Spin Torque and Nanorings

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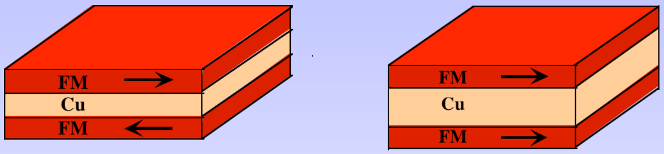
- Introduction
- Spin torque effect in a multilayer and a *single* FM layer
- Spin waves vs. switching
- Arrays of Nanorings with high areal densities
- Switching characteristics of Co nanorings
- Conclusions

Magnetic Nanostructures

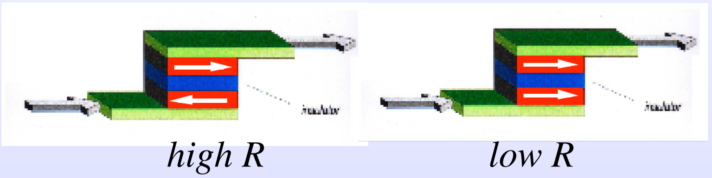
Oscillatory Interlayer coupling



Giant magnetoresistance (GMR)

Nanowire ferromagnets

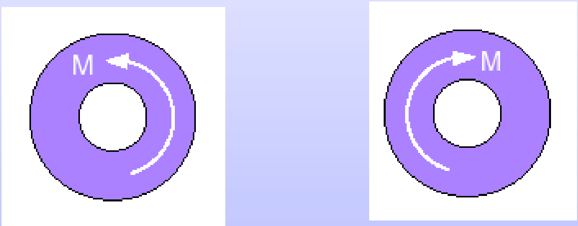
Tunneling magnetoresistance (TMR)



Half-metallic ferromagnets

Spin torque effects

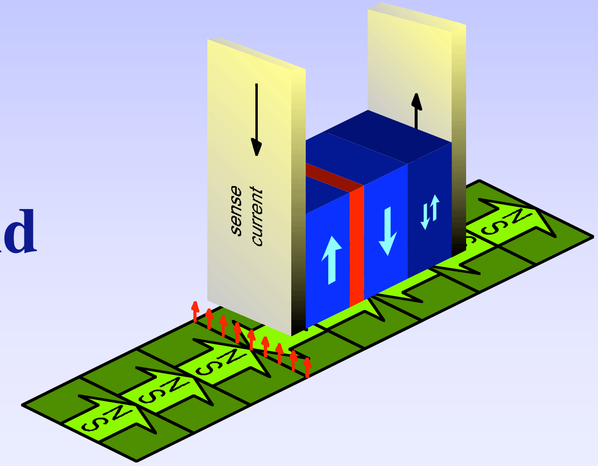
Magnetic dots, antidots, pillars, nanorings



Interplay of materials   nm length scale   small geometrical entities

Spin Torque Effects

Magnetization (M) Reversal



Previously

Reversal of M by a magnetic field

New

Switching and excitations by a spin-polarized current

$\propto P \hbar \boldsymbol{j}$

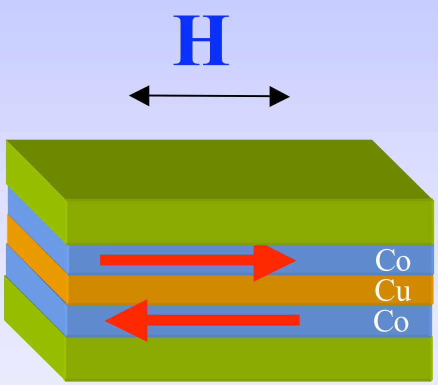
P = spin polarization

$\boldsymbol{j}$ = current density

High $\boldsymbol{j}$ of e^- with spin 1/2

Spin Torque (ST) Effects

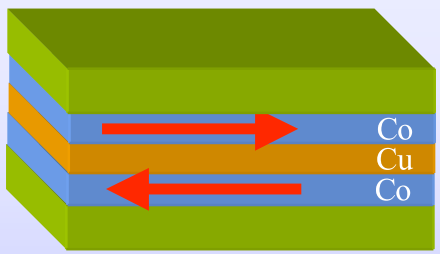
electrical current affects magnetic configurations



GMR

Magnetic configuration affects electrical properties.

Inverse Effect



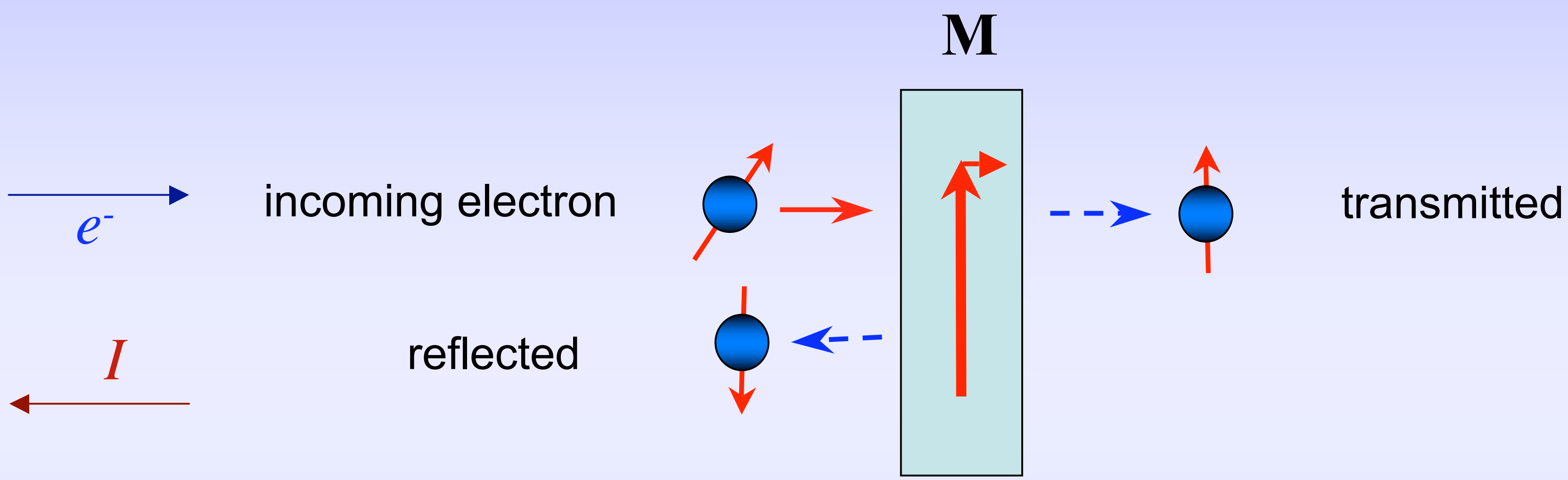
ST

Electrical current affects magnetic configurations.

without a magnetic field

Slonczewski, JMMM **159**, L1 (1996)
Berger, PR **B54**, 9353 (1996)

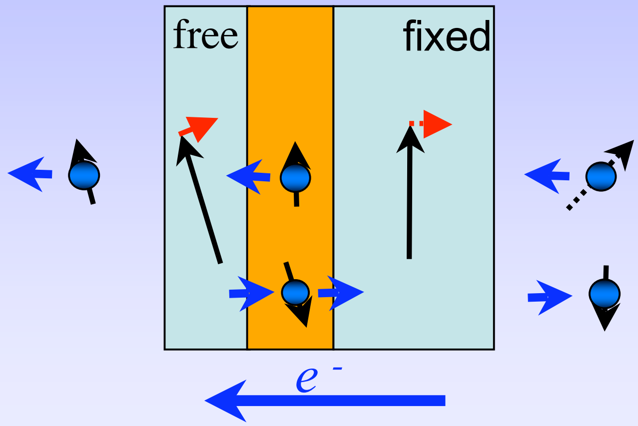
Spin-transfer torque in a single layer

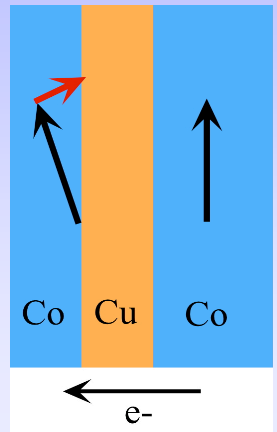


Large **M**: spin polarizer
Small **M**: **M** can be rotated

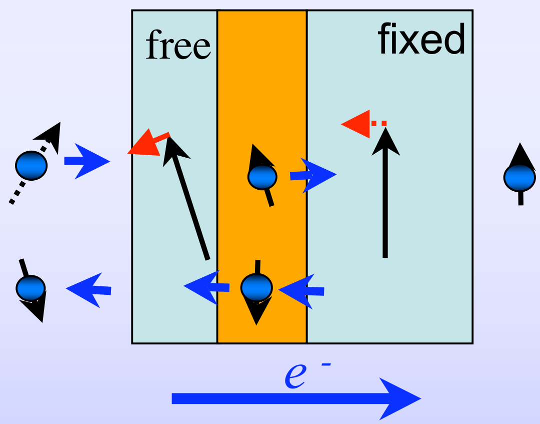
Slonczewski, JMMM **159**, L1 (1996); Waintal *et al*., PRB **62**, 12317 (2000)

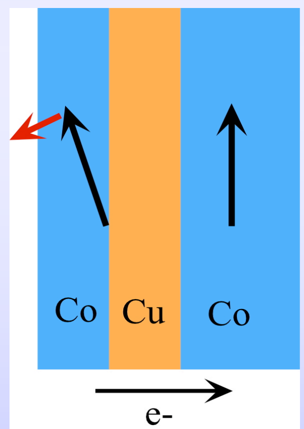
Spin Torque Effects in Trilayers





Favors parallel M





Favors antiparallel M (switching)

Electrons flow from thin (free) to thick (fixed)

Asymmetry in *I*

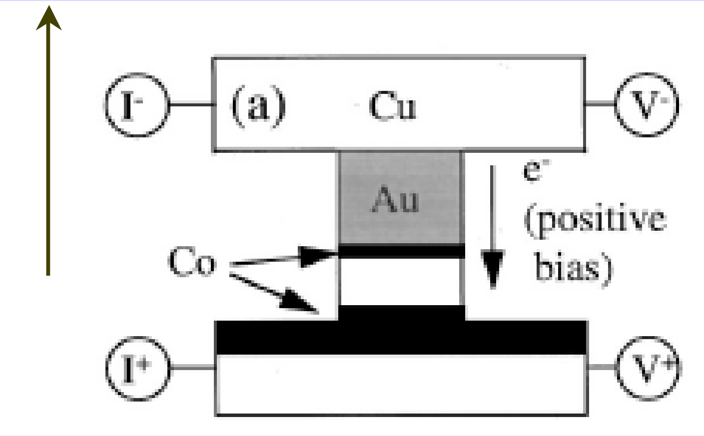
Theory:
- Switching @ low *H*
- Spin precession and spin waves @ high *H*

Switching in Low Magnetic Fields

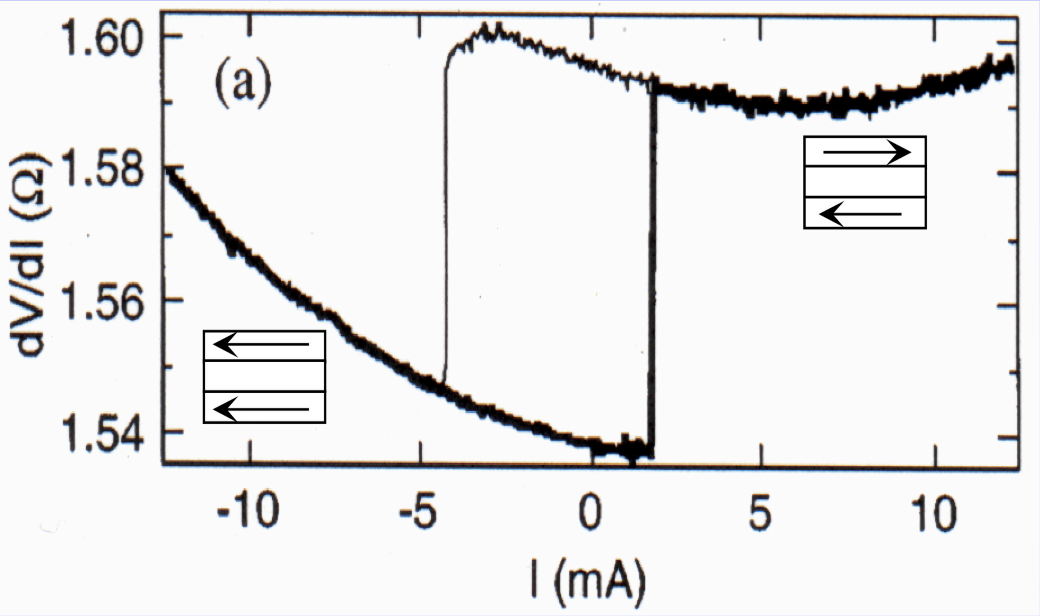
high current density required ~ 10^8 A/cm²

Albert, Katine, Buhrman, Ralph, **77**, 3809 APL (2000)

Positive polarity



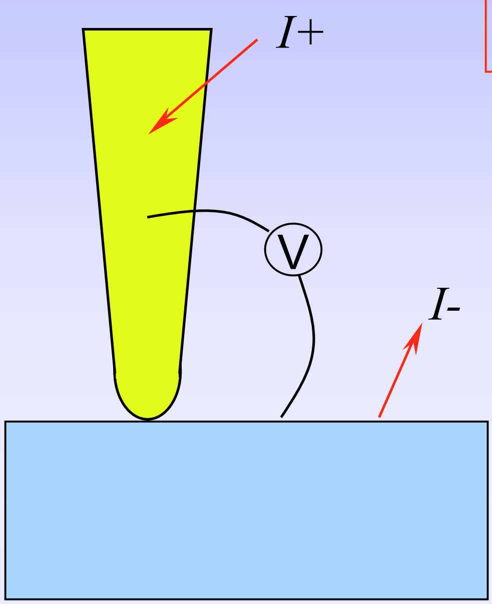
Nanopillars
Cross-section ≈ 100 nm
made by nanolithography



Asymmetry in *I*

- Non-collinear magnetizations (a free layer and a fixed layer).
  (thin layer) (thick layer)
- GMR to detect change of magnetizations.

Our Method: Point-Contact Spin Injection



High current density

Contact Resistance:

$$R_{Sharvin} = 4\rho l/3\pi a^2$$

l = mean free path

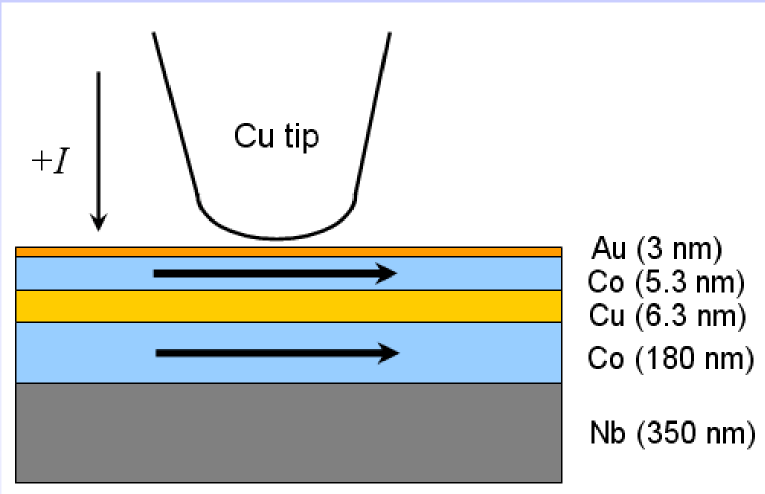
ρ = resistivity

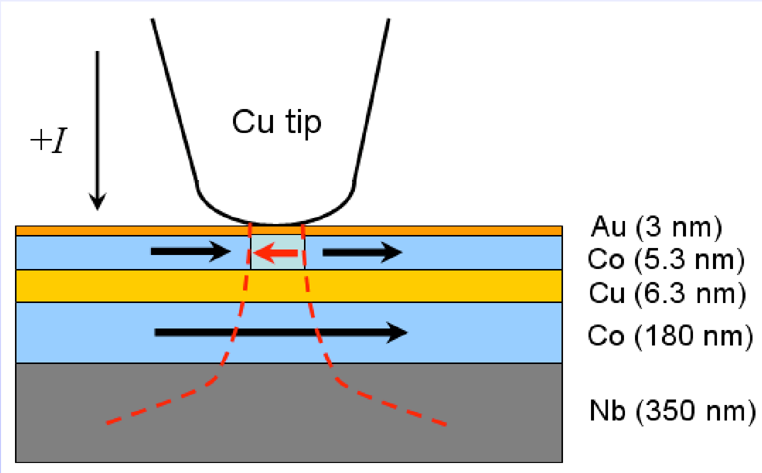
Contact size *(a)* can be inferred from contact resistance.

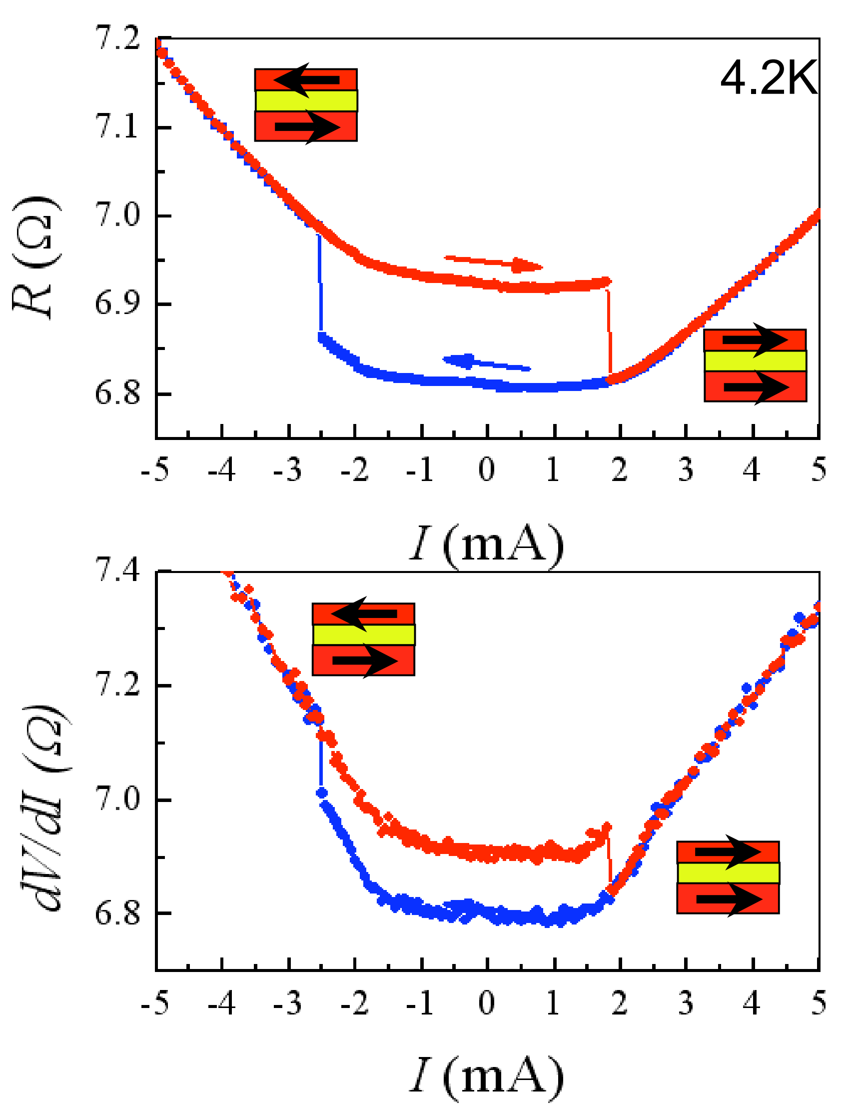
Applicable to any thin films or crystals

- **Point contact spin injection *without* nanolithography**
- **Spin torque effects in *continuous* multilayers**
- **Magnetic recording *without* a magnetic field**
- **Spin torque effects in a *single* layer**

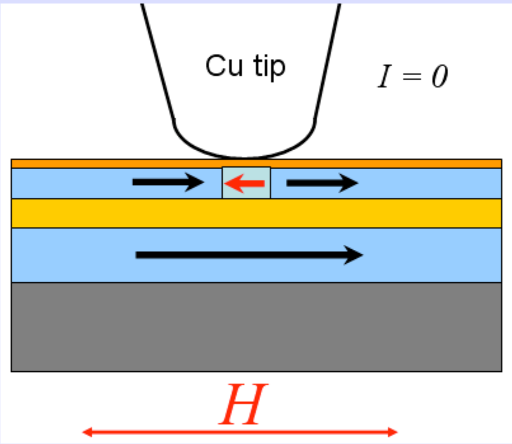
Spin Torque Effect in Continuous Trilayers

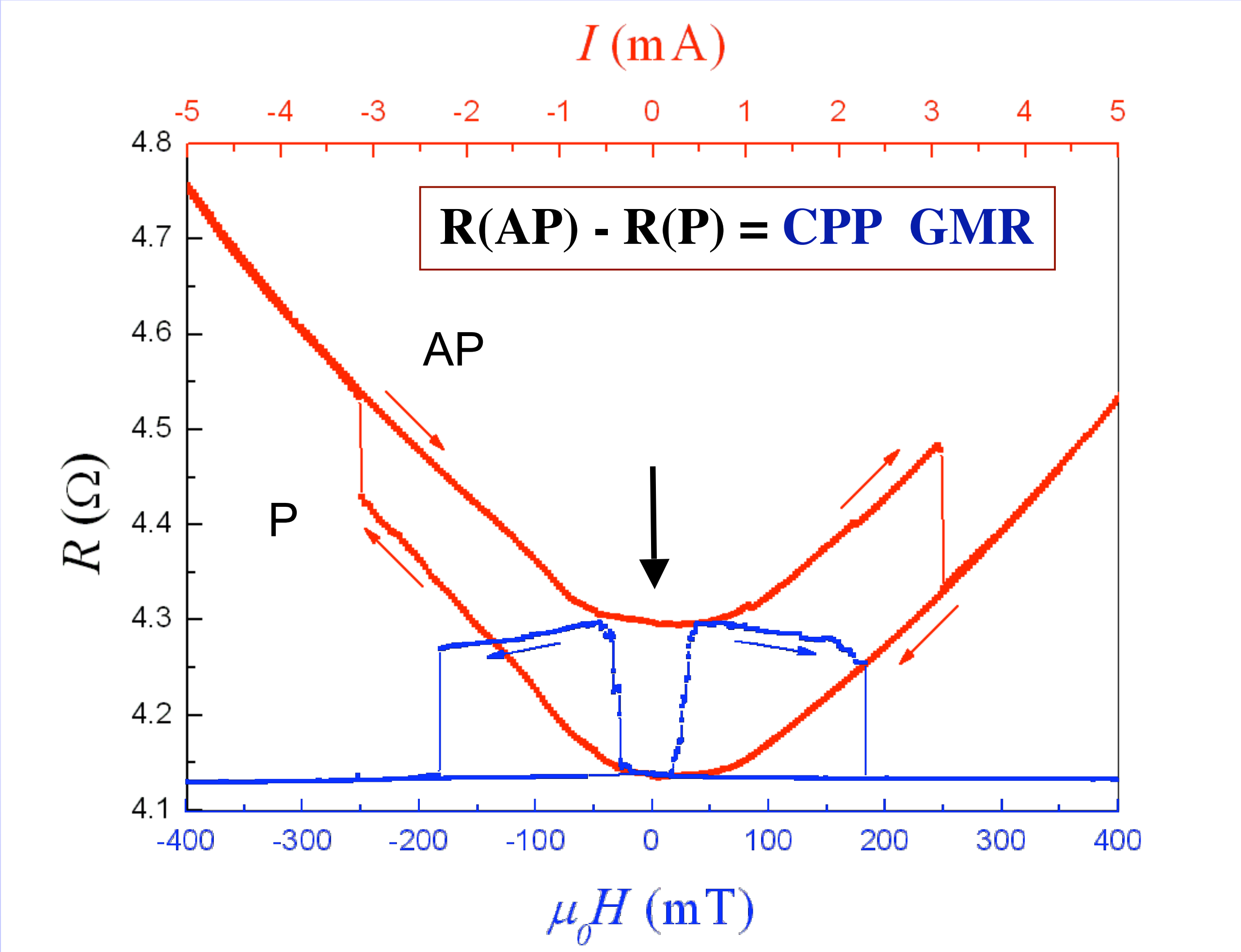






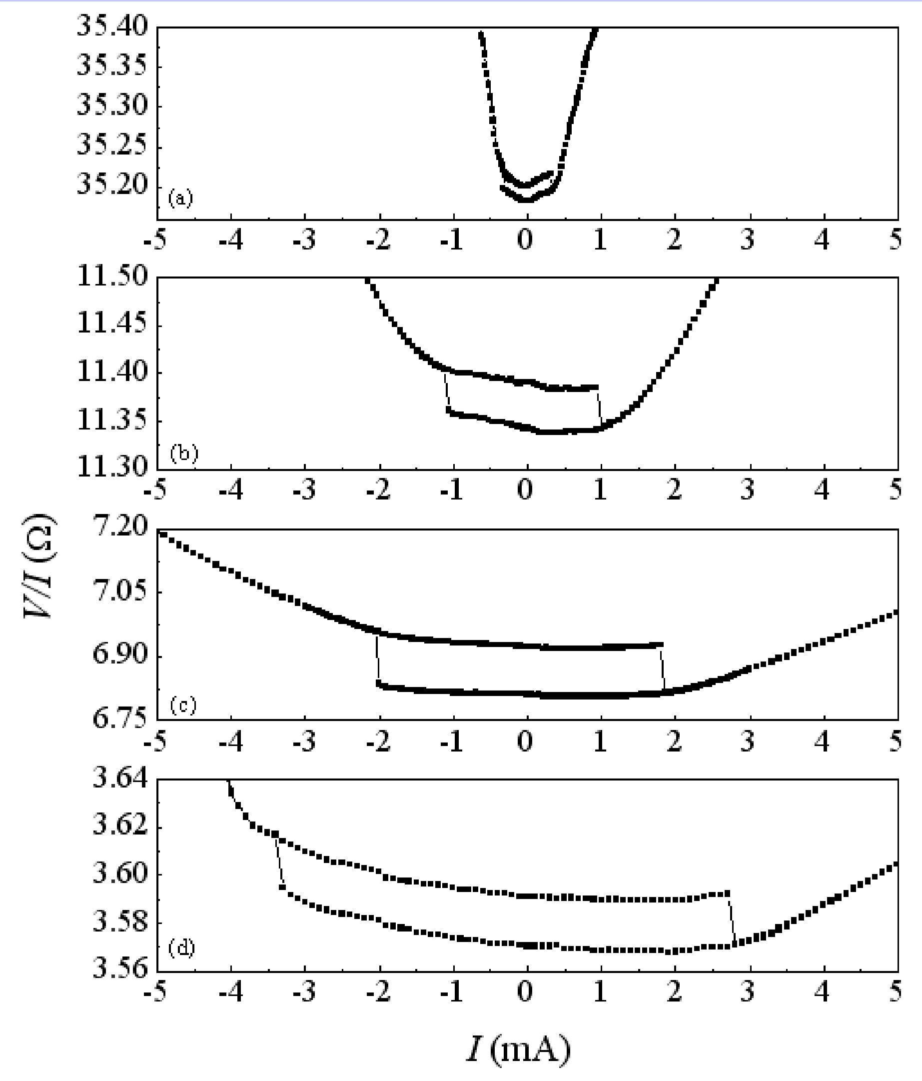
CPP-GMR at zero bias current

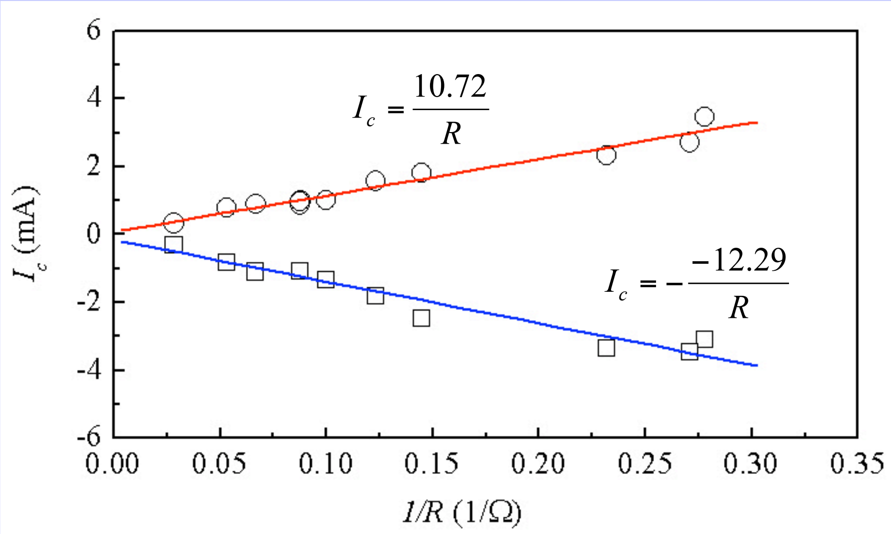




Chen, Ji and Chien, Appl. Phys. Lett. **84**, 380 (2004)

Switching Current $I_c \propto 1/R$





$$I_C \equiv \frac{V_C}{R}$$

V_C is unique.

$$V^+_C = 10.72mV$$

$$V^-_C = -12.29mV$$

Unique Switching Current Density j_C

$$R = \frac{4\rho l}{3\pi a^2}$$

Sharvin resistance

$$I_C = j_C \pi a^2$$

$$V_C \equiv I_C R = \frac{4 j_C \rho l}{3}$$

$\rho l \approx$ constant

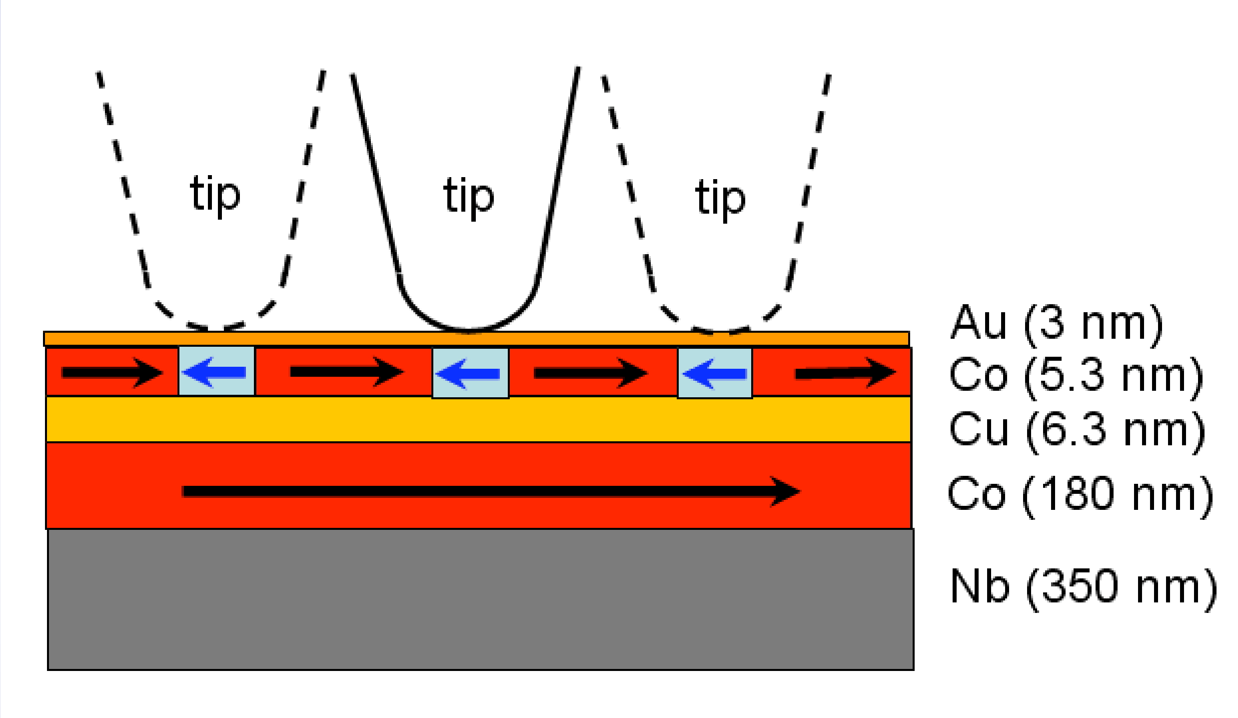
Unique V_C

$$V^+{}_C = 10.72 mV$$
$$V^-{}_C = -12.29 mV$$

Unique j_C

$$j^+{}_C = (5.0 \pm 1.4) \times 10^8 A/cm^2$$
$$j^-{}_C = -(6.0 \pm 1.3) \times 10^8 A/cm^2$$

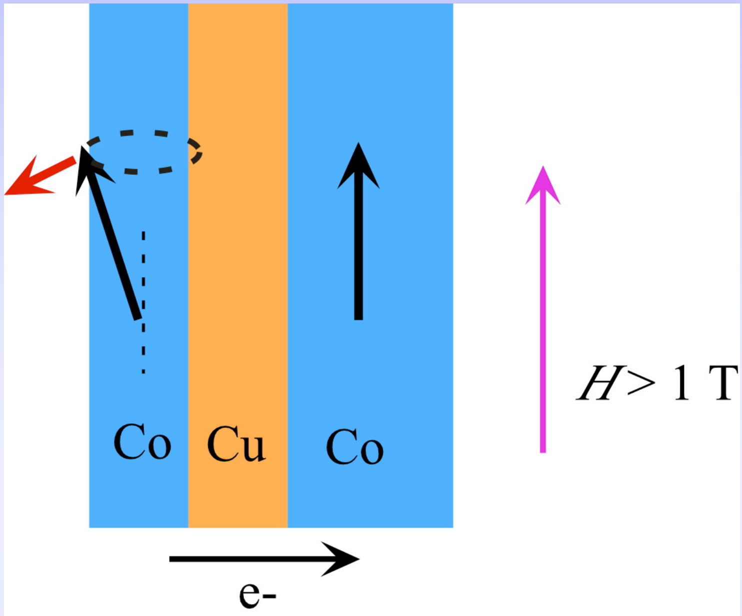
Magnetic Recording without a magnetic field: Point-Contact Spin Injection

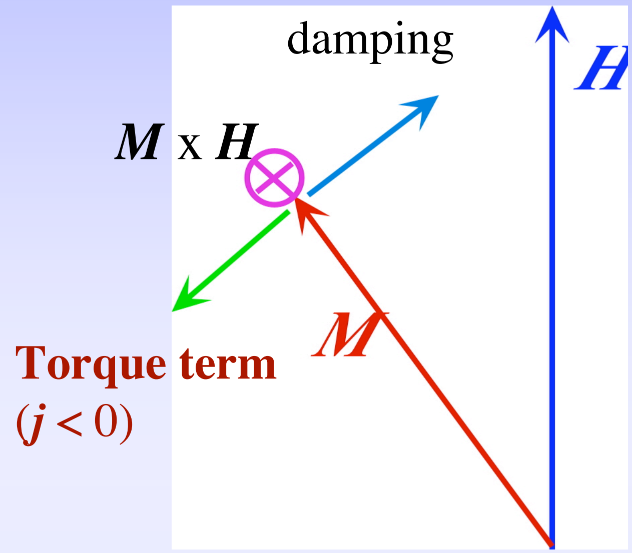


Recording voltage > V_C

Density: >100 Gbit/in^2 with contact resistance 1 Ω.

Spin-Wave Excitations in High Magnetic Fields





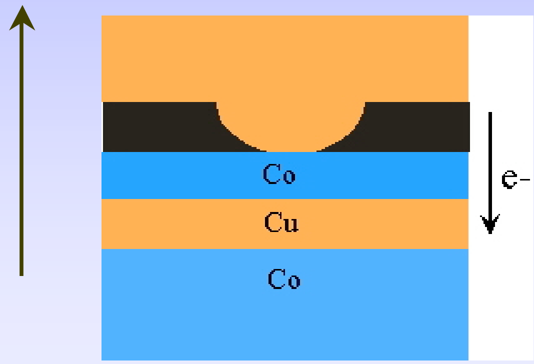
$$\frac{d\vec{M}}{dt} = \gamma(\vec{M}\times\vec{H}) - \frac{a_G}{M}\vec{M}\times\frac{d\vec{M}}{dt} - \gamma\hbar\frac{jg(\theta)}{et_1}\frac{\vec{M}}{M}\times\left(\frac{\vec{H}}{H}\times\frac{\vec{M}}{M}\right)$$

Precession Damping Spin-transfer torque

Slonczewski, JMMM **195**, L261 (1999)

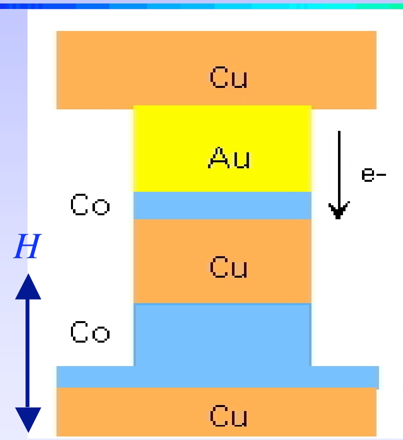
"Spin-Wave Excitations" in Multilayers in High Fields

Positive polarity



Myers *et al.*, Science 285, 867 (1999)

Point-contact



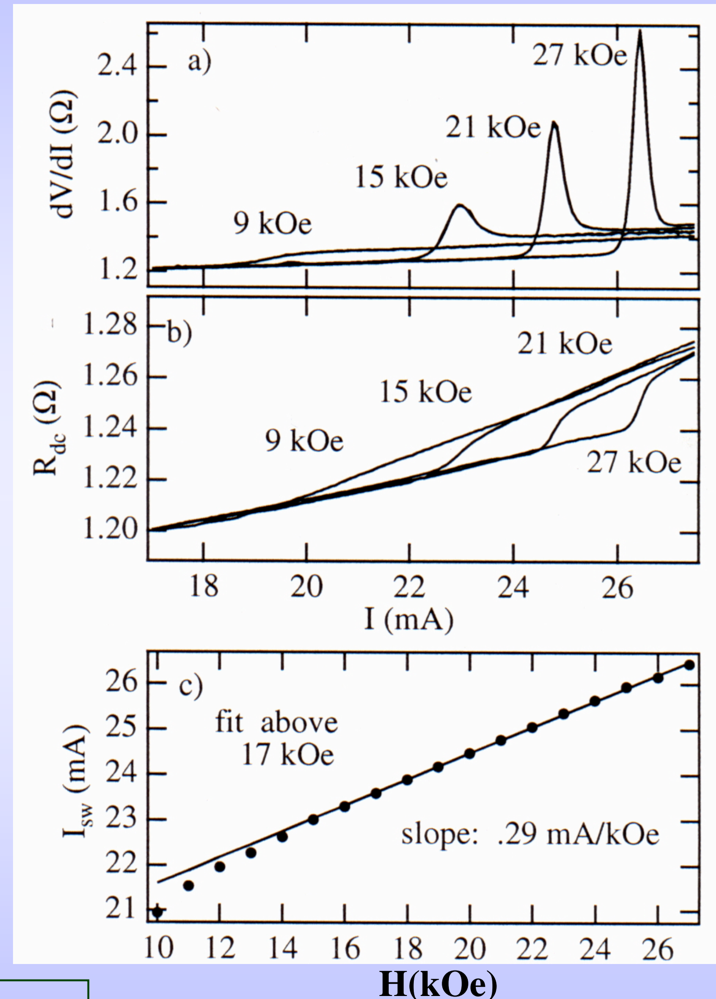
Katine *et al*,. PRL 84, 3149 (2000)

Nanopillar

- Peak in *dV/dI*
- Step in *V/I*
- Non-hysteric
- Critical I_c linear in H

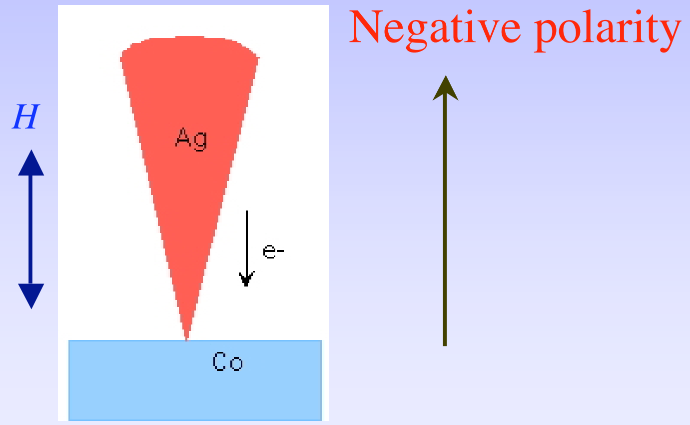
"free" thin layer
"fixed" thick layer

Spin transfer when electrons flow from free to fixed



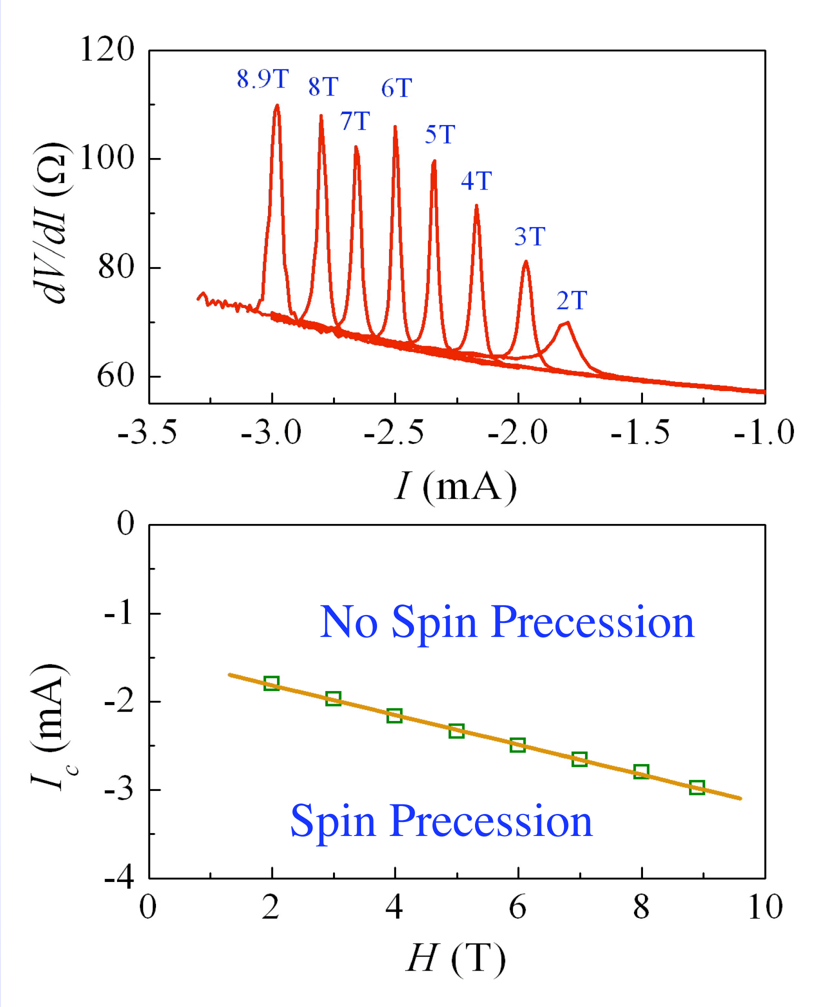
Katine *et al.*, PRL **84**, 3149 (2000)

Critical Current I_c and Phase Diagram (perpendicular H field)



- Similarity to results in multilayers
- Critical $I_c \propto H$
- Phase diagram

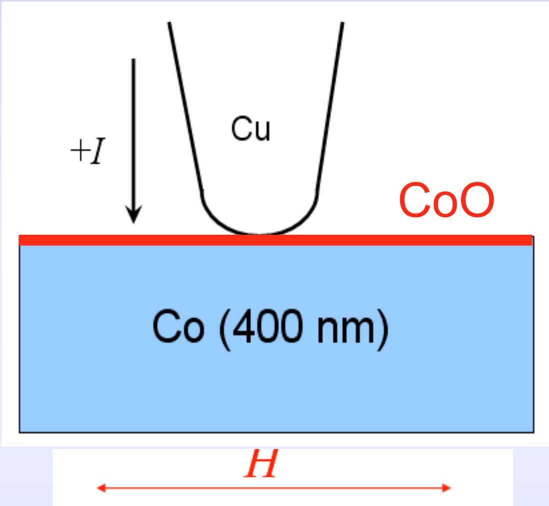
Really due to spin waves ?



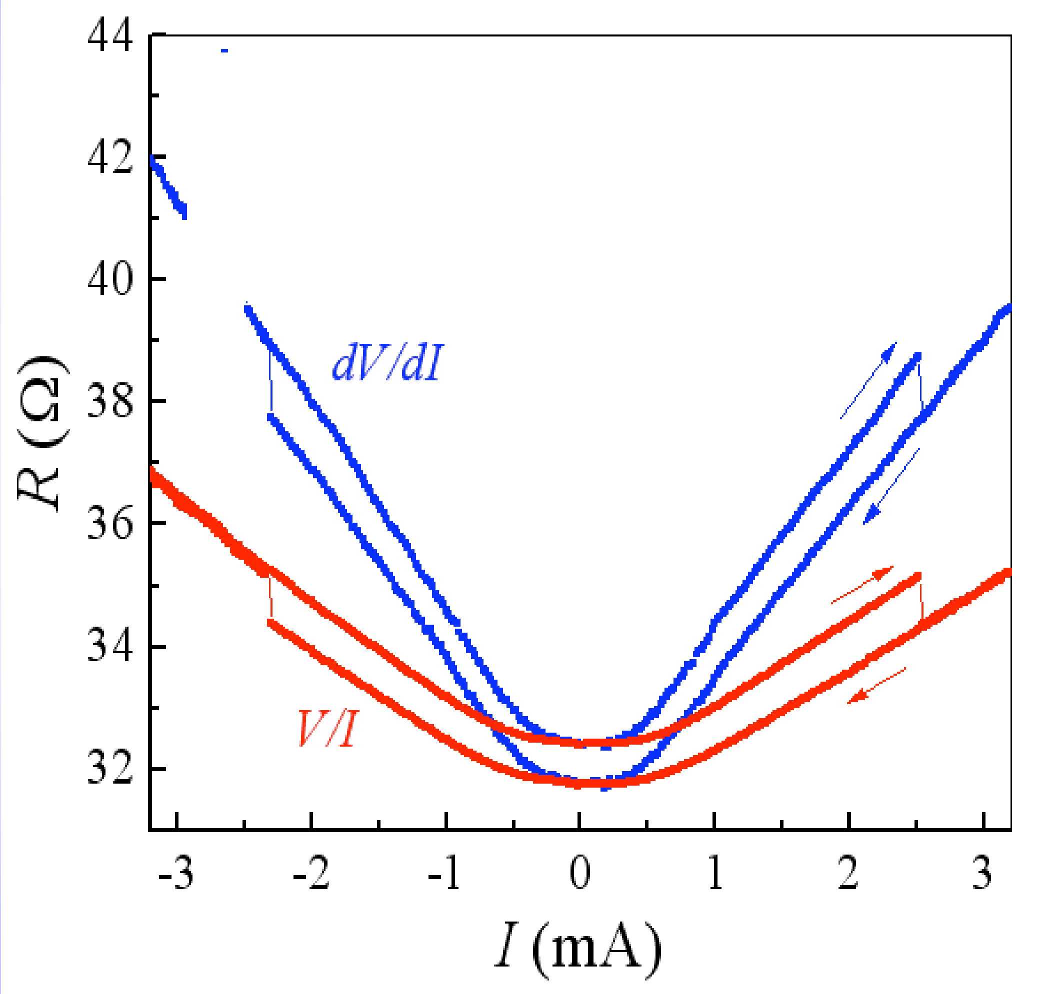
Ji, Chien and Stiles, Phys. Rev. Lett. **90**, 106601 (2003)

Single Layer Switching using point contact

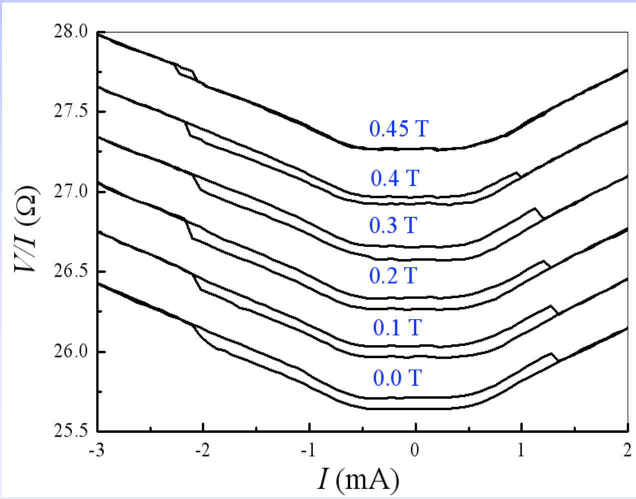
(in-plane H field)



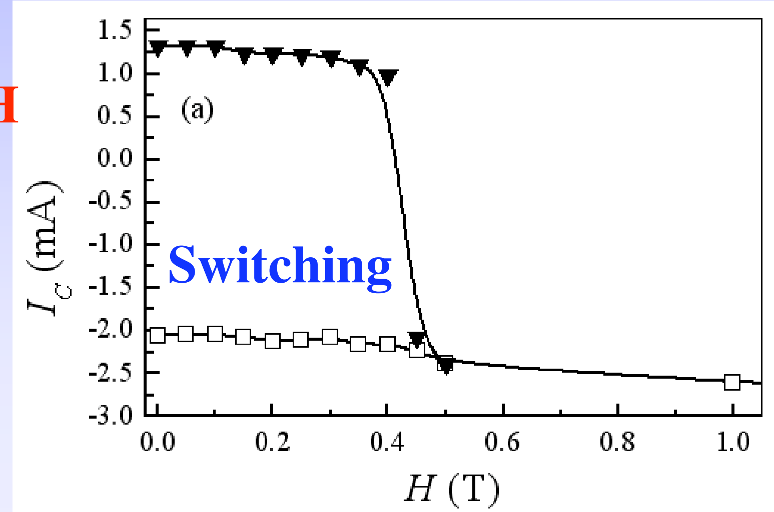
CoO makes the top and bottom surfaces different

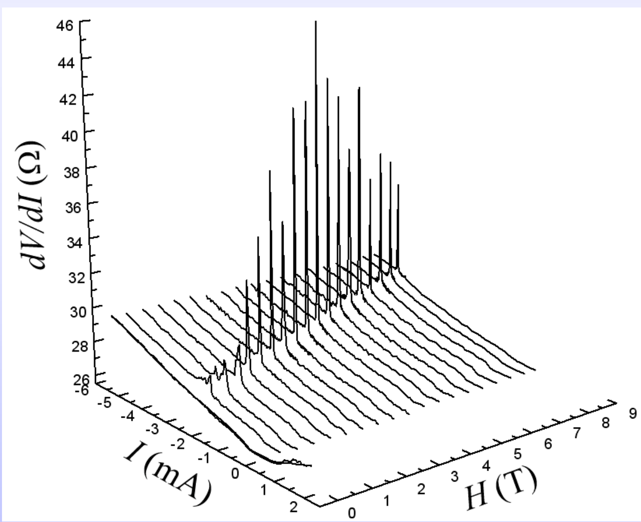


Phase Diagram
(in-plane H field)

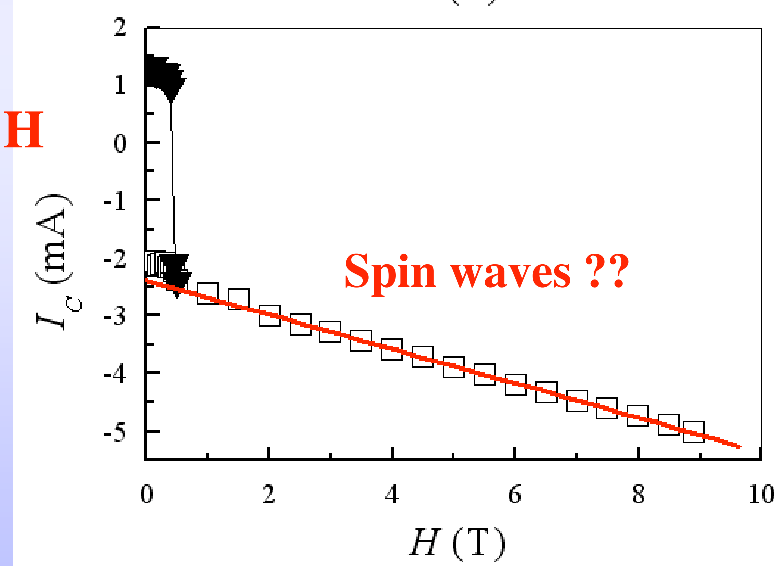


Low H

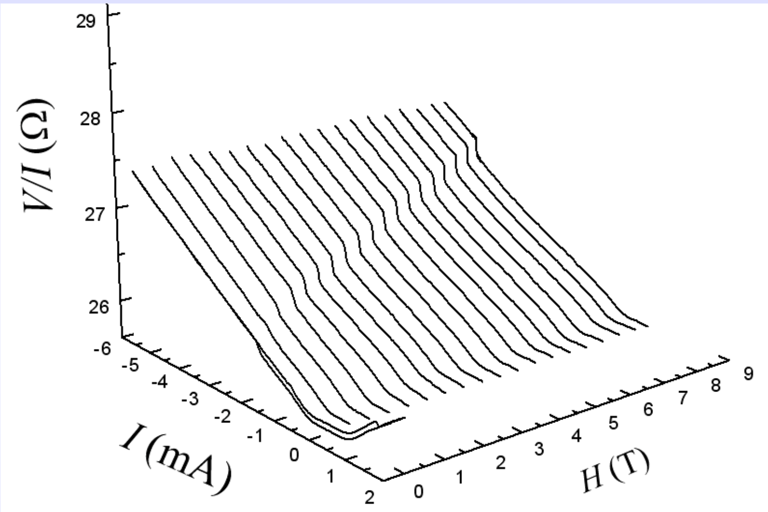


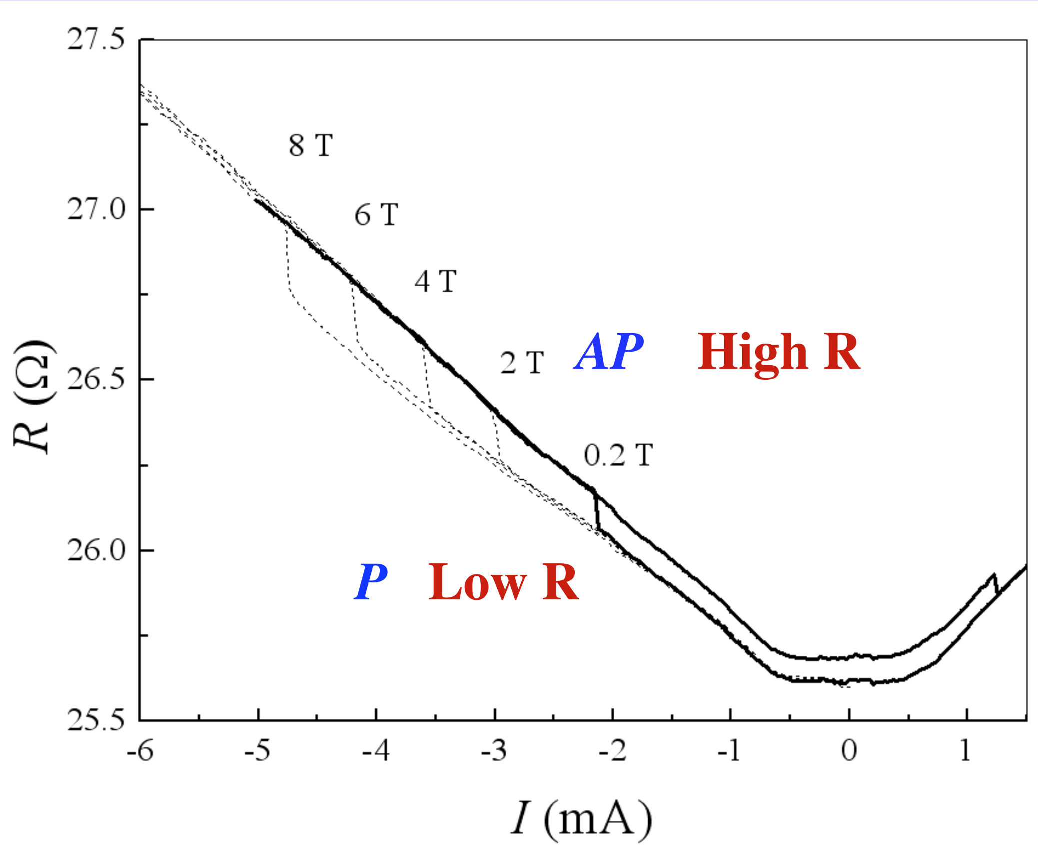


High H



Switching at high fields, ***not*** spin waves

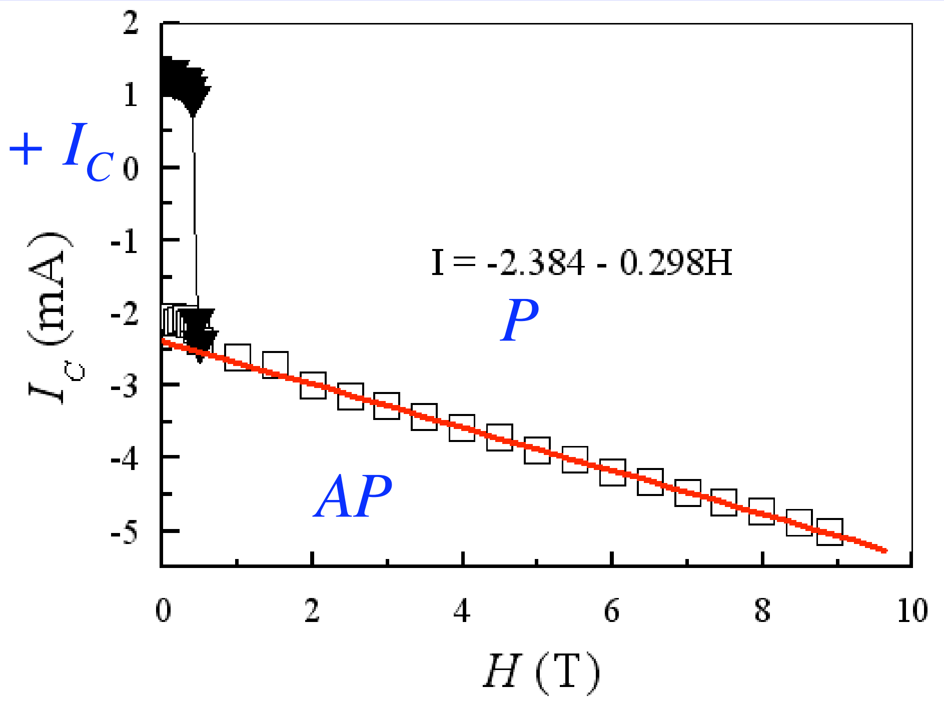




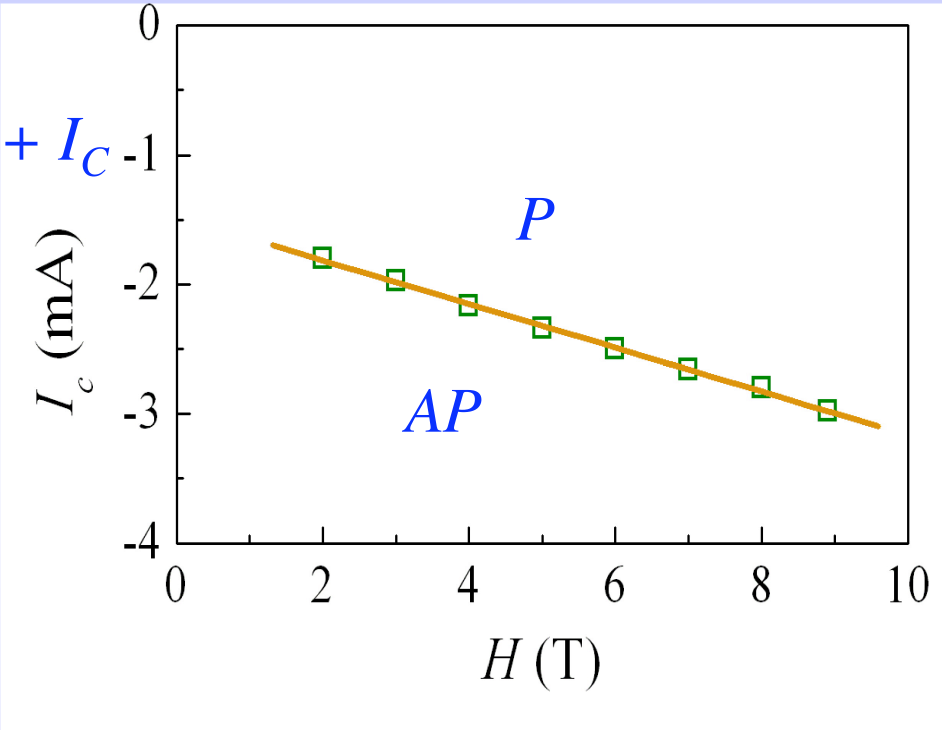
Switching between two resistance states.

Phase Diagram for Switching

(in-plane H field)



(perpendicular H field)

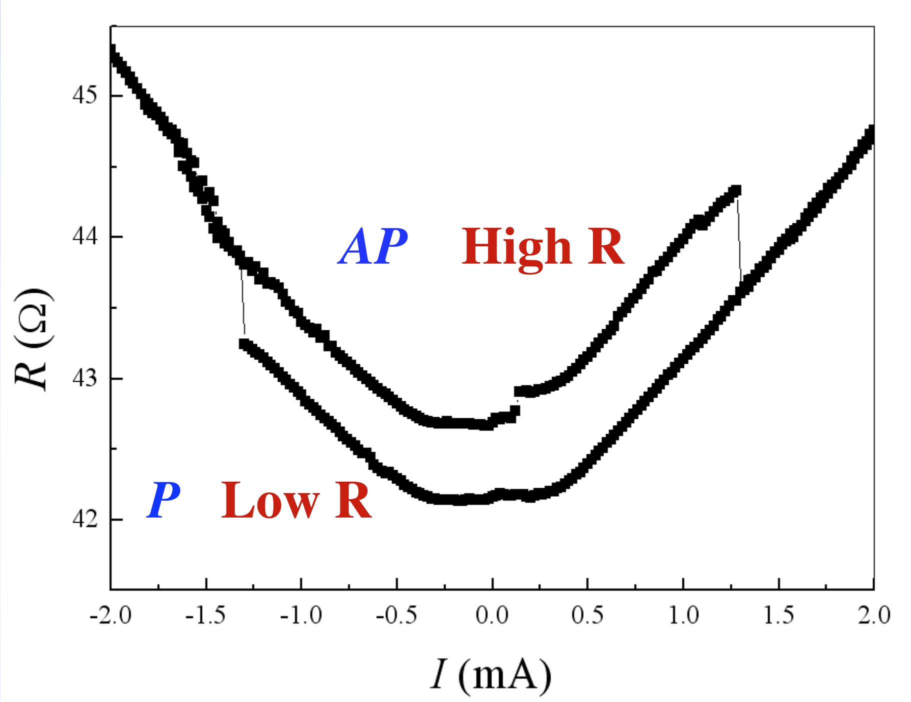


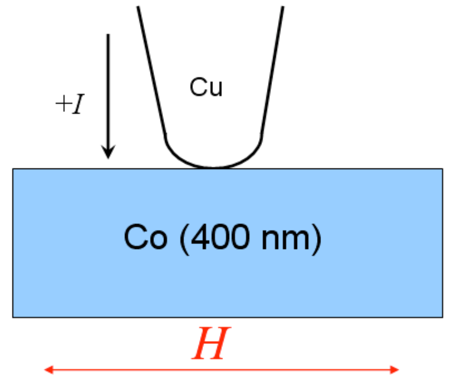
$I_C(mA) = -2.4 - 0.3\ \mu_o H(T)$

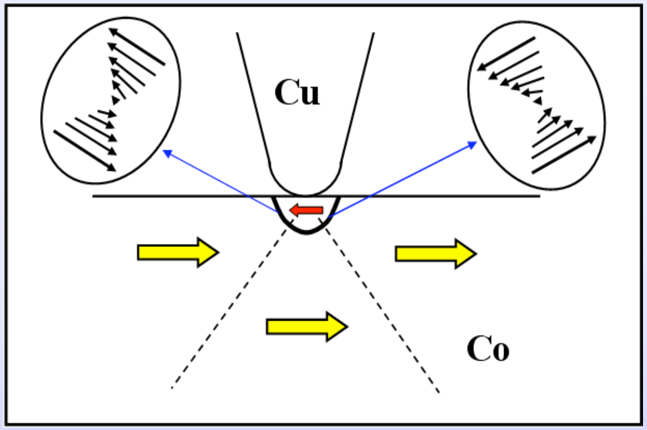
High magnetic field is no match for current

Physics of Switching in a Single Layer

(single layer has no GMR)





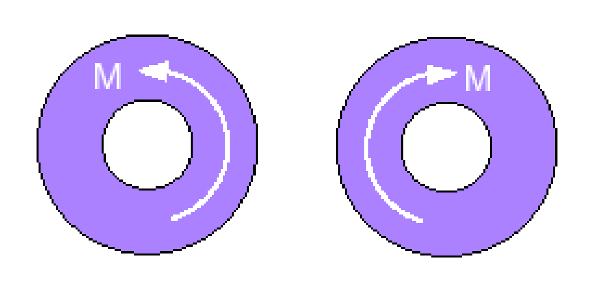


Large DMR = 0.7 Ω

Inverse Effect of Domain Wall Magntoresistance (DMR)

Chen, Ji, Chien and Stiles, Phys. Rev. Lett. **93**, 026601 (2004)

II. Nanorings



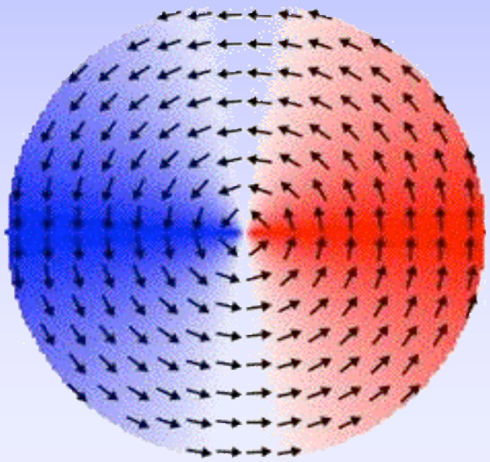
- Circular discs
- Unique attributes of nanorings
- Nanorings made by e-beam lithography
- New natural (e-beam-less) lithography method
- Arrays of Co nanorings

Circular Discs

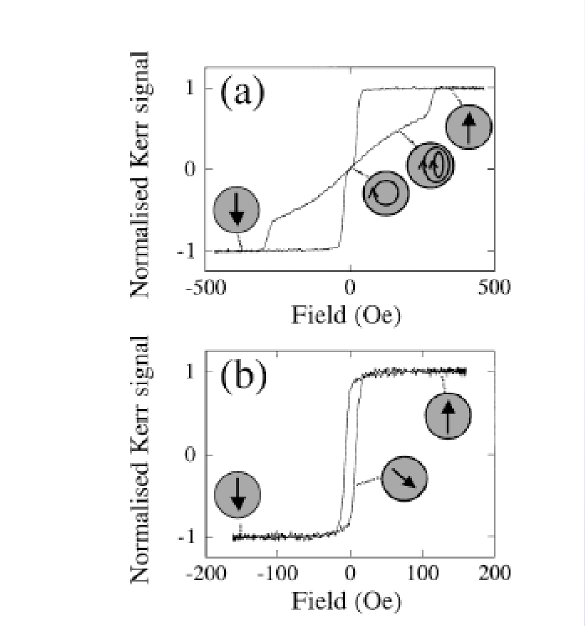
Vortex State-- no stray field

Only for discs ≥ 150 nm

Single domain state for discs < 150 nm



Singularity at vortex center



d = 300nm

d = 100nm

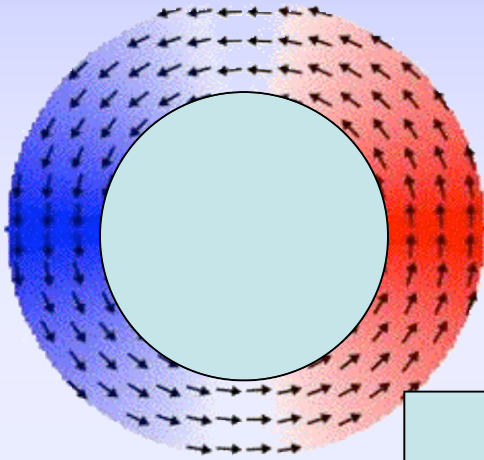
Cowburn *et al.*, PRL **83**, 1042 (1999)

Nanorings

Nanoring = Disc without the central region

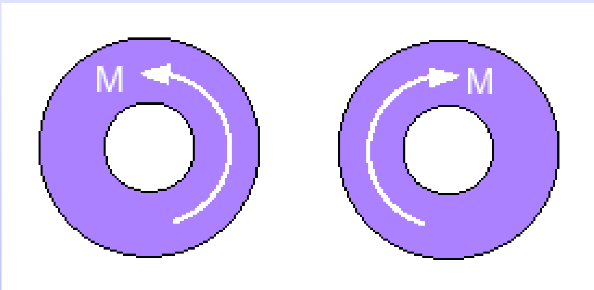
Stable Vortex State

(singularity removed)



No stray field

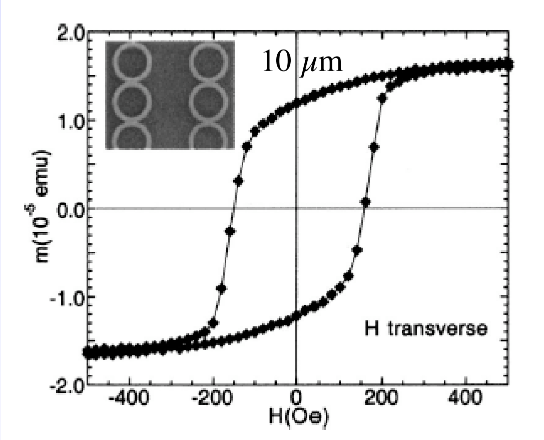
Two chiralities (magnetic bit for storage)



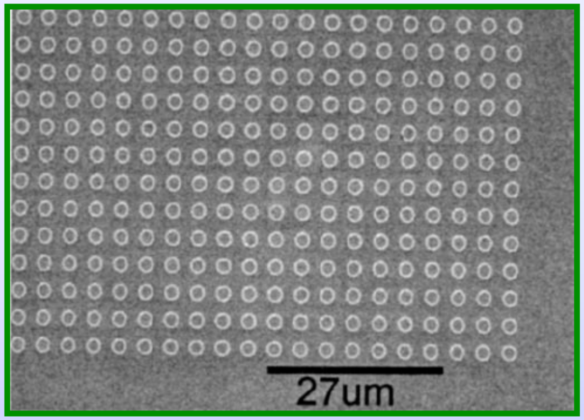
Nanorings by e-beam Lithography

Status Quo

- Diameter (μm)
- Small number of rings (10^2)
- Small area
- Low areal density
- Weak magnetic signal (surface MOKE)

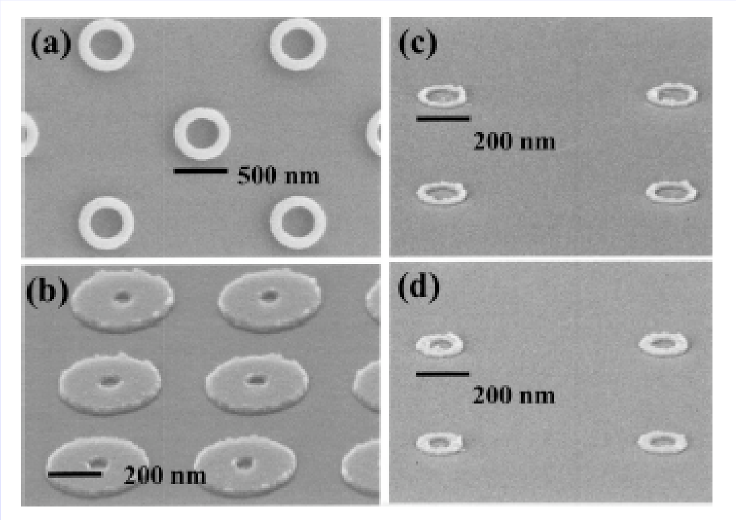


Welp *et al.*, JAP **93**, 7056 (2003)



Y. G. Yoo *at al.*, APL **82**, 2470 (2003)
20 x 20 rings, $D = 2$ μm, $w = 0.25$ μm

Areal density ≈ 0.05/μm^2



Casrano *et al.*, PR B **67**, 184425 (2003)

Challenges in Nanorings

Status Quo

- Diameter (μm)
- Few rings (10^2)
- Small area
- Low areal density

Challenges

- Sub-μm diameter (e.g., 500 nm)
- Many rings (e.g., 10^6)
- Macroscopic area (e.g., 1 mm^2)
- High areal density (e.g., 0.1 ring/μm^2)

Ultimately, without e-beam lithography

Accomplished

- **100 nm diameter**
- **5×10^9 rings**
- **100 mm^2**
- **45 rings/μm^2**

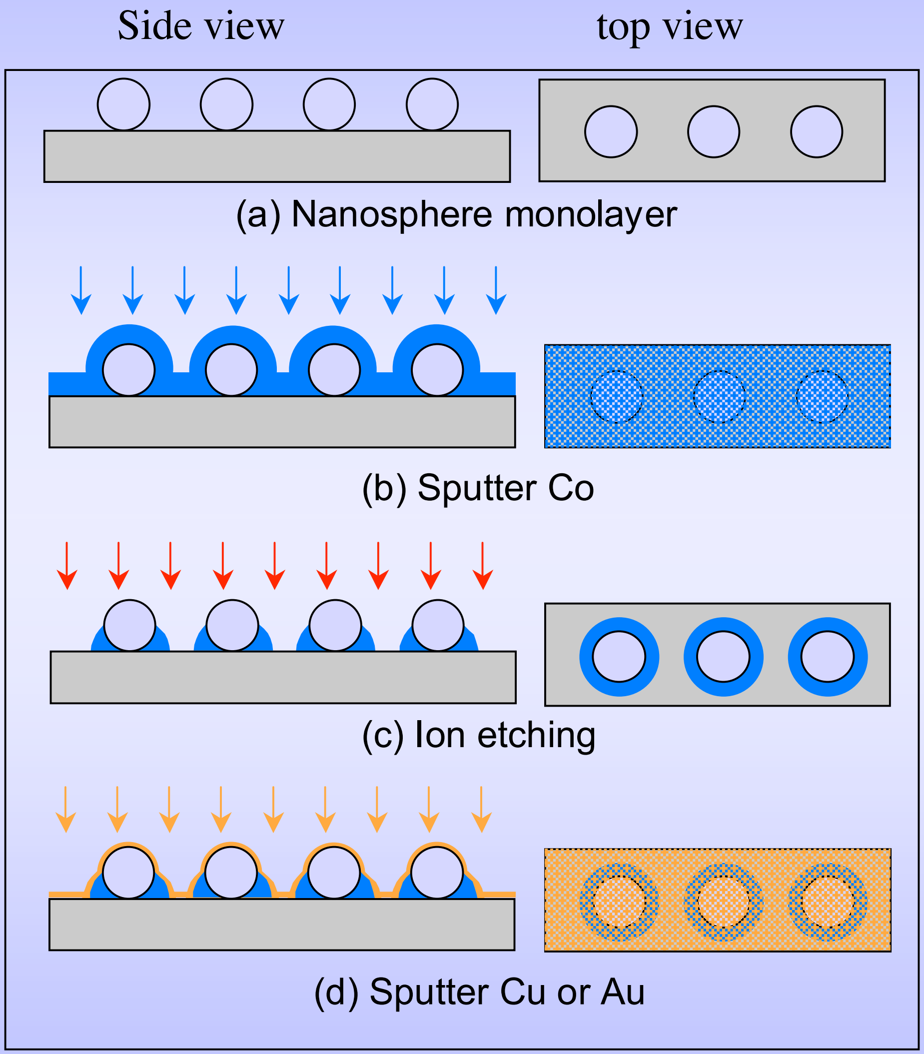
New method for making high density of nano-rings

Monolayer of Polystyrene (PS) particles

Sputter Co film

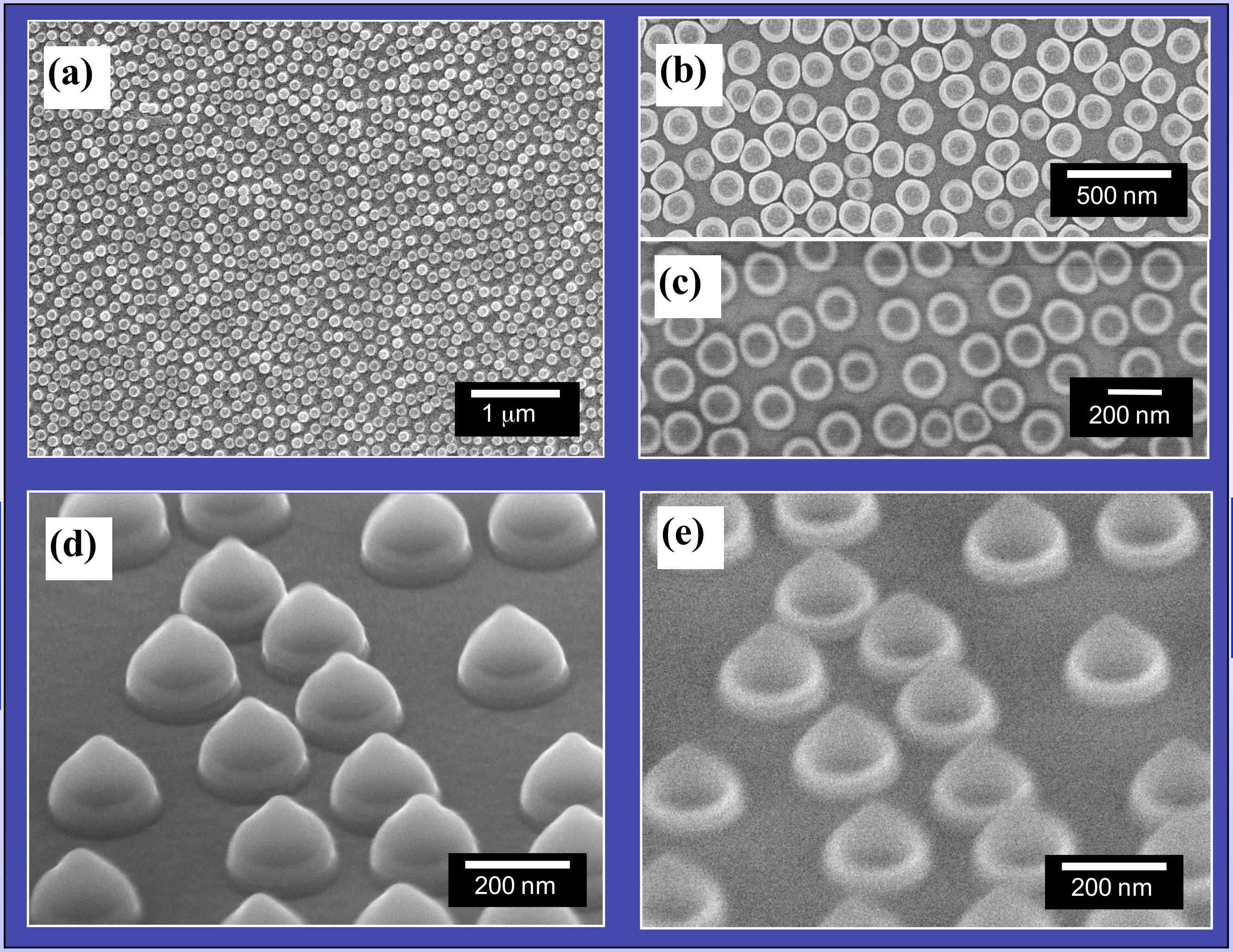
Ion Etching

Sputter capping layer



SEM: Topography and Composition (100 nm diameter nanorings)

Top view 100nm



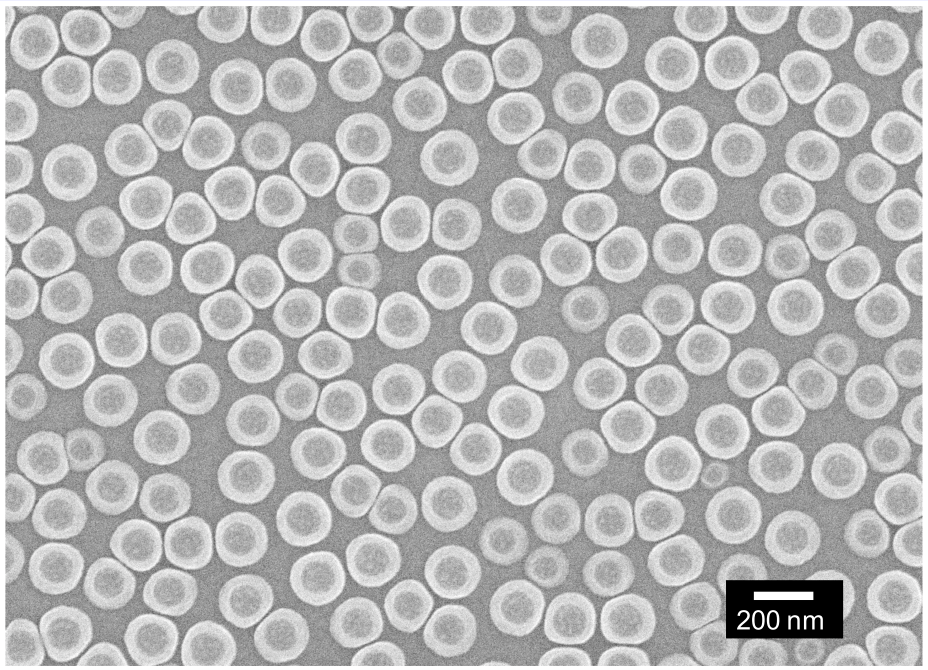
SEI detector

Composition detector

Tilt 50° 200nm SEI detector

Tilt 50° Composition detector

Areal Density



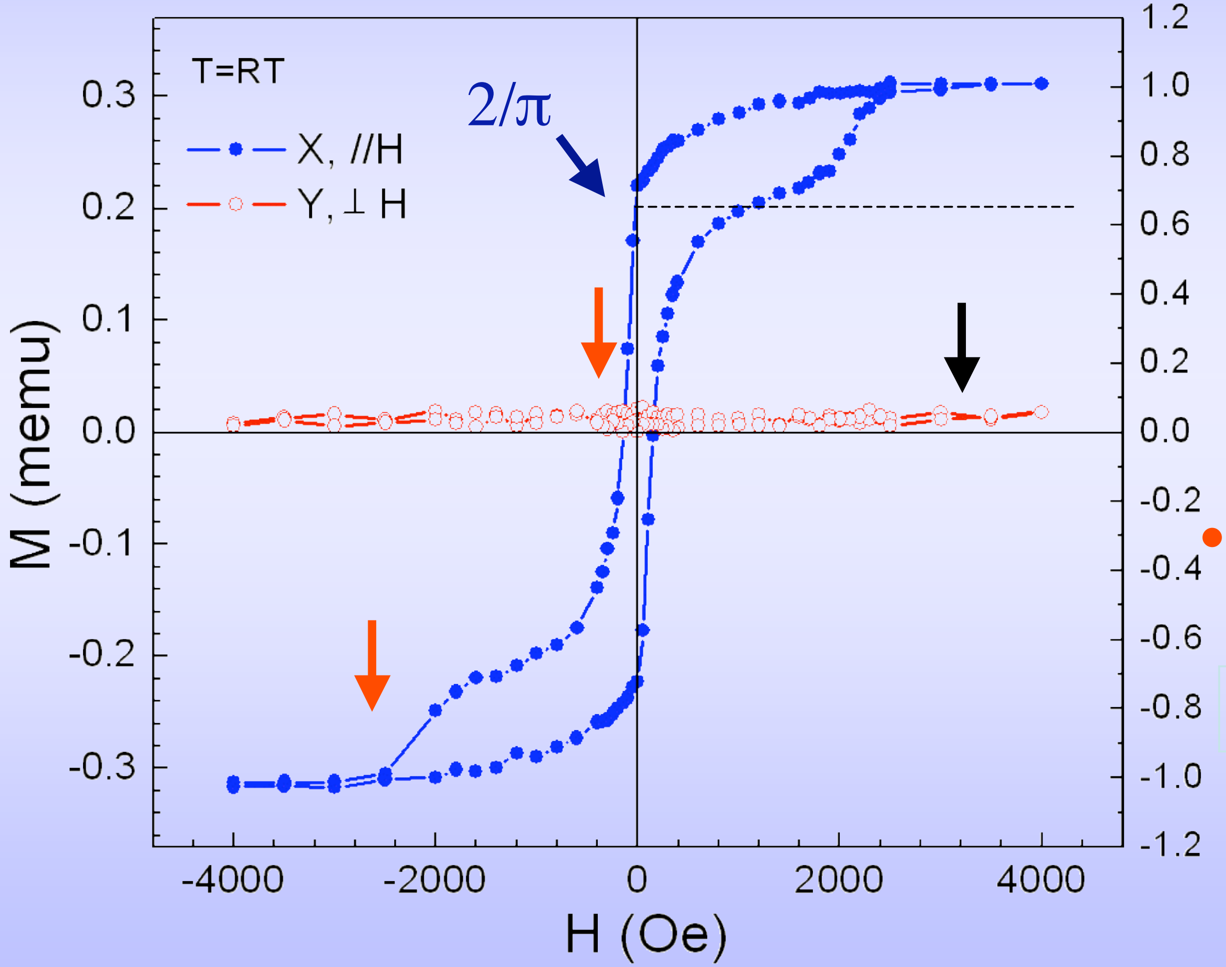
Inner diameter: 100 nm
Outer diameter: 140 nm
Ring width: 20 nm
Ring thickness: ~40 nm

100 nm rings
45 rings/μm^2 ~30 G rings/in^2

$$\rho_s \propto d^{-2}$$ For same areal coverage,

With 50nm rings
120 G rings/in^2

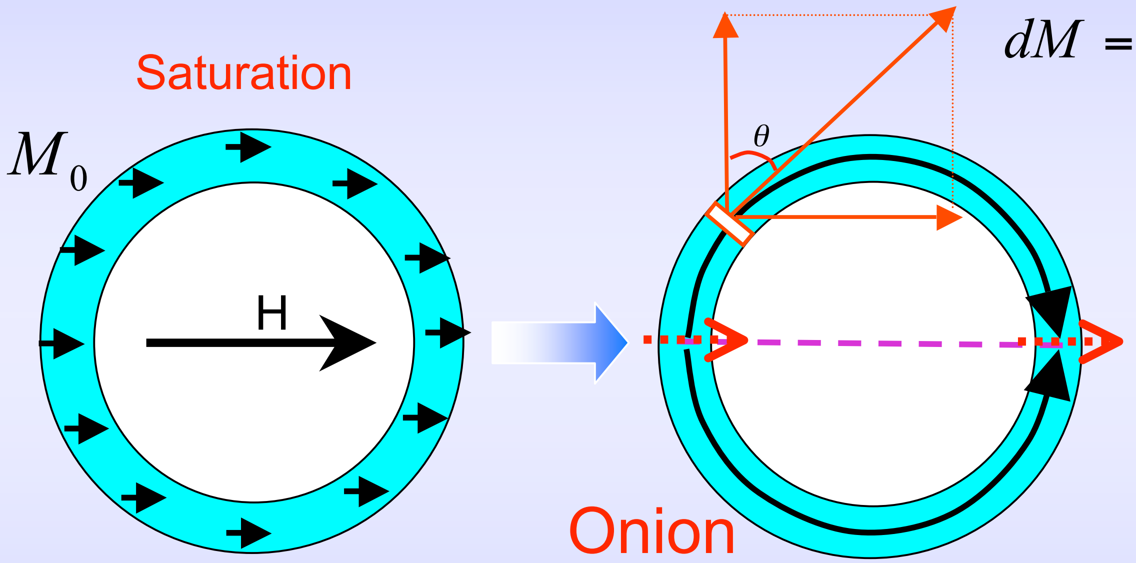
Hysteresis Loop of Co Nanorings



- 2-step switching
- Plateau
- Squareness ~65% (Onion State)
- No y-component
- No angular dependence

46 rings/μm²

Onion State



$$dM = M_0 d\theta / 2\pi$$

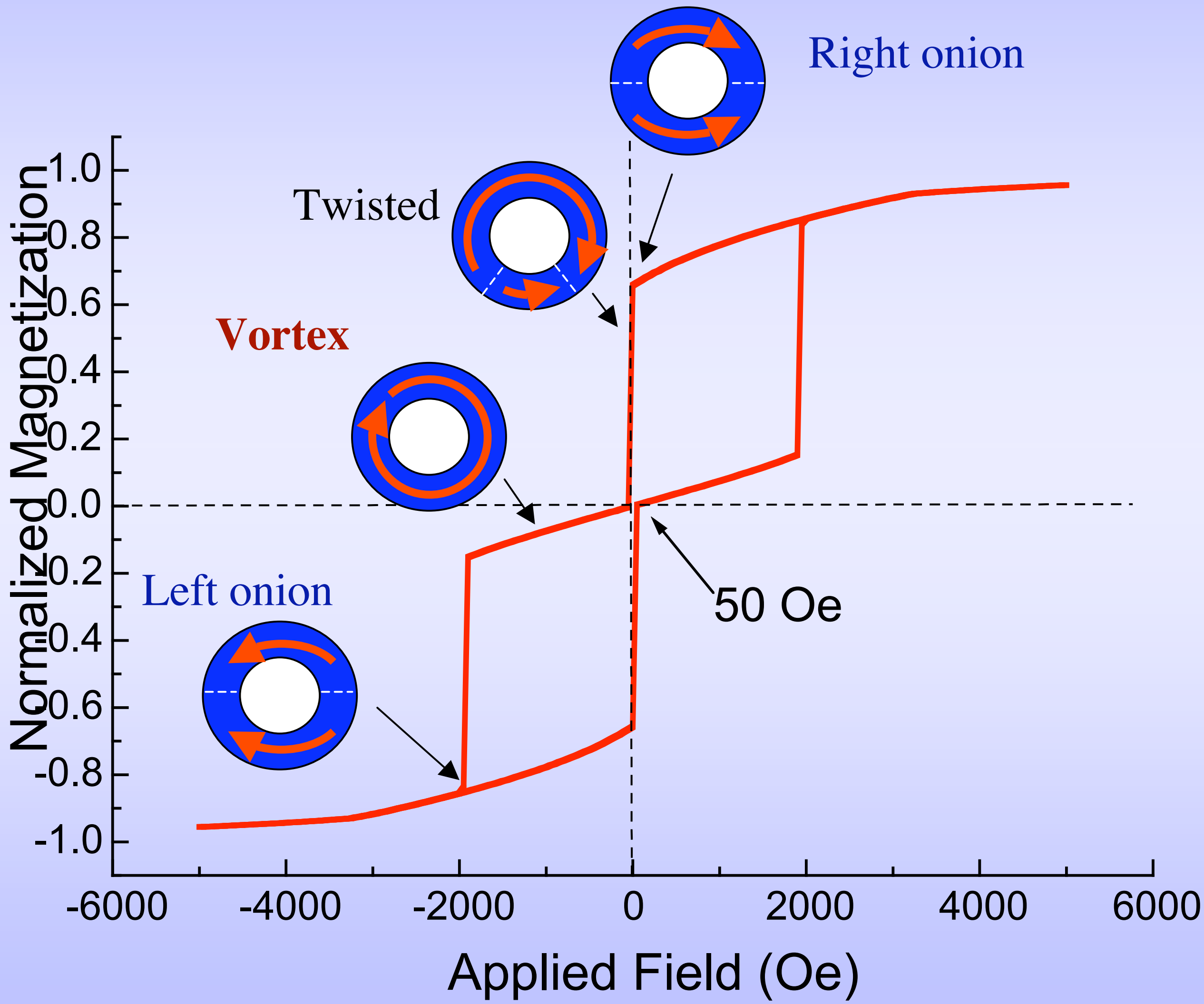
$$M_X = 2\int_0^{\pi} dM \sin\theta$$

$$= \frac{2}{\pi} M_0 = 0.64 M_0$$

$$M_Y = 2\int_0^{\pi} dM \cos\theta = 0$$

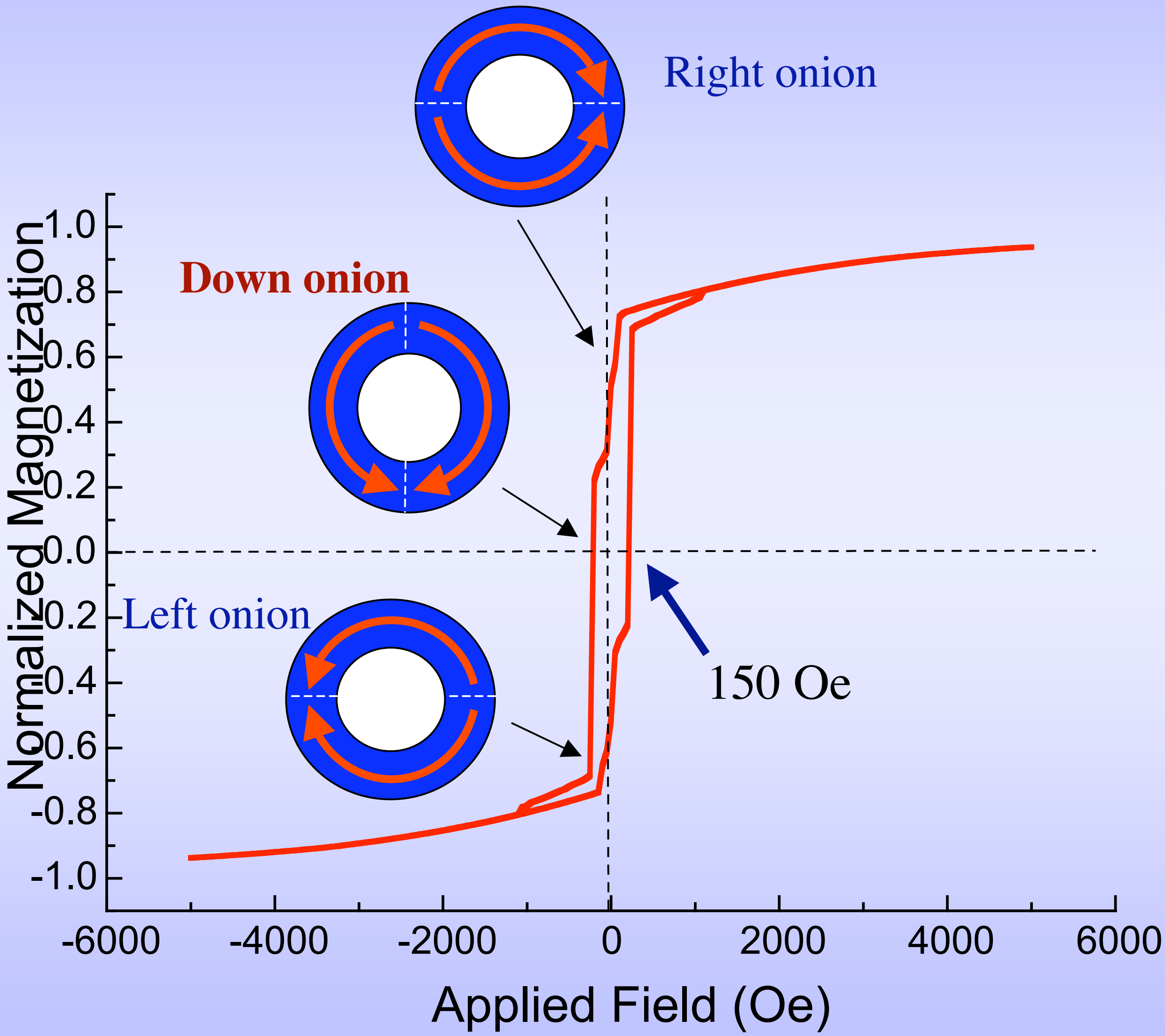
***Two* switching processes with roughly equal probability**

Switching Process 1: Vortex



J. Zhu(CMU)

Switching Process 2: Onion Rotation



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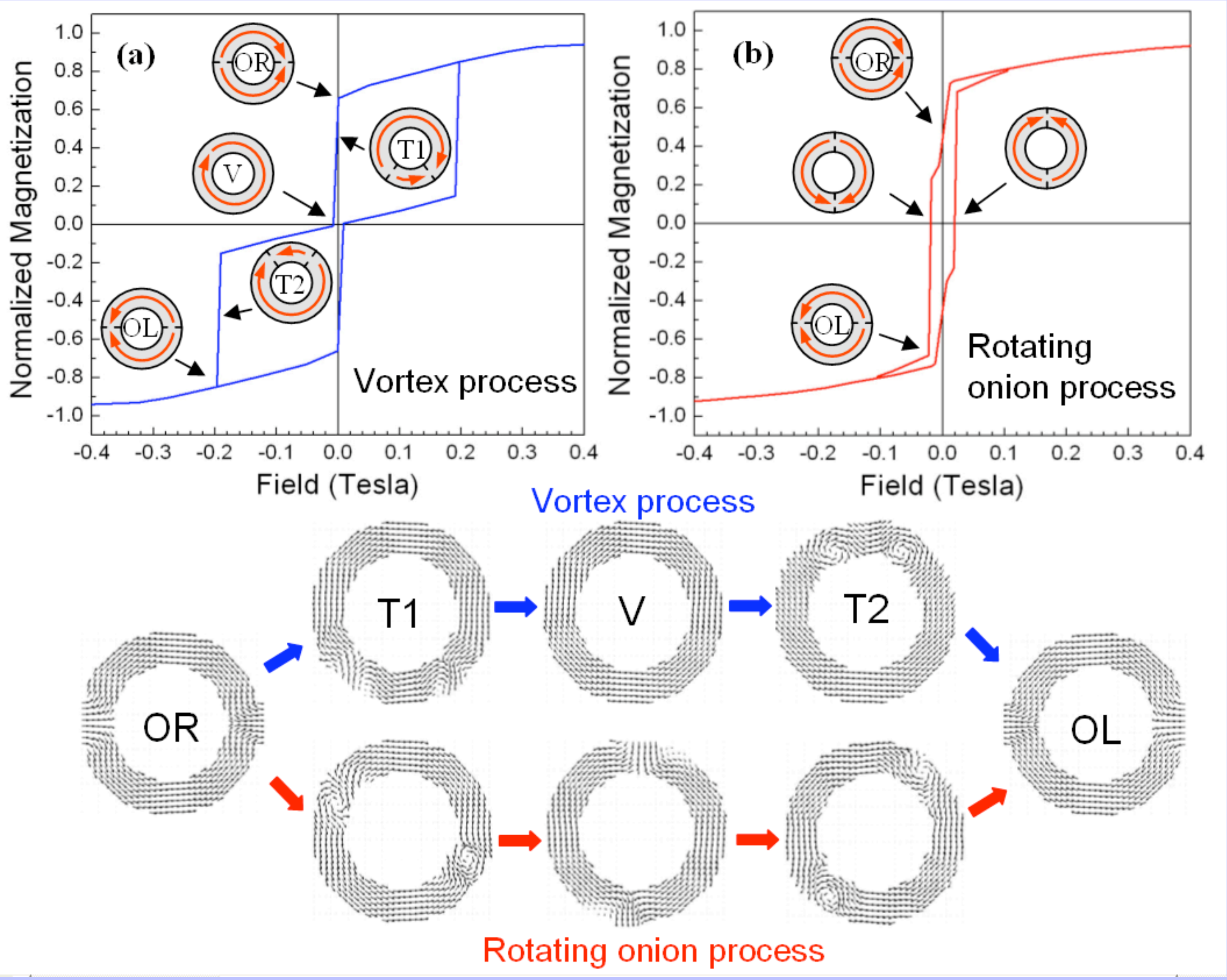
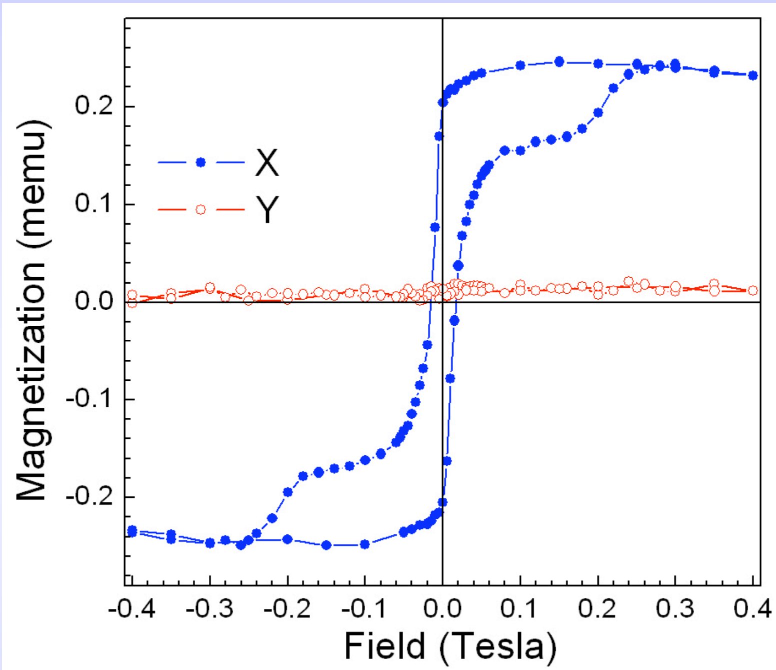
Two Switching Processes



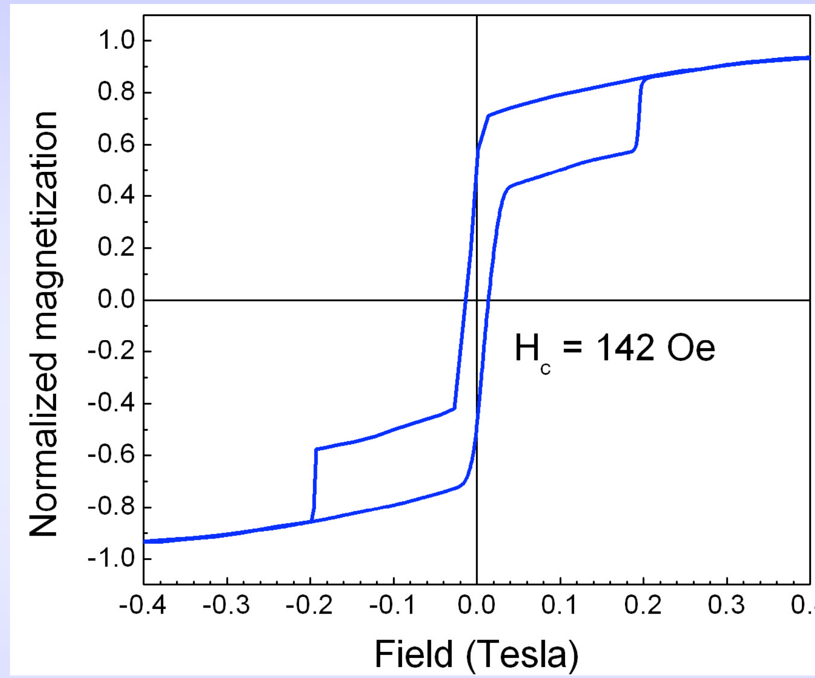
Similar probability

Experiment vs. Simulation

experiment



simulation



40% vortex, 60% onion rotation

Quantitative agreement

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Conclusions

1. Spin Torque

In trilayers (inverse effect of GMR)

In single layers (inverse effect of DMR)

Switching (not spin waves) in both low fields and higher fields

2. Arrays of Nanorings (Lithography-less)

100 nm diameter

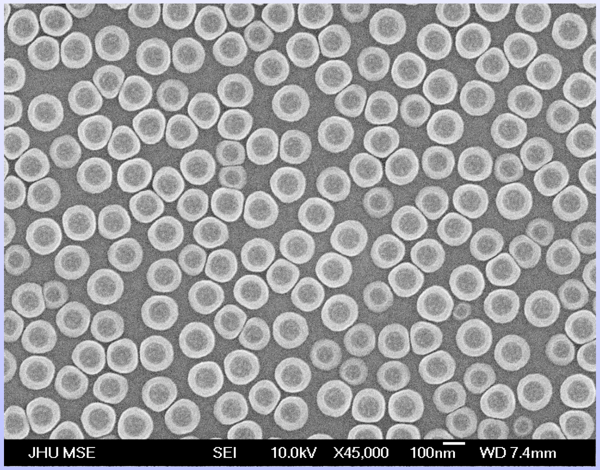
5×10^9 nanorings

Over 100 mm^2

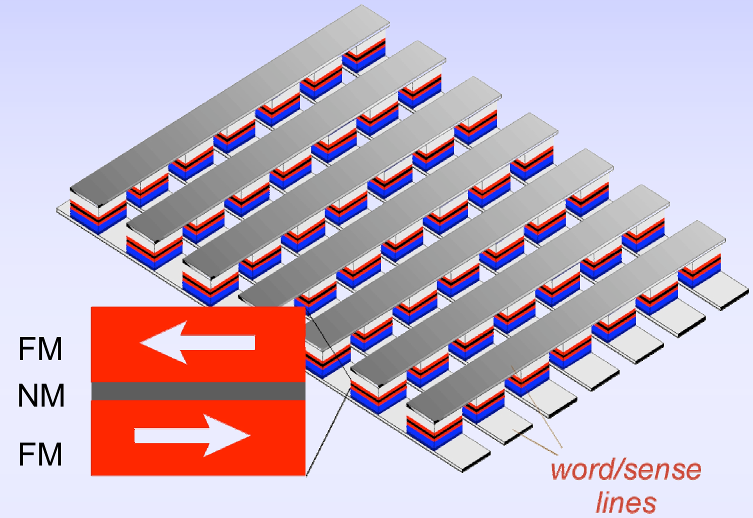
high areal density: 45 rings/μm^2

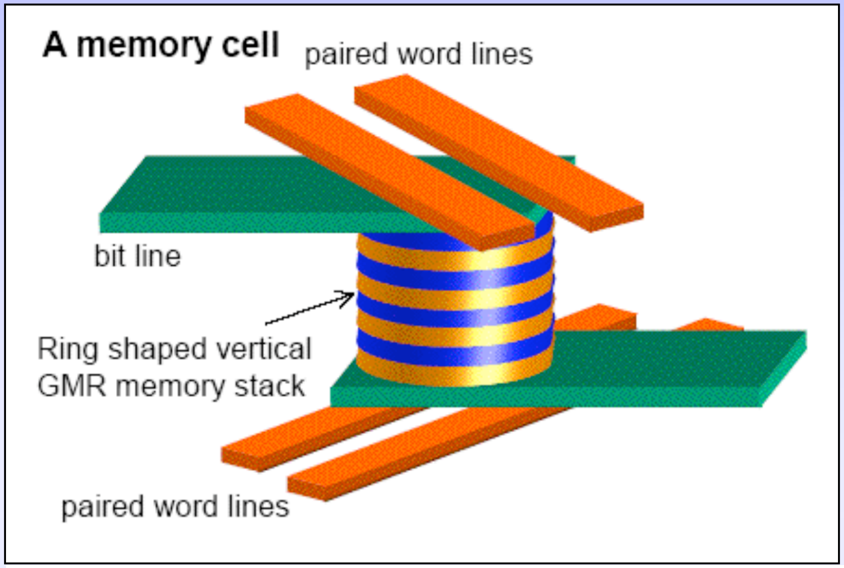
Single layers and multilayers

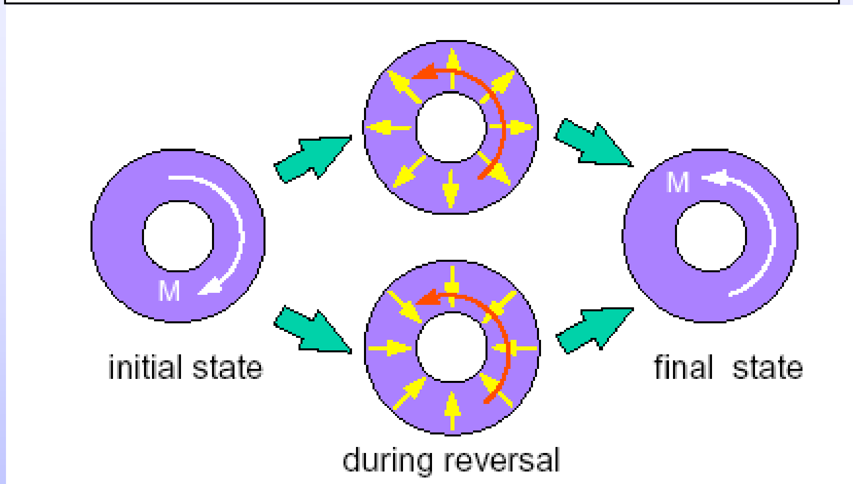
Unique switching



MRAM and VMRAM







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Spin torque in nanorings