# Thin films and Nanostructures

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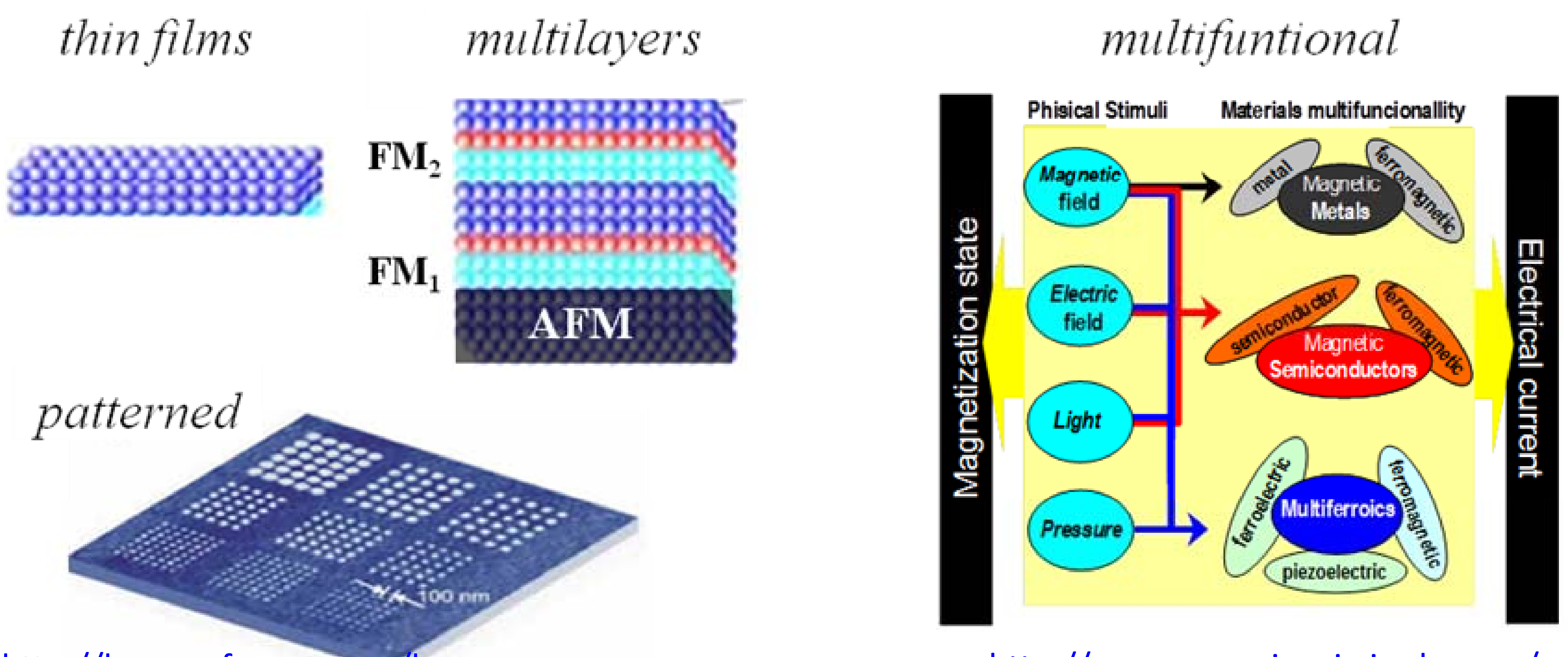


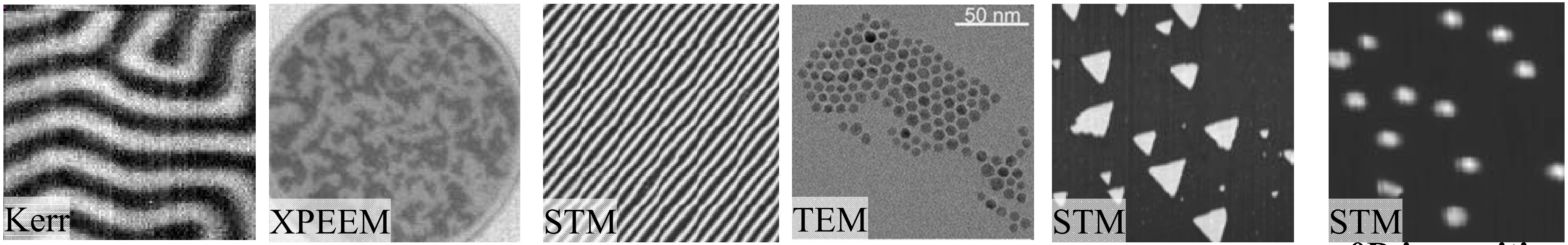

http://lasuam.fmc.uam.es/lasuam

http://www.nanociencia.imdea.org/

*Novel Frontiers in Magnetism*, Benasque 12th February 2014

# FROM *MACROSCOPIC* DOWN TO *NANOSCOPIC* SIZES

Nowadays we can design `complex magnetic systems' by controlling materials at the atomic scale, that is layer by layer, row by row, and ultimately atom by atom


**Magnetic domains in 2D films** | **1D chains & 3D-2D nanoparticles** | **0D impurities single molecules**

Magnetic thin films & nanostructures exhibit a wide range of fascinating phenomena:

- **Low dimensional effects**: (tailoring) anisotropies, critical temperatures, magnetic moments...
- **Proximity effects**: induced magnetization in non-magnetic systems (noble metals)…
- **Interfaces**: exchange coupling (FM/AFM), oscillatory coupling (FM/NM/FM),…
- **Magnetoresistance**: Giant Magneto-Resistance GMR, Tunneling Magneto Resistance TMR,…

# Outline

**Driven forces at the nanoscale**

**Tailoring Magnetic Properties**
- Critical Temperatures
- Magnetic anisotropy

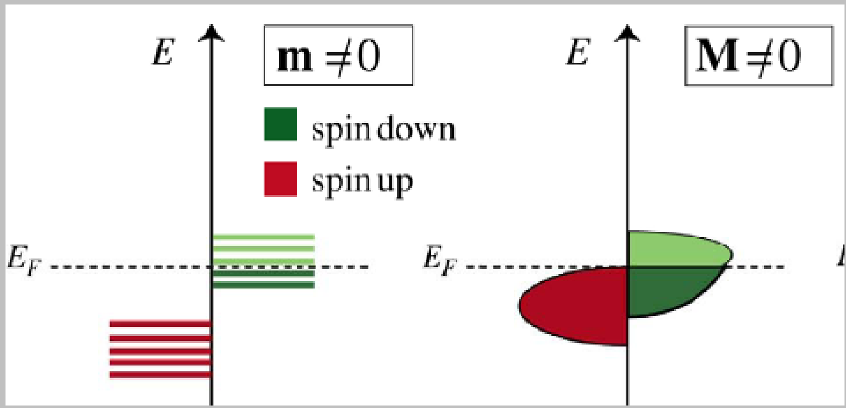
**Interfacial Phenomena**
- Induced Moments
- Exchange

**Reversal processes**
- Size and time scales
- Magnetic Symmetry

**Future Trends**

# Magnetism and driving forces in the *Nanoworld*

Atom Matter

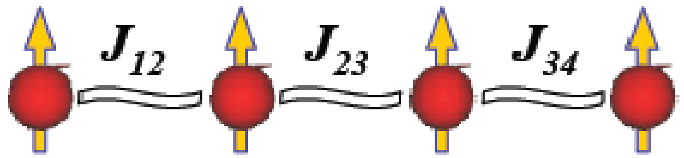



***unbalance*** of the electronic states with spin up and down

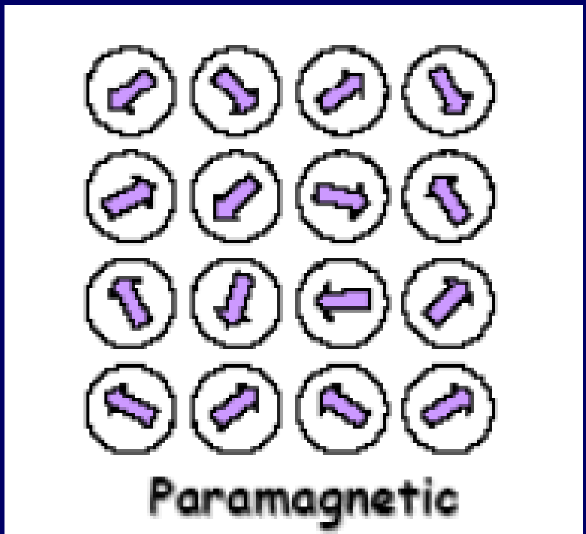
**Inter-atomic exchange:**

**MAGNETIC ORDER**

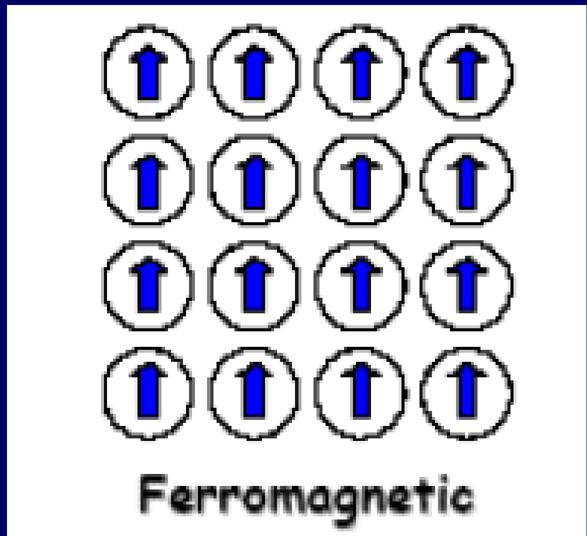
$$H_{exc} = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$



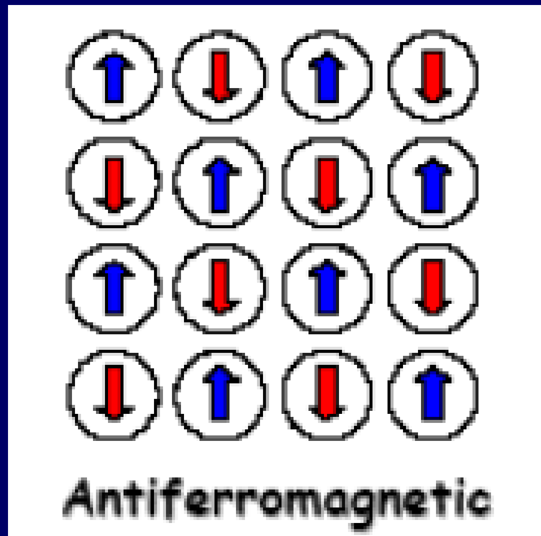

***J = 0***




***J > 0***

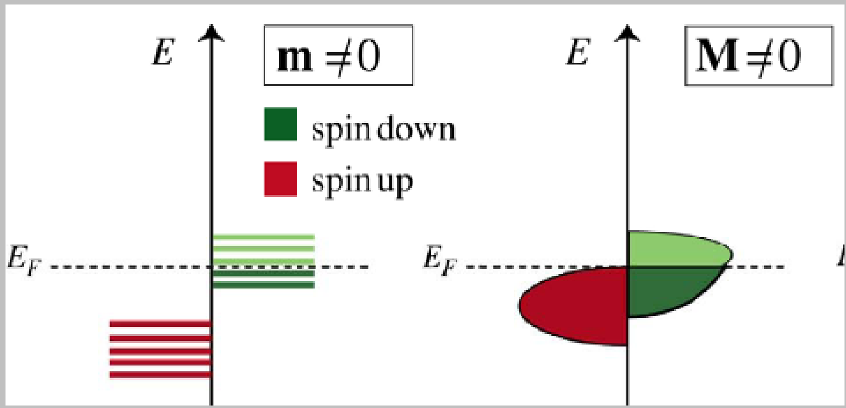



***J < 0***



# Magnetism and driving forces in the *Nanoworld*

Atom | Matter




*unbalance* of the electronic states with spin up and down

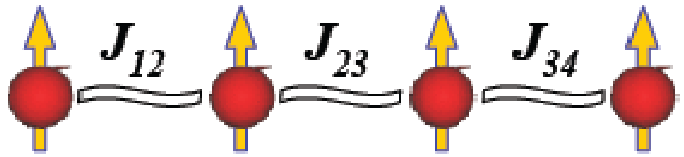
**Inter-atomic exchange:**

**MAGNETIC ORDER**

*isotropic*

0.1 eV/atom ($Fe_{bulk}$)

$$H_{exc} = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

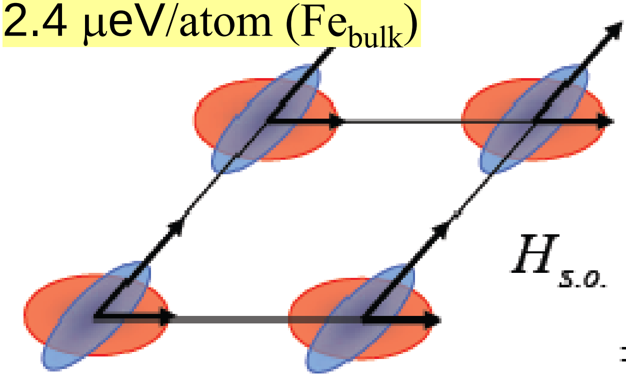



**Spin-Orbit Coupling:**

**MAGNETOCRYSTALLINE ANISOTROPY: K**

*anisotropic*

2.4 μeV/atom ($Fe_{bulk}$)

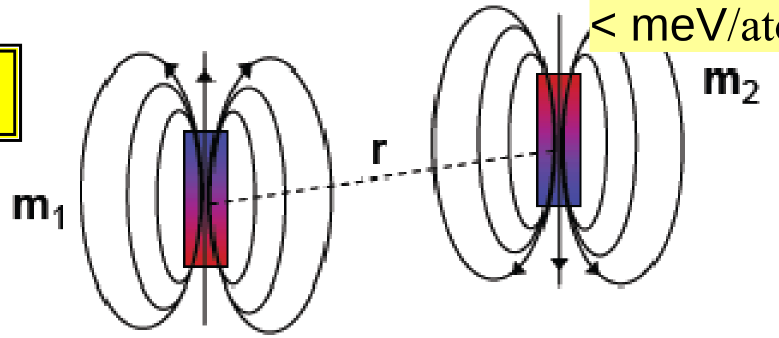


$$H_{s.o.} = \lambda \mathbf{L} \cdot \mathbf{S} = \sum \xi \, \mathbf{s}_i \cdot \mathbf{l}_i$$

**Dipolar Interaction:**

**SHAPE ANISOTROPY**

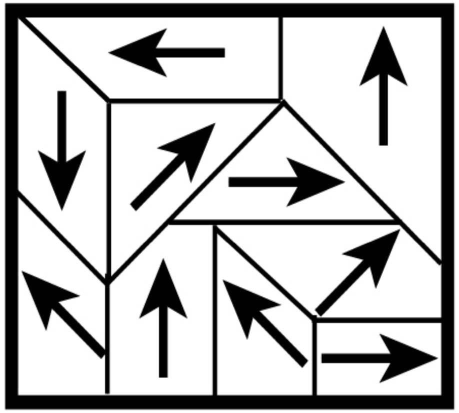
< meV/atom

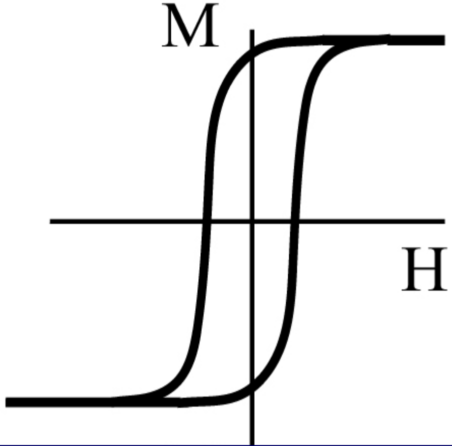



$$H_{dip} = \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - 3\frac{(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5}$$

# Magnetic Domains and Domain Walls

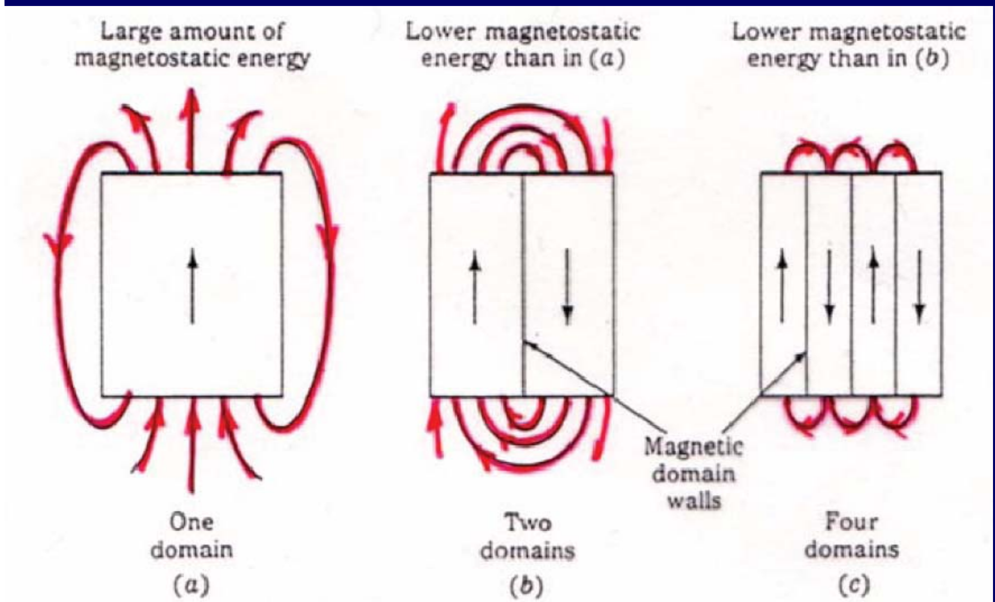
Multi-domain

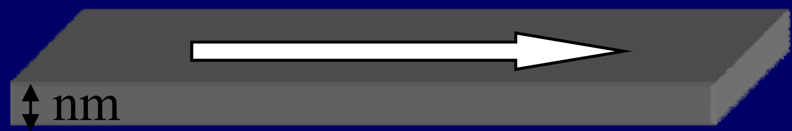


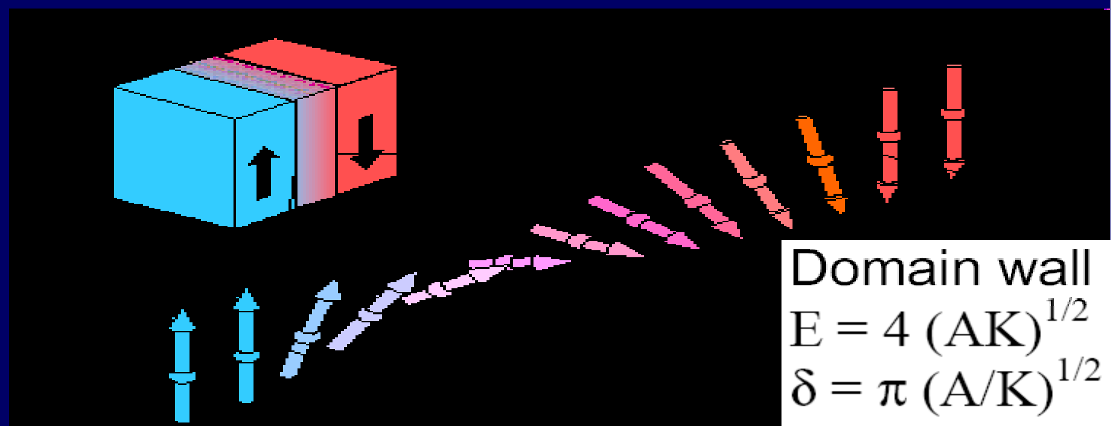



**Magnetostatic energy**

*magnetic domain formation*

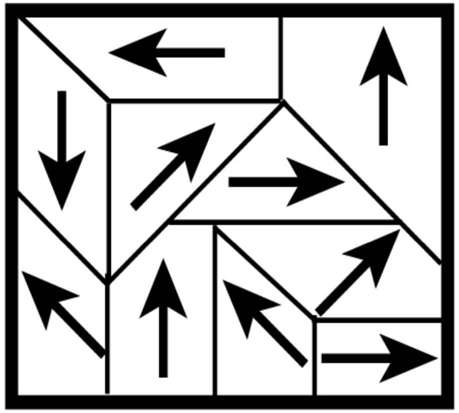


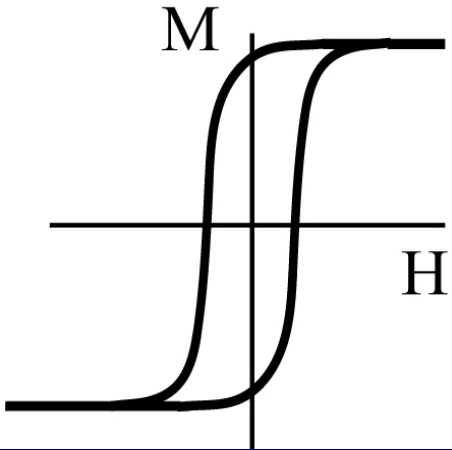



# Magnetic Domains and Domain Walls

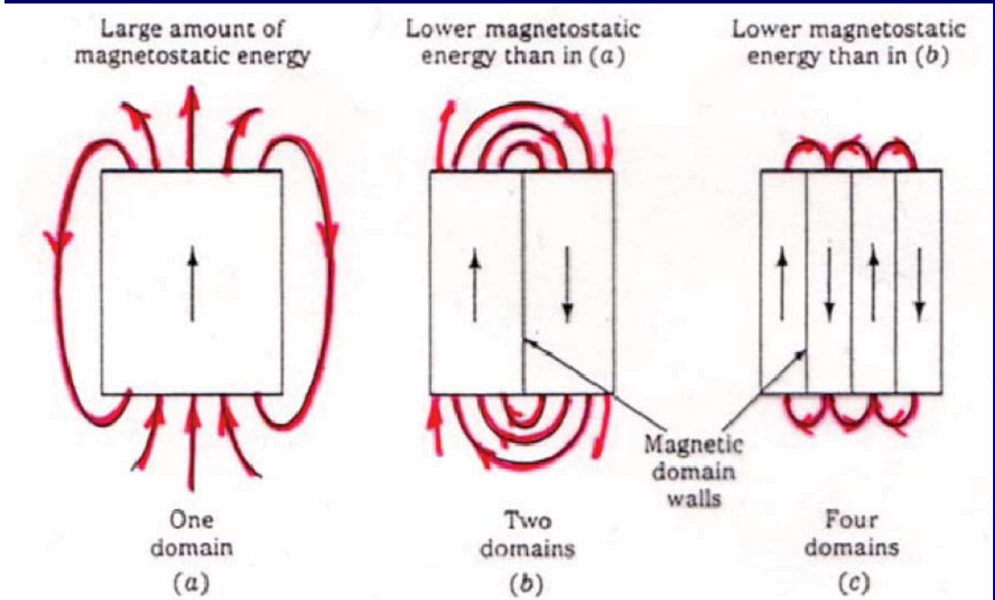
Multi-domain






## Magnetostatic energy

*magnetic domain formation*



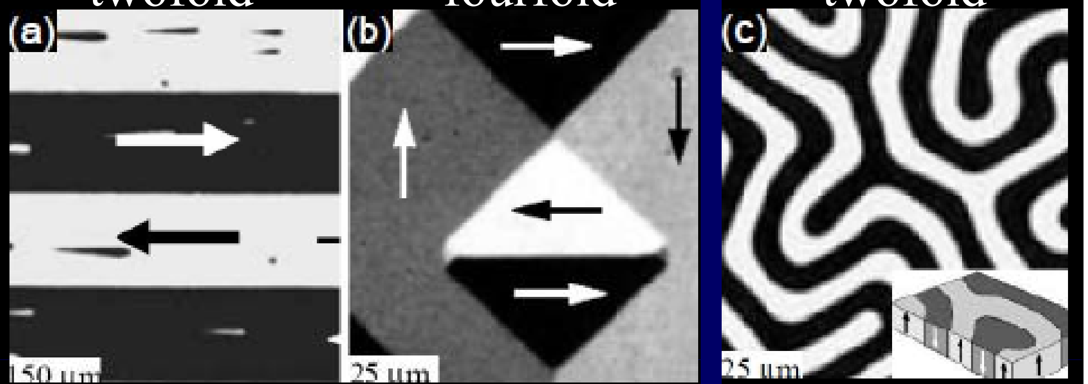

## Magnetic Anisotropy

*Preferential direction of the magnetization*

***in-plane***

***out-of-plane***

twofold | fourfold | twofold



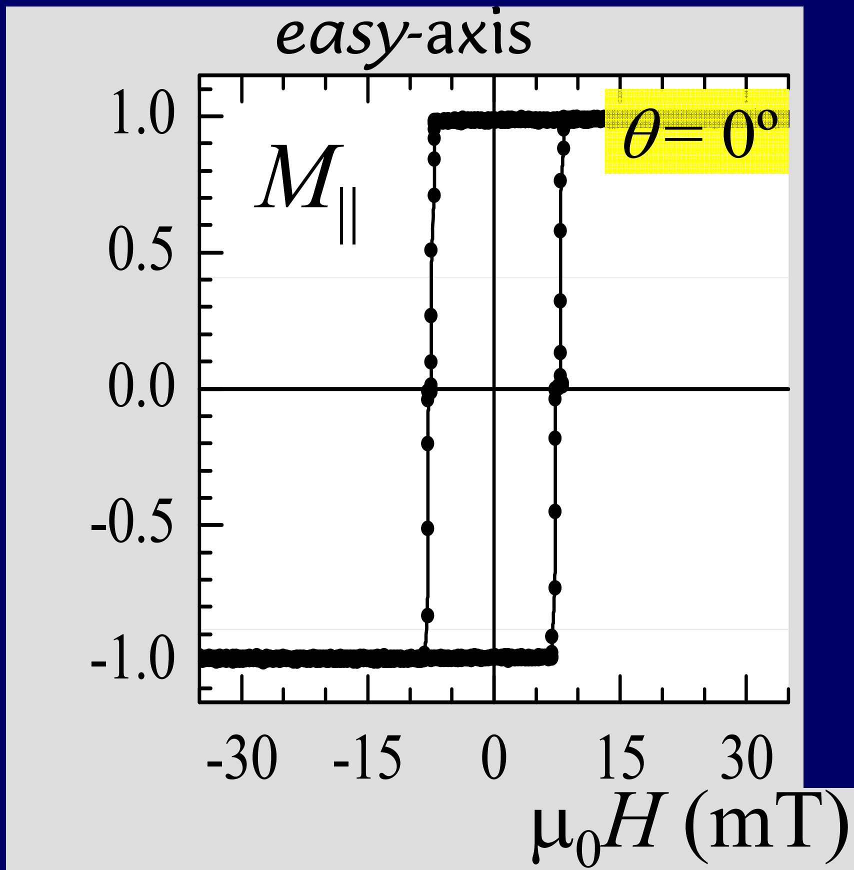

uniaxial | biaxial | uniaxial

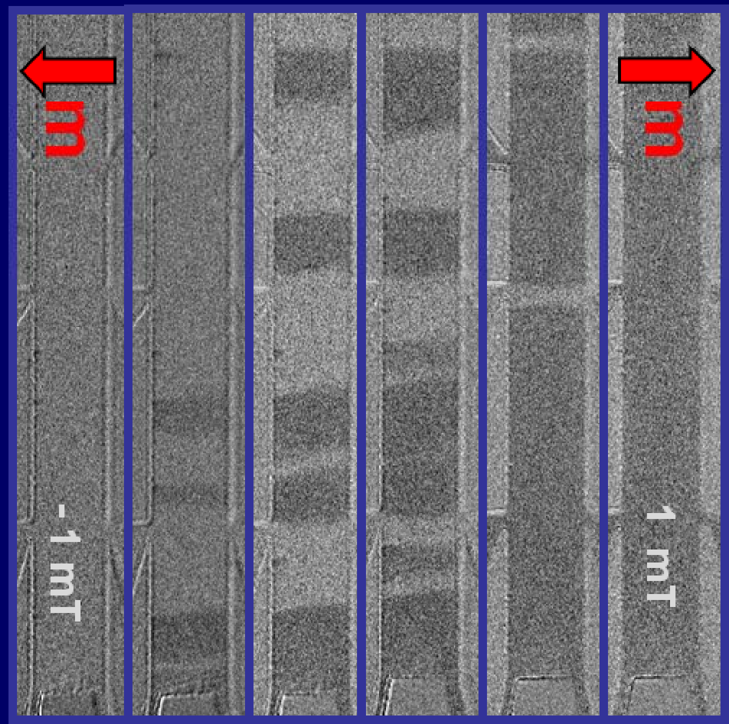
# Magnetic anisotropy

Magnetic anisotropy is the direction dependence of a material's magnetic properties.

A magnetically *isotropic* material has *no preferential direction* for its magnetic moment in zero field, while a magnetically *anisotropic* material will align its moment to an *easy axis*.

**FM ultrathin film with uniaxial anisotropy,**




New Journal of Physics 12, 103033 (2010)

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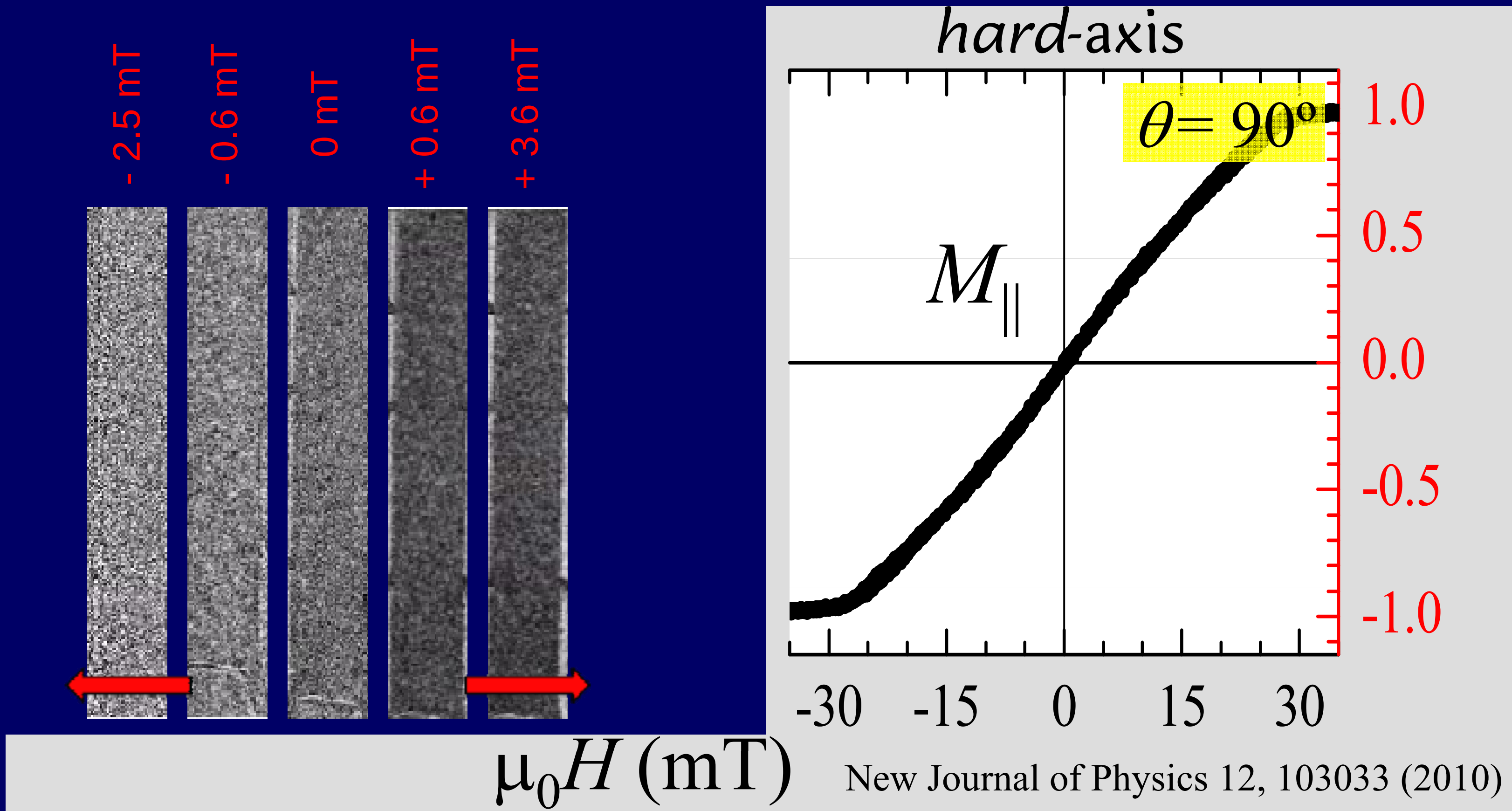
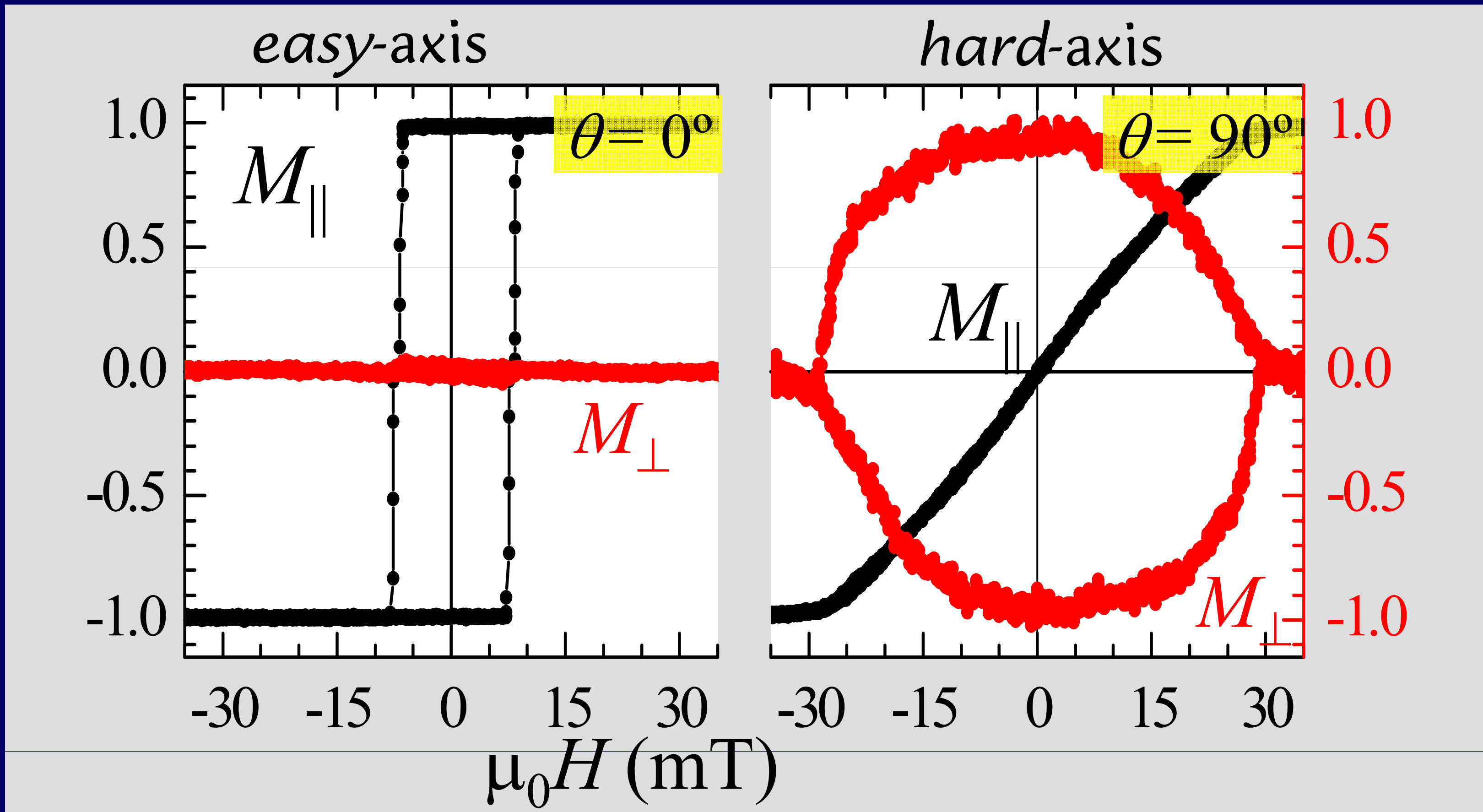



New Journal of Physics 12, 103033 (2010)

# Disentangling Magnetization reversal processes

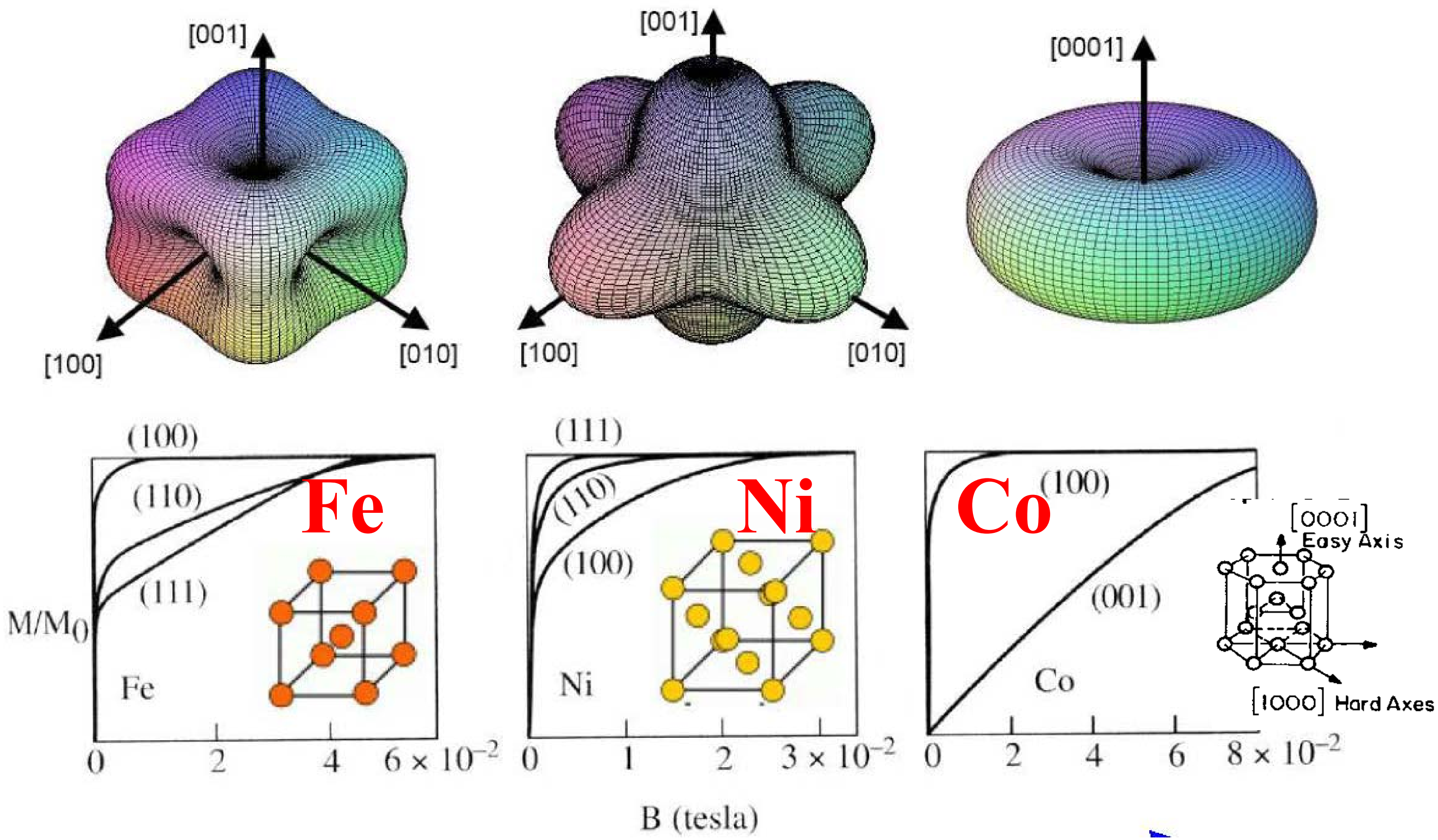
## by vectorial magnetometry

FM ultrathin film with uniaxial anisotropy, Appl. Phys. Lett. 90 032505 (2007)



# Sources of magnetic anisotropy
# (*broken symmetry*)

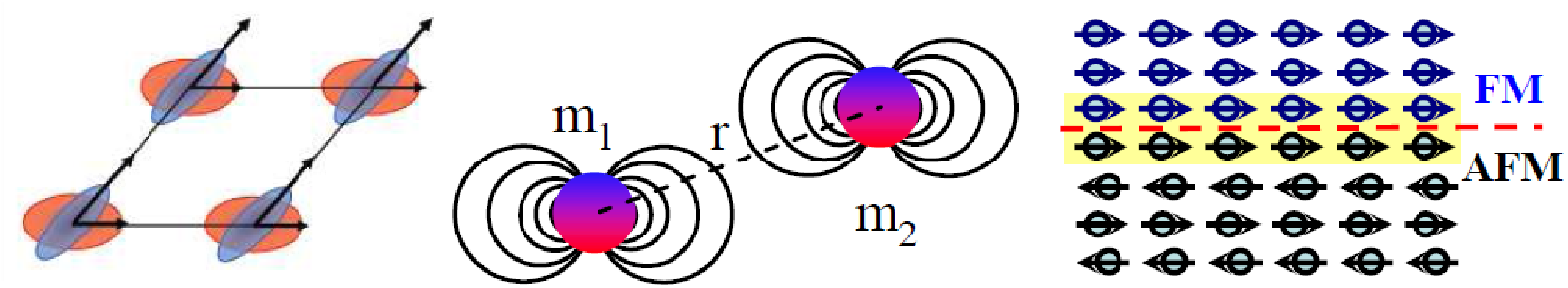
•Magnetocrystalline anisotropy (crystal & surface lattice symmetry)



# Sources of magnetic anisotropy
## (*broken symmetry*)

- Magnetocrystalline anisotropy (crystal & surface lattice symmetry)
- Magnetoelastic anisotropy (strain)
- Shape anisotropy (demagnetizing fields)
- Exchange anisotropy (e.g., FM/AFM)

***Spin-orbit coupling*** | ***Dipolar interaction*** | ***Exchange coupling***




$$\mathcal{H}_{s.o.} = \lambda L \cdot S = \sum_i \zeta s_i \cdot l_i$$

$$\mathcal{H}_{dip} = \left( \frac{m_1 \cdot m_2}{r^3} - 3\frac{(m_1 \cdot r)(m_2 \cdot r)}{r^5} \right) \frac{1}{4\pi\mu_0}$$

$$\mathcal{H}_E = \frac{\Delta\sigma_{FM/AFM}}{M_{FM}\, t_{FM}}$$

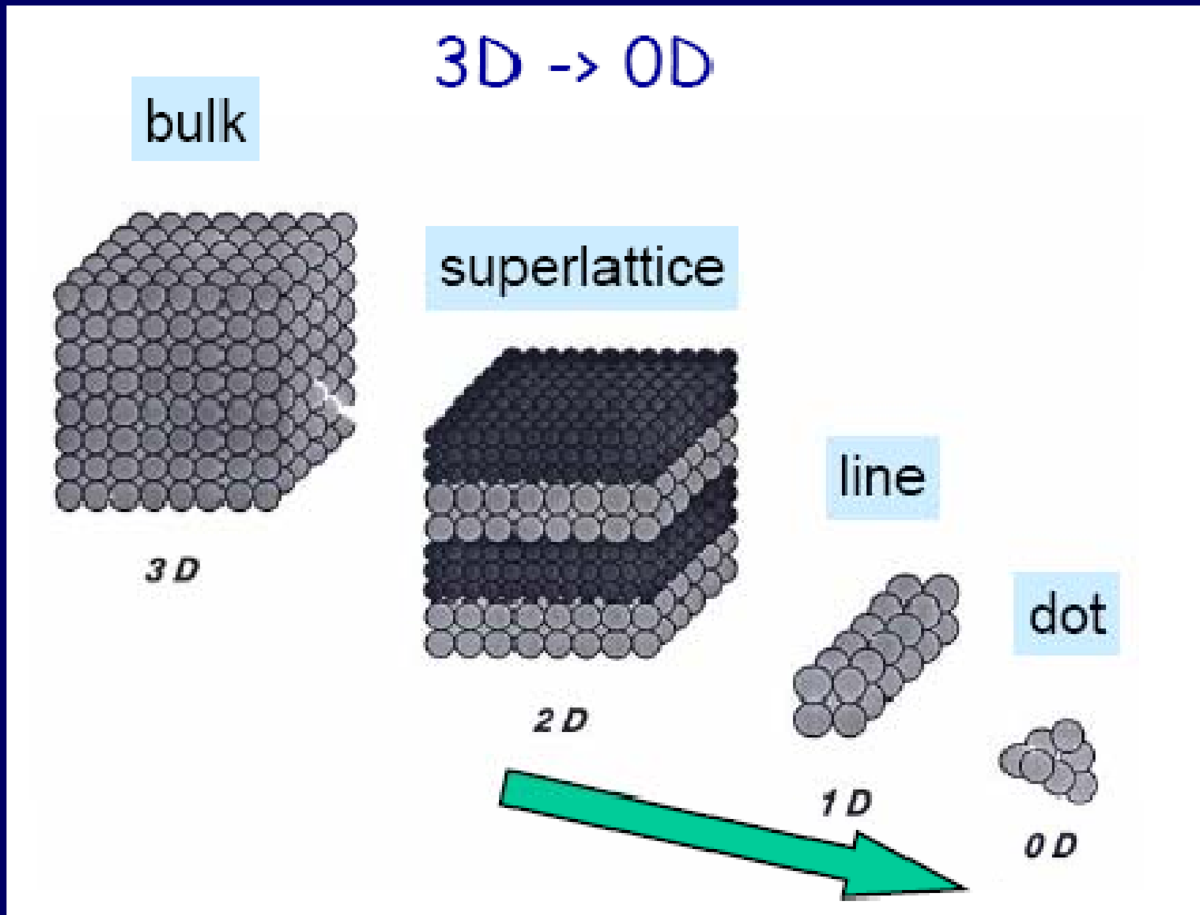
# *Tailoring* Magnetic Properties ← Interfacial Phenomena

Critical Temperature

Induced Moments

Magnetic anisotropy

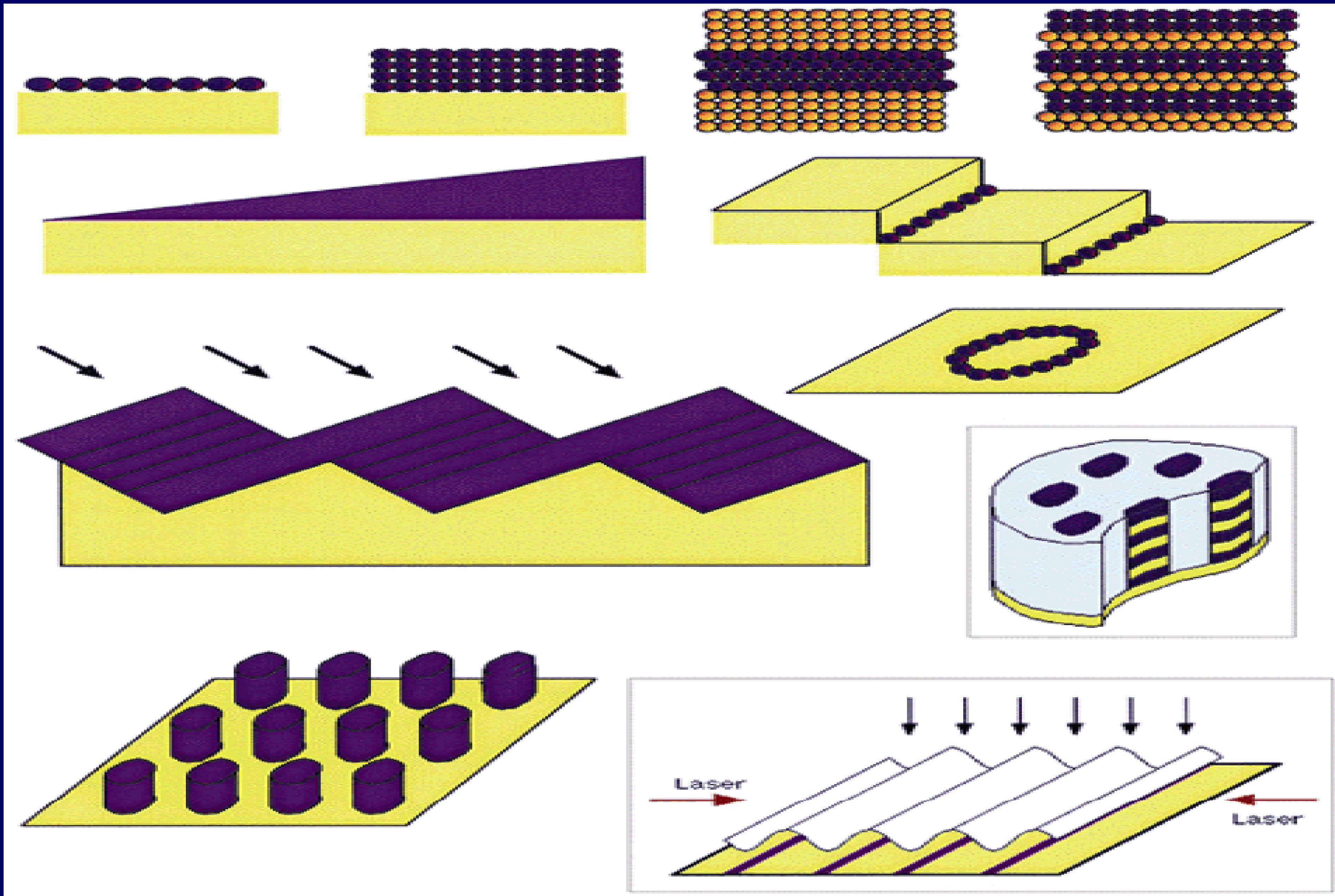
Exchange



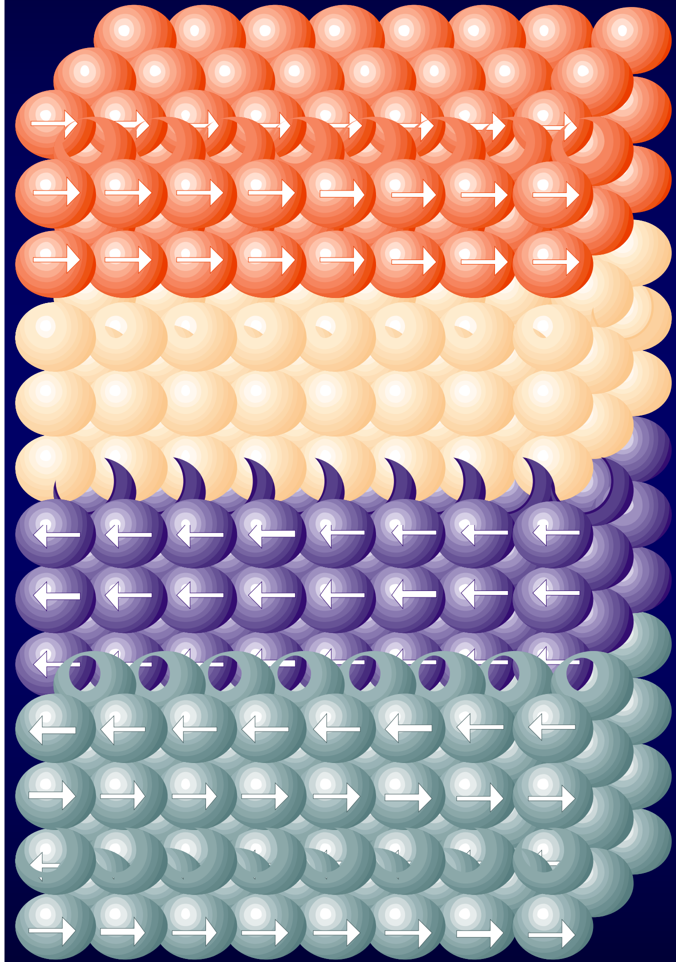
# Thermal evaporation

- Sputtering
- Pulsed laser deposition (PLD)
- Chemical vapor deposition (CVD)
- Molecular beam epitaxy (MBE)

Ultra-high -vacuum UHV conditions



# Ultrathin film Magnetic Superlattices




Exchange-biased spin-valve
MTJ

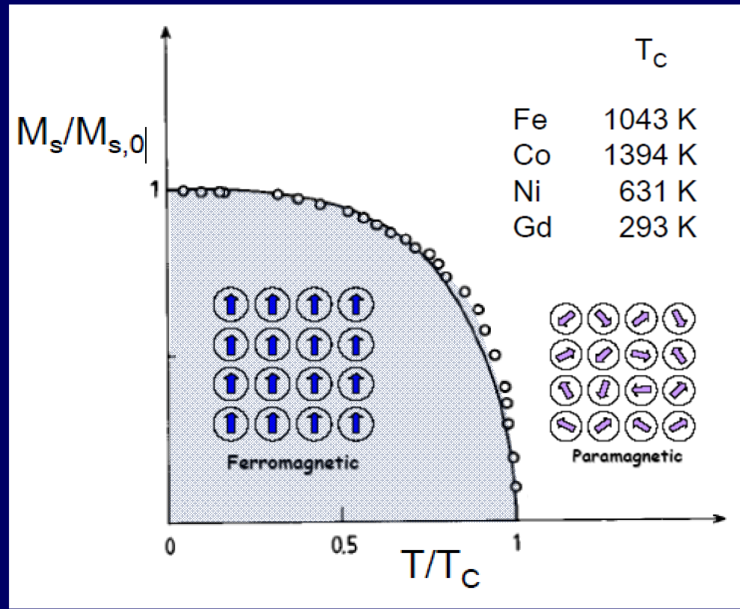
Julio Camarero, *Novel Frontiers in Magnetism*, Benasque 12th February 2014

# Critical Temperature in Magnetic Materials

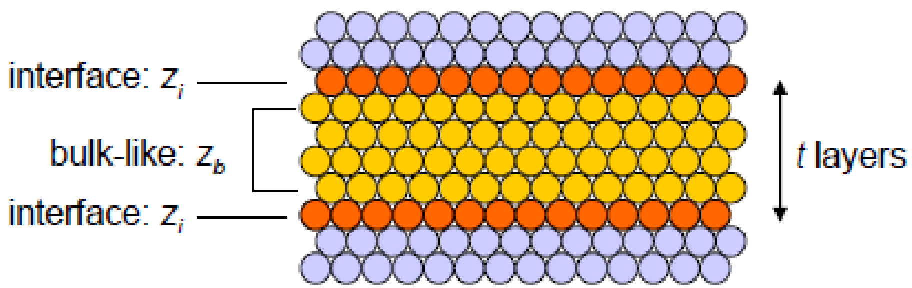
**The Curie temperature depends on the number of nearest neighbors *z*.**

$$T_C = \frac{S+1}{3S}\frac{J_{exc}z}{k}$$

**E.g., for bulk bcc Fe, $z = 8$, $T_C = 1040$ K, $S \approx 2$, $J \approx 0.02$ eV**




***Thin films*** **→ reduced number of magnetic neighbors**

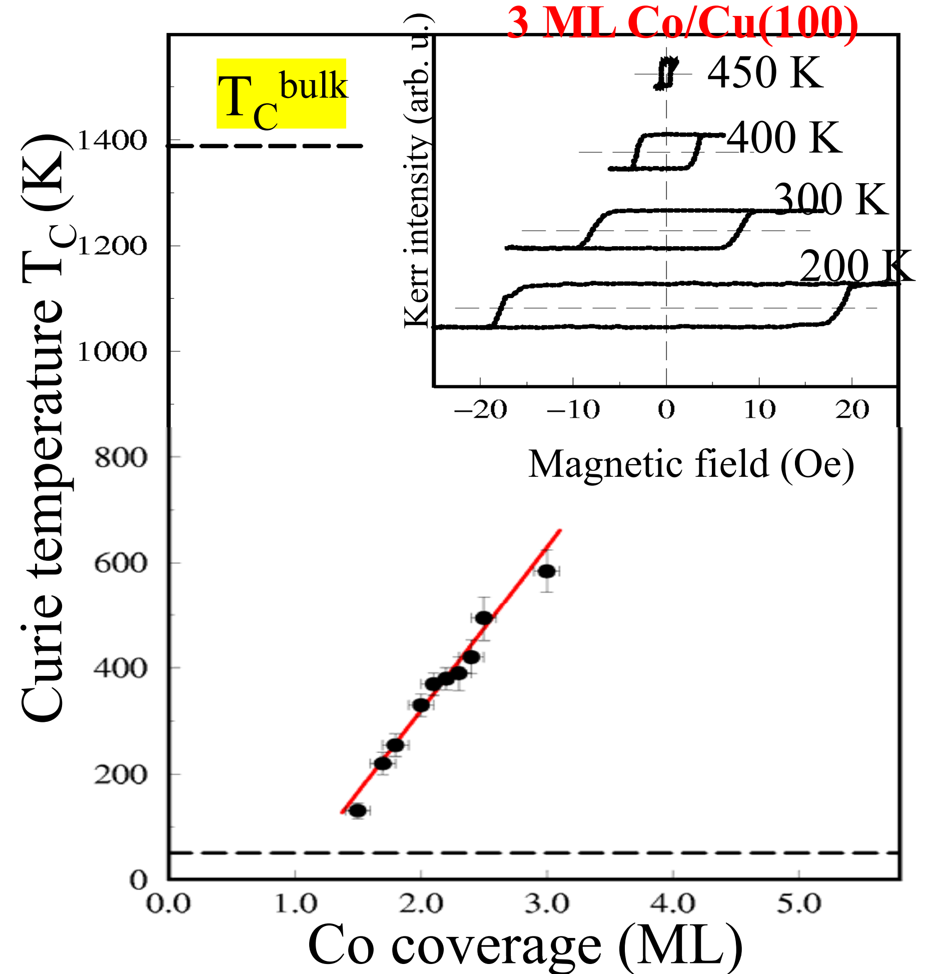



$$\overline{z} = \frac{t_b z_b + t_i z_i}{t_b + t_i} = z_b - 2\frac{z_b - z_i}{t}$$

**$1/t_{FM}$ dependence**

# Critical Temperature in Magnetic Materials

XMCD → $T_C(t_{FM})$




Schneider *et al*, Phys. Rev. Lett **64**, 1059 (1990)

XMLD → $T_N(t_{AFM})$

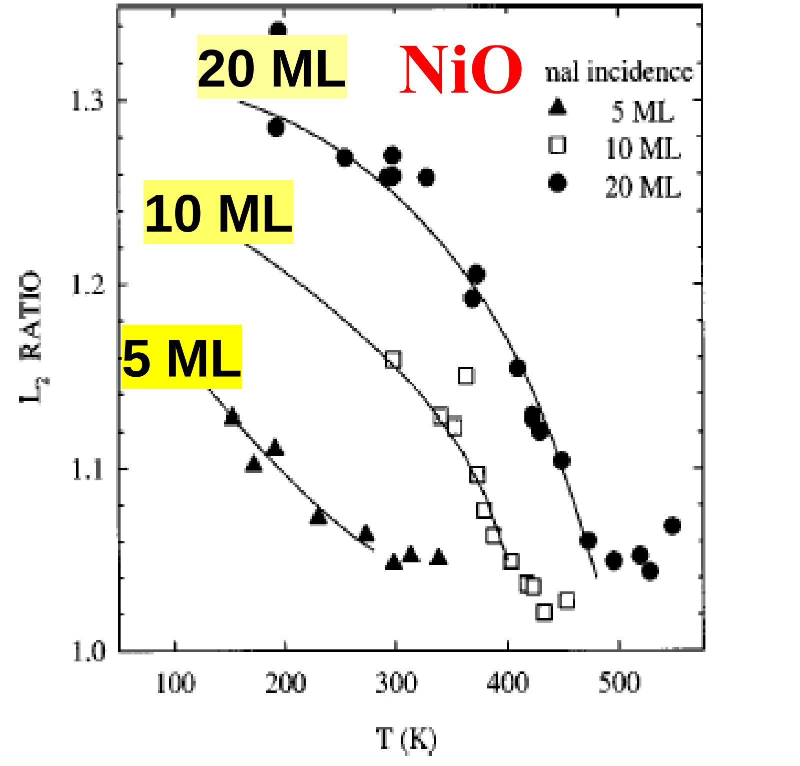



FIG. 12. Temperature and thickness dependence of the ratio of the two peaks in the Ni $L_2$-XAS of NiO(100) thin films, taken at normal incidence. Néel temperatures of $T_N$=295, 430, and 470 K can be found for the 5, 10, and 20 monolayer films, respectively.

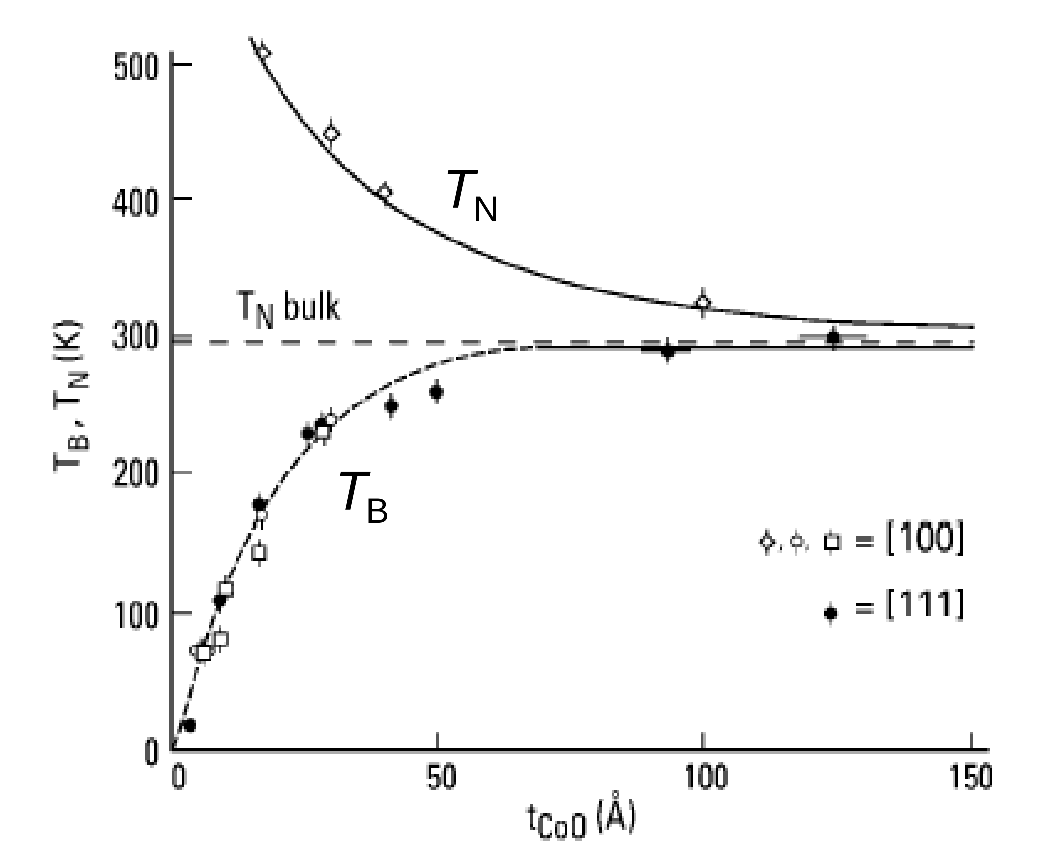
Alders *et al*, Phys. Rev. B **57**, 11623 (1998)

*Critical temperature decreases when thickness decreases*
*⇔ dimensionality effect*

# Proximity effects : interfacial exchange induced order

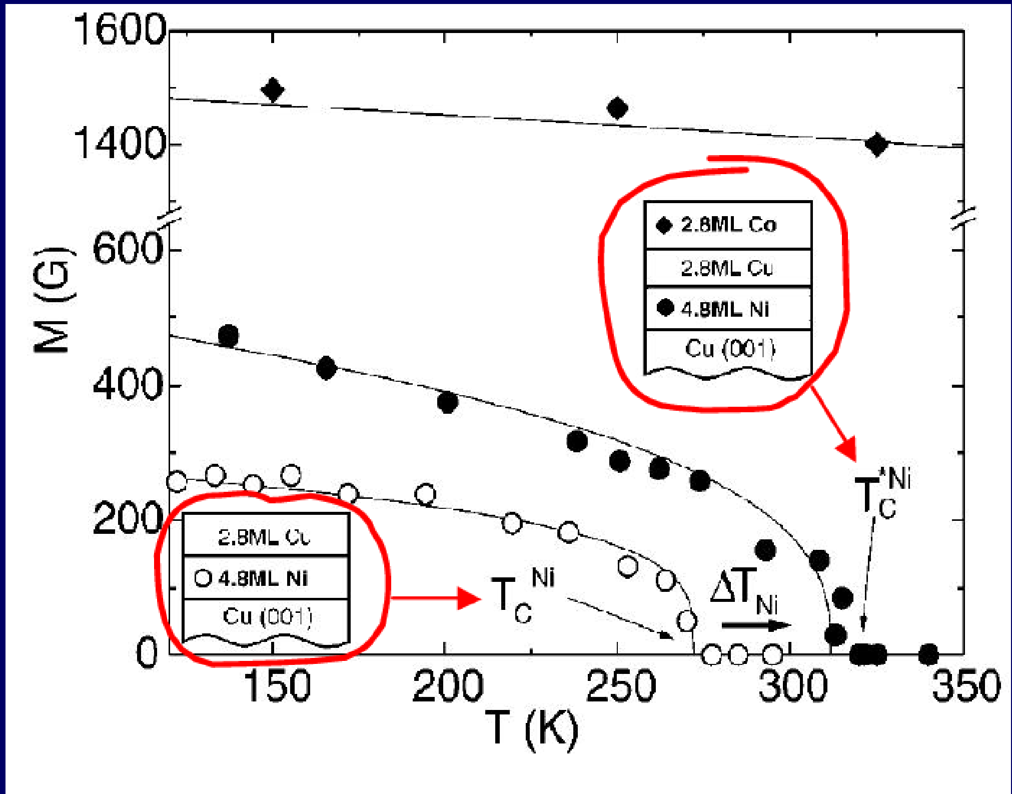
The ordering temperature of the AFM layers (FM nanoparticles) layers is *enhanced* above the bulk $T_N$ ($T_C$) due to the proximity of magnetic FM (AFM) layers.

Exchange-coupling increases of $T_N$




Van der Zaag et al, Phys. Rev. Lett. **84,** 6102 (2000)

Exchange-coupling increases of $T_C$



# PROXIMITY EFFECTS : INDUCED MOMENTS

Induced magnetic moments have been found in non magnetic materials such as Pt, Pd, Cu, W, Ir, C, N in contact with ferromagnetic ones

**Magnetic and element selective tool ⇒ XMCD**

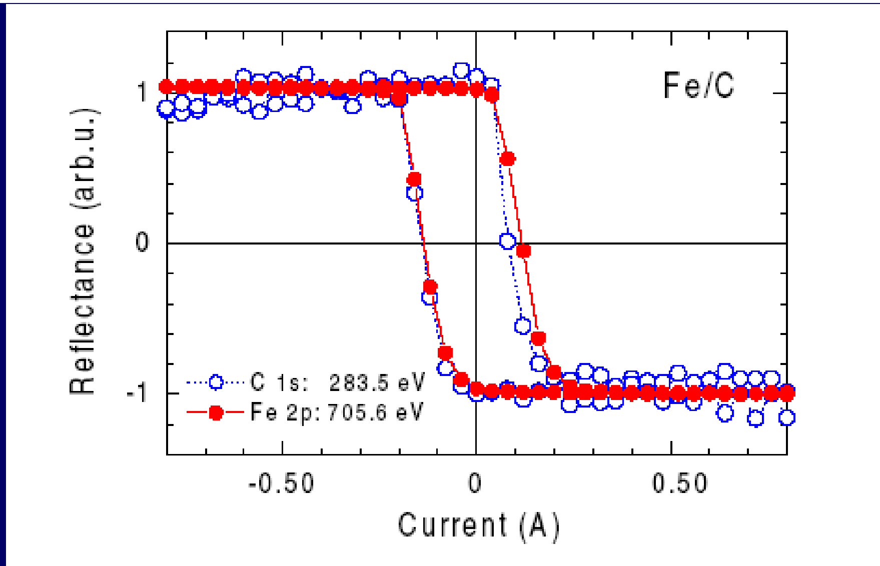
First evidence in Co/Cu multilayers by Samant *et al*, Phys. Rev. Lett **72**, 1112 (1994)

*Europhys. Lett.*, **66** (5), pp. 743–748 (2004)

DOI: 10.1209/epl/i2003-10253-5

## Direct observation of local ferromagnetism on carbon in C/Fe multilayers

H.-Ch. Mertins[1] (*), S. Valencia[2], W. Gudat[2], P. M. Oppeneer[3], O. Zaharko[4] and H. Grimmer[4]



# *Proximity effects* : Induced Moments

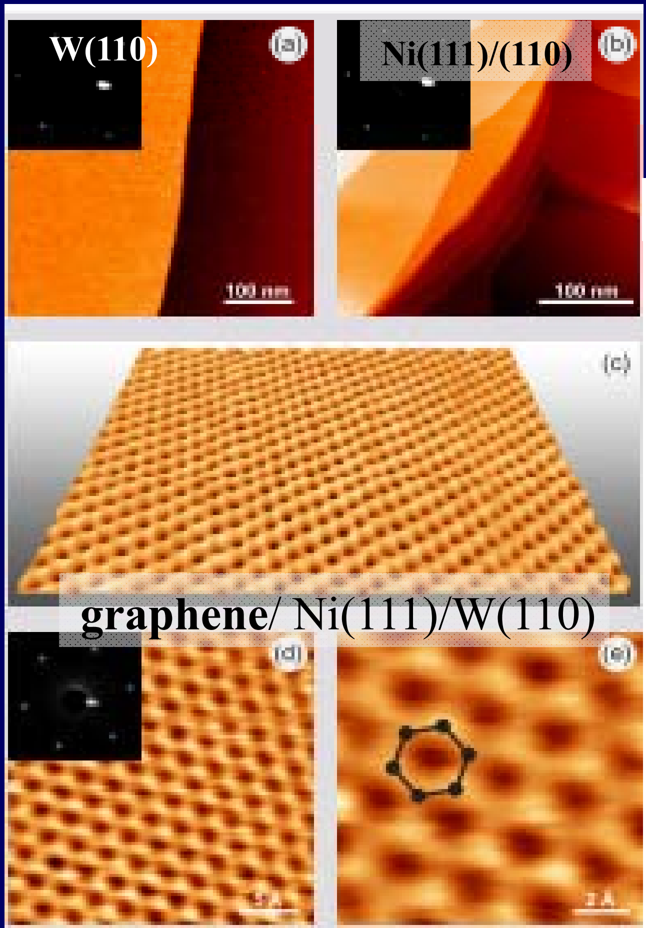
Induced magnetic moments have been found in non magnetic materials such as Pt, Pd, Cu, W, Ir, C, N in contact with ferromagnetic ones

## Magnetic and element selective tool ⇒ XMCD

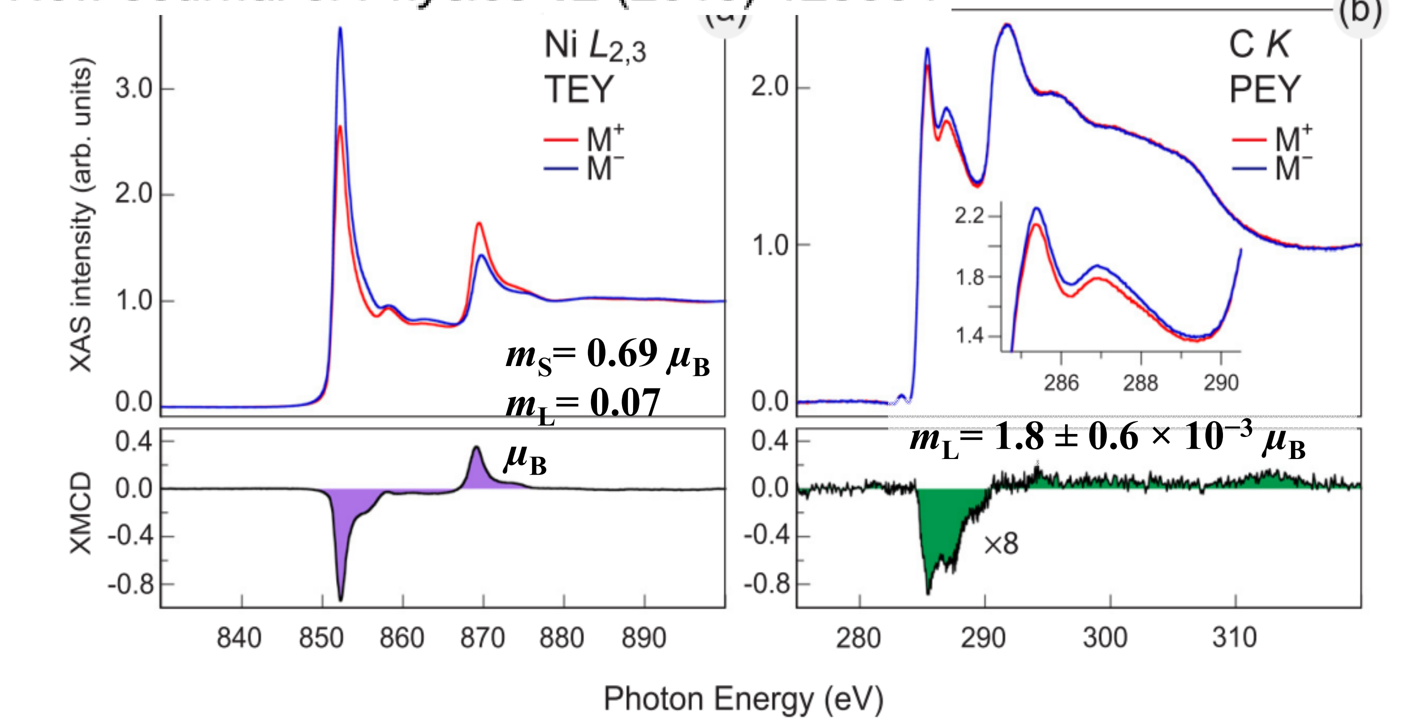
First evidence in Co/Cu multilayers by Samant *et al*, Phys. Rev. Lett **72**, 1112 (1994)

XAS → **existence of interface states**, originating from partial charge transfer from Ni to C atoms (***strong hybridization***)

→ ***induced magnetic moment in the graphene layer***

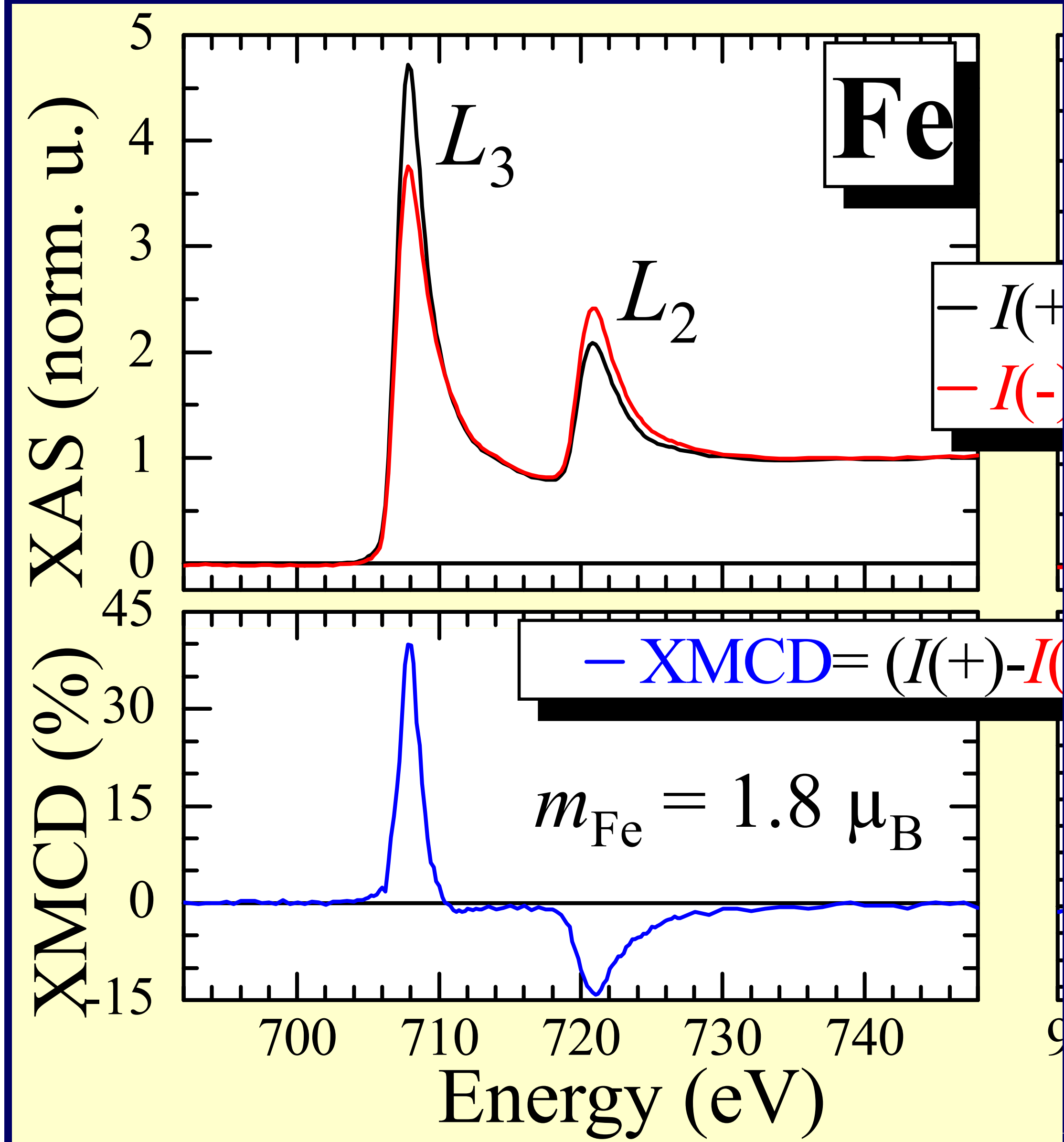



New Journal of Physics **12** (2010) 125004



# Metastable $Fe_xCu_{1-x}$ random alloys grown by surfactants

element-selective magnetic properties of 37 ML $Fe_{55}Cu_{45}$




Fe-Cu *codeposition* on (4x4)Pb/Cu(111)
→atomically disordered FeCu alloys with fcc-fct structure.

Niño *et al*,
J. Phys.: Cond. Matt. **20**, 265008 (2008)



Niño *et al* (2014), in preparation

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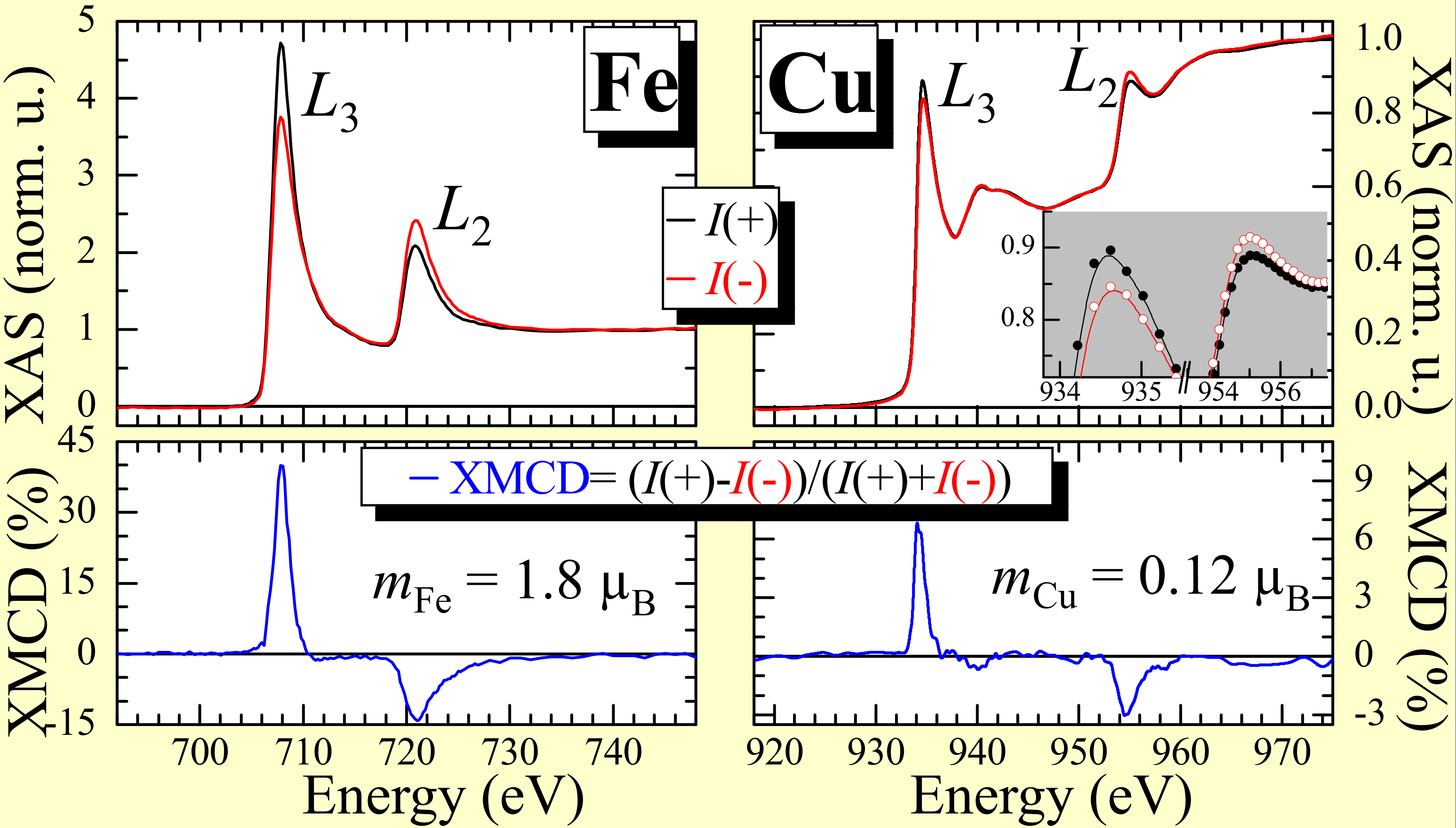
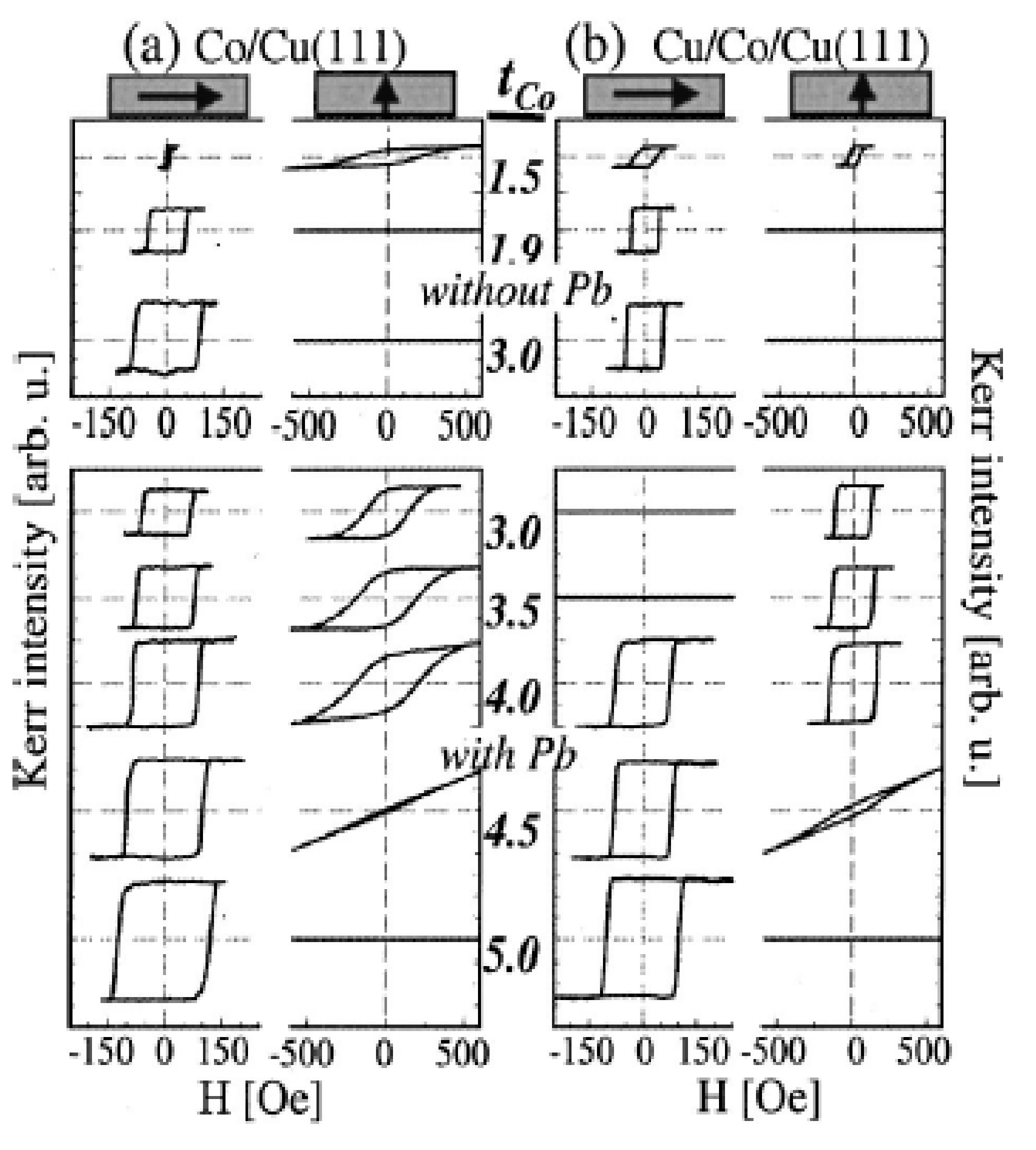



Parallel alignment between Fe and Cu (*induced*) magnetic moments

Julio Camarero, *Novel Frontiers in Magnetism*, Benasque 12th February 2014 — Niño *et al* (2014), in preparation

# Tailoring Magnetocrystalline anisotropy

## Surface-Interface effects

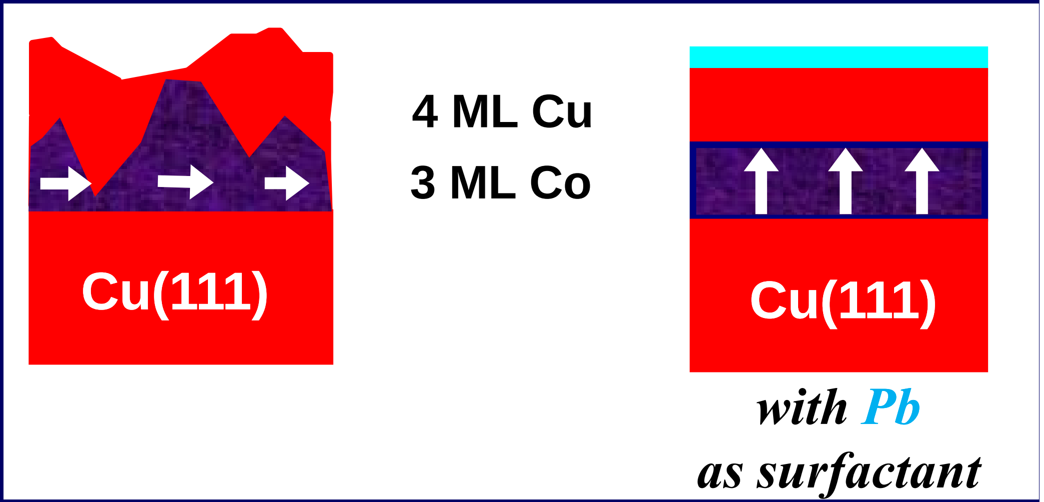



Camarero *et al* Phys. Rev. Lett. **76**, 4428 (1996)

**Interface engineering**

*Perpendicular Magnetic Anisotropy* (PMA)

*two* FM/NM interfaces

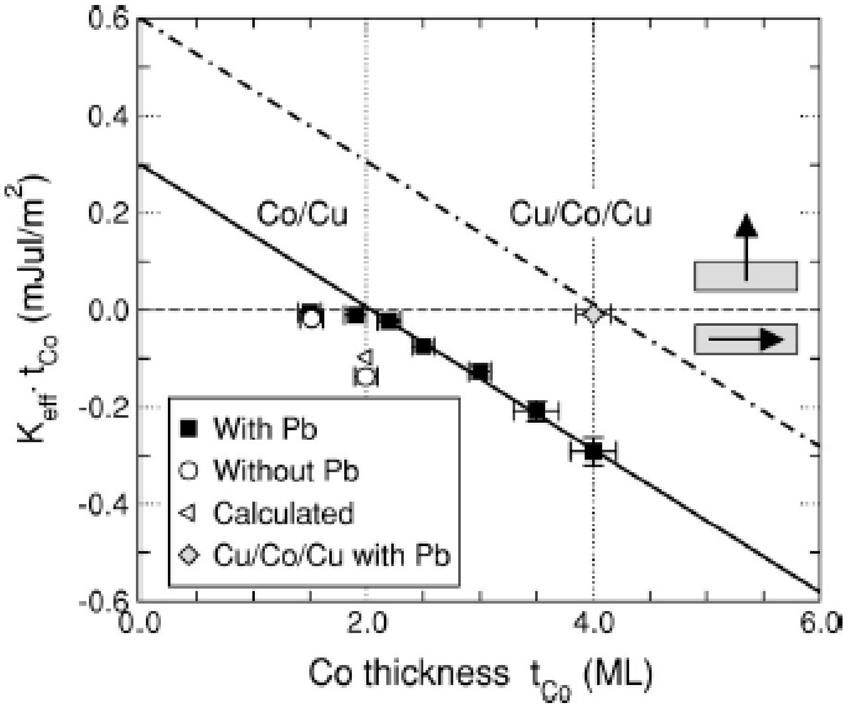



***roughness* vanishes interfacial effects**

# Tailoring Magnetocrystalline anisotropy

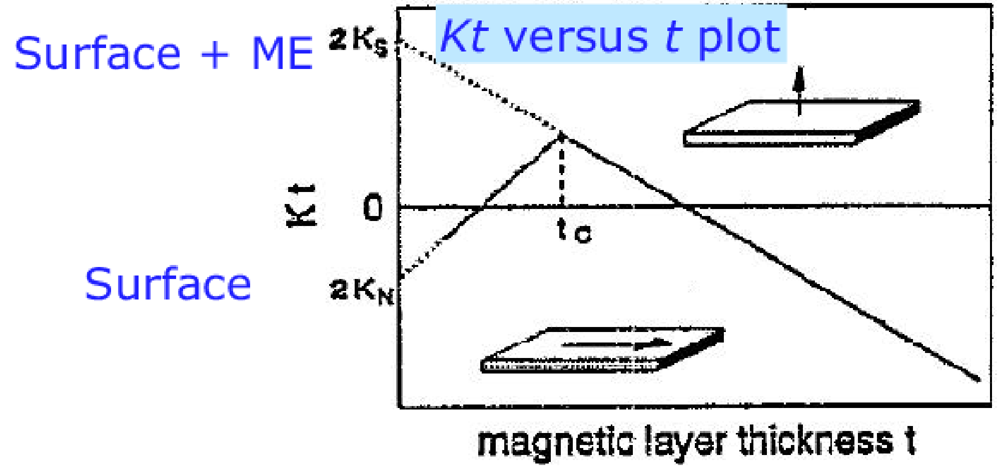
## Surface-Interface effects

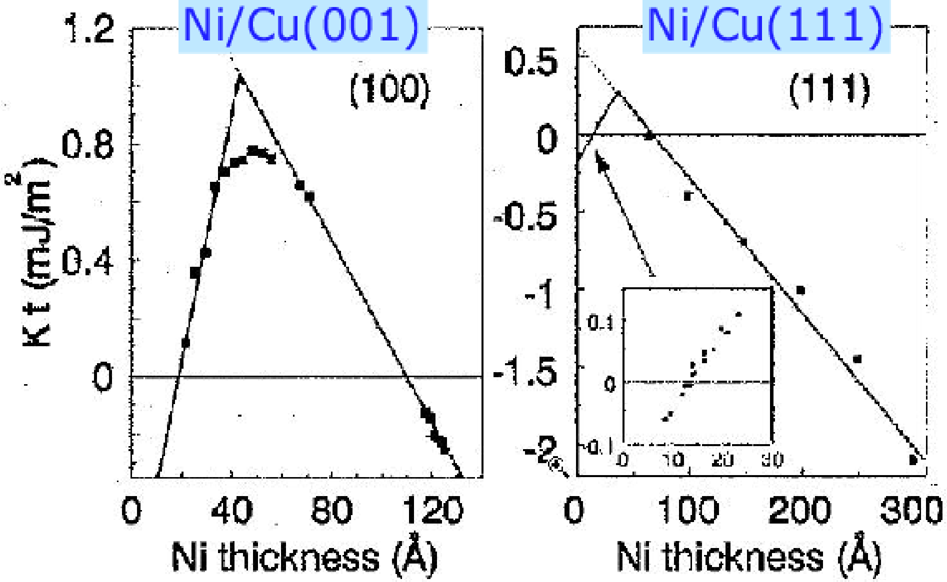
$$K_{eff} = K_V + nK_S\left(\frac{1}{t}\right),$$




Camarero *et al* Phys. Rev. B **64** 125406 (2001)

## Magnetoelastic effects

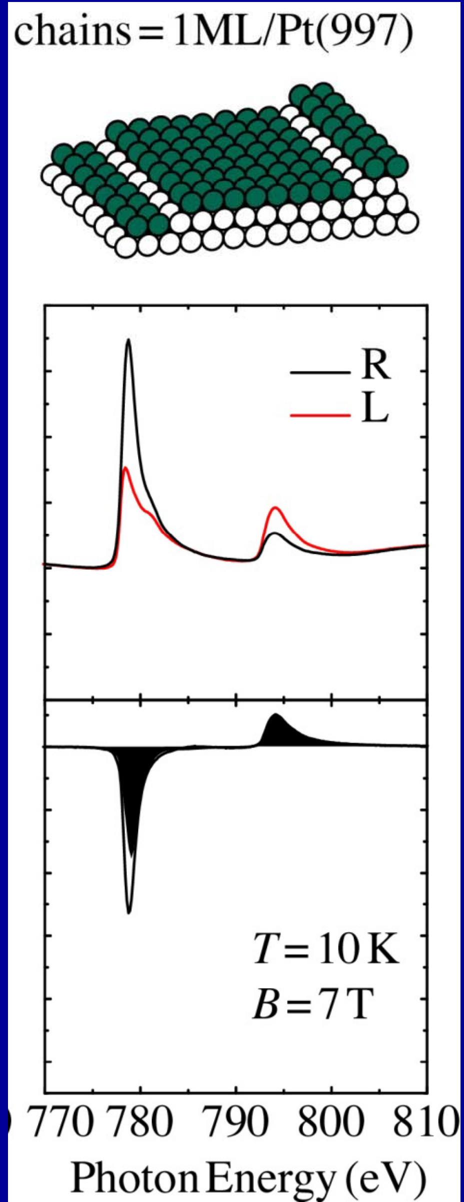



R. Jungblut *et al.*, JAP75, 6424 (1994)

# Dimension-dependent magnetic anisotropy

P. Gambardella *et al*., Nature **416**, 301 (2002); Phys. Rev. Lett. **93**, 077203 (2004).




**enhanced orbital magnetic** moment in 1 ML thick Co film

Signature: rising of $L_3$-XMCD signal

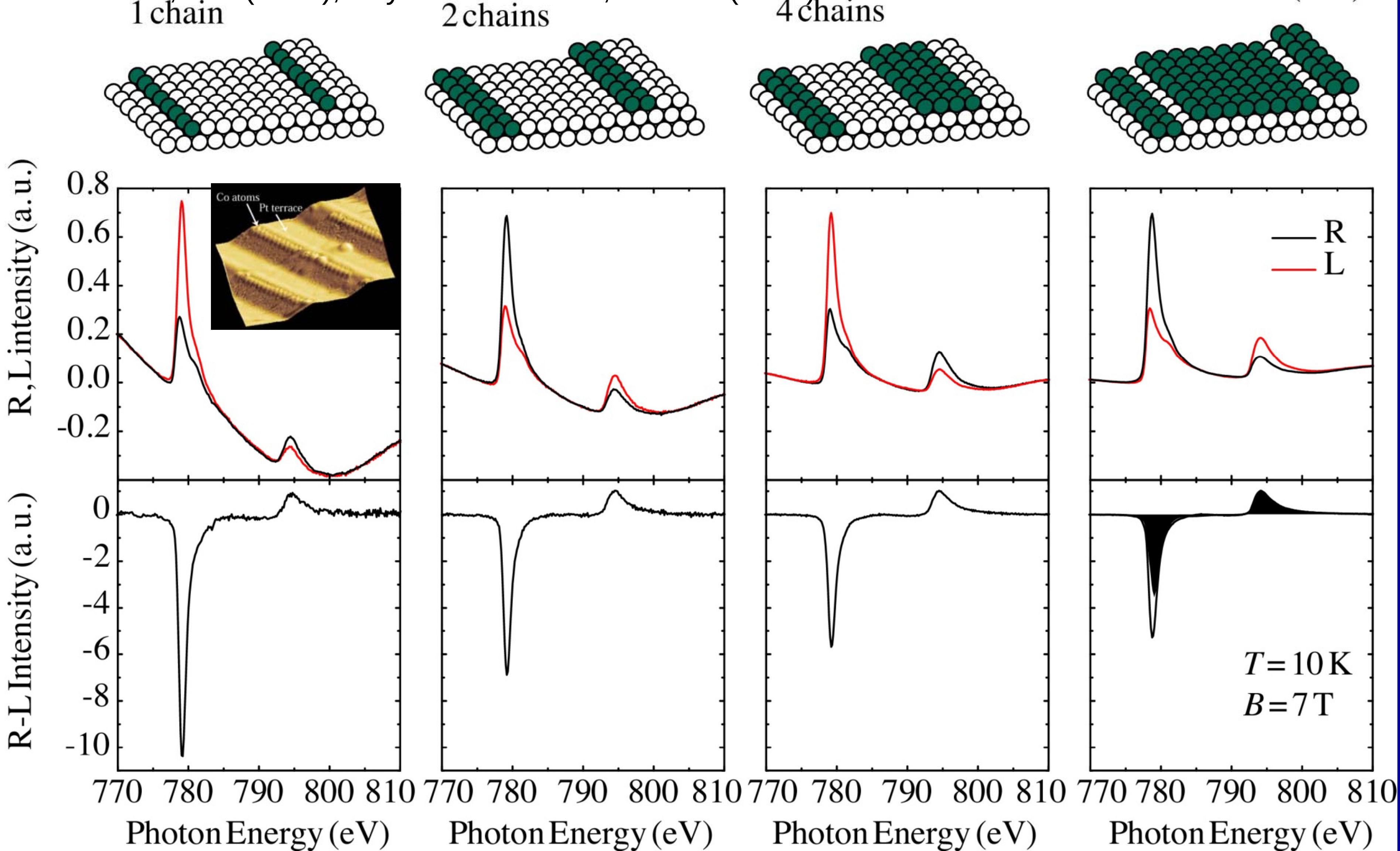
$m_L$

0.31 $\mu_B$

# Dimension-dependent magnetic anisotropy

enhanced orbital magnetic moment in 1D wires

Nature **416**, 301 (2002); Phys. Rev. Lett. **93**, 077203 (2004).

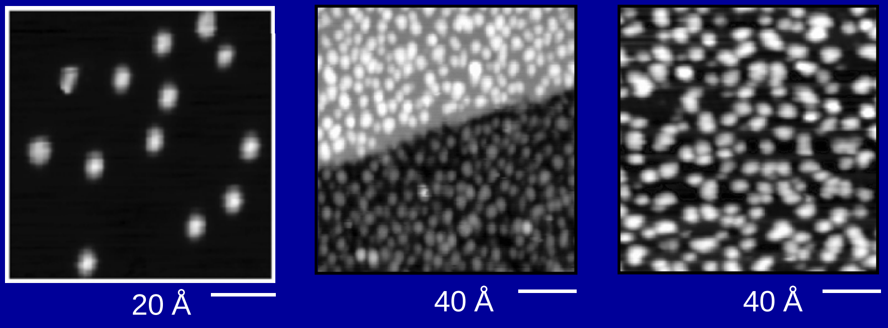


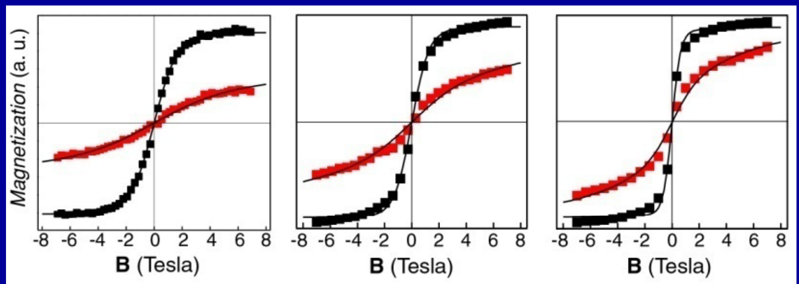

$m_L$ 0.68 $\mu_B$ 0.37 $\mu_B$ 0.33 $\mu_B$ 0.31 $\mu_B$

# Dimension-dependent magnetic anisotropy

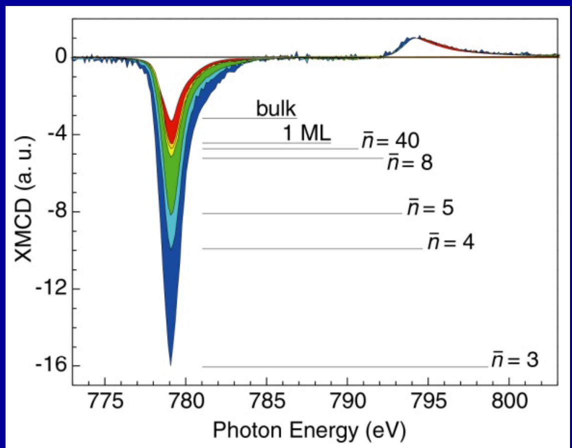
## finite-sized particles: the rise and fall of the magnetic anisotropy

$n = 1$, $T_{dep} = 10$ K | $n = 3$, $T_{dep} = 10$ K | $n = 8$, $T_{dep} = 83$ K

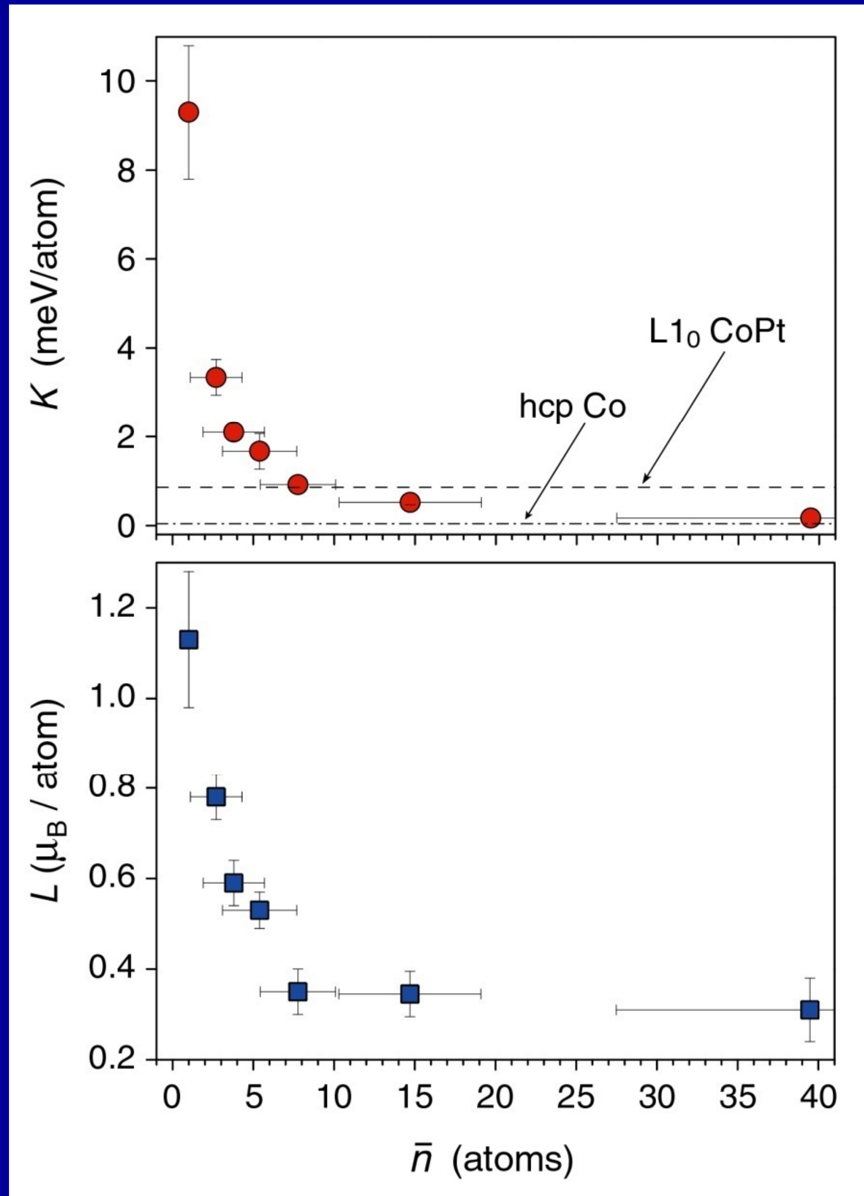



P. Gambardella *et al.*, Science **300**, 1130 (2003)




### coordination effect

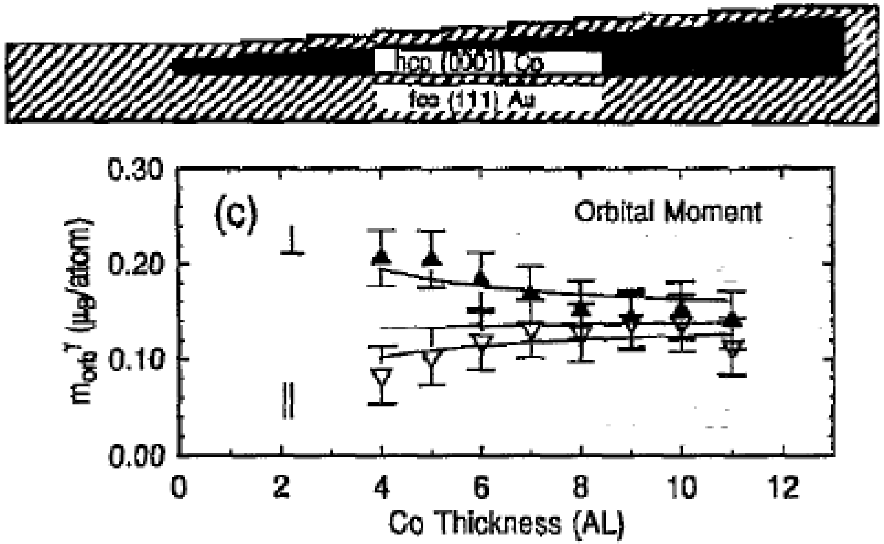


# Origin of Perpendicular magnetic anisotropy:
## Orbital moment in metal films: interface effect

VOLUME 75, NUMBER 20 PHYSICAL REVIEW LETTERS 13 NOVEMBER 1995

**Microscopic Origin of Magnetic Anisotropy in Au/Co/Au Probed with X-Ray Magnetic Circular Dichroism**

D. Weller,[1] J. Stöhr,[1] R. Nakajima,[2] A. Carl,[1,*] M. G. Samant,[1] C. Chappert,[3] R. Mégy,[3] P. Beauvillain,[3] P. Veillet,[3] and G. A. Held[4]

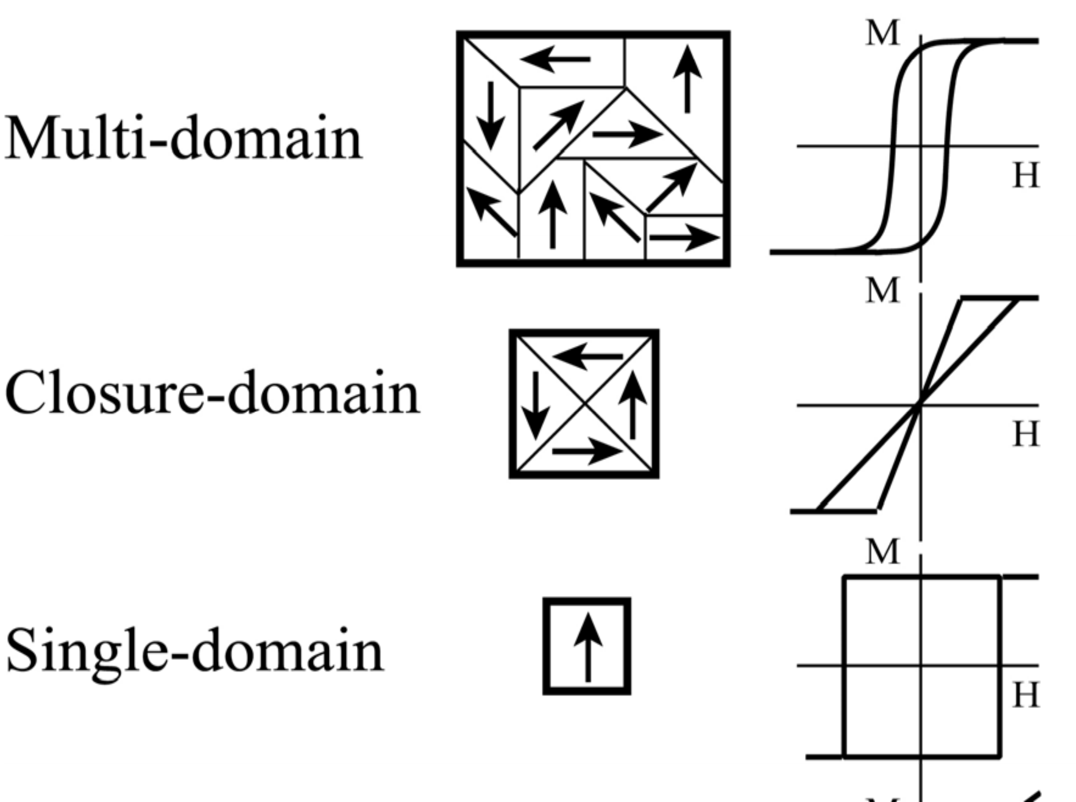



Co film free-standing $W_d^{||} > W_d^{\perp} \Rightarrow m_L^{\perp} < m_L^{||}$

Co film on Au $W_d^{||} < W_d^{\perp} \Rightarrow m_L^{\perp} > m_L^{||}$

# Size effects : Domains and Reversal

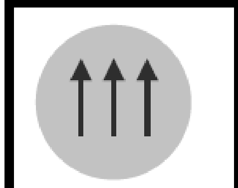
balance of the exchange, anisotropy, and magnetostatic energies




*reducing demagnetizing field*,
**but** energy cost of *domain wall formation*

*size at which the presence of a domain wall in the material is not energetically favorable*

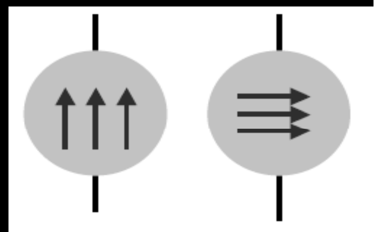
for spherical single crystal nanoparticles → $\Phi_{critical}$ ~ 6 nm (Fe); 30 nm (Co); 760 nm ($SmCo_5$)



Exchange: $A(d\Theta/dz)^2$
short range

Domain wall
$E = 4\,(AK)^{1/2}$
$\delta = \pi\,(A/K)^{1/2}$

Anisotropy: $K \sin^2\Theta$
local



# Size effects : Domains and Reversal

## Thermal effects

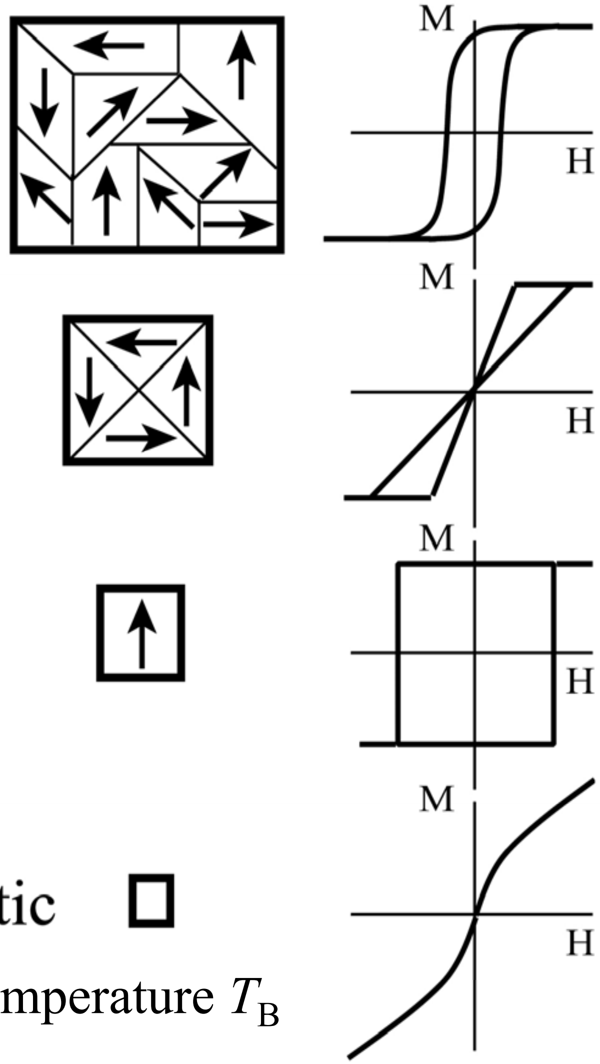
Multi-domain

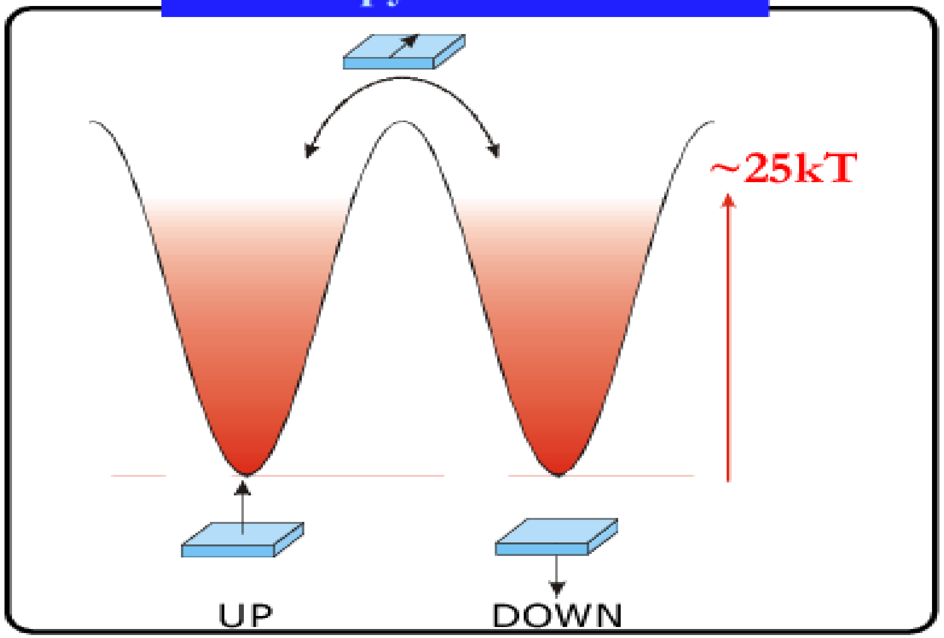
Closure-domain

Single-domain

Superparamagnetic

below blocking temperature $T_B$




**Arrhenius law**

L. Néel, *Ann. Geophys*. **5, 99** (1949)
Brown , PRB **130**,1677 (1963)

Phenomenological thermal activation

$$\tau = \tau_0 \exp\left(\frac{\Delta E}{k_B T}\right) \qquad \tau_0 \sim 10^{-9}\,\mathrm{s}$$

Precession

$$\Rightarrow \quad \Delta E = k_B T \ln(\tau / \tau_0) \sim 25 k_B T$$

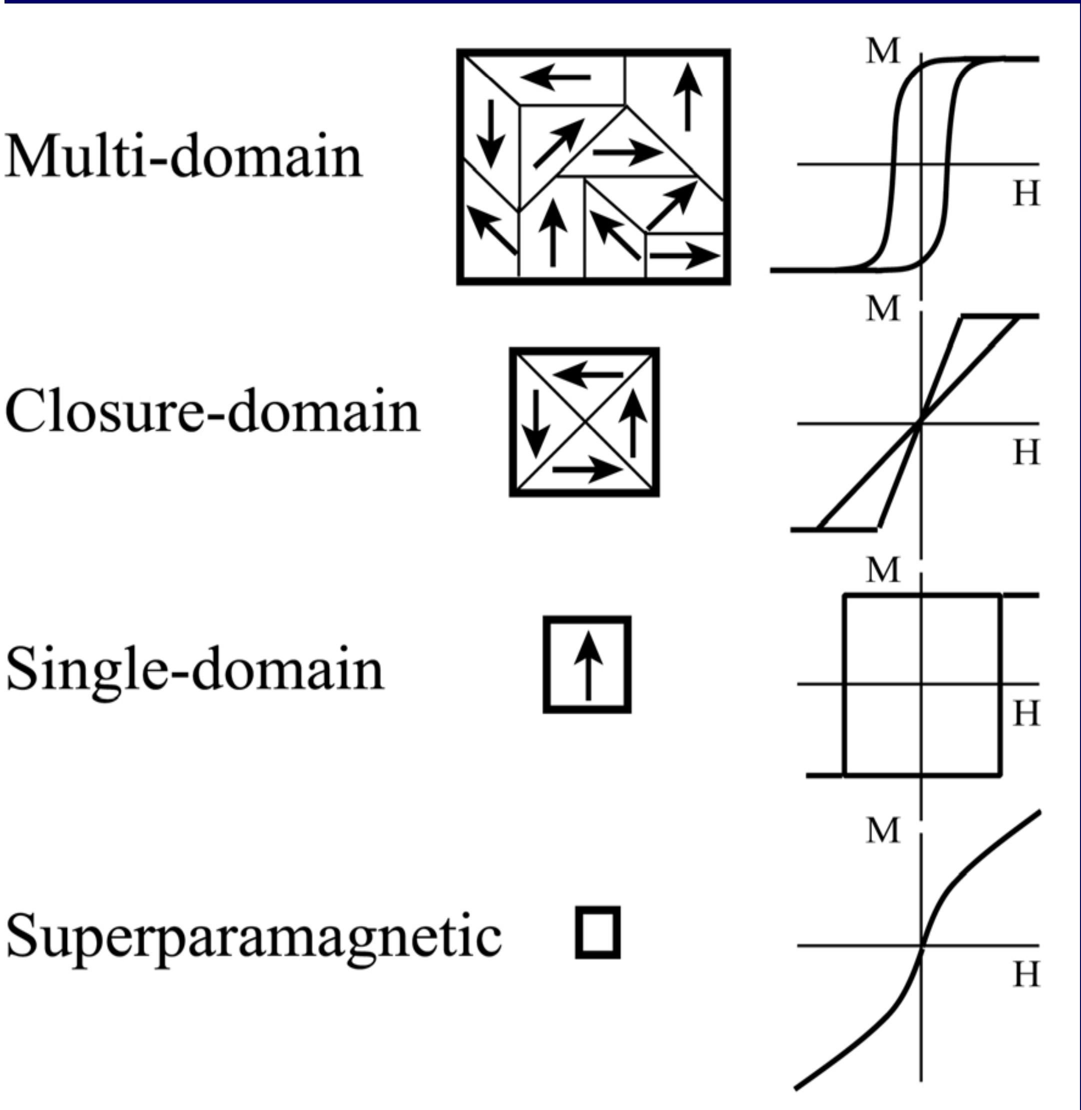
$\tau \sim 1\mathrm{s}$

Experiments

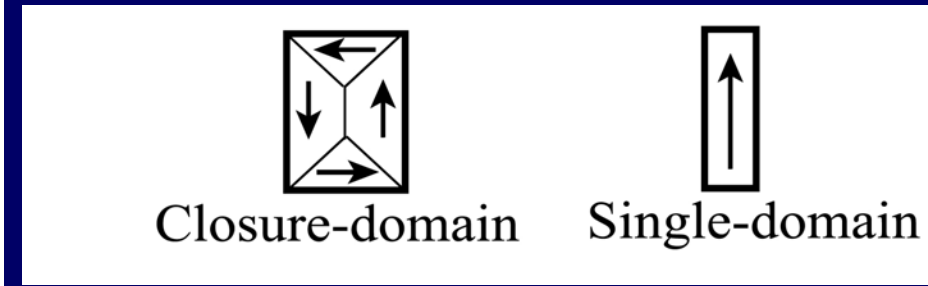
<u>*Superparamagnetism*</u> for $T > T_B = KV/25k_B$

# Size and Shape effects

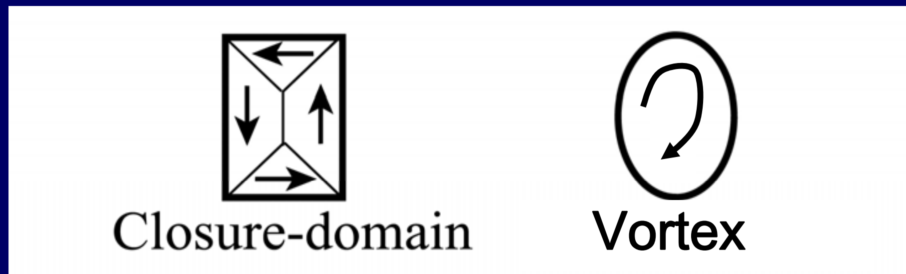
J.I. Martín *et al.*, J. Magn. Magn. Mater. **256**, 449 (2003)



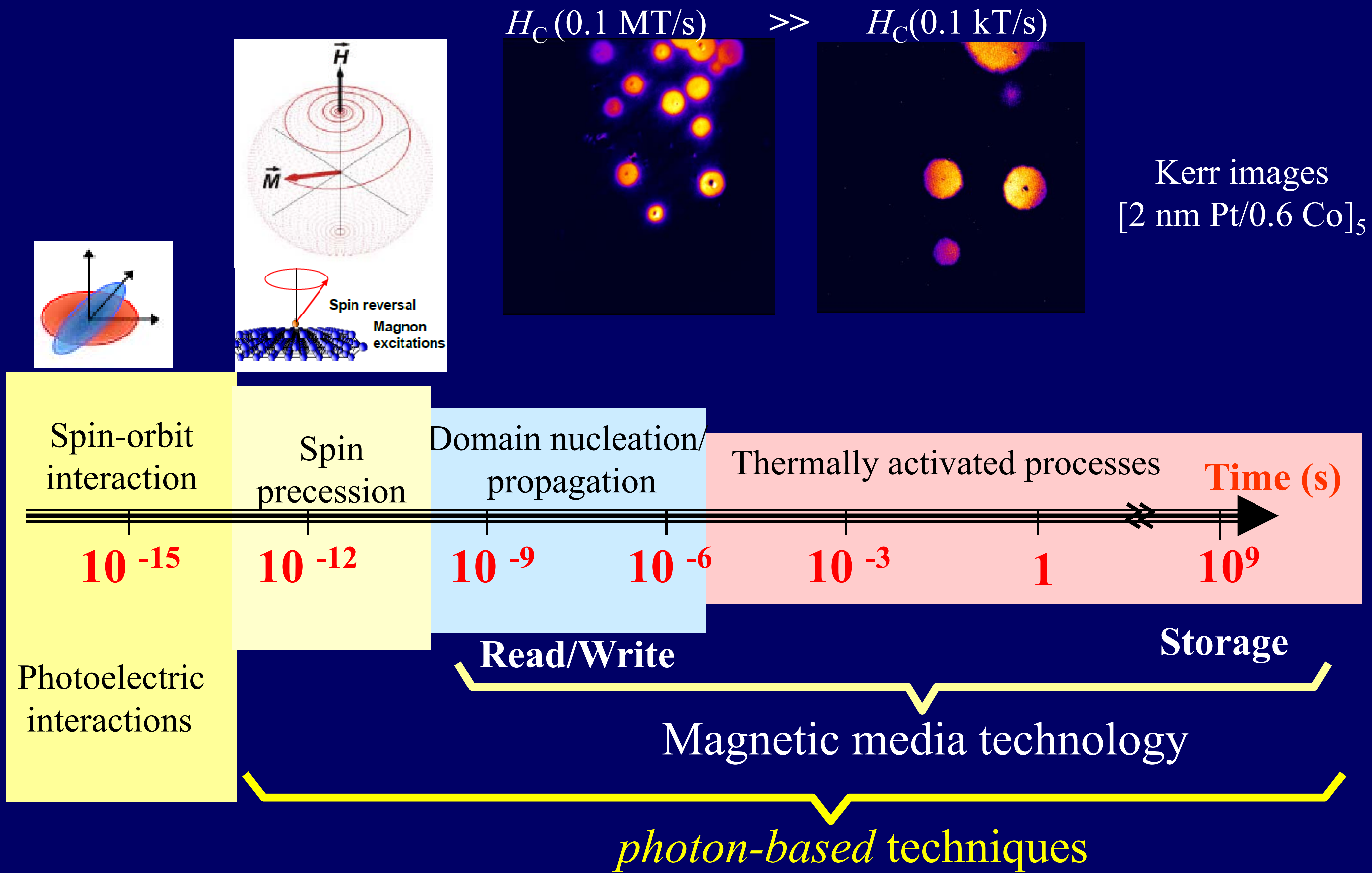

## ASPECT RATIO EFFECTS




## SHAPE EFFECTS

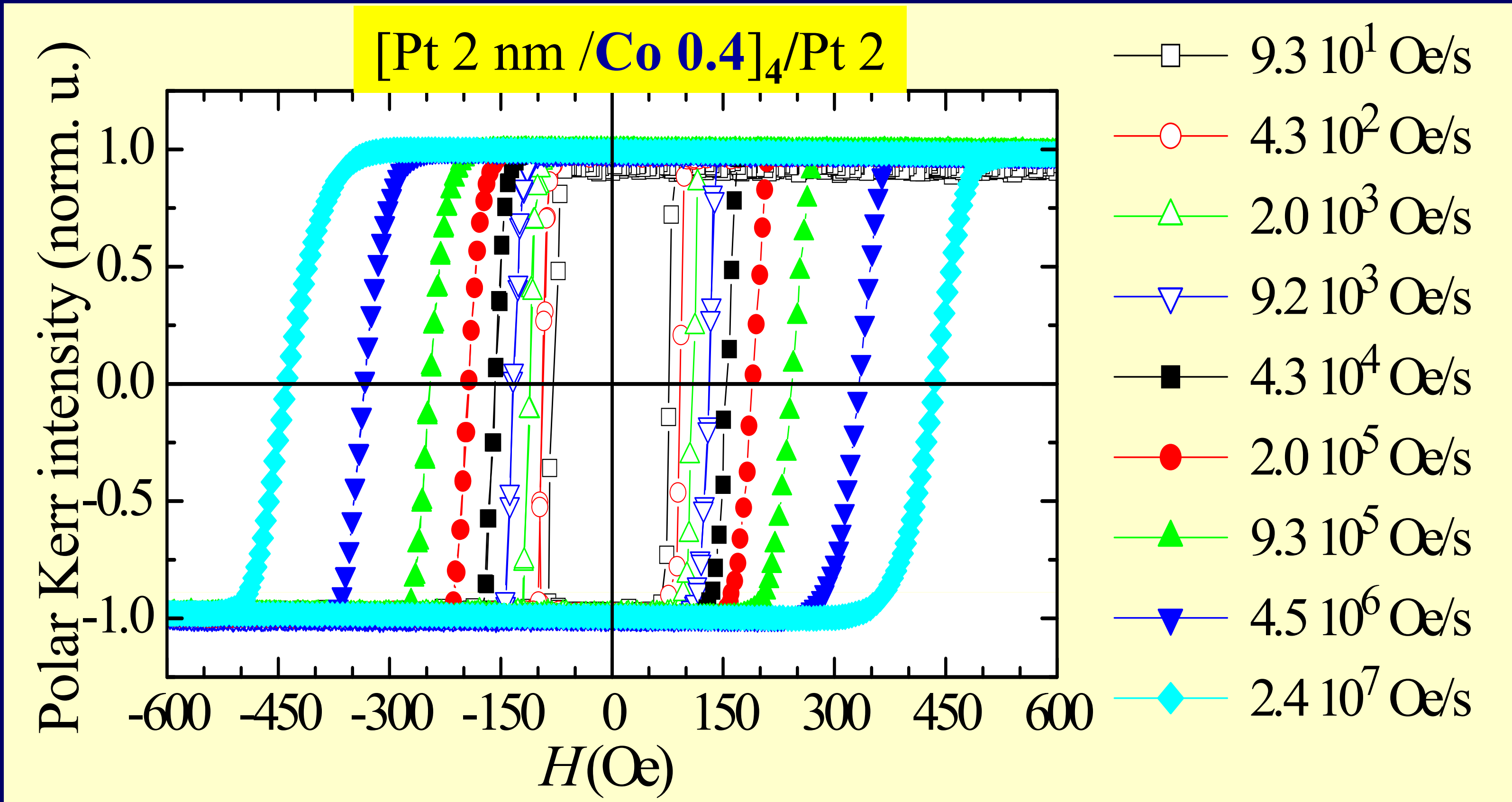


# Timescales in magnetic materials



# Magnetization reversal: dynamics *vs* quasi-static

Camarero *et al*, Phys. Rev. B Rapid Comm. **69**, 180402 (2004); *ibid* **71**, 100402 (2005)



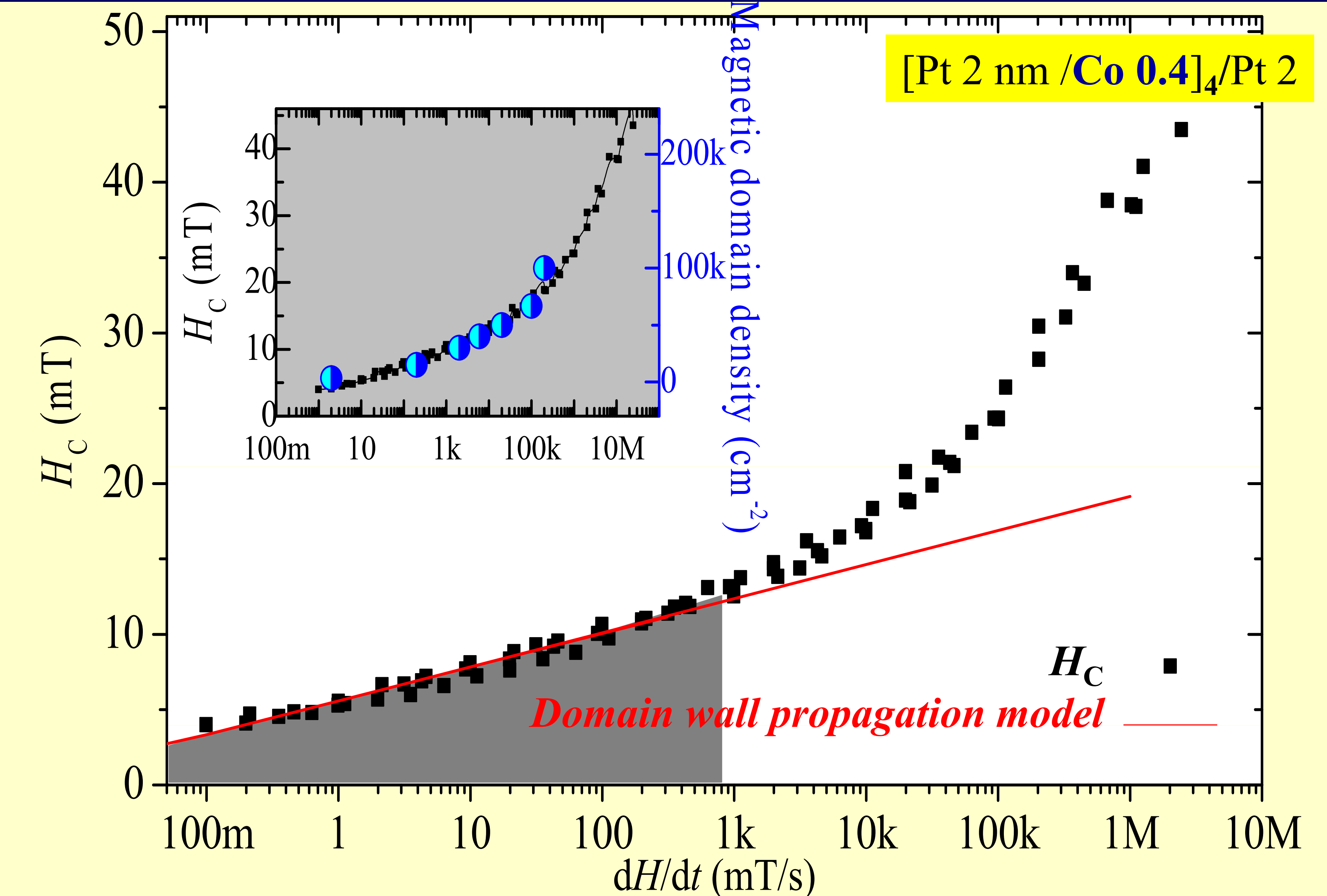

The evolution of both (i) shape and (ii) coercivity $H_C$ with d$H$/d$t$ stresses a *transition between propagation to nucleation regime increasing dH/dt*

(i) square (**lower d*H*/d*t***) ⇔ governed by **DW propagation** process;
smooth (**higher d*H*/d*t***) ⇔ **domain nucleation** process dominates.

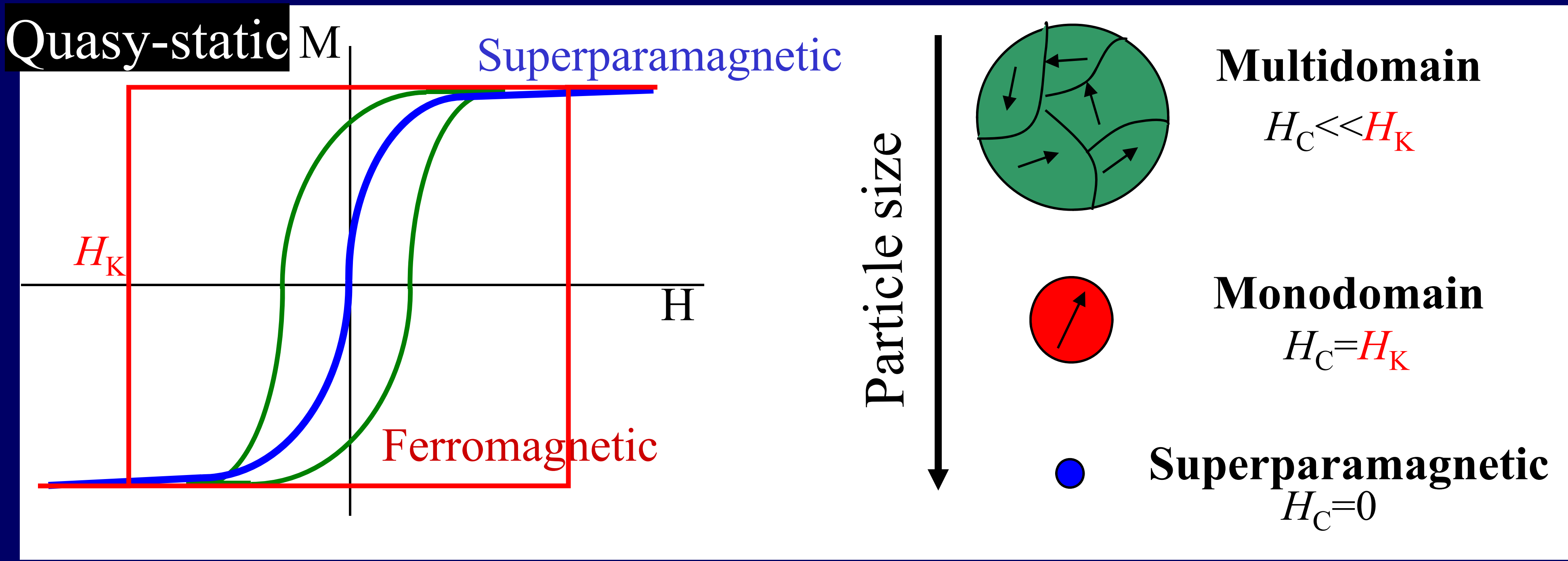
(ii) $H_C$ increases as d$H$/d$t$ increases

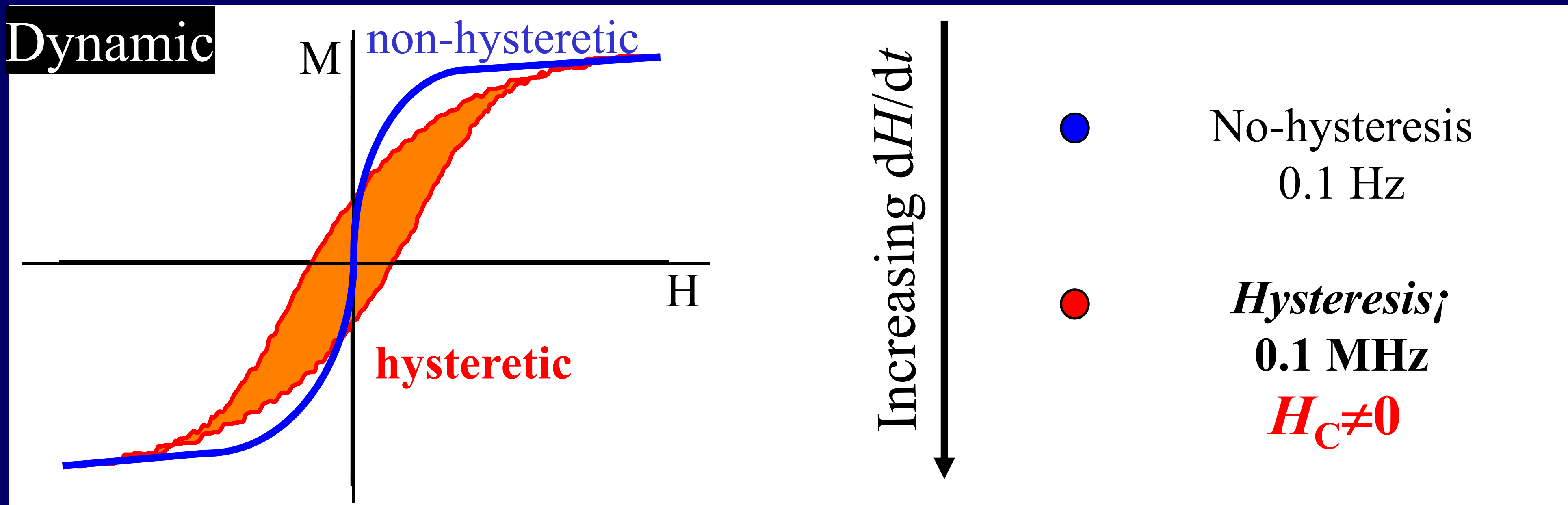
# Magnetization reversal: dynamics *vs* quasi-static

Camarero *et al*, Phys. Rev. B Brief Report **64**, 172402 (2004); J. Appl. Phys. **89**, 6585 (2001)



# Size +Thermal effects: *superparamagnetic limit*



# Interlayer magnetic coupling through a non magnetic spacer

## Metallic Spacer

•Ferromagnetic direct coupling


## Non Metallic Spacer

•Ferromagnetic direct coupling.

# Interlayer magnetic coupling through a non magnetic spacer

## Metallic Spacer

•Ferromagnetic direct coupling

•**Oscillatory** exchange coupling with spacer thickness. (~ several nm)

Fe/***Cr***/Fe: Grunberg *et al*, PRL **57**,2442 (86)

Co/**Cu**/Co: Cebollada *et al*, PRB **39**,9726 (89)

Parkin *et al*, PRL **66**, 2152 (91)

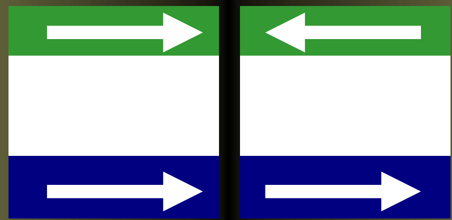
•Interactions propagated by s-p *e*-.

•Topology of the spacer metal Fermi surface (RKKY–type coupling).

Bruno and Chappert, PRL **67**, 1602 (91).

pinholes

spin polarized current



## Non Metallic Spacer

•Ferromagnetic direct coupling.

•**Monotonic nonoscillatory** variation with spacer thickness.

Slonczewski, PRB 39, 6995 (1989);

•*Fe/**Si**/Fe:* Toscano *et al* JMMM **114**, L6 (92)

Fullerton *et al* JMMM **117**, L301 (92)

•*Fe/**MgO**/Fe/Co*, AF coupling bellow 1nm

Faure-Vincent *et al*, PRL **89** 107206 (02)

•Spin asymmetry of the reflections at the interfaces. Bruno, PRB **49**, 13 231 (94).

# Interlayer magnetic coupling through a non magnetic spacer

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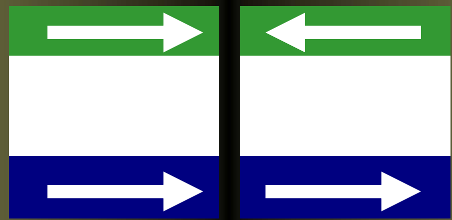

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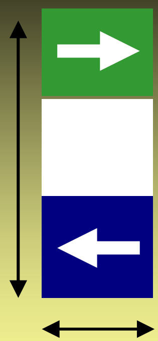
•Spin asymmetry of the reflections at the interfaces. Bruno, PRB **49**, 13 231 (94).

## magnetostatic

### *"stray-field"* coupling

Moon *et al*, APL **64**, 3690 (99)



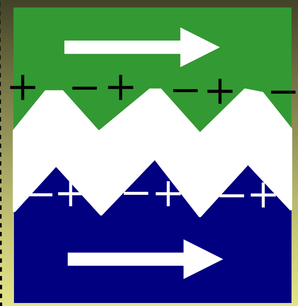
Negative interaction between magnetic charges created by the reduced in-plane dimensions of the structure.

⇒ uncompensated magnetic poles at the edges

⇒ **antiferromagnetic coupling**

### Néel *Orange-peel* coupling

L. Néel, Comptes Rendus **255**, 1676 (62)




$$H_N = \frac{J}{M_{soft} t_{soft}} = \frac{(\pi A)^2}{t_{soft}\sqrt{2}\lambda} M_{hard} \exp\left(-2\pi\sqrt{2}\, t_{NM}/\lambda\right)$$

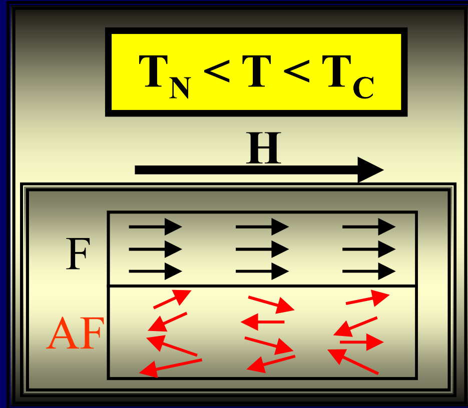
correlated topological roughness at F/NM interfaces

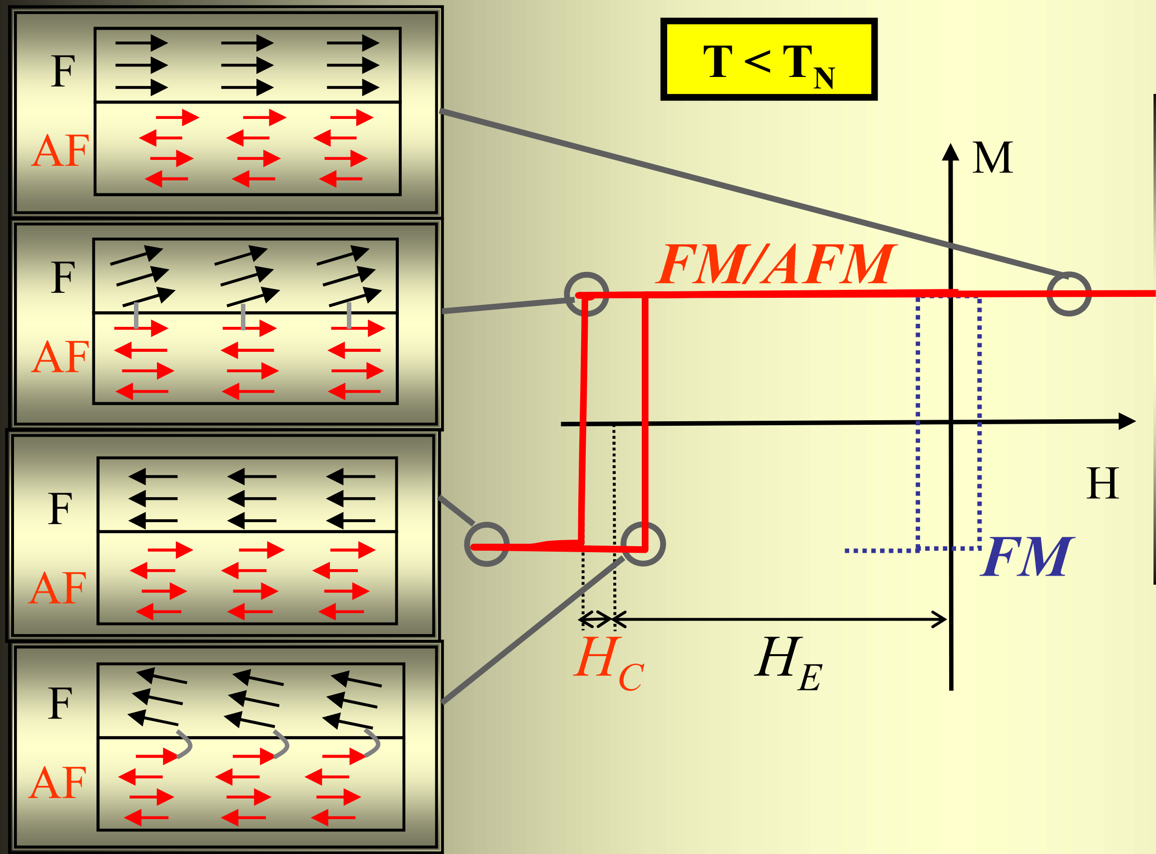
⇒ magnetic charges on topological bumps.

⇒ **ferromagnetic coupling**

# Exchange-coupled antiferromagnetic-ferromagnetic bilayers

__1956__ *"A new type of magnetic anisotropy has been discovered which is best described as an exchange anisotropy. This anisotropy is the result of an interaction between an antiferromagnetic material and a ferromagnetic material"*
W.H. Meiklejohn and C.P. Bean, Phys Rev B **102** (1956), 413.




☞ Unidirectional anisotropy,
(i.e. shift in the hysteresis loop)

$$H_E = \frac{\Delta\sigma}{M_F t_F}$$

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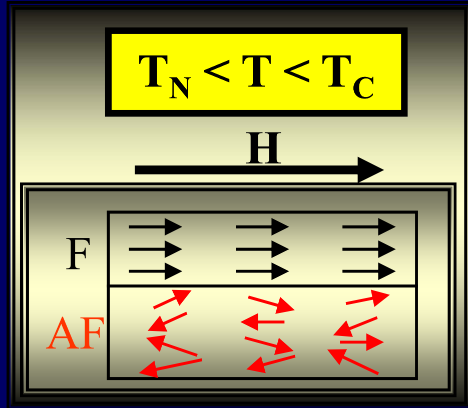
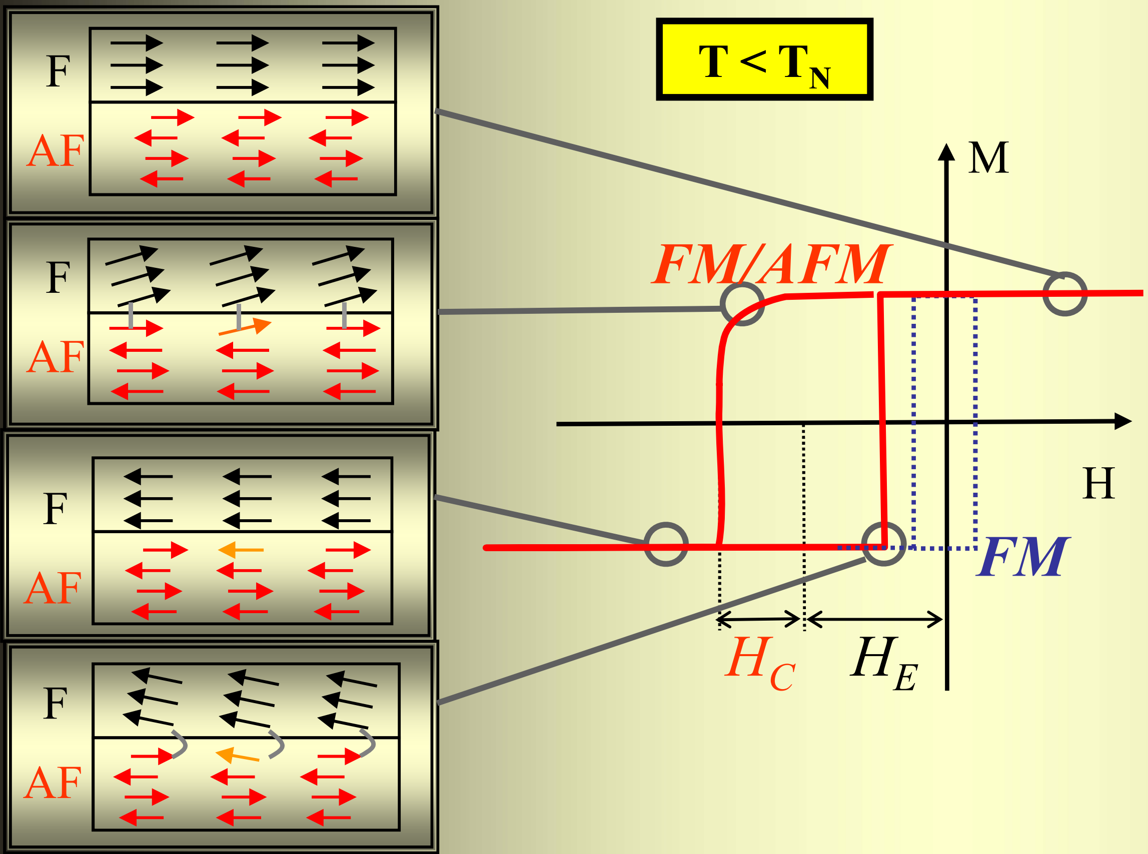



***Main experimental evidences***

- Unidirectional anisotropy,

$$H_E = 0.01 \times \frac{\Delta\sigma}{M_F t_F}$$

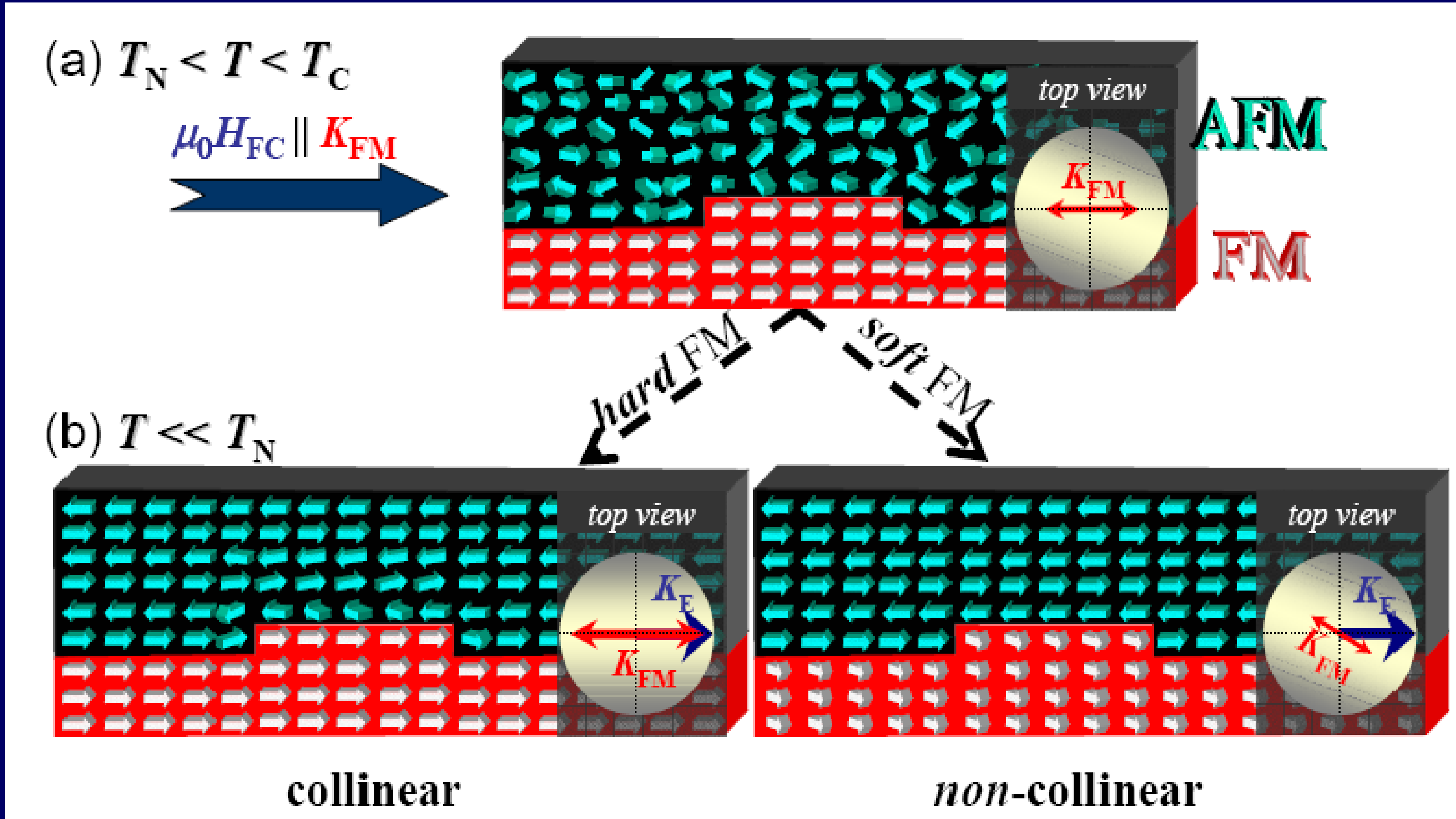
- Enhanced coercivity:

$H_C(FM/AFM) > H_C(FM)$

- Magnetization reversal asymmetry
- also in perpendicular anisotropy systems

# Interfacial spin frustration effects in FM/AFM systems

Jimenez *et al*. Phys. Rev. B **80**, 014415 (2009), J. Appl. Phys. **109**, 07D730 (2011)



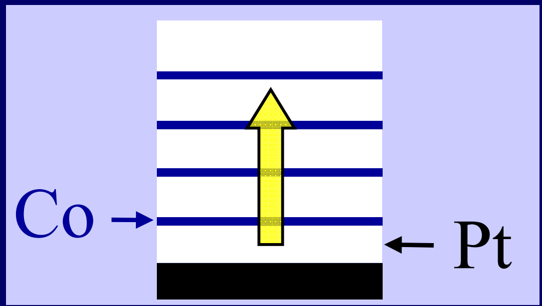

Inevitable atomically rough FM/AFM interfaces induces interfacial spin frustration

→ *magnetic reorientation in soft FM systems*

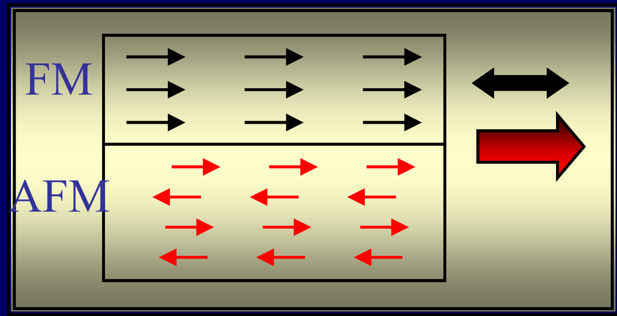
# Engineering magnetic anisotropy

## Electronic interactions

*perpendicular* (hybridisation)



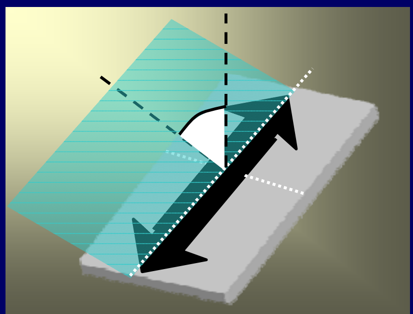

*unidirectional* (direct exchange)



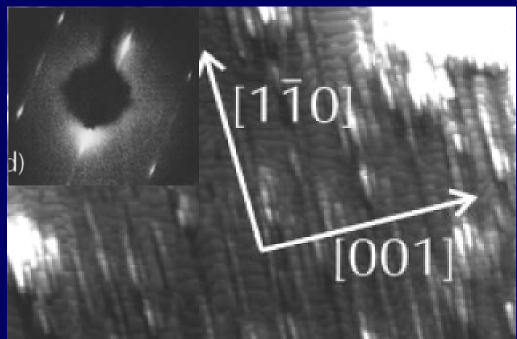

## Magnetostatic interactions

*uniaxial*

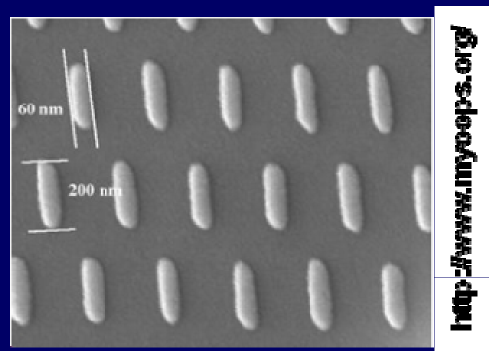
angle of deposition



anisotropic stress, diffussion

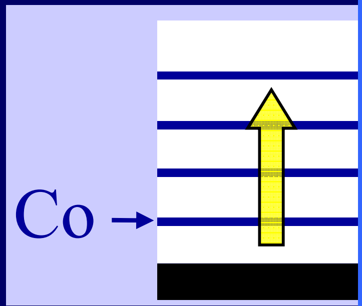



shape,…

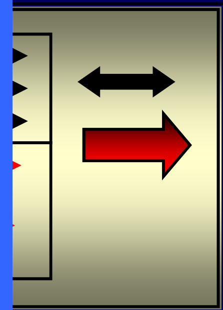


# ENGINEERING MAGNETIC ANISOTROPY

*perpendicular* (hyb




ct exchange)



**new (additional) magnetic anisotropy not only alters the anisotropy axes**

**New magnetic behavior**

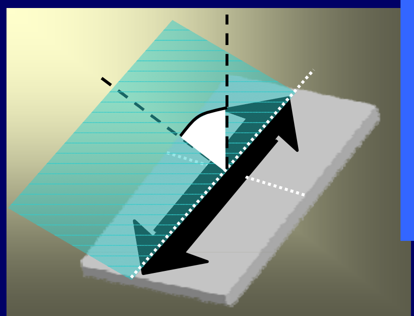
coercivity,

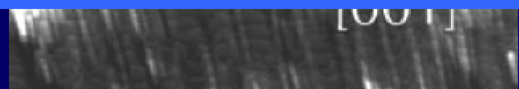
remanence,

magnetic stability,

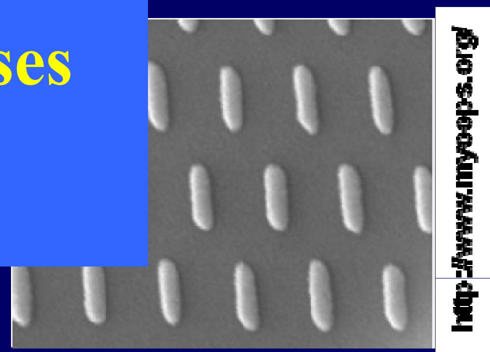
**magnetization reversal processes**

angle of depositio





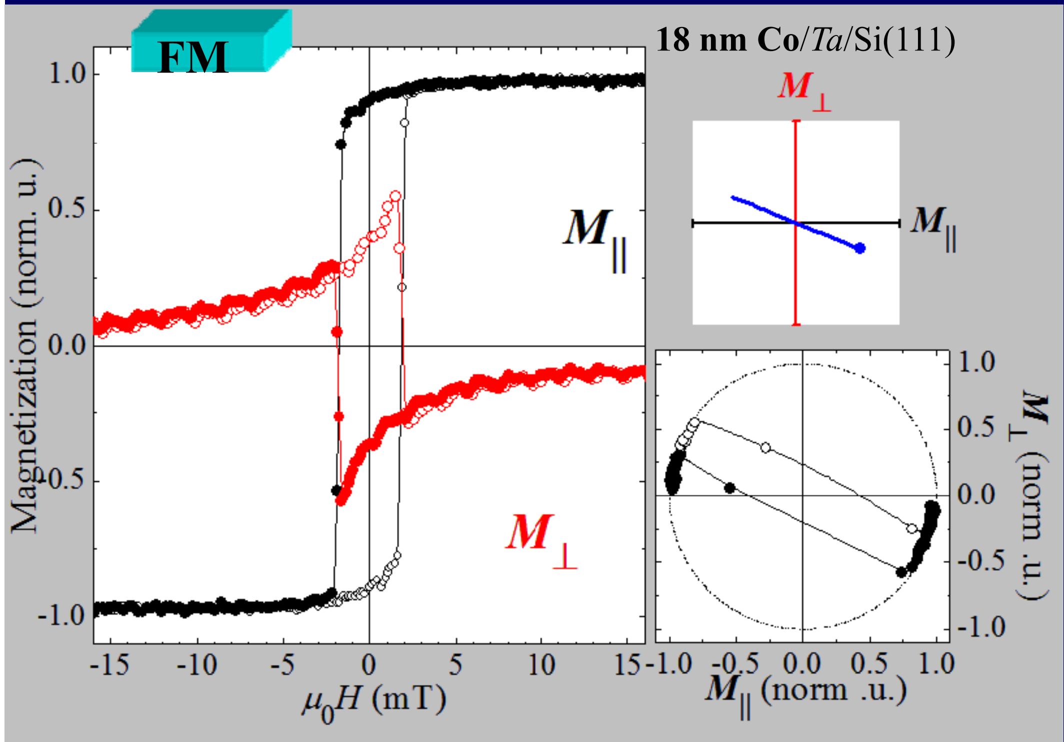
shape,…



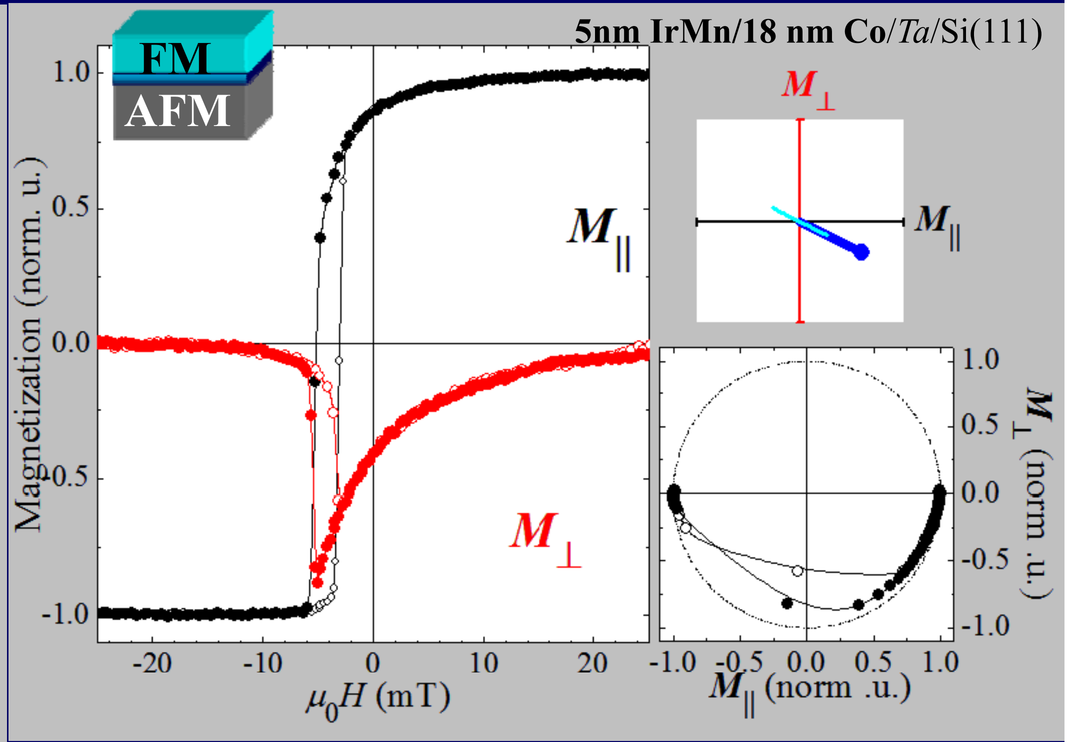
# Influence of anisotropy in magnetization reversal

*The (simultaneous) acquisition of the two in-plane magnetization components $M_{||}$ and $M_{\perp}$ provide direct information about the magnetization reversal processes*

## Uniaxial




## Uniaxial+Unidirectional



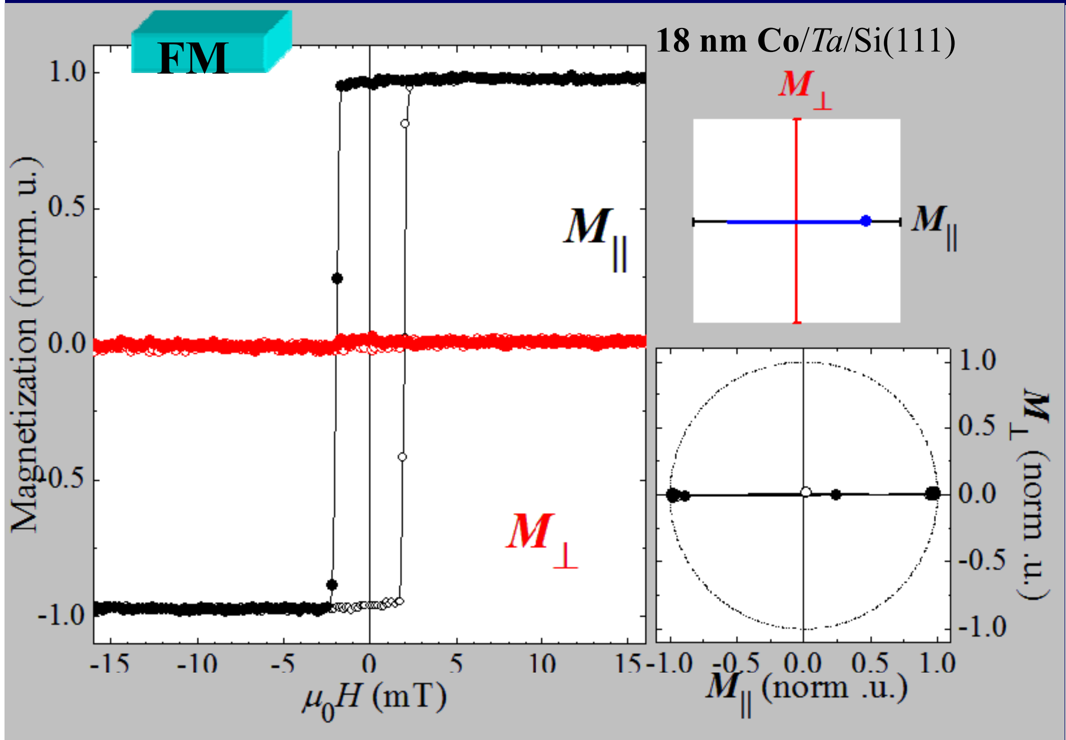

Sharp irreversible & smooth reversible transitions can be observed in both $M_{||}$ and $M_{\perp}$

The vectorial plot, $M_{\perp}$ vs. $M_{\perp}$, reflects the direction of magnetization

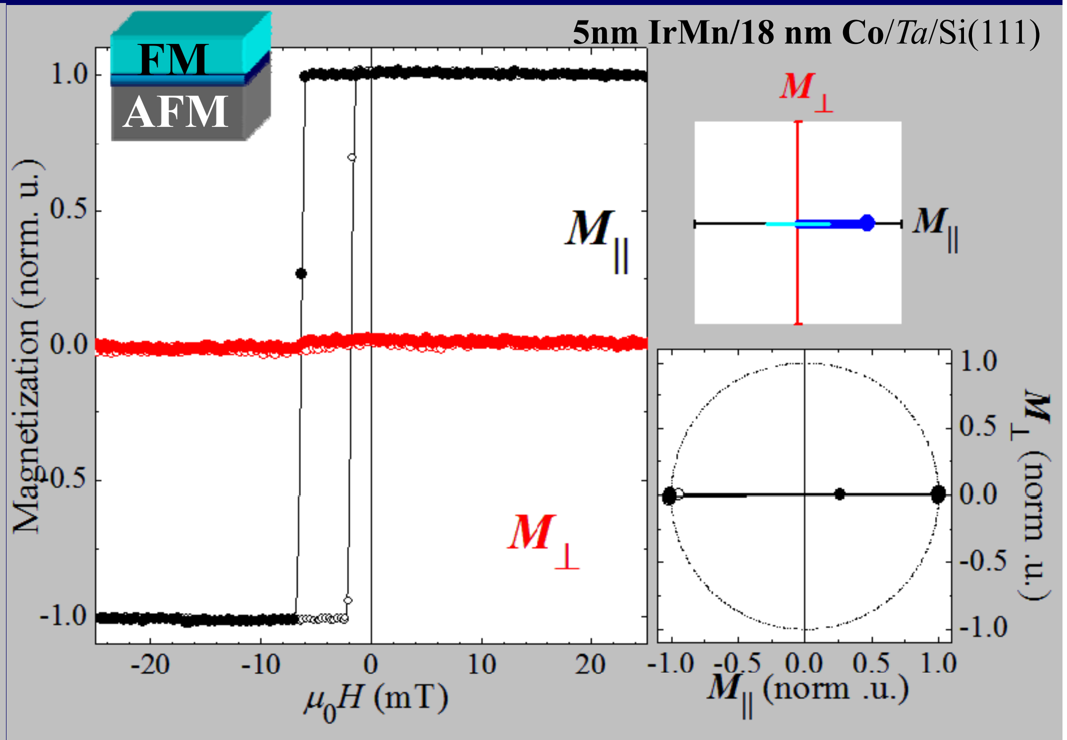
# Influence of anisotropy on Magnetization Reversal

*The magnetization reversal is determined by the anisotropy of the system*

## Uniaxial




## Uniaxial+Unidirectional




Close to the e.a.: **Sharp irreversible transition dominated** → magnetization reversal is governed by ***nucleation of magnetic domains and further domain wall propagation***

Close to the h.a.: **Smooth reversible transitions dominated** → magnetization reversal is governed by in-plane magnetization rotation processes

The asymmetric reversal phenomena is intrinsic to exchange-biased FM/AFM systems

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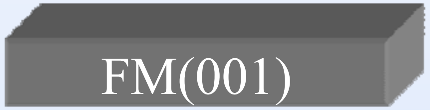
# Magnetization reversal of model systems I: easy axis

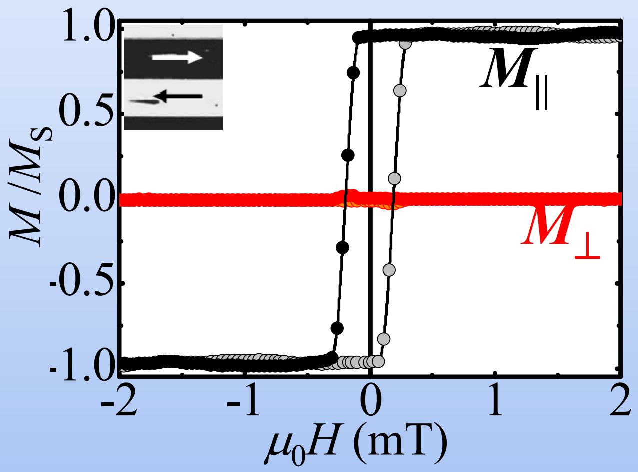
$\theta_H = 0^{o}$

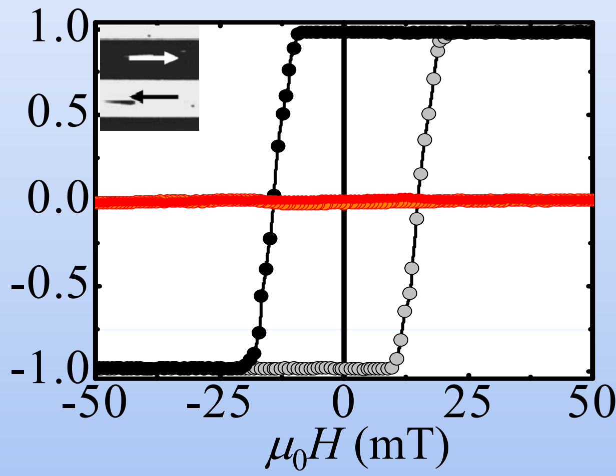

***Uniaxial*** *anisotropy*

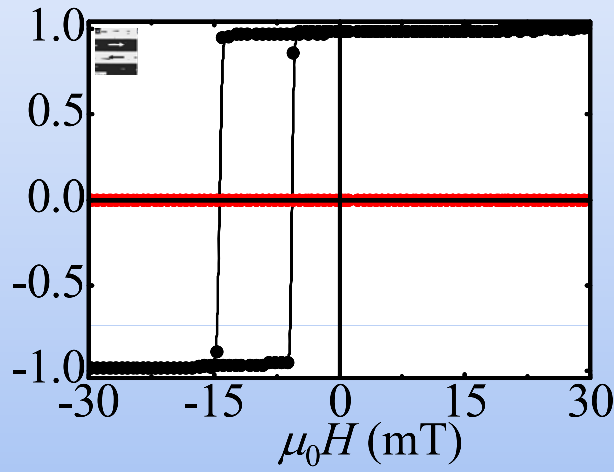


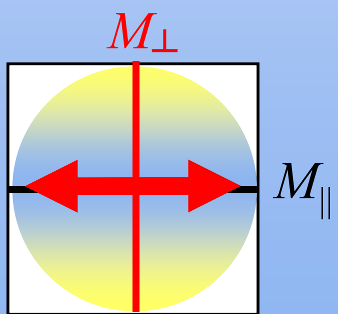

***Biaxial*** *anisotropy*

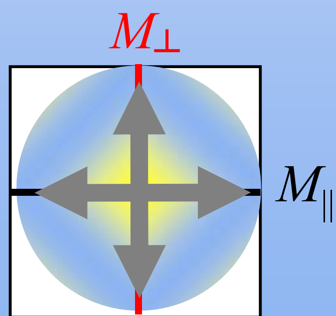

***Uniaxial*+*Unidirectional***
*collinear configuration*

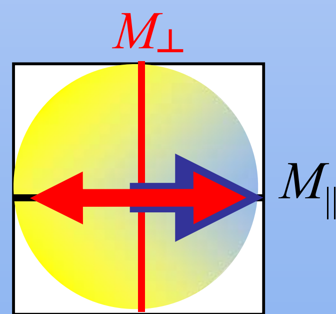



Jimenez et al., to be published

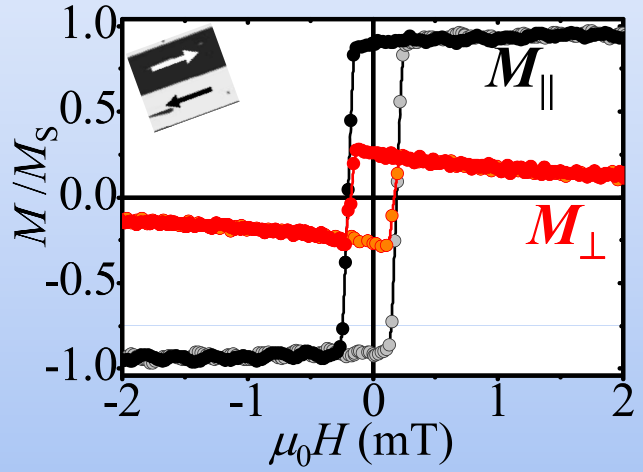
Phys. Rev. B **80**, 014415 (2009)
Appl. Phys. Lett. **95**, 122508 (2009)
J. Appl. Phys. **109**, 07D730 (2011)

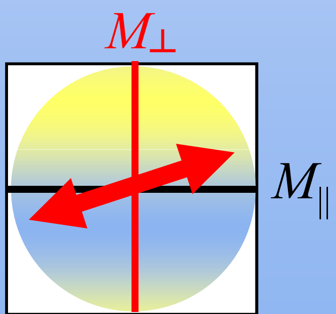
# Magnetization reversal of model systems II:

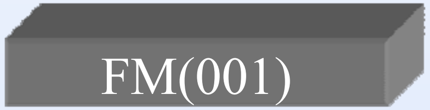
$\theta_H$=-18º



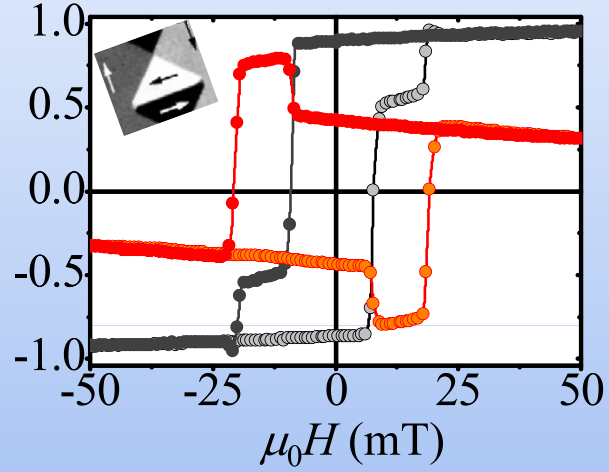

***Uniaxial*** *anisotropy*

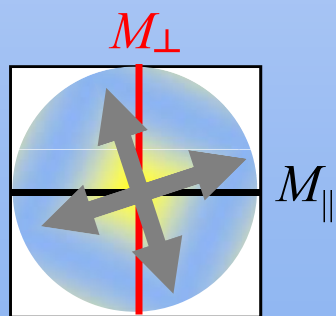



***Biaxial*** *anisotropy*

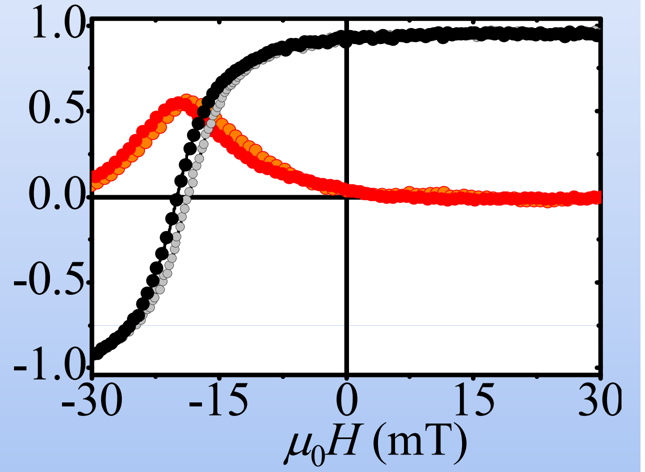


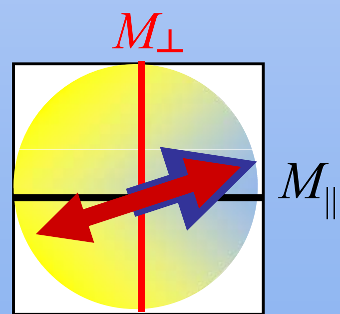





***Uniaxial***+***Unidirectional***

*collinear configuration*



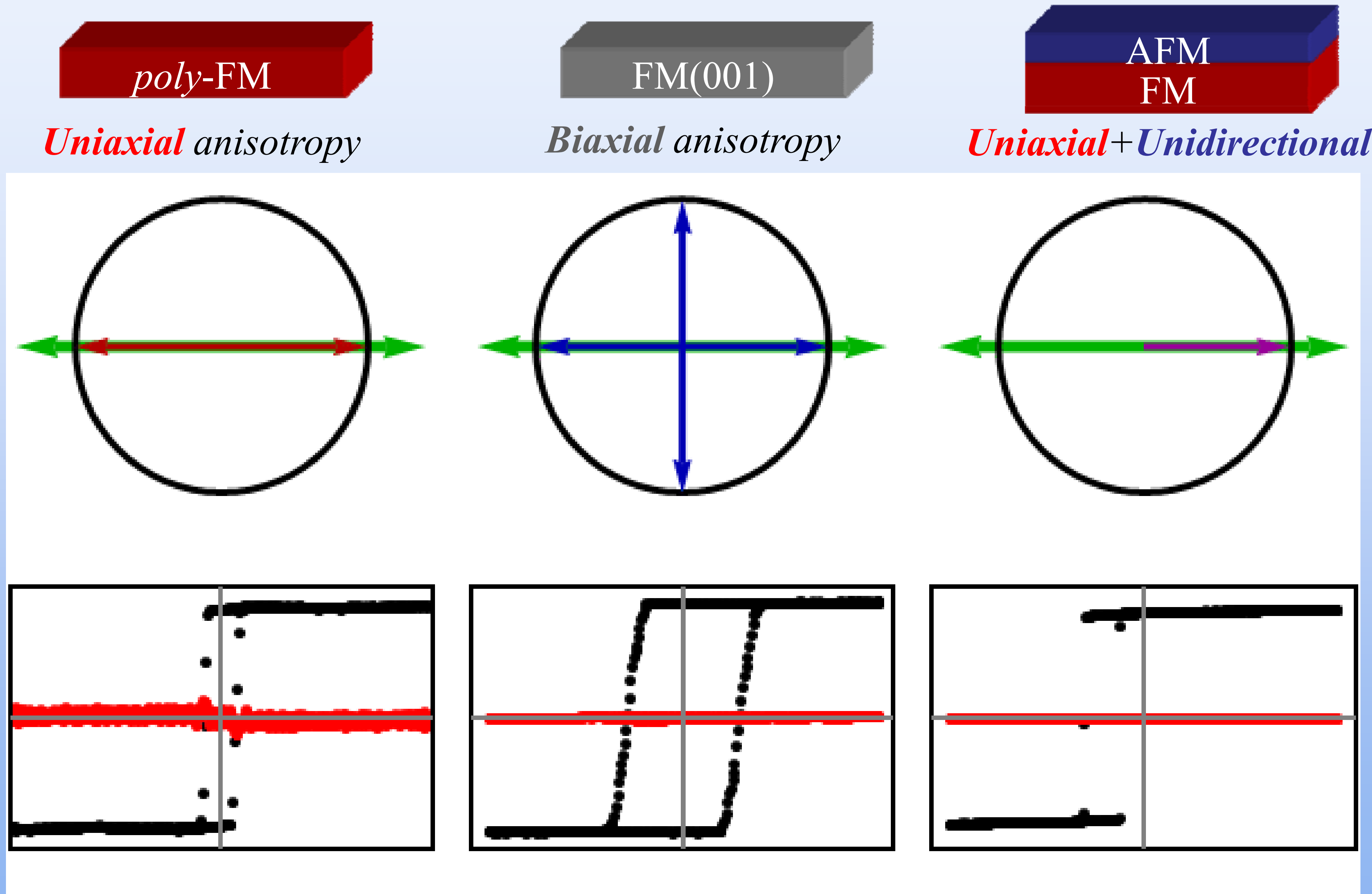




Jimenez et al., to be published

Phys. Rev. B **80**, 014415 (2009)
Appl. Phys. Lett. **95**, 122508 (2009)
J. Appl. Phys. **109**, 07D730 (2011)

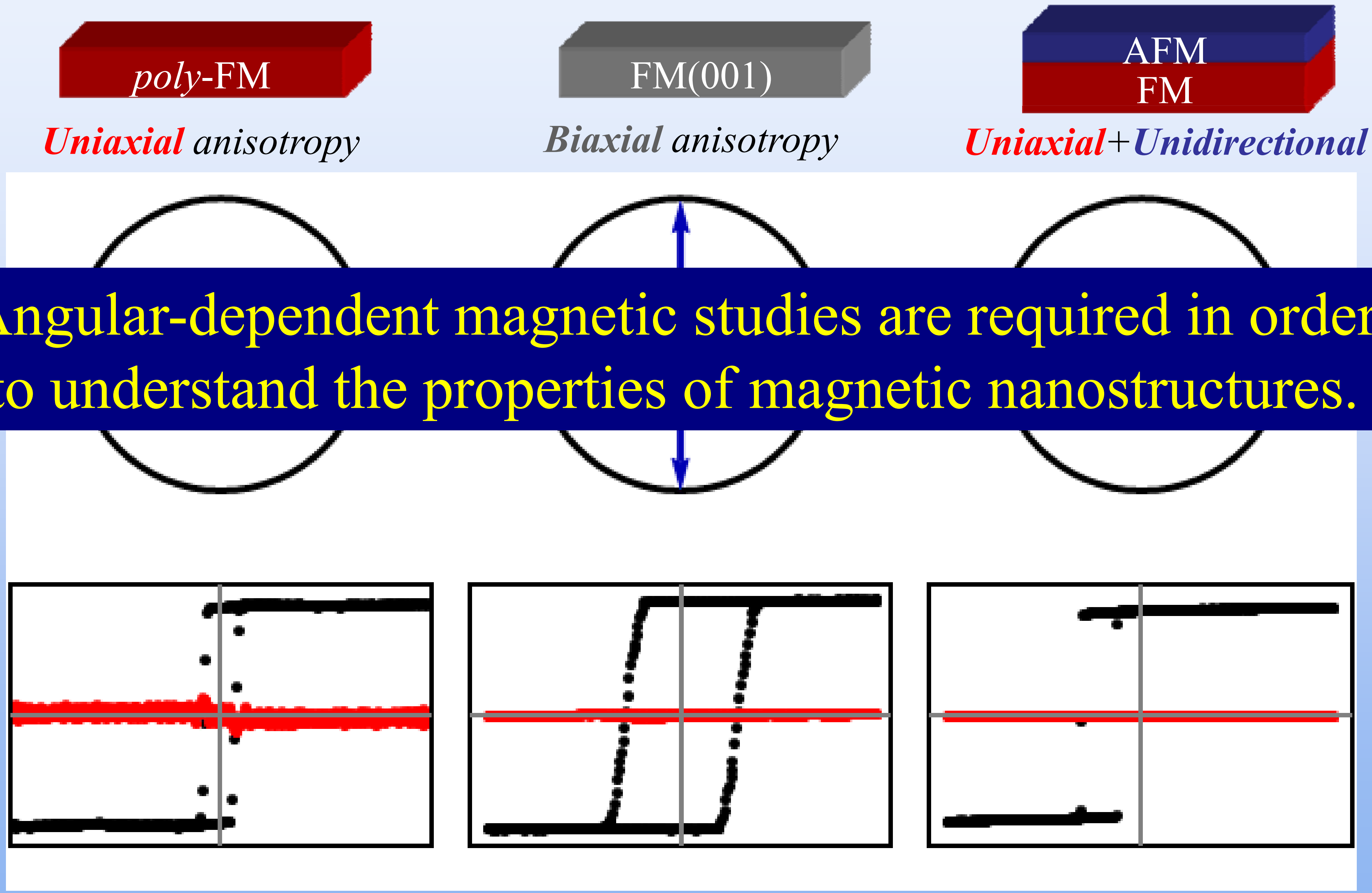
# Magnetization reversal of model systems: angular dependence

FACULTAD DE CIENCIAS
UNIVERSIDAD AUTÓNOMA DE MADRID




Jimenez et al., to be published

# Magnetization reversal of model systems: angular dependence

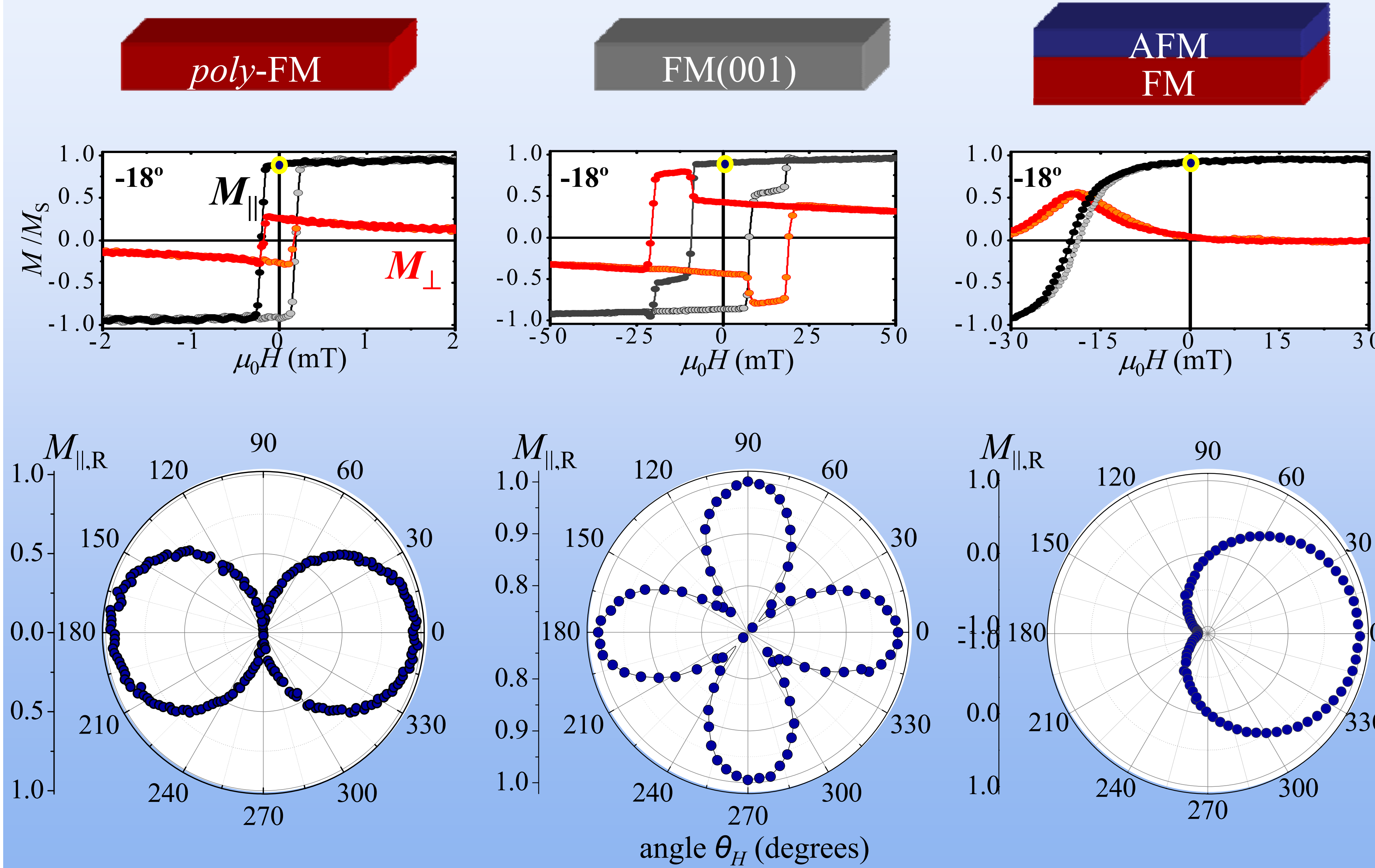



**Angular-dependent magnetic studies are required in order to understand the properties of magnetic nanostructures.**

Jimenez et al., to be published

# The symmetry is found in the magnetic behavior, $M_{\|,R}$ *vs.* $\theta_H$

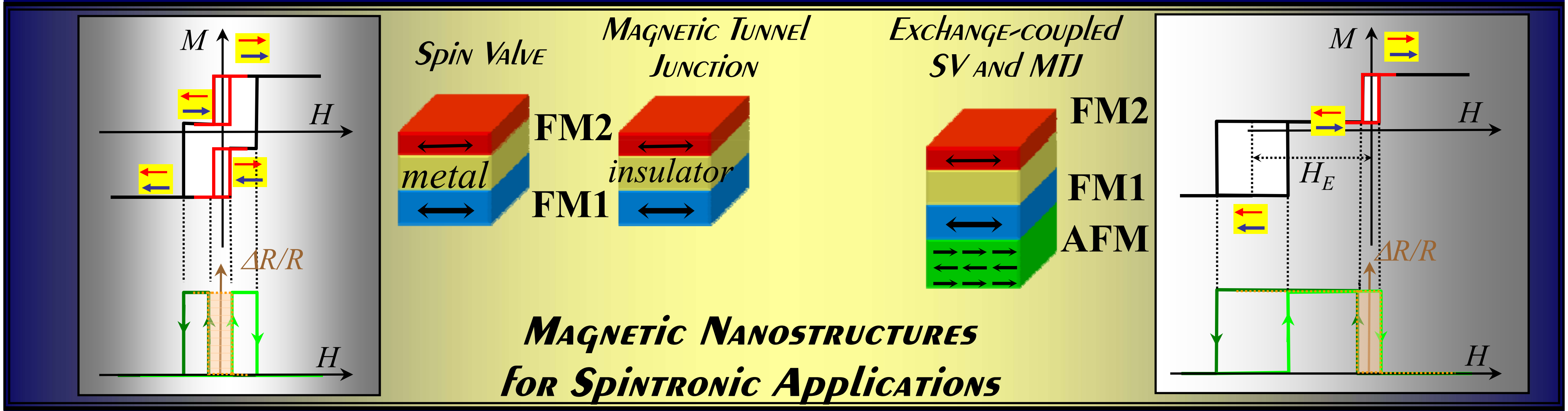
***Uniaxial*** *anisotropy* | ***Biaxial*** *anisotropy* | ***Uniaxial*+*Unidirectional***




Jimenez et al., to be published

# Spintronic

Up to now, >20000 experimental works dealt with GMR phenomena of complex multilayered magnetic nanostrucures with potential spintronic applications…



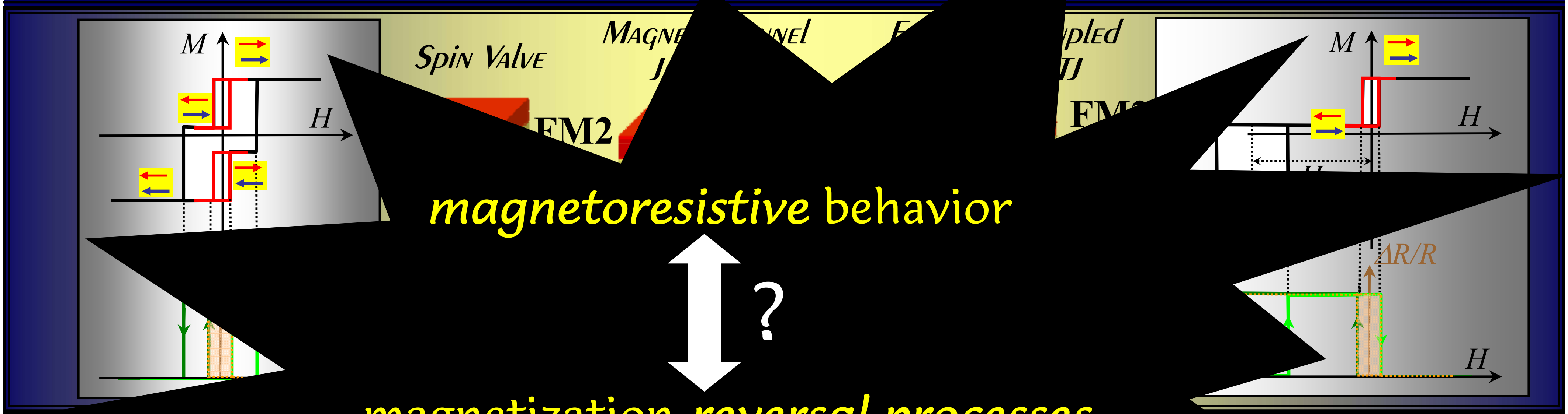

But, reported experiments rely on:

- magnetization or MR hysteresis curves acquired independently,
- measurements performed at a fixed angle of the applied field (~e.a.),
- only the parallel component of the magnetization curve is recorded.

*In addition*, widely different hysteretic magnetoresistance behaviors, including maximum MR values and curve shapes, are unexpectedly found for multilayers with similar structures.

# Origin of magnetoresistance

Up to now, >20000 experimental works dealt with GM[redacted] phenomena of complex multilayered magnetic nanostrucures with potenti[redacted]pintronic applications…




*magnetoresistive* behavior

↕ ?

magnetization *reversal processes*

Phys. Rev. B **86**, 024421 (2012)

But, [redacted]

- ma[redacted]qu[redacted]ependently,

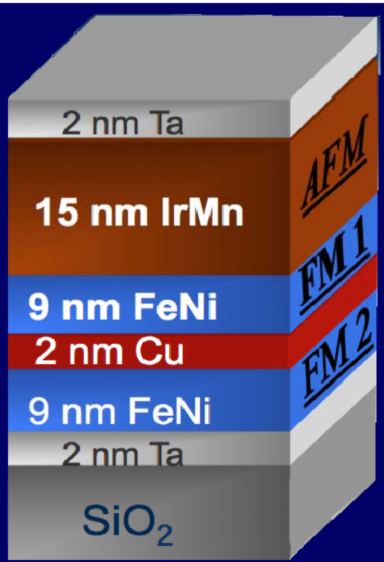
[redacted]e of the applied field (~e.a.),

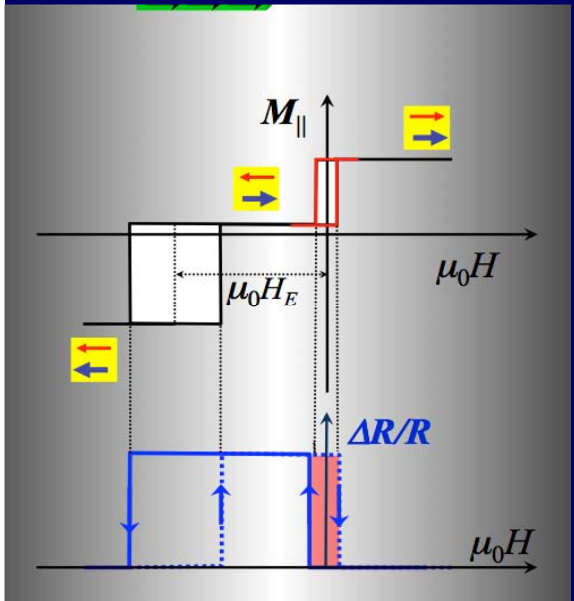
- only the pa[redacted]mpon[redacted] of the magnetization curve is recorded.

*In addition*, wi[redacted]ely different hysteretic magnetoresistance behaviors, including maximum MR values and curve shapes, are unexpectedly found for multilayers with similar structures.

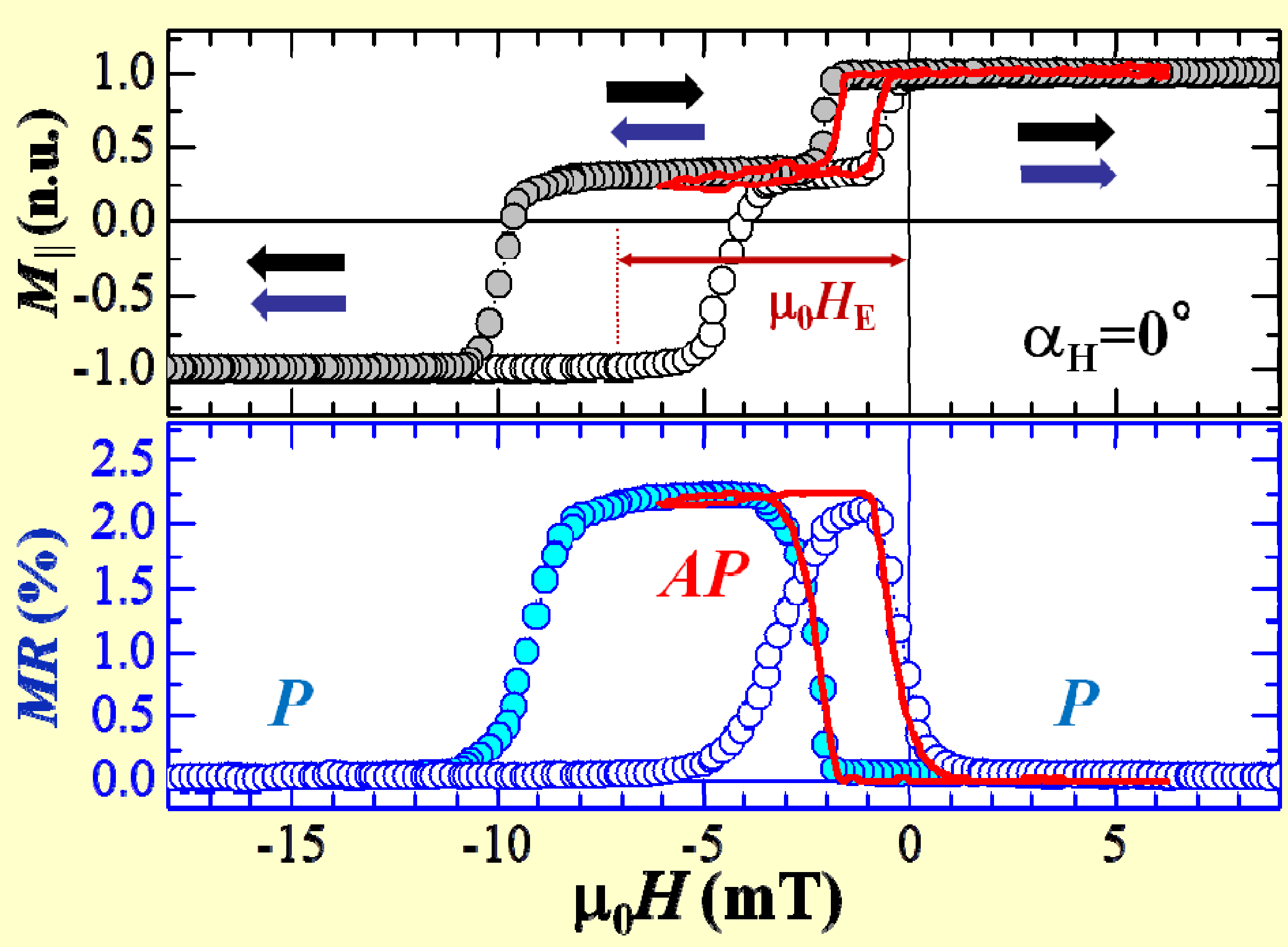
# EASY-AXIS behavior
# Simultaneous v-Kerr + MR: spin-valve

*Sample fabrication: M. Muñoz, J. L. Prieto, M. Romera, J. Akermann @* ISOM POLITÉCNICA

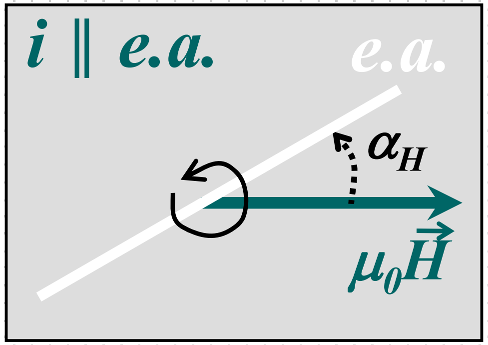


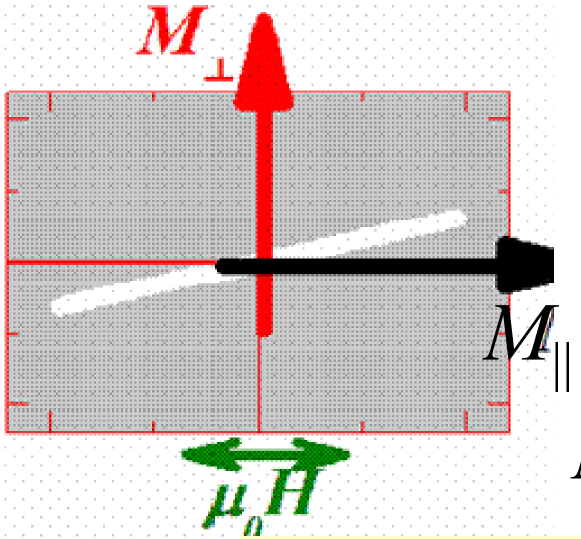



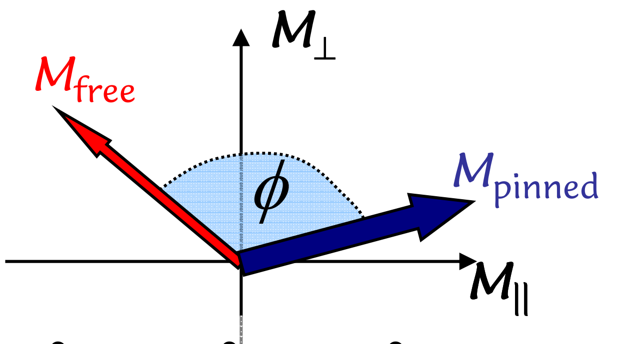

Perna *et al.*, Phys. Rev. B **86**, 024421 (2012)



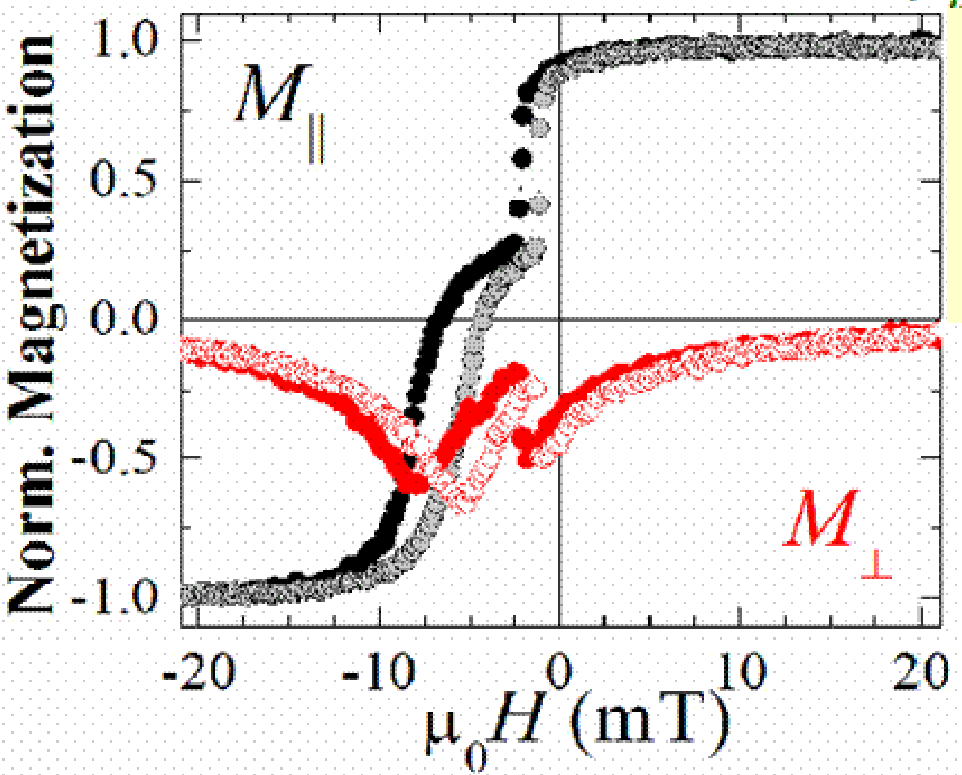
# Complete angular study



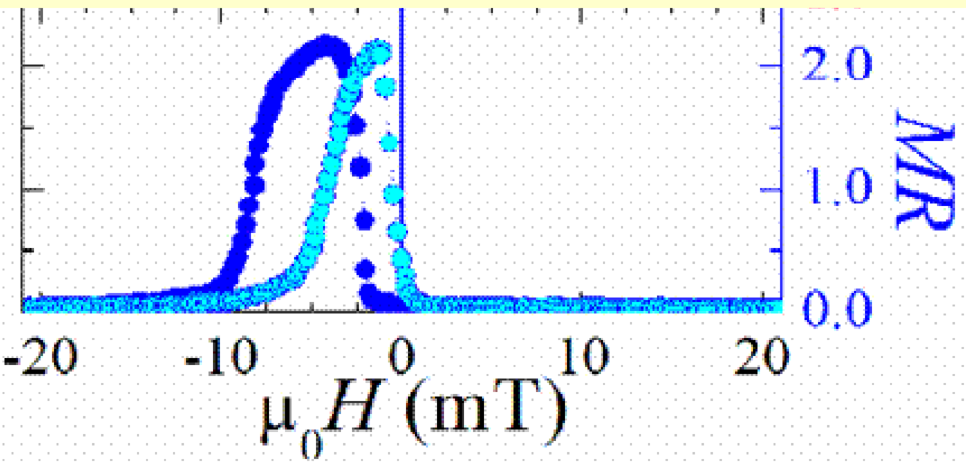



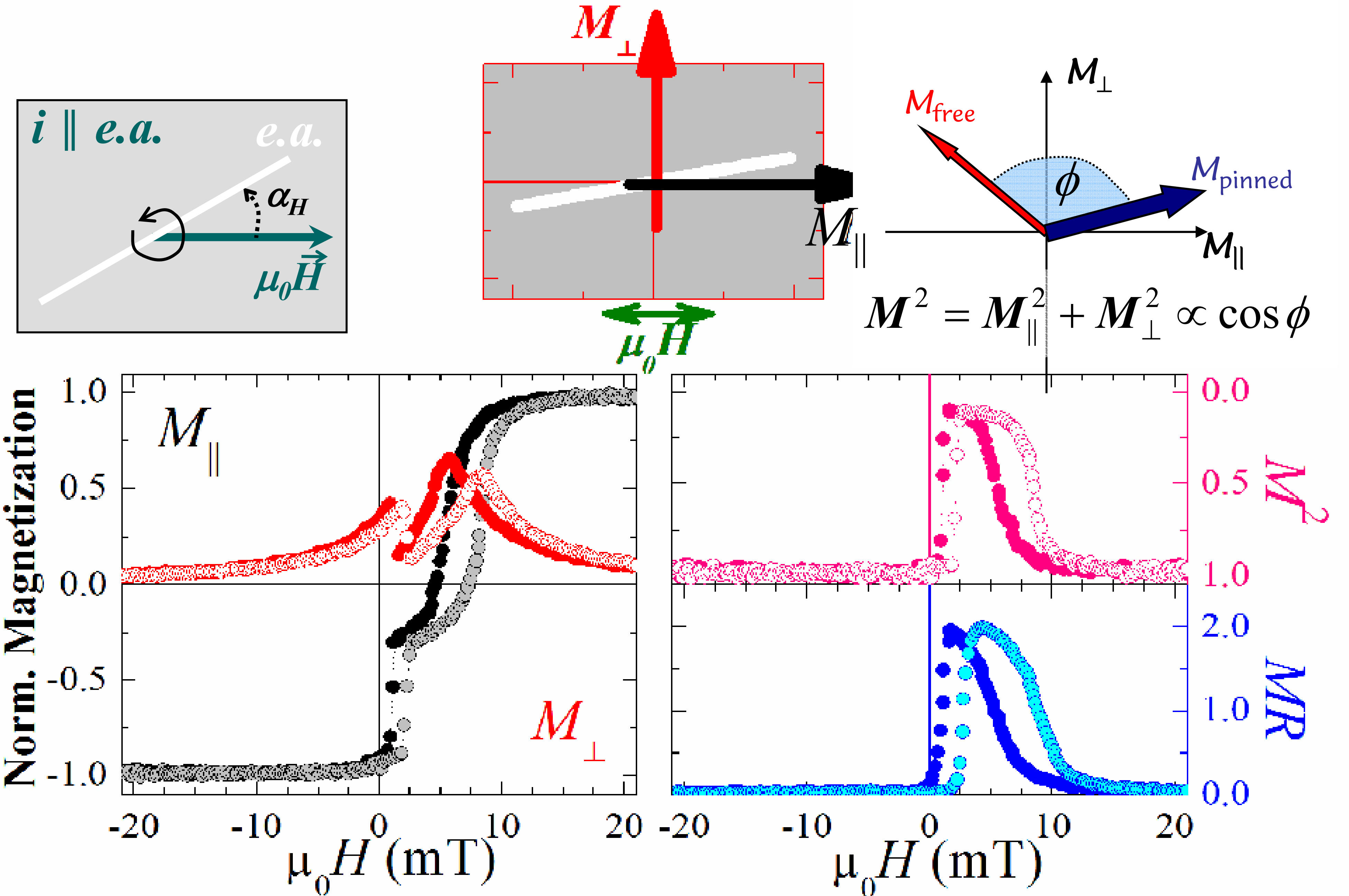

$$M^2 = M_{\parallel}^2 + M_{\perp}^2 \propto \cos\phi$$




Perna *et al.*, Phys. Rev. B **86**, 024421 (2012)



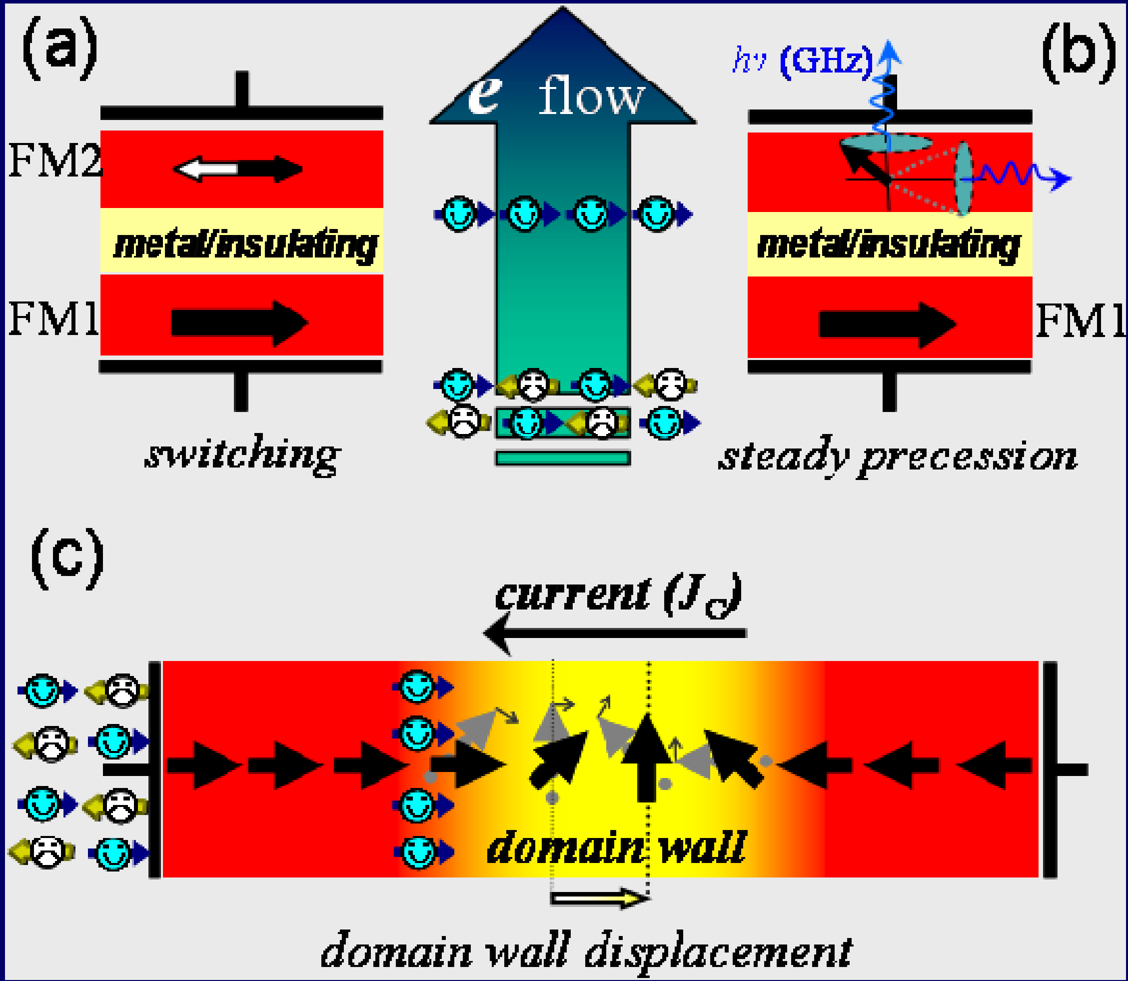
# Complete angular study




http://link.aps.org/supplemental/10.1103/PhysRevB.86.024421

# Spin transfer torque STT effect

Spin polarized current induces
- irreversible switching
- steady precession
- domain wall displacement

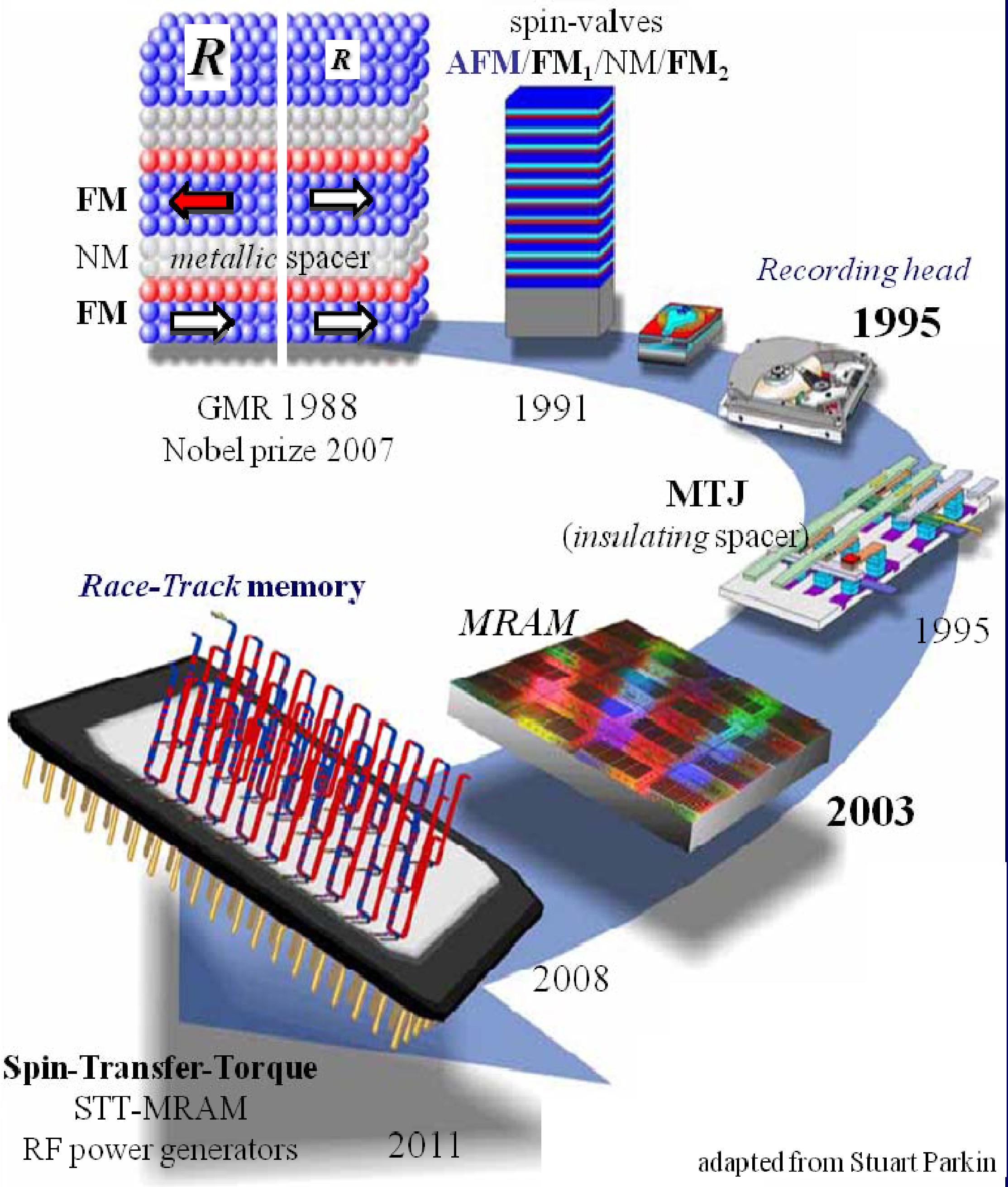



J. Mater. Chem. *Highlight* **19**, 1678 (2009)

Magnetic switching and microwave generation by spin transfer

# *Artificial* magnetic nanostructures

## Spintronic systems




Low dimensionality

Multilayered systems

Artificial interfaces

Shapes

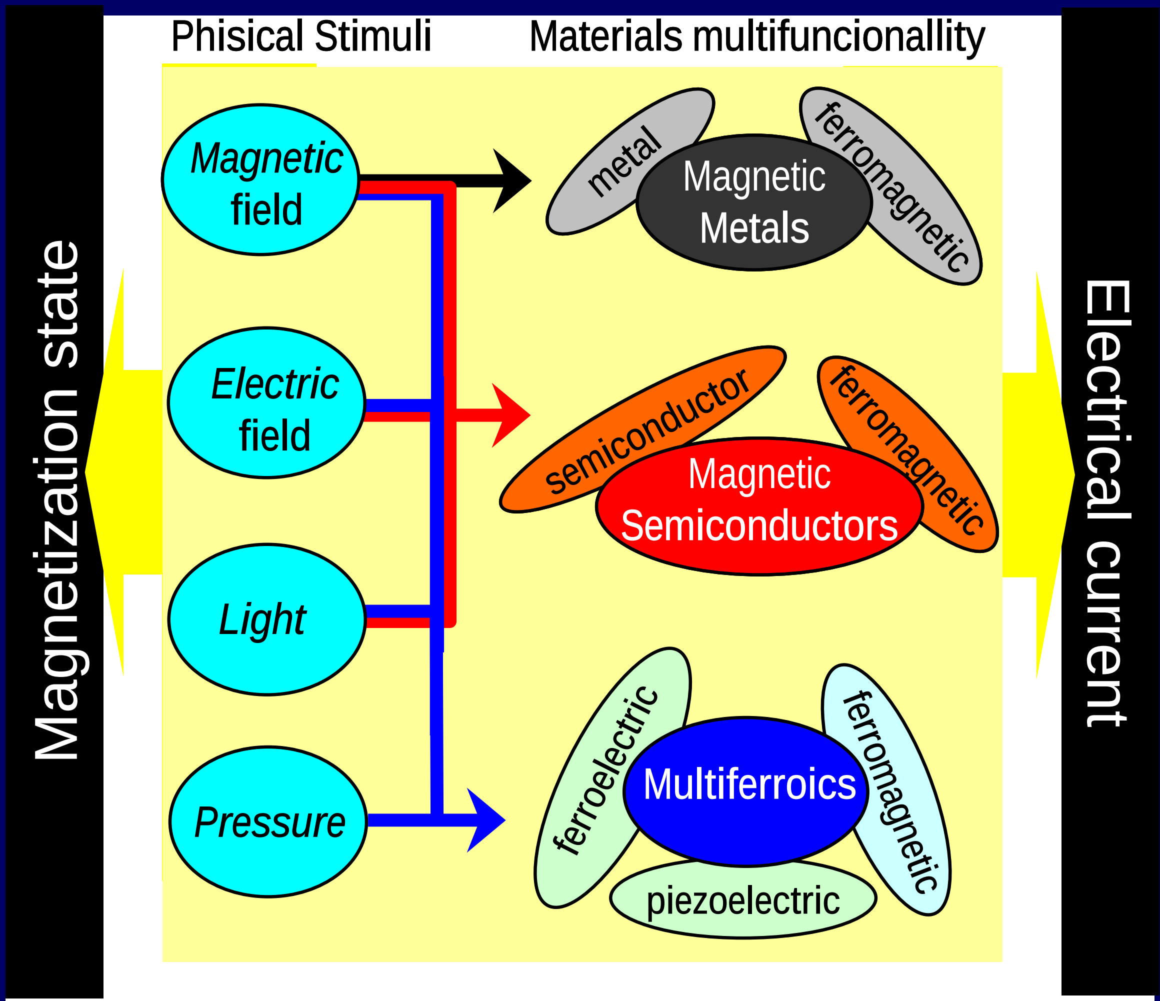
**Stimuli:**

Magnetic fields (Oersted)

Electric Currents (STT)

# Towards multifunctional materials.

*Spintronics is the link between the magnetization orientation of a material and its electrical resistance*. In conventional spintronics these two properties are **controlled by applying either a magnetic field or an electrical current and measuring the resistance**

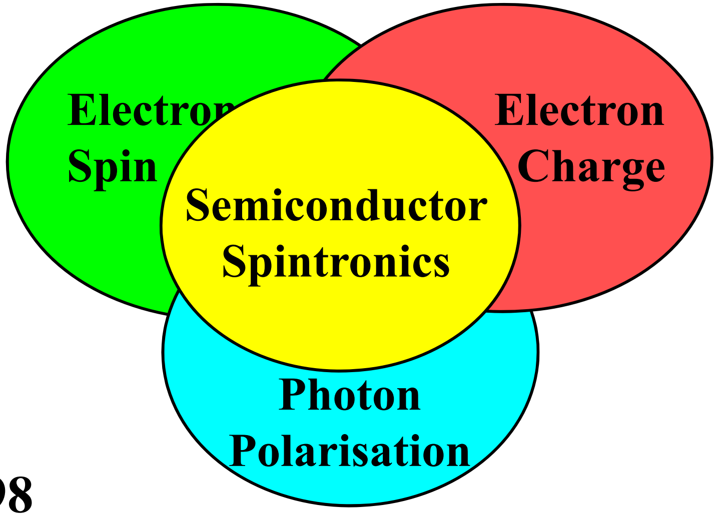



J. Mater. Chem. *Highlight* **19**, 1678 (2009)

The coexistence of **different functionalities allows the realization of devices with more than two-state logic**, as used in conventional spintronics.

# Multifunctional systems

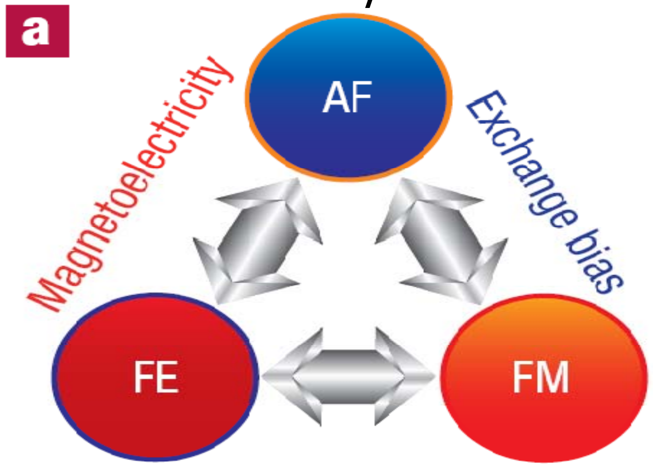
## Diluted Magnetic Semiconductors




**1998**

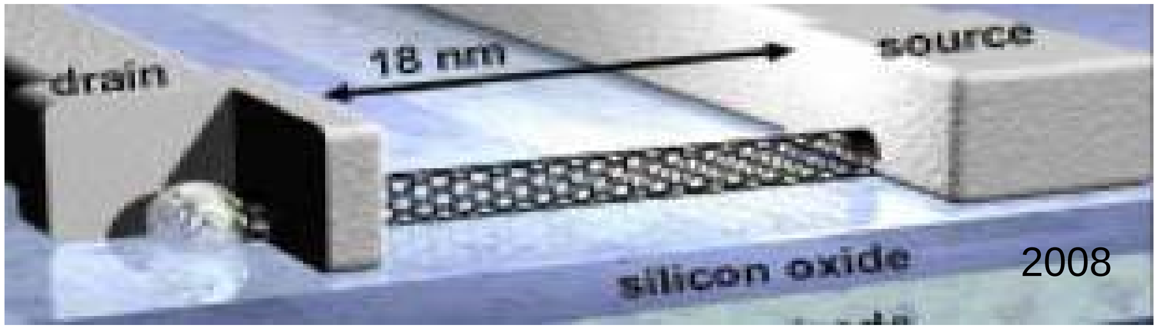
GaAs with 5% Mn, but **max. $T_C$=172K**

## Multifferroics: *magnetoelectric memory*

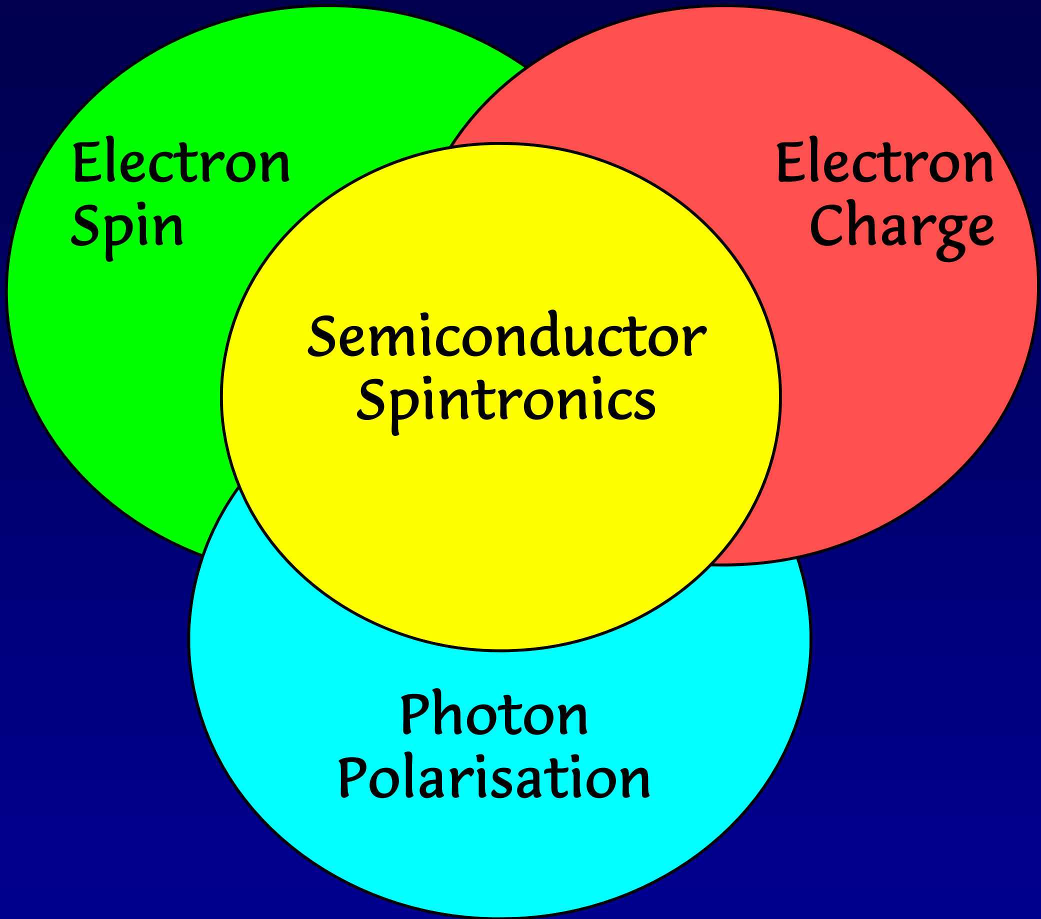



2008

## Magnetic molecules: *new funcionalities*

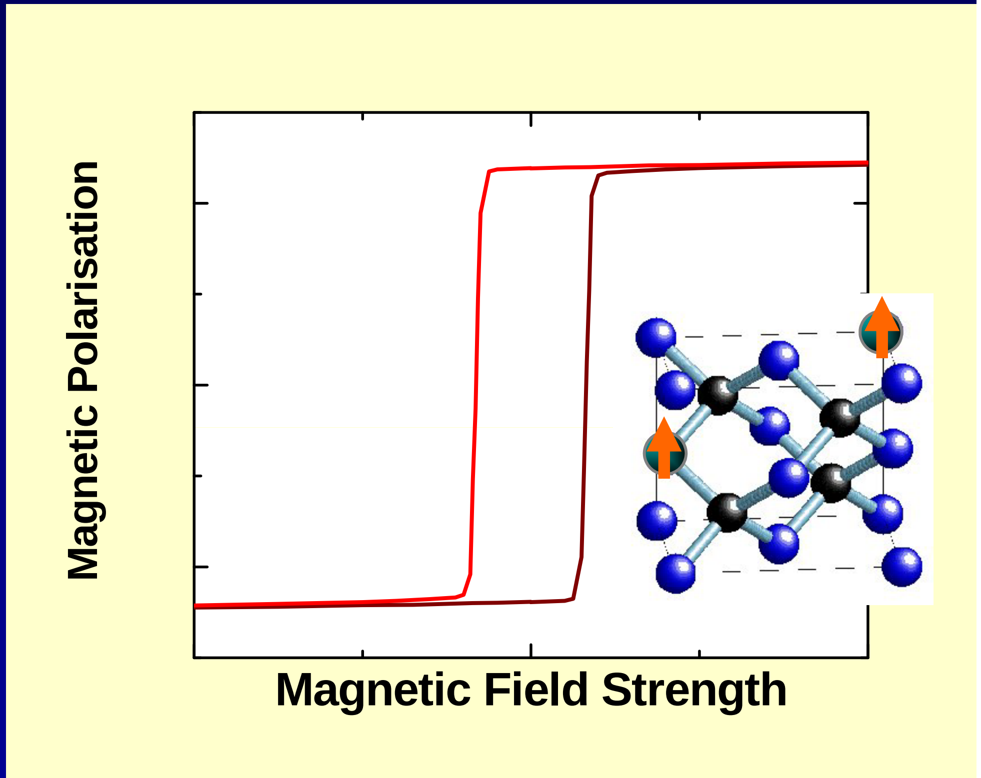


# Diluted magnetic semiconductors DMS




## (Ga,Mn)As

H. Ohno *et al.* (1996): ferromagnetism in GaAs thin films doped ~5% with Mn




Benefits: Fast, small, low dissipation devices

Quantum computation?

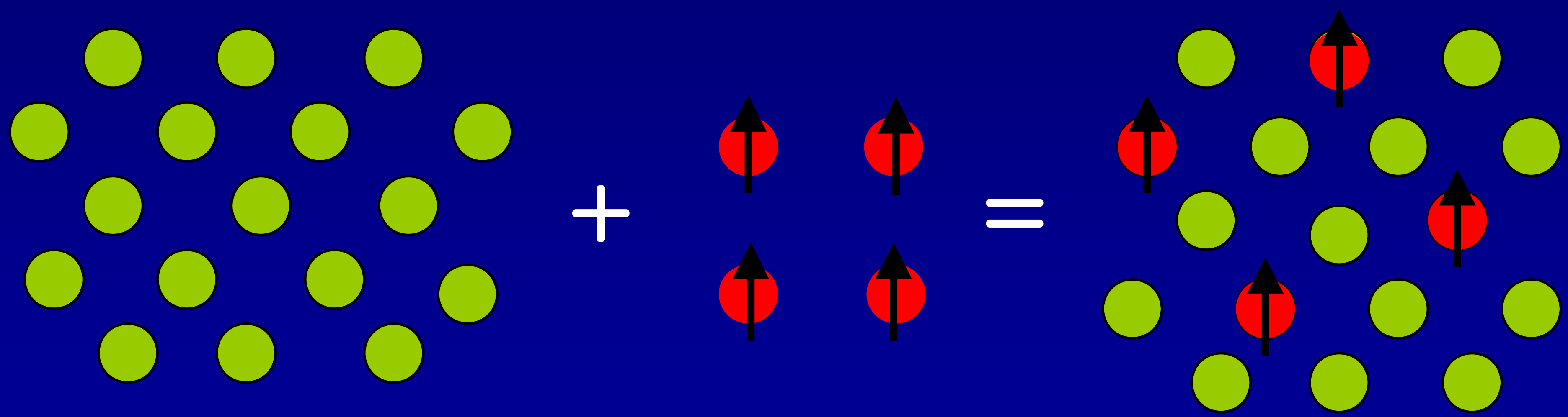
New physics

Growth by low temperature MBE to beat equilibrium solubility limit

# How make Dilute Magnetic Semiconductor

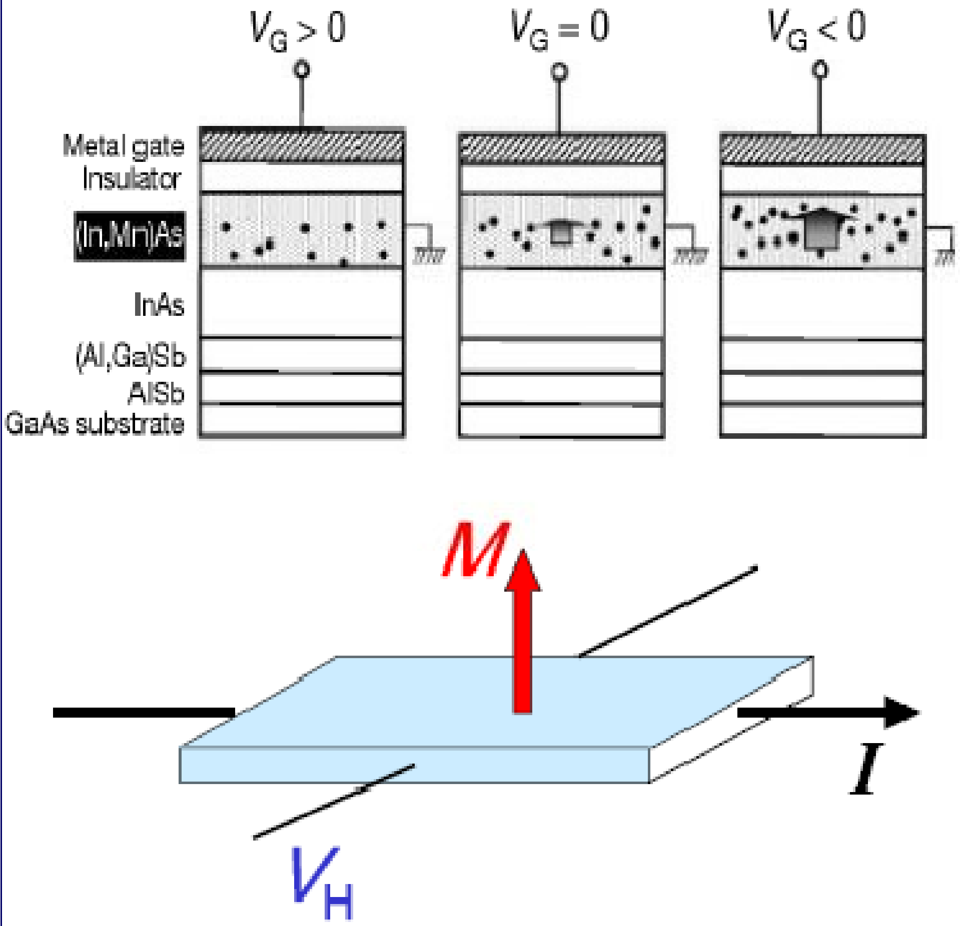
Injection of Spin-polarized electrons into semiconductor → Magnetic semiconductor → Realization of Spintronics devices

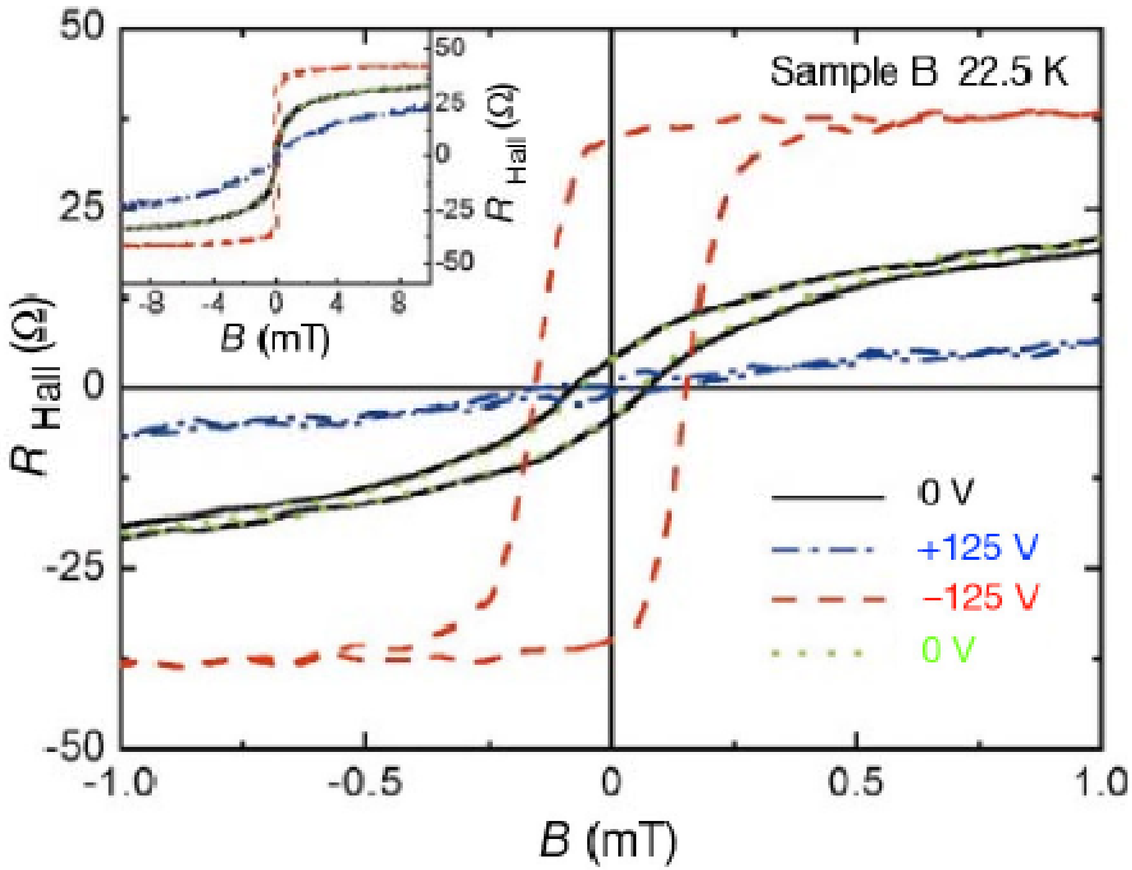
* magnetic semiconductor: An alloys of non-magnetic semiconductor and magnetic elements




**Semiconductor** **Magnetic elements** **DMS**

# Tuning of magnetic ordering by electric field (ferro-FET) (In,Mn)As

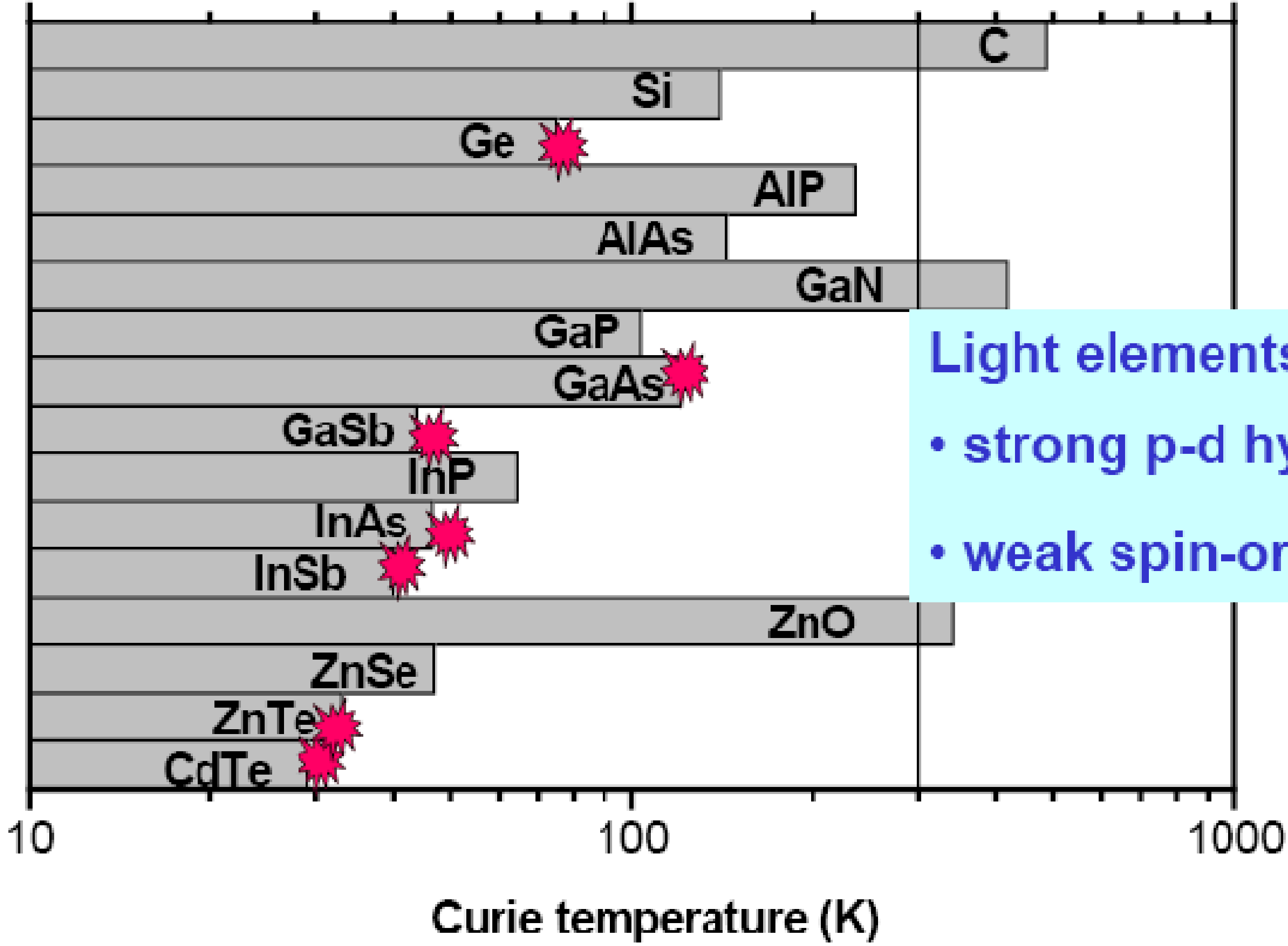



Ohno et al. (Tohoku, Warsaw) Nature '00

# p-d Zener model prediction of $T_C$

# 5% Mn $d^5$, p= $3.5\times10^{20}cm^{-3}$




**Light elements:**

- strong p-d hybridisation
- weak spin-orbit interaction

*T. D. et al. (Warsaw, Tohoku, Grenoble) Science'00, PRB'01*

# Materials showing hysteresis and spontaneous magnetization at 300 K

wz-c-(Ga,Mn)N, (In,Mn)N, (Ga,Cr)N, (Al,Cr)N, (Ga,Gd)N,

(Ga,Mn)As, (In,Mn)As, (Ga,Mn)Sb, (Ga,Mn)P:C

(Zn,Mn)O, (Zn,Ni)O, (Zn,Co)O, (Zn,V)O, (Zn,Fe,Cu)O

(Zn,Cr)Te

(Ti,Co)$O_2$, (Sn,Co)$O_2$, (Sn,Fe)$O_2$, (Hf,Co)$O_2$

(Cd,Ge,Mn)$P_2$, (Zn,Ge,Mn)$P_2$, (Zn,Sn,Mn)$As_2$

(Ge,Mn)

(La,Ca)$B_6$,C, $C_{60}$, HfO…

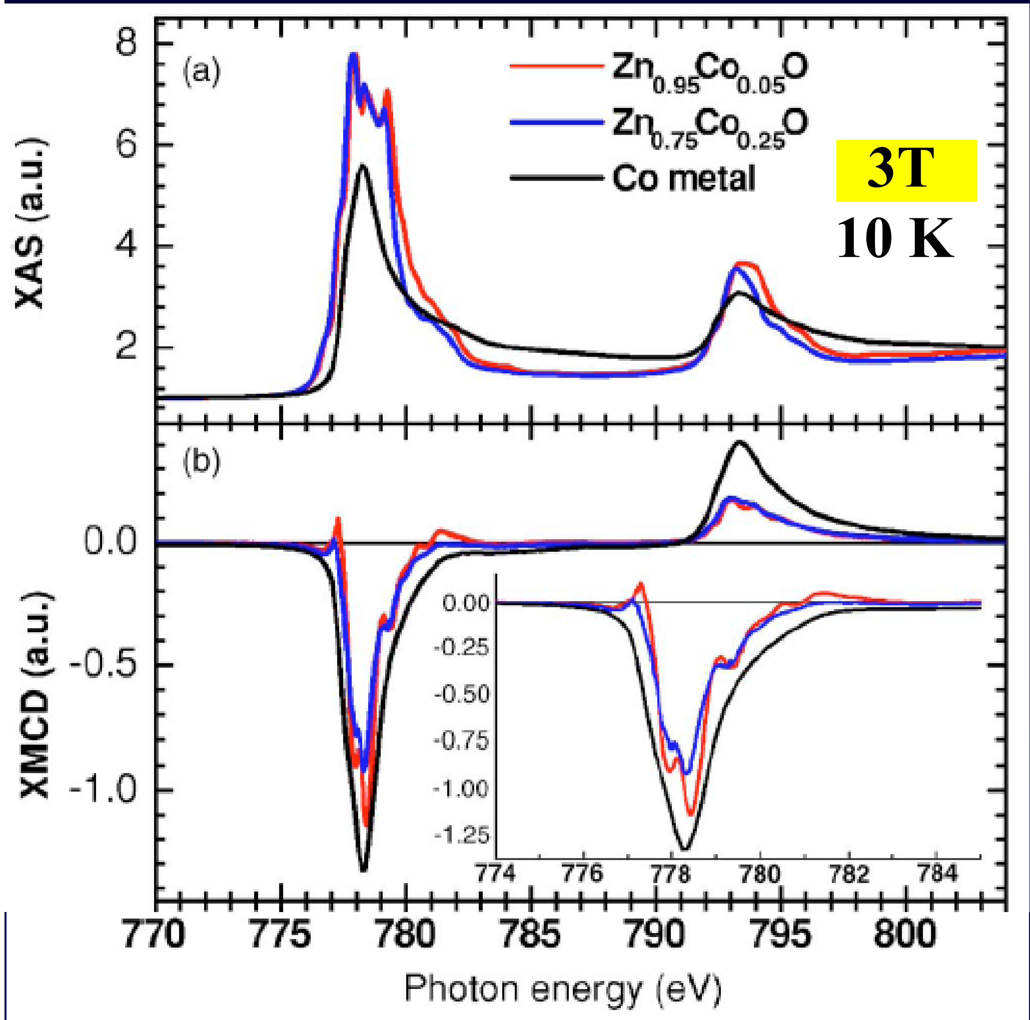
- ☞None proven to be 300 K ferromagnetic semiconductor
- ☞Each brings new challenges

*Moving beyond (Ga,Mn)As*, *Nature Materials* **84**, 195 (2005)

# Origin of ferromagnetism in RT *diluted* magnetic semiconductors



A meticulous XAS and XMCD investigation can reveal unequivocally the electronic and magnetic properties of diluted magnetic semiconductors.



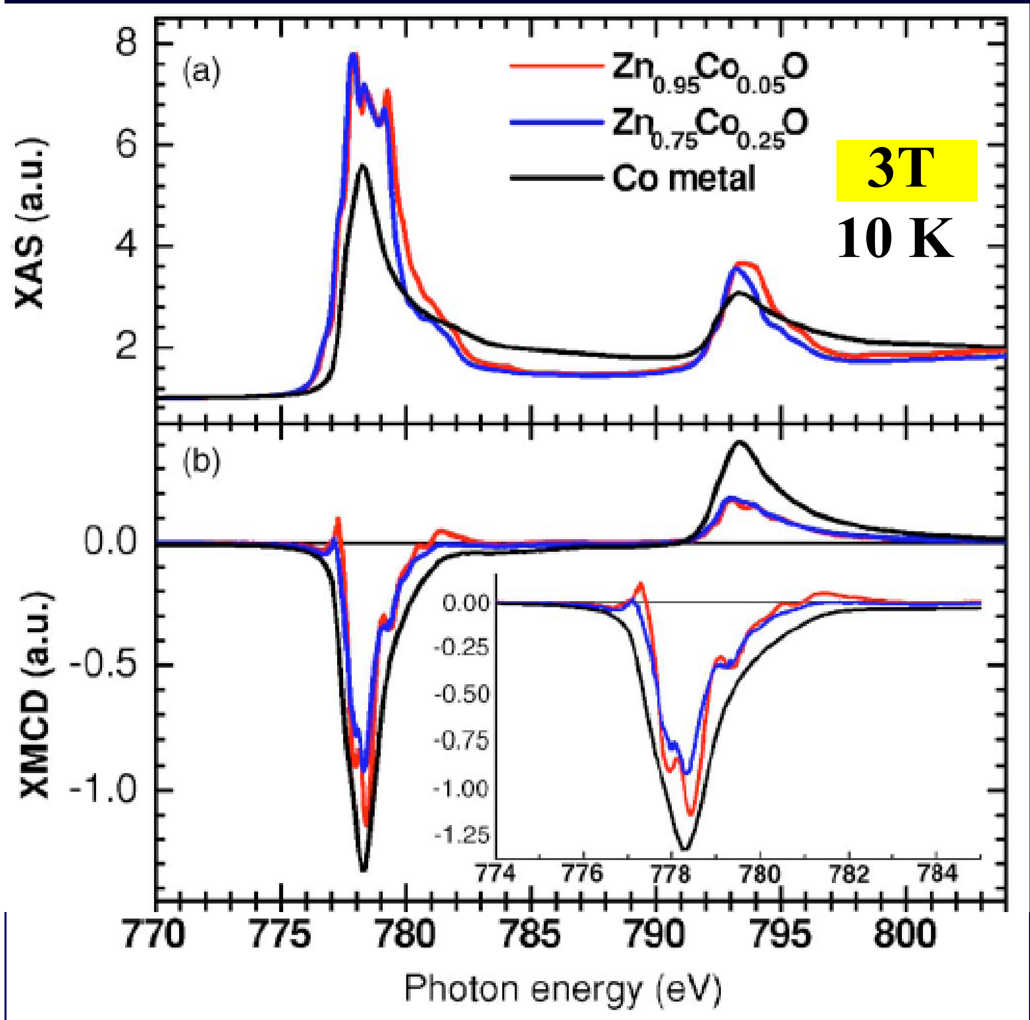

multiplets XAS → Co in an ionic state (diluted)

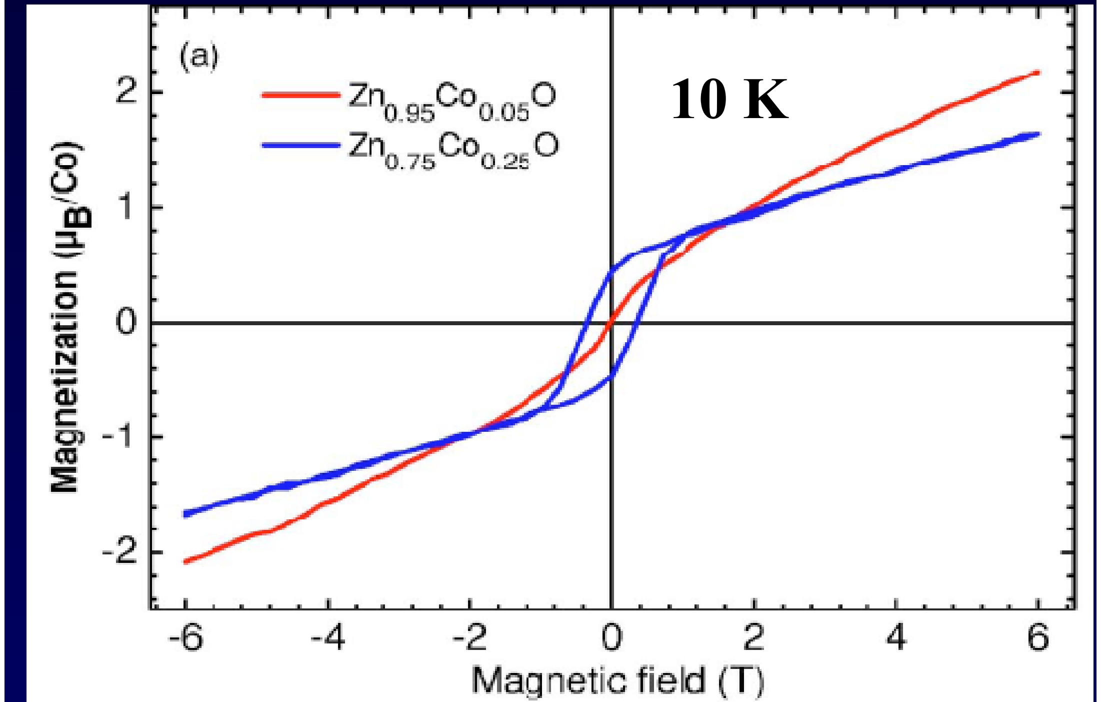
multiplets XMCD → the magnetic component at high magnetic field can be mainly attributed to Co in an ionic state

Rode *et al*., Appl. Phys. Lett. **92**, 012509 (2008)

# Origin of ferromagnetism in RT *diluted* magnetic semiconductors

A meticulous XAS and XMCD investigation can reveal unequivocally the electronic and magnetic properties of diluted magnetic semiconductors.




Rode *et al*., Appl. Phys. Lett. **92**, 012509 (2008)

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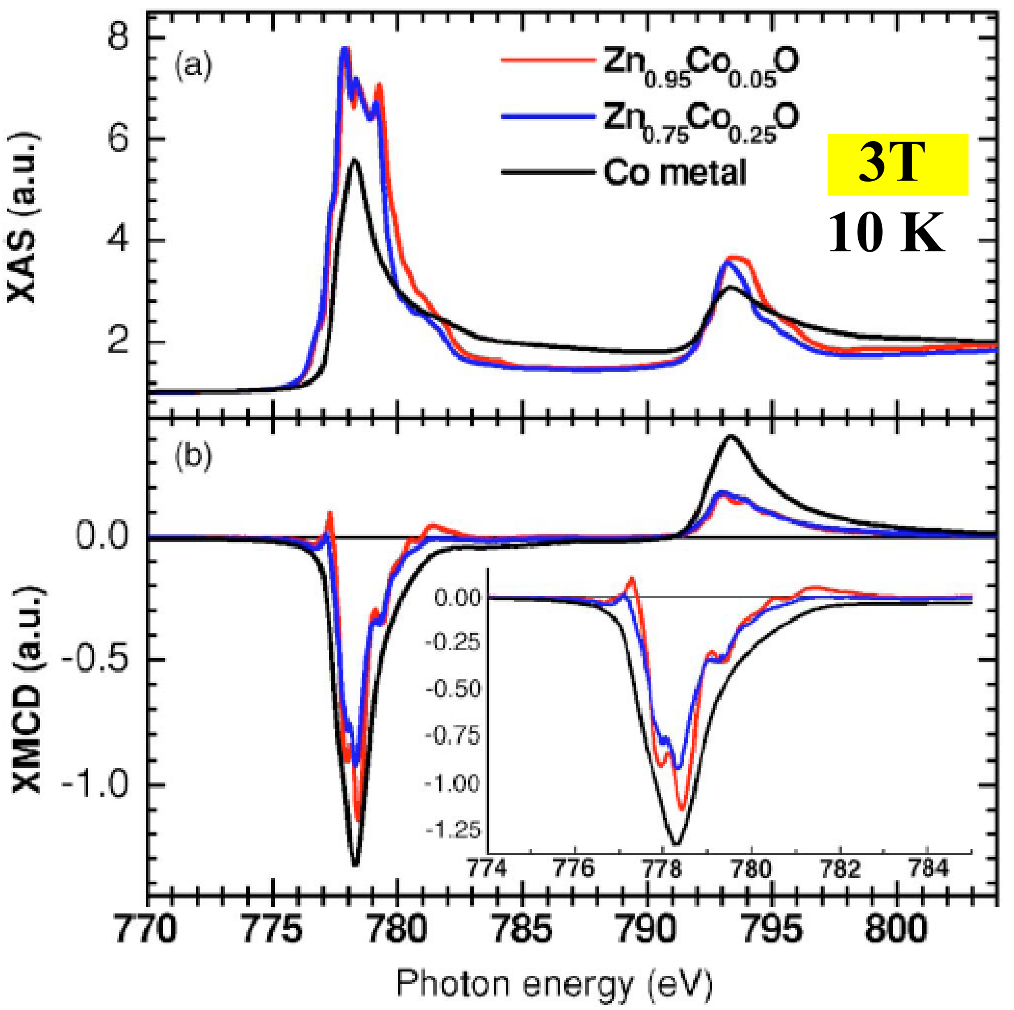
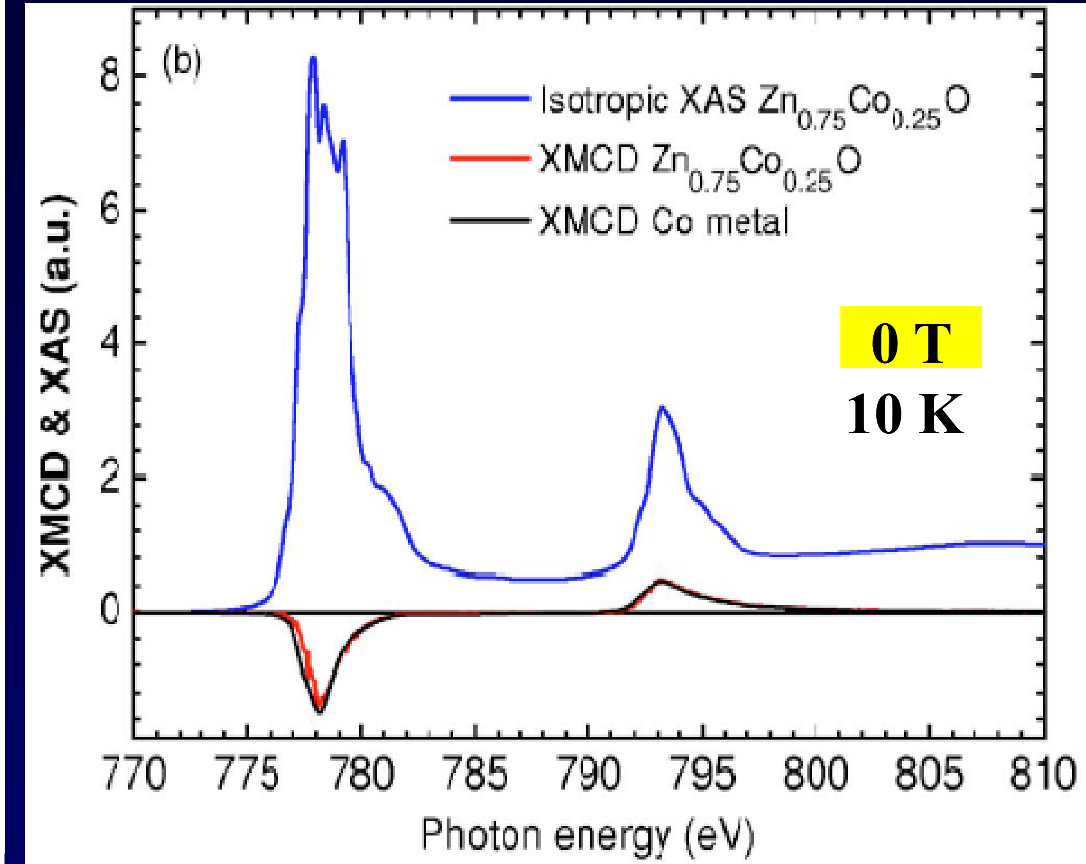



Rode *et al*., Appl. Phys. Lett. **92**, 012509 (2008)

Evidence that in Co-doped ZnO thin films two magnetic phases coexist, a paramagnetic phase associated to cobalt in ionic state and an **extrinsic FM phase associated to metallic cobalt clusters.**

instituto imdea nanociencia

nature materials

REVIEW ARTICLE

PUBLISHED ONLINE: 23 NOVEMBER 2010 | DOI: 10.1038/NMAT2898

LaSUAM

# A ten-year perspective on dilute magnetic semiconductors and oxides

Tomasz Dietl[1,2*]

pp965 - 974

editorial

Nature **December 2010**, Volume **9** No 12 pp951-957

## More than just room temperature

Diluted magnetic semiconductors and oxides are interesting for fundamental science and applications even without room-temperature ferromagnetism.

## A window on the future of spintronics

Hideo Ohno

Despite low transition temperatures, ferromagnetism in diluted magnetic semiconductors has been essential in exploring new ideas and concepts in spintronics, some of which have been successfully transferred to metallic ferromagnets.

## Is it really intrinsic ferromagnetism?

Scott Chambers has worked on epitaxial oxide films for the past eighteen years. *Nature Materials* asked him about his view on high-temperature ferromagnetism in diluted magnetic oxides.

## A model ferromagnetic semiconductor

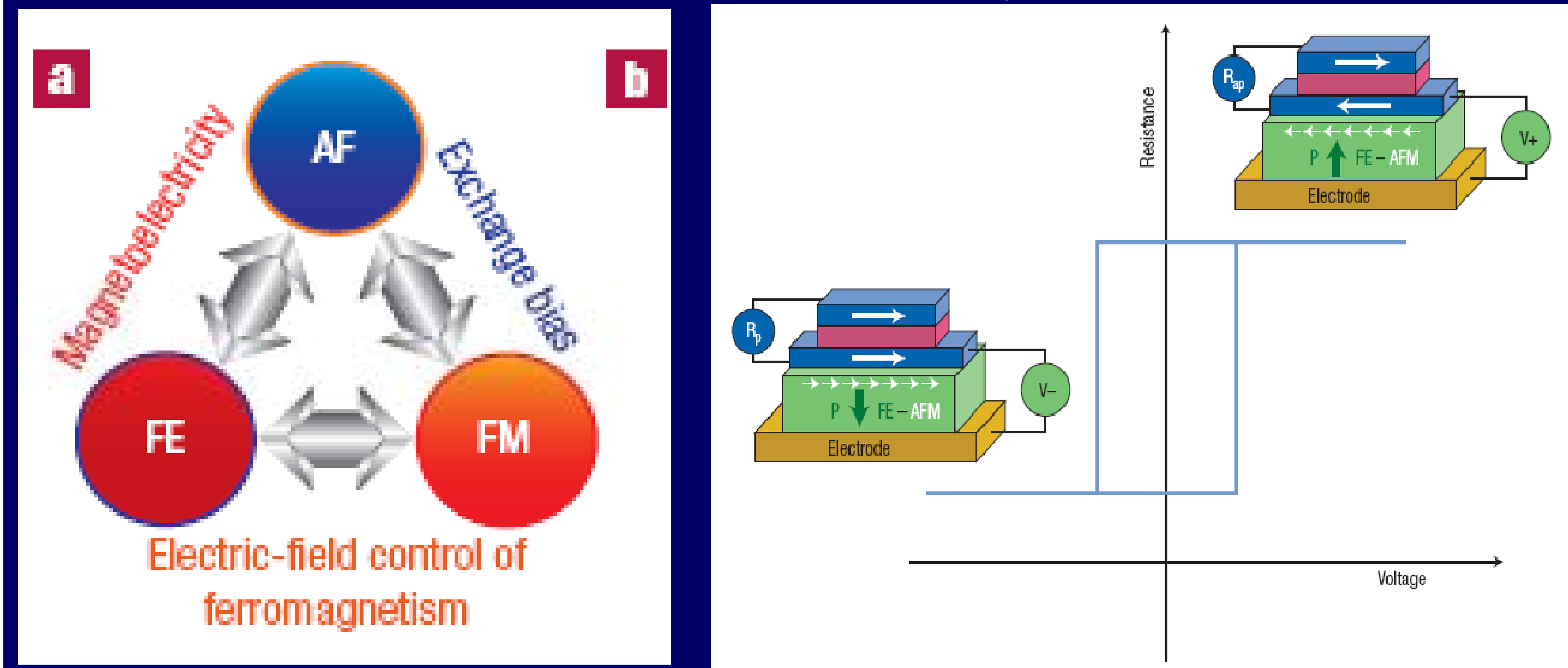
Nitin Samarth has extensive experience in studying the properties of (Ga,Mn)As. He told *Nature Materials* about the role that this compound has had in exploring the magnetic properties of semiconductors and, more generally, of spin-related phenomena.

# Electric-field control of local ferromagnetism using multiferroics

**Ferroelectric&AFM /** FM

$BiFeO_3$ / $Co_{0.9}Fe_{0.1}$

M. Bibes & A. Barthélémy, *Nature Materials* **7**, 425 (2008)

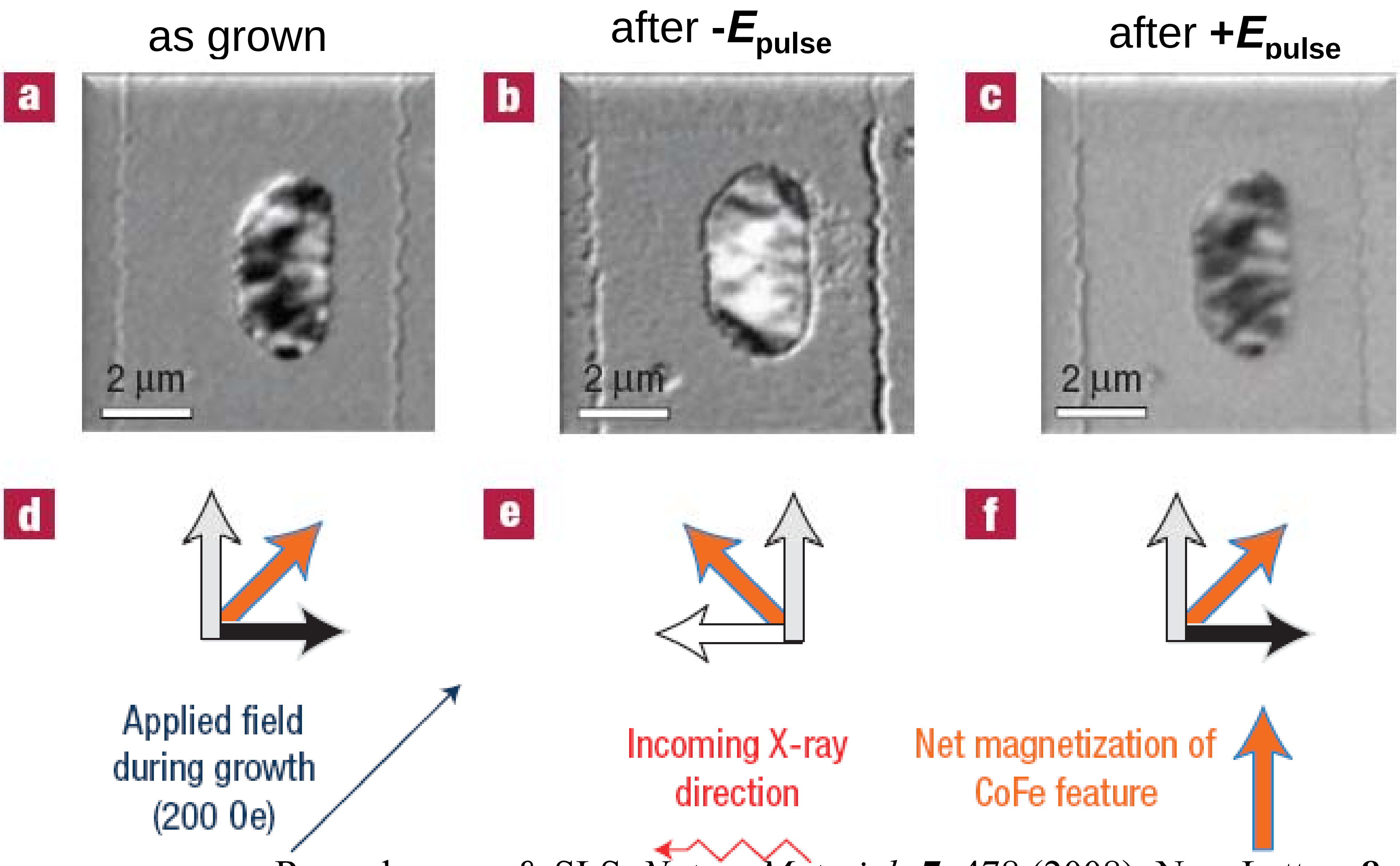


# Electric-field control of local ferromagnetism using multiferroics

**Ferroelectric&AFM** / FM

$BiFeO_3$ / $Co_{0.9}Fe_{0.1}$

XPEEM @ Co-edge

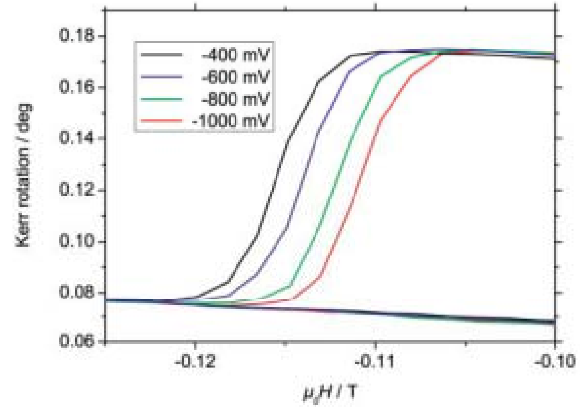



Ramesh group & SLS, *Nature Materials* **7**, 478 (2008); NanoLetters **8**, 2050 (2009)

# Voltage-driven metal-based spintronic devices

**Electric Field-Induced Modification of Magnetism in Thin-Film Ferromagnets**
Martin Weisheit, *et al.*
*Science* **315**, 349 (2007);
DOI: 10.1126/science.11366

**Fig. 2.** Magnetization switching of the 2-nm-thick FePt film for different $U$ values between the film and the Pt counter electrode. $\mu_0$, the permeability of vacuum.



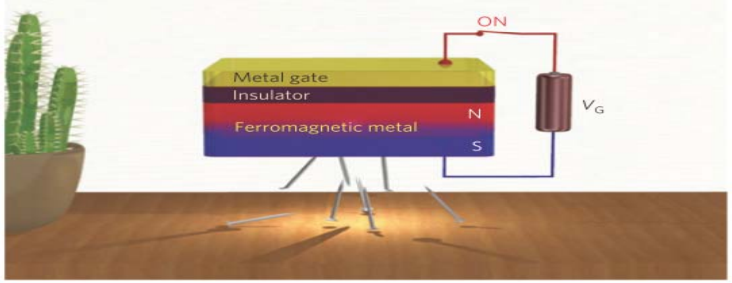

PRL **102**, 187201 (2009)
changes in the band structure introduced by the electric field

anisotropy
$H_C$
$T_C$

nature materials

LETTERS

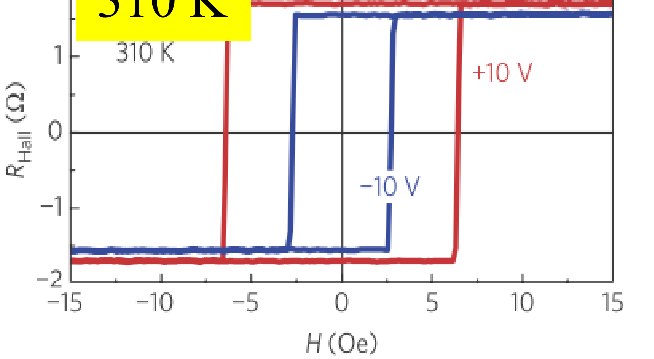
PUBLISHED ONLINE: 2 OCTOBER 2011 | DOI: 10.1038/NMAT3130



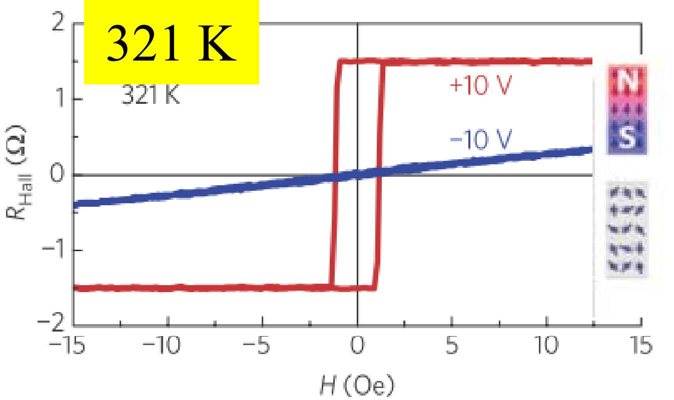

## Electrical control of the ferromagnetic phase transition in cobalt at room temperature

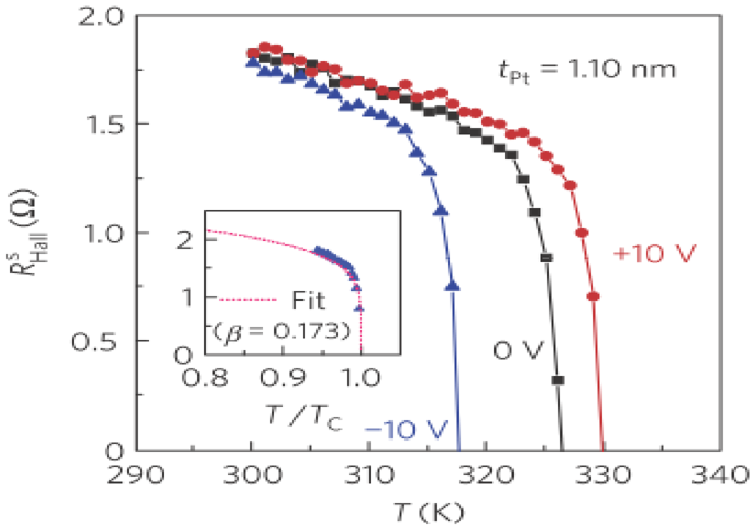
D. Chiba[1,2]*, S. Fukami[3], K. Shimamura[1], N. Ishiwata[3], K. Kobayashi[1] and T. Ono[1]

310 K




321 K



# Electric toggling of magnets

Electric-field-induced toggle switching of nanoscale thin-film magnets signifies an important step towards energy-efficient magnetic data storage.

Evgeny Y. Tsymbal

NATURE MATERIALS | VOL 11 | JANUARY 2012 | www.nature.com/naturematerials

nature materials
LETTERS
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NMAT3172

## Induction of coherent magnetization switching in a few atomic layers of FeCo using voltage pulses

Yoichi Shiota[1], Takayuki Nozaki[1,2†], Frédéric Bonell[1], Shinichi Murakami[1,2], Teruya Shinjo[1] and Yoshishige Suzuki[1,2]*

ARTICLES
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NMAT3171
nature materials

## Electric-field-assisted switching in magnetic tunnel junctions

Wei-Gang Wang*, Mingen Li, Stephen Hageman and C. L. Chien*

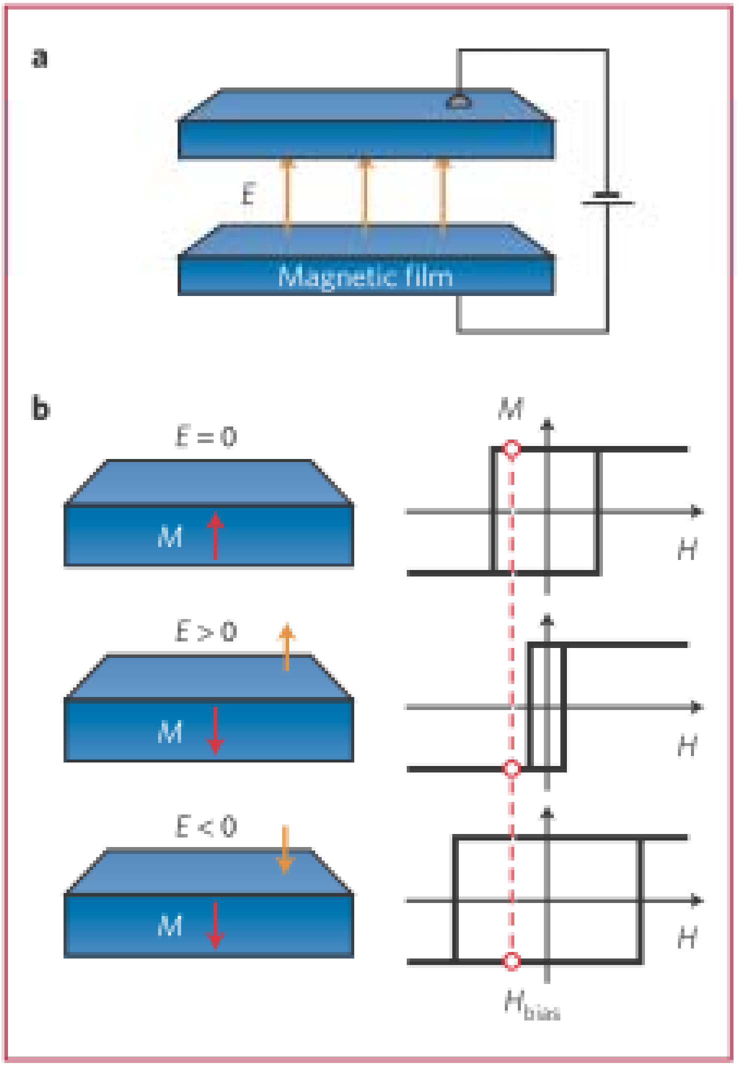



Figure 1 | Electric field effect on magnetization.

commentary

NATURE MATERIALS | VOL 11 | MAY 2012 |

# Nanoferronics is a winning combination

Manuel Bibes

Progress in controlling different ferroic orders such as ferromagnetism and ferroelectricity on the nanoscale could offer unprecedented possibilities for electronic applications.

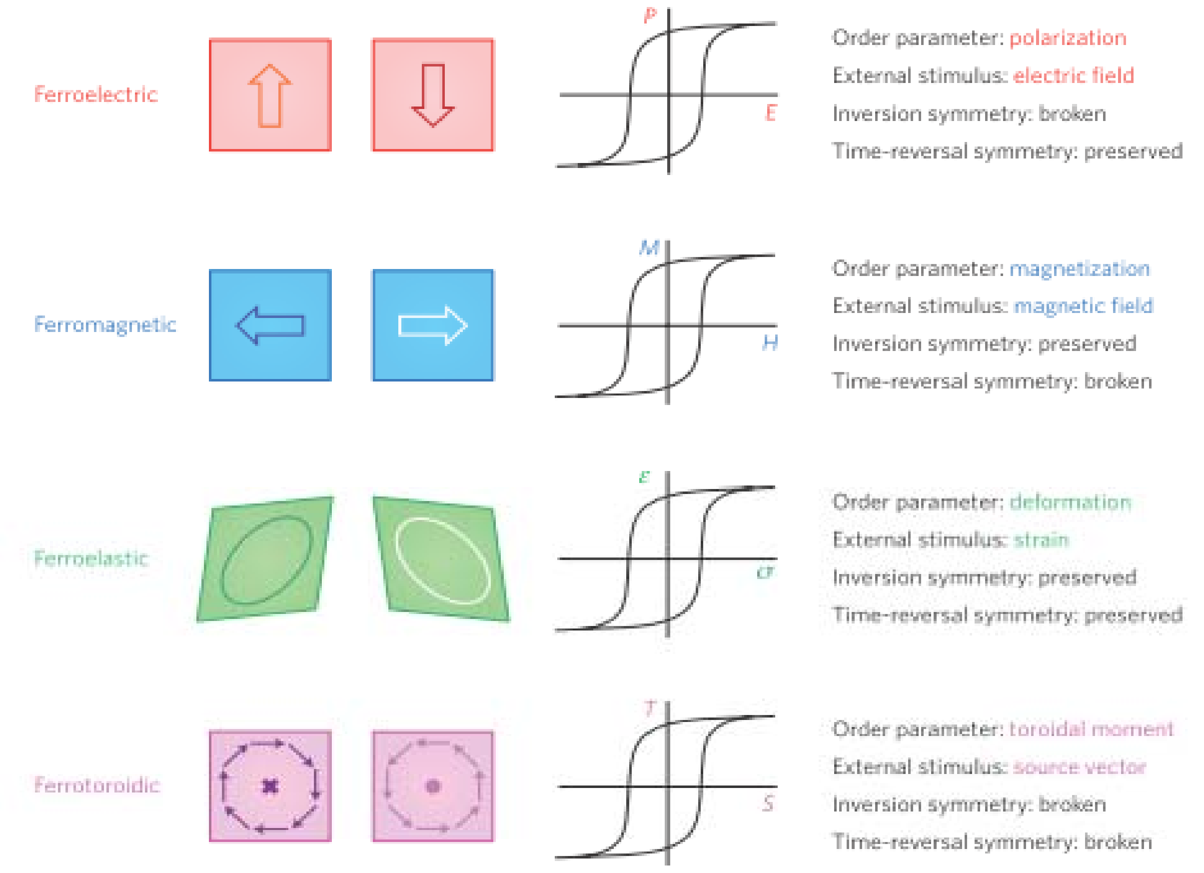



**Figure 1 |** Schematic representation and hysteresis cycles of the four primary ferroic orders. Figure adapted

# Towards organic Nanomagnetism

Our **challenge** is to start from **molecules**, existing as such in powders, suitably designed to build magnetic solid thin films and multilayer structures where:

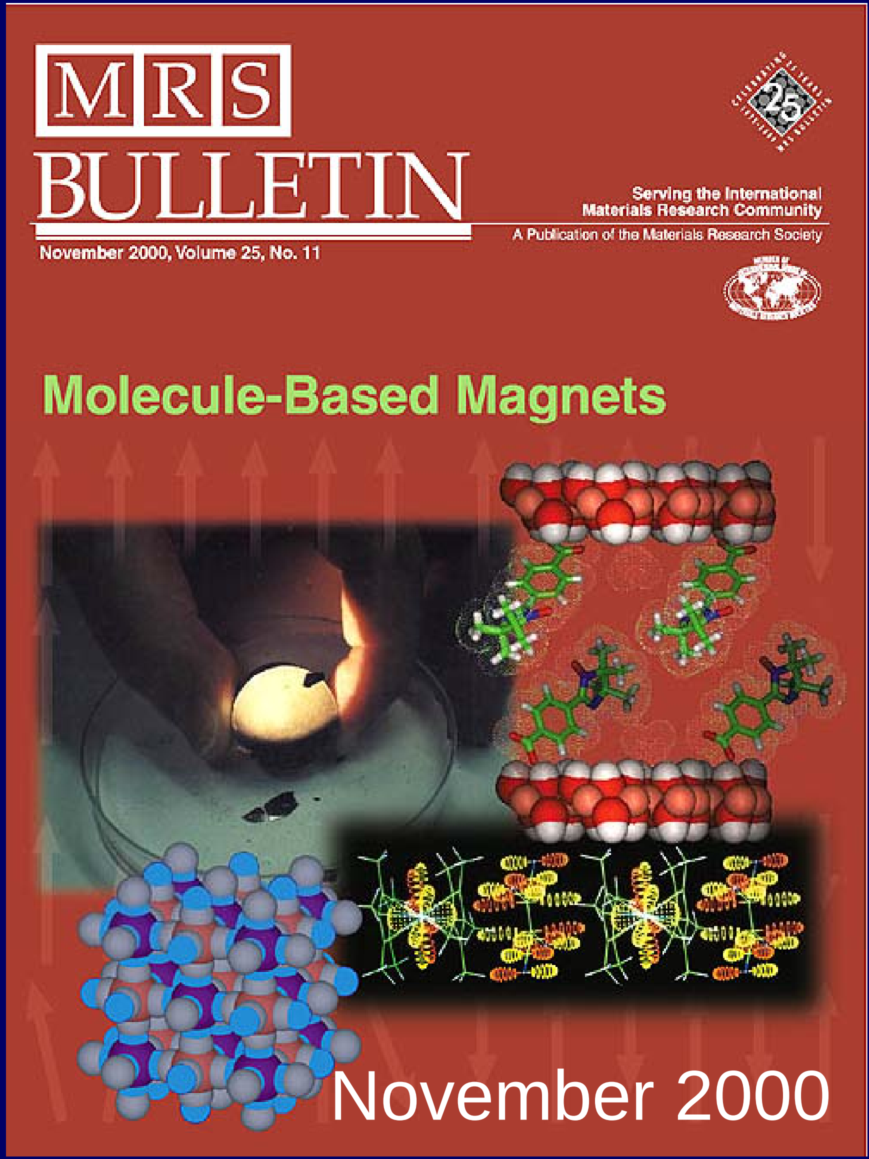
- ☞ *intermolecular interactions are strong enough*
- ☞ *large (magnetic anisotropy times magnetization) values*

for the **magnetic ordering** to survive **at room temperature**.

Long spin diffusion length,
Multifunctionality,
Plastic technology,
Low cost,

# Why Study Molecule-Based Magnets ?

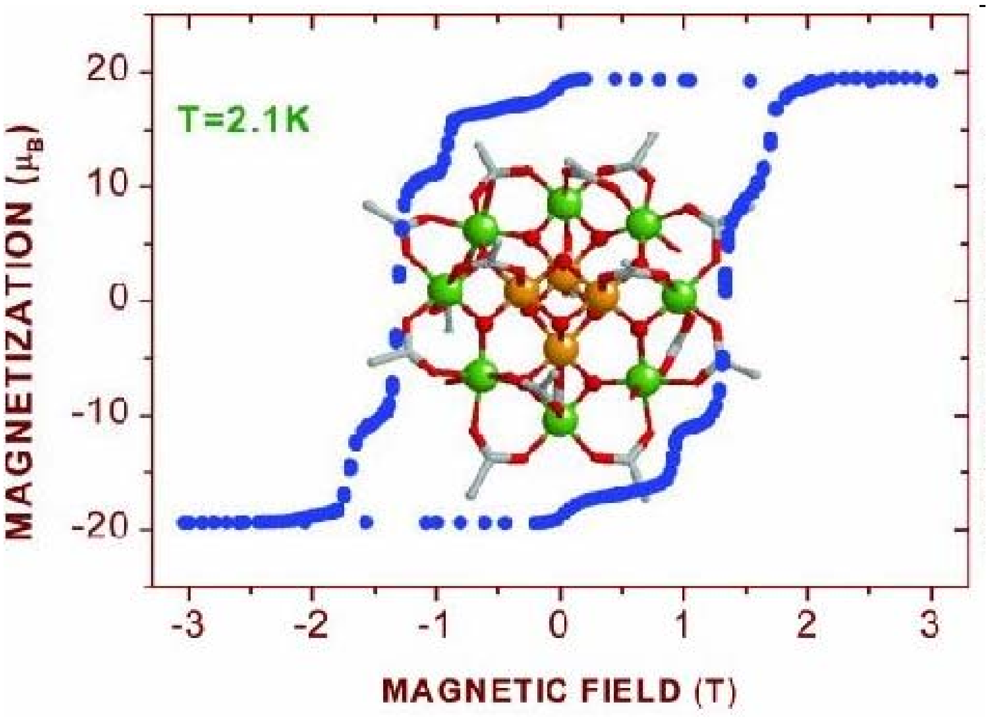
- New phenomena observed, not in conventional magnets
- Tunable properties ('magnets by design')
- Light-weight, bio-compatible alternative to conventional magnets
- Low-cost, low-temperature, flexible syntheses




adapted from A. J. Epstein, Ohio State University, USA

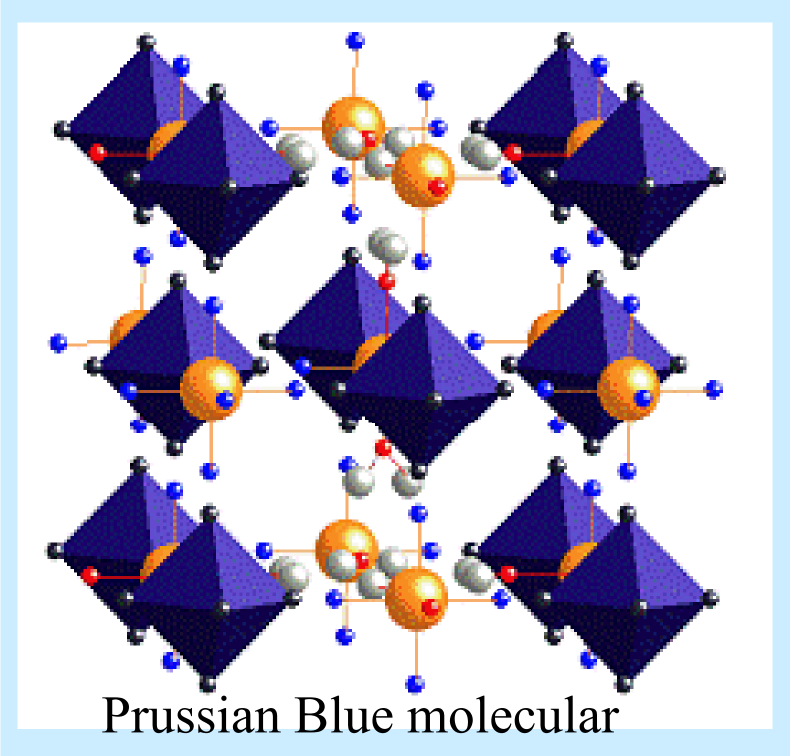
# Intermolecular interactions are important ¡

***Non-interacting molecules***:
Single Molecular Magnets (SMM)




Large relaxation times (large K)
Very low $T_C$
Quantum phenomena

***Interacting molecules***:
RT organic magnetic systems



Prussian Blue molecular structure

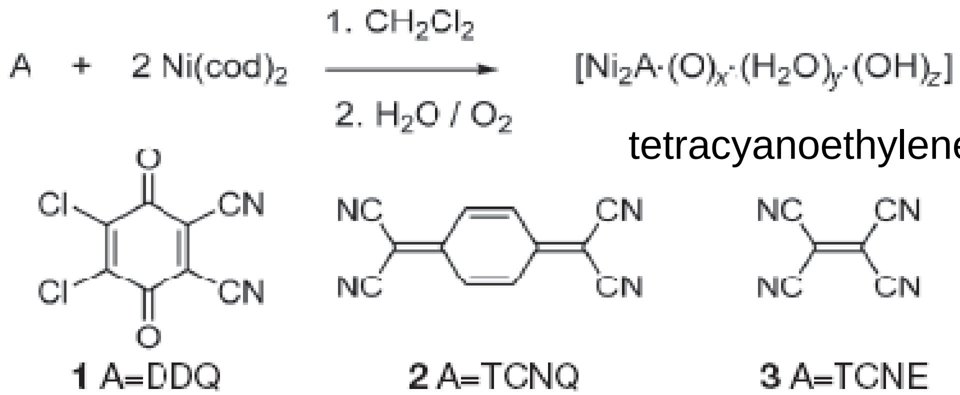
Long magnetic order
\+ new functionalities

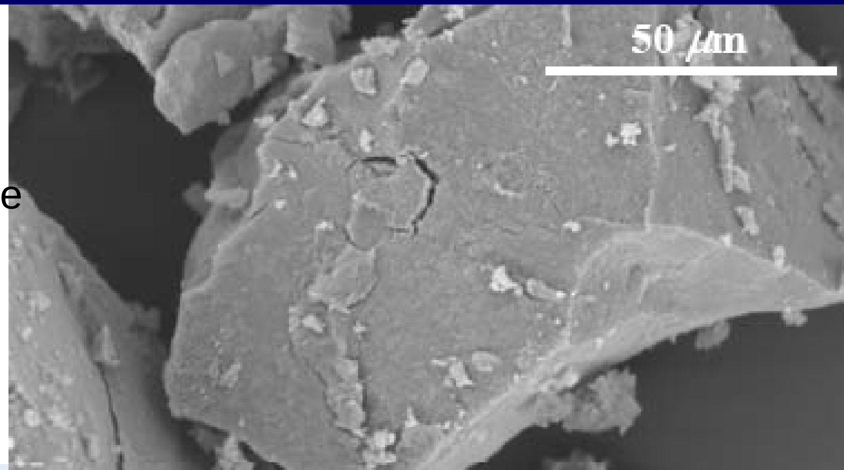
Vol 445|18 January 2007|doi:10.1038/nature05439

# High-temperature metal–organic magnets

Rajsapan Jain[1], Khayrul Kabir[1], Joe B. Gilroy[1], Keith A. R. Mitchell[2], Kin-chung Wong[2] & Robin G. Hicks[1]

Selected metal-cyanide-based organometallic magnets order near or above RT



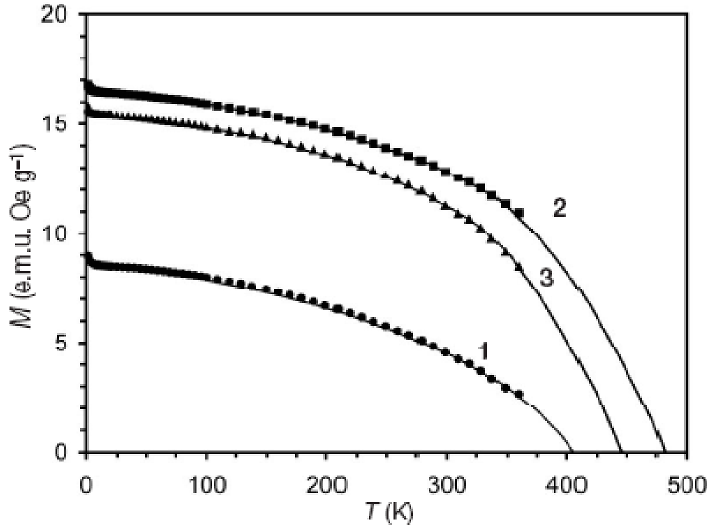




**Figure 1 | Temperature dependence of field-cooled (25 Oe) magnetization for 1–3.** Solid lines are extrapolations.

~350 mg of the $Ni_2$TCNE-based material

instituto imdea nanociencia

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LaSuAM

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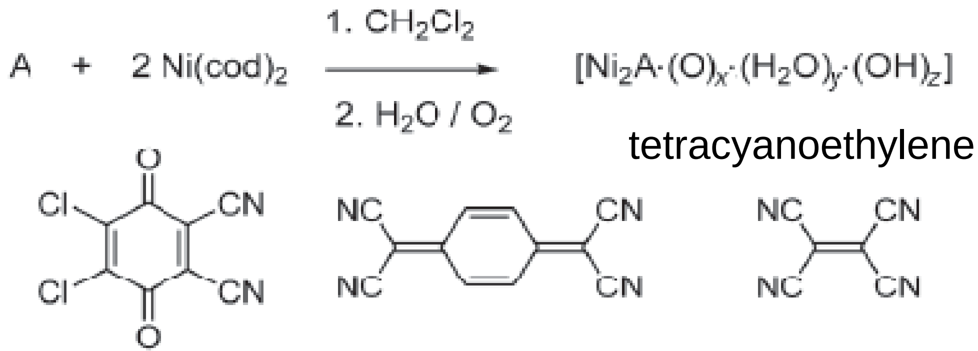
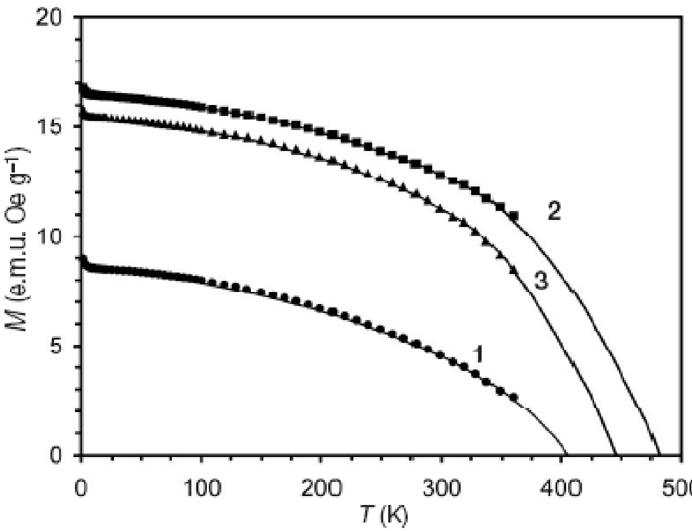



**1** A=DDQ **2** A=TCNQ **3** A=TCNE

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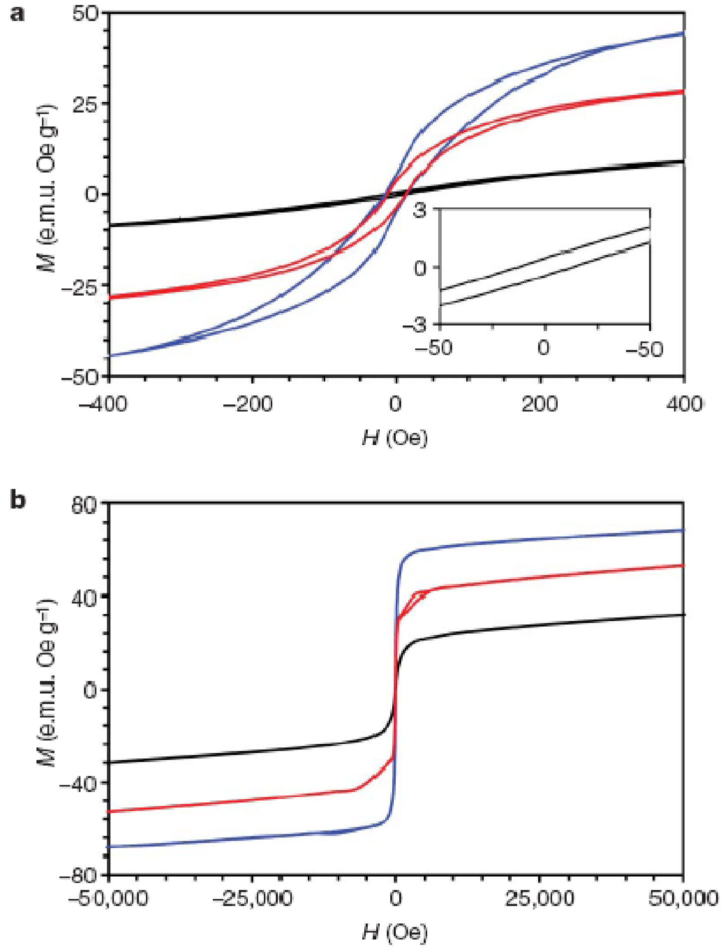


**Figure 2 | Magnetic hysteresis loops for 1 (black line), 2 (blue line), and 3 (red line) at 300 K. a,** ±400 Oe. Inset shows expansion of the loop for **1. b,** ±50,000 Oe.

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Selected metal-cyanide-based organometallic magnets order near or above RT

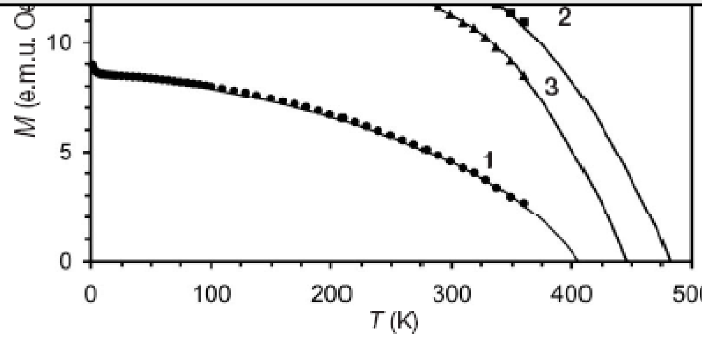
**Chemistry World (June 2007): Magnetic dreams disputed¡¡**

The holy grail is still to make a stable, well-characterised, RT molecular magnet.

J. Miller & K. I. Pokhodnya, J. Mater. Chem. **17**, 3585 (2007)

**Conclusion**

Presumably the magnetic material made upon dissolution of $Ni(COD)_2$ in $CH_2Cl_2$ consists of 'nano'- or greater-sized particles of nickel metal. This black powder magnetic material may also have chlorine, carbon, and/or hydrogen present, but it certainly lacks the organic species used in the aforementioned paper. The

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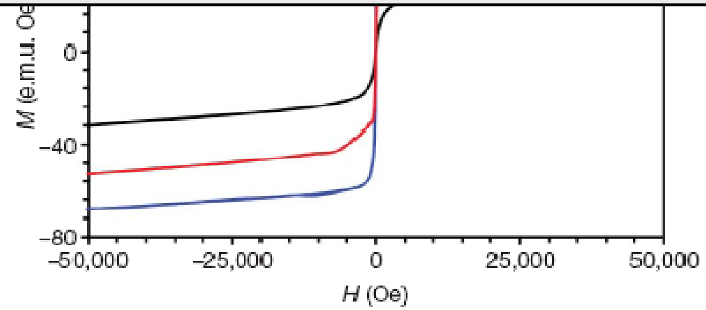


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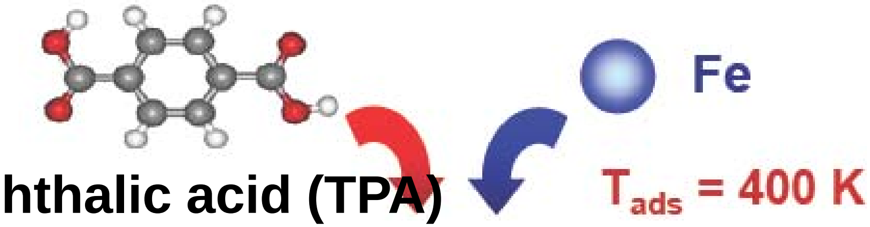
# 3d metals on supramolecular self-assembled structures




nature materials

LETTERS

PUBLISHED ONLINE: 1 FEBRUARY 2009 | DOI: 10.1038/NMAT2376

## Supramolecular control of the magnetic anisotropy in two-dimensional high-spin Fe arrays at a metal interface

Pietro Gambardella[1,2,3*], Sebastian Stepanow[1,4], Alexandre Dmitriev[4,5], Jan Honolka[4], Frank M. F. de Groot[6], Magalí Lingenfelder[4], Subhra Sen Gupta[7], D. D. Sarma[7], Peter Bencok[8], Stefan Stanescu[8], Sylvain Clair[3], Stéphane Pons[3], Nian Lin[4], Ari P. Seitsonen[9], Harald Brune[3], Johannes V. Barth[10] and Klaus Kern[3,4]

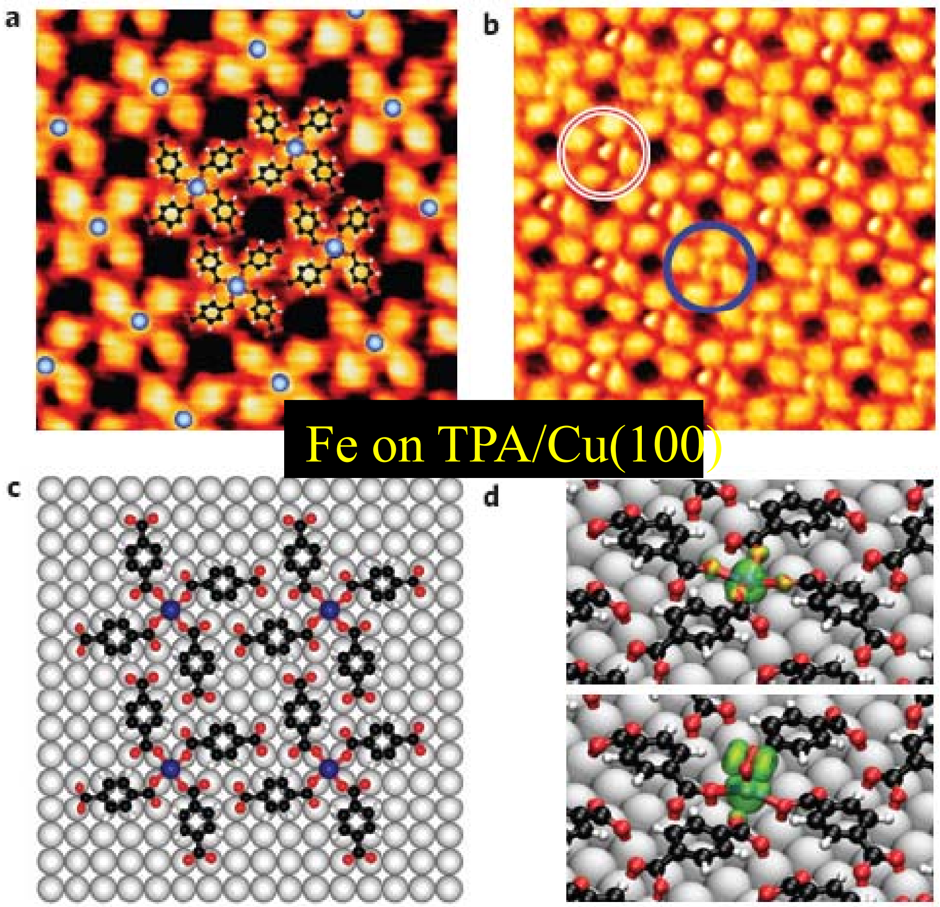
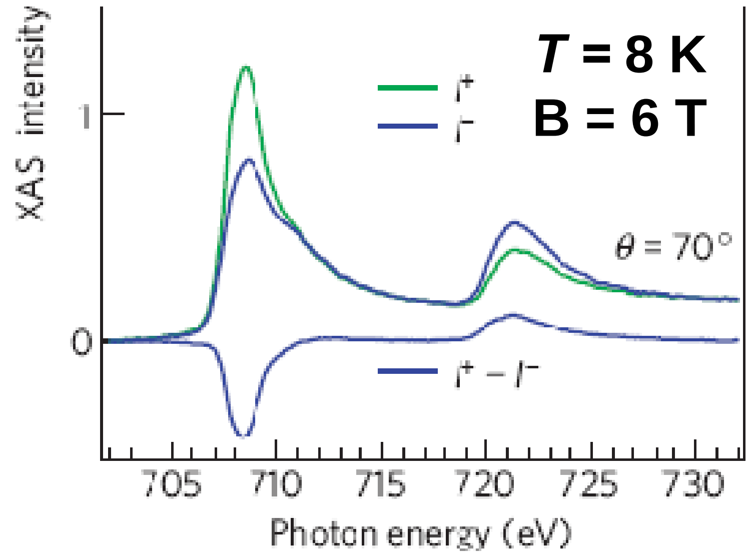
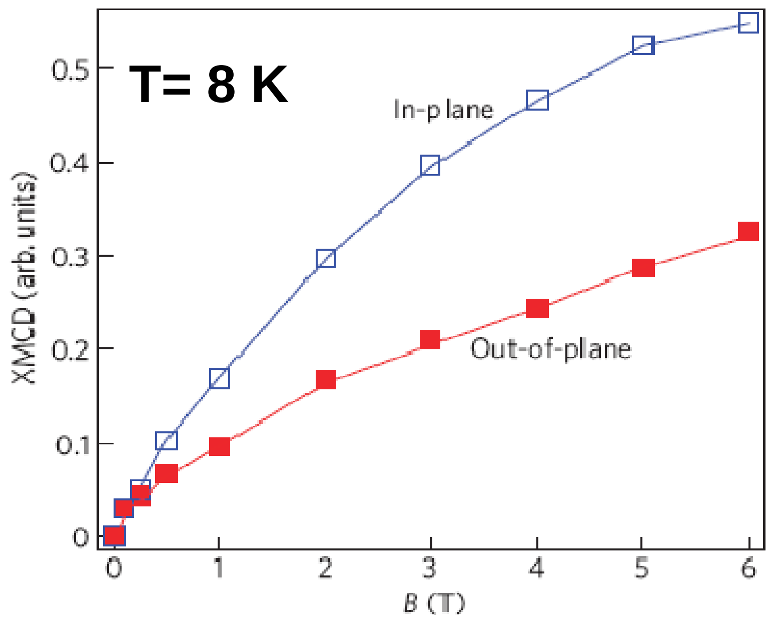



**Figure 1 | Planar supramolecular layers of Fe-TPA complexes self-assembled on Cu(100). a**, Fe(TPA)$_4$ array; blue dots indicate the

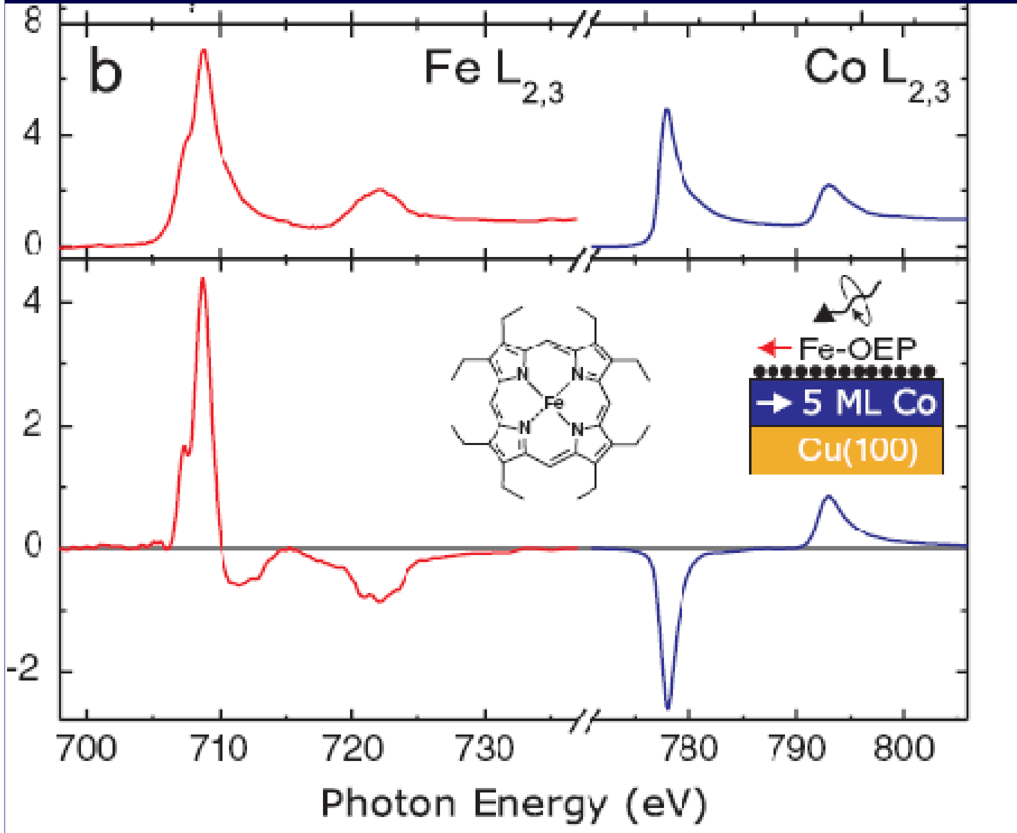


# Tailoring the Nature of Magnetic Coupling of Fe-Porphyrin Molecules to Ferromagnetic Substrates

M. Bernien,[1,*] J. Miguel,[1] C. Weis,[2] Md. E. Ali,[3] J. Kurde,[1] B. Krumme,[2] P. M. Panchmatia,[3,†] B. Sanyal,[3] M. Piantek,[1] P. Srivastava,[2,‡] K. Baberschke,[1] P. M. Oppeneer,[3] O. Eriksson,[3] W. Kuch,[1] and H. Wende[2]
[1]Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany

**Antiferromagnetic coupling** between paramagnetic Fe-porphyrin molecules and ultrathin Co and Ni magnetic films on Cu(100) substrates can be established by an ***intermediate layer of atomic oxygen***.



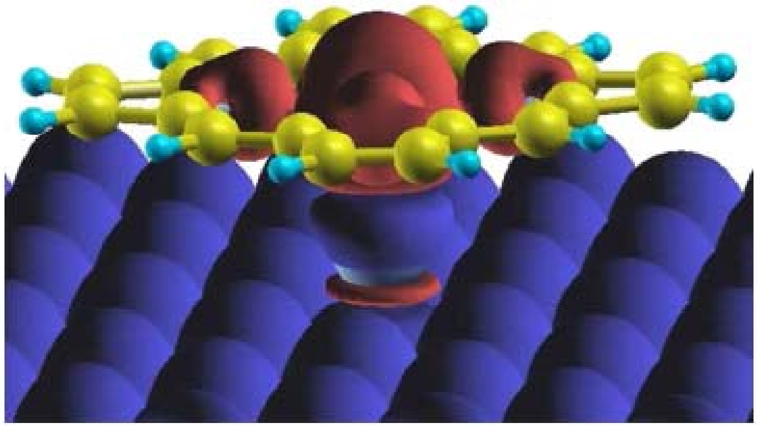



FIG. 4 (color online). *Ab initio* computed magnetization densities. Blue or dark gray color depicts majority-spin magnetiza-

the responsible coupling mechanism is antiferromagnetic superexchange mediated by the oxygen $p_z$ orbitals.

# Program 3. Nanomagnetism

http://www.nanoscience.imdea.org/research/research-lines/nanomagnetism

- Development of new hybrid (inorganic-organic) magnetic nanostructures
- Magnetization reversal and magnetoresistive studies
- Polarization dependent element-resolved x-ray spectroscopy and microscopy studies.
- Biomedical aplications

- Multi-porpuse UHV growth/spectroscopy Lab.
- Advanced planetary milling Lab.
- Chemical synthesis magnetic nanoparticles Lab.
- Incubation room lab for biomedical studies / Cell Culture
- Advanced Magneto-Optics Lab.
- Magnetic microsocopy Lab.
- Magnetometry Lab.
- Magnetic Hiperthermia Lab.

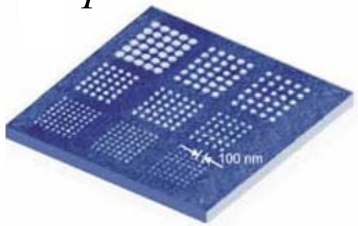
# NANOMAGNETISM GROUP RESEARCH

## Program 3. Nanomagnetism

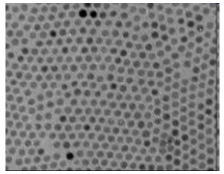
## Artificial magnetic nanomaterials

*thin films*

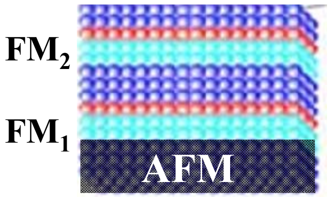
*patterned*



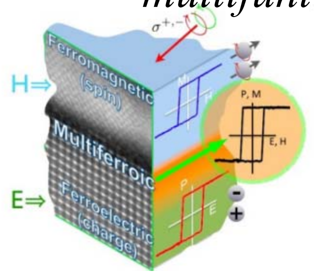

*nanoparticles*

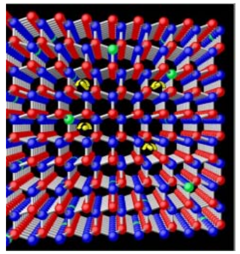


*multilayers*



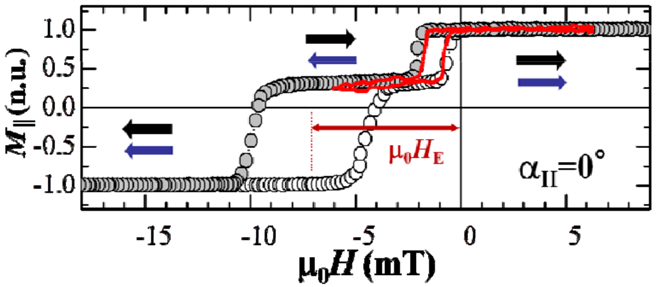

*multifuntional*



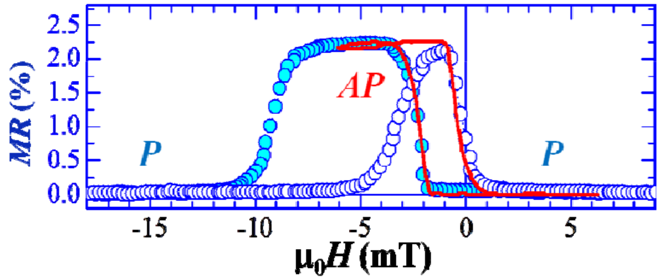



## Magnetic & transport properties

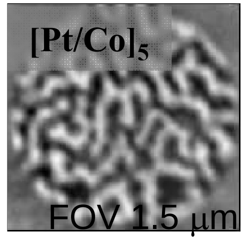
*magnetization reversal*



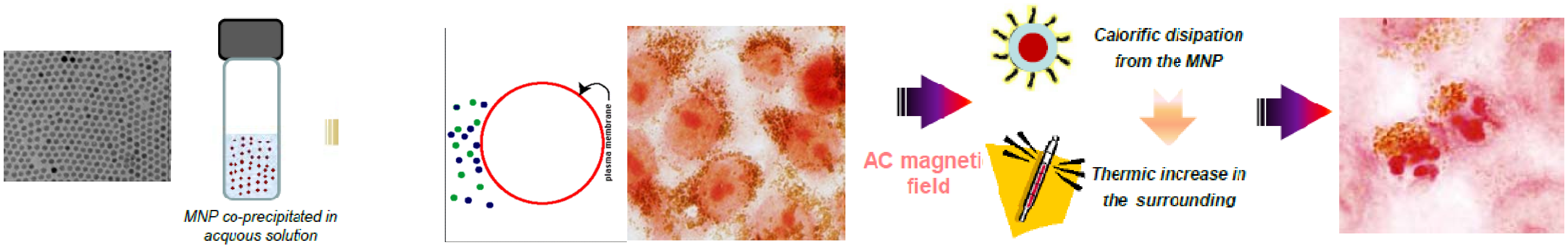

*magnetoresistive response*




*static vs dynamics*




## Biomedical Applications




www.nanociencia.imdea.org

# Nanomagnetism group Research

## Program 3. Nanomagnetism

Artificial magnetic nanomaterials

**Study of Low Dimensional Artificial Magnetic Systems**

- Growth Modes
- Crystalline Structure
- Electronic Structure
- Magnetic Properties: static *vs* dynamic
- Transport Properties
- Magneto-caloric Properties

Magnetic & transport properties

**Development of new experimental tools**

Bi… Applications

*Basic understanding of the growth processes and physical properties of new materials as a first step towards the development of devices with custom-chosen properties*