Memory of frozen and rotatable antiferromagnetic spins in epitaxial CoO(111)/Fe and NiO(111)/Fe bilayers

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- **Antiferromagnets - motivation**
- **Introduction:** Spin reorientation transition in **ferromagnet** as a tool to control magnetic state of AFM overlayers
- **XMCD and XMLD**
- **Frozen AFM spins in CoO(111)/Fe(110)**
- **Rotatable AFM spins in NiO(111)/Fe(110)**
- **AFM vortex states in individual NiO(111)/Fe(110) nanostructures**
- **Summary**

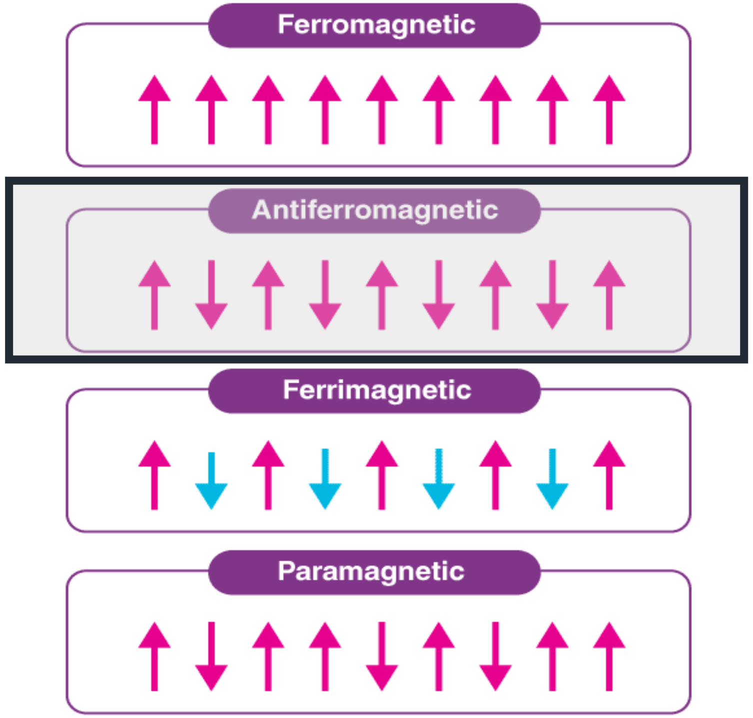
Antiferromagnets - motivation

LOUIS NÉEL

Magnetism and the local molecular field

Nobel Lecture, December 11, 1970

„They are **extremely interesting** from the theoretical viewpoint, but do not seem to have **any applications**"



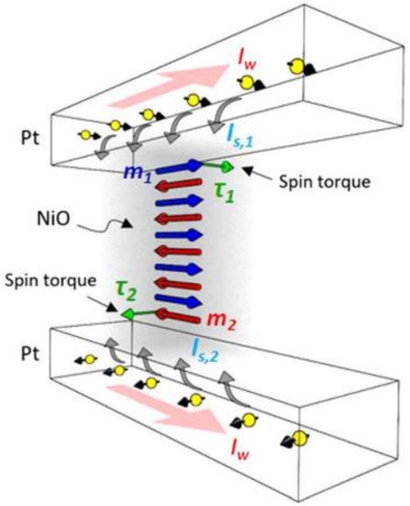
The 2020 magnetism roadmap

E. Y. Vedmedenko et al 2020 J. Phys. D: Appl. Phys.53 453001

„the future of spintronics is related to new materials, with **antiferromagnets** as promising nominees."

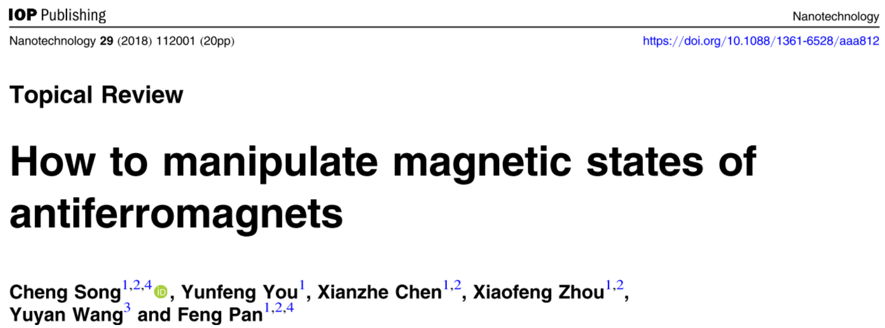
- robust against external magnetic fields
- produce no stray fields
- display ultrafast dynamics
- large magnetotransport effects

Electrical control



Moriyama T. et al., *Sci. Rep.* **8**, 14167 (2018)

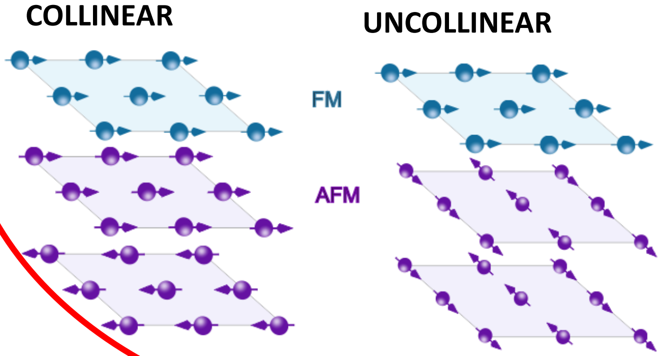
How can we control magnetic state in AFMs?



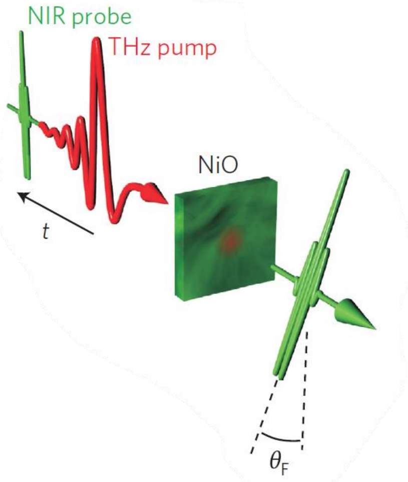
Magnetic control

Strong external magnetic field

Exchange coupling at FM/AFM interface

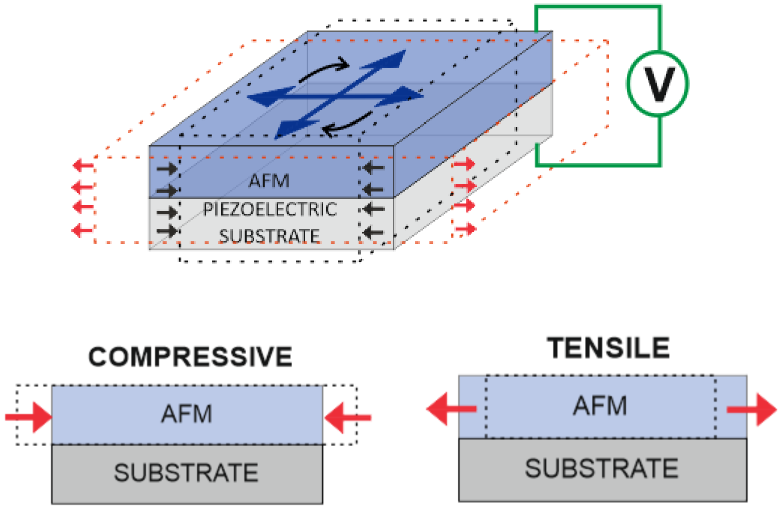


Optical control



Kampfrath T., et al. Nat. Photon., **5**, 31-34 (2011)

Strain control



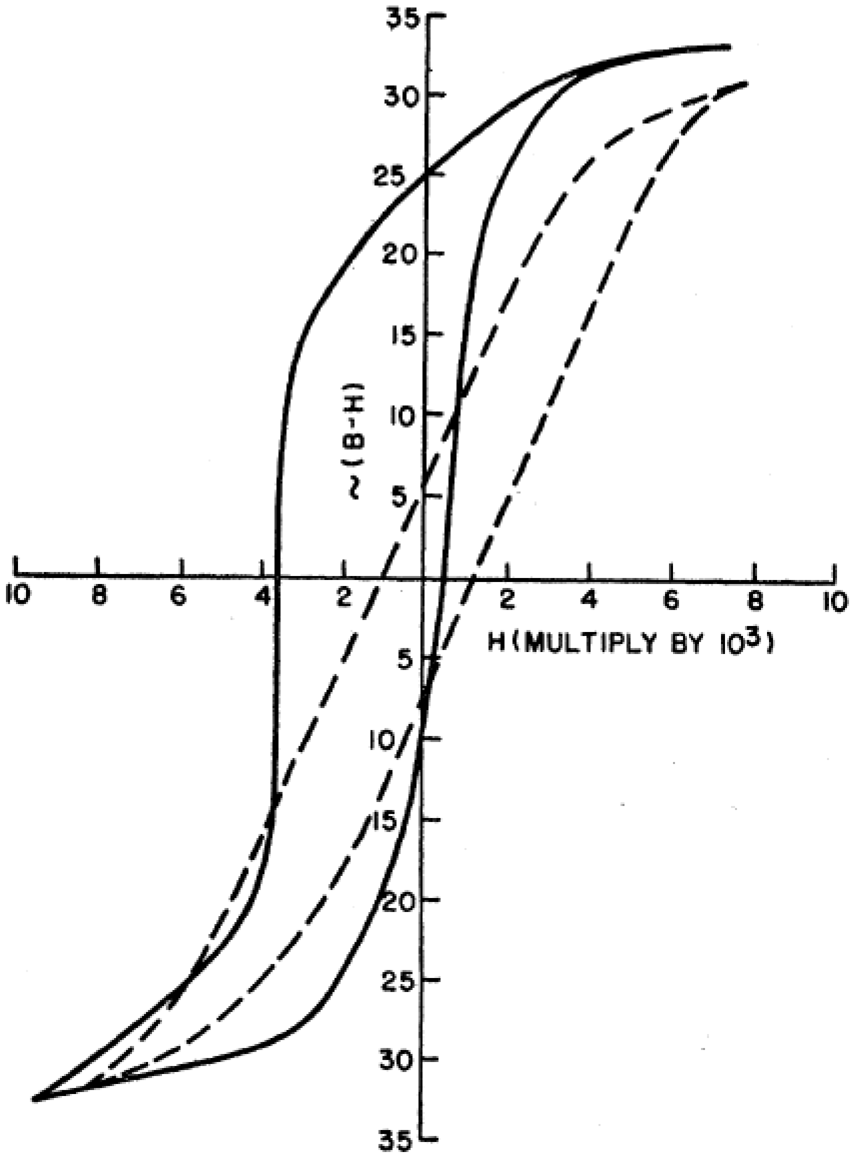
Discovery of *exchange bias*

Phys. Rev., 105, 904 (1957)

New Magnetic Anisotropy

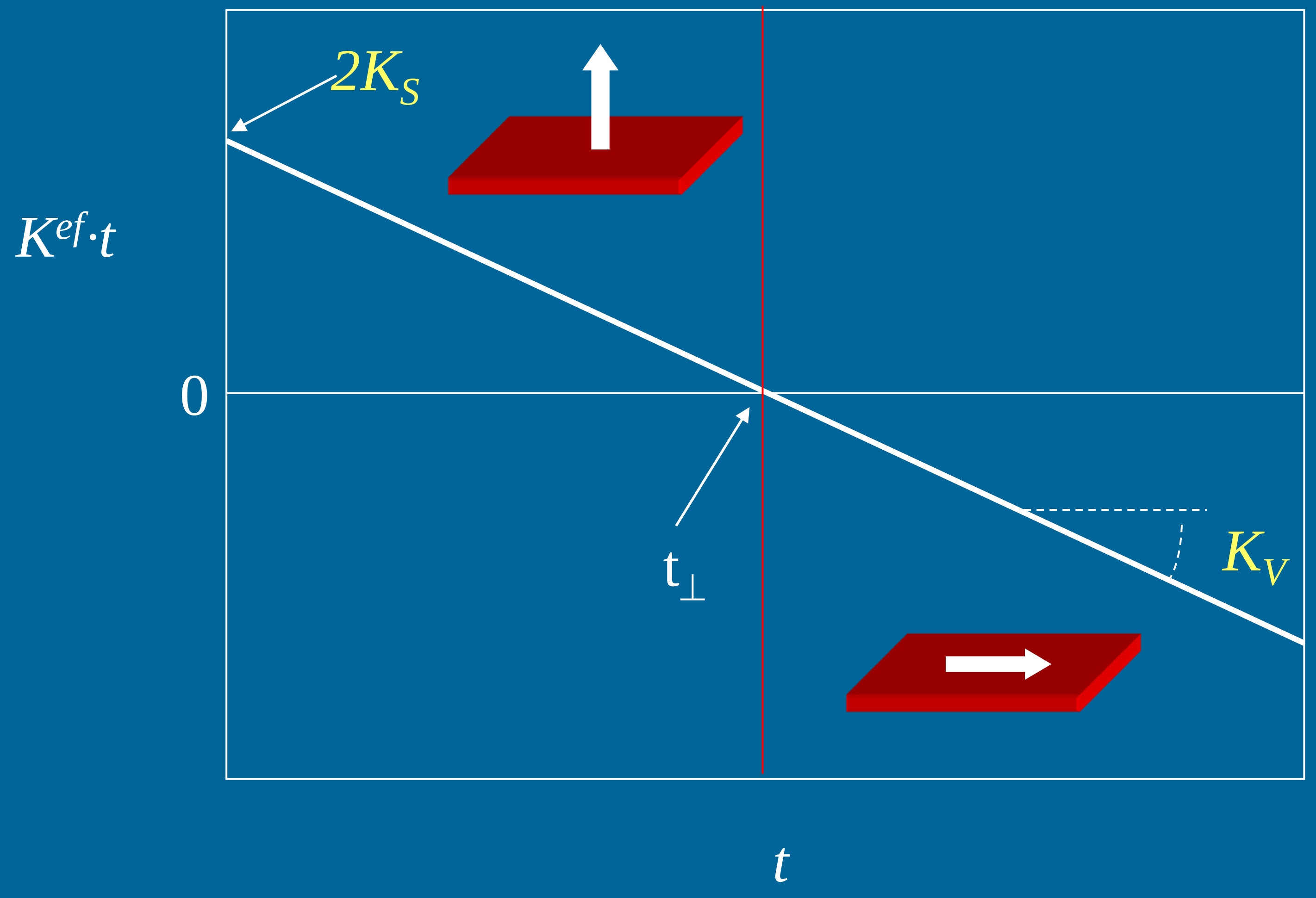
W. H. Meiklejohn and C. P. Bean
General Electric Research Laboratory, Schenectady, New York
(Received March 7, 1956)

Co particles embedded in their native antiferromagnetic oxide CoO



W. H. Meiklejohn and C. P. Bean, Phys. Rev. 102, 1413 (1956).
W. H. Meiklejohn and C. P. Bean, Phys. Rev. 105, 904 (1957).

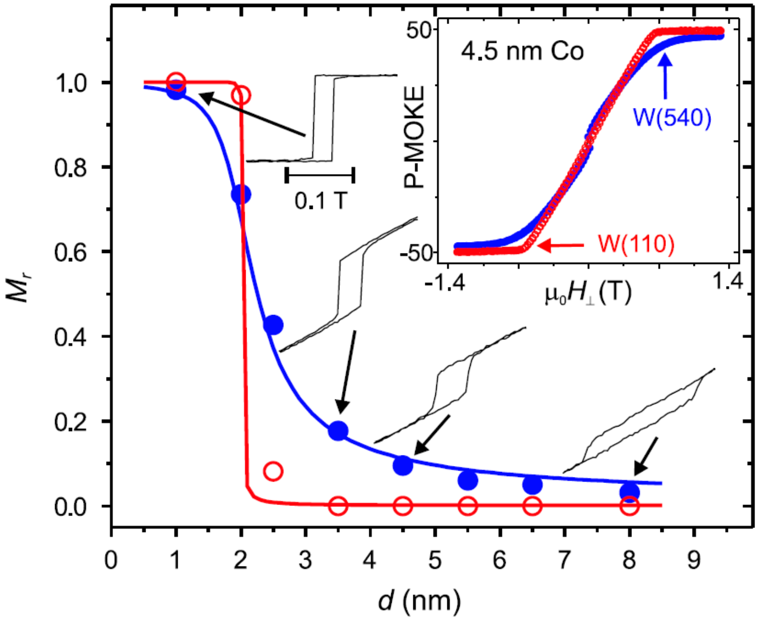
Reorientacja spontanicznego namagnesowania wywołana zmianą grubości **FERROMAGNETYKA**



$$K^{ef} t = K_V t + 2K_S$$

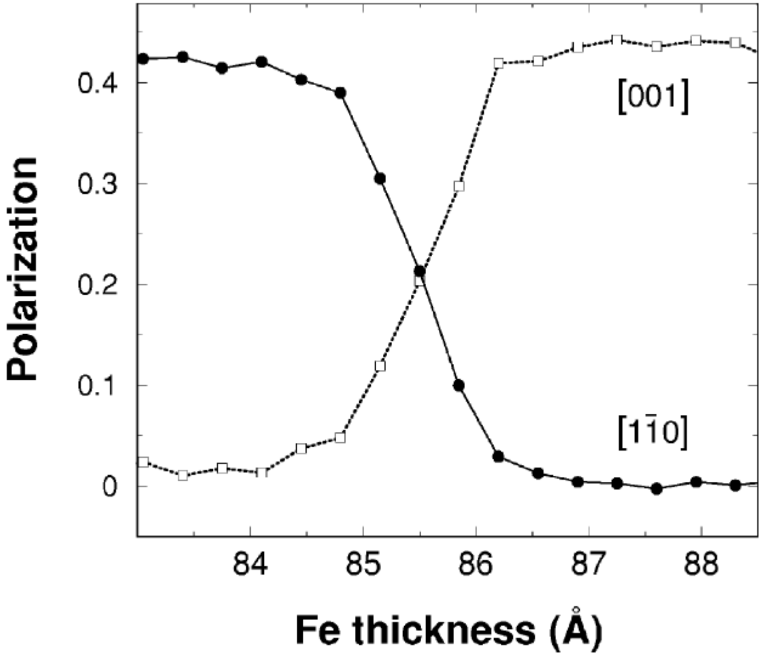
Thickness induced SRT:

out-of-plane to **in-plane**
Co/Au(111)



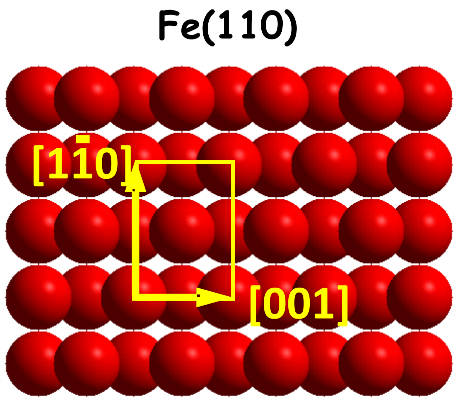
PRL 101, 217202 (2008)

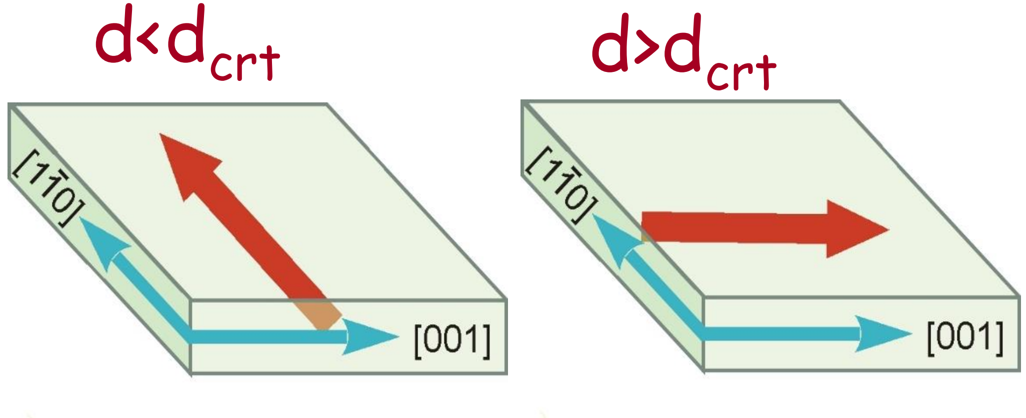
in-plane to **in-plane**
Fe/W(110)



PHYSICAL REVIEW B **67**, 075401 (2003)

Thickness induced in-plane SRT



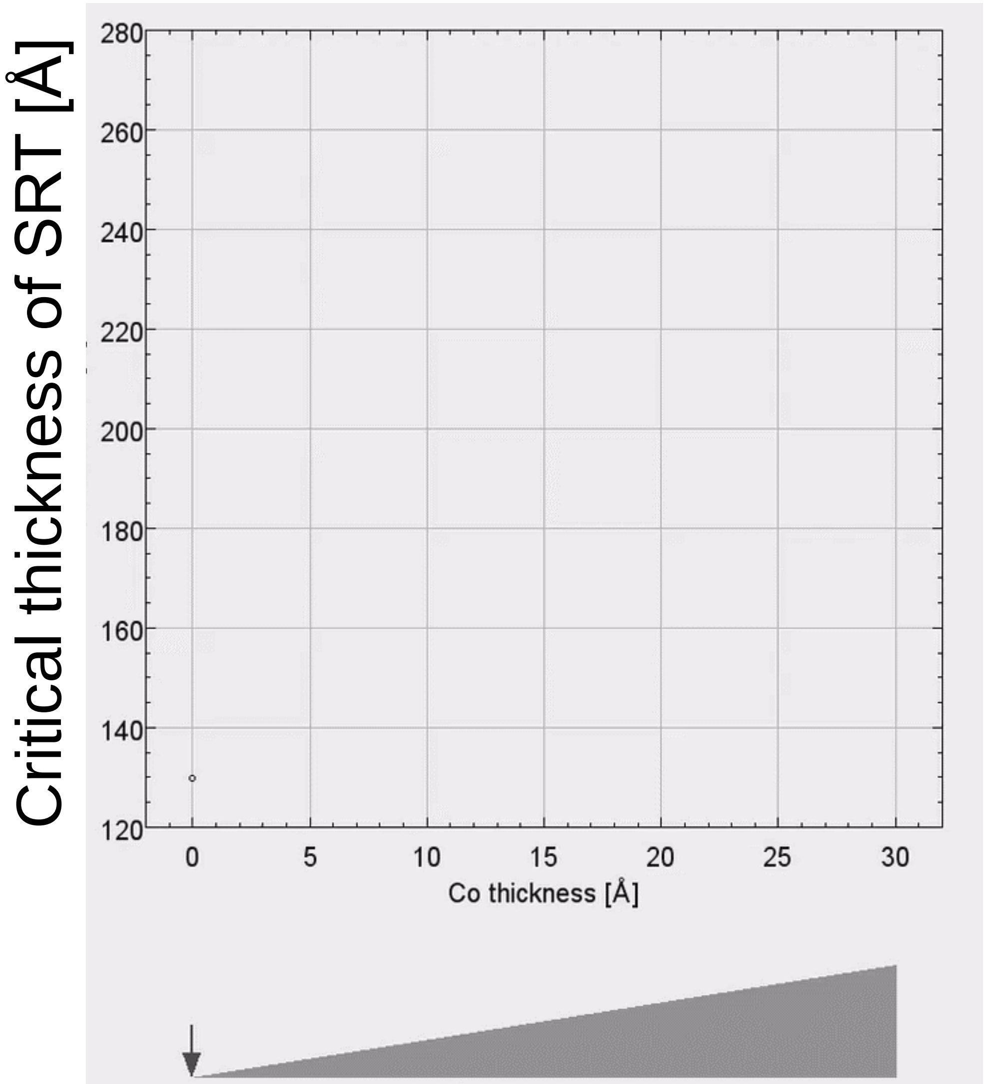


d_{crt} ~ 60 Å
for RT growth of Fe

Gradmann et al., Appl. Phys. A 39, 101-108 (1985)

Introduction

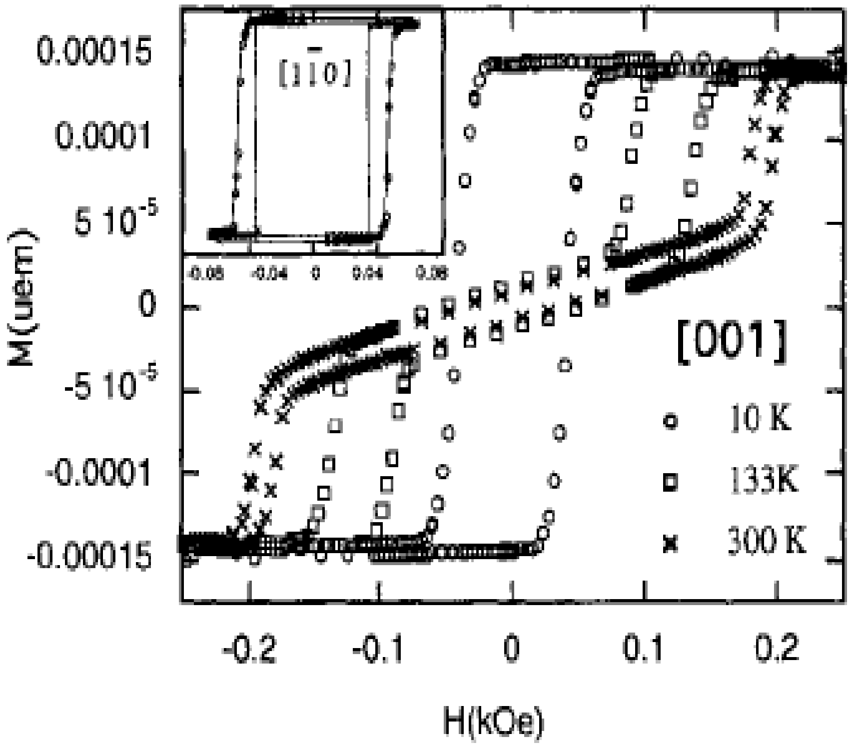
Magnetic Anisotropy and SRT in Co/Fe(110)



M. Ślęzak, T. Ślęzak, K. Matlak, B. Matlak, P. Dróżdż, T. Giela, D. Wilgocka-Ślęzak,N. Pilet, J. Raabe, A. Kozioł-Rachwał, J. Korecki, **Phys. Rev. B** 94 (2016) 014402

Temperature induced SRT in Fe(110)

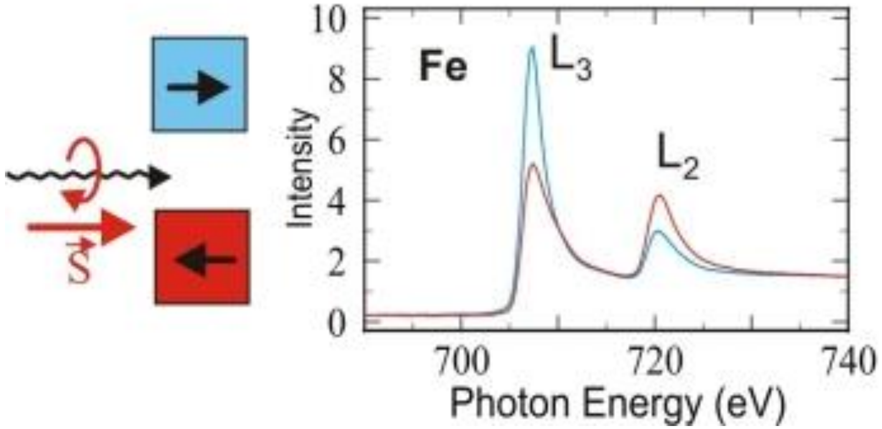
d = 60 Å



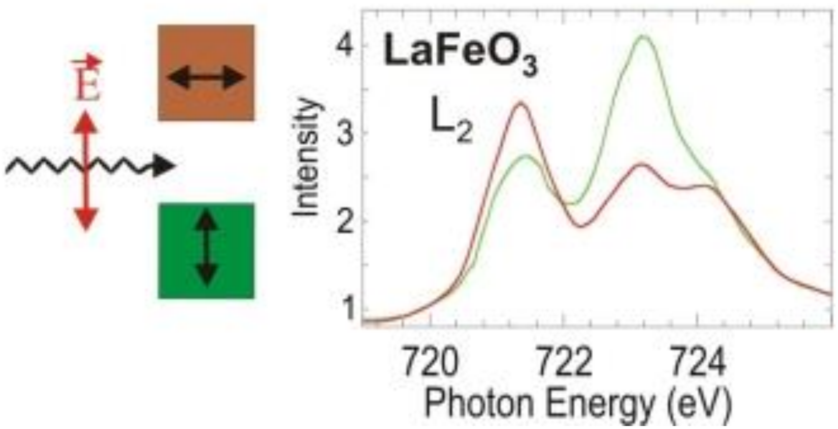
Fruchart et al., *JMMM 165 (1997) 508-511*
Baberschke et al. *PRB 47 (1993) 11204*

XMCD and XMLD

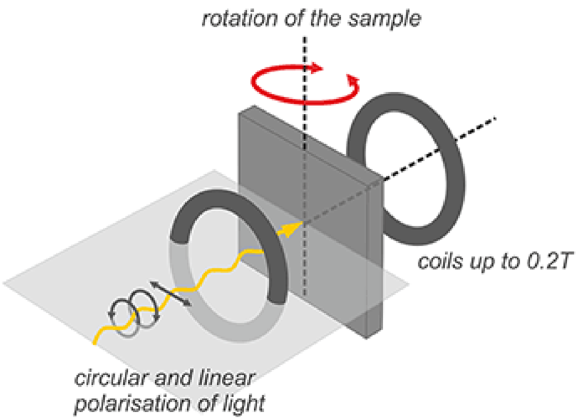
Circular Dichroism - Ferromagnets



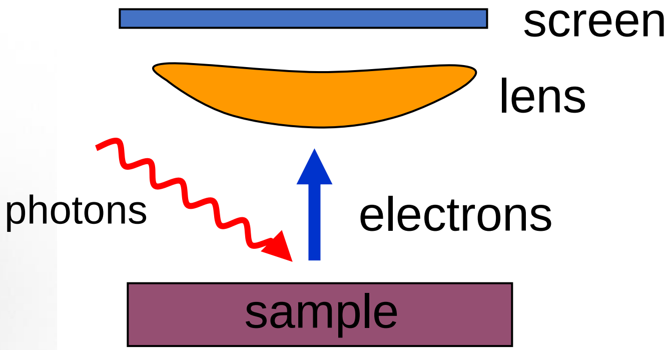
Linear Dichroism - Antiferromagnets

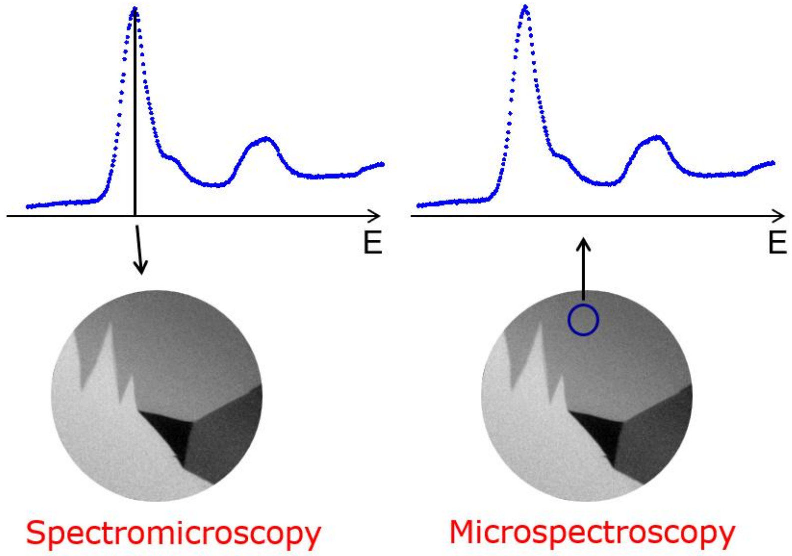


PIRX end-station

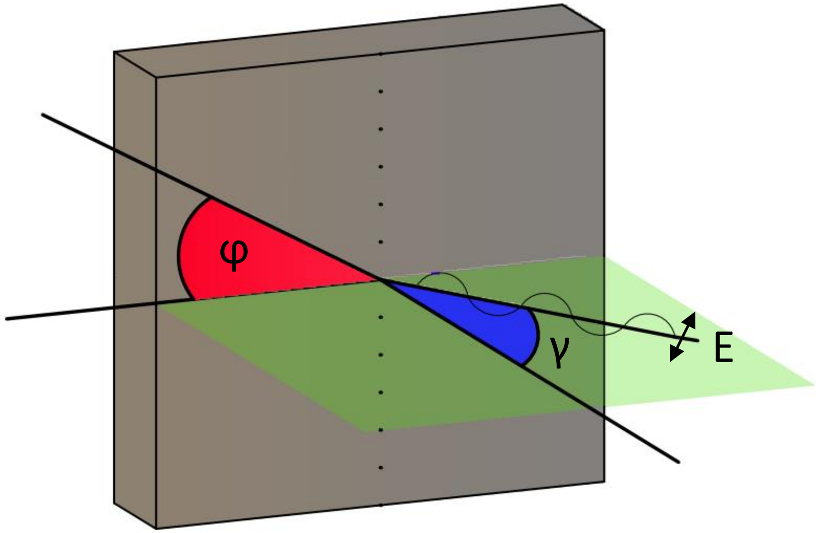


DEMETER (Solaris)
Nanospectroscopy (Elettra)

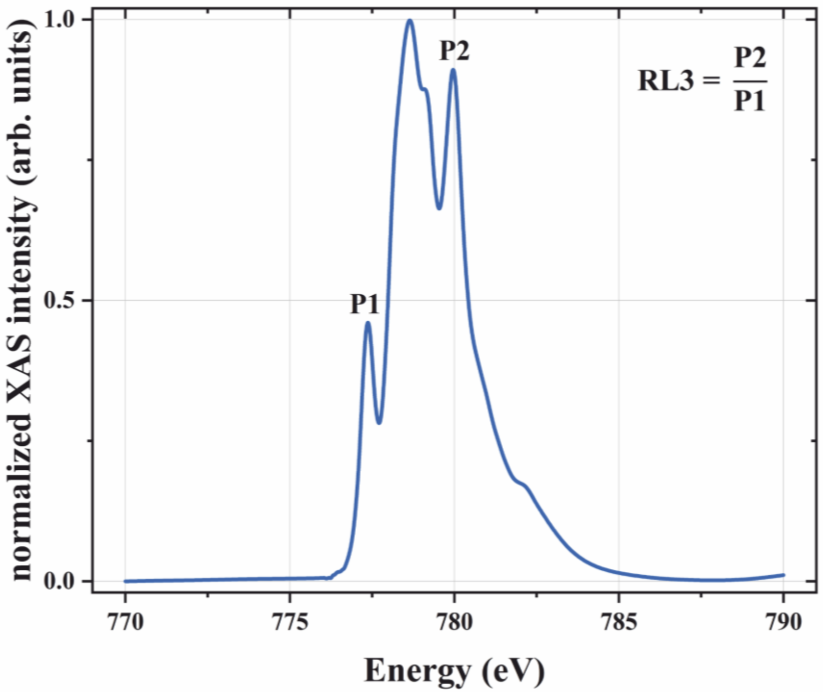




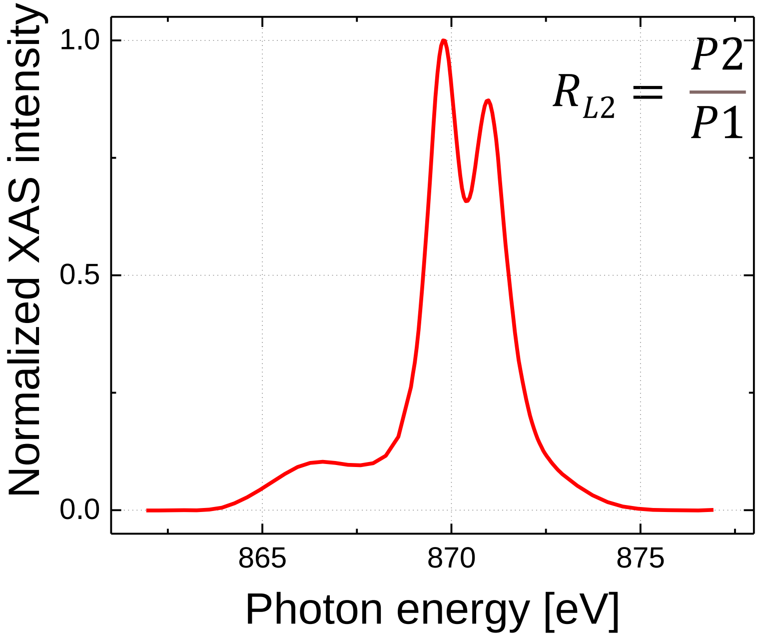
XMLD: CoO and NiO



CoO

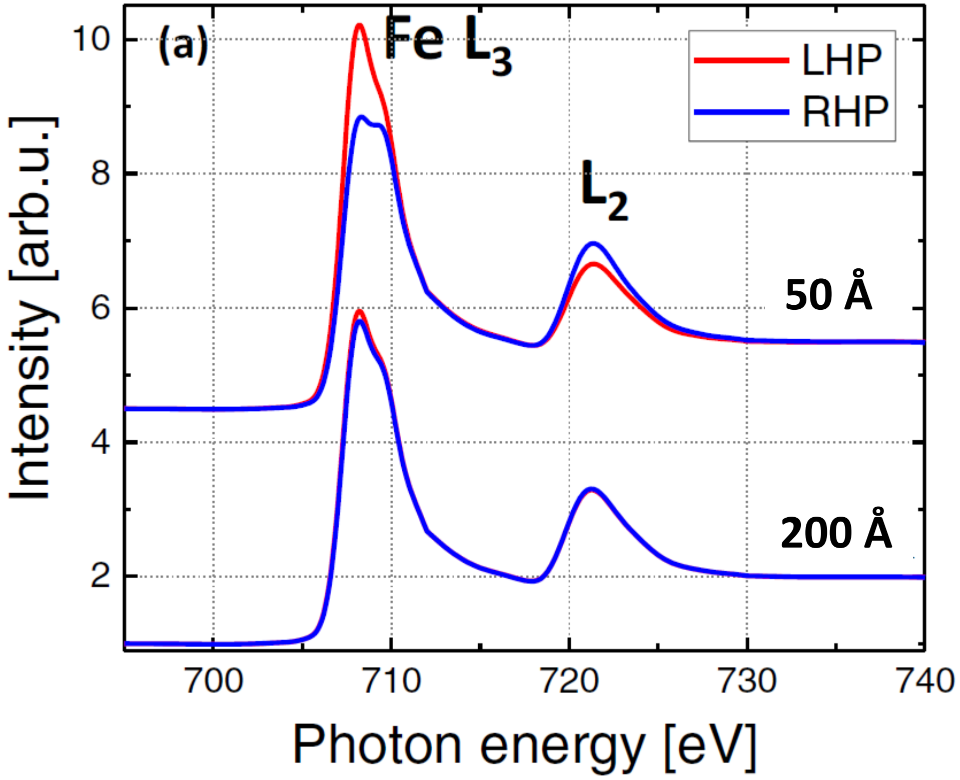


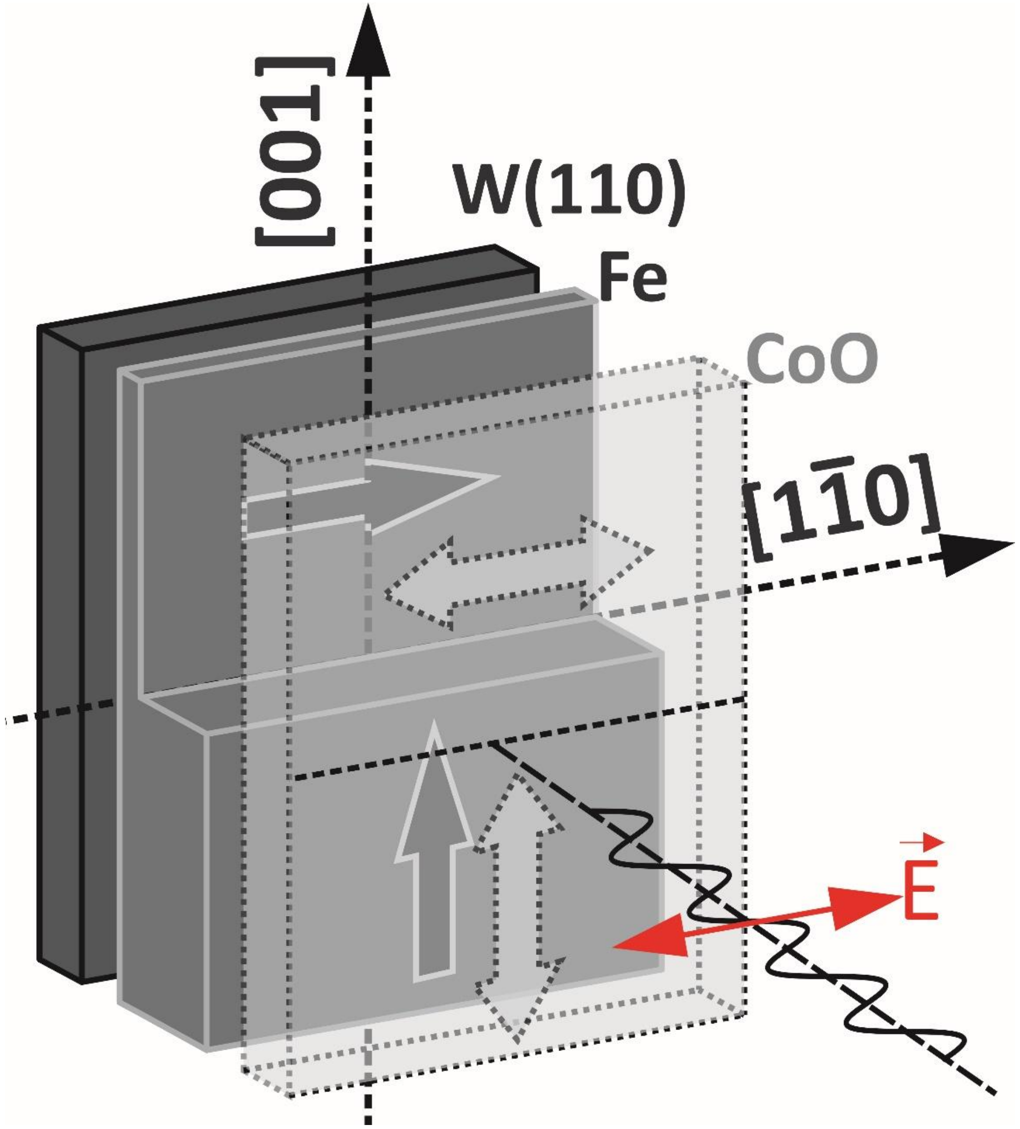
NiO



CoO(111) on Fe(110)

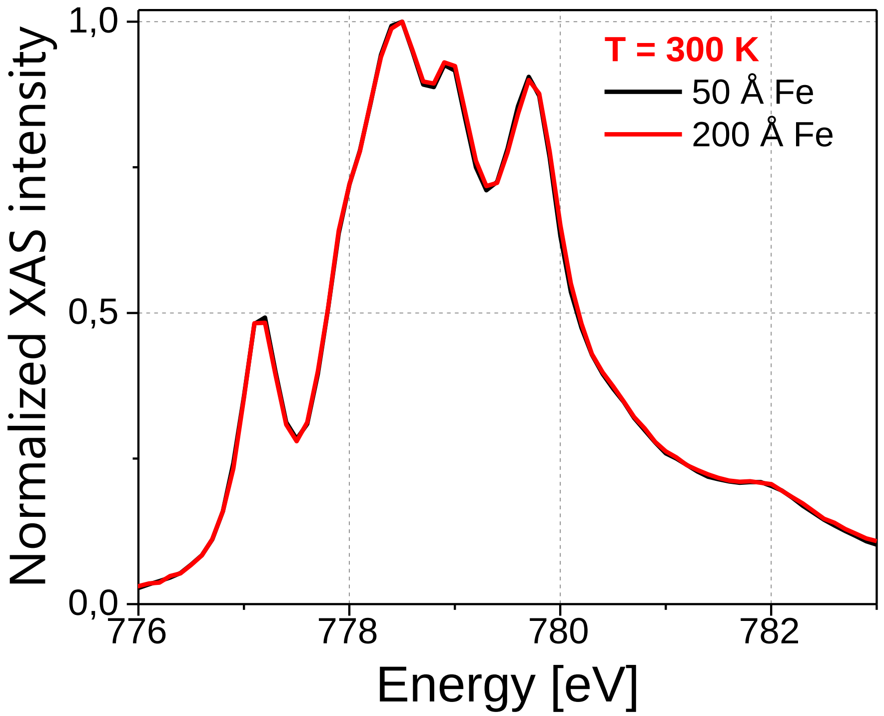
Looking for SRT in antiferromagnetic CoO





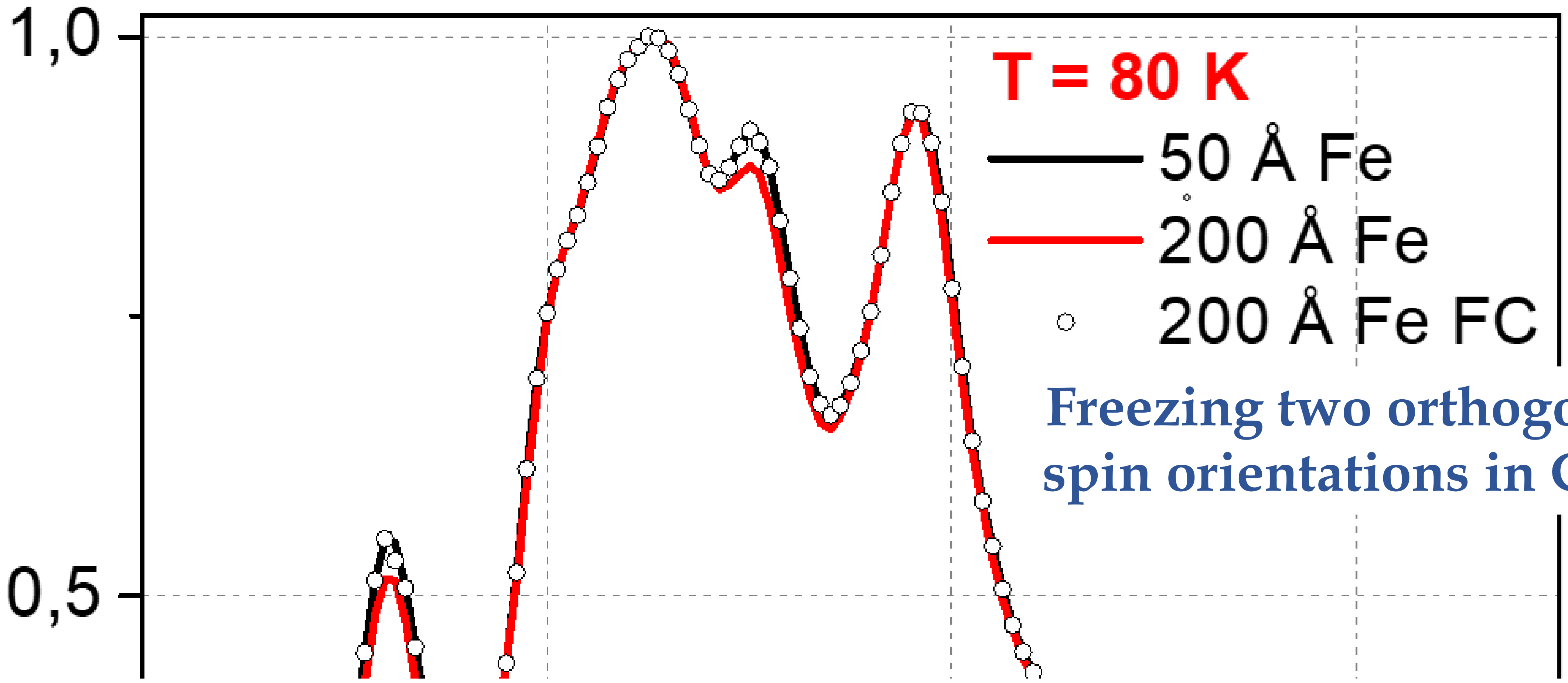
?

Freezing AFM spins in CoO(111)?



M. Ślęzak, T. Ślęzak, P. Dróżdż, B. Matlak, K. Matlak, A. Kozioł-Rachwał, M. Zając, J. Korecki, **Scientific Reports** 9 (2019) 889
M. Ślęzak, P. Dróżdż, W. Janus, M. Szpytma, H. Nayyef, A. Kozioł-Rachwał, M. Zając, T. Ślęzak, **Journal of Magnetism and Magnetic Materials** 545 (2022) 168783

Freezing AFM spins in CoO(111)?



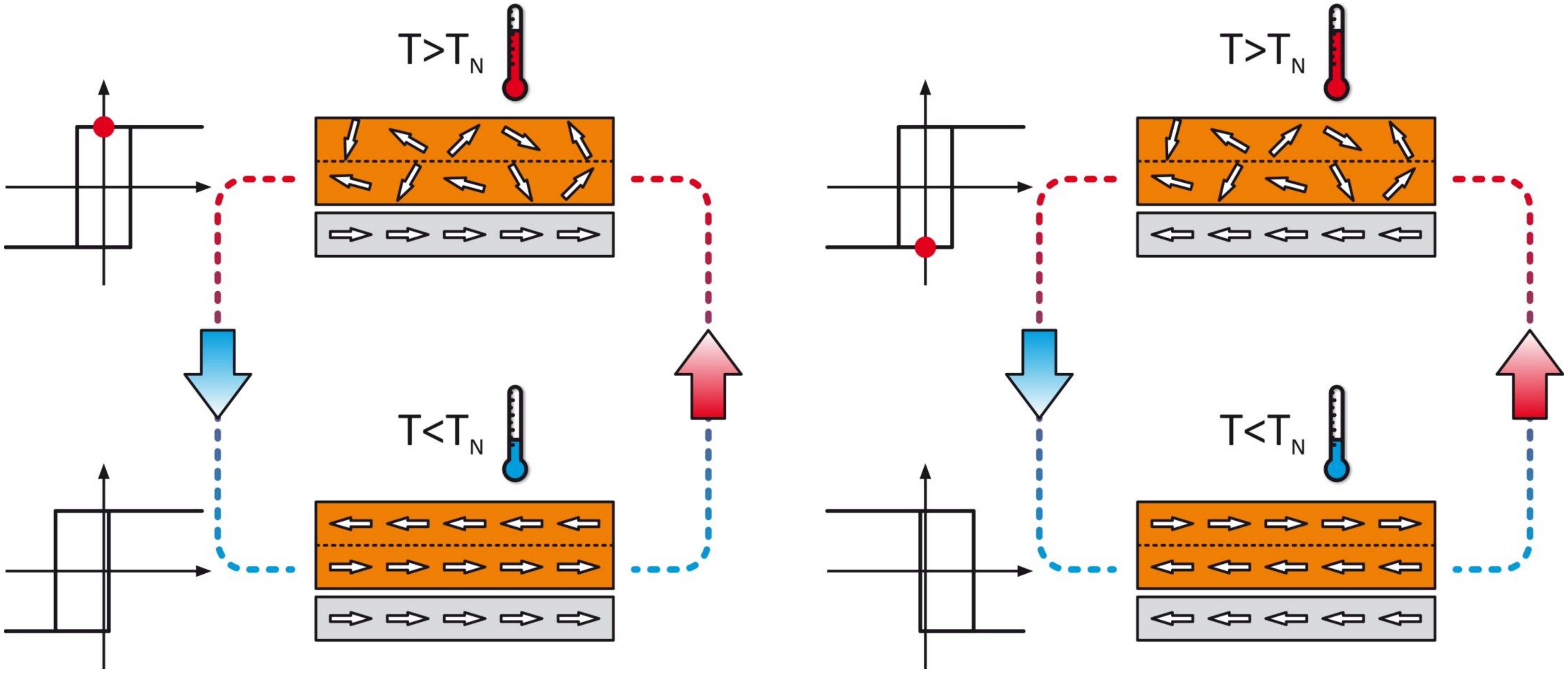
Freezing two orthogonal spin orientations in CoO

M. Ślęzak, T. Ślęzak, P. Dróżdż, B. Matlak, K. Matlak, A. Kozioł-Rachwał, M. Zając, J. Korecki, **Scientific Reports** 9 (2019) 889
M. Ślęzak, P. Dróżdż, W. Janus, M. Szpytma, H. Nayyef, A. Kozioł-Rachwał, M. Zając, T. Ślęzak, **Journal of Magnetism and Magnetic Materials** 545 (2022) 168783

Can we freeze two 180° orientations of <u>interfacial</u> CoO spins?

XMLD is blind
but MOKE is sensitive → exchange bias

Frozen antiferromagnetic spins of CoO(111)

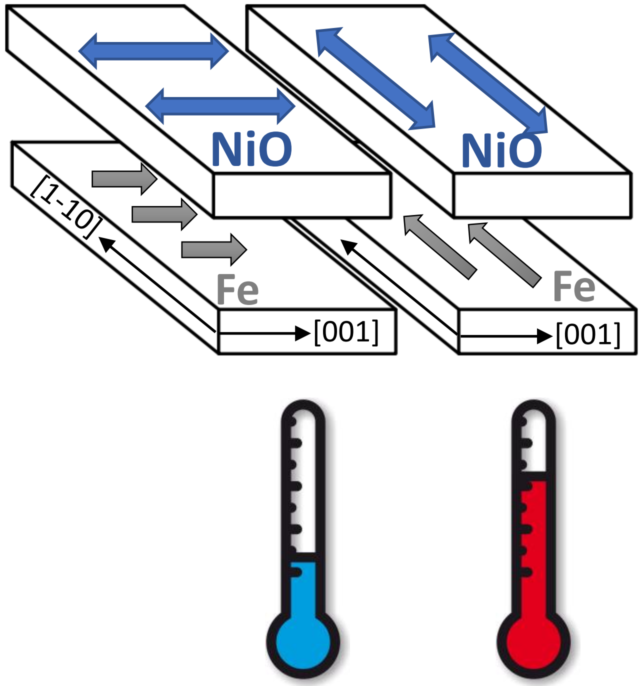


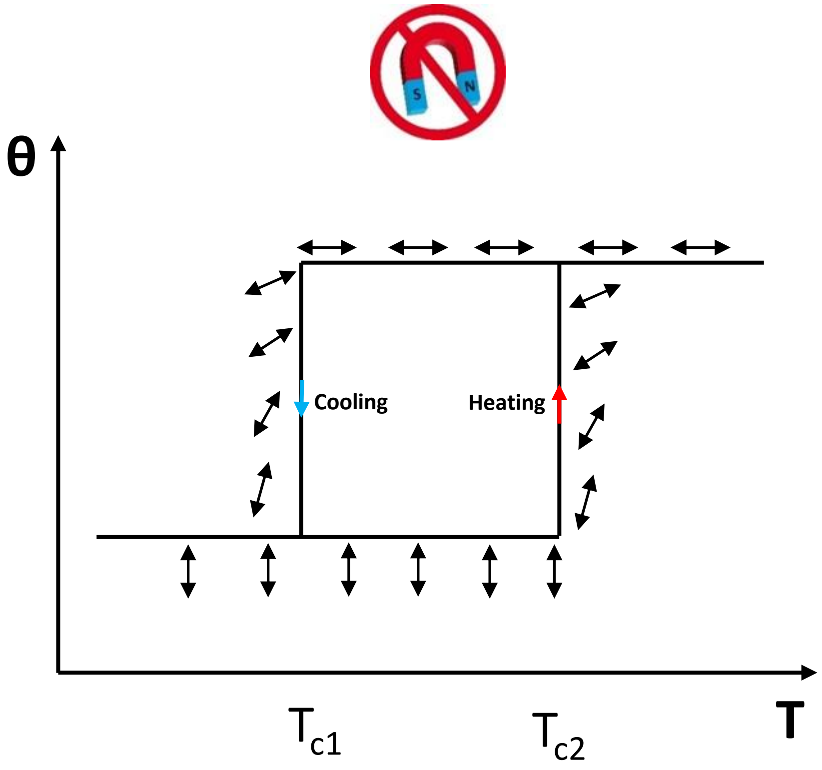
M. Ślęzak, P. Dróżdż, W. Janus, M. Szpytma, H. Nayyef, A. Kozioł-Rachwał, M. Zając, T. Ślęzak, Journal of Magnetism and Magnetic Materials 545 (2022) 168783

NiO(111) on Fe(110)

NiO(111)/Fe(110): field-free switching of AFM spins in a uniform thickness system

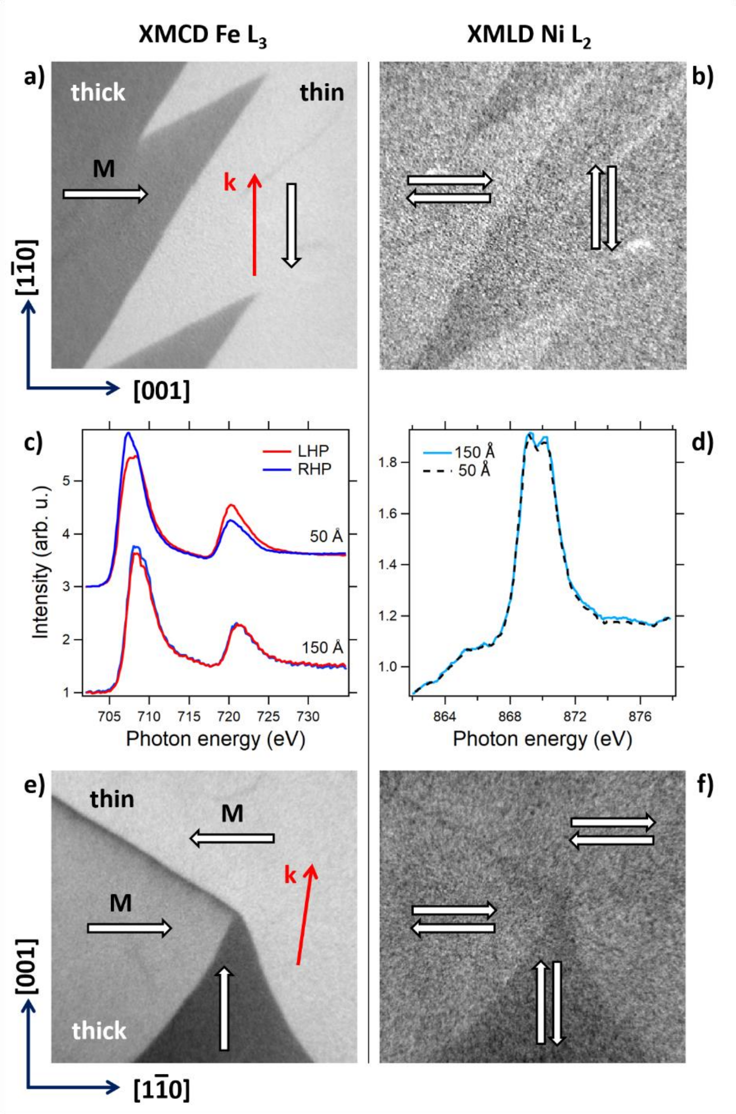
Idea





Ferromagnets: Y.Millev, J. Kirschner, PRB 54 (1996) 6

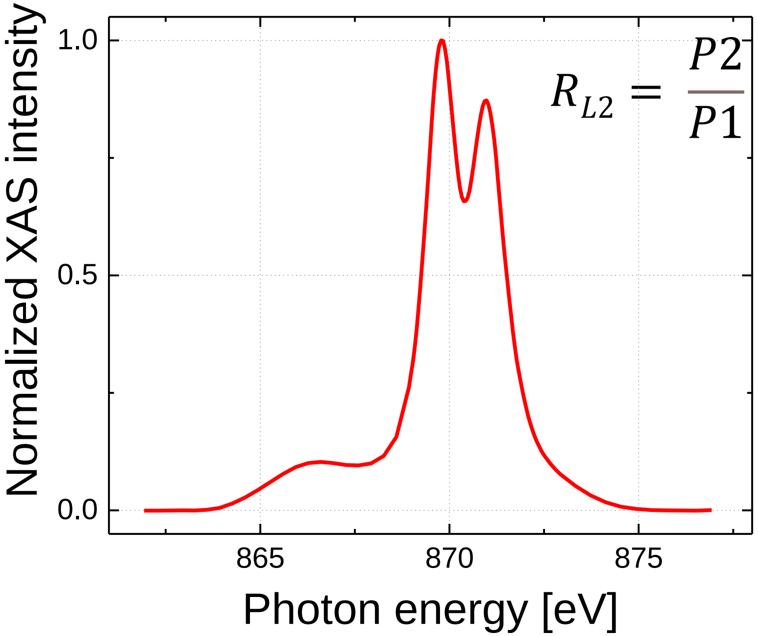
NiO(111)/Fe(110): SRT seen by XPEEM



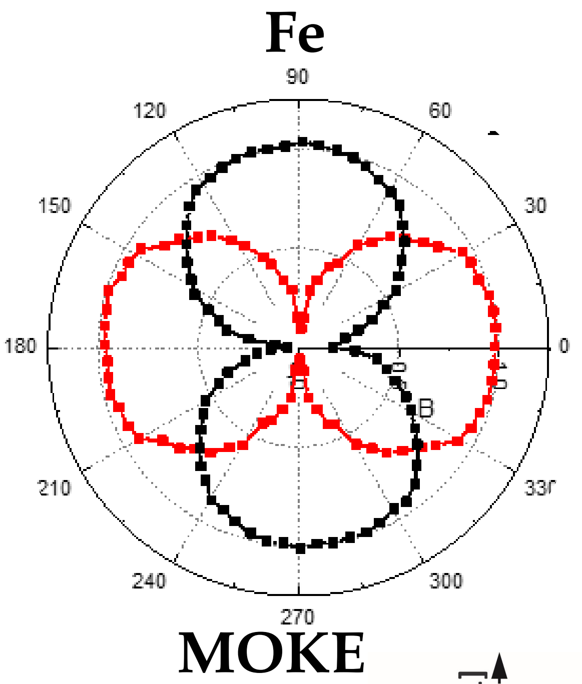
XMLD-PEEM at Nanospectroscopy beamline (Elettra, Trieste)

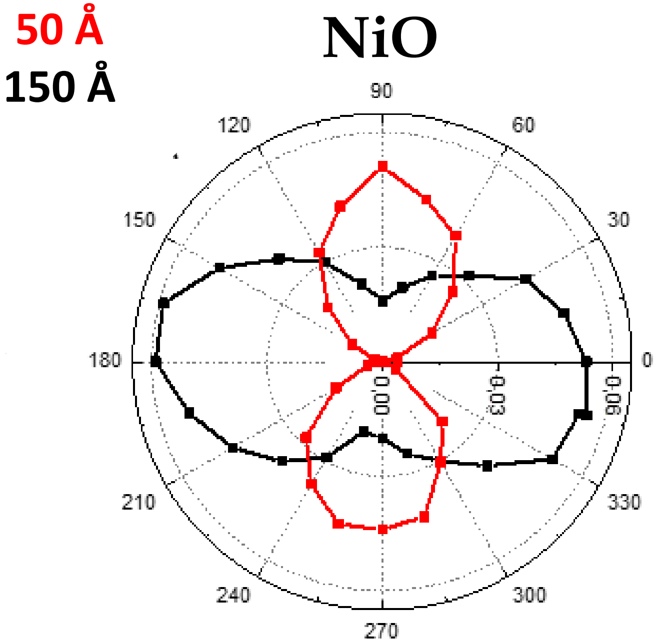
M. Ślęzak, P. Dróżdż, W. Janus, H. Nayyef, A. Kozioł-Rachwał, M. Szpytma, M. Zając, T. O. Menteş, F. Genuzio, A. Locatelli, T. Ślęzak,
Nanoscale 12 (2020) 18091

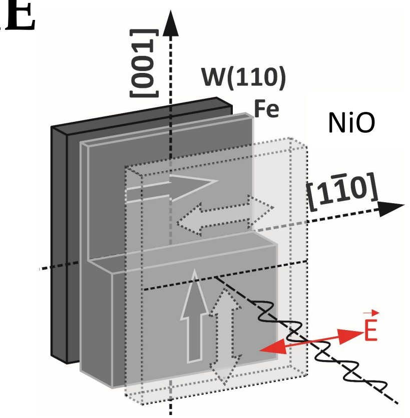
NiO(111)/Fe(110): m. anisotropy and rotatable AFM spins

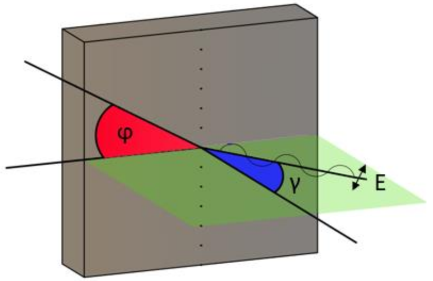


NiO in-plane magnetic anisotropy determined by Fe





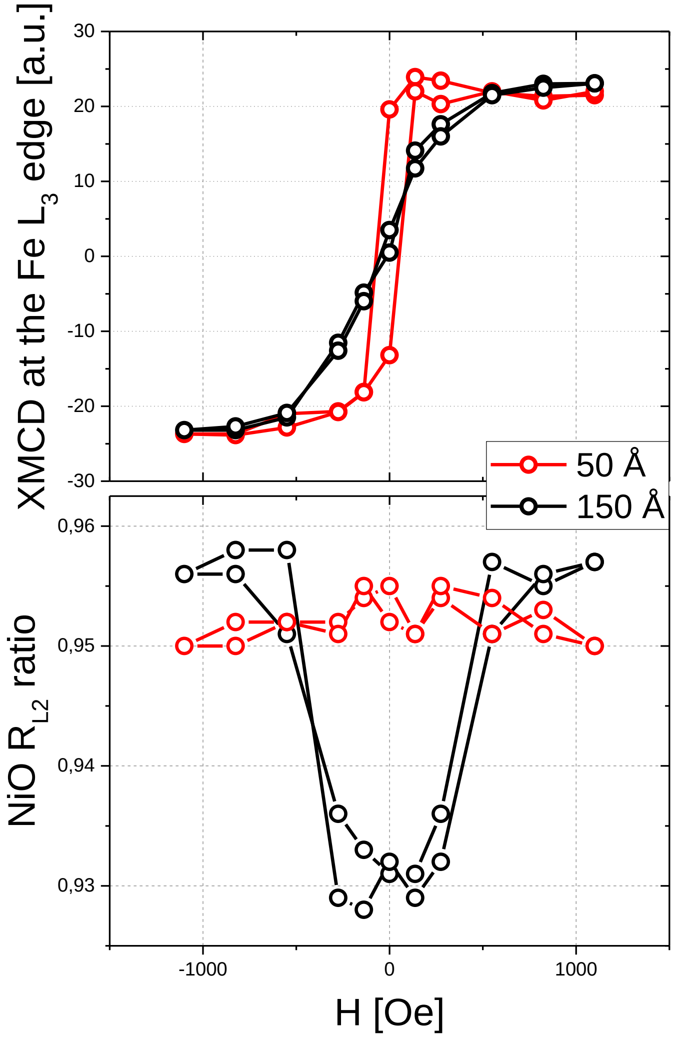




Nayyef, P. Dróżdż, W. Janus, A. Kozioł-Rachwał, M. Szpytma,
). Menteş, F. Genuzio, A. Locatelli, T. Ślęzak, **Phys. Rev. B** 104, 134434 (2021)

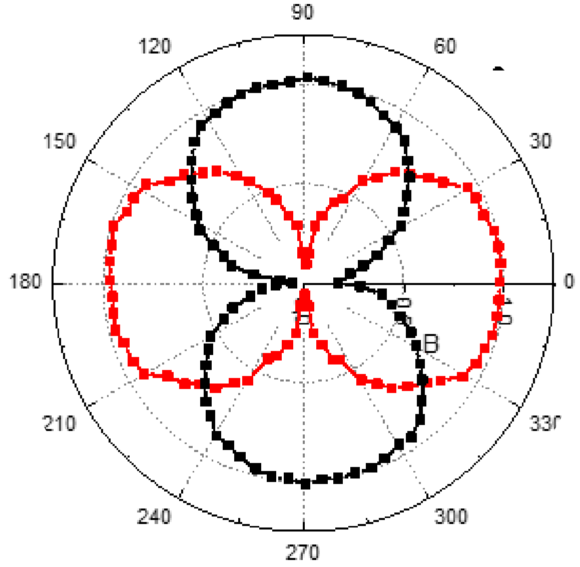
NiO(111)/Fe(110): m. anisotropy and rotatable AFM spins

Rotatable NiO spins



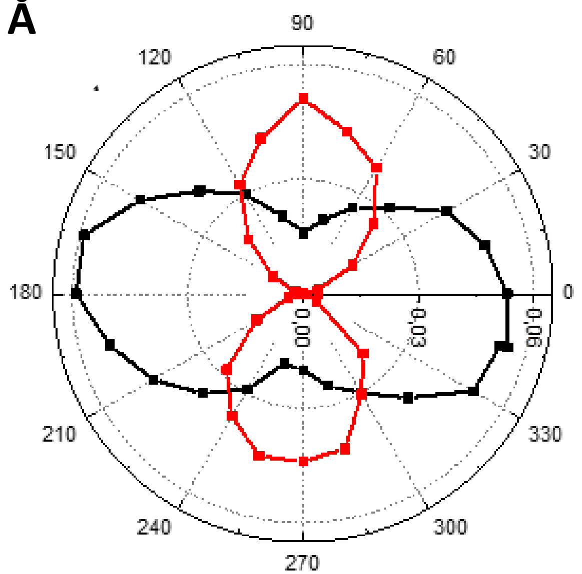
NiO in-plane magnetic anisotropy determined by Fe

Fe

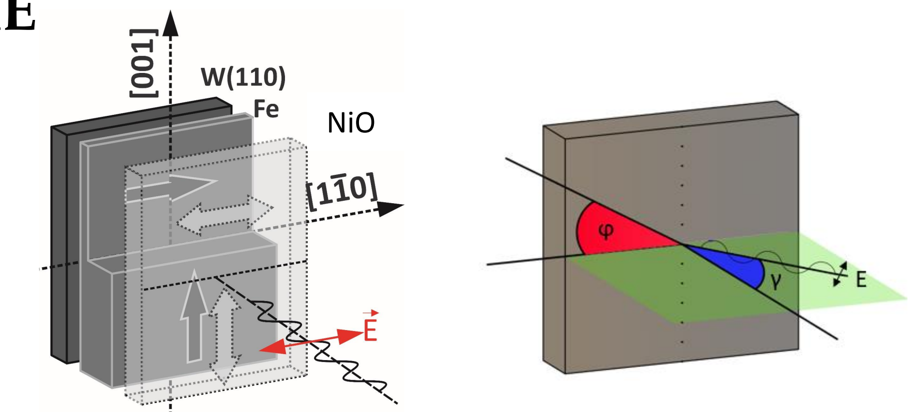


50 Å
150 Å

NiO



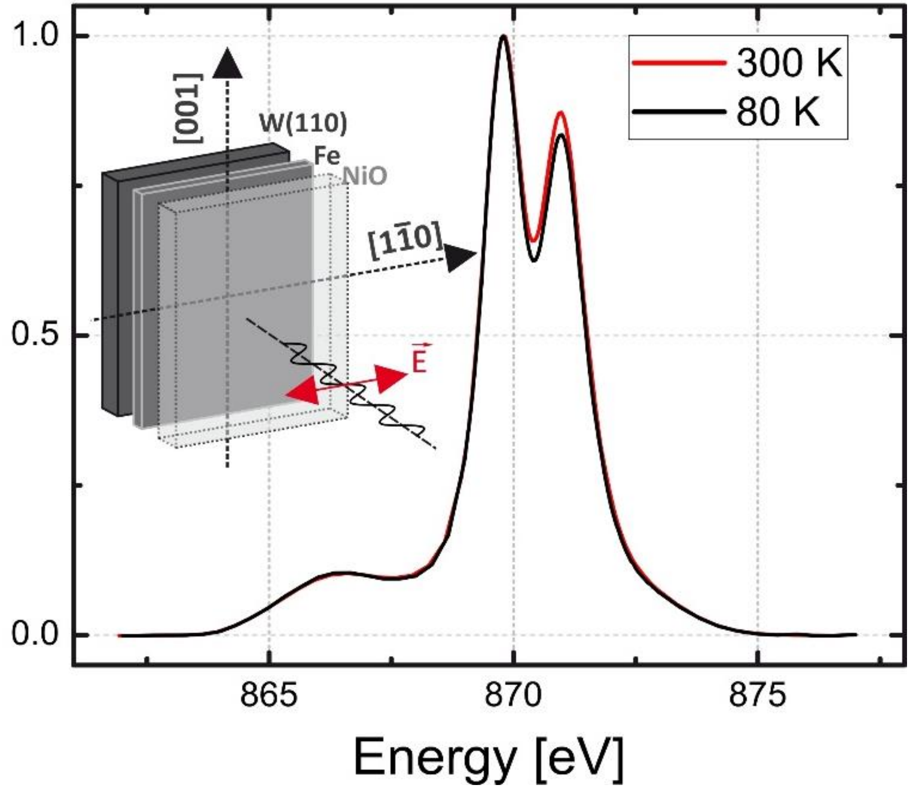
MOKE



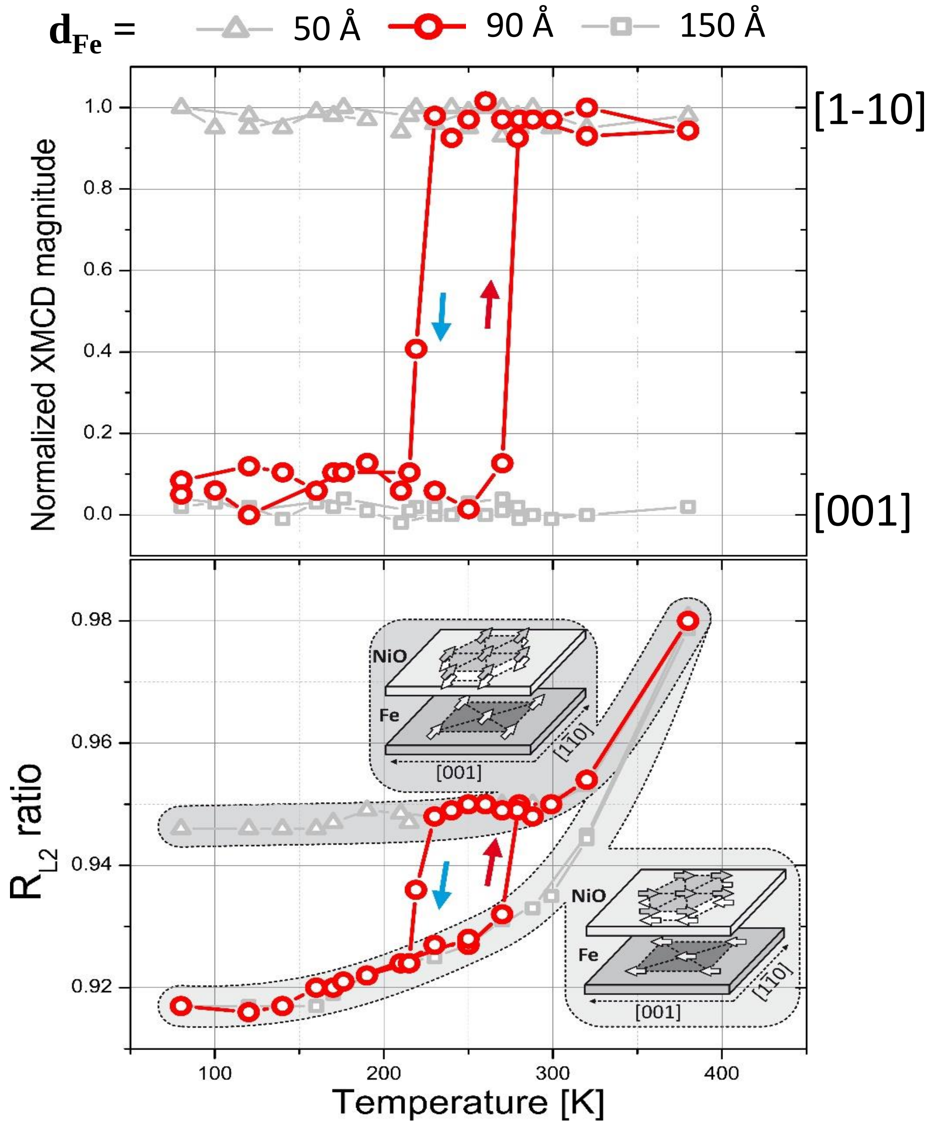
M. Ślęzak, H. Nayyef, P. Dróżdż, W. Janus, A. Kozioł-Rachwał, M. Szpytma,
M. Zając, T. O. Menteş, F. Genuzio, A. Locatelli, T. Ślęzak, **Phys. Rev. B** 104, 134434 (2021)

Temperature induced SRT in AFM

Temperature induced SRT in NiO on Fe(110)

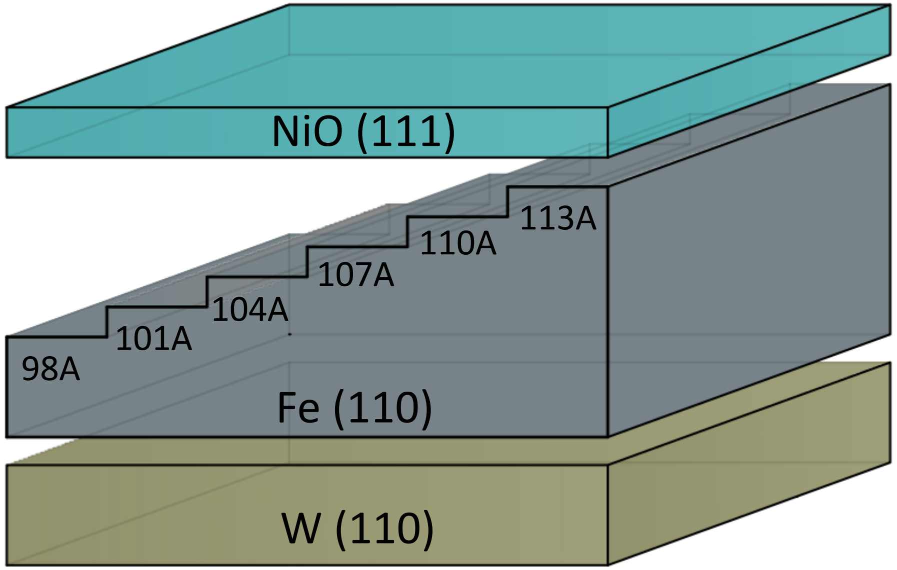


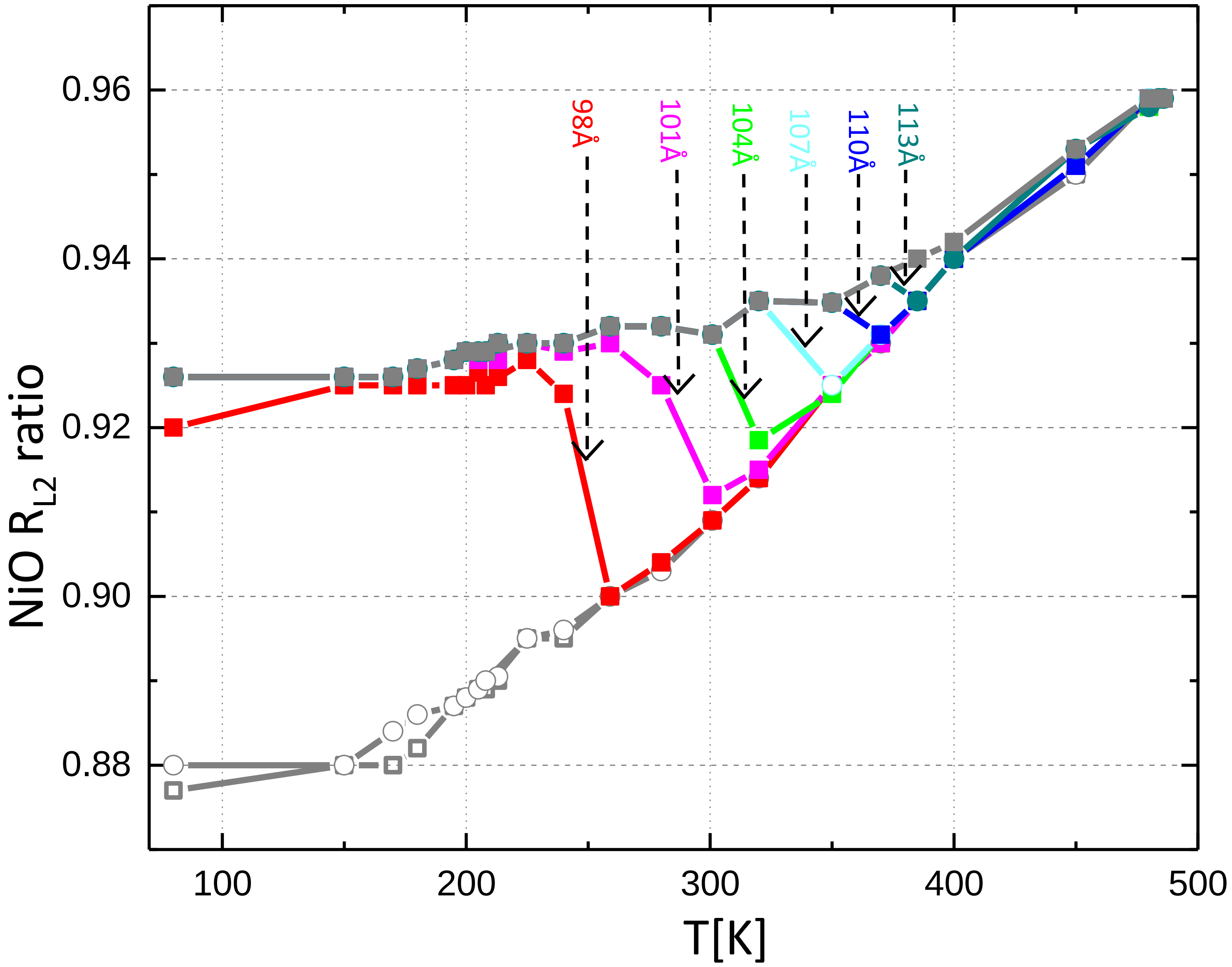
Field-free switching of AFM spins



M. Ślęzak, P. Dróżdż, W. Janus, H. Nayyef, A. Kozioł-Rachwał, M. Szpytma, M. Zając, T. O. Menteş, F. Genuzio, A. Locatelli, T. Ślęzak,
Nanoscale 12 (2020) 18091

Can we tune NiO switching temperature?

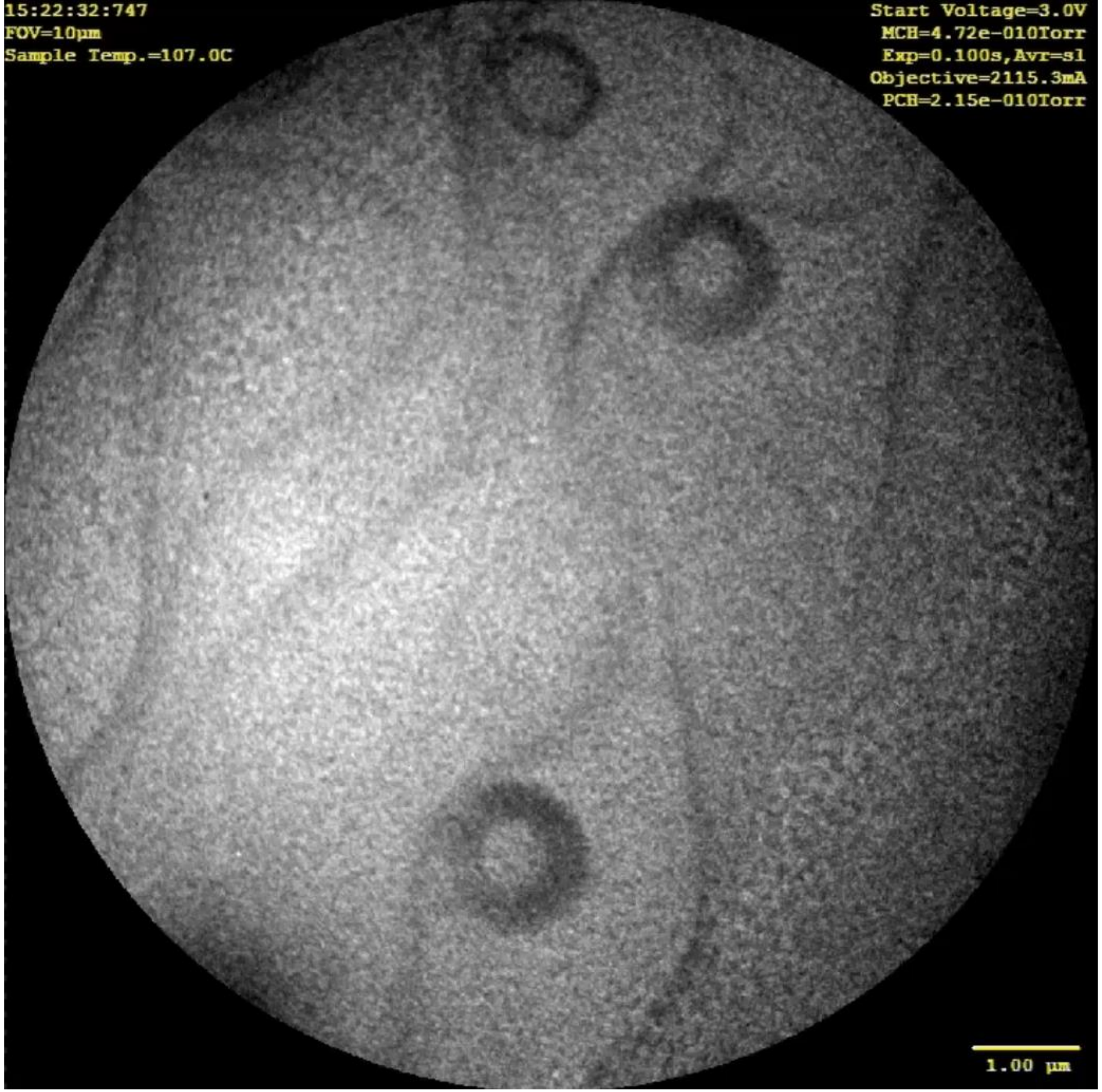




M. Ślęzak, H. Nayyef, P. Dróżdż, W. Janus, A. Kozioł-Rachwał, M. Szpytma,
M. Zając, T. O. Menteş, F. Genuzio, A. Locatelli, T. Ślęzak, **Phys. Rev. B** 104, 134434 (2021)

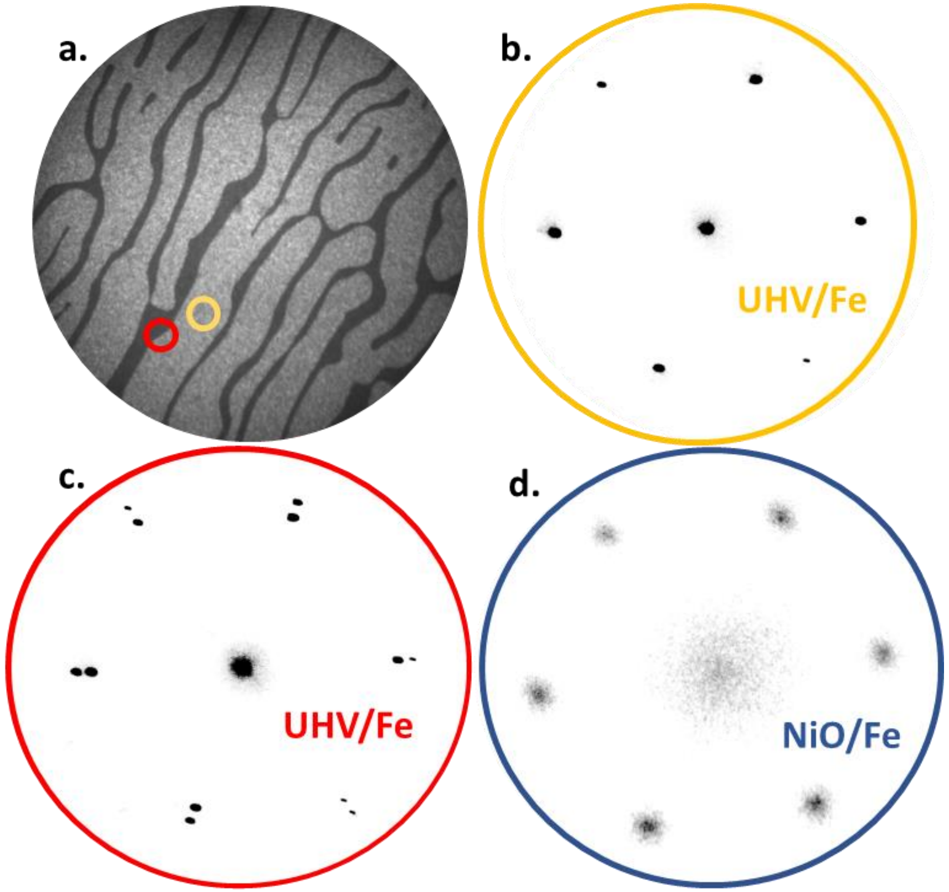
Looking on individual nanostructures

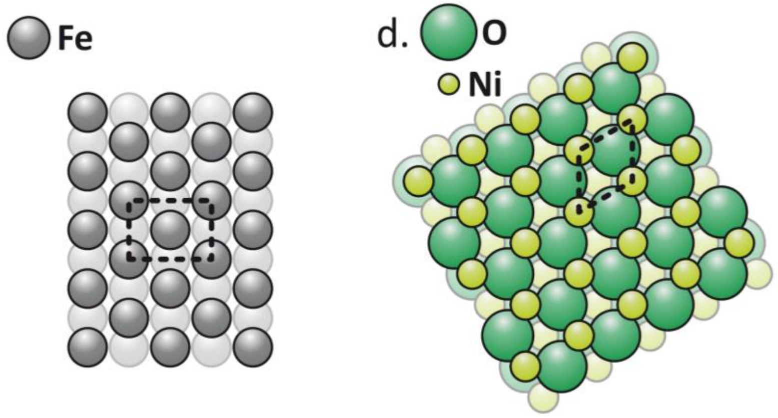
LEEM movie recorded during annealing of 5 atomic layers of Fe on W

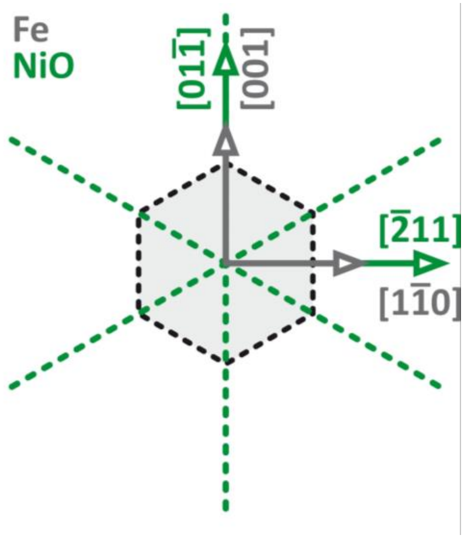


Recorded with D. Wilgocka-Ślęzak and T. Giela in Jerzy Haber Institute of Catalysis and Surface Chemistry PAS, Kraków, Poland

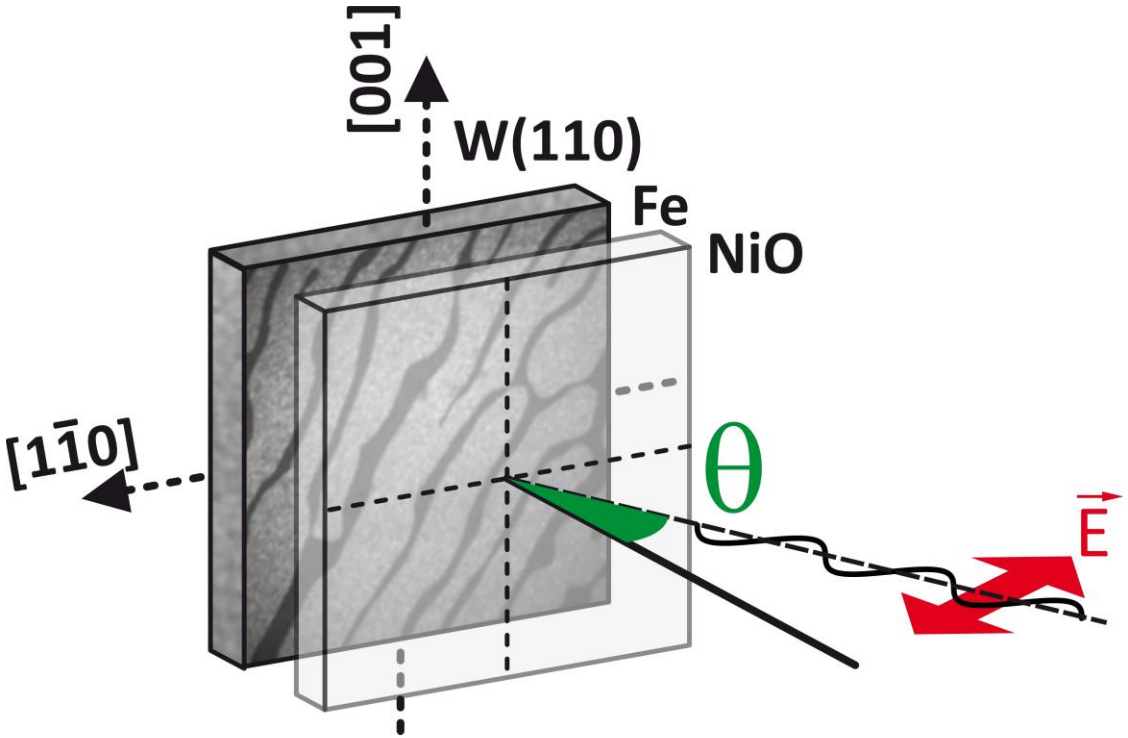
LEEM and μLEED for local crystal structure determination

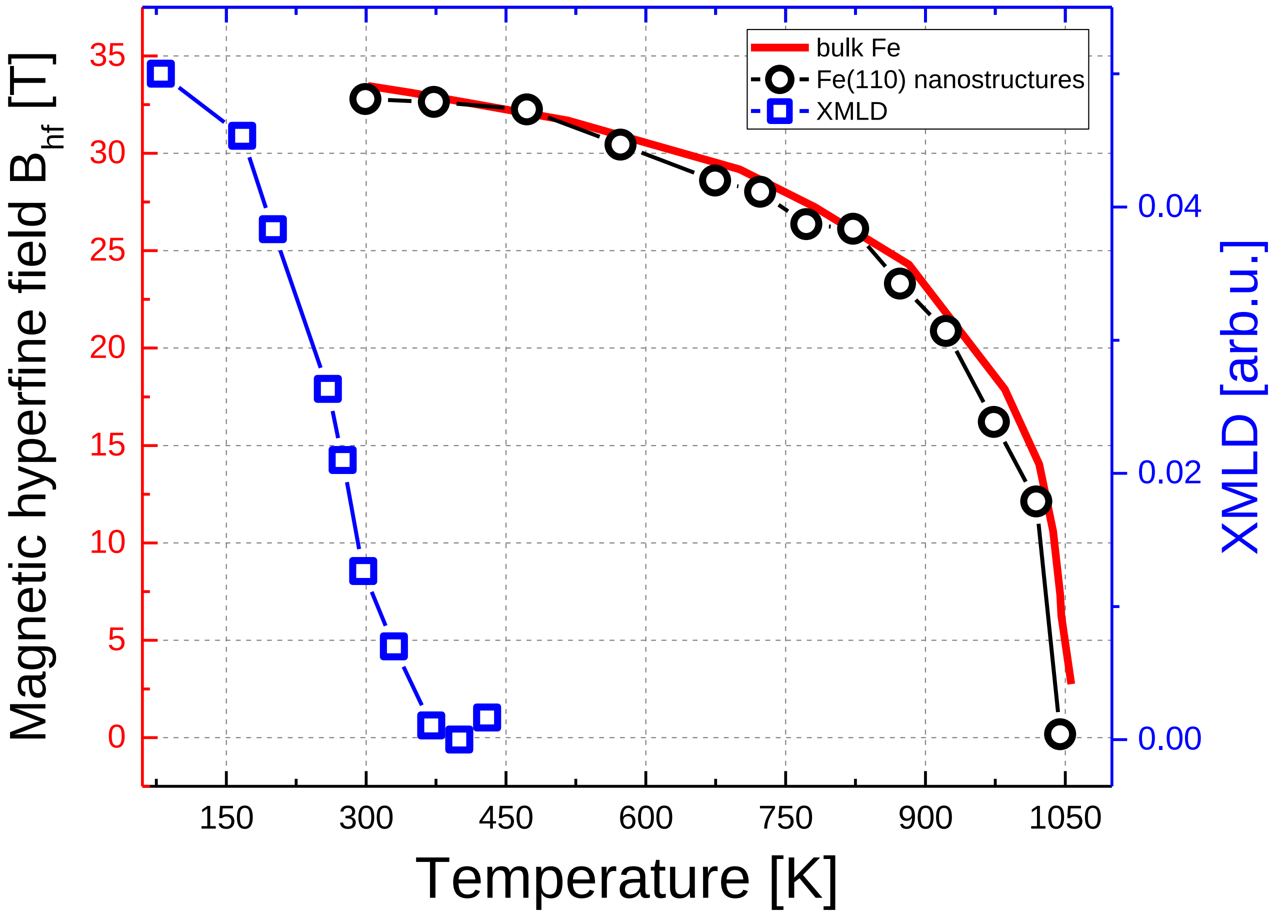






M. Ślęzak et al., **in preparation**





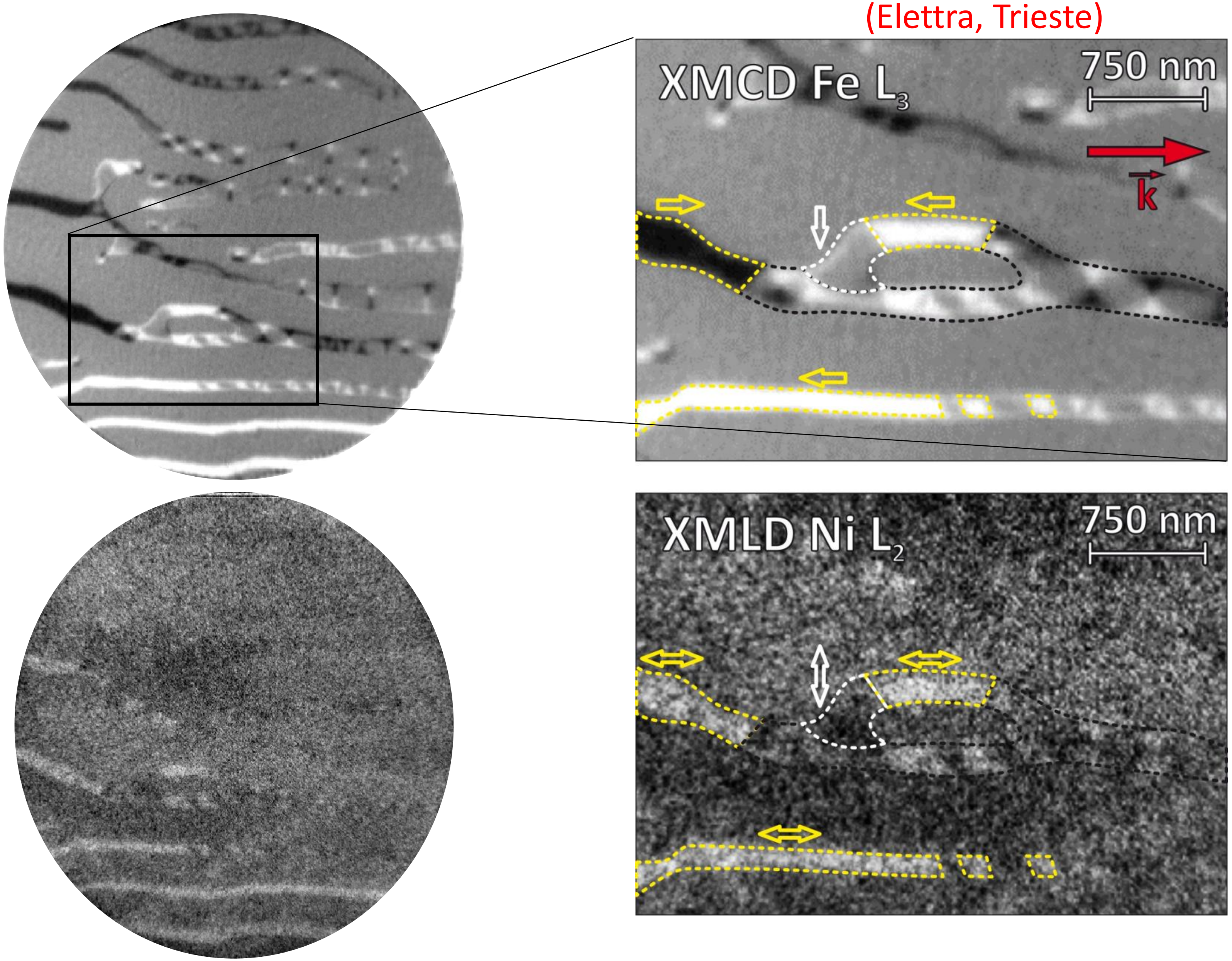
M. Ślęzak et al., **in preparation**

Self-organized NiO(111)/Fe(110) nanostructures

XML(C)D-PEEM at Nanospectroscopy beamline
(Elettra, Trieste)

XMCD: Fe

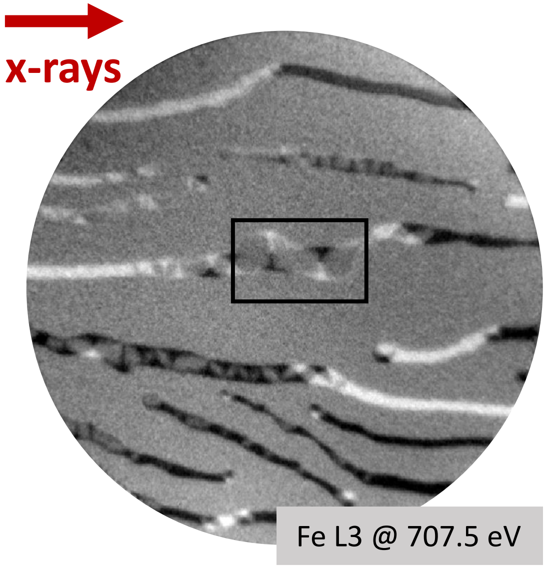
XMLD: NiO



M. Ślęzak et al., **in preparation**

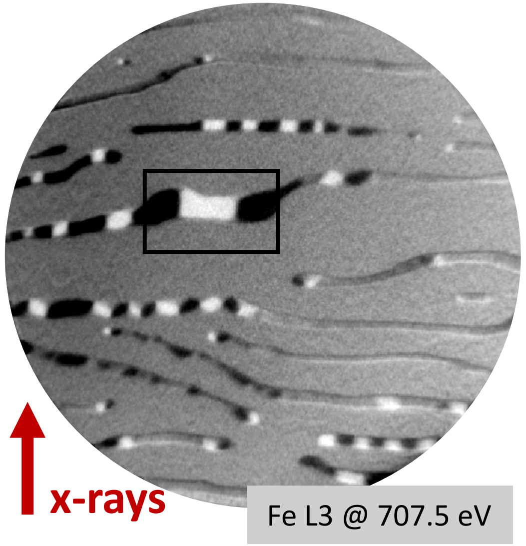
NiO(111)/Fe(110) nanostructures

XMCD



XMCD

After sample rotation



XML(C)D-PEEM at Nanospectroscopy beamline (Elettra, Trieste)

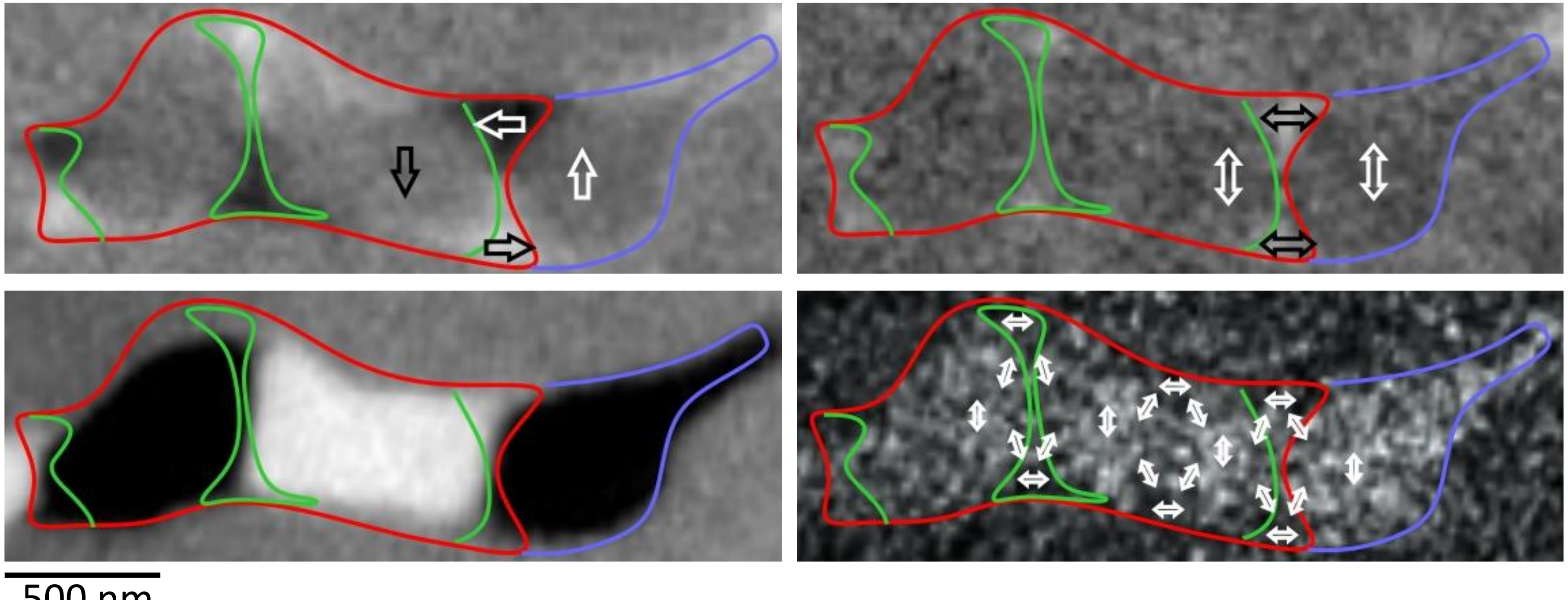
M. Ślęzak et al., **in preparation**

NiO(111)/Fe(110) nanostructures

XMCD

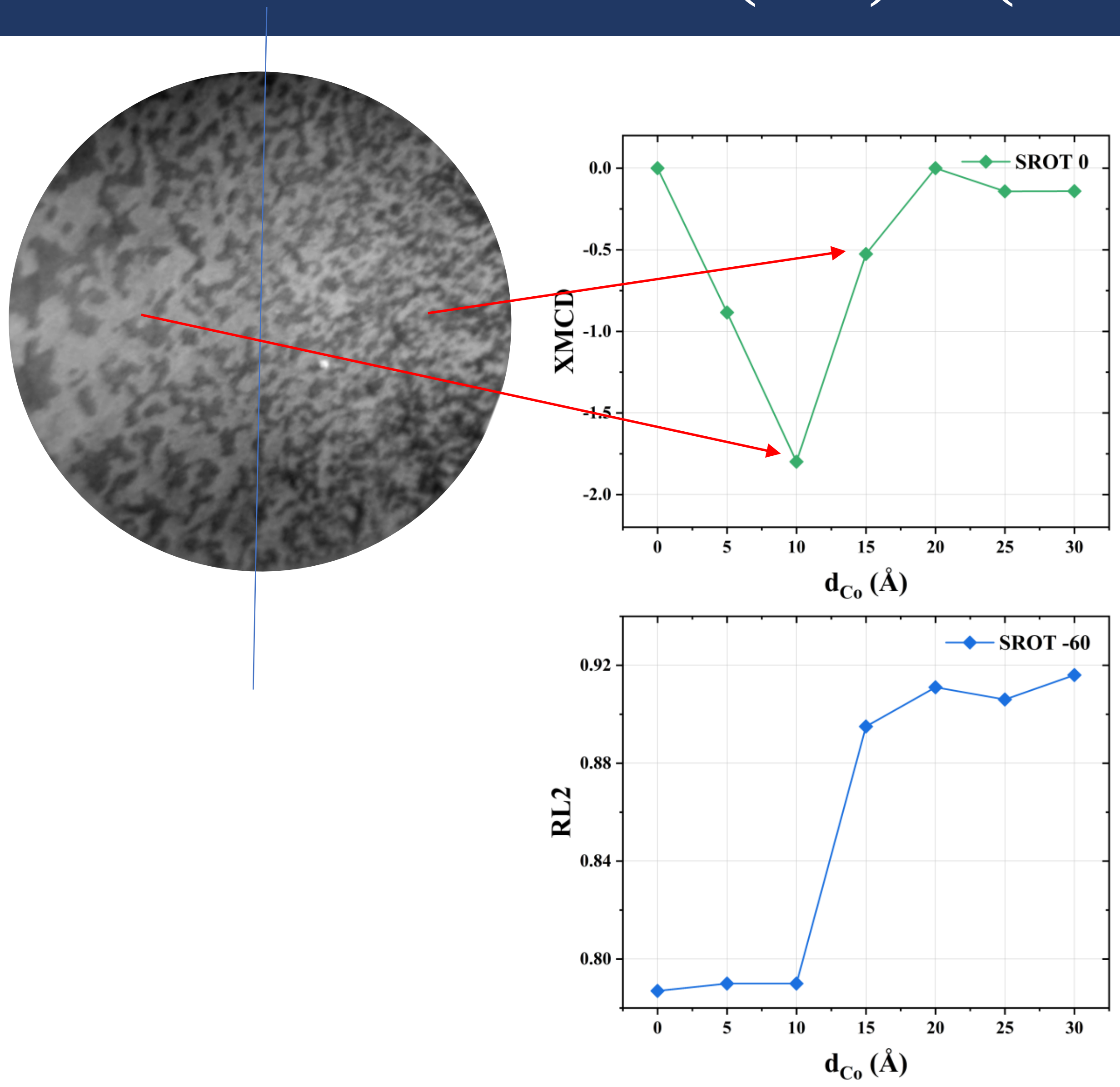
XMLD

After sample rotation



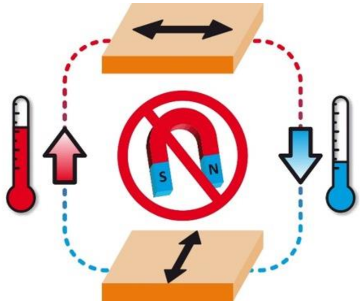
XPEEM: T. O. Menteş, F. Genuzio, A. Locatelli, XML(C)D-PEEM, Nanospectroscopy beamline (Elettra, Trieste)

Out-of-plane to in-plane SRT in: NiO/Co/Au(111)/W(110)



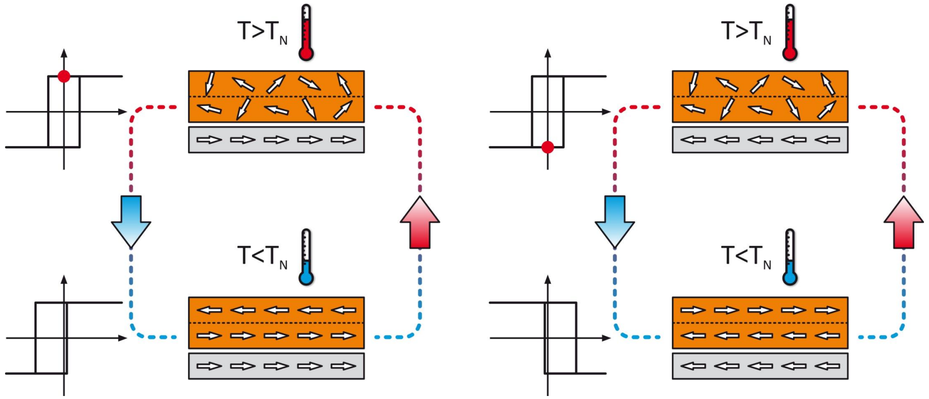
Summary

- Temperature induced, field-free switching of AFM spins - rotatable NiO



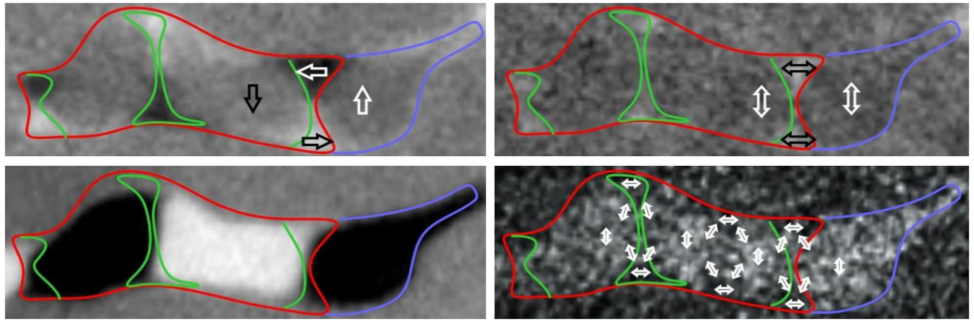
Nanoscale 12 (2020) 18091
Phys. Rev. B 104 (2021)134434

- Memory effects in CoO/Fe



Scientific Reports 9 (2019) 889
JMMM 545 (2022) 168783

- Imprinting magnetic domain structure in individual AFM/FM nanostructures

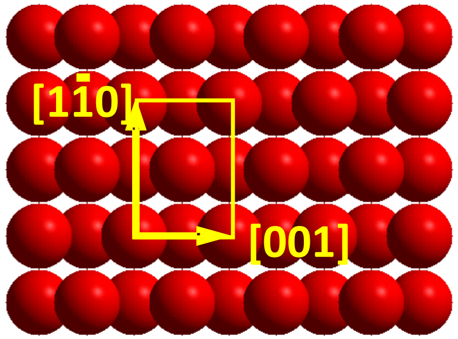


in preparation

Introduction

Spin Reorientation Transition in Fe/W(110)

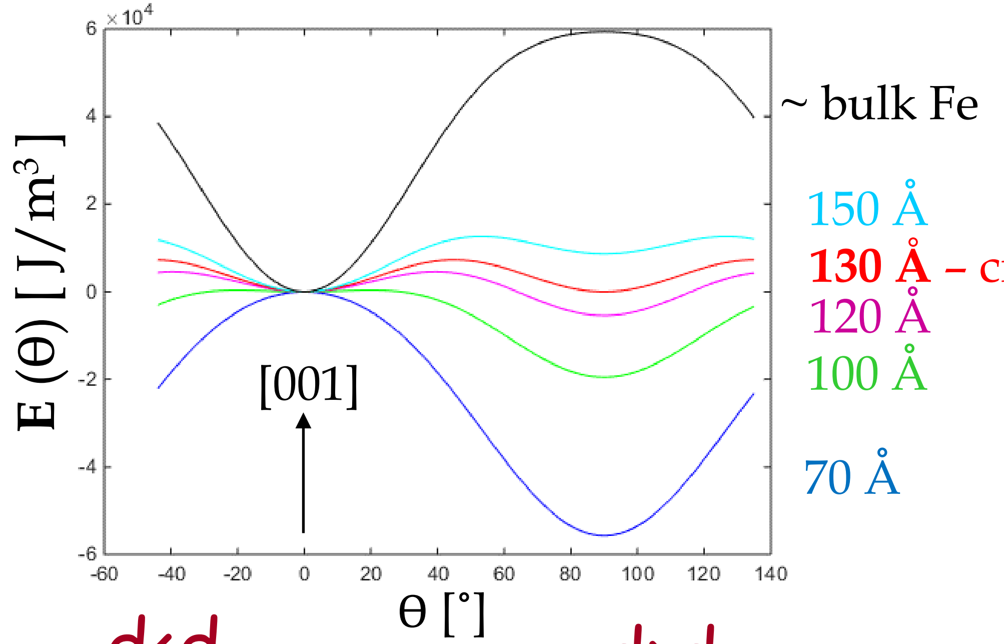
Fe(110)



$$E_{m\ in\text{-}plane}(\Theta) = A\sin^2(\Theta) + B\sin^4(\Theta)$$

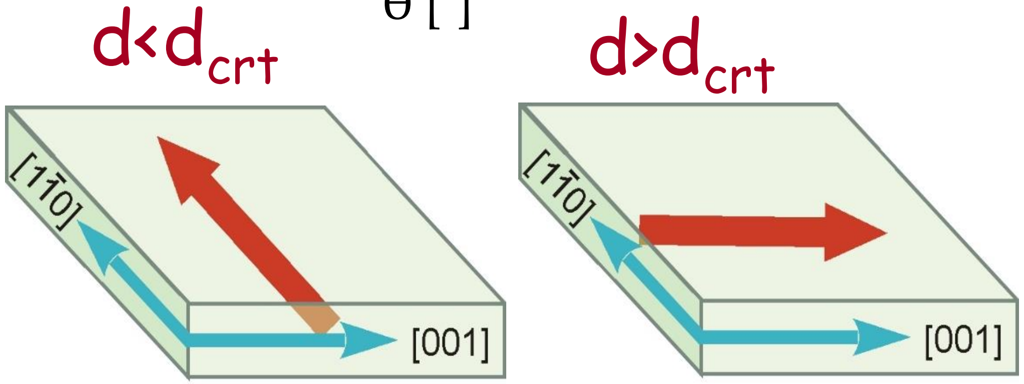
$$A = K_{vp} - K_{sp}/d$$
$$B = K_{vpp} - K_{spp}/d$$

[1-10] anisotropy

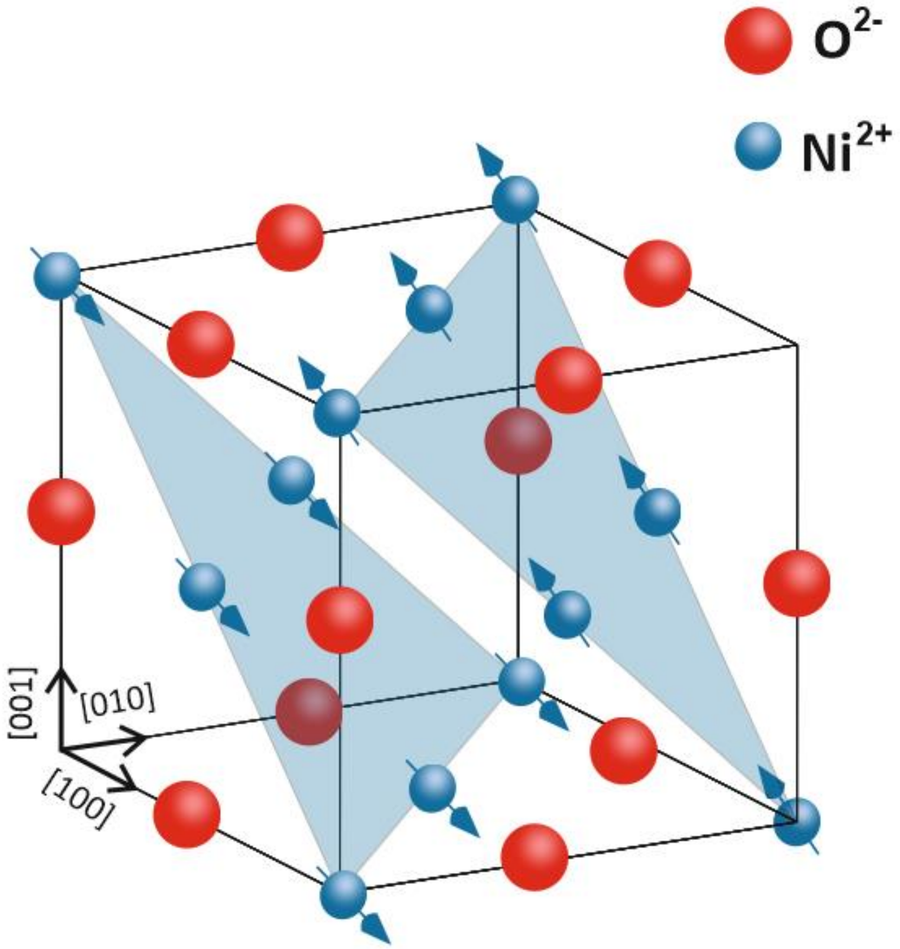


$K_{vp} = 10.60 * 10^4\ J/m^3$
$K_{vpp} = -\ 0.60 * 10^4\ J/m^3$
$K_{sp} = 0.82 *\ mJ/m^2$
$K_{spp} = 0.48 *\ mJ/m^2$

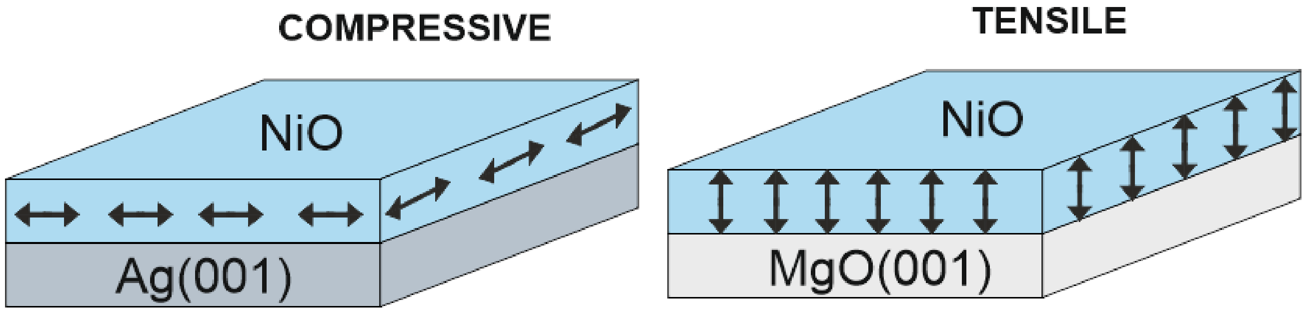
d_{crt} is a good measure of in-plane magnetic anisotropy



Gradmann et al., Appl. Phys. A 39, 101-108 (1985)



- rocksalt crystal structure
- lattice constant a = 4.17 Å
- Néel temperature T_N = 523 K
- FM alignment within each (111) plane,
  AFM alignment between adjacent (111) planes
- In thin NiO(001) films spin direction can be modified by strains imposed by the substrate

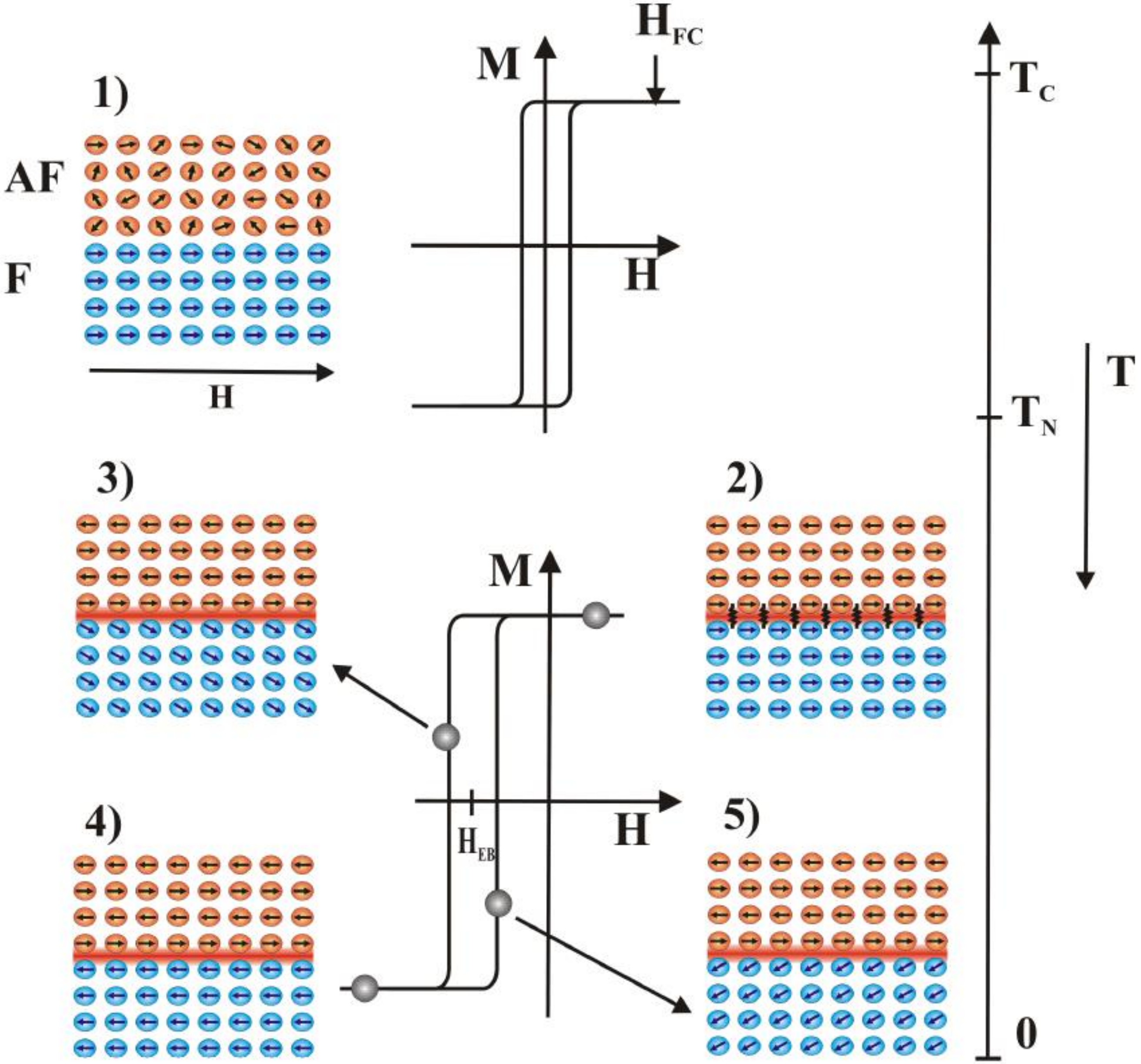


D. Spanke et al., Rev.Rev. B 58, 5201 (1998)

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

Introduction

exchange bias



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AFM/FM systems

nature COMMUNICATIONS

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Readout of an antiferromagnetic spintronics system by strong exchange coupling of Mn_2Au and Permalloy

S. P. Bommanaboyena[1], D. Backes[2], L. S. I. Veiga[2], S. S. Dhesi[2], Y. R. Niu[3], B. Sarpi[3], T. Denneulin[4], A. Kovács[4], T. Mashoff[1], O. Gomonay[1], J. Sinova[1], K. Everschor-Sitte[1], D. Schönke[1], R. M. Reeve[1], M. Kläui[1], H.-J. Elmers[1] & M. Jourdan[1]✉