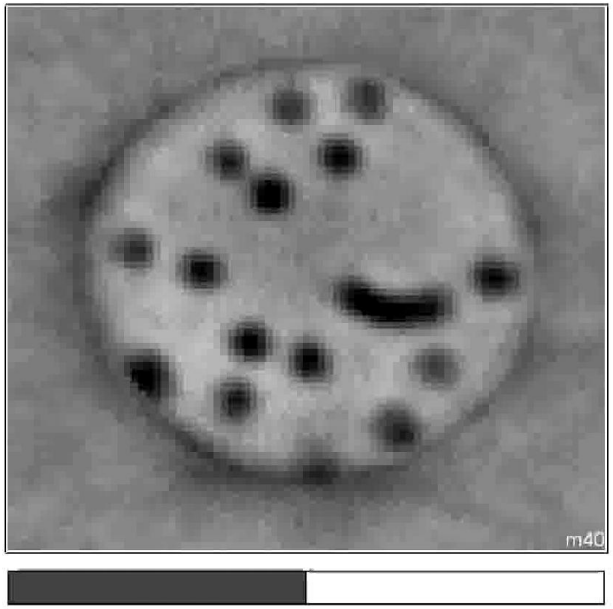
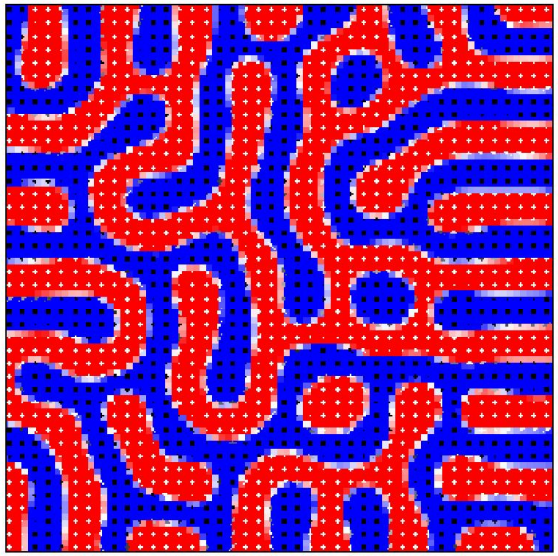
Magnetism at Nanoscale:
Nano-small meets Ultra-fast

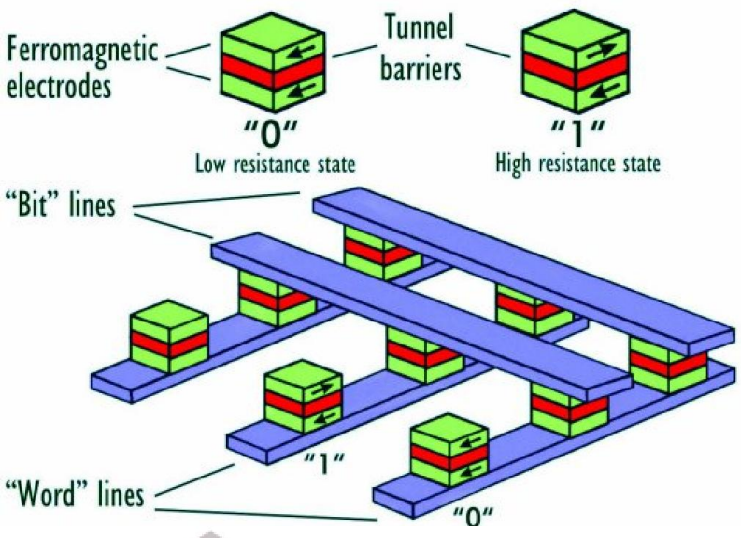


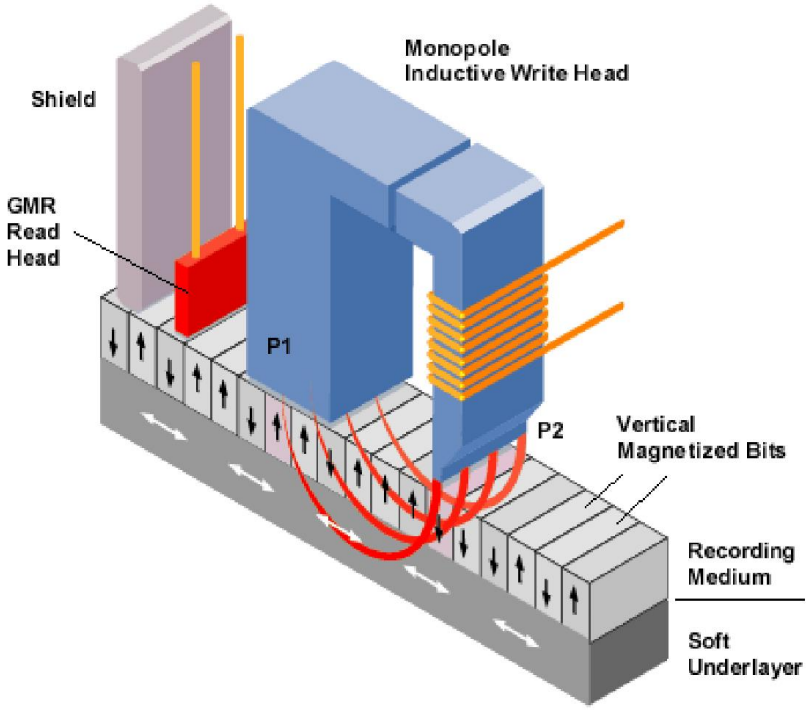


Jyoti Mohanty

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Motivation



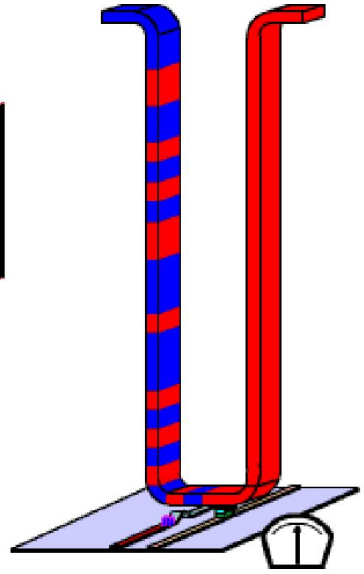


hard disks, read/write heads and Magnetic Sensors, spintronics devices

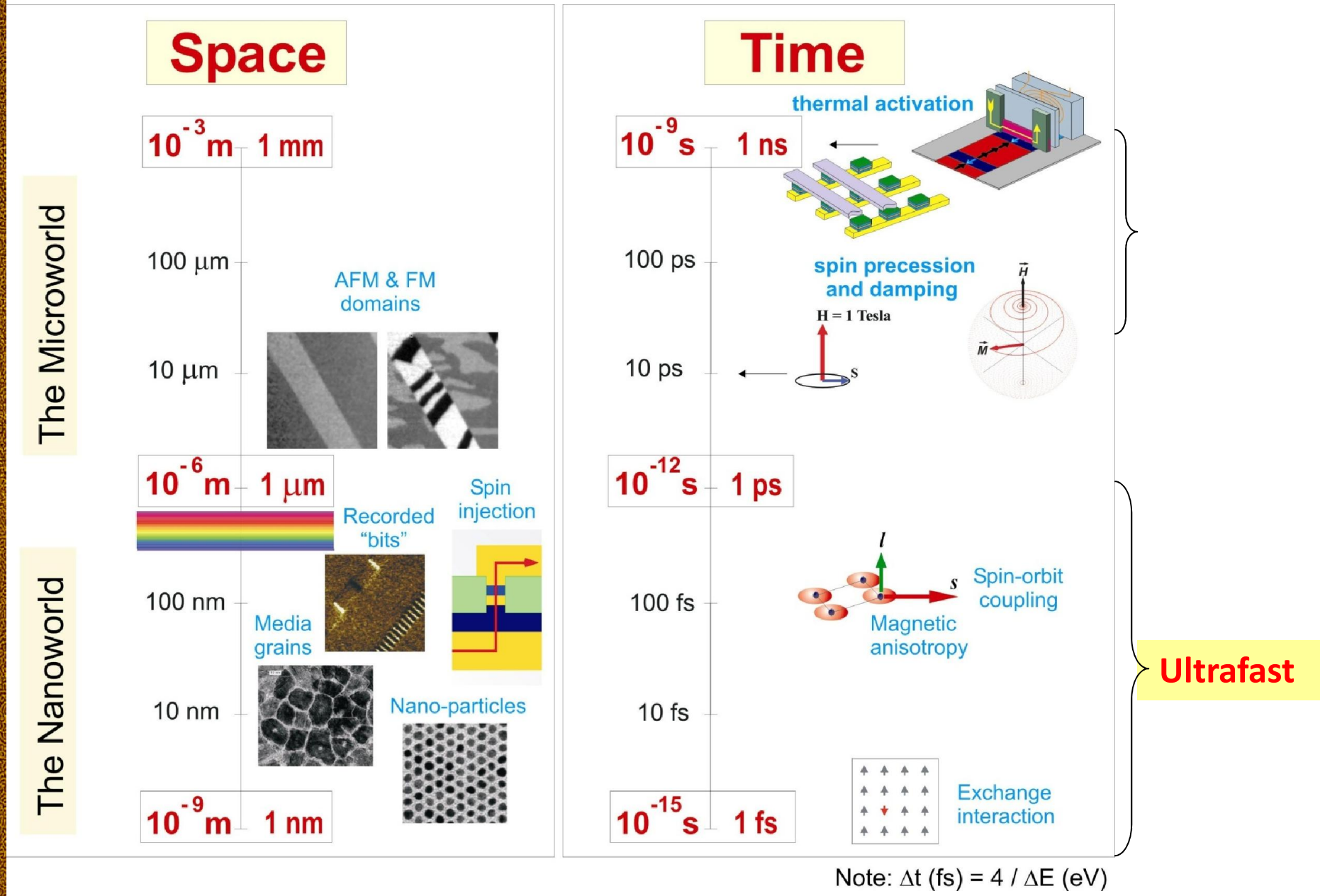
Thin film, Nanostructure, self-assembly

Magnetic domain & domain walls

Nano-small
Ultra-fast



Stuart S. P. Parkin, *et al.* ***Science 320, 190 (2008)***


Space
Time
The Microworld
The Nanoworld
10-3 m 1 mm
100 μm
10 μm
10-6 m 1 μm
100 nm
10 nm
10-9 m 1 nm
AFM & FM domains
Recorded "bits"
Spin injection
Media grains
Nano-particles
10-9 s 1 ns
100 ps
10 ps
10-12 s 1 ps
100 fs
10 fs
10-15 s 1 fs
thermal activation
spin precession and damping
H = 1 Tesla
Spin-orbit coupling
Magnetic anisotropy
Exchange interaction
Ultrafast
Note: Δt (fs) = 4 / ΔE (eV)

Space

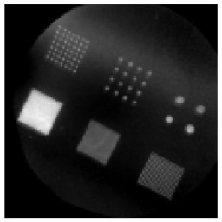
1 μm

100 nm

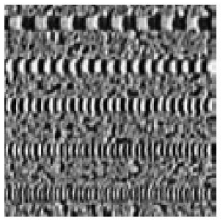
10 nm

1 nm

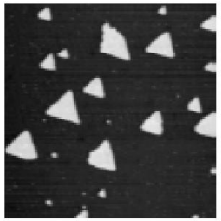
1 A



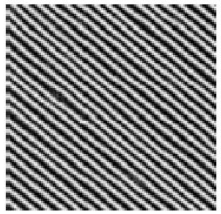
Patterned media



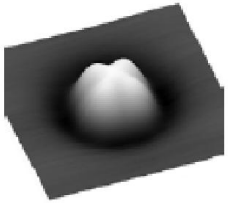
Granular/ multilayer media



Nanoparticles



Nanowires



Molecules
Atoms

Time

1 yr

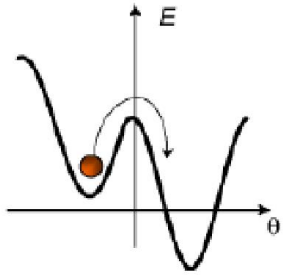
1 s

1 μs

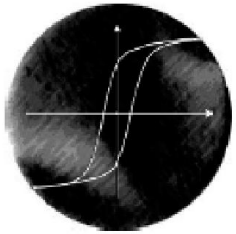
1 ns

1 ps

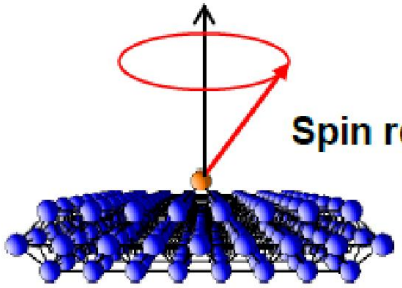
Permanent magnets



Magnetic relaxation

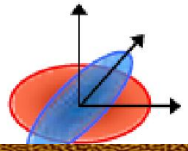


Domain wall propagation

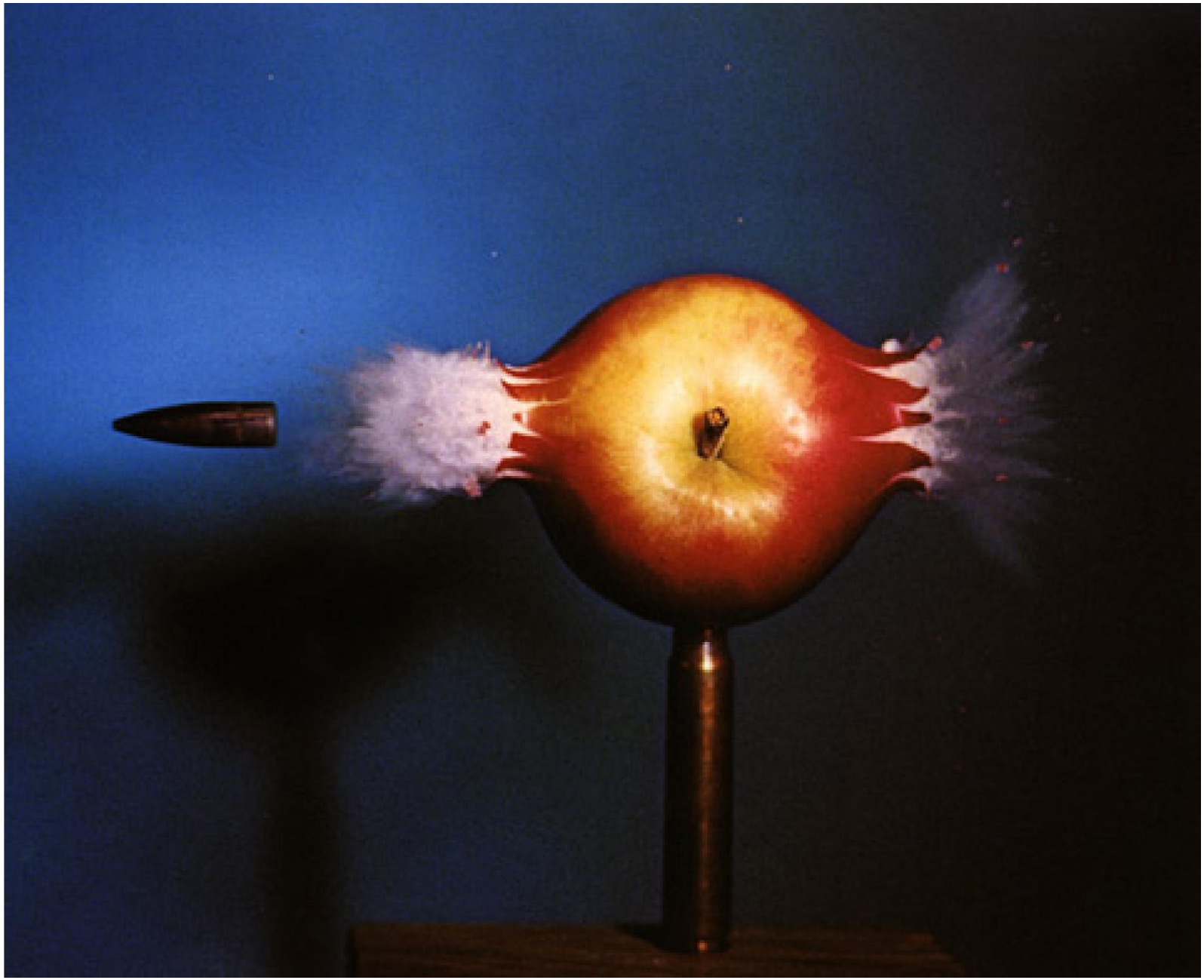


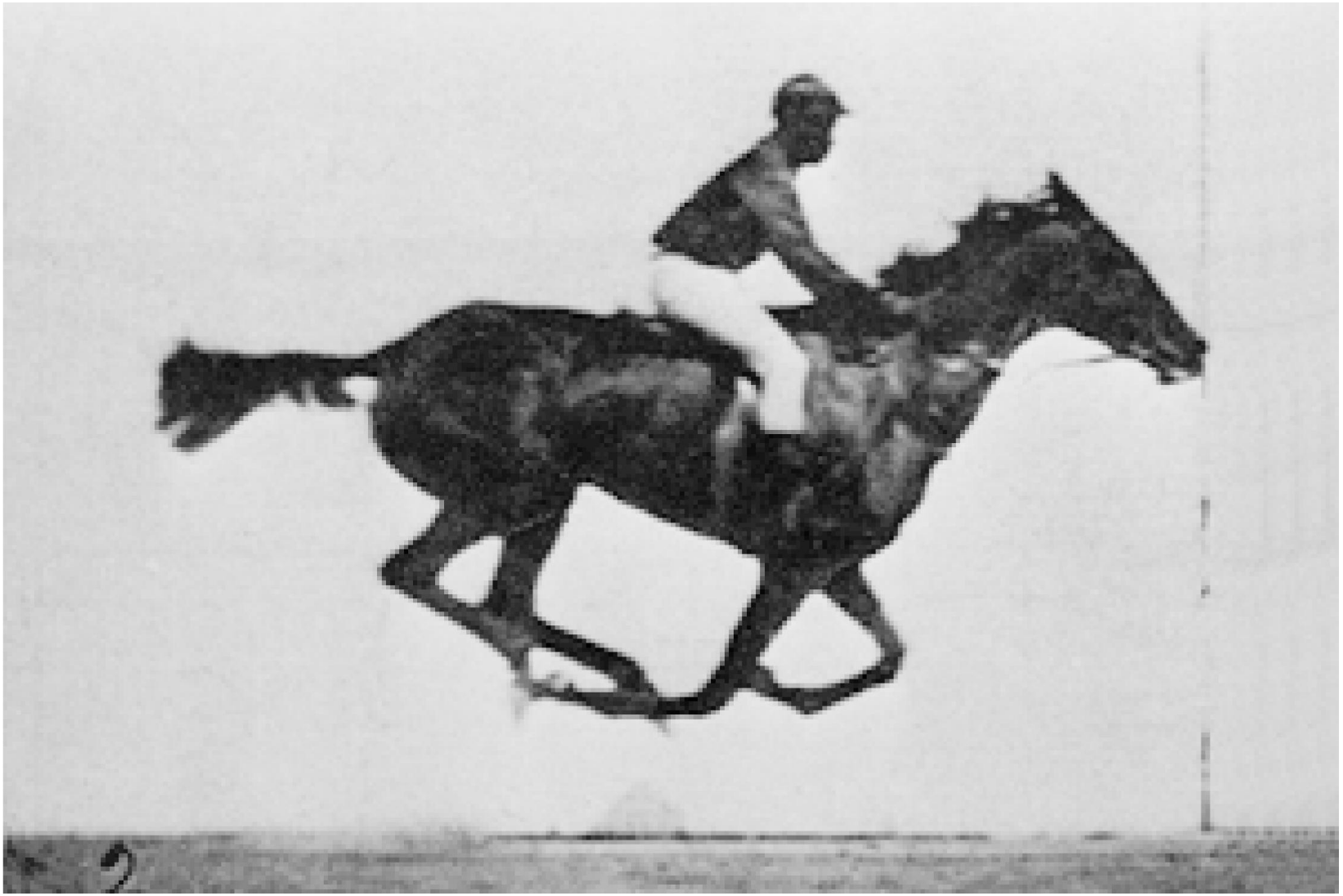
Spin reversal

Magnon excitations

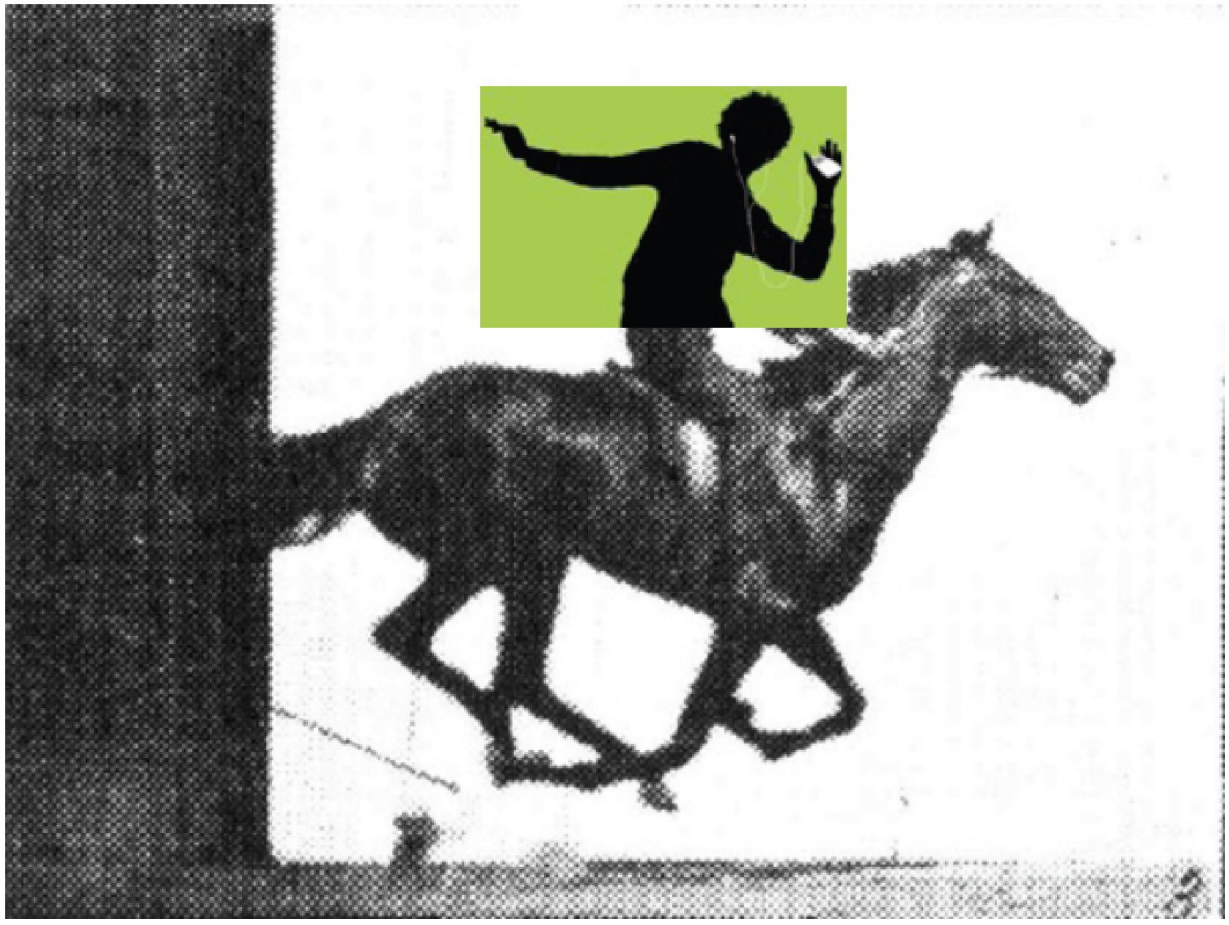


Spin-orbit coupling



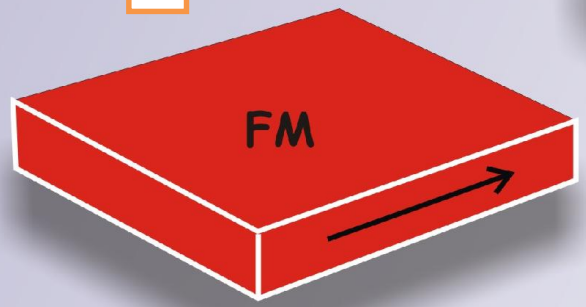


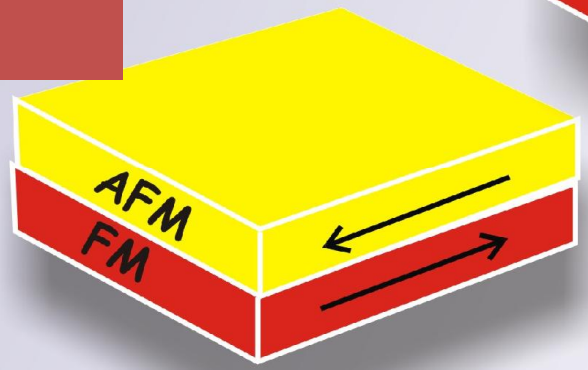
$(10^{-3}\,s;\ 10^{-3}\,m) \rightarrow (10^{-15}\,s;\ 10^{-9}\,m)$

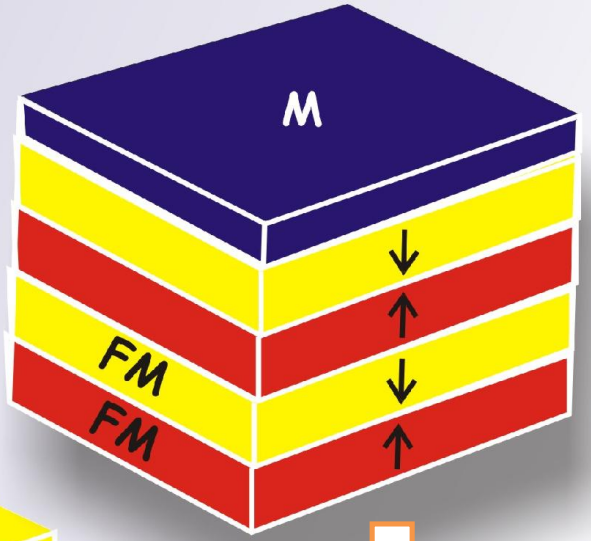


Nanomagnetism:

- Strain-Magnetism
- FM-PM
- Dipolar Coupling
- M reversal (microscopic)
  MFM, X-PEEM







- Ferri-Magnet
- Imaging without lens
- Ultrafast M dynamics

Coherent Magn Scattering,
X-ray Holography

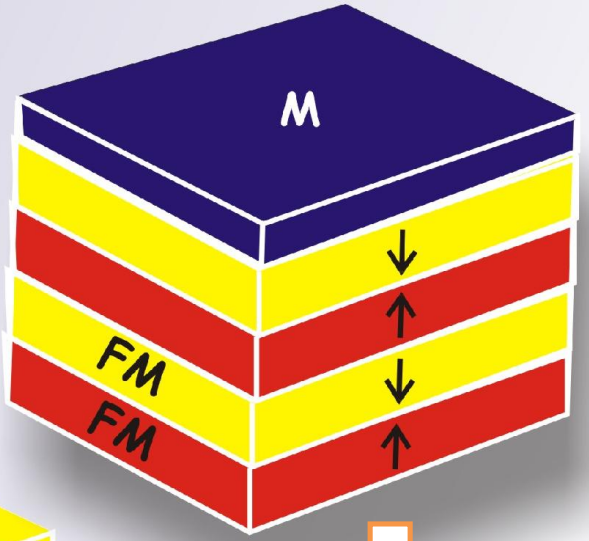
- Exchange Bias
- Interface Frozen spins

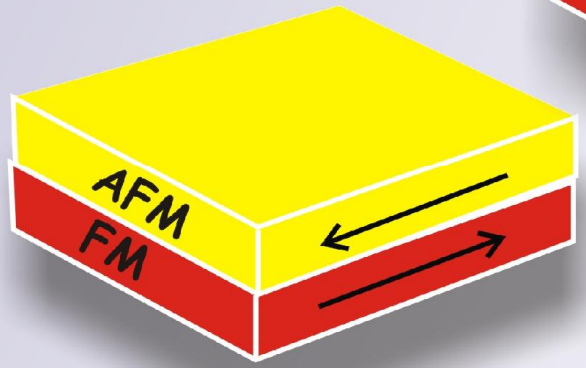
XMCD, Element specific M-H loop, XMLD

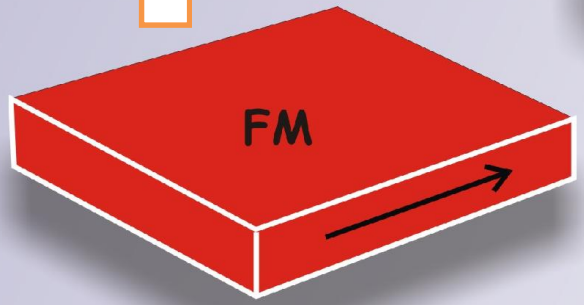
Nanomagnetism:

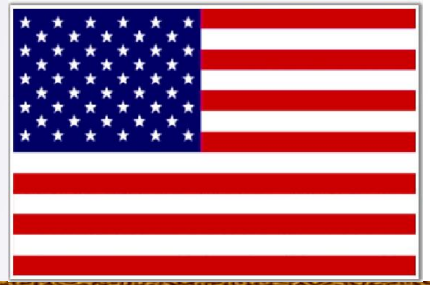
ng basics

n



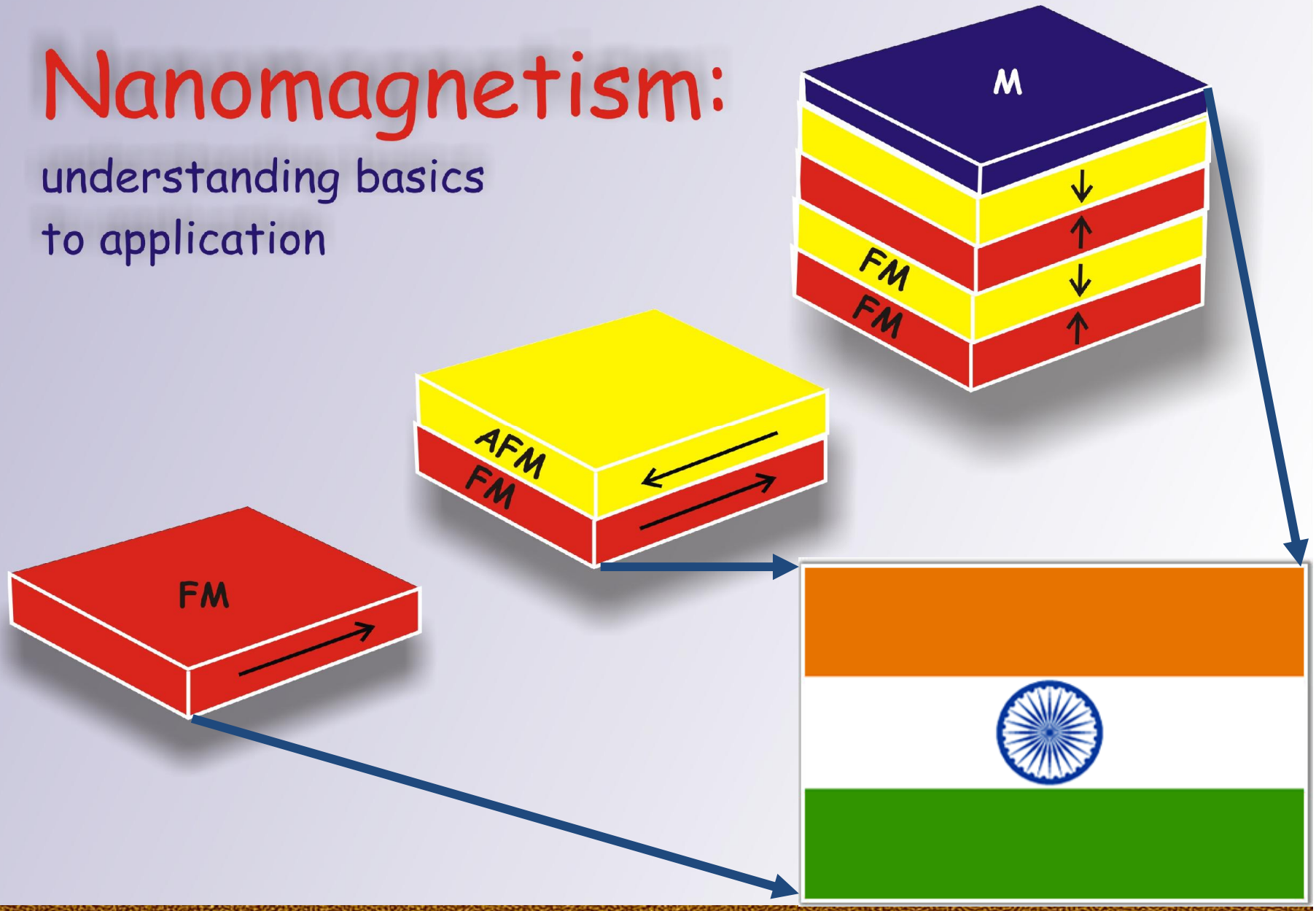






Nanomagnetism:

understanding basics
to application



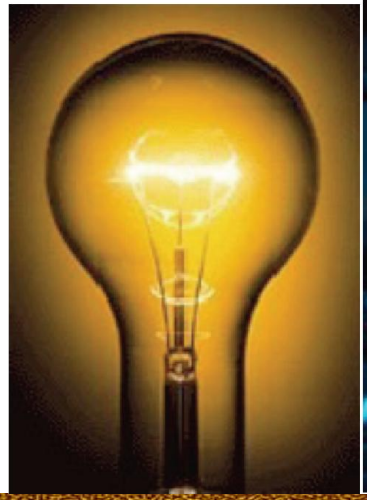
What we need

General requirements:	*Technique requirements:*
see the invisible	nanoscale spatial resolution
separate spin and orbital contributions	sensitive to s-o coupling
study thin films and interfaces	large cross section for "signal"
look below the surface	depth sensitivity
distinguish components	elemental (chemical) specificity
resolve dynamic motions	time resolution < 1 nanosecond

Why use X-rays?

- x-ray cross section and flux
- x-ray tunability: resonances and sum rules
- x-ray polarization
- x-ray spatial resolution
- x-ray temporal resolution

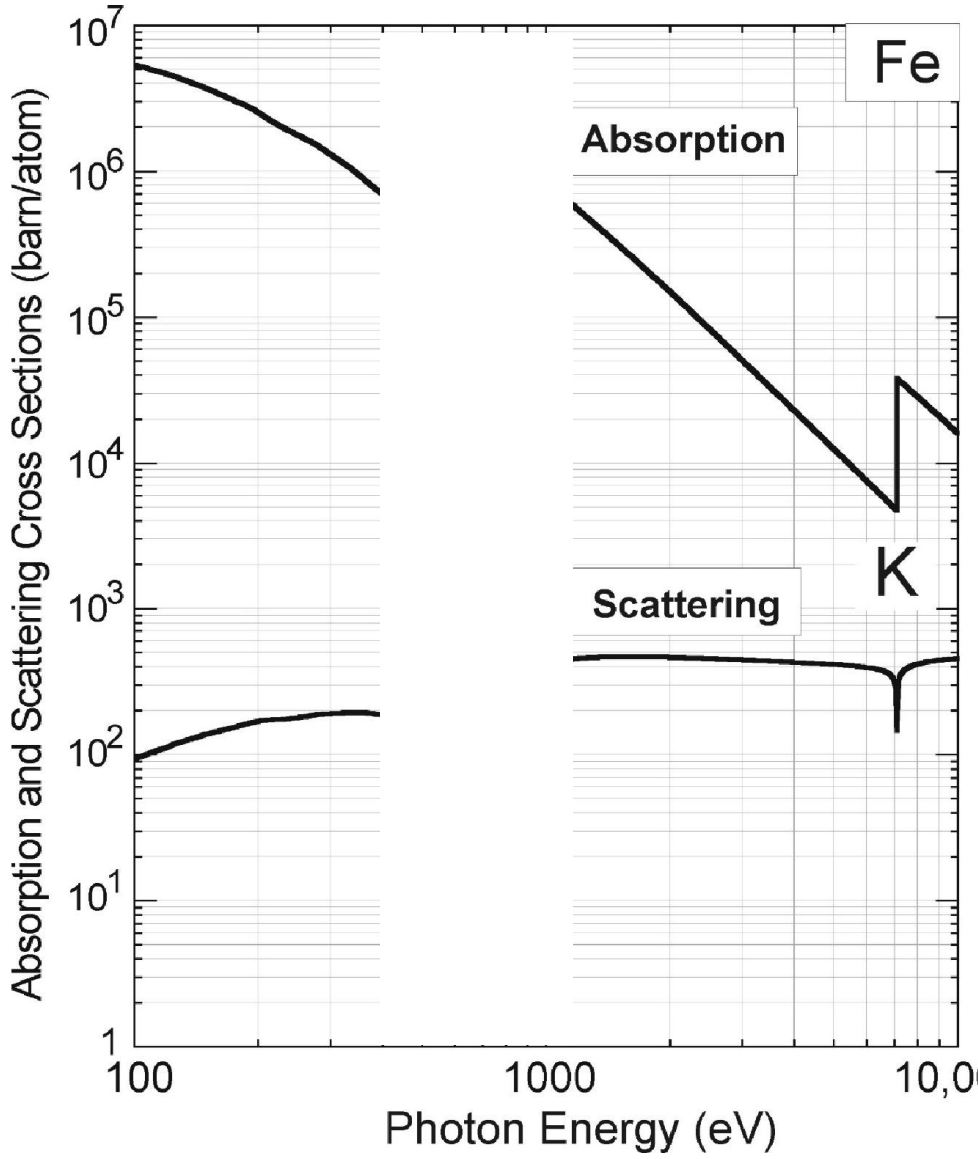
* Coherence Properties



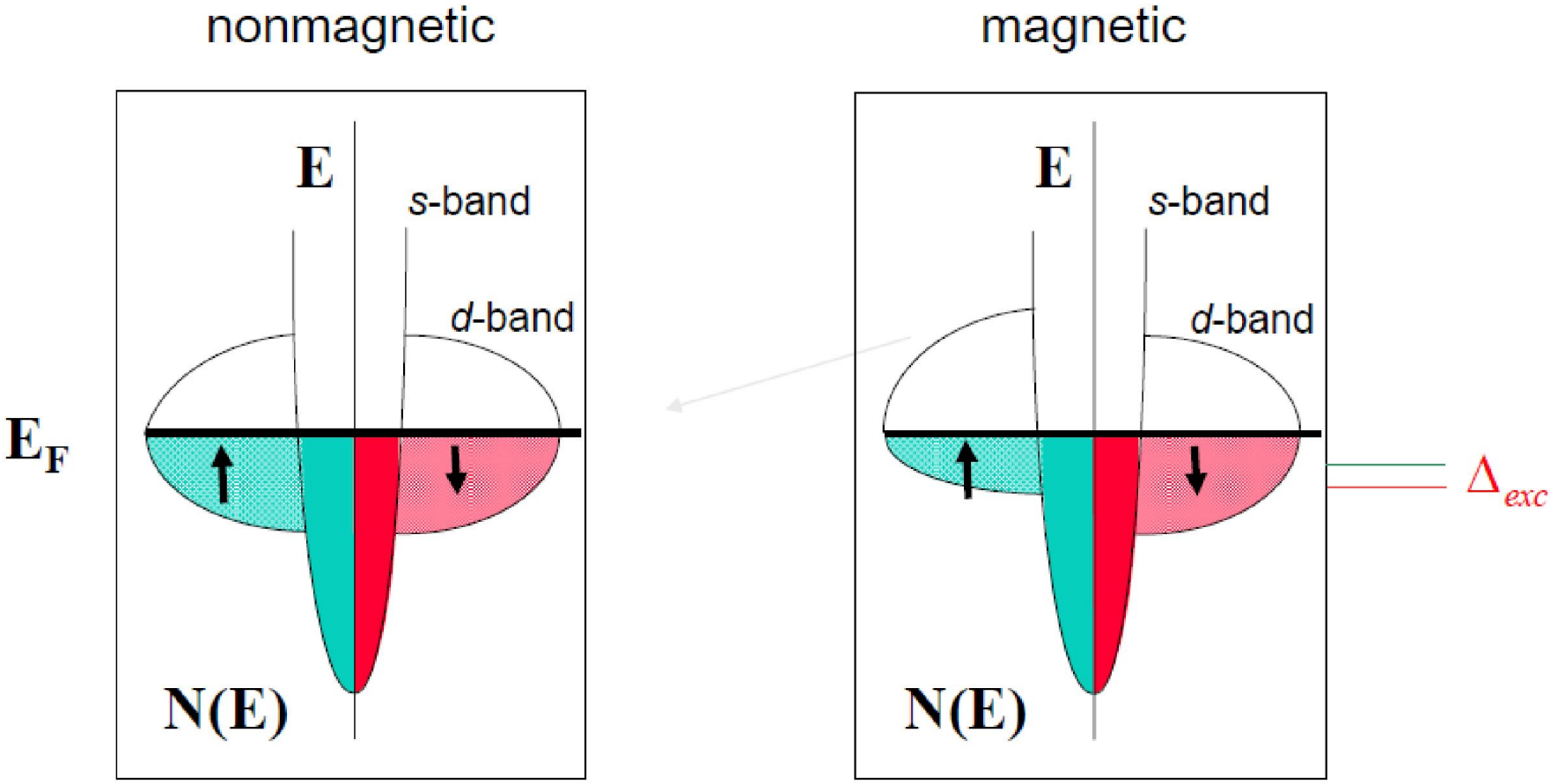
Tunable x- rays offer large interaction cross s tions

optical light

electrons

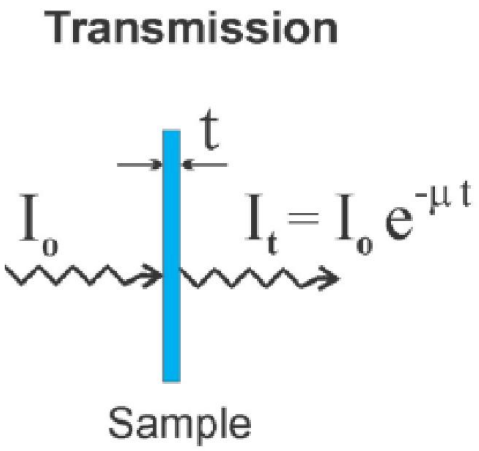


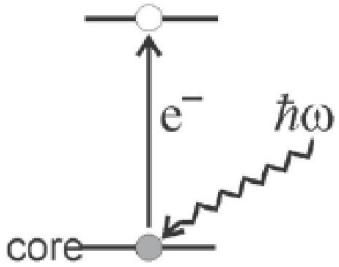
neutrons

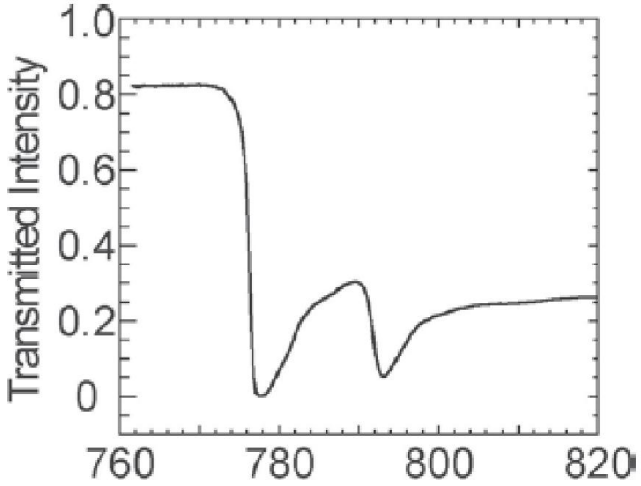


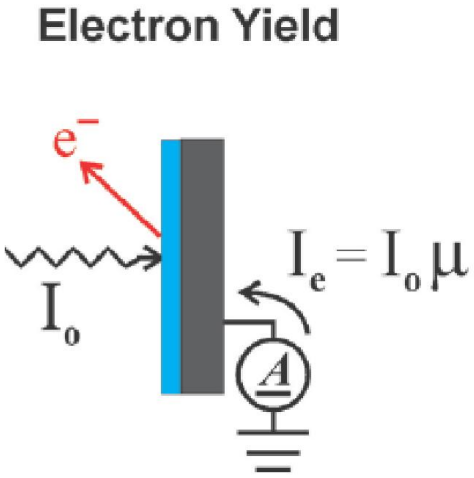
E.P. Wohlfarth, Iron, Cobalt and Nickel,
in *Ferromagnetic Materials*, vol.1, North Holland, Amsterdam, (1988)

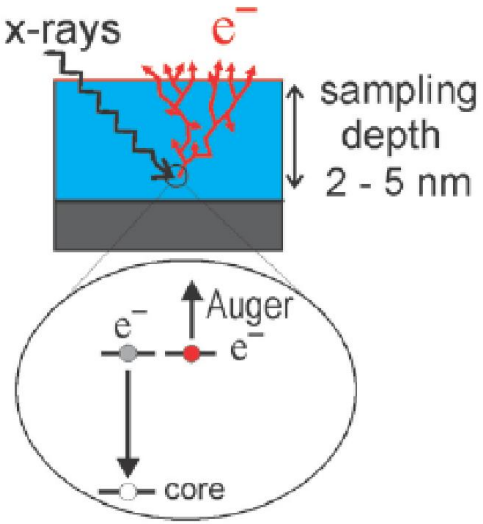
X-ray absorption

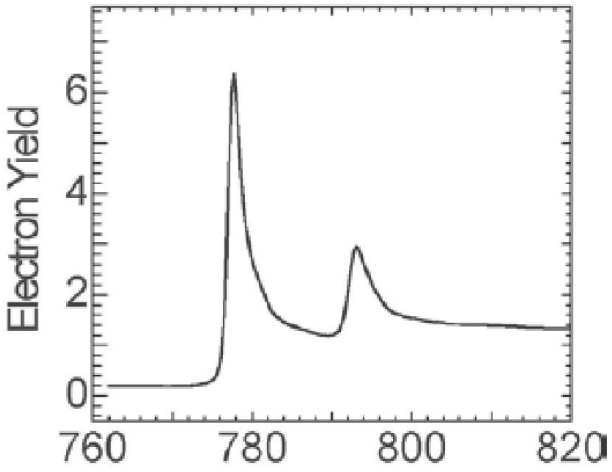




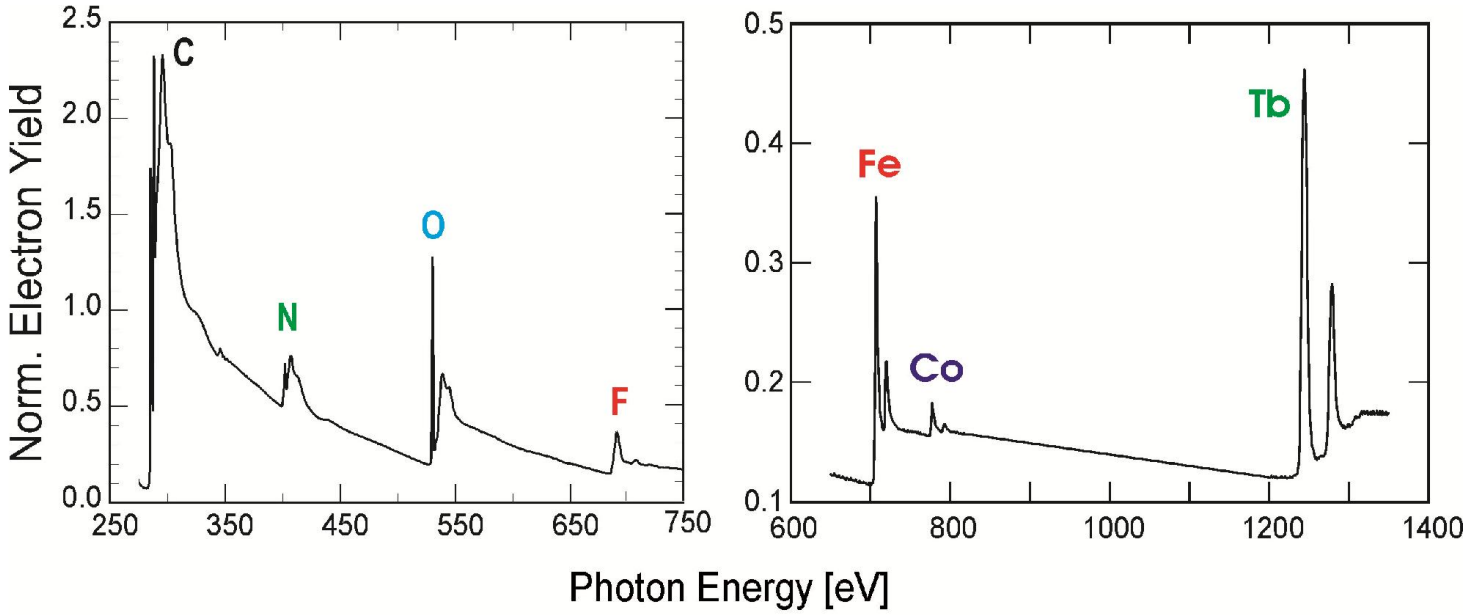


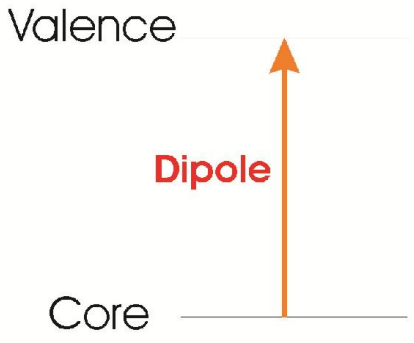






Tunable x-rays offer elemental specificity

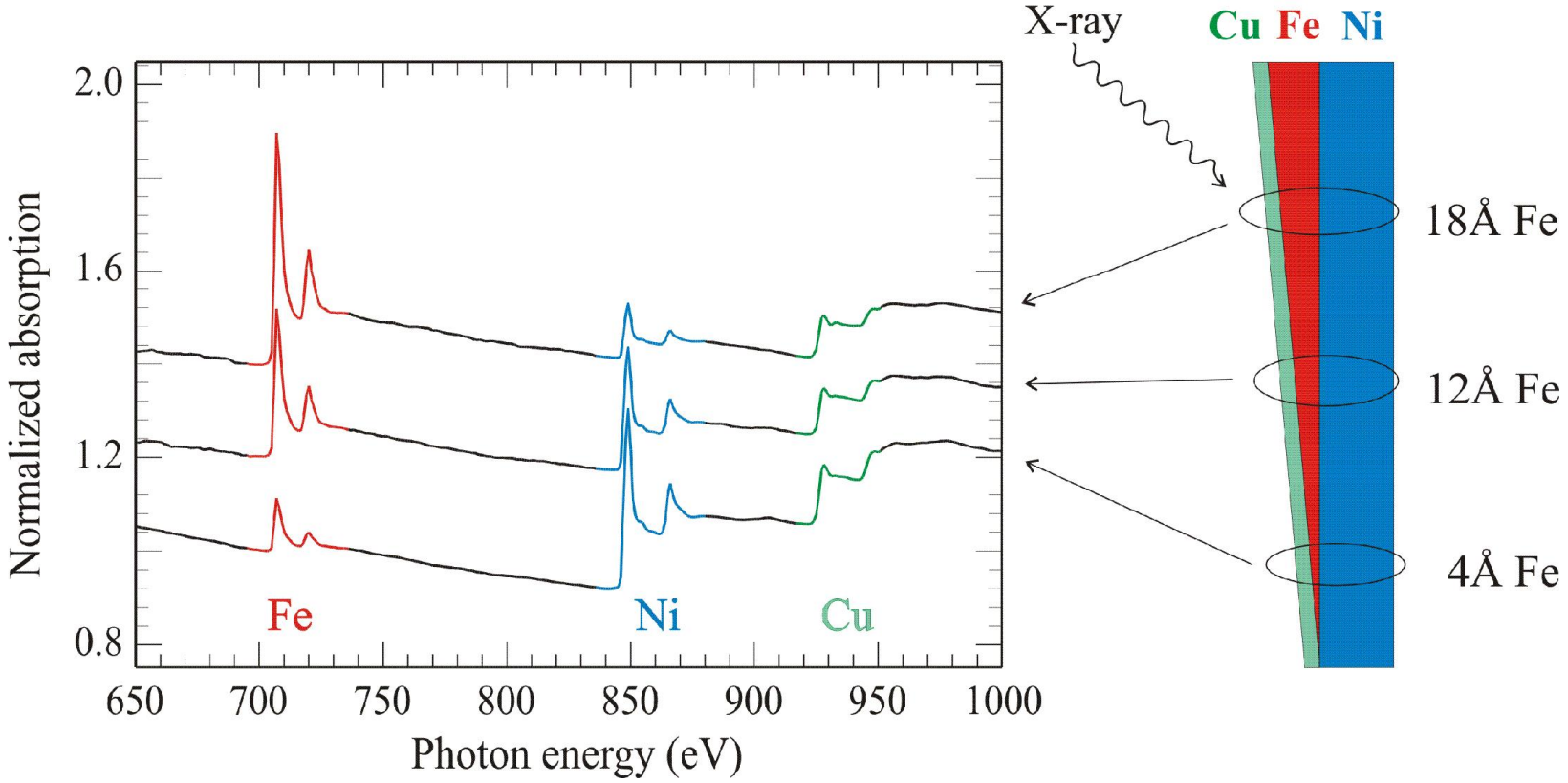




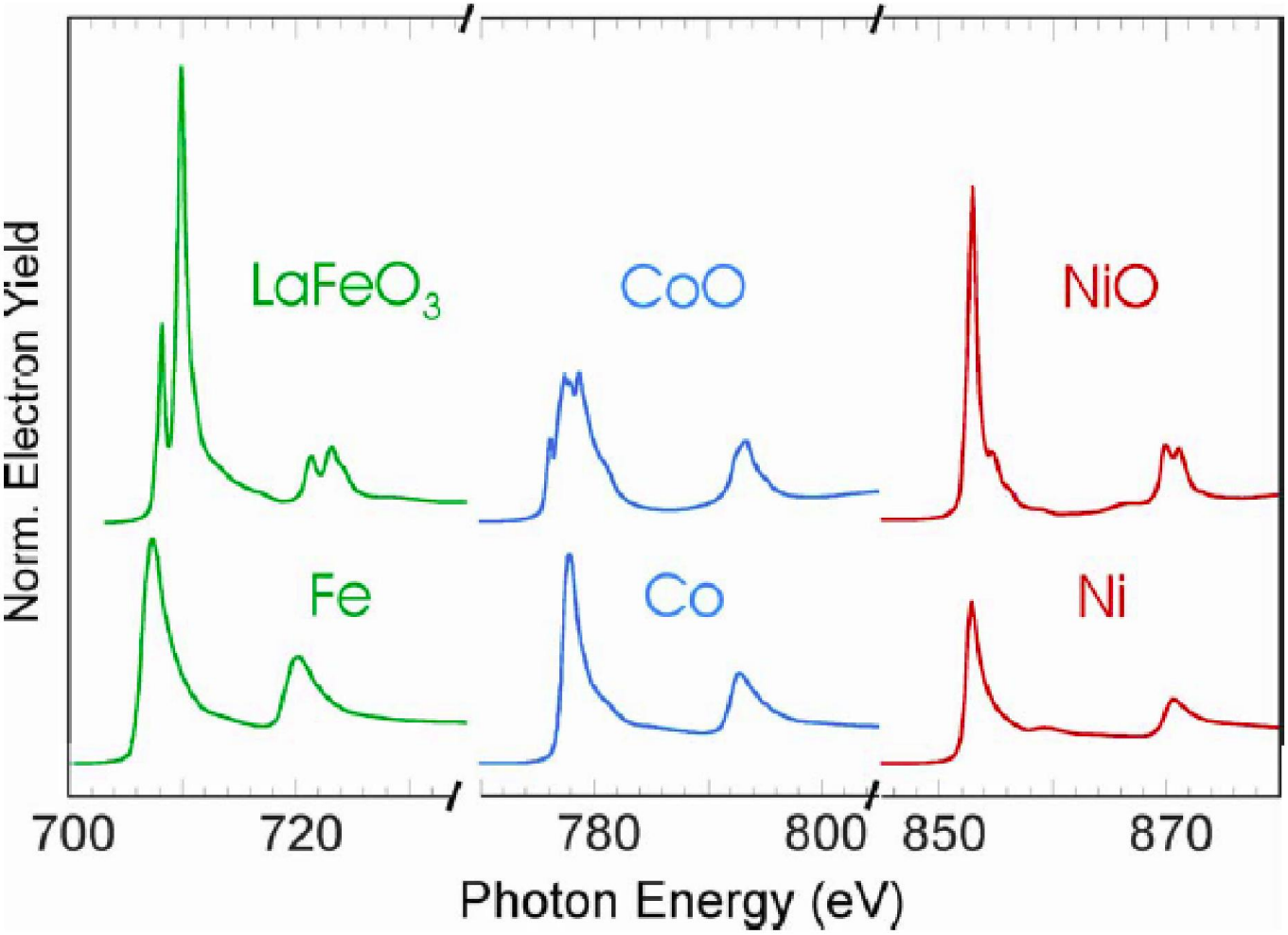
Polymers: p-orbitals
Trans. Met.: d-orbitals
Rare Earths: f-orbitals

1s K-edge
2p L edge
3d M edge

X-rays can pick materials apart: layer-by-layer

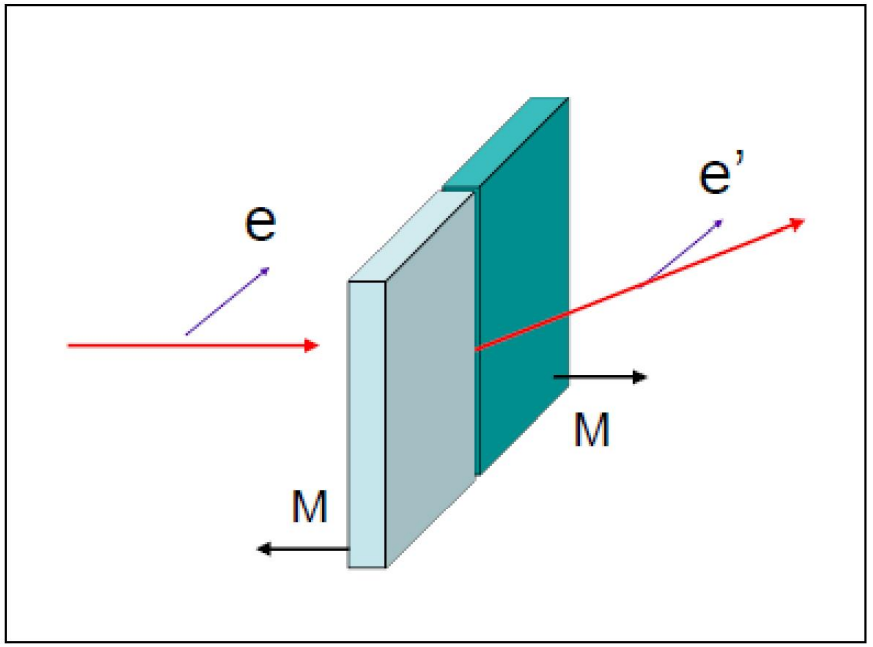


Rich “multiplet structure” reveals local bonding

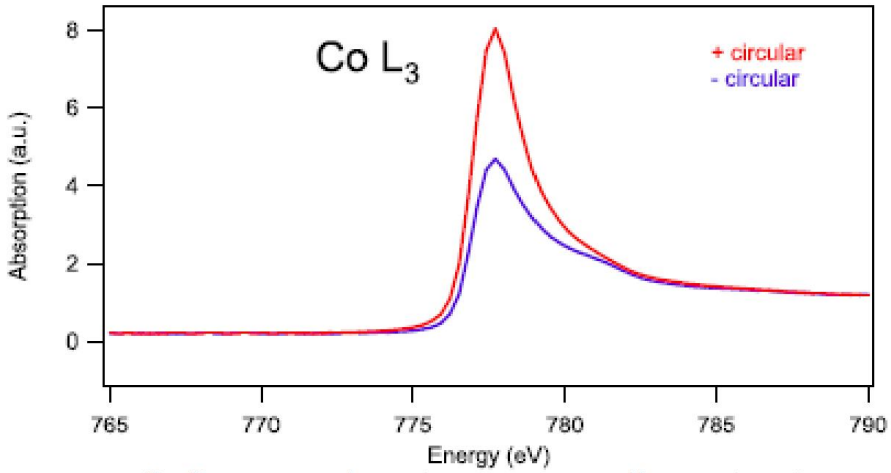


Resonant Magnetic Scattering

Photon-in photon-out: possible in applied fields



X-Ray Magnetic Circular Dichroism (XMCD)



$$I \propto \left| \sum_n \exp(i\mathbf{q}\cdot\mathbf{r}_n) f_n \right|^2$$

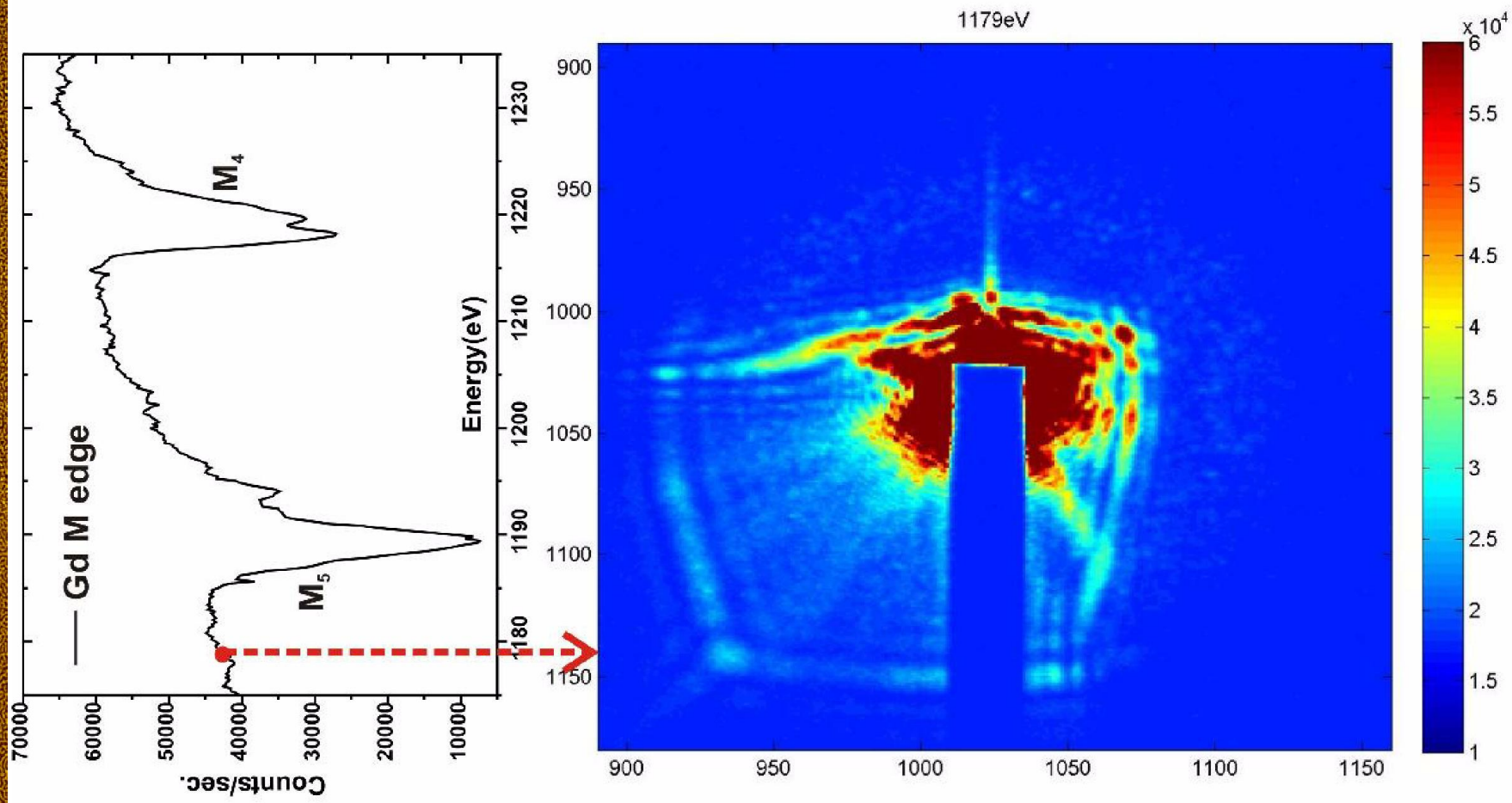
charge magnetic magnetic

$$f_n = \mathbf{e'}\cdot\mathbf{e}\, F_n^c - i(\mathbf{e'}\times\mathbf{e})\cdot\mathbf{M}_n F_n^{m1} + (\mathbf{e'}\cdot\mathbf{M}_n)(\mathbf{e}\cdot\mathbf{M}_n) F_n^{m2}$$

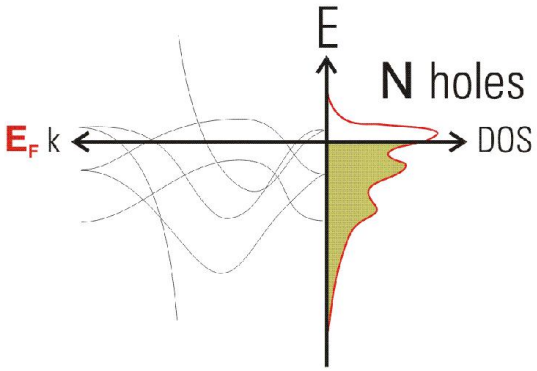
zero in our geometry

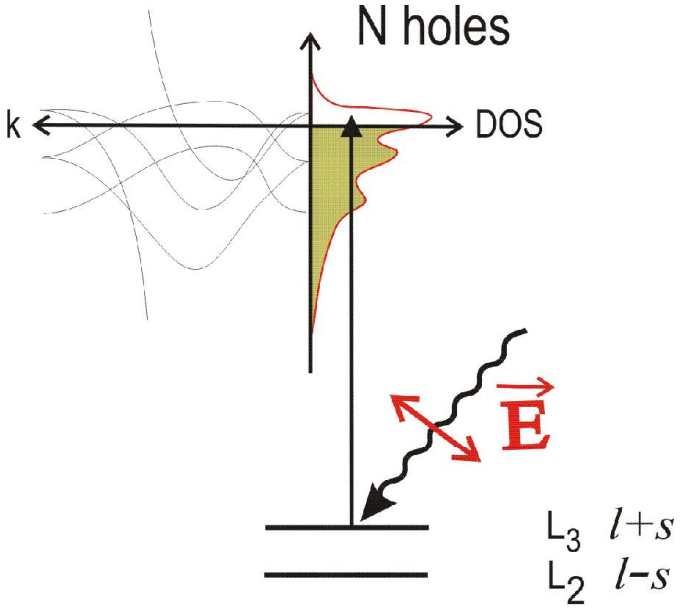
J. P. Hannon, G. T. Trammell, M. Blume, D. Gibbs, Phys. Rev. Lett 61, 1245 (1988)

Resonant Magnetic Scattering

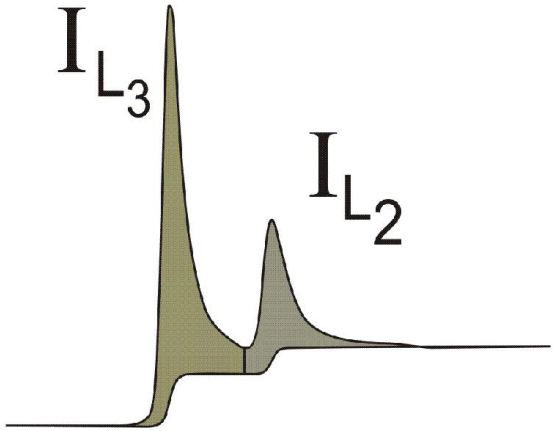


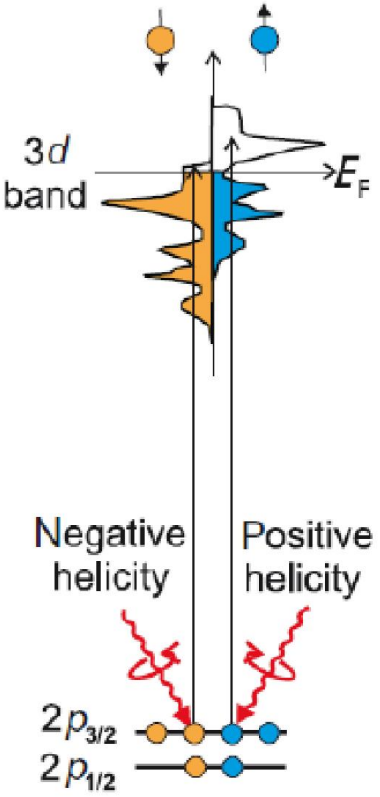
Properties of 3d Transition Metals

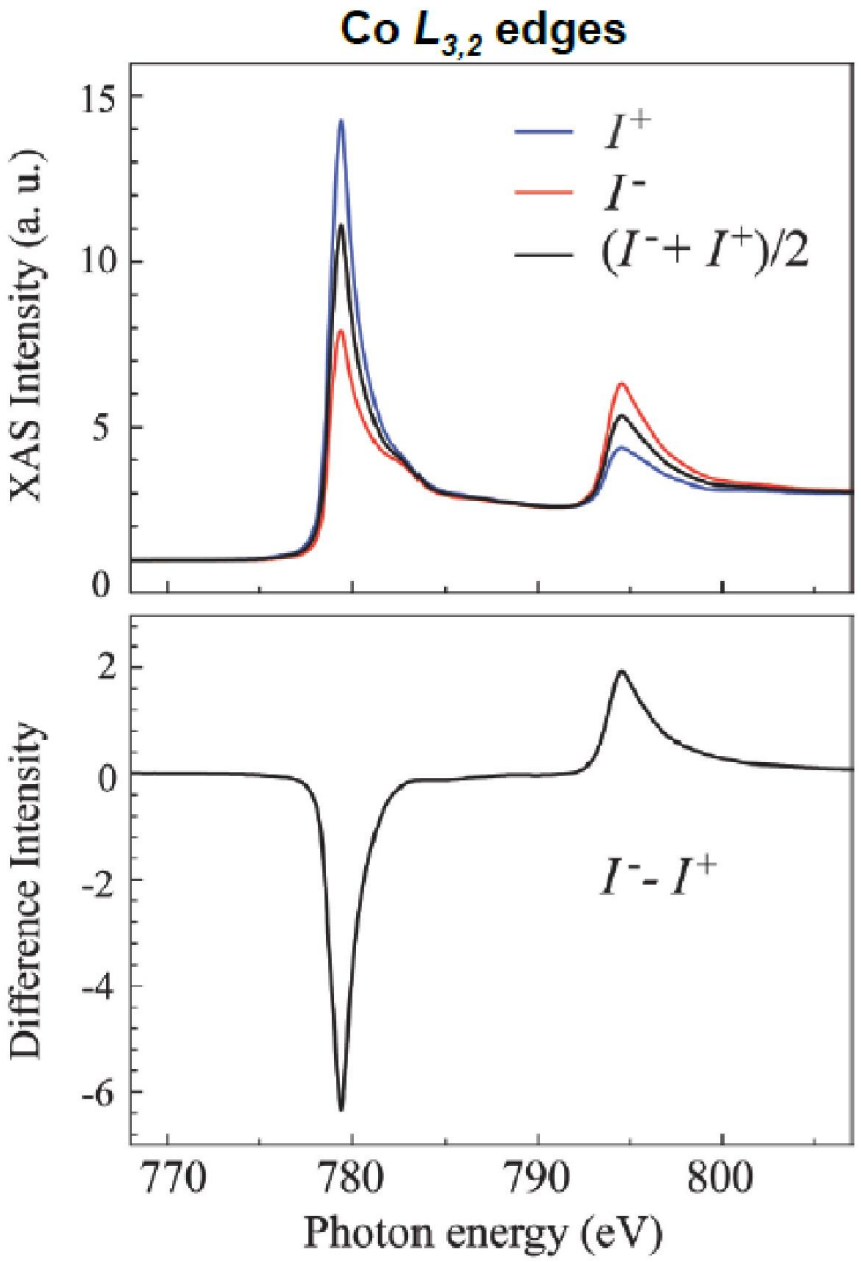


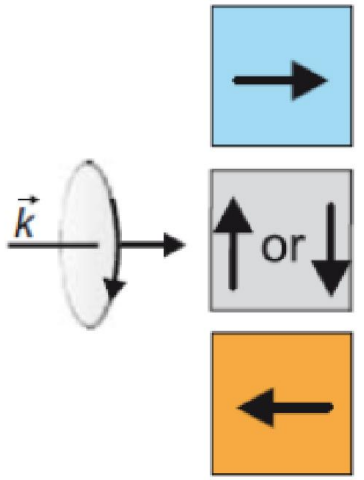


	holes
Fe	3.4
Co	2.5
Ni	1.5

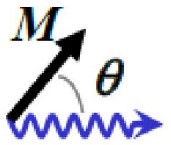




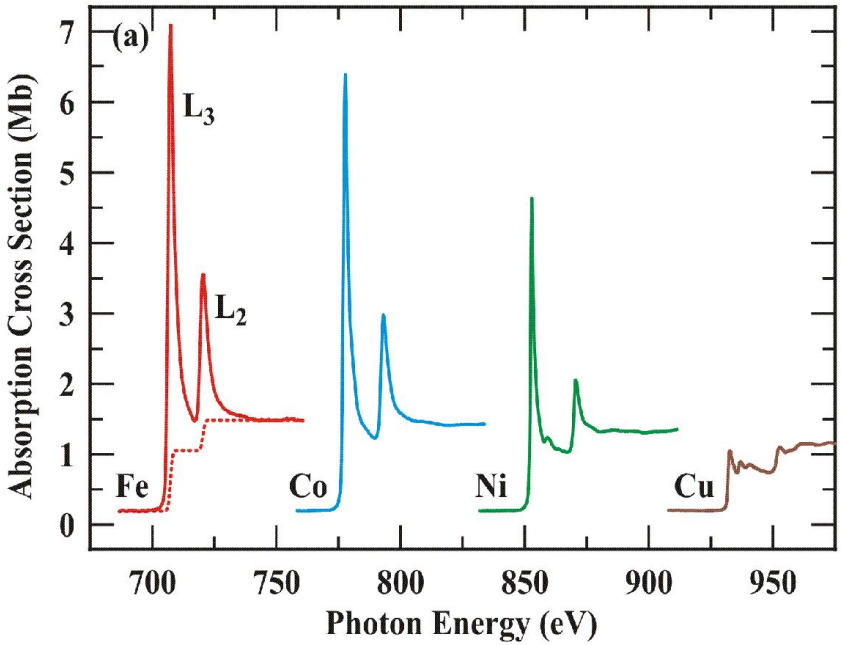


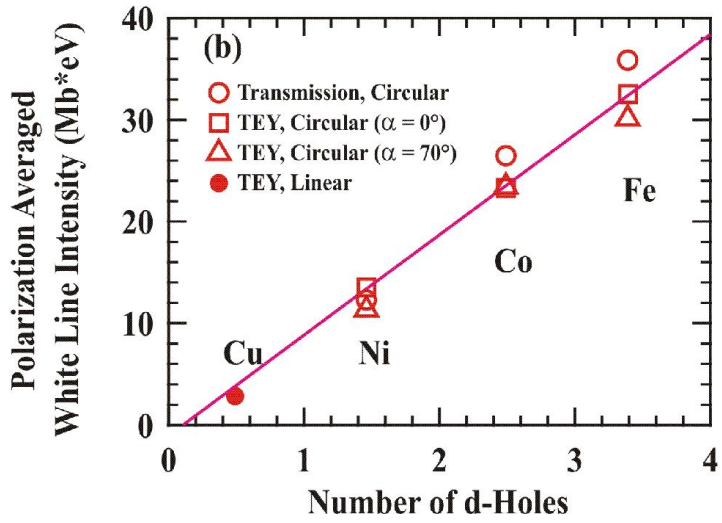


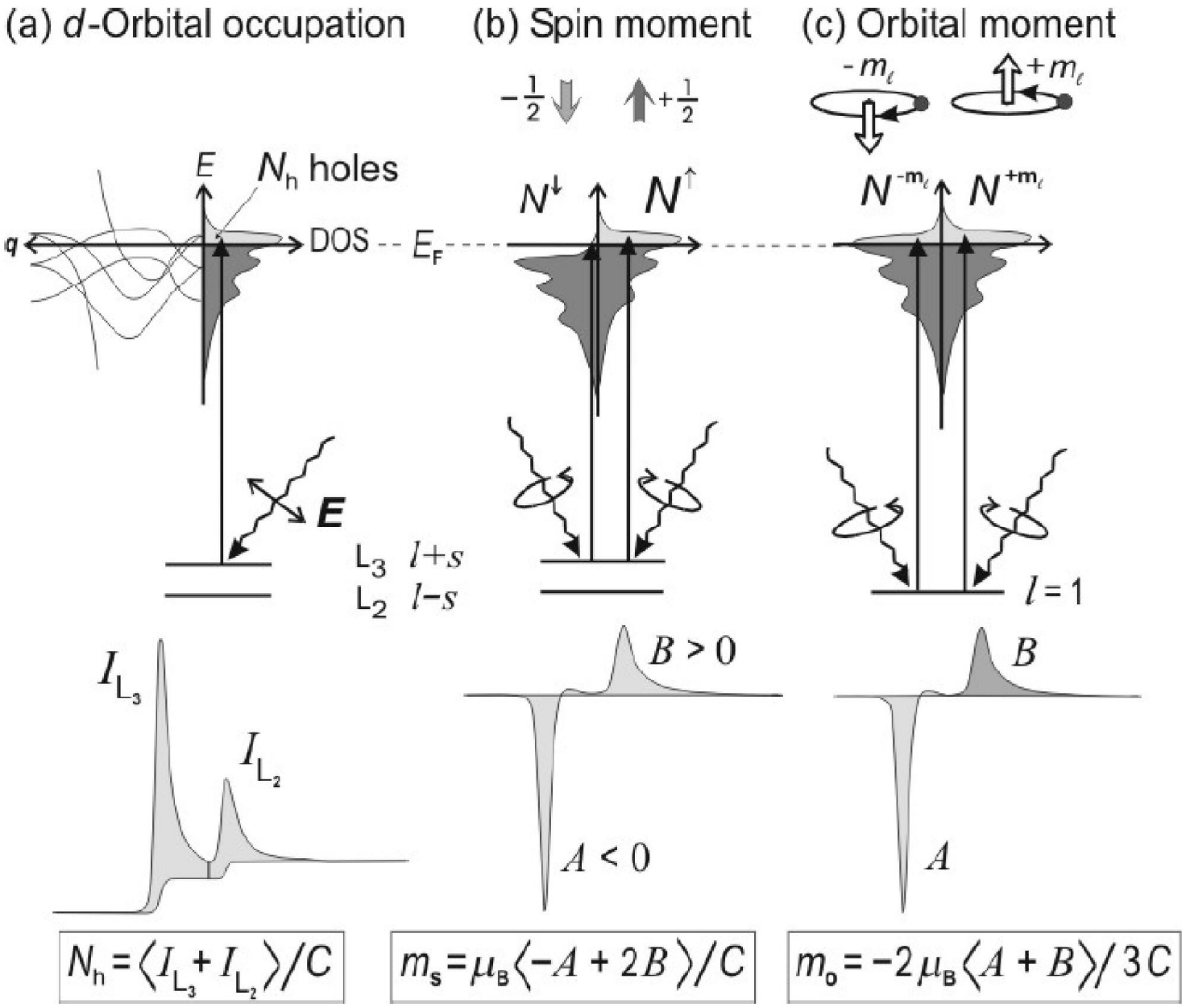
$I_{XMCD} \propto M\cos\theta$



White Line Intensity in 3d Metals

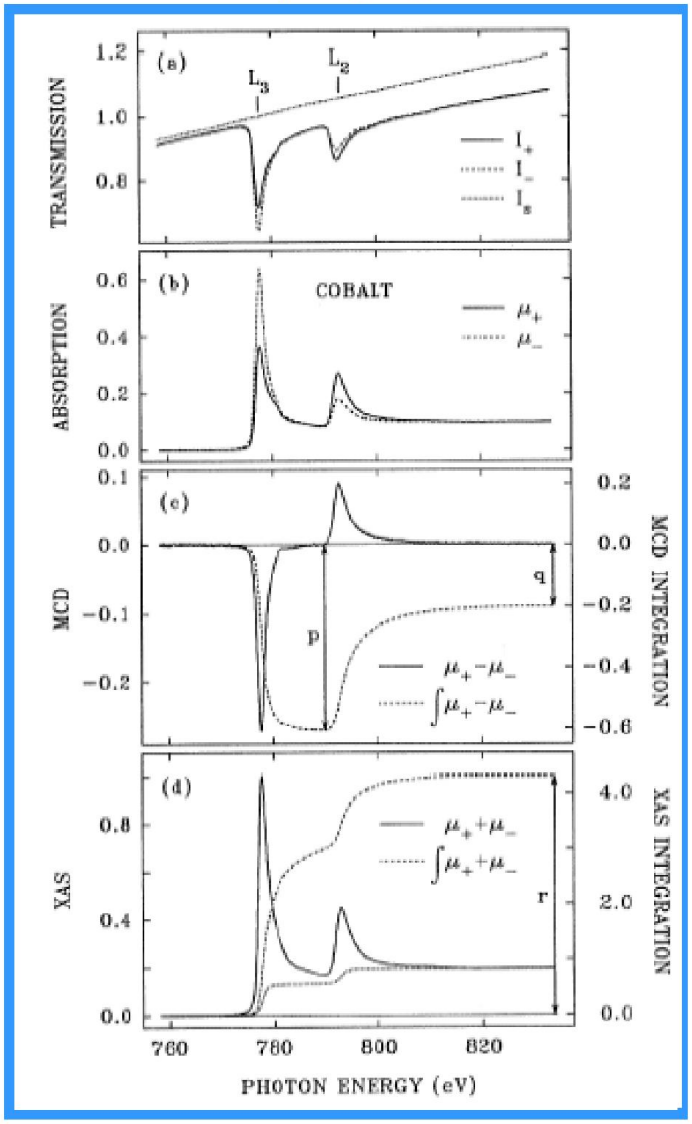






Carra, *et al.*, PRL **70**, 694 (1993); Thole *et al.*, PRL **68**, 1943 (1992);

Transmission through 50 Å Co on 1 μm parylene



C.T. Chen et al., PRL 75, 152 (1995)

$$m_L = 2n_h \frac{\int_{L_3+L_2} (\mu^+ - \mu^-) dE}{\int_{L_3+L_2} (\mu^+ + \mu^- + \mu^0) dE}$$

ORBITAL

$$m_S + m_T = 3n_h \frac{\int_{L_3} (\mu^+ - \mu^-) dE - 2\int_{L_2} (\mu^+ - \mu^-) dE}{\int_{L_3+L_2} (\mu^+ + \mu^- + \mu^0) dE}$$

SPIN

where

$$m_L = -\langle L_\alpha \rangle$$

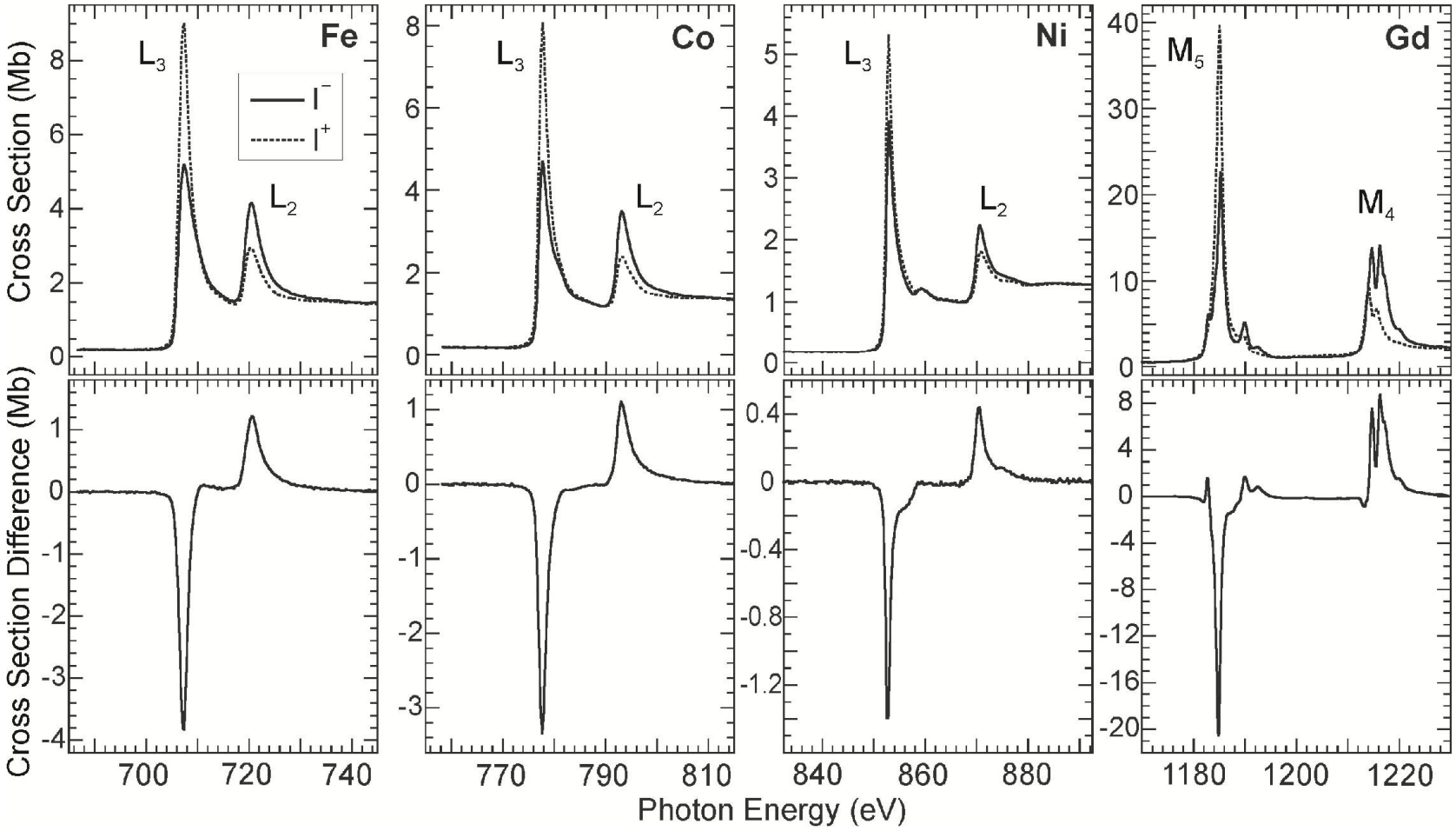
$$m_S = -\langle 2S_\alpha \rangle; \quad m_T = -7\langle S_\alpha - 3\hat{r}(\hat{r} \cdot S_\alpha) \rangle$$

Sum-rules results:

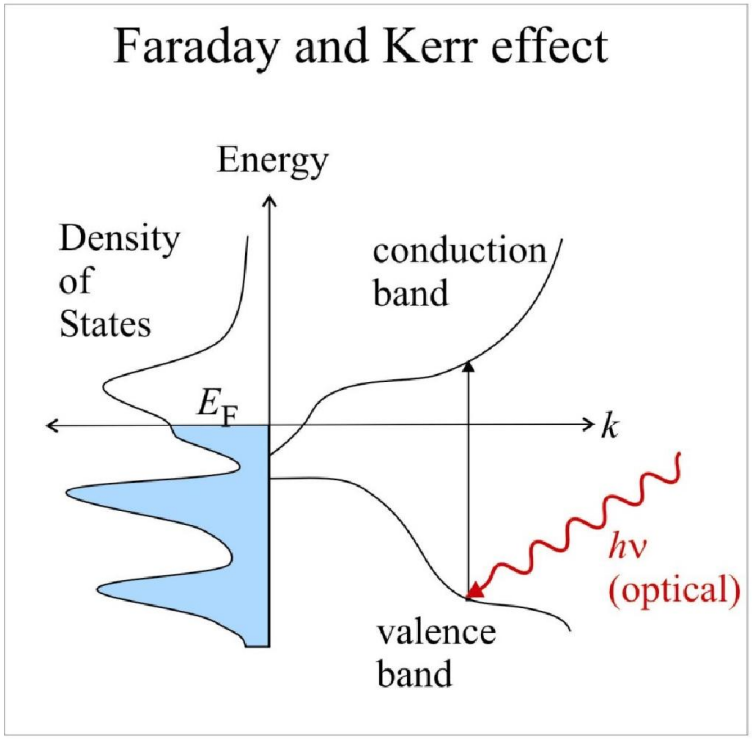
Fe (n_{3d} = 6.61): m_{orb} = 0.086, m_{spin} = 1.98

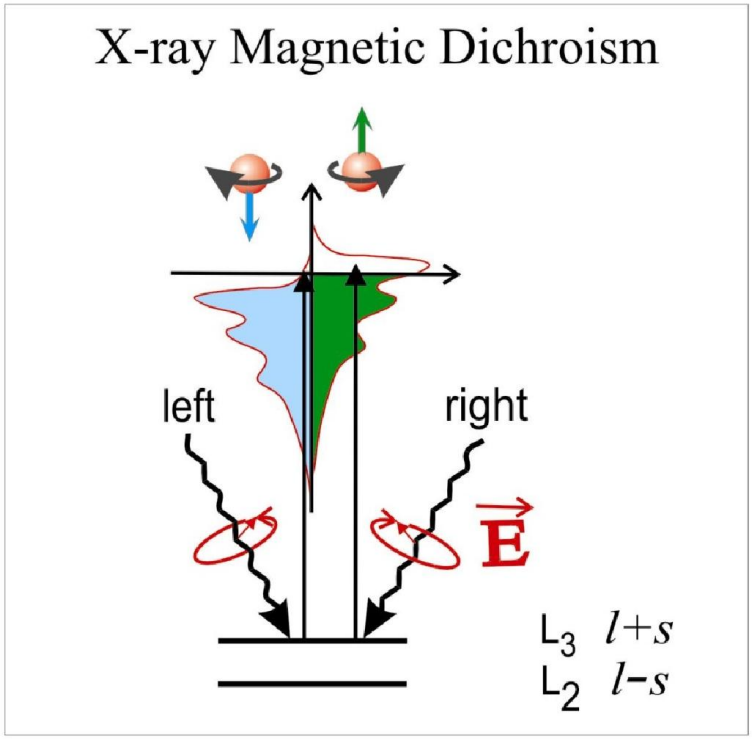
Co (n_{3d} = 7.51): m_{orb} = 0.153, m_{spin} = 1.55

XMCD spectra of the pure ferromagnetic metals



Magnetic Circular Dichroism





Magneto-optical response:
weak, *k*-dependent

X-ray response:
strong, k-integrated quantities
number of holes, spin monent, orbital moment

- **spin moments,**
- **orbital moments**
- **nanoscale resolution**

Magnetic Semiconductor:MnAs/GaAs

- MnAs on GaAs integrates magnetic and semiconducting properties
- room temperature ferromagnetism
- spin injection demonstrated

Ramsteiner *et.al,* Phys. Rev. B, 66, 081304(R), 2002.

MnAs bulk properties

- phase transition: 1st order
- volume change ~ 2%

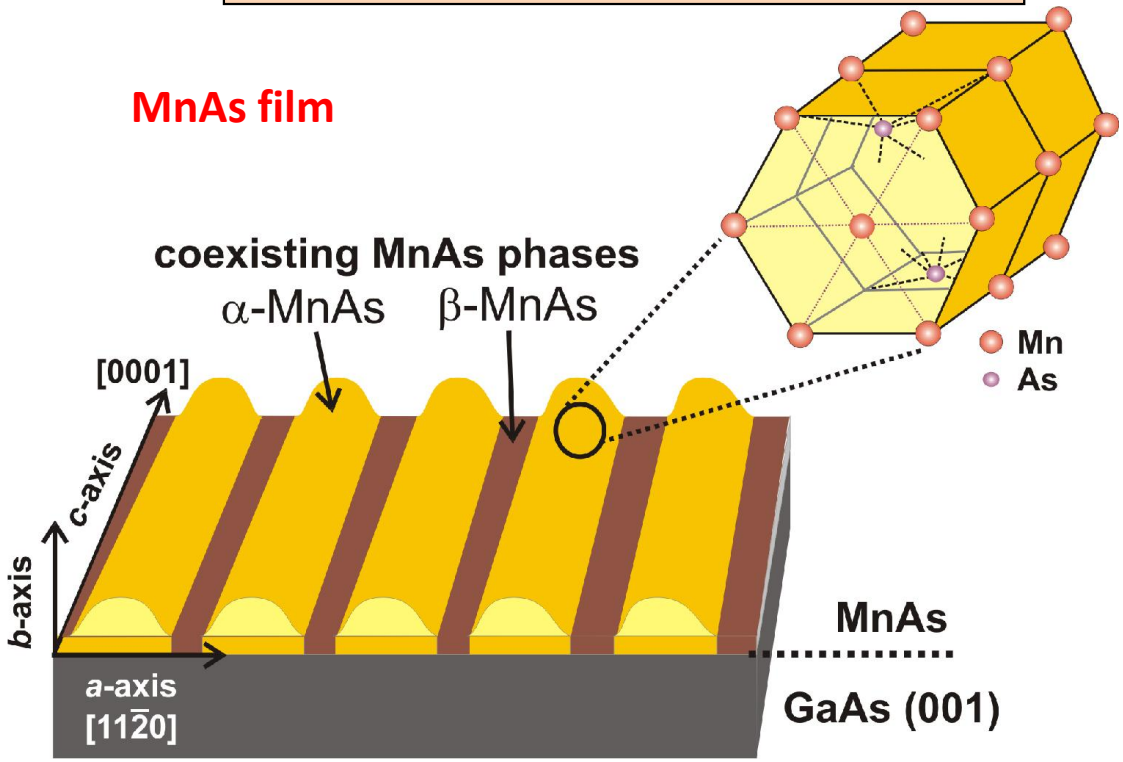
Ferromagnetic	Paramagnetic	Paramagnetic
α-MnAs	β-MnAs	γ-MnAs
(Hexagonal)	(Orthorhombic)	(Hexagonal)

40°C

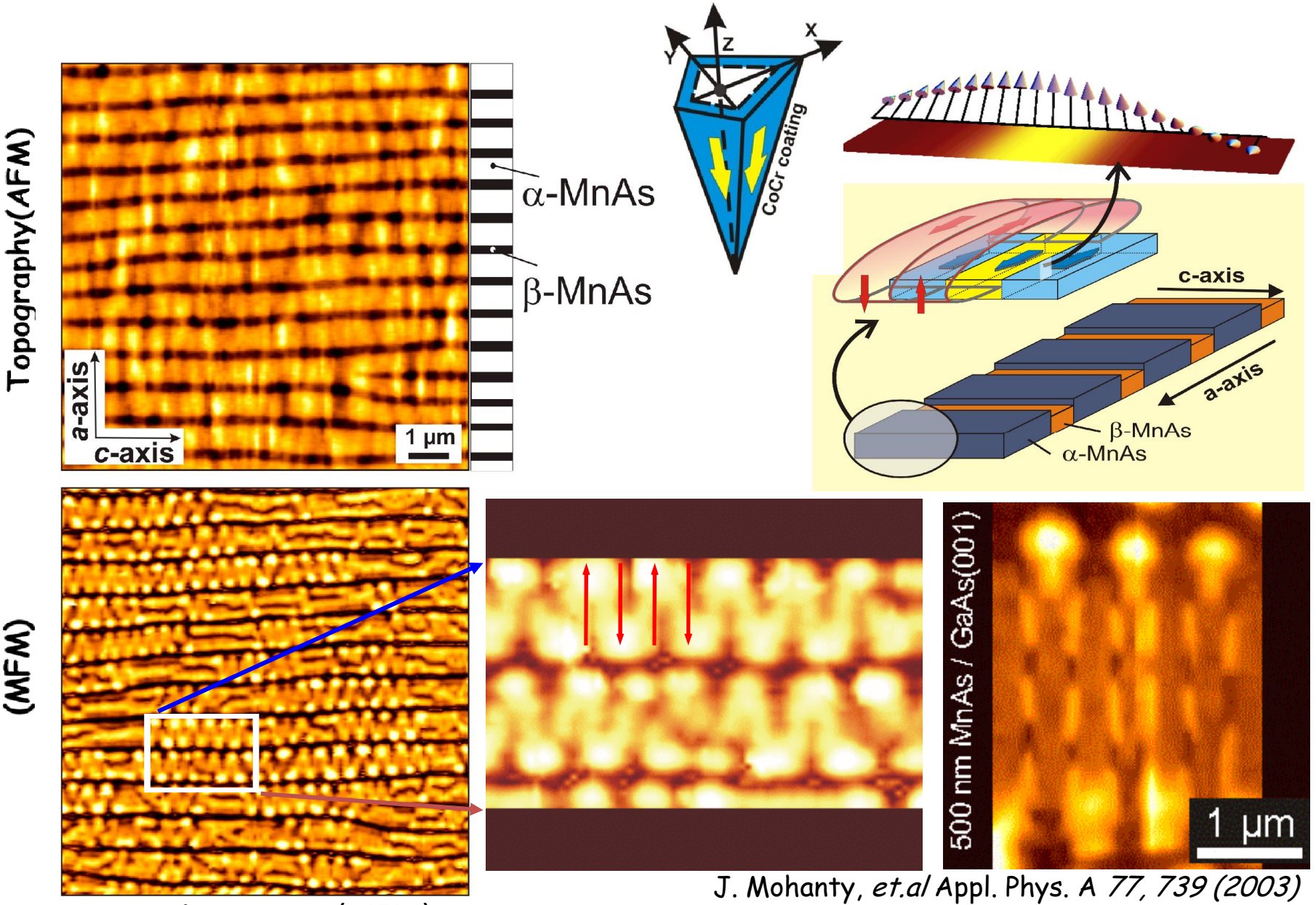
125°C

- strain induced phase coexistence
- thermal expansion mismatch between film and substrate

- stripe width function of temperature
- stripe periodicity function of film thickness
- magnetic easy and hard axes in the film plane

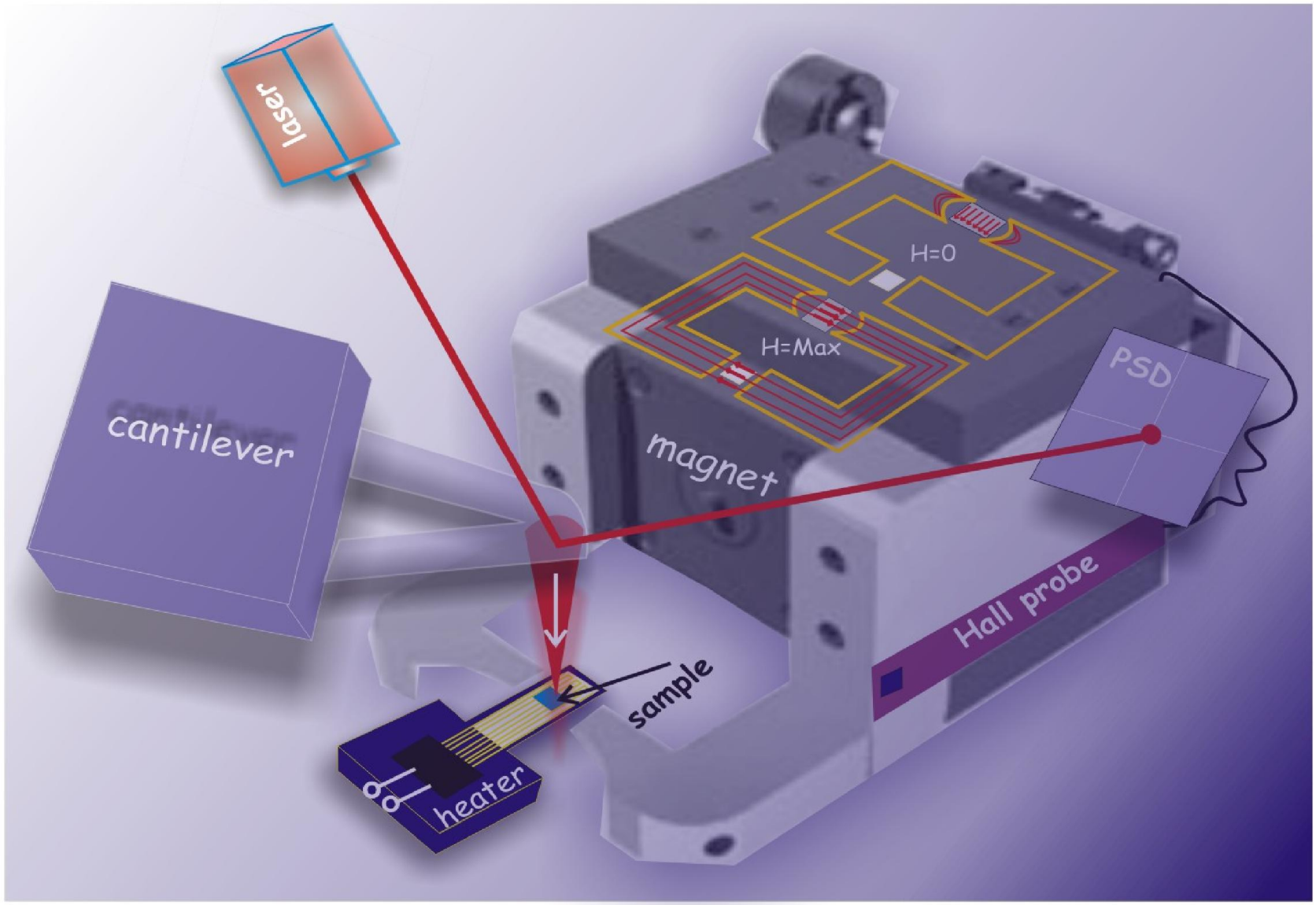


MFM Contrast of MnAs Films



J. Mohanty, *et.al* Appl. Phys. A *77, 739 (2003)*

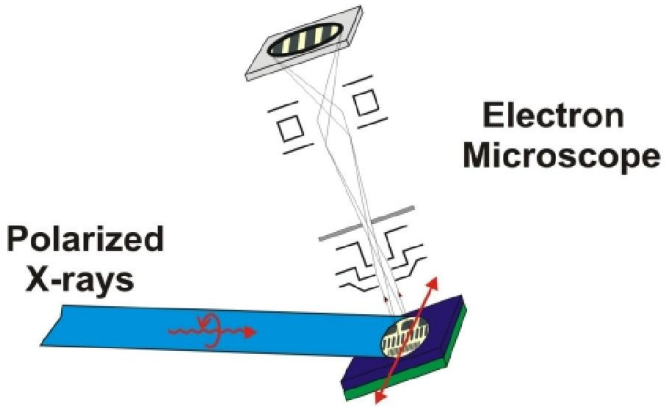
MFM Set-up

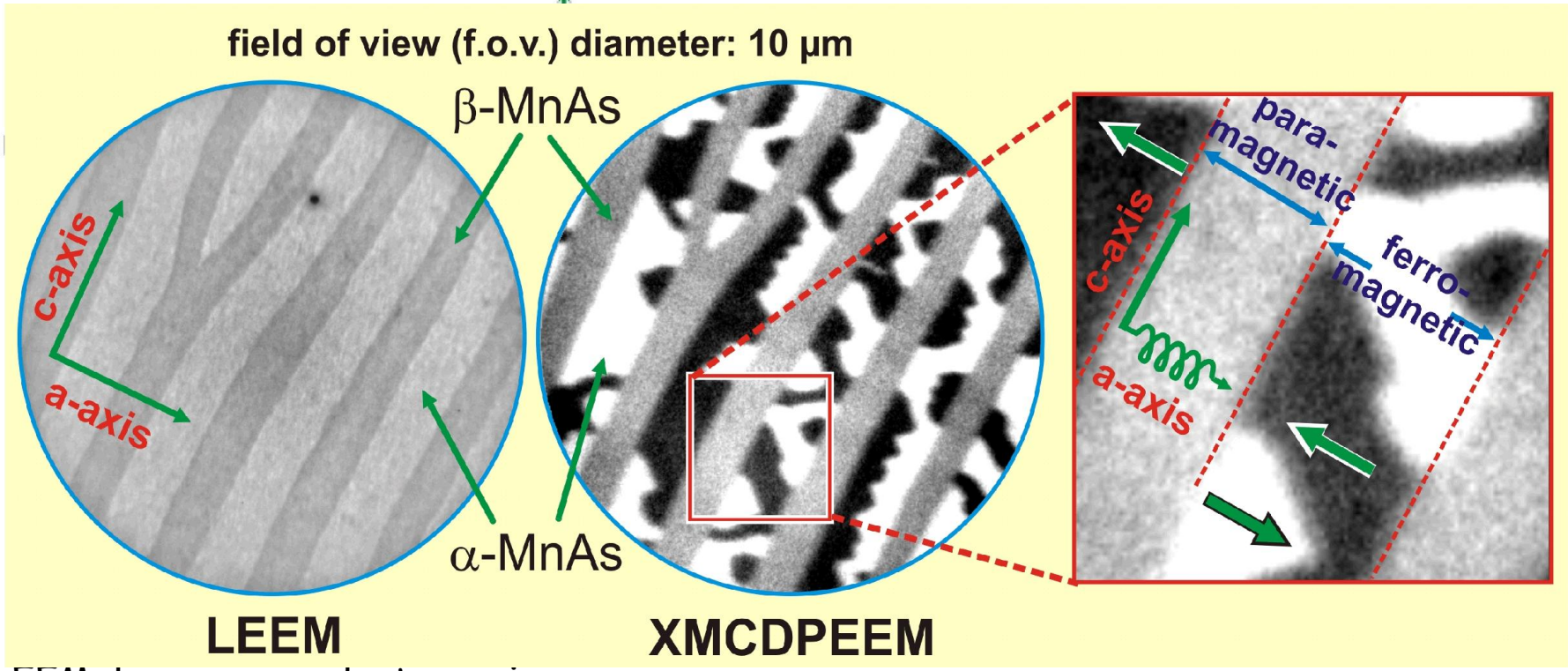


J. Mohanty, *et.al* Appl. Phys. A *81, 1359 (2005)*

X-ray Magnetic Imaging

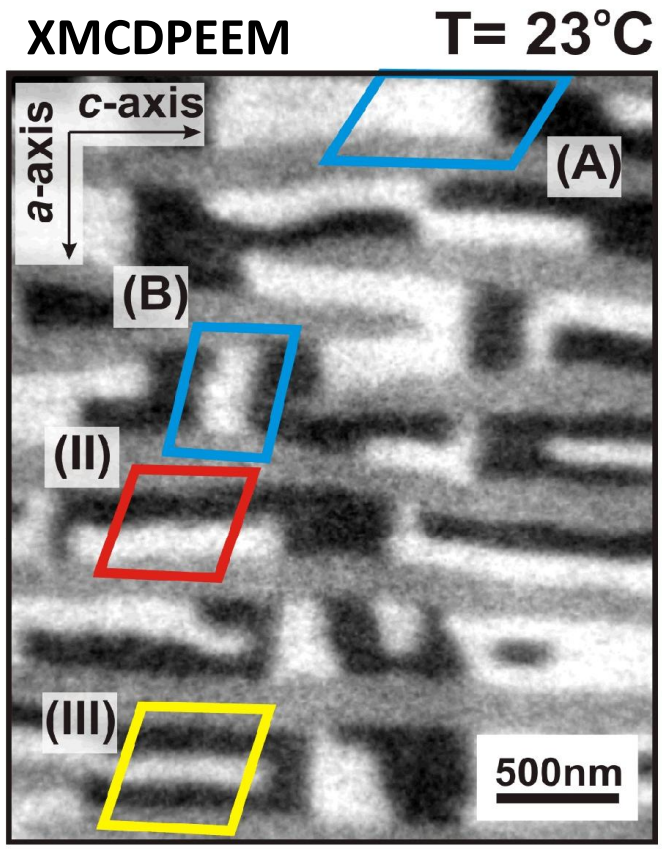
- Excitation: XMCD (X-ray magnetic circular dichroism)
- Imaging: PEEM (photoemission electron microscopy)
- SE yield = σ x M, σ: incident photon, M: magnetization
- $C_{XMCDPEEM} = (I_+ - I_-) / (I_+ + I_-)$
- Element specific

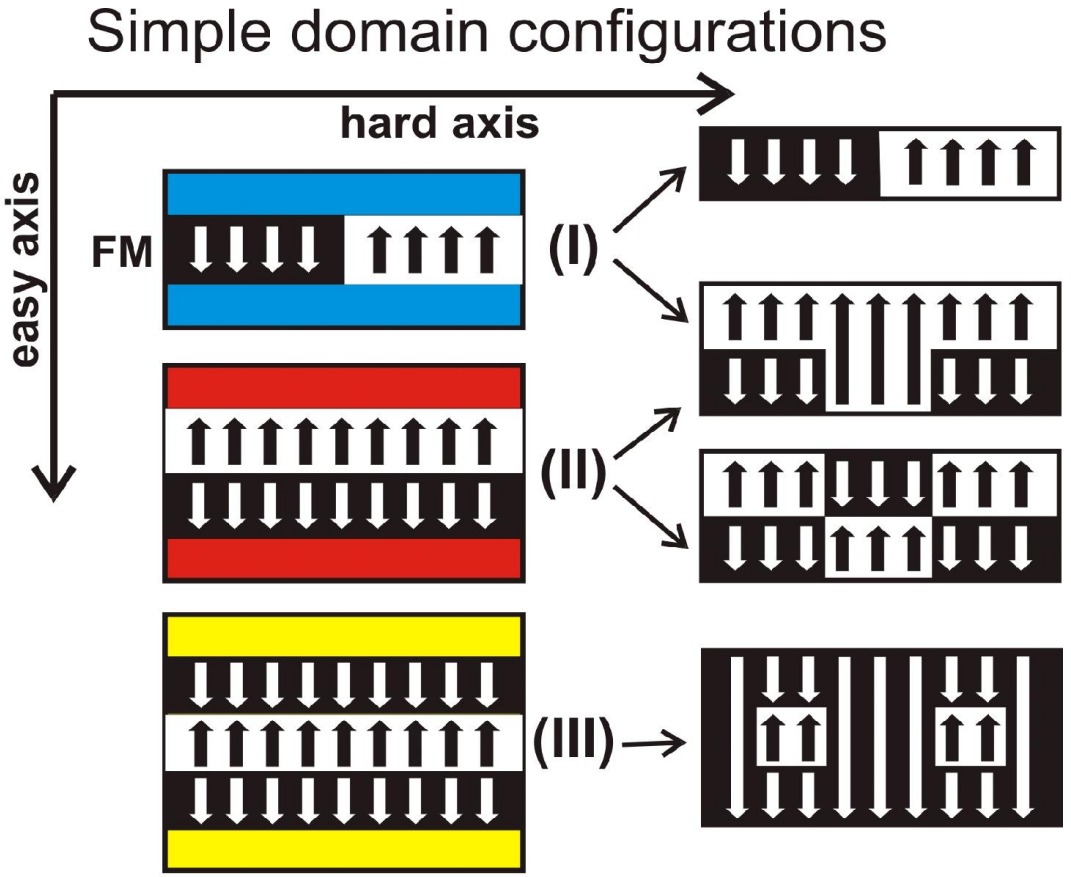


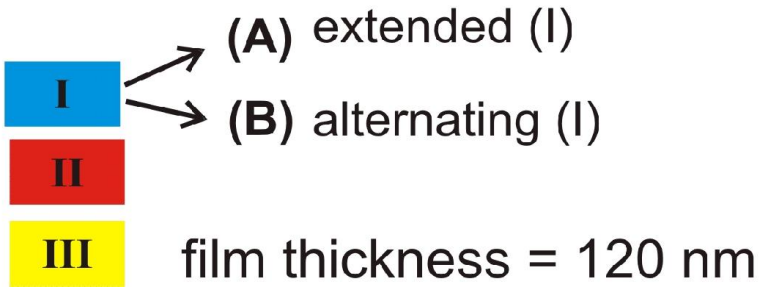


LEEM: Low energy electron microscopy

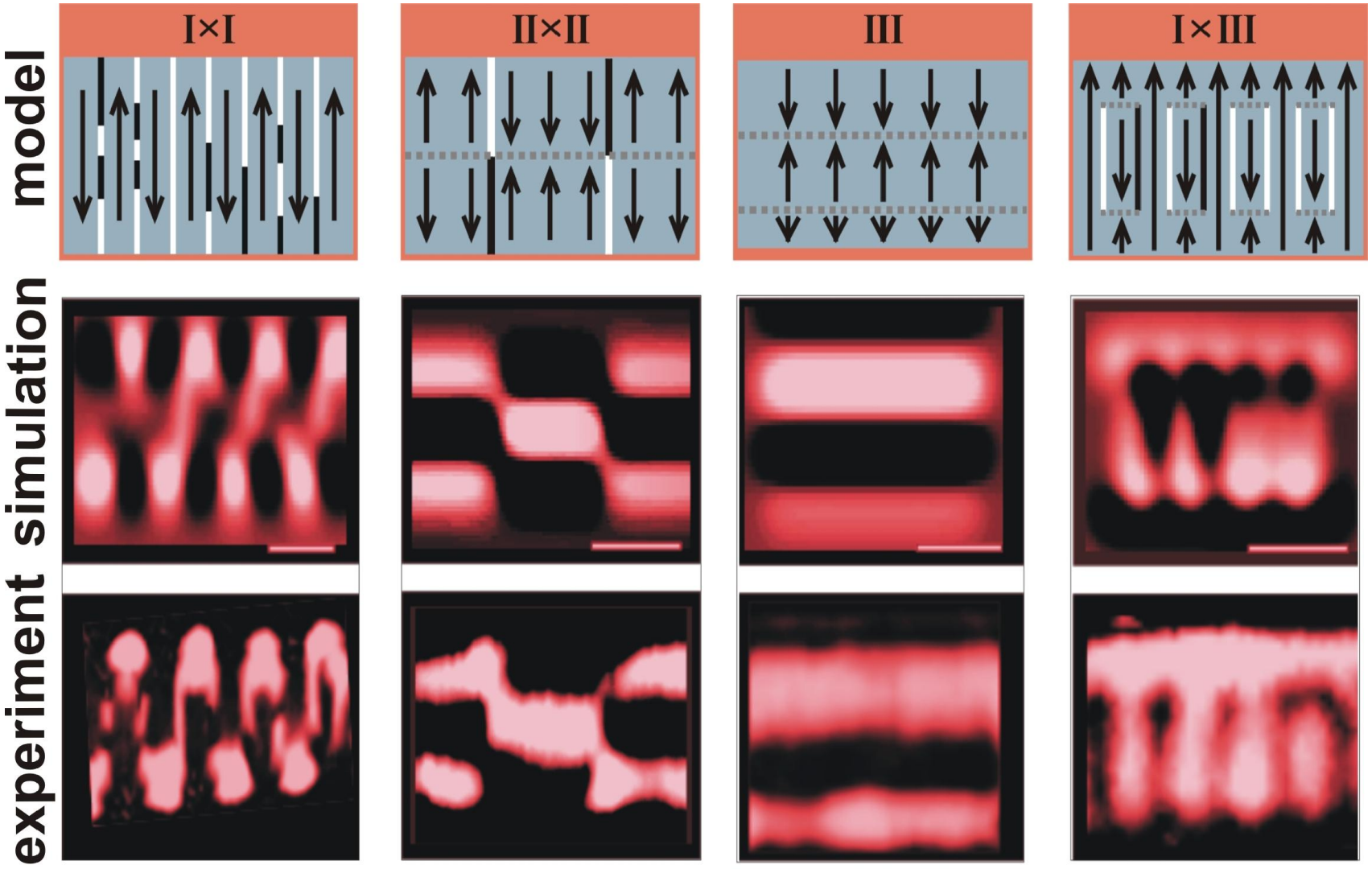
Domain Classification



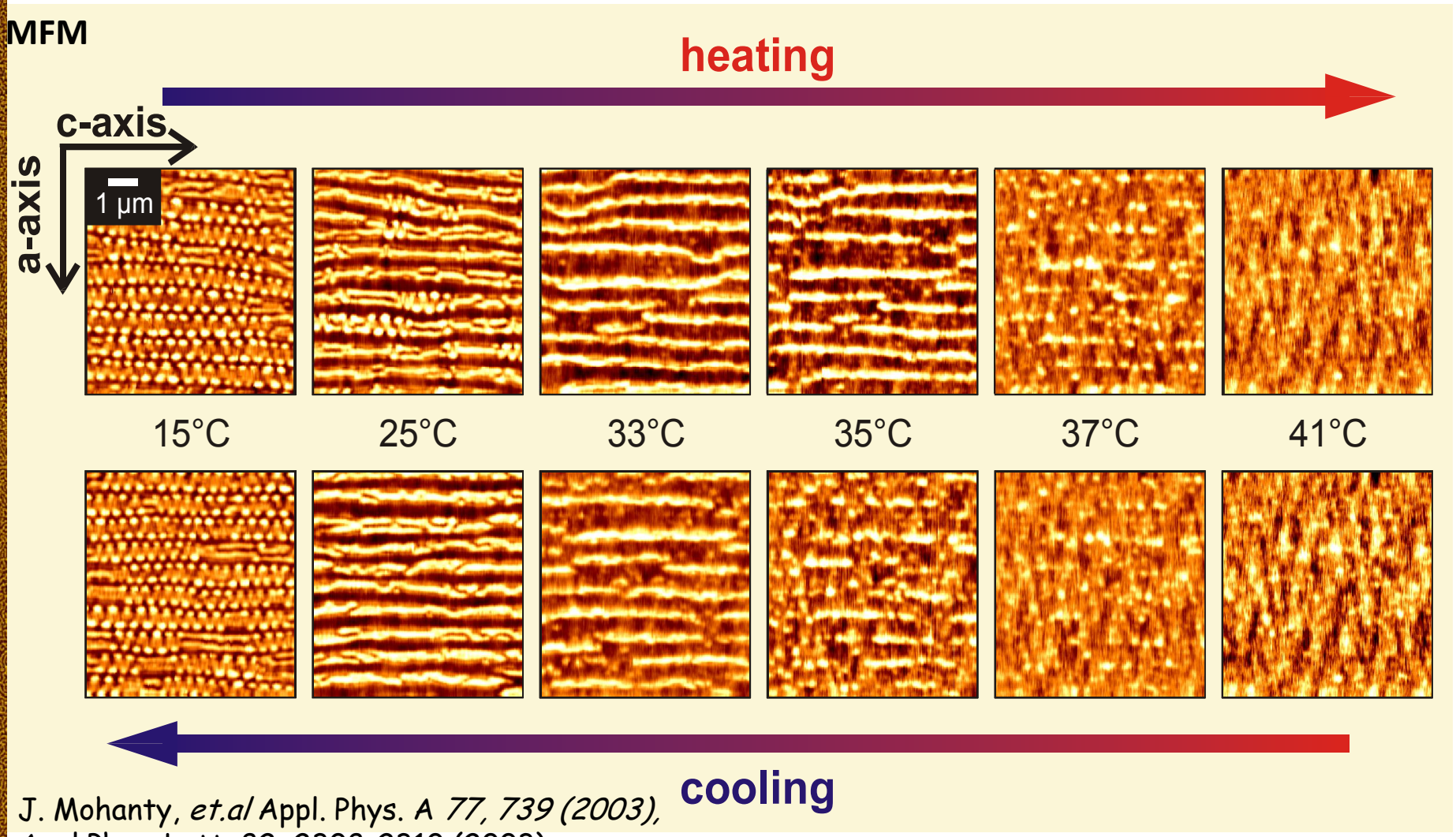




Micromagnetic Modeling

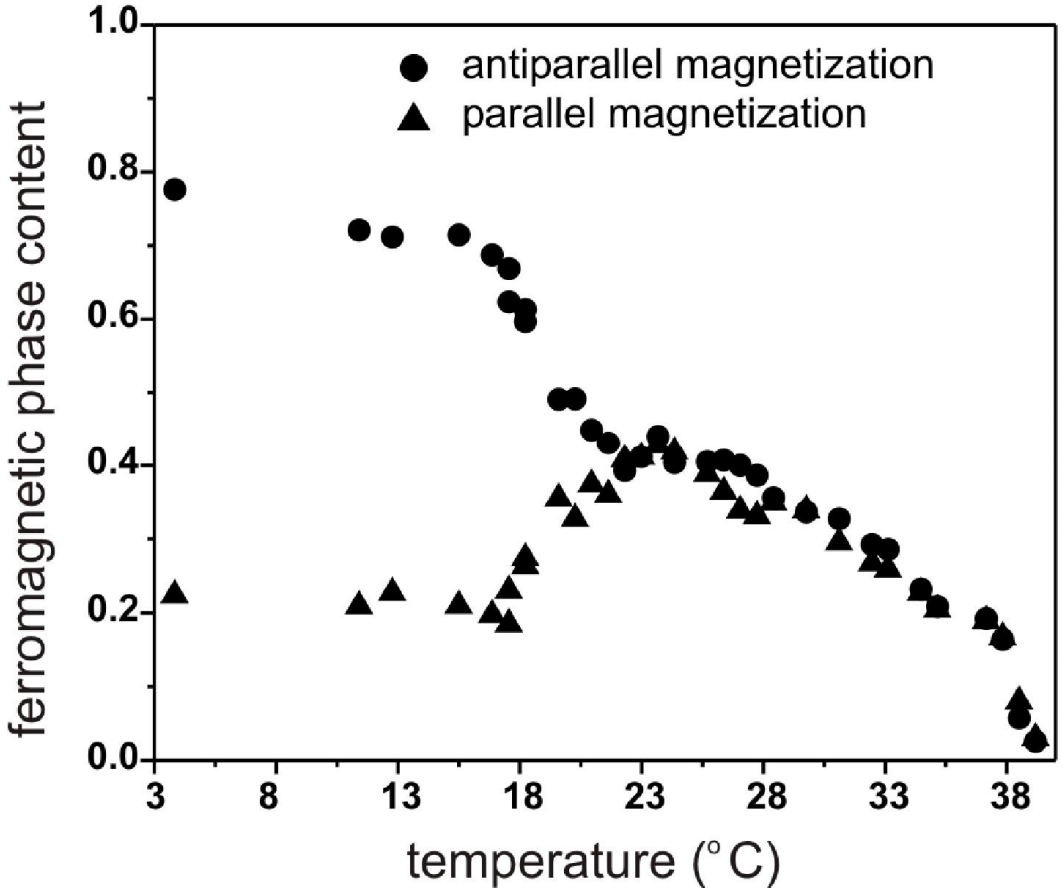


Structural and Magnetic Phase Transition

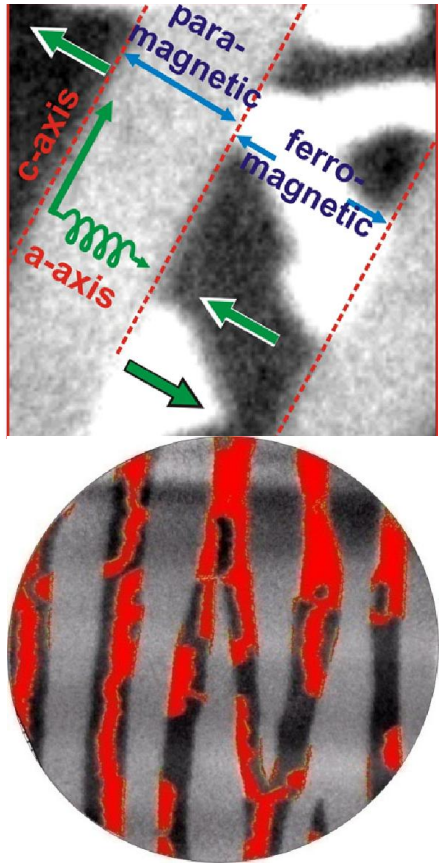


J. Mohanty, *et.al* Appl. Phys. A *77, 739 (2003),*
Appl.Phys. Lett. 82, 2308-2310 (2003).

Temperature Dependence of the Domain Structure



XMCDPEEM

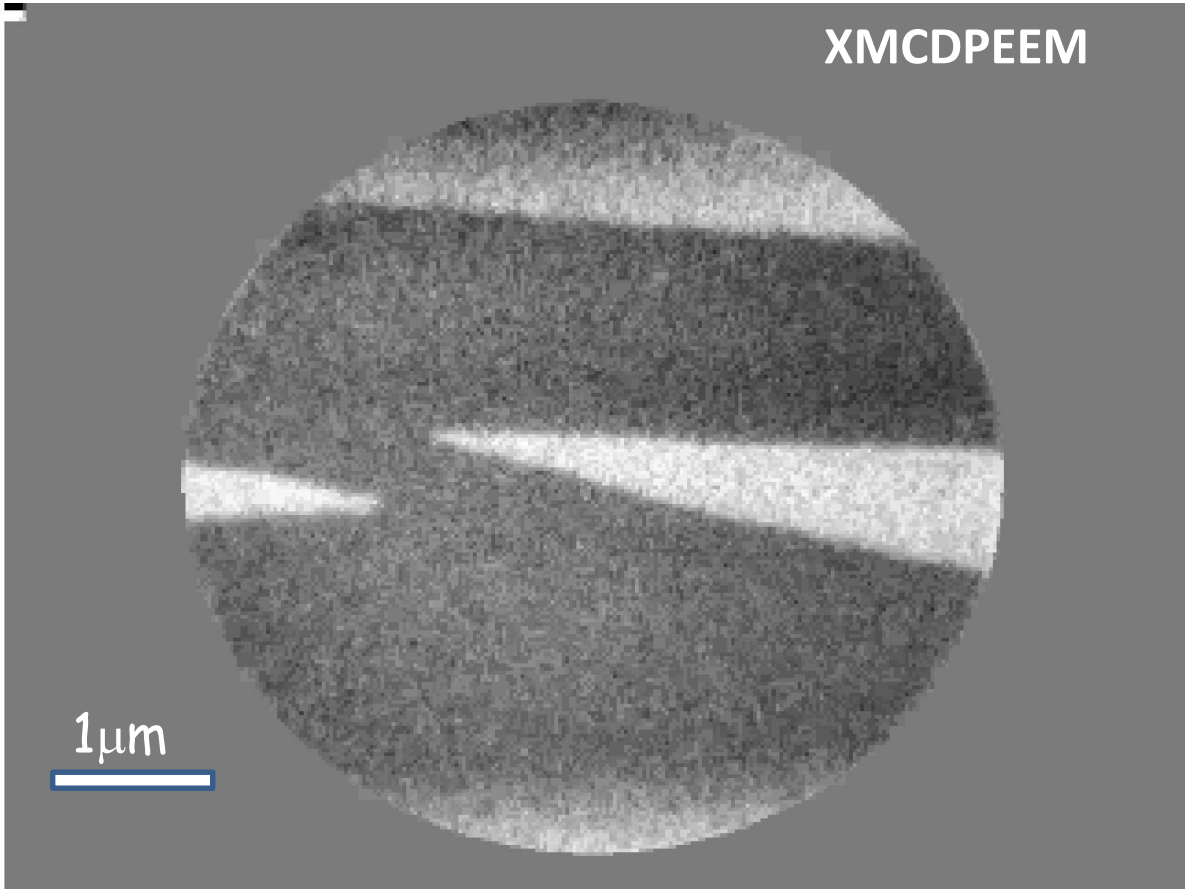


- magnetic stripe demagnetize at 22°C
- small distance favors inter-stripe dipole-dipole coupling

Appl. Phys. A 84, 231 (2006)

Temperature Dependence of the Domain Structure

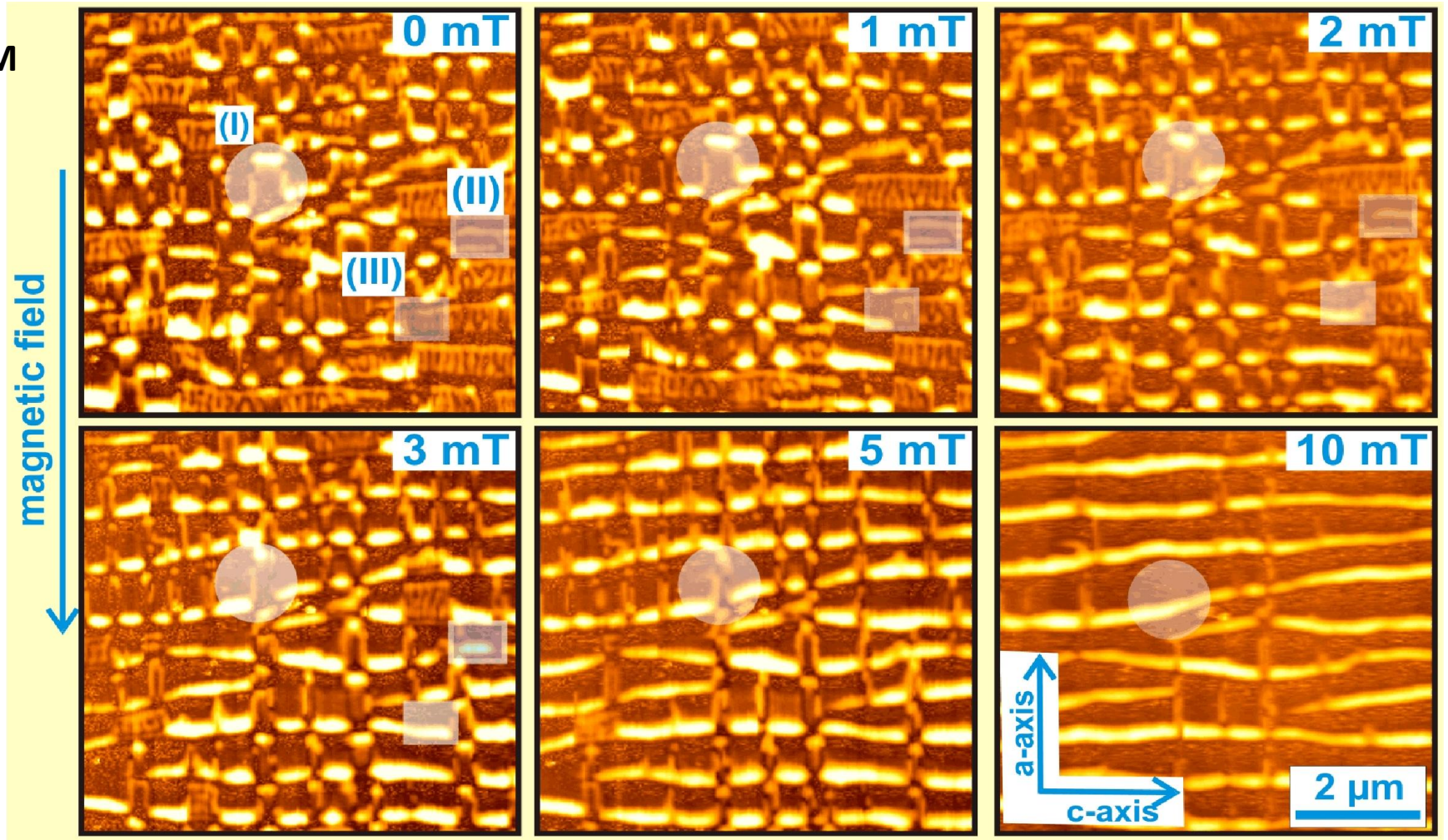
Stripe direction



MnAs/GaAs(001) f.o.v.diameter = 5μm Thickness=120nm

Field Dependence of Magnetic Domains

MFM

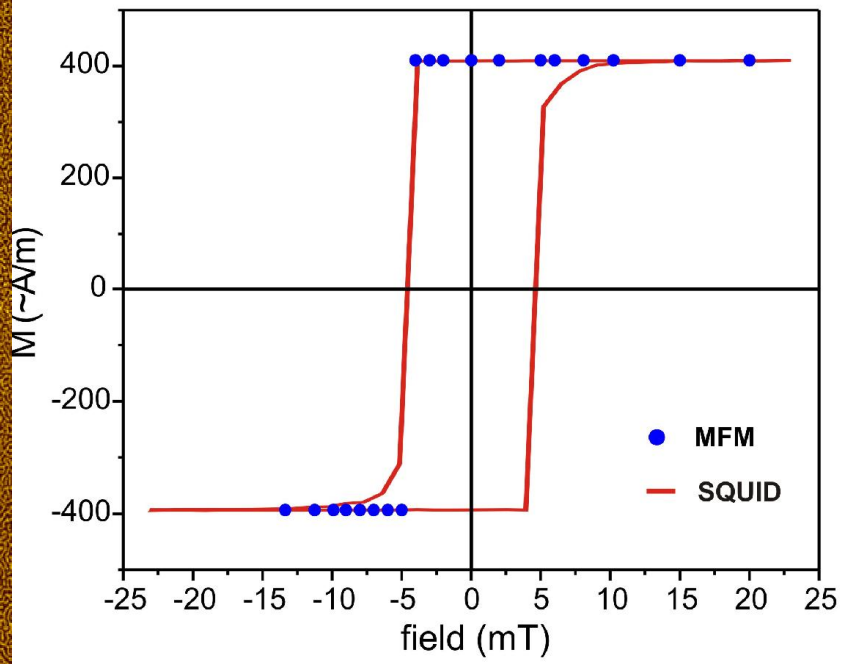


- type (III) domains **vanish first** (already at 3 mT)
- **type (I) domains** are the **most stable domains**

J. Appl. Phys. 98, 063909 (2005)

Microscopic Magnetization Reversal

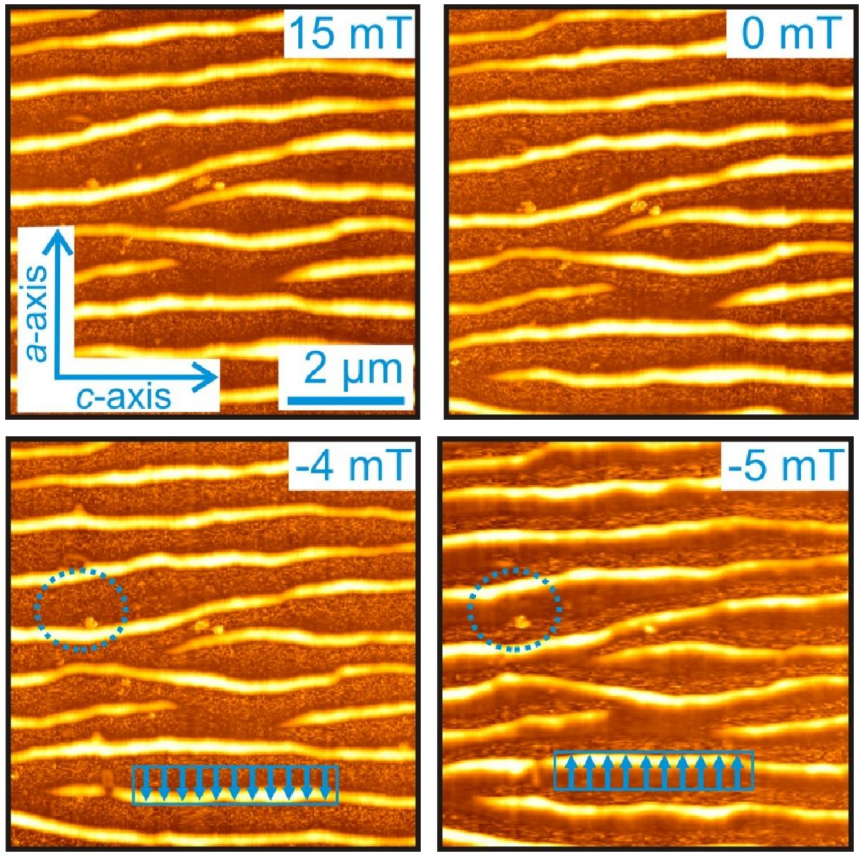
180nm thick MnAs on GaAs (001)



measured along the easy magnetization direction of MnAs

Phys. Rev. B. 73, 104441 (2006)

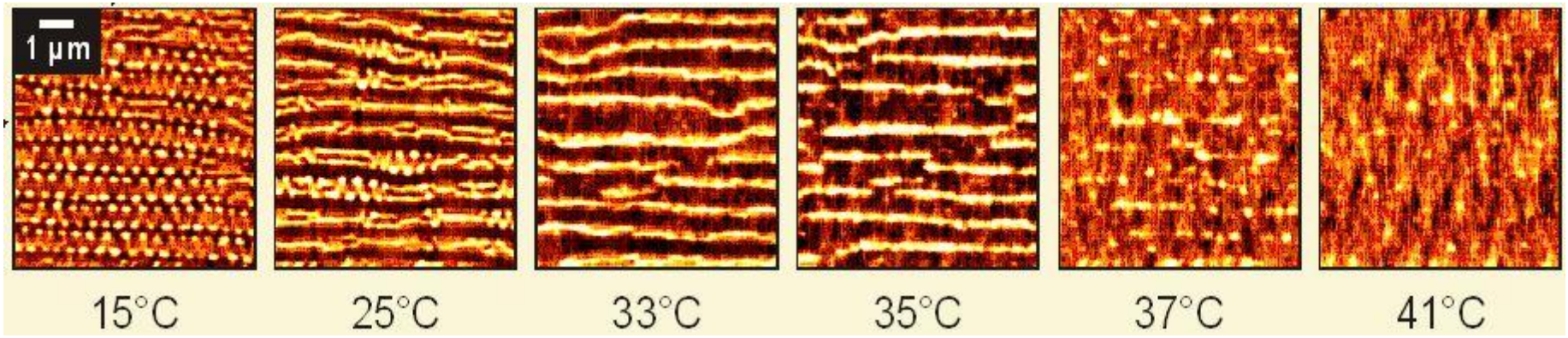
MFM

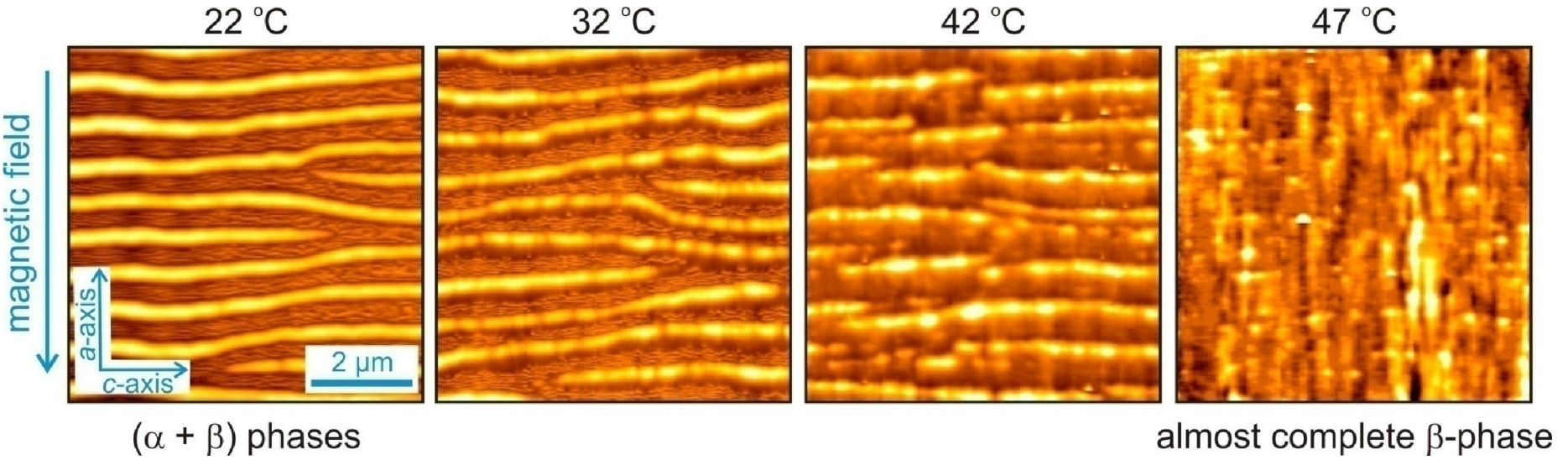


- coercive field (magnetization reversal): 5 mT
- microscopic MFM measurements agree well with the integral SQUID measurements

Field Dependence of Phase Transition

MFM

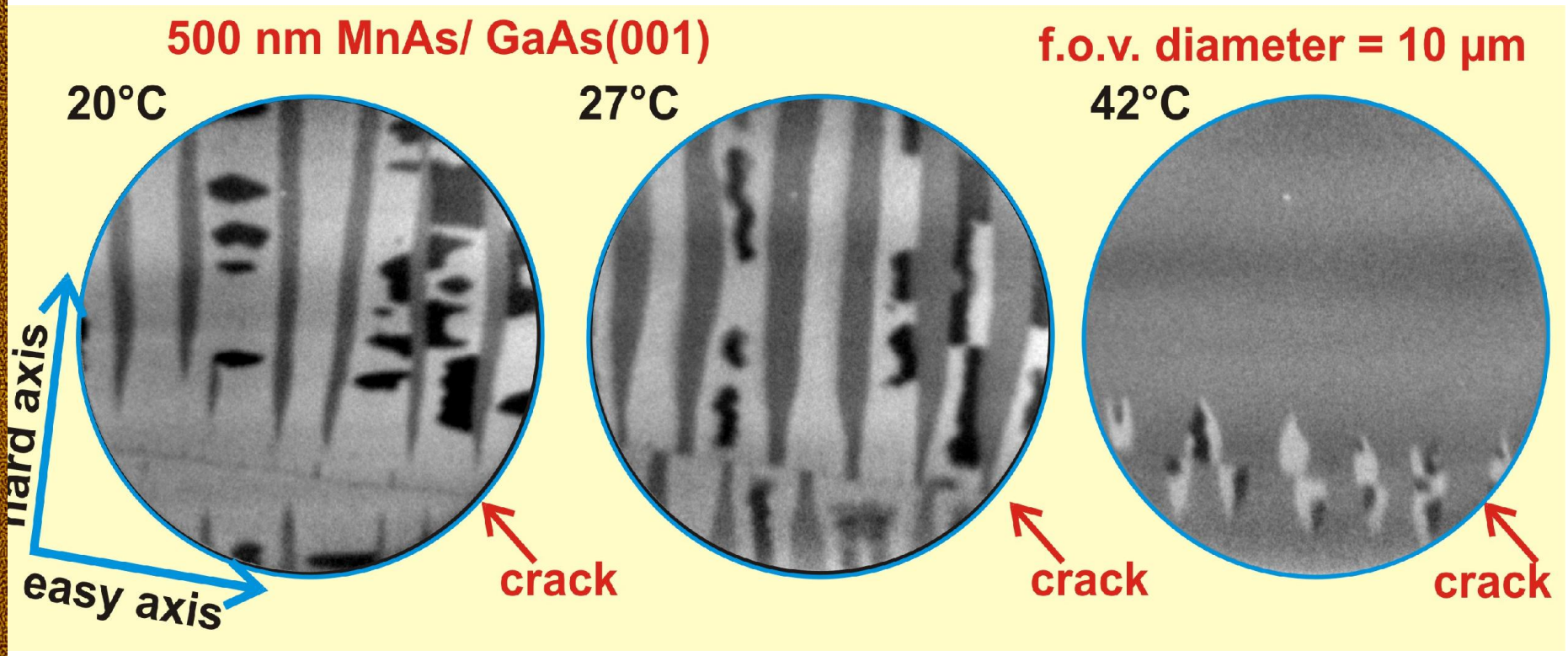




Ferromagnetic phase stabilized above the bulk phase transition temperature by an external magnetic field: **Magnetism→ Structure**

Strain Effect on the Phase Transition

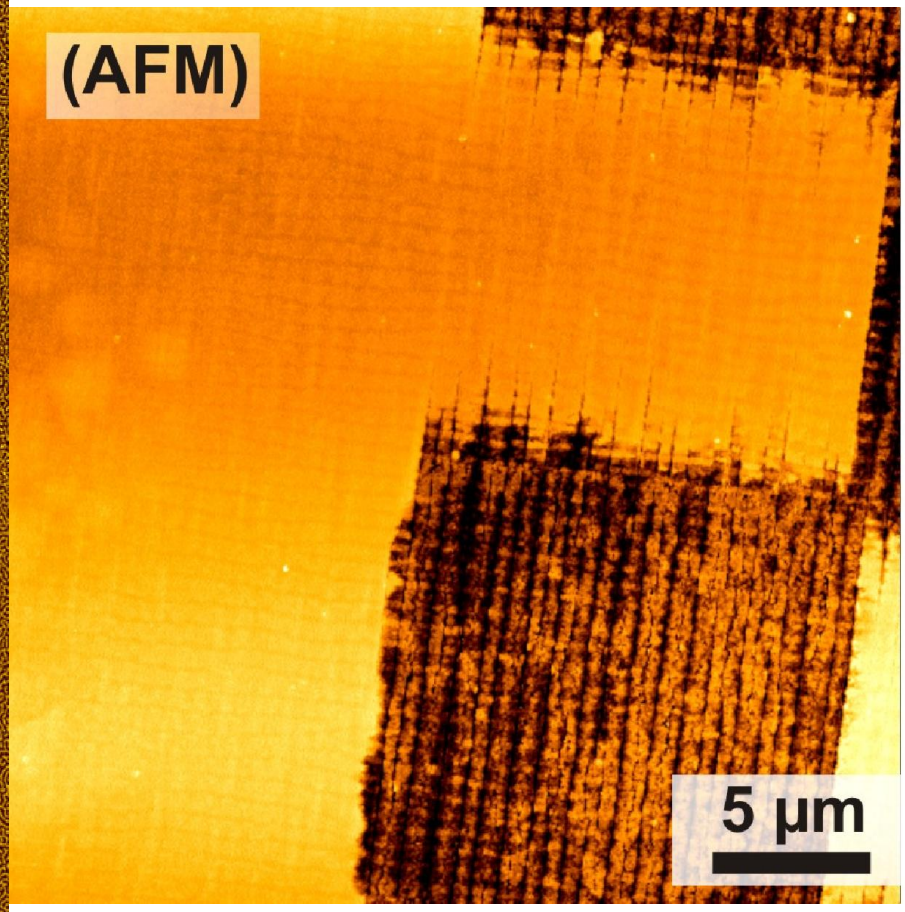
XMCDPEEM

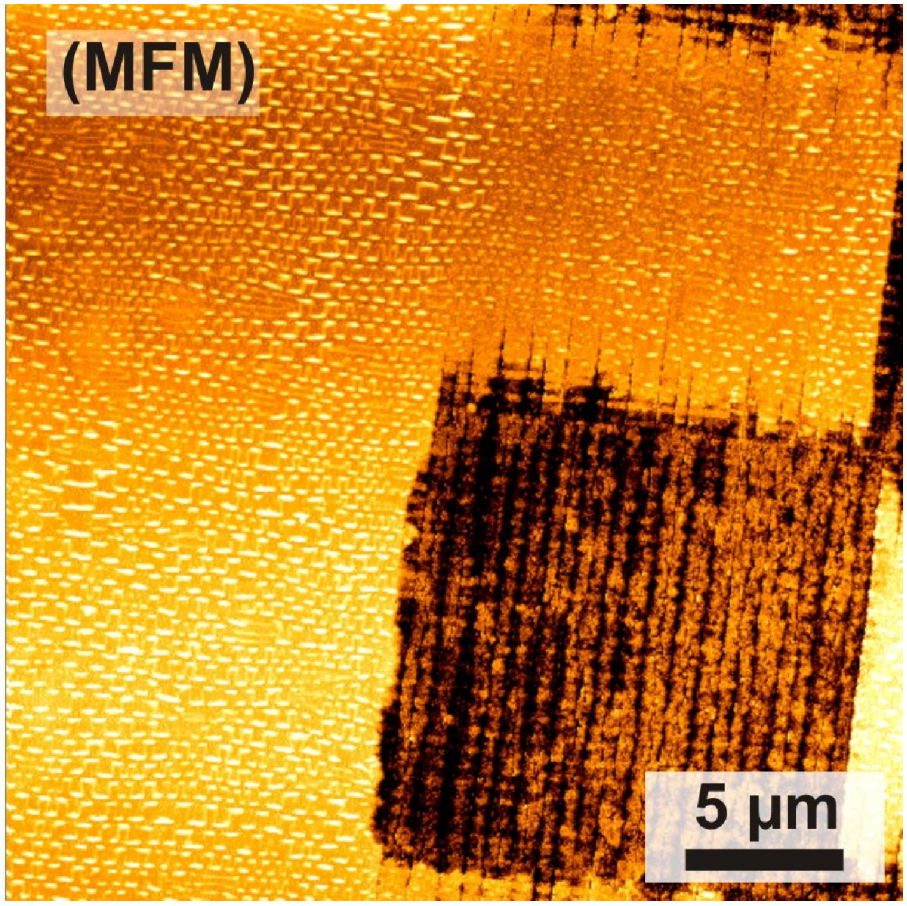


- Higher phase transition temperature due to strain relaxation: Structure→ Magnetism

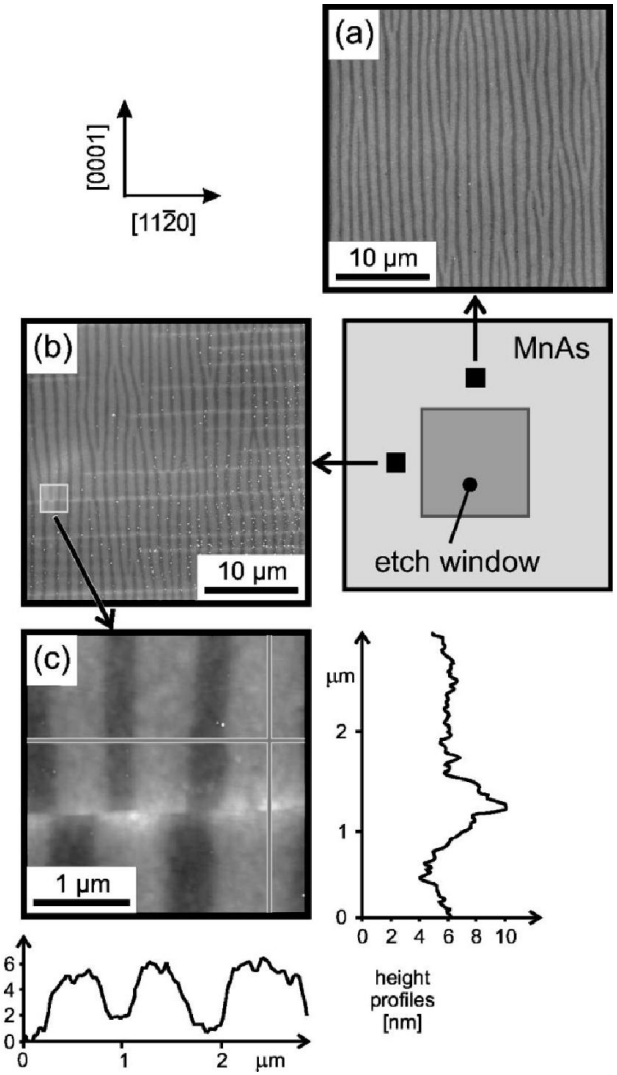
J. Mohanty, *et.al* Appl. Phys. Lett. 83, 2829-2831 (2003)
J. Appl. Phys. 98, 013907(2005).

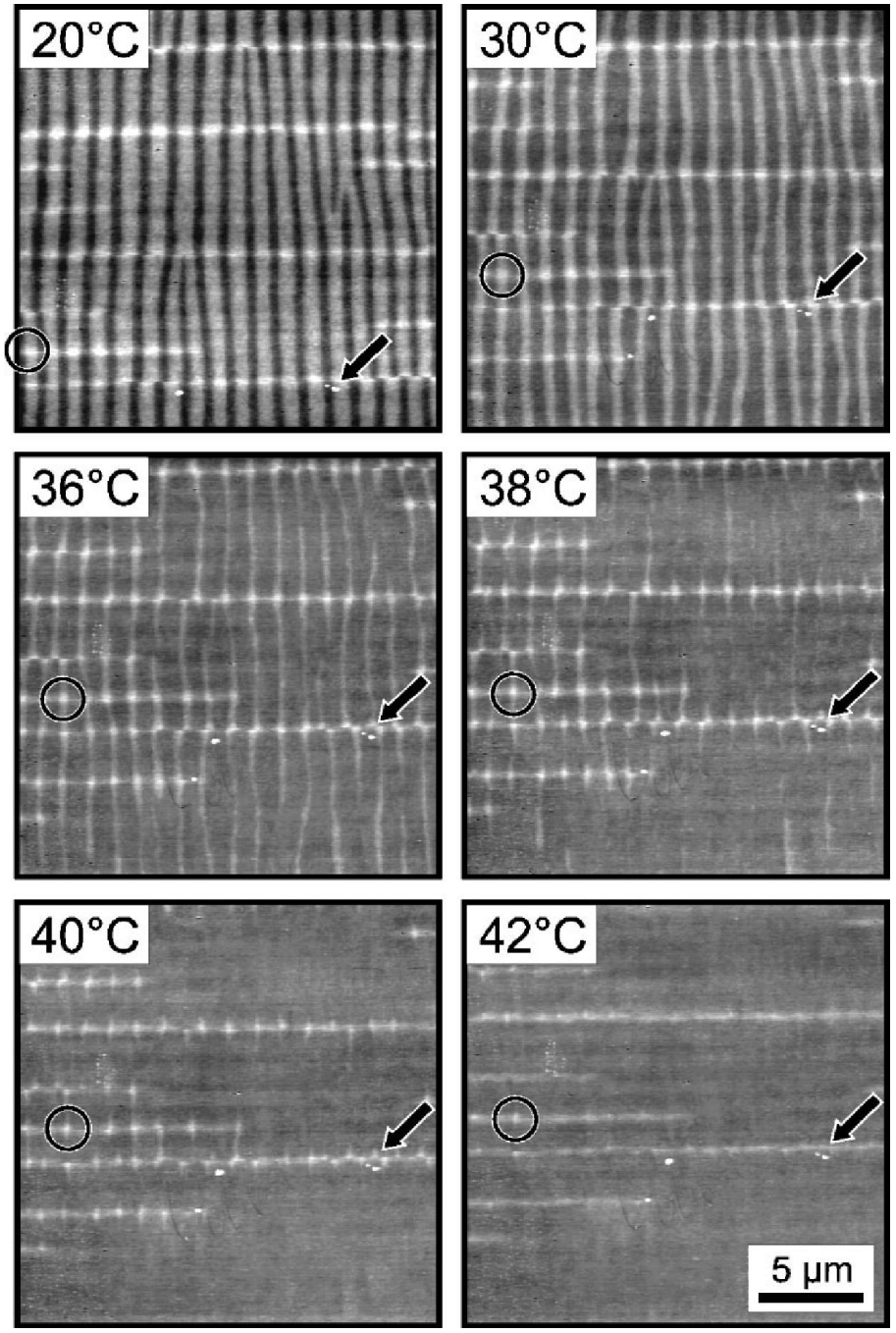
Etching



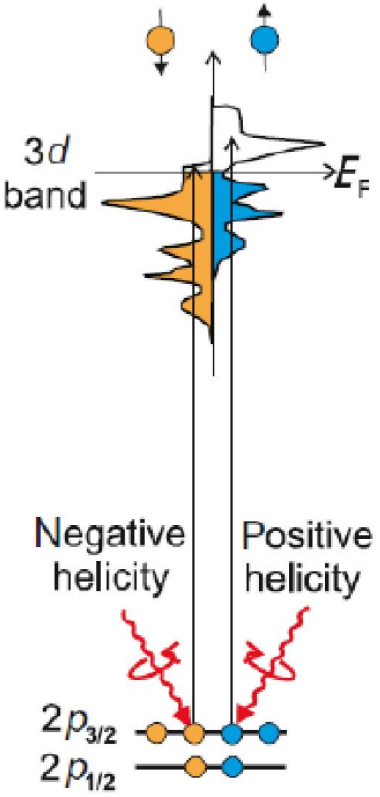


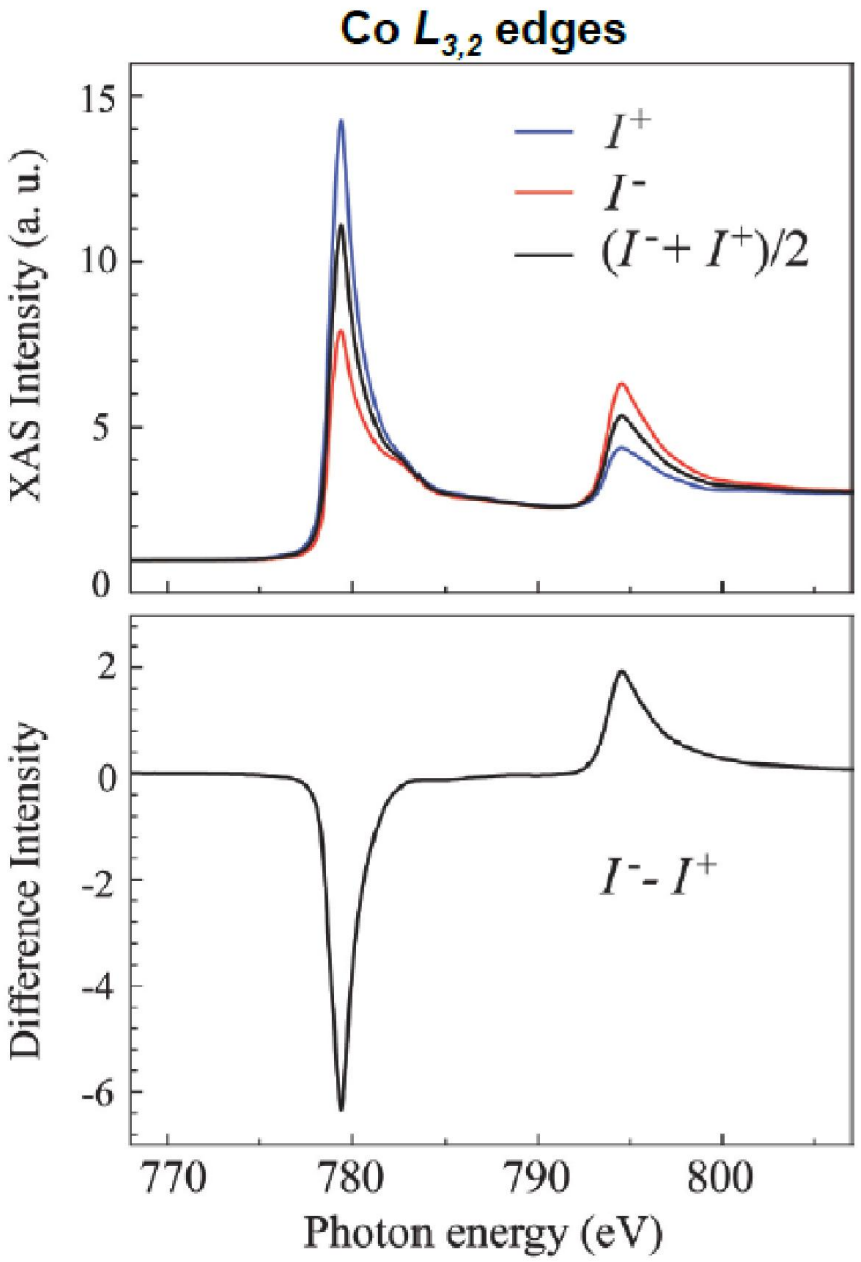
Etching and AFM Measurements

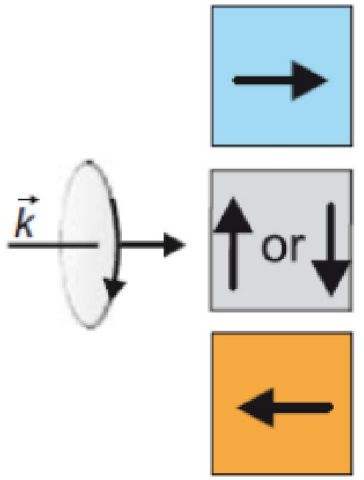




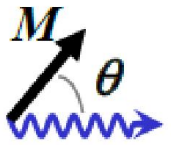
J. Mohanty, *et.al* Appl. Phys. Lett. 83, 2829-2831 (2003)
J. Appl. Phys. 98, 013907(2005).



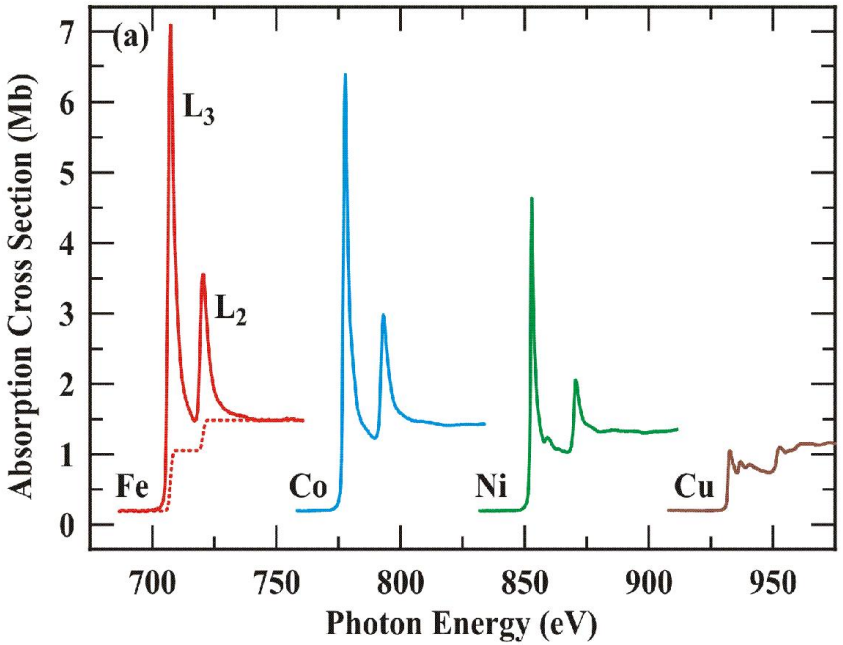


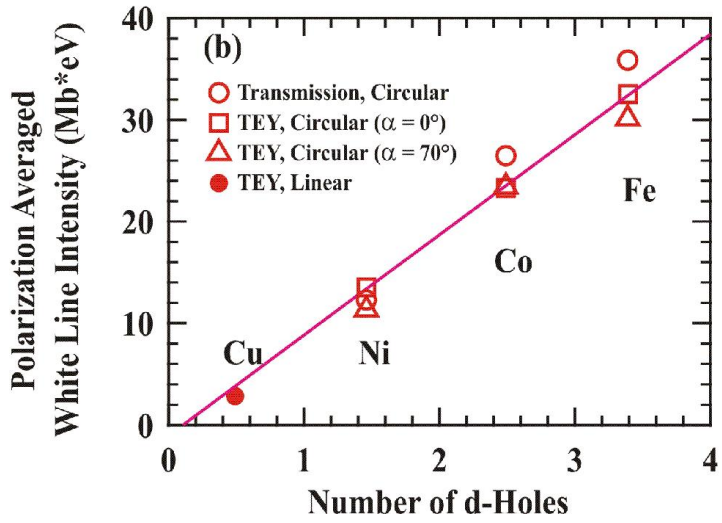


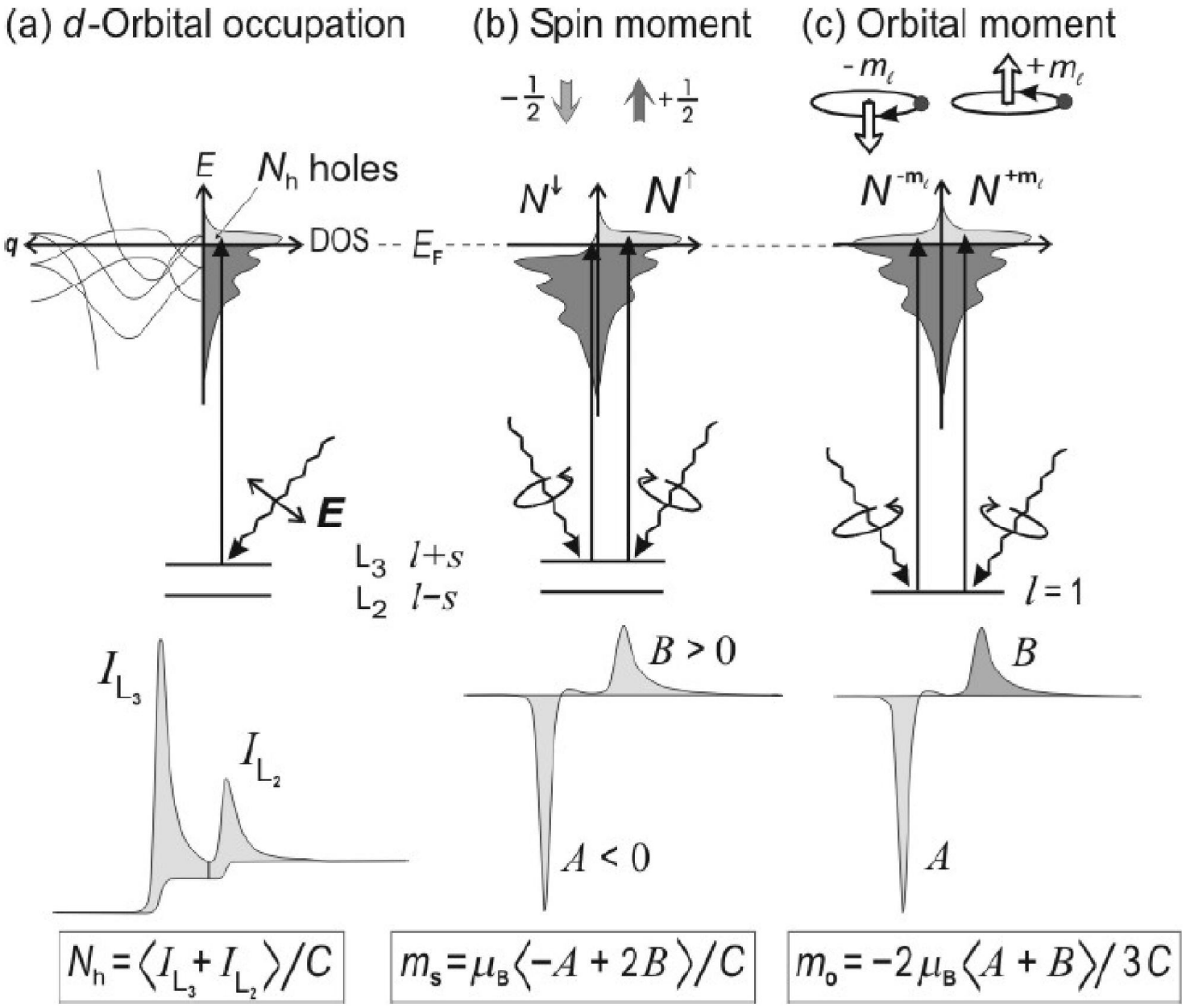
$I_{XMCD} \propto M\cos\theta$



White Line Intensity in 3d Metals

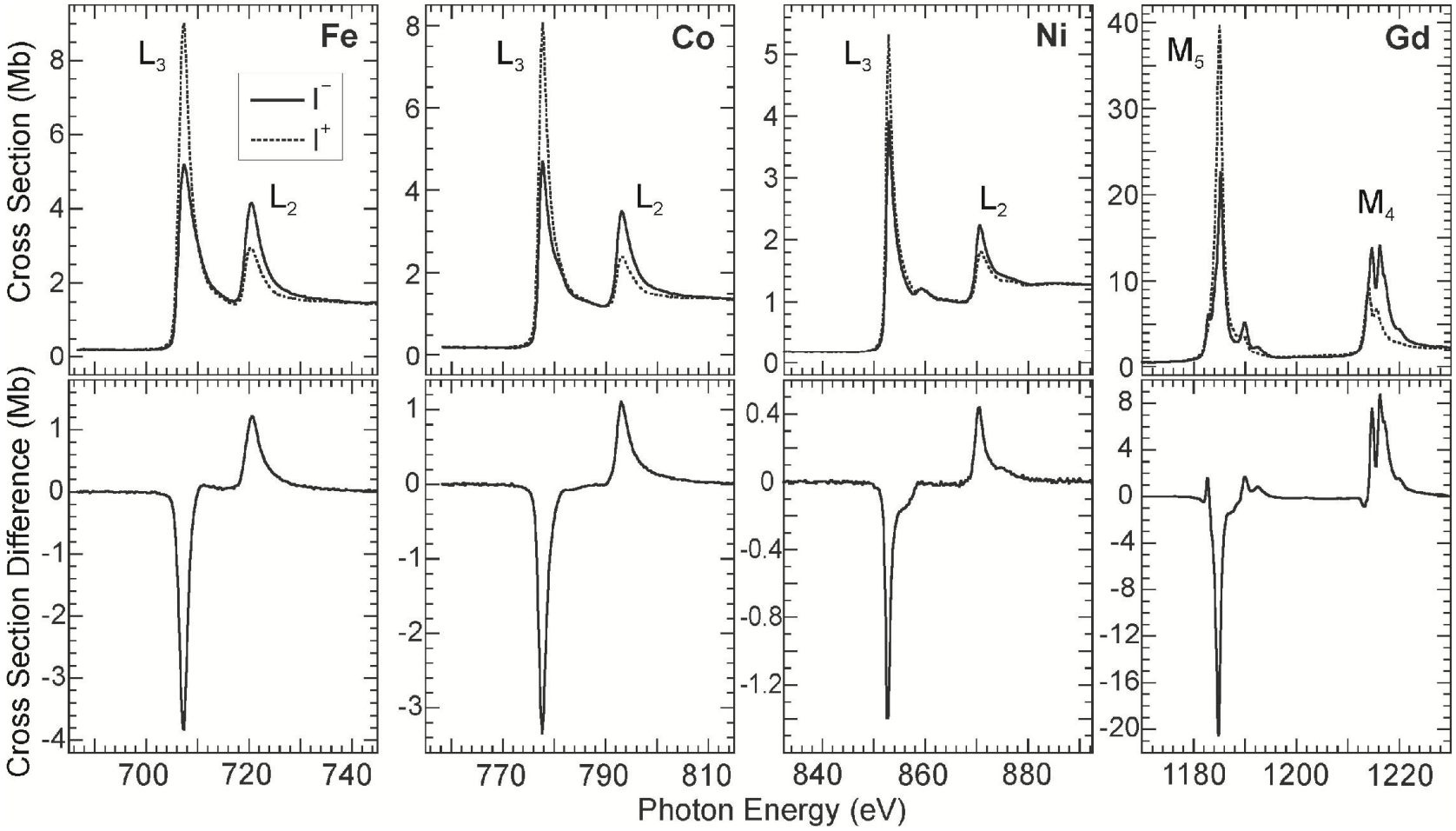






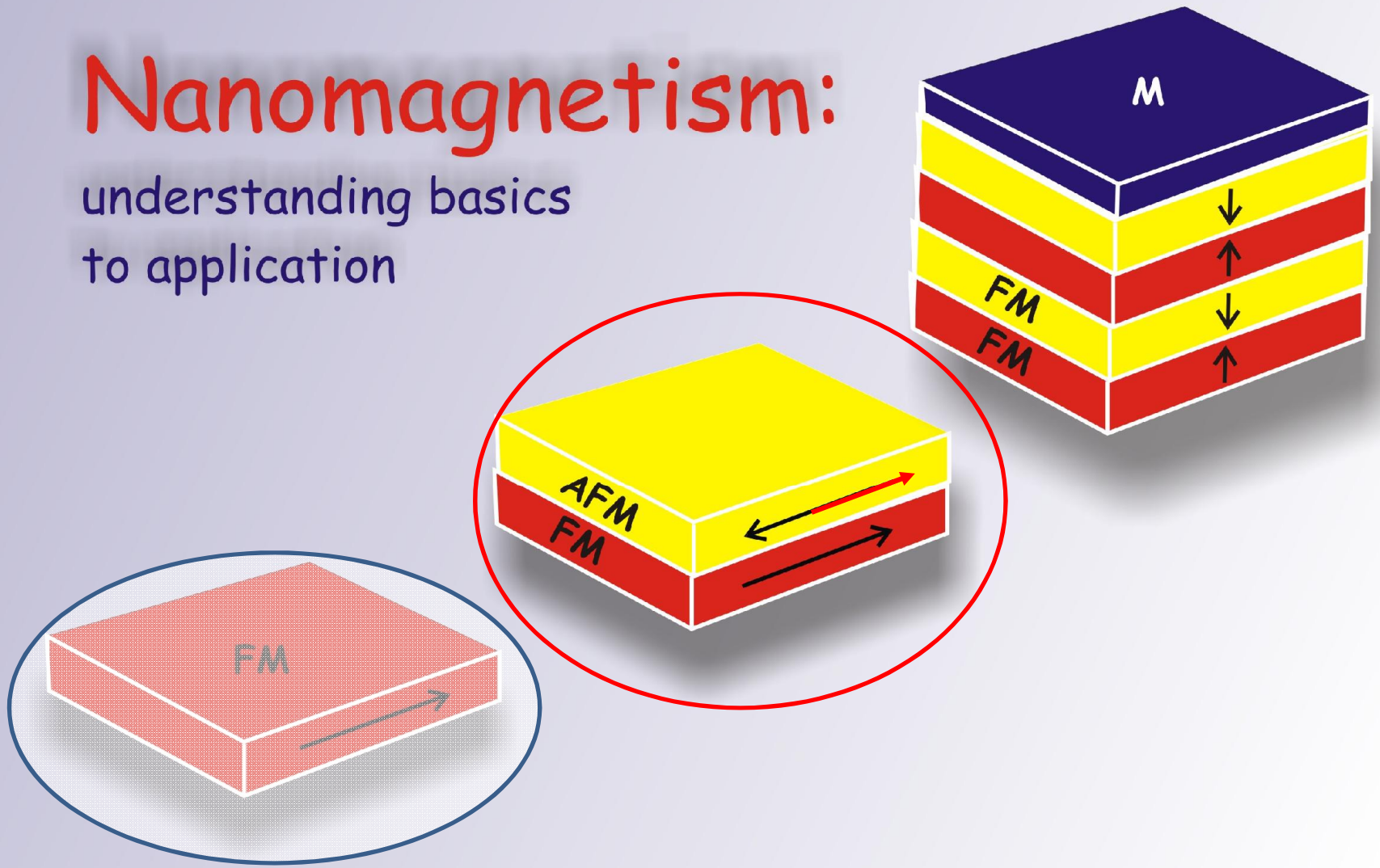
Carra, *et al.*, PRL **70**, 694 (1993); Thole *et al.*, PRL **68**, 1943 (1992);

XMCD spectra of the pure ferromagnetic metals

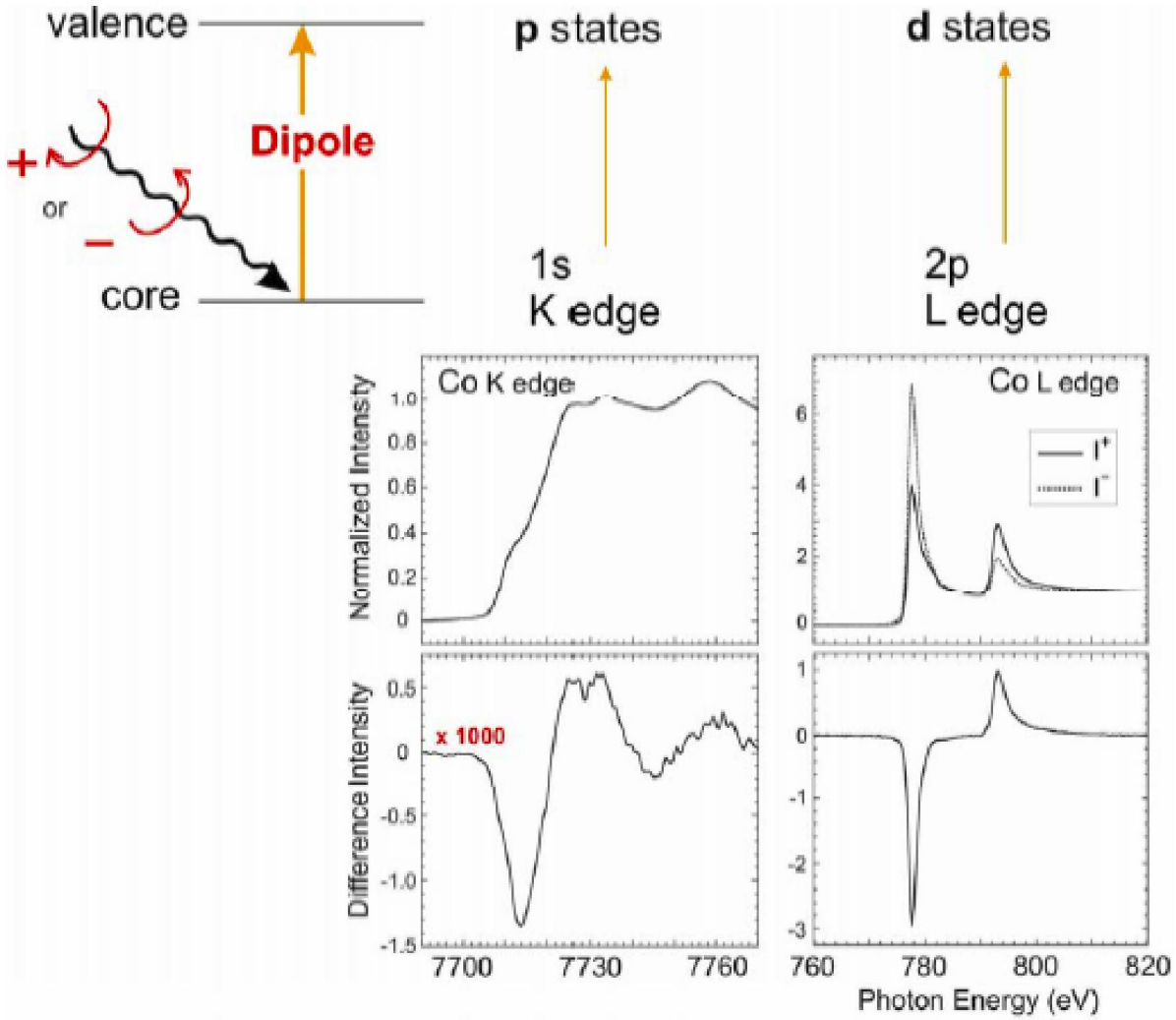


Nanomagnetism:

understanding basics
to application

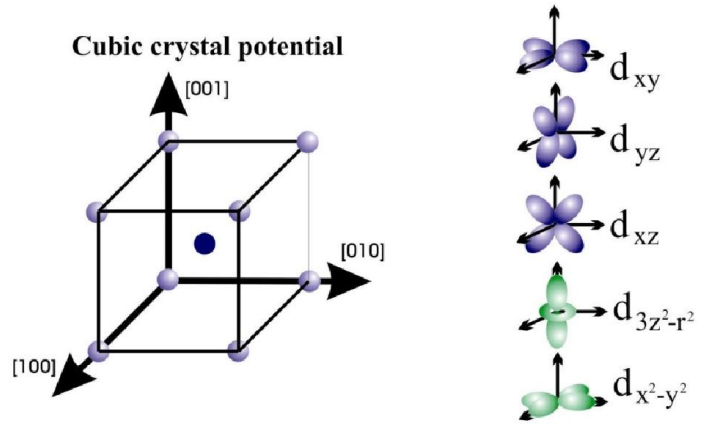


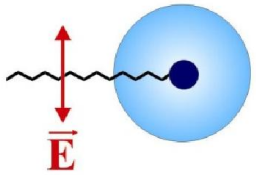
Soft x-rays are best for magnetism



X-Ray Magnetic Linear Dichroism

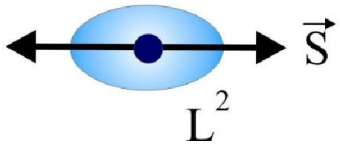
Non-magnetic state





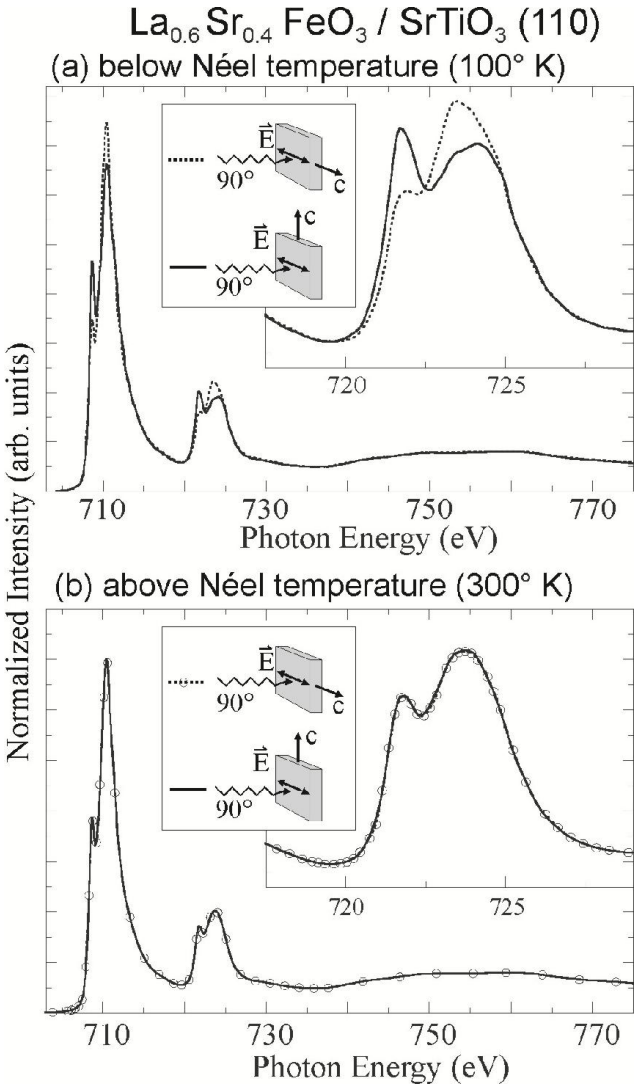
d electron charge density is isotropic
no polarization dependence

Magnetic state - preferred spin axis



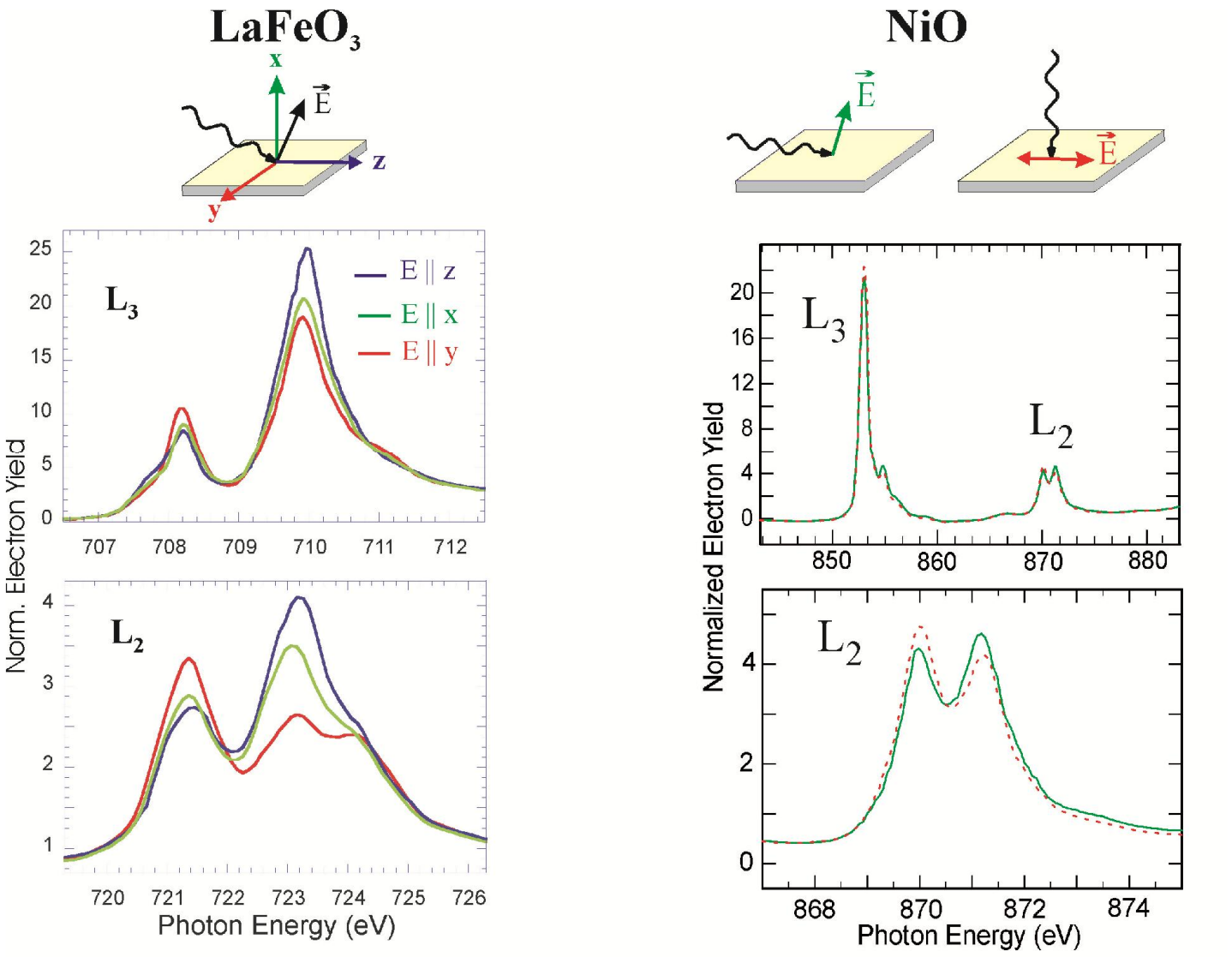
spin-orbit coupling distorts charge
creates polarization dependence

XMLD – spectra below and above T_N



Lüning et al. Phys. Rev. B 67, 214433 (2003)

XMLD spectra of two oxides



Kuiper *et al.*, Phys. Rev. Lett. **70**, 1549 (1993)
Lüning *et al.* Phys. Rev. B **67**, 214433 (2003)

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

XMLD

- E of linearly polarized x-rays acts as a search light for the number of valence holes in different directions of the atomic volume.

- Charge in the atomic volume is caused by an anisotropy in the bonding, i.e. by the electrostatic potential. In the absence of spin order, linear dichroism can only determine charge order in systems where the absorbing atom has lower than cubic symmetry.

- In the presence of spin order the spin-orbit coupling leads to preferential charge order relative to the spin direction even in cubic systems.

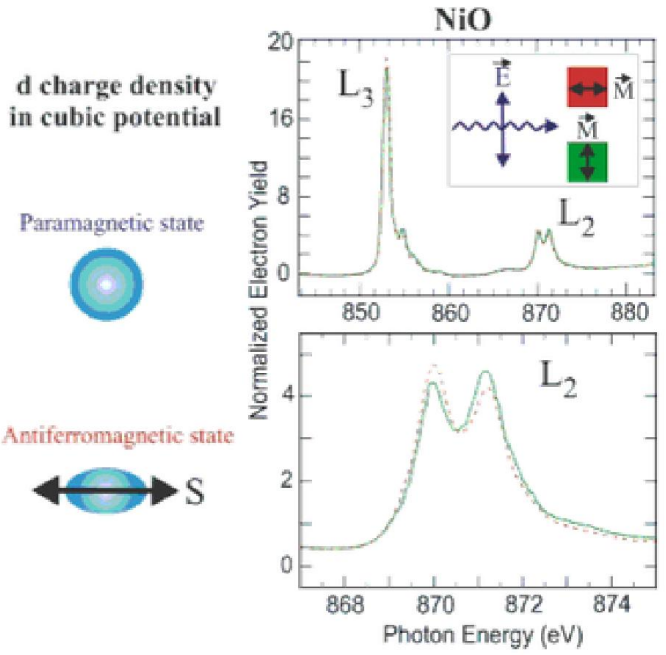
- determination of the spin axis in ferromagnetic and especially AFM systems by means of XMLD spectroscopy.

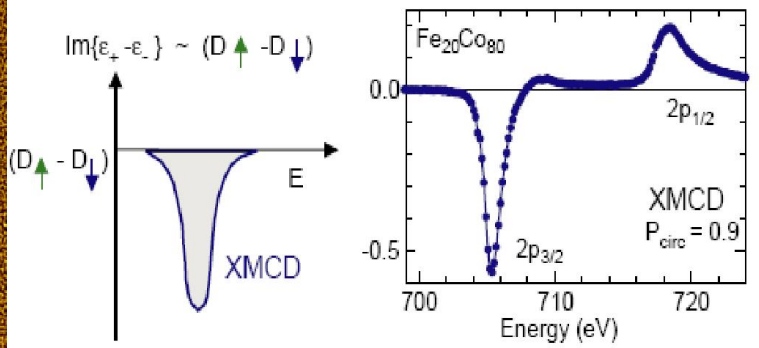
- Since the electric field vector oscillates in time along an axis and the radiation may be absorbed at any time, linearly polarized x-rays are only sensitive to axial not directional properties. Hence one can determine the orientation of the AFM or FM axis, but the spin direction itself cannot be determined.

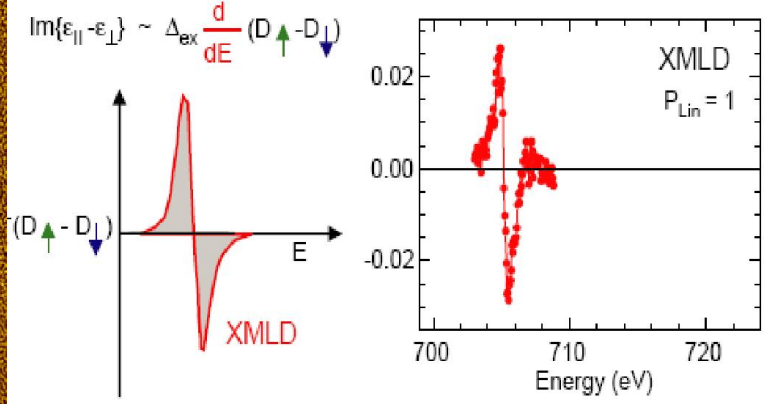
XMLD

- E parallel versus E perpendicular to the magnetic axis
- $\cos^2\theta$ dependence, where θ is the angle between E and the magnetic axis.
- small in 3d metals due to small size of the spin orbit interaction and the large band width, resulting in a small charge anisotropy when the d states are summed over the Brillouin zone.

- XMLD effect (10-30%) may be observed in the presence of multiplet splitting.
- At a particular multiplet energy only selected d valence states are probed through matrix element effects that enhance the XMLD effect.
- In a simple picture we can view each multiplet as a strongly coupled spin-orbit state whose spatial extent is non-spherical, giving rise to the large XMLD effect.
- Since XMLD can arise from electric and magnetic asymmetries, care needs to be taken to distinguish magnetic order effects from ligand field effects. This is typically done through temperature dependent measurements.







. 1. Comparison of the predicted (left) and measured (right) pes of XMCD and XMLD spectra. The experimental ICD and XMLD spectra are measured at the Fe L_3-edge an amorphous $Fe_{20}Co_{80}$ film (symbols).

JMM 272 2146 04

- The XMLD signal is much smaller than that of the widely used XMCD, therefore not many studies of the XMLD were carried out
- XMCD signal is odd in the magnetization M
- XMLD is even in M; i.e., to lowest order quadratic in M

- The XMLD comes about as the intensity difference between resonant p-d transitions having $\Delta m = 0$ and the average of the transitions with $\Delta m = \pm 1$:
- The relatively small exchange splitting of the 2p core states is crucial: without this exchange splitting the XMLD signal vanishes

- In a ferromagnetic transition metal the XMCD fraction of the absorption coefficient $\{(n_+-n_-)/(n_++n_-)\}$is larger than the XMLD fraction $\{(n_+-n_-)/(n_++n_-)\}^2$

  $n_{+(-)}$ is the hole occupation number of the spin up (down)bands.

  For example, in bulk Fe the peak XMCD at the 2p edge is 150% (normalized to the edge jump), while here the peak XMLD is only 8%.

- At the L_2 edge of Fe, both $2p_{1/2}$ multiplets contribute positively to the $\langle S_z \rangle$ component of the XMCD.
- These multiplets have equal and opposite contributions to the $\langle S_z \rangle$ component of the XMLD.

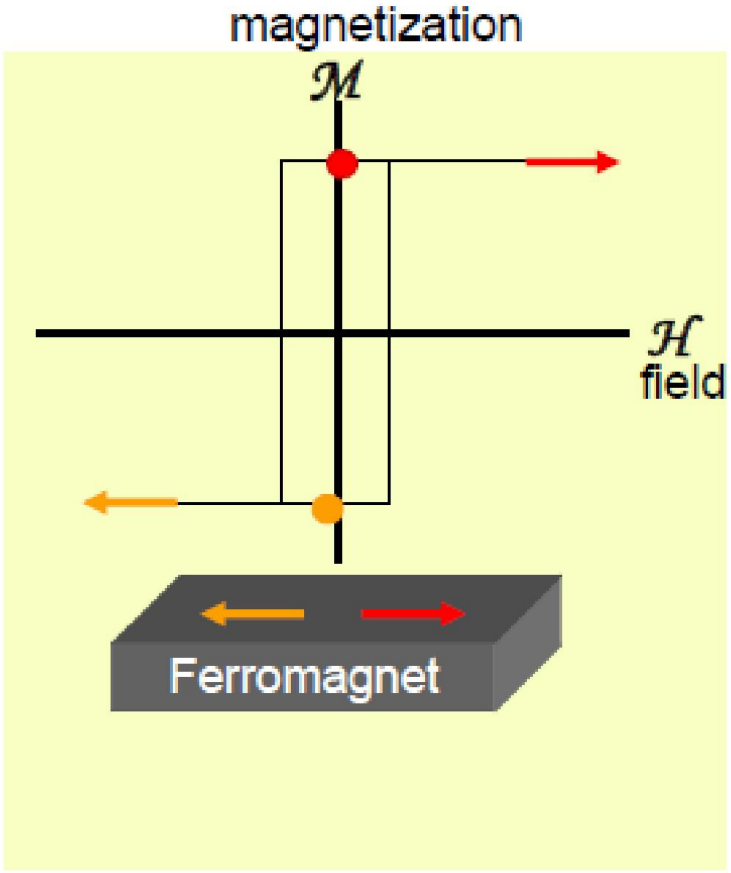
- To measure $\langle S_z \rangle$ with XMCD, one needs only to distinguish the L_3 and L_2 edges (separated by 13 eV in Fe). XMLD is more difficult, since it requires resolution of the individual multiplet states (separated by 1 eV).

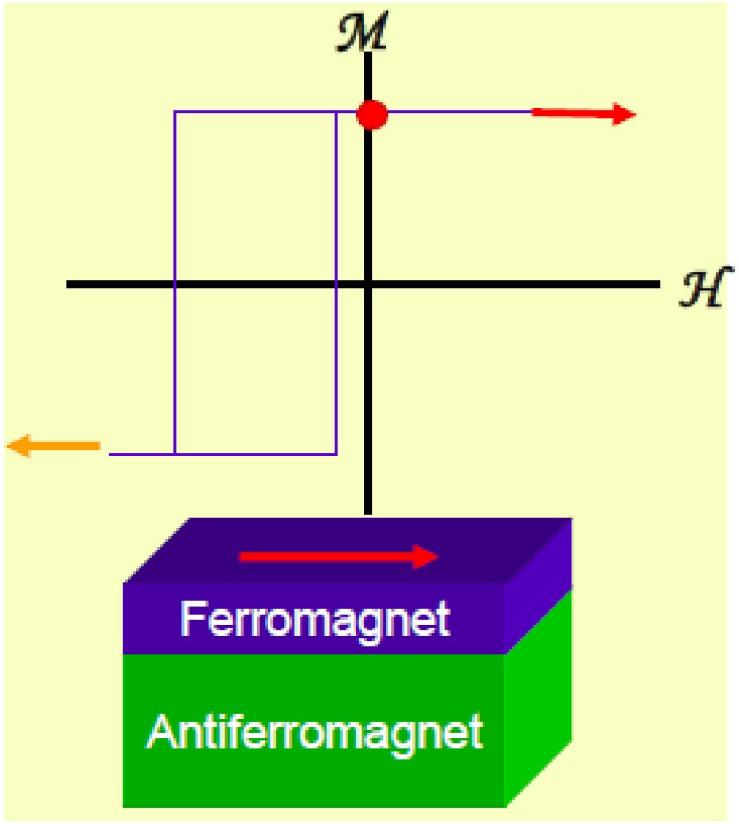
- Each multiplet has an intrinsic broadening that is inversely proportional to the core-hole lifetime. In the solid state the atomic multiplets are further broadened into bands. Thus, if the core-hole lifetime is short or the hybridization strong, the $\langle S_z \rangle$ component *of the XMLD* spectrum is strongly suppressed. This is exactly the situation in transition metal systems, hence XMLD may not be measurable in a metal.

- Indeed, the two extant studies reporting nonzero TM XMLD have focused on metal oxides, where the multiplet peaks are narrow and well separated.

An important problem: Exchange Bias

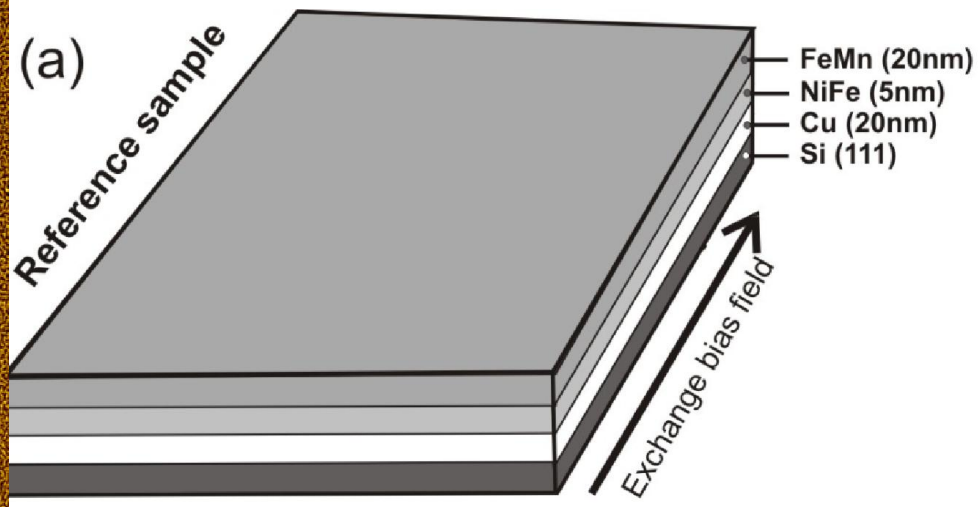
discovered in 1956, technologically used for many years, ill understood

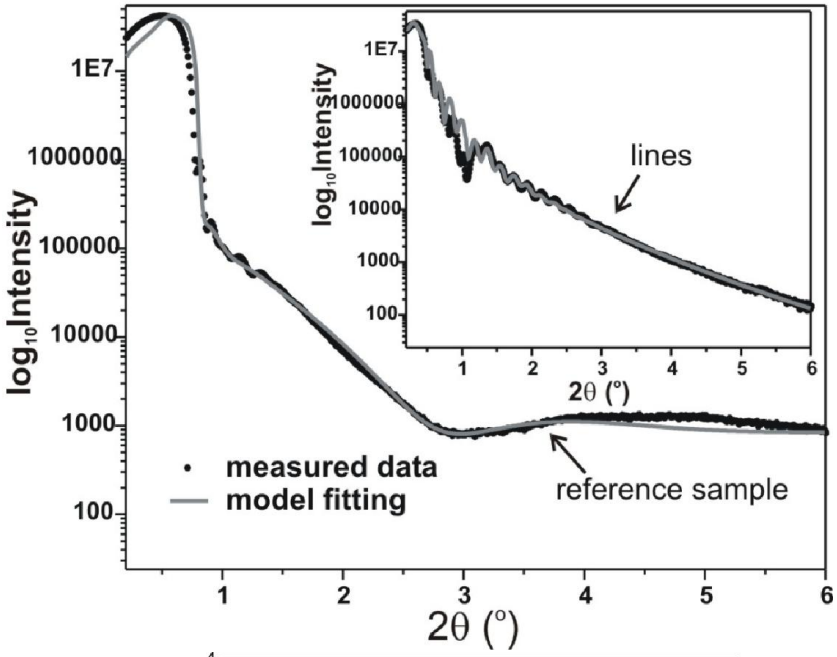


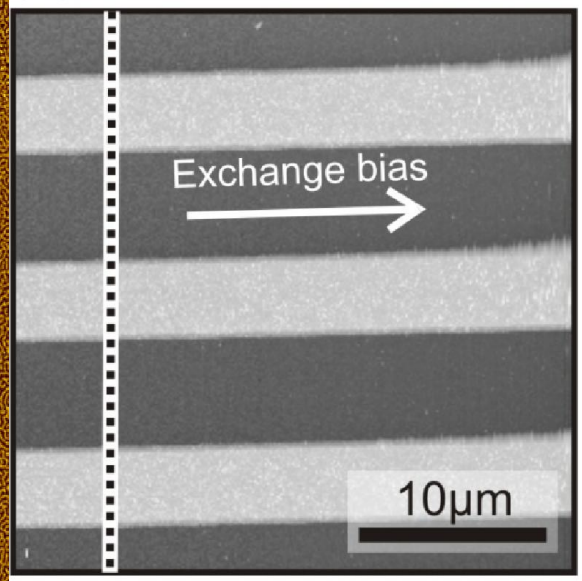


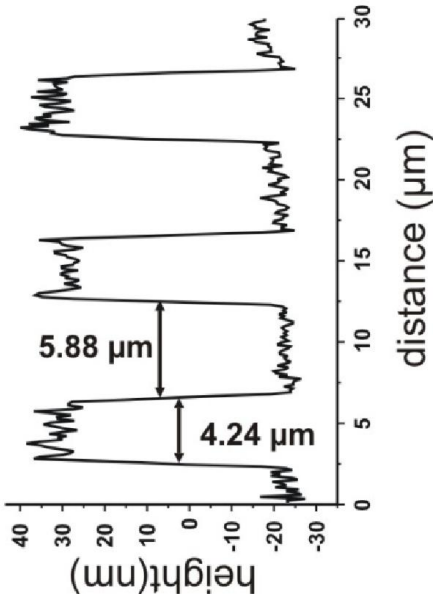
$\mathcal{M}$ of blue layer is "pinned"
or "exchange biased"

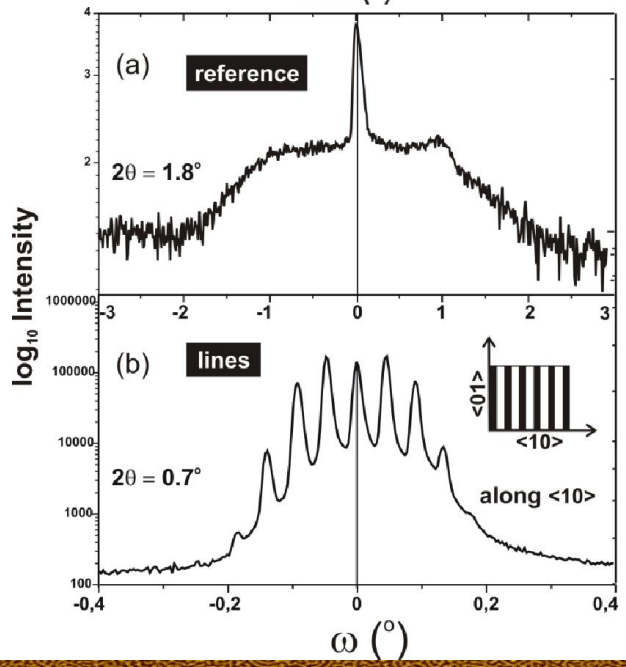
Structural Characterization





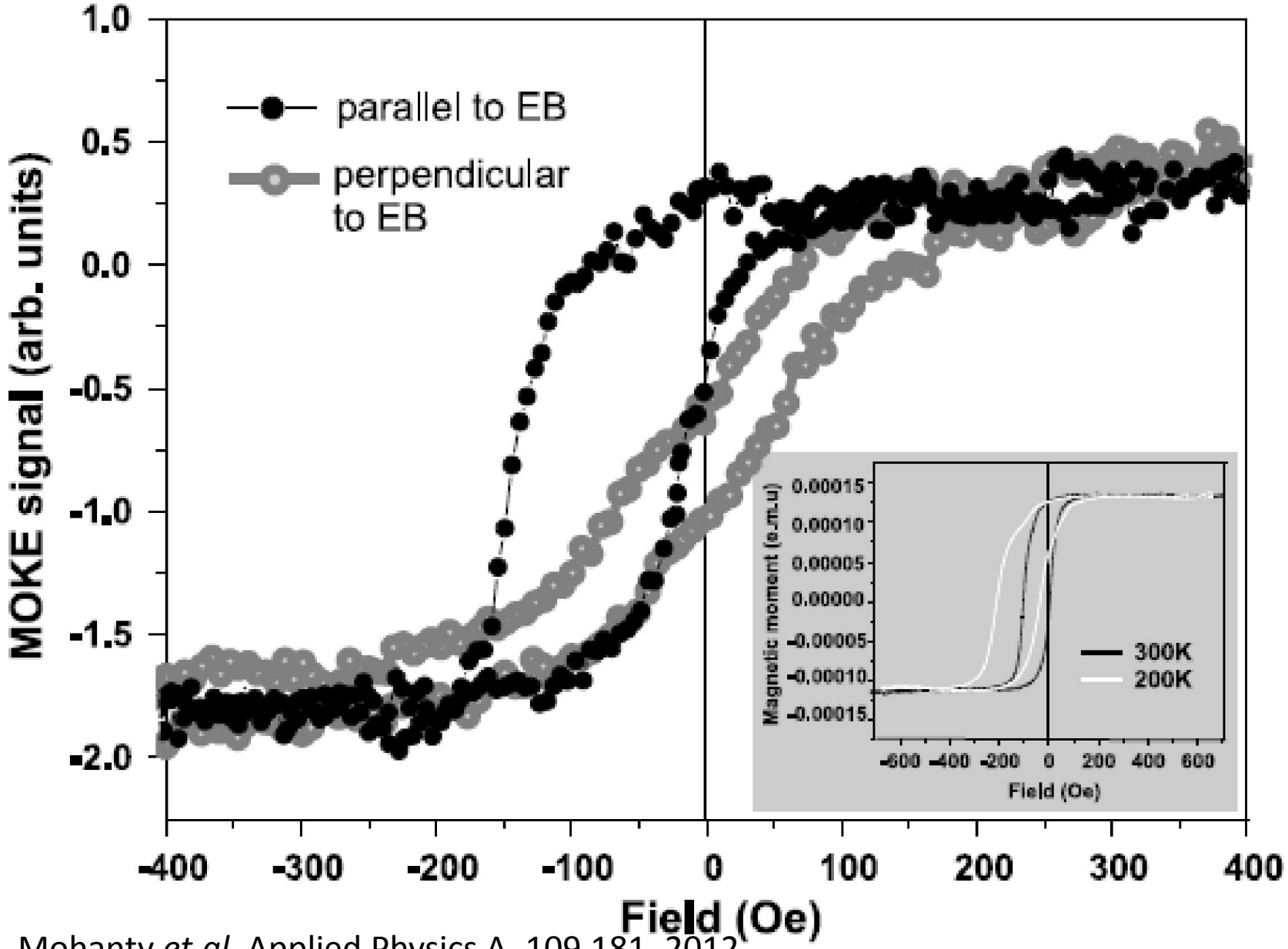






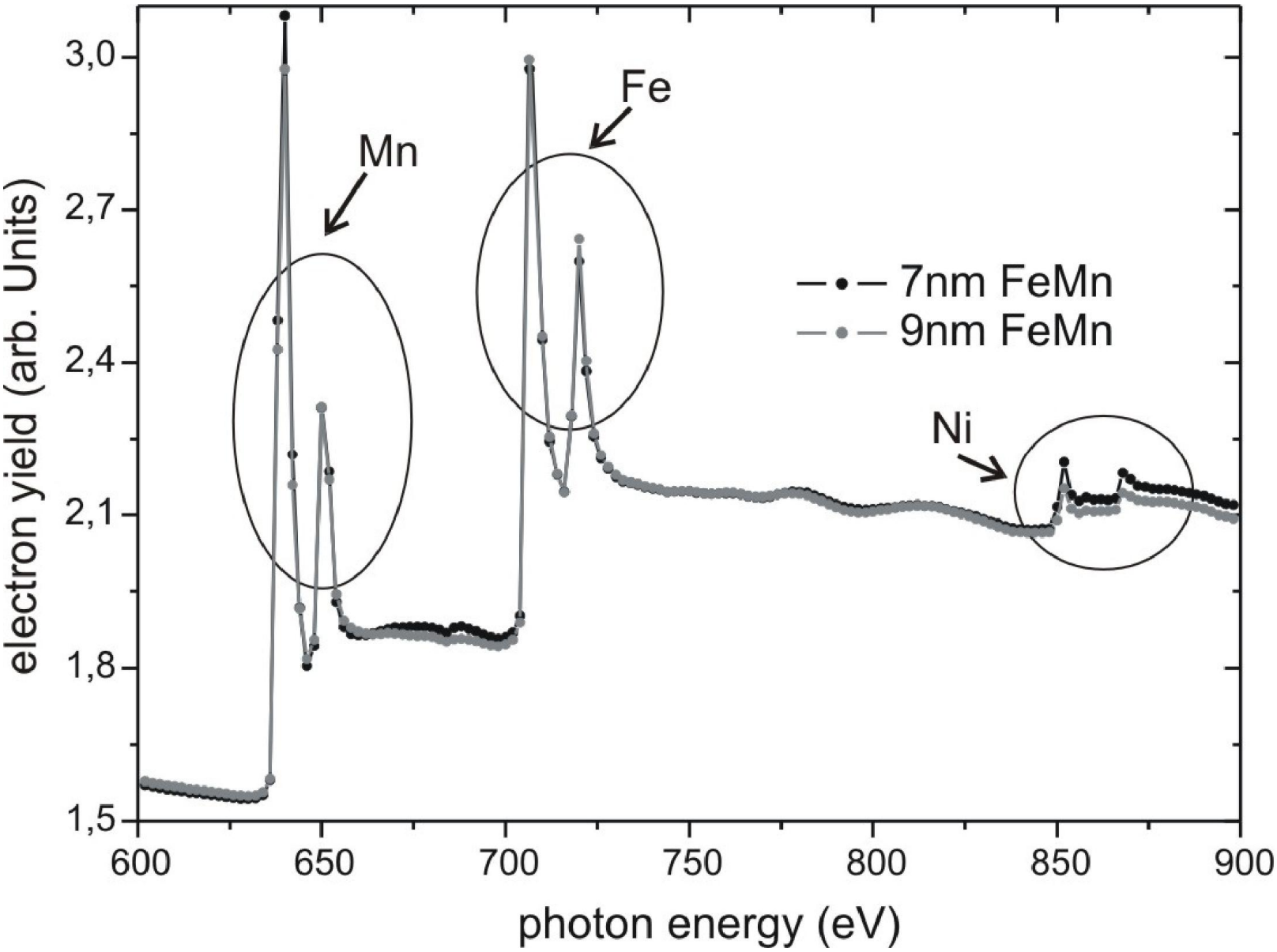
J. Mohanty *et.al*, Applied Physics A, 109,181, 2012

Magnetic Characterization

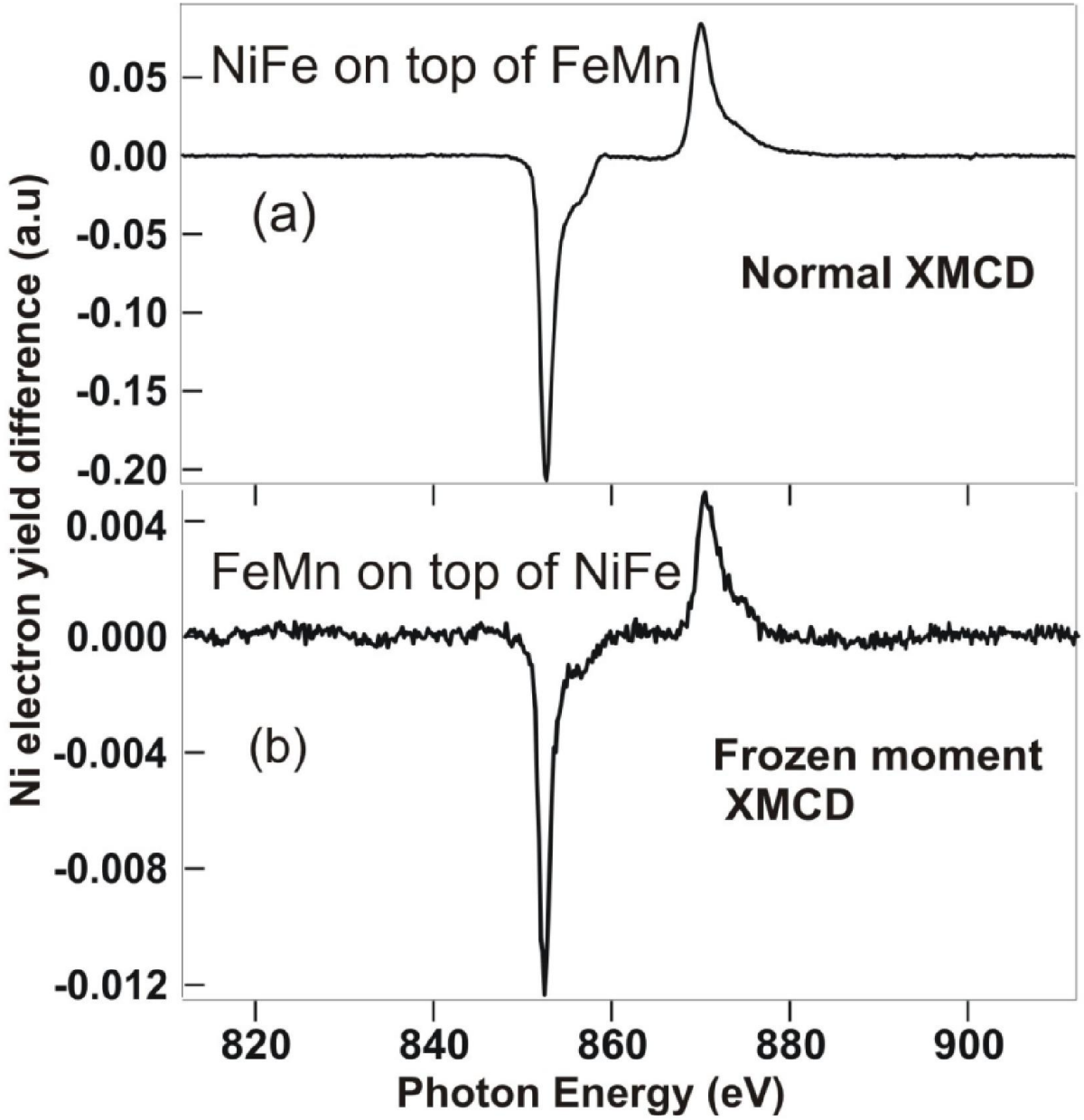


J. Mohanty *et.al*, Applied Physics A, 109,181, 2012

Element specific magnetic information

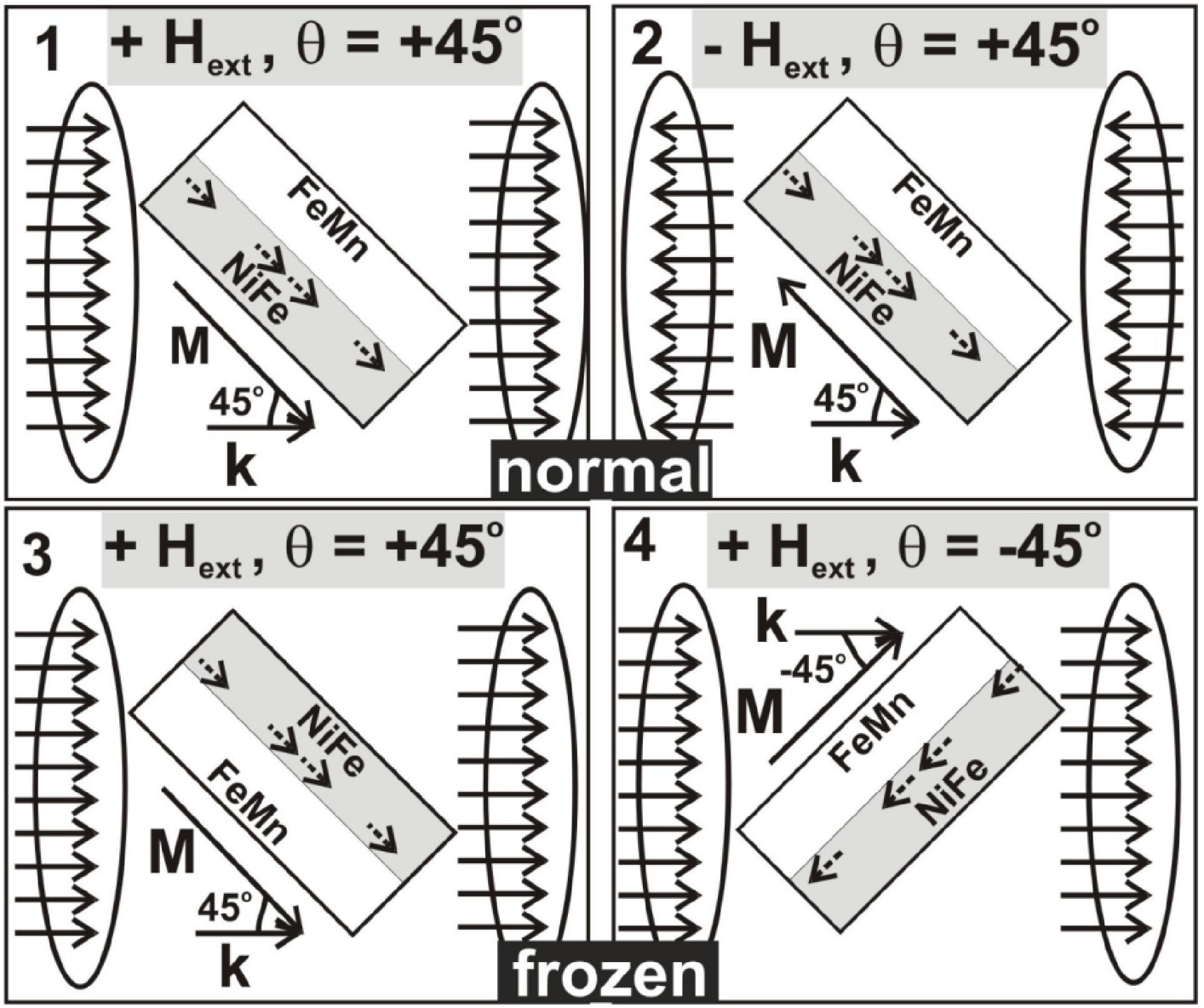


Looking at the frozen interface spins



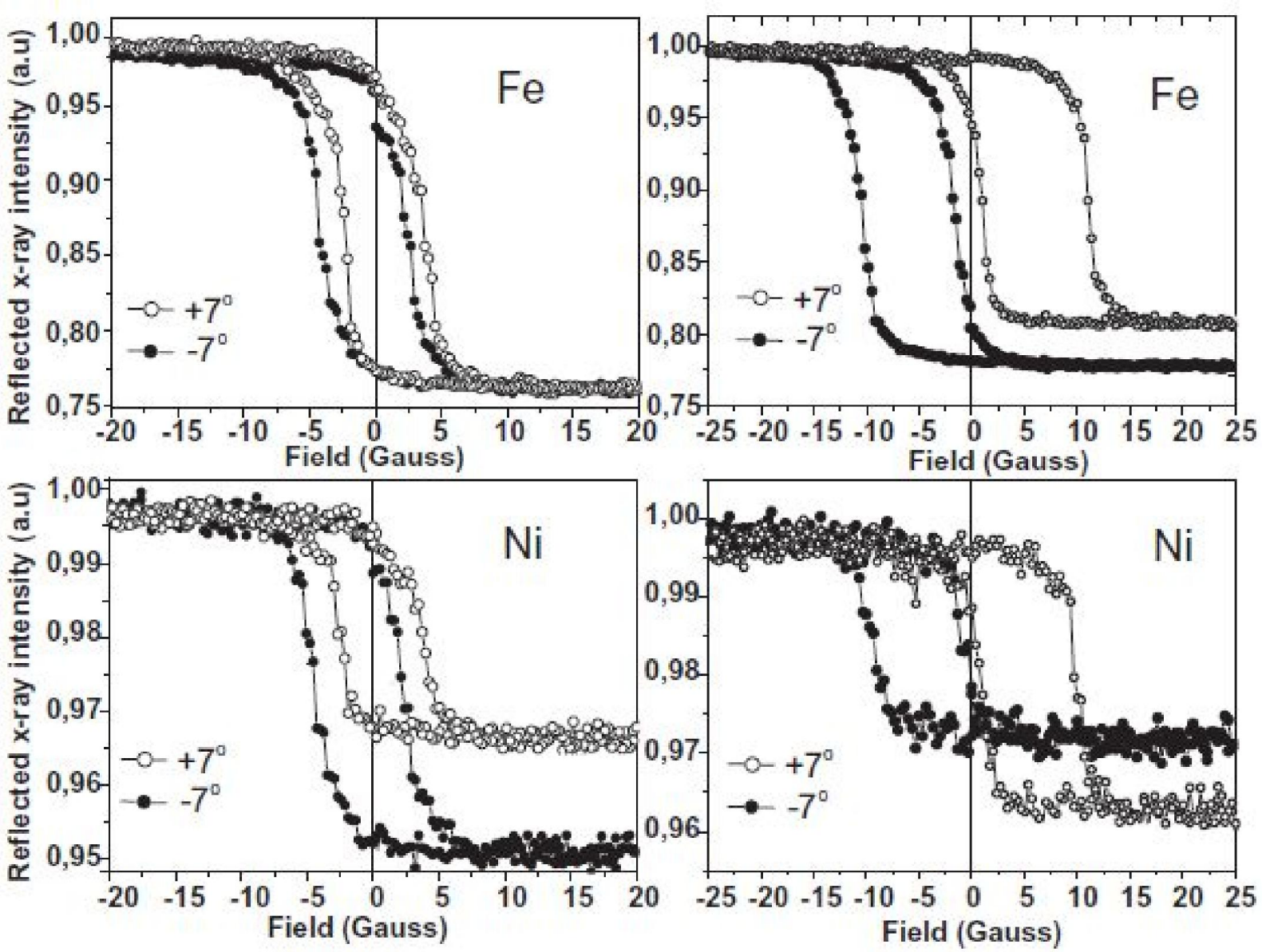
J. Mohanty *et.al*, New Journal of Physics, **15**, 033016, 2013

Looking at the frozen interface spins



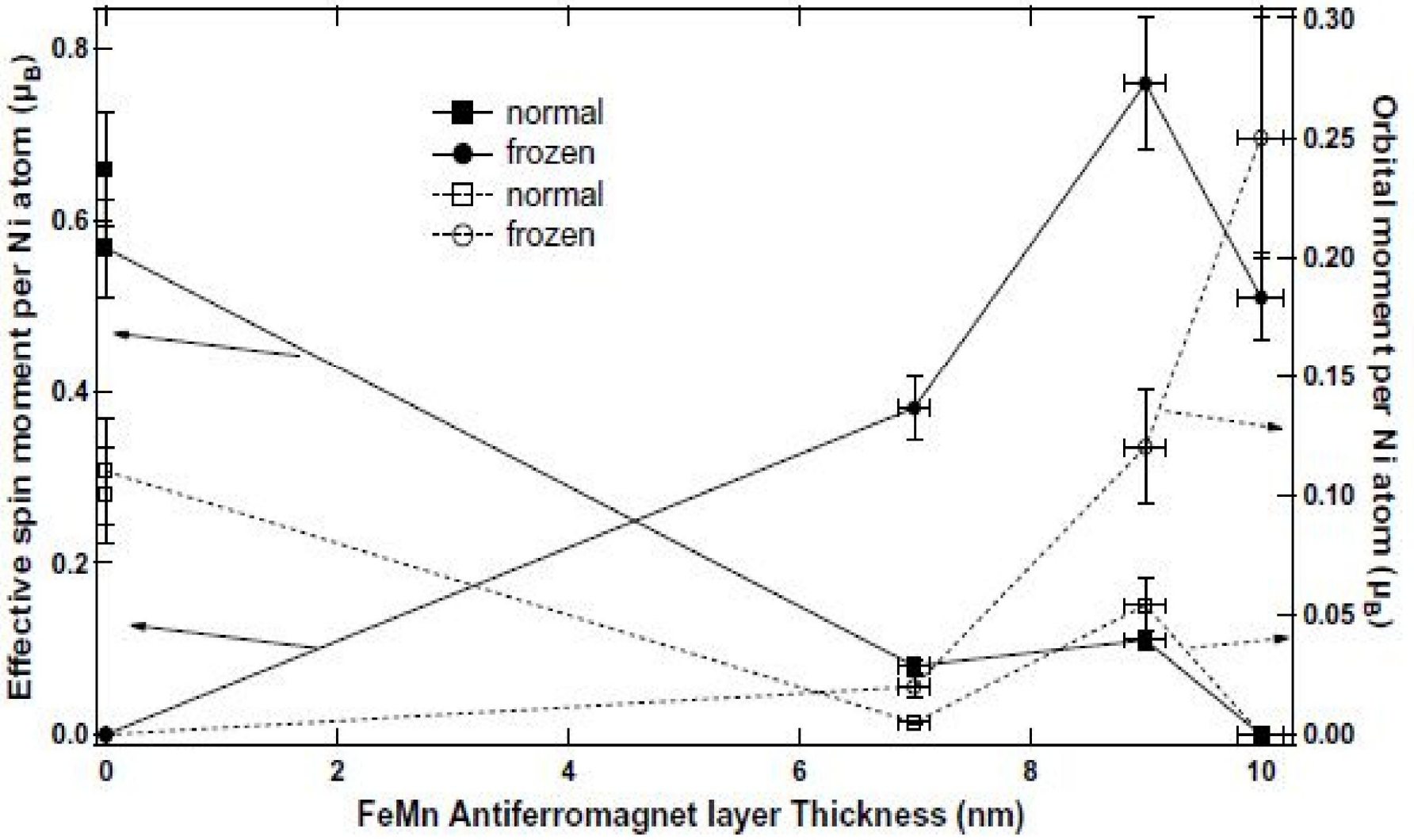
J. Mohanty *et.al*, New Journal of Physics, **15**, 033016, 2013

Where are the frozen spins?



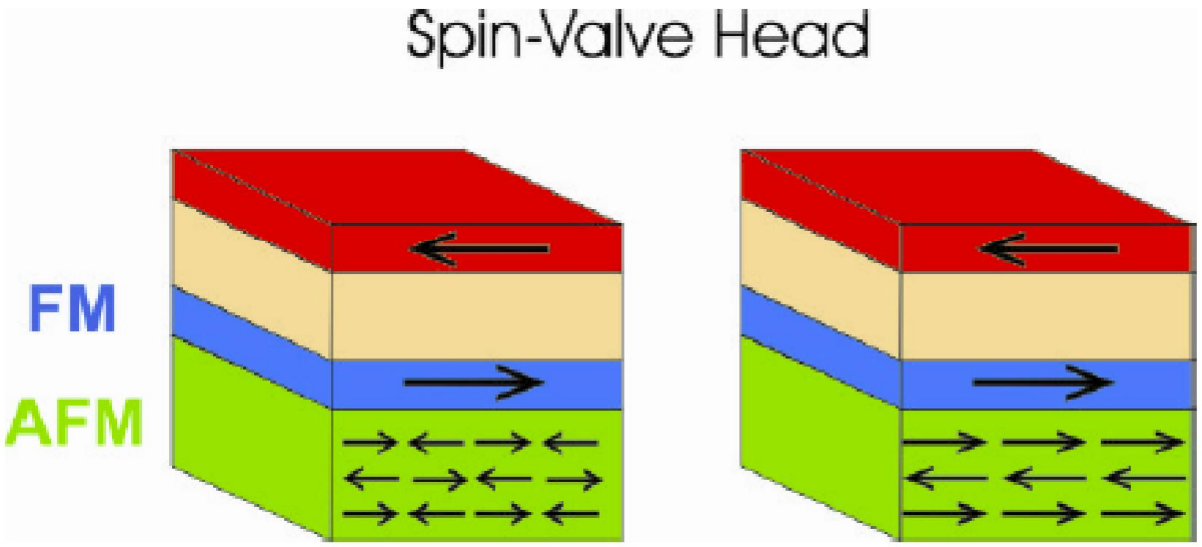
J. Mohanty *et.al*, New Journal of Physics, **15**, 033016, 2013

Our stand point: XMCD analysis



J. Mohanty *et.al*, New Journal of Physics, **15**, 033016, 2013

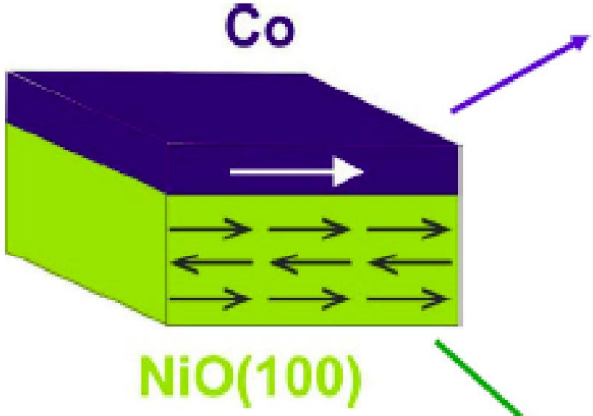
Example : The Spin Valve Sensor



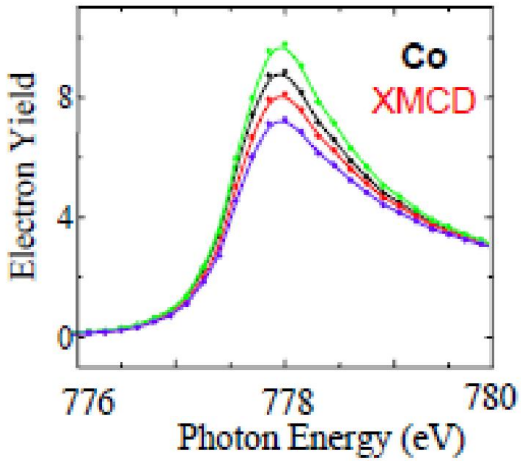
AFM is “neutral”

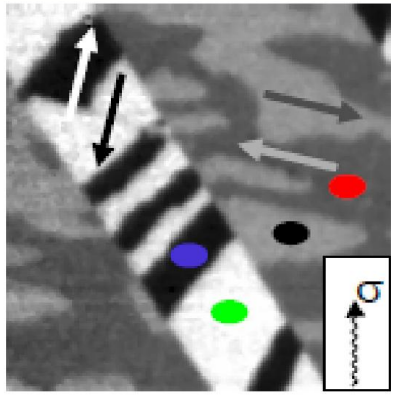
AFM is “magnetic” at surface

Coupling of ferromagnetic and antiferromagnetic domains

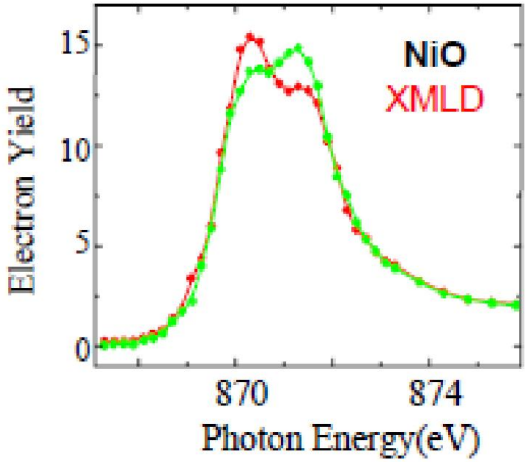


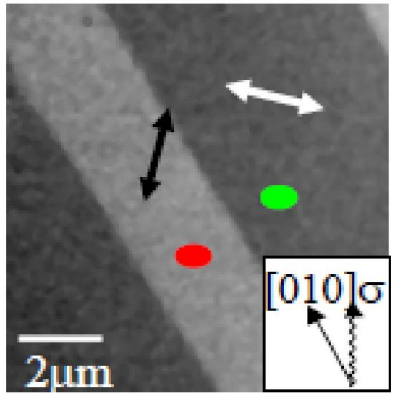
Co edge – use **circular** polarization – **ferromagnetic** domains





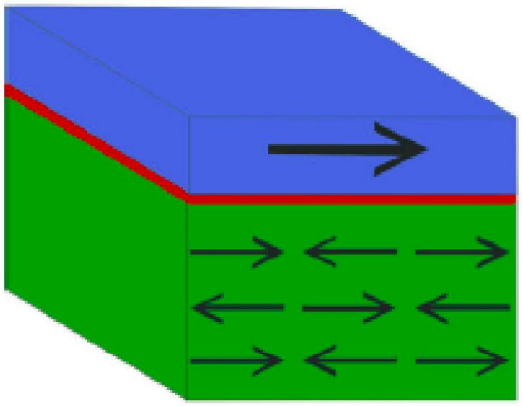
Ni edge – use **linear** polarization – **antiferromagnetic** domains

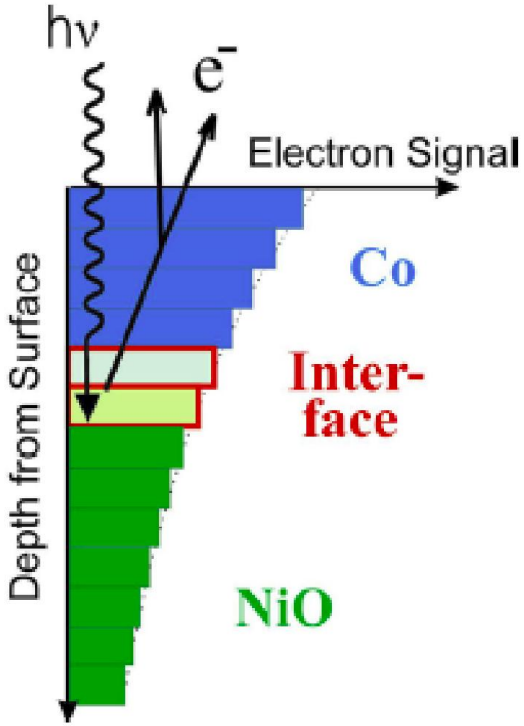




H. Ohldag *et al.*, PRL **86**, 2878 (2001)

X-Rays-in / Electrons-out - A way to study Interfaces



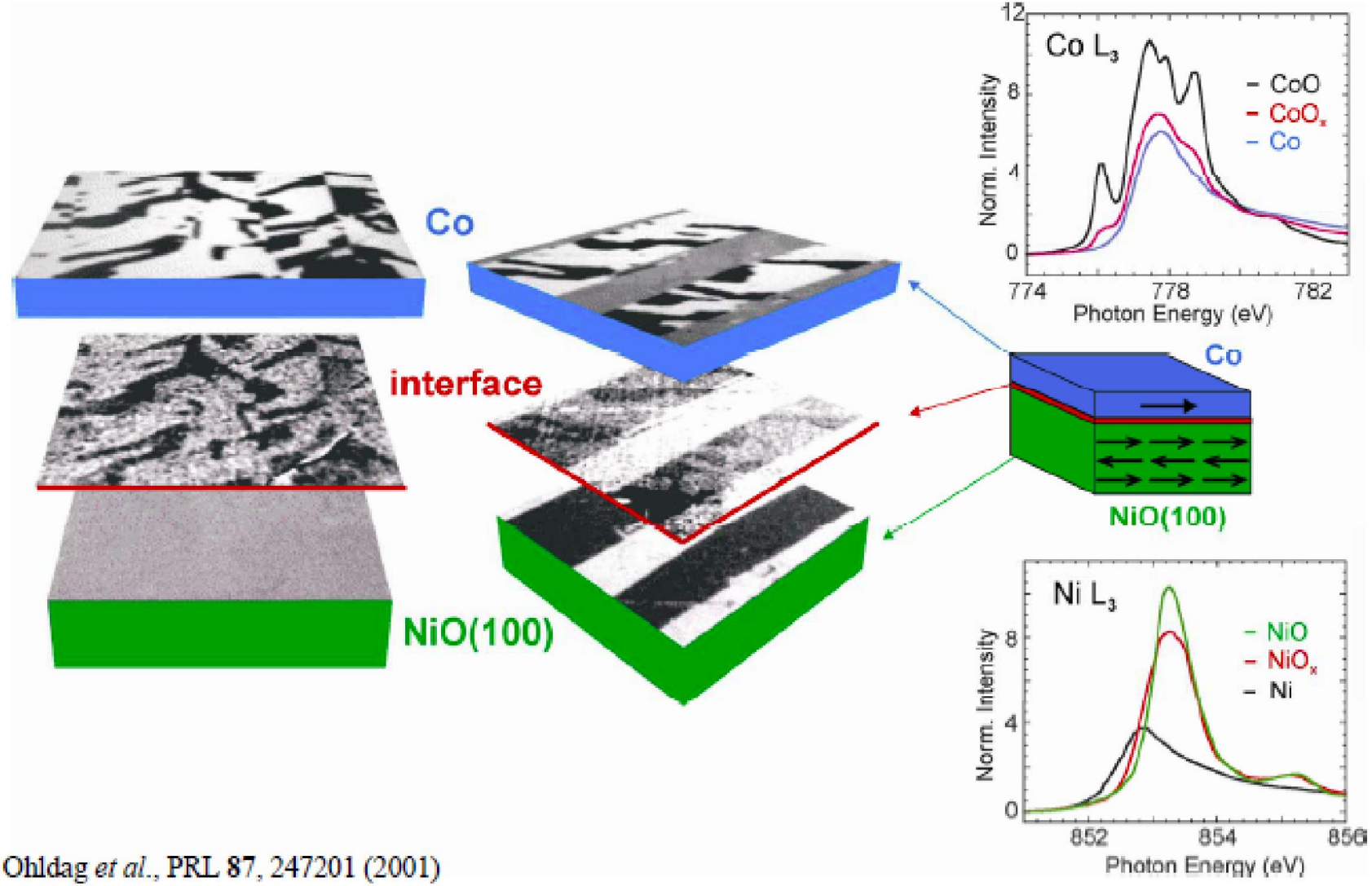


FM Co – tune to Co edge – circular polarization

AFM NiO – tune to Ni edge – linear polarization

FM Ni(O) – tune to Ni edge – circular polarization

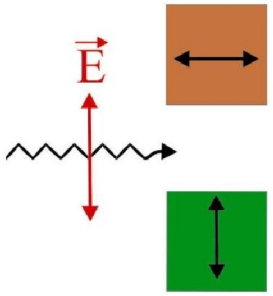
Images of the Ferromagnet-Antiferromagnet Interface

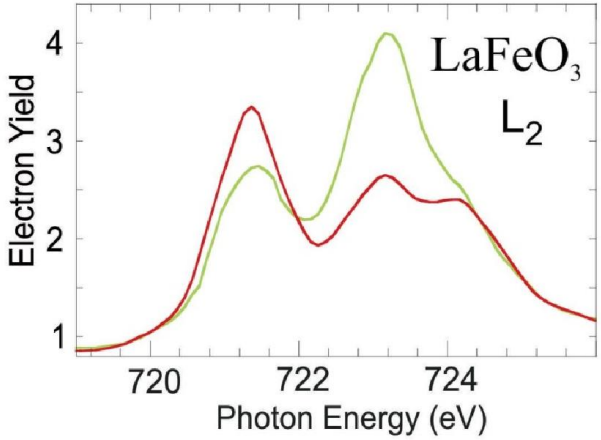


Ohldag *et al.*, PRL **87**, 247201 (2001)

Magnetic Spectroscopy and Microscopy

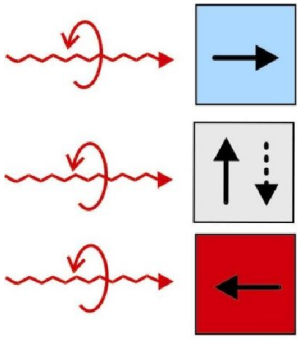
X-ray Magnetic Linear Dichroism: Antiferromagnets



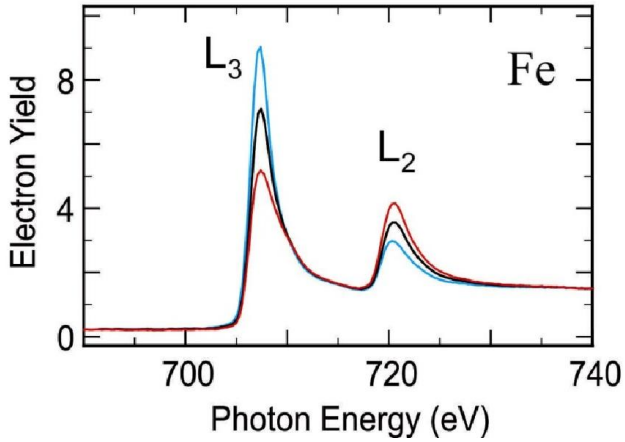


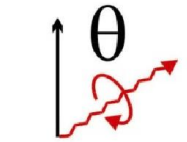
$I \sim \cos^2\theta$

X-ray Magnetic Circular Dichroism: Ferromagnets



x-ray "spin"





$I \sim \cos\theta$

Soft X-Rays are best for magnetism!