# Spin transfer torques in high anisotropy magnetic nanostructures

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*5) University of California, San Diego*

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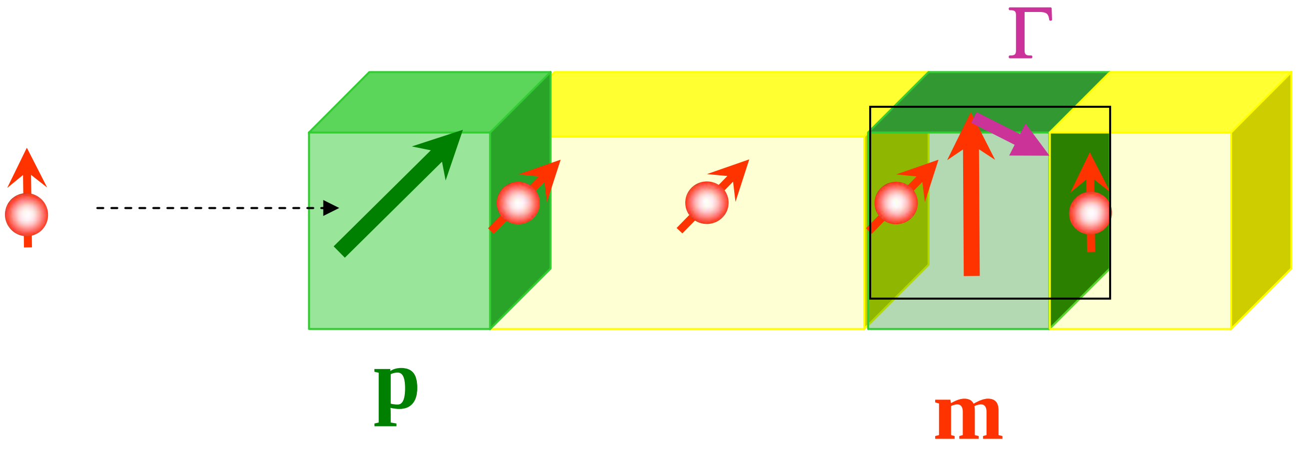
# Spin transfer torques in high anisotropy magnetic nanostructures

- Motivation
- Co/Ni multilayers
- 2 layer results (⊥-⊥)
    - switching currents
    - angular dependence (SW astroid)
- Conclusions

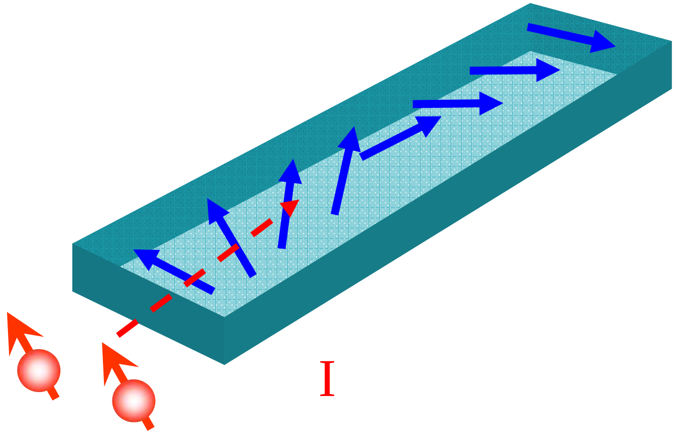
# Spin transfer torques in heterostructures



Angular momentum conservation
➔ spin transfer torques

$$\boxed{\Gamma_m = \frac{d\mathbf{L}_e}{dt}}$$

see J. Magn. Magn. Mater. **320** (2008)
articles on spin torque edited
by M. Stiles and D. Ralph



# Spin torque dynamics (LLG)

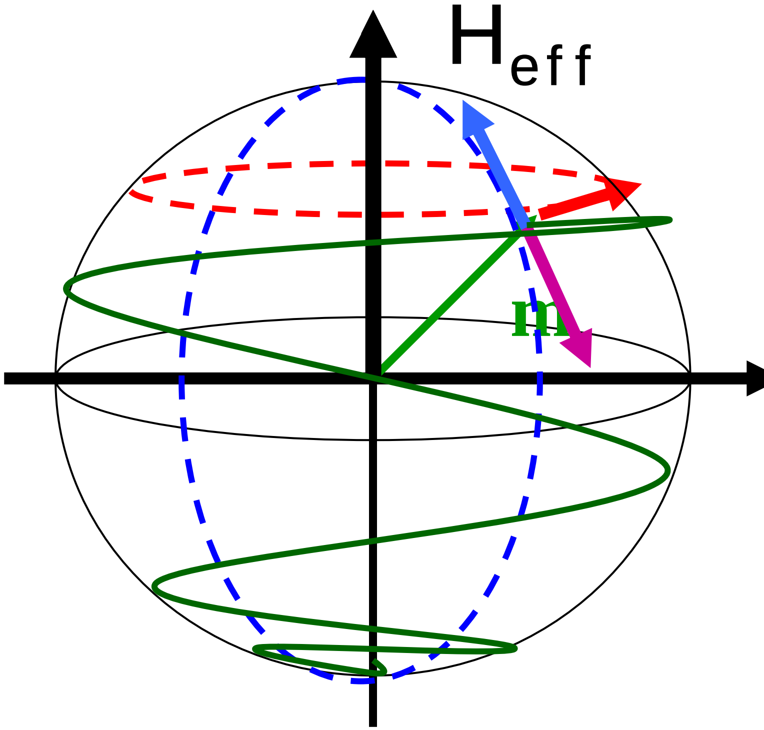
$$\frac{d\mathbf{m}}{dt} = \gamma_0 \mathbf{H} \times \mathbf{m} + \alpha\left(\mathbf{m} \times \frac{d\mathbf{m}}{dt}\right)$$

**Field torque (precession)**

**Damping torque (dissipation)**

$$-\frac{I P_i g \mu_B}{e M_s t}\left(\mathbf{m} \times \left(\mathbf{m} \times \mathbf{p}\right)\right)$$

**Spin torque (negative friction )**

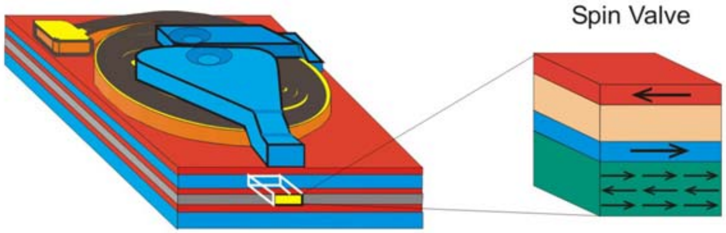


$$I_C \propto \alpha H_{eff}$$

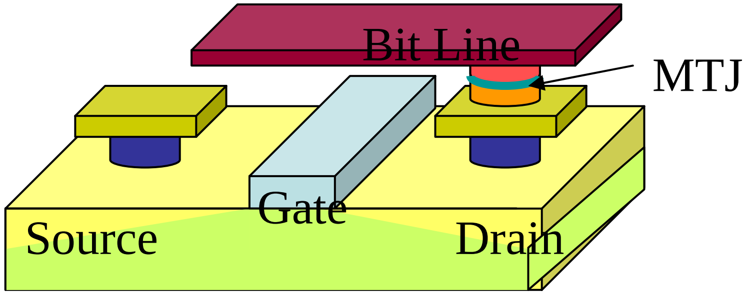
J. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

# Spin transfer torque nanotechnologies

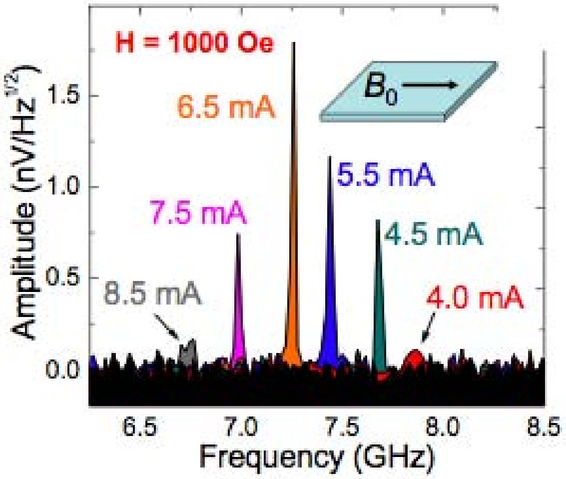
## Noise in read heads



## STT MRAM

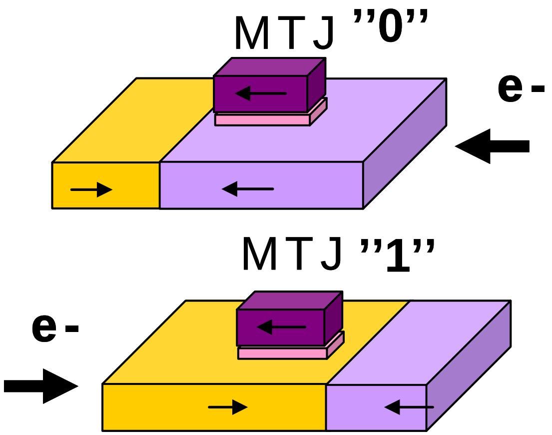


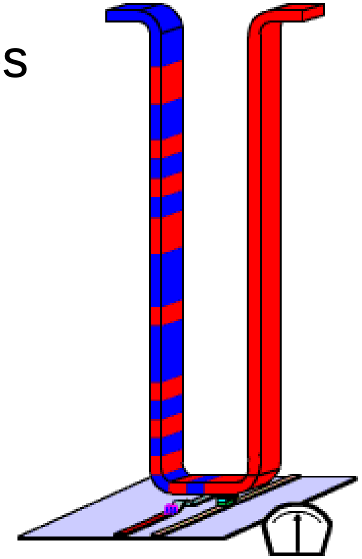
## Oscillators



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

## Domain wall devices

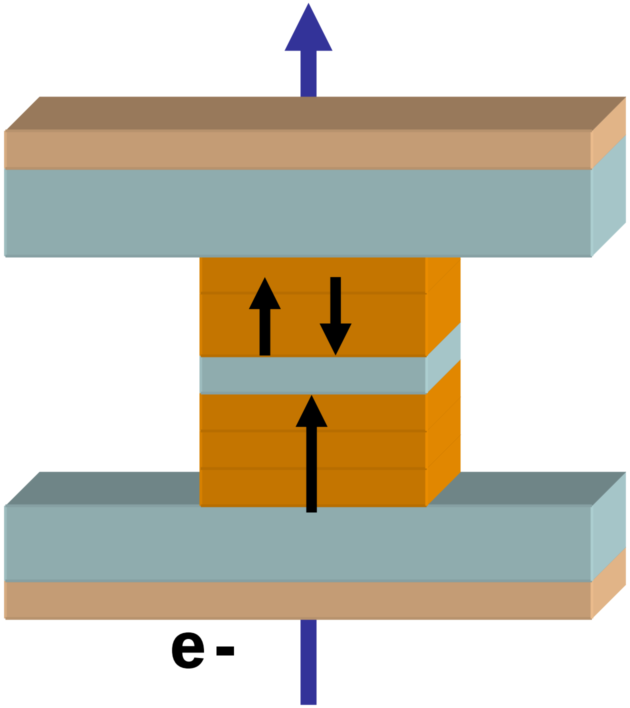




*Parkin et al., Science* **320**, 190 (2008).

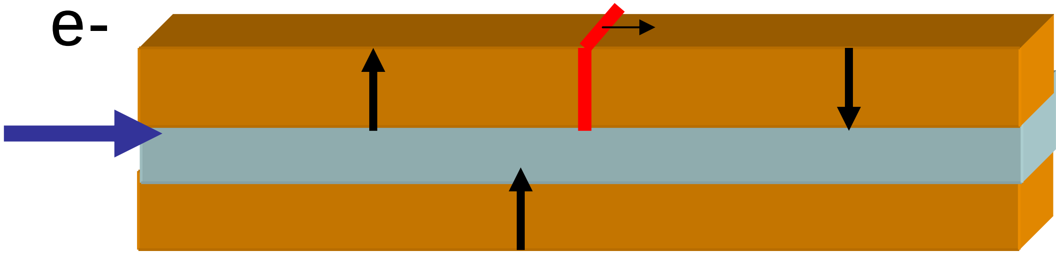
Chappert, Fert, and Van Dau, *Nature Mater.* **6**, 813 (2007).
Katine and Fullerton, J. Magn. Magn. Mater. **320**, 1217 (2008).

# Perpendicular anisotropy devices



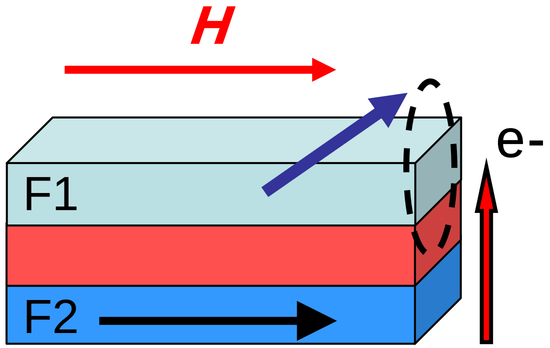
- **Less sensitive to structure/lithography**
- **Higher thermal stability**
- **More efficient reversal** ←
- **Higher frequency oscillations**
- **Narrow domain walls**
- **New functionality**

*Mangin et al.,*
*Nature Mater.* ***5****, 210 (2006)*



*Burrowes et al.*, APL **93**, 172513 (2008).
*Mihai et al, Nature Phys. (in press)*

# *Stability analysis of the LLG equations*



**in-plane magnetization**

**Demagnetization field suppresses out-of-plane precessions**

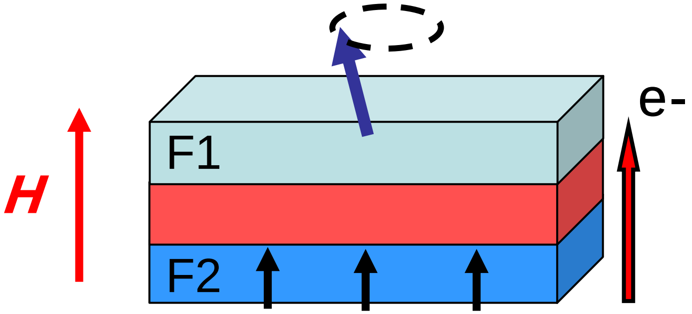
$$I_C \approx \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\theta)p}\left(\cancel{H + H_{dip}} + H_{K//} + 2\pi M_S\right)$$

$\mathbf{H}$: in-plane applied fied, $\mathbf{H_{dip}}$: dipole field, $\mathbf{H_{k//}}$ in-plane anisotropy field

***Stability*** $U_K = M_S V H_{K//} / 2$

***Critical current must overcome*** $2\pi M_S$ ***~ 5-10 kOe***

# Stability analysis of the LLG equations



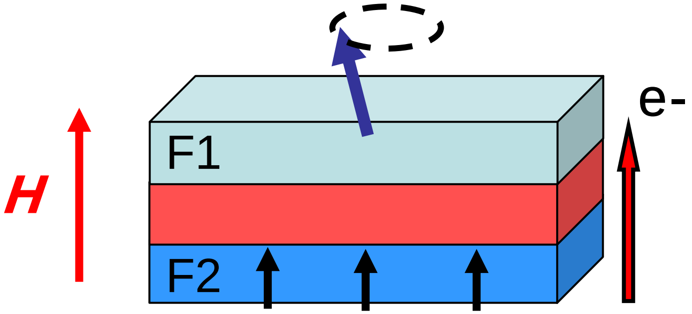
**out-of-plane magnetization**
**($H_{K\perp} > 4\pi M_S$)**

$$I_C \approx \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\theta)p}\left(H + H_{dip} + \overbrace{H_{K\perp} - 4\pi M_S}^{H_{K,eff}}\right)$$

**$H_{k\perp}$** out of plane anisotropy field

$$U_K = \left(M_S V H_{K,eff}\right)/2$$

# Stability analysis of the LLG equations



**out-of-plane magnetization**
**($H_{K\perp} > 4\pi M_S$)**

$$I_C \approx \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}U_K$$

Zero applied field

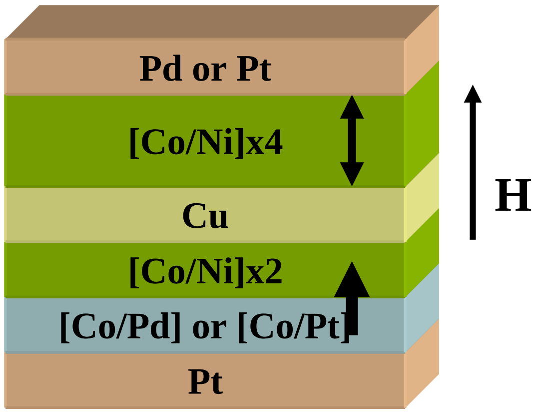
**Critical current directly proportional to thermal stability**

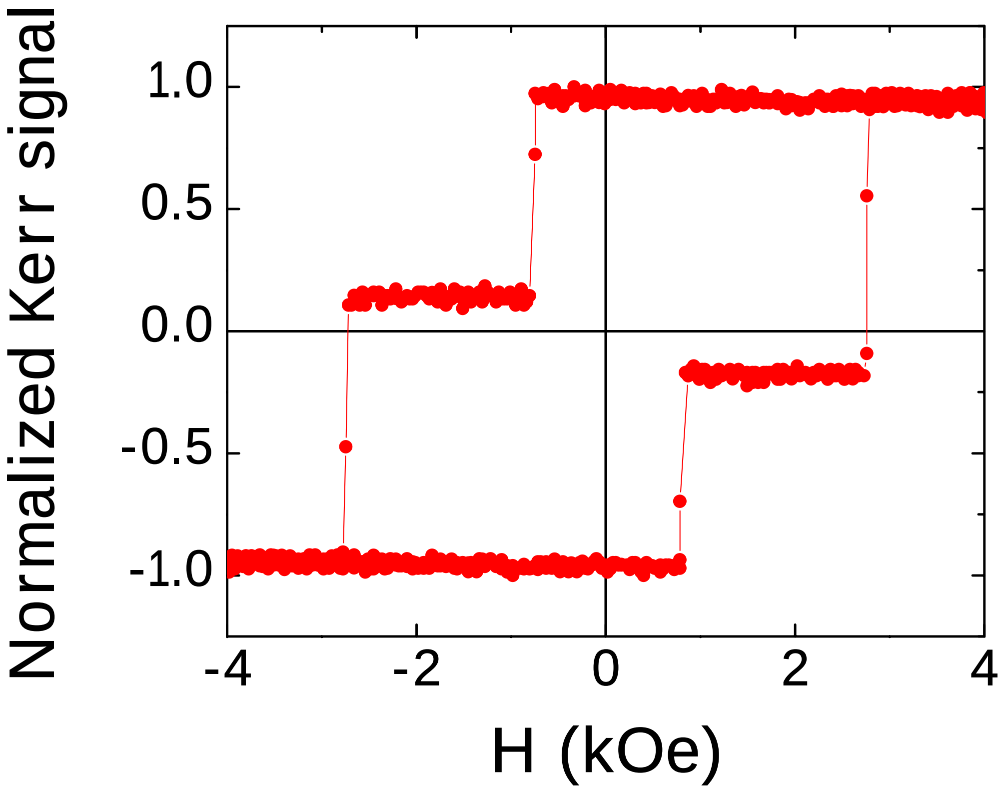
More efficient reversal assuming low $\alpha$ and high $p$

# Magnetic layers

Films grown on 5 inch Si wafers by e-beam and sputtering

(111) - Co(1Å)/Ni(6Å)





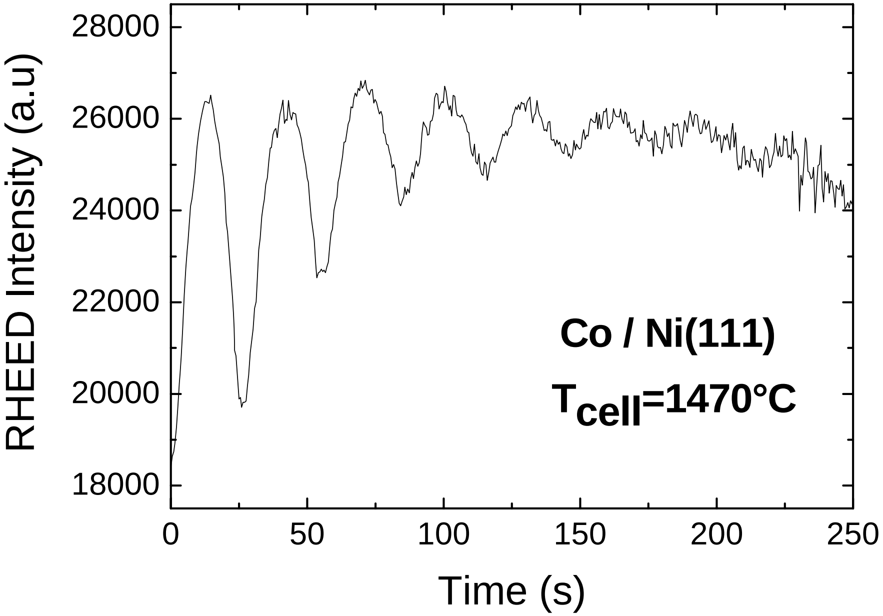
$K_u \sim 4\text{x}10^6$ erg/cm$^3$
$M_s = 650$ emu/cm$^3$

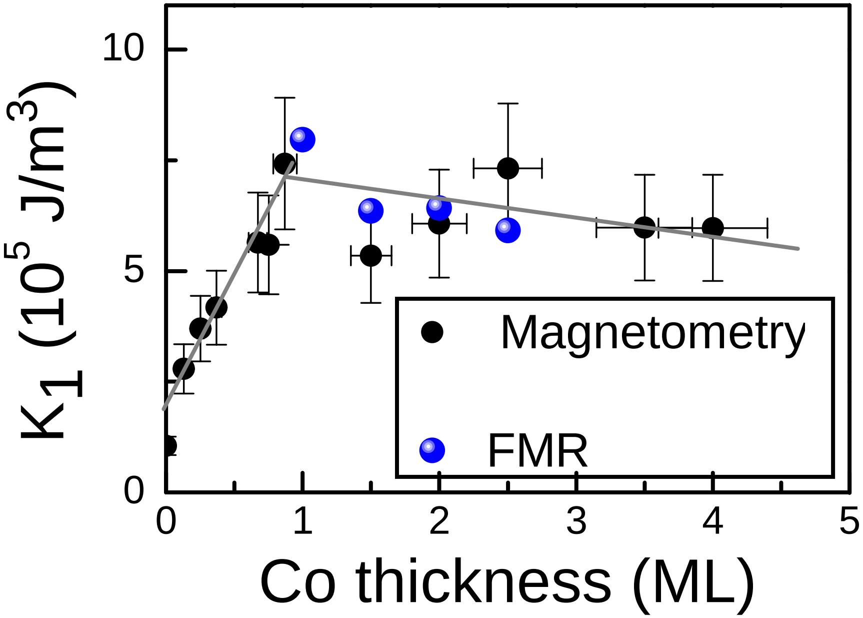
(daalderop et al, Phys. Rev. Lett **68** (1992))

$H_{C1} = 0.7$ kOe
$H_{C2} = 2.7$ kOe

# Co/Ni multilayers

MBE grown (111) - Co(X)/Ni(3 ML)



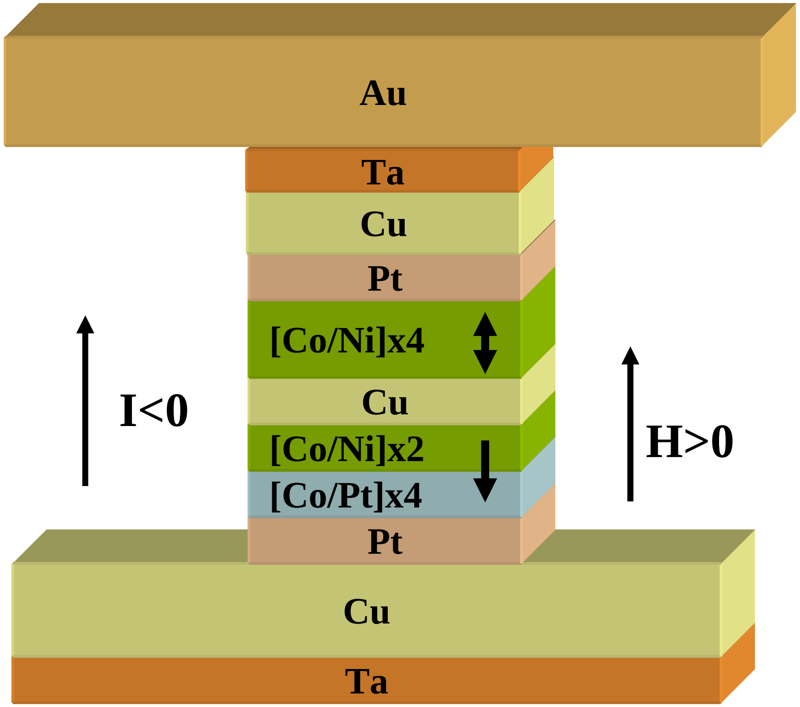


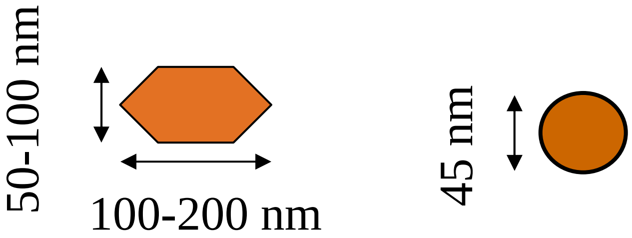
S. Girod *et al.* , Appl. Phys. Lett. **94,** 262504 (2009)

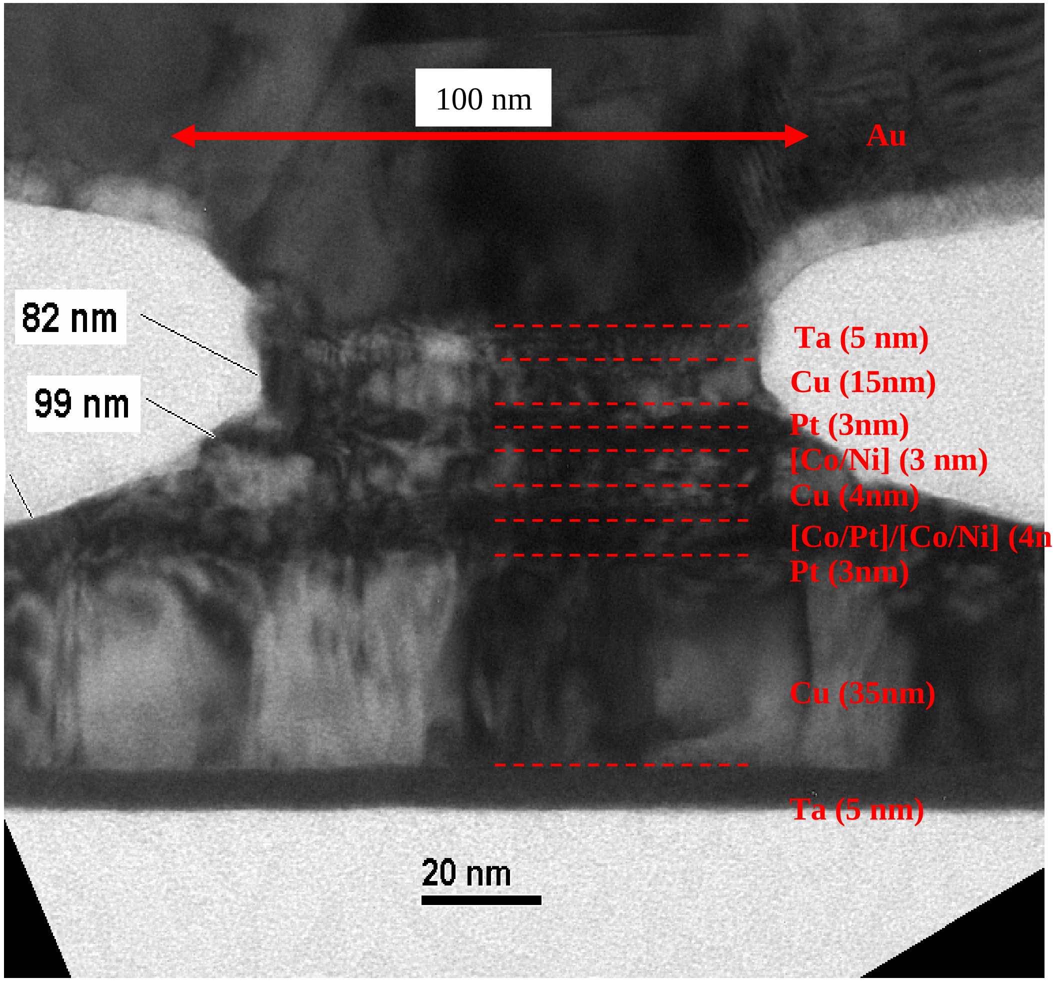
# *Nanopillars fabrication*

- Use of negative HSQ resist as a high fidelity mask

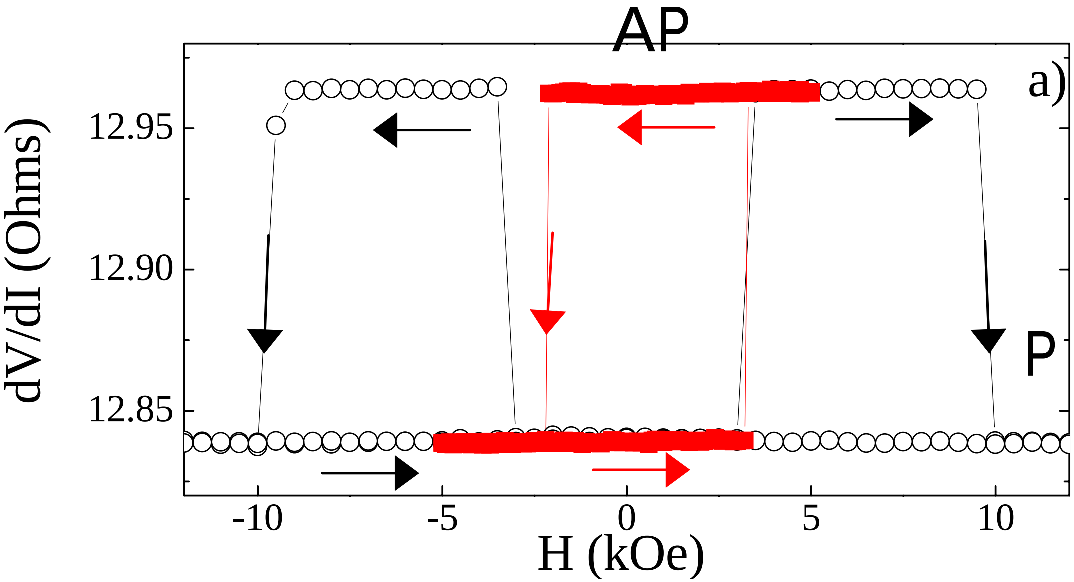
-~1000 devices/5 inch wafer: circles and hexagons from 45nm to 1500nm





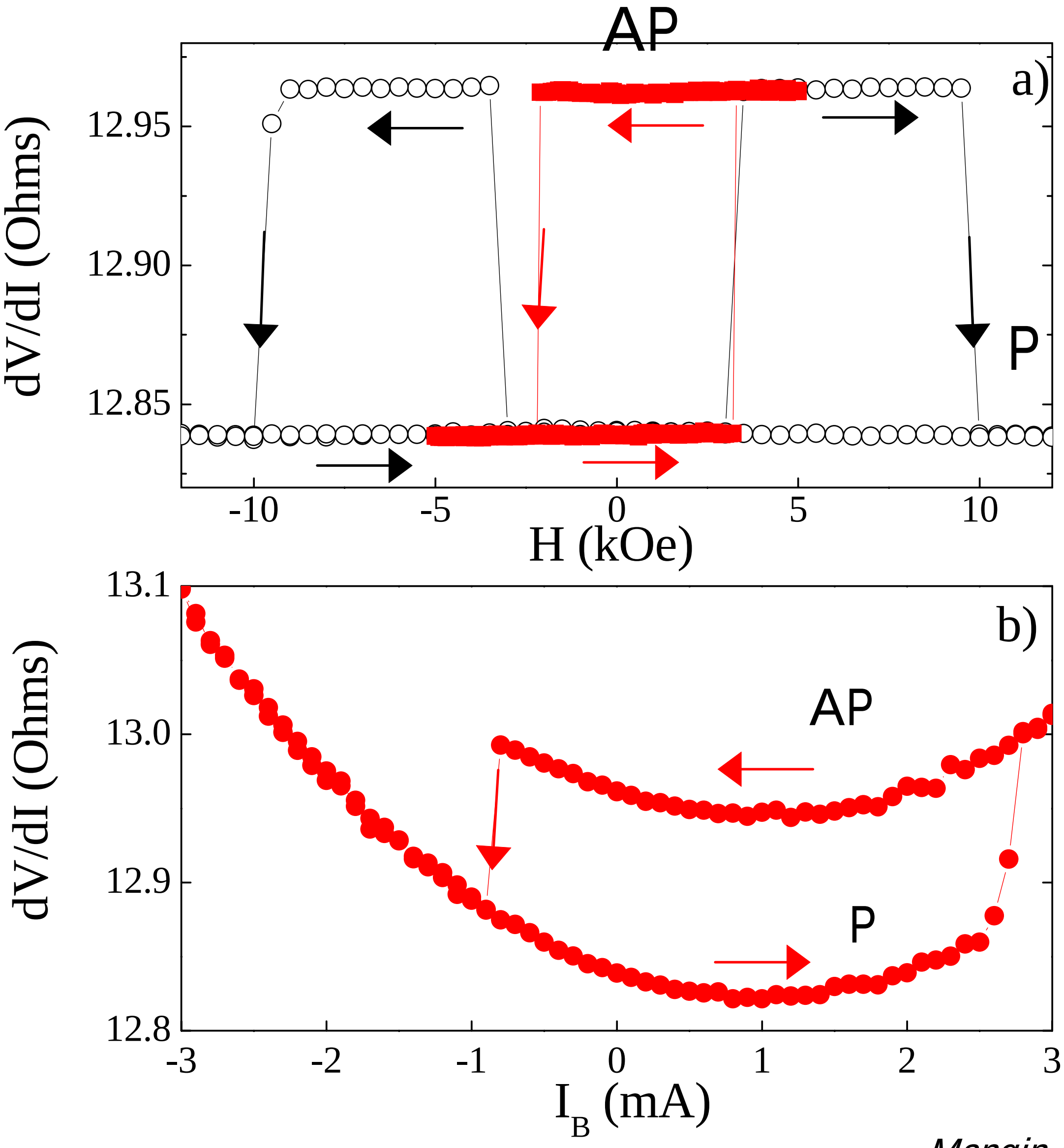


# *Field switching in 50x100nm$^2$ nanopillars*



$Hc_{free}$= 2.65 kOe
$Hc_{ref}$= 10 kOe
$H_d$= 650 Oe

# *Current induced switching in $50x100nm^2$ nanopillars*



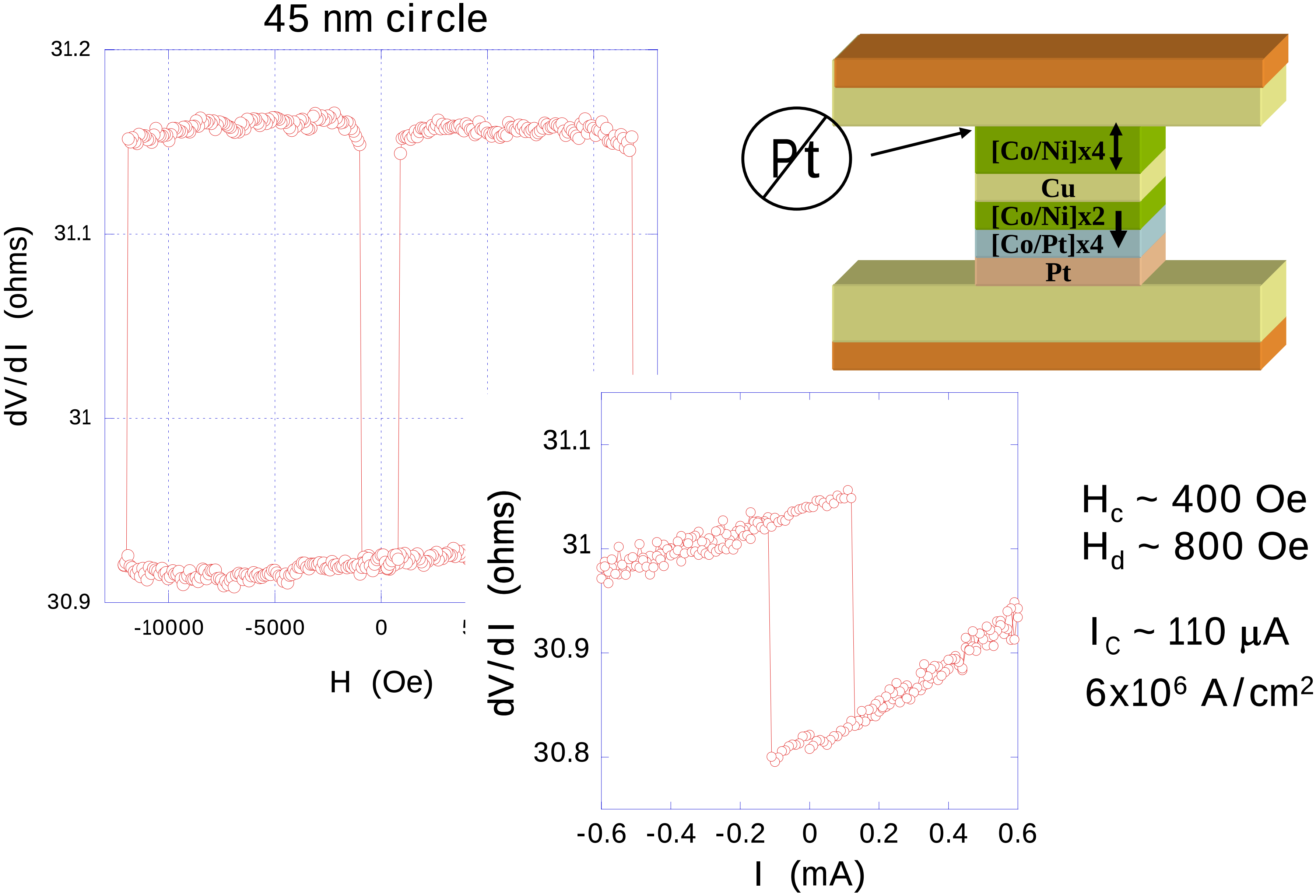
$Hc_{free}$= 2.65 kOe
$Hc_{ref}$= 10 kOe
$H_d$= 650 Oe

$I_C^{AP-P}$= -2.6x$10^7$ A/cm$^2$
$I_C^{P-AP}$ = 7x$10^7$ A/cm$^2$

$I_c$(Co/Pt)~4x$I_c$(Co/Ni)

*Mangin et al., Nature Materials **5**, 210 (2006)*
*Ravelosona et al., Phys. Rev. Lett. **96**, 186604 (2006)*

# Lower anisotropy free layer



$H_c$ ~ 400 Oe

$H_d$ ~ 800 Oe

$I_C$ ~ 110 μA

$6x10^6$ A/cm$^2$

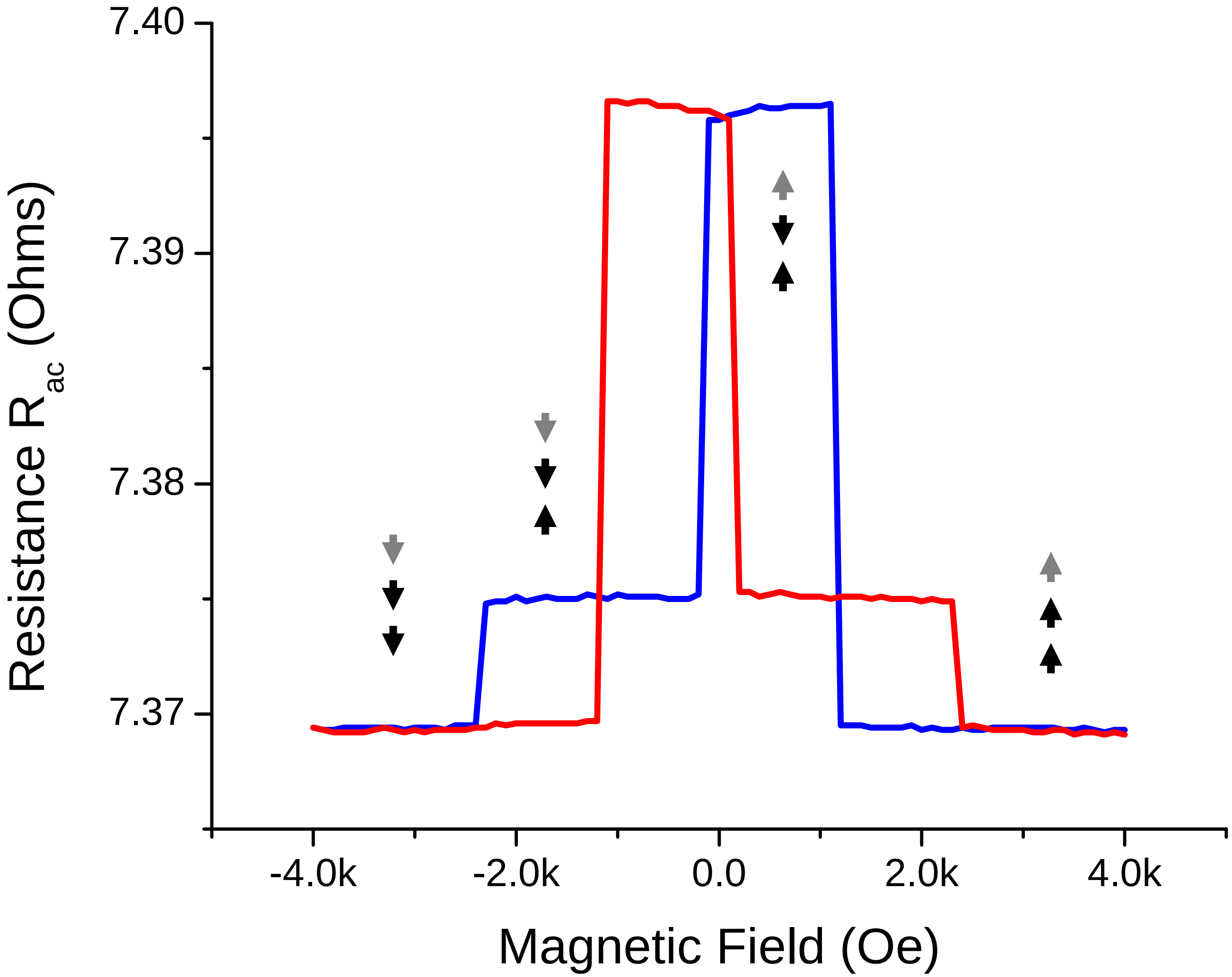
# *Critical currents*

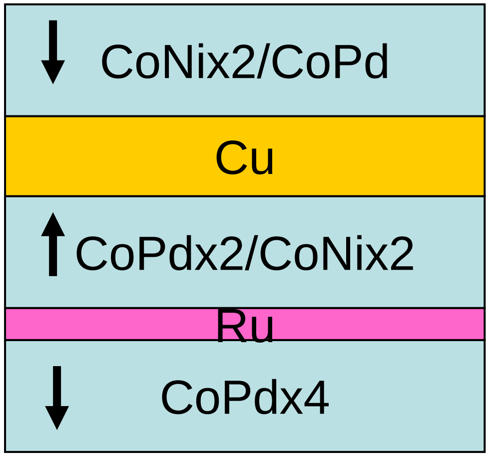
$$I_C \approx \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}U_K$$

| | **sample 1** | **sample 2** | **ratio** |
|---|---|---|---|
| **$I_C$ (mA)** | 1450 | 110 | 13 |
| **V ($10^{-18}$ cm$^3$)** | 11.25 | 5.8 | 2 |
| **$H_C$ (Oe)** | 2650 | 420 | 6.5 |

*Mangin et al., Appl. Phys. Lett.* ***94****, 012502 (2009)*

# *AF-coupled pinned layer*




CoNix2/CoPd

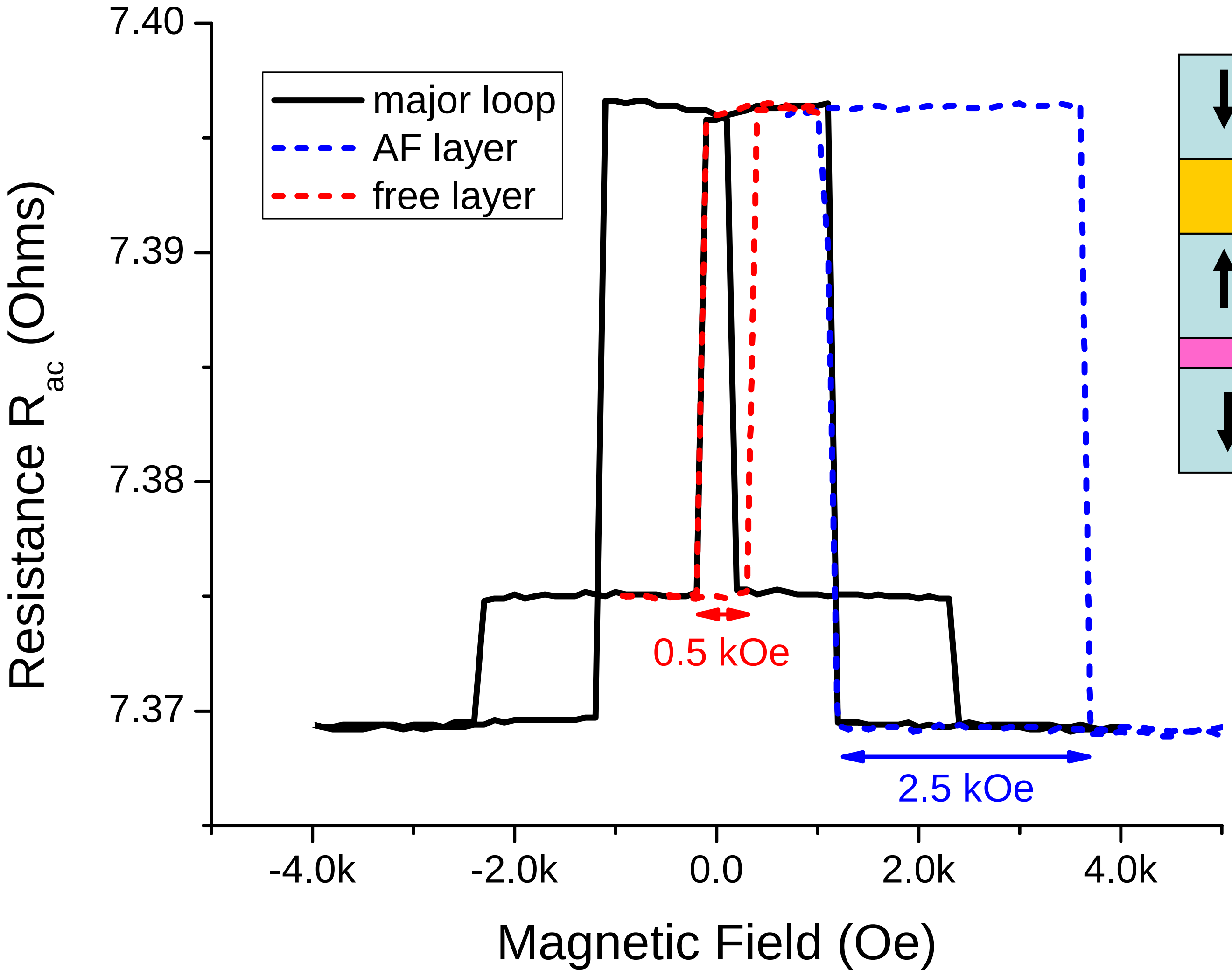
Cu

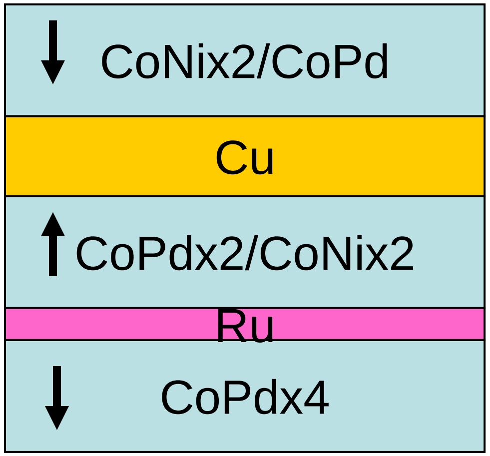
CoPdx2/CoNix2

Ru

CoPdx4

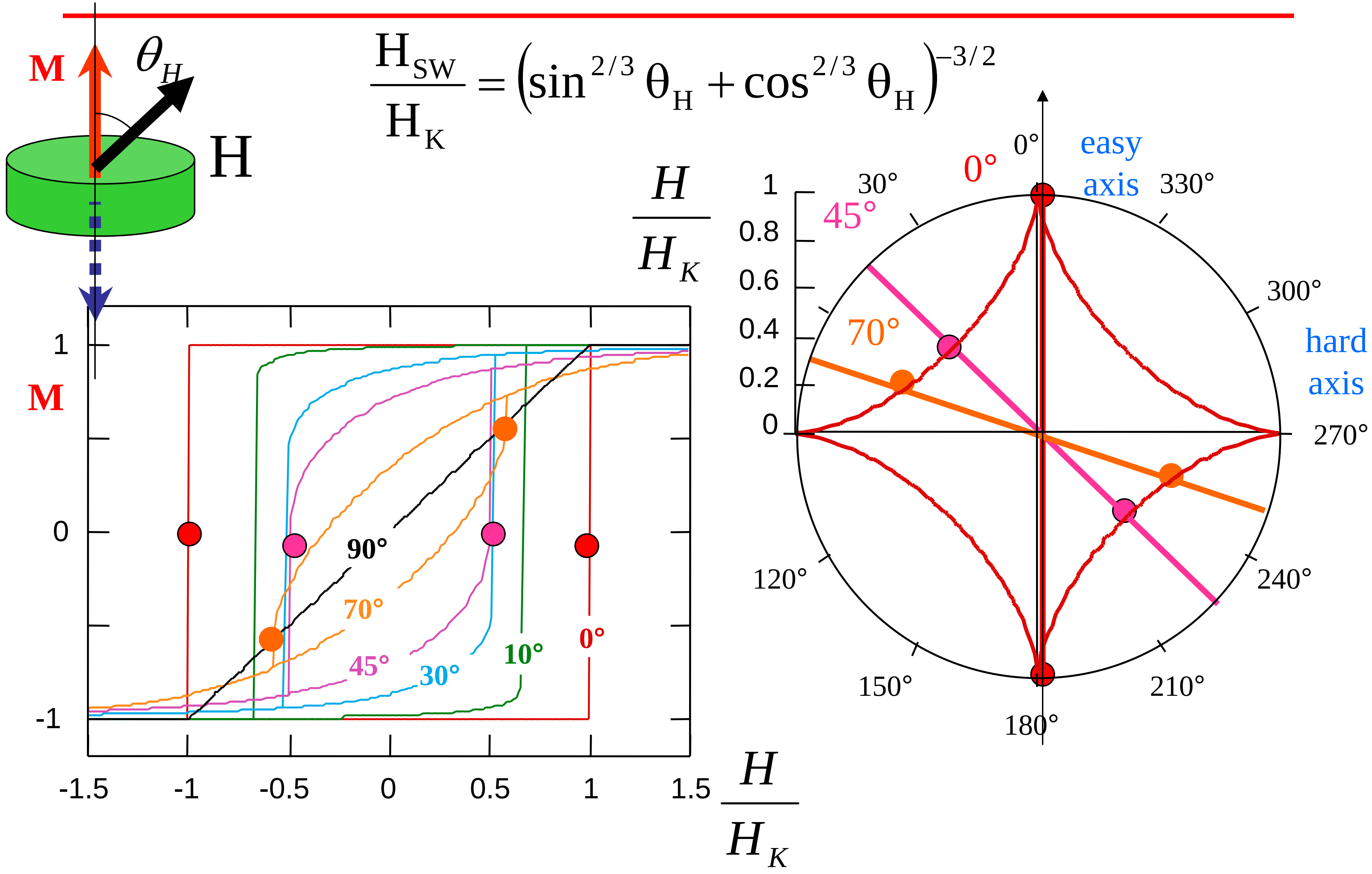
# *AF-coupled pinned layer*



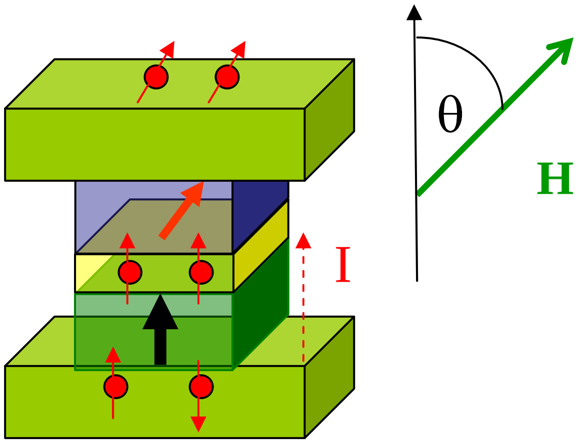


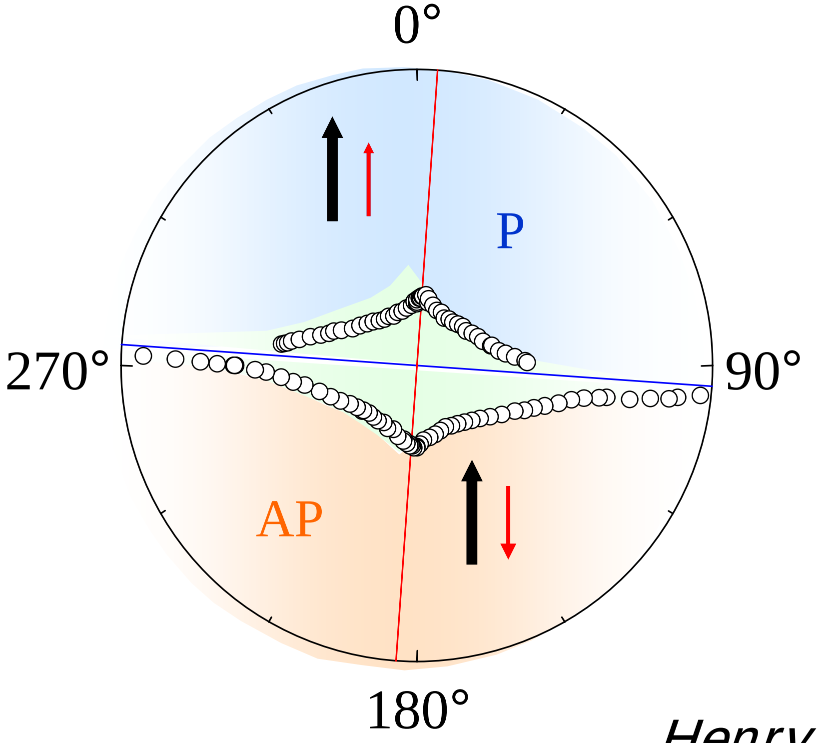
# Stoner-Wohlfarth astroid

$$\frac{H_{SW}}{H_K} = \left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{-3/2}$$

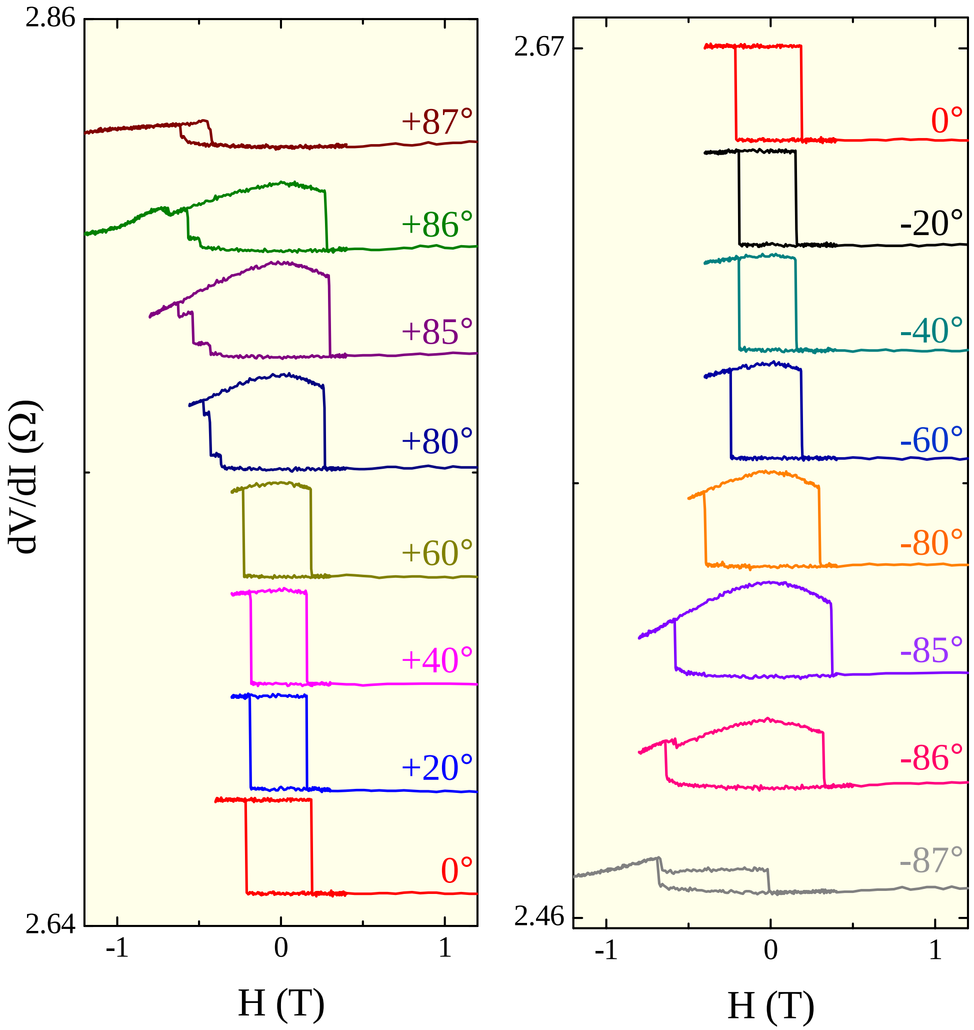


# *Angle-dependent field switching*



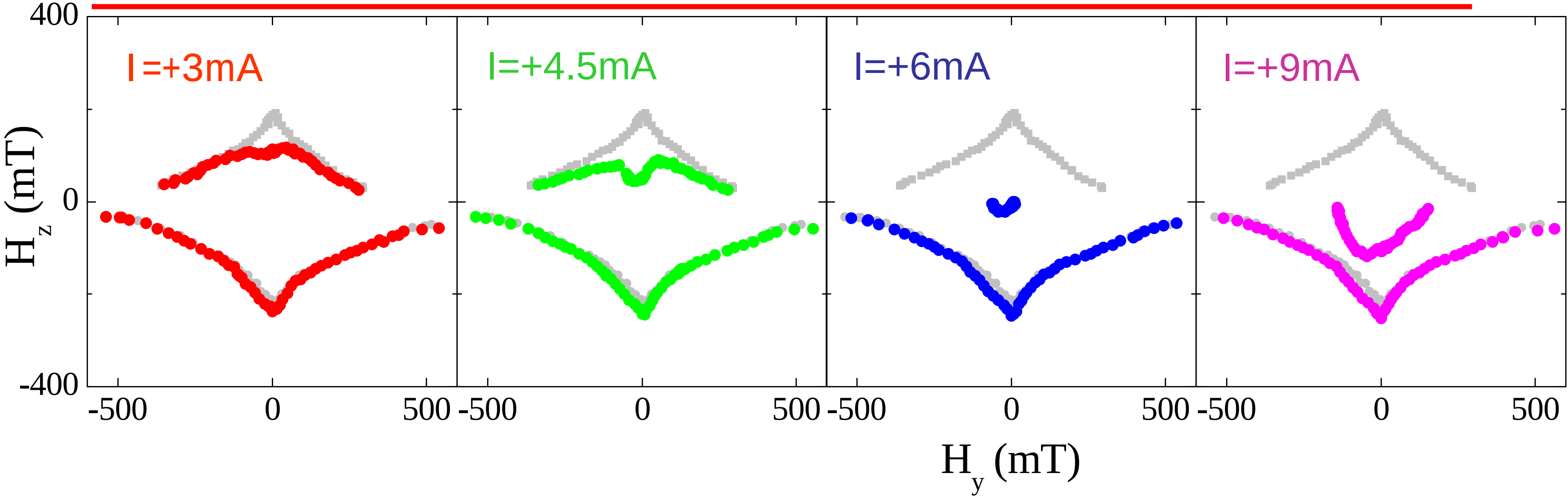


*100x200nm²*



*Henry et al.*, Phys. Rev. B, **79**, 214422 (2009).

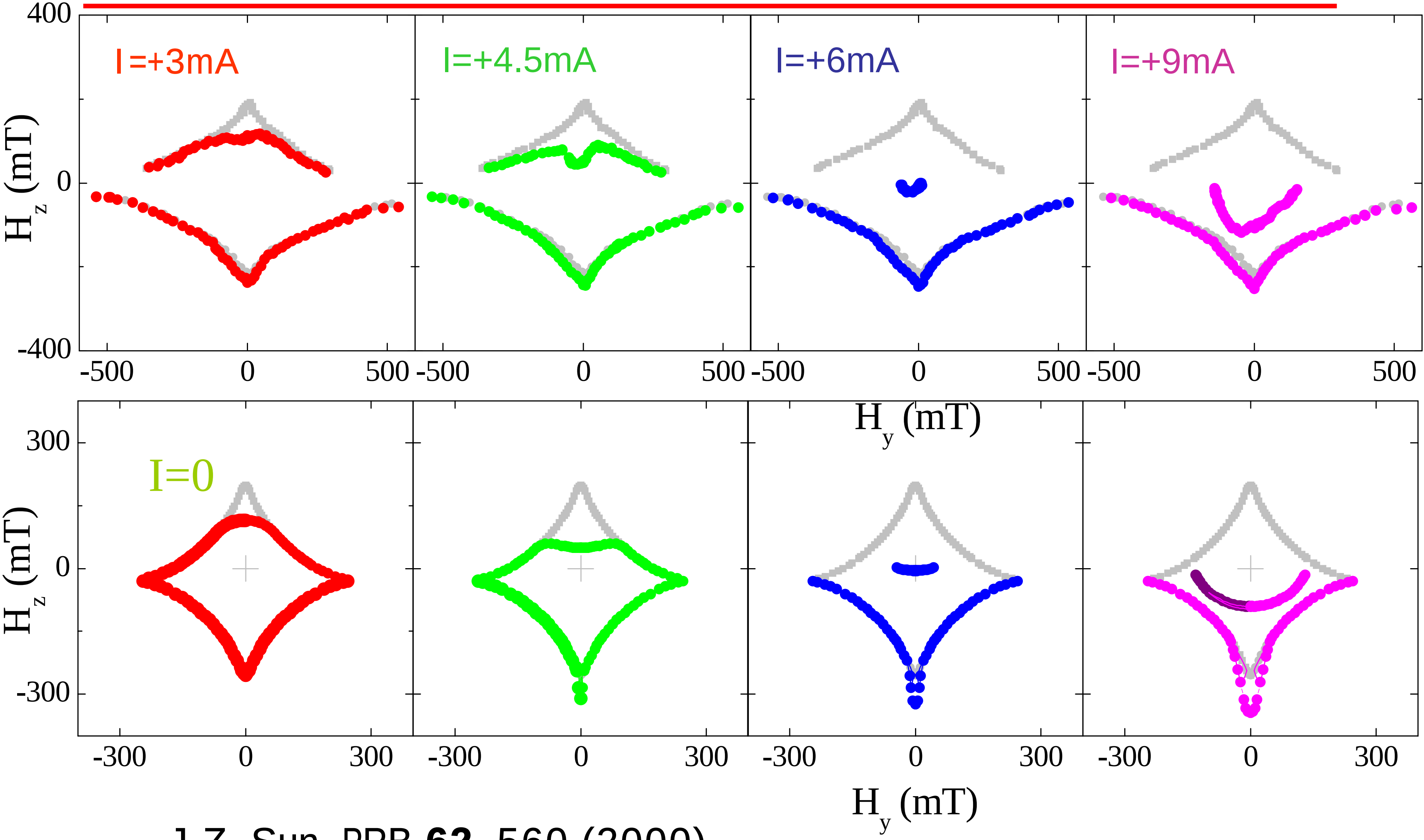
# Comparison theory-experiment



**Field torque** **Damping torque** **Spin torque**

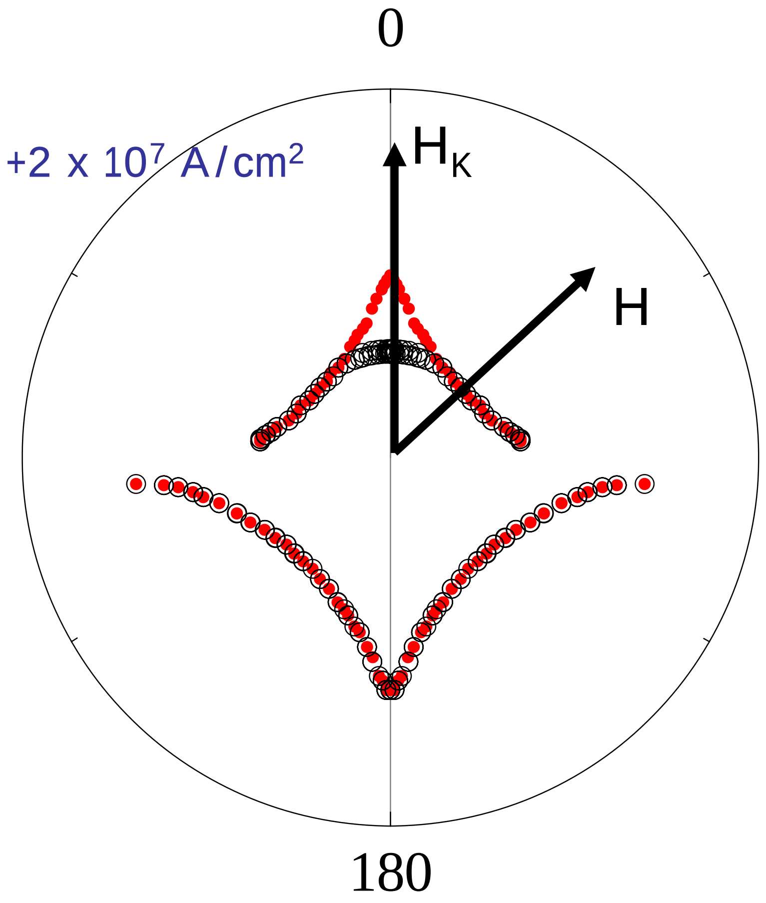
$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m}\times\mathbf{H}_{eff} + \alpha\left(\mathbf{m}\times\mathbf{m}\times\mathbf{H}_{eff}\right) + \beta\,\mathbf{I}\left(\mathbf{m}\times\mathbf{m}\times\mathbf{u}_z\right)$$

# Comparison theory-experiment



J.Z. Sun, PRB **62**, 560 (2000).

# Angular dependence of the spin torque



Current has large effect H // $H_K$

Threshold current for H ∠ $H_K$

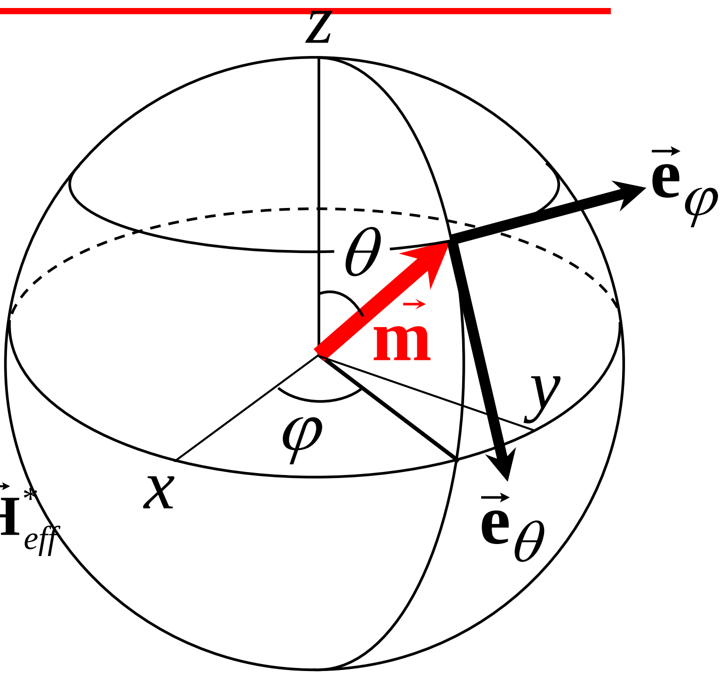
$$I_{onset} \propto \alpha \left| H_{eff} \right|$$

on the SW astroid

$$|H_{eff}| = H_K \sin^2(\theta_M)$$

Y. Henry et al., Phys. Rev. B, **79**, 214422 (2009).

# Analytic solution



$$\frac{\partial \vec{\mathbf{m}}}{\partial t} = -\gamma(\vec{\mathbf{m}}\times\vec{\mathbf{H}}^*_{eff}) + \alpha\left(\vec{\mathbf{m}}\times\frac{\partial\vec{\mathbf{m}}}{\partial t}\right)$$

where $\vec{\mathbf{H}}^*_{\mathrm{eff}} = \vec{\mathbf{H}}_{\mathrm{eff}} + \frac{\beta}{\gamma} I(\vec{\mathbf{m}}\times\vec{\mathbf{z}})$

Equilibrium conditions: magnetization $\vec{\mathbf{m}}$ parallel to $\vec{\mathbf{H}}^*_{eff}$

Stability condition: total "*damping*" positive

Linear stability analysis **<u>in the small current limit</u>** (2D problem)

$$\boxed{\frac{\partial}{\partial\theta}\left[\alpha\gamma(\vec{\mathbf{H}}_{\mathrm{eff}}\cdot\vec{\mathbf{e}}_\theta) - \beta I \sin\theta\right]\Bigg|_{\theta=\theta_0} \le 0}$$

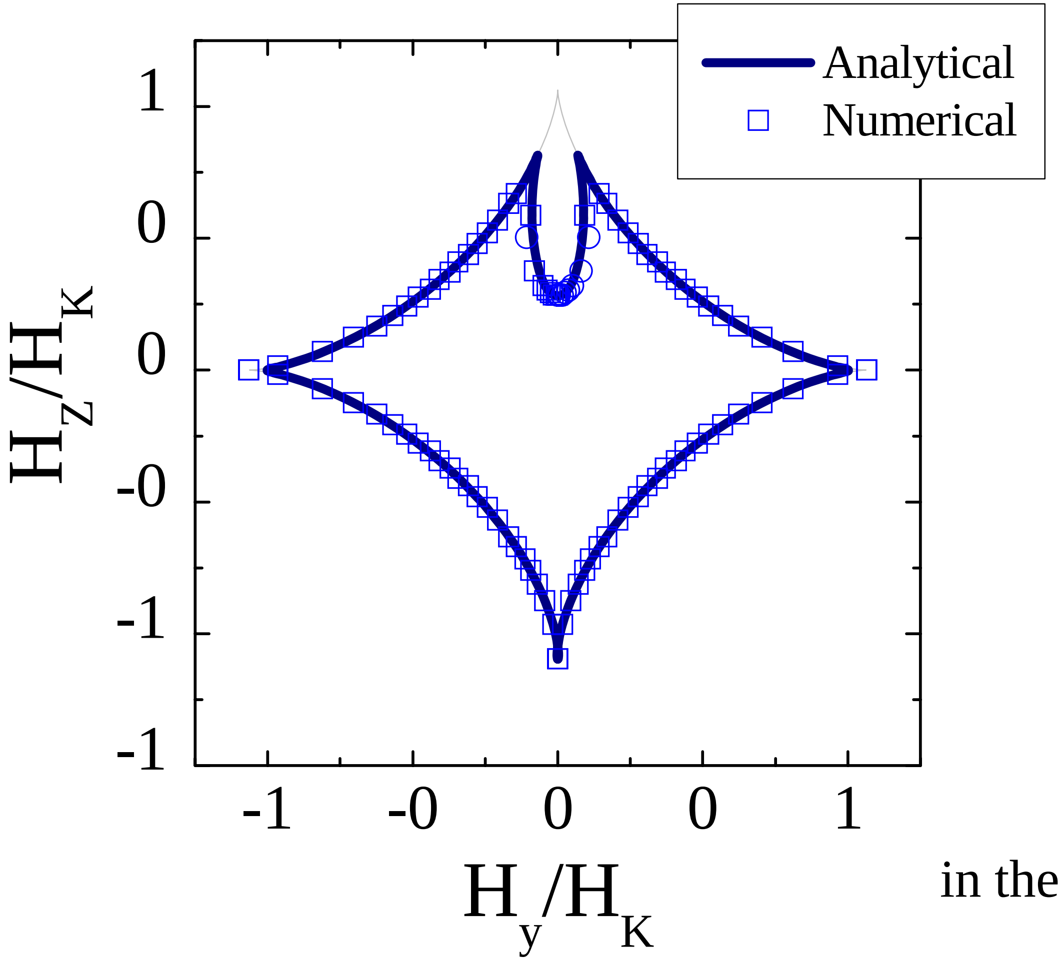
*N. Smith et al, IEEE Trans Mag.* ***41****,2935 (2005)*

Y. Henry et al., Phys. Rev. B, **79**, 214422 (2009).

# Analytic expression for the astroid

$$\begin{cases} h_y = \ \ \sin\theta_0[\sin^2\theta_0 - C(\theta_0)] \\ h_z = -\cos\theta_0[\cos^2\theta_0 + C(\theta_0)] \end{cases}$$

with $C(\theta_0) = \frac{1}{\alpha\gamma H_K} \left.\frac{\partial(\beta I \sin\theta)}{\partial\theta}\right|_{\theta=\theta_0}$



in the small current limit

# Conclusions

➔ ***Demonstration of efficient spin transfer in Nano-pillars with perpendicular anisotropy***

***$I_c$ scales with thermal stability***

***(Co/Ni multilayers: higher p and lower $\alpha$ compared to Co/Pt)***

➔ ***Role of current on the SW astroid.***

*Mangin et al., Nature Materials* ***5****, 210 (2006)*
*Ravelosona et al., Phys. Rev. Lett.* ***96****, 186604 (2006)*
*Mangin et al., Appl. Phys. Lett.* ***94****, 012502 (2009)*
*Cucchiara et al., Appl. Phys. Lett.* ***94****, 102503 (2009)*
*Henry et al*., Phys. Rev. B, **79**, 214422 (2009).
*S. Girod, et al*, Appl. Phys. Lett. **94**, 262504 (2009).