NanoMaterials

Nanometer-(nm)-The

1nm = 1 μ m/10^3 = 10^{-9} m

Nano-materials: At least, one

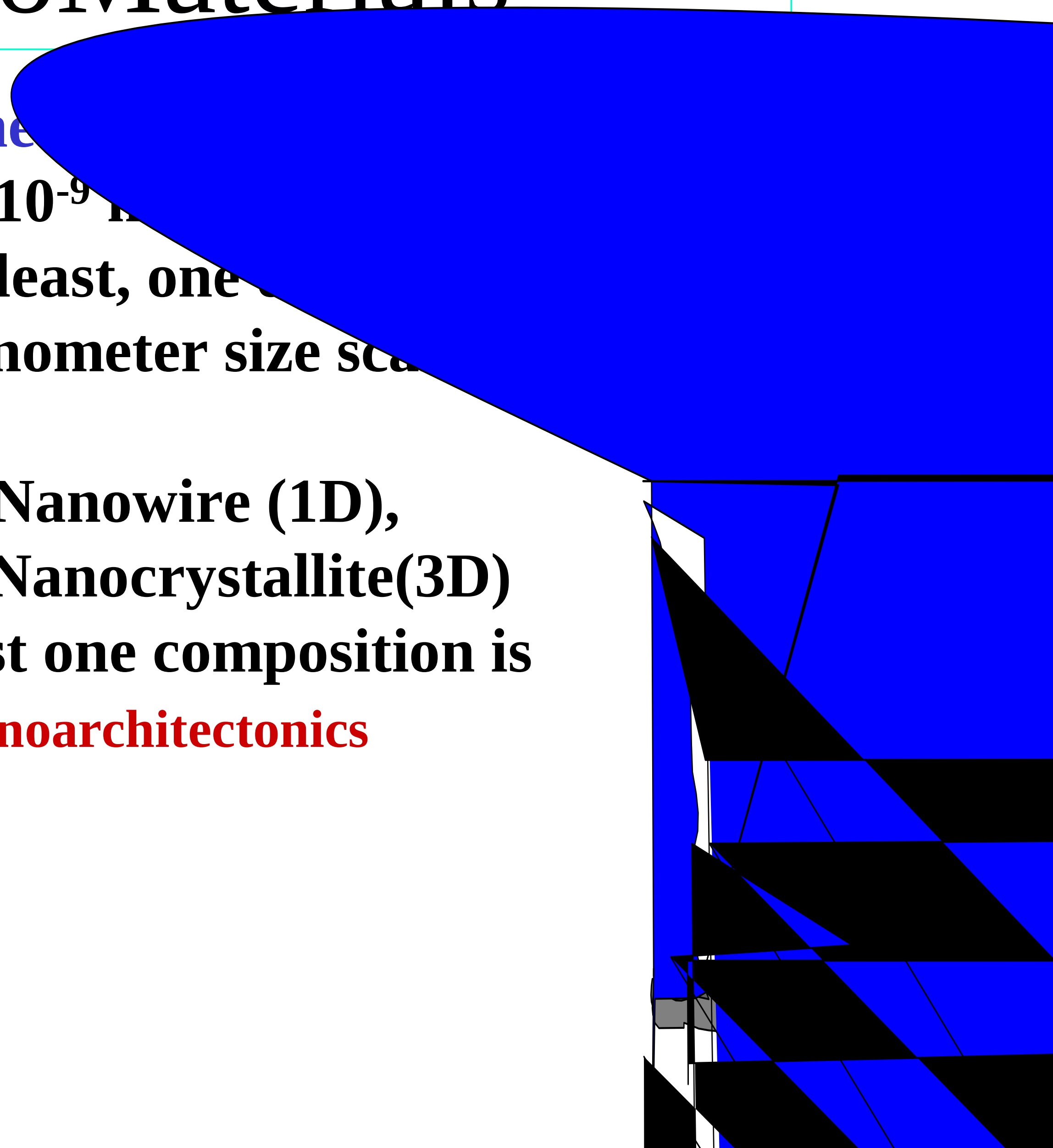
of object on the nanometer size sca

1-100nm.

Nanoparticle (0D), Nanowire (1D),

Nanofilm (2D), Nanocrystallite(3D)

Composites : At least one composition is nanomaterial. **Nanoarchitectonics**



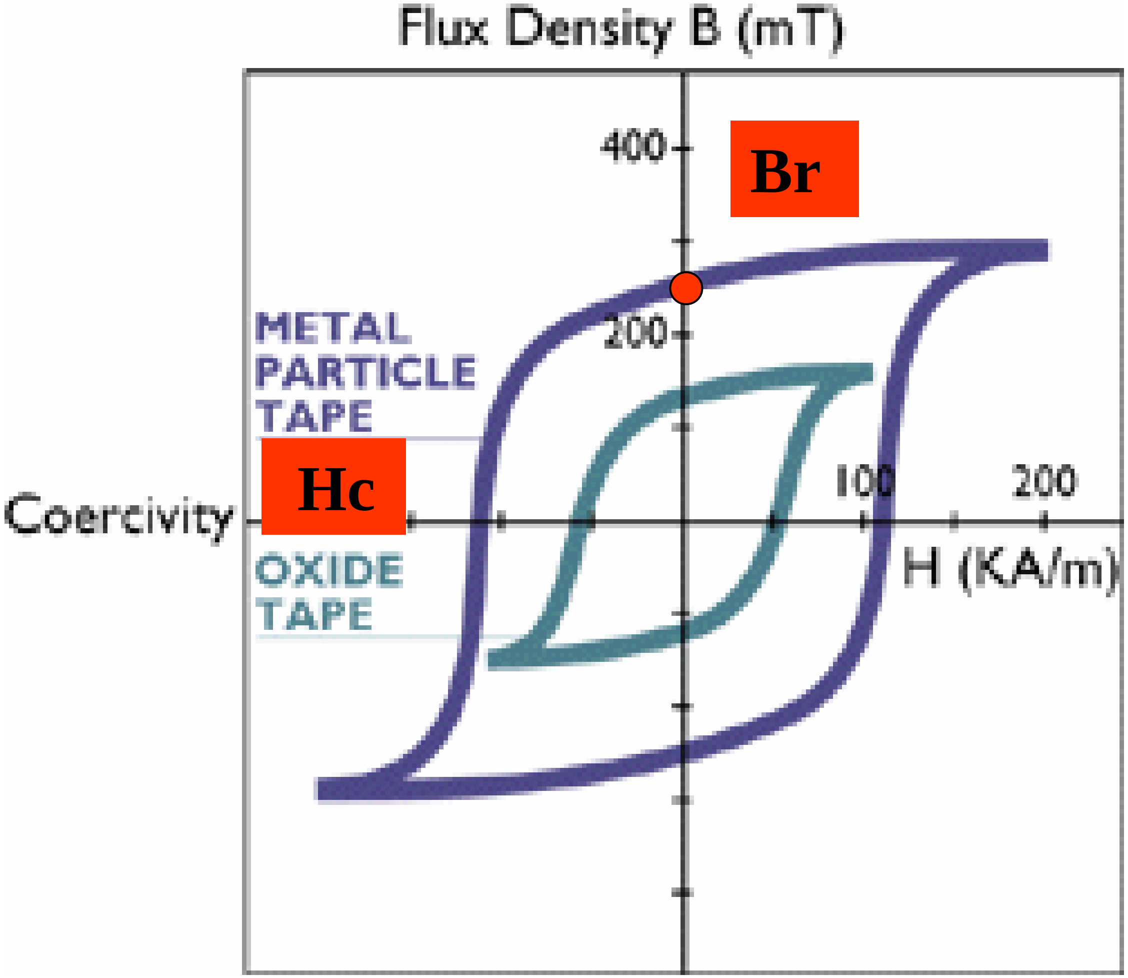
Characteristic Physical Length-L_{ch}

Magnetic single domain	10nm 1 μ
Superparamagnetic	1 10nm
Exchange correlation length	10-40nm
Mean free path of electron	1 10nm
Spin diffusion length	10nm- 1 μ
Wave length of light	400/700nm

Small size effect; Quantum size effect;

MQT (Macroscopic quantum tunneling)

Surface effect Sv= S/V ~ 1/d


Flux Density B (mT)
Br
400
200
METAL
PARTICLE
TAPE
Hc
Coercivity
100
200
H (KA/m)
OXIDE
TAPE

(

(   ).Magnetic Nano particles & Applications

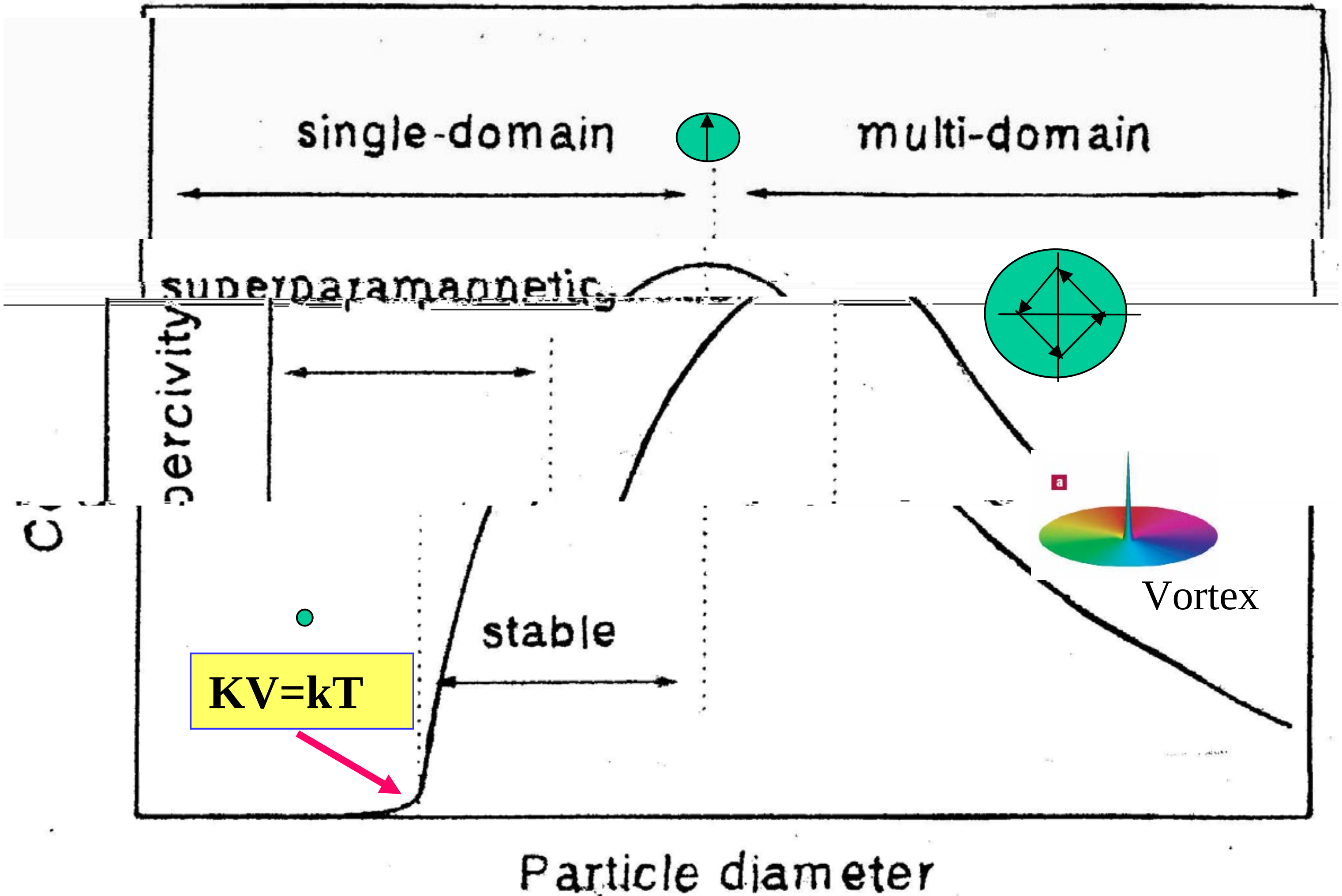


Fig. 1. Size dependence of coercivity.

The characteristic physical length

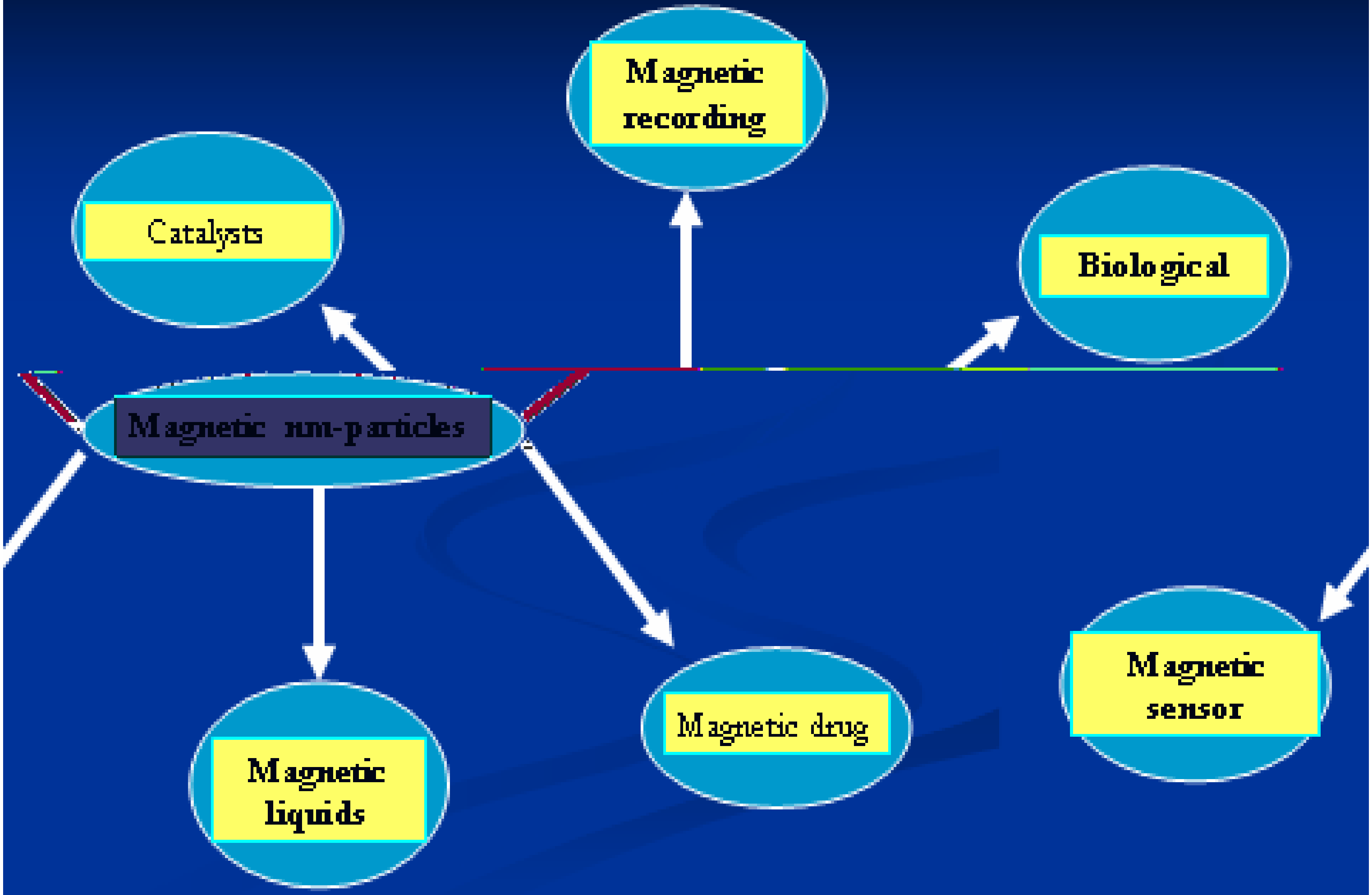
*** Single domain : Rc $(AK)^{1/2}$**

M	Fe	Co	Ni	BaM	$Nb_2Fe_{14}B$	$SmCo_5$	$Sm_2Co_{17}N_{2.3}$
Rc (nm)	8.0	11.4	21.2	450	125	400	180

***Superparamagnetism: $KV=25k_BT_B$**

M	Fe_3O_4	Ni	Fe	Co
D(nm)	10	4.0	6.3	5
T_B(K)	300	25	78	55

The Applications of Magnetic Nano-Particles



Nanomedicine

Targeted drugs for lung cancer

The aerosols containing magnetic nanoparticles with drugs can be guided to specific regions in the lung of mice with an external magnetic field. With this technique, higher doses of drugs can be delivered to the cancerous region without increasing side effects.

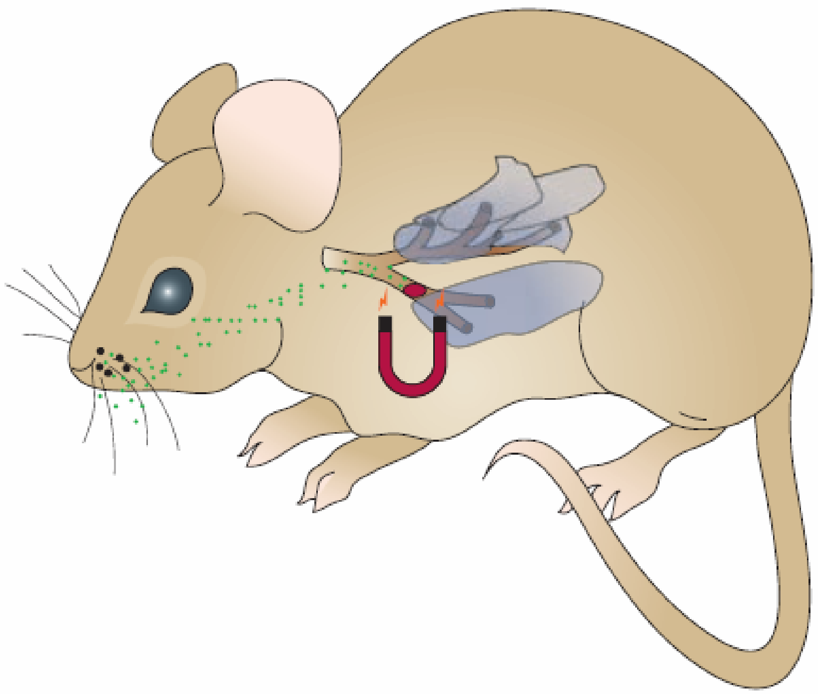
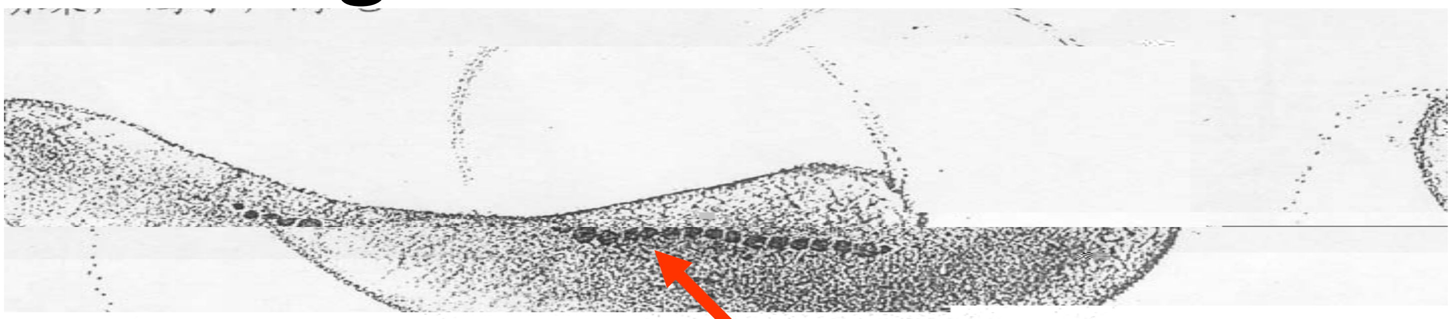
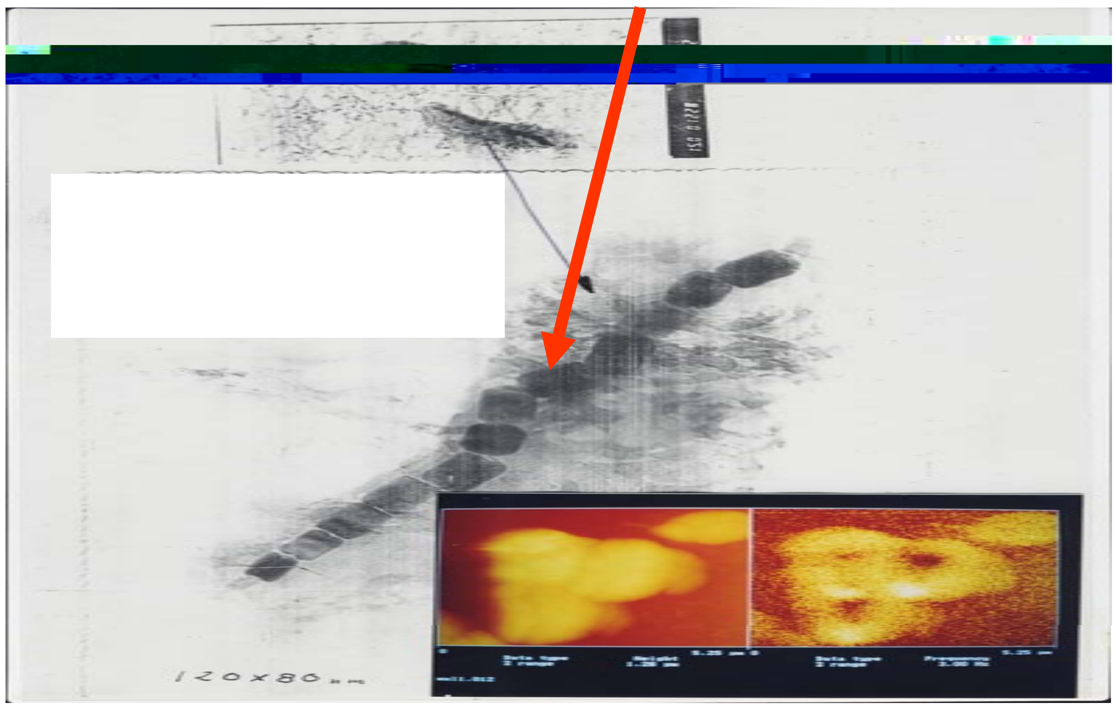


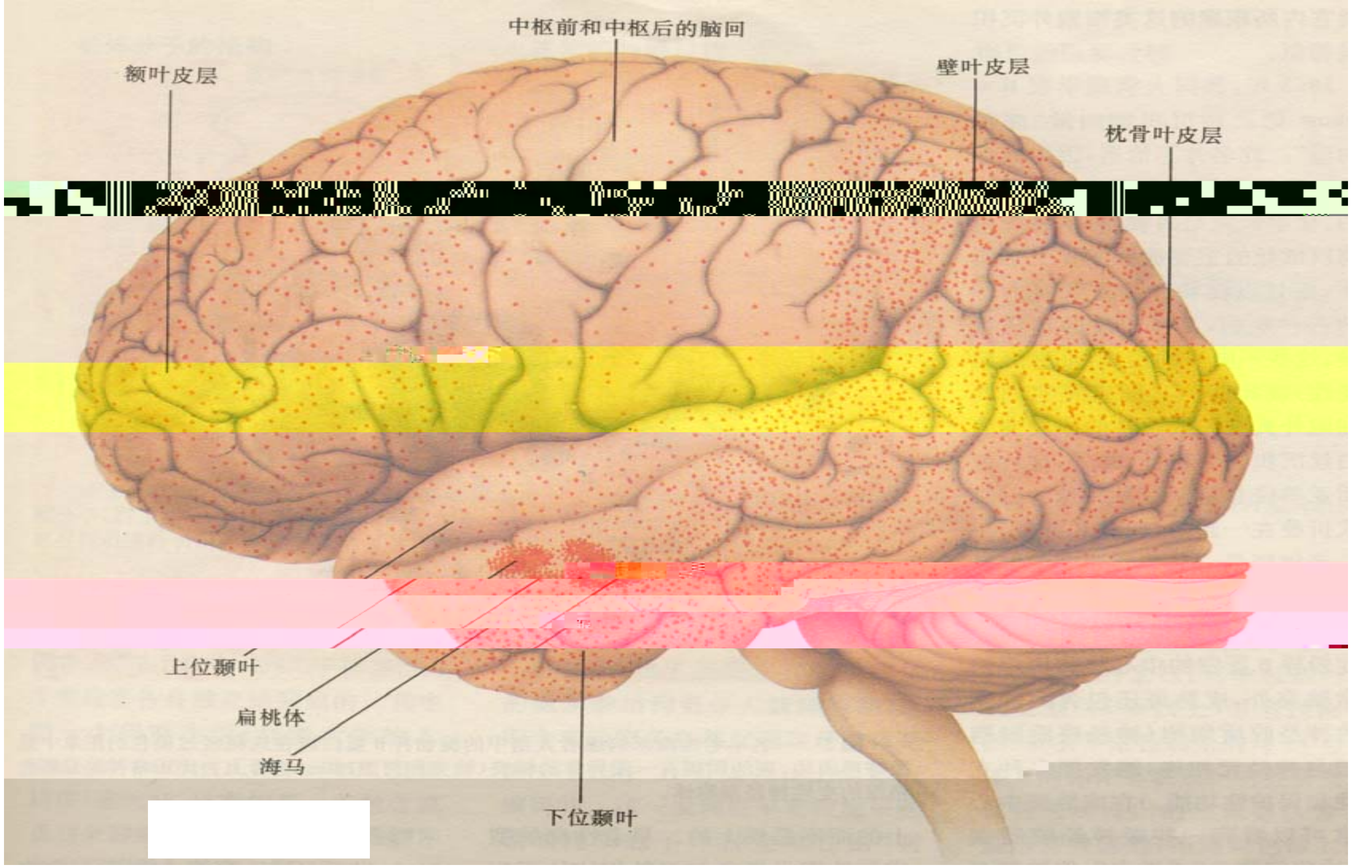
Figure 1 Magnetic-field guided drug delivery with magnetic aerosols. Superparamagnetic nanoparticles are placed in microdroplet aerosols (green) and delivered along the airways (brown) toward the lungs (grey). A localized magnetic field causes large numbers of nanoparticles to accumulate in a specific region, shown here in red.

Magnetotactic bacteria



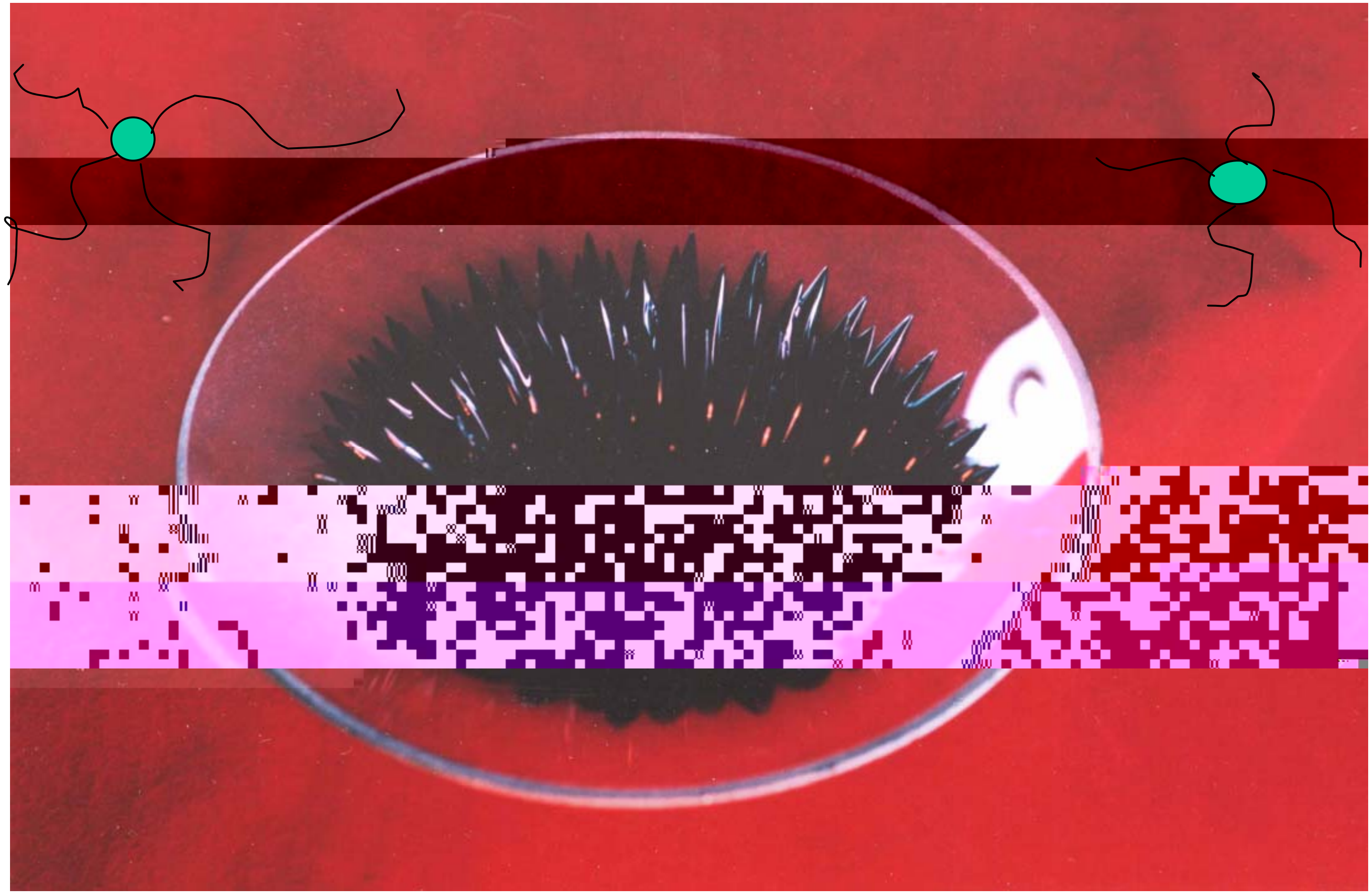
Magnetic nanochain assembled by magnetosome





500

The first product in nano-materials is "Ferrofluid" in 1965.



Magnetic liquid(Fe_3O_4)

Interface for magnetic particles with Core/shell structure

- **Antiferromagnet (AFM) / Magnetic particle**
- **Ferromagnet (FM) or Ferrimagnet (FIM)/ Magnetic particle**
- **Nonmagnetic organic, Inorganic or metal /Magnetic particle**

The functions of the shell

1. To control the magnetic properties

2. To prevent grain growth and agglomeration

3. To enhance chemical stability

4. To get some exchange couple effect

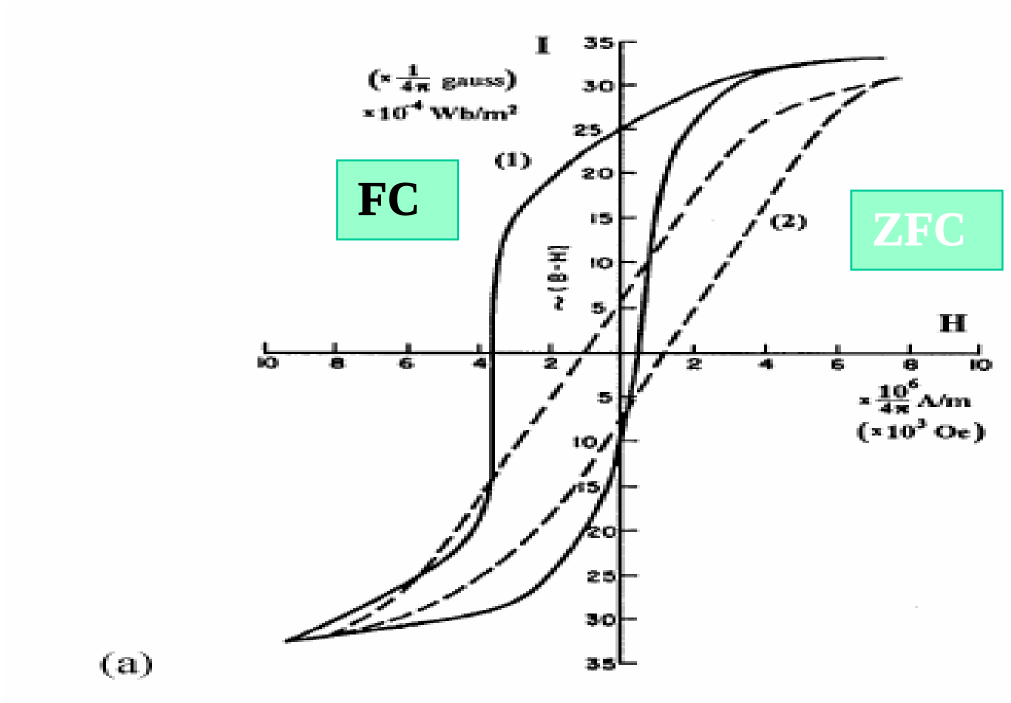
Exchange couple in (Co/CoO) nanoparticles

a). Hysteresis loops at 77K of CoO/Co particles.

(1). After cooling the sample in a 10kOe field. (2).ZFC

$$F = HM_S \cos\theta - K_U \cos\theta + K_1 \sin^2\theta,$$

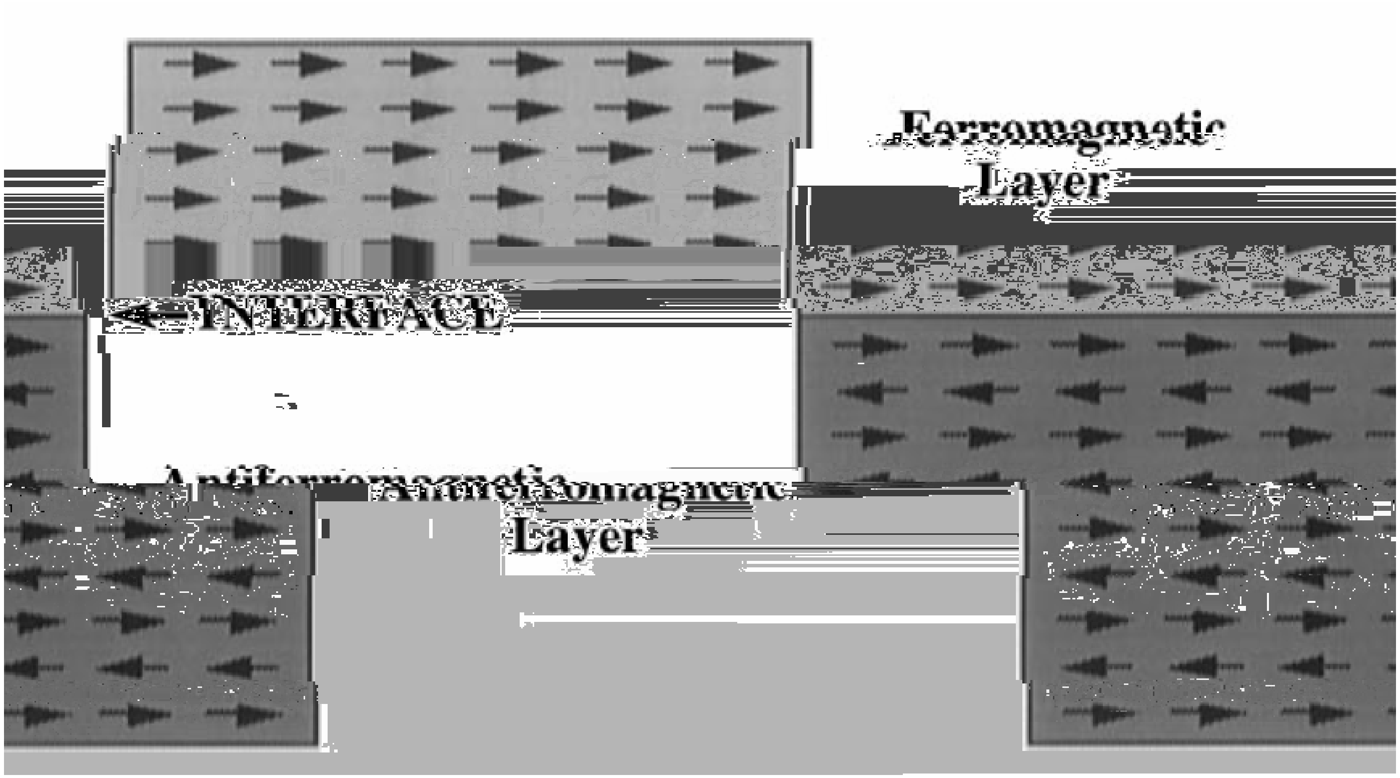
K_U unidirectional anisotropy energy constants.



FM/AFM

Co/CoO

T_N=293K

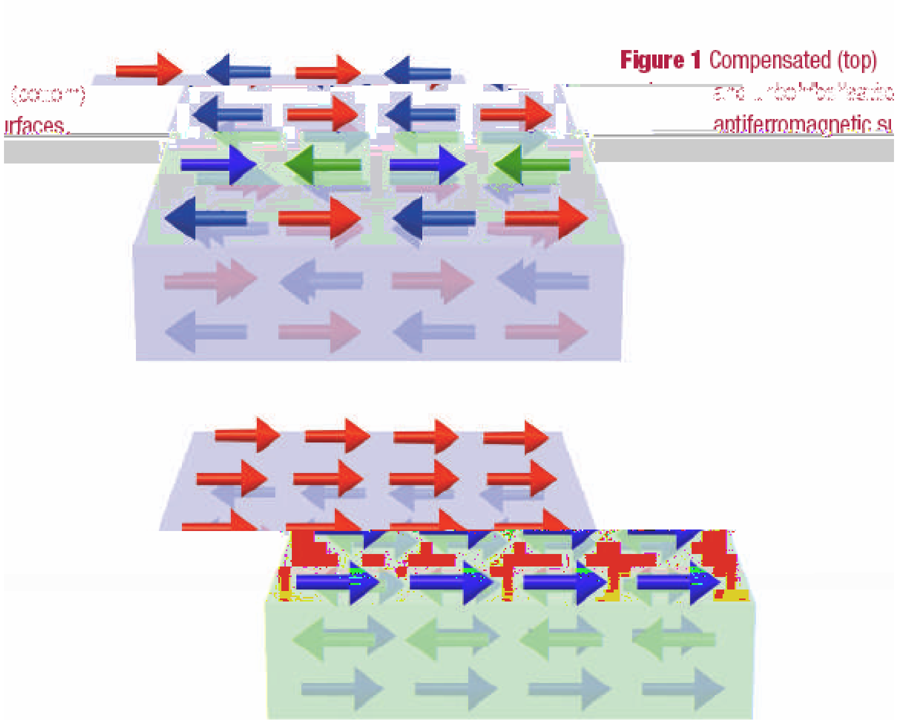


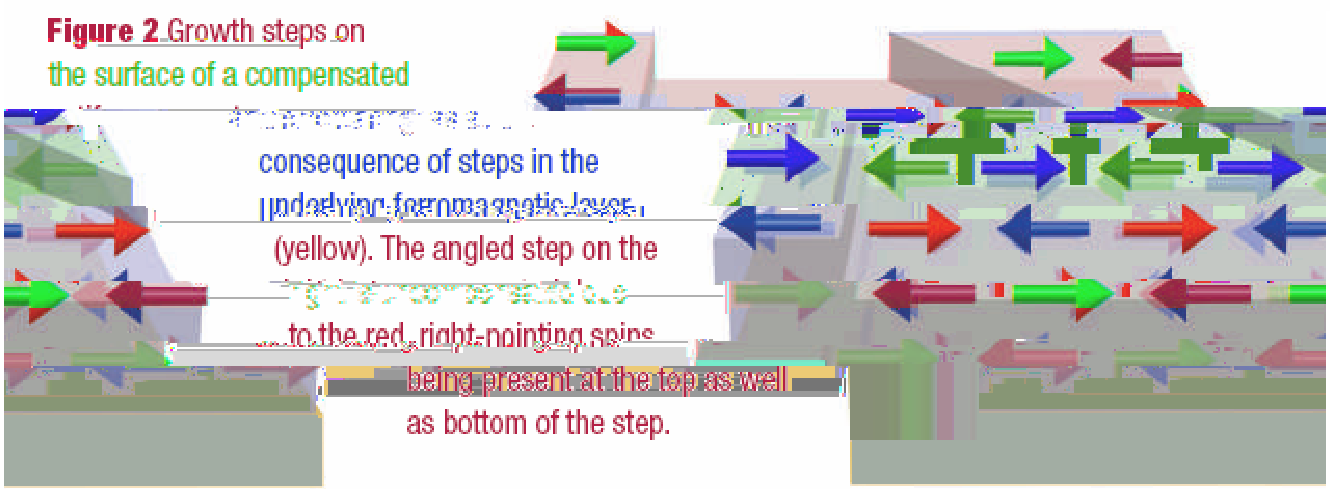
Schematic of the ideal FM / AFM interface

$$H_E = \frac{\Delta\sigma}{M_{FM} t_{FM}} = \frac{2J_{ex} S_{FM} \cdot S_{AFM}}{a^2 M_{FM} t_{FM}},$$

	CoO	NiO	CuO	Ir-Mn	Pt-Mn	Rh-Mn	Fe-Mn
T_N(K)	293	525	453	**600-750**	**485-975**	**850**	**425-525**

The surface spin of antiferromagnet can either be compensated (the magnetic moments with the atomic surface layer cancel out) or uncompensated





Kuch W. et al.Nature Material 5(2006)128; Blamire M. and Hickey B.ibid,5(2006)87

Beating the superparamagnetic limit with exchange bias

The blocking temperature ,T_B , increases almost two orders magnitude for 4nm Co/CoO nano particles in the CoO matrix. This leads to a marked improvement in thermal stability. This mechanism provides a way to beat the superparamagnetic limit in isolated particles.

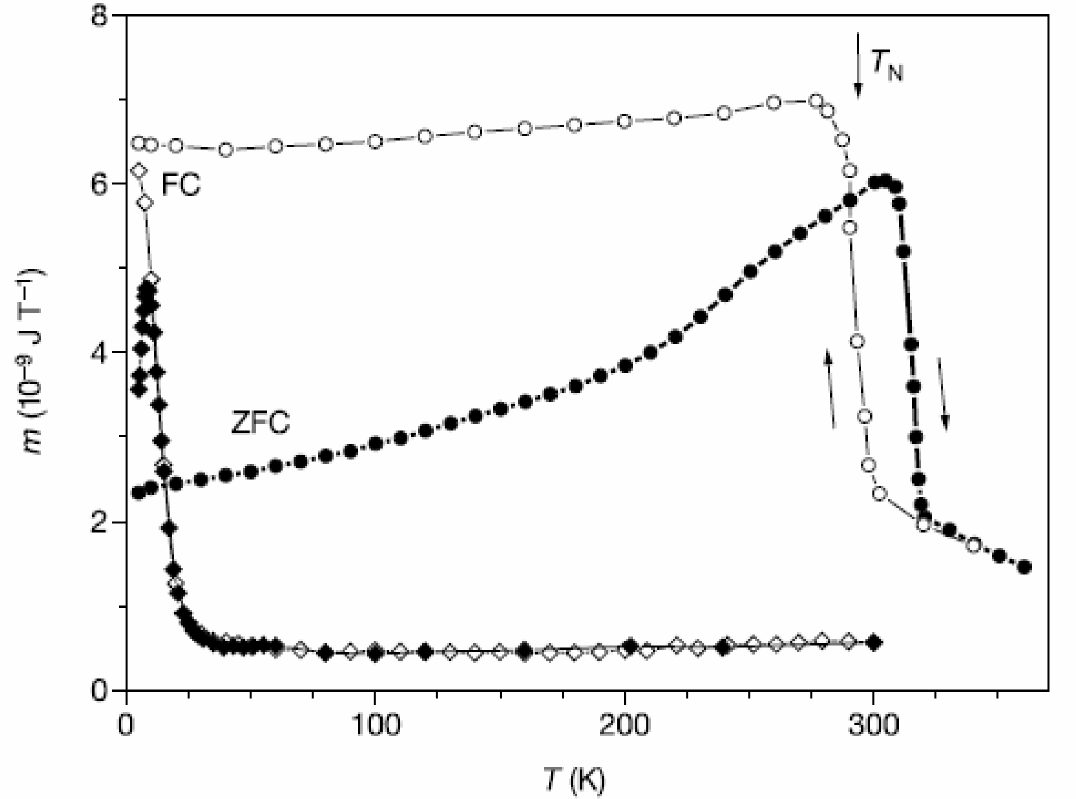
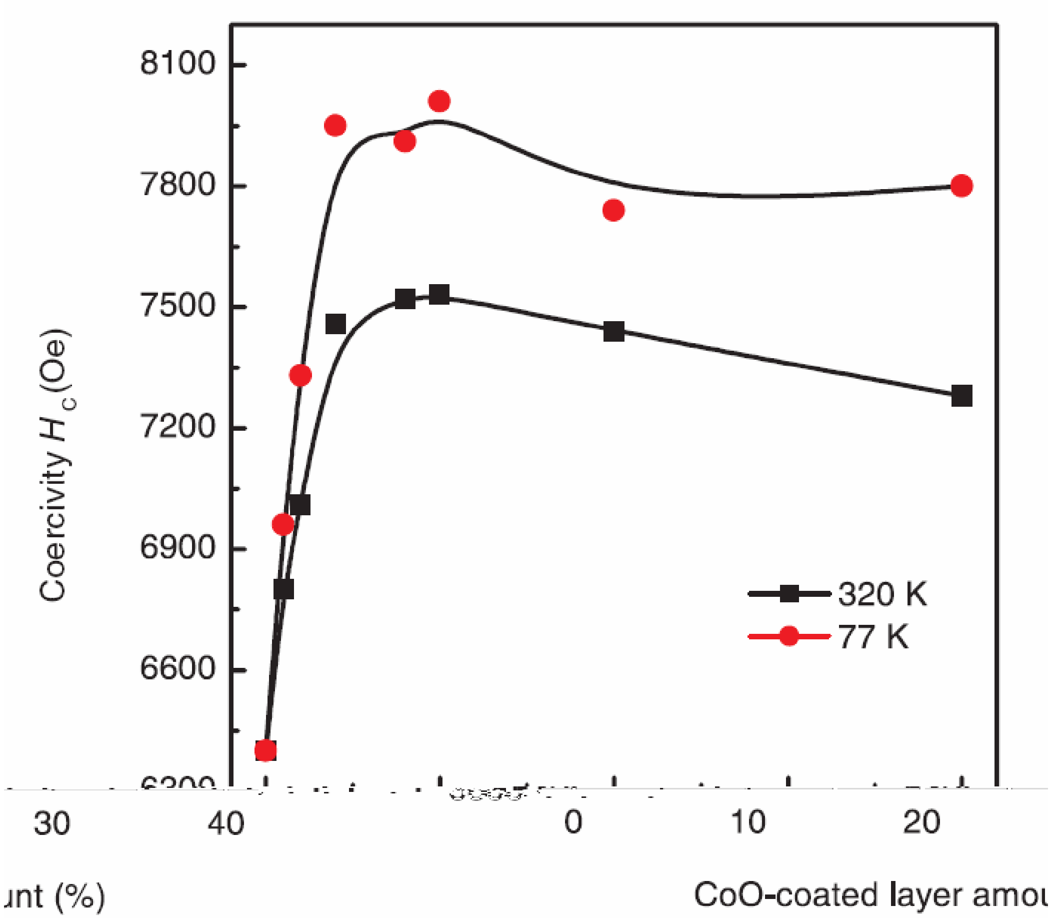


Figure 2 Magnetic moments of 4-nm $Co_{core}CoO_{shell}$ particles. Shown is the temperature dependence of the zero-field cooled (ZFC; filled symbols) and field-cooled (FC; $\mu_0 H_{FC} = 0.01$ T, open symbols) magnetic moment (m) of 4-nm $Co_{core}CoO_{shell}$ particles. were embedded in a paramagnetic (Al_2O_3) matrix (diamonds), or in an AFM (CoO) matrix (circles). The measuring field is $\mu_0 H = 0.01$ T. The Néel temperature of CoO is indicated by an arrow. The lines are guides to the eye.

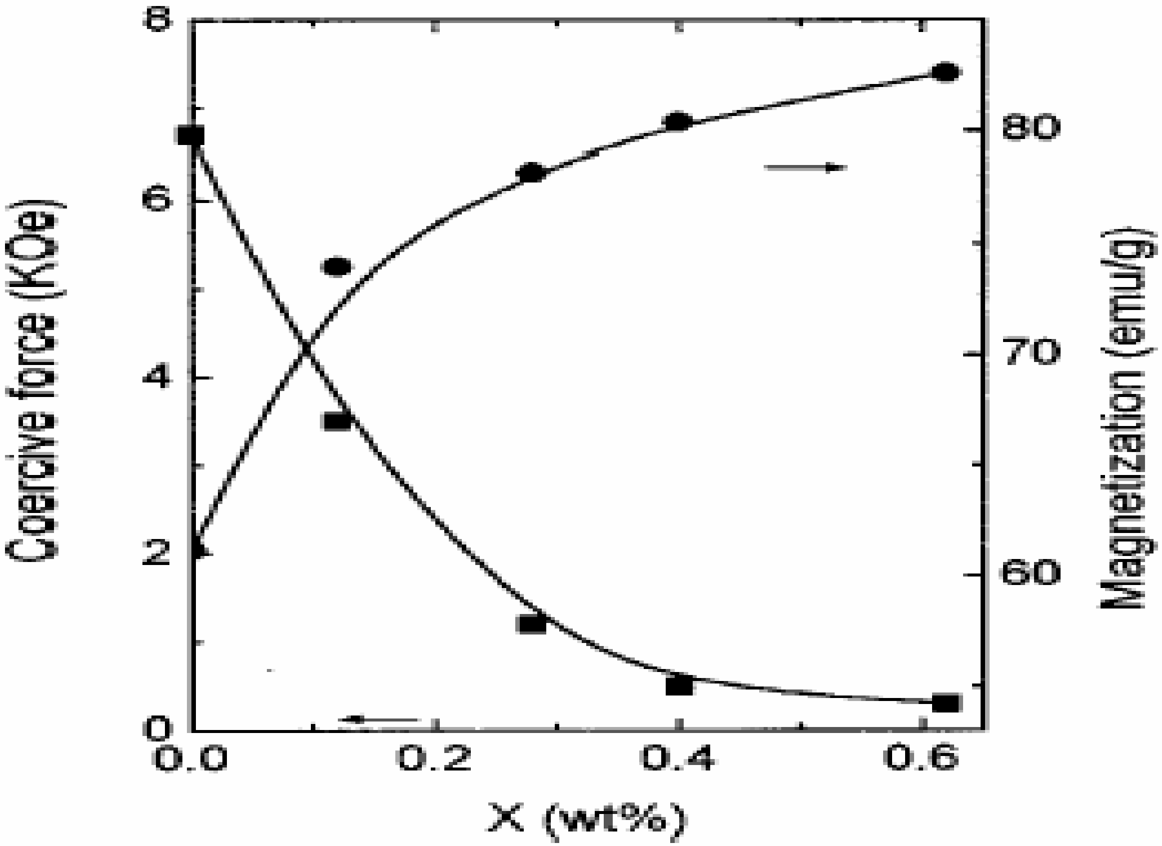
γ

1. $SrFe_{12}O_{19}$ / CoO

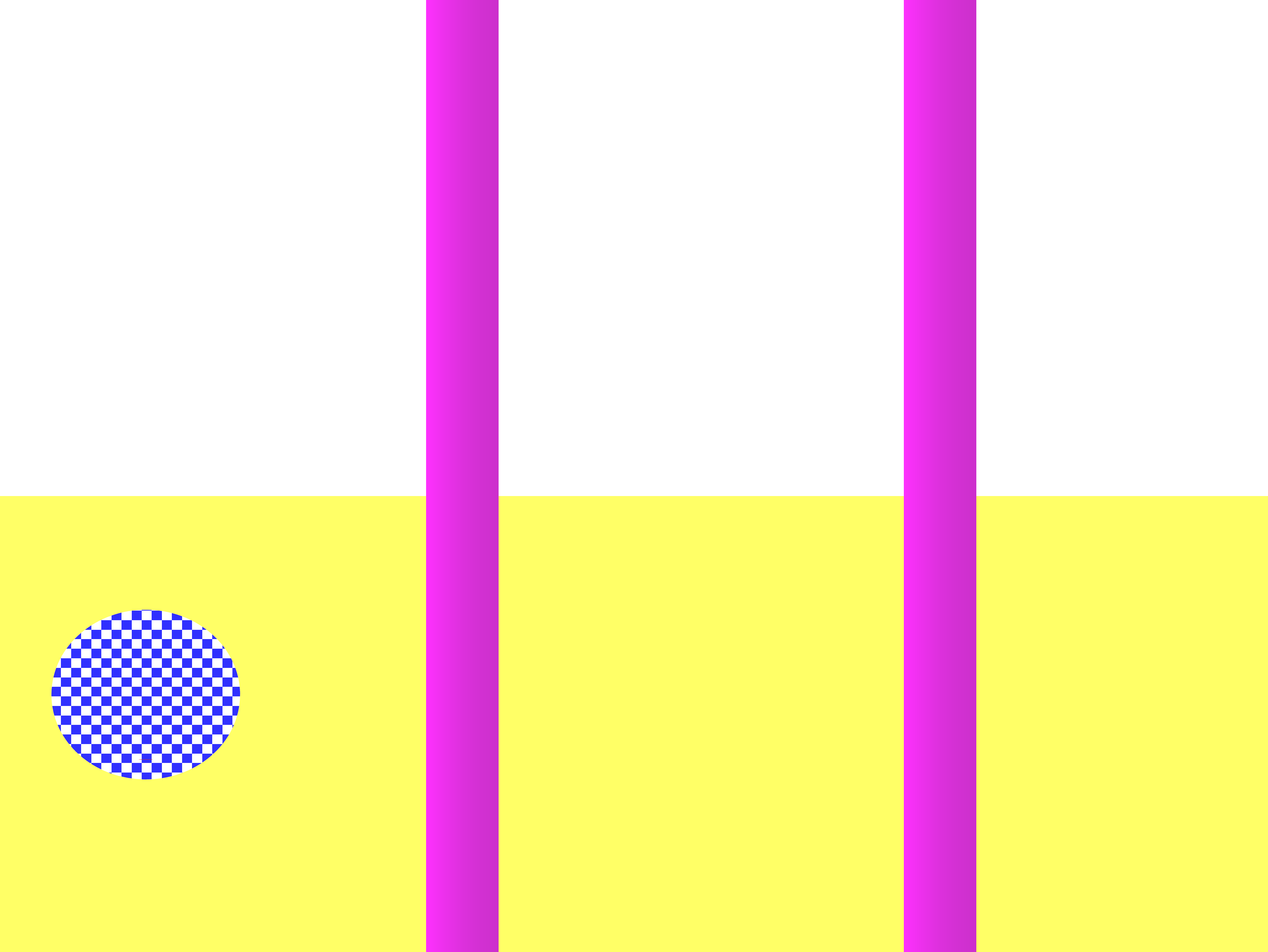


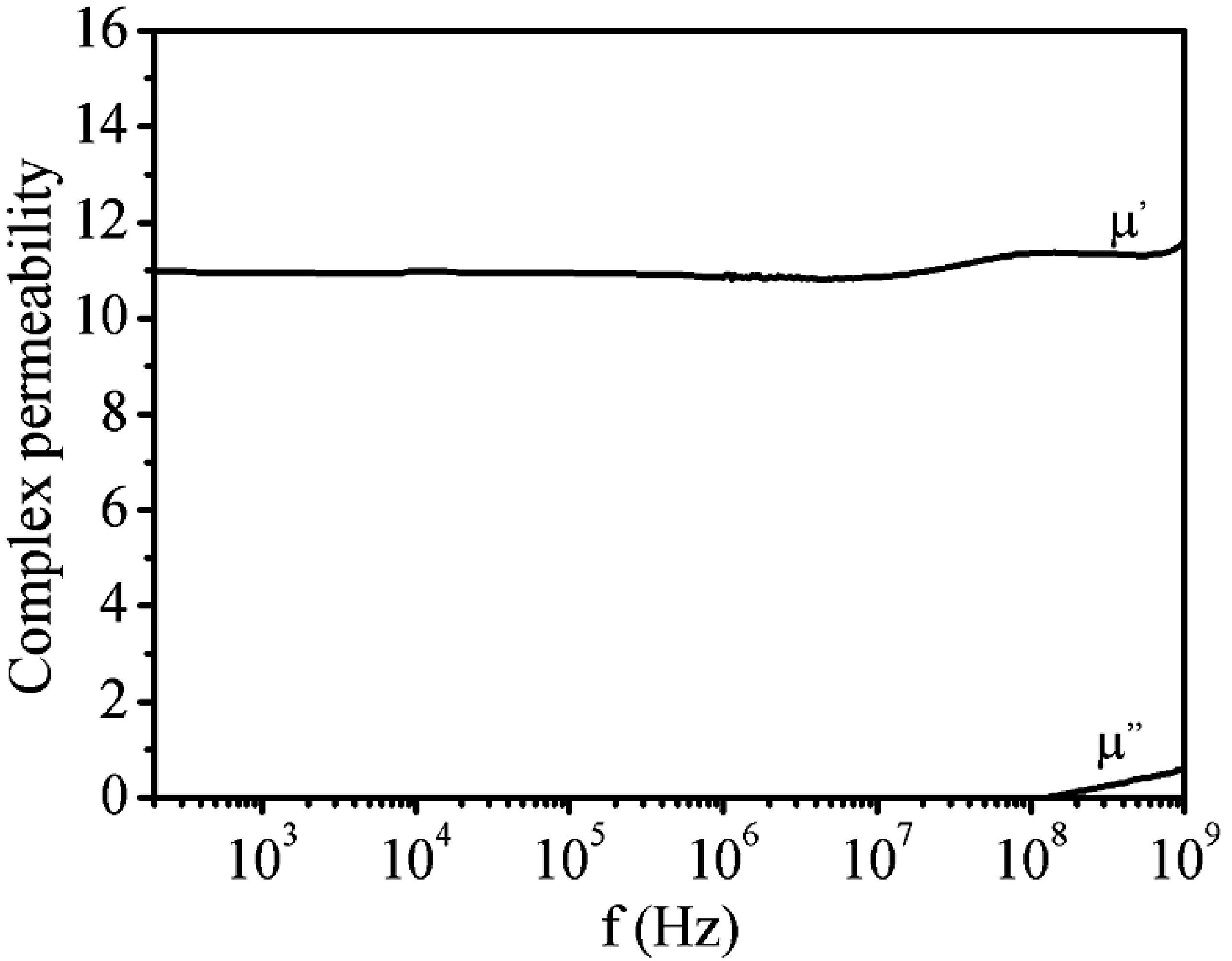
Hc sharply increases for small CoO content, then reaches a maximum at 10% of the coating amount

2. SrM / Fe3O4



SrM particles coated with soft magnetic materials Fe3O4 , Ms increases and Hc decreases very obviously with the rise of Fe3O4 coating . The Hc can be controlled by coated quantity.





The permeability spectra of $Fe/SiO_2/C$ particles sample at room temperature

). Magnetic Nanocrystalline Materials

- The nanocrystalline material is composed of nanocrystallines. It may be considered as a densely assembly of nano-particles which are interacted through interface.
- Huge interface
- Interaction
- Exchange interaction
- Magnetic interaction

Exchange length , $L_{ex}=(A/Ms^2)^{1/2}$. (within L_{ex} the spins of ferromagnet remain parallel, L_{ex} 1-6 nm)

Domain wall width, $\pi\delta_o$,

$\delta_o=(A/K)^{1/2}$. (exchange correlation length or domain wall parameter, the distance over which the variations of the spin orientation are correlated)

$\delta_o \approx L_{ex}$ (for hard magnets, while , $\delta_o >> L_{ex}$ for soft magnetic materials)

Single domain size for a sphere, $R_{SD}=(AK)^{1/2}$

	L_{ex}(nm)	$\pi\delta$ o(nm)	D_{SD}(nm)	J. Nogués et al., Physics Reports, 422(2005)65-117
Fe	1.5	40	18	
Co(hcp)	2.0	12	70	
Ni	3.4	80	60	
$Ni_{80}Fe_{20}$	4.0	100	22	
$SmCo_5$	4.9	4.0	764	

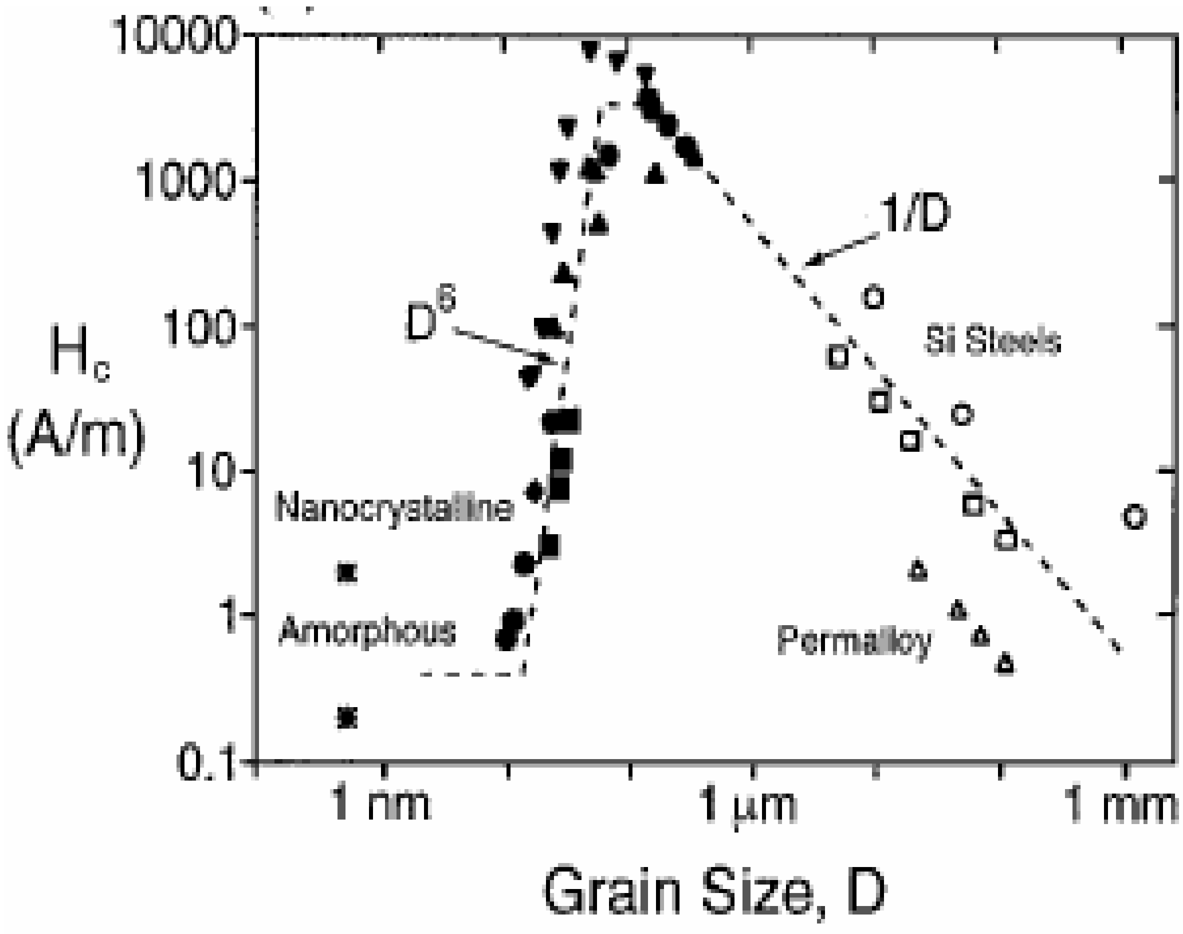
(2.1). Nano-Crystalline Soft Magnetic Materials

- **The progress of soft magnetic materials**
- **Fe**
- **→ FeSi(1900)**
- **→ FeNi(1920)**
- **→ Ferrites (1935-1946)**
- **→ Amorphous (1970)**
- **→ Nano-Crystalline Soft Materials**

Magnetic nanocrystalline system. FM/FM interface

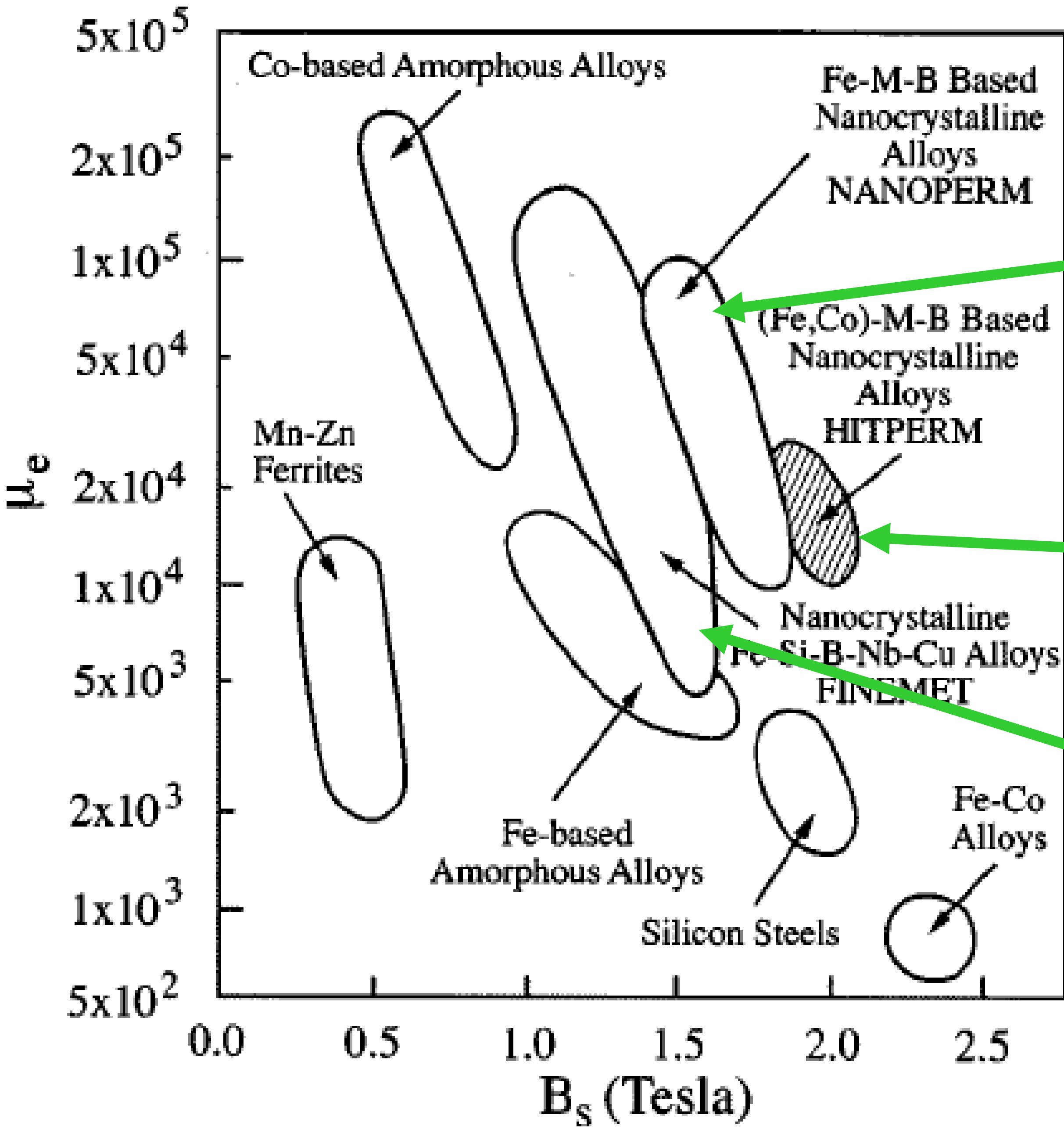
Random anisotropy theory---Herzer JMMM.294(2005)99

$Lo=(A/K)^{1/2}$, If D< Lo,
$Ke = K/N^{1/2}$,
$N=(Lo/D)^3$
$Hc \sim D^6$



M	α -Fe	α -Fe_{amr}	$Nd_2Fe_{14}B$	$SmCo_5$	$Sm_2Fe_{17}N$
L_o(nm)	23	35	2.1	5.2	2.6

Commercial Nanocrystlline Alloy

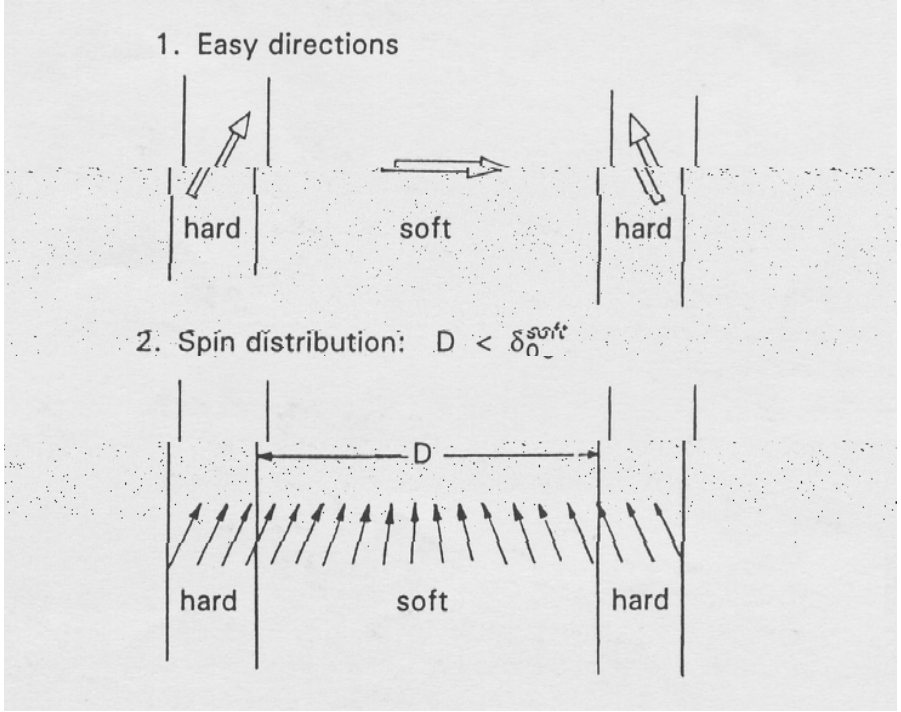


2. NANOPERM
Fe-M-B-Cu
(M=Zr,Nb,Hf--)

3. HITPERM
(FeCo)-M-B-Cu

1. Finemet (1988)
Fe73.5Si13.5B9Nb3Cu1

(2.2). Nanocomposite exchange coupled magnets



Remanence:

Mr/Ms>1/2

Reduced the quantity of rare earth element

Ms;Tc;K for some soft and hard magnetic materials

	Fe	Ni	Co	Fe_2Co	SrM	NdFeB
Ms(kA/m)	1714	484	1422	1933	370	1281
Tc (K)	1043	631	1404		733	585
K(kj/m^3)	42	-51	530		370	4400

- Saturation magetization Ms: Hard < soft
- Anisotropy K : Hard > Soft
- Nanocomposity exchange coupled of hard and soft phases maybe have both high Ms and Hc
- **BH)m=1 MJ/m3 (120 MG Oe),** RE ¯ **5 wt %.** for

2.4 nm $(Sm2Fe17N)_3$ /9 nm $(Fe_{65}Co)_{35}$

R.Skomski and J.M.D.Coey, Phys.Rev.B 48(1993)15812

The best magnetic properties for

$(Nd,Pr,Dy)_2Fe_{14}B/\alpha$-Fe

Br = 1.438T(14.38kG)

Hcj = 995KA/m (12.5kOe)

(BH)m = 405KJ/m3 (50.97MGOe)

DAYTON University

Lee D et al.,Proc. Of 18thInternational Workshop on HPMA(Annecy, france,August-September,2004).Vol. 2, 667-9\678

Nanocomposite exchange coupled is diffusing to other applications:

1 Magnetic recording : FePt/FeRh reduced reversely field

2 Magnetostriction : TbFe/Fe (FeCo) multylayer reduced Hc

Magnetic Nanowire & Nanotube

- Magnetic nanowires have various applications such as: perpendicular magnetic recording media for high density magnetic recording.
- Sensor in MEMS
- Magnetic multilayered nanowires for CPP-GMR
- The spin diffusion length can be determined.

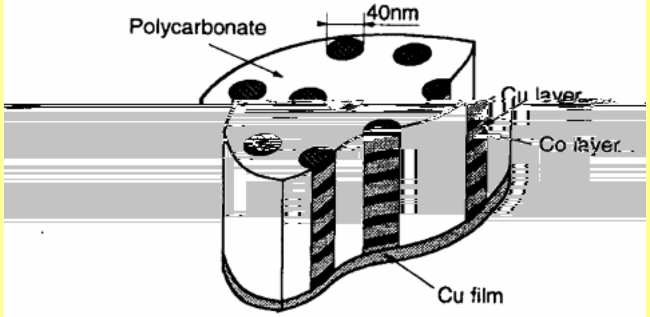


Fig. 1. Schematic of an array of multilayered nanowire nanoporous track-etched polymer membrane.

SUL-Soft magnetic underlayer

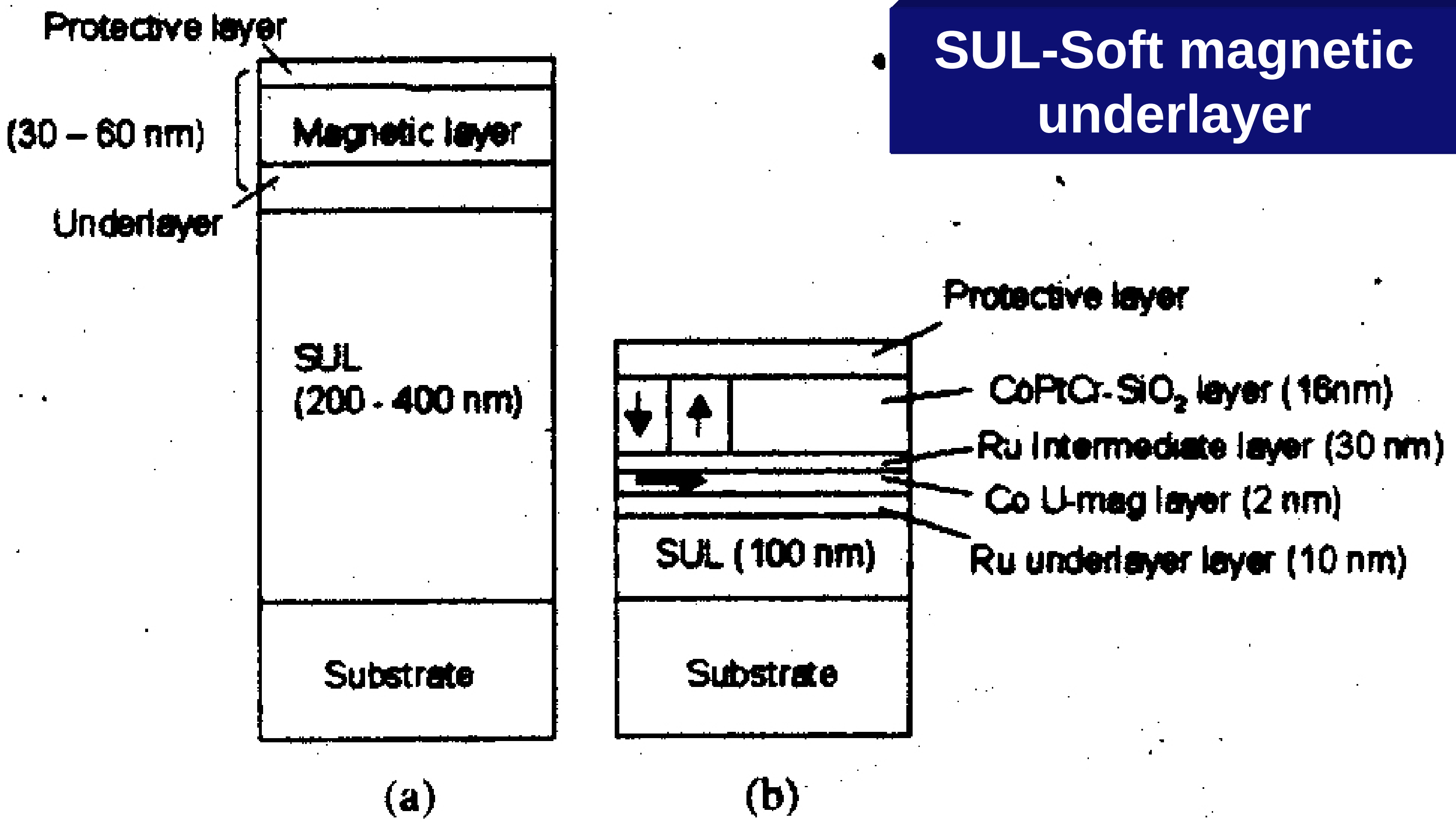
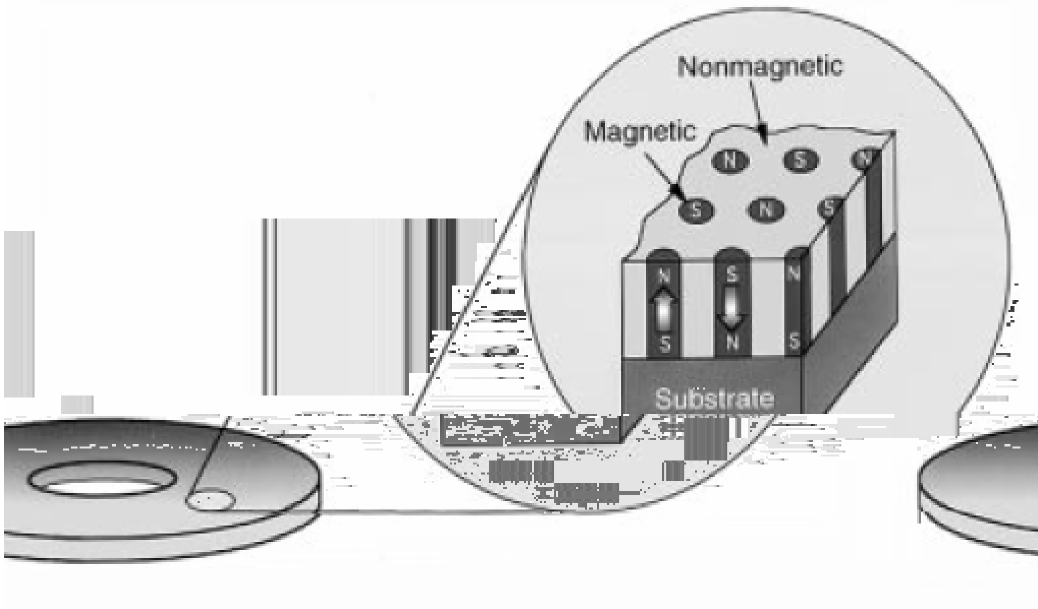
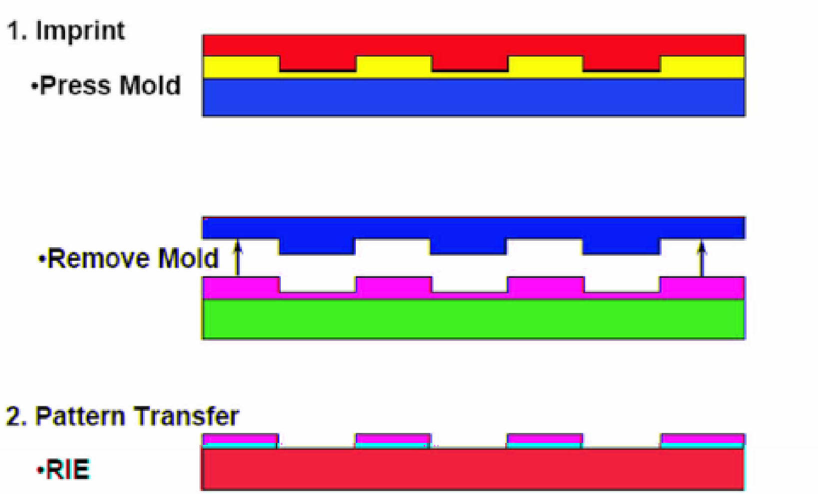


Fig. 1. Cross-sectional structures of (a) a conventional perpendicular recording and (b) the U-mag media.

Longitudinal to Perpendicular Magnetic Recording model.





Bit –Patterned media (Quantized magnetic disk)

Patterned magnetic nanostructures give us new freedom in controlling magnetic material properties.

Schematic of nanoimprint lithography consisting of 1).imprint and 2). pattern transfer

For mass production

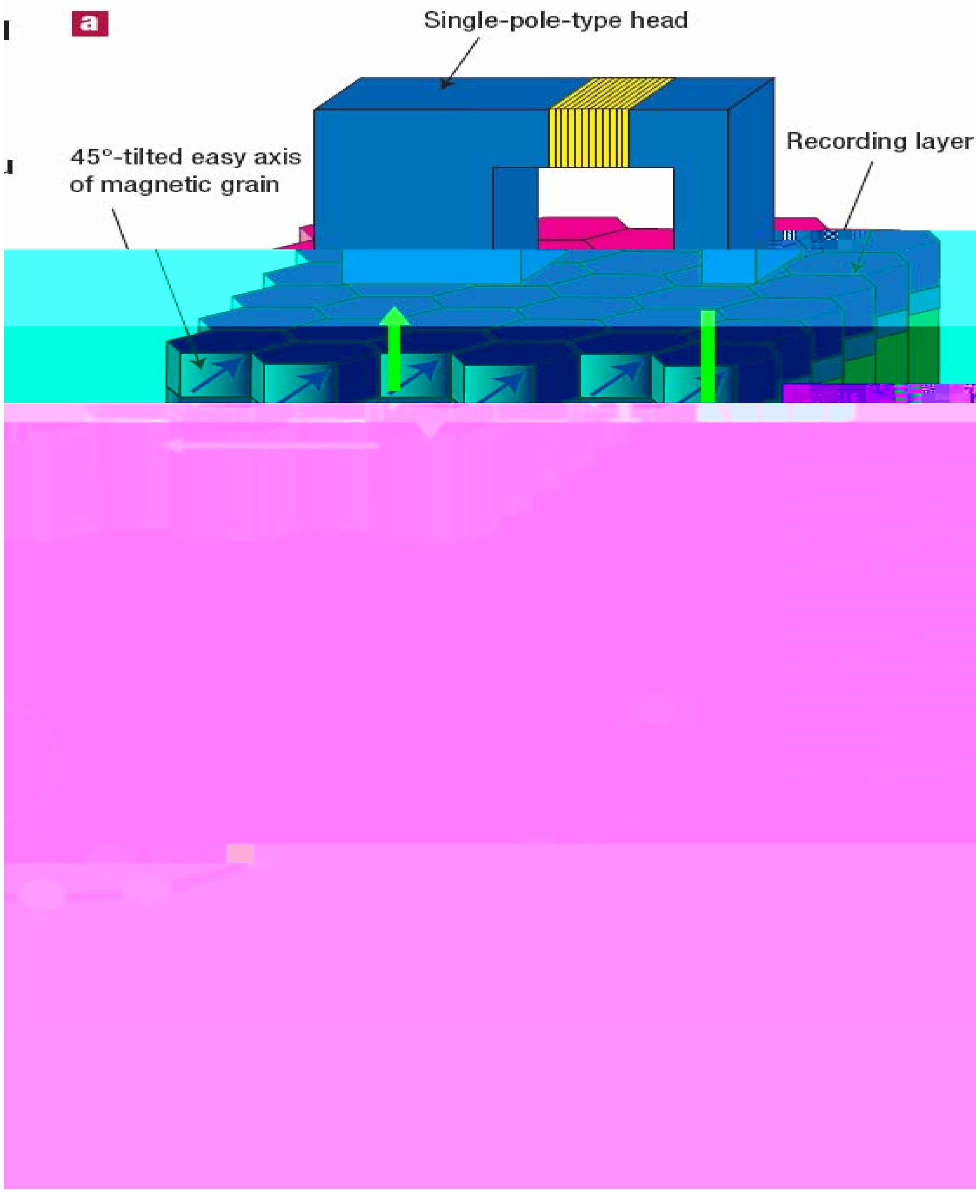


Figure 1 Tilted magnetic media. **a**, A perpendicular recording system with a single-pole-type writing head and a 45°-tilted medium. The yellow arrows indicate the magnetic flux from pole to pole. (Not to scale. Magnetic grain size should be around 5 nm for 1 Terabit in^{-2} recording. The single pole dimension will ... around 80 nm or less.)

J.P.Wang,Nature Materials4 (2005)191

$Fe_{48}C0_{52}$ nmwires

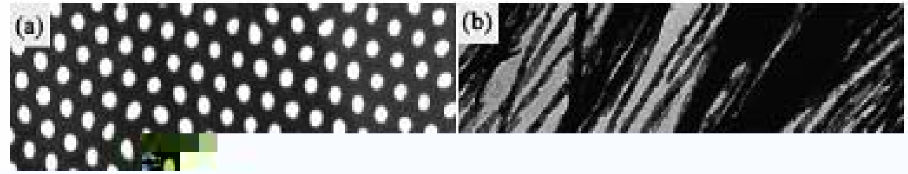
Porous alumina template

D~22nm

Interpore distance~ 50nm

Hc=3.89 kOe

Mr / Ms=0.954



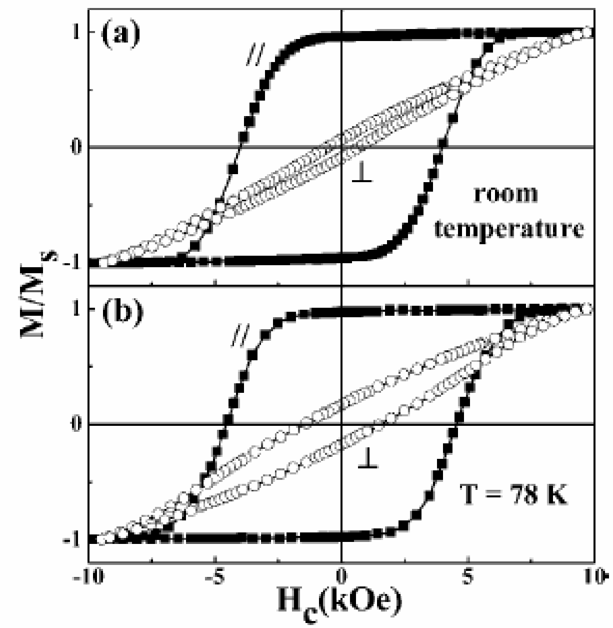
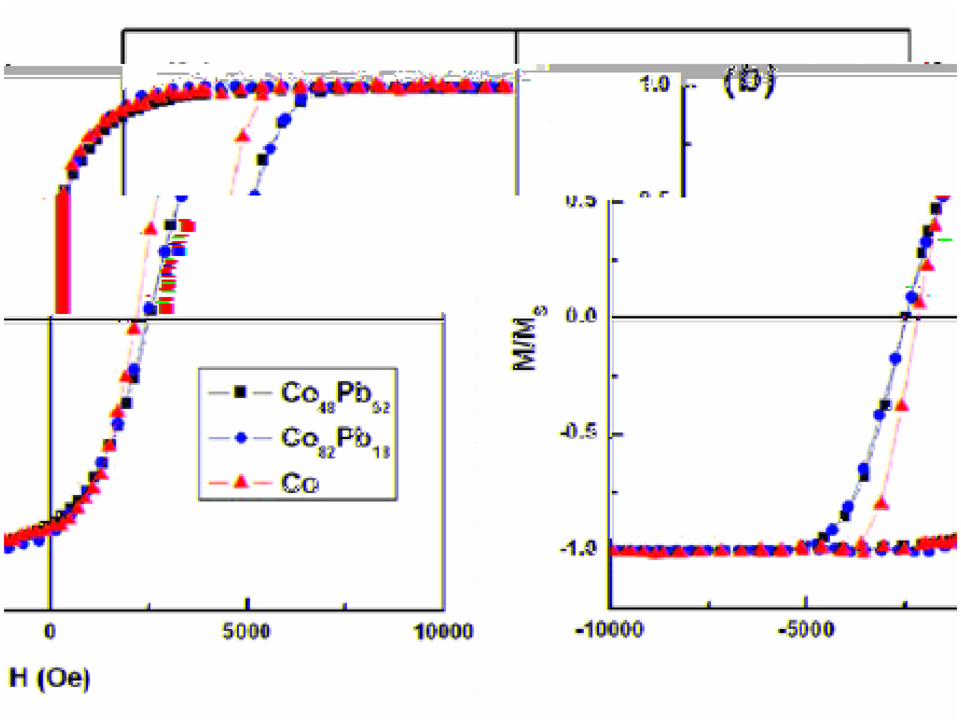
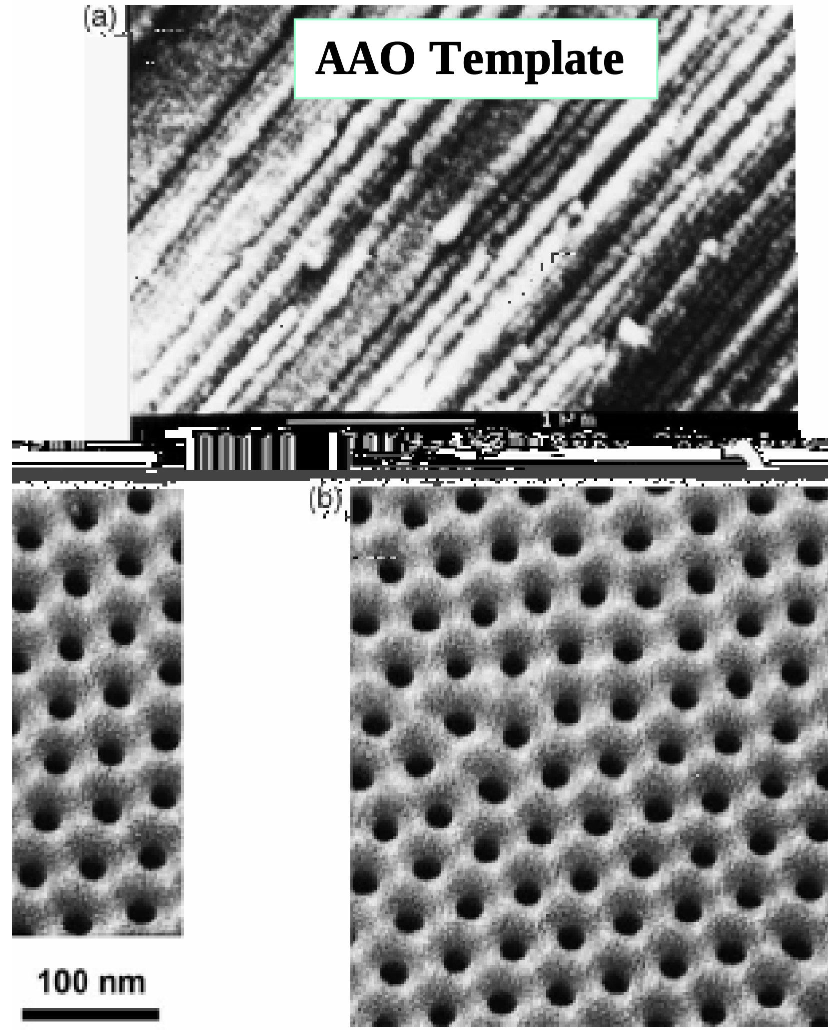


Figure 5. Hysteresis loops of the arrays with a diameter of about 22 nm and an interpore distance of about 50 nm measured at room
) and at 78 K (b).

Co-Pb heterogeneous alloy nanowire arrays



Annealing at 700 with the applied field of 10kOe. D~20nm



mplate with pores
(b) the top view.

Fig. 1. SEM images of the anodic alumina oxide te
of 20 nm in diameter: (a) The cross section view.

Hc=2500Oe ;Mr/Ms=0.9 for Co_{36}-Pb_{64} ,Ta=700

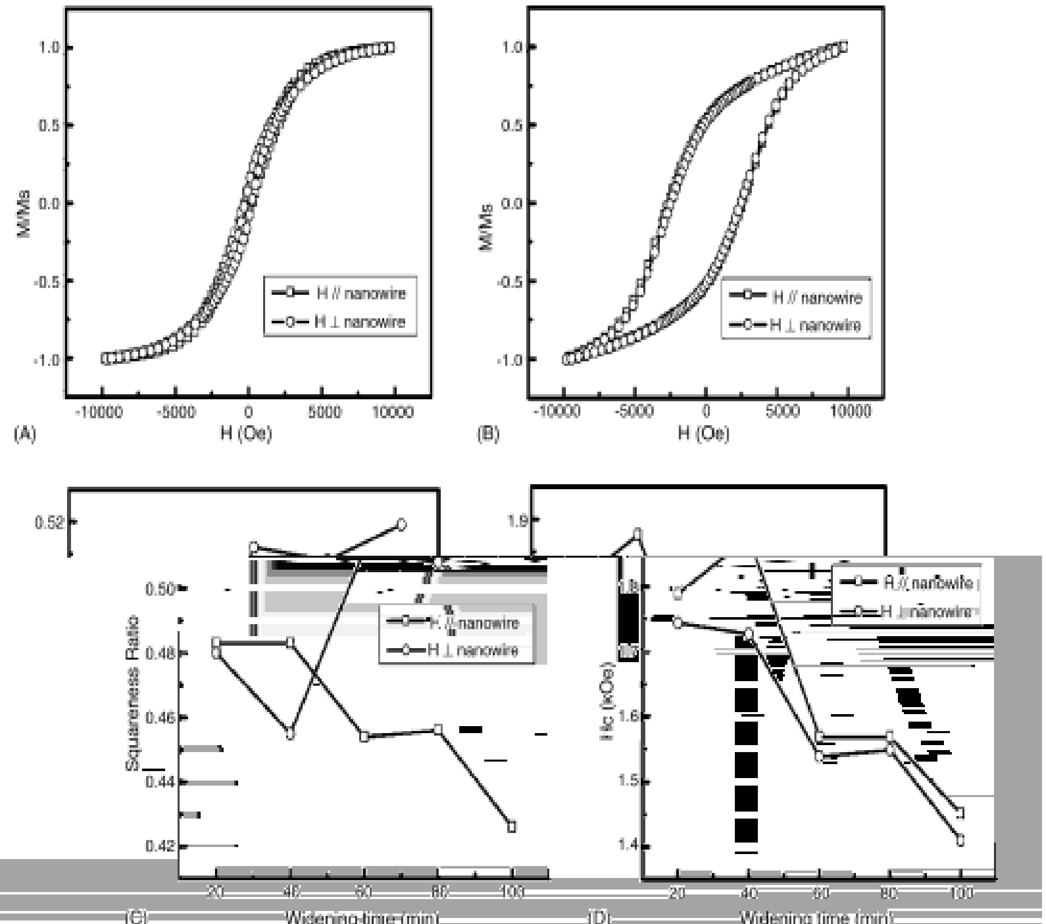
$CoFe_2$ → $CoFe_2O4$

$CoFe_2O_4$ nanowire

$CoFe_2$

nanowire array prepared by AAO template-electrodeposition method and further oxidization

$CoFe_2O_4$ nanowire



function of
90 min. All
ires at room

Fig. 3. Hysteresis loops of nanowire arrays (widened for 40 min): (A) $CoFe_2$ and (B) $CoFe_2O_4$. (C) Squareness ratio of $CoFe_2O_4$ nanowire arrays as a
pore widening time. (D) H_c of $CoFe_2O_4$ nanowire arrays as a function of pore widening time. All templates were dc anodized for 8 h and deposited for
$CoFe_2O_4$ nanowires were annealed at 620 °C for 30 h. The magnetic properties were measured with the applied field parallel and vertical to the nanow
temperature.

Magnetic Nano-film, Multlayer

- Films have been an important subject in basic and applied science.
- Thin film
- Granular film
- Multlayer

Spintronics(   )

- Electrons have both charge and spin two degree of freedom.
- Microelectronic industry is solely based on the charge degree of freedom of electrons.
- Spintronics is a spin- based electrons .
- From physical point if enhance spin degree to the electronic devices, marvelous new devices based on the spintronics should be produced.
- The charge currents may be replaced by the spin currents in the future electronic devices.

2007

Peter Grünberg (1939- 5-18)

Albert Fert (1938-3-7)

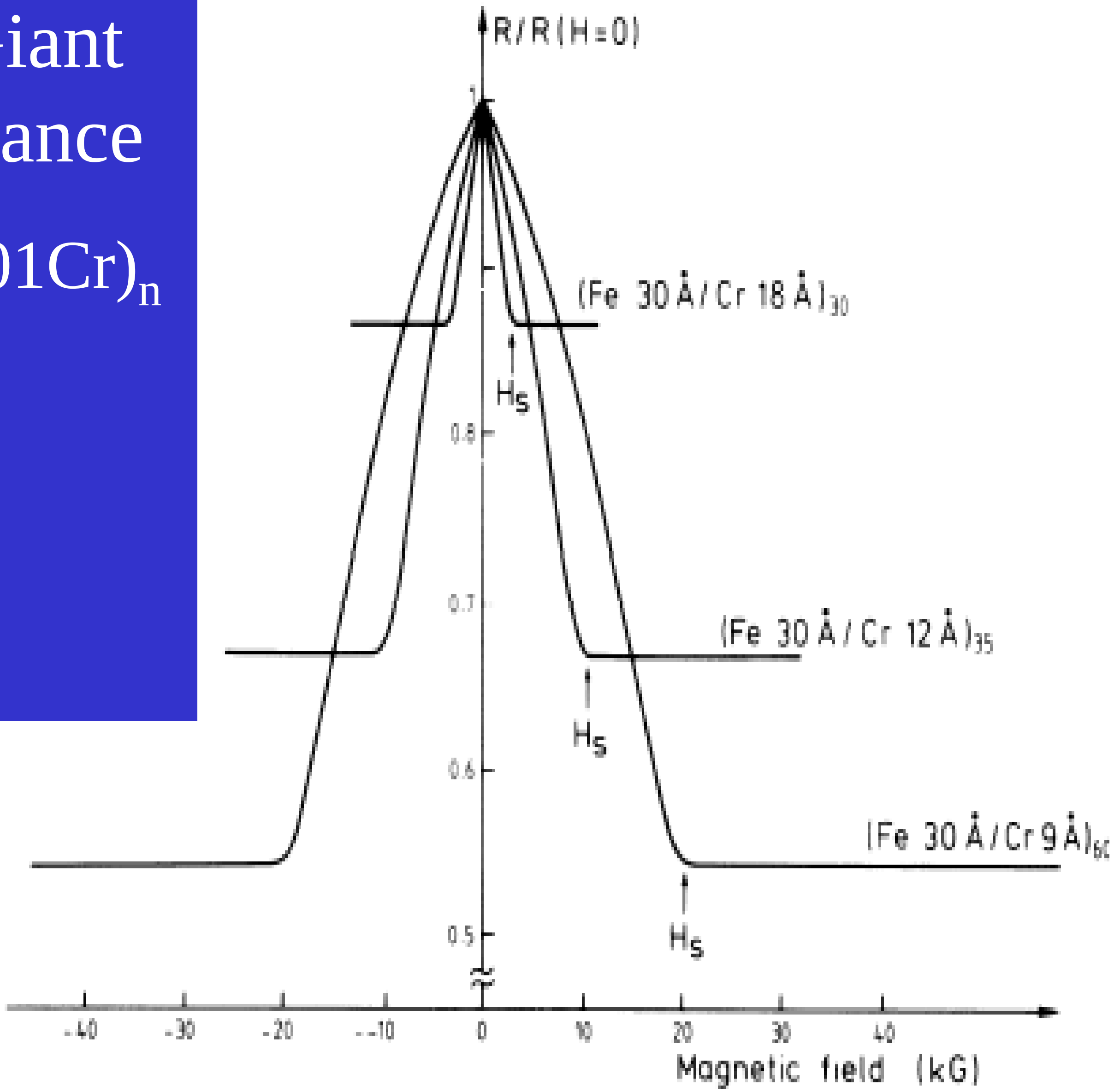
GMR—Giant Magnetoresistance

$(GaAs/001Fe/001Cr)_n$

MBE

Fe-

Cr-



$(Fe/Cr)_n$

Baibich, A.Fert et al., Phys.Rev.Lett.61(1988)2472

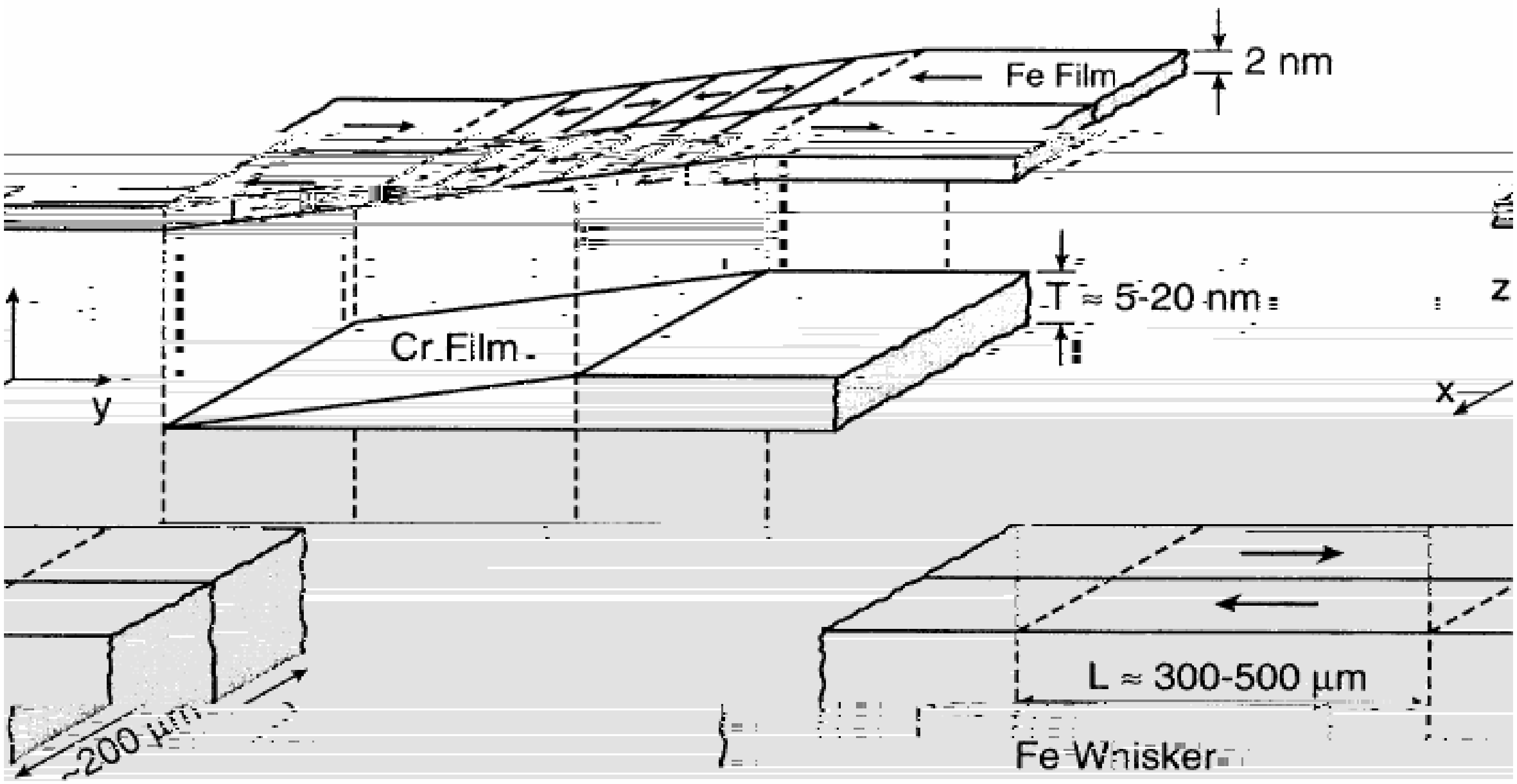
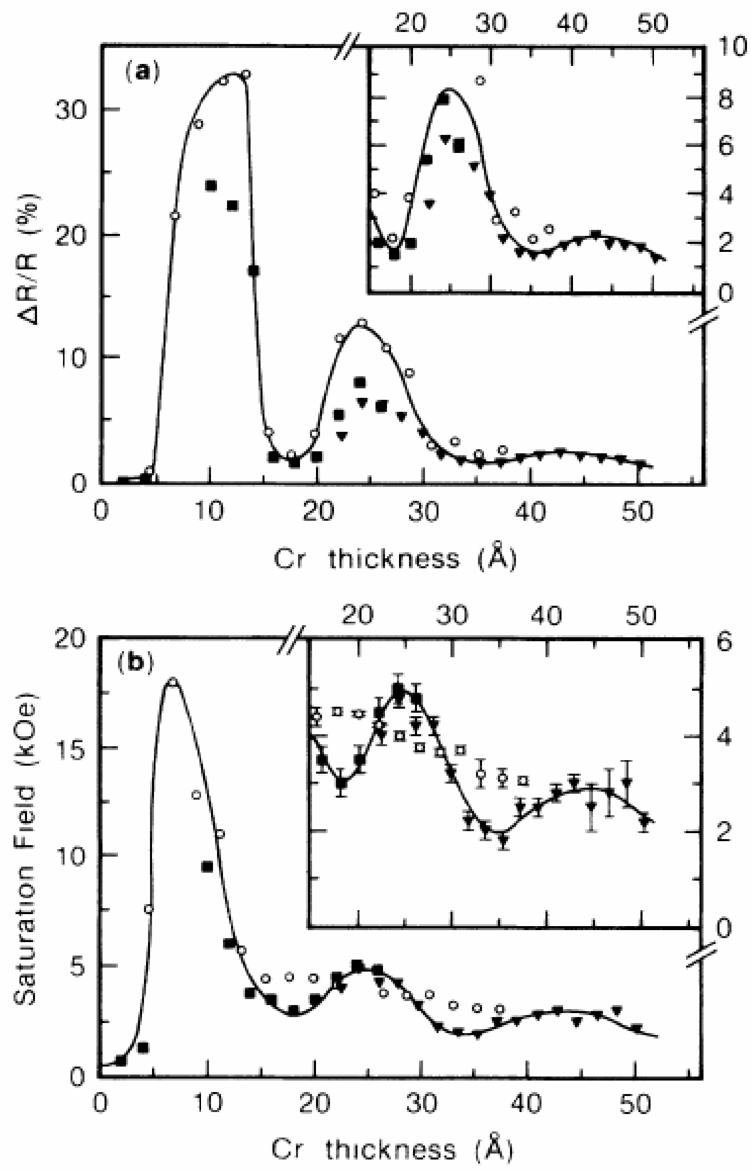


FIG. 1. A schematic exploded view
showing the Fe(100) single-crystal wh
porated Cr wedge, and the Fe overlaye
show the direction of the magnetizatior
scale is expanded approximately 5000
angle is of order 10^{-3} deg.

of the sample structure
isker substrate, the eva-
r. The arrows in the Fe
ı in each domain. The *z*
times; the actual wedge

J.Unguiris.et al.,Phys.Rev.Lett.,67(1991)140



Parkin

GMR

RKKY

Fe/Cr;

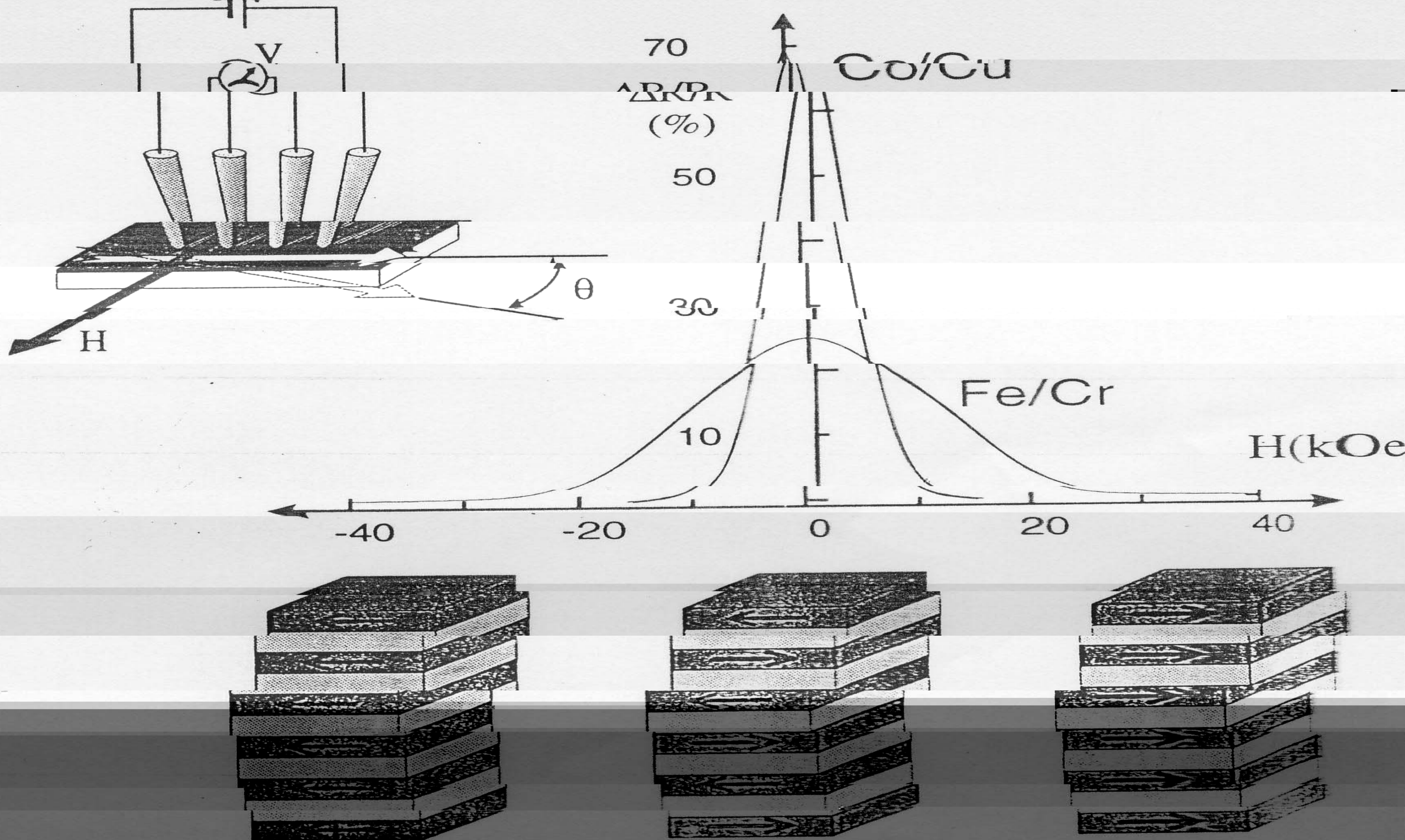
Co/Cr

Co/Ru

Parkin S.S.P et al., PRL,64(1990)2304

Giant Magnetoresistance

3 GMR

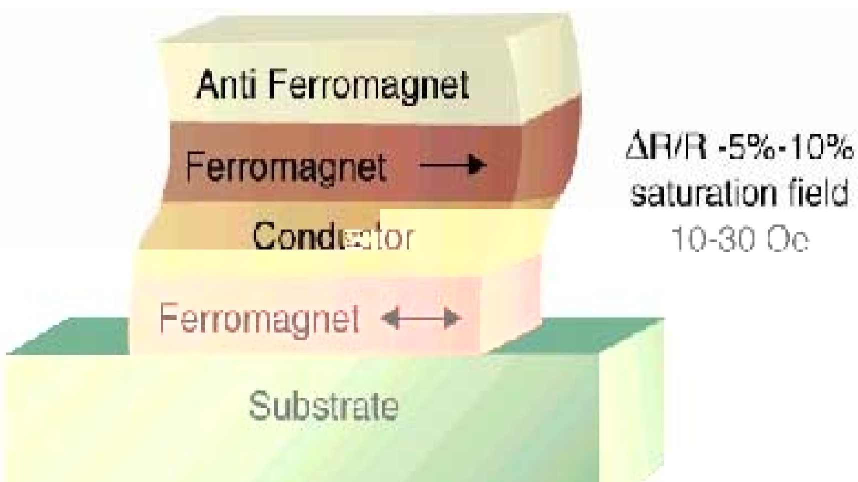


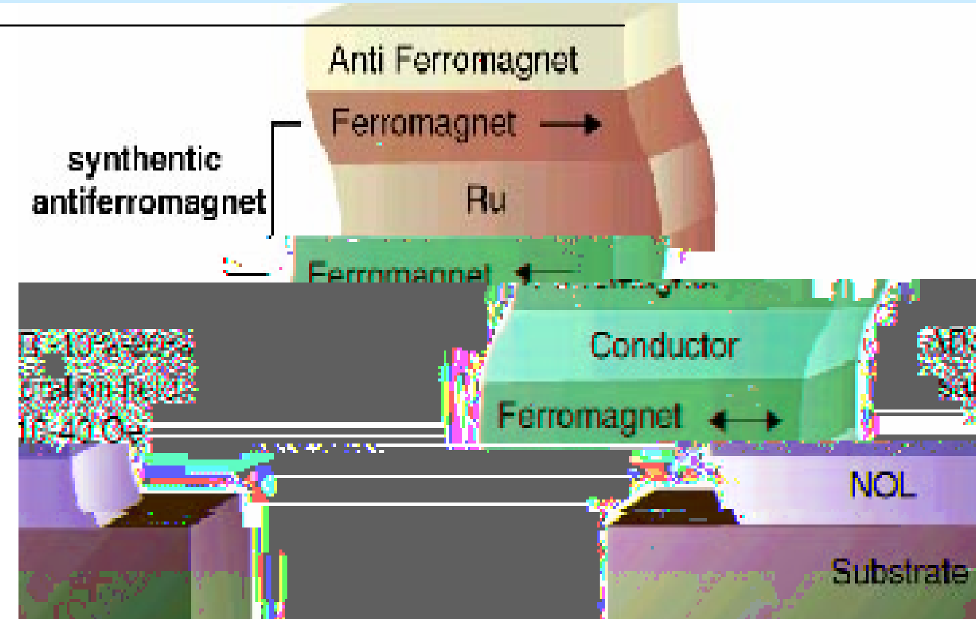
(Spin valve)

$Ni_{80}Fe_{20}$

,NiFe; FeCo)

FeMn;MnIr)





$\lambda^{\uparrow} \neq \lambda^{\downarrow}$

λ (nm)	Fe	Co	NiFe	Cu
$\lambda^{\uparrow}$	1.5 ± 0.2	5.5 ± 0.4	4.6 ± 0.3	20.5
$\lambda^{\downarrow}$	2.1 ± 0.5	≤ 1.0	≤ 0.6	20.5

Cu : $\lambda\uparrow$ $\lambda\downarrow$ 20.5 nm.

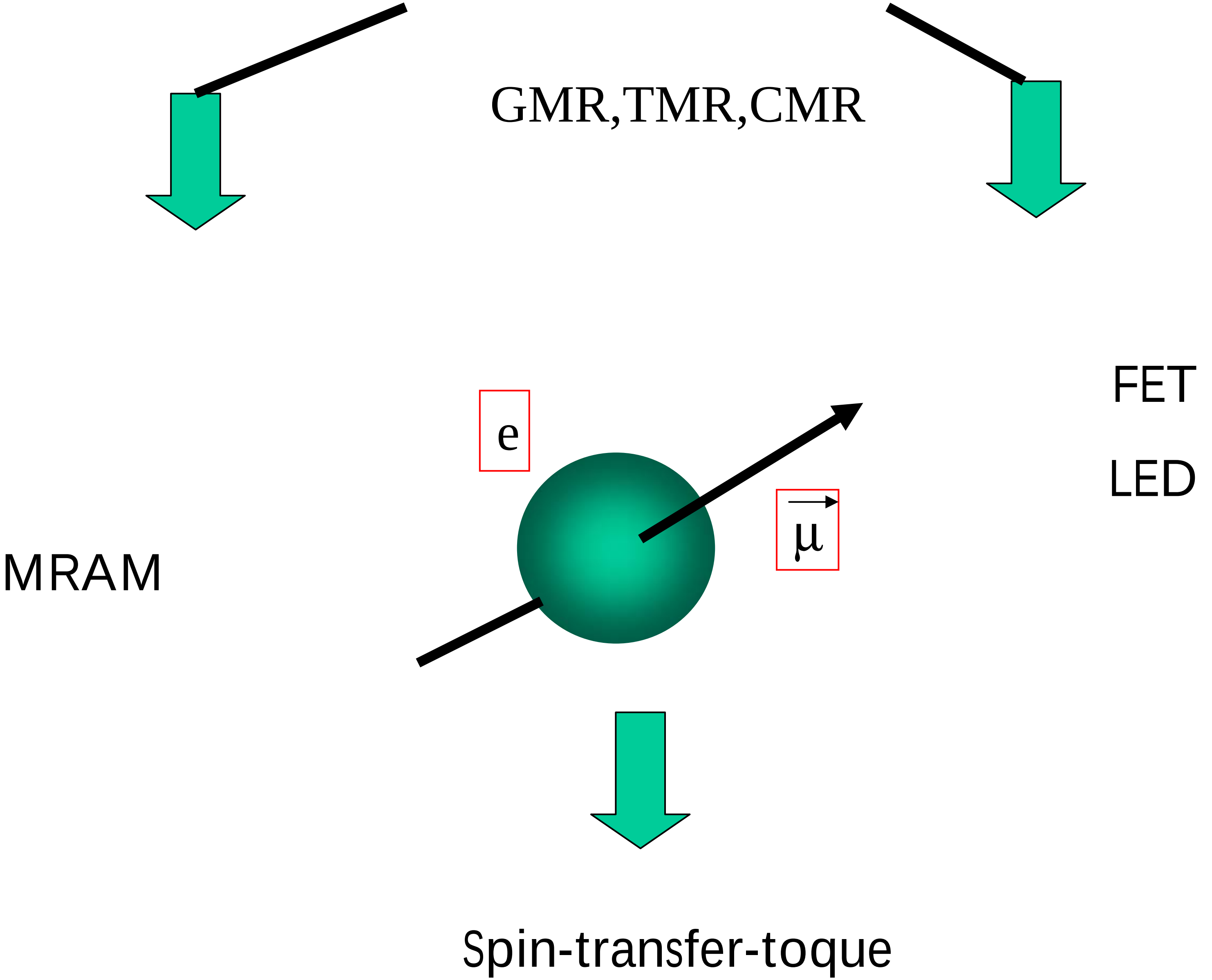
($L_s = D\tau_s$) 50-100nm

(Cu,Au,Ag, Al etc.). L_s 1-10

P

Metals						
Materials	Ni	Co	Fe	$Ni_{80}Fe_{20}$	$Co_{50}Fe_{50}$	$Co_{84}Fe_{16}$
P (%)	33	45	44	48	51	49
J.S.Moodera, G.Mathon, ***J.M.M.M.***,200(1999)248-273						

Oxide Compounds			
Materials	CrO_2	Fe_3O_4	$La_{0.61}Sr_{0.23}MnO_3$
P (%)	$90 \pm 3.6\%$ [a]	40 [b]	72 [c]


GMR,TMR,CMR
MRAM
FET
LED
e
$\vec{\mu}$
Spin-transfer-toque

-
-

AMR,GMR,TMR,CMR----

-

MRAM

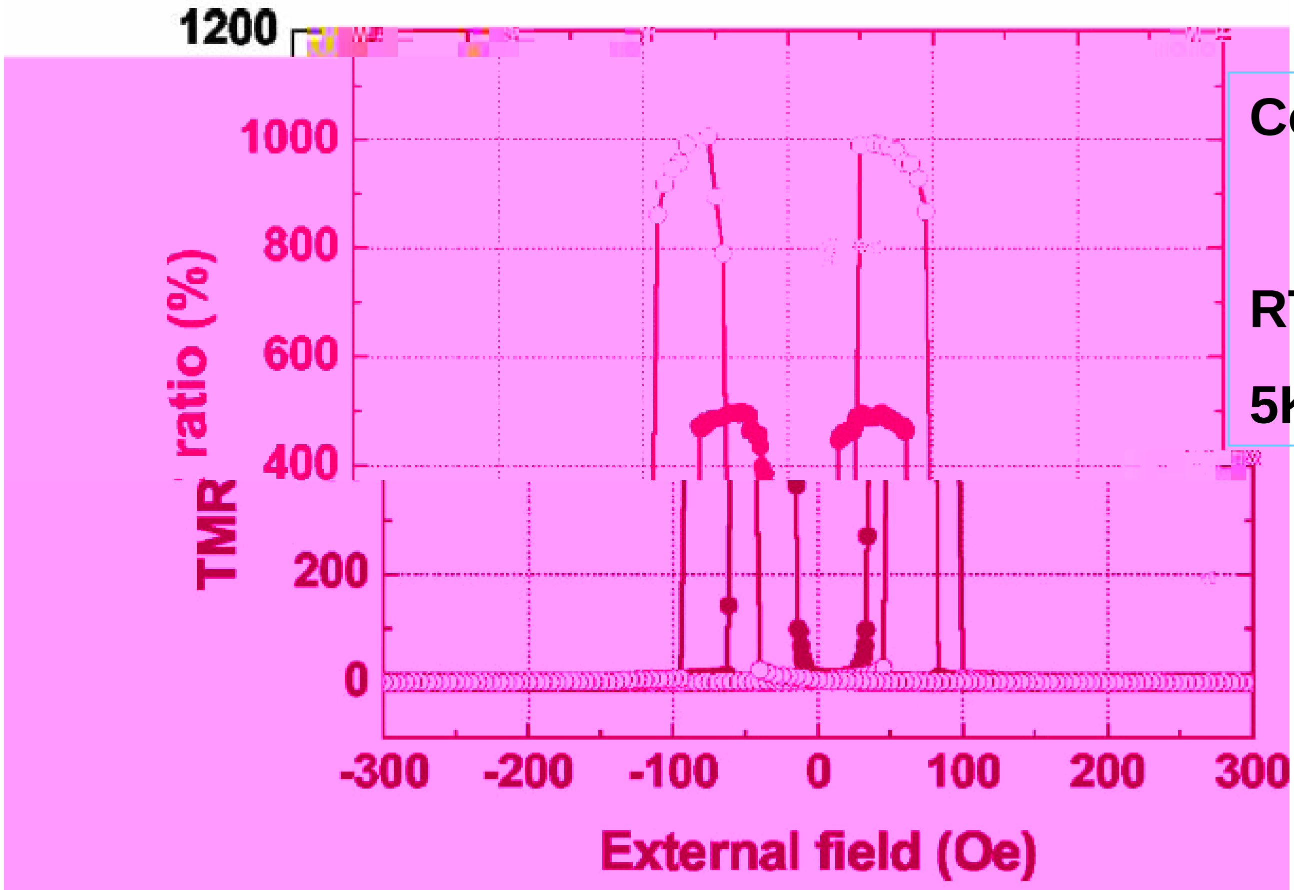


FIG. 2. TMR loops of a MTJ having 4 and 4.3 nm $(Co_{25}Fe_{75})_{80}B_{20}$ electrodes and a 2.1-nm-thick MgO annealed at 475 °C measured at RT (black circles) and 5 K (open circles).

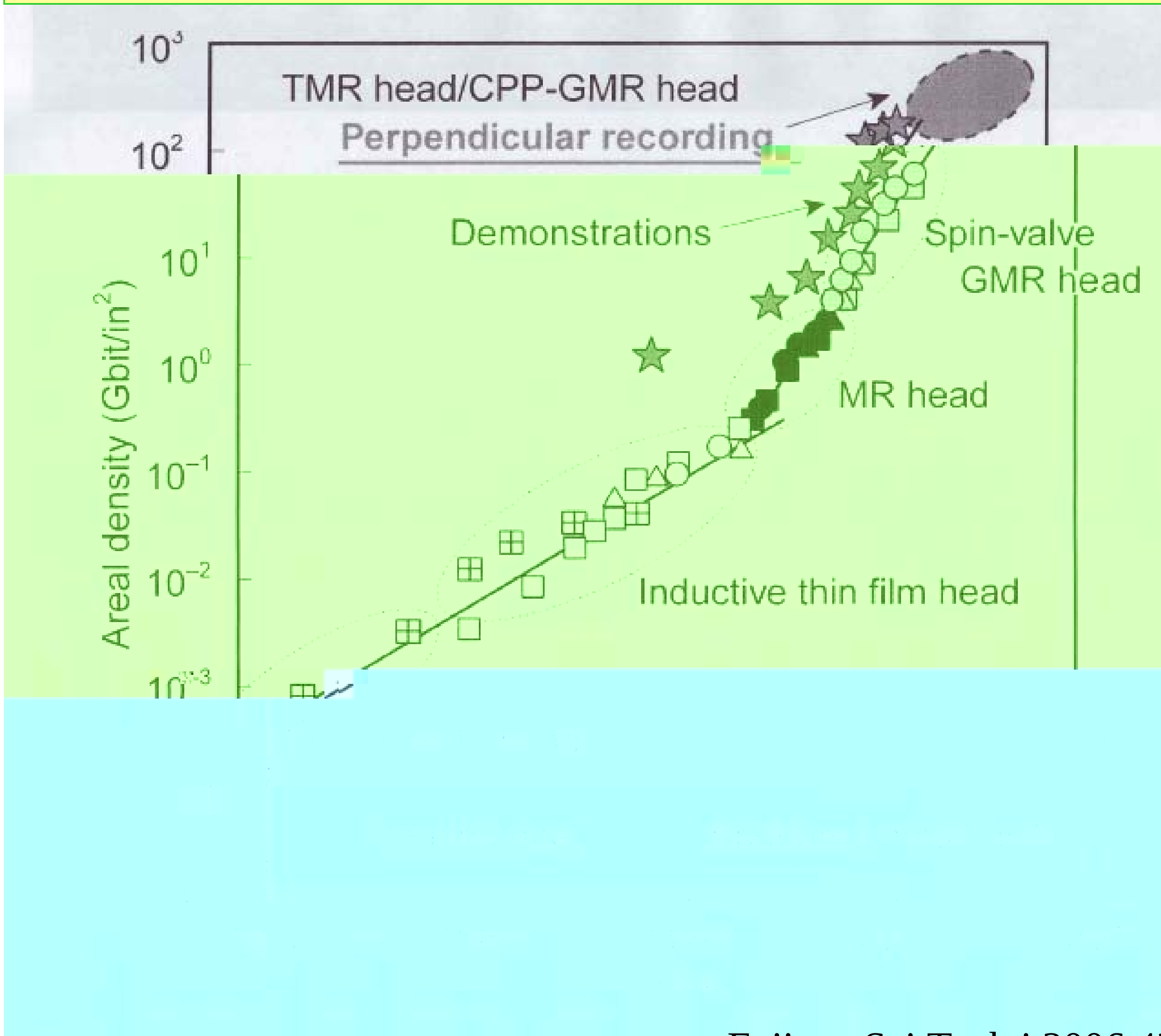
CoFeB/MgO/CoFeB

TMR

RT:500%

5K:1010%

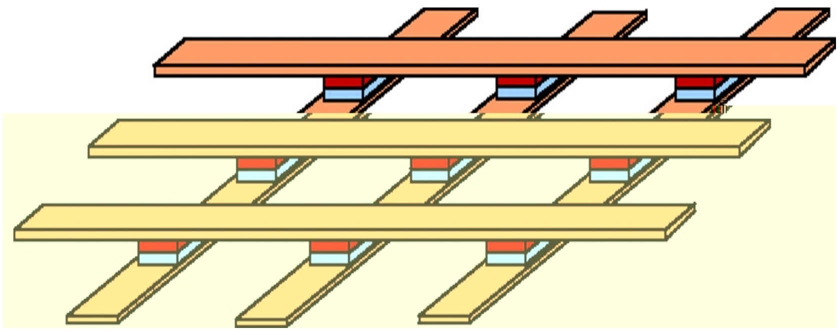
Lee,Y.M..et al.,A.P.L. 90(2007) 212507

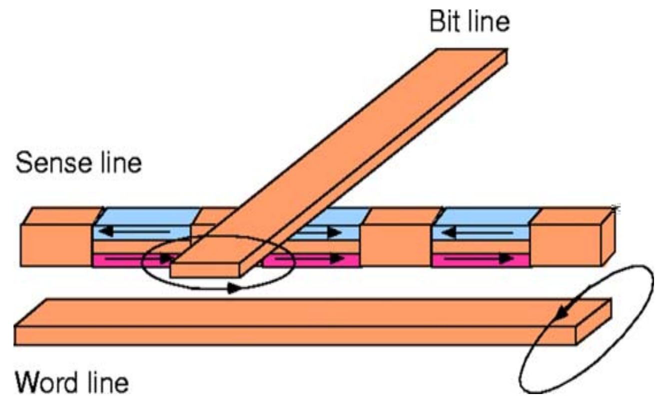


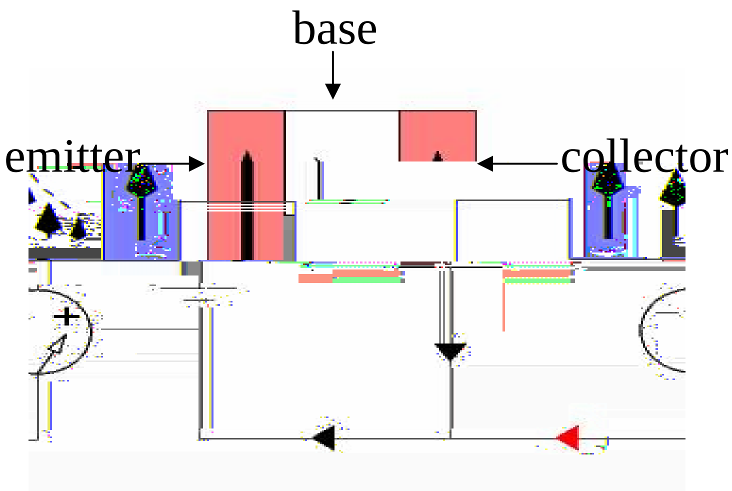
Fujitsu. Sci.Tech.j.2006,42,122

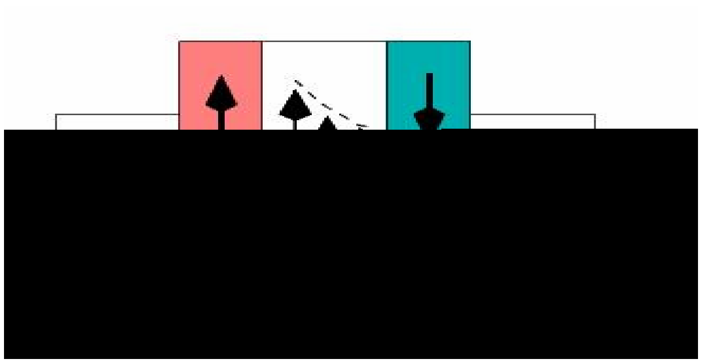
☺MRAM ; Spin Transistor

Nonvolatility, increased data processing speed, decreased electric power consumption, increased integration densities , and anti-irradiation









Spin transistor: three-terminal,bipolar device

MRAM

♥

♥ DRAM

♥ Flash

Flash

♥ MRAM

♥ MgO Spin-

transfer torque) MRAM

industrial production.

In July 2006, Freescale started selling the first commercial MRAM module, with 4Mbit of memory, for 25$ a piece.

2008:Freescale launches independent company-EverSpin to accelerate MRAM business

Toshiba - advances in 1Gb MRAM. Expects MRAM to take over DRAM in 2015

Samsung and Hynix to launch STT-MRAM JV in September, expect the chip to mature around 2012

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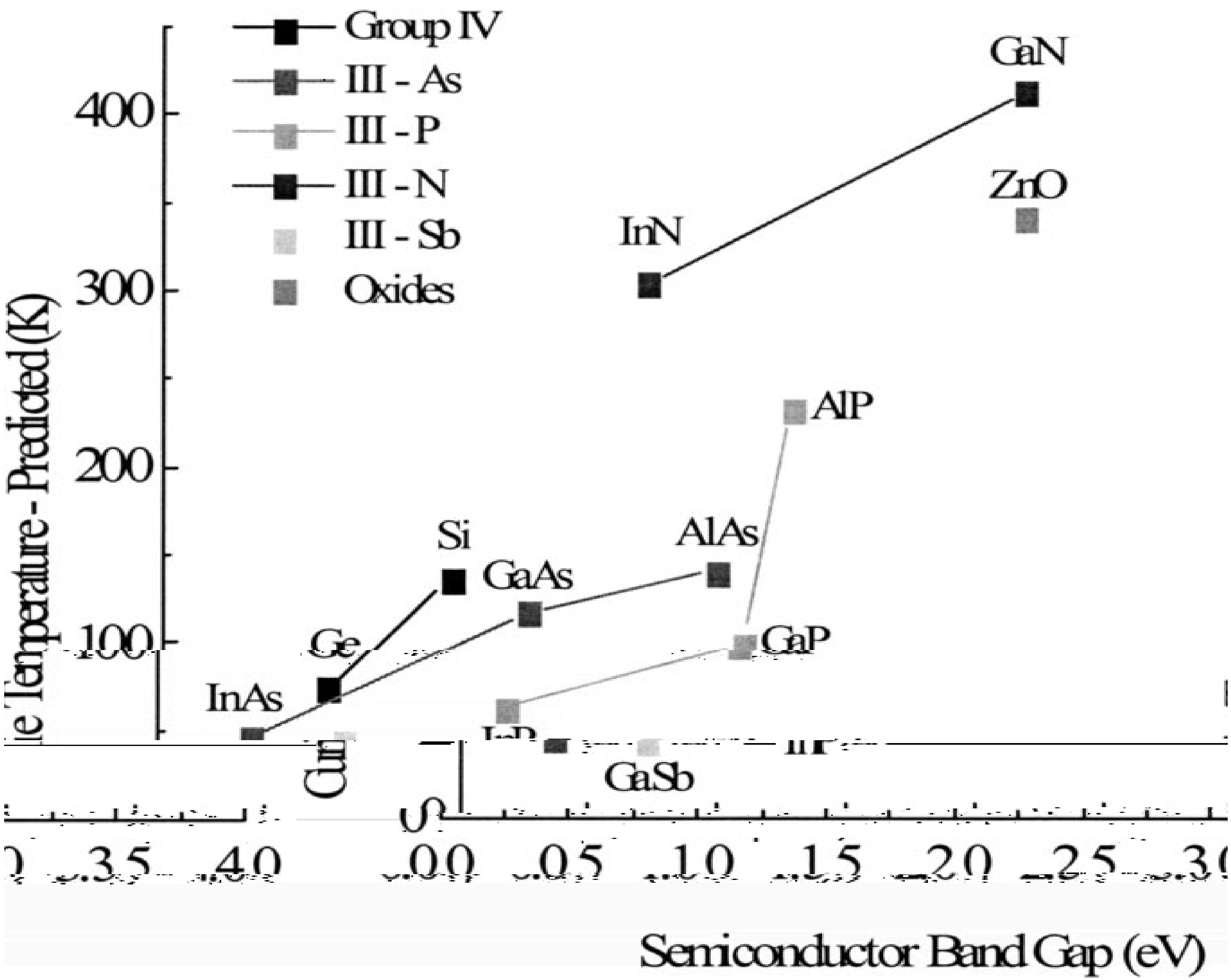
2

3

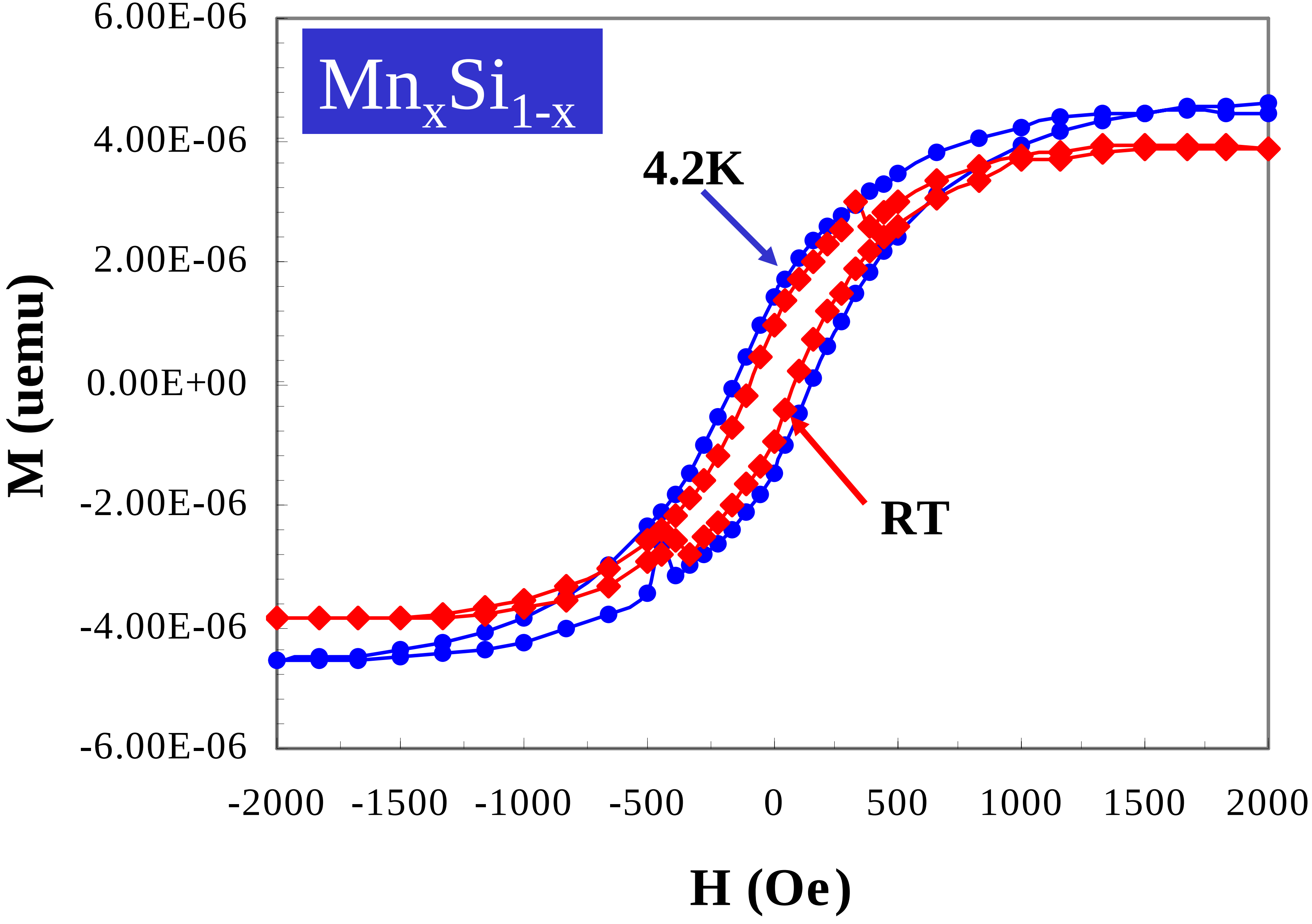
4.

5. TMR,

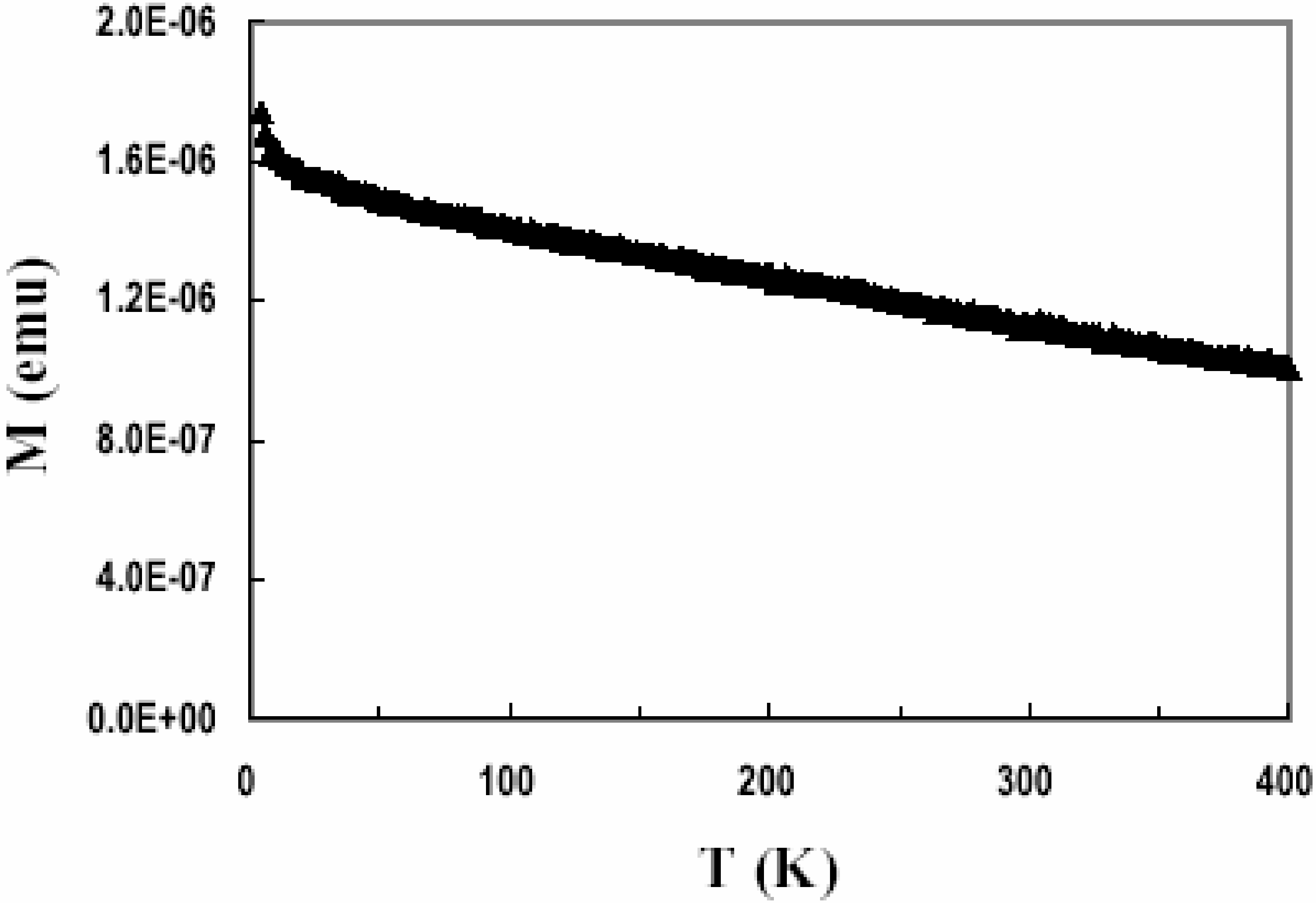


The predicted Curie temperatures as a function of the band gap

T. Dietl , et al., Science 287, (2000)1019

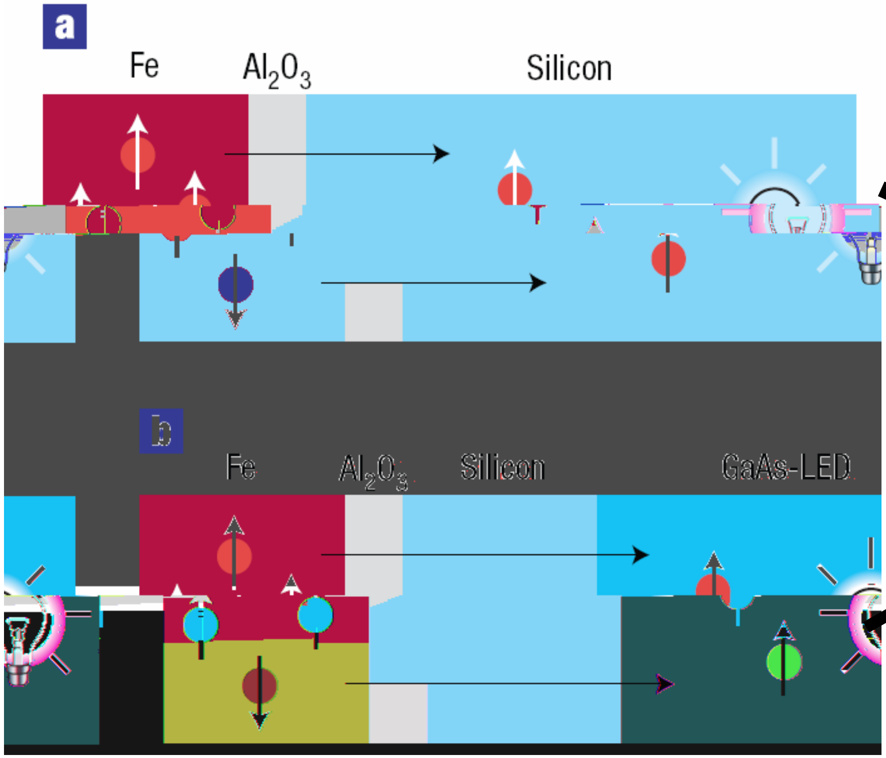


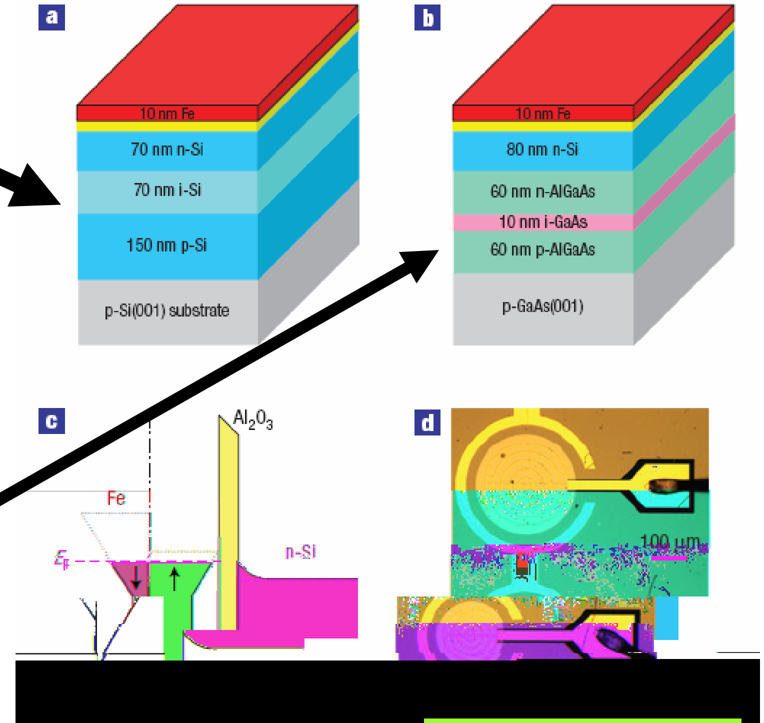
Magnetic hysteresis loops for MnSi alloy



2.0E-06
1.6E-06
1.2E-06
8.0E-07
4.0E-07
0.0E+00
M (emu)
0
100
200
300
400
T (K)

Demonstration of the injection of spin into silicon





LED-Light emitting diode

R.Jansen,Nature physics,3(2007)521; B.T.Jonker,et al.,ibid,(2007)542

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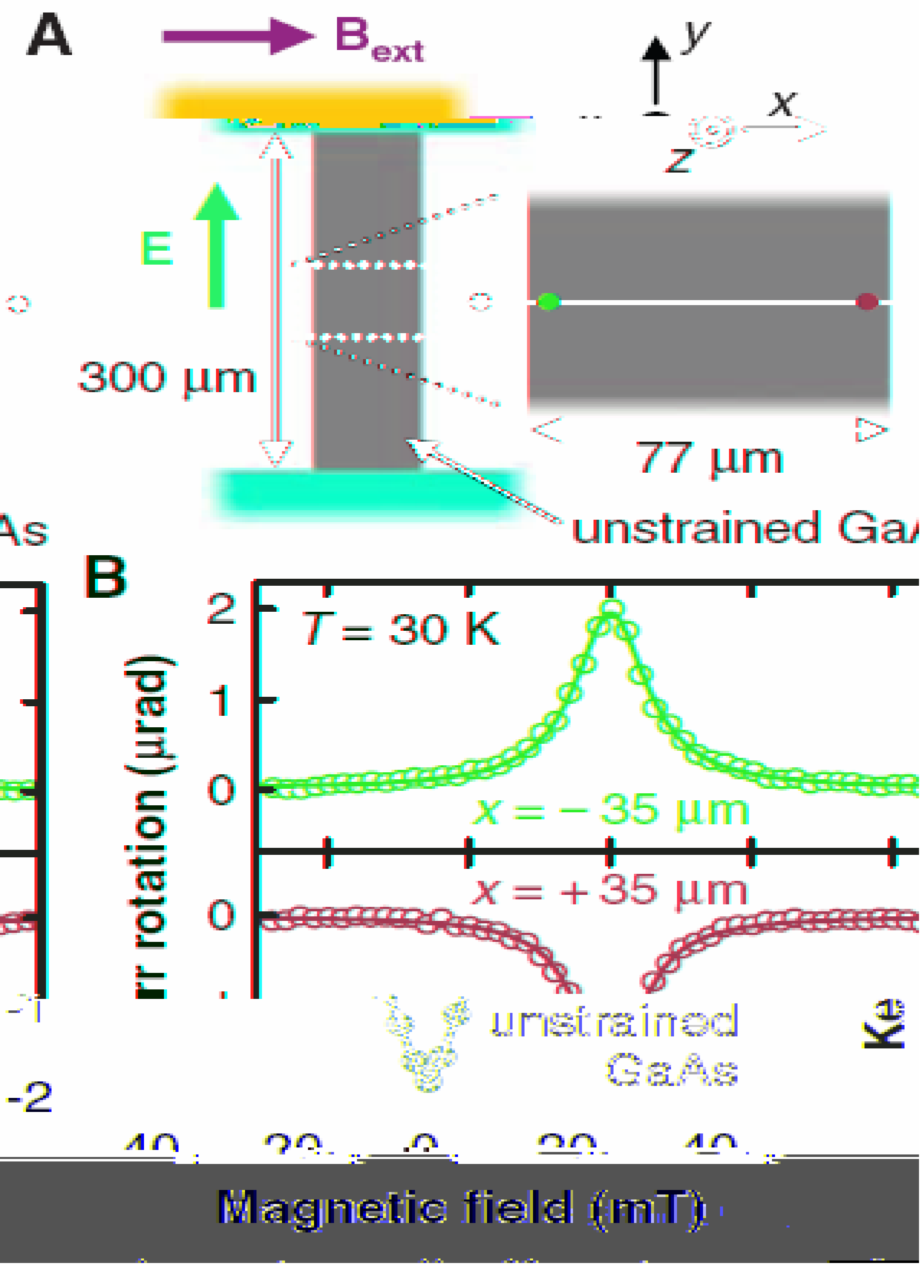
S.J.Xiong and Y.W.Du,Physics Letters A 372(2008)2114



GaAs Spin Hall Effect

GaAs

Kerr

Kato Y.K.etal., Science 306(2004 1910

Rashba spin-orbit

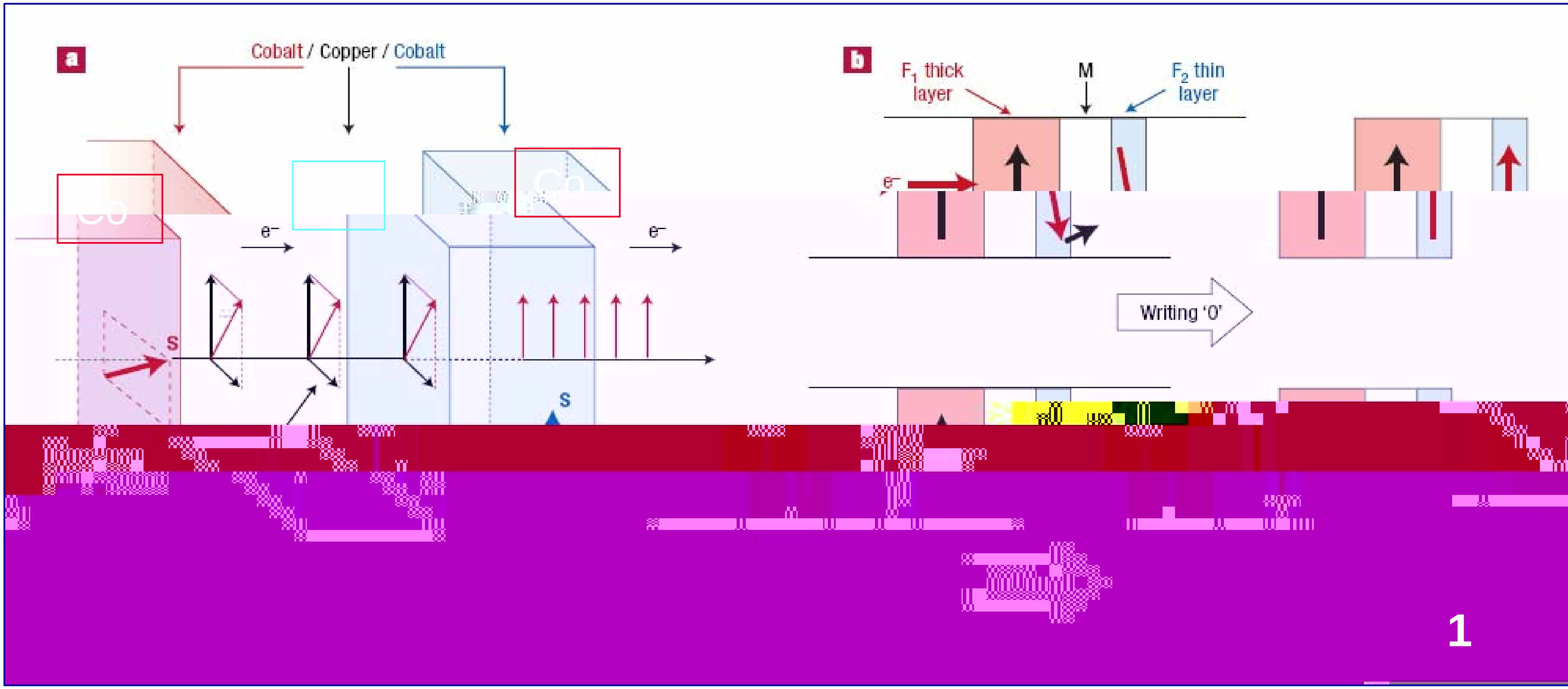
J Sinova et al.,

PRL26(2004)126603

GMR ; TMR

Principle of Spin Transfer Torque (STT)

STT-RAM



$$\frac{\partial \vec{M}(\vec{r},t)}{\partial t} = \underbrace{-|\gamma|\vec{M}\times\vec{H}_{\mathrm{eff}}}_{\text{PRECESSION}} + \underbrace{\frac{\alpha}{M_s}\vec{M}\times\frac{\partial \vec{M}}{\partial t}}_{\text{DAMPING}} + \underbrace{\frac{\sigma I}{M_s}\vec{M}\times(\vec{M}\times\vec{P})}_{\text{SPIN TRANSFER}}$$

The magnetization direction in the centre of a submicrometre mgnetic disk can now be switched by an electrical current. This discovery demonstrates the potential of realizing all-electrically controlled magnetic memory devices.

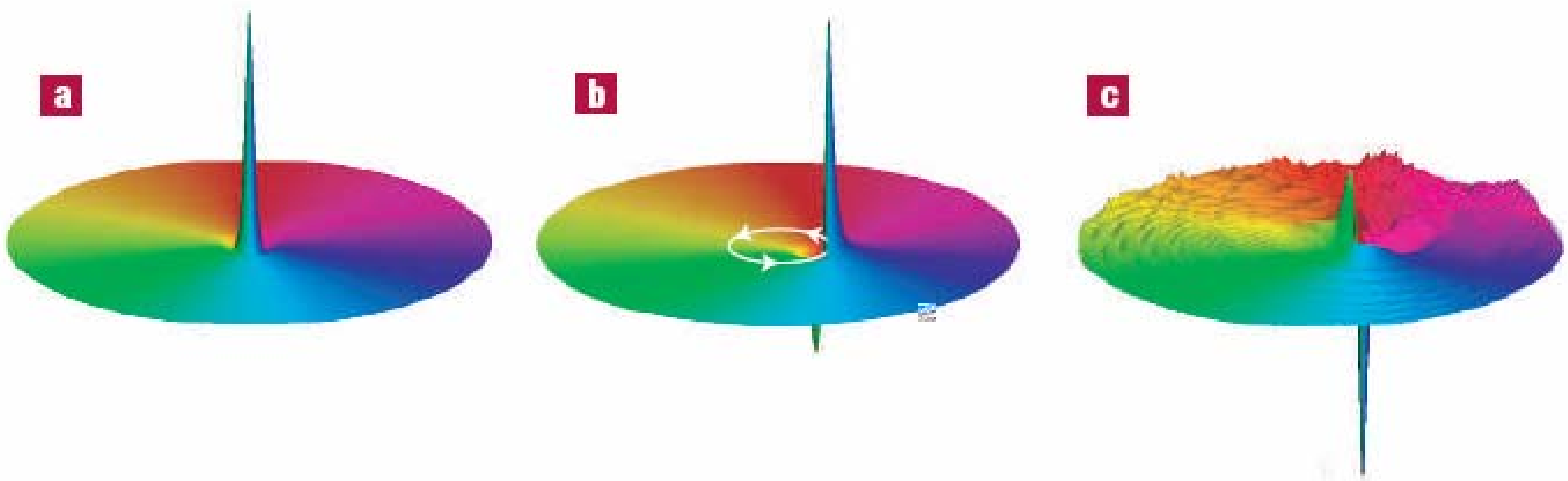
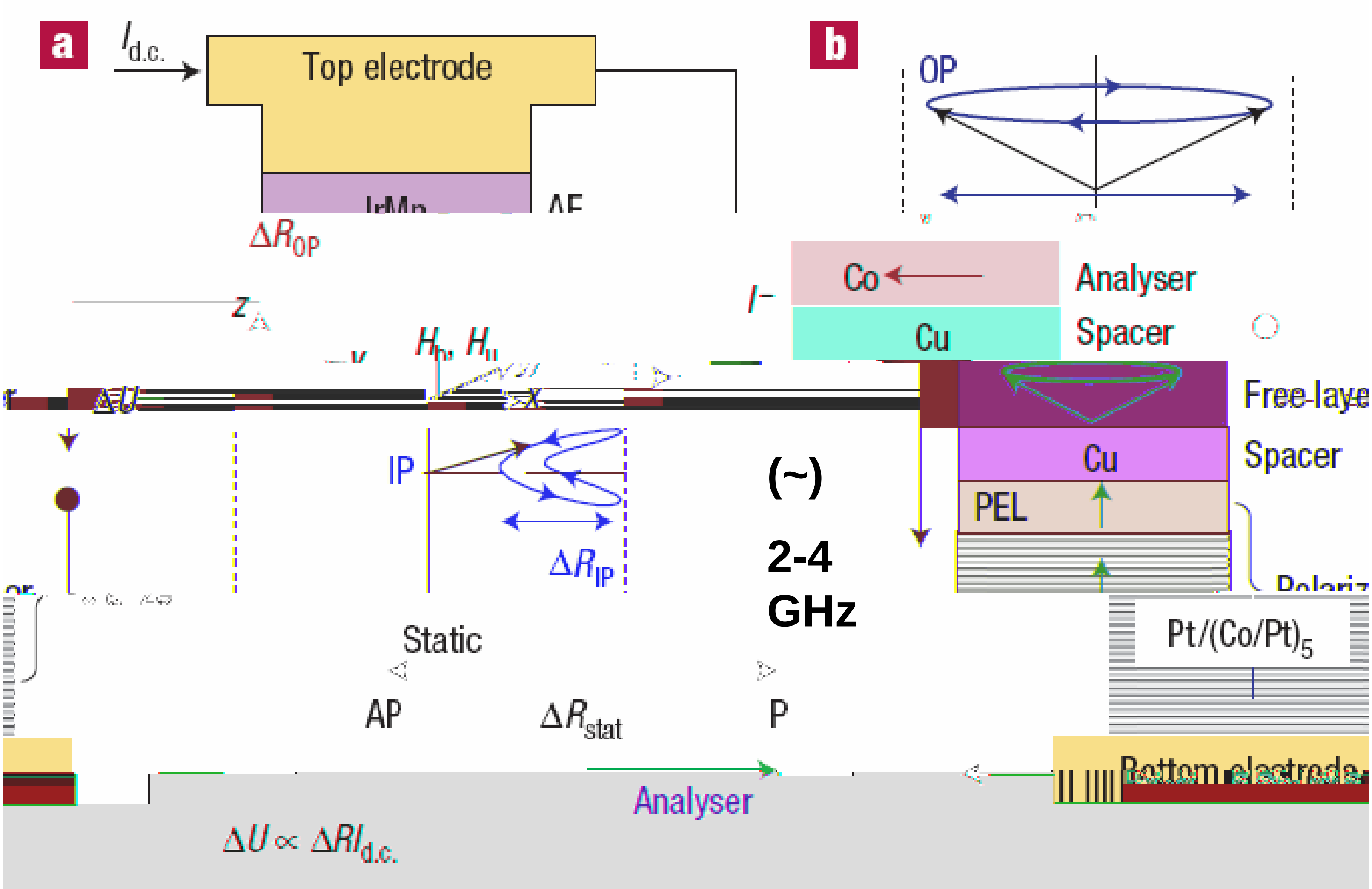


Figure 1 Magnetic vortex-core reversal. **a**, A magnetization vortex with its core shown in the centre. The height is proportional to the out-of-plane component (see text). **b**,**c**, When an oscillating electrical current is applied, the core begins to orbit the centre (**b**), and eventually switches to its other bistable state (**c**).

R.P.Cowbum, Nature Materials, 6 (2007) 255

Spin-torque oscillator-RF Device



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2-4 GHz

D.Houssameddine et al.,Nature materials 6(2007)447

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