Spin transfer & Current-induced magnetization reversal

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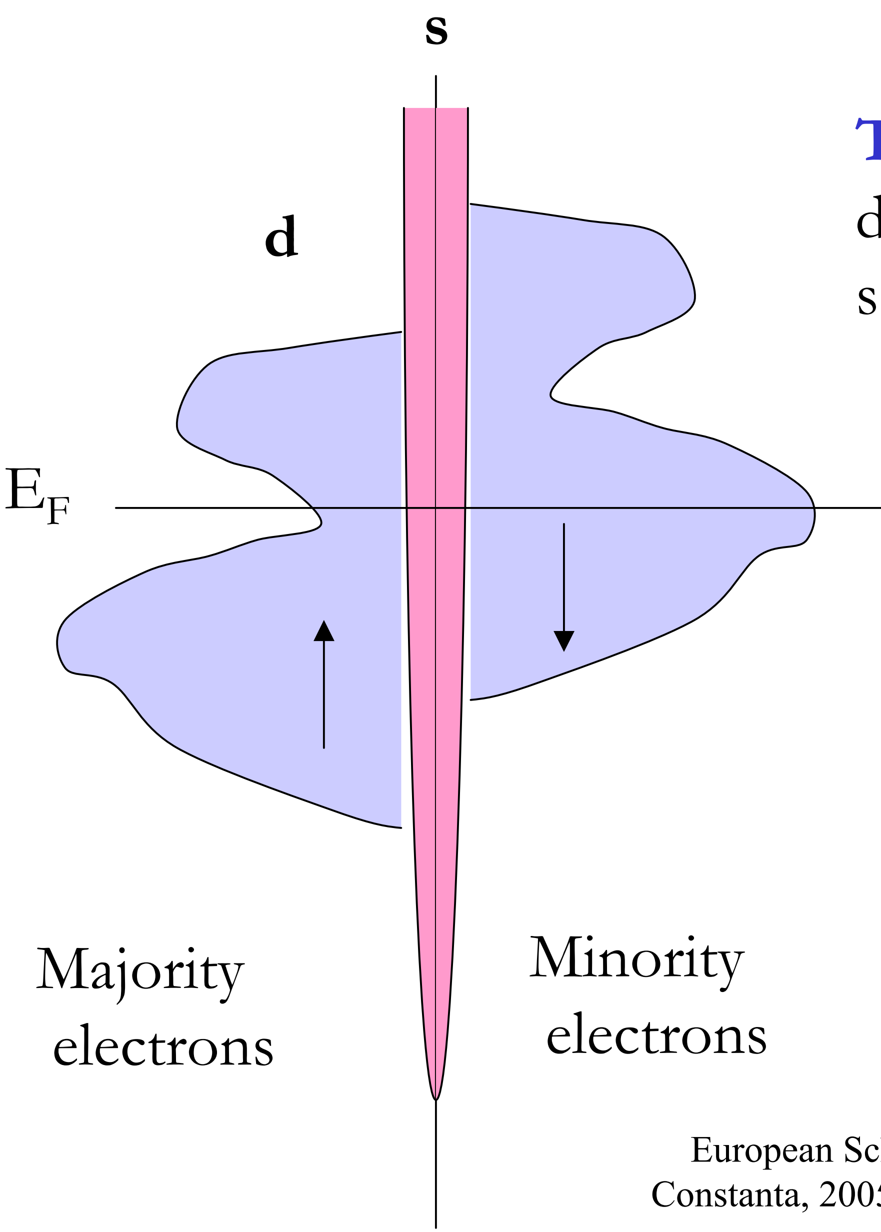
Electronic structure of magnetic 3d metals



The simple s-d model

d electrons : localized, carry magnetism

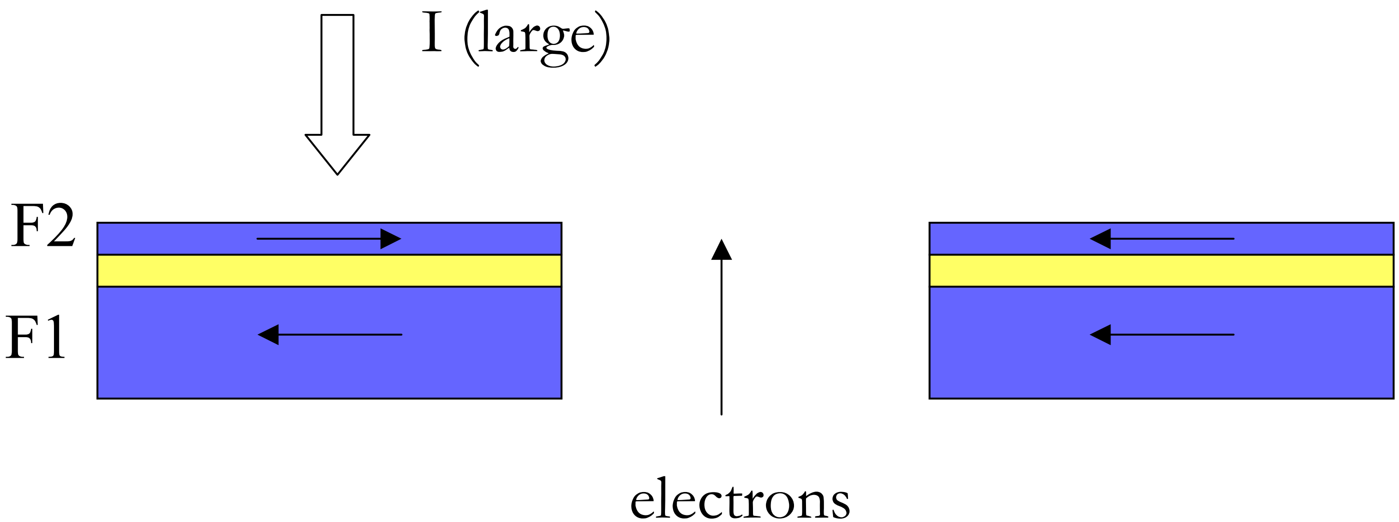
s electrons : delocalized, carry current

$$\sigma = \frac{ne^2\tau}{m}$$

$$\frac{1}{\tau} = \frac{2\pi}{\hbar}\left|V_{diff}\right|^2 k_B T \, N(E_F)$$

$\sigma_\uparrow > \sigma_\downarrow$ usually

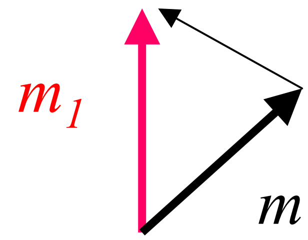
Spin transfer : principle



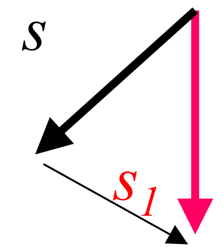
After reorientation of their spin to *m*, an angular momentum has been given

Magnitude of the spin transfer effect

J : current density [C/(m^2 s)]



$$\frac{J}{e}\,dt\,\frac{\hbar}{2}\left(\vec{s}_1-\vec{s}_2\right)P = d\vec{L} \qquad \text{per unit surface}$$

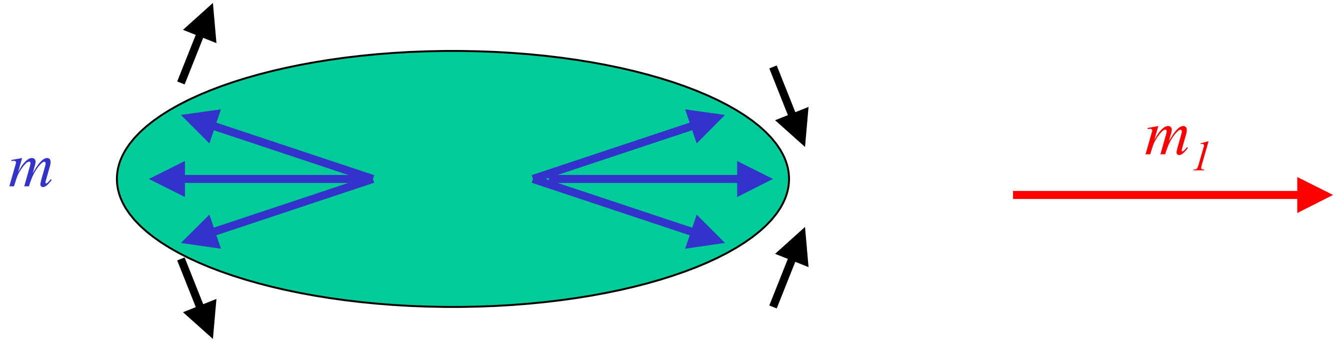


Ultrathin layer of thickness D $\quad \vec{L} = -\frac{M_s}{\gamma}\,D\,\vec{m}$

$$\left.\frac{d\vec{m}}{dt}\right)_{spin-transfer} = \frac{Jg\mu_B P}{2eM_s D}\left(\vec{m}_1-\vec{m}\right)_{\perp} = \frac{1}{\tau}\,\vec{m}\times\left(\vec{m}_1\times\vec{m}\right)$$

LLG + spin transfer term

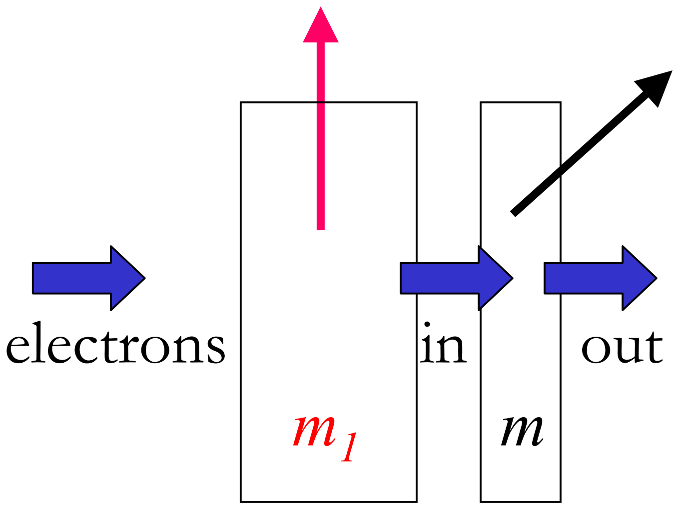
$$\frac{d\vec{m}}{dt} = \gamma_0 \vec{H}_{eff} \times \vec{m} + \alpha\, \vec{m} \times \frac{d\vec{m}}{dt} + \frac{1}{\tau}\, \vec{m} \times \left(\vec{m}_1 \times \vec{m}\right)$$

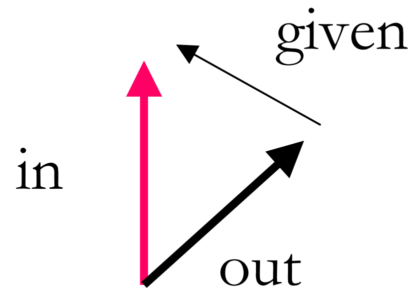


$$\left.\frac{d\vec{m}}{dt}\right)_{spin\ transfer}$$

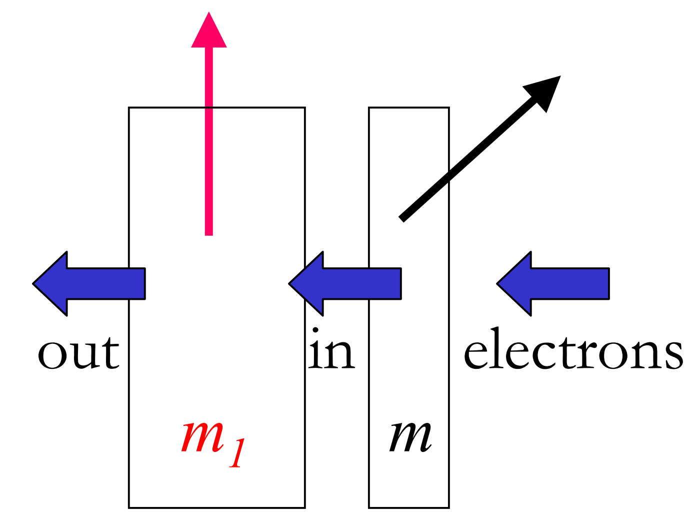
destabilizing stabilizing

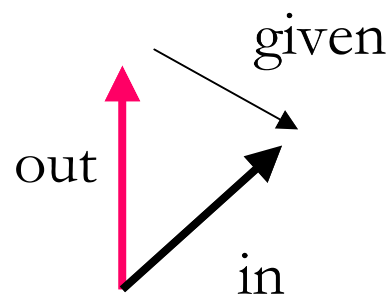
Sign of the spin transfer effect (mnemonics)





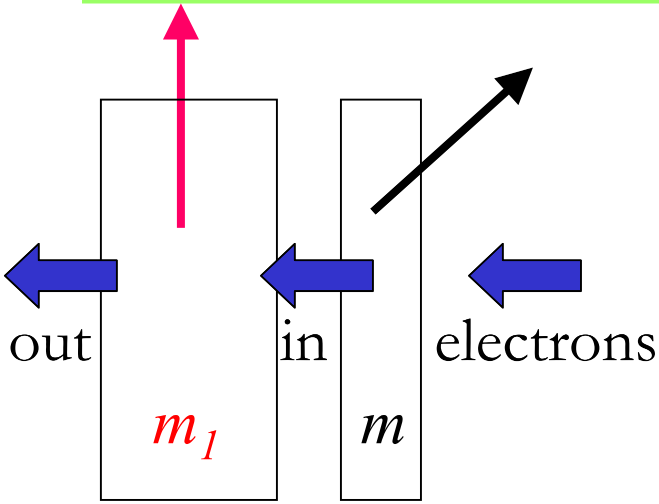
Favors a parallel alignment of F to F1





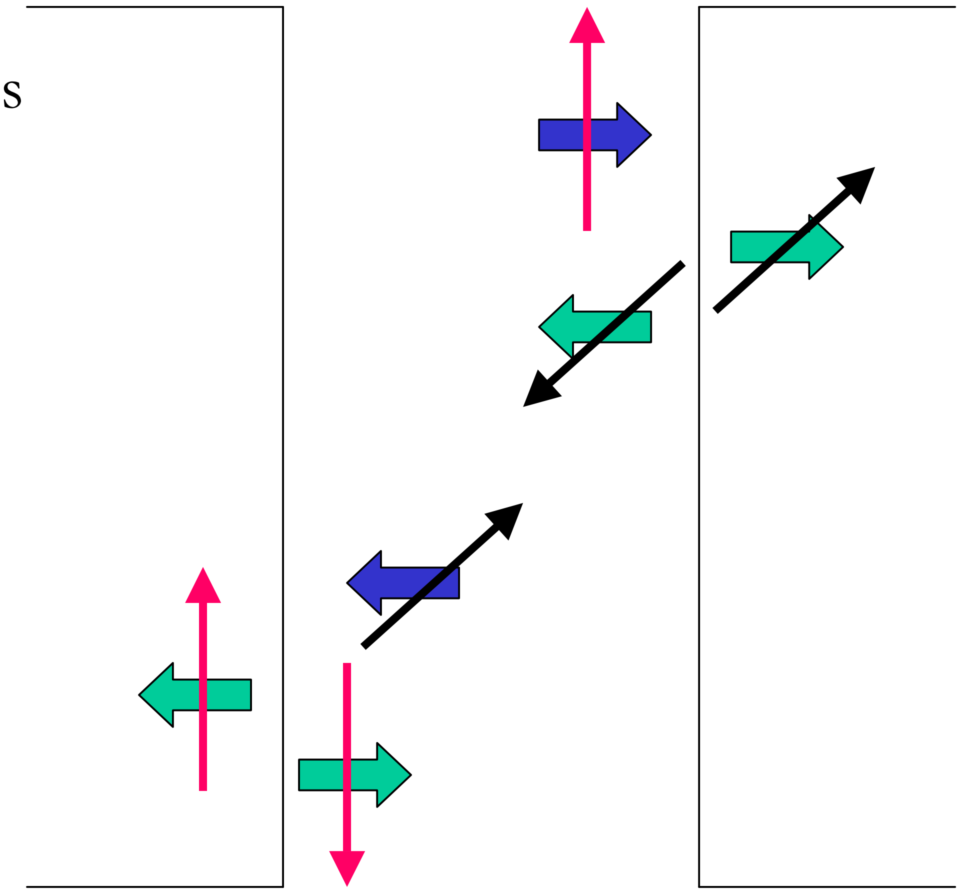
Favors an anti-parallel alignment of F to F1

Electron motion through a multilayer



$$|\theta> = \cos(\theta/2)\,|\uparrow> + \sin(\theta/2)\,|\downarrow>$$

Spin-dependent transmission and reflection



Order of magnitude of the current needed

$$\frac{d\vec{m}}{dt} = \gamma_0 \vec{H}_{eff} \times \vec{m} + \alpha\, \vec{m} \times \frac{d\vec{m}}{dt} + \frac{1}{\tau} \vec{m} \times \left(\vec{m}_1 \times \vec{m} \right)$$

Stability calculation

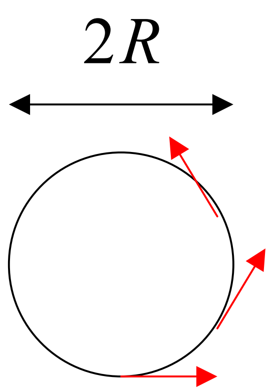
$$\left.\frac{1}{\tau}\right|_{critical} = \alpha \gamma_0 M_s$$

$$J_{critical} = \frac{\alpha \mu_0 M_s^2 e D}{\hbar P}$$

$$\alpha = 0.01,\ M_s = 0.8 MA/m,\ D = 3nm,\ P = 30\%$$

$$\Rightarrow J_c = 1.3\ 10^{11}\ A/m^2$$

Samples have to be small



$$I = J\pi R^2$$

Oersted field associated with the current

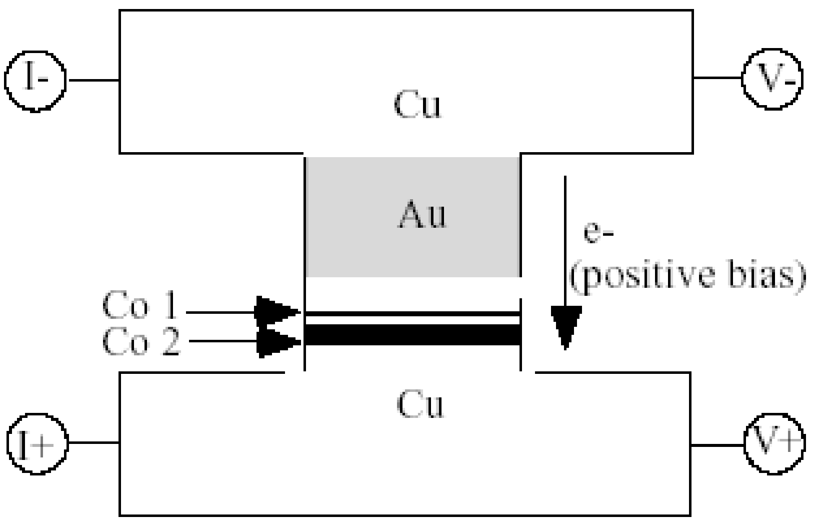
$$H_{Oersted} = \frac{I}{2\pi R} = J\frac{R}{2}$$

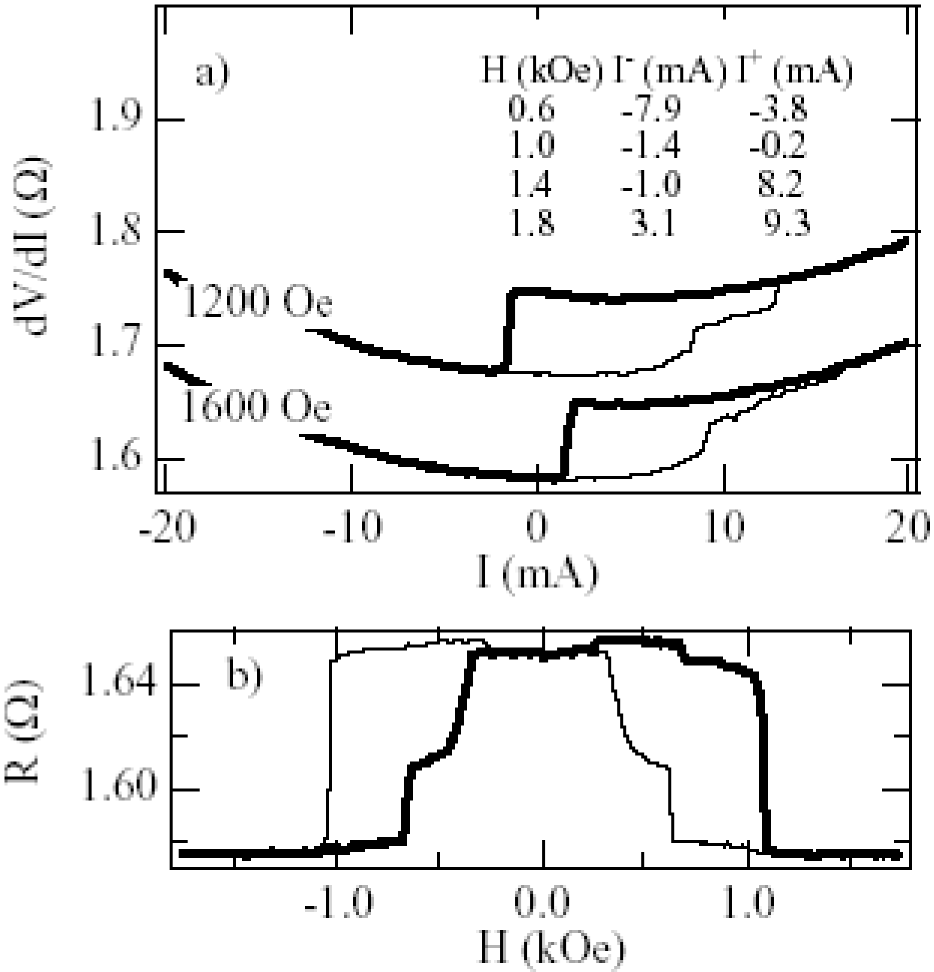
$$\gamma_0 H_{spin-transfer} = \frac{1}{\tau}$$

$$H_{spin-transfer} > H_{Oersted} \Leftrightarrow R < \frac{\hbar P}{e\mu_0 M_s D}$$

$$P = 1, \mu_0 M_s = 1\,T, D = 3\ nm \rightarrow R < 200\ nm$$

First demonstration of current-induced magnetization reversal





diameter ≈ 150 nm

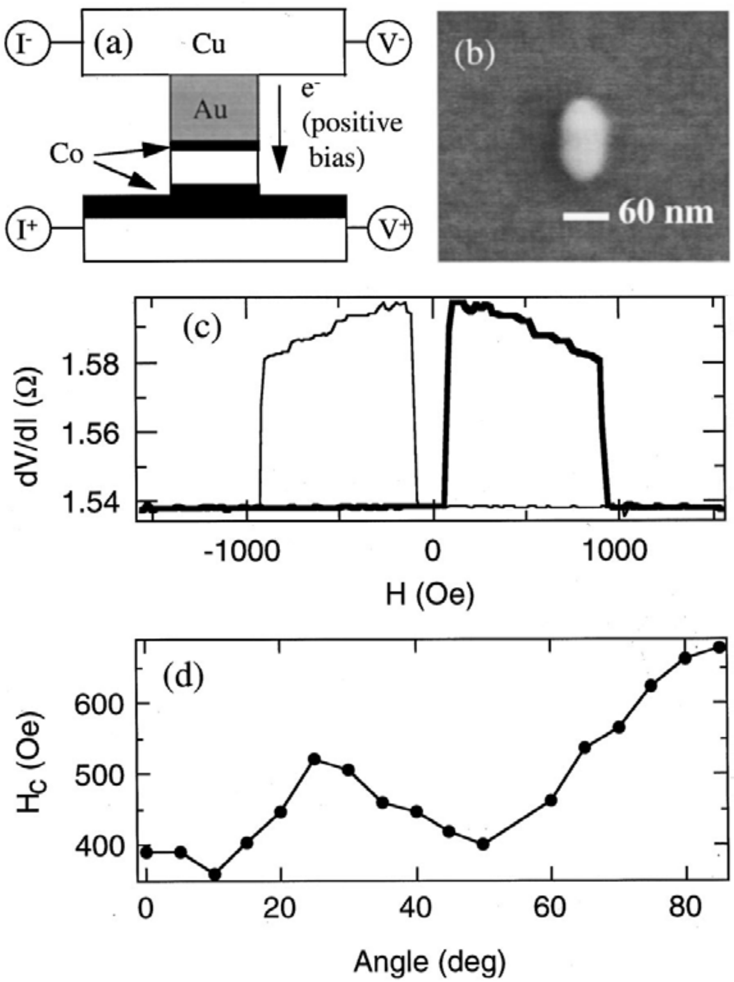
$5\ 10^{11}$ A/m^2

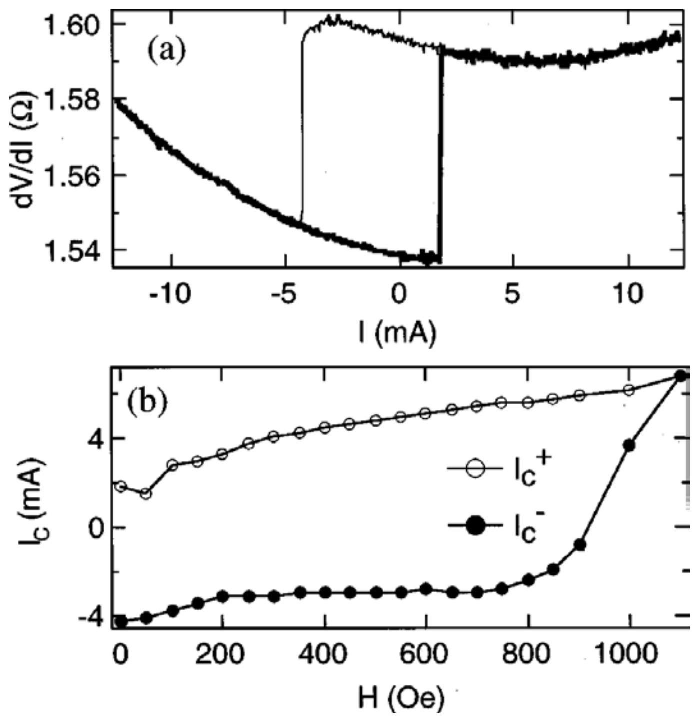
J.A. Katine et al.

Phys. Rev. Lett. **84**, 3149 (2000)

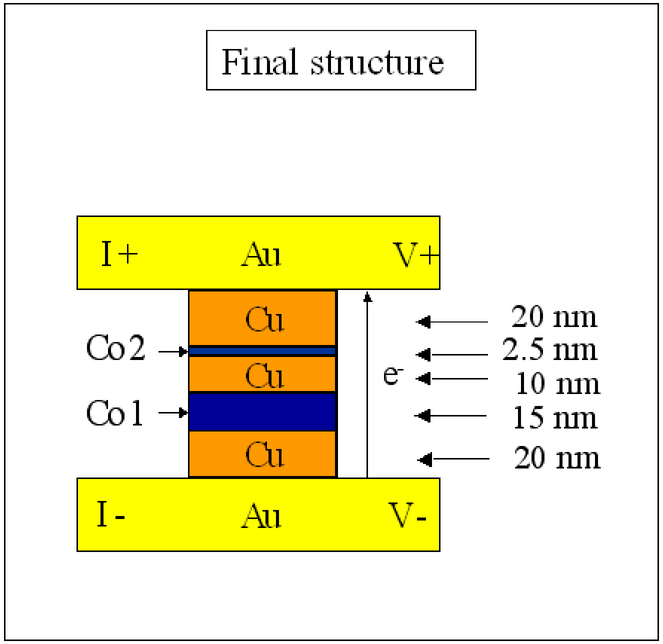
size ≈ 60x100 nm^2
5 10^{11} A/m^2

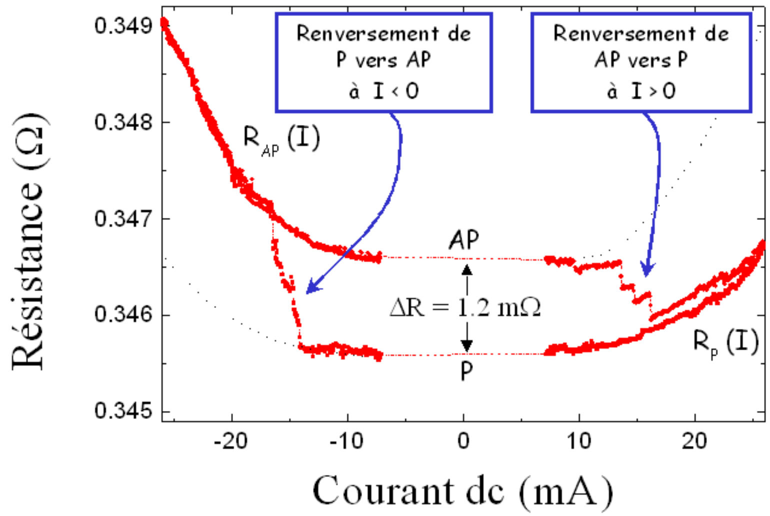
F.J. Albert et al.
Appl. Phys. Lett. **77** (2000)



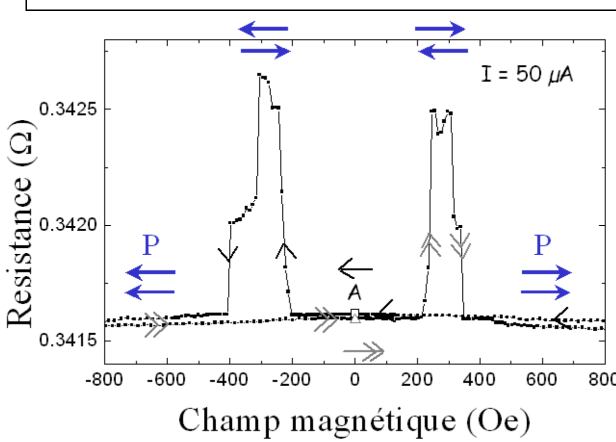


The second experimental demonstration of current-induced magnetization reversal





30 K



30 K

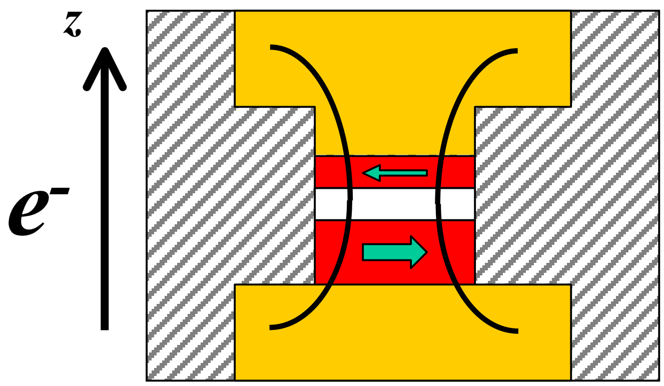
ΔR ≈ 1.2 mΩ

Pillar cross-section : 200 x 600 nm^2

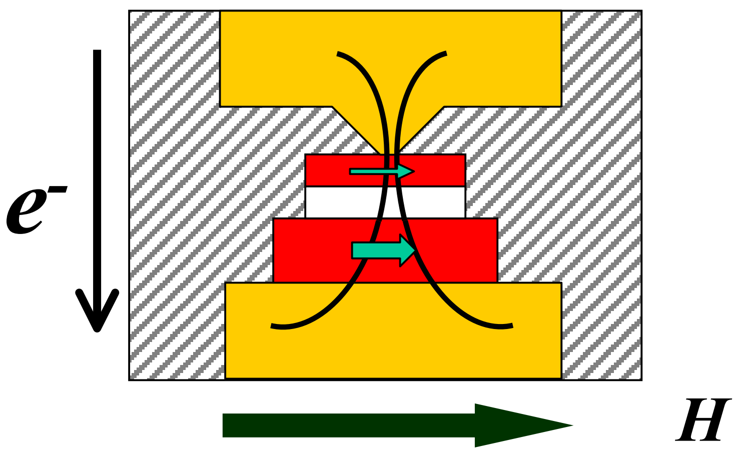
J. Grollier et al.,
Appl. Phys. Lett. 78, 3663 (2001)

Main sample architectures

Pillars

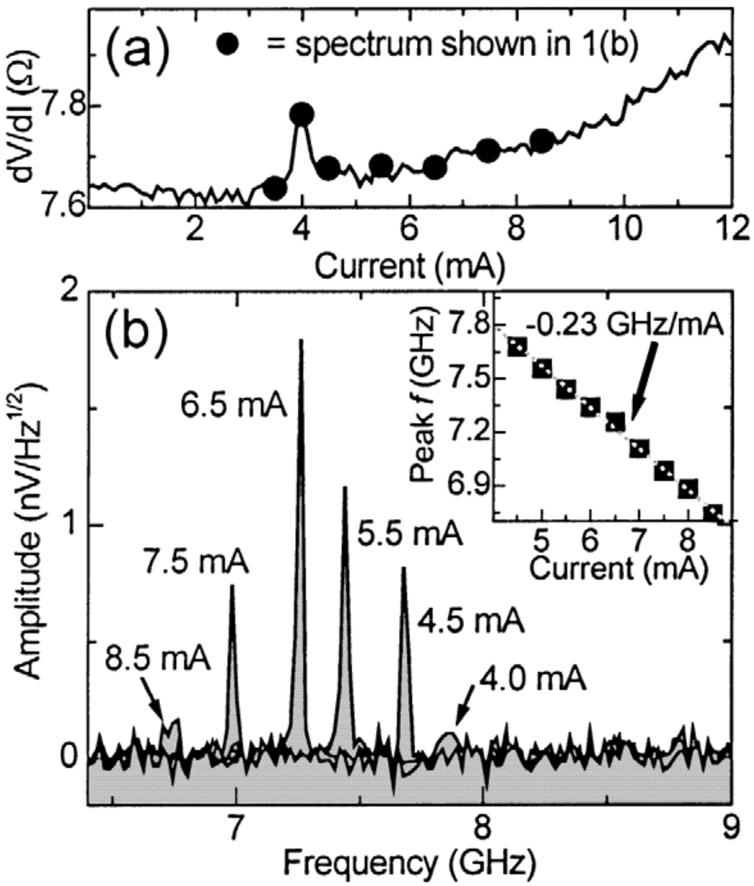


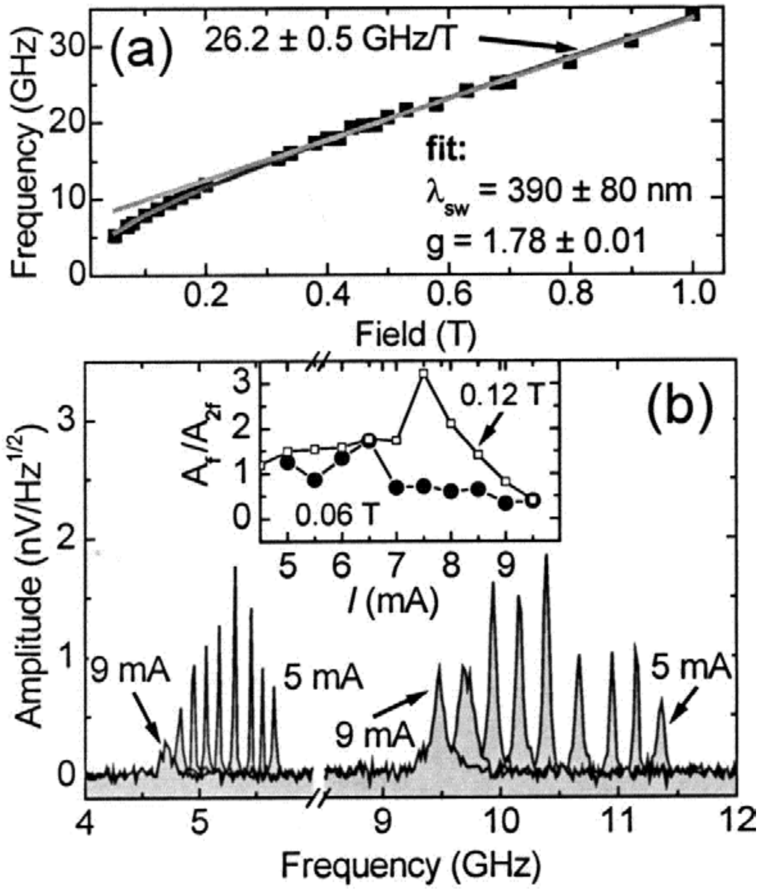
Point Contacts



Experimental results : point contact geometry

W. H. Rippard et al., PRL'2004



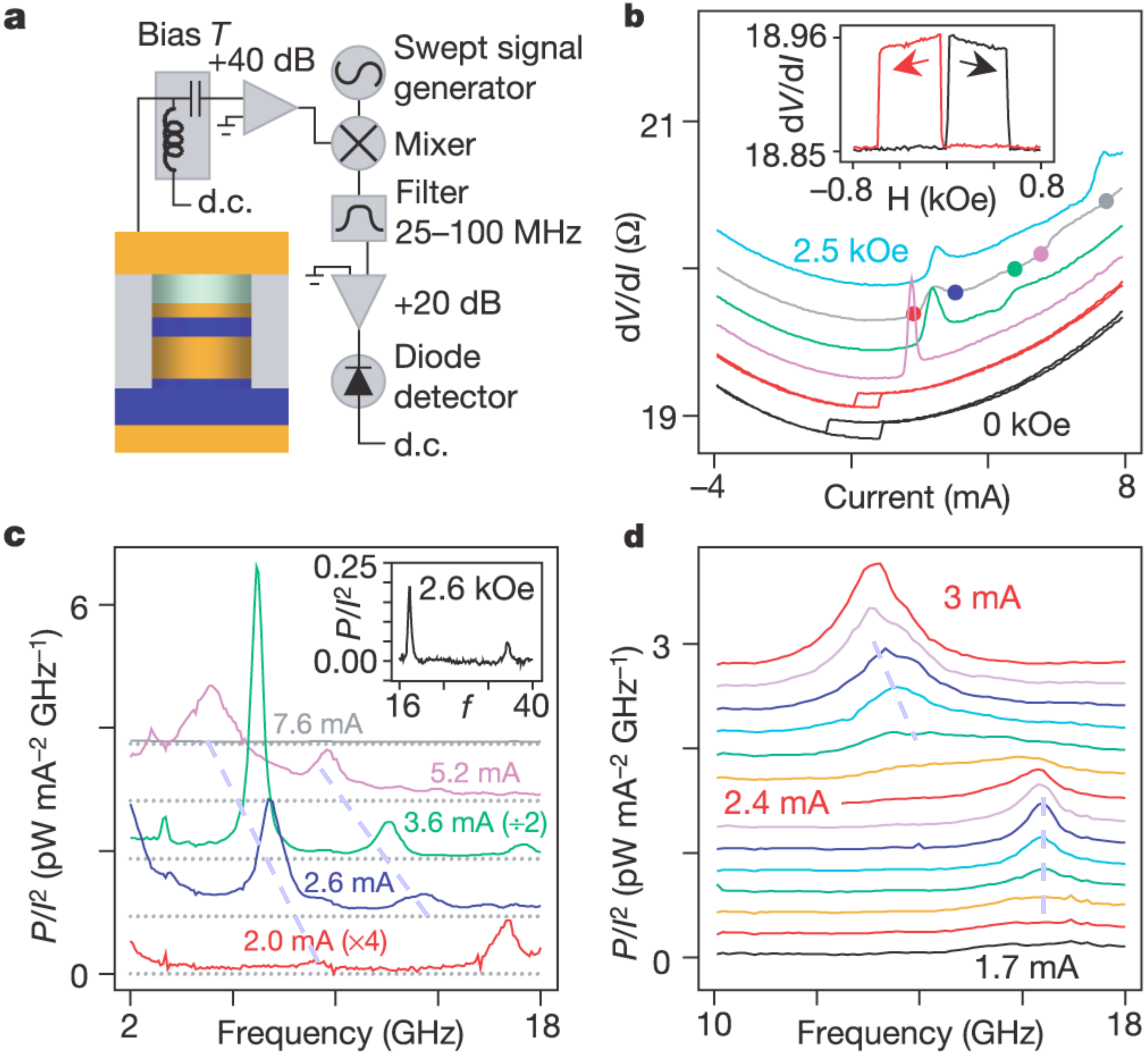


Point Contact Geometry : ≈ 40 nm diameter

$$\Delta R \approx \Delta R_{Max}\left(1 - \mathbf{m}_1 \cdot \mathbf{m}_2\right)$$

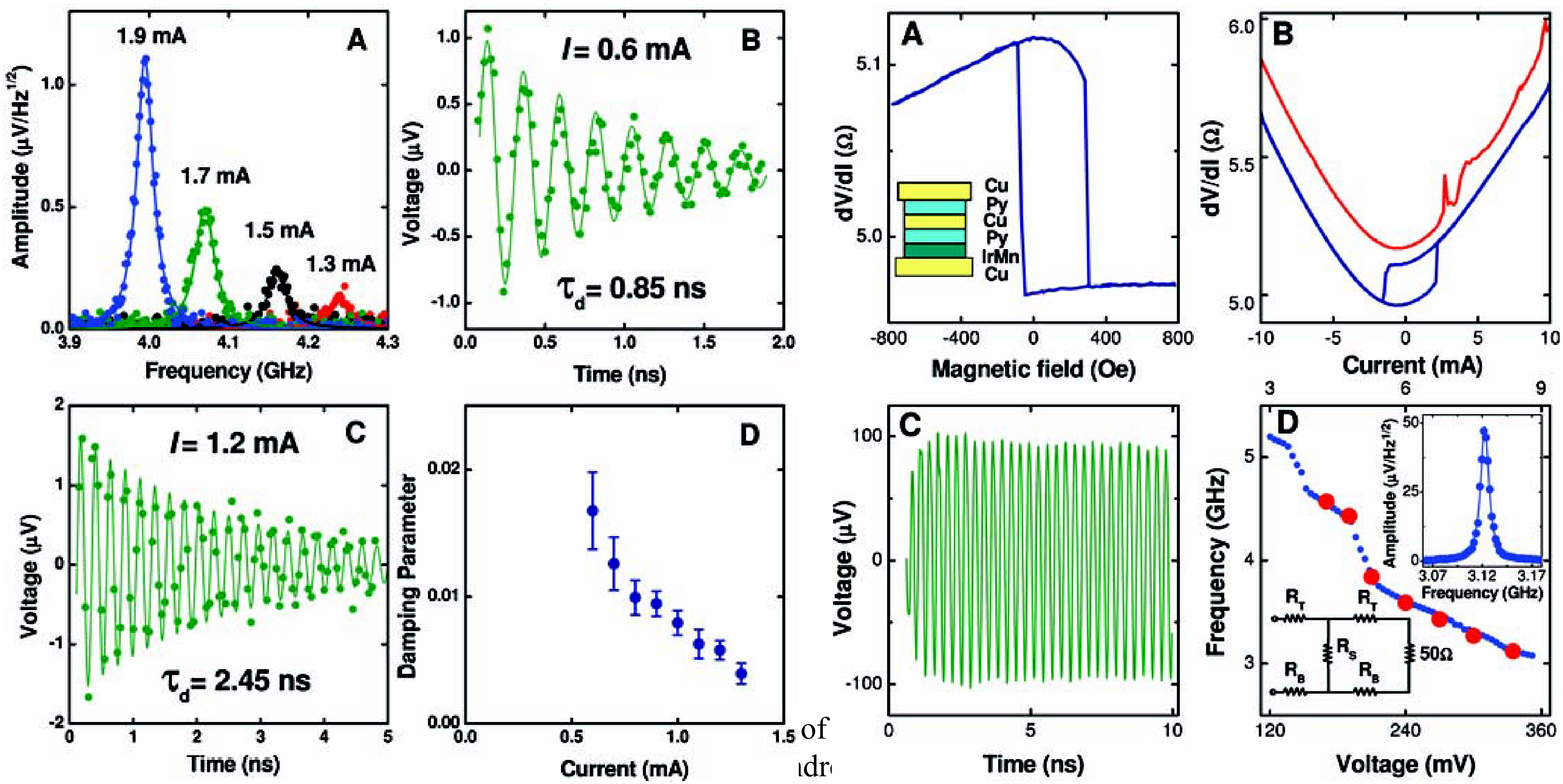
Experimental Results : Pillar Geometry
A Rather Complex Set of Experimental Results

S. I. Kiselev et al., NATURE'2003



Experimental Results : Pillar Geometry with Exchange Biasing at a Skewed Angle

I. Krivorotov et al., Science'2005

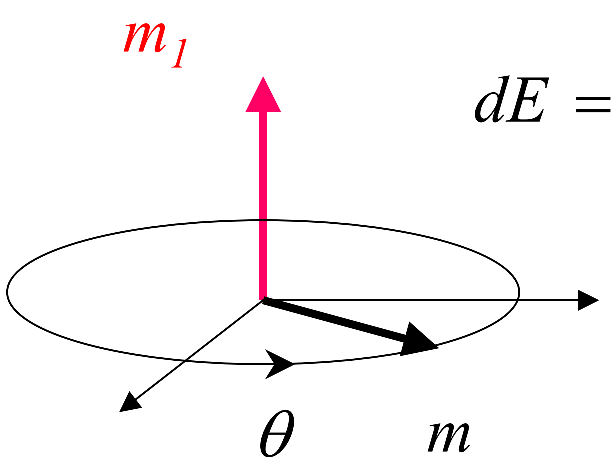


Energy and spin transfer effect

$$\left.\frac{d\vec{m}}{dt}\right)_{spin-transfer} = \frac{Jg\mu_B P}{2eM_s D}\left(\vec{m}_1 - \vec{m}\right)_\perp = \frac{1}{\tau}\vec{m}\times\left(\vec{m}_1\times\vec{m}\right)$$

Effective field for the spin transfer term

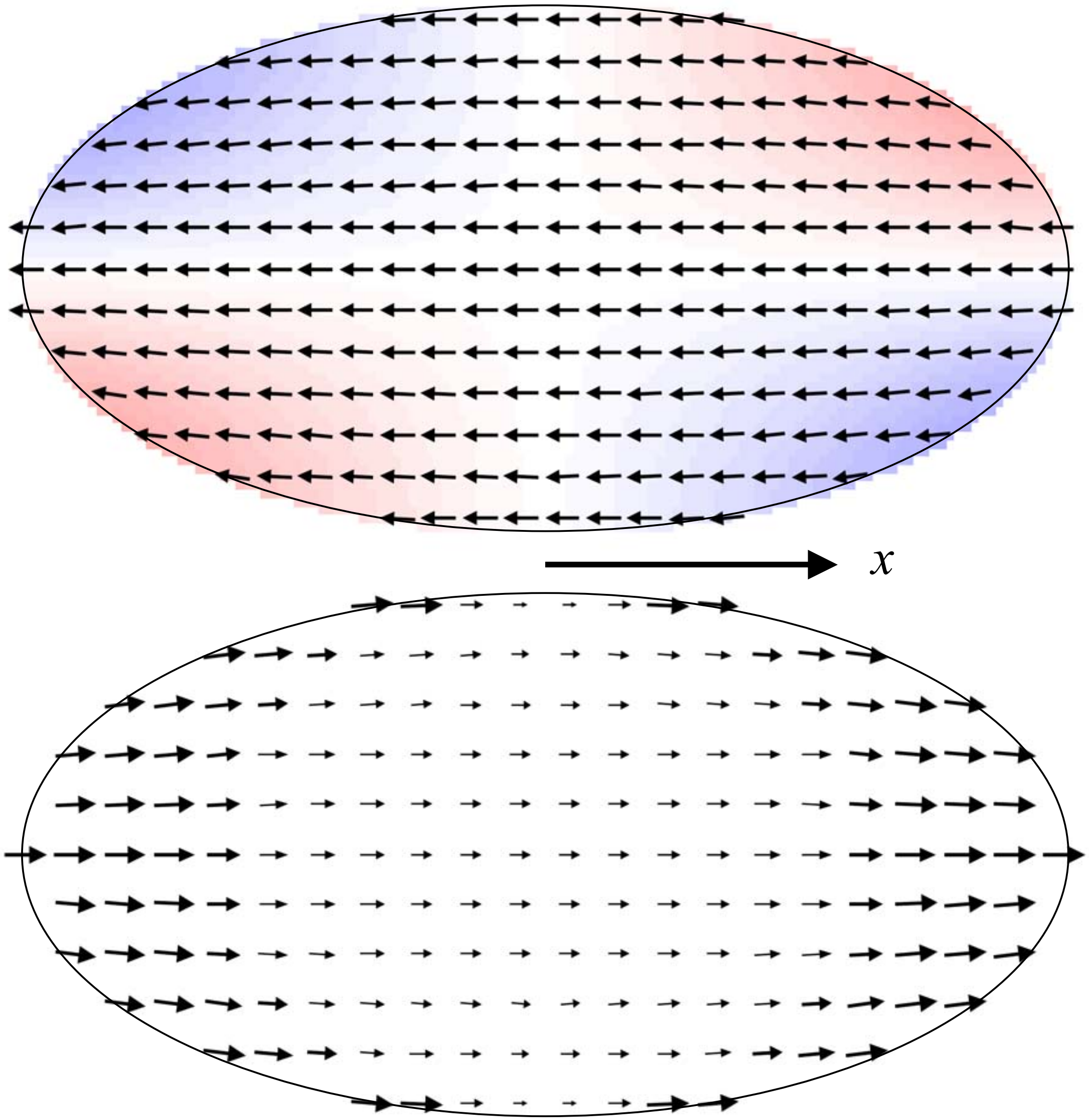
$$H_{\text{eff, spintransfer}} = \frac{1}{\gamma_0\tau}\vec{m}\times\vec{m}_1$$



$$dE = -\mu_0 M_s \vec{H}_{eff}.d\vec{m} = \frac{1}{\gamma\ \tau}(\vec{m}_1\times\vec{m}).d\vec{m} = \frac{d\theta}{\gamma\tau}$$

No energy term to be associated with the spin transfer torque term !

Elliptical Elements



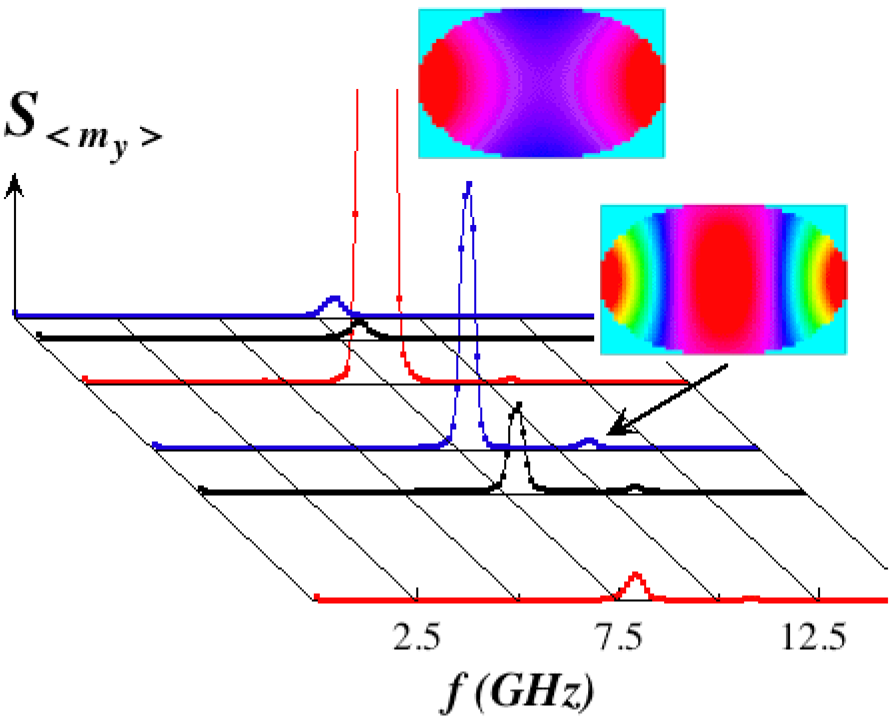
M

H_{Eff}

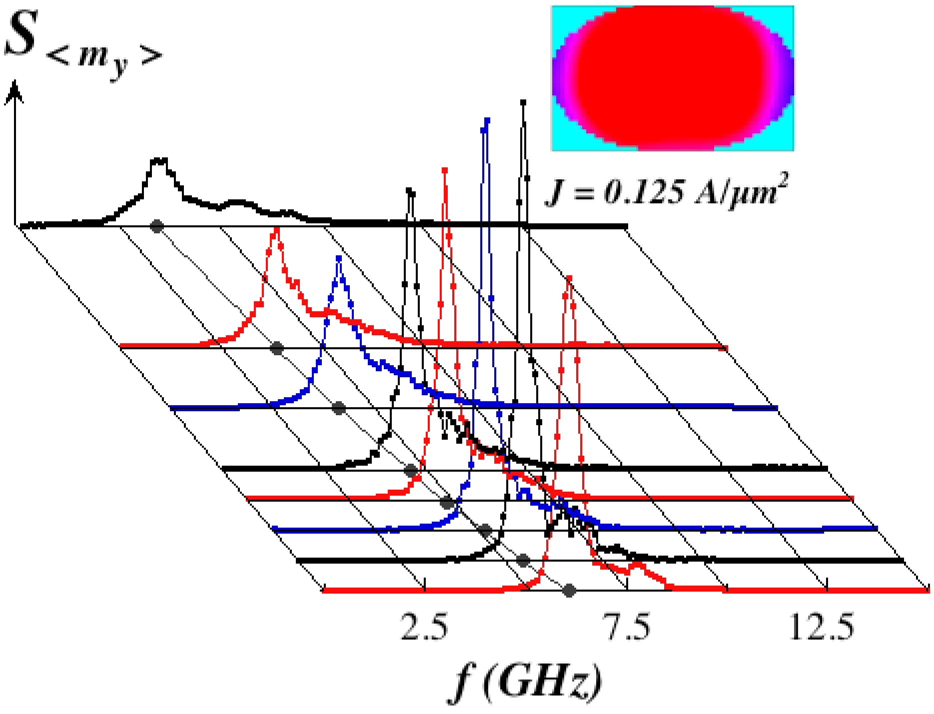
LE

Micromagnetic Regime:
Precessional States (T=300 °K)

Eigenmode



Driven Mode



B. Montigny & J. Miltat, J. Appl. Phys. **97** 10C708 (2005)

Micromagnetics vs experiments

✓Switching, generation of microwaves, are qualitatively reproduced perfectly, but

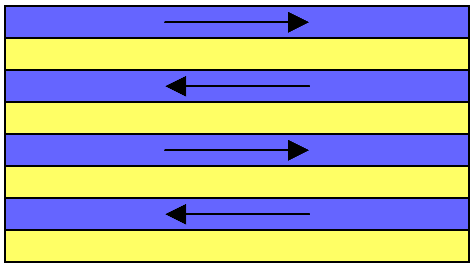
✕ Computed Power Spectral Density line widths ***too large*** when compared to experimental data even in the MS approximation

✕ Comparison between experiments and micromagnetic simulations strongly suggest that micromagnetics leads to ***excessive spatial incoherence***

✕ At the same time, extremely narrow line widths, even in the pillar geometry, call for ***markedly weakly damped systems***

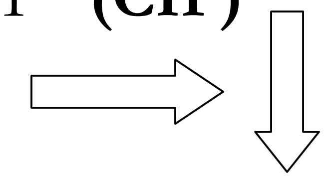
✕ Such features seem ***hardly compatible*** within the framework of existing theories

Giant magnetoresistance (GMR)

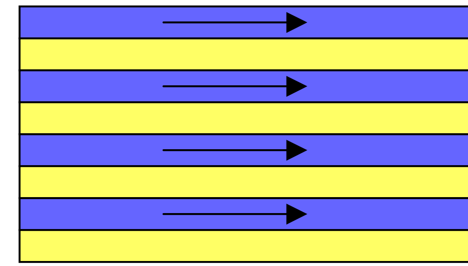


$R_{AP} = 2R_P$

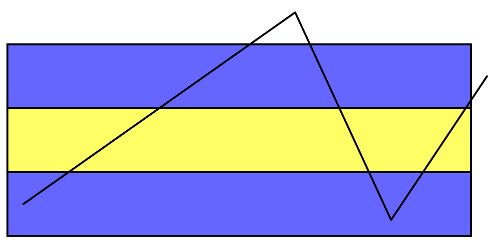
I (CIP)

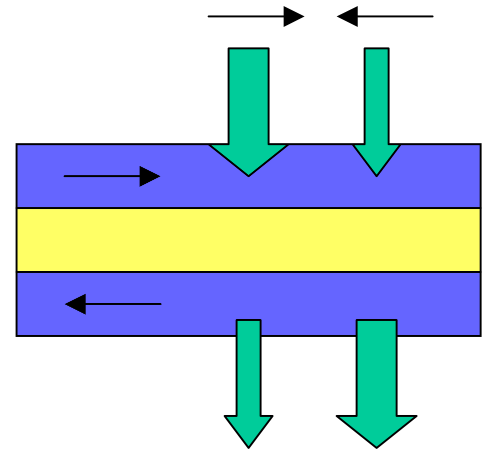


I (CPP)



R_P

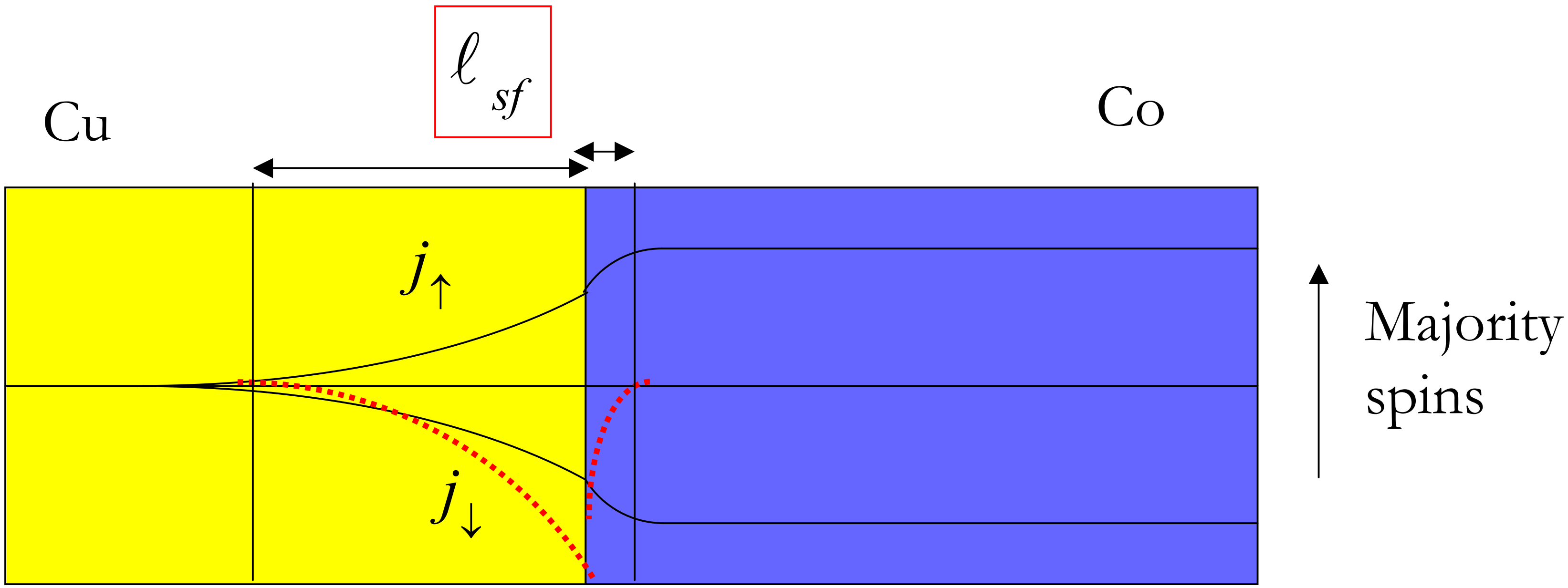




CIP : needs layers thinner than the mean free path

CPP : needs layers only thinner than the spin diffusion length

Current polarization variation



$$j_\uparrow = j_\downarrow = j/2$$

$$P = 0$$

δm

Spin accumulation

$$j_\uparrow / \sigma_\uparrow = j_\downarrow / \sigma_\downarrow$$

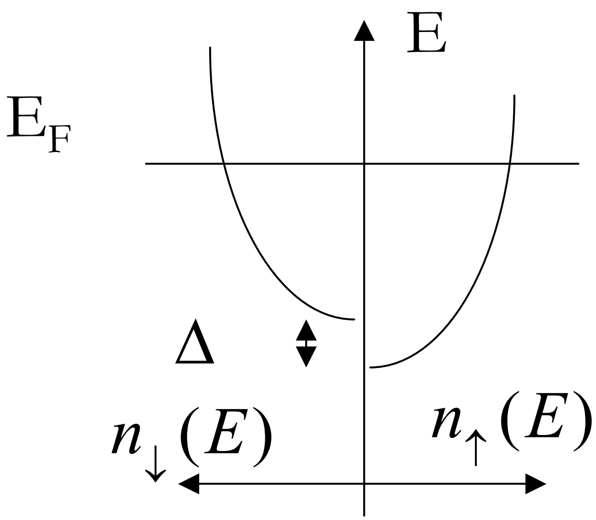
$$j_\uparrow / j_\downarrow = \sigma_\uparrow / \sigma_\downarrow = \alpha$$

$$P = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow} = \frac{\alpha - 1}{\alpha + 1} = \beta$$

M.D. Stiles, A. Zangwill,
J. Appl. Phys. **91**, 6812 (2002)

A non-collinear spin enters

Ferromagnetic metal



$$k_\uparrow(E) > k_\downarrow(E)$$

$$|\theta>(0) = \cos(\theta/2)|\uparrow> + \sin(\theta/2)|\downarrow>$$

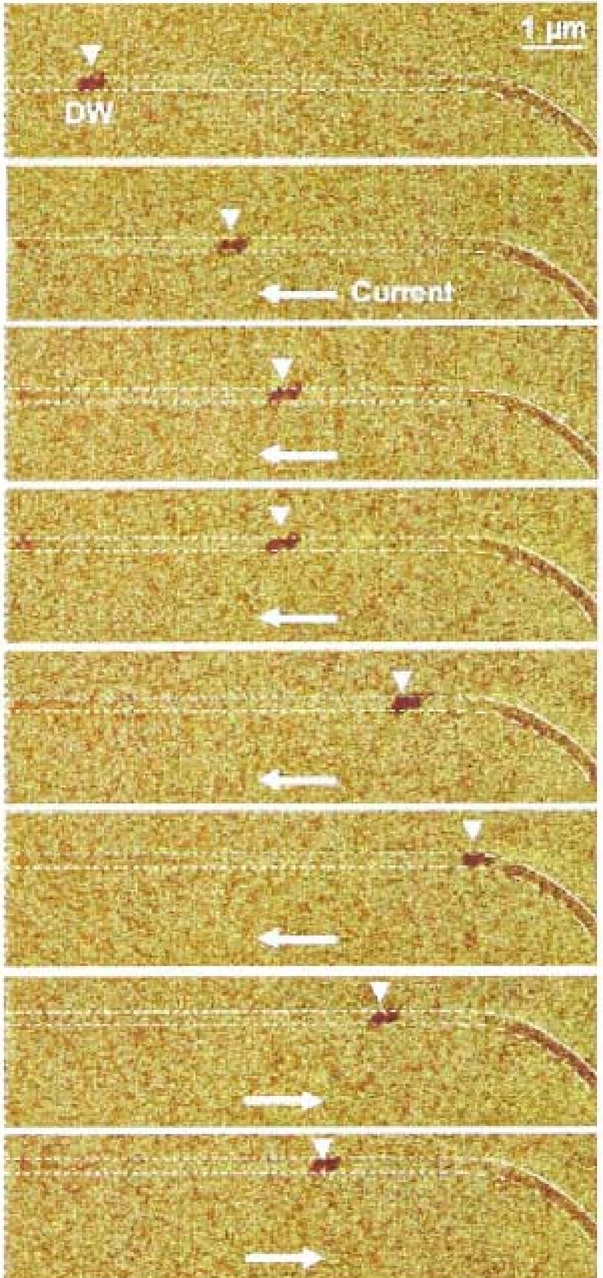
$$|\theta>(x) = \exp(ik_\uparrow x)\cos(\theta/2)|\uparrow>$$

$$+ \exp(ik_\downarrow x)\sin(\theta/2)|\downarrow>$$

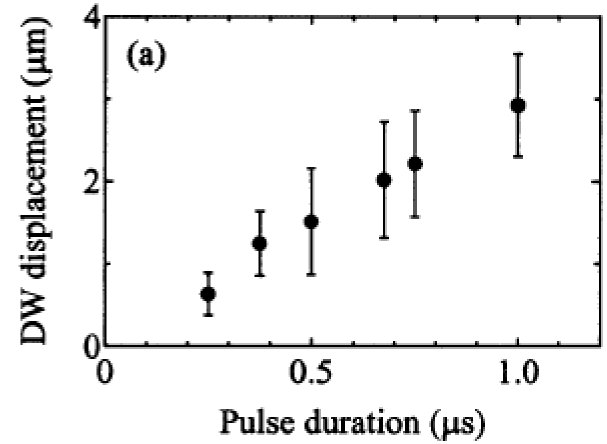
$$\frac{2\pi}{k_\uparrow - k_\downarrow} = \frac{4\pi}{k_F}\frac{E_F}{\Delta} \approx 1\,nm$$

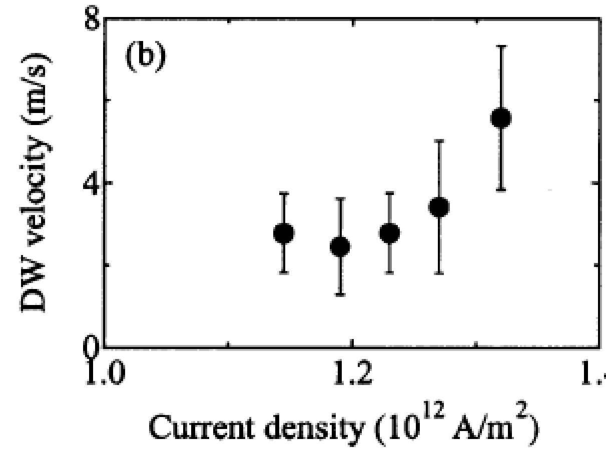
Disparition of the transverse component

Wall displacement by current



Pulses :
0.5 µs
1.2 10^{12} A/m^2





A. Yamaguchi et al.
Phys. Rev. Lett. 92 077205 (2004)

Conclusions

A fascinating field

Experiments are far away before theory

Just putting the simple Slonczewski term into LLG does not suffice to explain quantitatively everything