Chapter 5

Spin Transfer Torque

韩伟

量子材料科学中心

2015年11月8日

Review of last class

1. Semiconductor Spin Valves

When spintronics meets semiconductor

GaAs

Silicon and Germanium

Complex oxides

Spin FET

Review of last class

2. Spin valves based on Quantum materials

石墨烯	➢ 弱自旋-轨道耦合→ 长自旋寿命
二硫化钼等	➢ 自旋-谷
拓扑绝缘体	➢ 自旋流的拓扑保护

Outline

1. Spin transfer torque

2. Spin orbit torque and spin Hall effect

3. Spin orbit torque and Rashba-Edelstein effect

This Class

1. Spin transfer torque

Outline

1. Theory and observation of spin transfer torque

2. Spin transfer torque and spin pumping

3. Spin transfer torque in MTJ

4. Spin transfer torque in domain wall motion

5. Thermal spin transfer torque

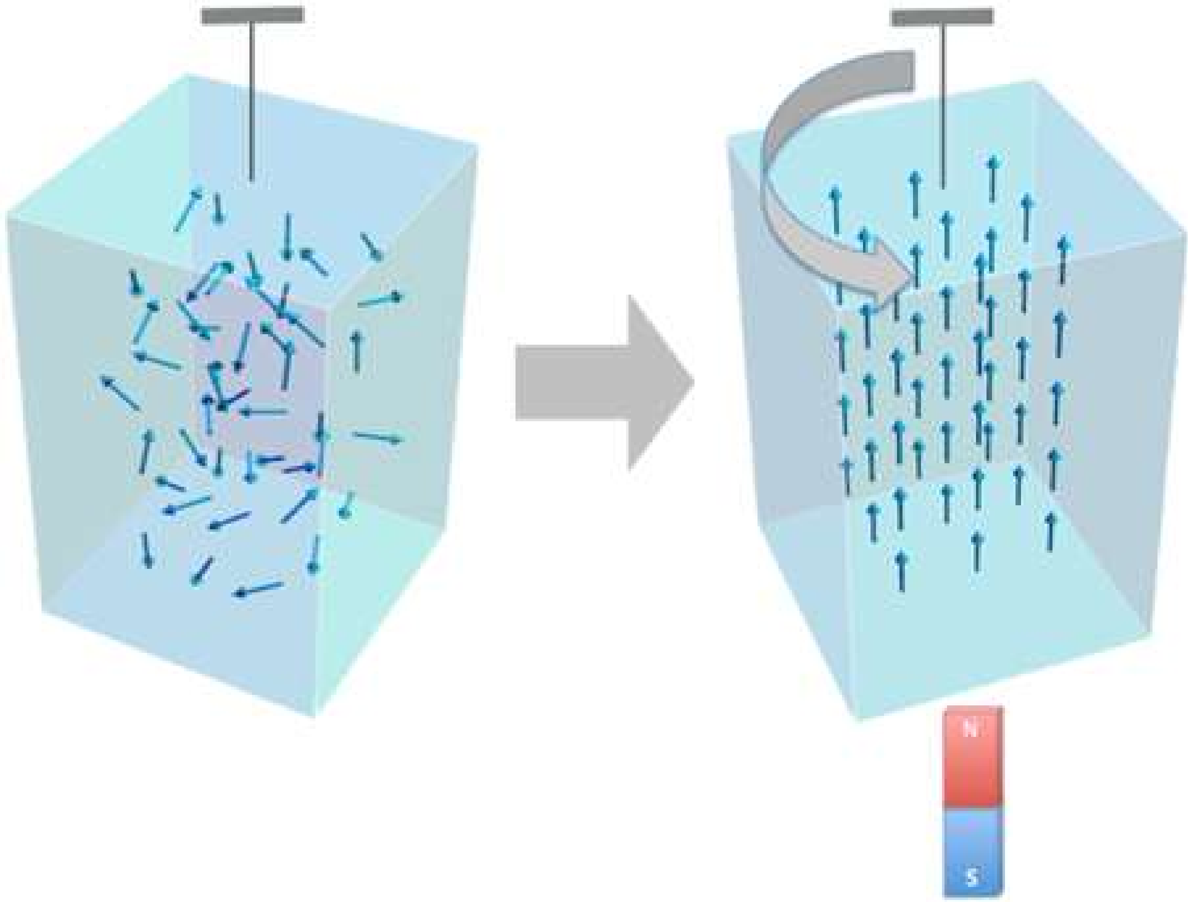
6. Pure spin current transfer torque

Outline

1. Theory and observation of spin transfer torque

Spin angular momentum

The Einstein–de Haas effect



Spin transfer torque

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2013 Oliver E. Buckley Condensed Matter Physics Prize Recipient

Citation:

"For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures."

Spin transfer torque

John Slonczewski

Luc Berger

Citation:

"For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures."

Spin transfer torque

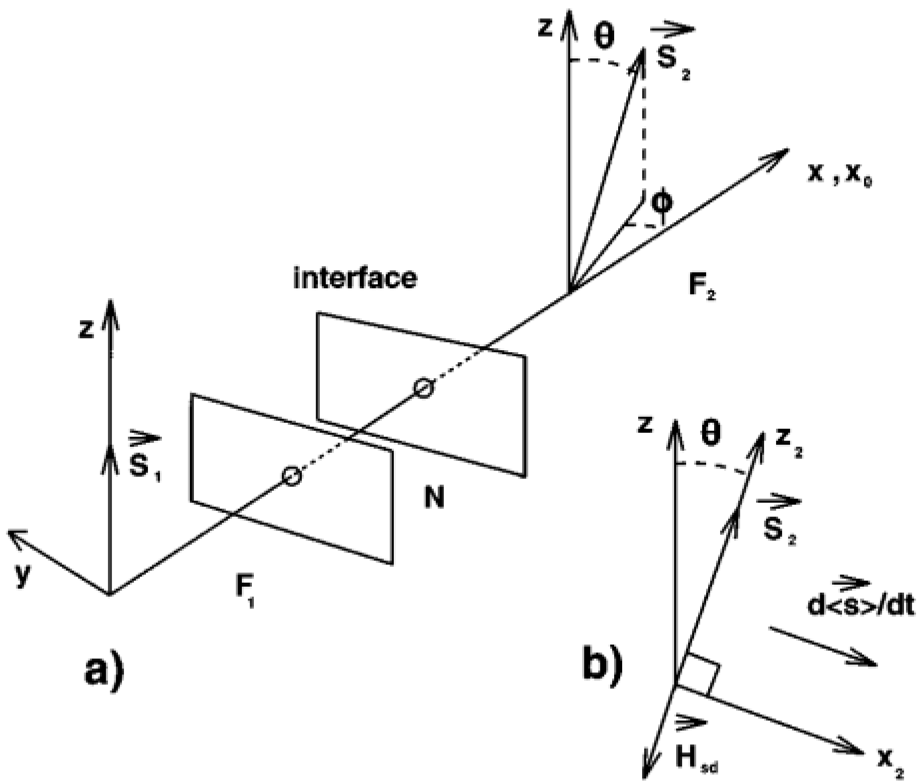
PHYSICAL REVIEW B VOLUME 54, NUMBER 13 1 OCTOBER 1996-I

Emission of spin waves by a magnetic multilayer traversed by a current

L. Berger
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213-3890
(Received 31 January 1996)

The interaction between spin waves and itinerant electrons is considerably enhanced in the vicinity of an interface between normal and ferromagnetic layers in metallic thin films. This leads to a local increase of the Gilbert damping parameter which characterizes spin dynamics. When a dc current crosses this interface, stimulated emission of spin waves is predicted to take place. Beyond a certain critical current density, the spin damping becomes negative; a spontaneous precession of the magnetization is predicted to arise. This is the magnetic analog of the injection laser. An extra dc voltage appears across the interface, given by an expression similar to that for the Josephson voltage across a superconducting junction. [S0163-1829(96)00237-8]

Spin transfer torque



Spin transfer torque

Journal of Magnetism and Magnetic Materials 159 (1996) L1–L7

journal of magnetism and magnetic materials

Letter to the Editor

Current-driven excitation of magnetic multilayers

J.C. Slonczewski *

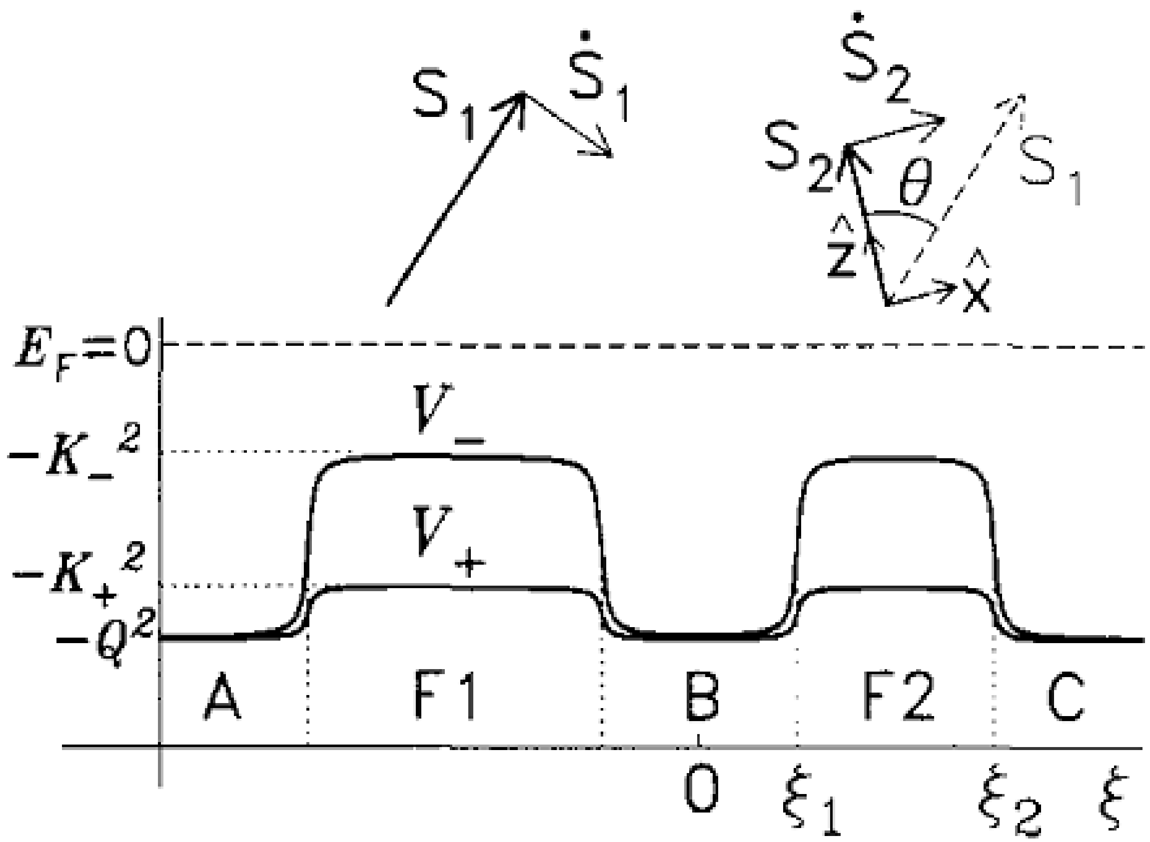
IBM Research Division, Thomas J. Watson Research Center, Box 216, Yorktown Heights, NY 10596, USA

Received 27 October 1995; revised 19 December 1995

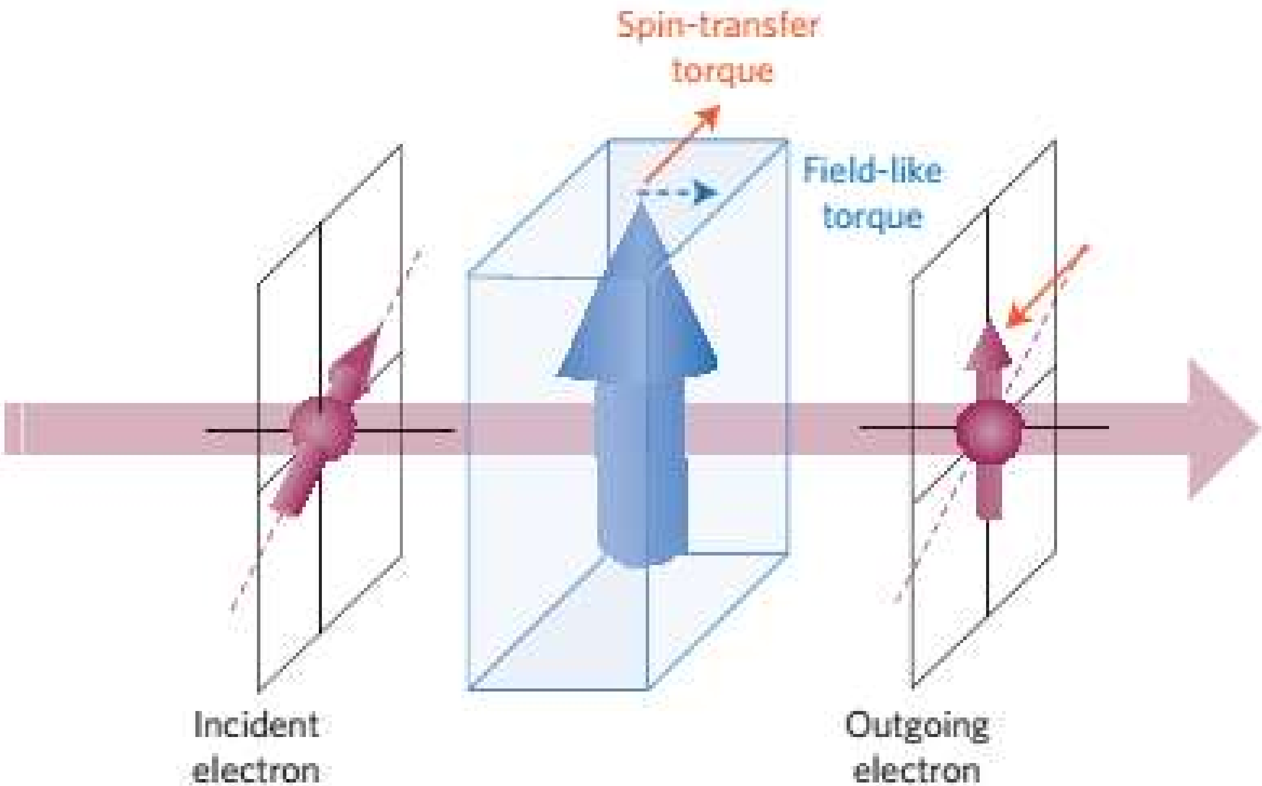
Abstract

A new mechanism is proposed for exciting the magnetic state of a ferromagnet. Assuming ballistic conditions and using WKB wave functions, we predict that a transfer of vectorial spin accompanies an electric current flowing perpendicular to two parallel magnetic films connected by a normal metallic spacer. This spin transfer drives motions of the two magnetization vectors within their instantaneously common plane. Consequent new mesoscopic precession and switching phenomena with potential applications are predicted.

Spin transfer torque

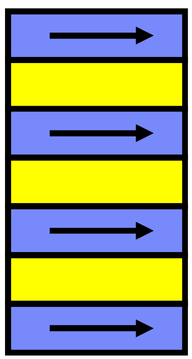


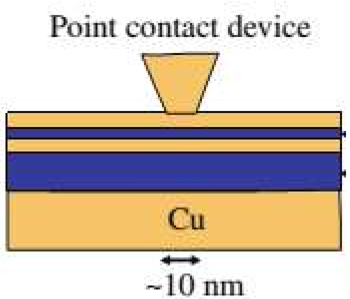
Spin transfer torque

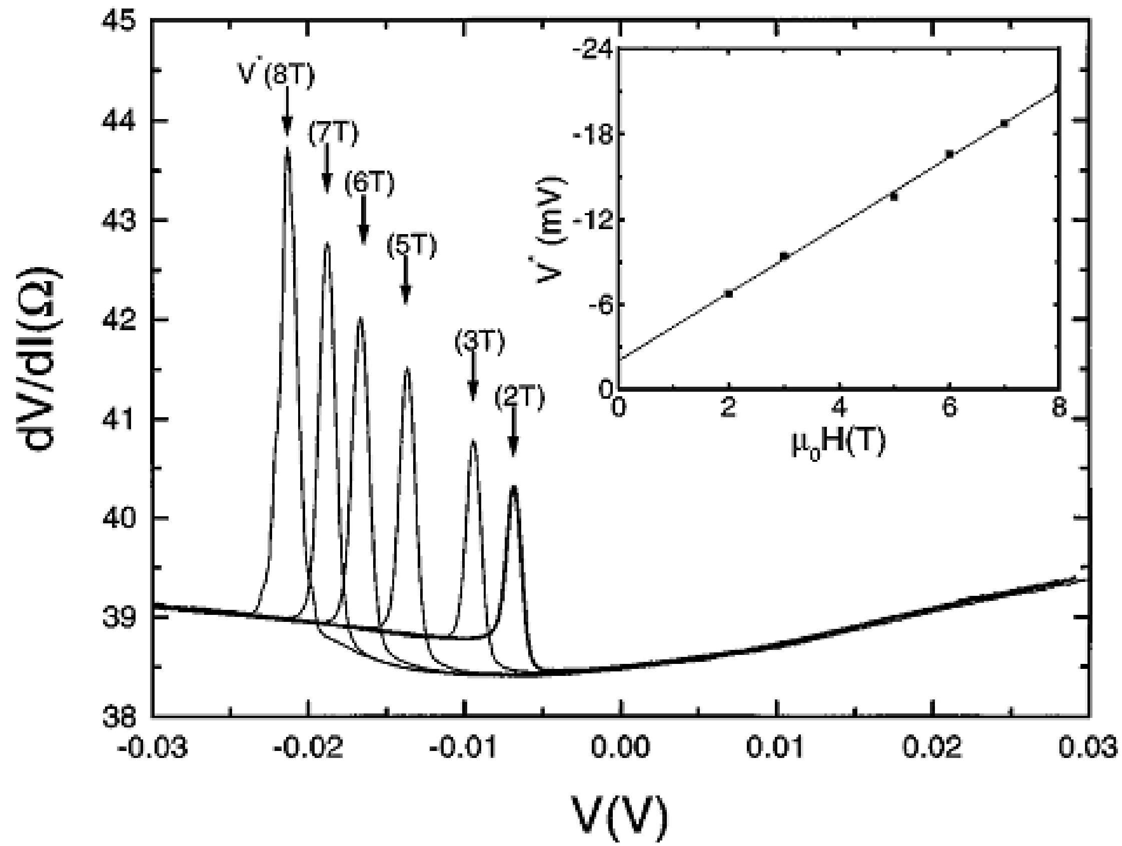


Experimental discovery of STT

$(Co/Cu)_N$
N= 20-50

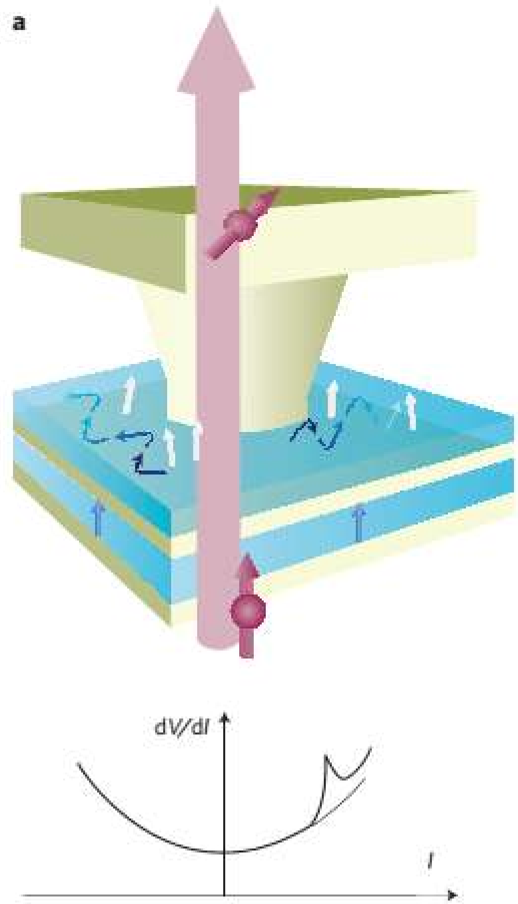


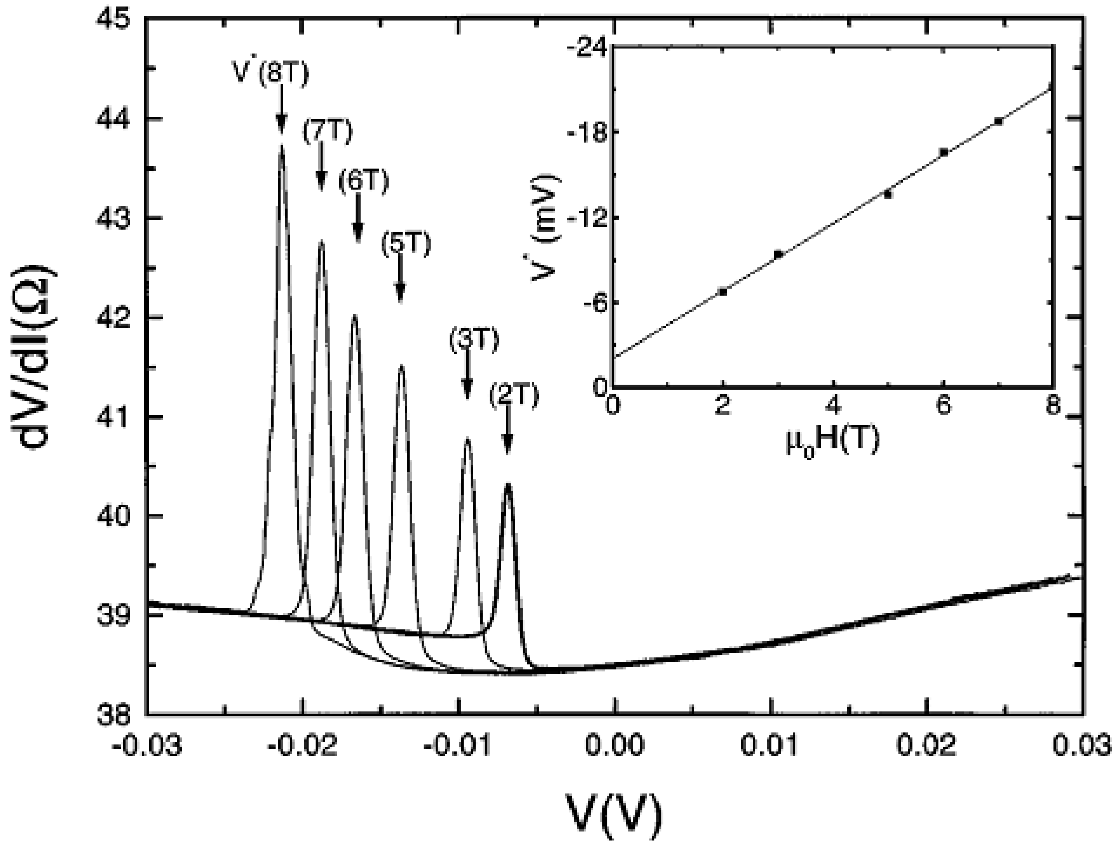




Tsoi, et al, PRL (1998)

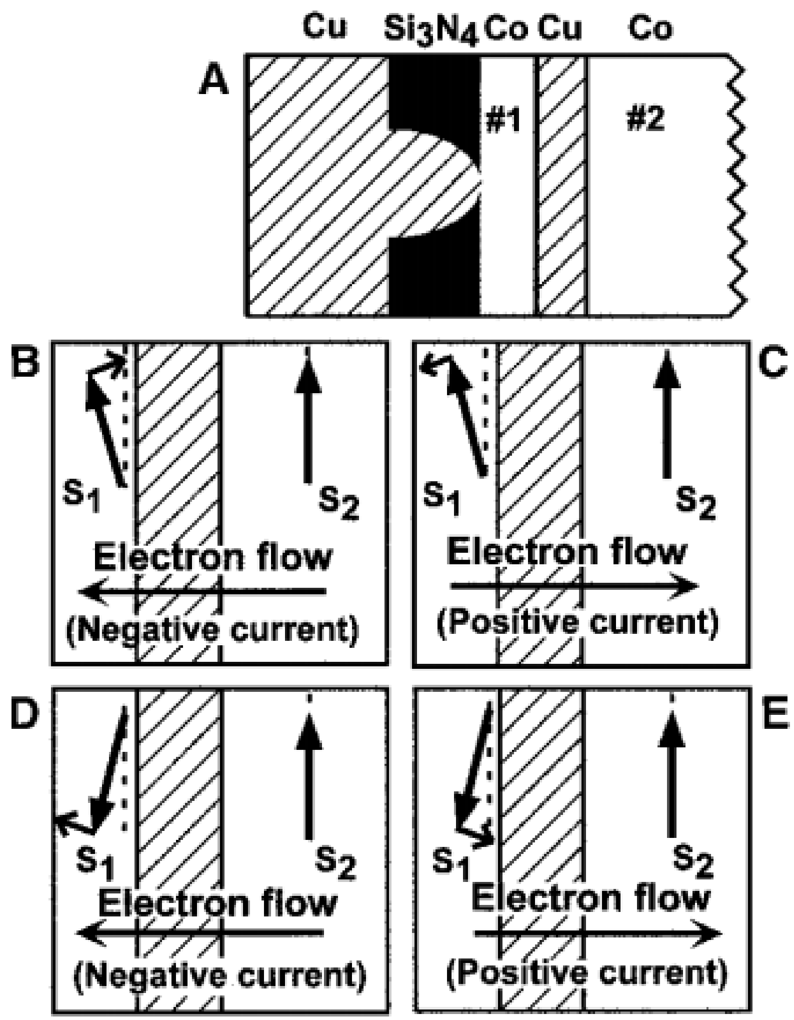
Experimental discovery of STT





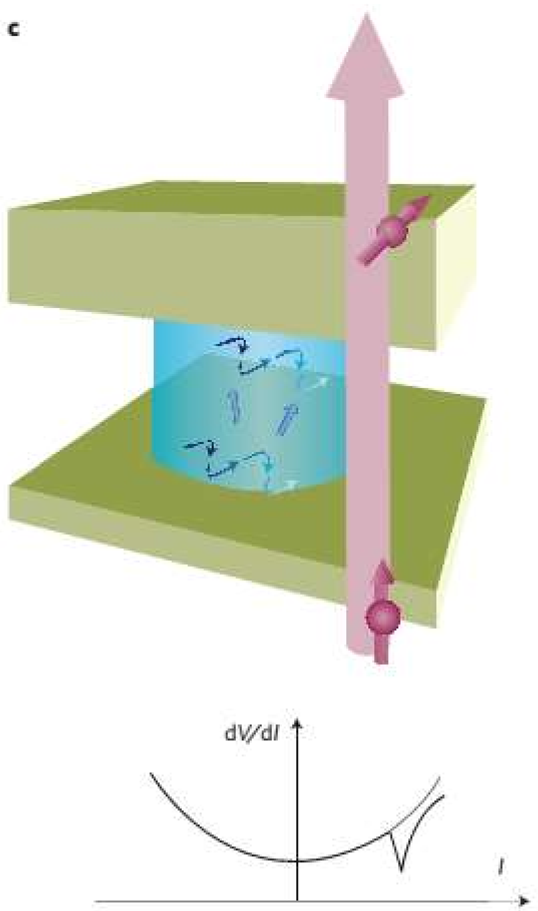
Tsoi, et al, PRL (1998)

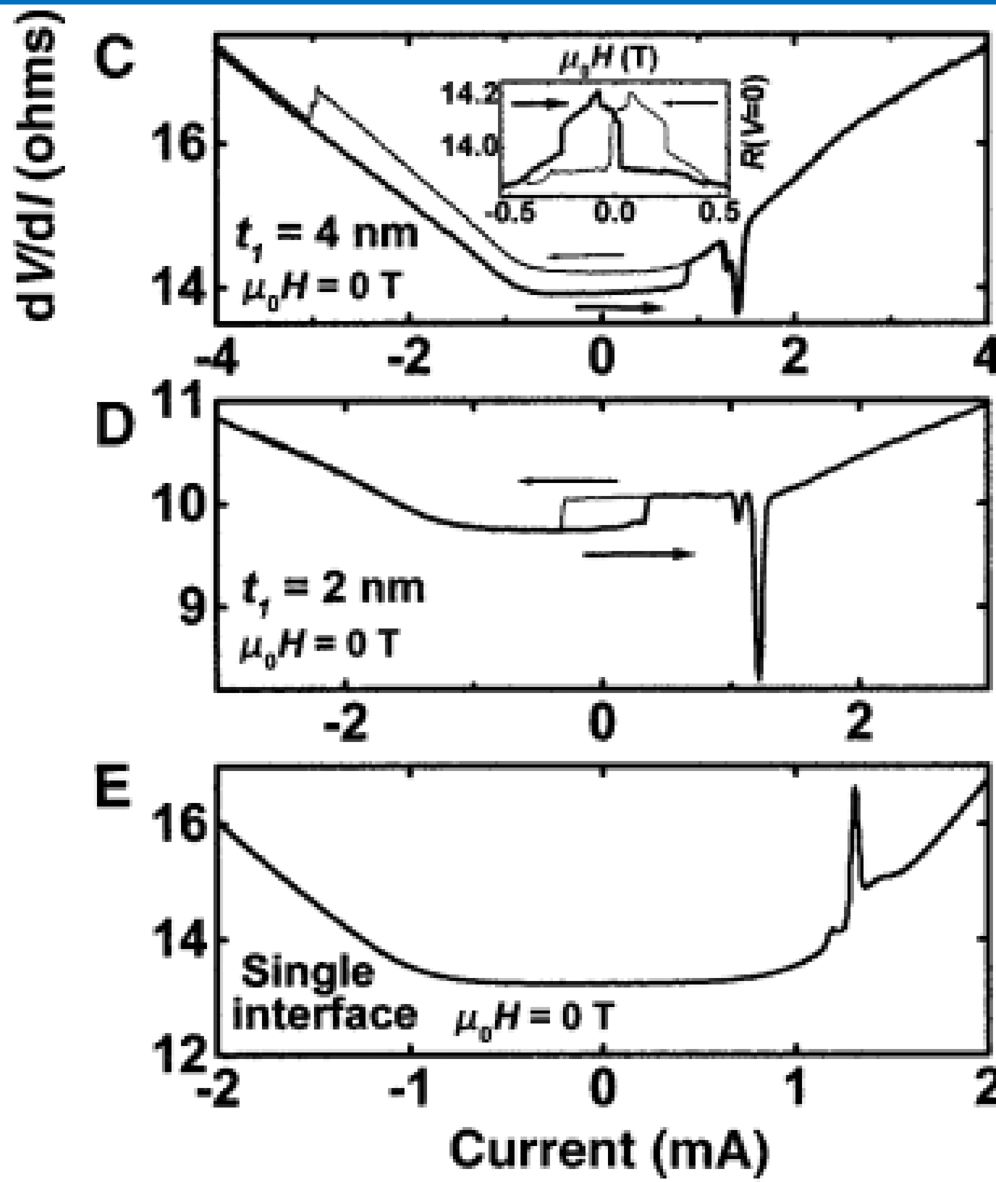
Experimental discovery of STT



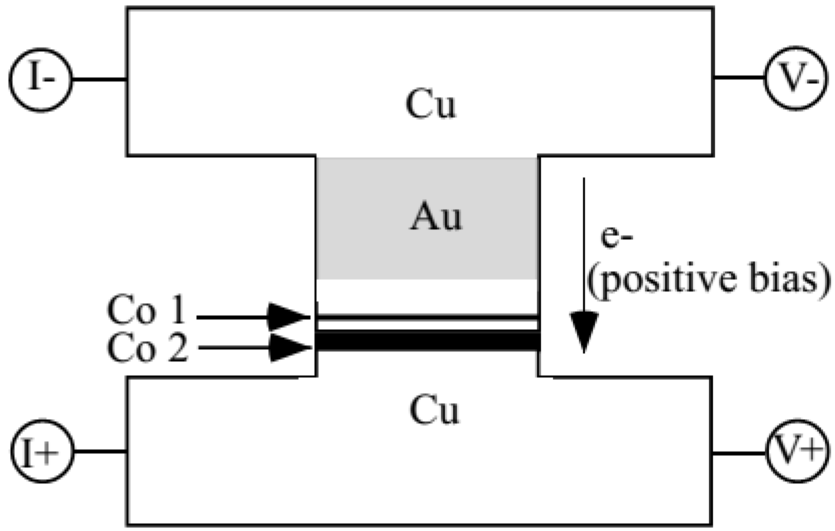
Myers, et al, Science (1999)

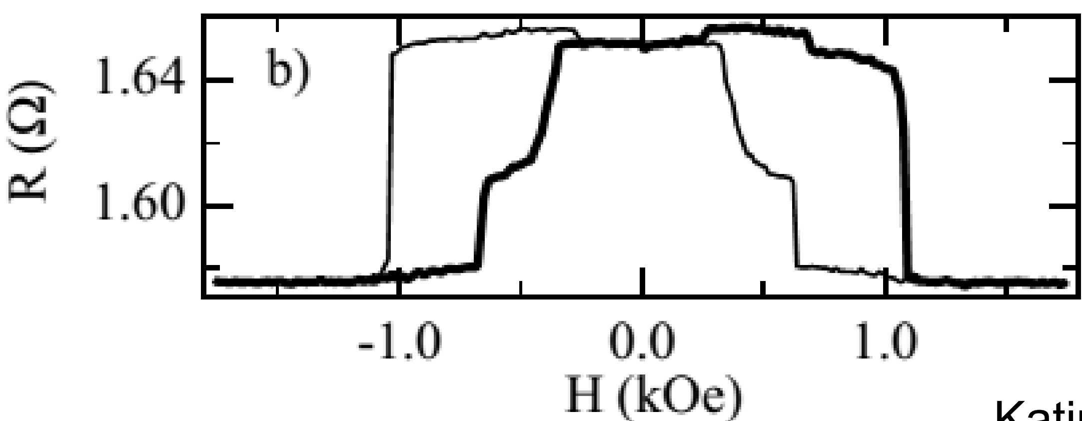
Experimental discovery of STT





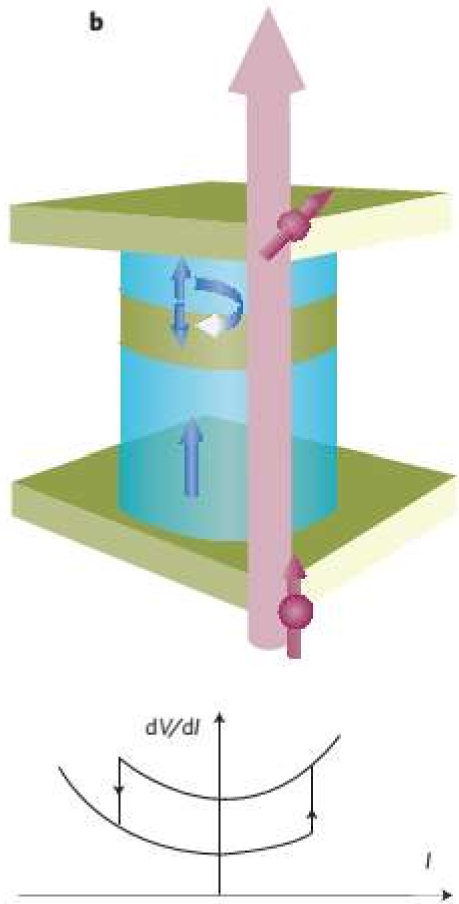
Experimental discovery of STT

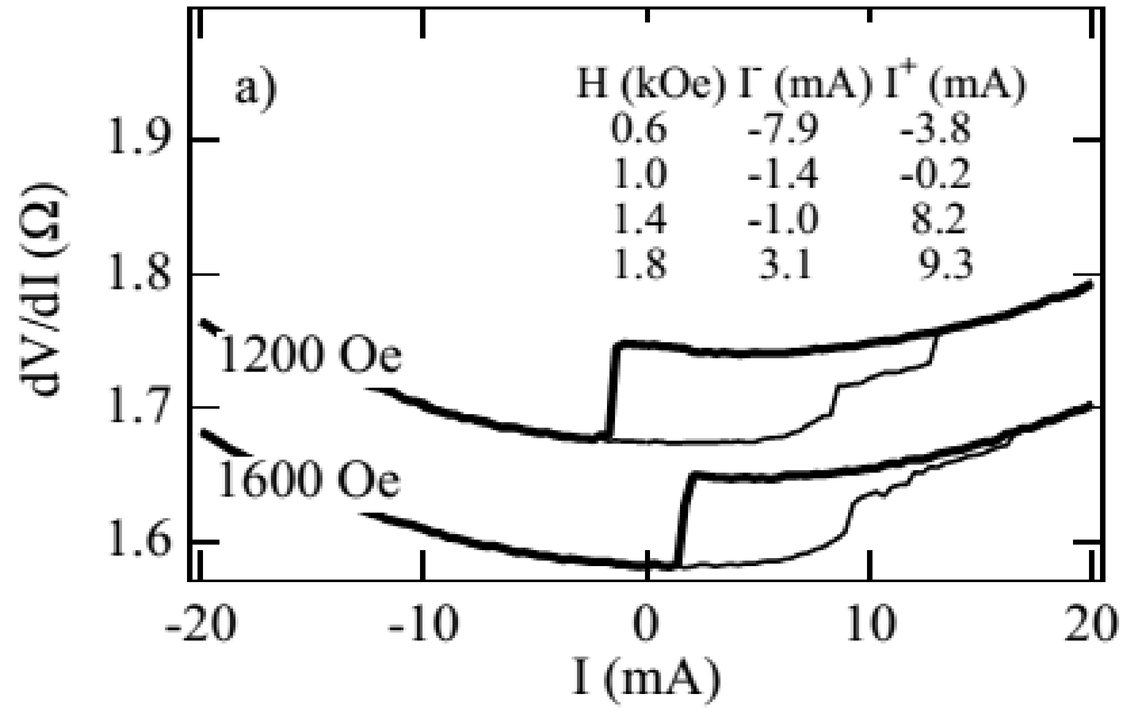




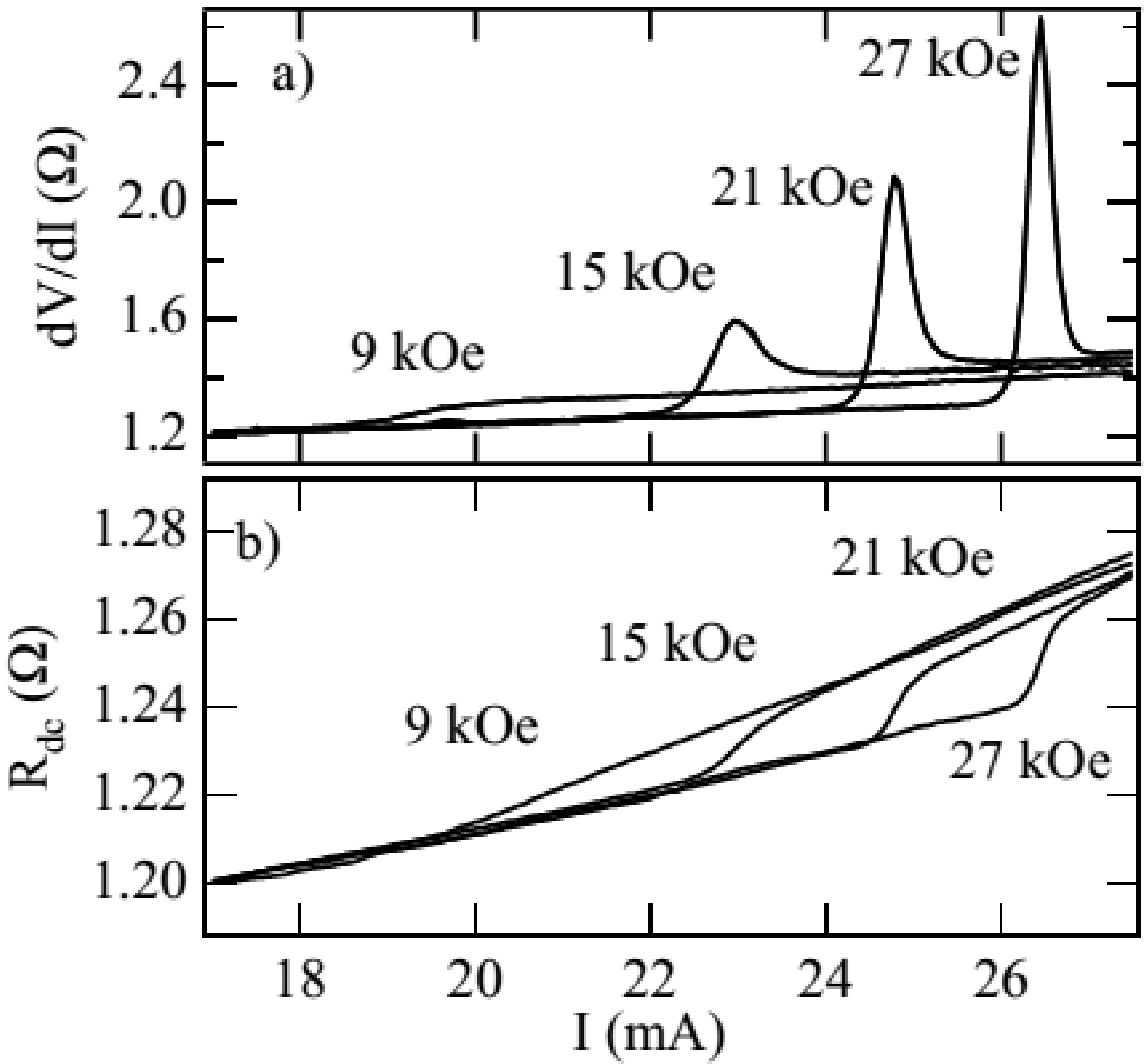
Katine, et al, PRL (2000)

Experimental discovery of STT

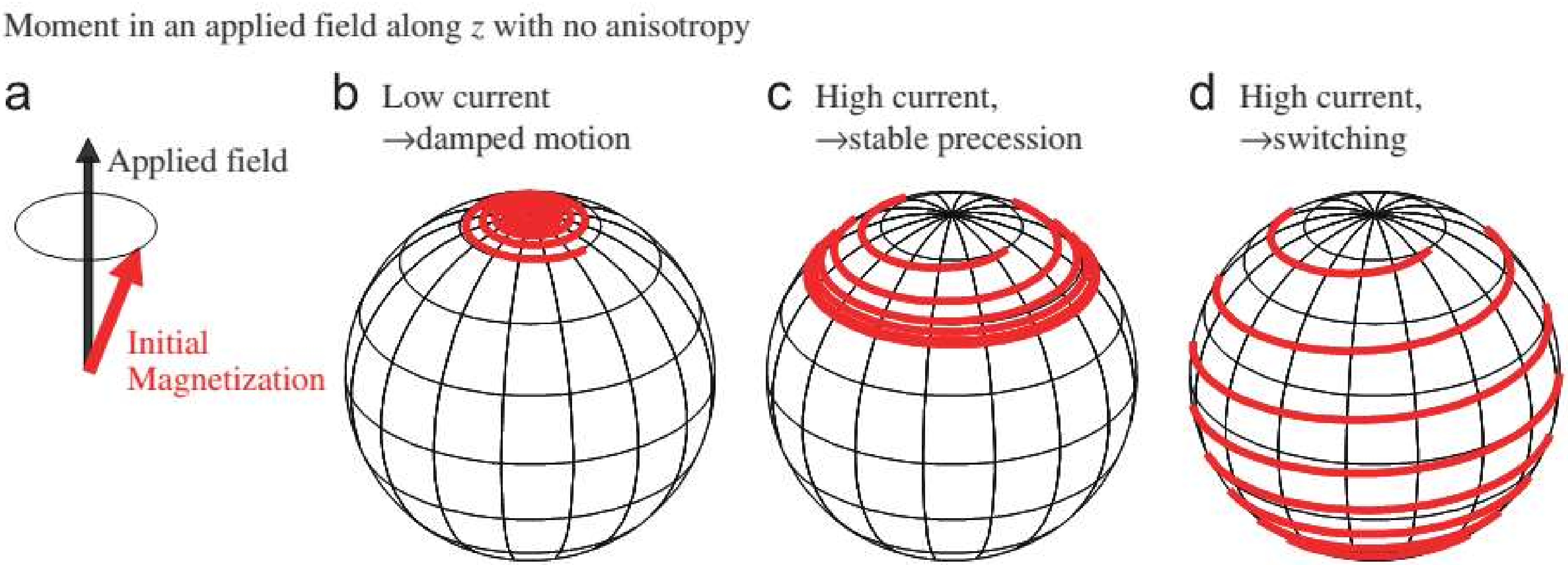




Experimental discovery of STT



Spin transfer torque switching

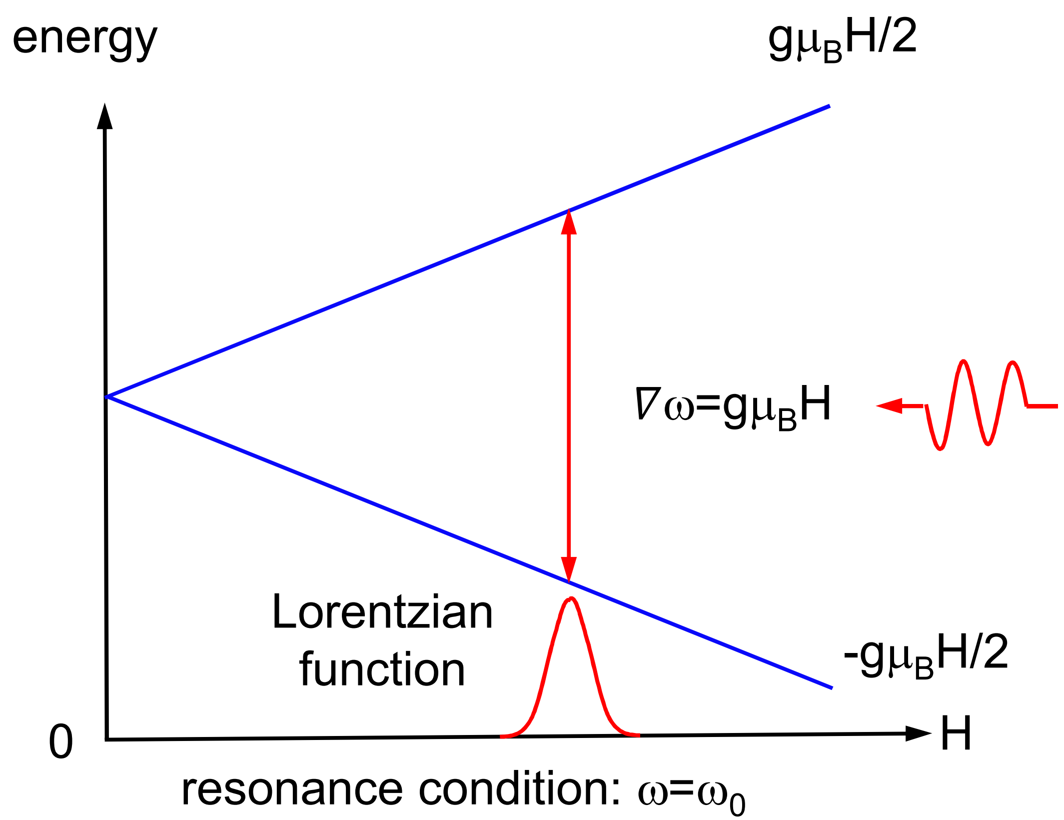


Ralph & Stiles, JMMM (2008)

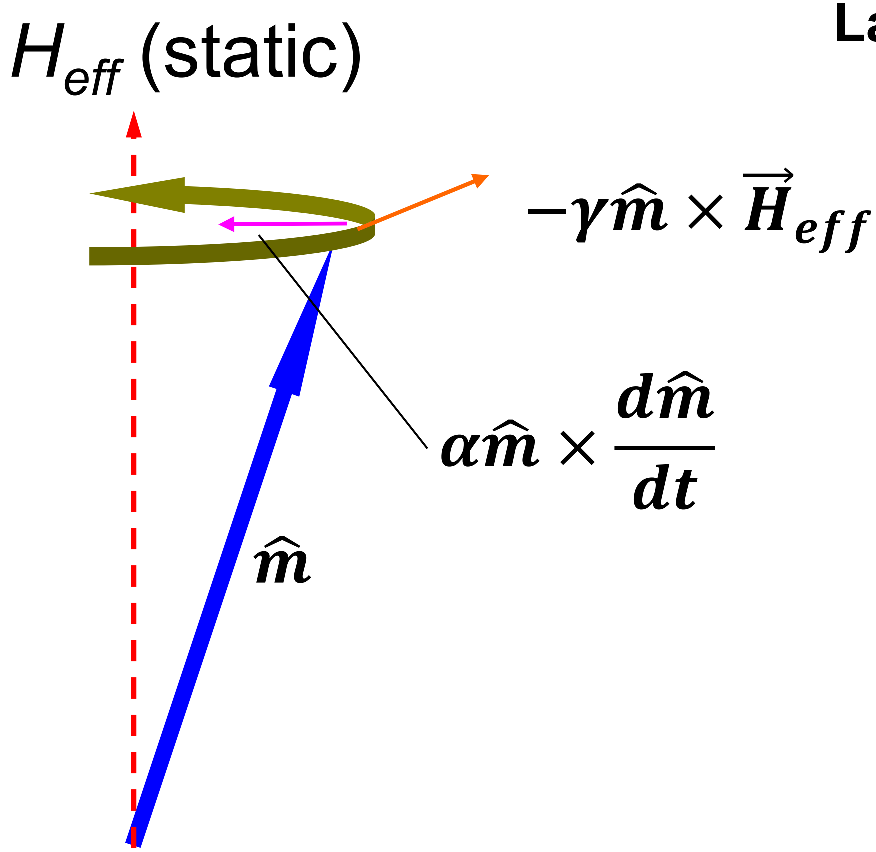
Outline

2. Spin transfer torque and spin pumping

Ferromagnetic resonance



Ferromagnetic resonance



$H_x\, e^{i\omega t}$ (rf): small perturbation

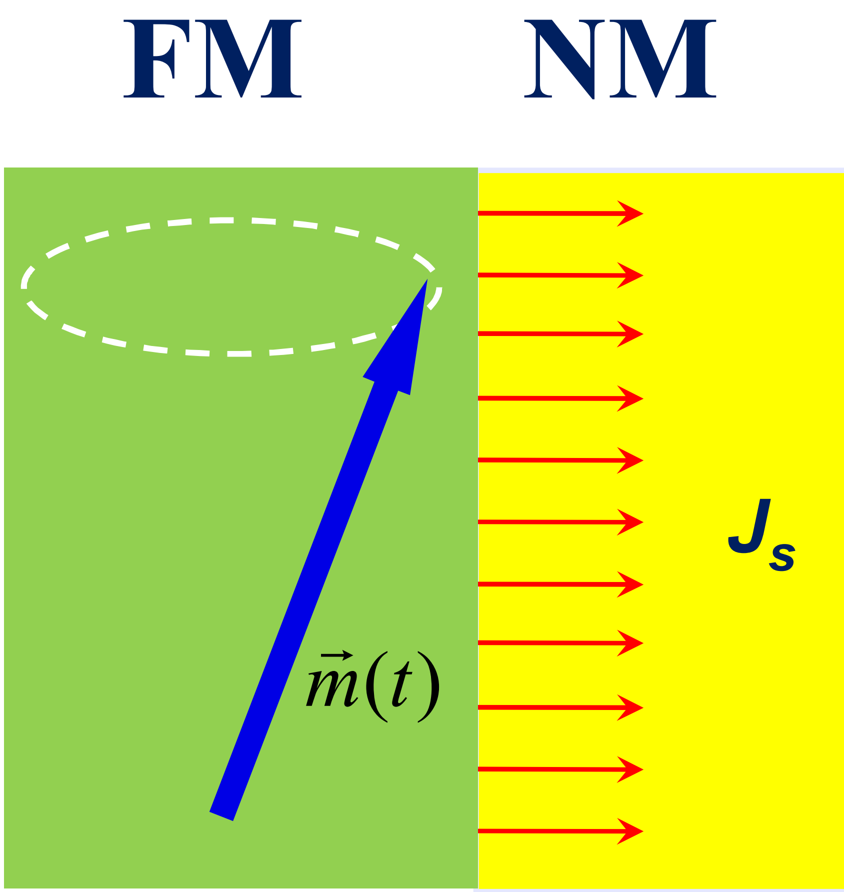
Landau-Lifshitz-Gilbert equation

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

$\gamma = \frac{g\,e}{2\,m_e c}$ is gyromagnetic ratio

α is the Gilbert damping

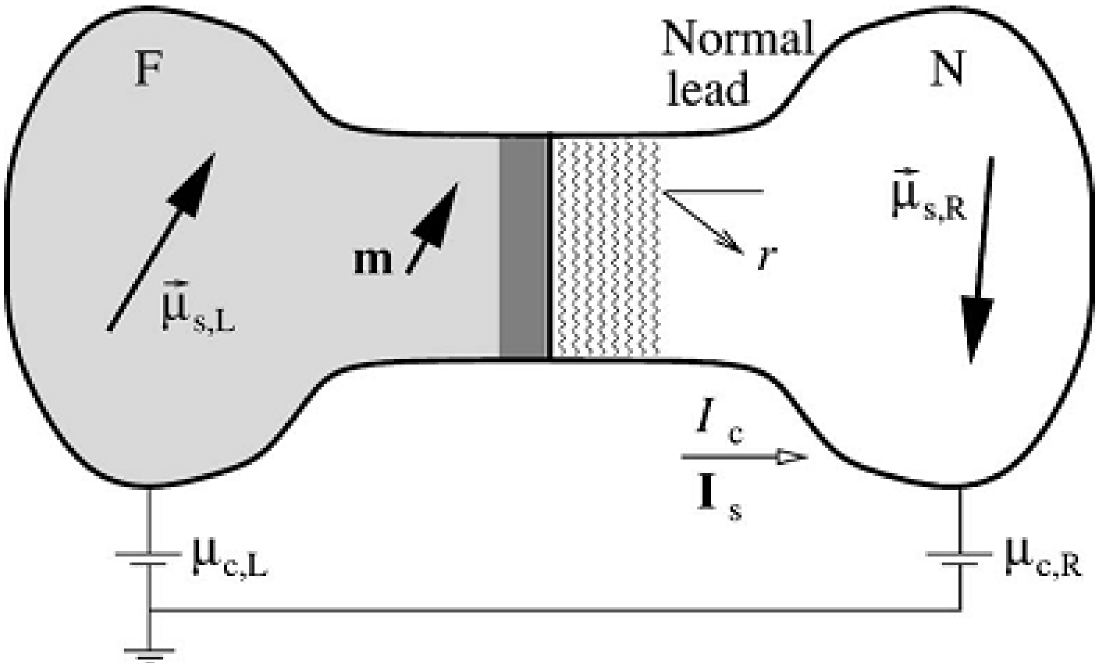
Spin angular momentum



$$\vec{J}_S = \frac{\hbar g_r^{\uparrow\downarrow}}{4\pi M^2}\left(\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right)$$

Precessing magnetization in FM layer pump spin current into NM layer (Angular momentum conservatoin)

Spin transfer torque

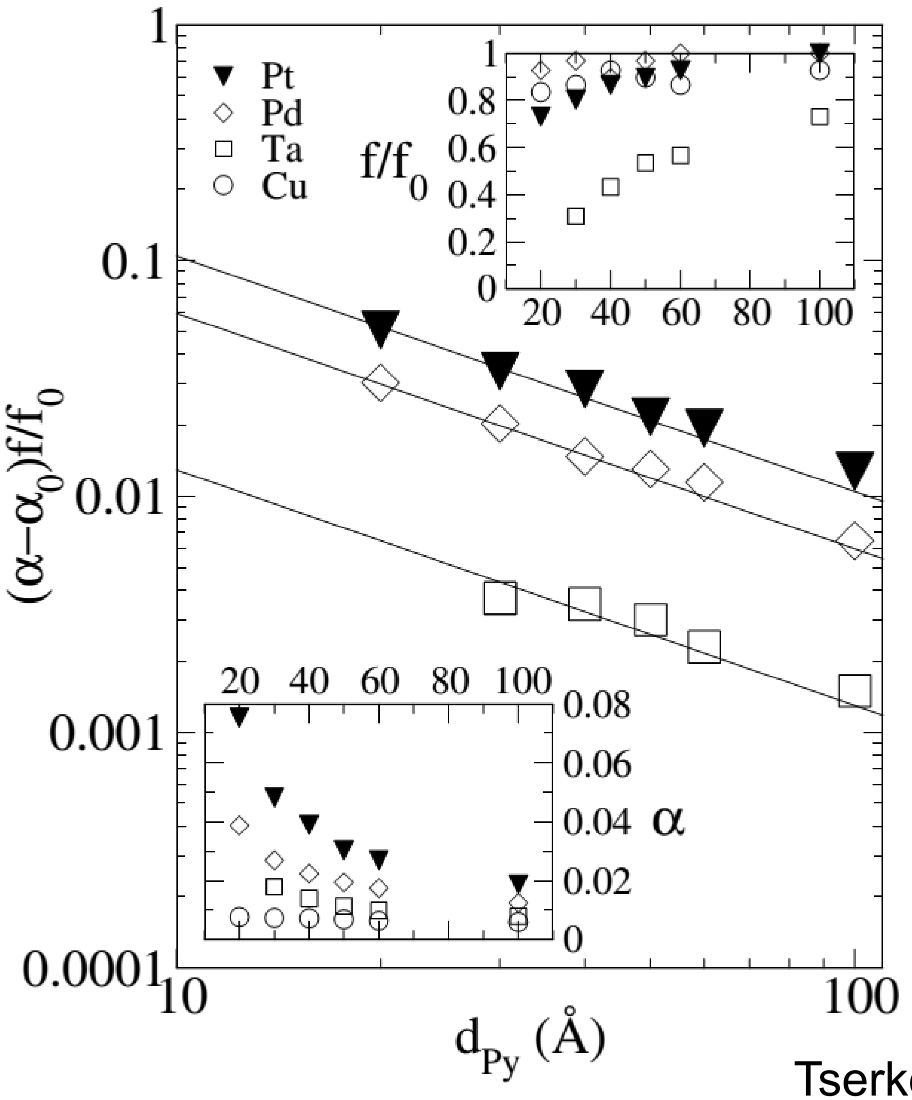


$$\boldsymbol{\tau} = -\mathbf{m} \times \mathbf{I}_s \times \mathbf{m}.$$

$$\mathbf{I}_{s,R}^{\mathrm{pump}} = \frac{\hbar}{4\pi}\left(\mathcal{A}_r^{\uparrow\downarrow}\mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathcal{A}_i^{\uparrow\downarrow}\frac{d\mathbf{m}}{dt}\right),$$

Tserkovnyak, et al, Rev Mod Phys (2005)

Enhanced Gilbert damping



Tserkovnyak, et al, PRL (2002)

Enhanced Gilbert damping

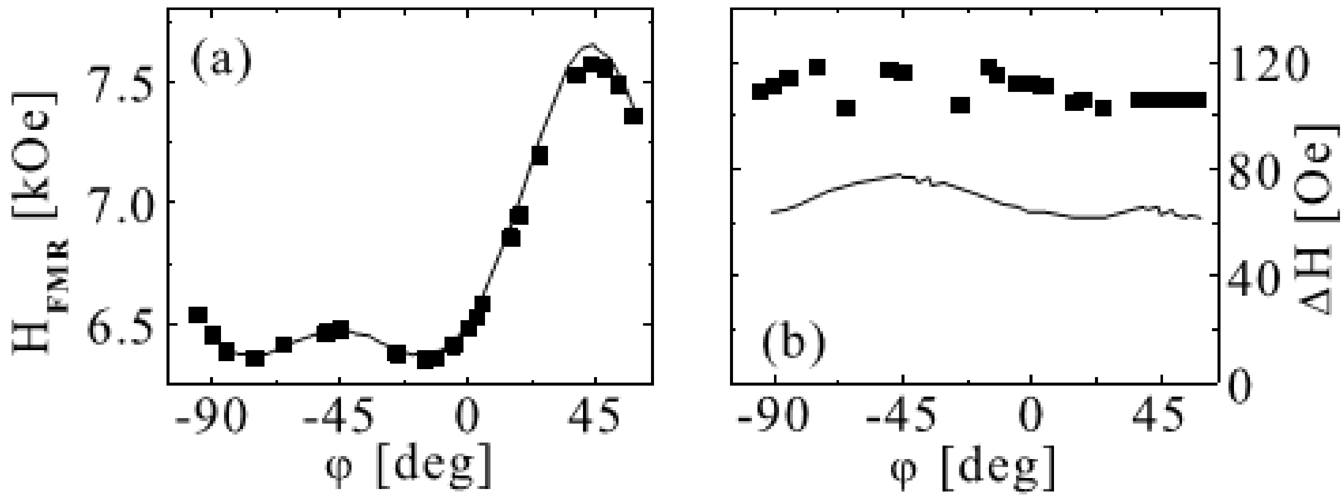


FIG. 3. (a) The FMR field, H_{FMR}, and (b) FMR linewidth, ΔH, for the 16 ML Fe film as a function of the azimuthal angle φ at $f = 36$ GHz. The solid lines correspond to the GaAs/16 Fe/20 Au structure, and the squares (■) correspond to the GaAs/16 Fe/40 Au/40 Fe/20 Au structure. The integers represent the number of MLs.

Urban et al, PRL (2001)

Enhanced Gilbert damping

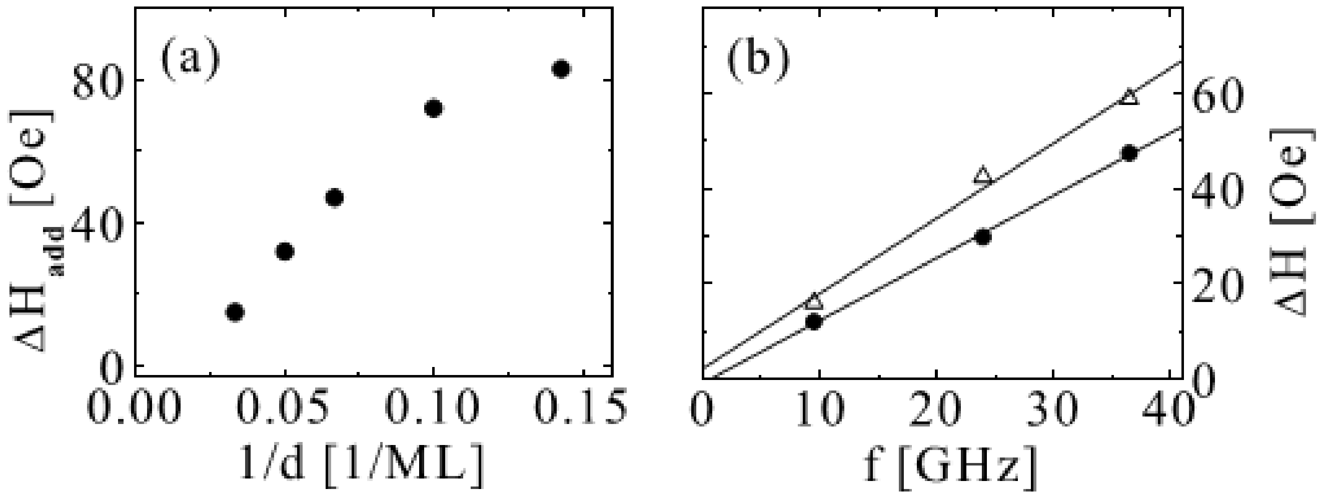
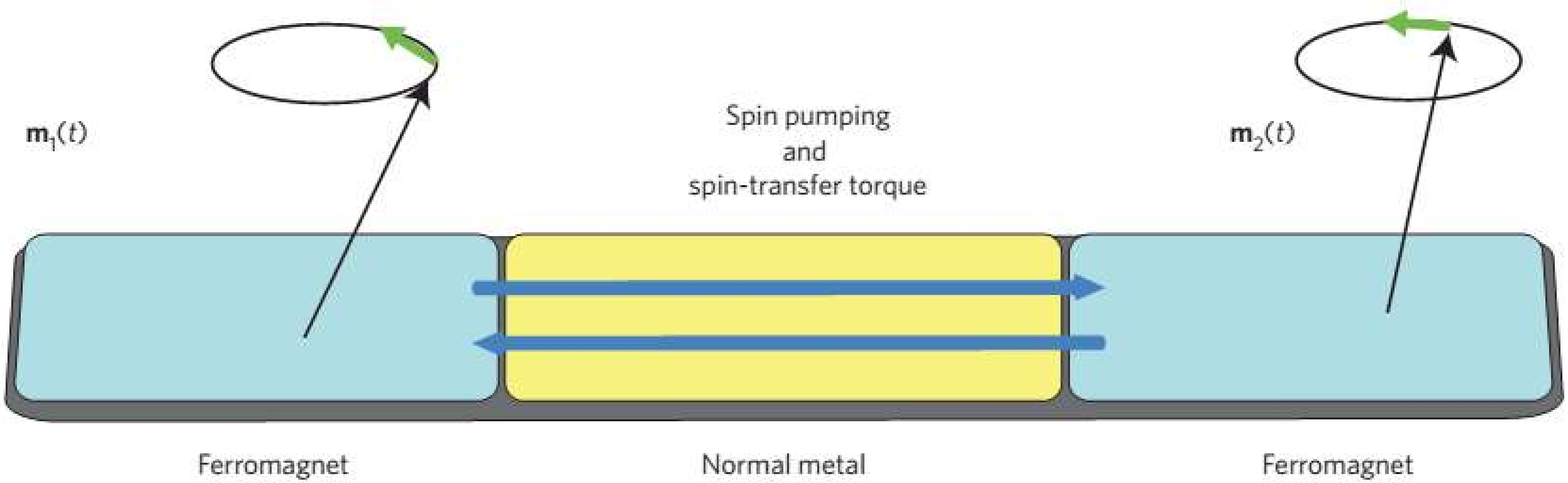


FIG. 4. (a) The dependence of the additional FMR linewidth, ΔH_{add}, along the Fe cubic axis on $1/d$ at $f = 36$ GHz, where d is the thickness of the thin Fe films. (b) The FMR linewidth, ΔH, as a function of the microwave frequency f. The triangles (△) correspond to the 16 ML Fe film in the single layer structure. The dots (●) show the additional FMR linewidth, ΔH_{add}, for the 16 ML Fe film. The solid lines are linear fits to the data.

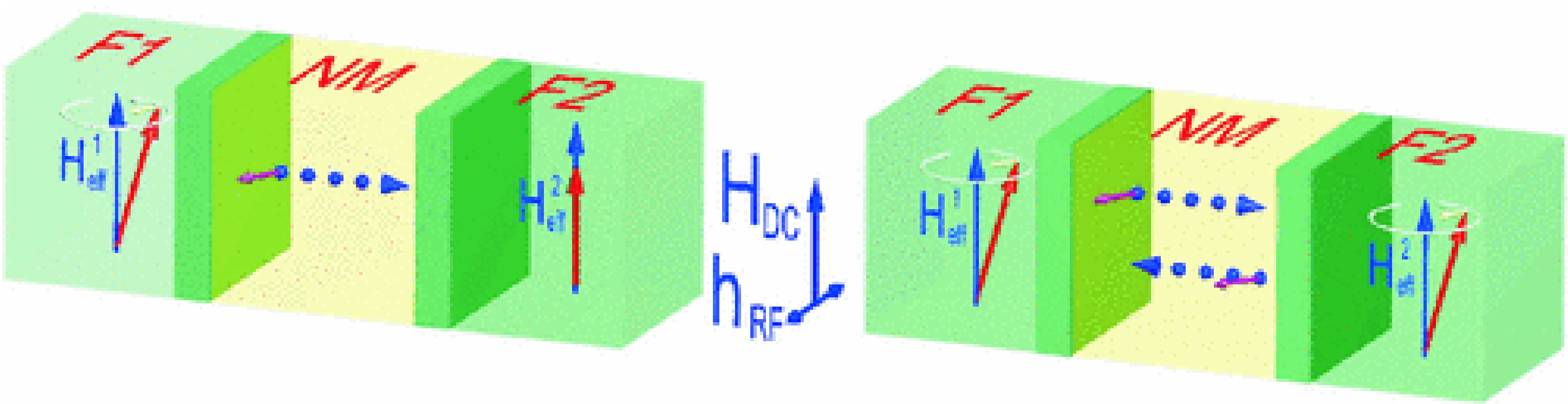
Urban et al, PRL (2001)

Enhanced Gilbert damping and torque



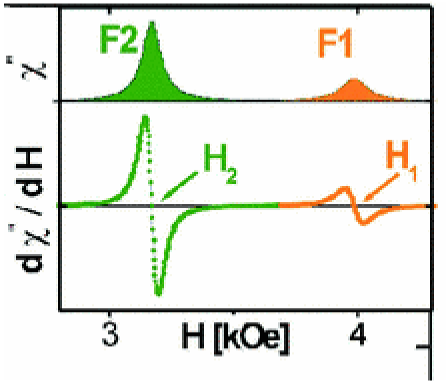
Urban et al, PRL (2003)

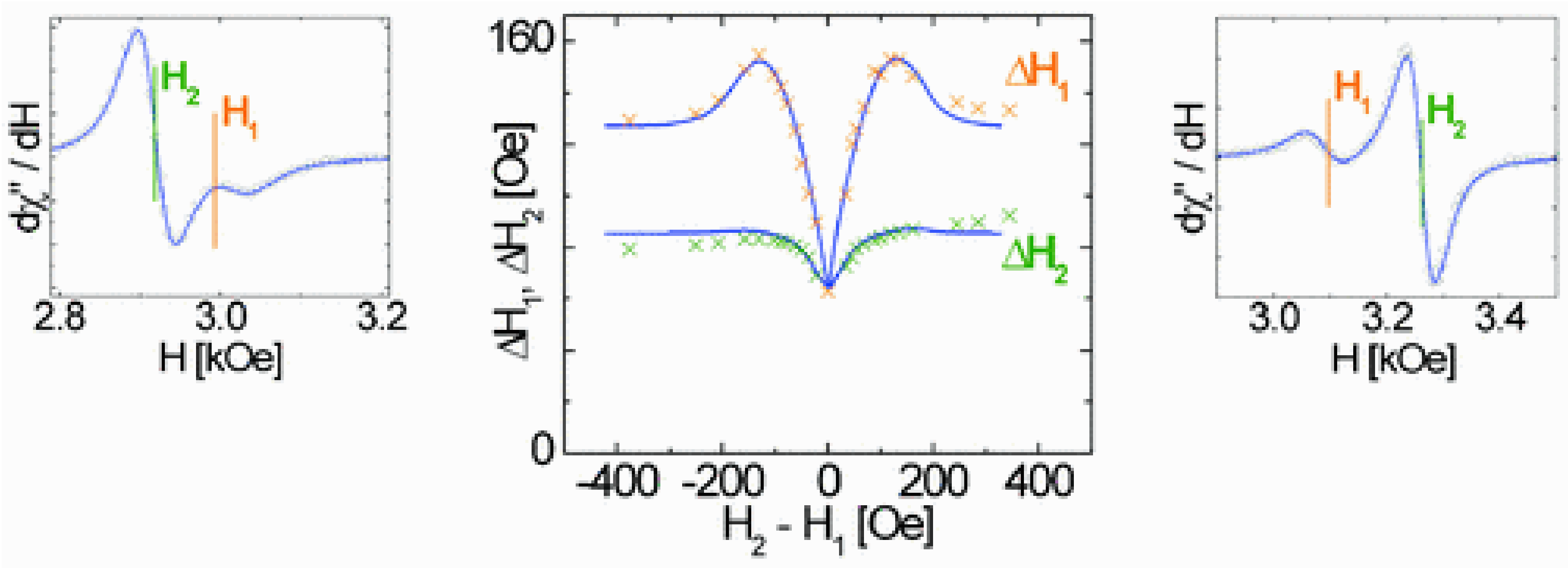
Enhanced Gilbert damping and torque



Urban et al, PRL (2003)

Enhanced Gilbert damping and torque





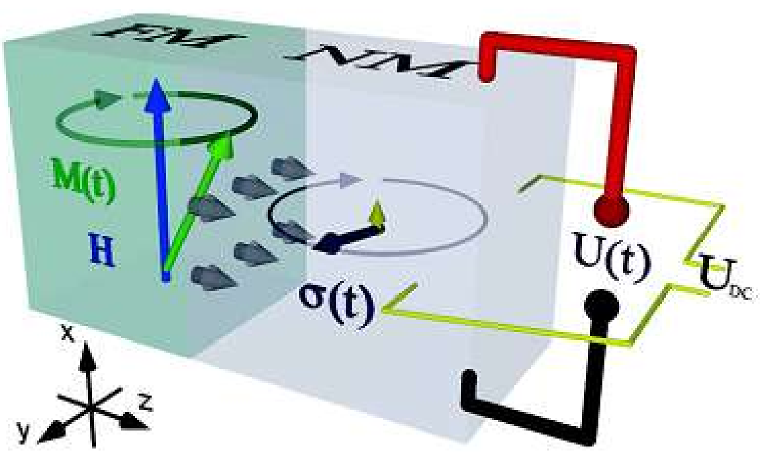
Spin transfer torque

APPLIED PHYSICS LETTERS **88**, 182509 (2006)

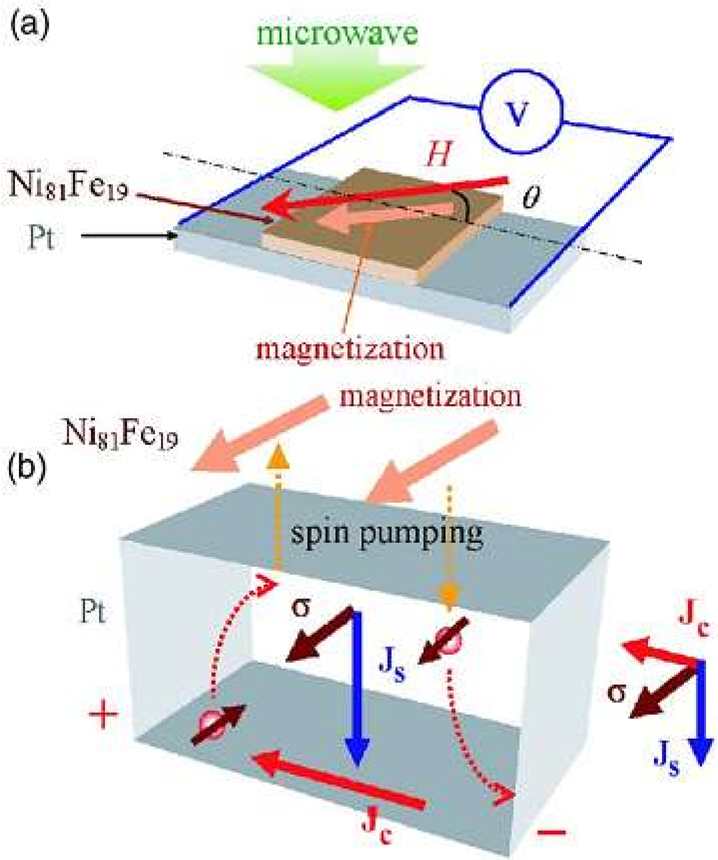
Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect

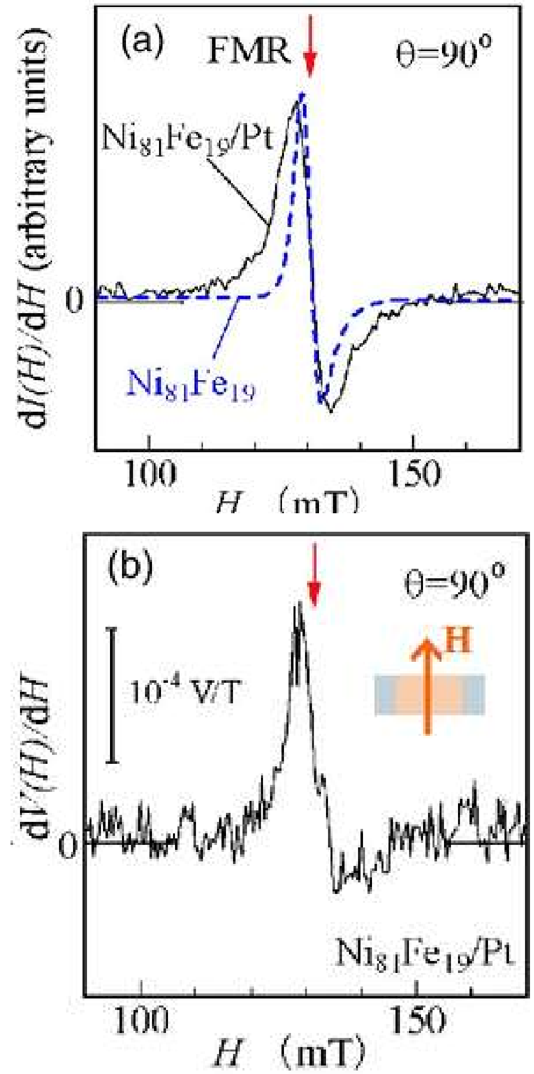
E. Saitoh,[a] M. Ueda, and H. Miyajima
Department of Physics, Keio University, Yokohama 223-8522, Japan

G. Tatara
PRESTO, Japan Science and Technology Agency (JST), Department of Physics, Tokyo Metropolitan University, Tokyo 192-0397, Japan

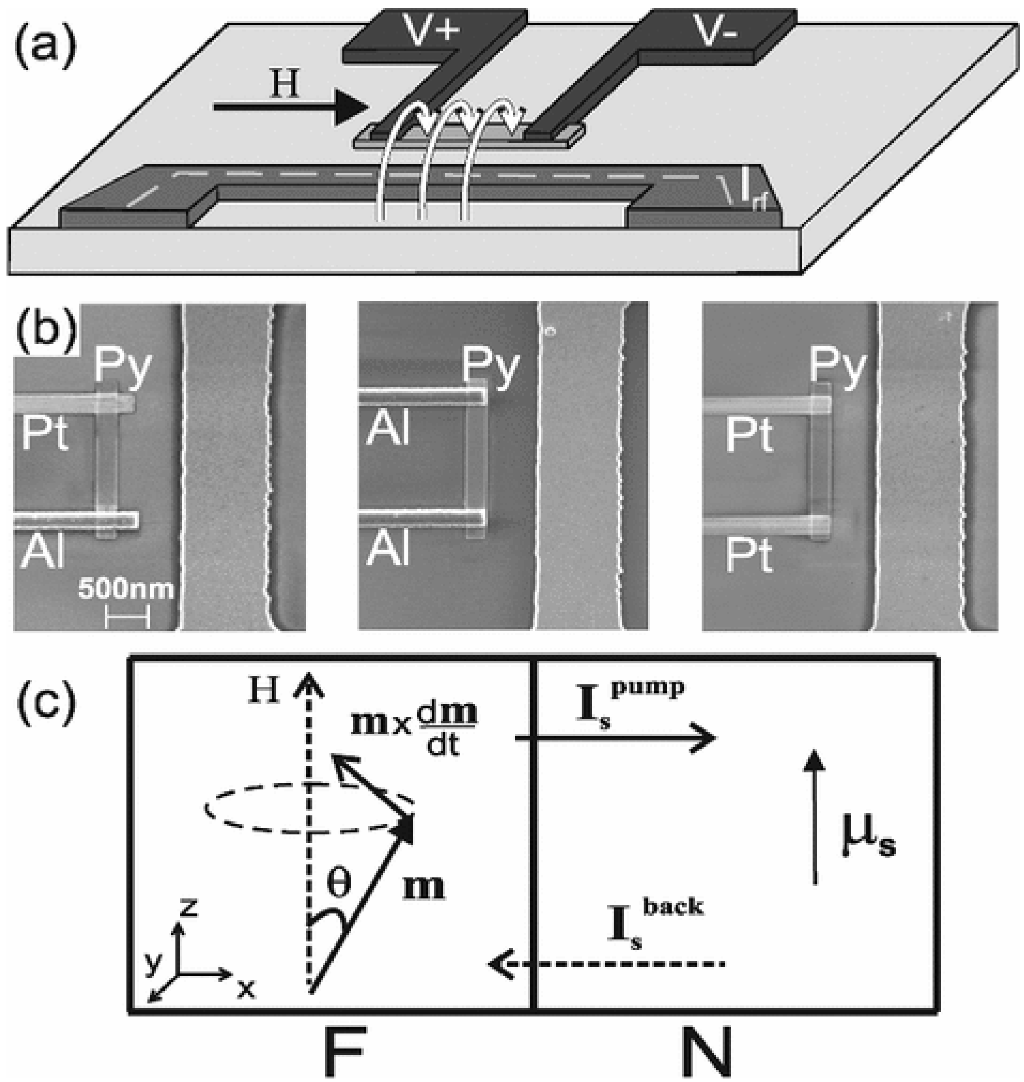


Spin transfer torque

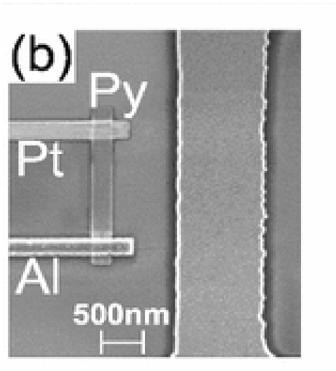


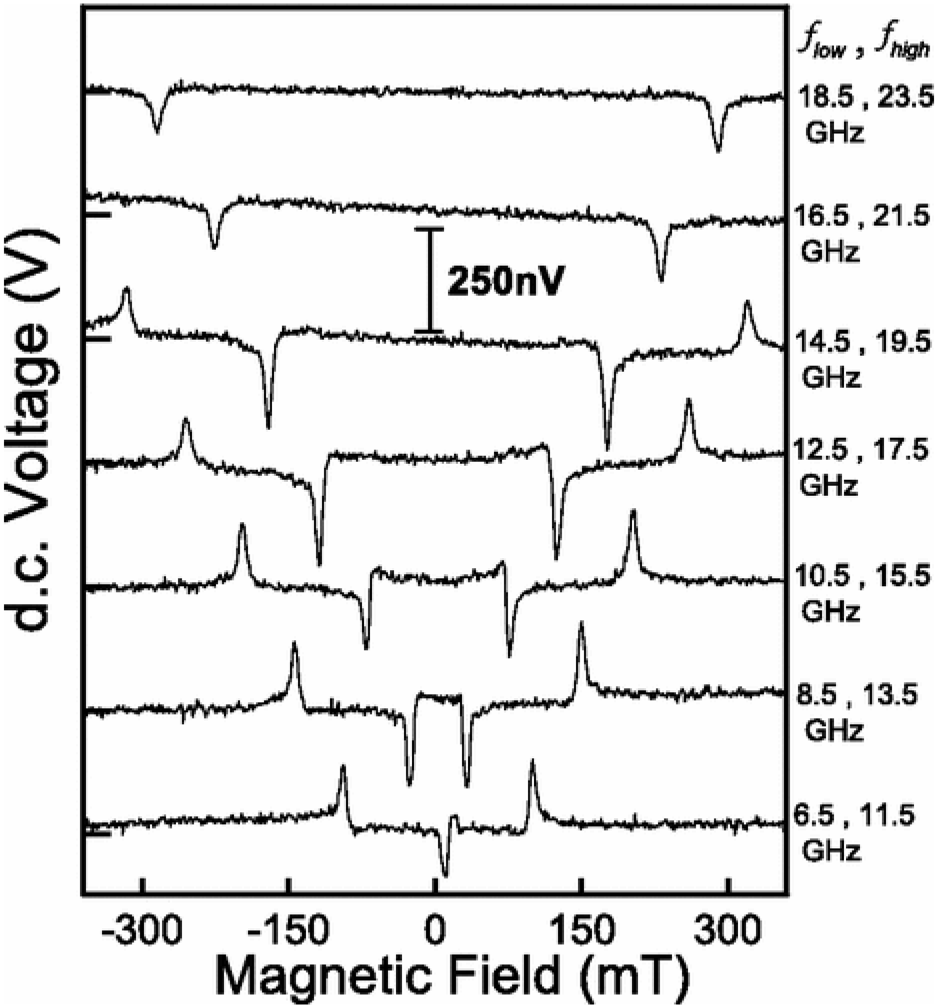


Spin transfer torque

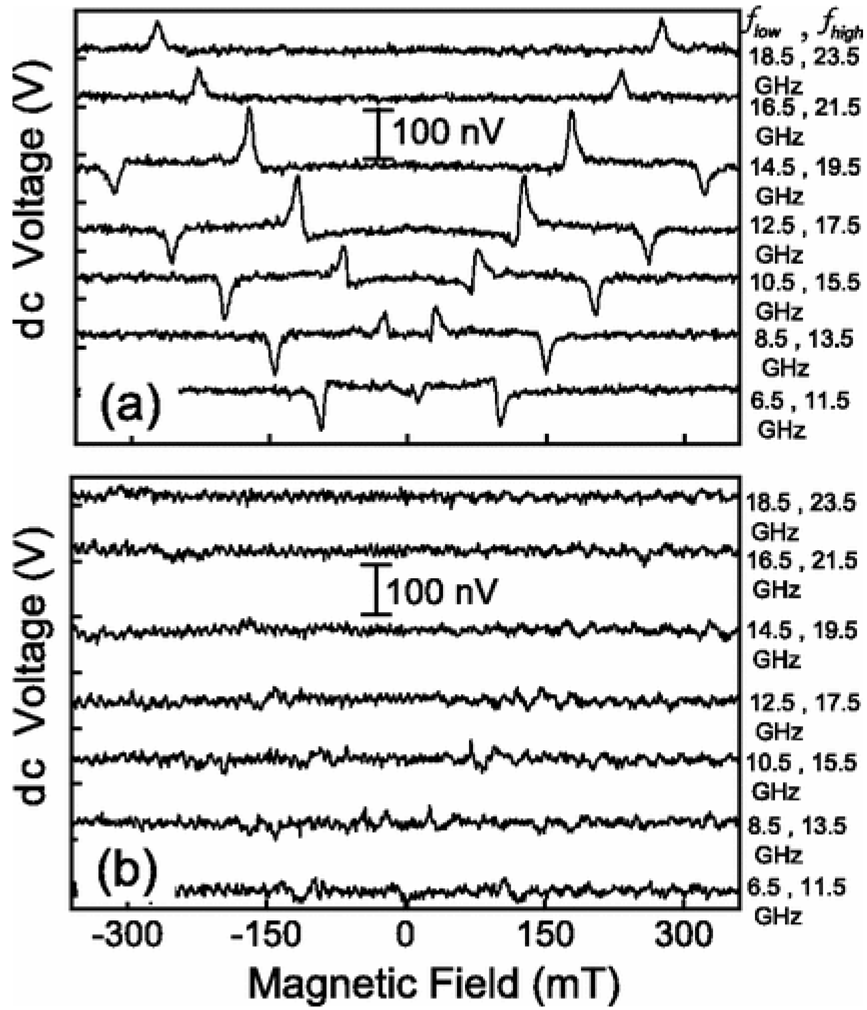


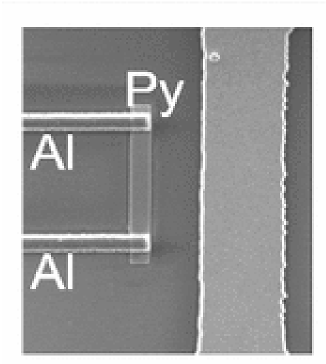
Spin transfer torque

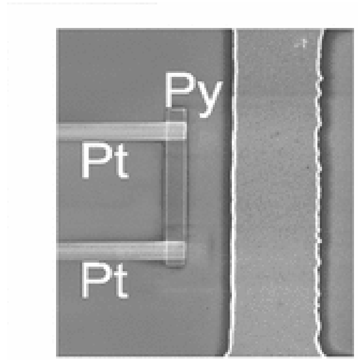




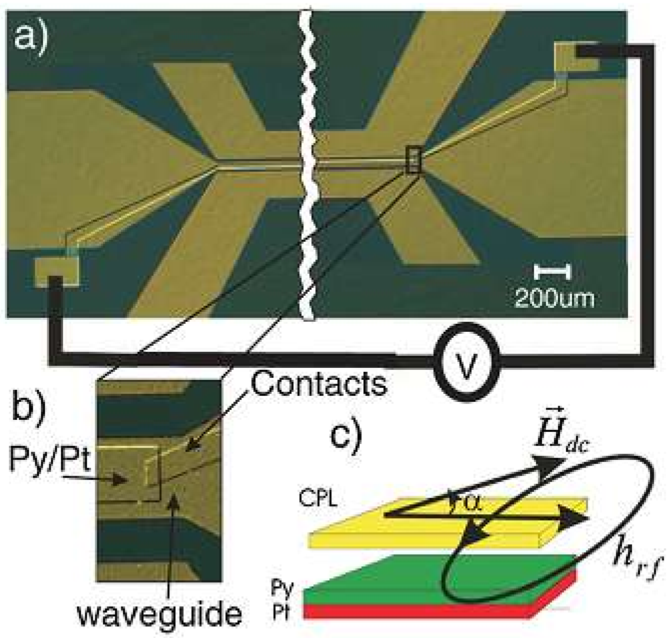
Spin transfer torque

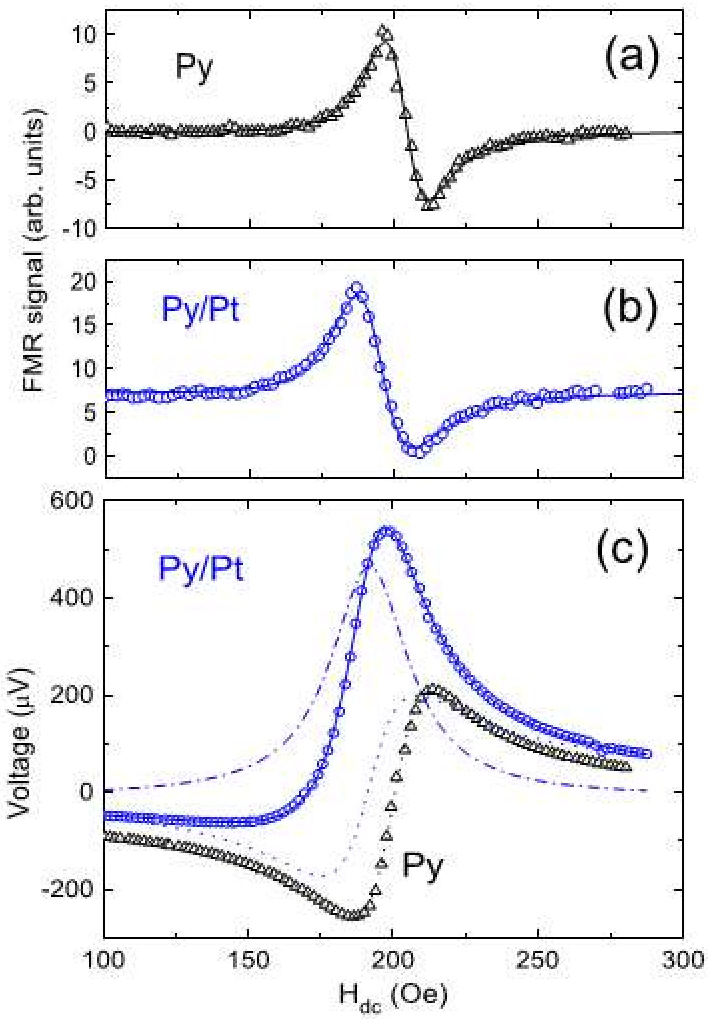






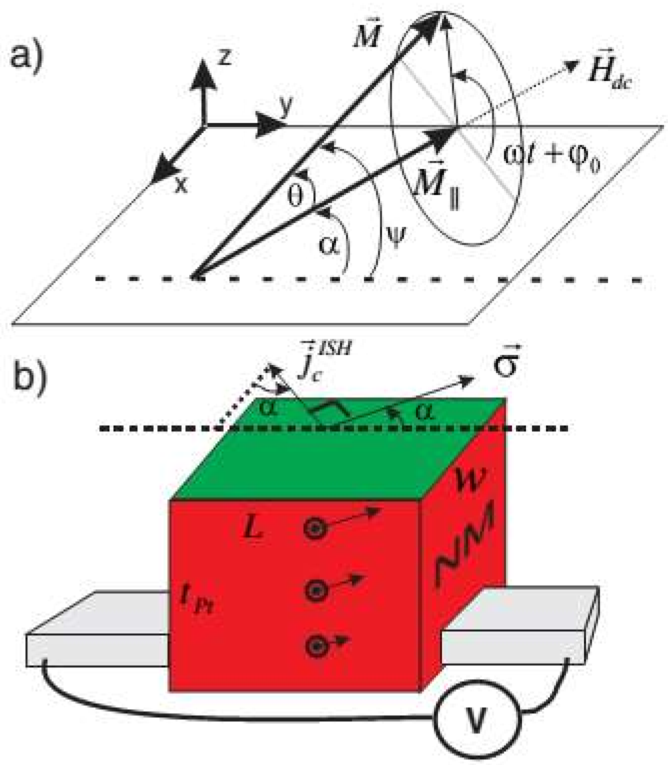
Spin transfer torque

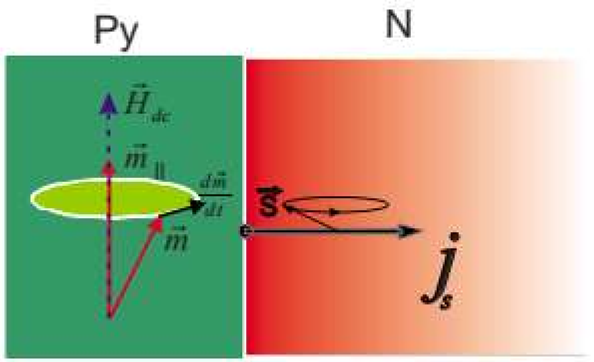


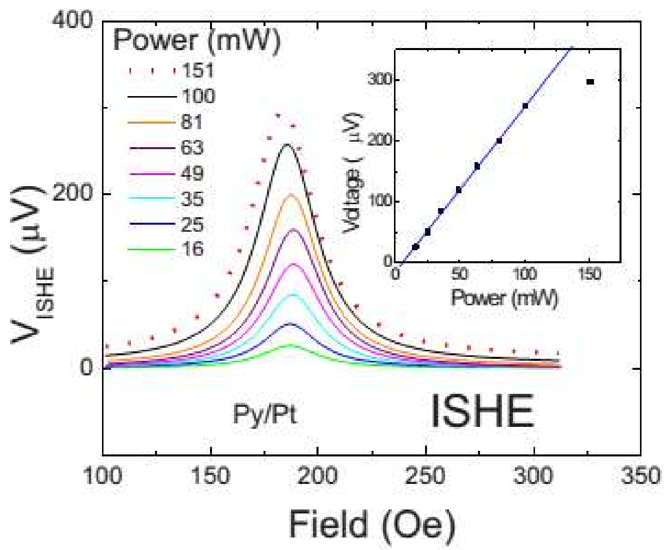


Mosendz, et al, PRL (2010)

Spin transfer torque







Spin transfer torque

TABLE I. Spin Hall angle γ determined using λ_{sd} and σ_N from data measured at 11 GHz.

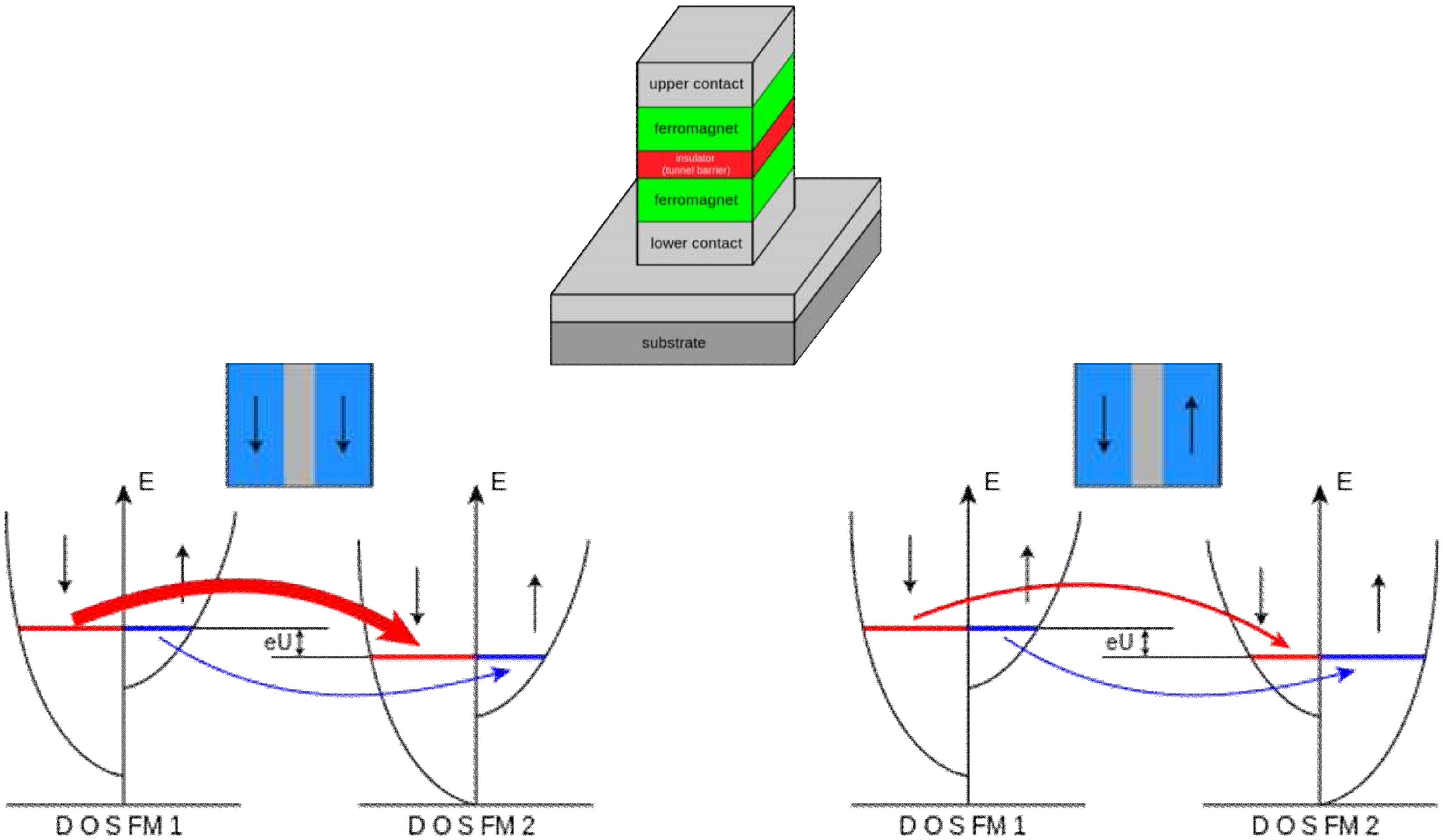
Normal metal	λ_{sd} (nm)	σ_N $1/(\Omega\ \mathrm{m})$	γ
Pt	10 ± 2	$(2.4 \pm 0.2) \times 10^6$	0.013 ± 0.002
Pd	15 ± 4	$(4.0 \pm 0.2) \times 10^6$	0.0064 ± 0.001
Au	35 ± 3	$(2.52 \pm 0.13) \times 10^7$	0.0035 ± 0.0003
Mo	35 ± 3	$(4.66 \pm 0.23) \times 10^6$	-0.0005 ± 0.0001

休息10分钟

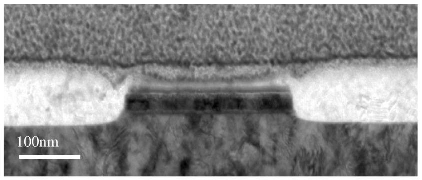
Outline

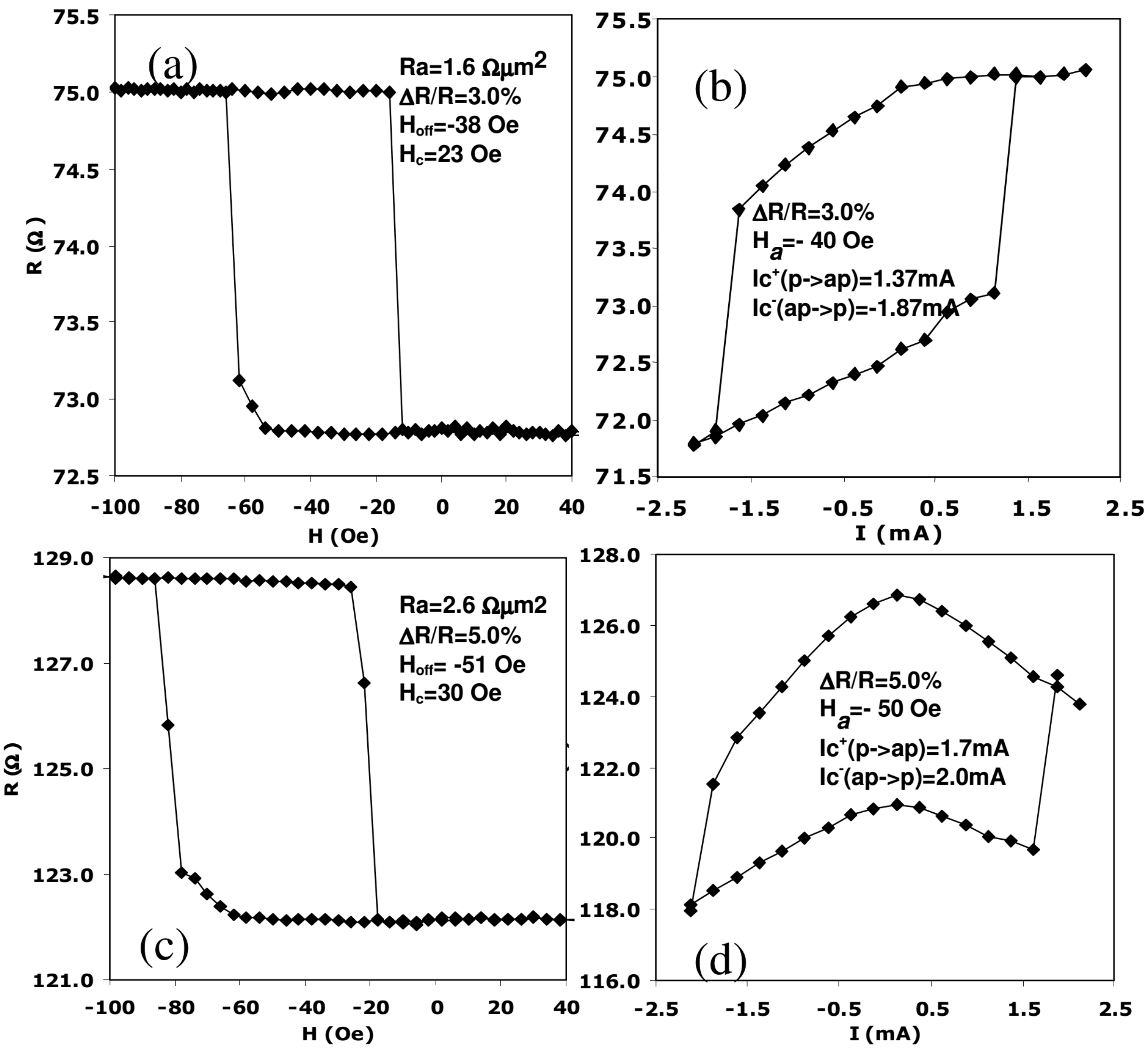
3. Spin transfer torque in MTJ

Magnetic tunnel junction (MTJ)



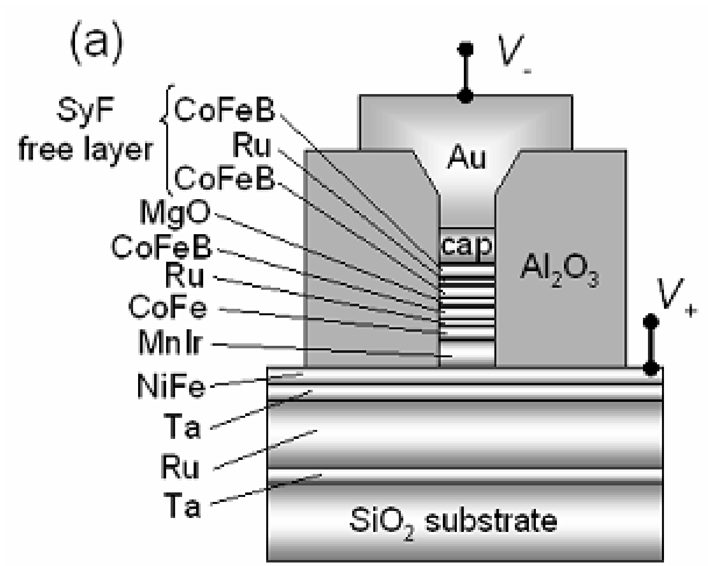
SST in MTJ for MRAM

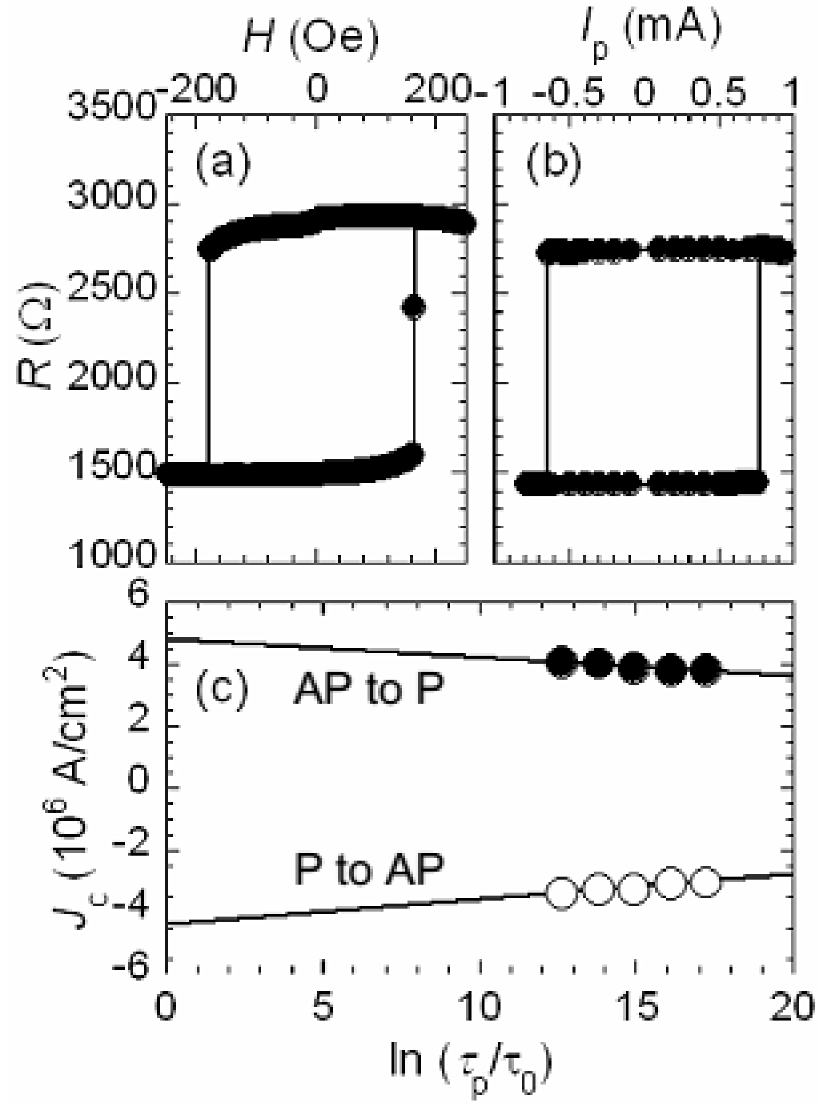




Yuan, et al, APL (2004)

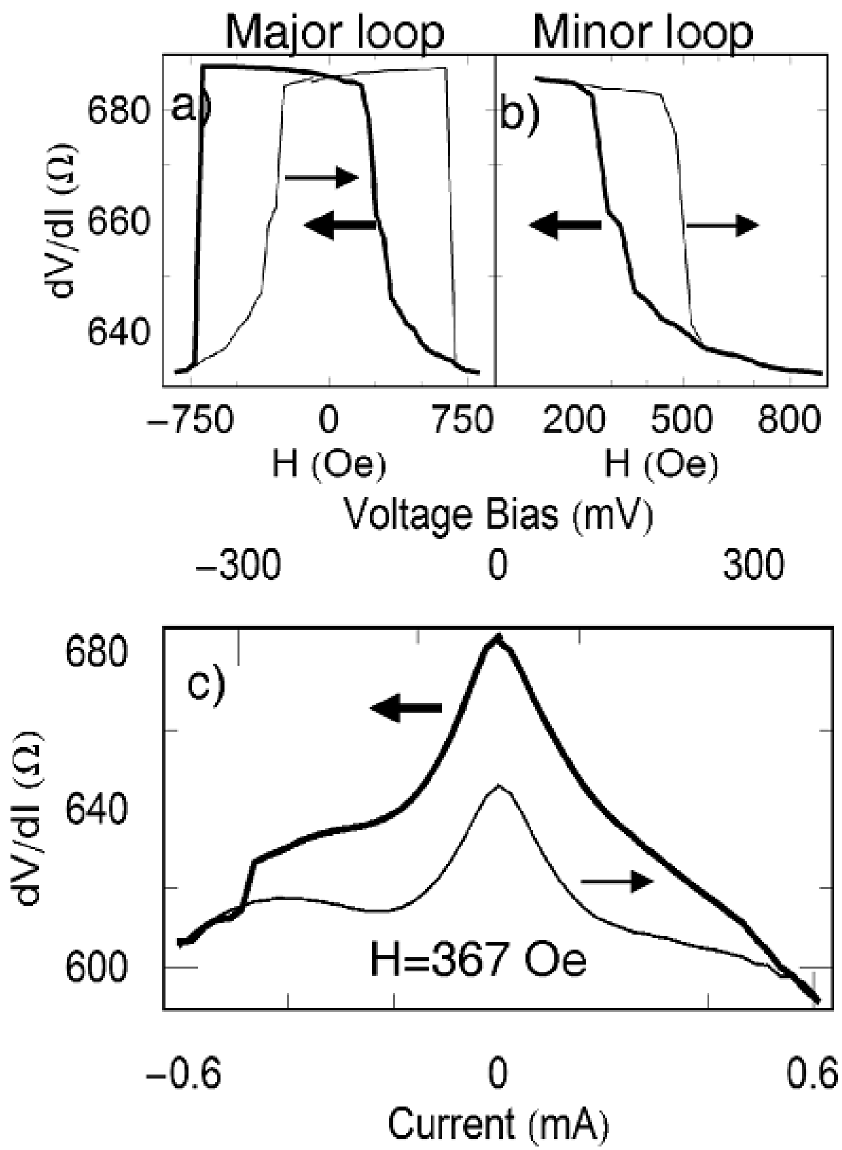
SST in MTJ for MRAM





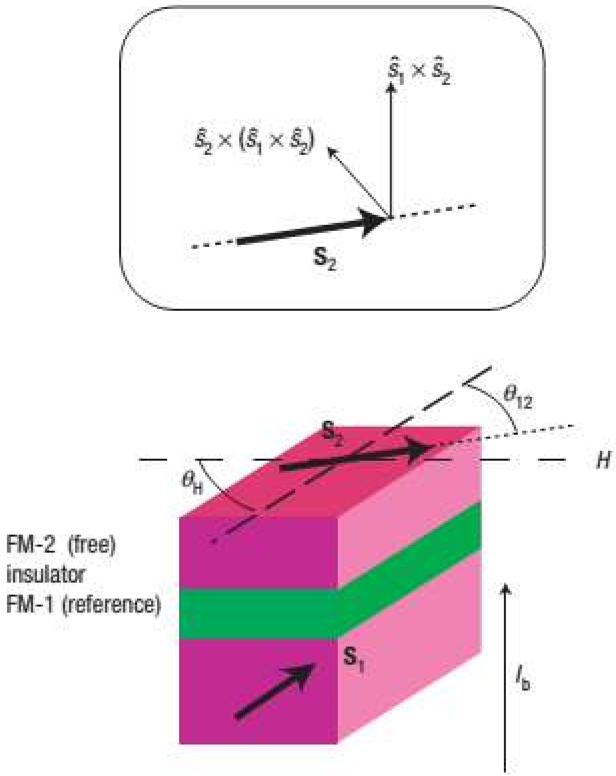
Huai, et al, APL (2004)

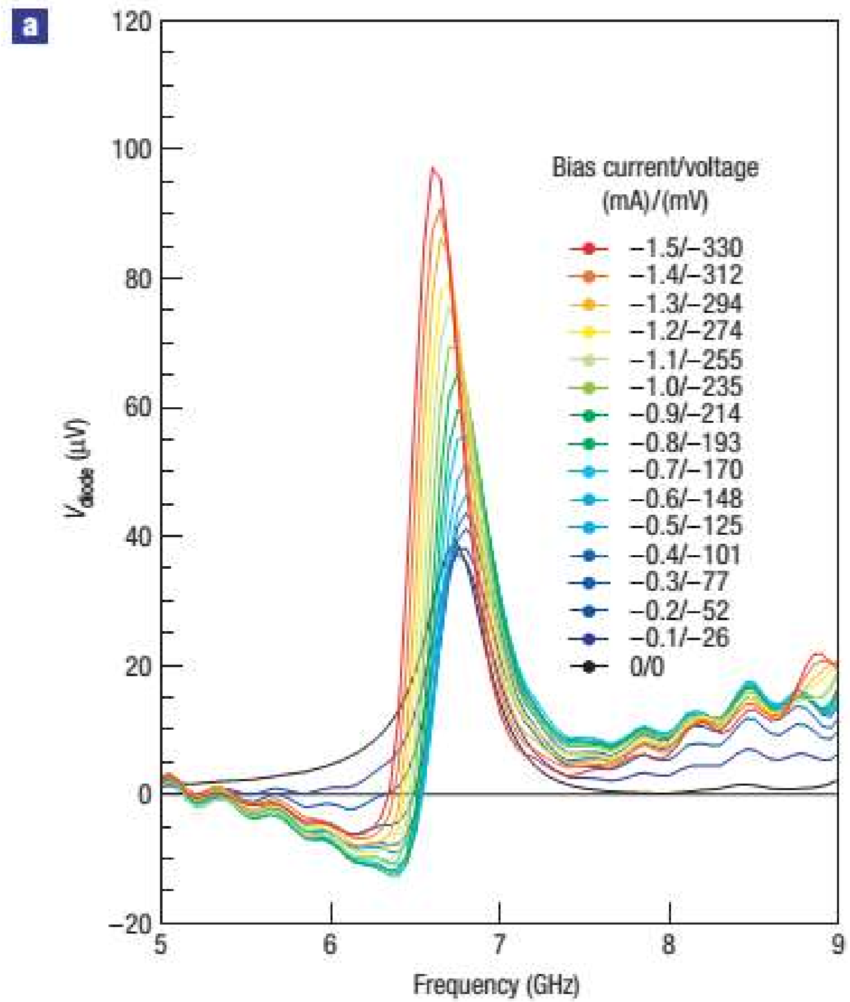
SST in MTJ for MRAM



Fuchs, et al, APL (2004)

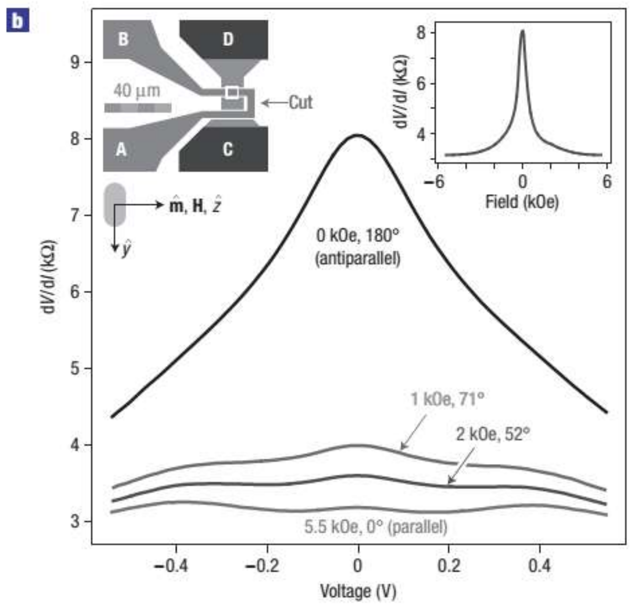
Measurement of STT in MTJ

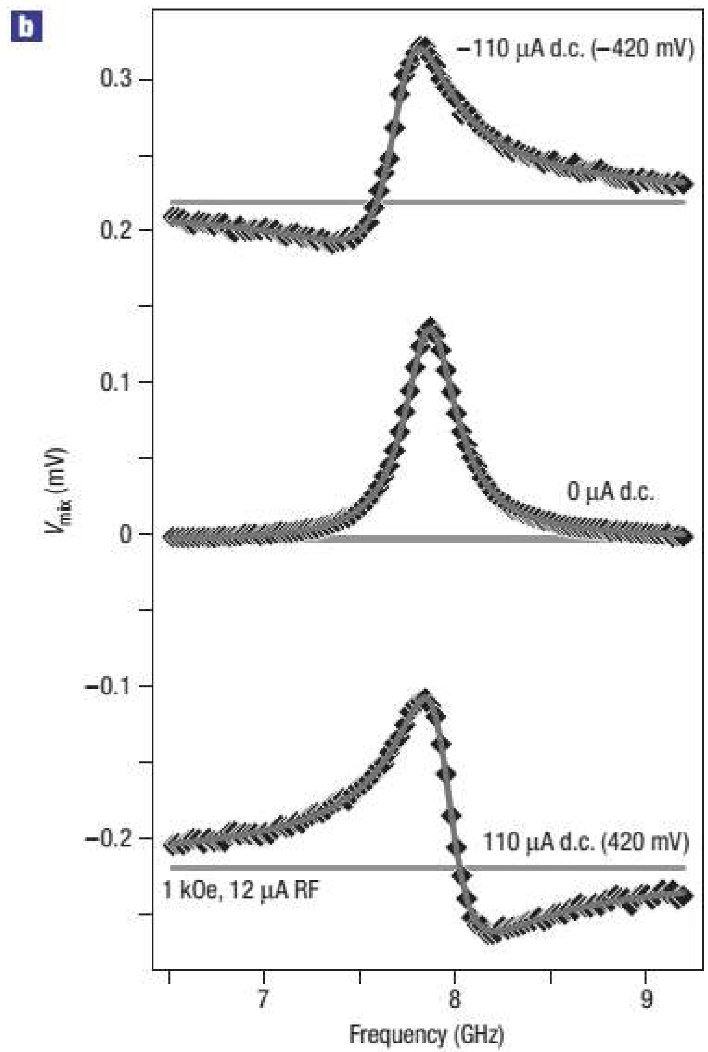




KUBOTA, et al, Nature Physics (2008)

Measurement of STT in MTJ





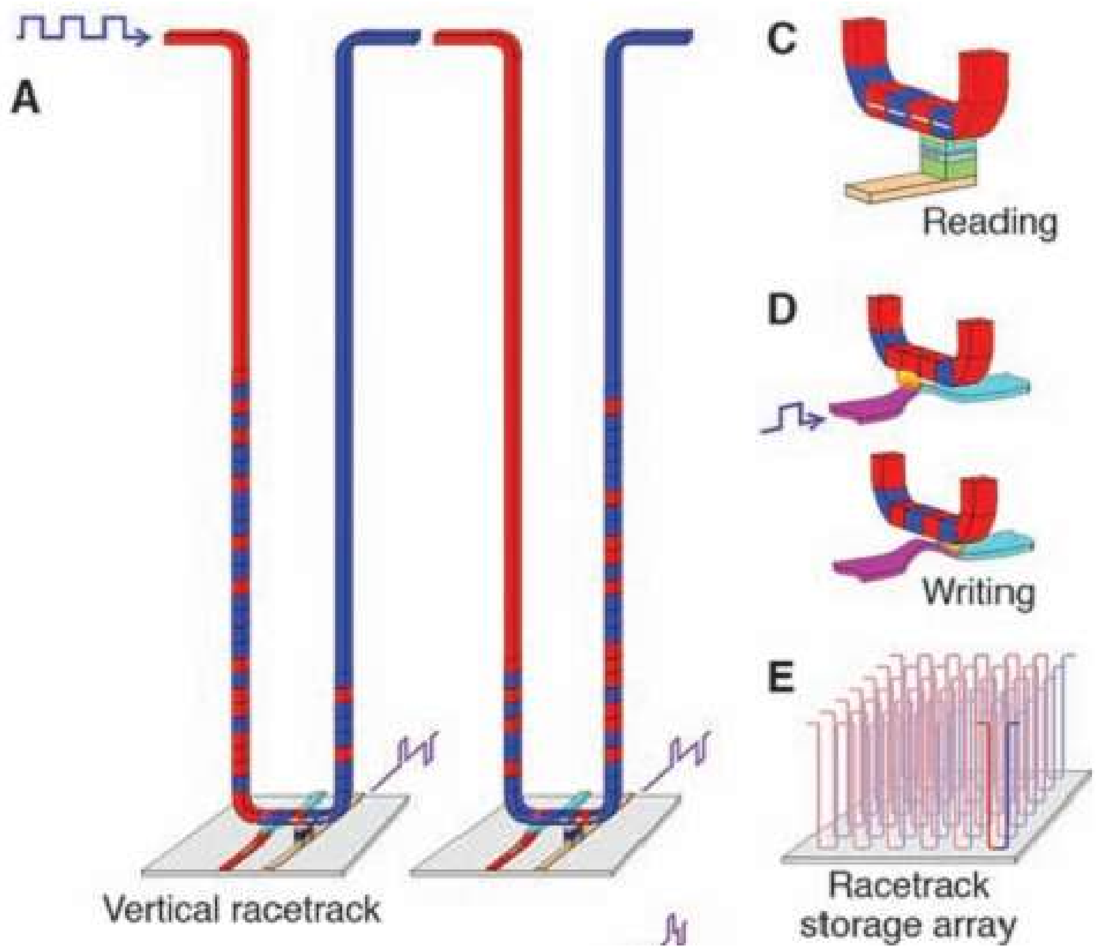
Sankey, et al, Nature Physics (2008)

Outline

4. Spin transfer torque in domain wall motion

Why domain wall

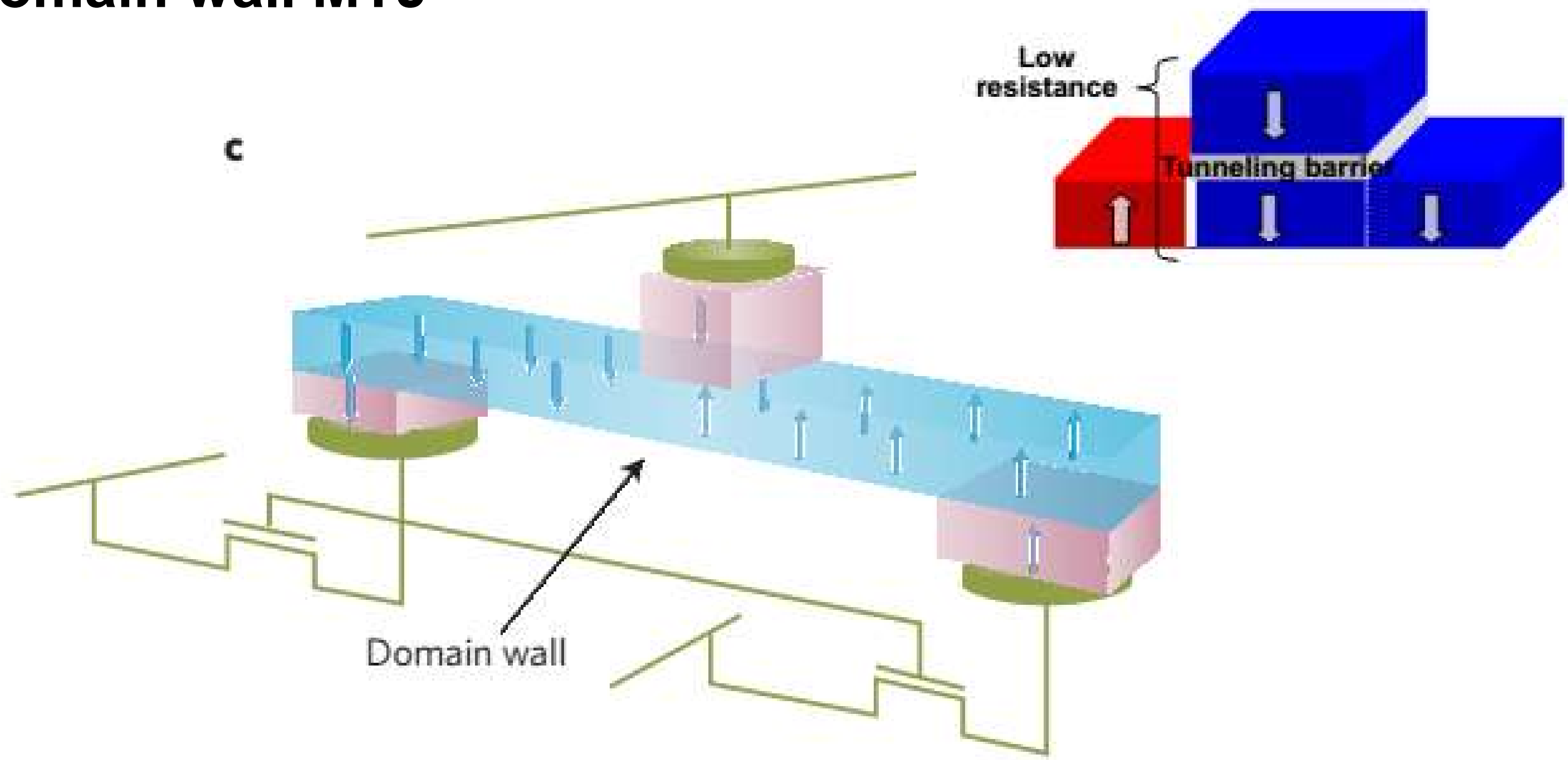
Racetrack Memory



Parkin, et al, Science (2008)

Why domain wall

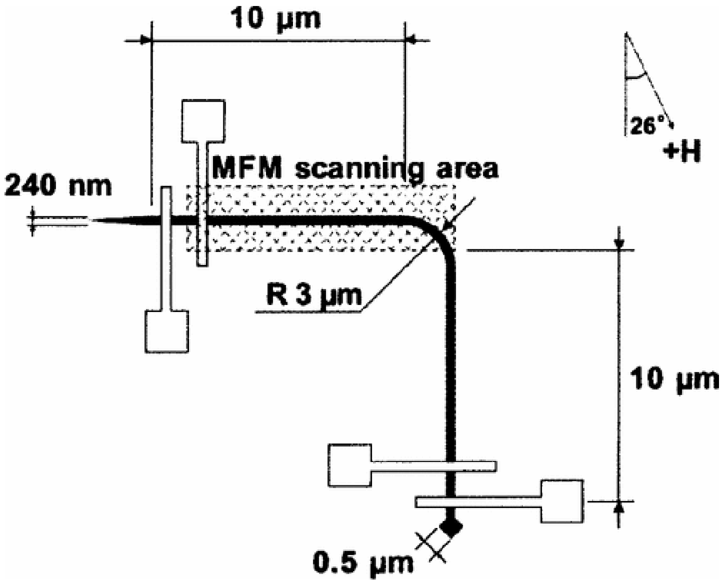
Domain wall MTJ

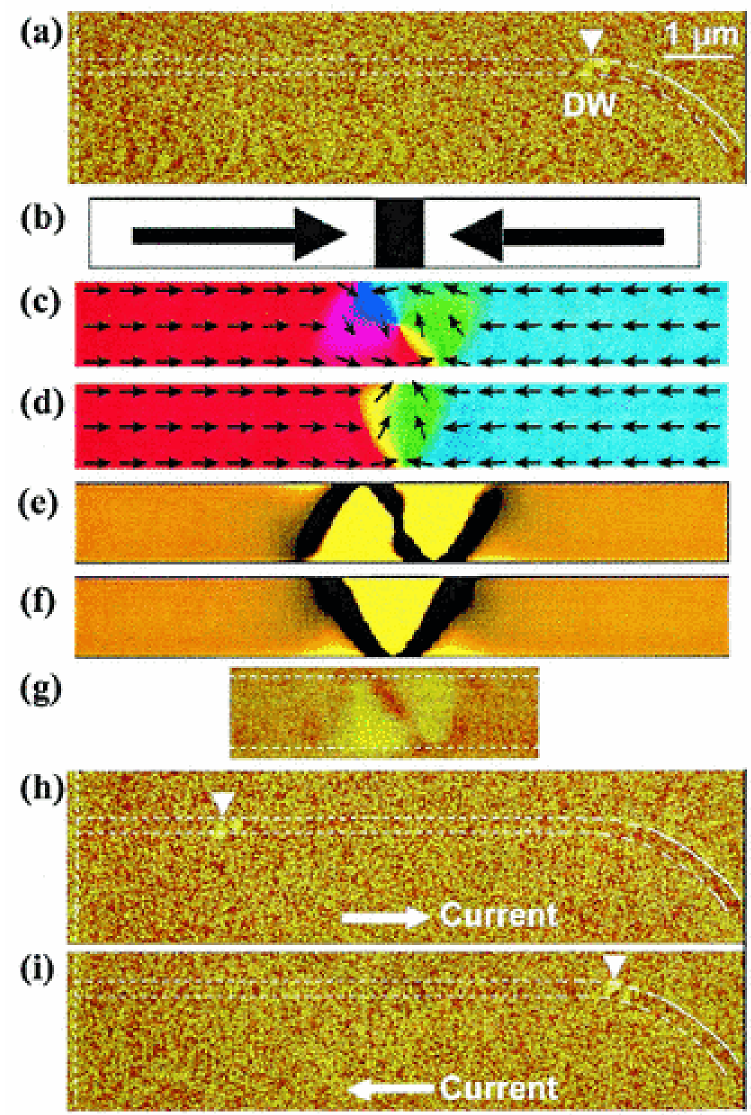


Fukami et al., 52nd Conference on MMM (2007)

Domain wall motion by STT

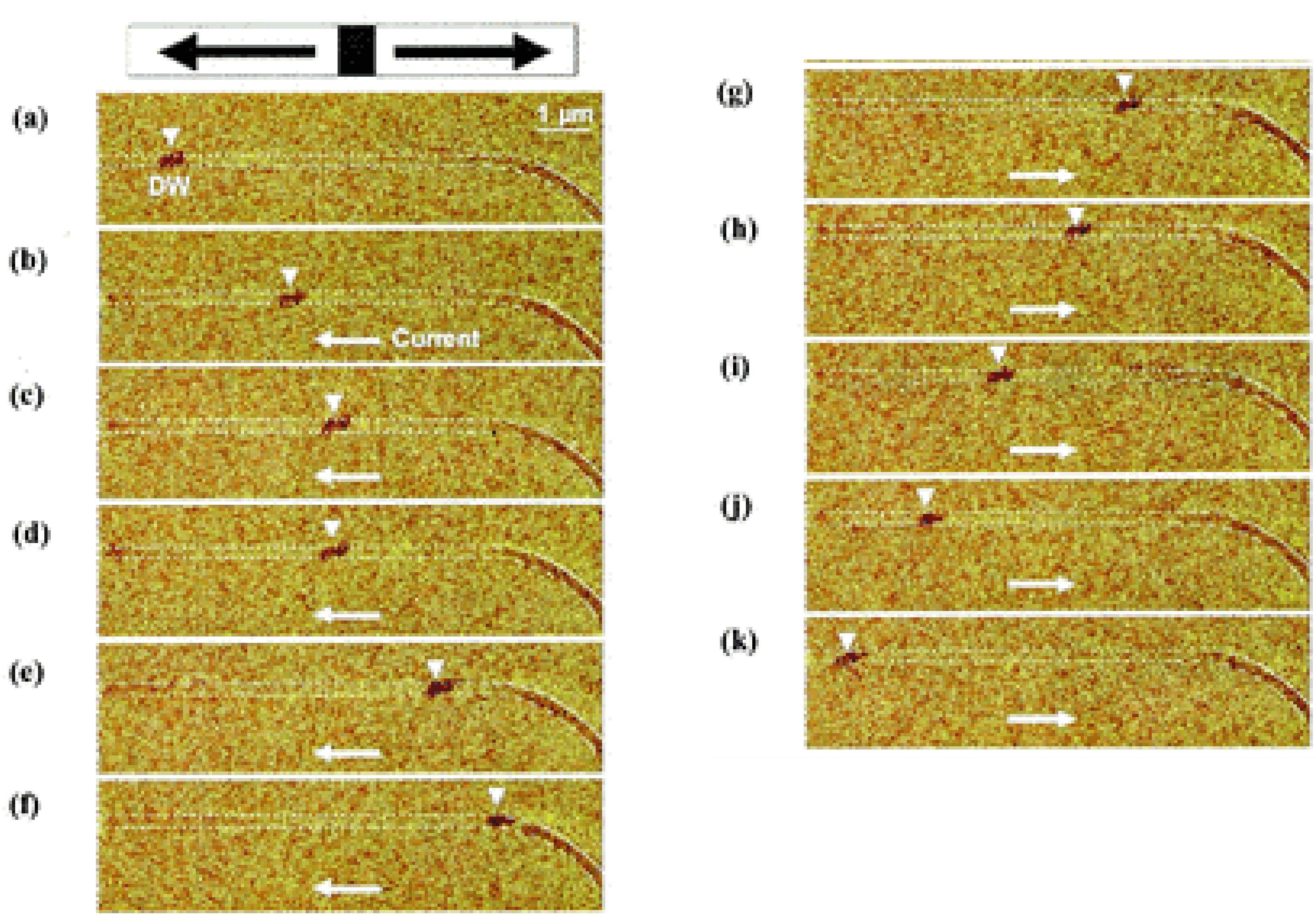
FM Metal



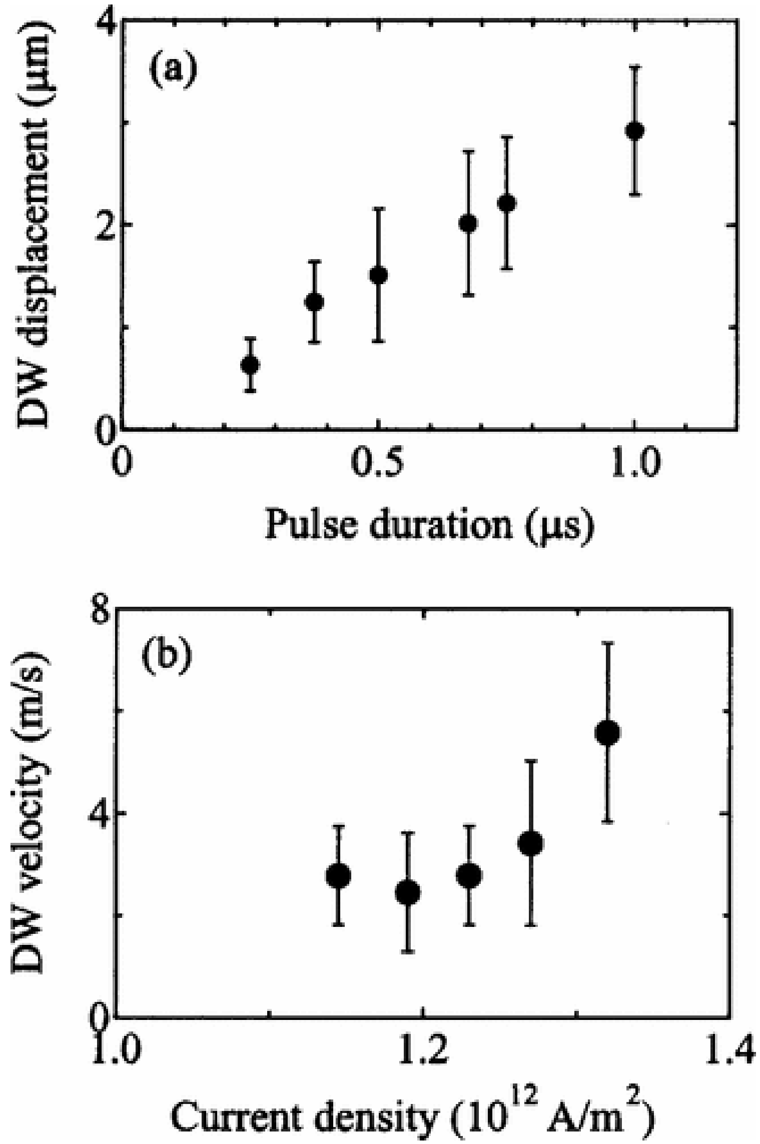


Yamaguchi, et al, PRL (2004)

Domain wall motion by STT

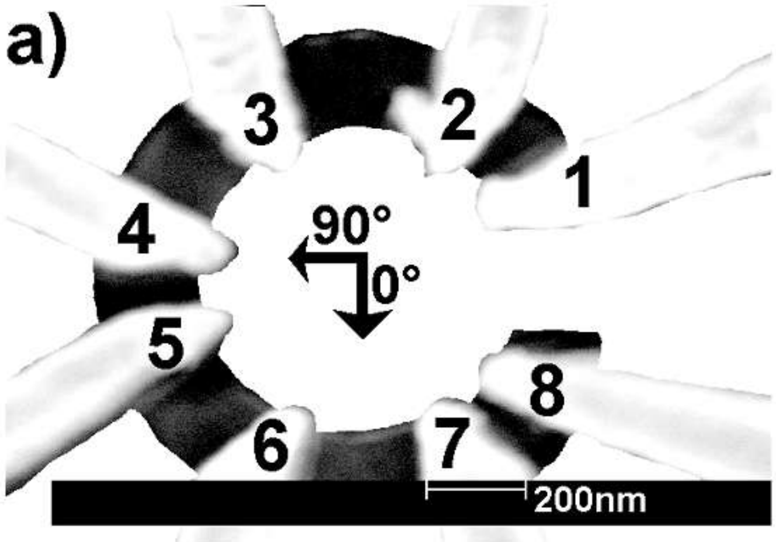


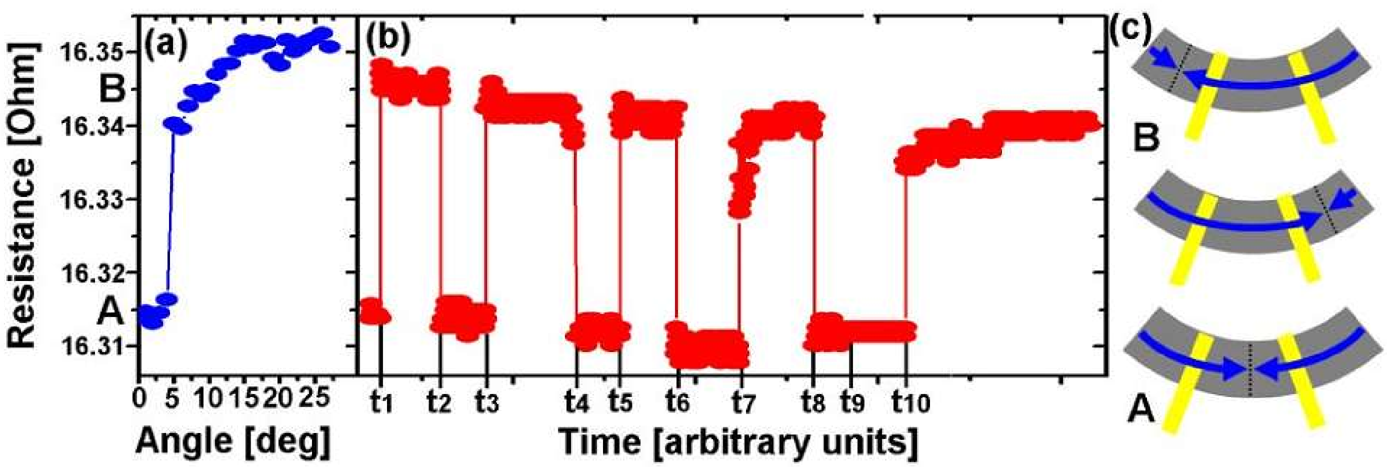
Domain wall motion by STT



Domain wall motion by STT

FM Metal

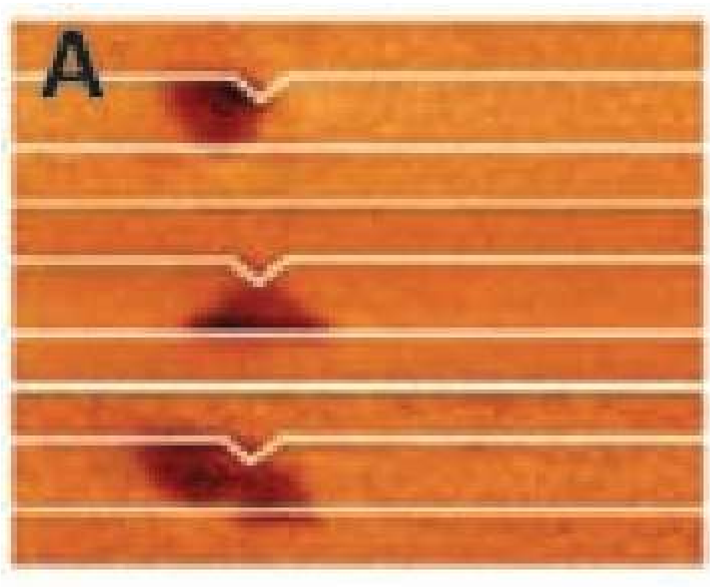


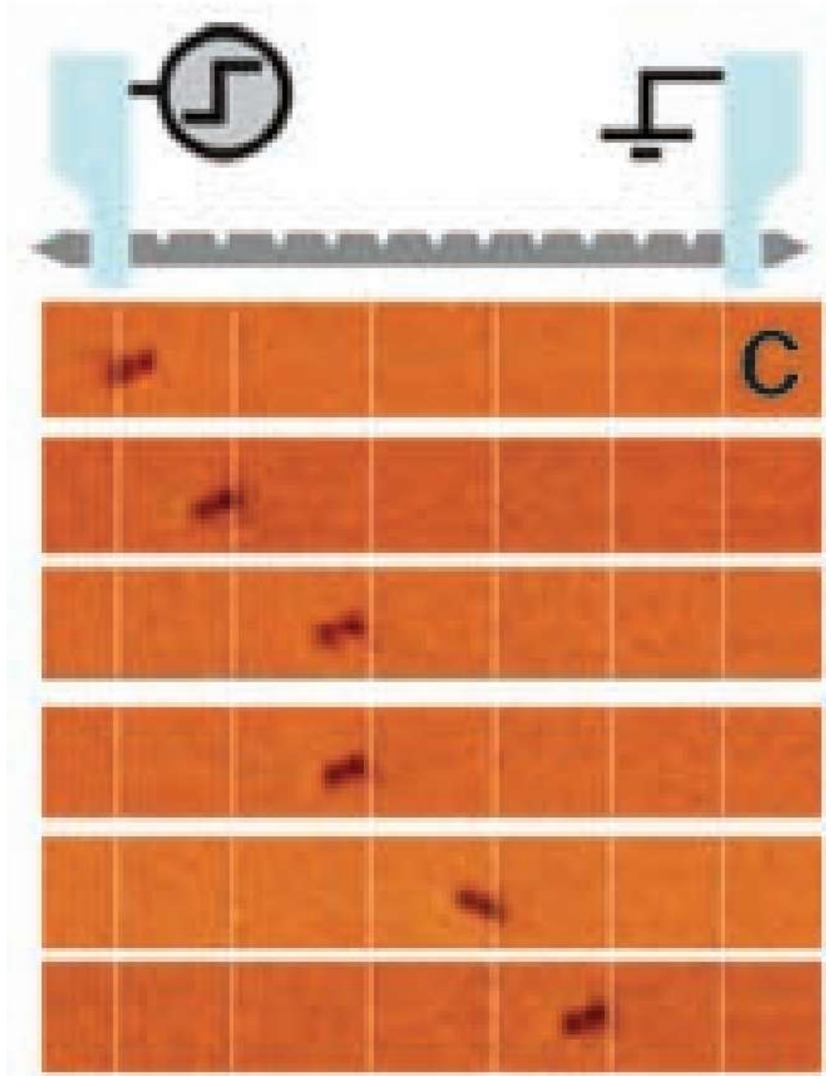


Kalui, et al, PRL (2005)

Domain wall motion by STT

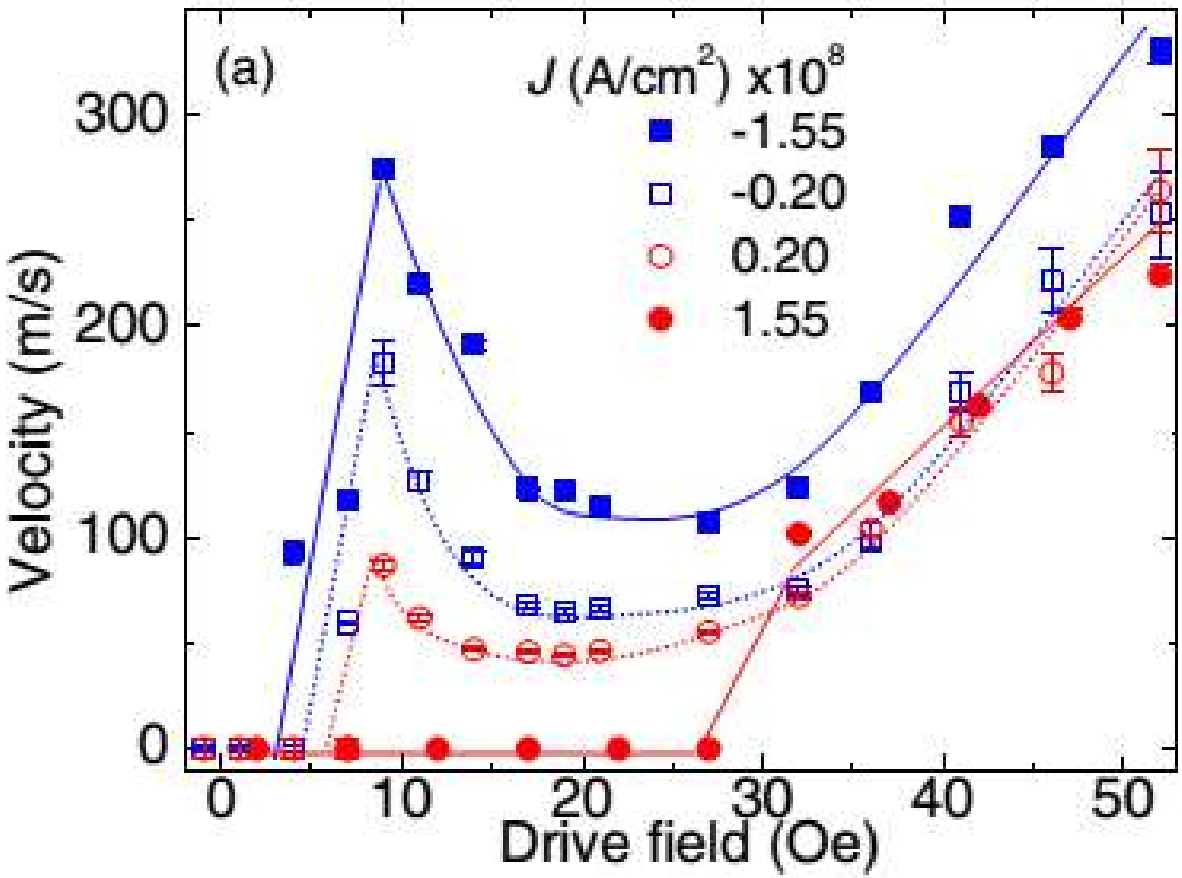
A notch





Domain wall motion by STT

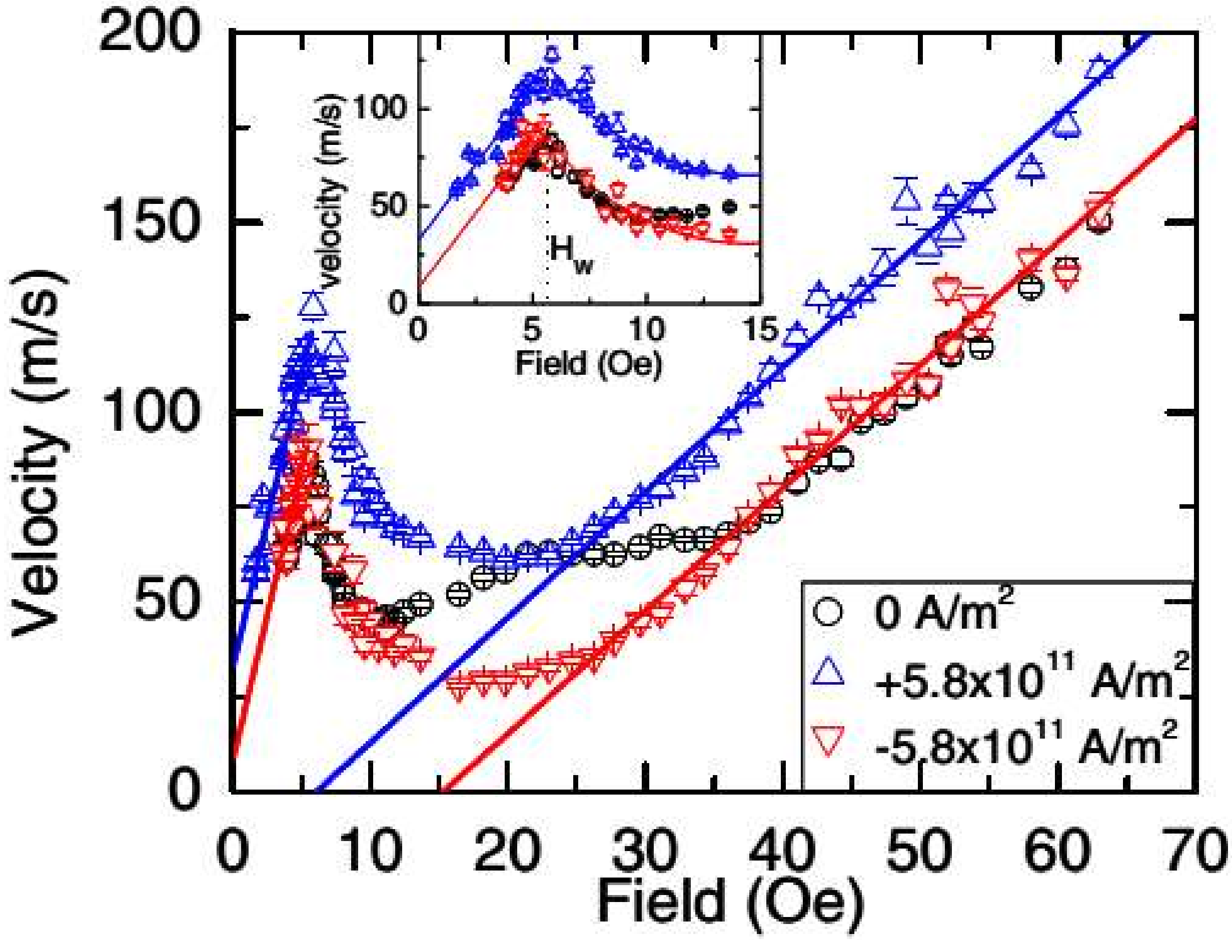
Critical Current and velocity increase



Hayashi, et al, PRL (2006)

Domain wall motion by STT

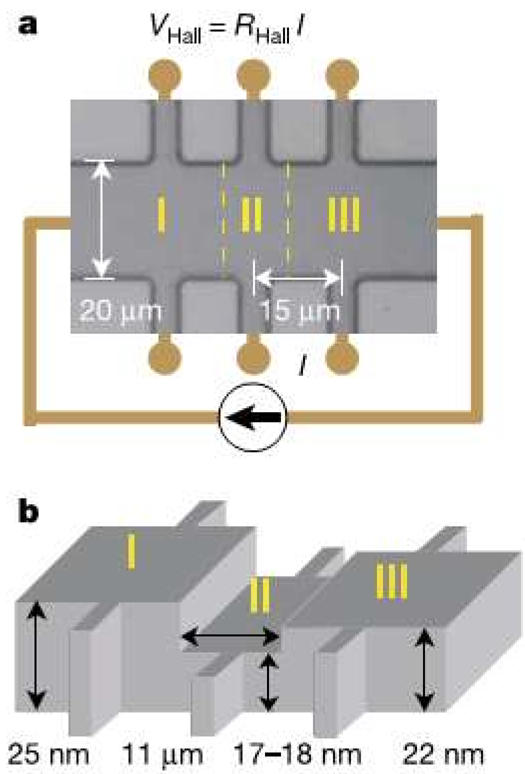
Critical Current

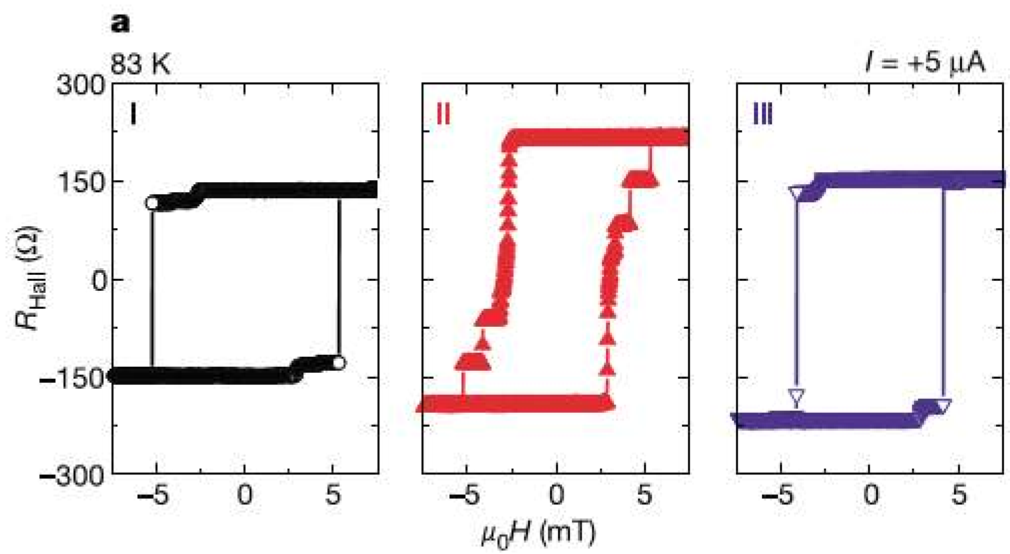


Beach, et al, PRL (2006)

Domain wall motion by STT

FM Semiconductor: GaMnAs

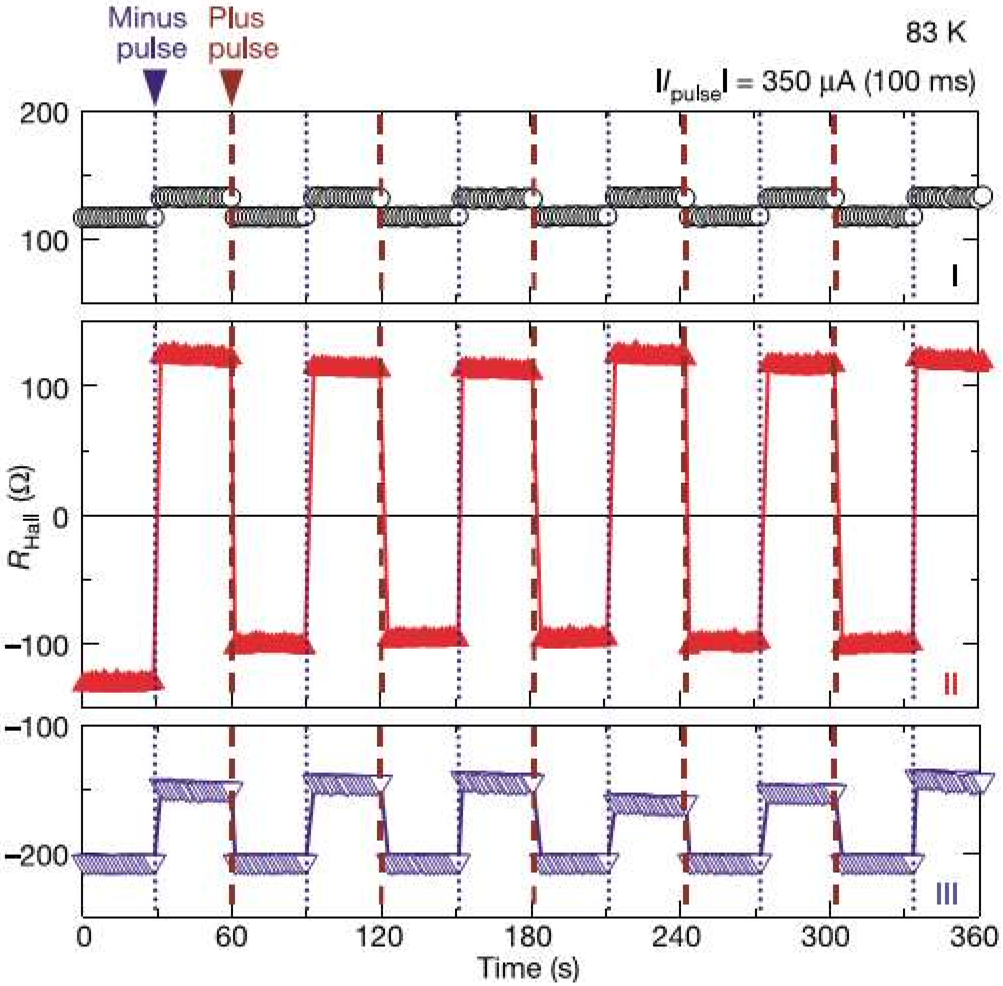




Yamaguchi, et al, Nature (2004)

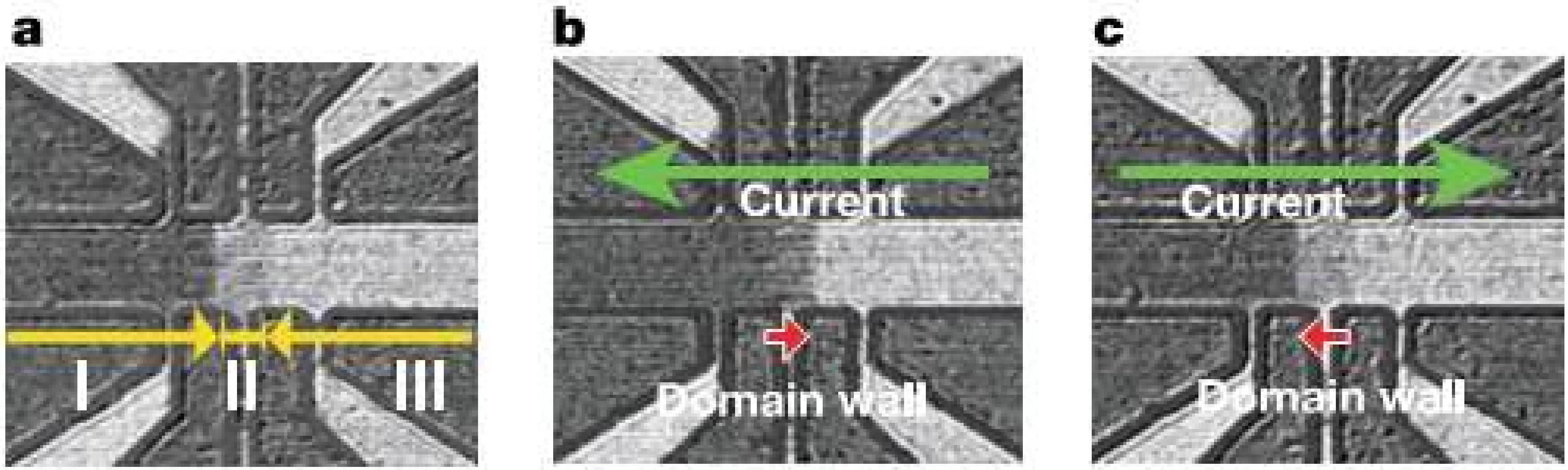
Domain wall motion by STT

FM Semiconductor: GaMnAs



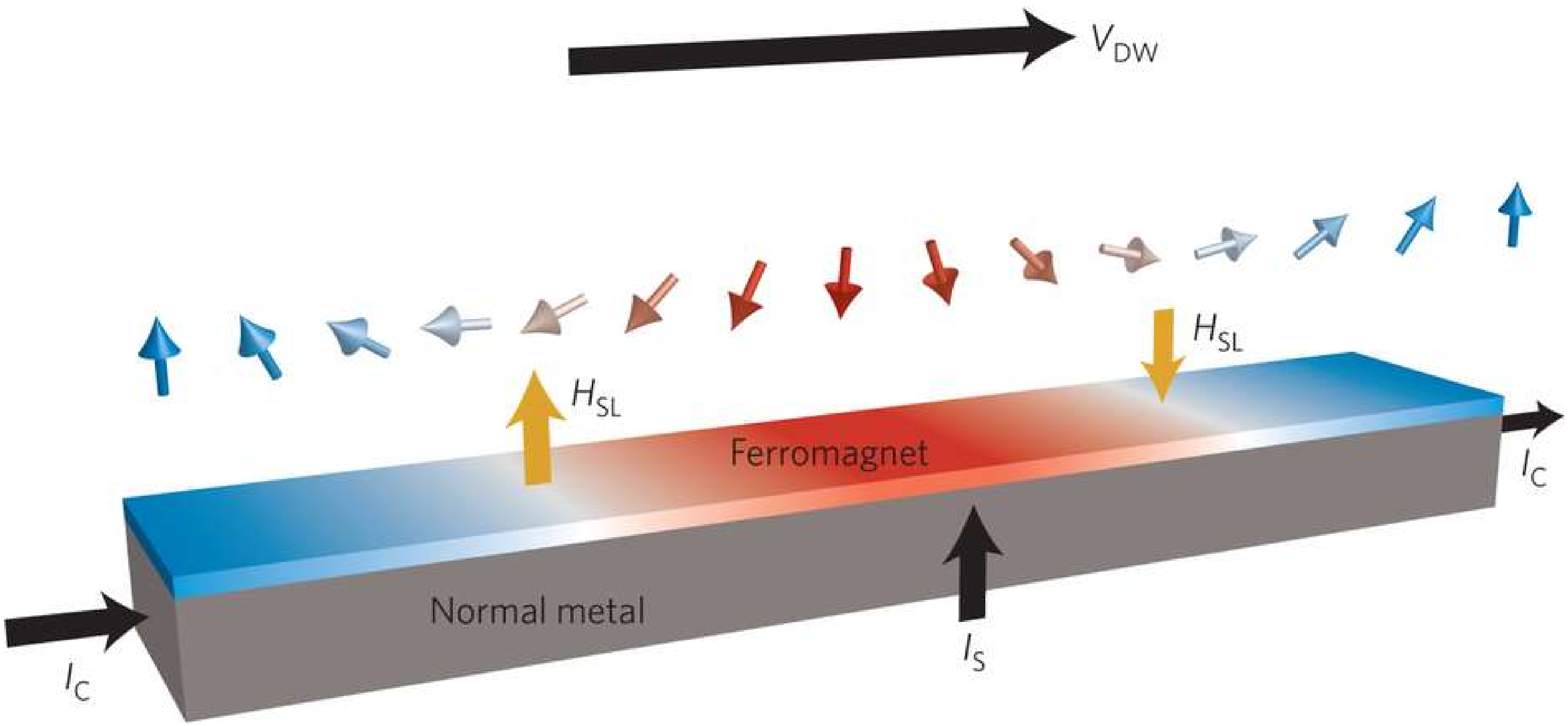
Domain wall motion by STT

FM Semiconductor: GaMnAs



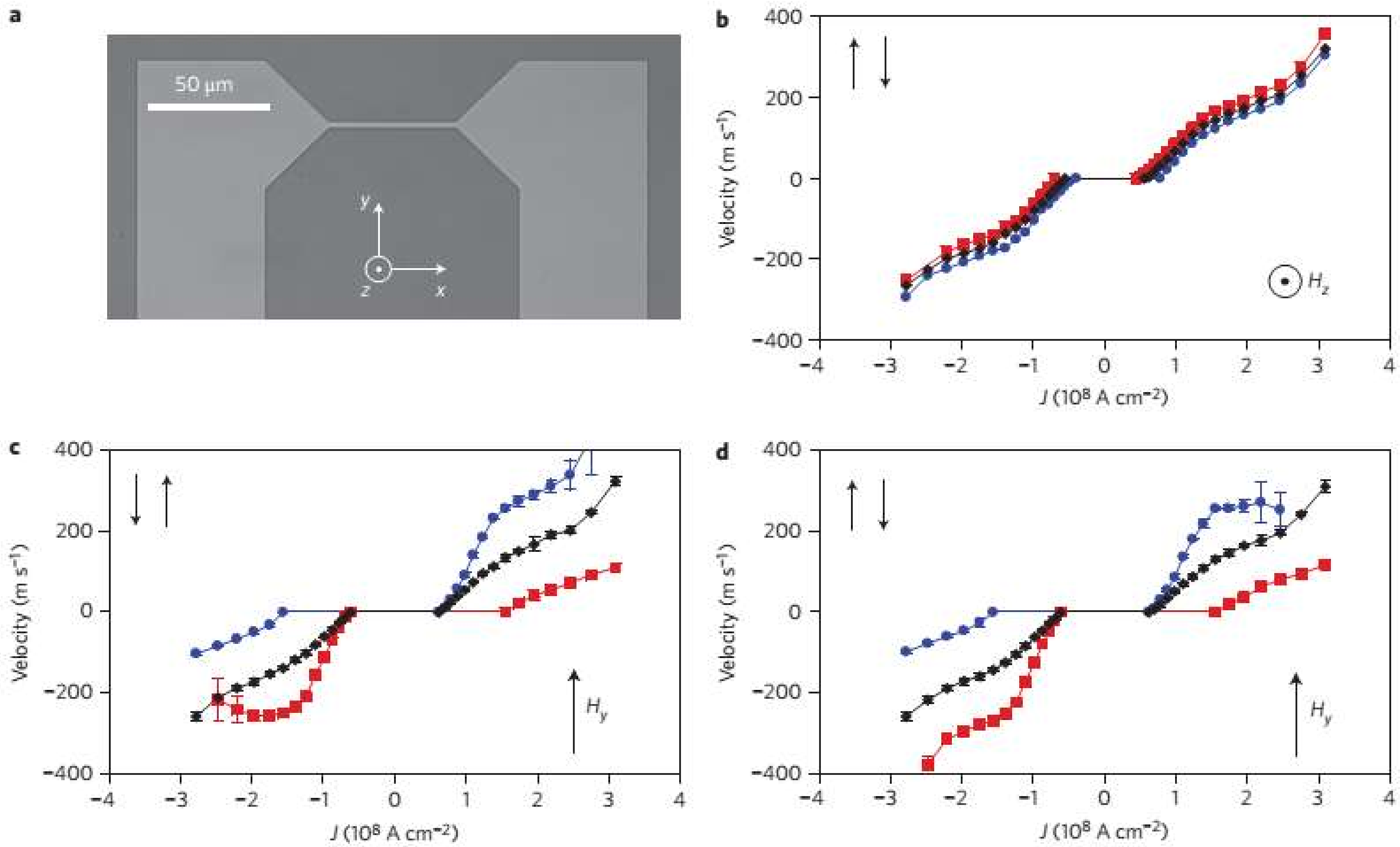
Initial state | After I = −300 μA (100 ms) | After I = +300 μA (100 ms)

Fast domain wall motion



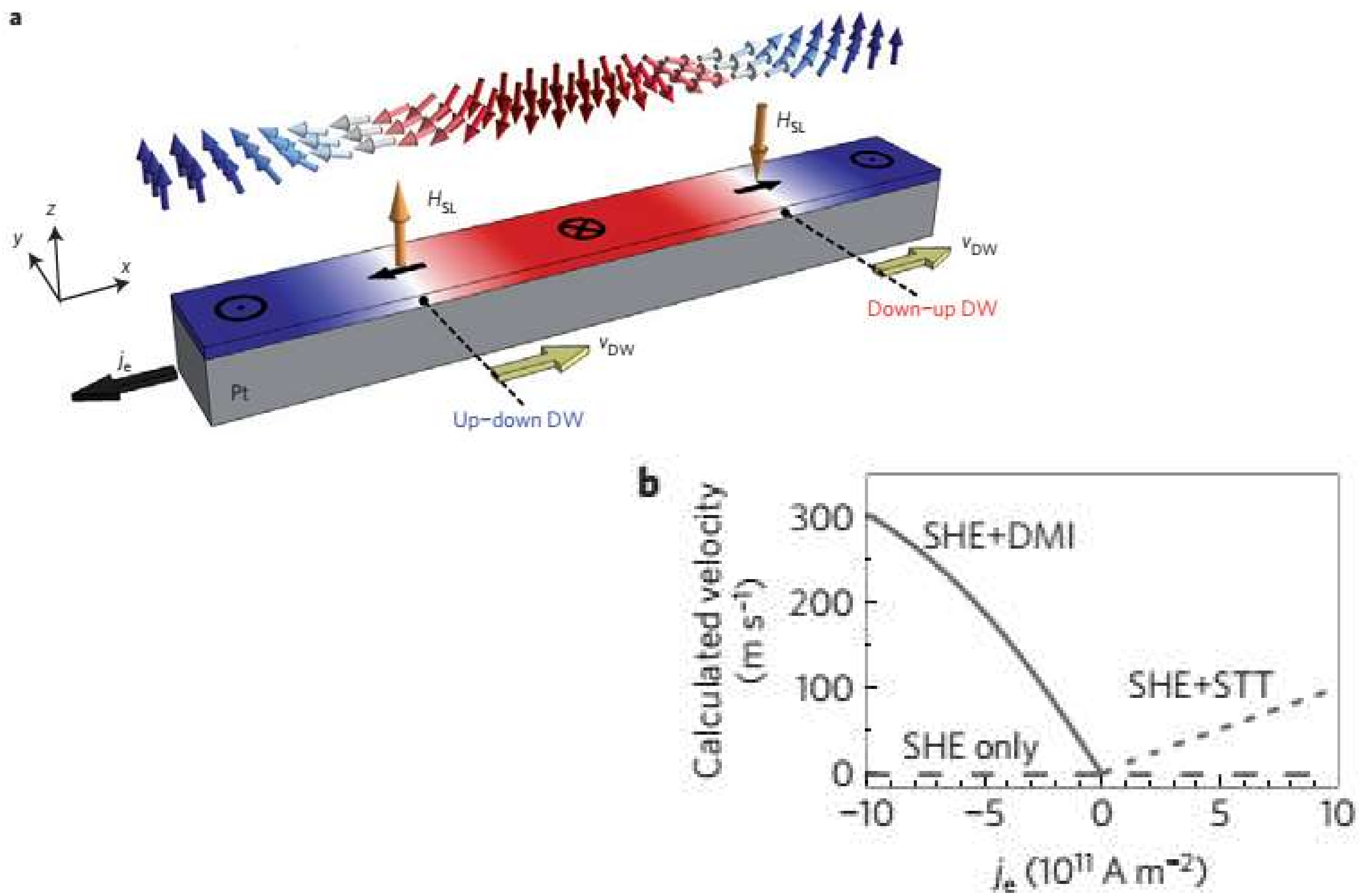
Brataas, Nature Nanotech (2013)

Fast domain wall motion



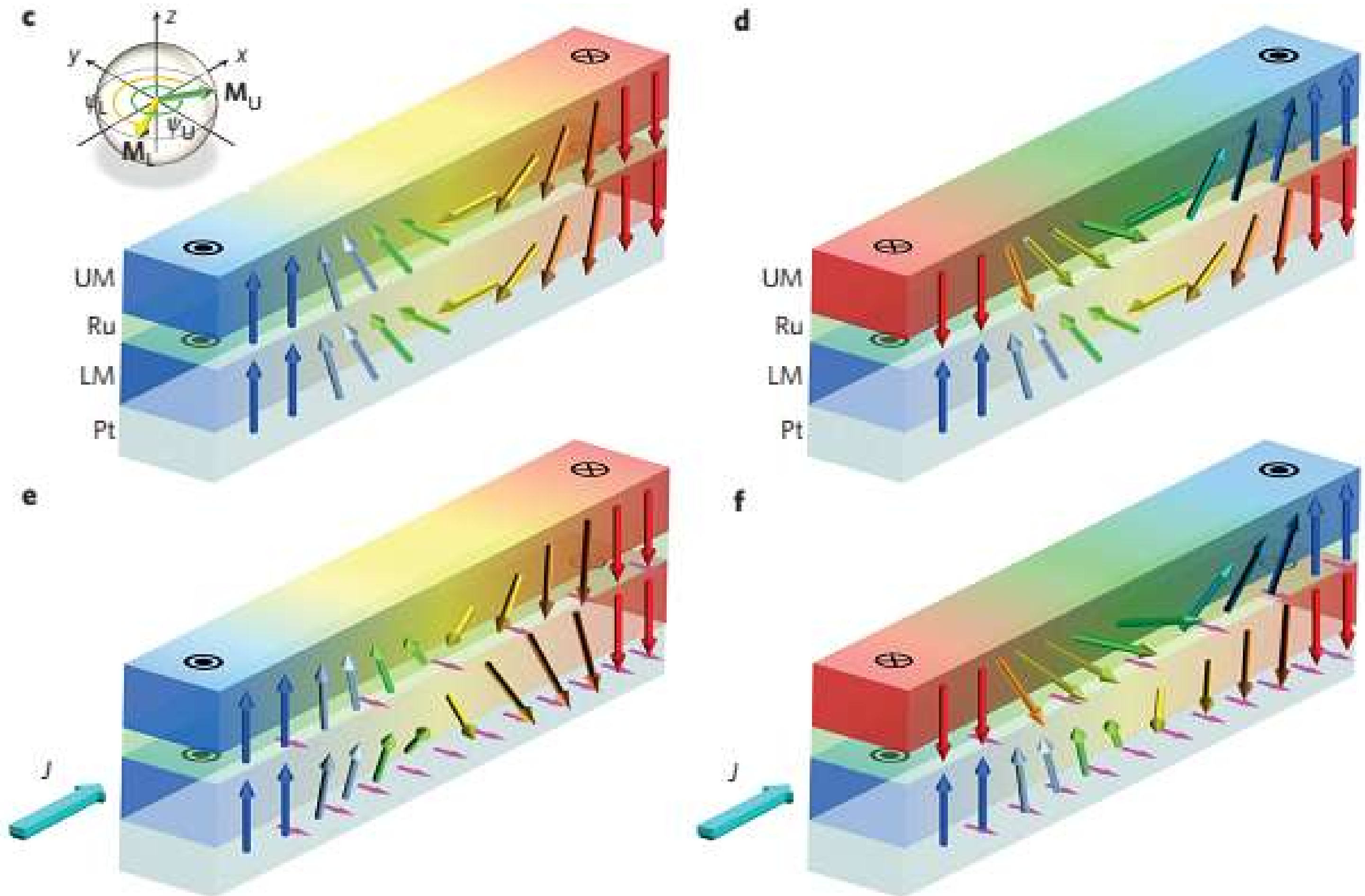
Ryu, et al, Nature Nanotech (2013)

Fast domain wall motion



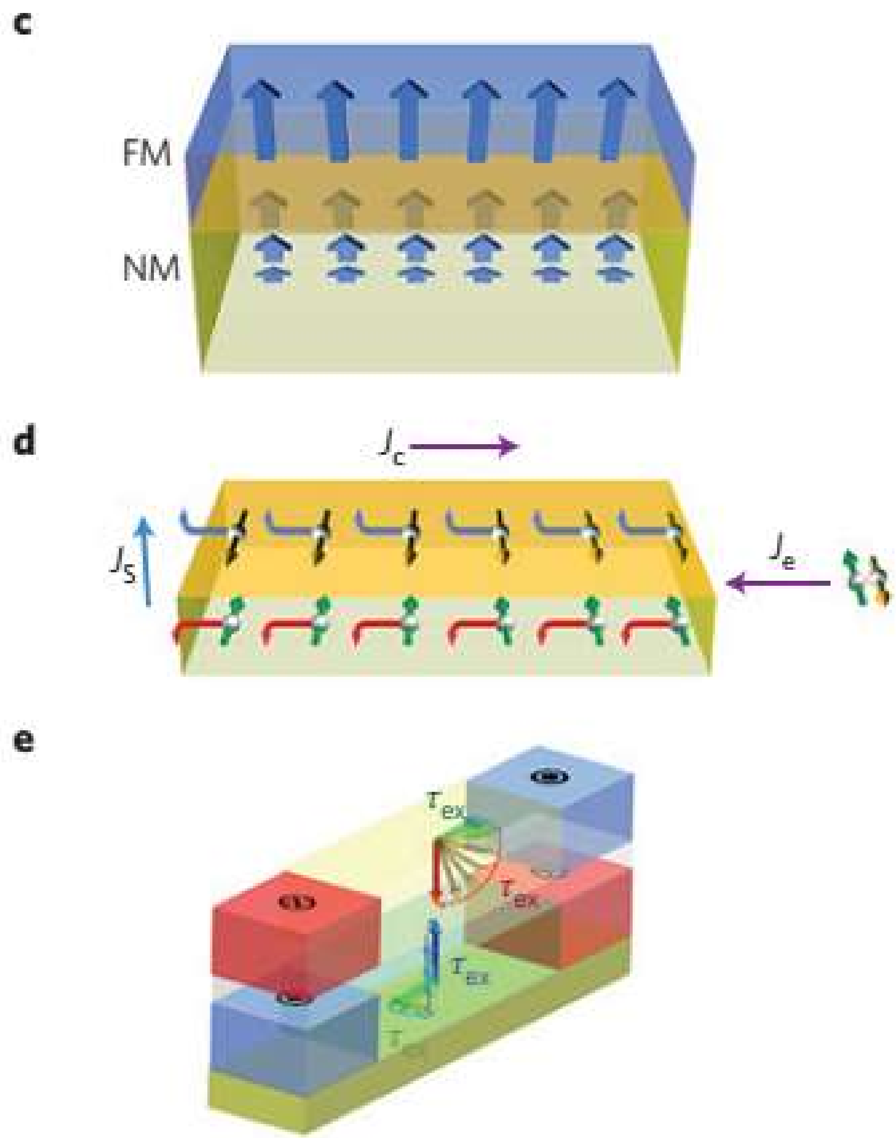
Emori, et al, Nature Materials (2013)

Fast domain wall motion

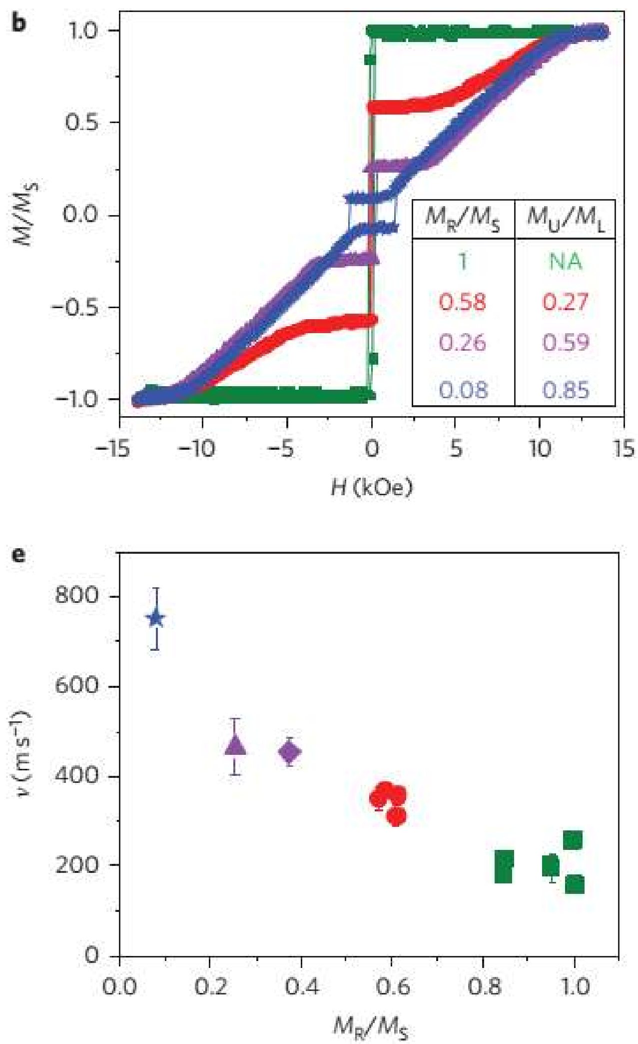


Yang, et al, Nature Nanotech (2015)

Fast domain wall motion

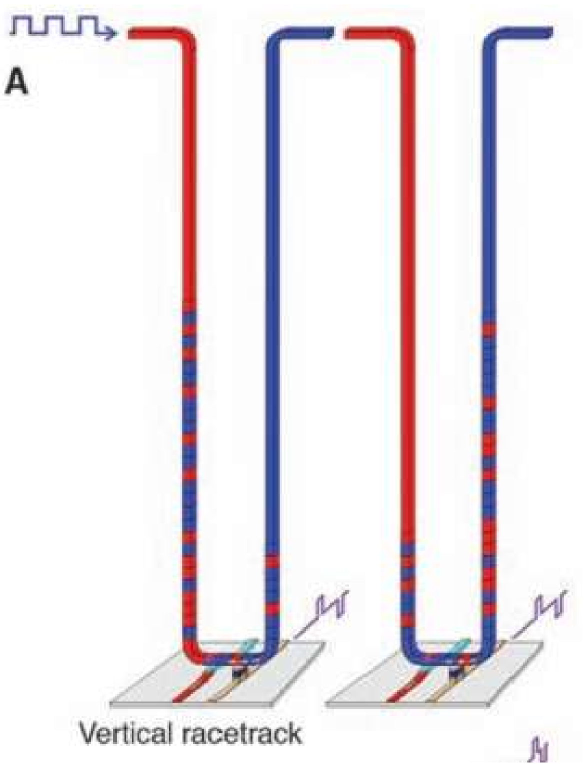


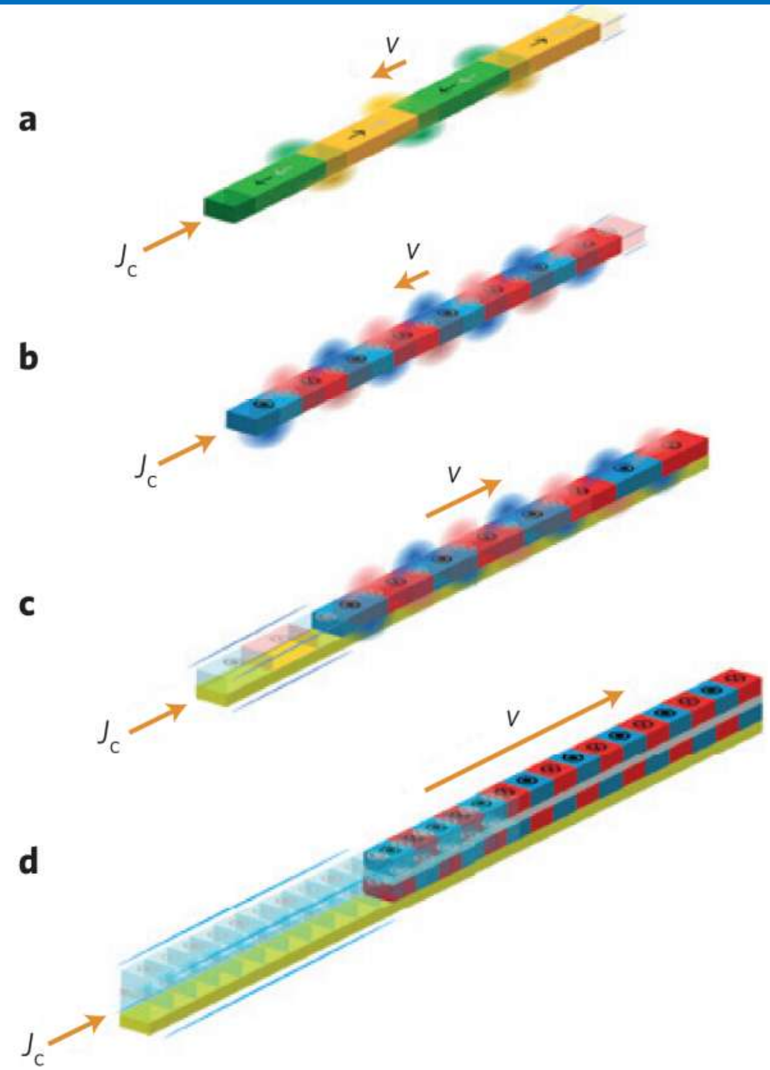
Fast domain wall motion



Yang, et al, Nature Nanotech (2015)

Fast domain wall motion



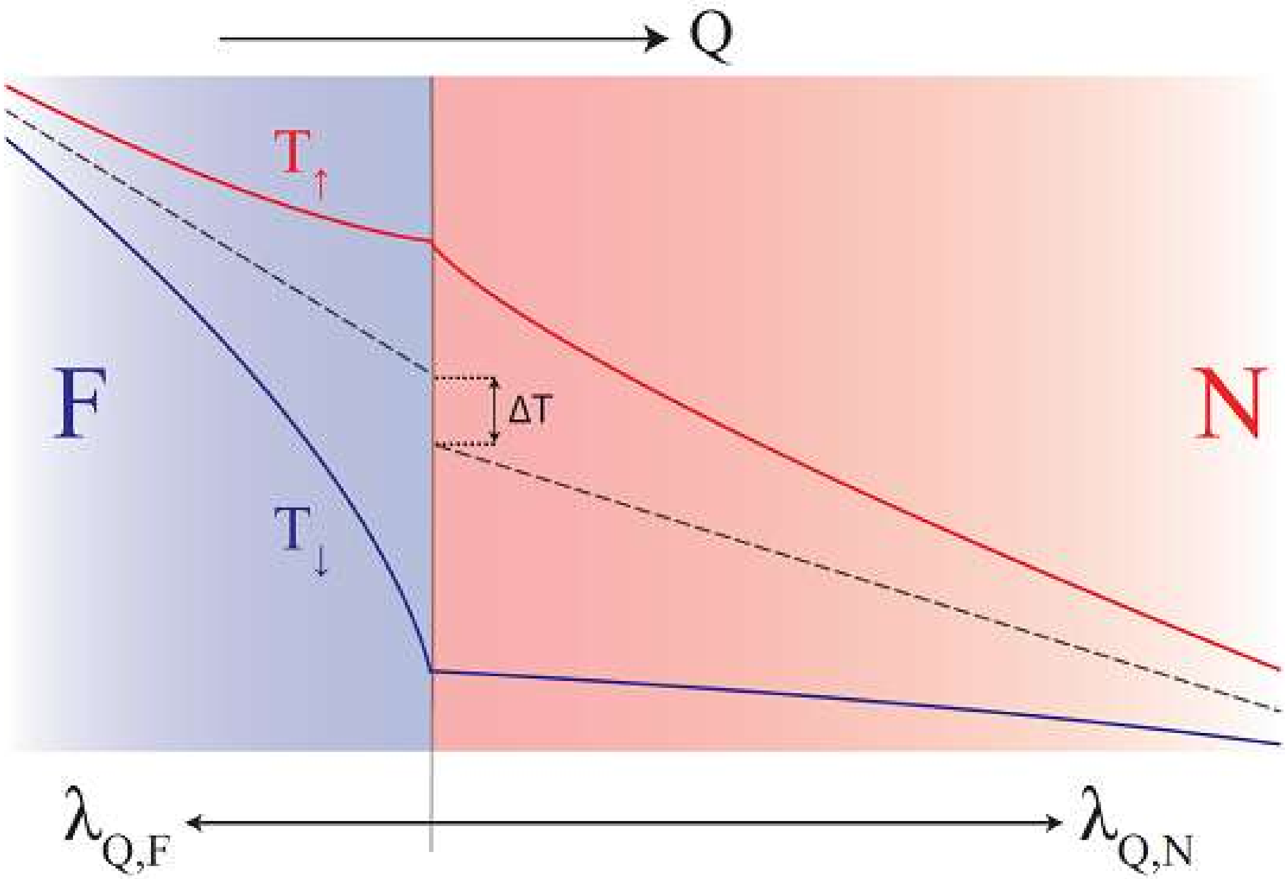


Parkin & Yang, et al, Nature Nanotech (2015)

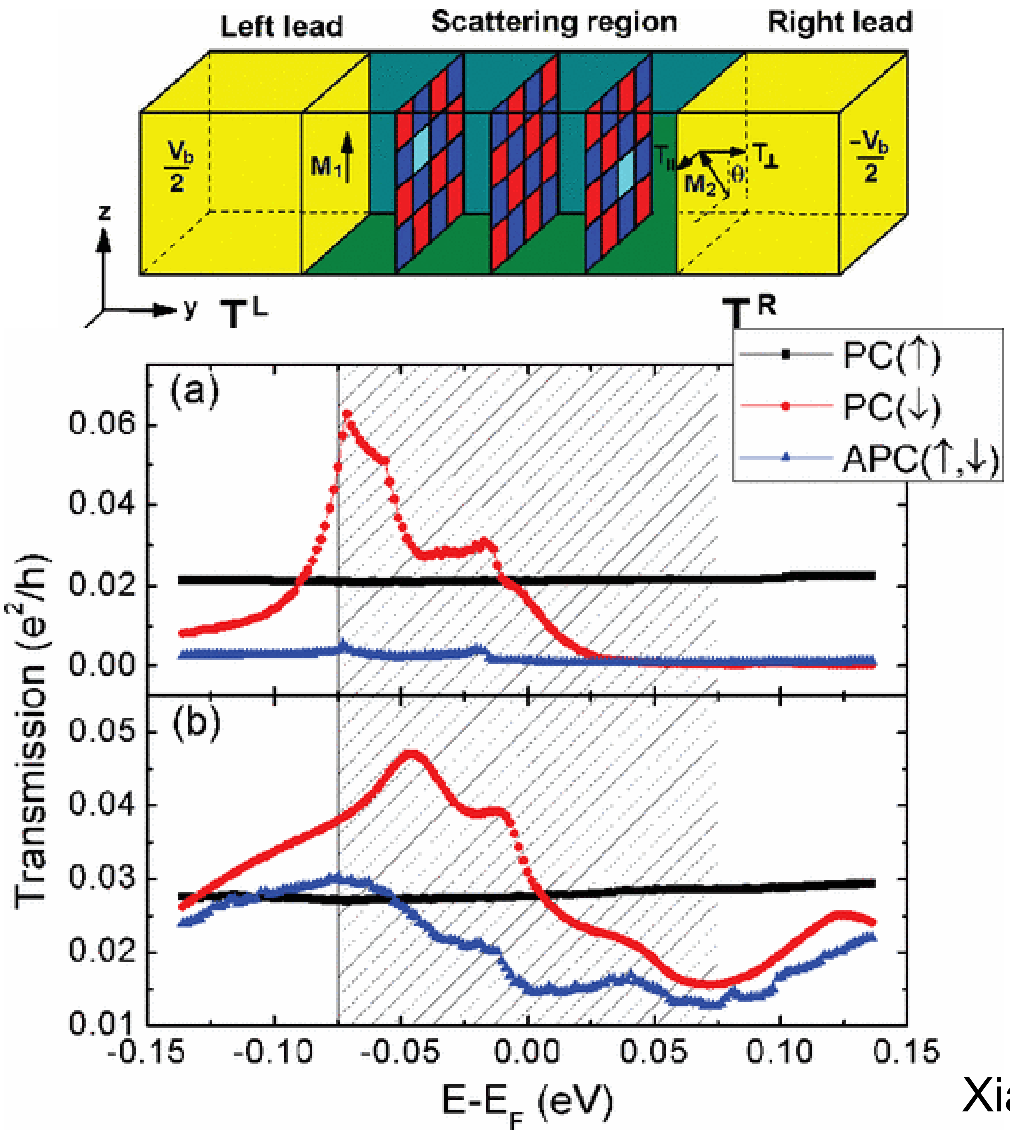
Outline

5. Thermal spin transfer torque

Thermal Spin Injection

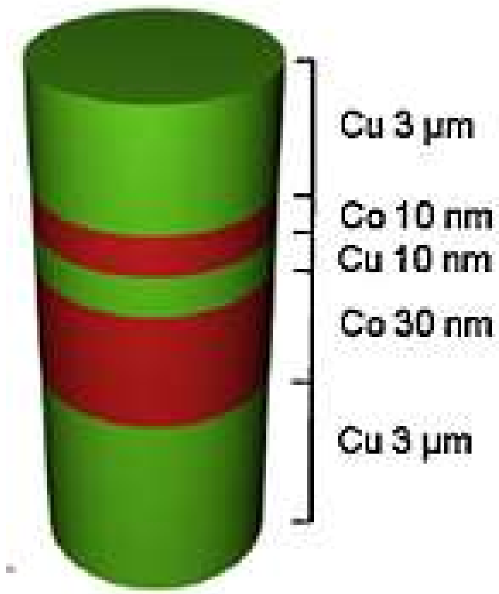


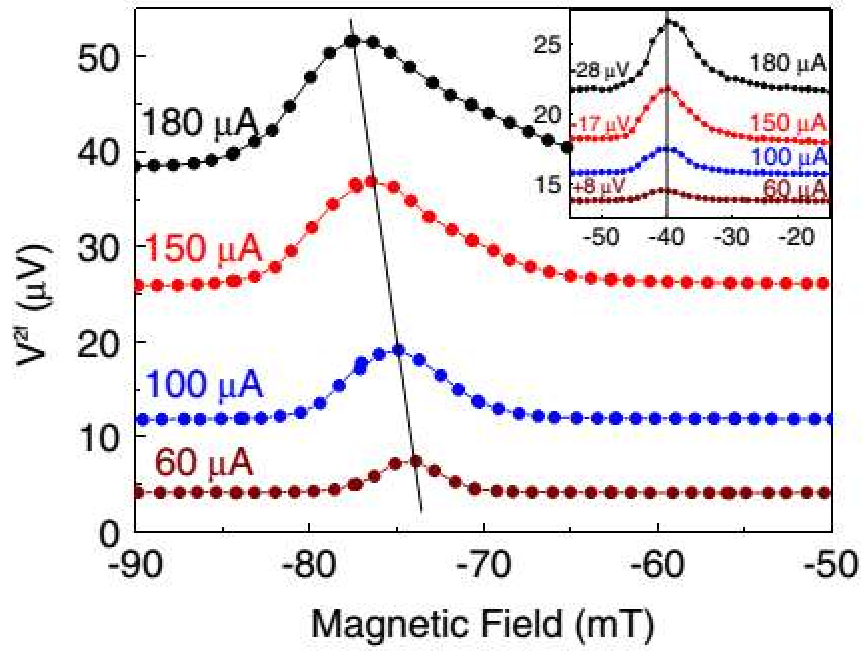
Thermal Spin torque



Xia, et al, PRL (2011)

Thermal Spin torque

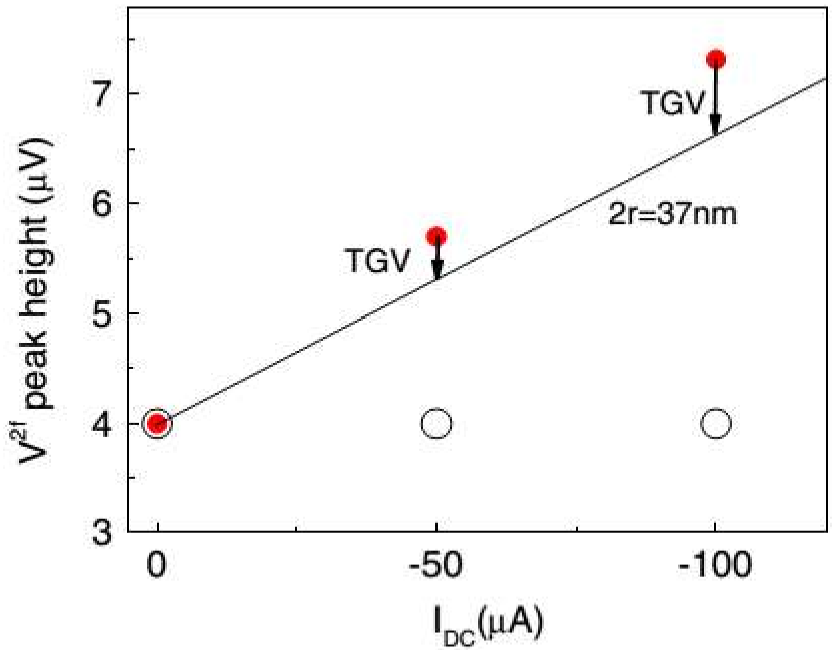


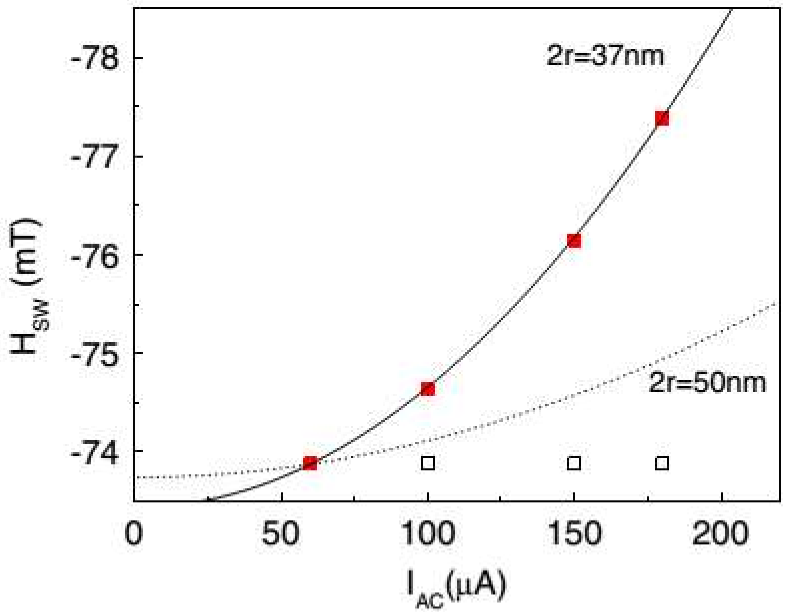


Yu, et al, PRL (2010)

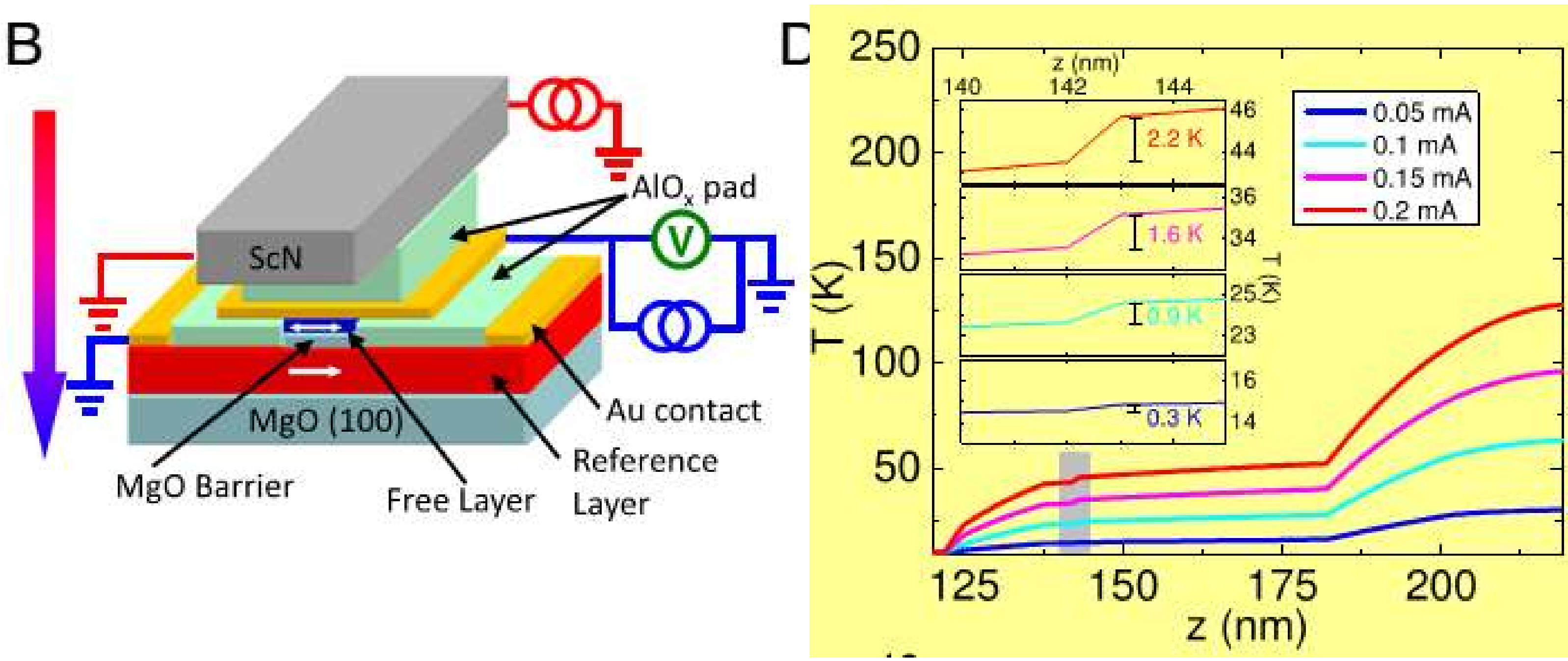
Thermal Spin torque

$$\tau \propto P\Delta V + P' S \Delta T,$$



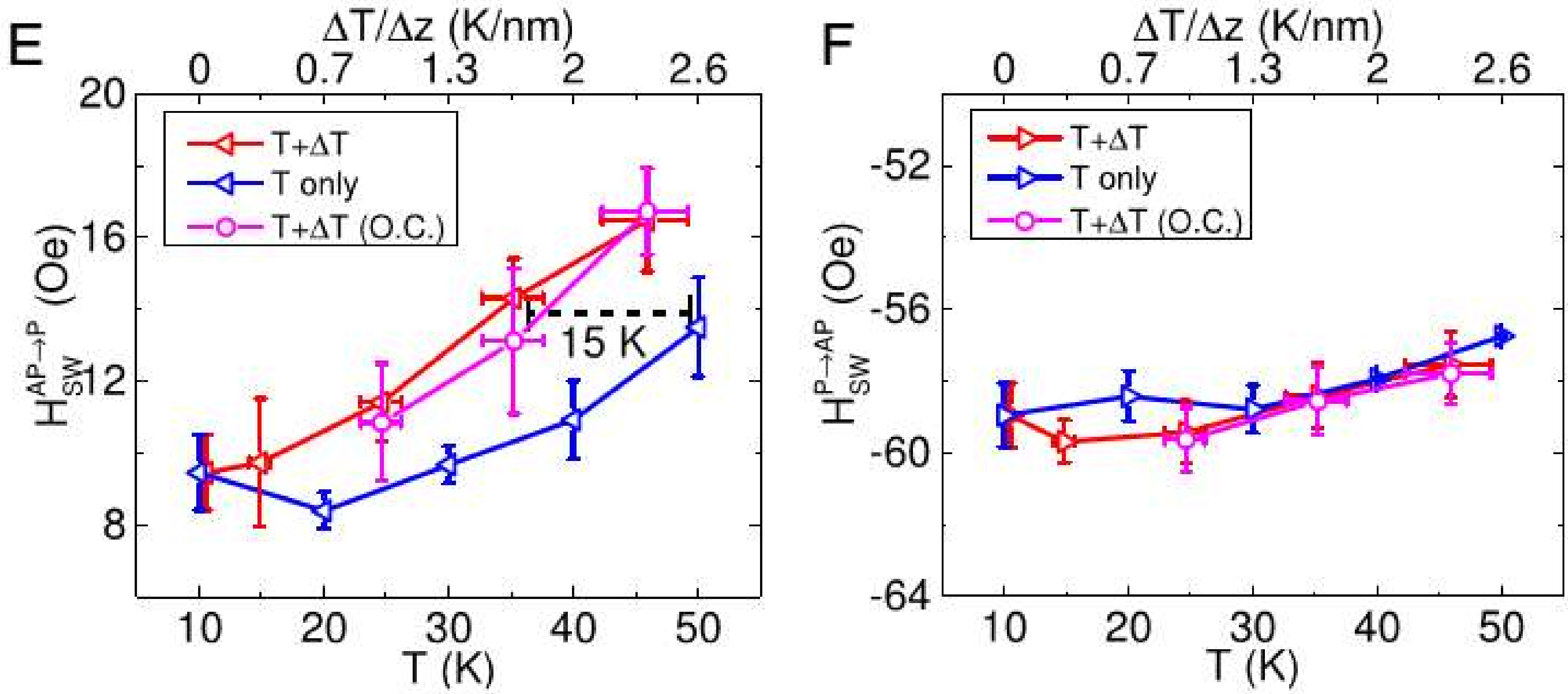


Thermal Spin torque



Pushup, et al, PNAS (2015)

Thermal Spin torque

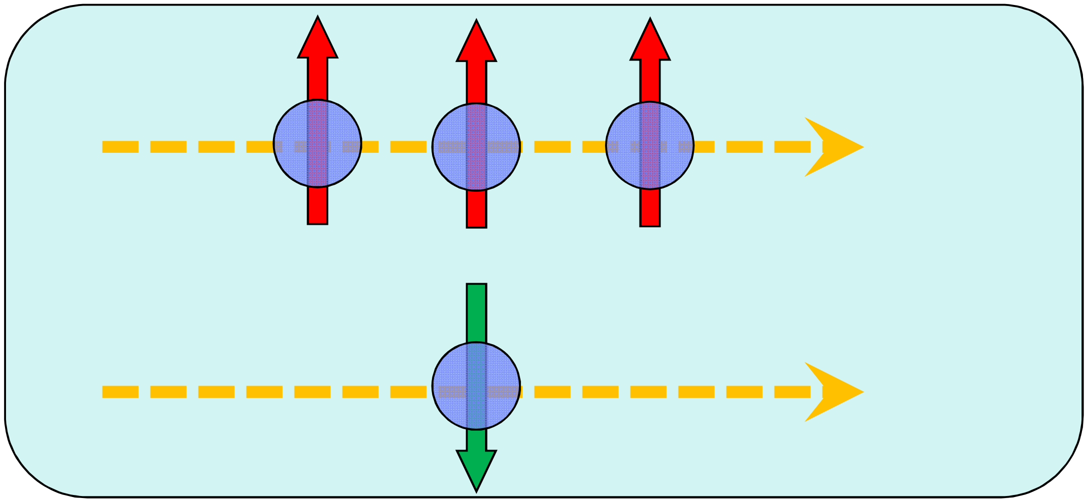


Outline

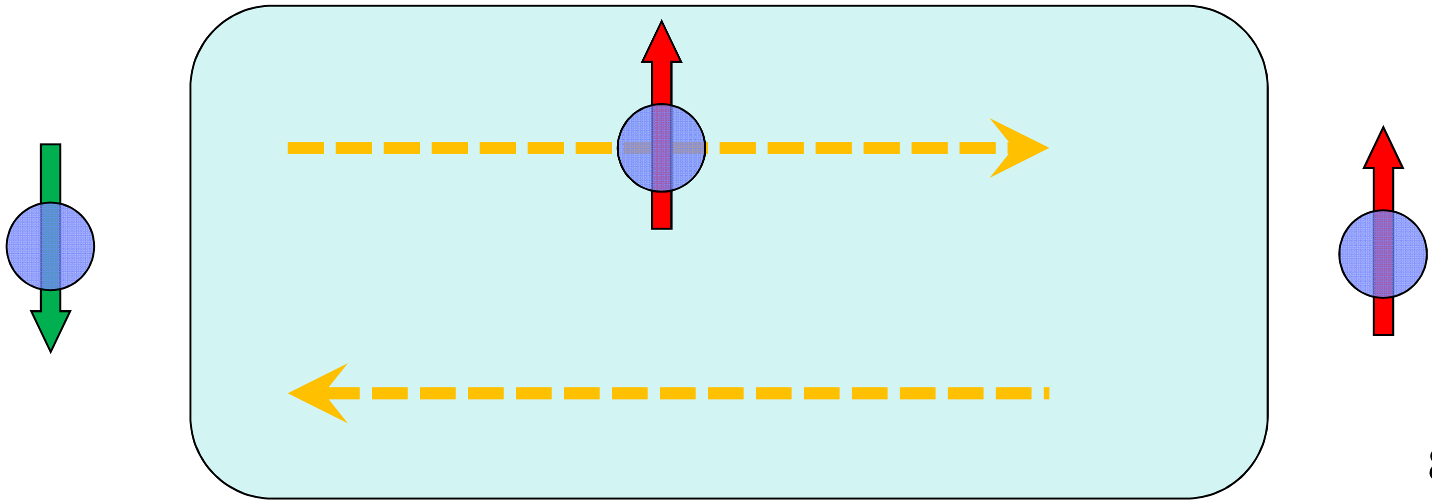
6. Pure spin current transfer torque

Pure spin current

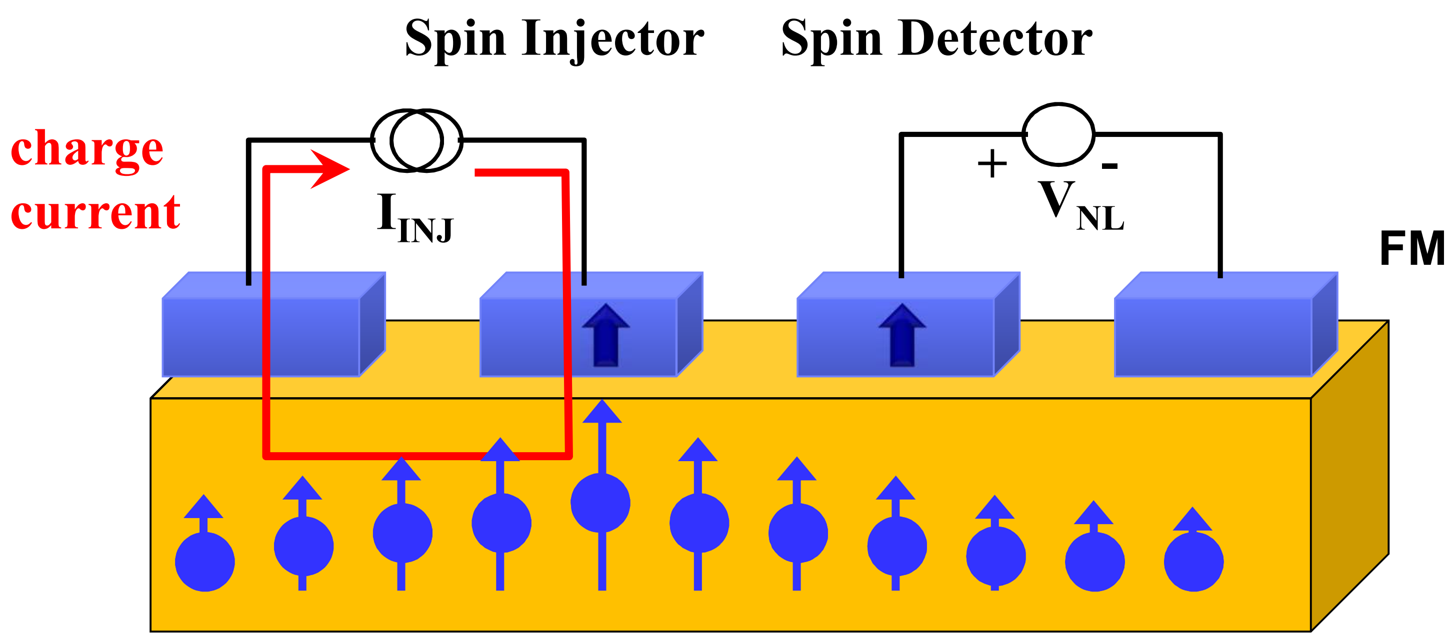
Spin polarized current



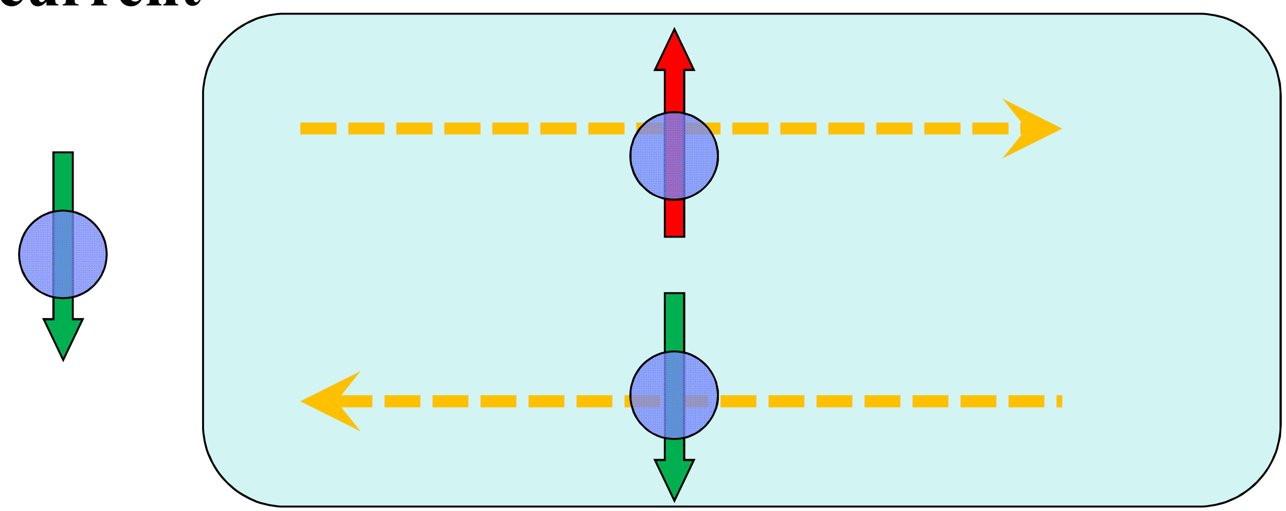
Pure spin current



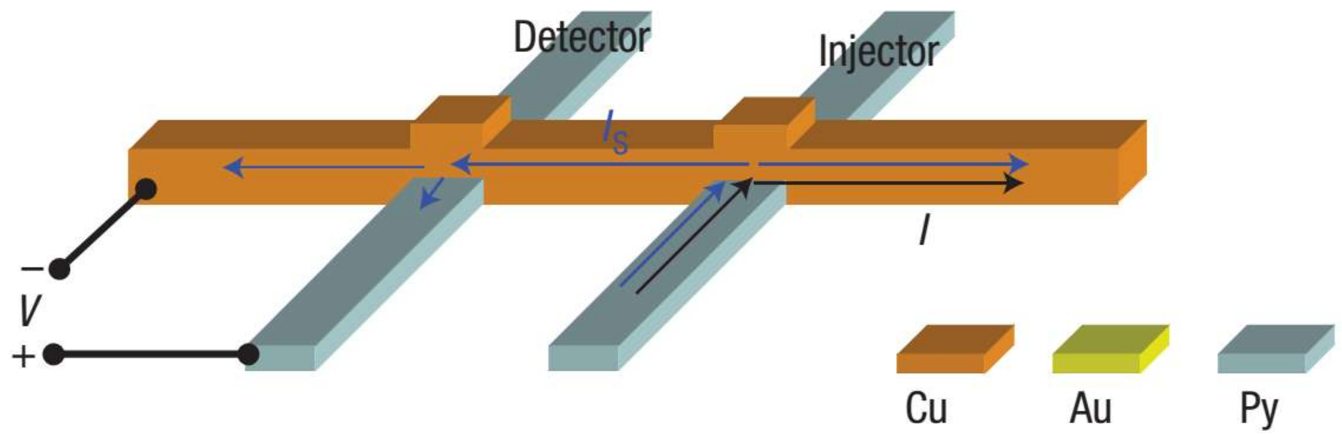
Pure spin current

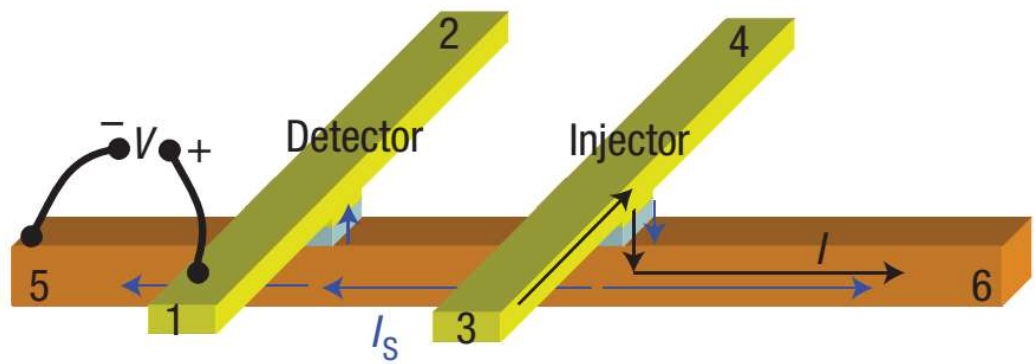


Pure spin current



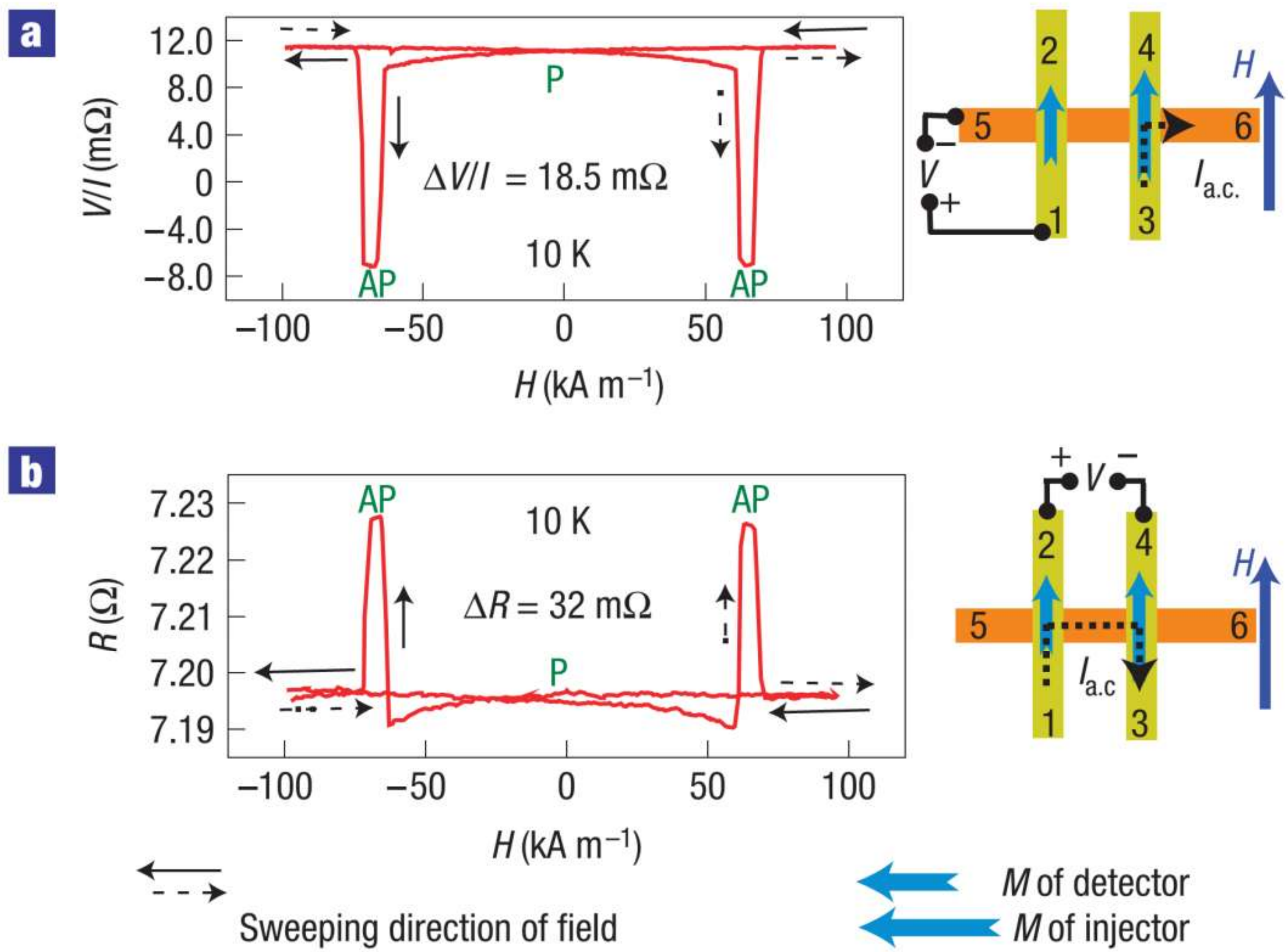
Pure spin current torque



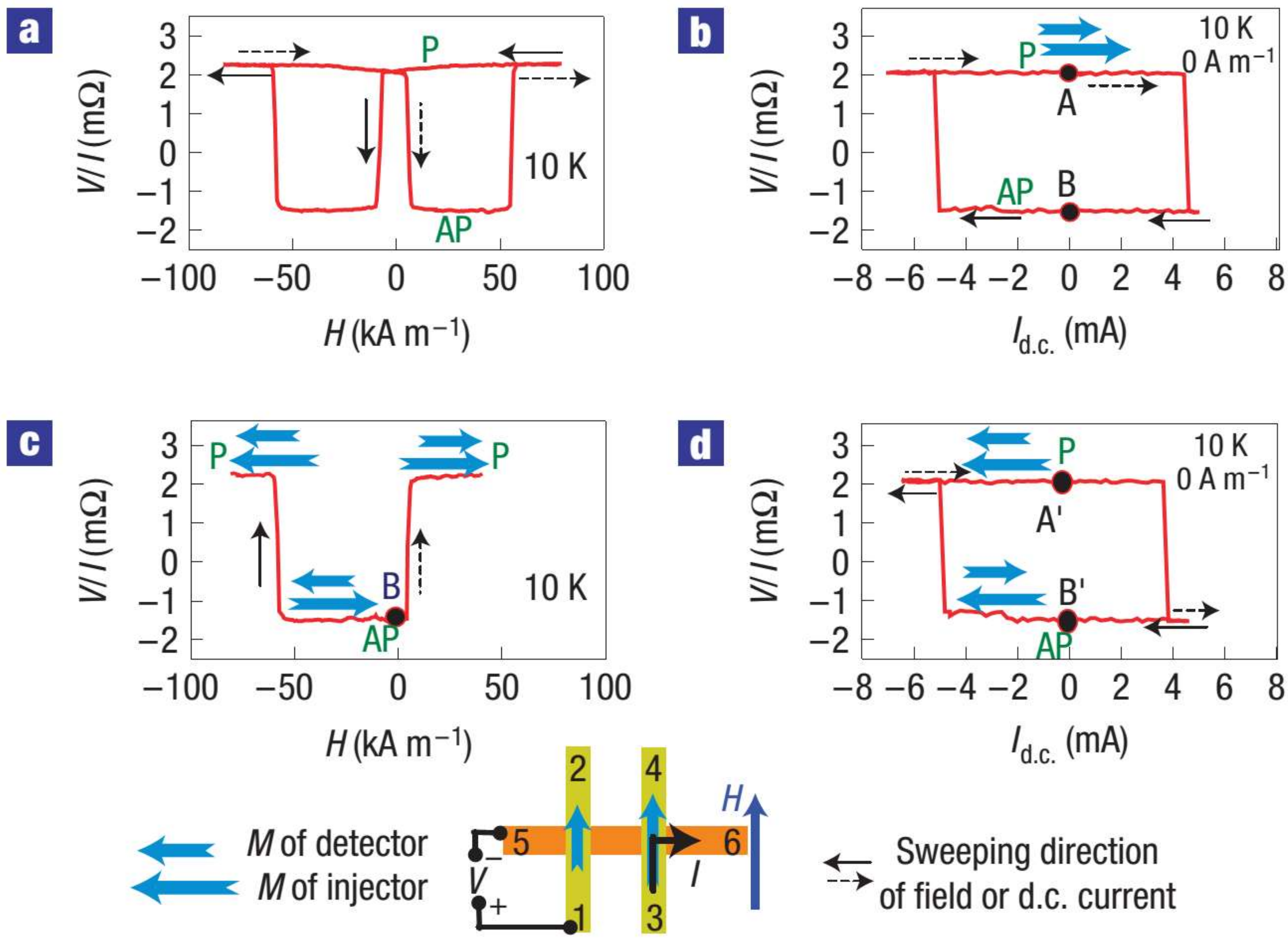


Yang, et al, Nature Physics (2008)

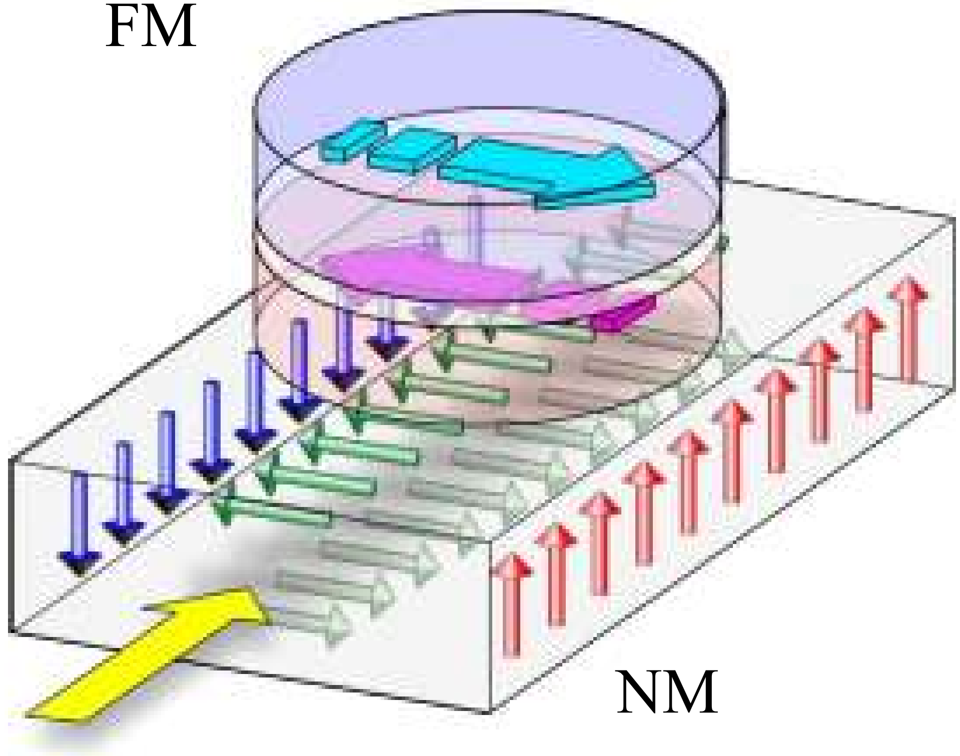
Pure spin current torque



Pure spin current torque



Spin orbit torque

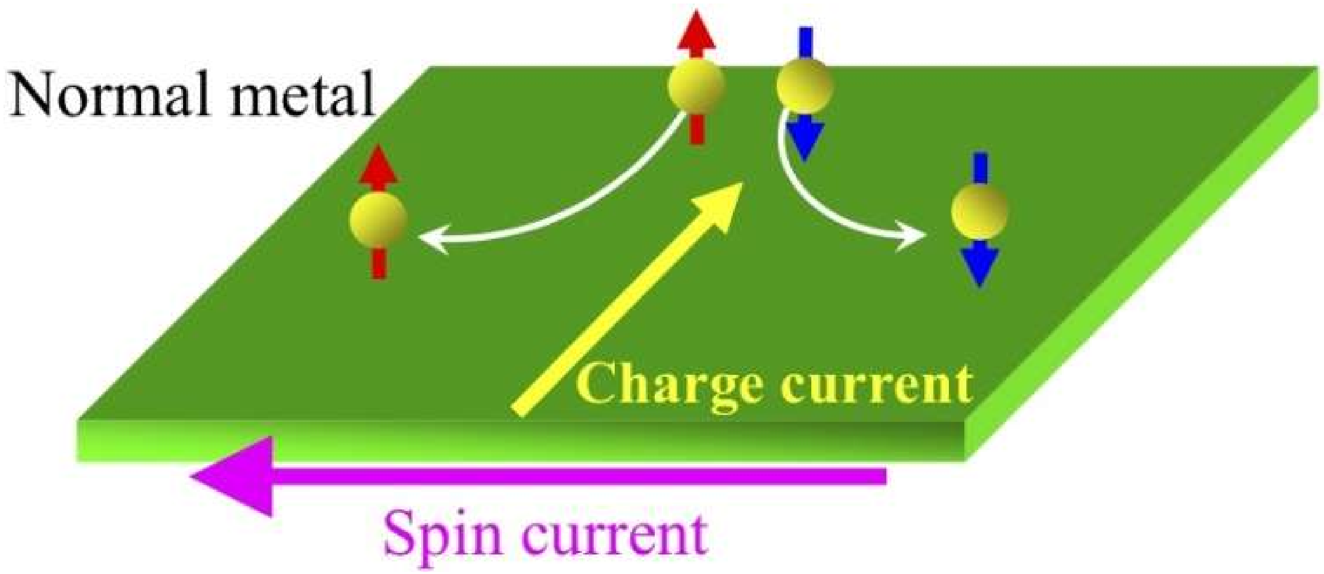


$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$

Brataas, Nature Nano (2014)

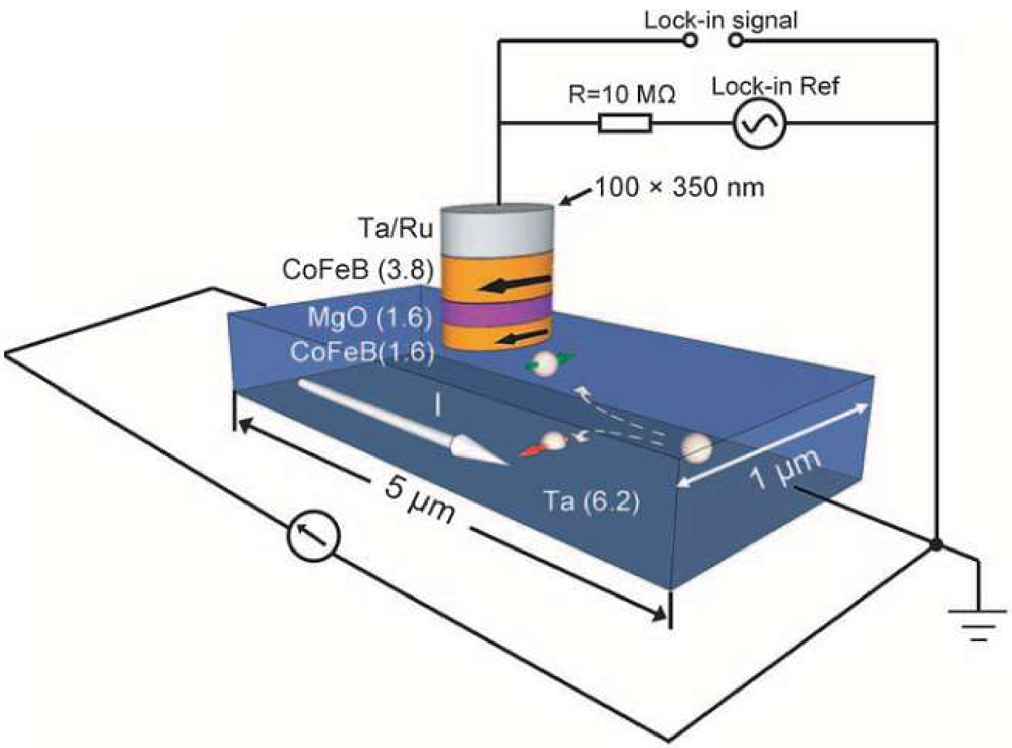
Other ways for pure spin current

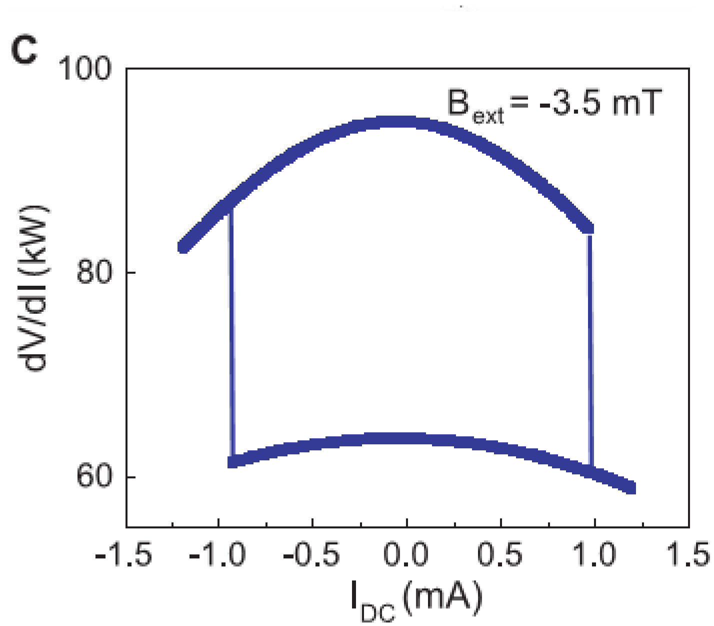
Spin Hall effect



D'yakonov, M. I. & Perel', J. Exp. Theor. Phys. Lett. 13, 467-469, (1971).
Hirsch, J. E. Phys. Rev. Lett. 83, 1834-1837, (1999).
Zhang, S. Phys. Rev. Lett. 85, 393-396, (2000).

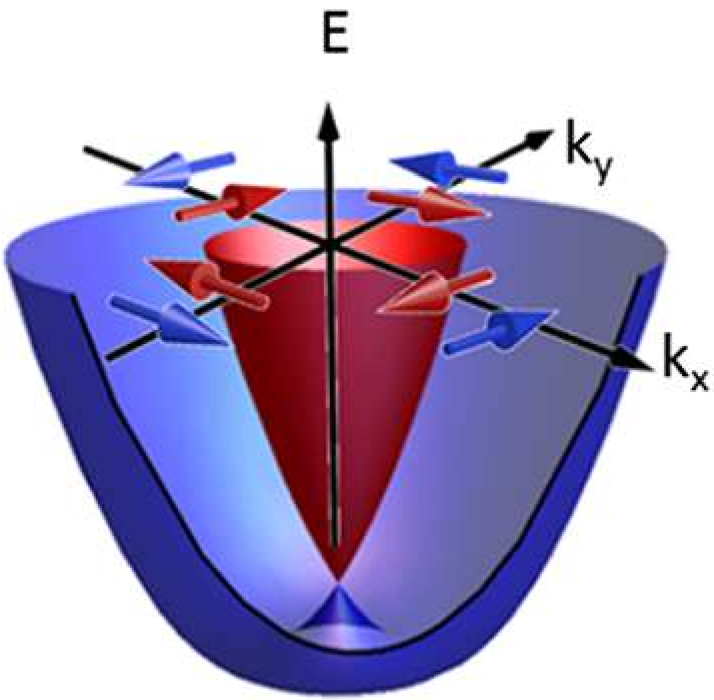
Spin Hall torque

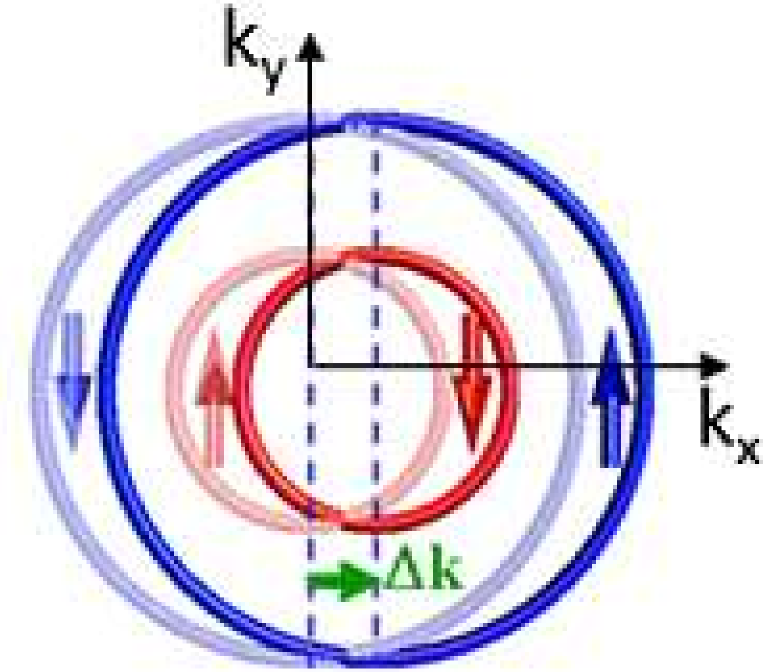




Liu, et al, Science (2012)

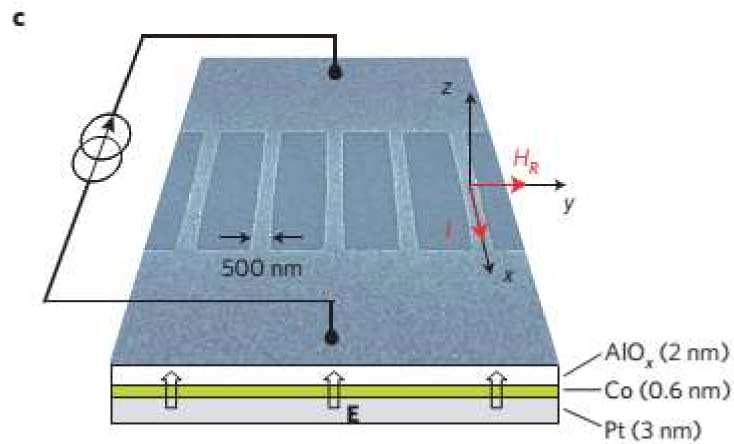
Other ways for pure spin current

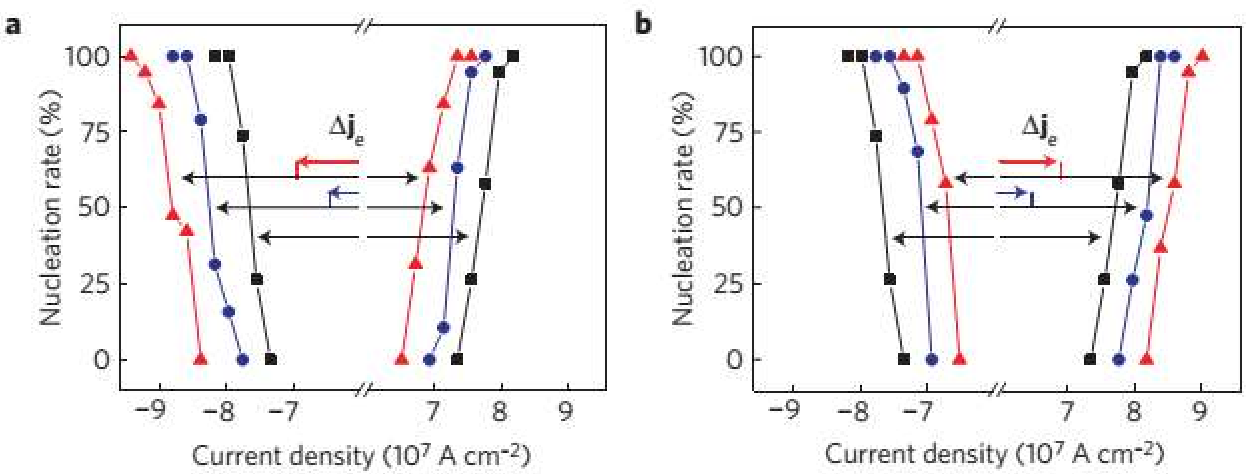




V. M. Edelstein, Solid State Commun. 73, 233 (1990)
A. Manchon, et al, Nat. Mater. 14, 871 (2015)
J. C. R. Sánchez, et al, Phys. Rev. Lett. 116, 096602 (2016)

Rashba field torque





Miron, et al, Nature Materials (2011)

Summary

1. Theory and observation of spin transfer torque

2. Spin transfer torque and spin pumping

3. Spin transfer torque in MTJ

4. Spin transfer torque in domain wall motion

5. Thermal spin transfer torque

6. Pure Spin current transfer torque

Summary

John Slonczewski

Luc Berger

下一节课: Nov. 15th

Chapter 5: Spin Orbit Torque, spin Hall effect, Rashba-Edelstein effect

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

谢谢！