Magnetic Nanostructures: Intricate Science and Technology

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Nano is Now

Nano Science
Nano Biology
Nano Medicine
Nano Magnetism
Nano Materials
Nano Machines
Nano Technology
Nano ………….

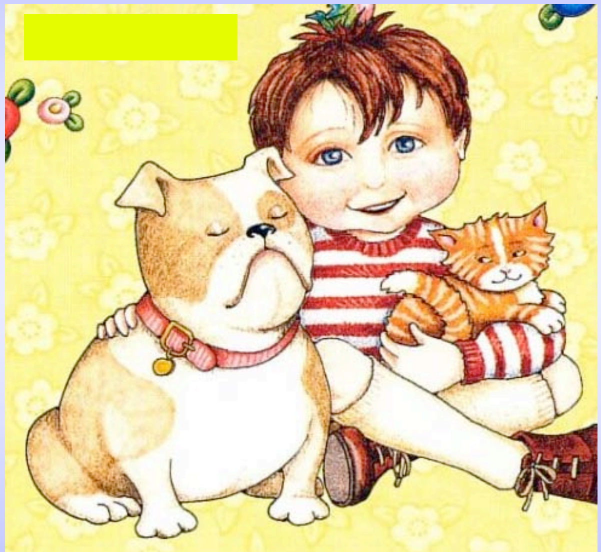
Mega $$$

1 nanometer (nm) = 10^{-9} m = 10^{-3} μm = 10 Å

Length scale < 100 nm

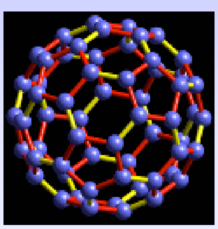
Why Small ?

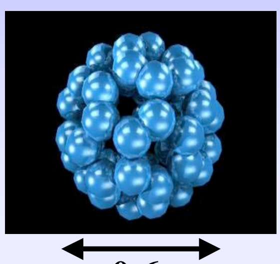
Human and Animals ≈ 1 m



Small is Different Small is Strong

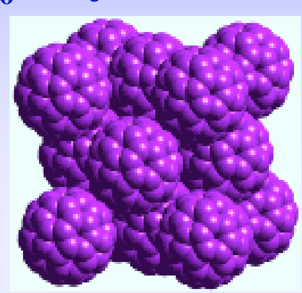
C_{60} Buckyball



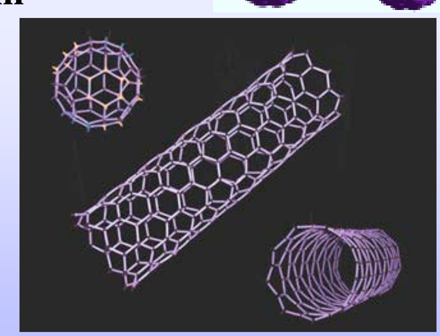


0.6 nm

C_{60} Crystal

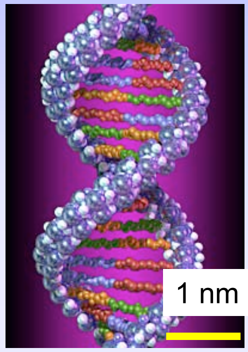


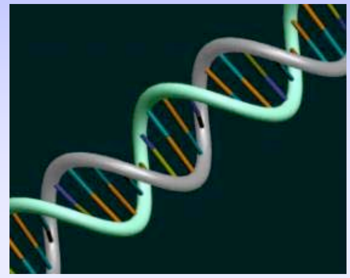
Carbon Nanotubes



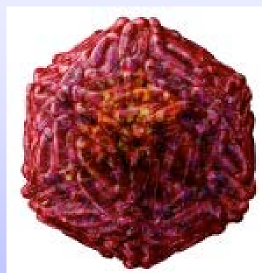
Small is Beautiful   Small is breathtaking

DNA





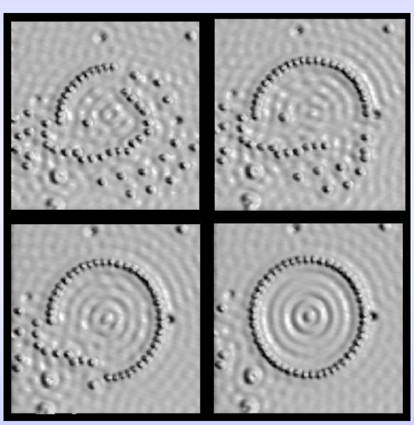
50 nm

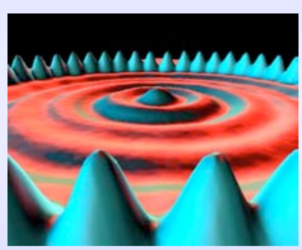


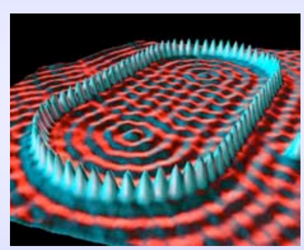
West Nile Virus

Small is Unique

STM arranged Atoms (quantum corral)







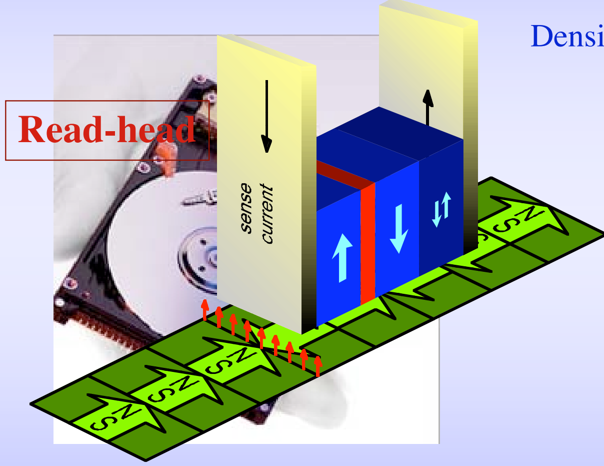
(IBM)

Fe atoms on Cu

Small is Fast Small is Cheap

Nanotechnology in Magnetic Recording

Read-head flight height ≈ 10 nm



Density doubled every 18 months

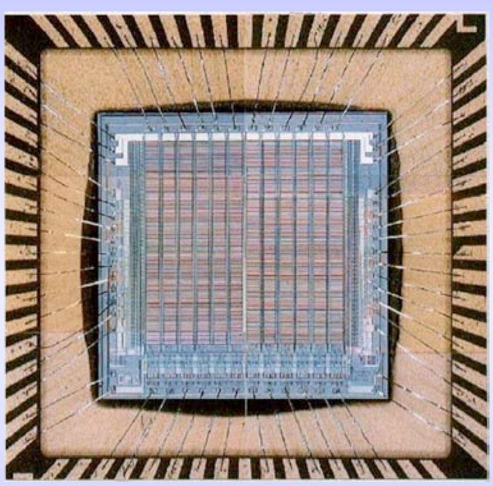
Density increased 100 M fold
Cost decreased 5 M fold

Medium

Bit size ≈ 30 nm

100 Gb/in^2 = 10^{11} bit/in^2

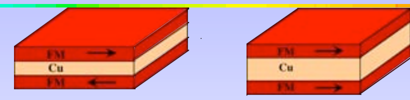
Small is Fast



Integrated electronics

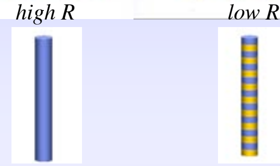
Magnetic Nanostructures (Examples)
(1 nm = 10 Å)

- **Oscillatory Interlayer coupling** (1986)



- **Giant magnetoresistance (GMR)** (1988)

Nanowire ferromagnets (1993)

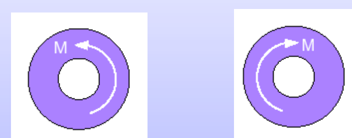


- **Tunneling magnetoresistance (TMR)** (1995)

Half Metals

Spin torque effects

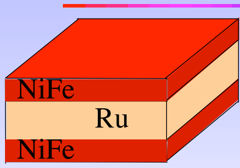
MgO MTJ (2004)

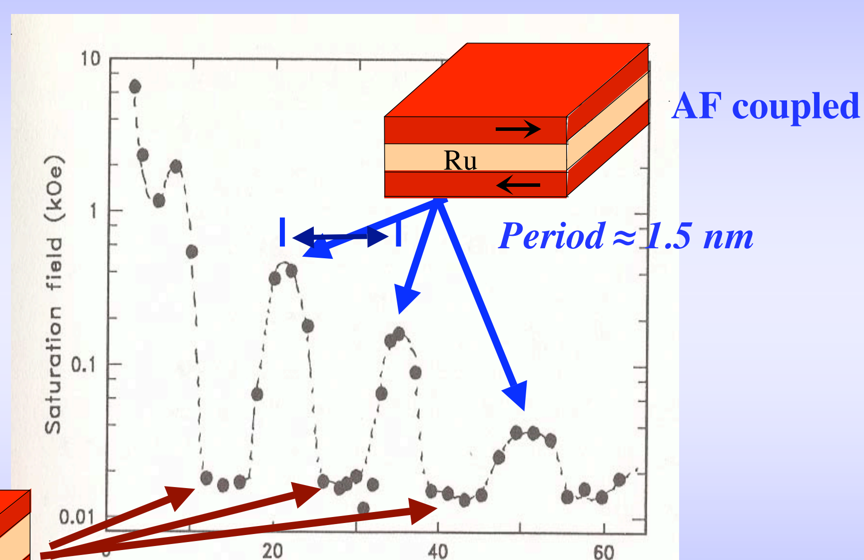


Magnetic dots, antidots, pillars, nanorings

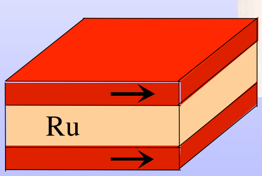
Interplay of materials **nm length scale** **small geometrical entities**

Oscillatory coupling in FM/Ru(t)/FM trilayers





FM coupled

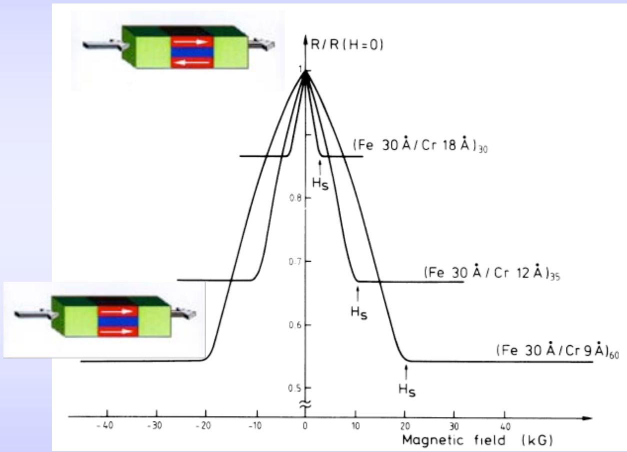


Ru thickness (Å)

(Parkin et al.)

Giant Magnetoresistance (GMR)

Giant MR: in multilayers and granular solids
(spin-dependent scattering) (1988)



$\rho(\theta) = \rho_0 - \Delta\rho \cos\theta/2$

$\theta = \angle\,(\mathbf{M_1}, \mathbf{M_2})$

$0.1\% \leq \Delta\rho/\rho \leq 150\%$

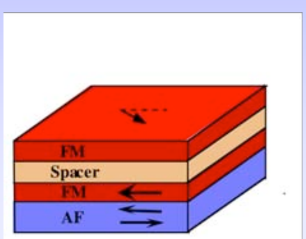
Magnetic configuration affects *R*

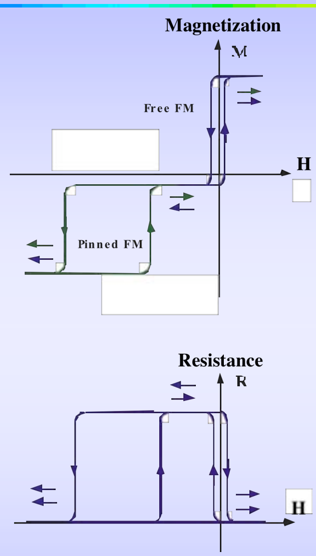
Baibich *et al.*, PRL **61**, 2472 (1988)

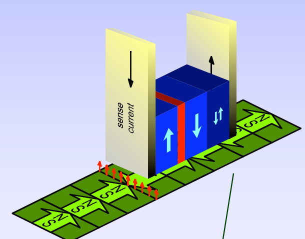
Spin-Based Application I: Spin-Valve GMR Devices

Free

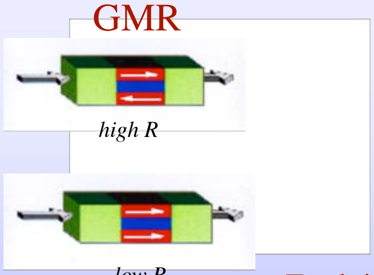
Pinned

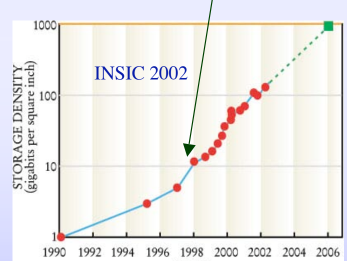






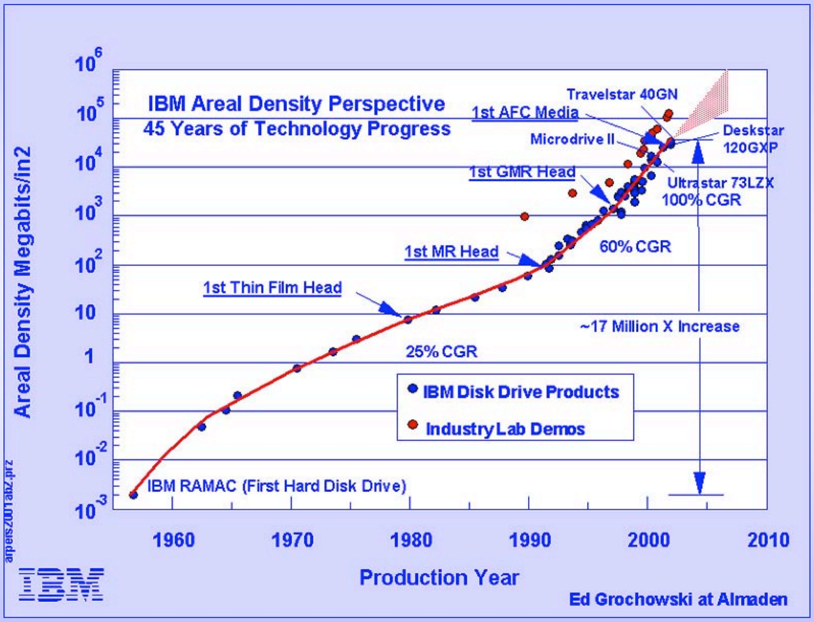
GMR





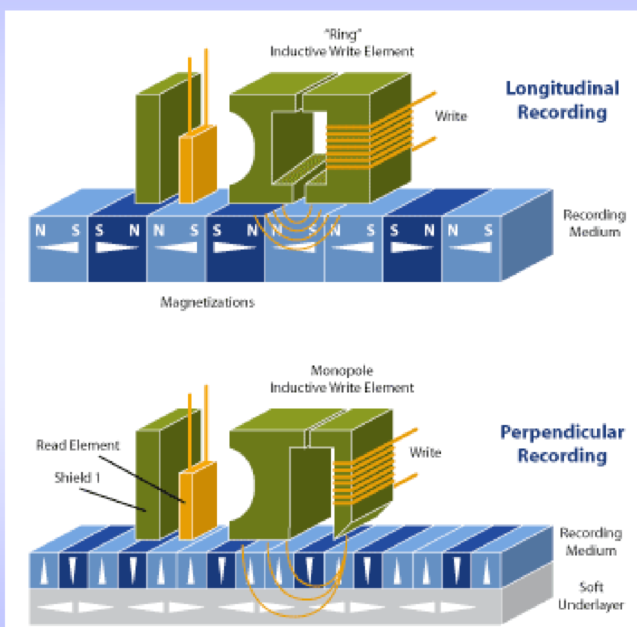
Exploitation of oscillatory interlayer coupling
Pinning of FM via FM/AF exchange coupling
Field sensing via giant magnetoresistance (GMR)

Areal Density



Cost decreased 5 M fold

Magnetic Recording

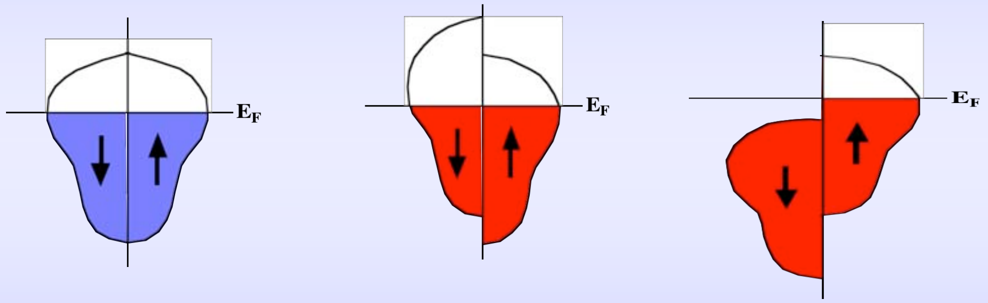


Spin Polarization (P)

Spin polarization (P)

$$P = \frac{N_\uparrow(E_F) - N_\downarrow(E_F)}{N_\uparrow(E_F) + N_\downarrow(E_F)}$$

Density of states at E_F



NM metal (Cu)
$P = 0$

FM metal (Co)
$0 < P < 1$

Half Metal (CrO_2)
$P = 1$

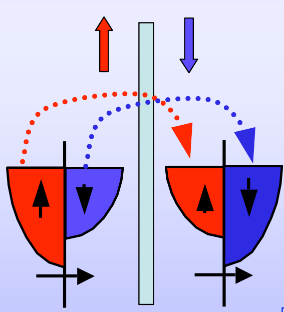
Fully Polarized Metal

Tunnel Magnetoresistance (TMR)
(across 1 nm insulating barrier)

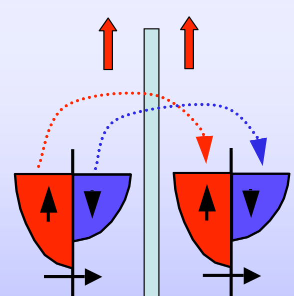
Tunnel MR: in tunnel junctions (1995)

(spin-selective conduction)

AP R_{AP} ***High R***



P R_P ***Low R***



$R_P < R_{AP}$

TMR = $(R_{AP} - R_P)/R_P \approx 2P^2/(1 - P^2)$

Spin-Based Application II: Magnetic Random Access Memory (MRAM)

Magnetic Tunnel Junction (MTJ)

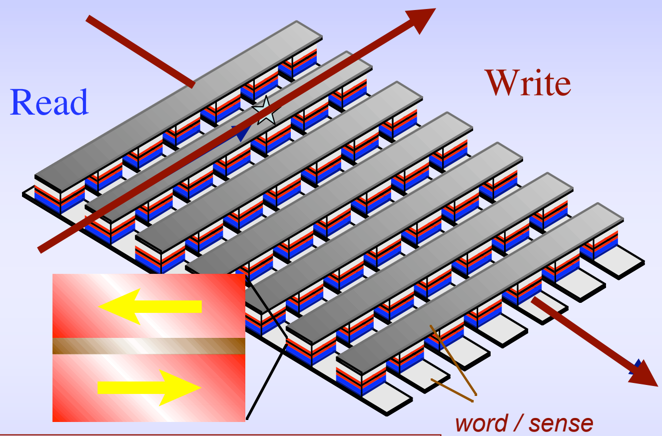
"1"

high R

"0"

low R

TMR ≈ $2P^2/(1 - P^2)$



word / sense lines

Advantages:
- Non-volatile memory
- Short access time
- Low power consumption

Key Challenges:
- Eliminate field writing and stray field
- High density

4 Mb prototypes (Motorola)

Universal memory: speed as SRAM, density as DRAM, rewritability as flash

Two Recent Topics

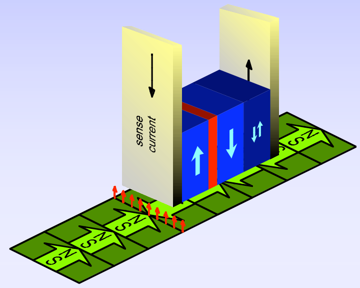
1. **Spin Torque**
2. **Nanorings**

- **New phenomena and physics**
- **New applications**
- **Importance of geometrical shape**
- **New obstacles and challenges**

Magnetization (*M*) Reversal

Previously

Reversal of *M* by a magnetic field *H*



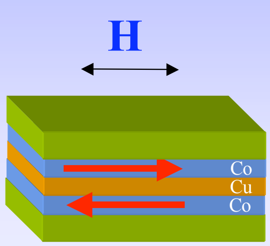
New (Spin Transfer Torque)

Switching and excitations of *M* by a spin-polarized current *I*

- Physics
- Applications

Spin Torque (ST) Effects

electrical current affects magnetic configurations



GMR

Magnetic configuration affects electrical properties.

Inverse Effect

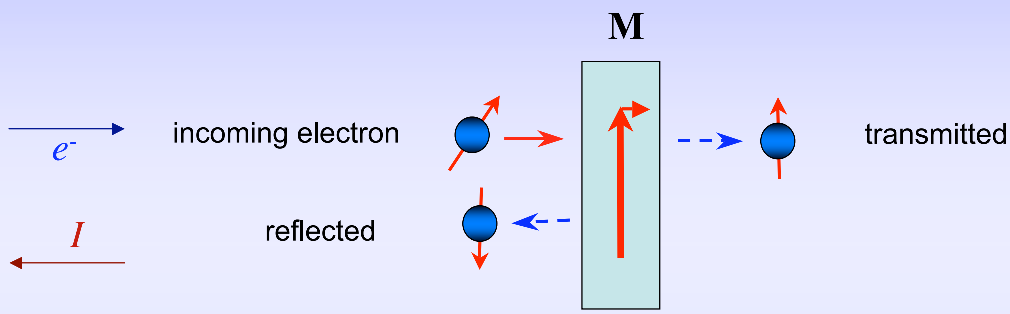
ST

Electrical current affects magnetic configurations.

without a magnetic field

Slonczewski, JMMM **159**, L1 (1996)
Berger, PR B **54**, 9353 (1996), JAP **57**, 1266 (1984), JAP **49**, 2156 (1978)

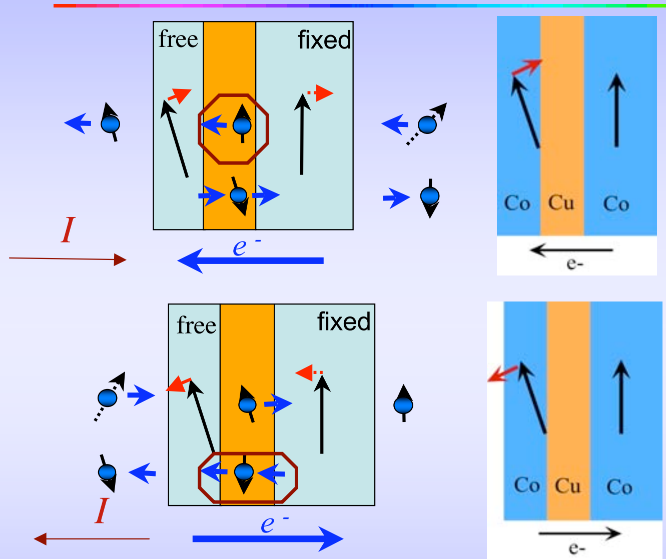
Spin torque in a single layer



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)

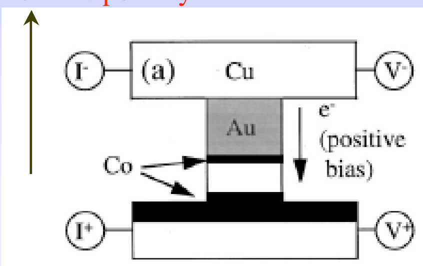
Asymmetry in *I*

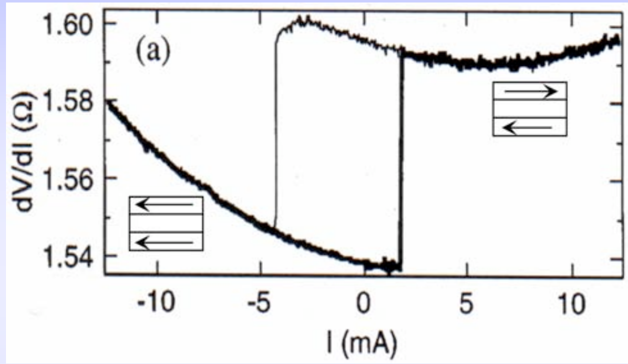
Switching at H ≈ 0

high current density required ~ 10^8 A/cm^2

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

Positive polarity



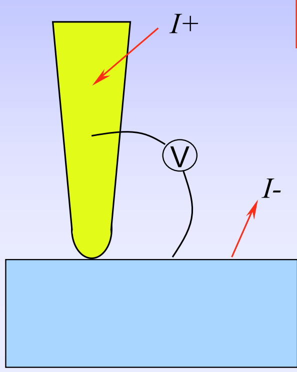


Nanopillars
Cross-section ≈ 100 nm
made by nanolithography

Asymmetry in *I*

- Hysteretic
- A free (thin) layer and a fixed (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

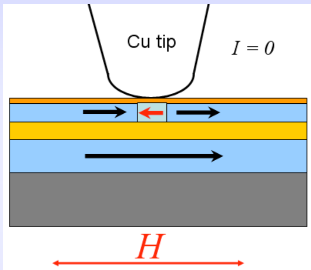
ρ = resistivity

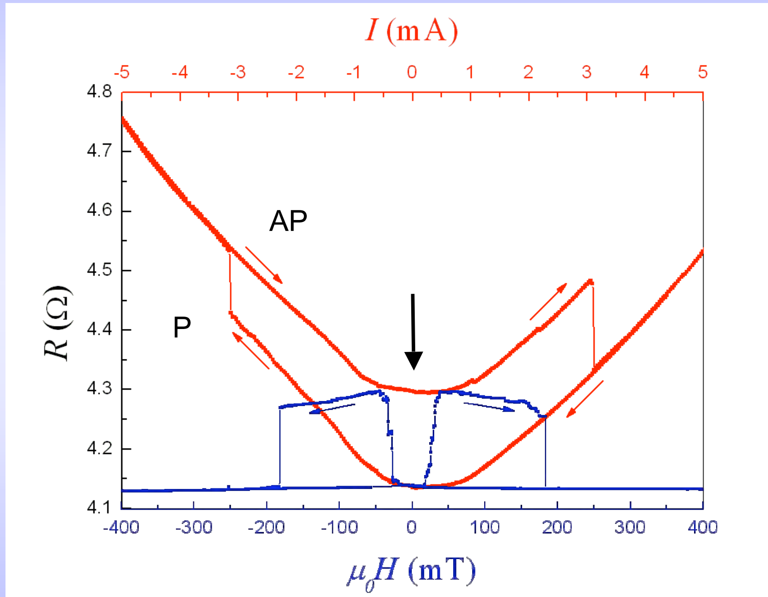
Contact size (a) can be inferred from contact resistance.

Applicable to 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**

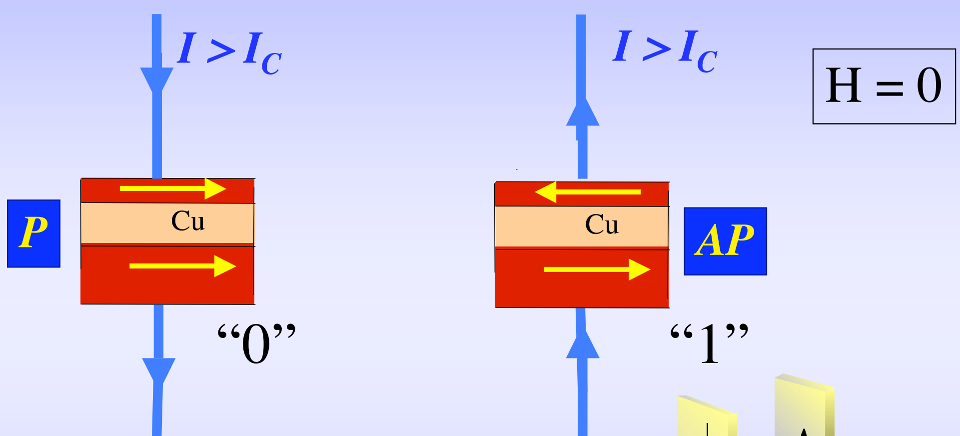
Spin Torque Effect in Continuous Trilayers

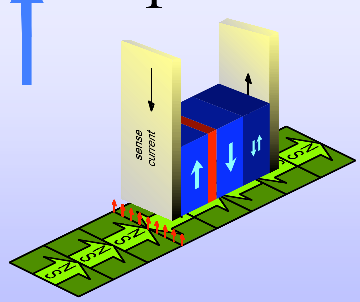




Chen, Ji and Chien, Appl. Phys. Lett. **84**, 380 (2004)

Switching by current

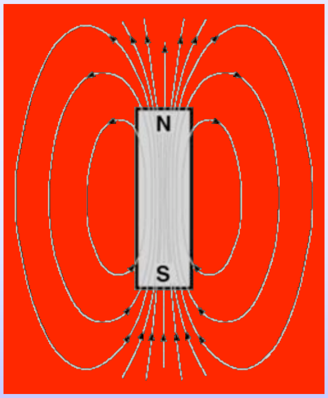


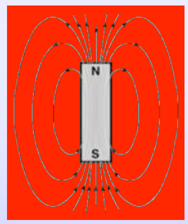


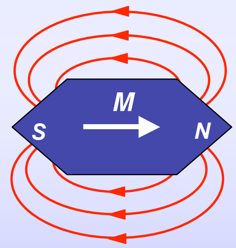
CPP read heads must prevent Spin Torque switching

2. Nanorings

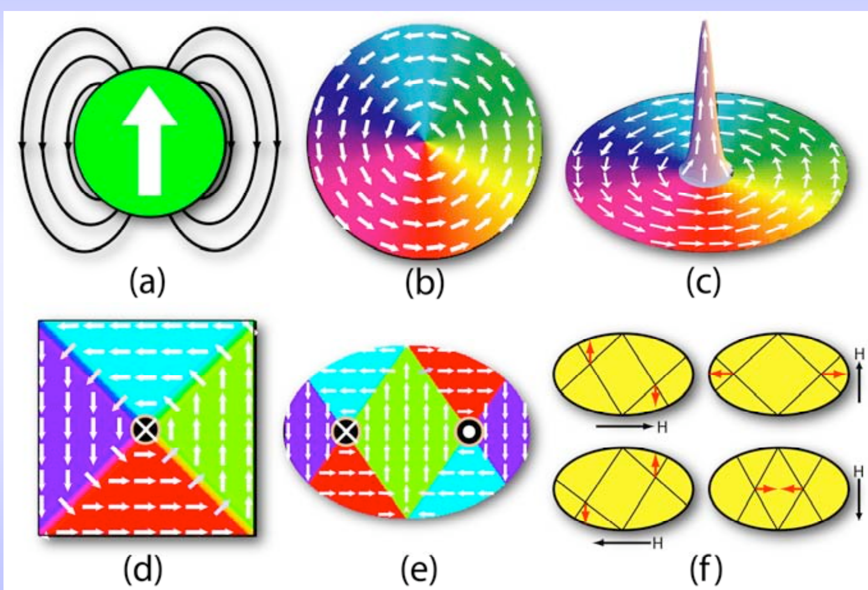
A bar-magnet always has 2 poles and stray field



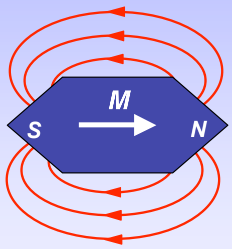




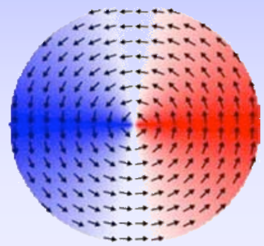
Nanomagnets



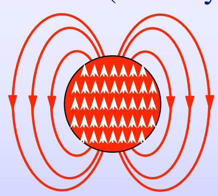
Nanomagnets



Nanodiscs

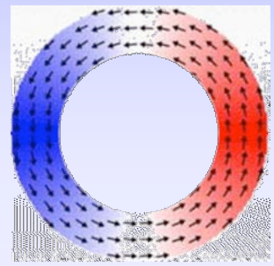


Vortex State(no stray field)



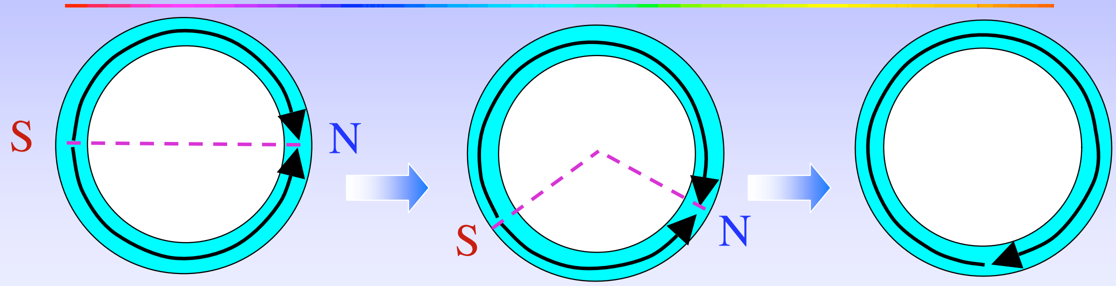
Small discs (< 150 nm for Co)
Single domain state
(with stray field)

Nanorings



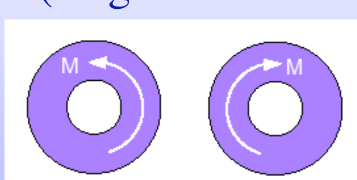
Vortex State(no stray field)

Nanorings
Annihilation of Magnetic Monopoles



Onion	Twisted	Vortex
Two poles		**No poles**
		No stray field

Two chiralities (magnetic bit for storage)

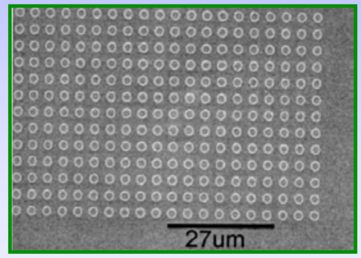


Width ≤ 50 nm

Fabrication of Nanorings

Status Quo using e-beam lithography

- Ring diameter (μm)
- Few rings (10^2)
- Small area (0.01 mm^2)
- Low areal density(0.1 ring/μm^2)



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

Our method

- **100 nm diameter rings**
- **5 x 10^9 rings**
- **20 nm ring width**
- **Over 100 mm^2**
- **Areal density of 45 rings/μm^2**

Without e-beam lithography

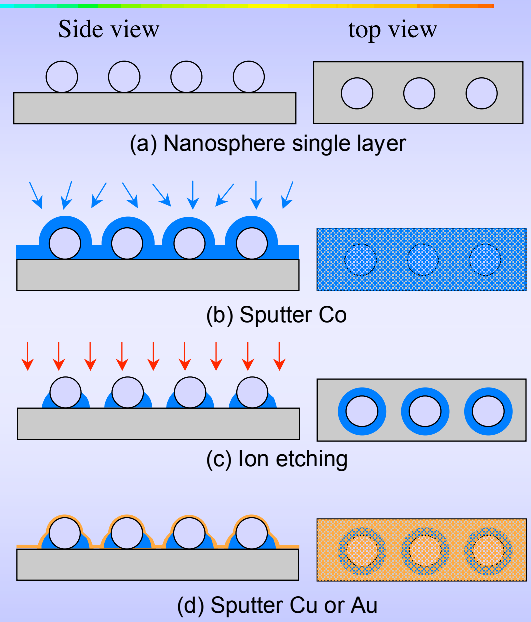
New method for making high-density nanorings

Single layer of Polystyrene (PS) spheres

Sputter Co film

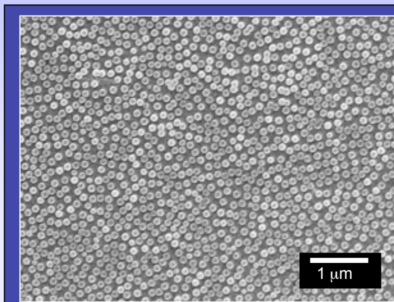
Ion Etching

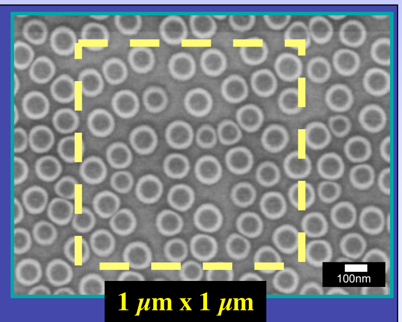
Sputter capping layer



SEM: Topography and Composition (100 nm diameter nanorings)

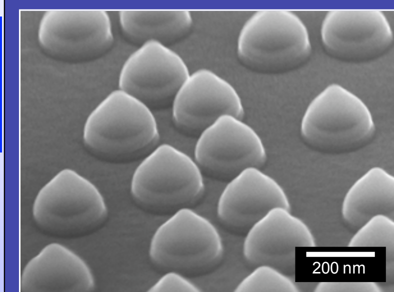
Top view 100nm





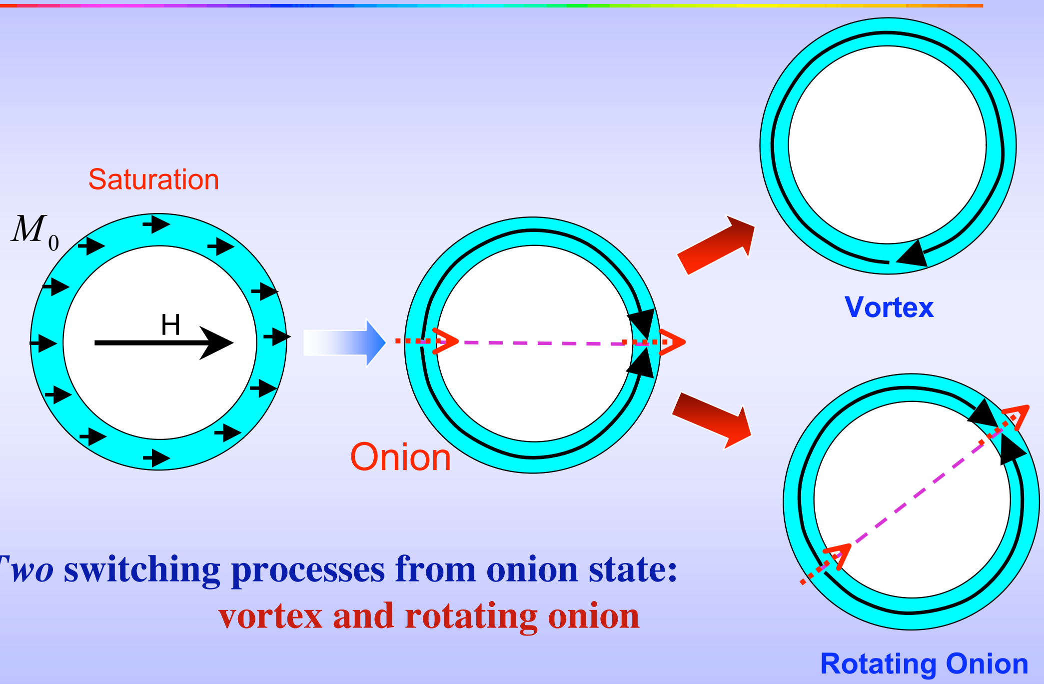
Composition detector

Tilt 50º 200nm SE detector



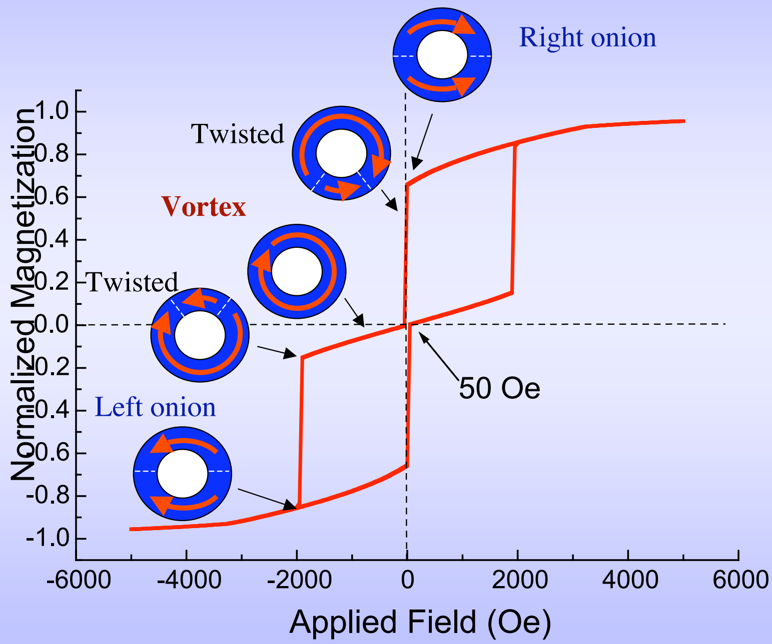
5×10^9
100-nm rings
20 nm ring width
45 rings/μm^2

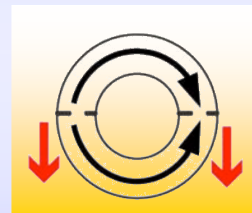
Nanoring (3 configurations)



Two **switching processes from onion state:**
vortex and rotating onion

Switching Process 1: Vortex





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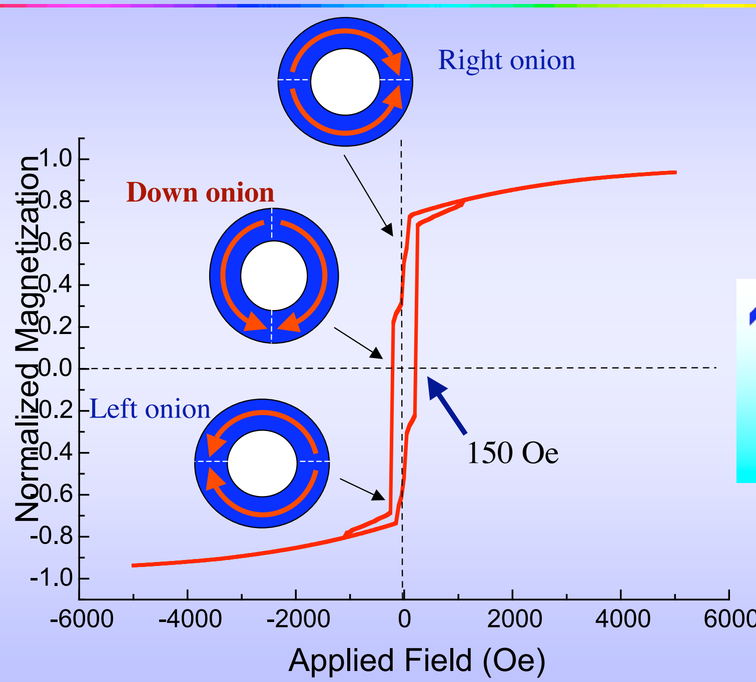
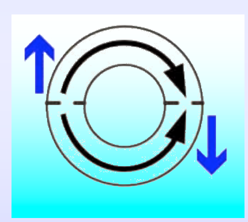
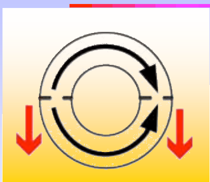
Switching Process 2: Onion Rotation

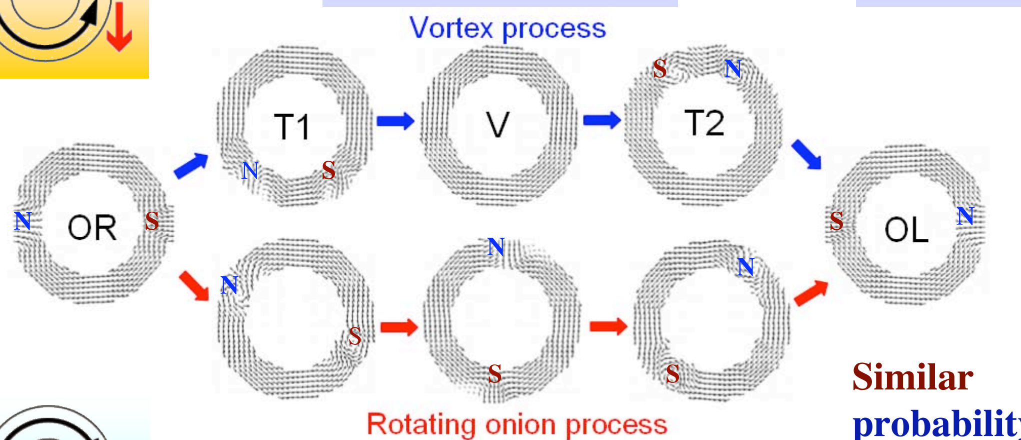


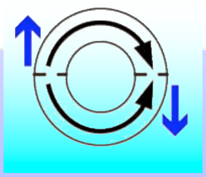


J. Zhu(CMU)

Two Switching Processes



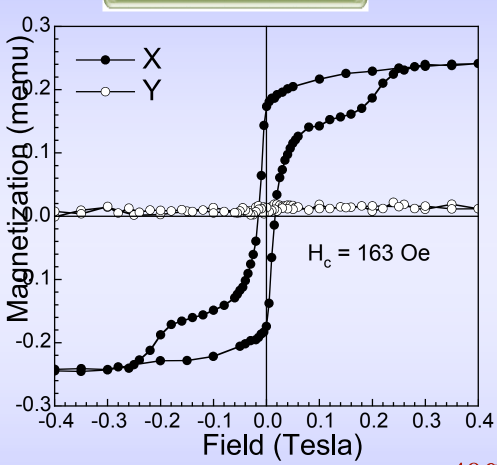




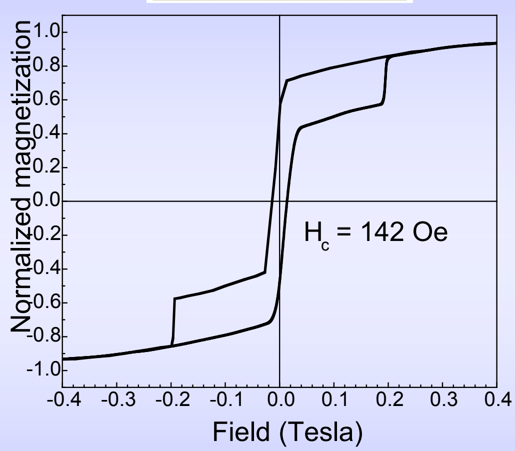
Similar probability for 100 nm nanorings

Experiment vs. Simulation

Experiment



Simulation



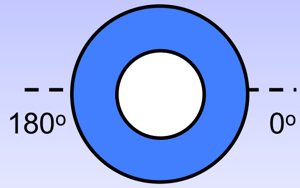
40% vortex, 60% onion rotation for 100 nm rings

Quantitative agreement

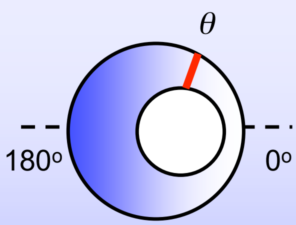
Zhu[3], Fan, Cammarata, CLC, Adv. Mater. **16**, 2155 (2004).

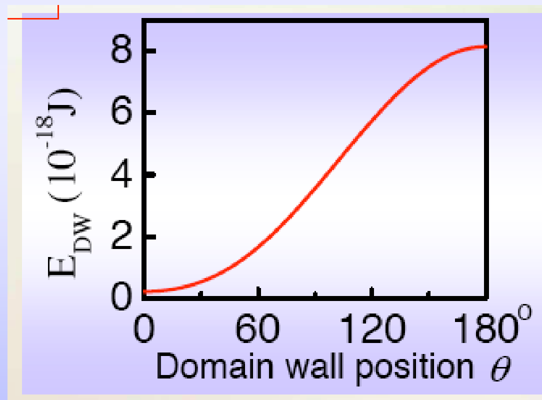
Pole (DW) prefers narrower path

Symmetrical Nanorings
(uniform cross section)



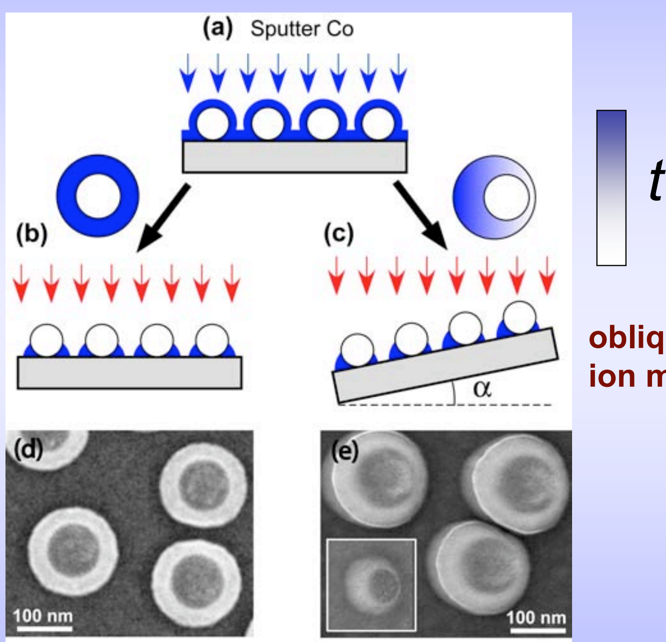
Asymmetrical Nanorings





Asymmetrical Nanorings

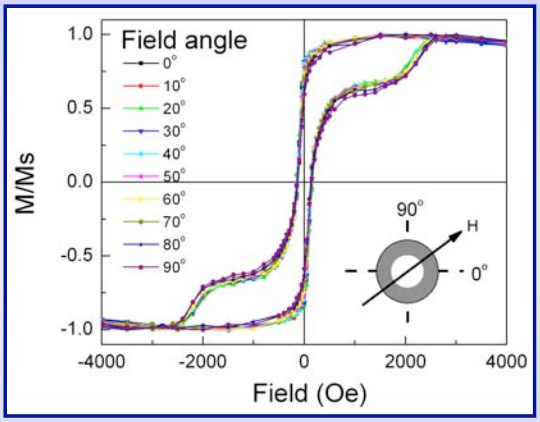
ion milling



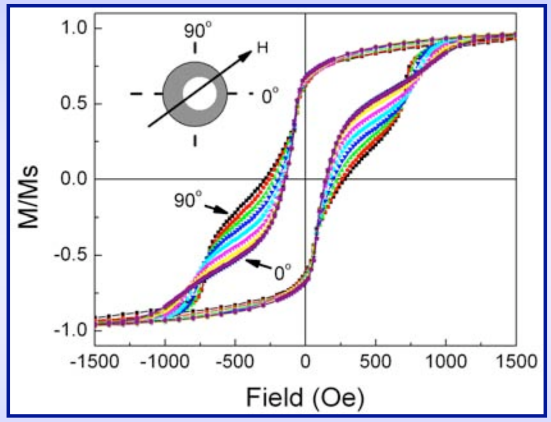
oblique angle ion milling

Angular Anisotropy in Asymmetrical Nanorings

Uniform nanorings



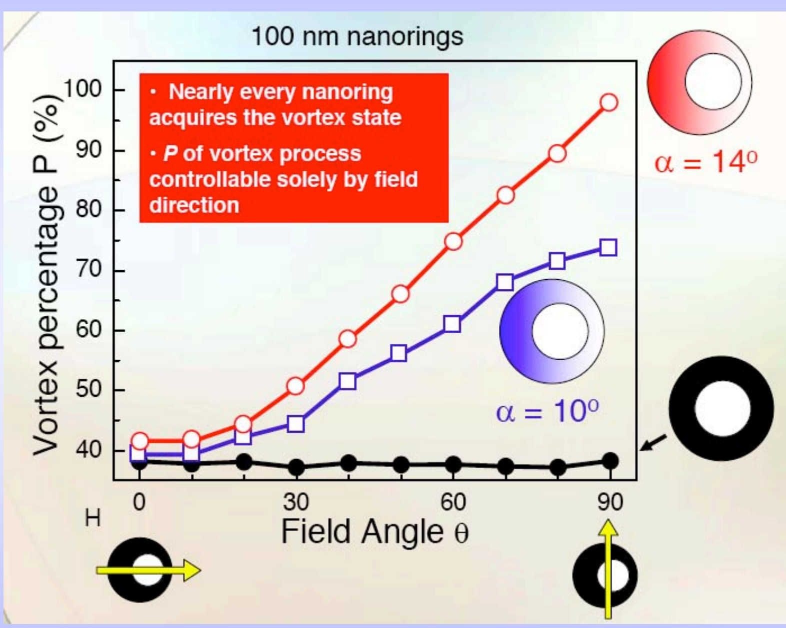
Asymmetrical nanorings

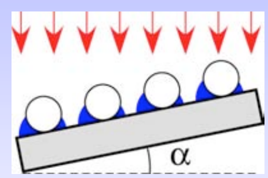


Percentage of vortex process increases with θ.

Zhu, Chern, Tchernyshyov, Zhu, Zhu, and CLC, Phys. Rev. Lett. ***96****, 027205 (2006)*

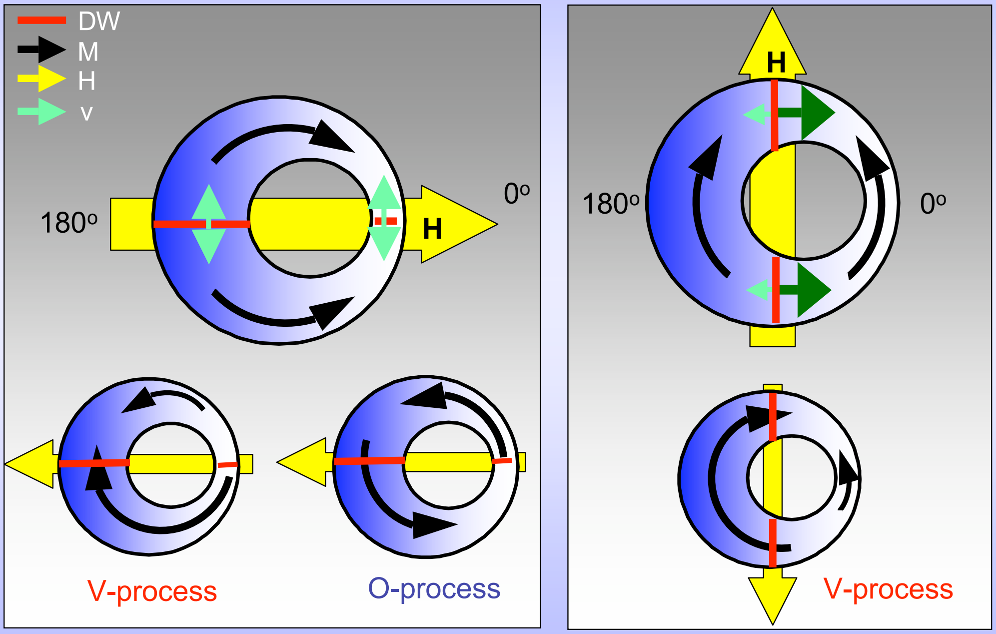
Enhancement of Vortex State in Asymmetrical Nanorings



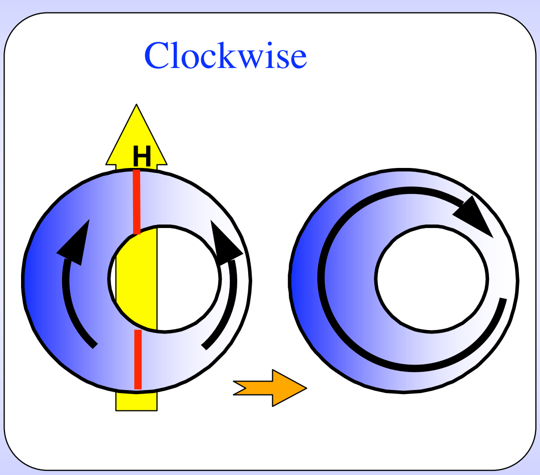


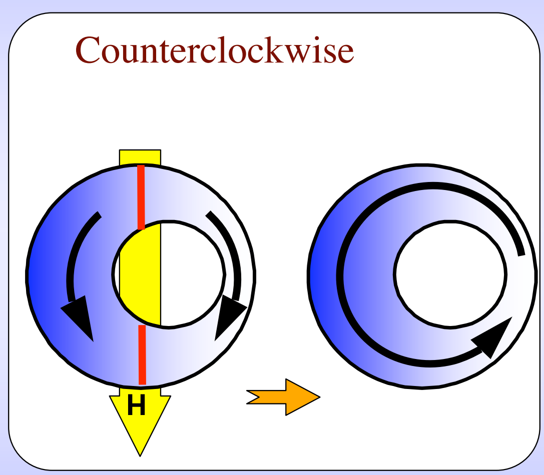
Controllable magnetic switching

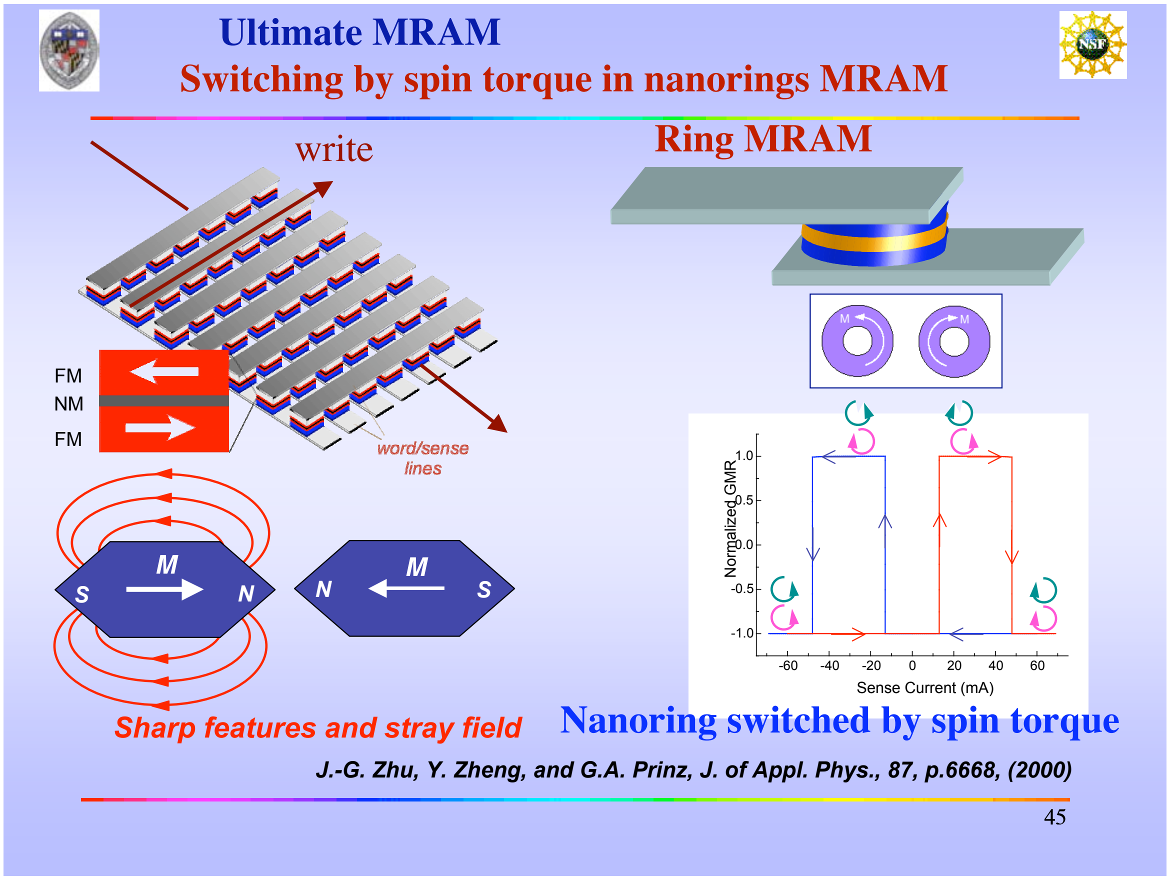
Direction of external field determines the initial DW positions



Control of vortex chirality






Ultimate MRAM
Switching by spin torque in nanorings MRAM
write
Ring MRAM
FM
NM
FM
word/sense lines
M
S
N
M
N
S
M
M
Normalized GMR
1.0
0.5
0.0
-0.5
-1.0
-60
-40
-20
0
20
40
60
Sense Current (mA)
Sharp features and stray field
Nanoring switched by spin torque
J.-G. Zhu, Y. Zheng, and G.A. Prinz, J. of Appl. Phys., 87, p.6668, (2000)
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