

# Chapter 5

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## Spin Transfer Torque

韩伟

量子材料科学中心

2017年11月10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

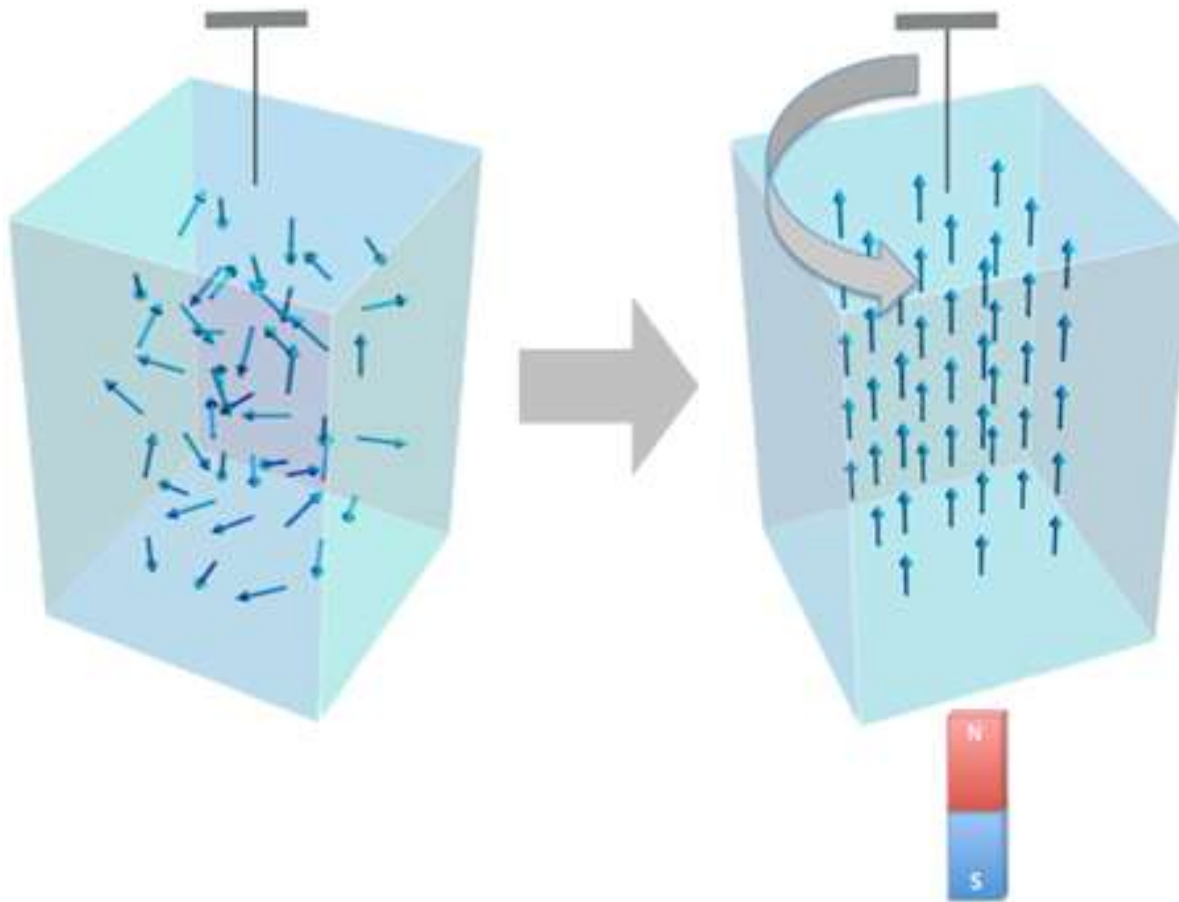
- 1. Theory and observation of spin transfer torque**
- 2. Spin transfer torque and spin pumping**
- 3. Spin transfer torque in MTJ**
- 4. Spin transfer torque in domain wall motion**
- 5. Thermal spin transfer torque**
- 6. Pure spin current transfer torque**

# 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

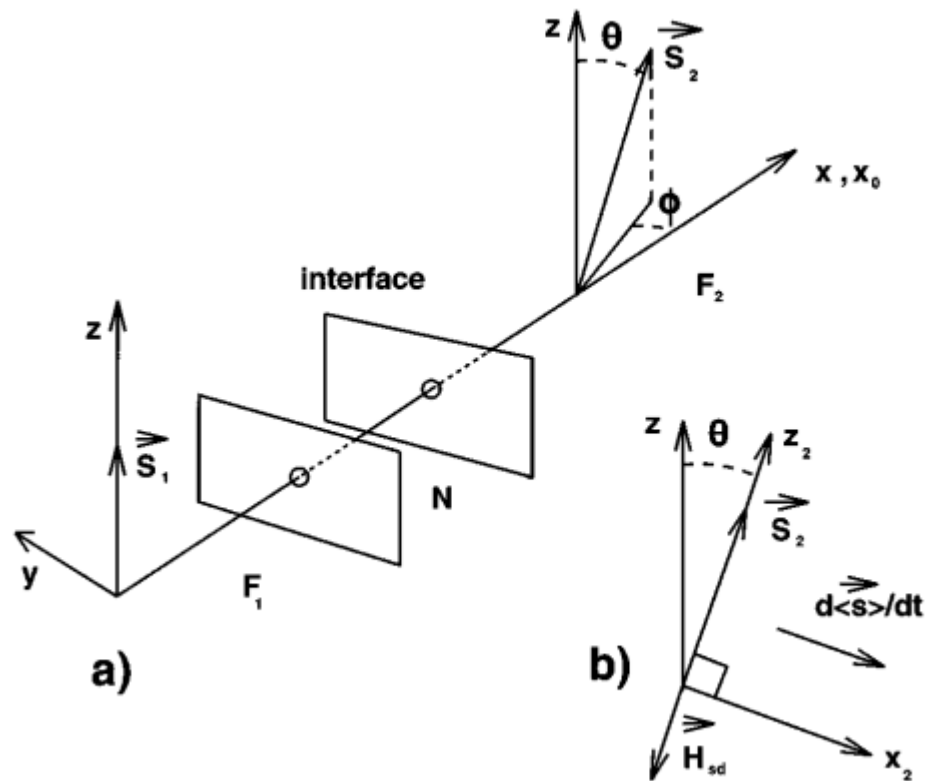
*Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213-3890*

(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



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*

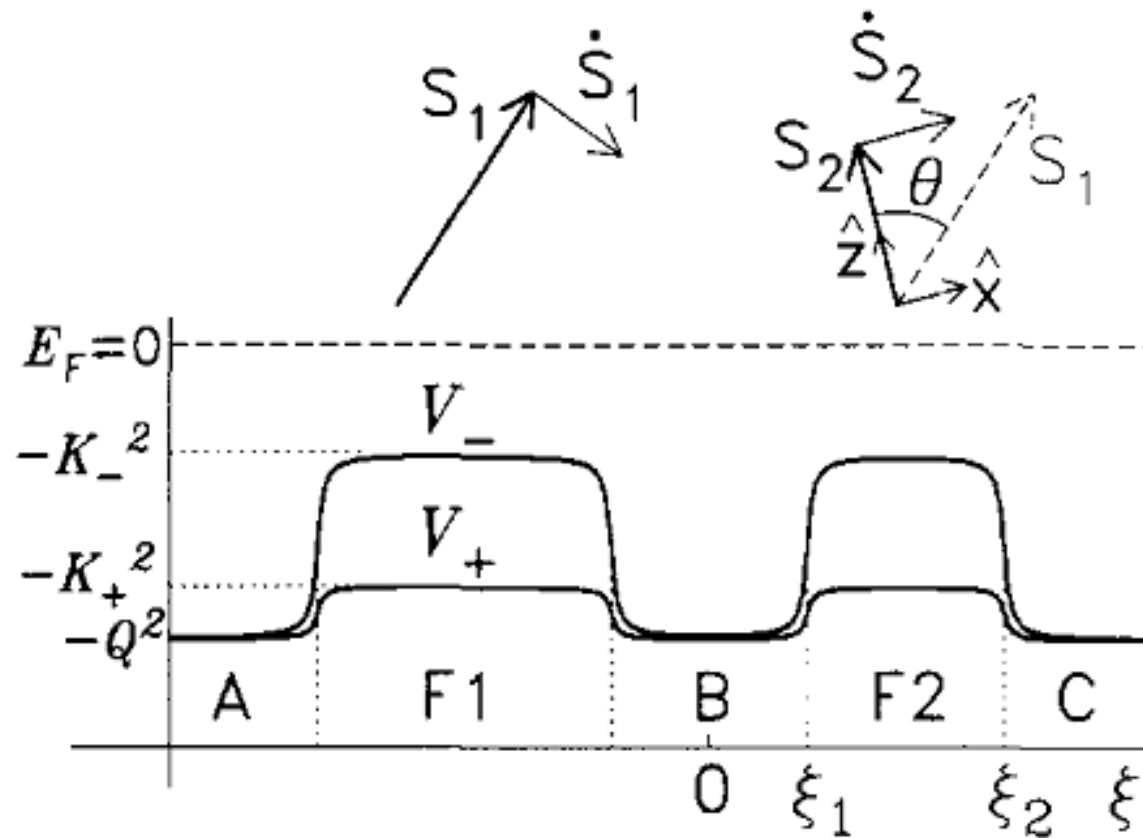
Received 27 October 1995; revised 19 December 1995

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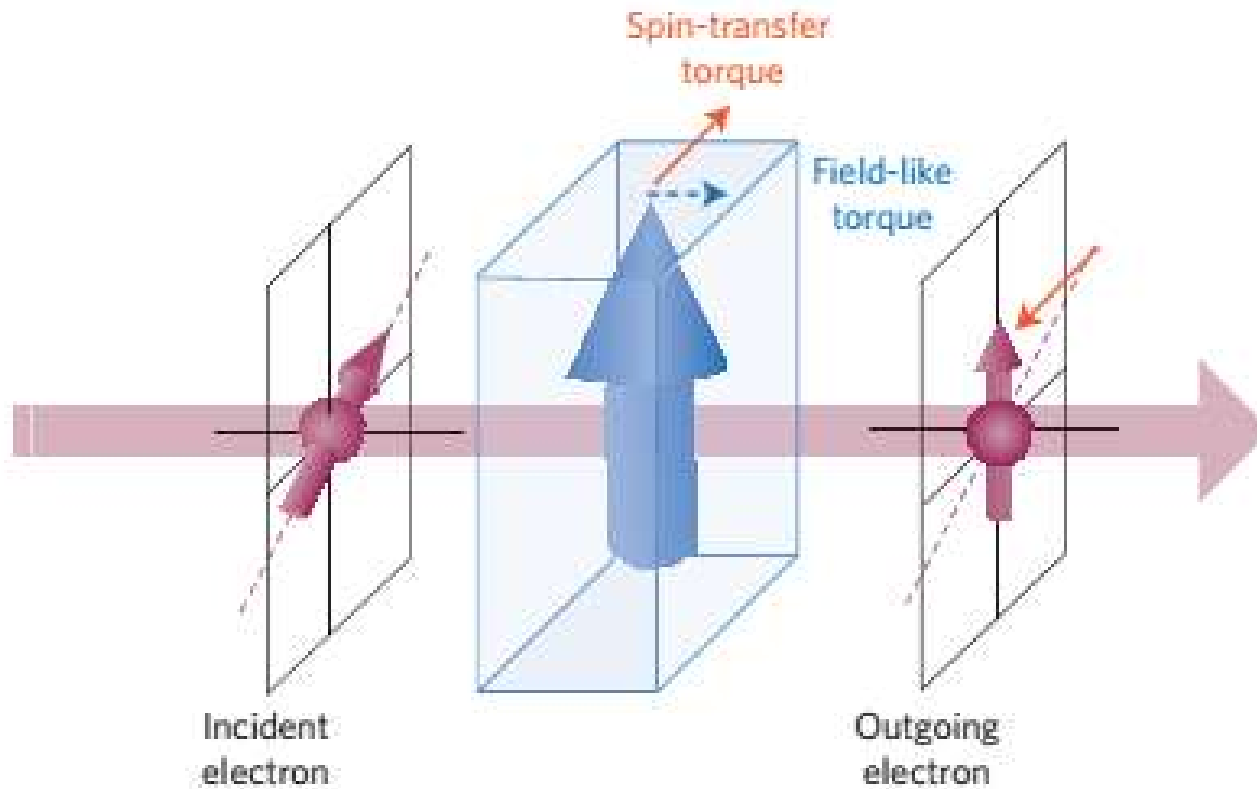
### Abstract

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

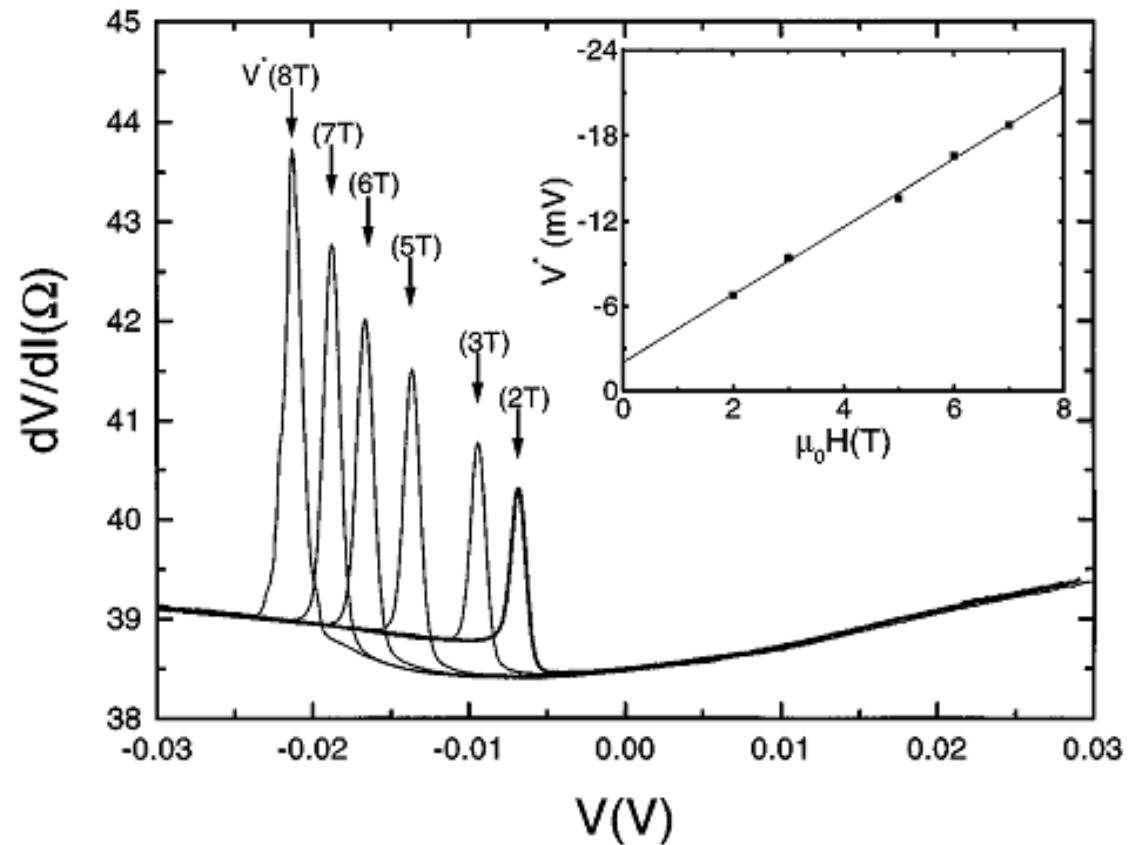
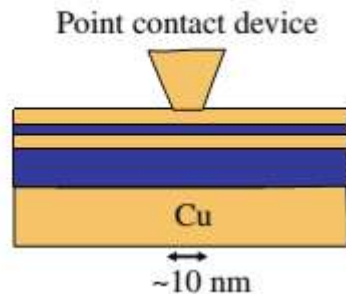
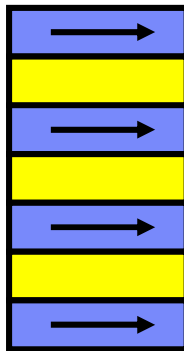


# Spin transfer torque



# Experimental discovery of STT

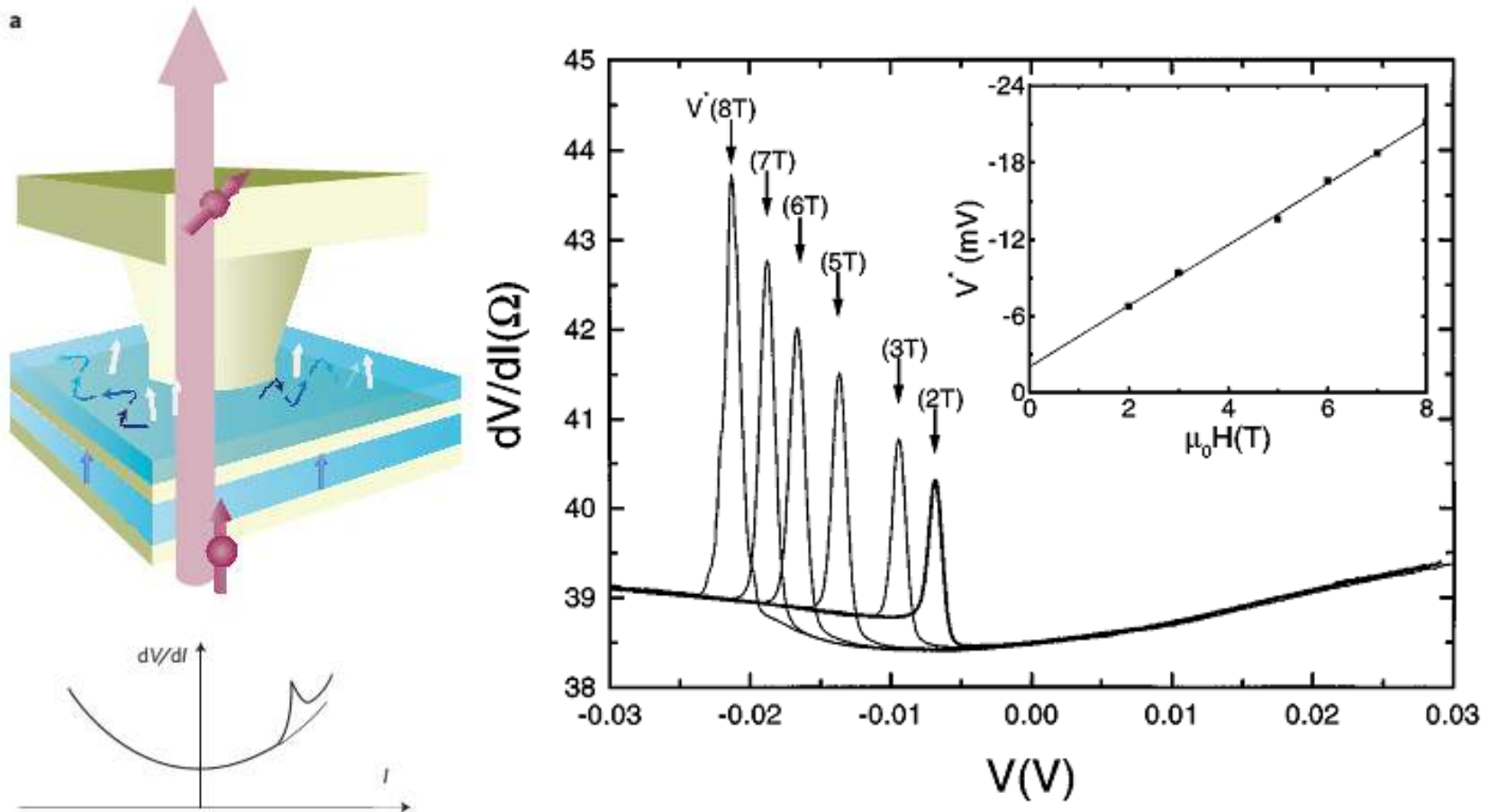
$(\text{Co/Cu})_N$   
 $N = 20-50$



Tsoi, et al, PRL (1998) 16

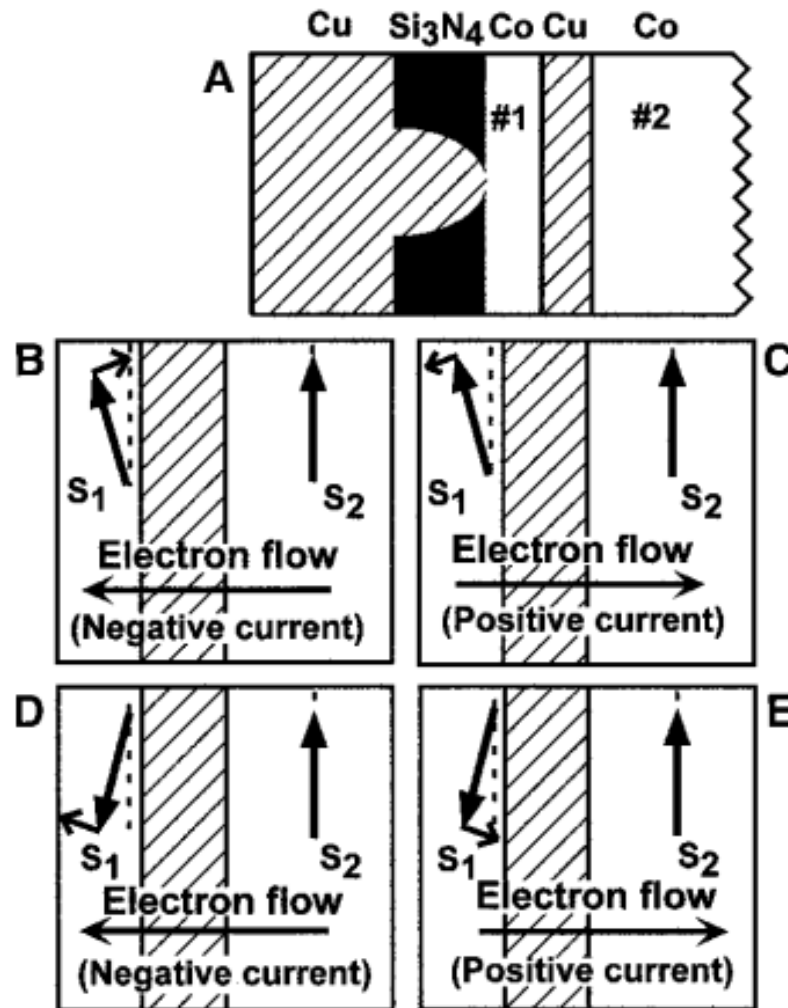


# Experimental discovery of STT



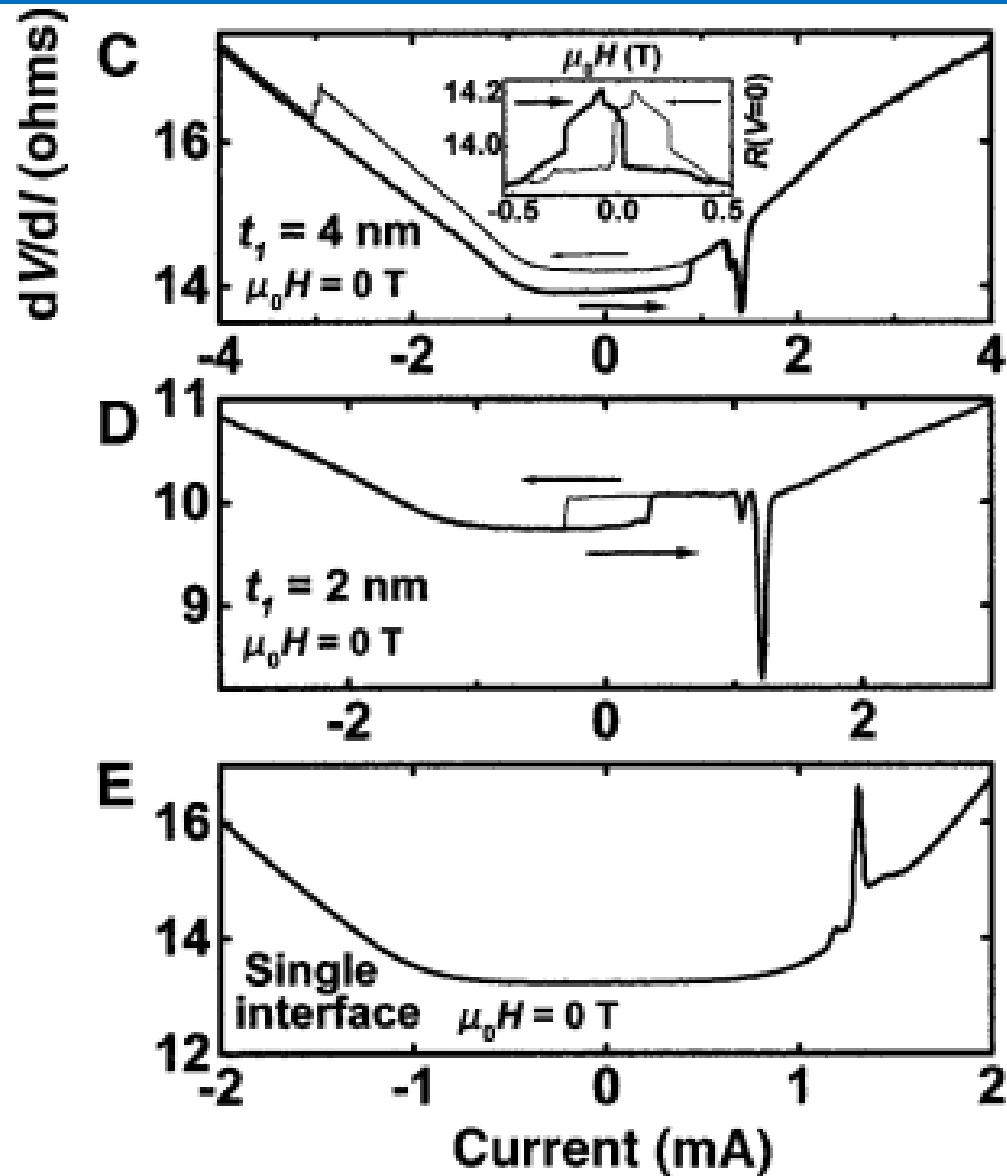
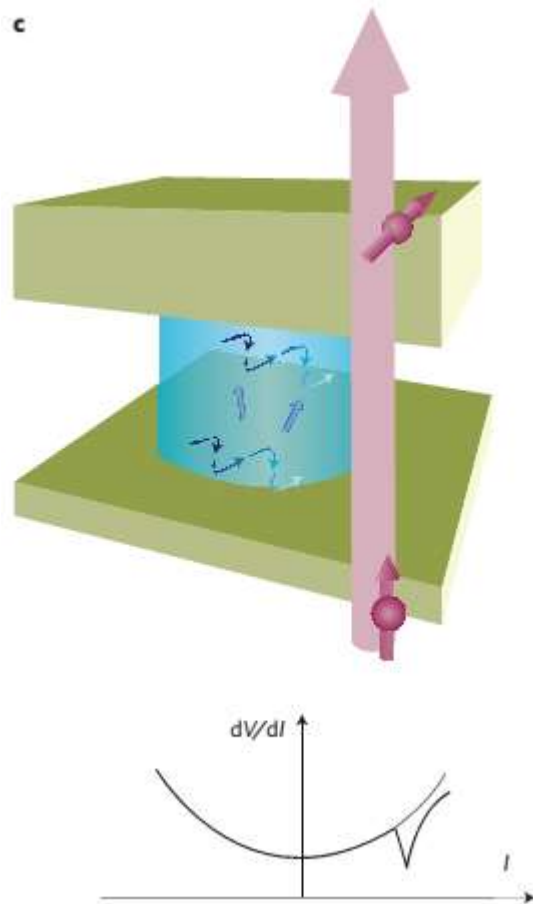
Tsoi, et al, PRL (1998) 17

# Experimental discovery of STT

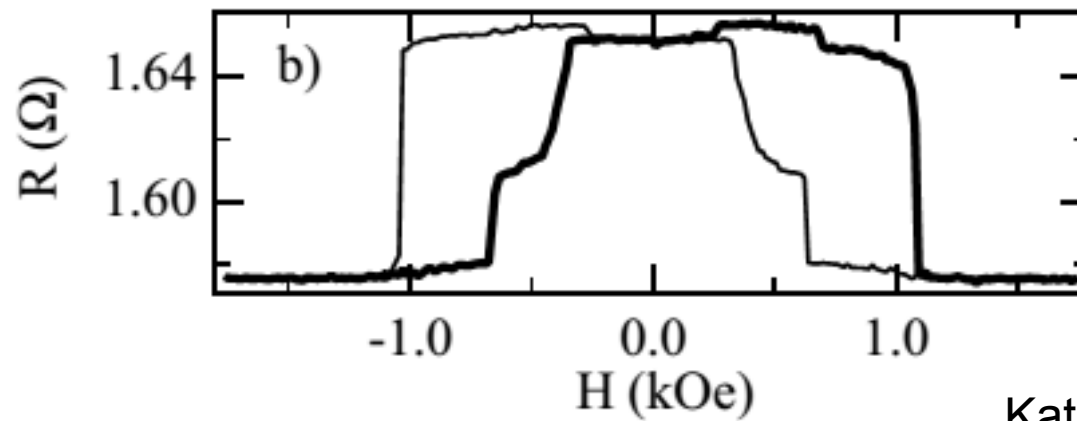
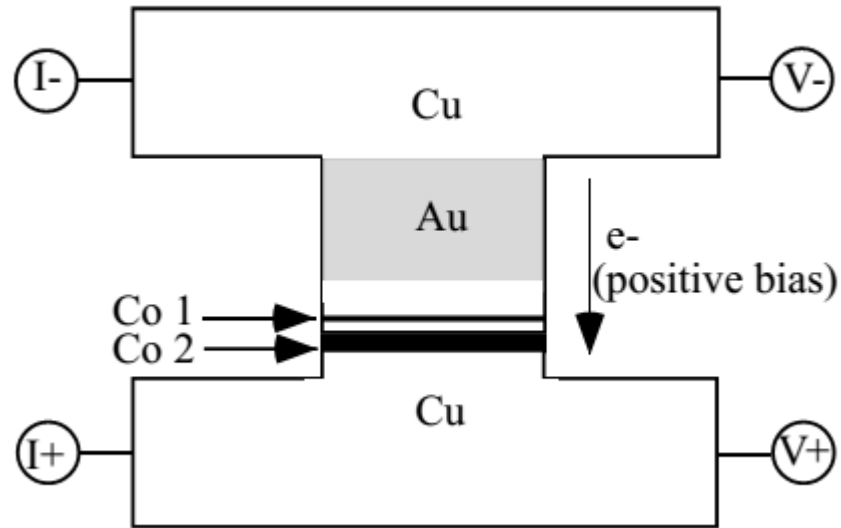


Myers, et al, Science (1999) 18

# Experimental discovery of STT

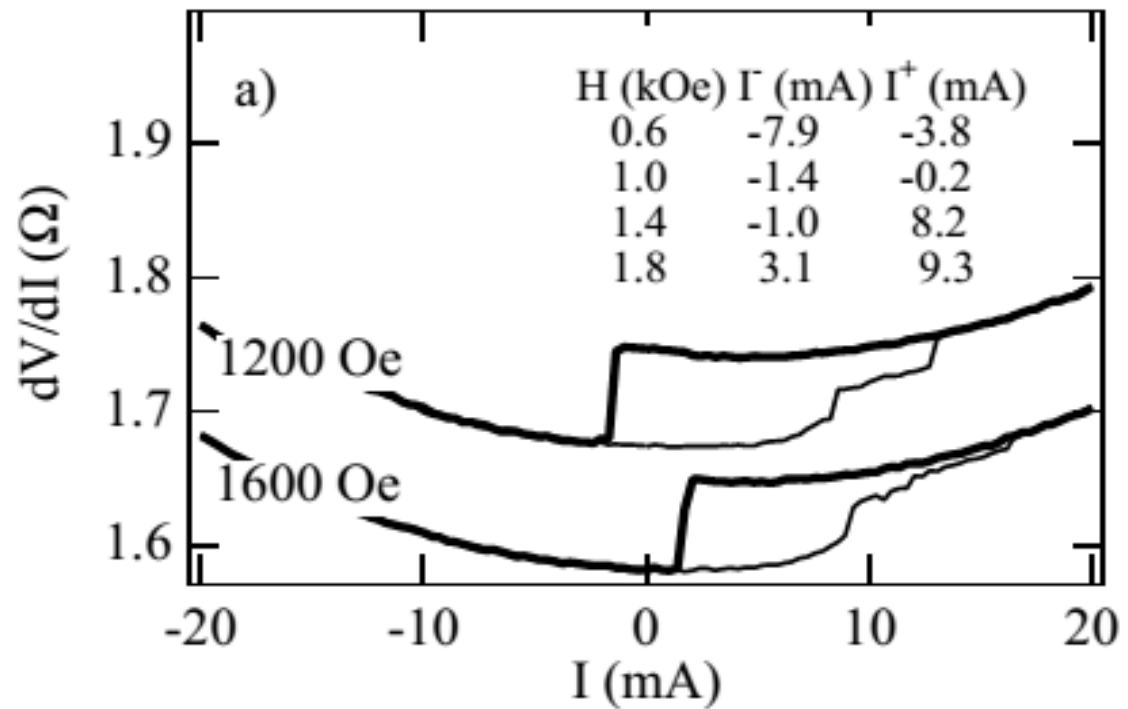
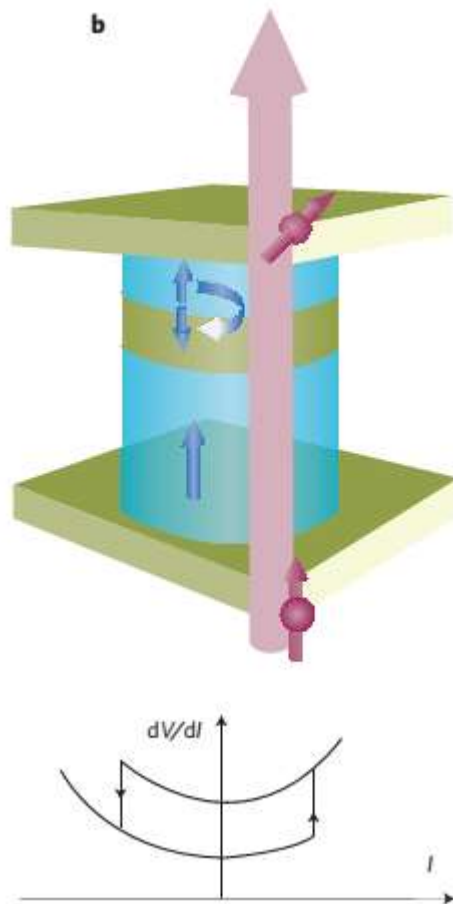


# Experimental discovery of STT

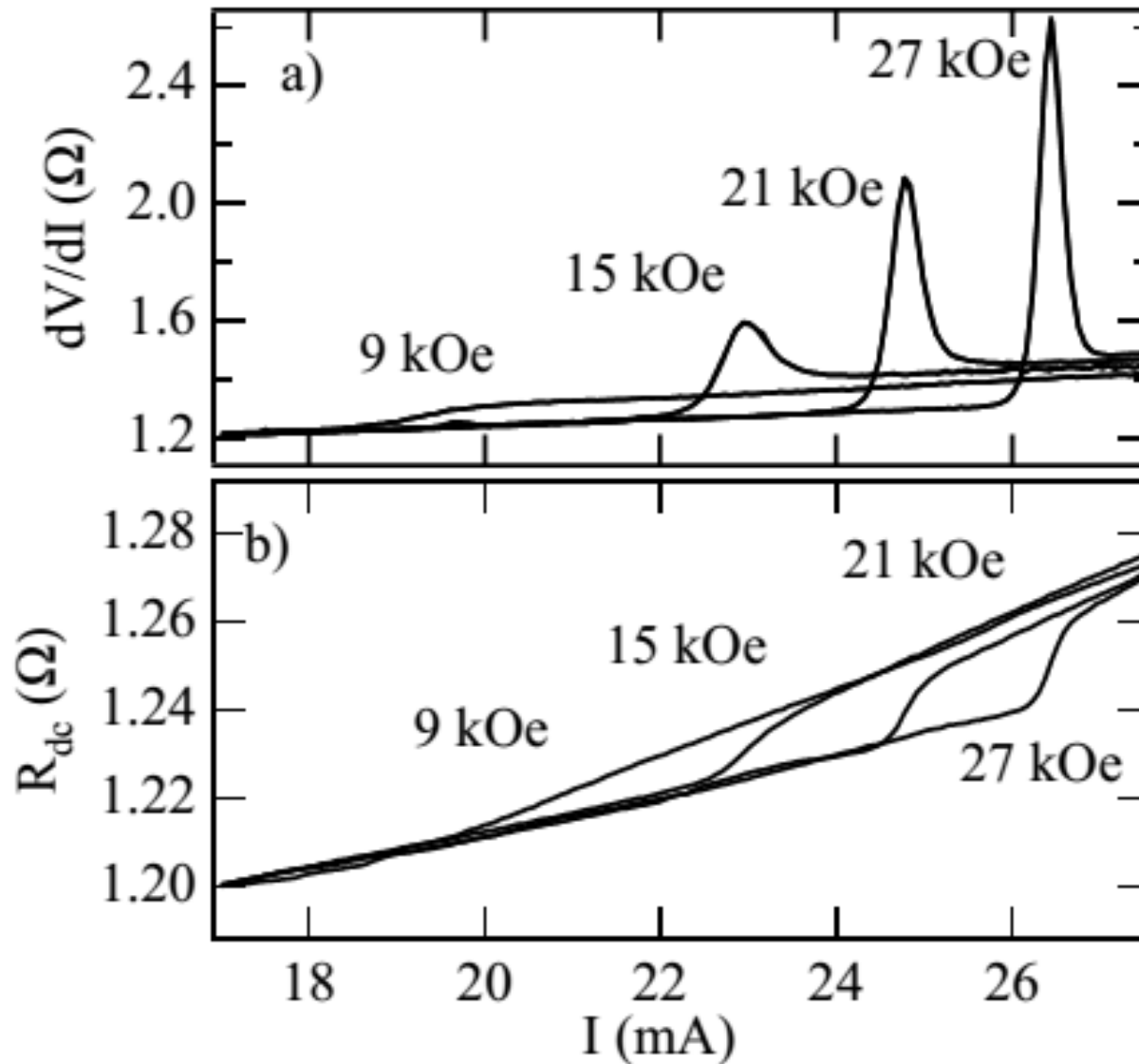


Katine, et al, PRL (2000) 20

# Experimental discovery of STT

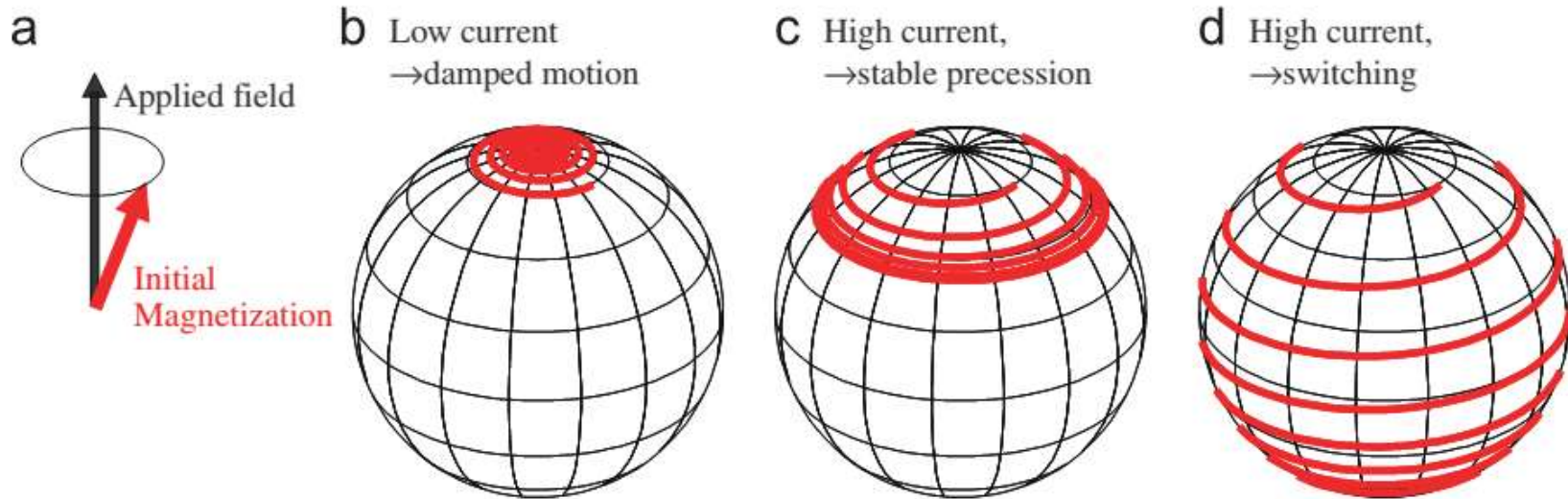


# Experimental discovery of STT



# Spin transfer torque switching

Moment in an applied field along  $z$  with no anisotropy

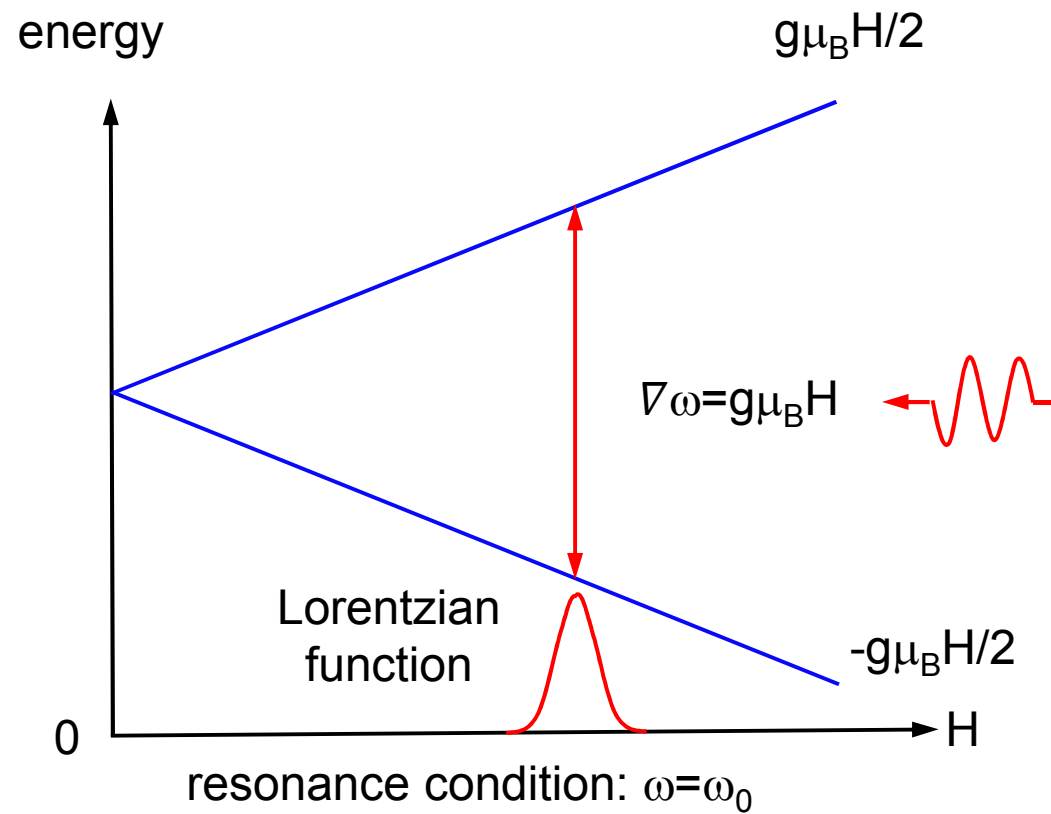


# Outline

## **2. Spin transfer torque and spin pumping**



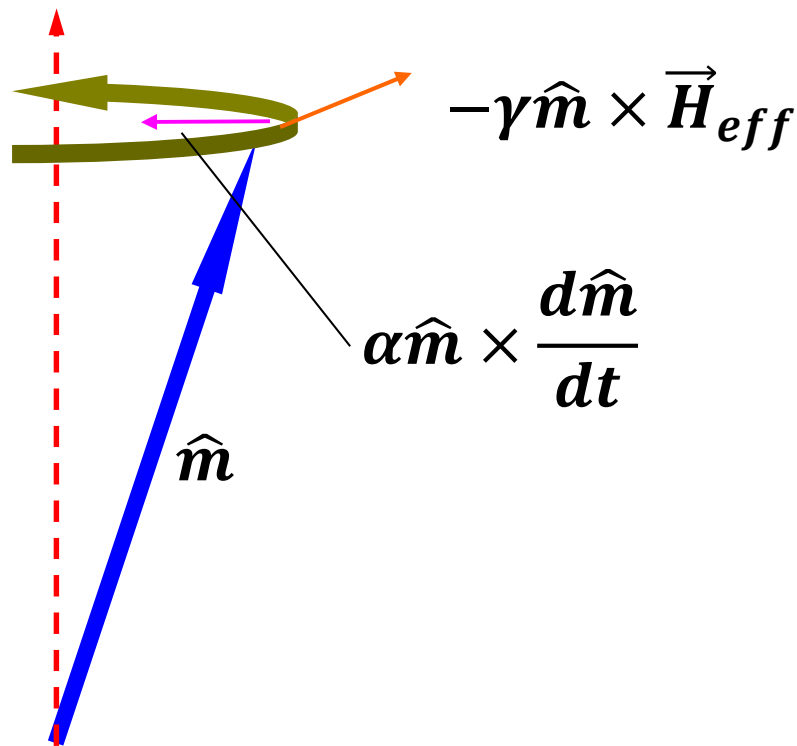
# Ferromagnetic resonance



# Ferromagnetic resonance

## Landau-Lifshitz-Gilbert equation

$H_{eff}$  (static)



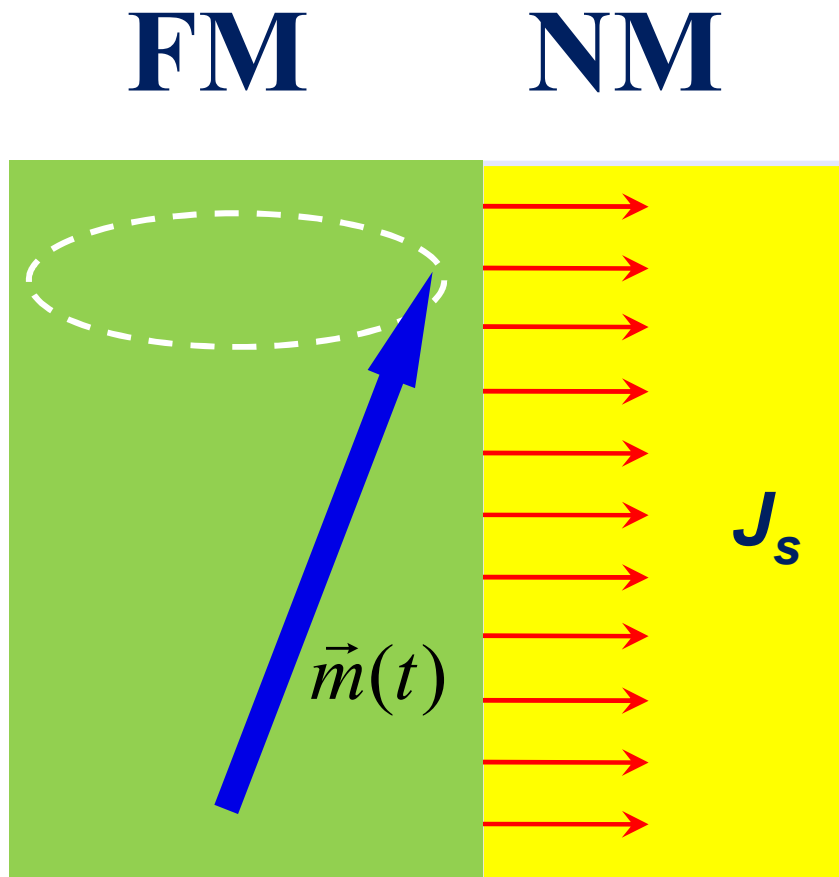
$$\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \vec{H}_{eff} + \alpha \hat{m} \times \frac{d\hat{m}}{dt}$$

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

$\alpha$  is the Gilbert damping

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

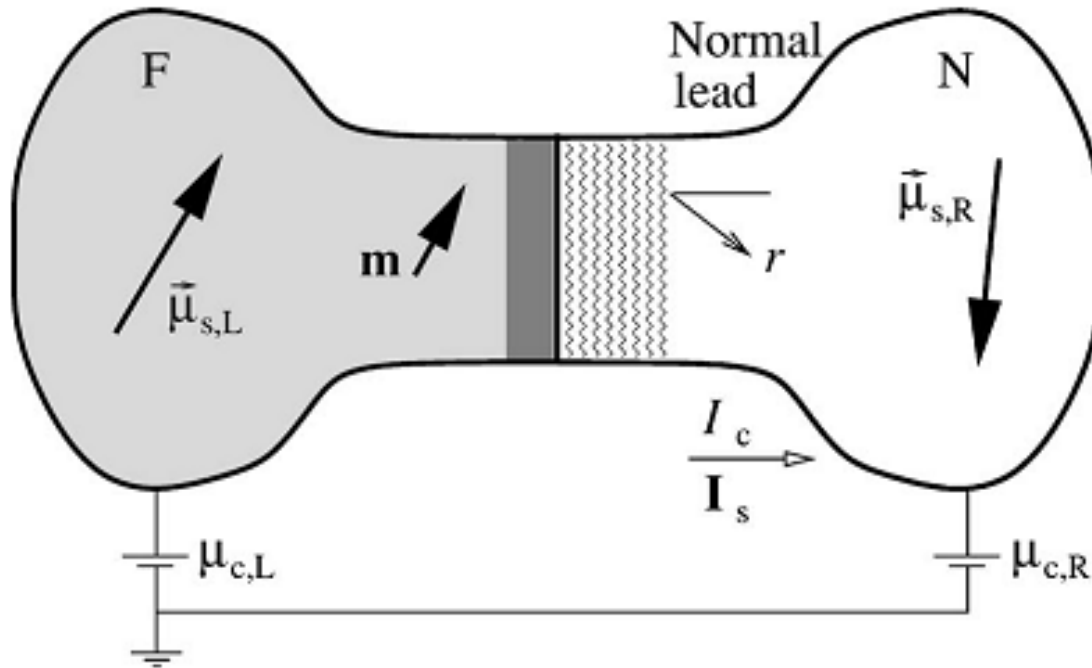
# Spin angular momentum



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

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

# Spin transfer torque

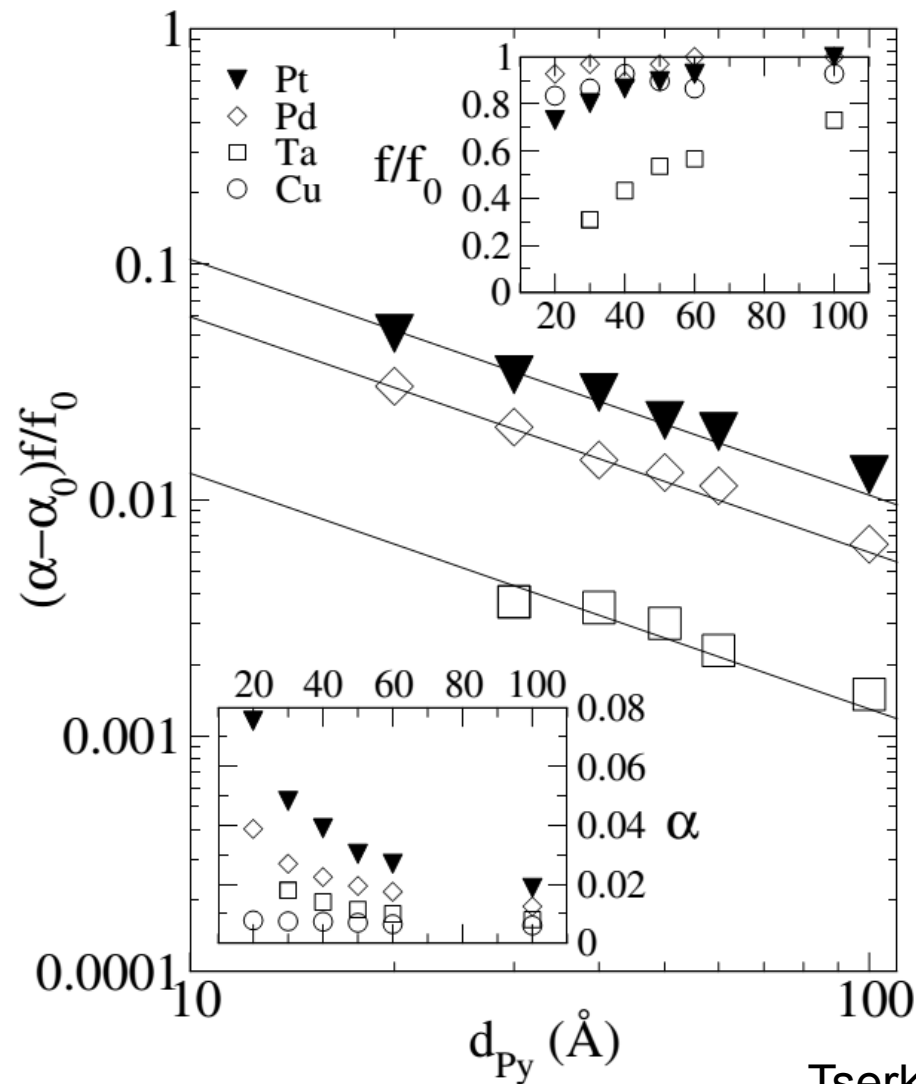


$$\boldsymbol{\tau} = -\mathbf{m} \times \mathbf{I}_s \times \mathbf{m}.$$

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

Tserkovnyak, et al, Rev Mod Phys (2005)

# Enhanced Gilbert damping



Tserkovnyak, et al, PRL (2002)

# Enhanced Gilbert damping

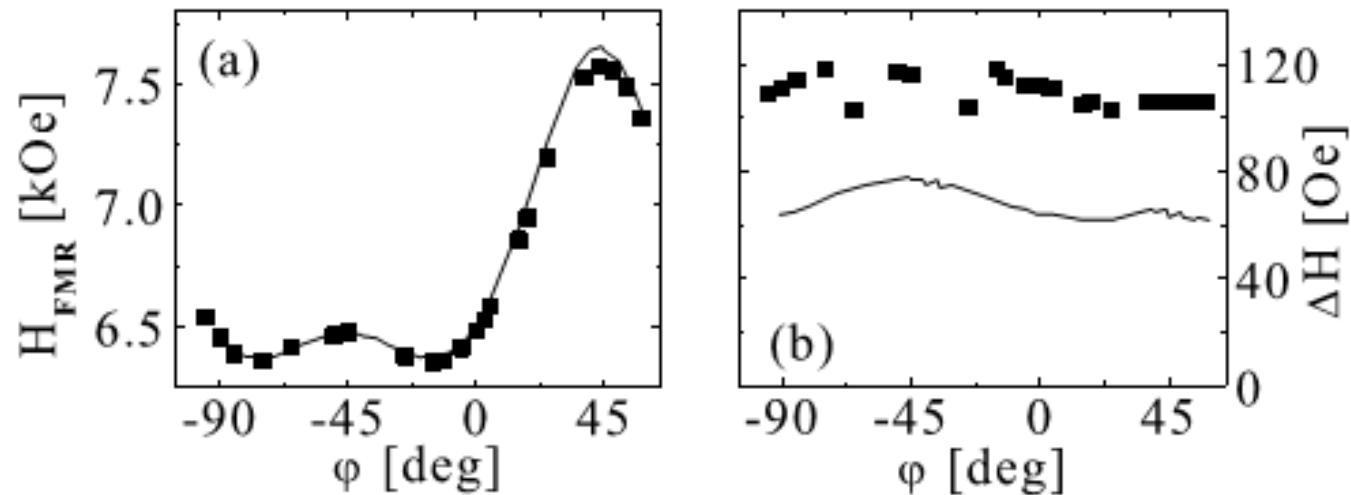


FIG. 3. (a) The FMR field,  $H_{\text{FMR}}$ , and (b) FMR linewidth,  $\Delta H$ , for the 16 ML Fe film as a function of the azimuthal angle  $\phi$  at  $f = 36$  GHz. The solid lines correspond to the GaAs/16 Fe/20 Au structure, and the squares (■) correspond to the GaAs/16 Fe/40 Au/40 Fe/20 Au structure.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

# Enhanced Gilbert damping

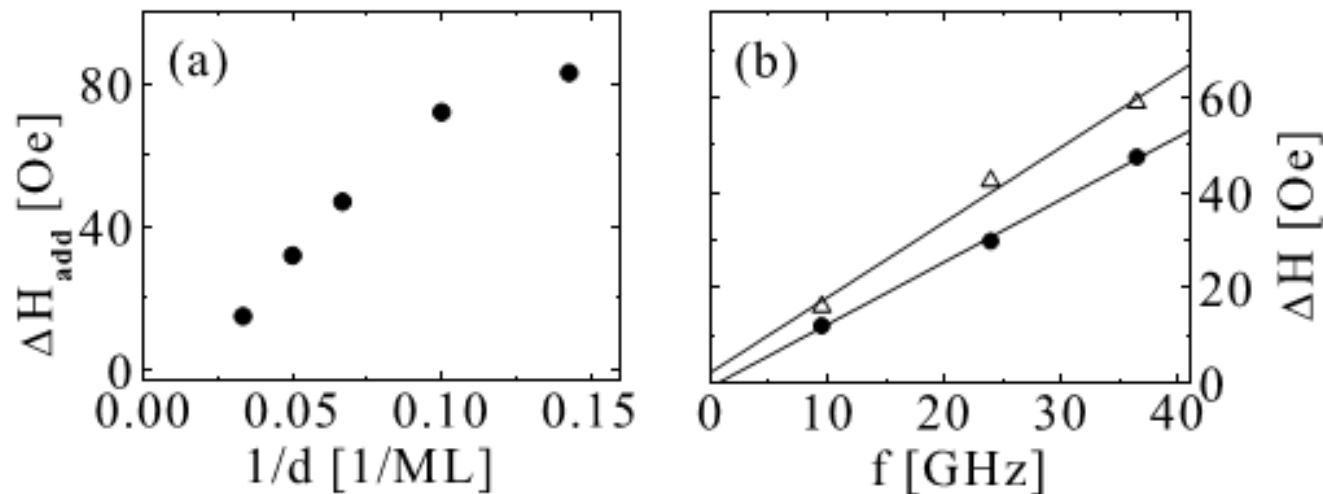
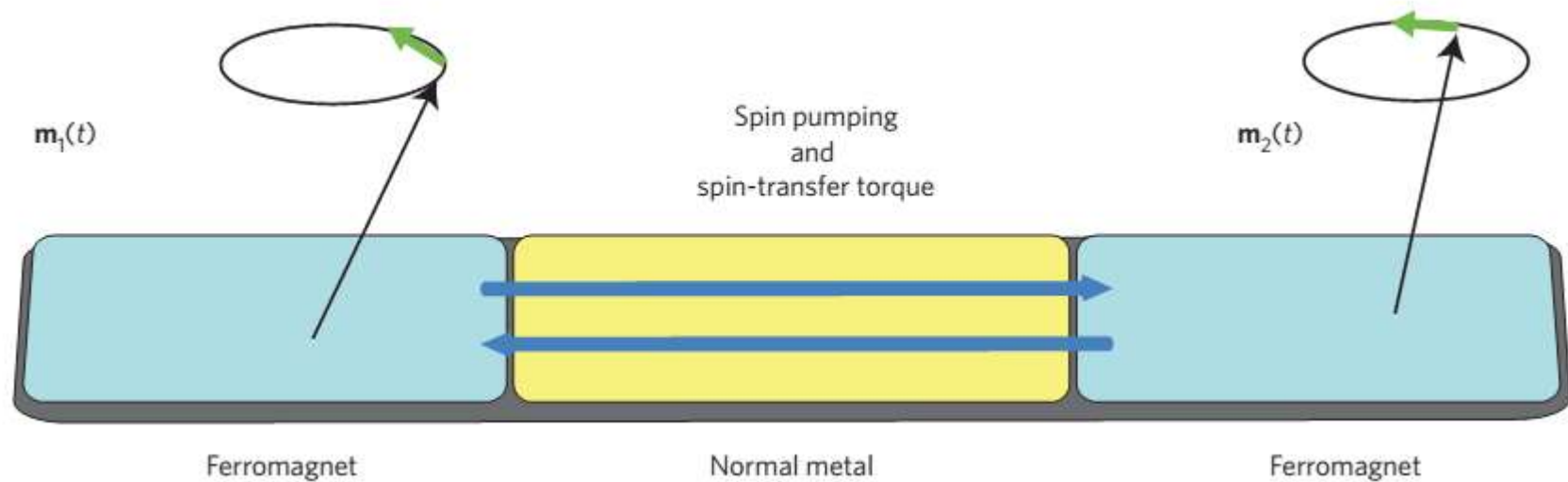


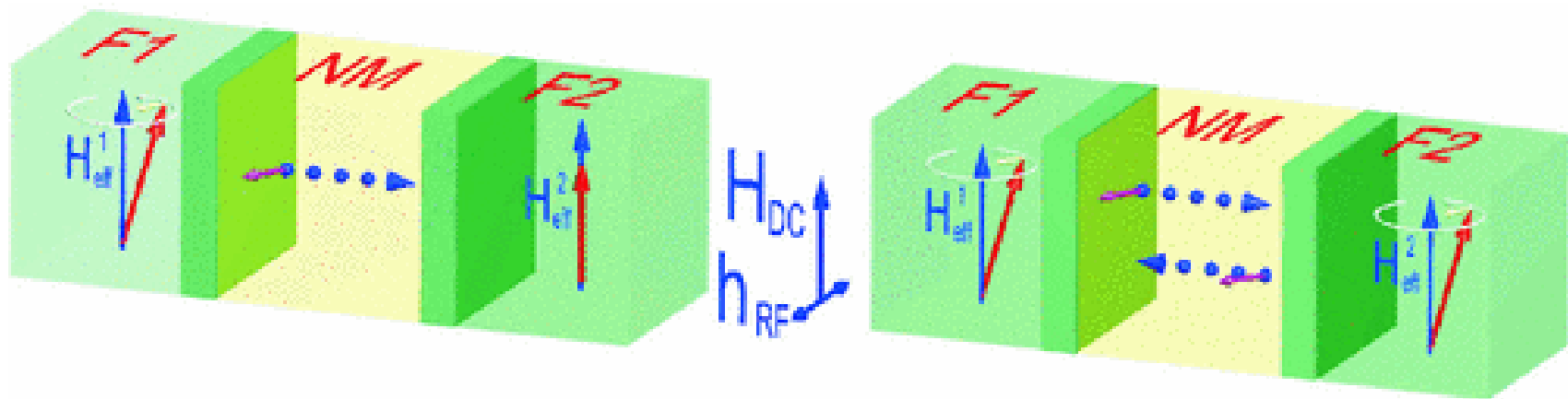
FIG. 4. (a) The dependence of the additional FMR linewidth,  $\Delta H_{\text{add}}$ , along the Fe cubic axis on  $1/d$  at  $f = 36$  GHz, where  $d$  is the thickness of the thin Fe films. (b) The FMR linewidth,  $\Delta H$ , as a function of the microwave frequency  $f$ . The triangles ( $\triangle$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

# Enhanced Gilbert damping and torque



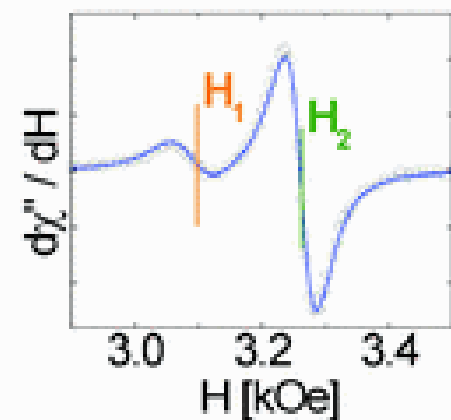
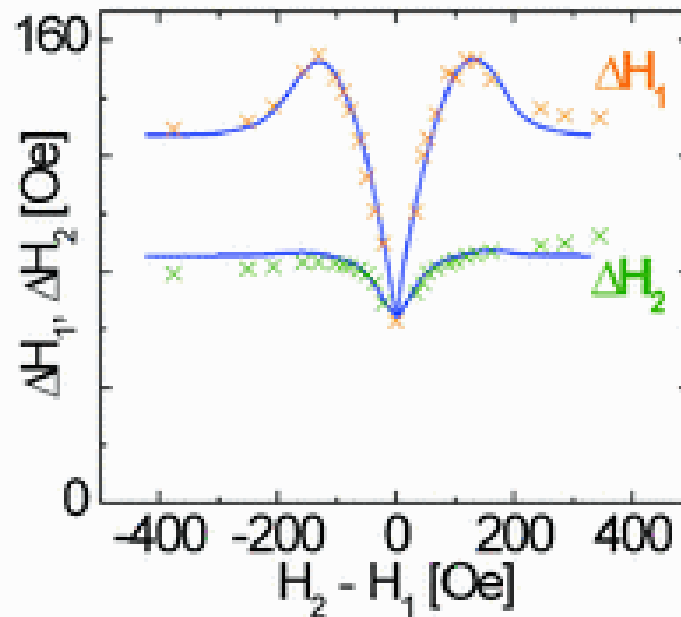
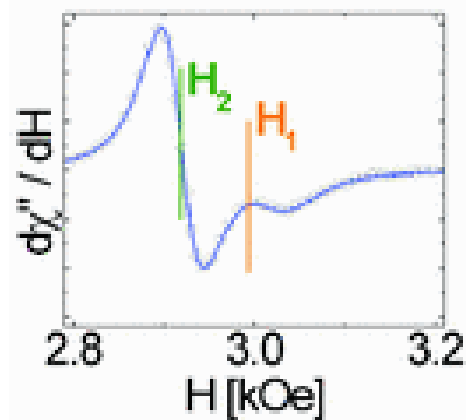
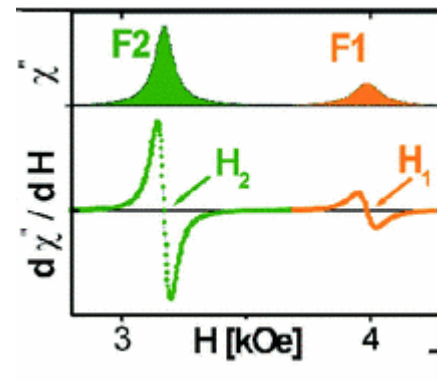


# Enhanced Gilbert damping and torque



Urban et al, PRL (2003)

# Enhanced Gilbert damping and torque



# Spin transfer torque

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

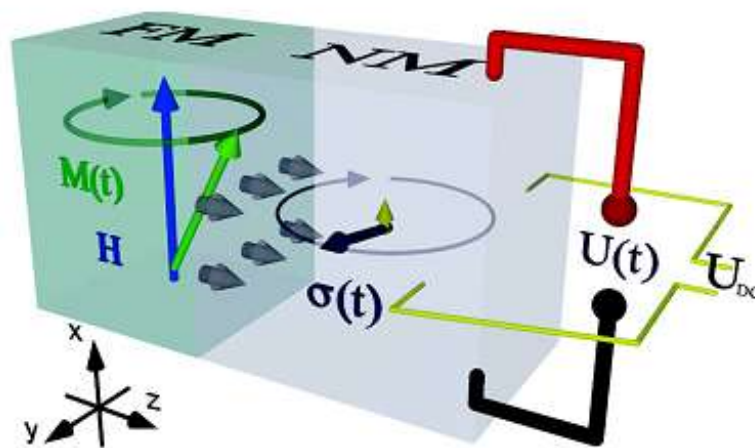
## Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect

E. Saitoh,<sup>a)</sup> M. Ueda, and H. Miyajima

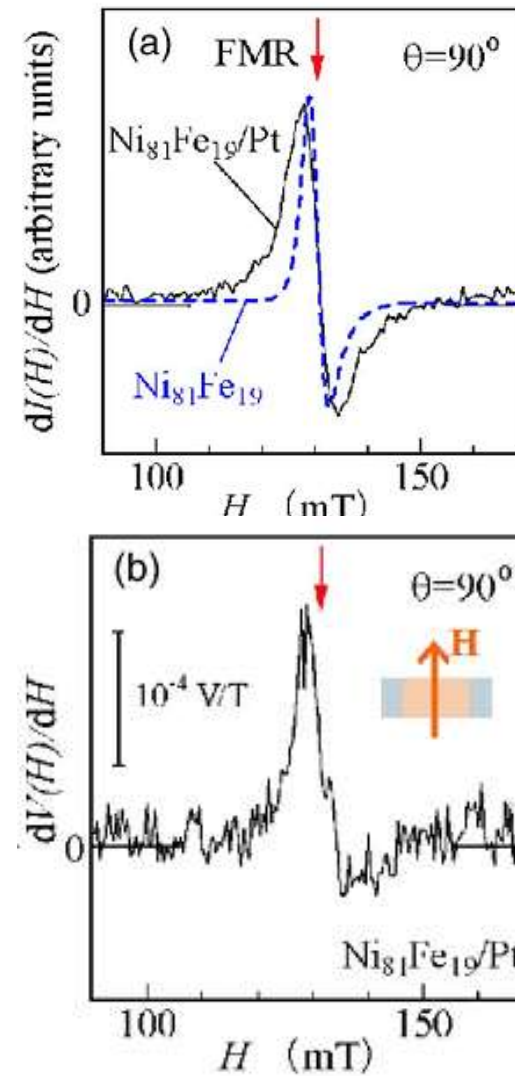
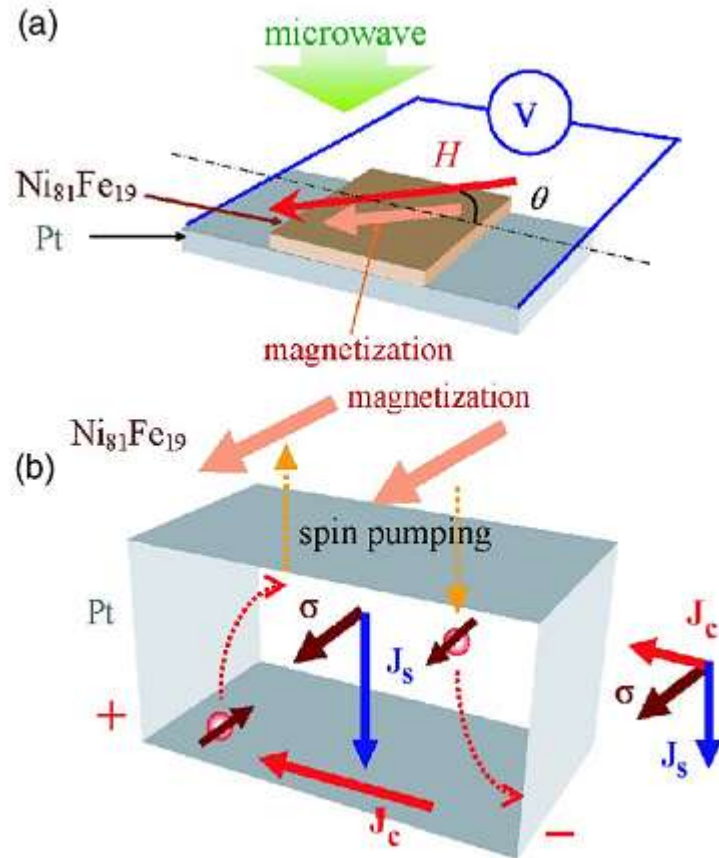
*Department of Physics, Keio University, Yokohama 223-8522, Japan*

G. Tatara

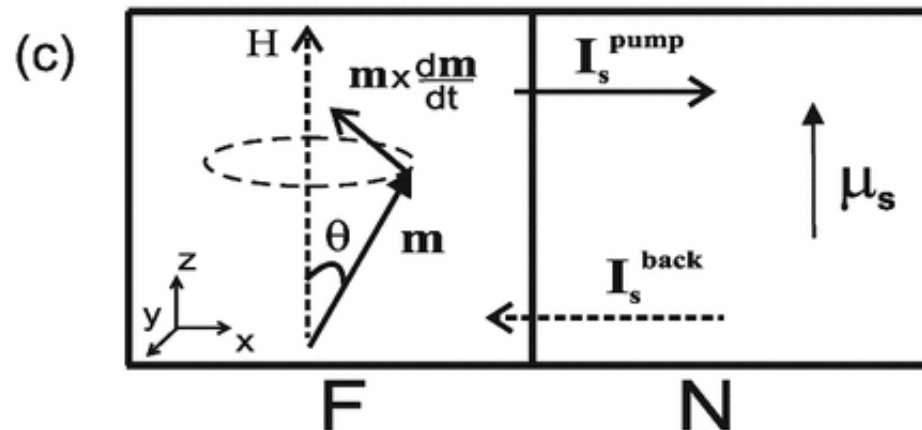
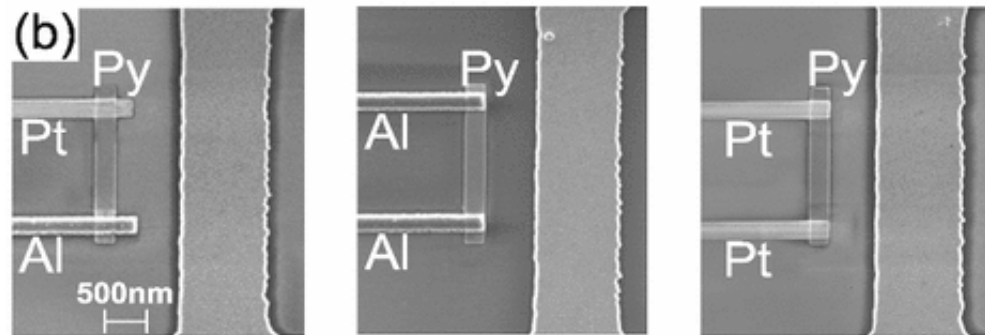
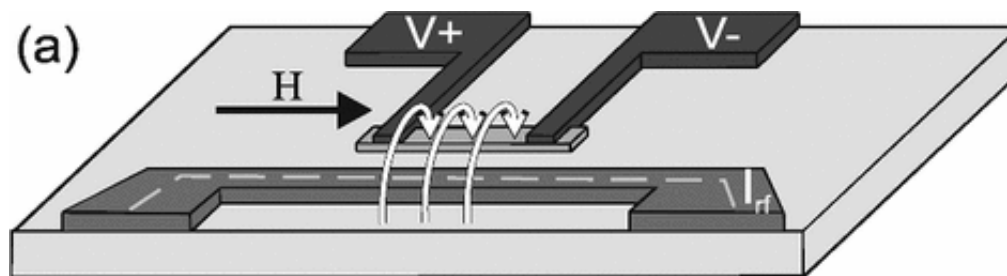
*PRESTO, Japan Science and Technology Agency (JST), Department of Physics,  
Tokyo Metropolitan University, Tokyo 192-0397, Japan*



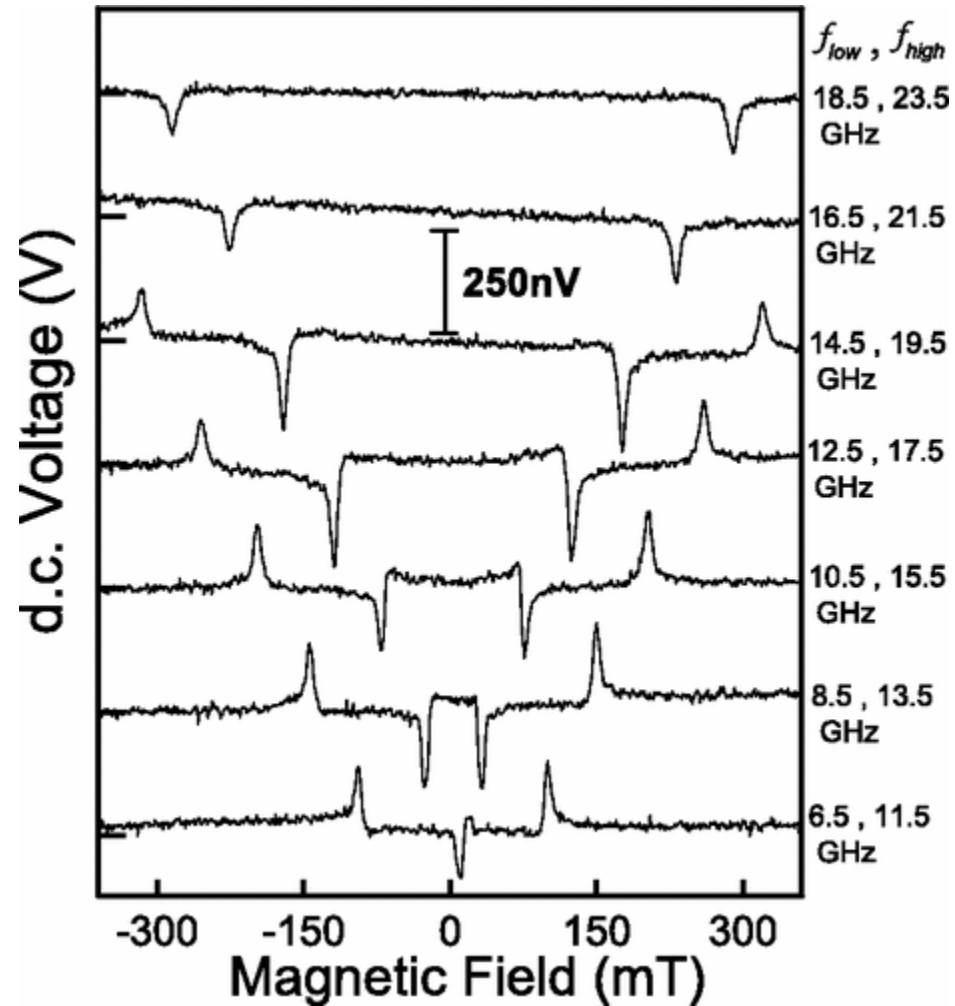
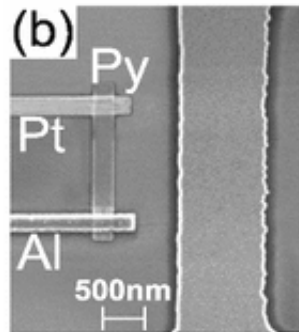
# Spin transfer torque



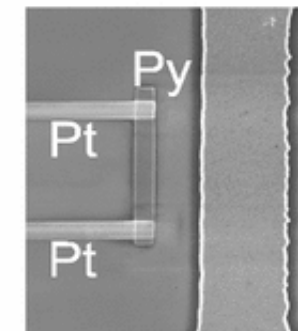
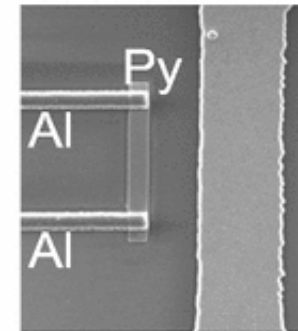
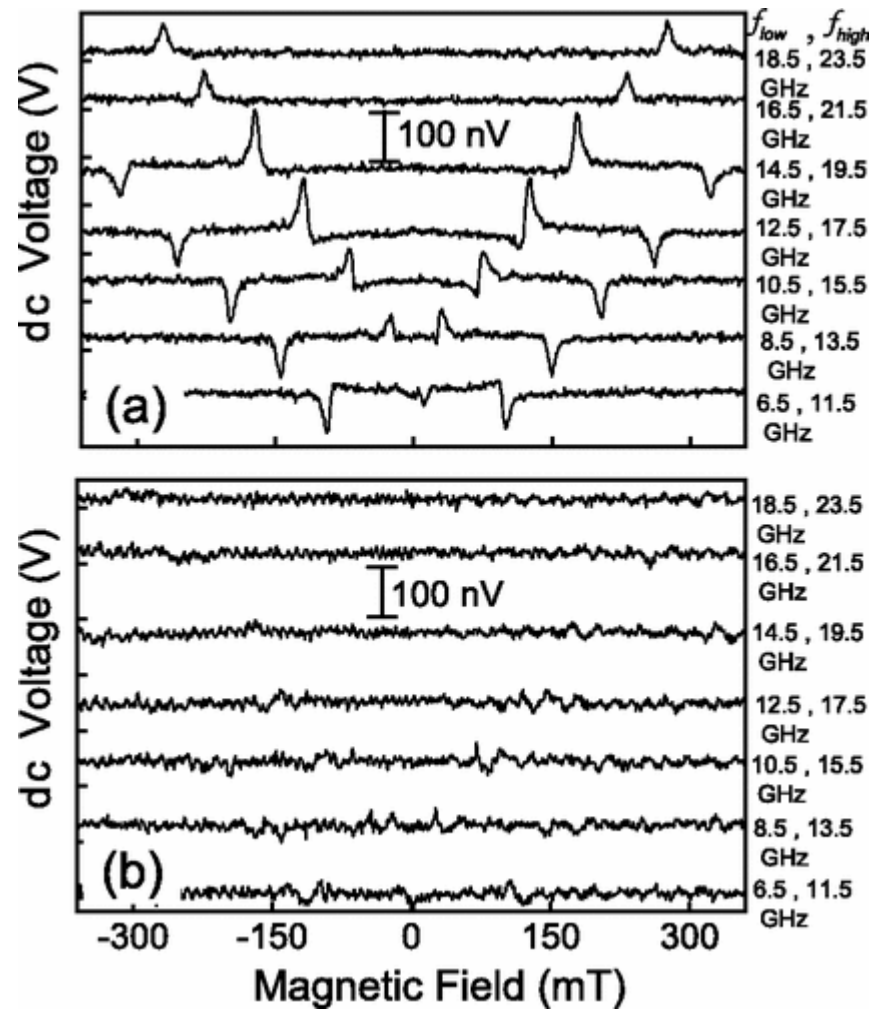
# Spin transfer torque



# Spin transfer torque

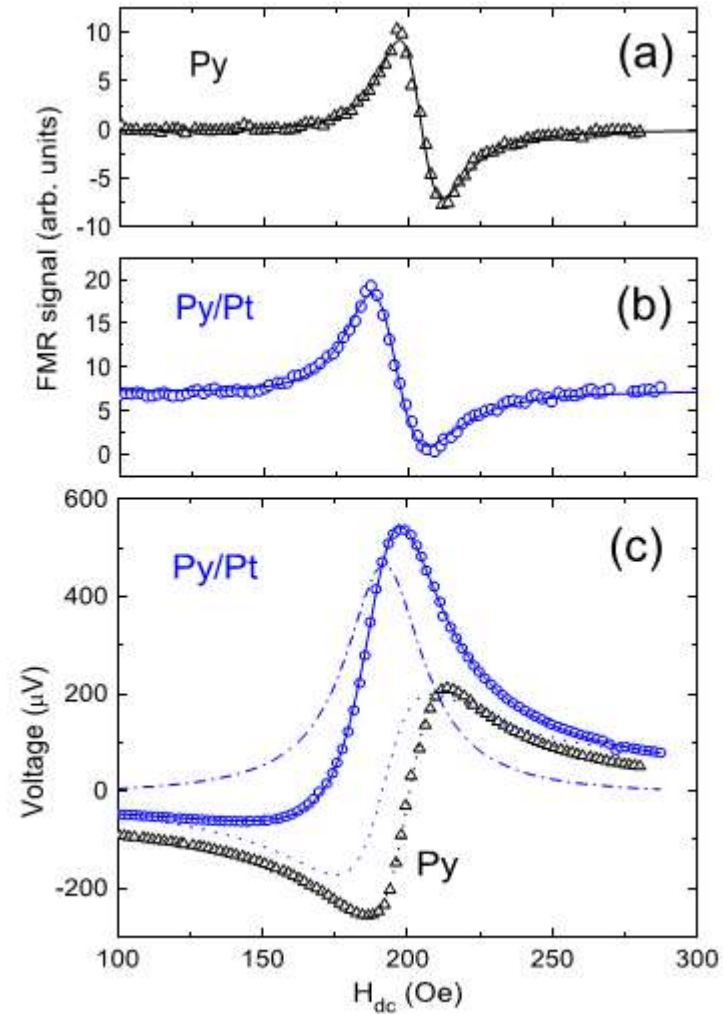
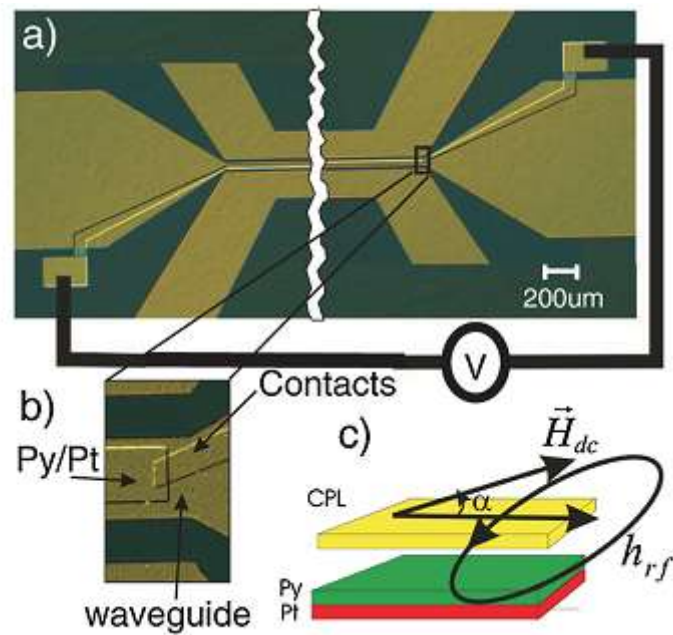


# Spin transfer torque





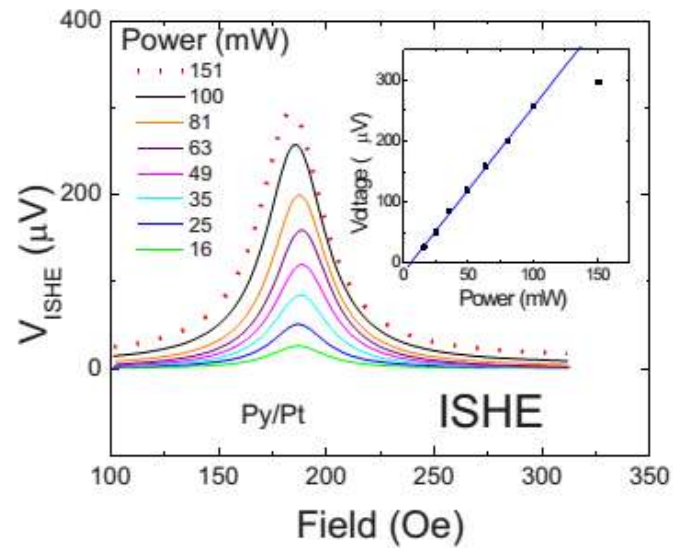
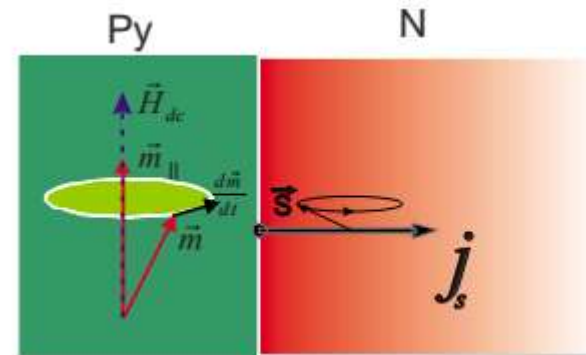
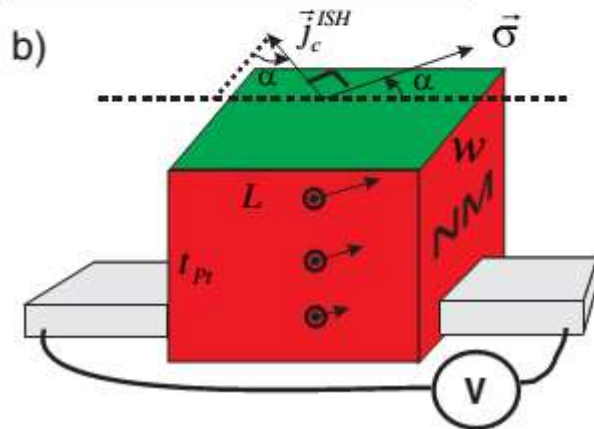
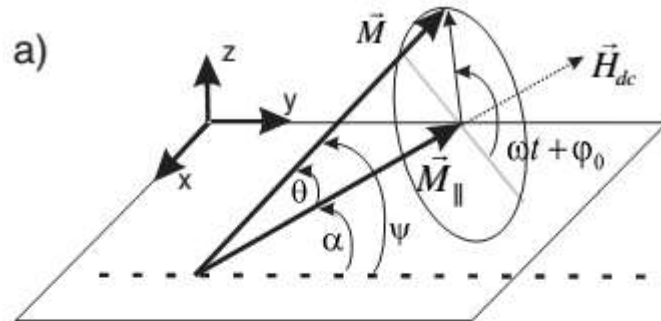
# Spin transfer torque



Mosendz, et al, PRL (2010)



# Spin transfer torque



# Spin transfer torque

TABLE I. Spin Hall angle  $\gamma$  determined using  $\lambda_{sd}$  and  $\sigma_N$  from data measured at 11 GHz.

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

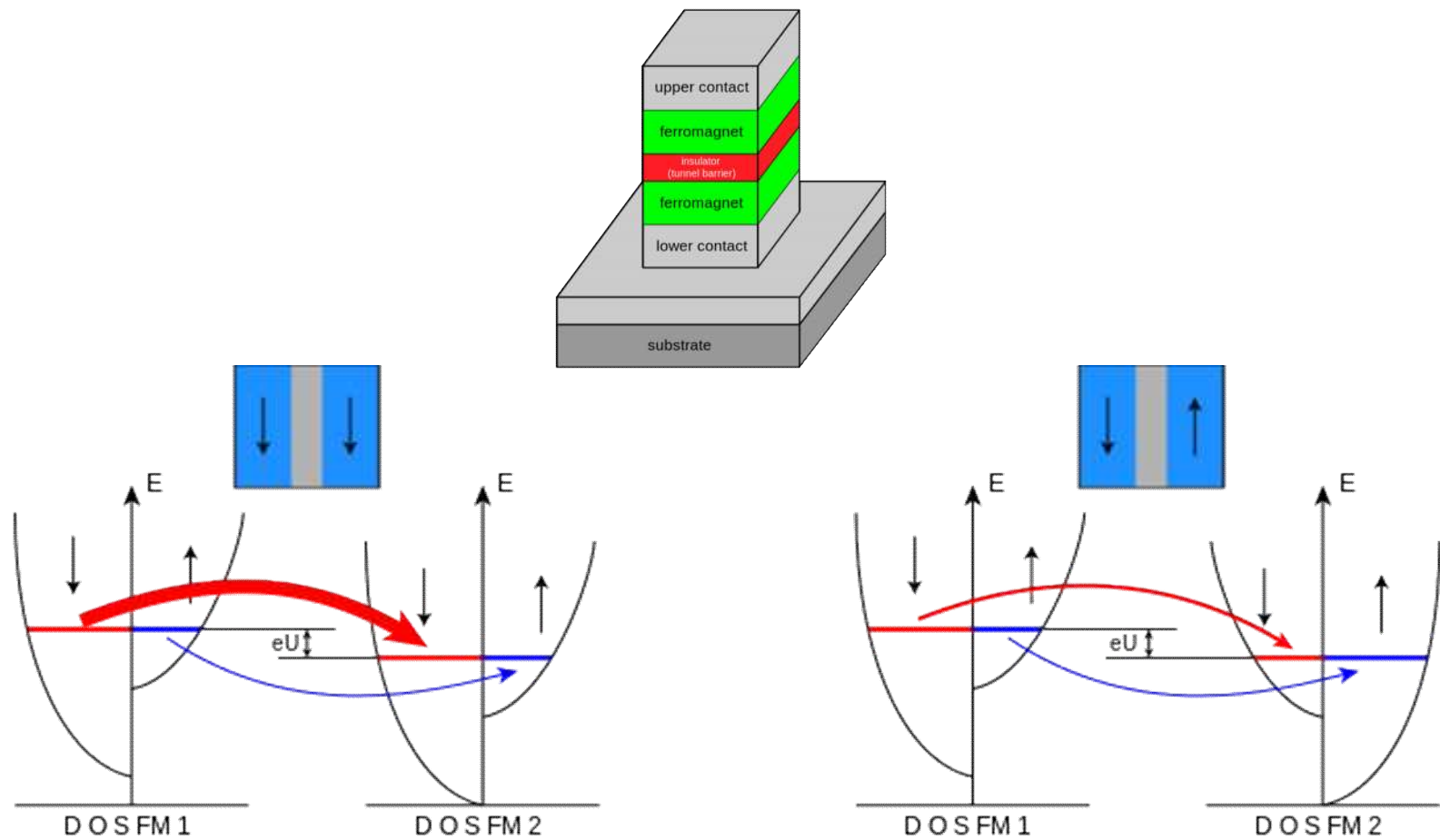
**休息10分钟**



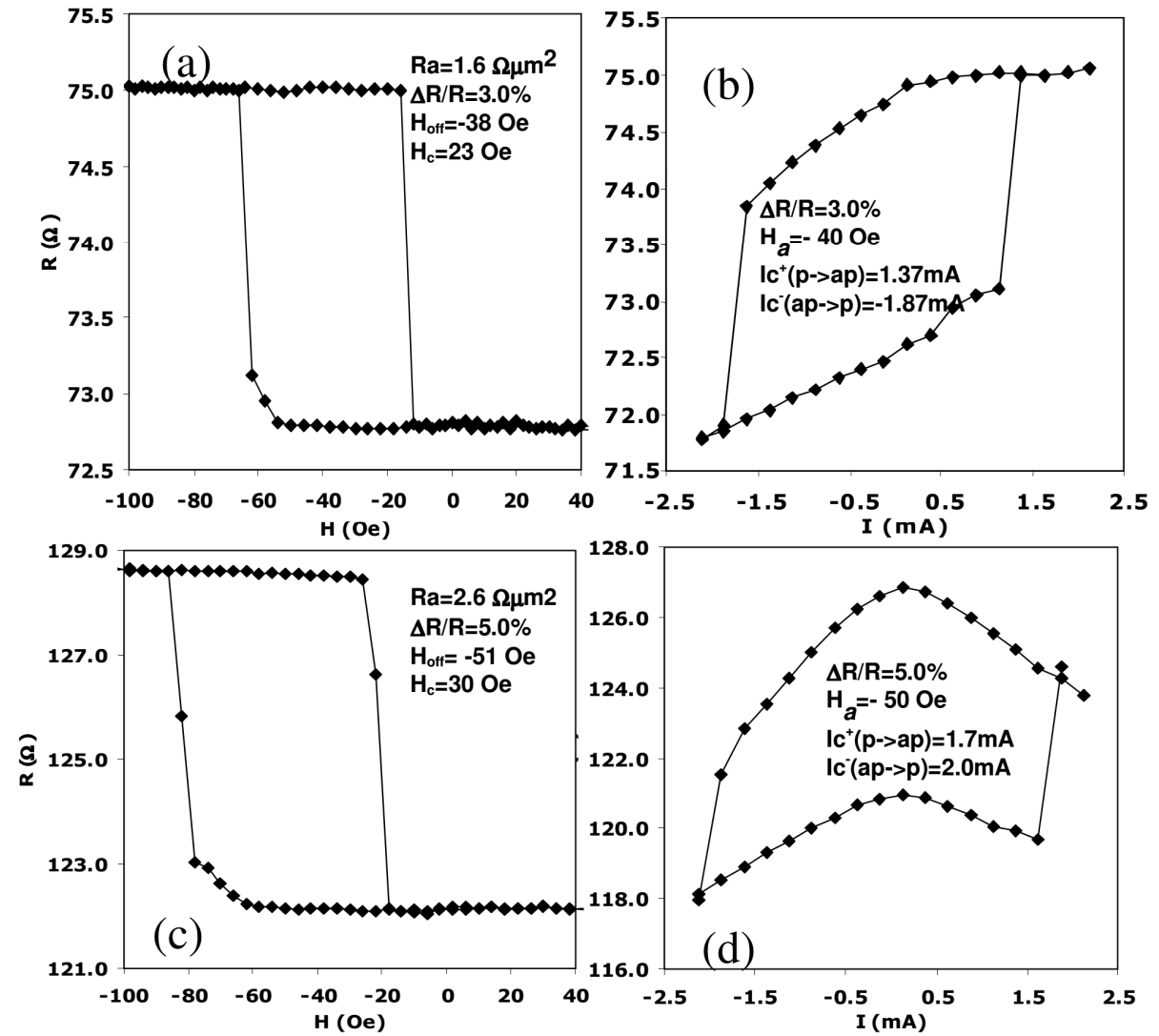
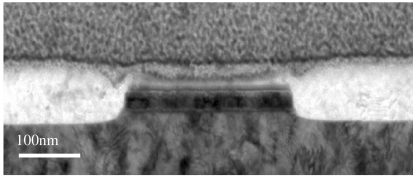
# Outline

## **3. Spin transfer torque in MTJ**

# Magnetic tunnel junction (MTJ)

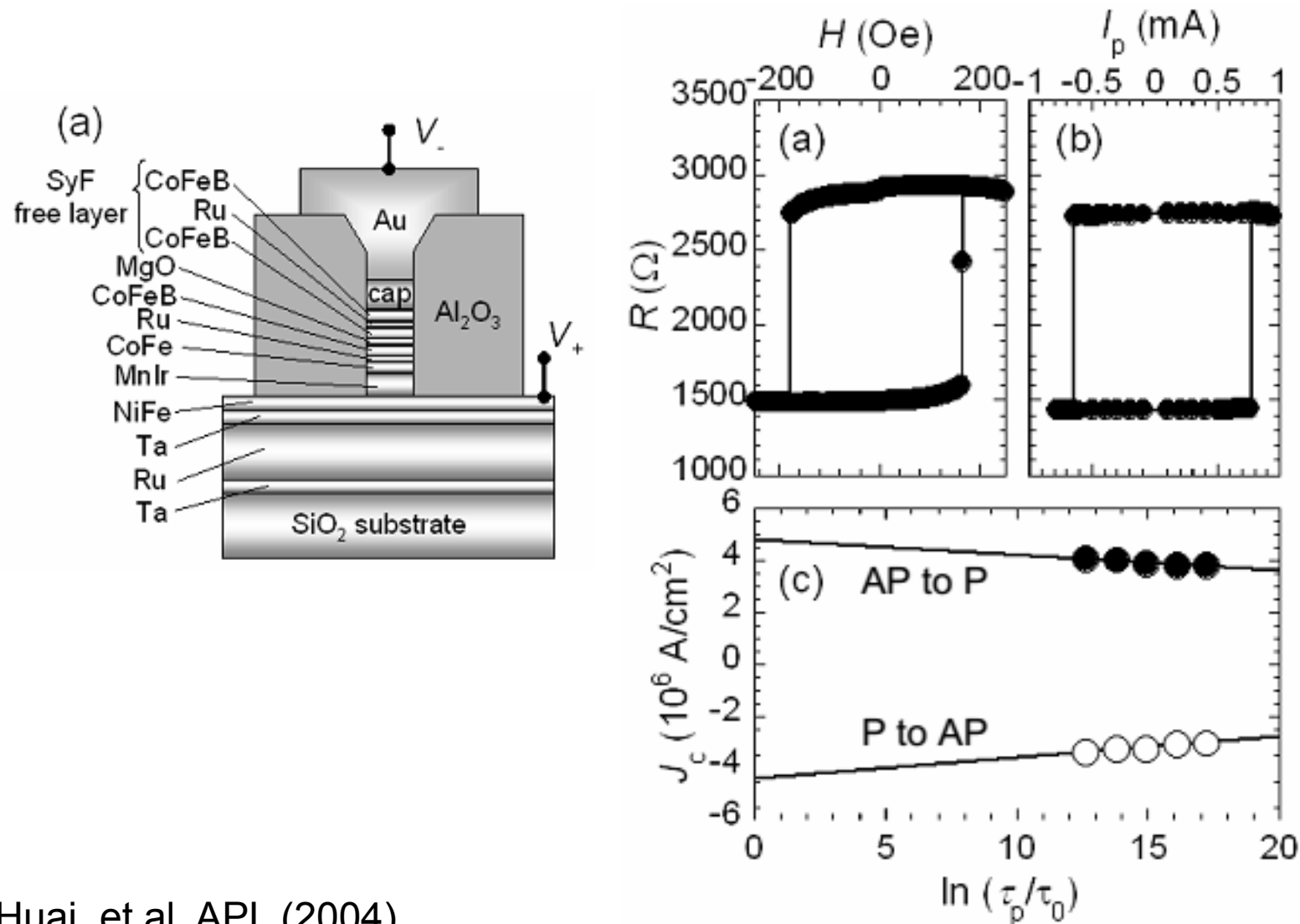


# SST in MTJ for MRAM



Yuan, et al, APL (2004)

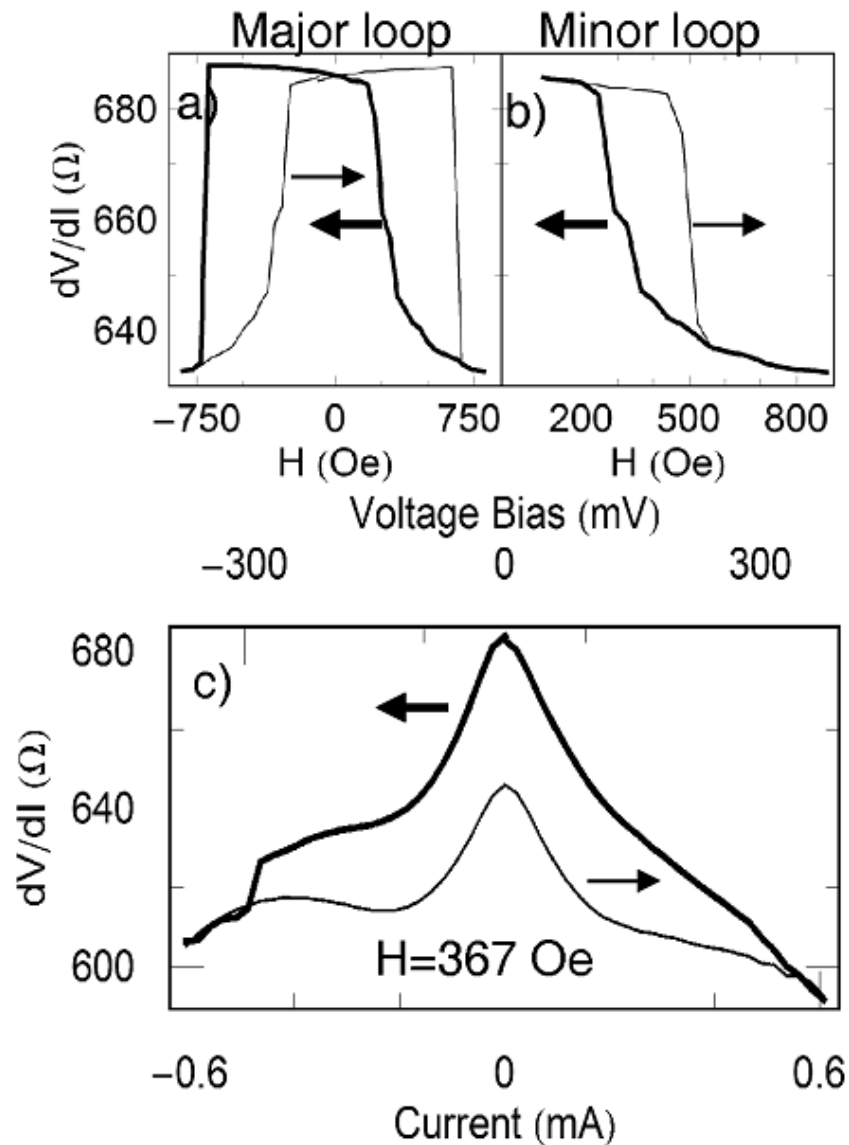
# SST in MTJ for MRAM



Huai, et al, APL (2004)

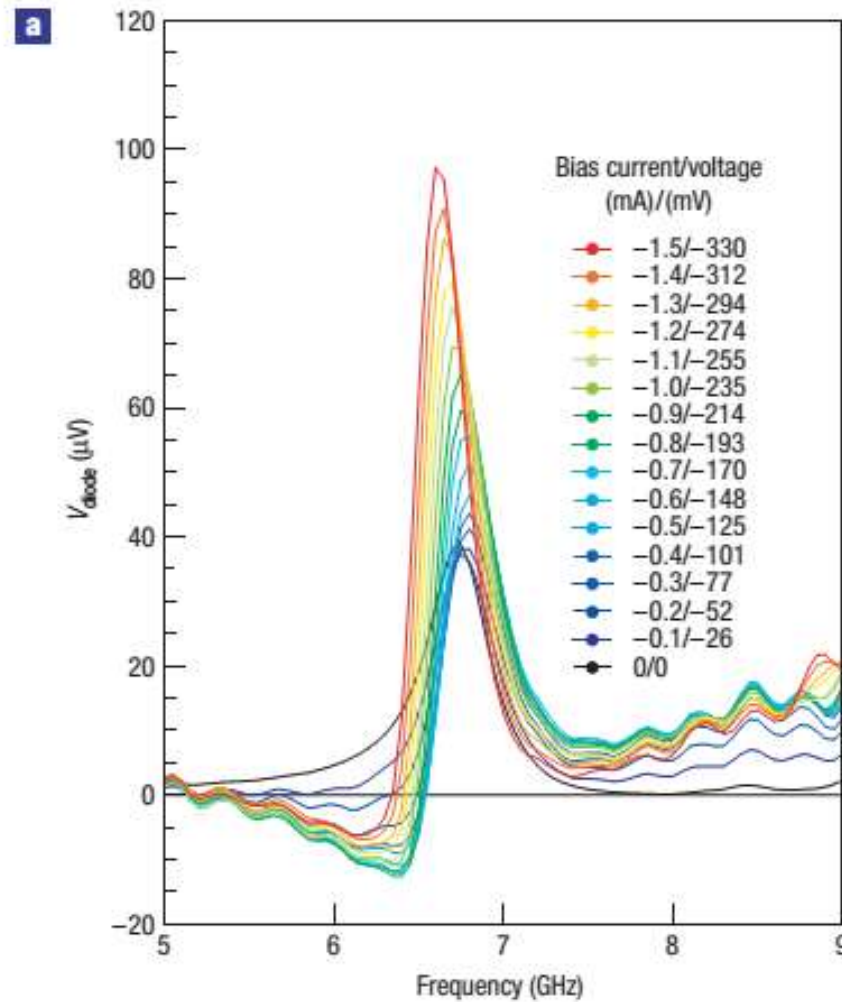
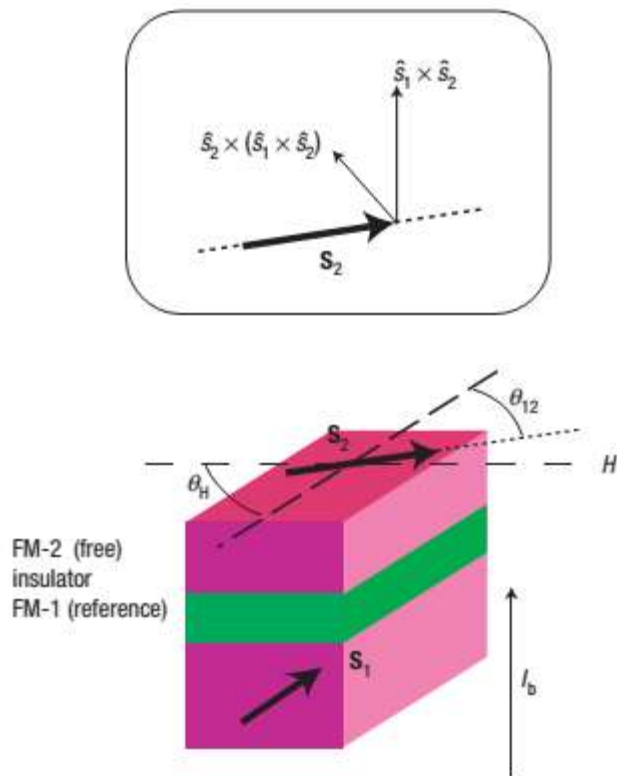


# SST in MTJ for MRAM



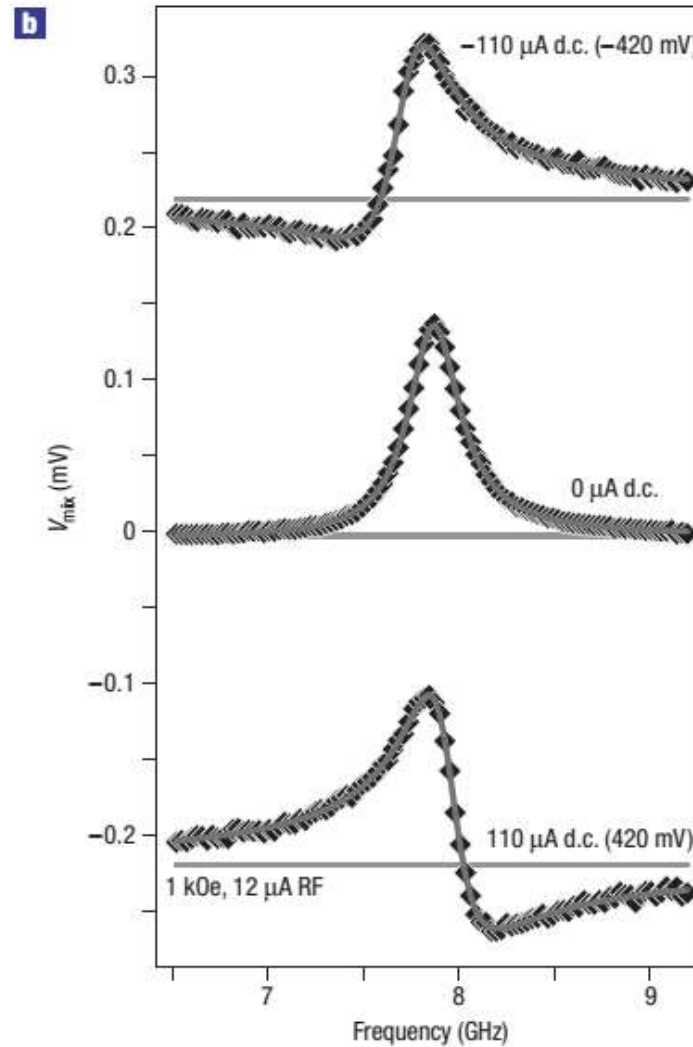
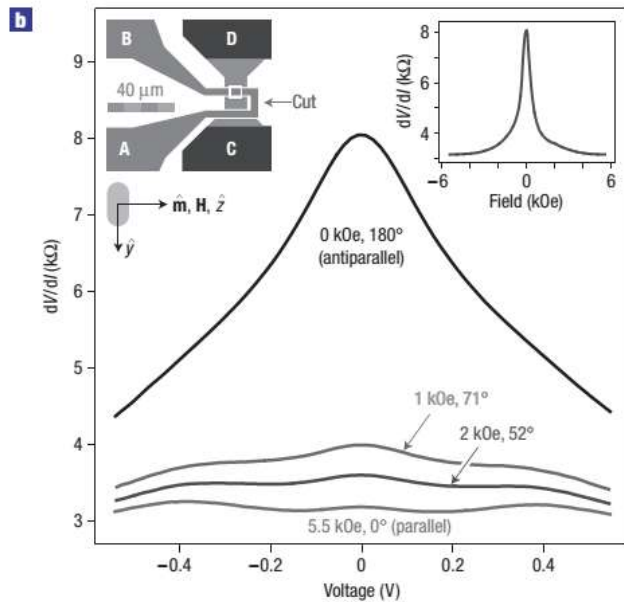
Fuchs, et al, APL (2004)

# Measurement of STT in MTJ



KUBOTA, et al, Nature Physics (2008)

# Measurement of STT in MTJ

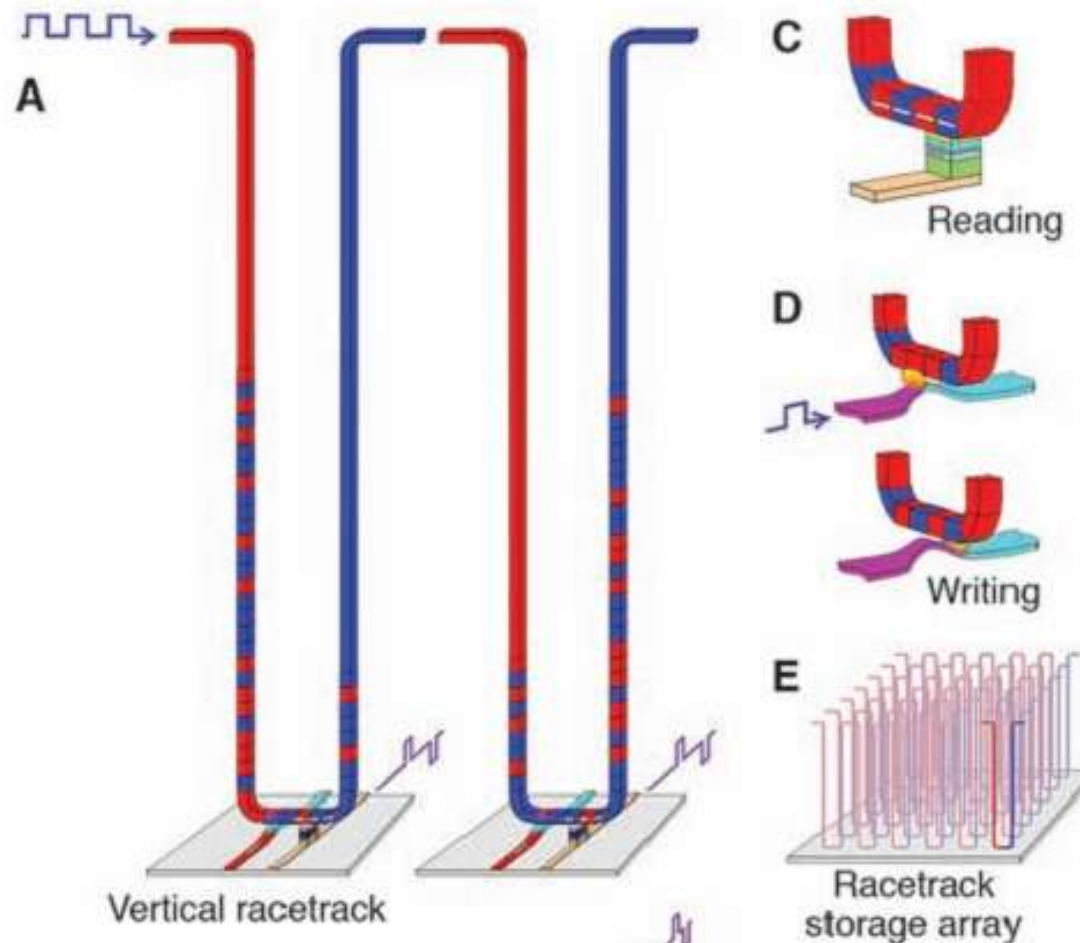


# Outline

## **4. Spin transfer torque in domain wall motion**

# Why domain wall

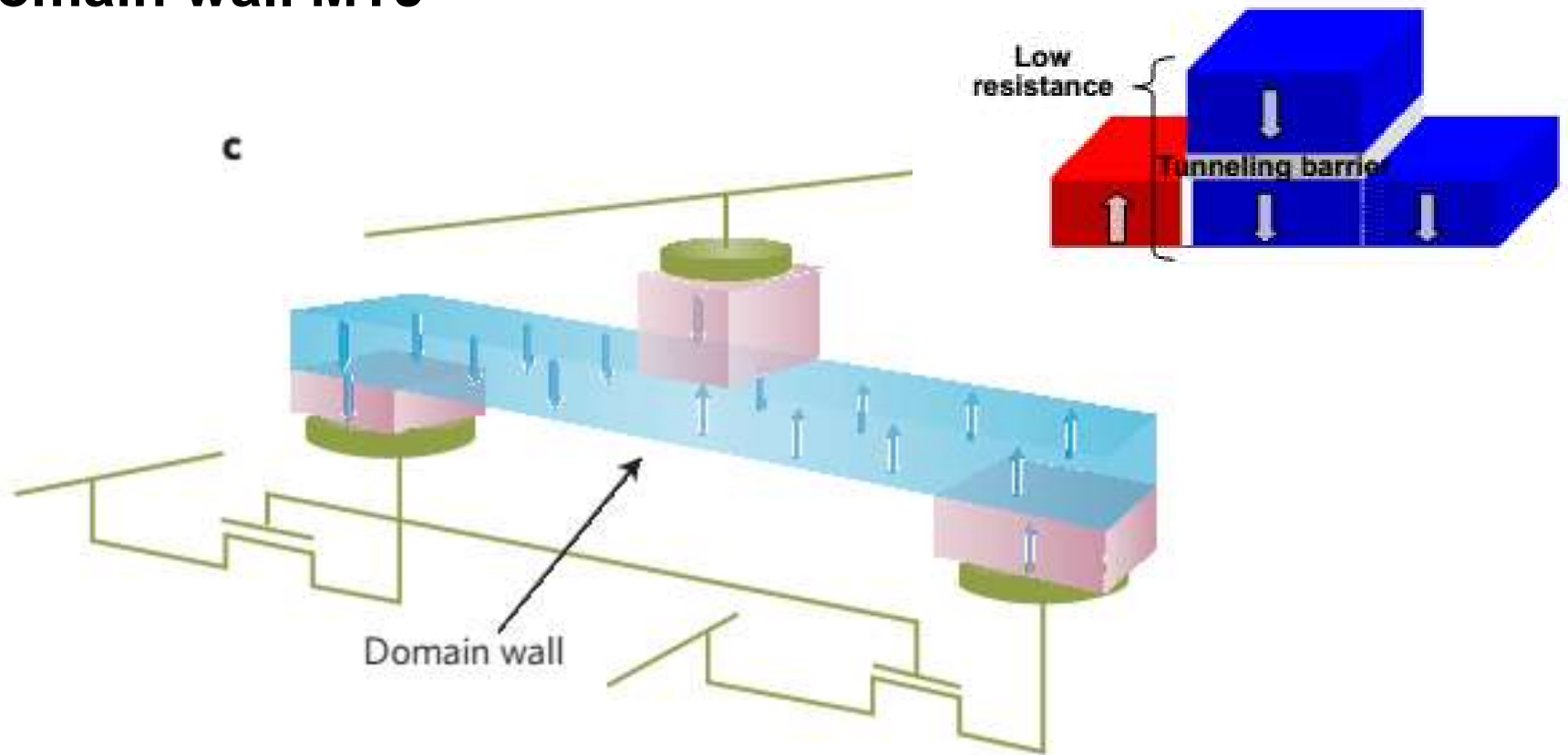
## Racetrack Memory



Parkin, et al, Science (2008)

# Why domain wall

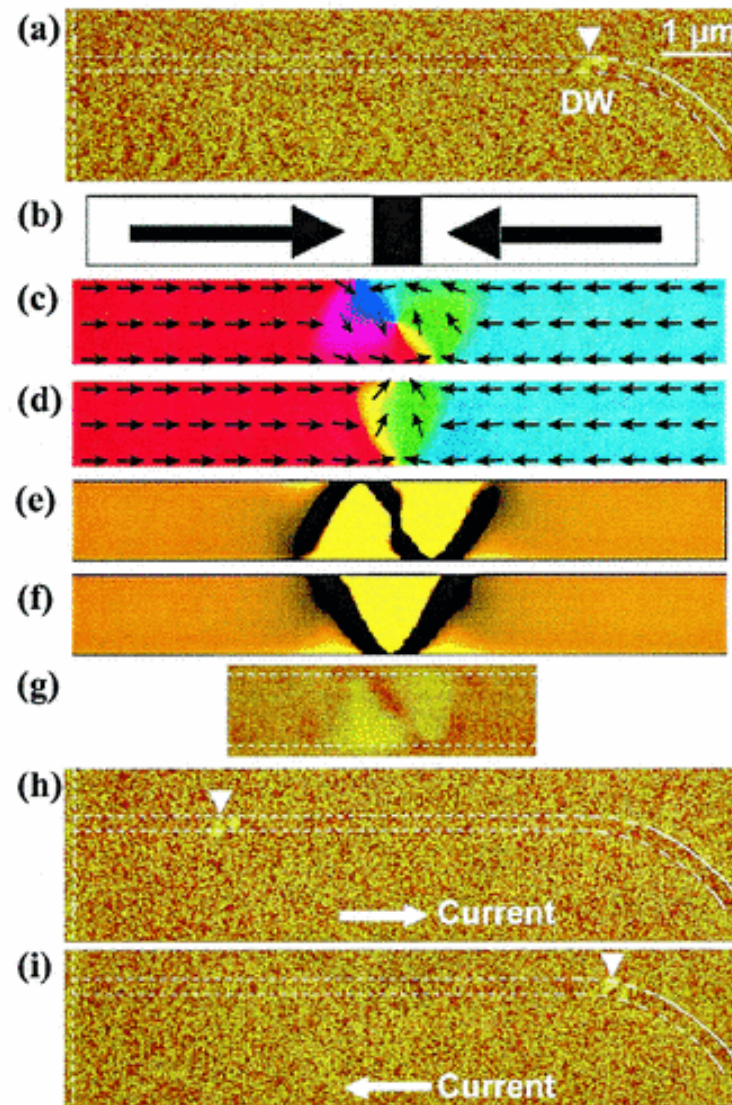
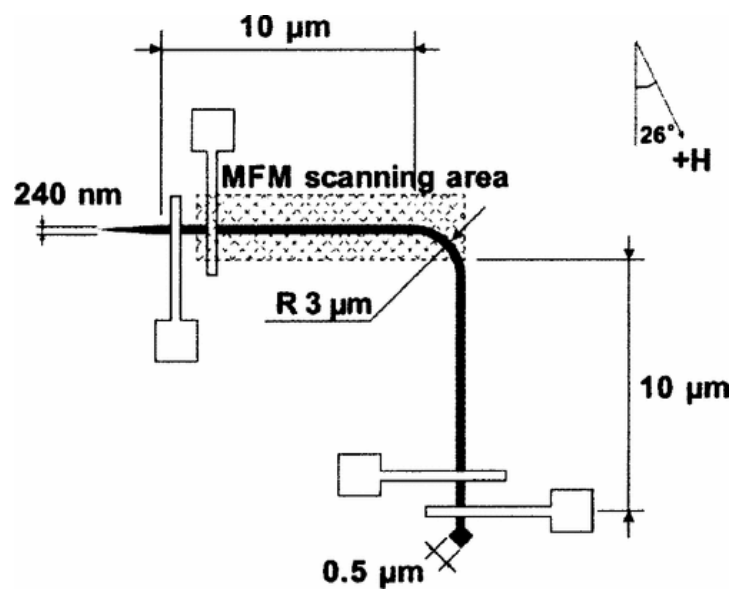
## Domain wall MTJ



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

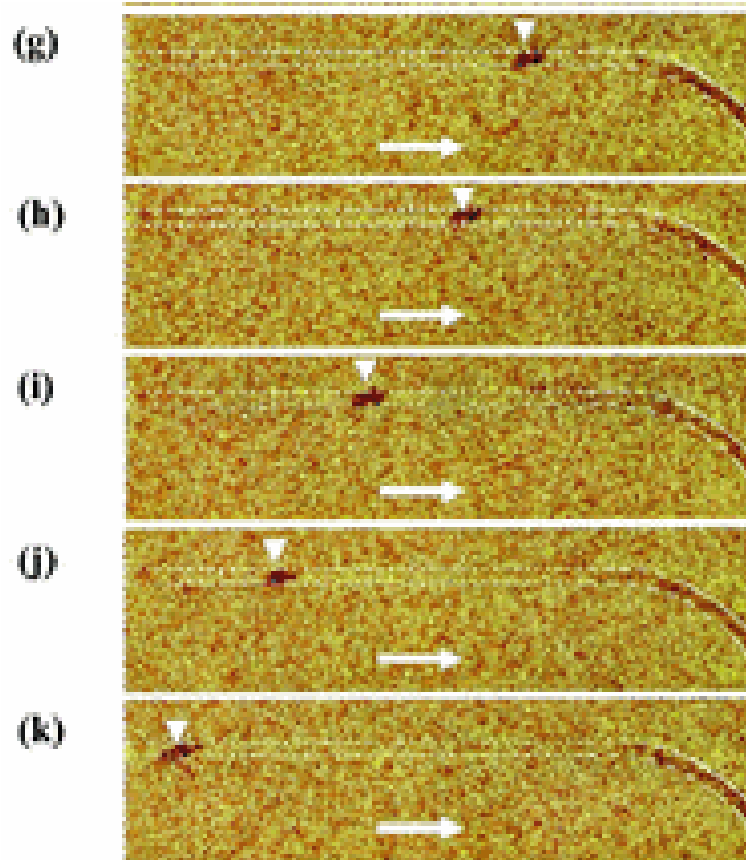
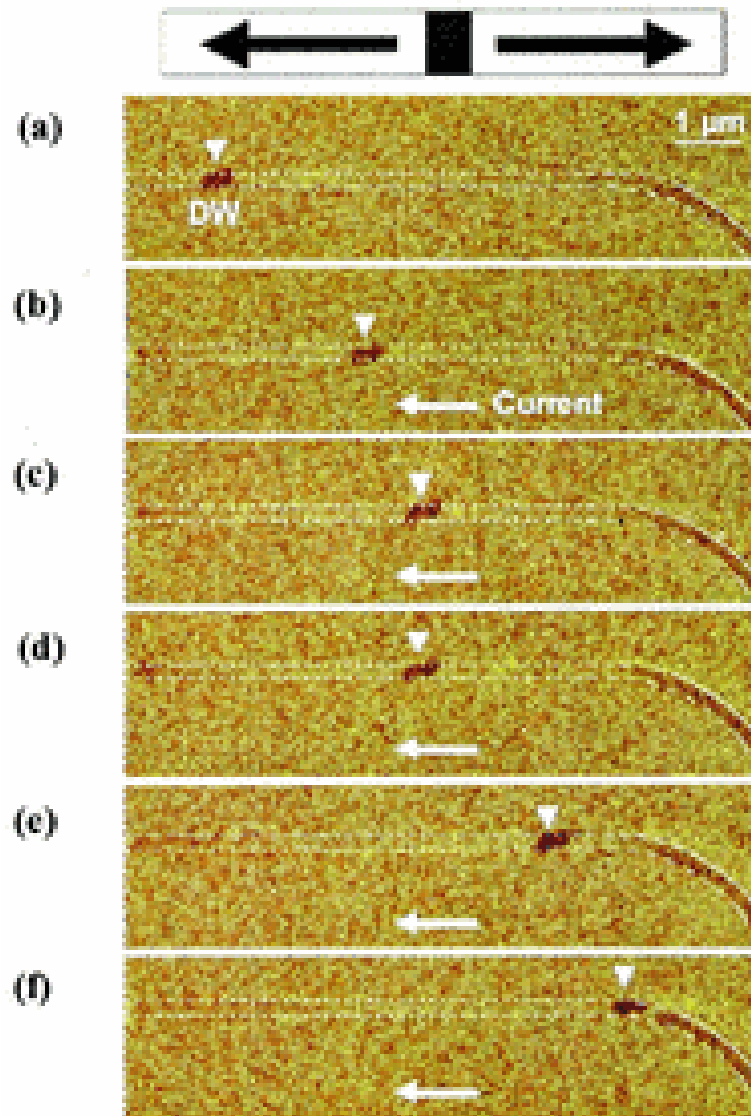
# Domain wall motion by STT

## FM Metal



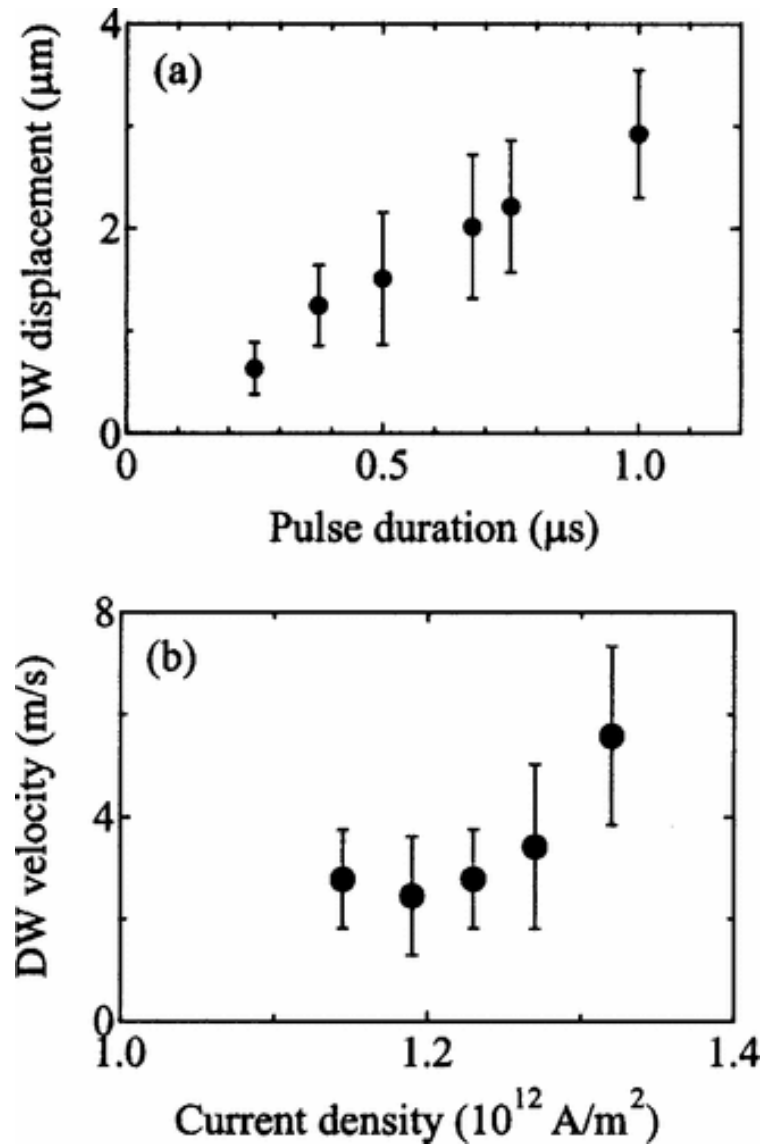
Yamaguchi, et al, PRL (2004)

# Domain wall motion by STT



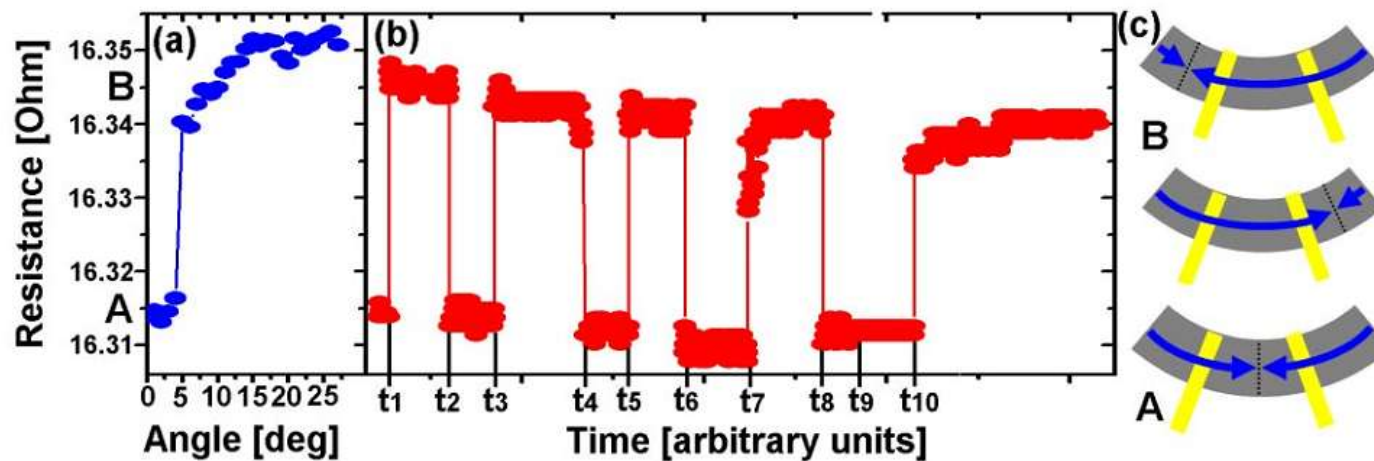
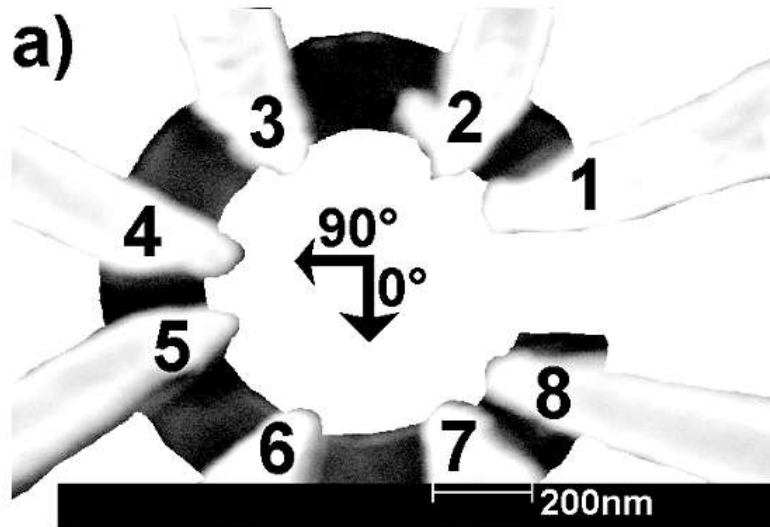


# Domain wall motion by STT



# Domain wall motion by STT

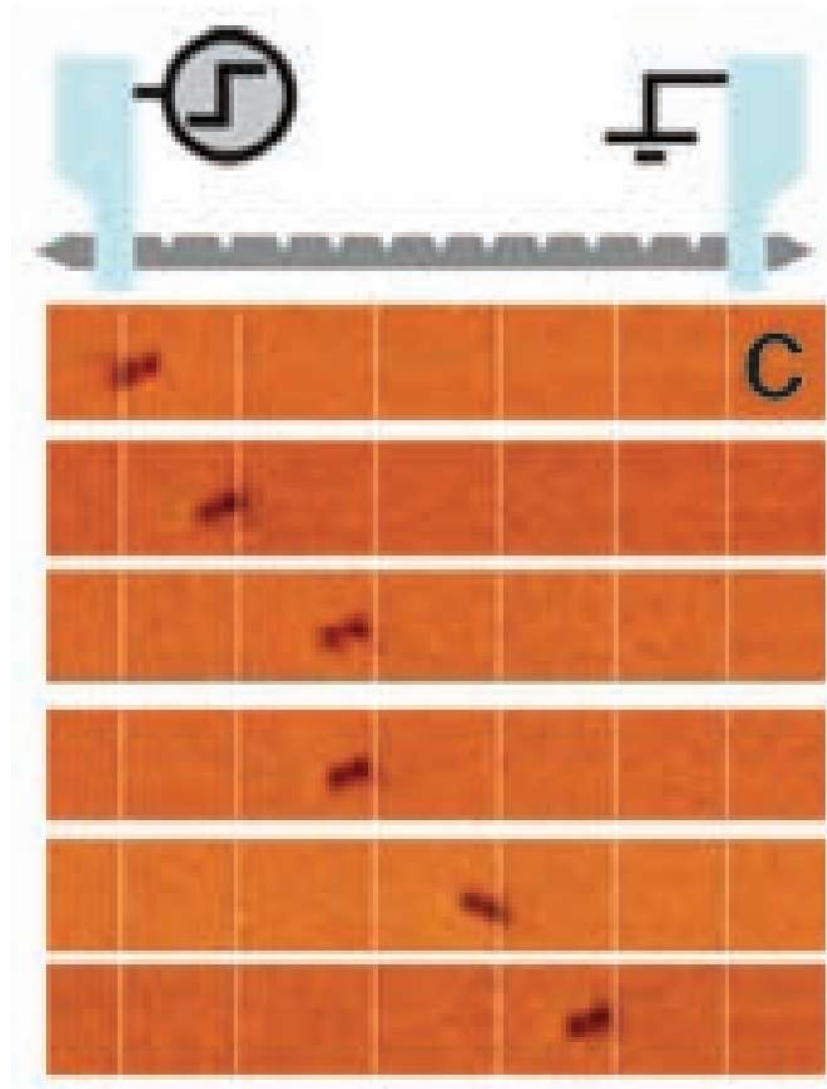
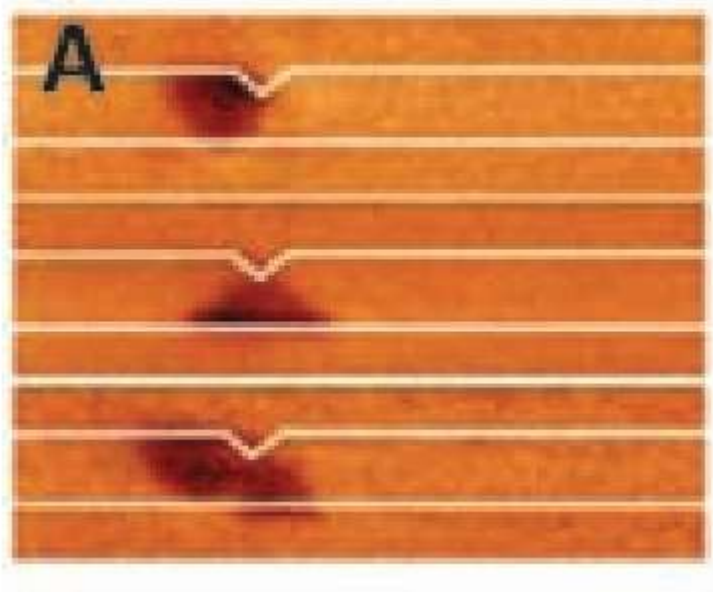
FM Metal



Kalui, et al, PRL (2005)

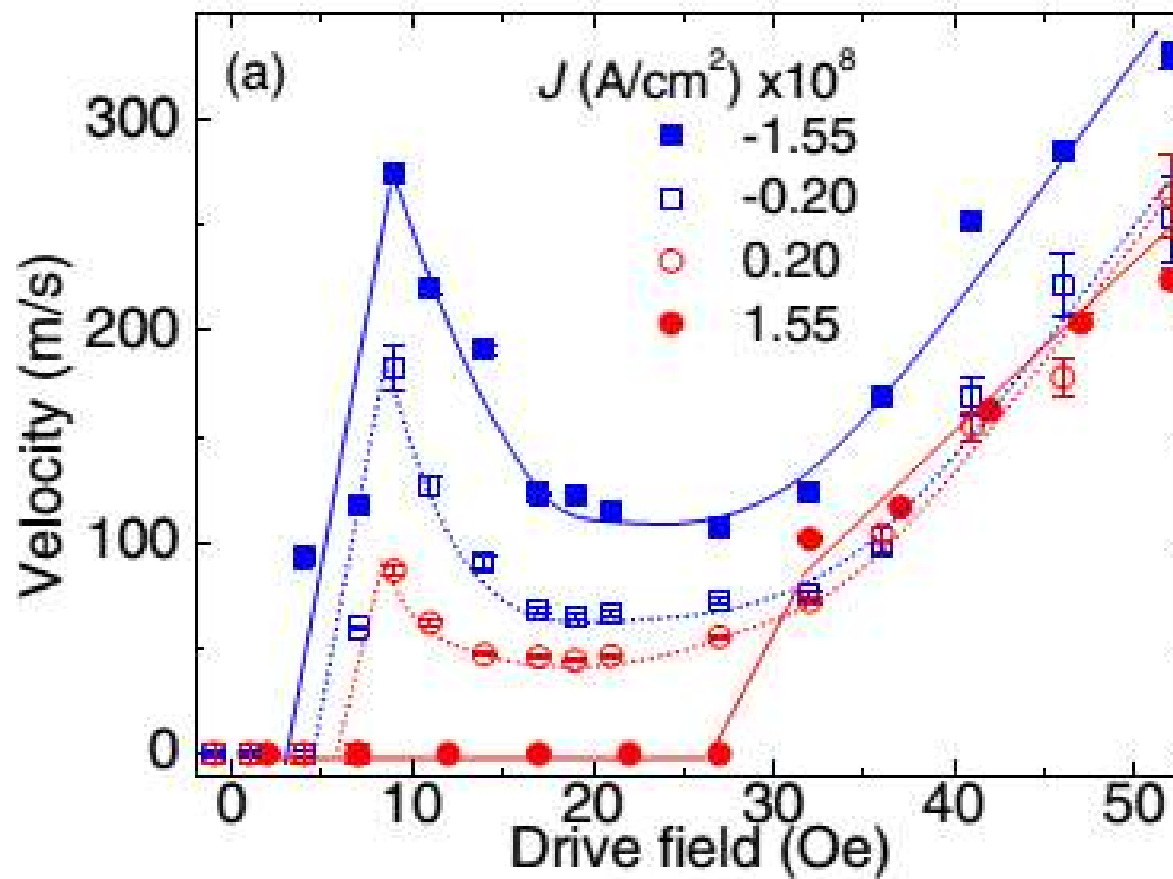
# Domain wall motion by STT

## A notch



# Domain wall motion by STT

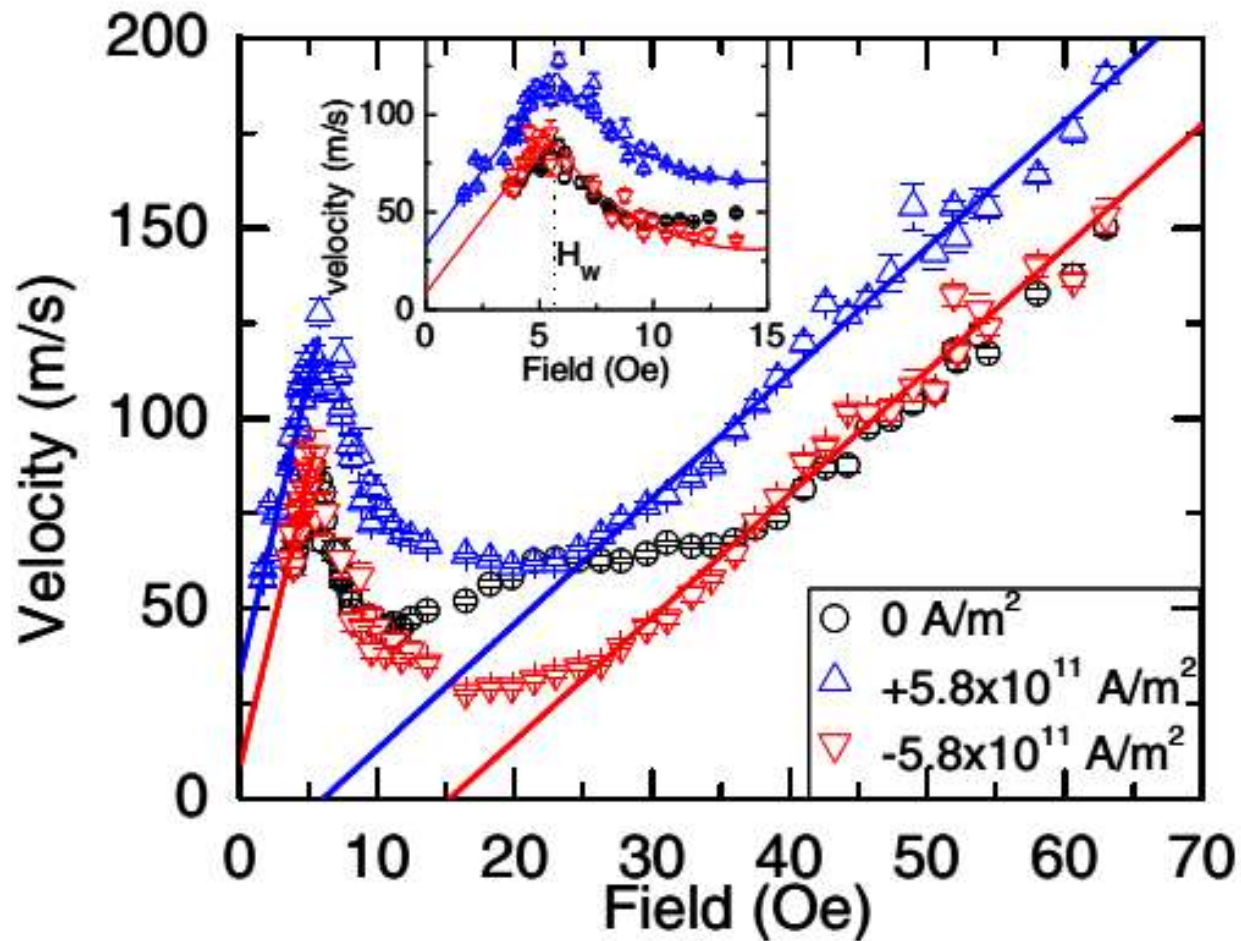
## Critical Current and velocity increase



Hayashi, et al, PRL (2006)

# Domain wall motion by STT

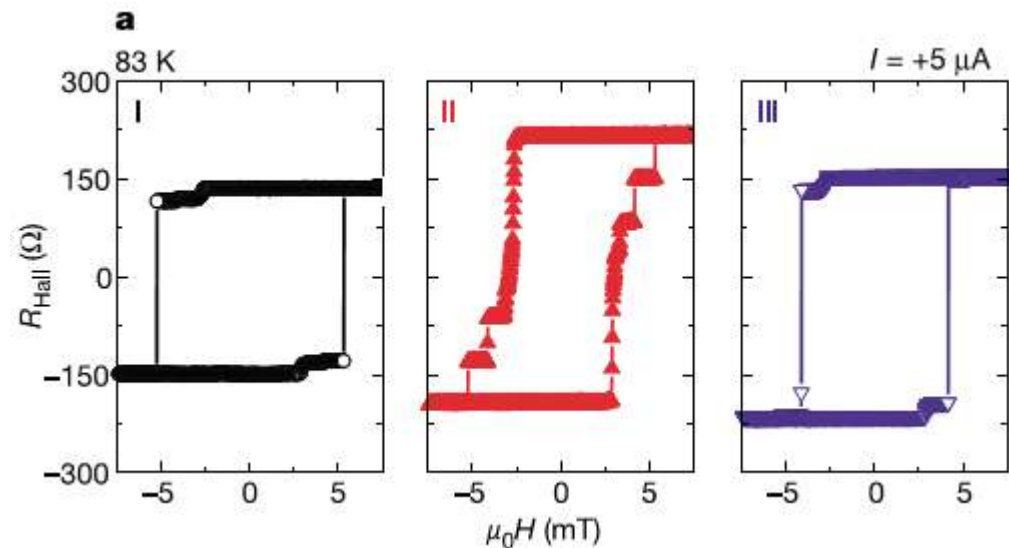
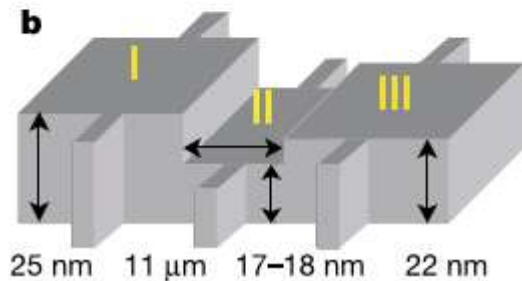
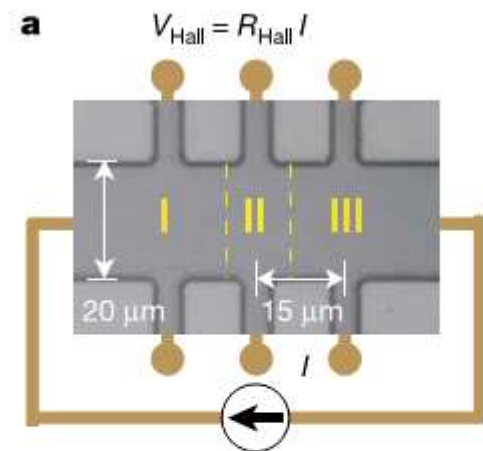
## Critical Current



Beach, et al, PRL (2006)

# Domain wall motion by STT

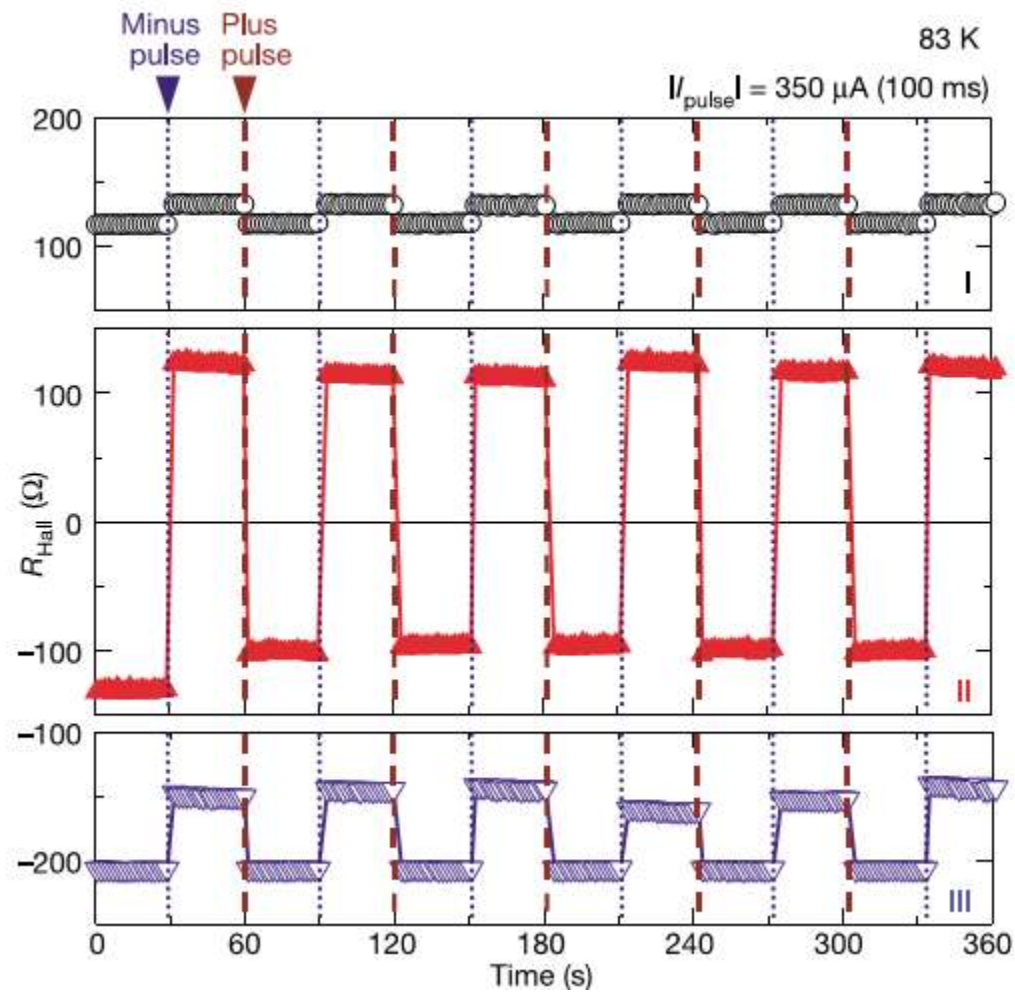
## FM Semiconductor: GaMnAs



Yamaguchi, et al, Nature (2004)

# Domain wall motion by STT

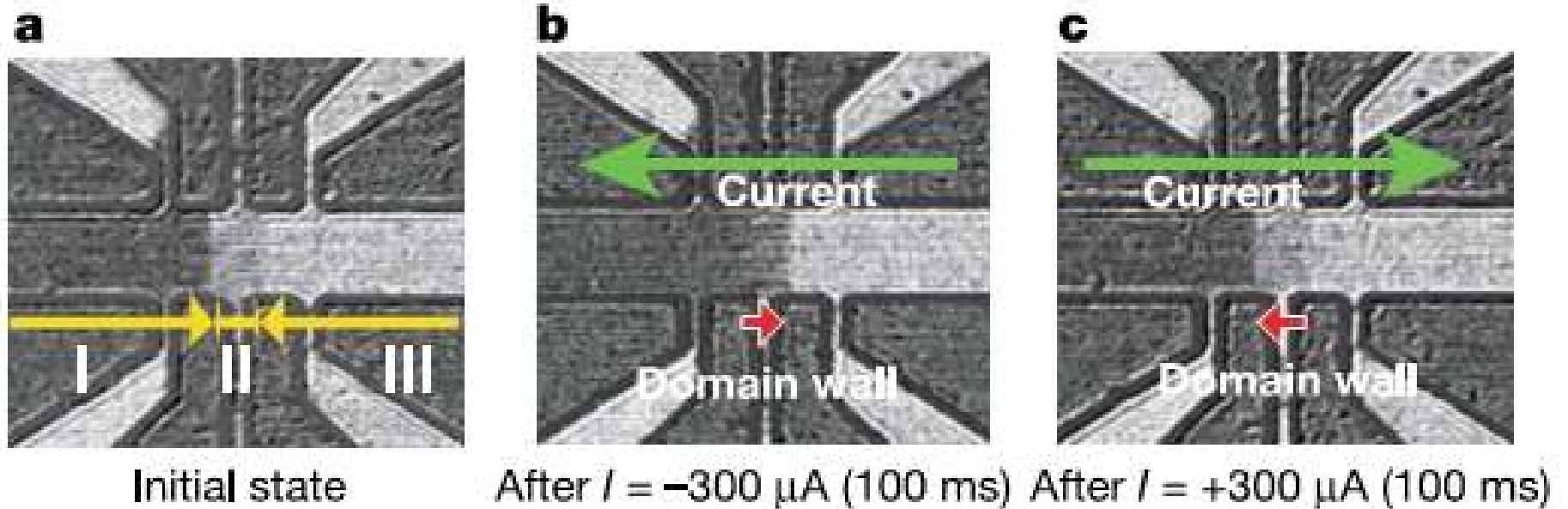
## FM Semiconductor: GaMnAs





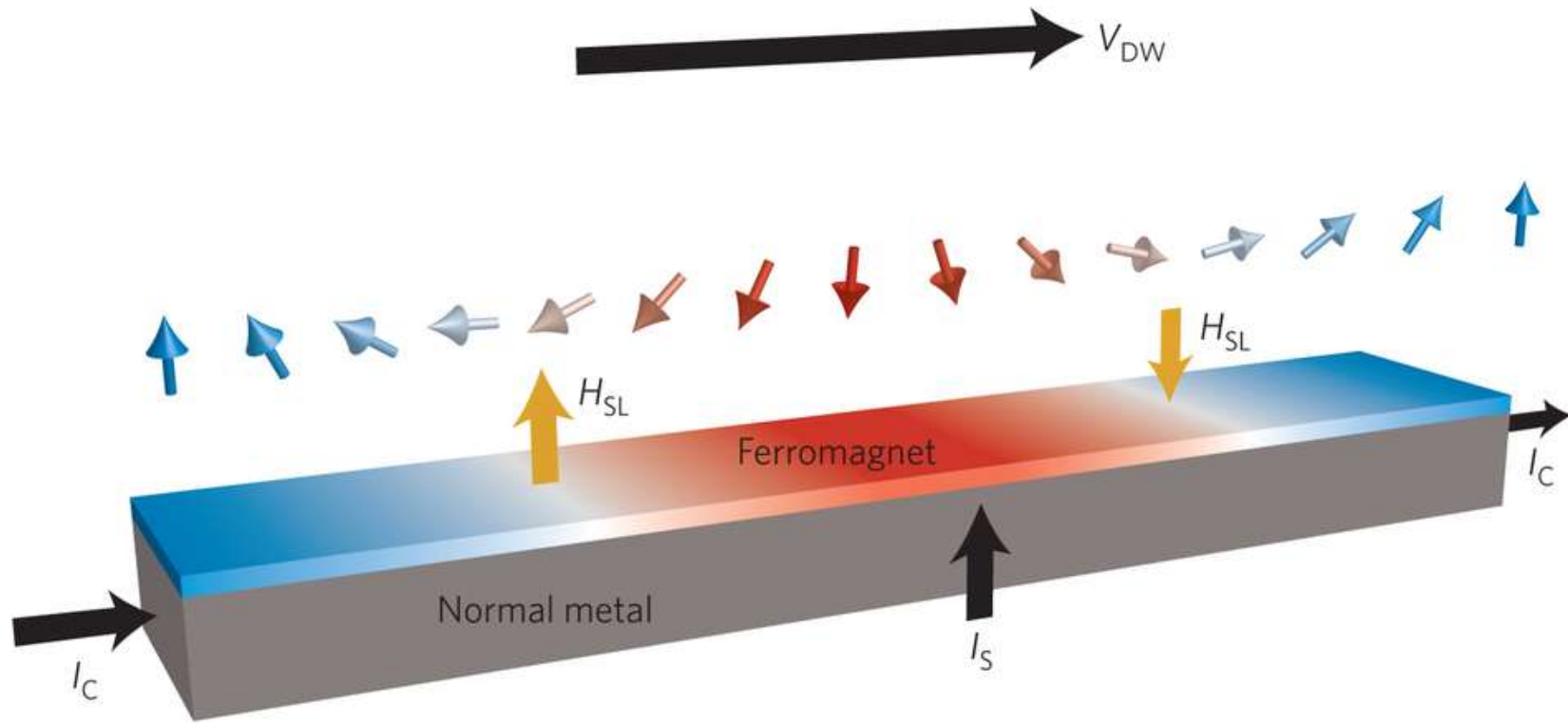
# Domain wall motion by STT

FM Semiconductor: GaMnAs



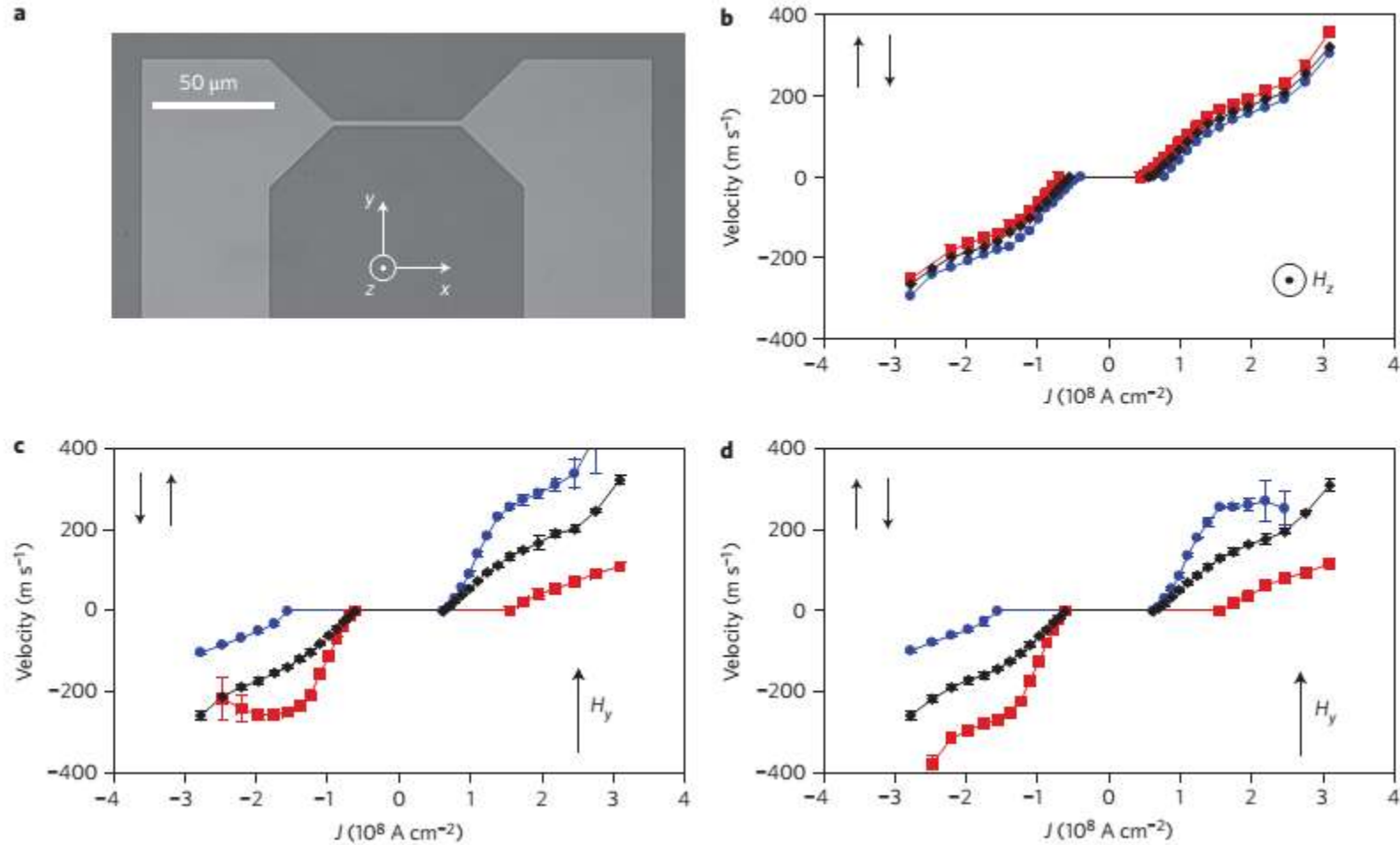


# Fast domain wall motion



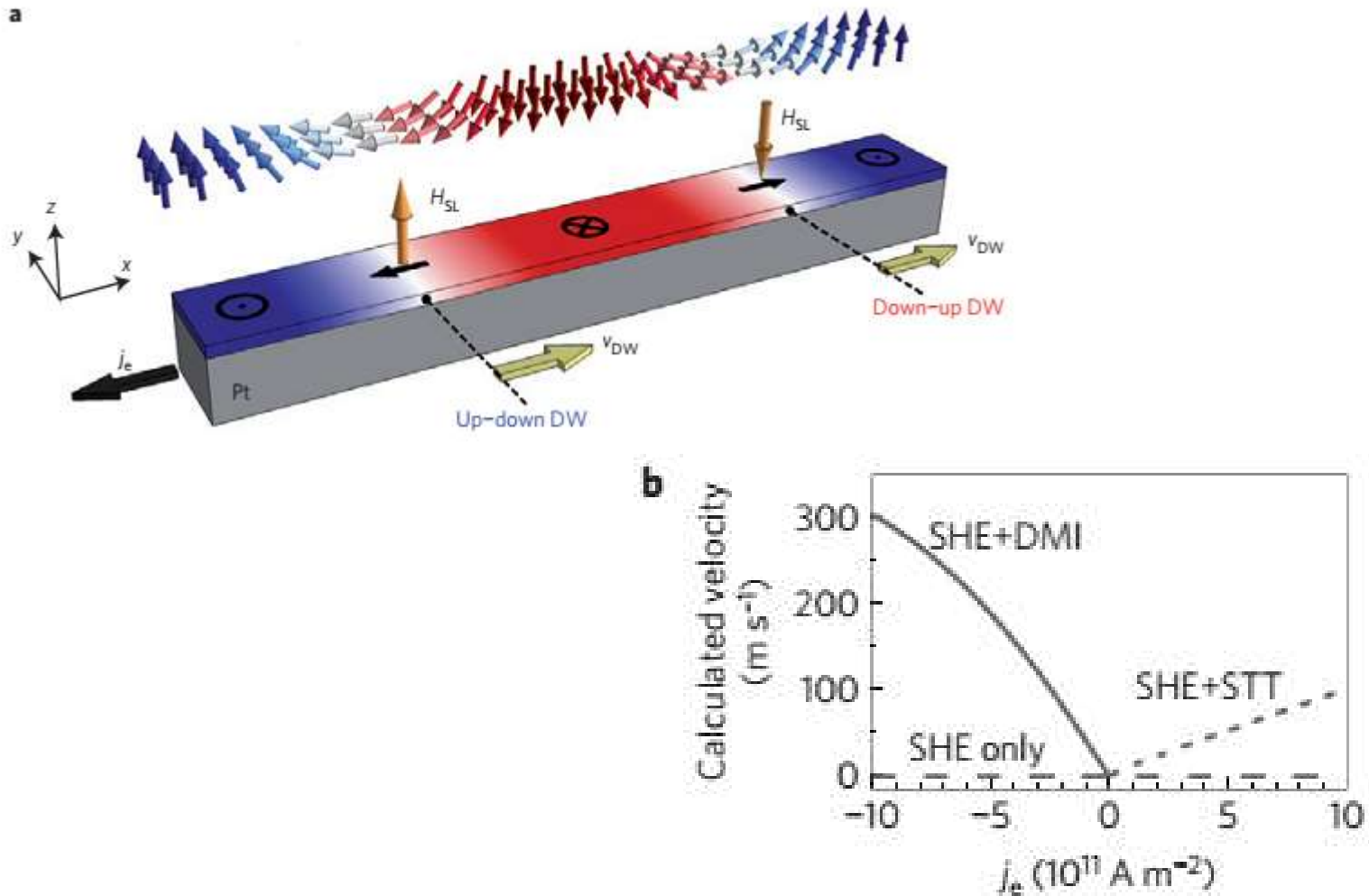
Brataas, Nature Nanotech (2013)

# Fast domain wall motion



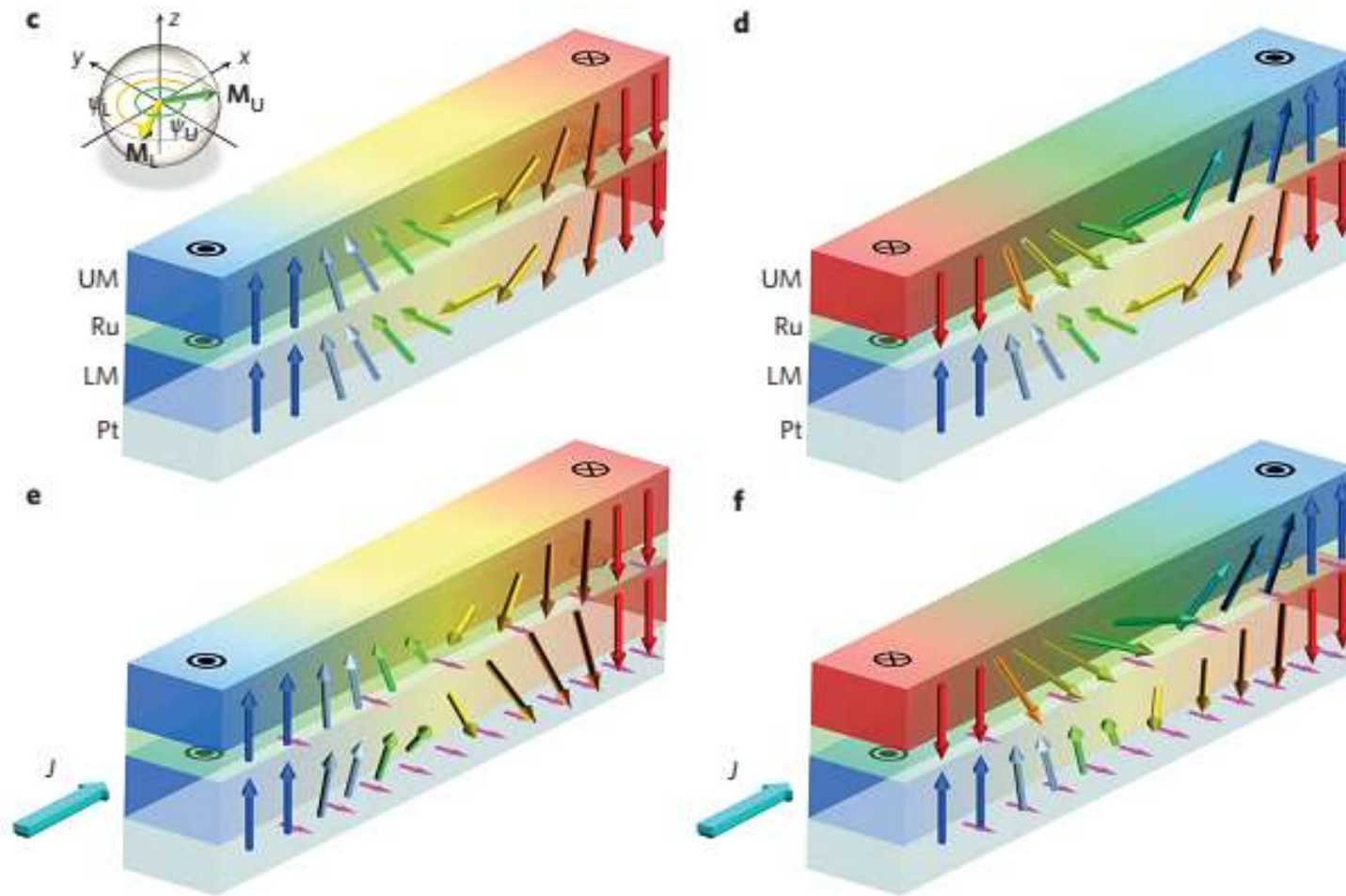
Ryu, et al, Nature Nanotech (2013)

# Fast domain wall motion



Emori, et al, Nature Materials (2013)

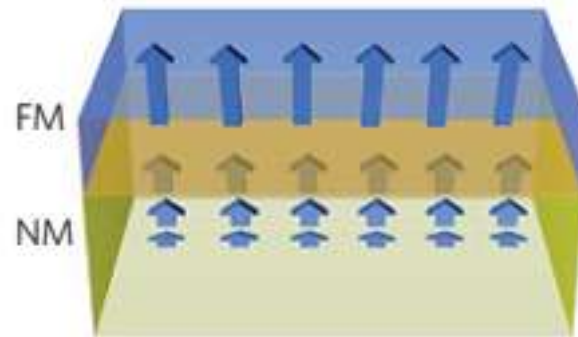
# Fast domain wall motion



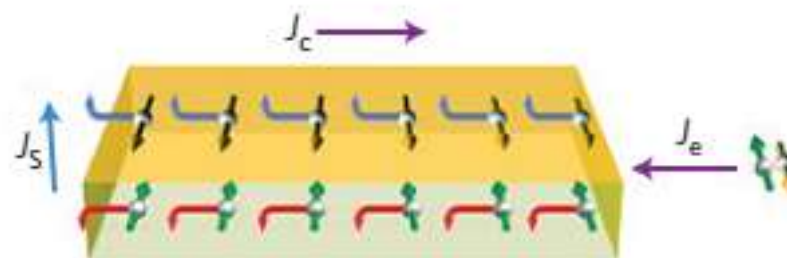
Yang, et al, Nature Nanotech (2015)

# Fast domain wall motion

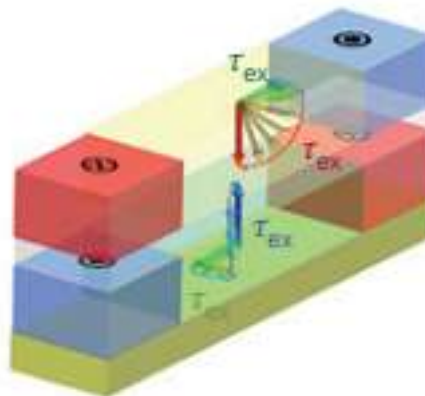
c



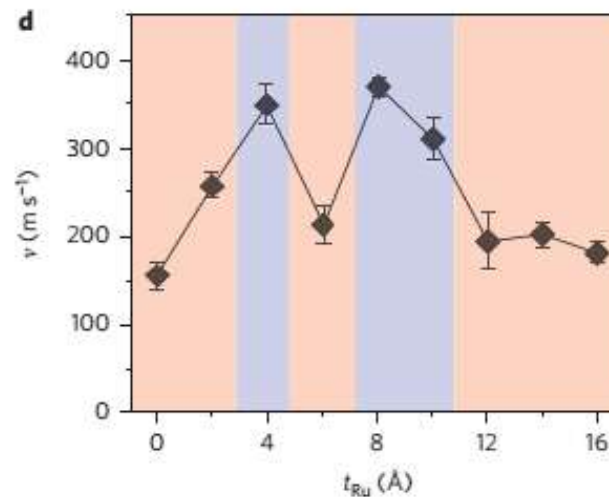
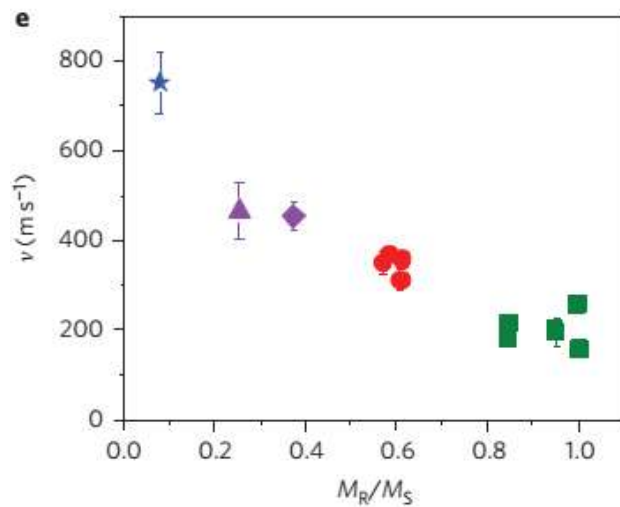
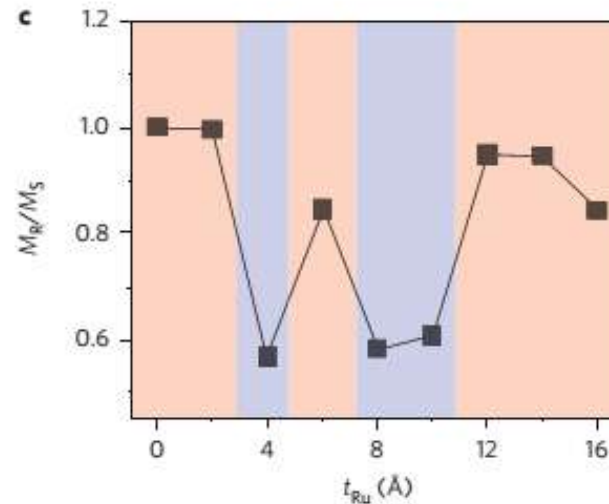
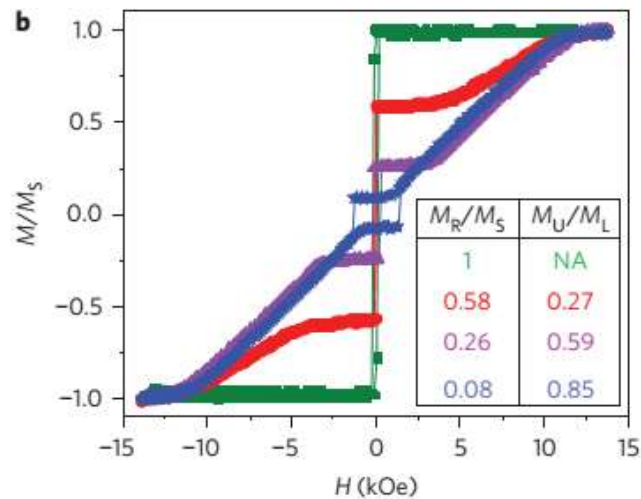
d



e

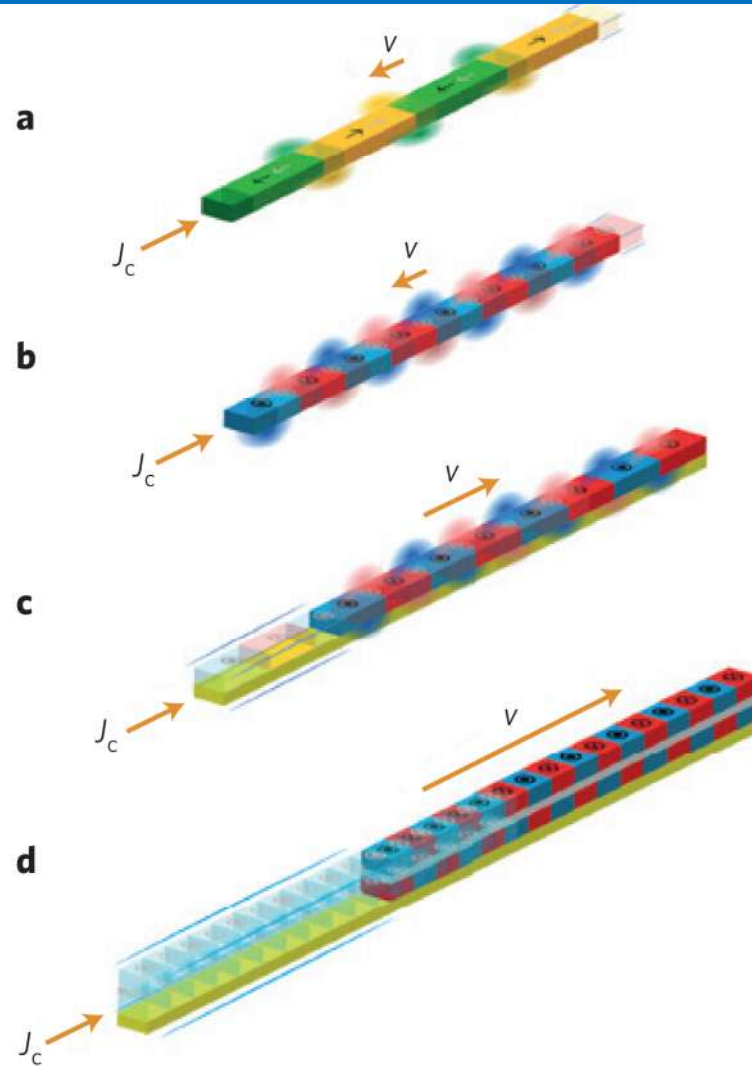
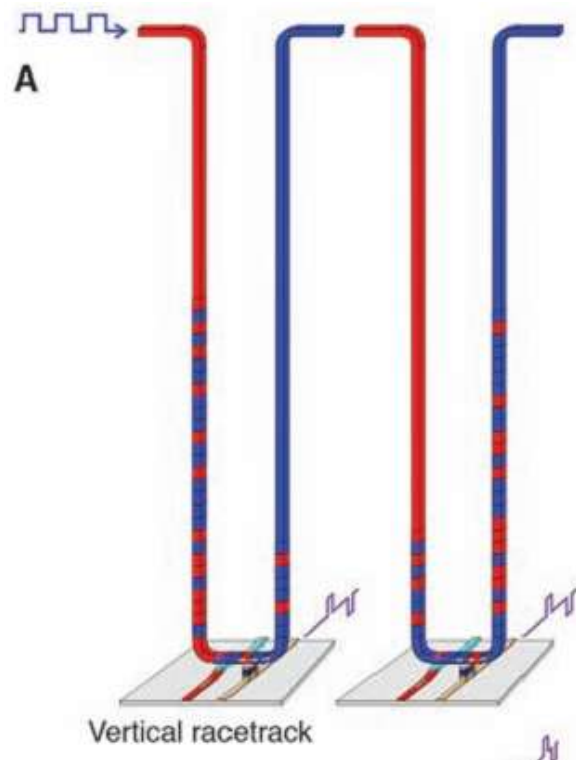


# Fast domain wall motion



Yang, et al, Nature Nanotech (2015)

# Fast domain wall motion



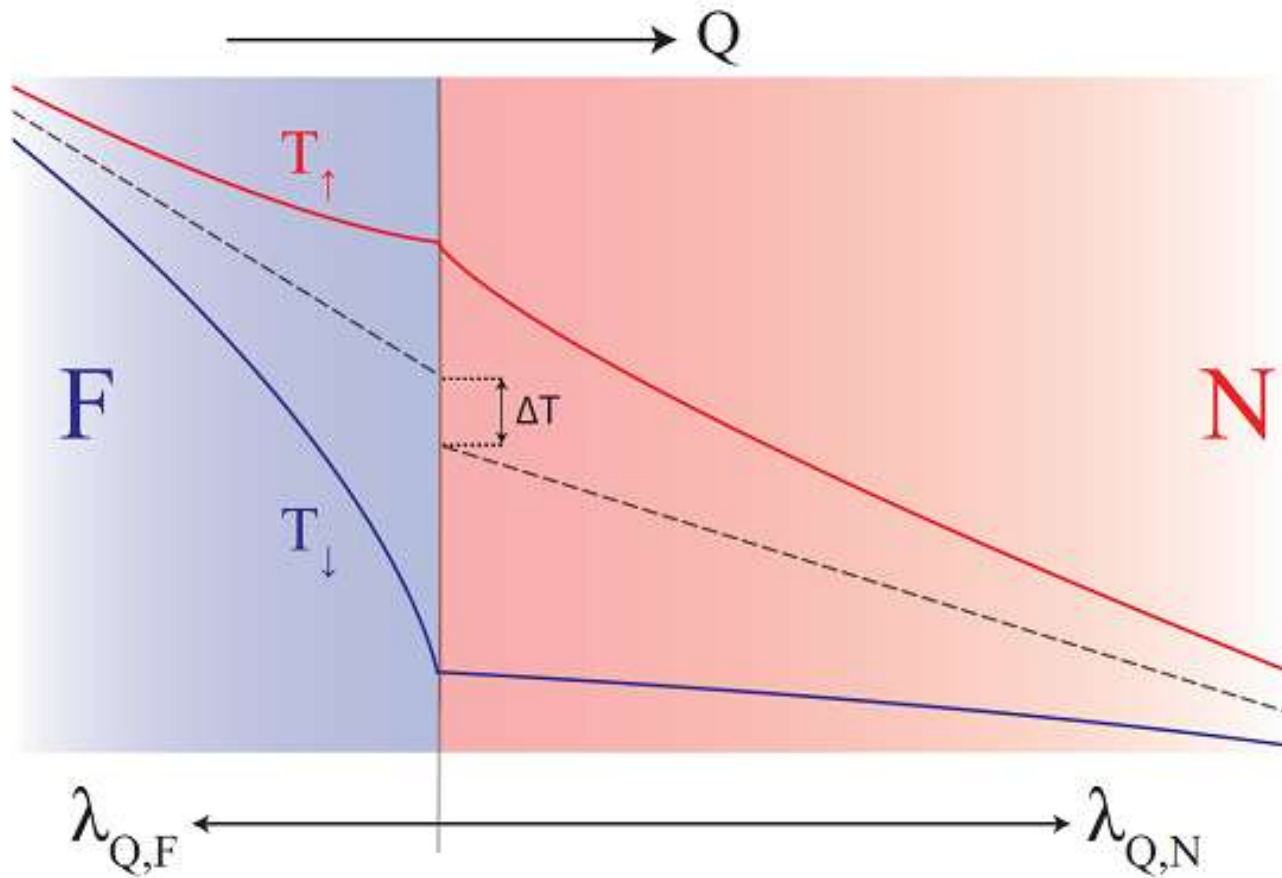
Parkin & Yang, et al, Nature Nanotech (2015)

# Outline

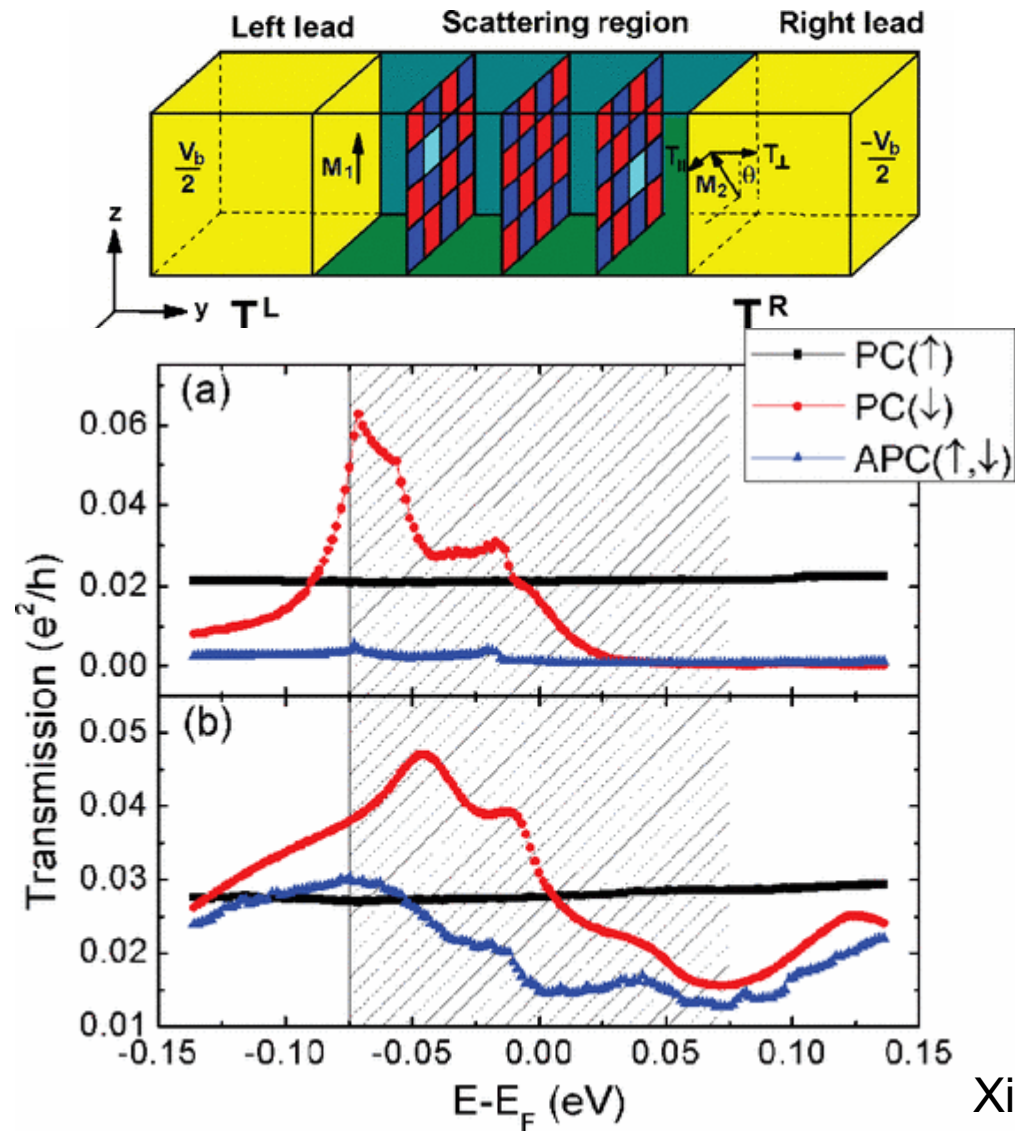
## **5. Thermal spin transfer torque**



# Thermal Spin Injection

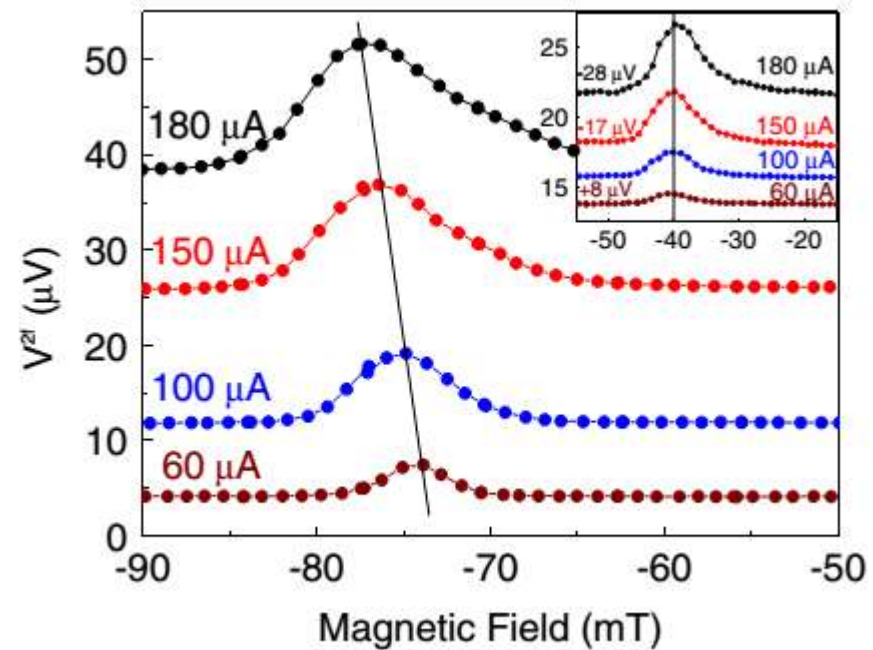
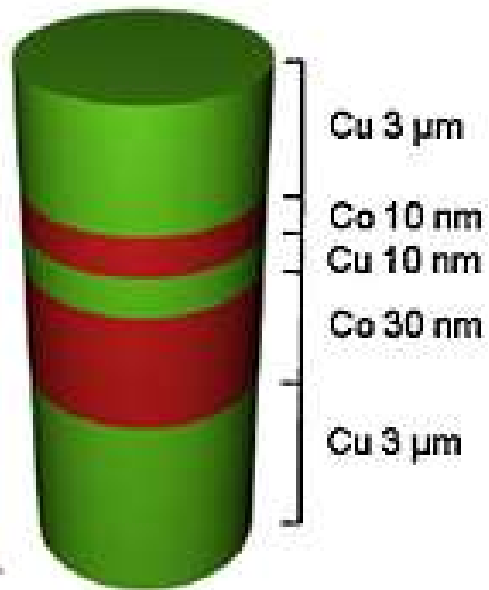


# Thermal Spin torque



Xia, et al, PRL (2011)

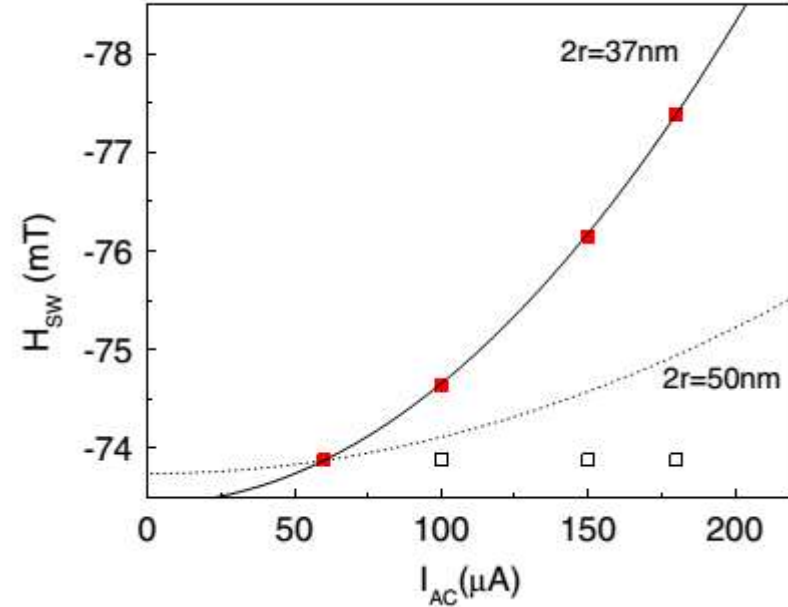
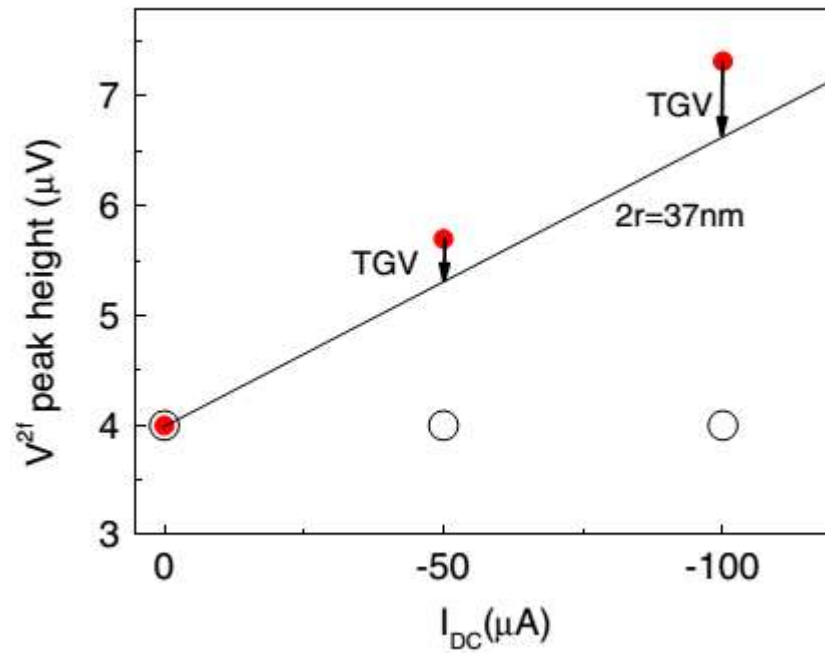
# Thermal Spin torque



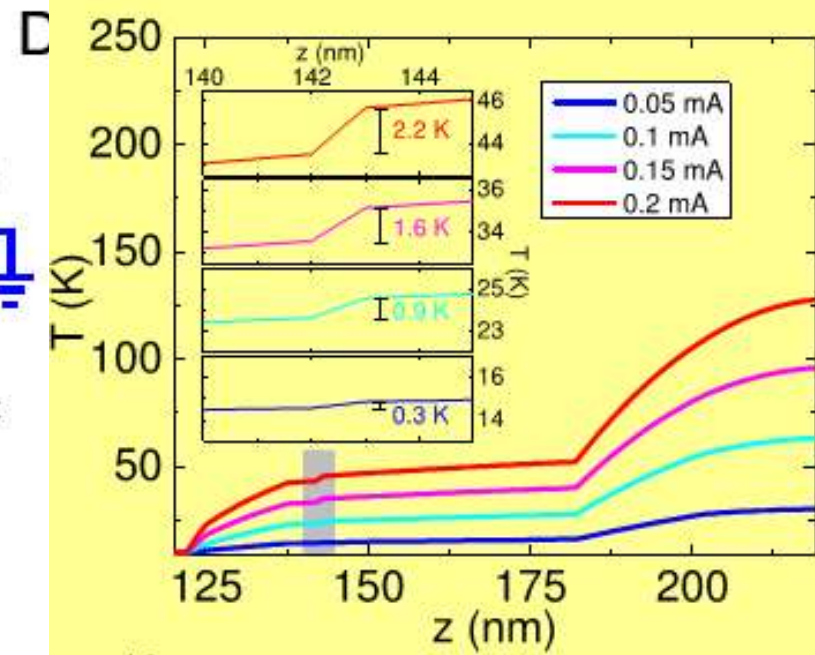
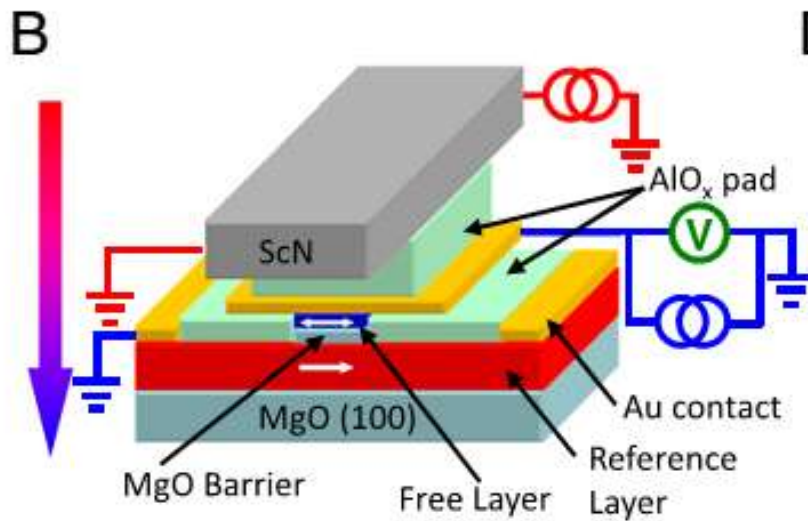
Yu, et al, PRL (2010)

# Thermal Spin torque

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

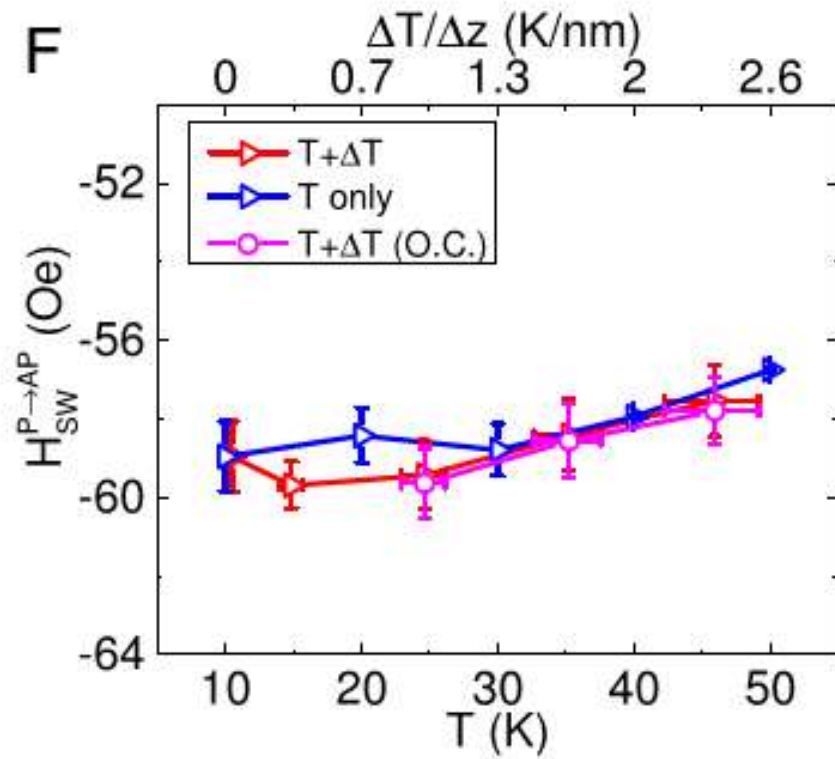
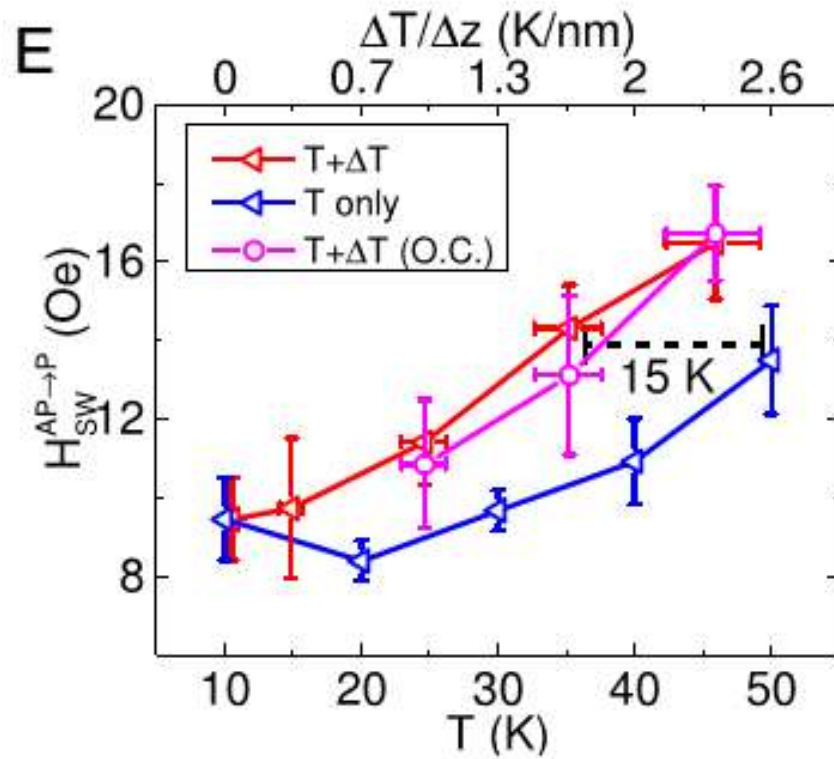


# Thermal Spin torque



Pushup, et al, PNAS (2015)

# Thermal Spin torque

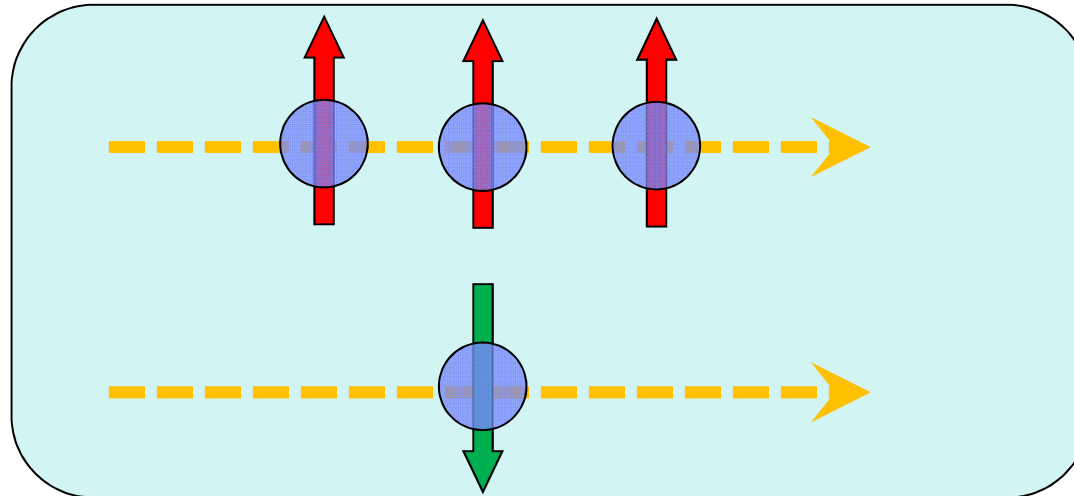


## Outline

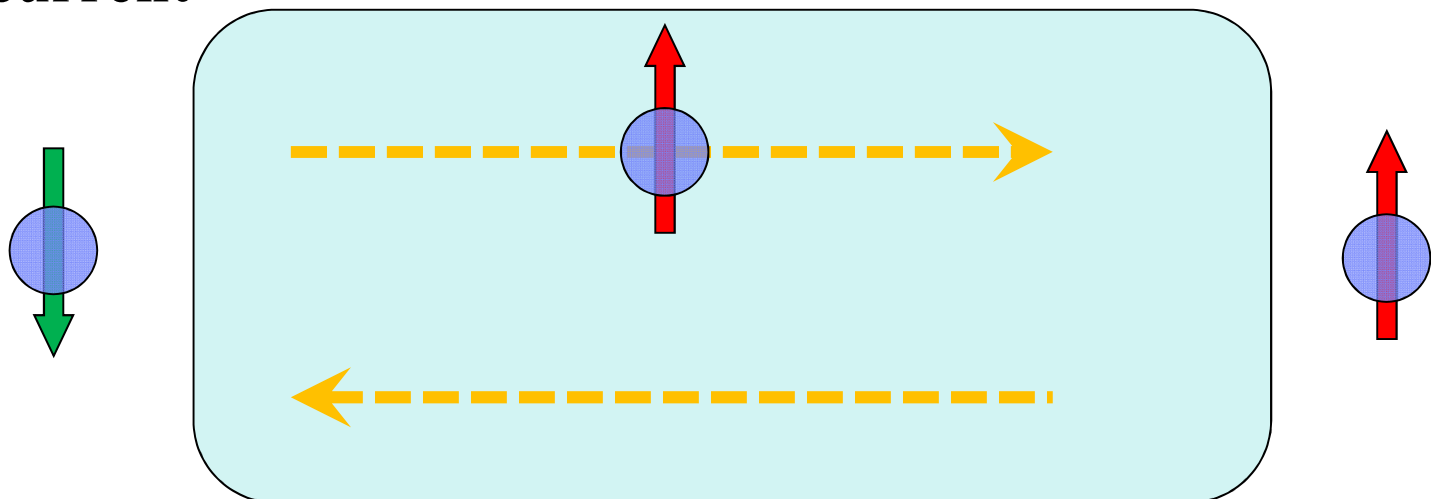
# 6. Pure spin current transfer torque

# Pure spin current

## Spin polarized current

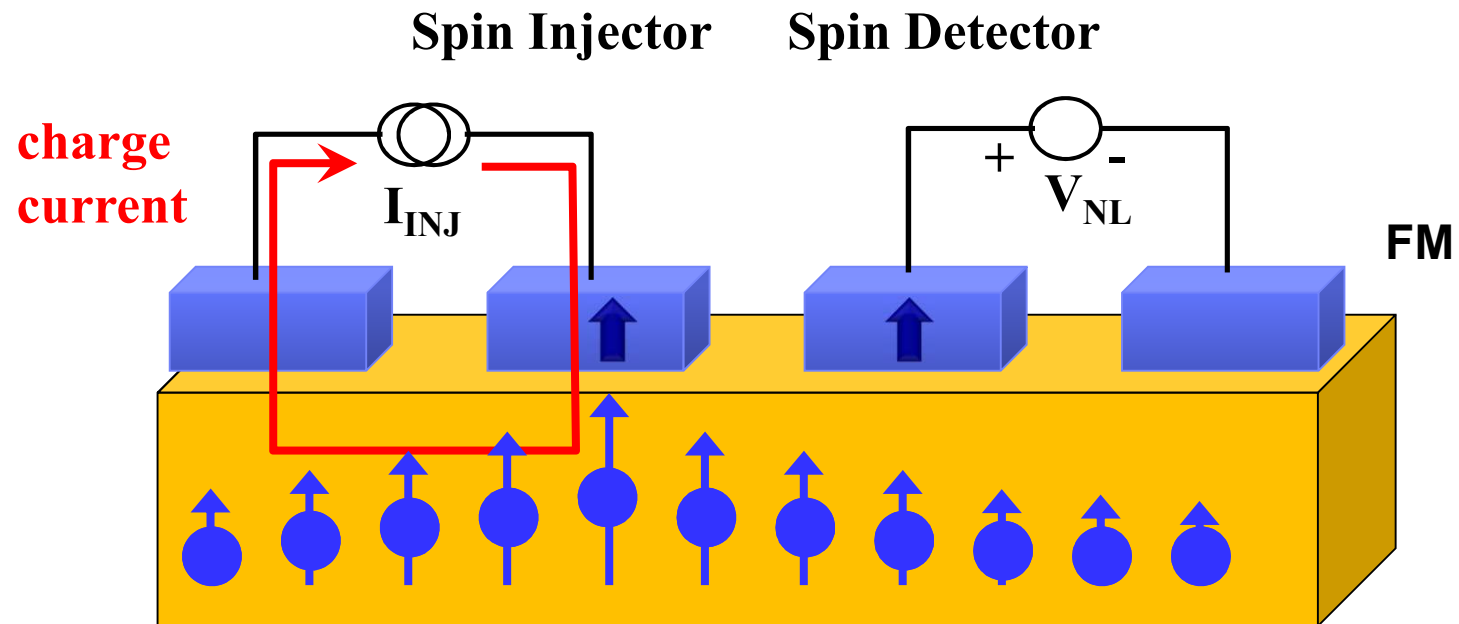


## Pure spin current

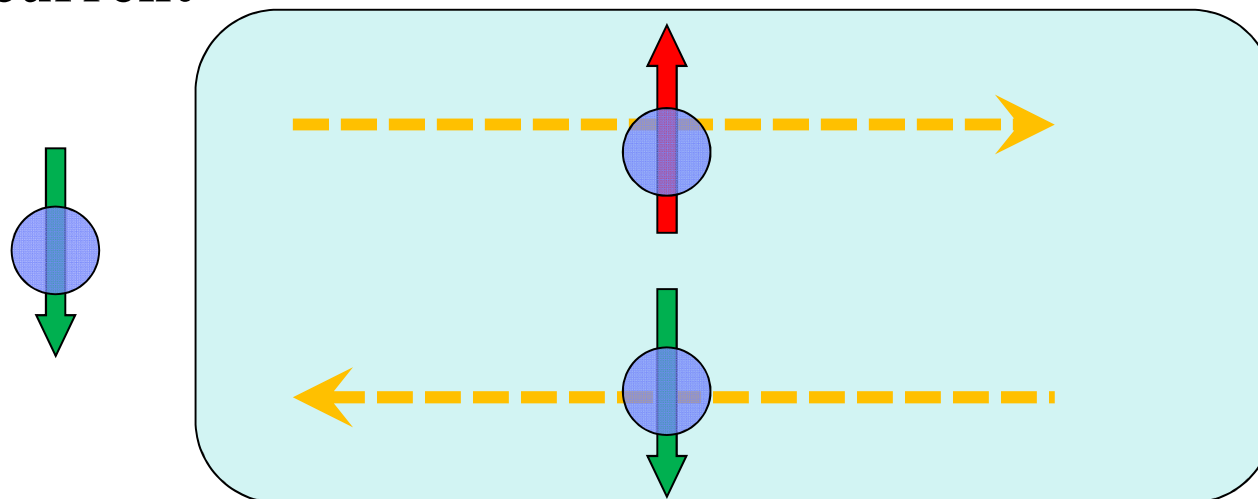




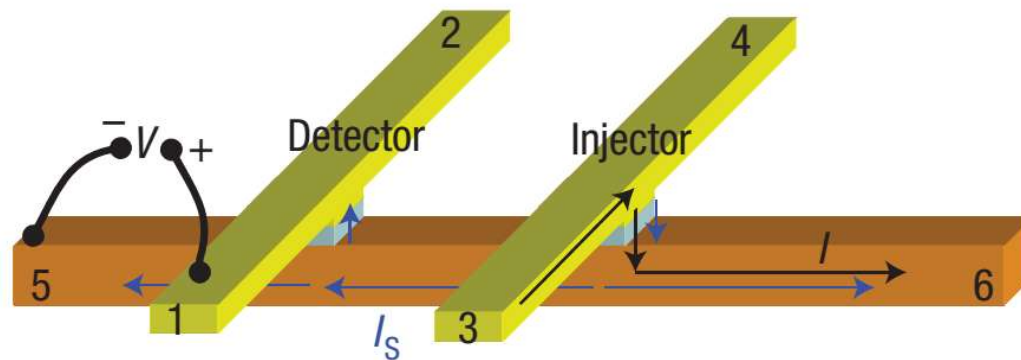
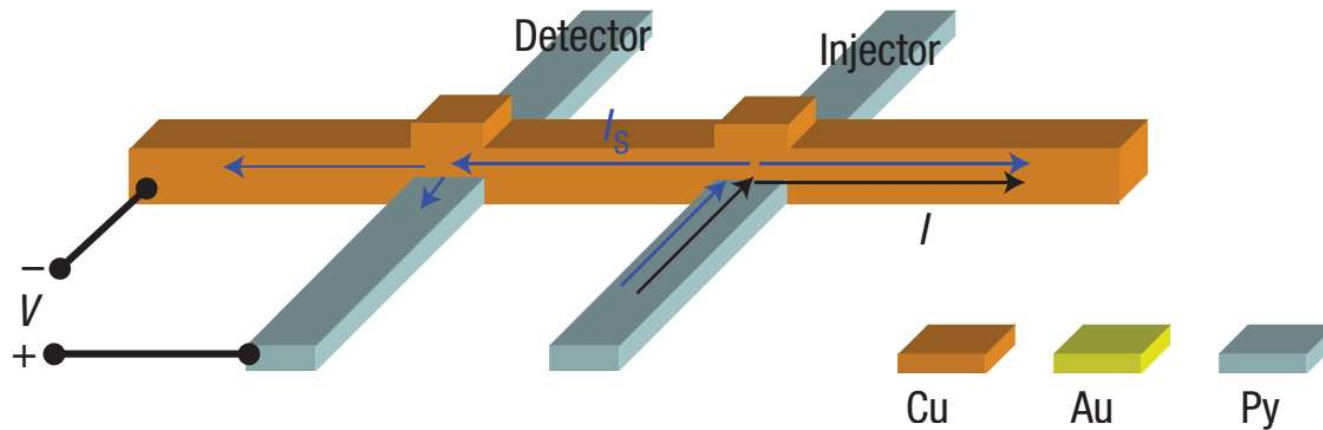
# Pure spin current



Pure spin current

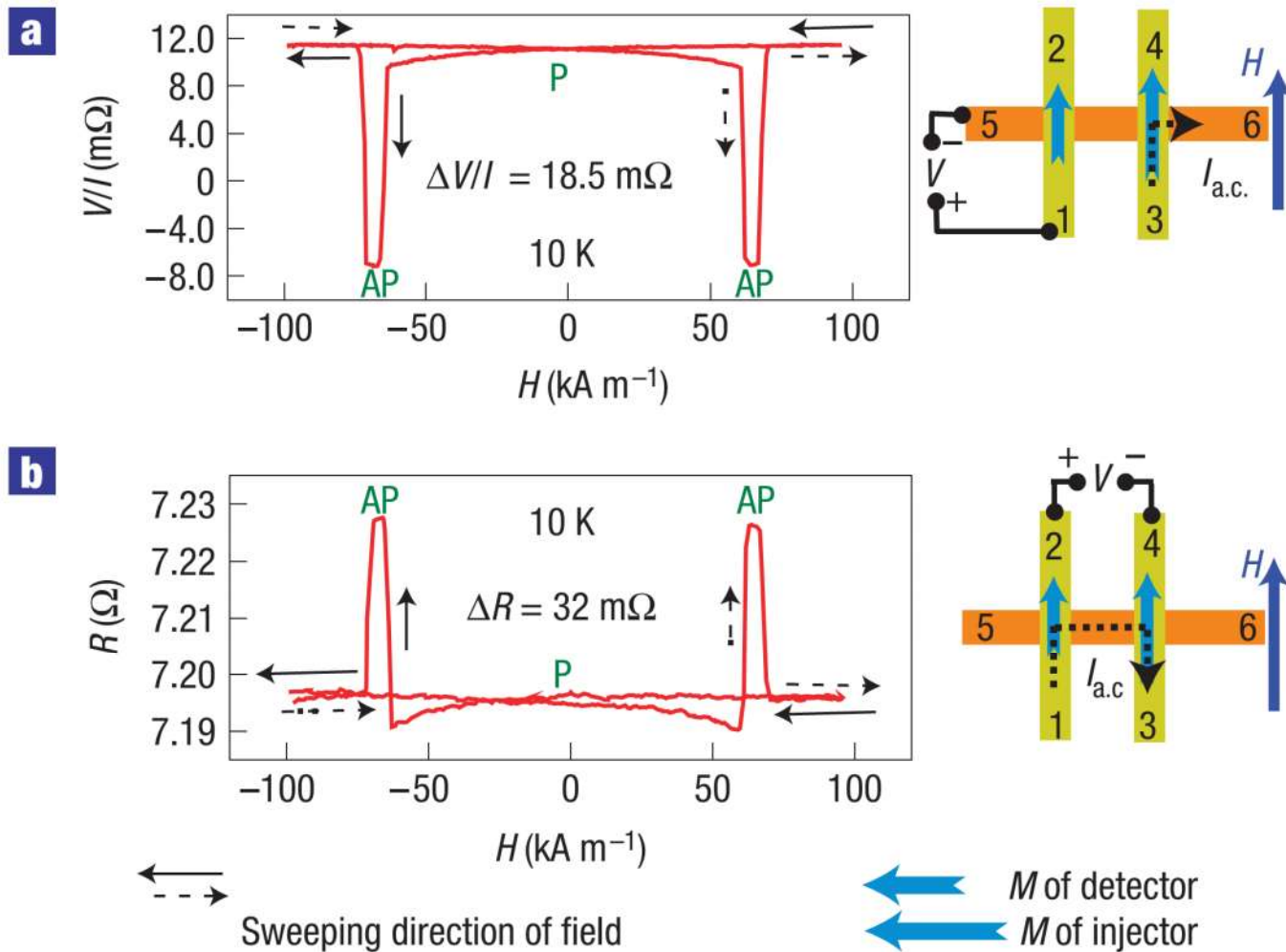


# Pure spin current torque

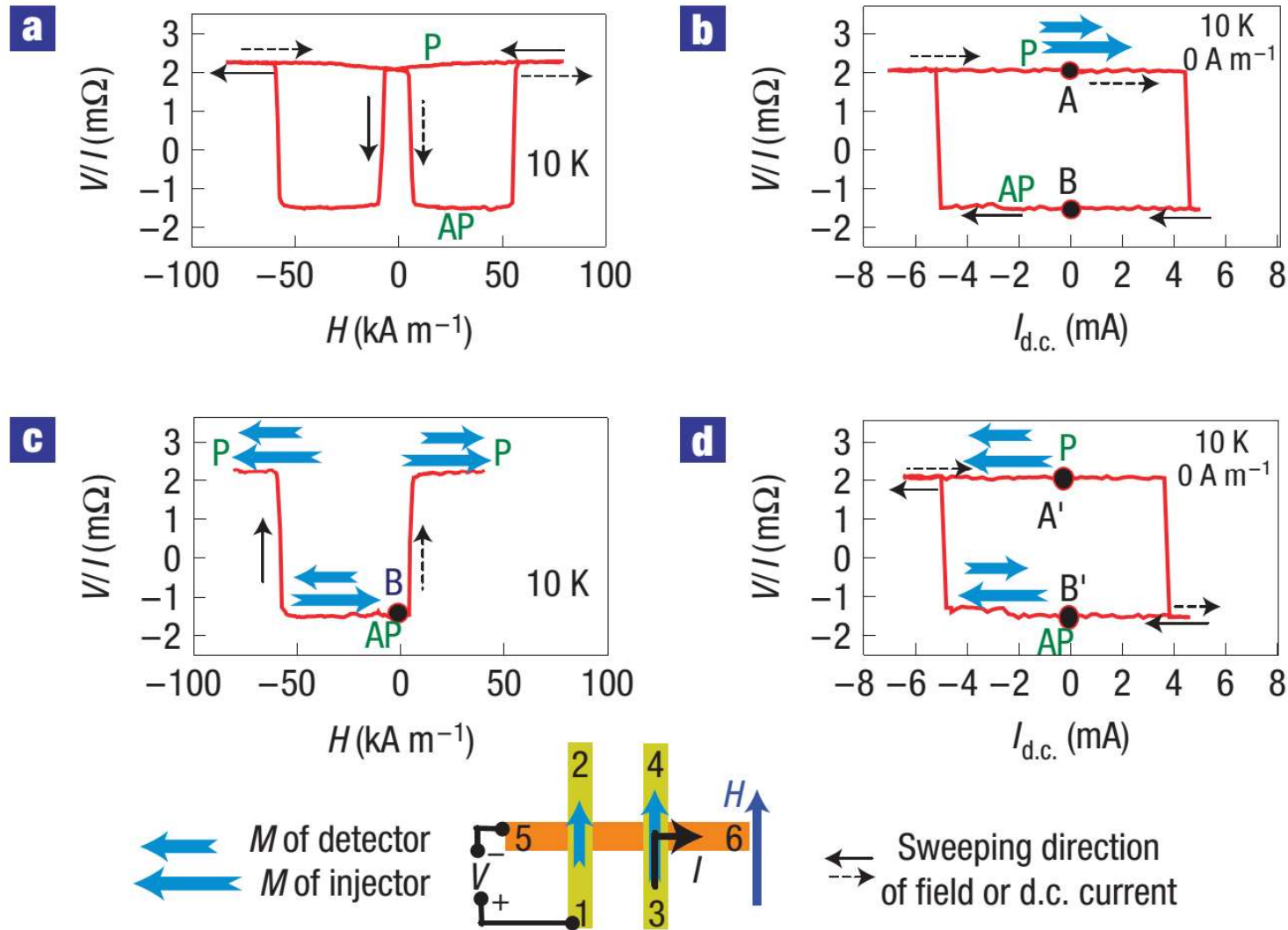


Yang, et al, Nature Physics (2008)

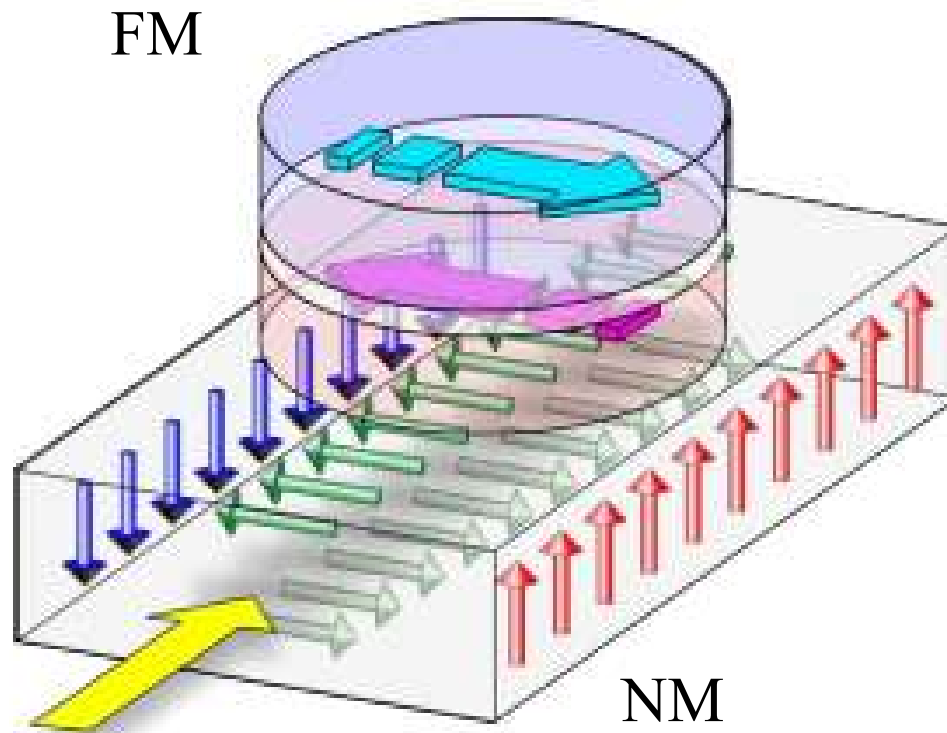
# Pure spin current torque



# Pure spin current torque



# Spin orbit torque

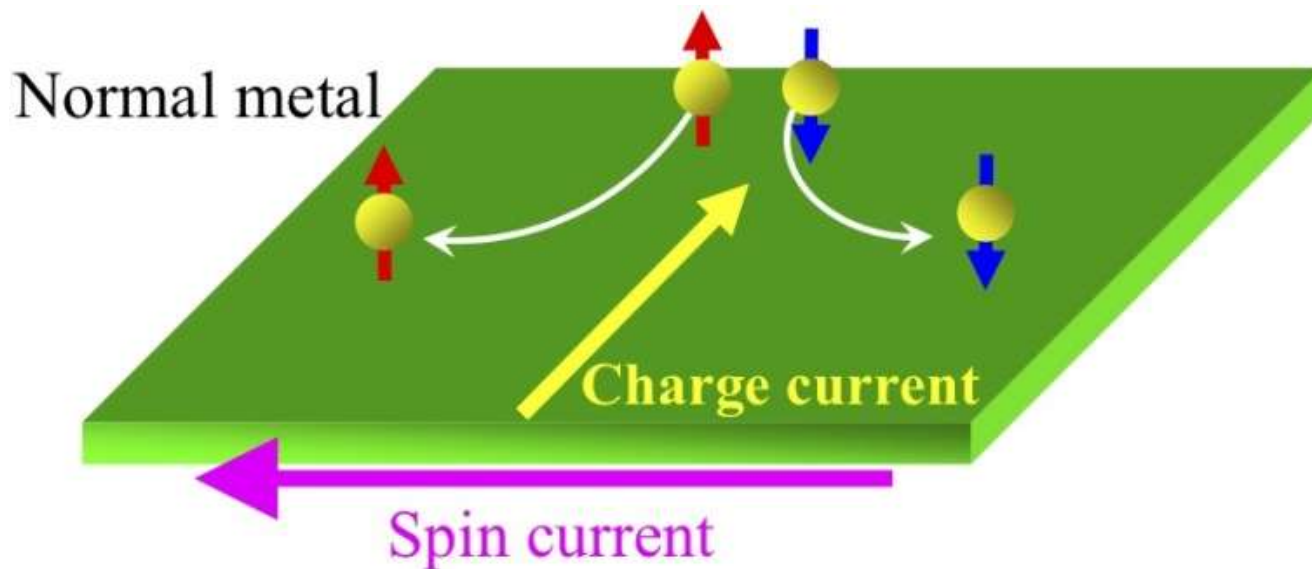


$$\tau_{ST} = \frac{\hbar}{2} \hat{m} \times (\hat{\sigma} \times \hat{m})$$

Brataas, Nature Nano (2014)

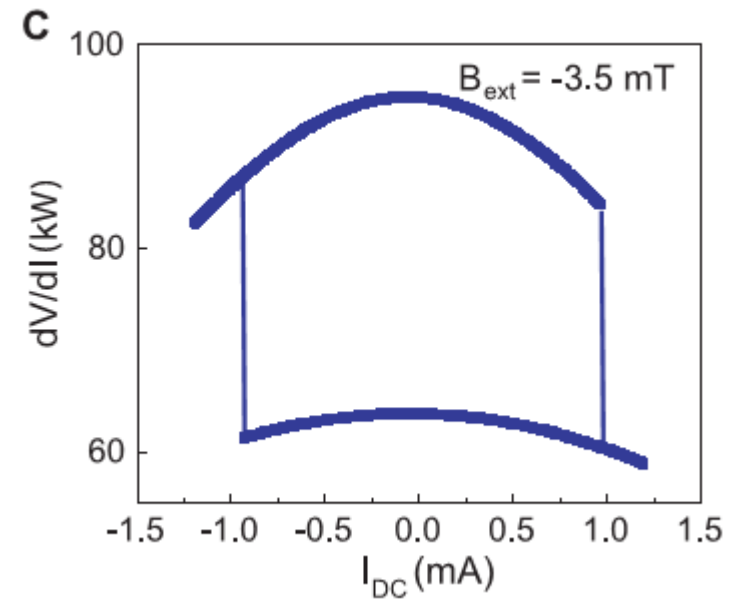
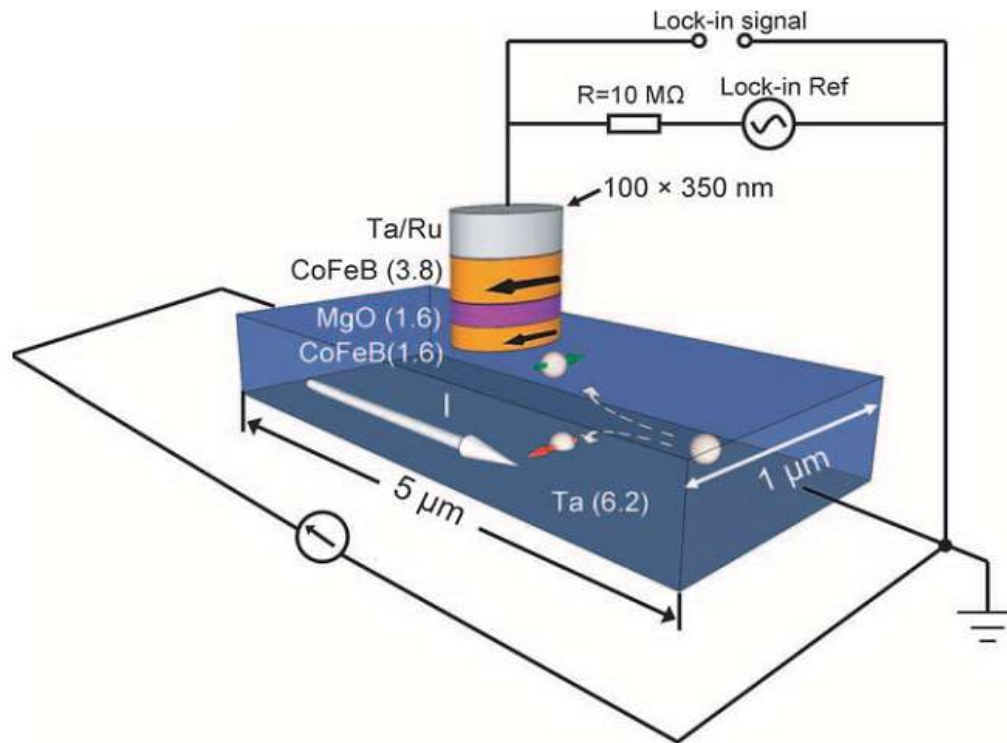
# Other ways for pure spin current

## Spin Hall effect



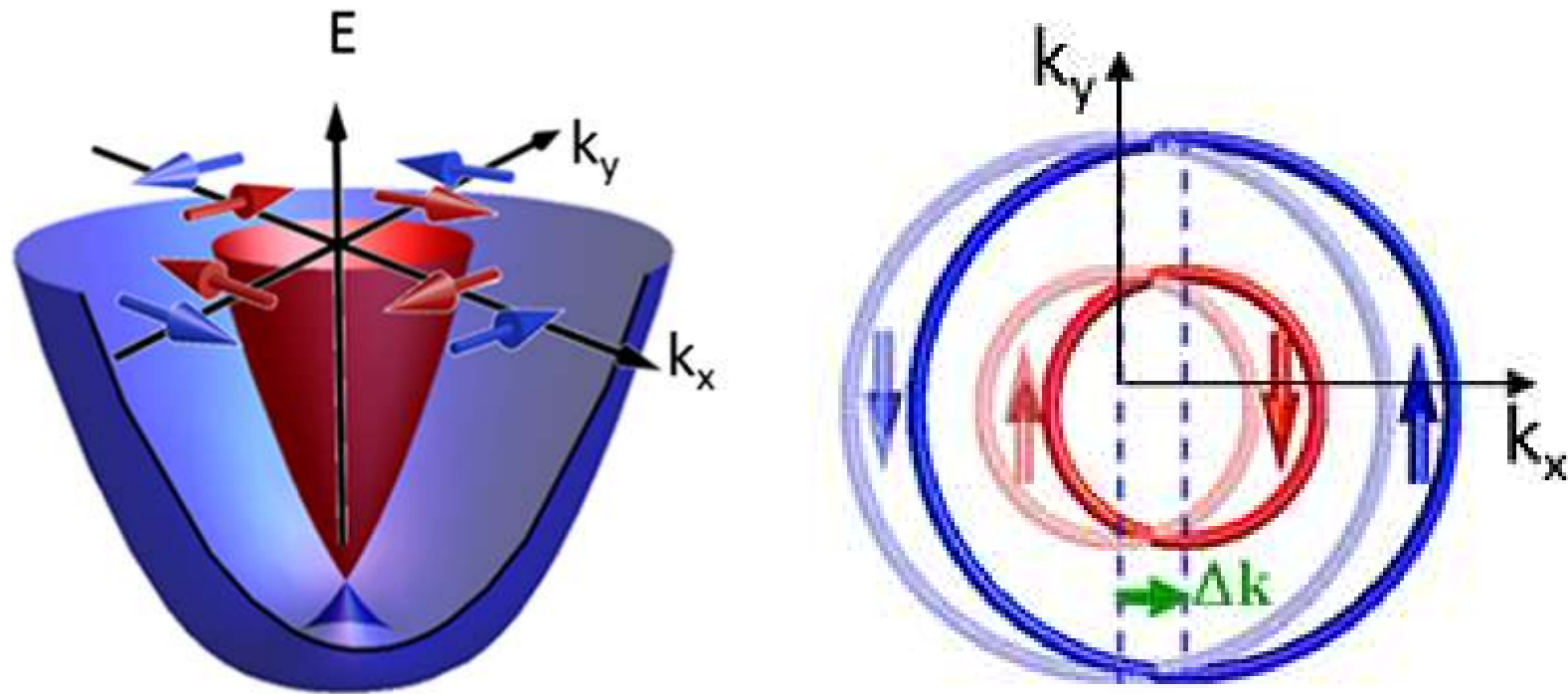
D'yakonov, M. I. & Perel', J. Exp. Theor. Phys. Lett. 13, 467-469, (1971).  
Hirsch, J. E. Phys. Rev. Lett. 83, 1834-1837, (1999).  
Zhang, S. Phys. Rev. Lett. 85, 393-396, (2000).

# Spin Hall torque



Liu, et al, Science (2012)

# Other ways for pure spin current



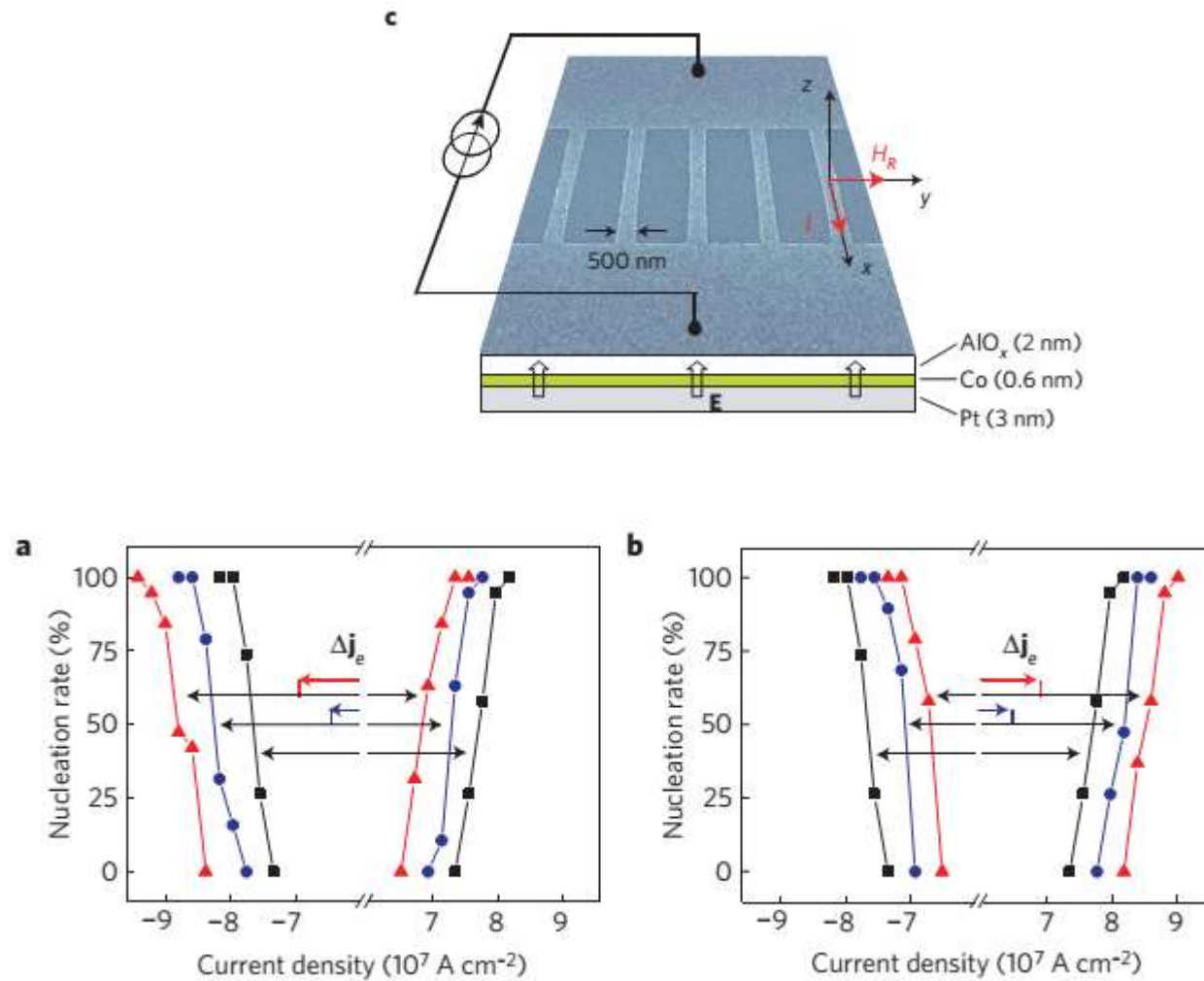
V. M. Edelstein, Solid State Commun. 73, 233 (1990)

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. 17th

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**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！**