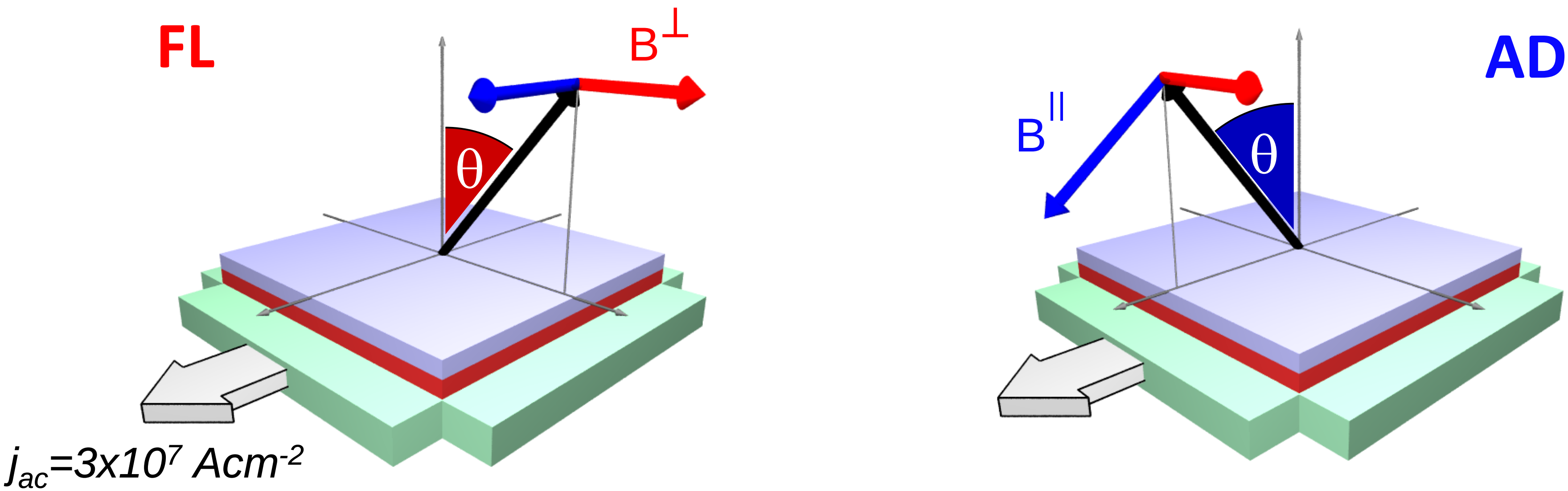


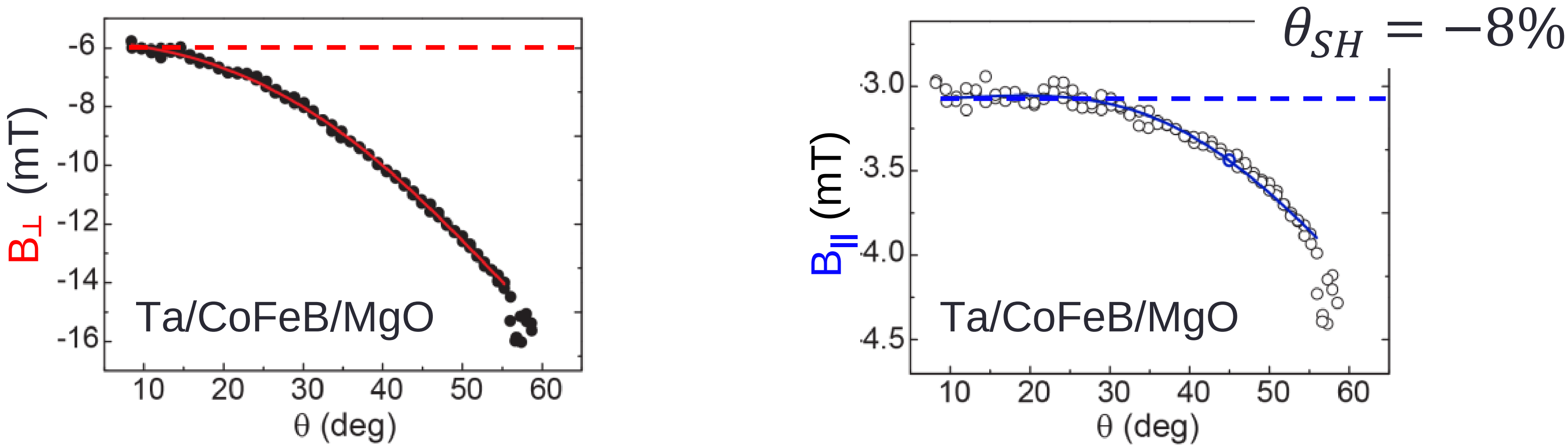


$\theta_{SH}^{eff} = 16\%$

Garello et al. *Nature Nanotech.* **8,** 587 (2013)

Amplitude and angular dependence of SOTs: Ta/Co

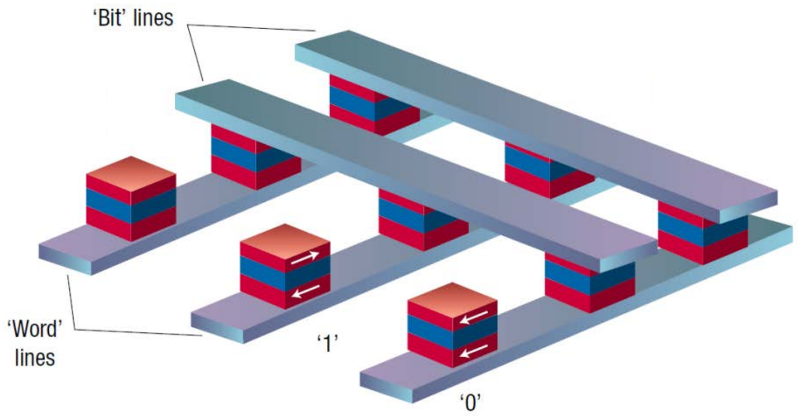




Garello et al. *Nature Nanotechnol.* **8,** 587 (2013); *Avci et al., Phys. Rev. B* **89**, 214419 (2014).

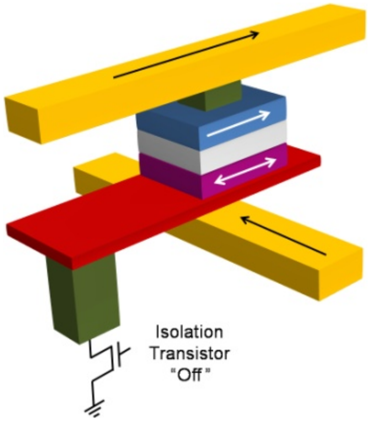
Applications: SOT - MRAM

"universal memory": rapid / dense / non-volatile



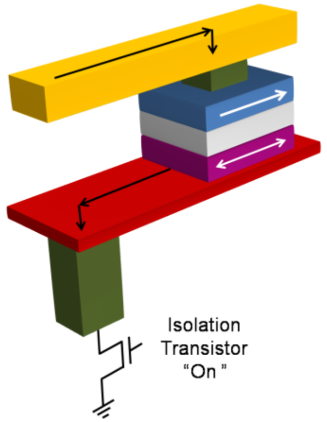
- **Reading – TMR**
- **Writing:**

magnetic field



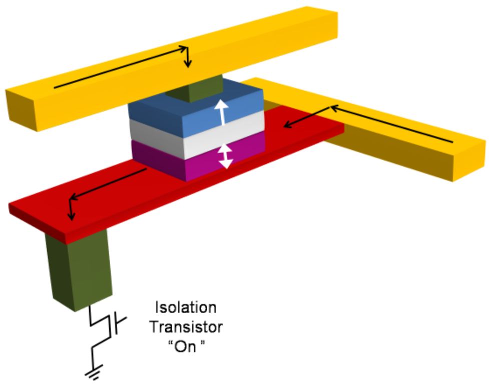
➕ high endurance
➖ limited scalability

spin transfer (STT)



➖ limited endurance
➕ high scalability

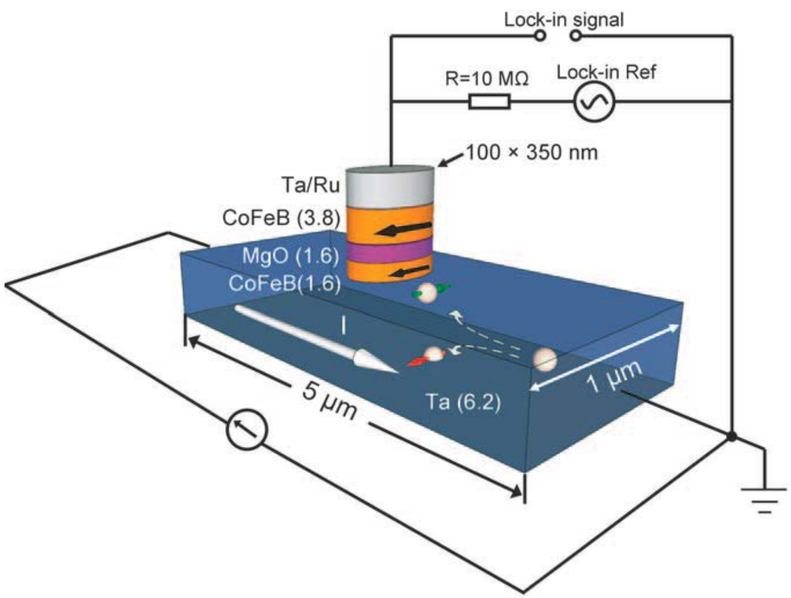
spin-orbit torque (SOT)



➕ high endurance
➕ high scalability

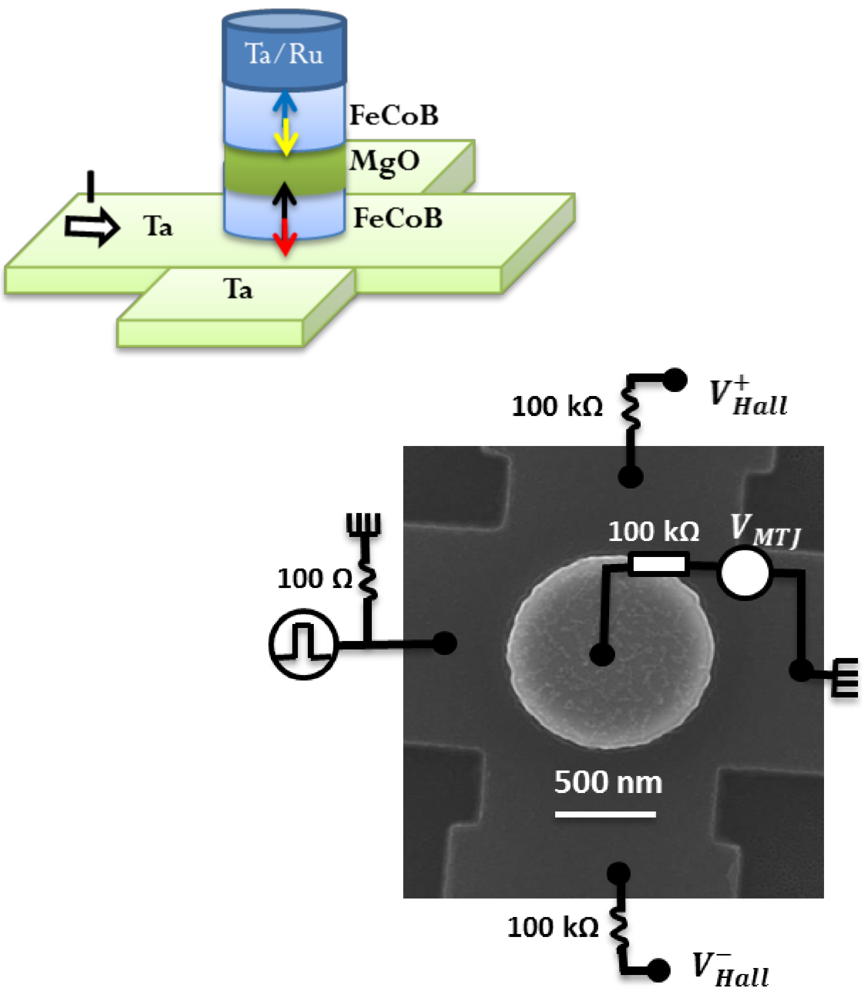
Three-terminal SOT-MTJ

In-plane MTJ



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

Perpendicular - MTJ

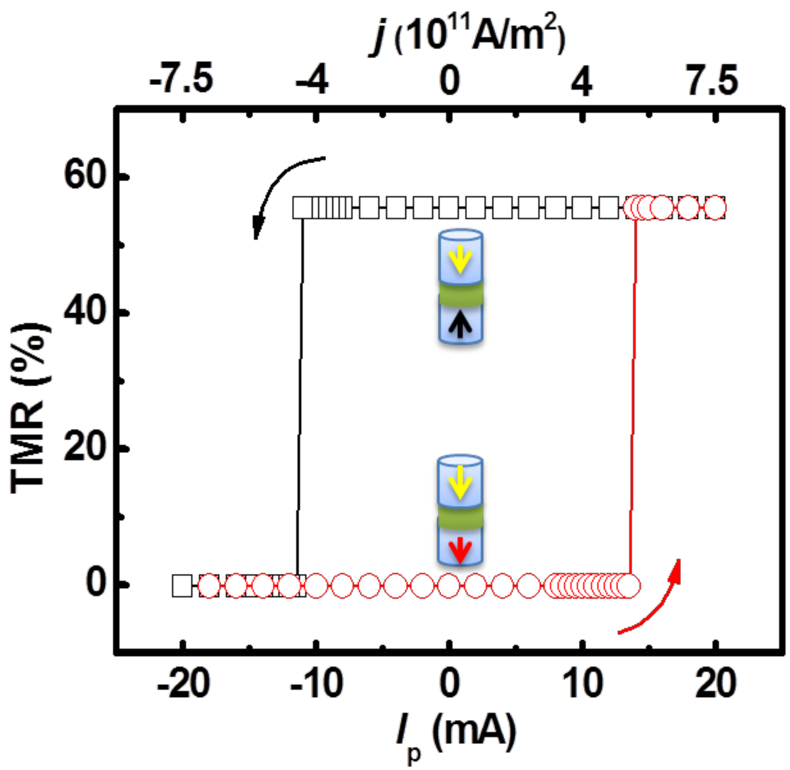


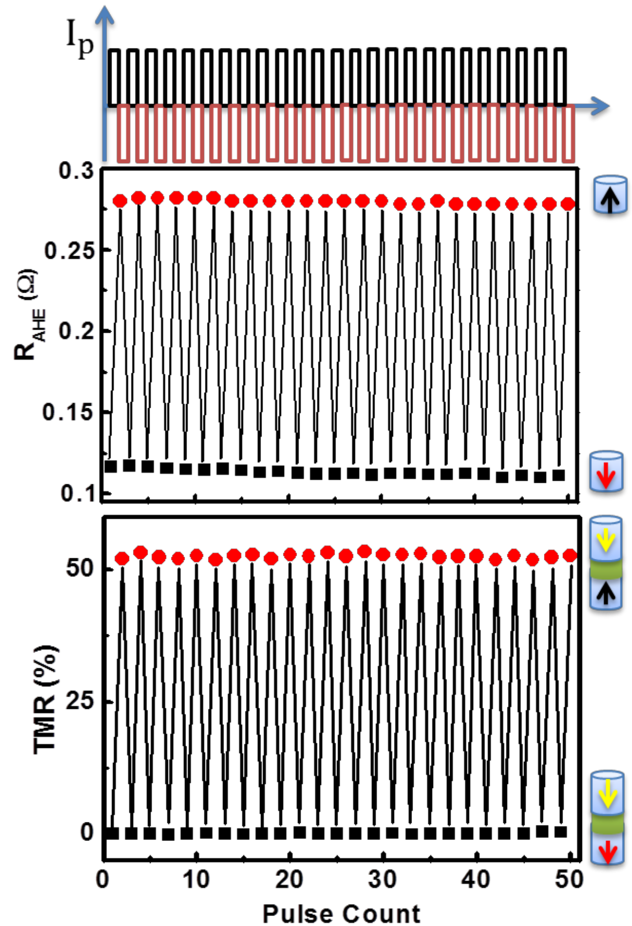
Cubukcu et al., APL **104**, 042406 (2014)

SOT write and TMR read out in perpendicular MTJ

CURRENT DEPENDENCE

B_{ext} = 400 Oe

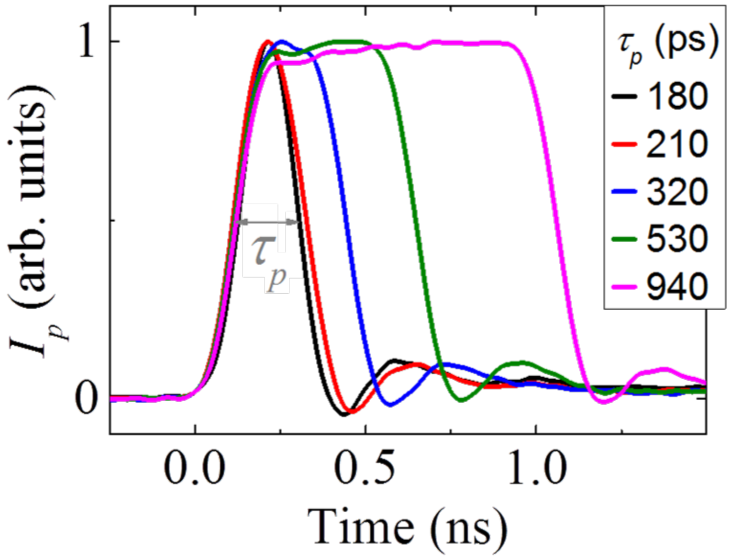




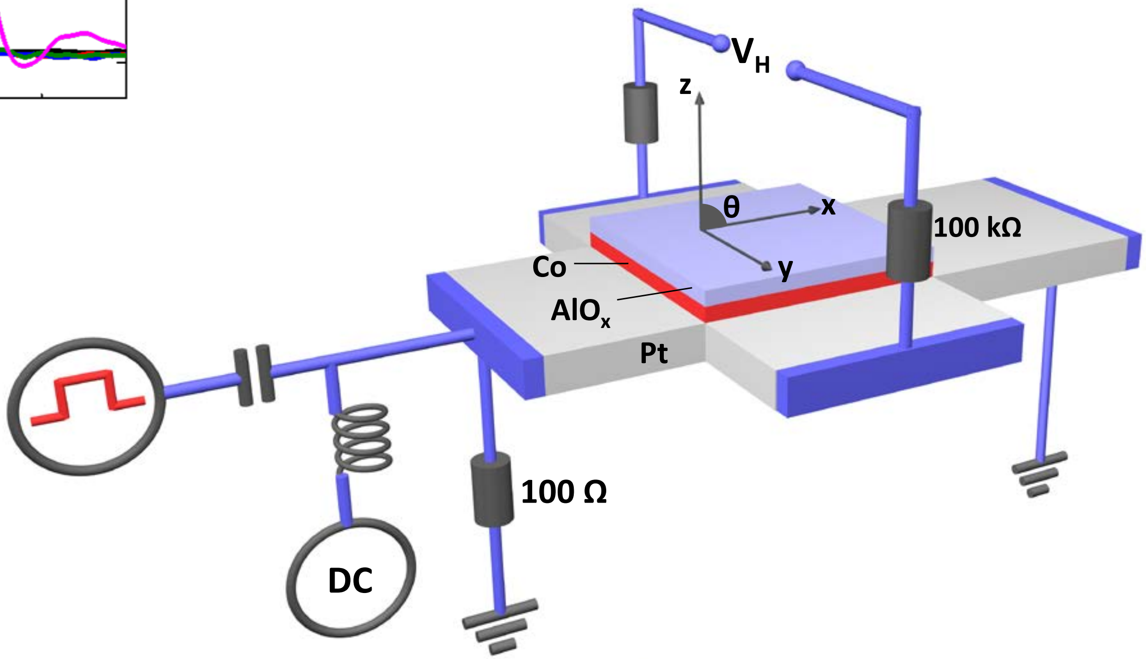
- Ta(20)/$Fe_{60}Co_{20}B_{20}$(1)/MgO/$Fe_{60}Co_{20}B_{20}$(1.5)/Ta(5)/Ru(7) annealed 1h at 240C
- TMR: 55%, RA = 1.15 kΩ.μm²

Cubukcu et al., APL **104**, 042406 (2014)

Ultrafast SOT-induced switching

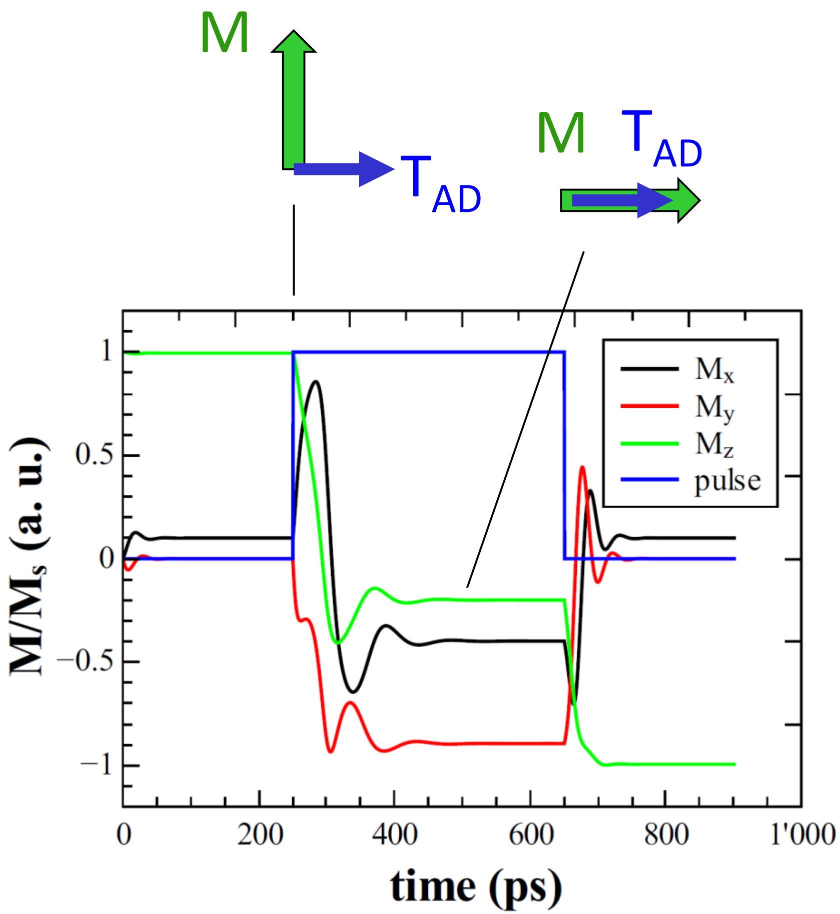


Pulser
(0.2 ns – 10 ms)

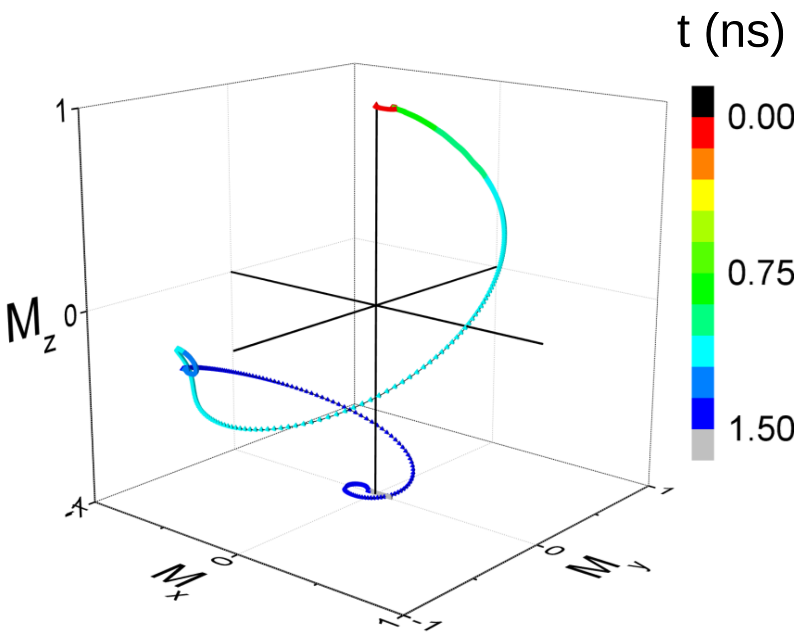


K. Garello et al., Appl. Phys. Lett. **105**, 212402 (2014)

SOT-induced magnetization dynamics



T_{AD} ~ 50 mT/10^8 Acm^{-2}



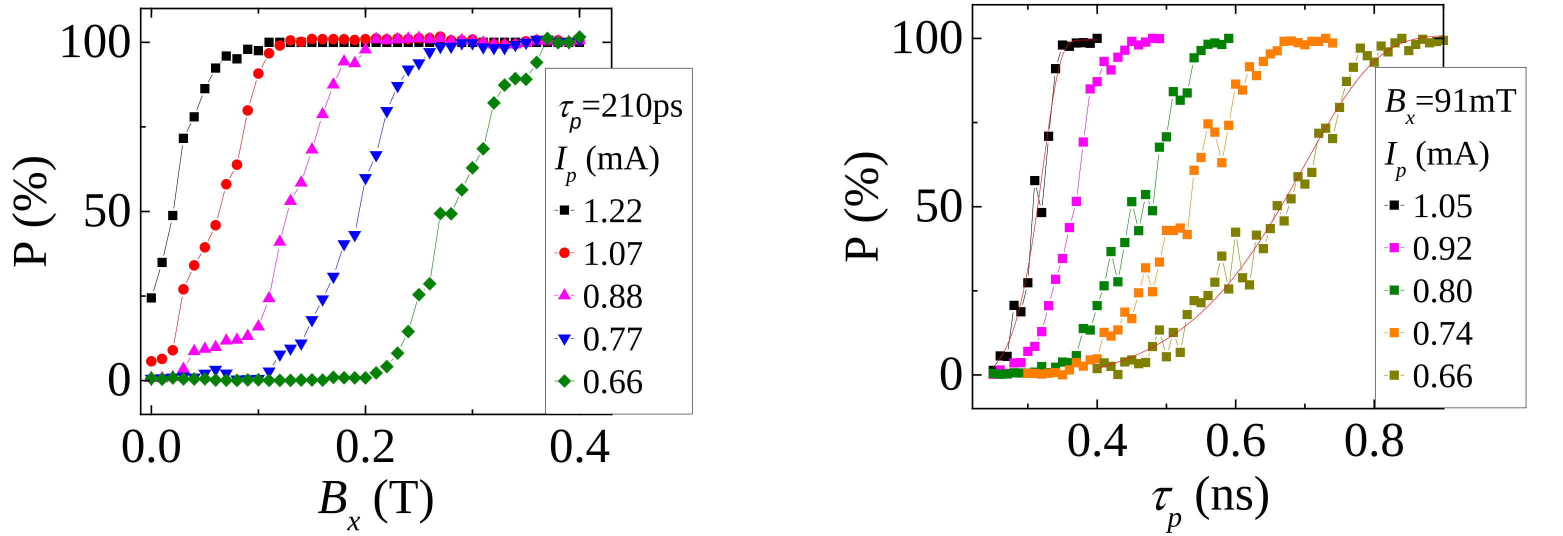
α = 0.5

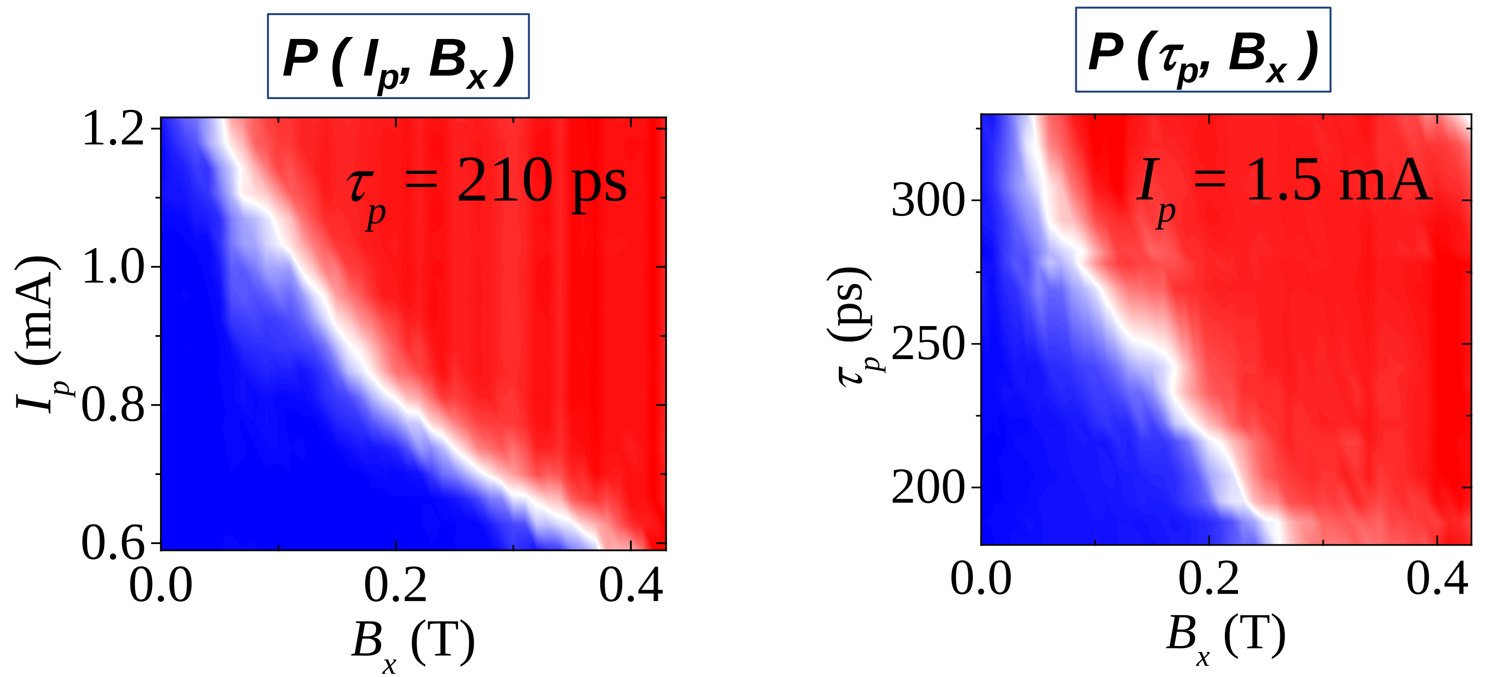
B_k = 1 T

B_{ext} = 0.1 T

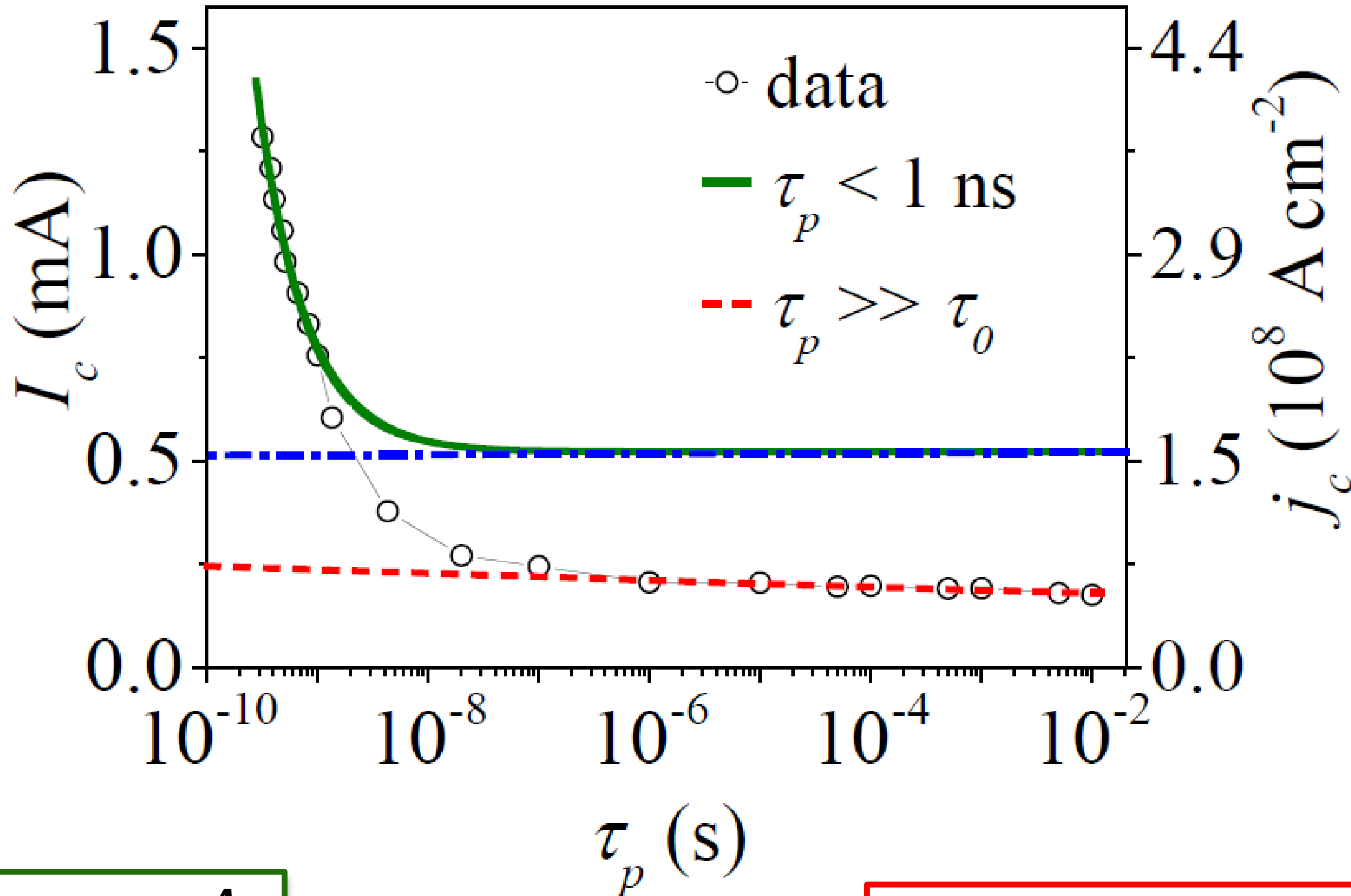
$J_p = 8 \cdot 10^8$ Acm^{-2}

Switching probability





Short- and long-time regimes



$$I_c = I_{c0} + \frac{\boldsymbol{A}}{\boldsymbol{\tau_p}}$$

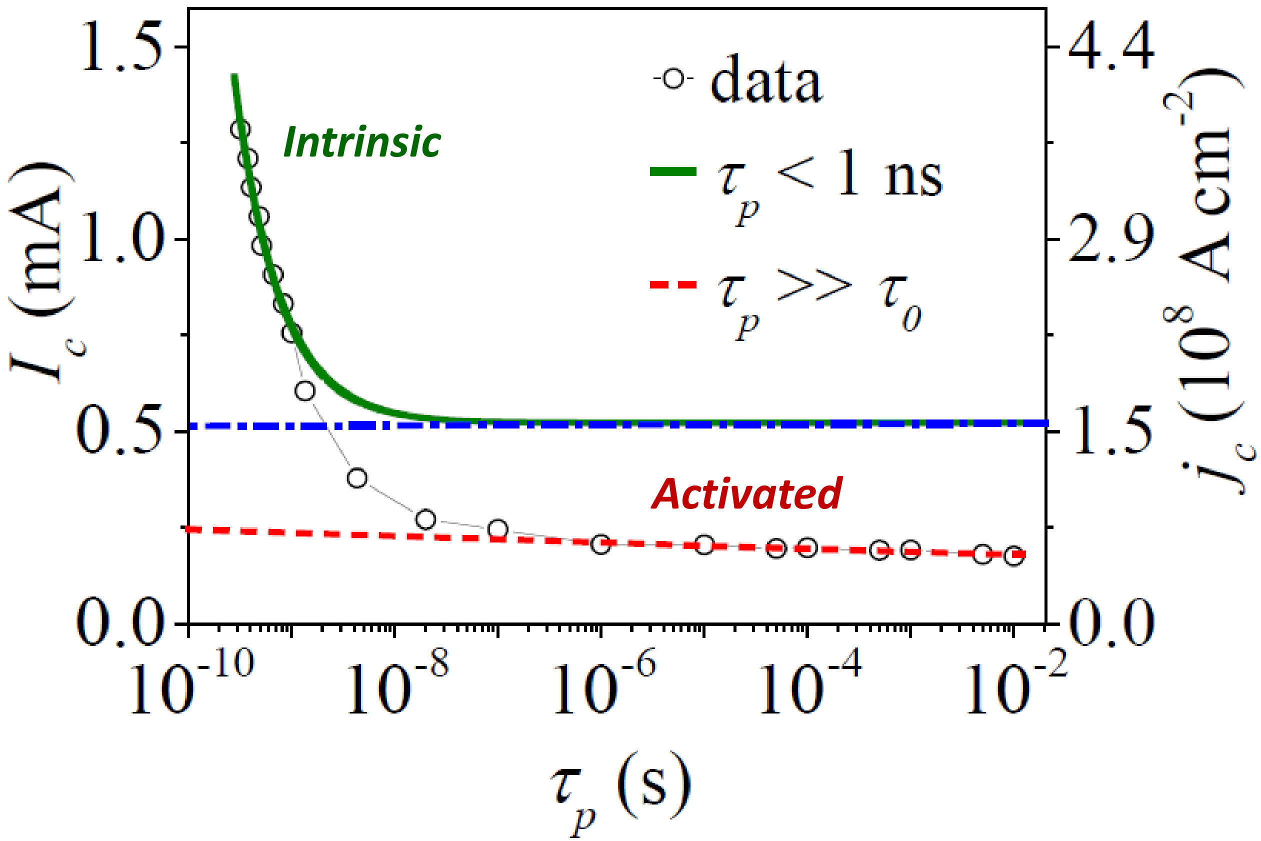
intrinsic regime

$$I_c = I_{c0}\left(1 - \frac{k_b T}{\mathrm{E}} \ln \boldsymbol{\tau_p}/\boldsymbol{\tau_0}\right)$$

activated regime

K-J. Lee et. al., Appl. Phys. Lett. 104, 072413 (2014)

200 ps to dc switching



- τ_p < 1 ns: Intrinsic short-time regime
- τ_p > 1 ns: Thermally activated
- Switching down to 180 ps

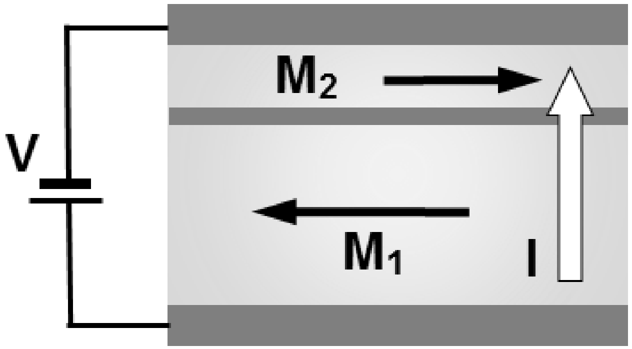
- Nonprecessional
- Incubation time ≈ 0

K. Garello et al., Appl. Phys. Lett. **105**, 212402 (2014)

SOT vs STT

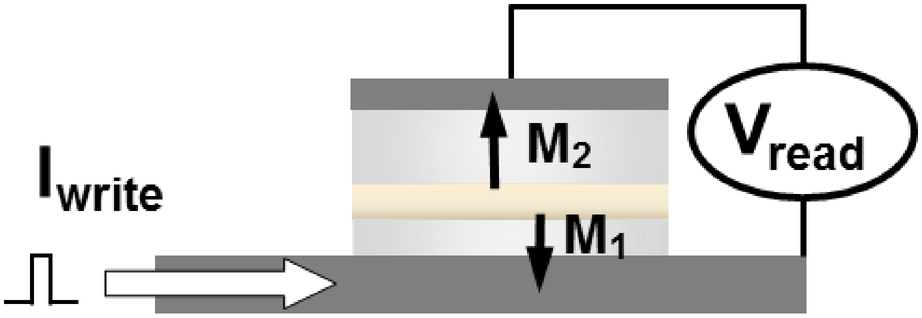
STT - MTJ

- ST by spin filtering
- Torque ~ J_s = J *Polarization
- J = I / Transverse Area
- Incubation time ~ 50 ps + jitter



SOT - MTJ

- ST by spin-orbit coupling
- Torque ~ J_s = J * Θ_{SH}
- J = I / Longitudinal Area
- No incubation time



$$I_{c0}^{SOT} / I_{c0}^{STT} = \frac{1}{2\alpha} \frac{\eta}{\theta_{SH}^{eff}} \frac{t_{FM} + t_{HM}}{w}$$

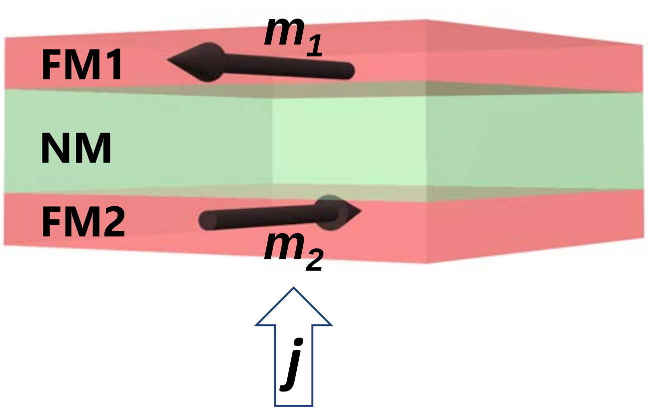
Garello et al., APL 105, 212402 (2014)

Summary I

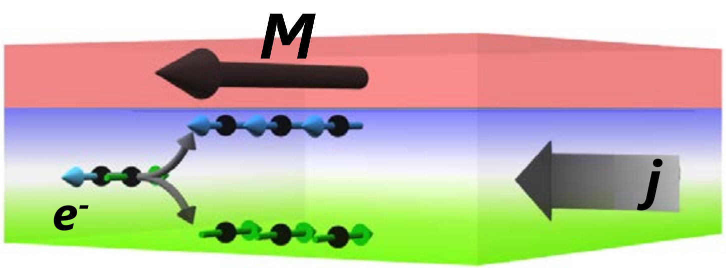
Spin transfer and spin-orbit coupling can be used to

- Generate spins. Spin injection
- Transport spins from the source
- Manipulate spins/macrospin
- Detect spins

STT and GMR



STT and USMR



Avci et al., Nat. Phys. 2015

Spin transfer and spin-orbit torques can be combined in devices

Summary II

- Spin-orbit torques are very efficient to manipulate the magnetization of nanoscale magnets: Switching, spin waves, DW motion
- New type of devices are possible: 3-terminal MTJ, MW oscillators, logic gates
- Materials compatible with CMOS processing
- High coercivity, radiation hard magnetic bits
- MTJ stacks: 120-180 % TMR, 2-200 Ω μm^2 RA
- Ultrafast switching (<200 ps), deterministic, bipolar

To do:

- Material optimization to obtain a larger SOT/current ratio and/or lower resistivity of write line.
- Scaling of MTJ devices below 40 nm
- Integrate in-plane bias field in MTJ stack or design structures that do not need a bias field
- And more…

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