Low dimensional magnetism – Experiments

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Compared to the abstract, some paragraphs have been omitted or shrunk

- No time to speak of everything in 2 hours
- Some slides prepared on the spot. For missing items, see reference:
  URSUS: Regele berii in Romania – Bere Cluj…(Fondat 1878)

(1. Introduction)

- **2. Ferromagnetic order**
- **3. Magnetic anisotropy**

4. Layered systems: from concepts to functional building bricks

- **5. Superparamagnetism**

References

2.1 Methods

- **2.2 Metastable phases**
- **2.3 Magnetic order versus temperature**
- **2.4 Surface magnetization**

Avoid structural transition

- Stabilization by:
  - Epitaxial misfit
  - In-plane stress

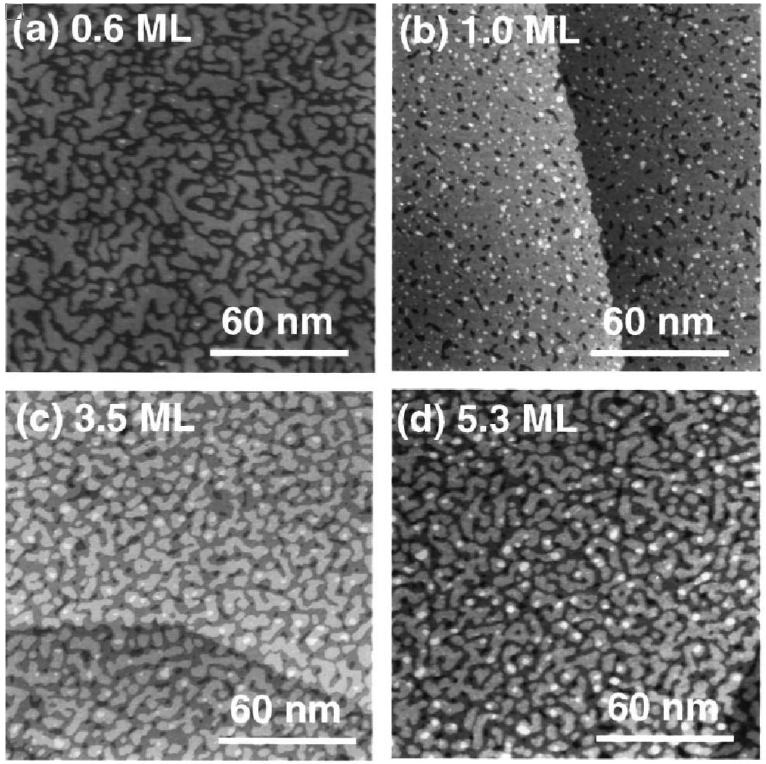
  | Films, or clusters in a matrix

- Optimize growth methods and parameters

Cf lecture by Stéphane ANDRIEU

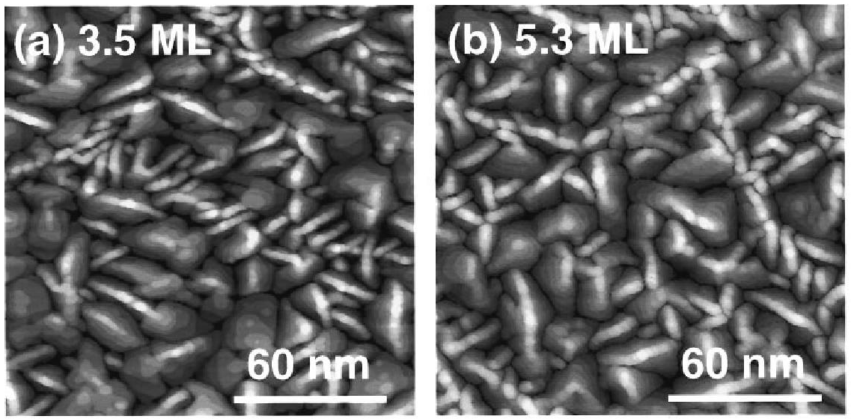
Fe/Cu(001)

300K growth with PLD: fcc



Fe/Cu(001)

300K growth with MBE: fcc>bcc

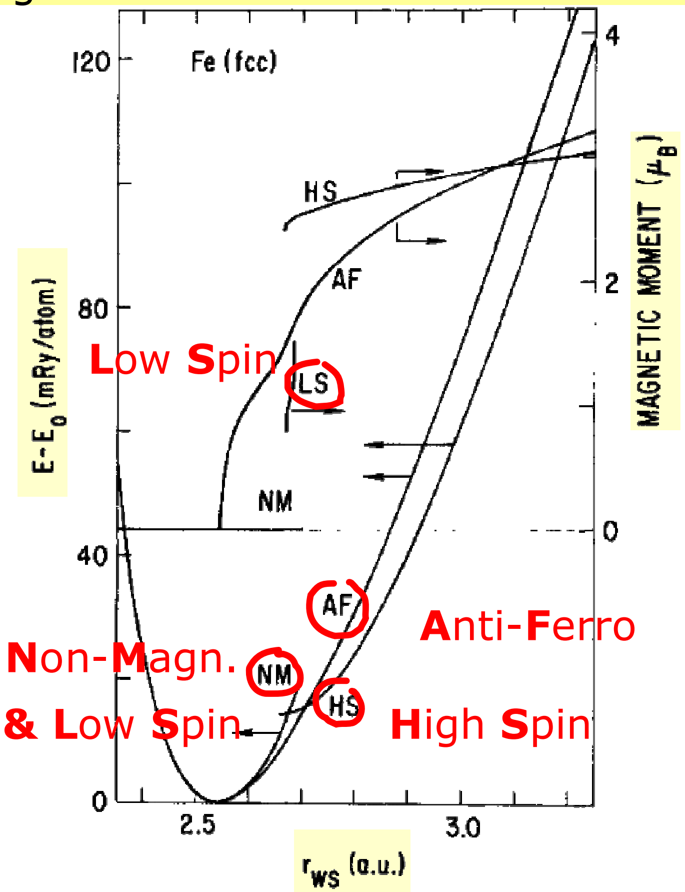


P. Ohresser et al., PRB59, 3696 (2001)

fcc γ-Fe

Theory (*e.g.*)

- fcc γ-Fe for T>1185K: non-magnetic
- 'ground-state': sensitive on lattice parameter

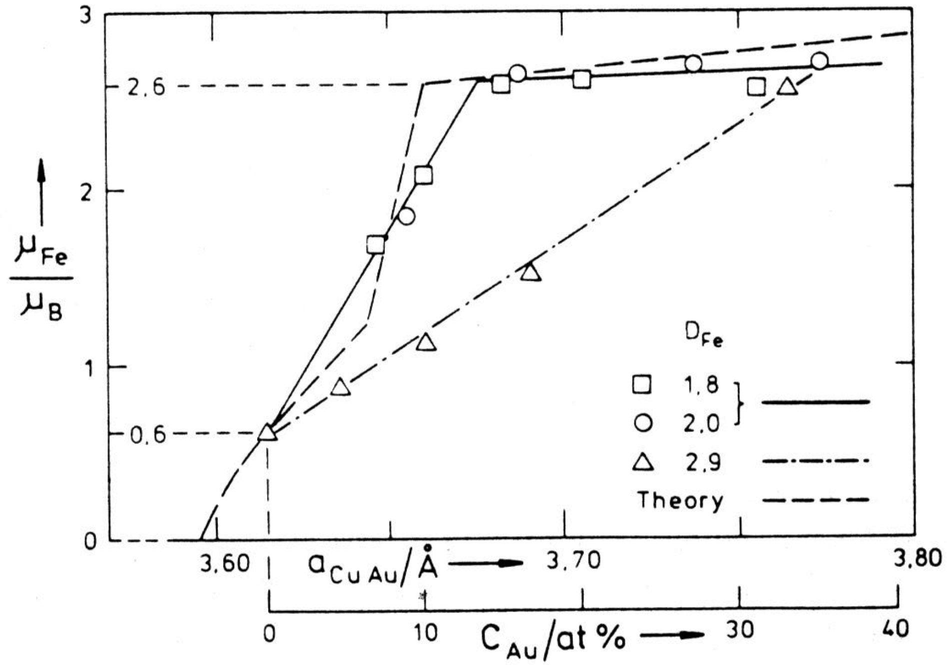


V. L. Moruzzi *et al.*, PRB39, 6957 (1989)

FIG. 2. Zero-field magnetic moments and total energies as a function of r_{WS} showing nonmagnetic (NM), antiferromagnetic (AF), low-spin (LS) and high-spin (HS) solutions for fcc iron. The LS total-energy branch is indistinguishable from the NM branch on this scale.

Thin films

fcc Fe/CuAu(111)



U. Gradmann *et al.*, JMMM 15-18, 1109 (1980)

- Agreement with theory?
- What happens for thicker films?

See also: O.K. Andersen, Physica B 86, 249 (1977)

Spin-density wave antiferromagnetism

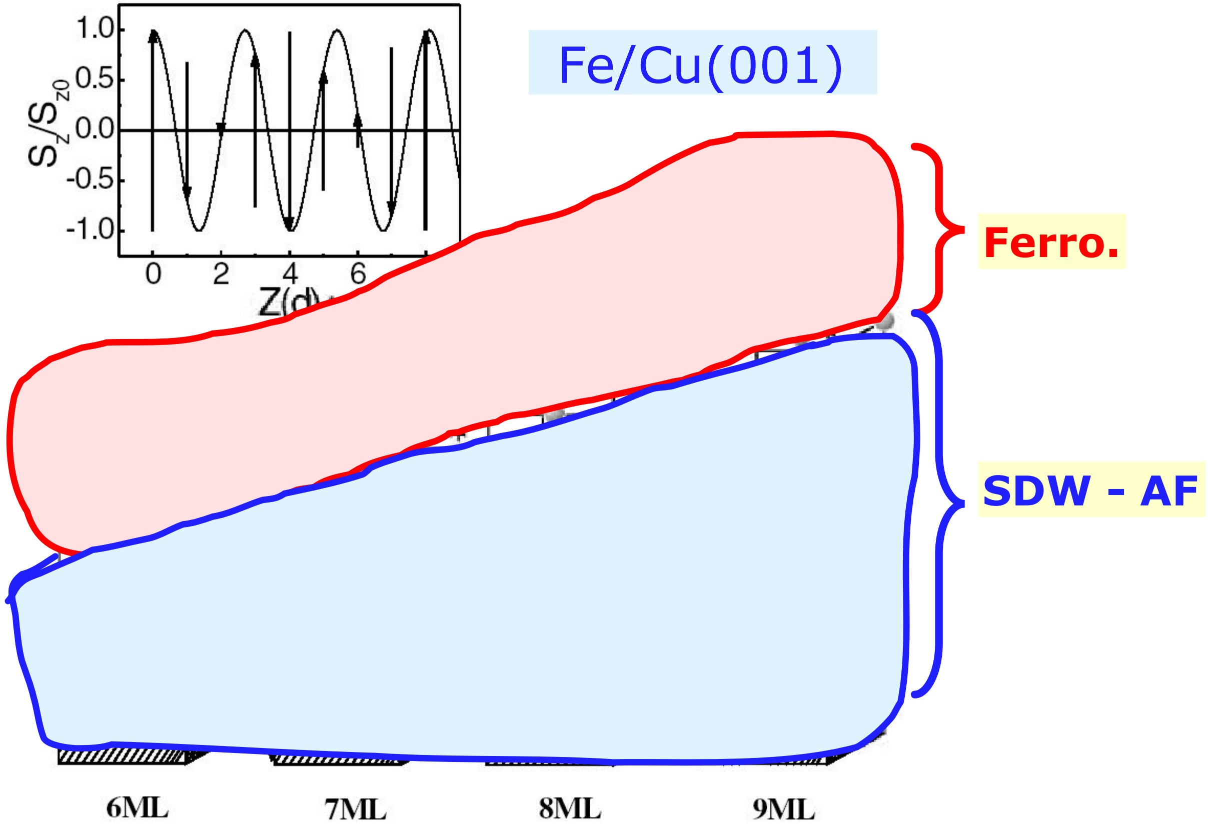


FIG. 4. Magnetic structures proposed for 6, 7, 8, and 9 ML Fe on Cu(100); the inset gives the layer dependent magnetic moments for fcc Fe along the z direction, $z(d) = 0$ corresponding to the first AFM layer. (Note: all the moments drawn here are lying in the planes parallel to the front plane of the structure section.)

D. Qian et al., PRL87, 227204(2001)

See also V. Cros et al., Europhys. Lett. 49, 807 (2000)

Stabilization of fcc Co

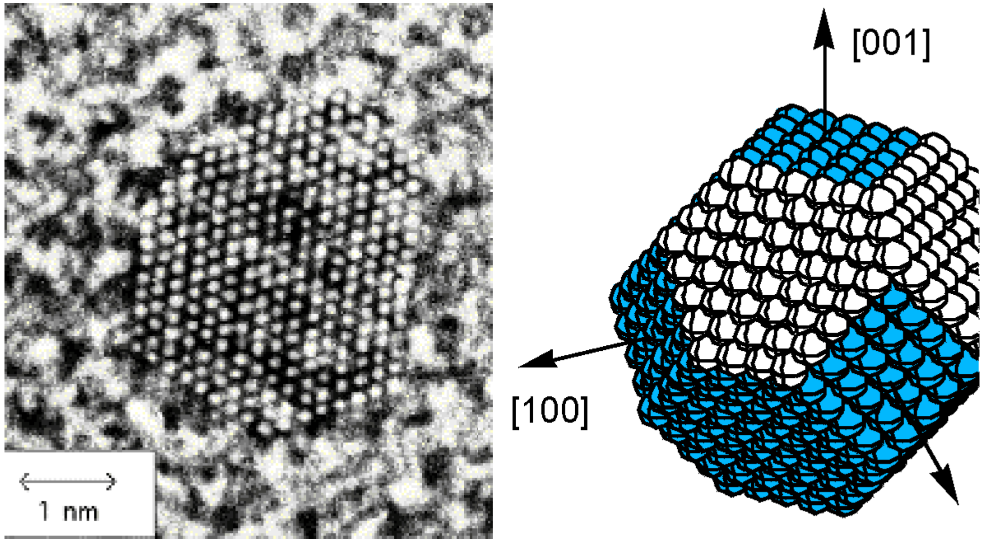
- Stabilization by:
  - Epitaxial misfit
  - Surface stress

  Films, or clusters (matrix, or free)
  - Surface orientation. e.g. (001)
- Optimize growth methods and parameters

Clusters

DPM, CNRS, Lyon, France : LASER vaporization and inert gas condensation source

M. Jamet, V. Dupuis, M. Negrier, J. Tuaillon, A. Perez



HRTEM along a [110] direction
fcc - structure, faceting

Cf lecture by Edgar BONET

Model system: shape, magneto-crystalline anisotropy

fcc Co films

300K MBE: stacking faults 300K PLD: fcc

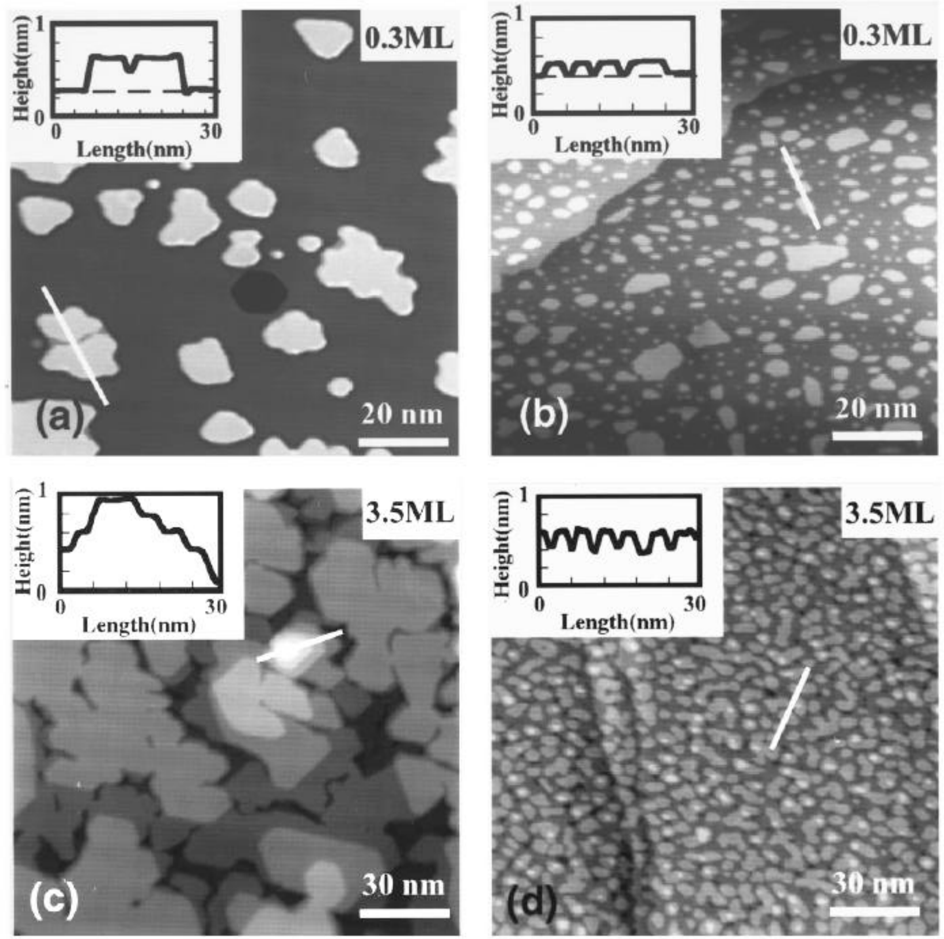


FIG. 2. STM topography images of Co/Cu(111) films prepared by therm deposition (a), (c) and pulsed laser deposition (b), (d). The height scale the line scans are shown in the insert. The islands of TD films are alrea double-layer high in the beginning state of film growth (a), where the PI films consist of one monolayer high islands only (b). At higher thickness t TD films show a pronounced 3D growth (c), while the pulsed laser depc ited films continue to grow layer-by-layer (d).

M. Zheng *et al.*, APL74, 425 (1999)

Cf lecture by Stéphane ANDRIEU

Co/Cu(001)

I-V LEED curves

- stacking faults for MBE
- pure fcc for PLD

Elements of theory

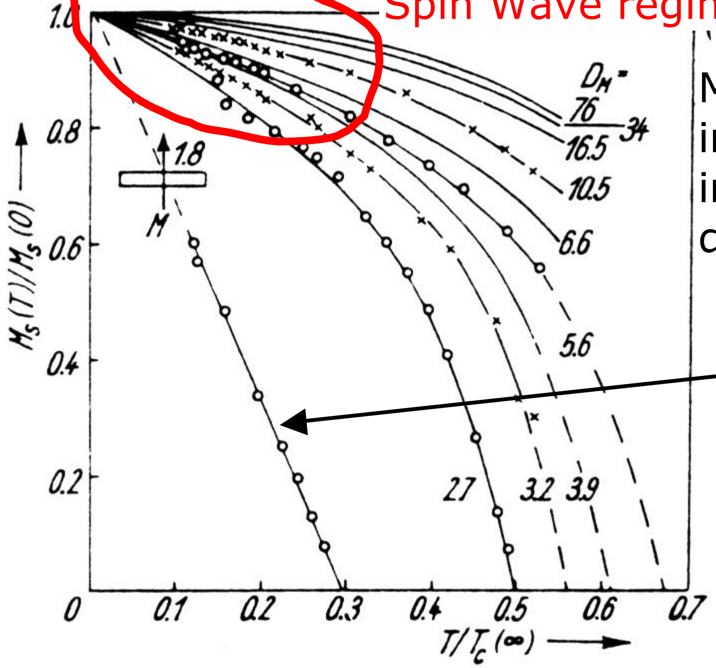
- Bloch (1930). No magnetic order at T>OK in 2D. (spin-waves; isotropic Heisenberg)
- Onsager (1944) + Yang (1951). 2D Ising model: Tc>0K

Magnetic anisotropy stabilizes ordering

Experiments: Tc(t)

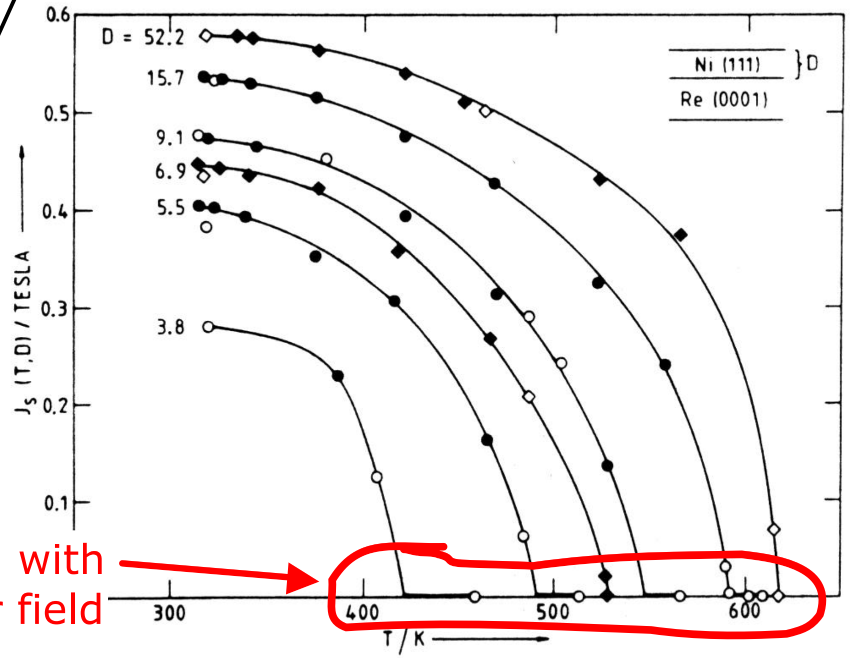
fcc 48Ni/52Fe(111)/Cu(011)

Spin Wave regime



Mean field inacurate in low dimension...

Cf lecture by Dominique GIVORD



Tc interpreted with molecular field

U. Gradmann and J. Müller, Phys. Status Solidi 27, 313 (1968)

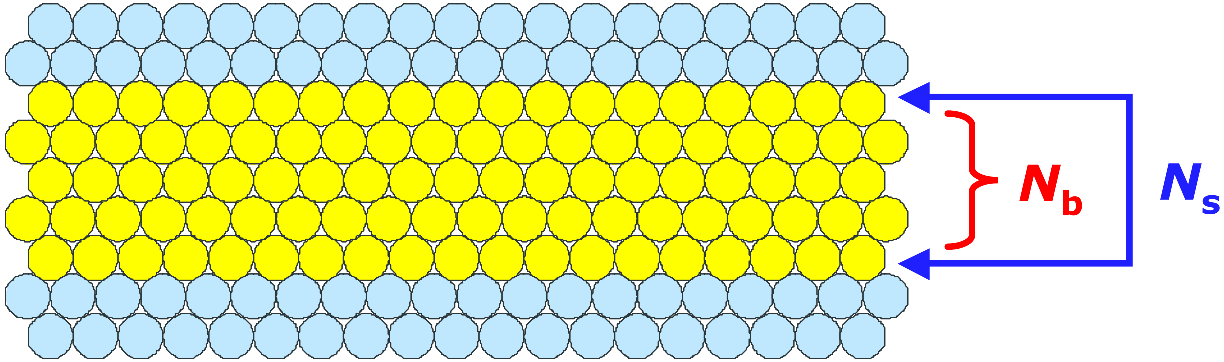
R. Bergholz and U. Gradmann, JMMM45, 389 (1984)

Naïve model

Molecular field

$$T_c = m_0 . \frac{J+1}{3J} . \frac{N w_0 M_0 \, m_0}{k_B}$$

N neighbors



$$\overline{N} = N_b - \frac{2(N_b - N_s)}{t} \Rightarrow \Delta T_c(t) \sim t^{-1}$$

Less naïve...

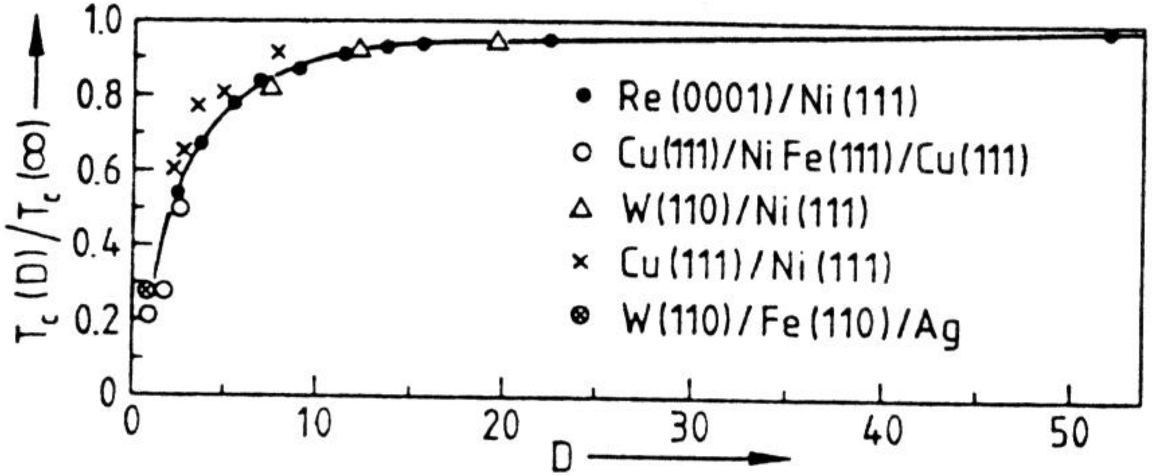
Thickness-dependant molecular field

$$\Delta T_c(t) \sim t^{-l}$$

$$l = 1$$

G.A.T. Allan, PRB1, 352 (1970)

Experiments



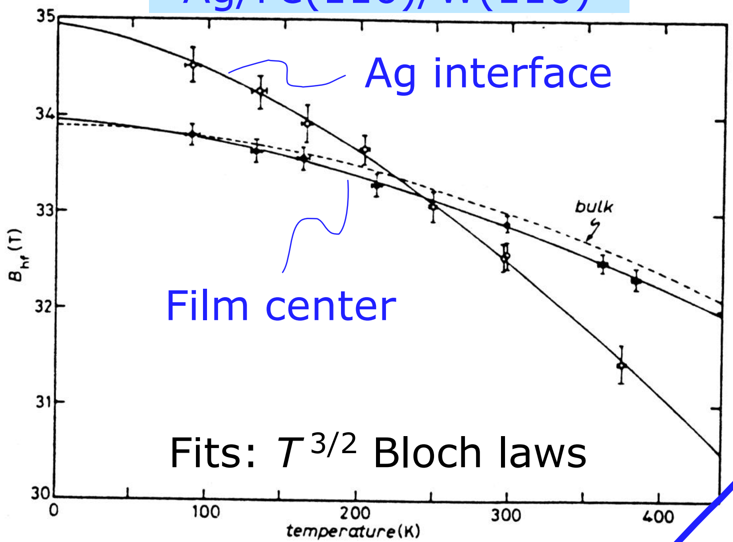
U. Gradmann,
Handbook of Magn. Mater. Vol.7, ch.1 (1993)

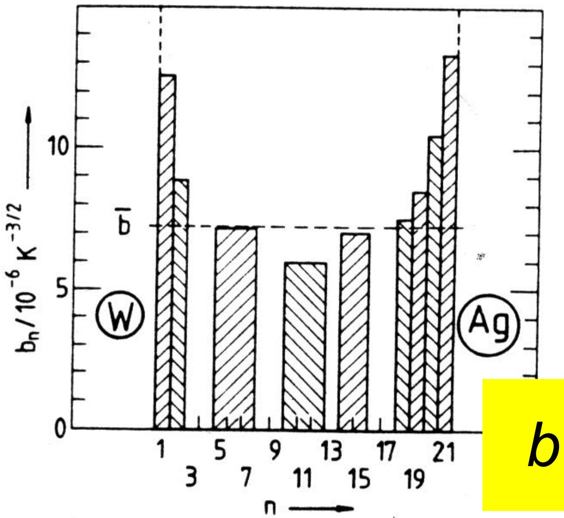
Conclusion:
Naïve views are roughly correct

BLOCH LAW

Results

Ag/Fe(110)/W(110)





$b(\text{surface}) \sim 2.5 b(\infty)$

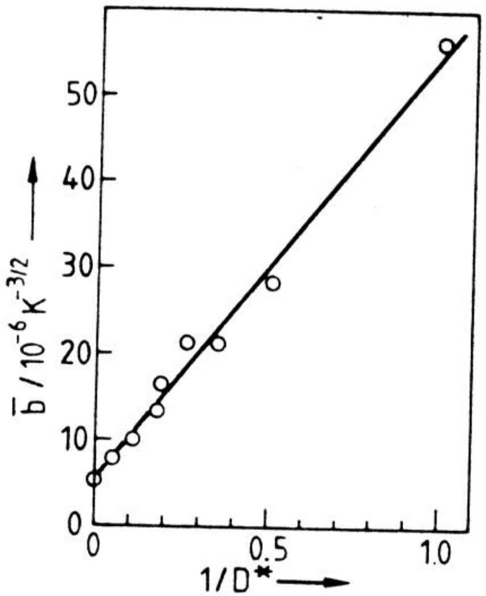
Analysis

FIT: $B_{hf}(T) = B_{hf}(0)\left[1 - bT^{3/2}\right]$

Remarkable result [Fe/W(110)]:

$$\bar{b}(t) = b(\infty) + \left[b(1) - b(\infty)\right]/t$$

$$b(1) \sim 10 b(\infty)$$



BLOCH LAW AND DEAD LAYERS

Analysis

Idea:
Determine surface magnization, enhanced or reduced.

Ideal measurement

$$M_s(0\,\mathrm{K},t) = M_s(0\,\mathrm{K},\infty)(t + t)$$

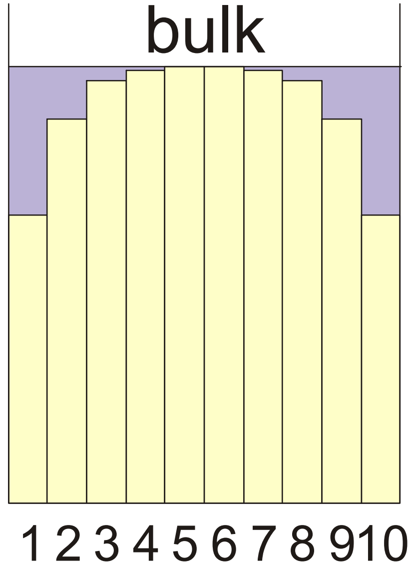
Real measurement: $T>0$K

$$M_s(T,t) = M_s(0\,\mathrm{K},t)\left[1-\bar{b}(t)T^{3/2}\right]$$

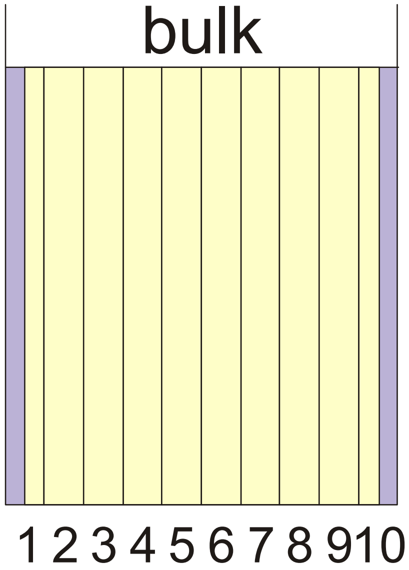
BACK

Interpretation

Reality



Misinterpretation

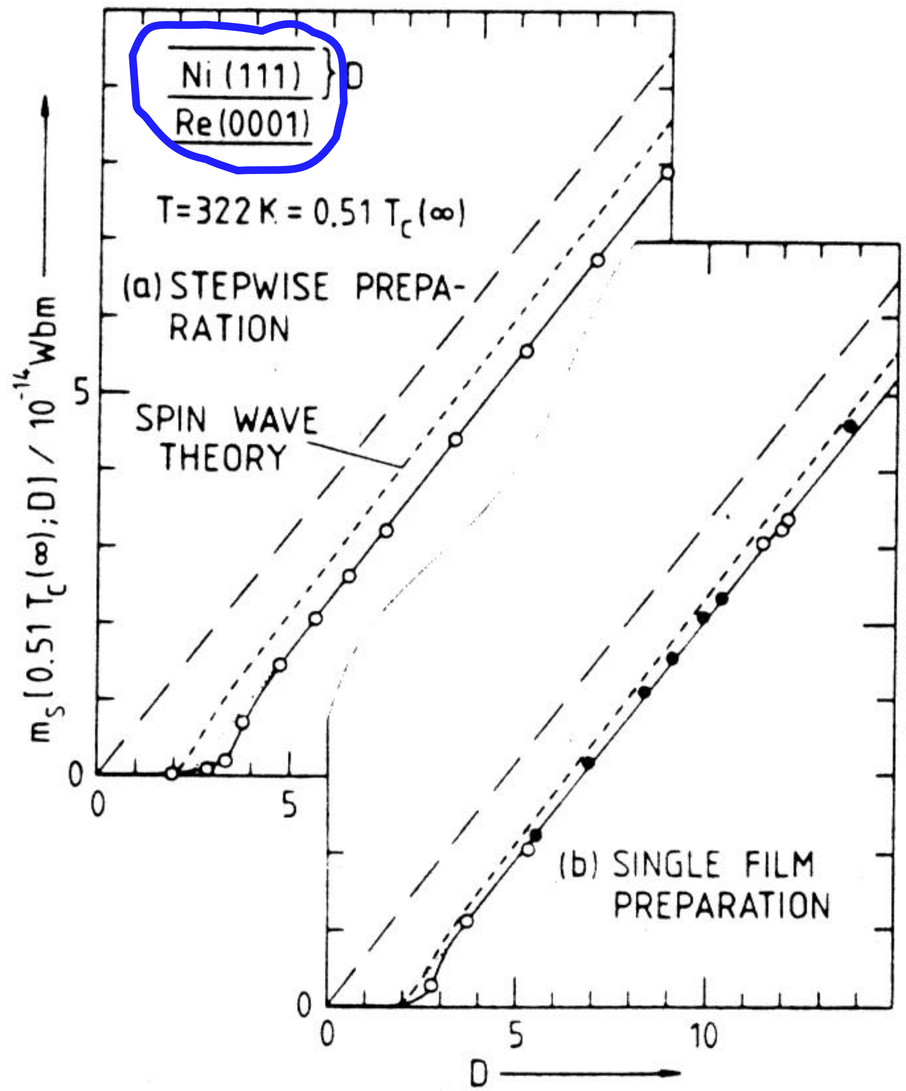


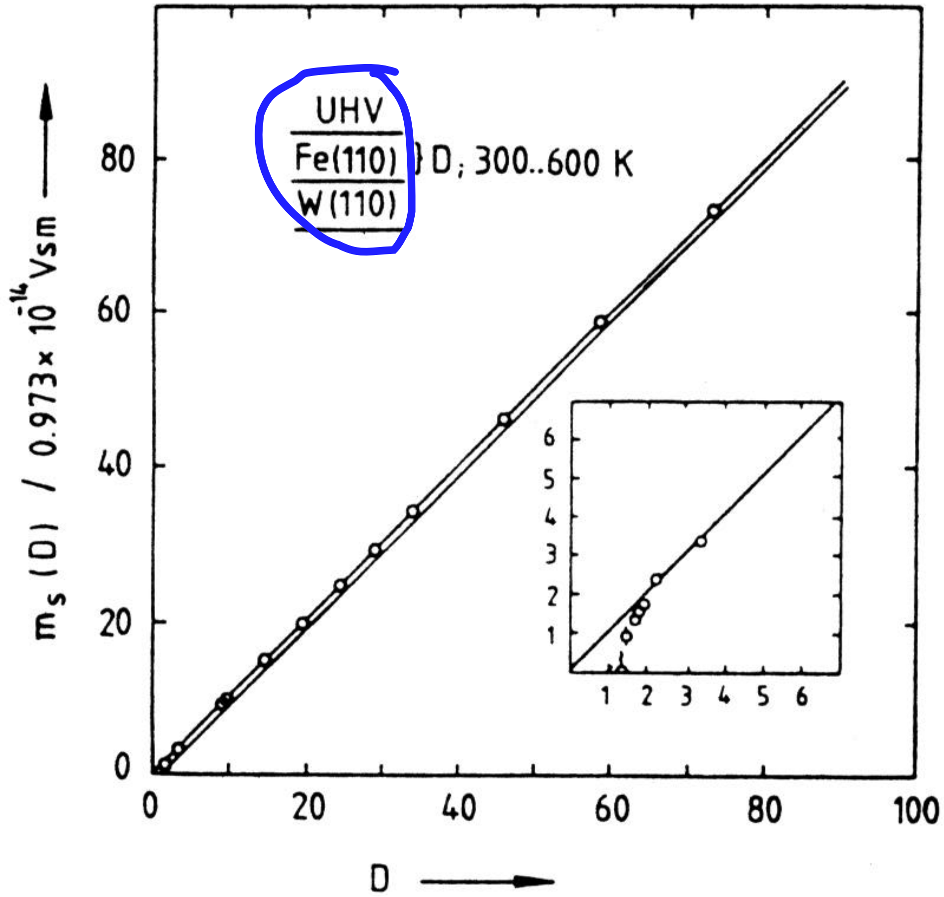
$$M_s(T,t) \approx M_s(0\,\mathrm{K},\infty)\times\left[t(1-b_\infty T^{3/2}) + t - b_1 T^{3/2}\right]$$

Slope — Shift — Spurious effect

Study of surface versus bulk magnetization must be undertaken at low temperature

BLOCH LAW AND DEAD LAYERS: Experiments





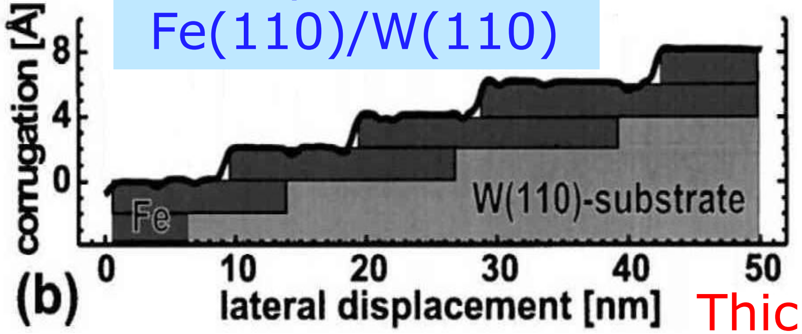
Ni(111): surface magn. reduced

Fe(110): surface magn. Enhanced

- $\tau_{\text{apparent}} = +0.14$
- $\tau_{\text{SW-corrected}} = +0.42$

U. Gradmann, Handbook...

Example: Vicinal Fe(110)/W(110)



Spin-Polarized Scanning Tunneling Spectroscopy

Thickness = 1.25AL

Cf lecture by Dominique GIVORD

Atomically-narrow domain walls

Cf lecture by André THIAVILLE

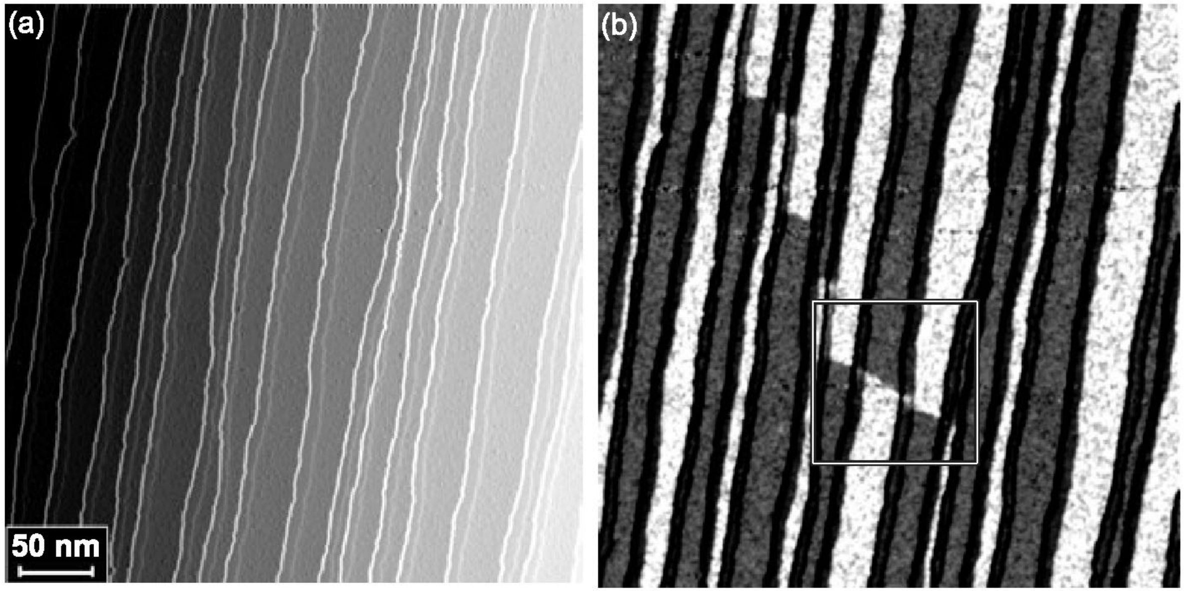


Figure 35. (*a*) Topography and (*b*) magnetic dI/dU signal as measured with a Fe tip on Fe ML stripes on W(110). Adjacent ML stripes exhibit opposite in-plane magnetization directions. Obviously, the domain walls in the ML are very sharp. The region in the rectangle will be shown in more detail in figure 36.

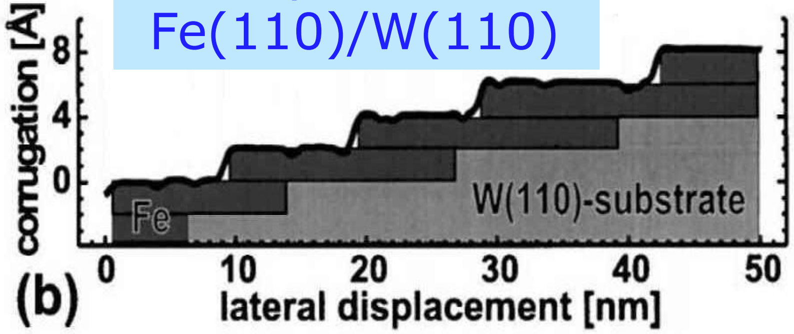
M. Bode et al, Rep. Prog. Phys. 66, 523 (2003)

- In-plane magnetization imaged (reflects out-of-plane)

Conclusion

- Dipolar fields stabilize magnetic order

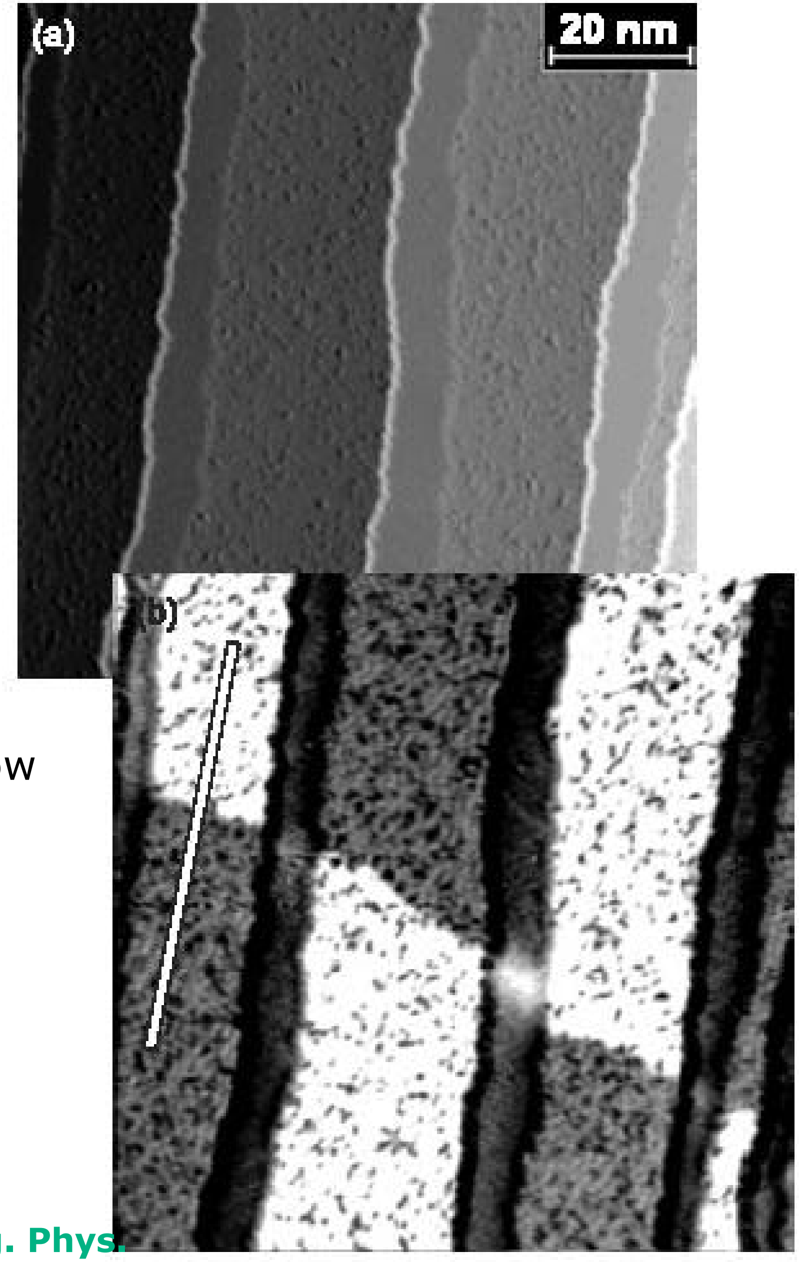
Example: Vicinal Fe(110)/W(110)



Spin-Polarized Scanning Tunneling Spectroscopy

Thickness = 1.25AL

Atomically-narrow domain walls



M. Bode et al, Rep. Prog. Phys. 66, 523 (2003)

Discrete number of atomic layers

Fe/Ir(100) single or multilayers

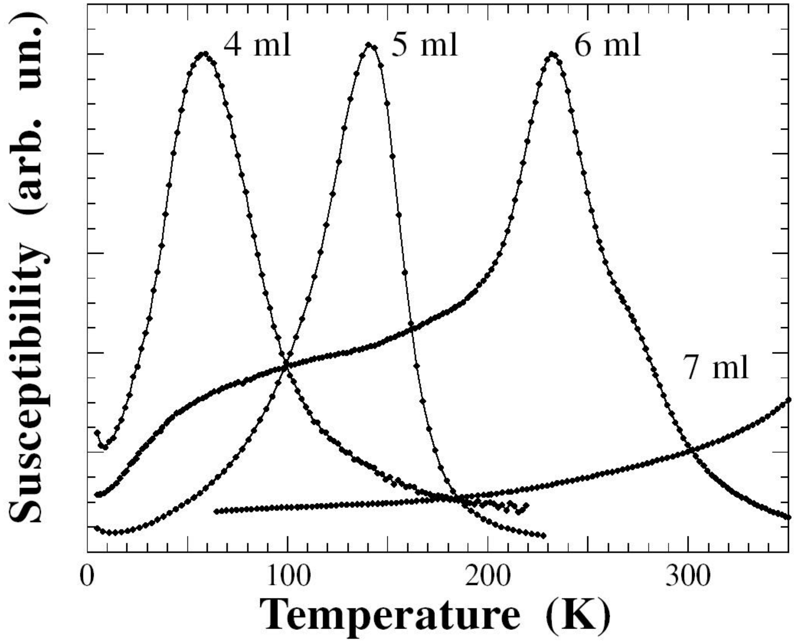


FIG. 1. ac susceptibility peaks observed for Fe/Ir multilayers of 20 periods with Ir spacer thickness of 15 Å, and integer numbers of Fe atomic planes.

Rough growth
Island size < magn. correlation length

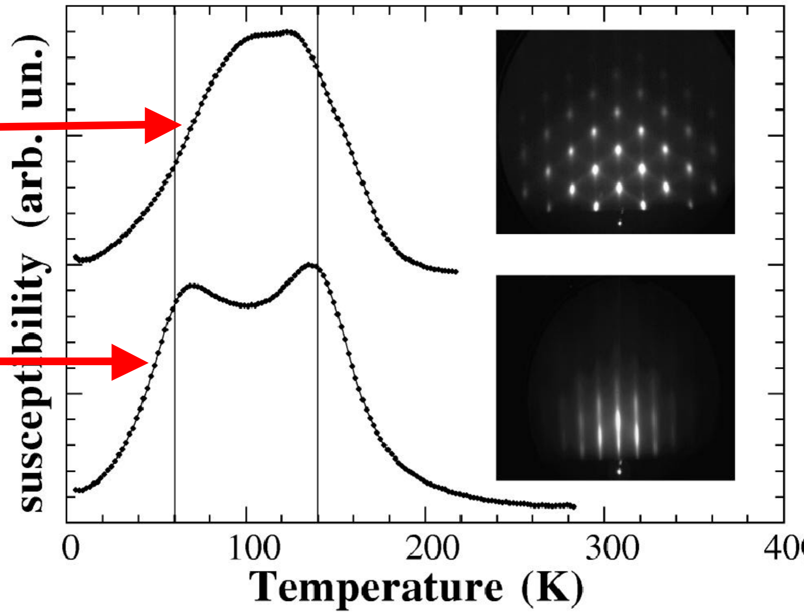
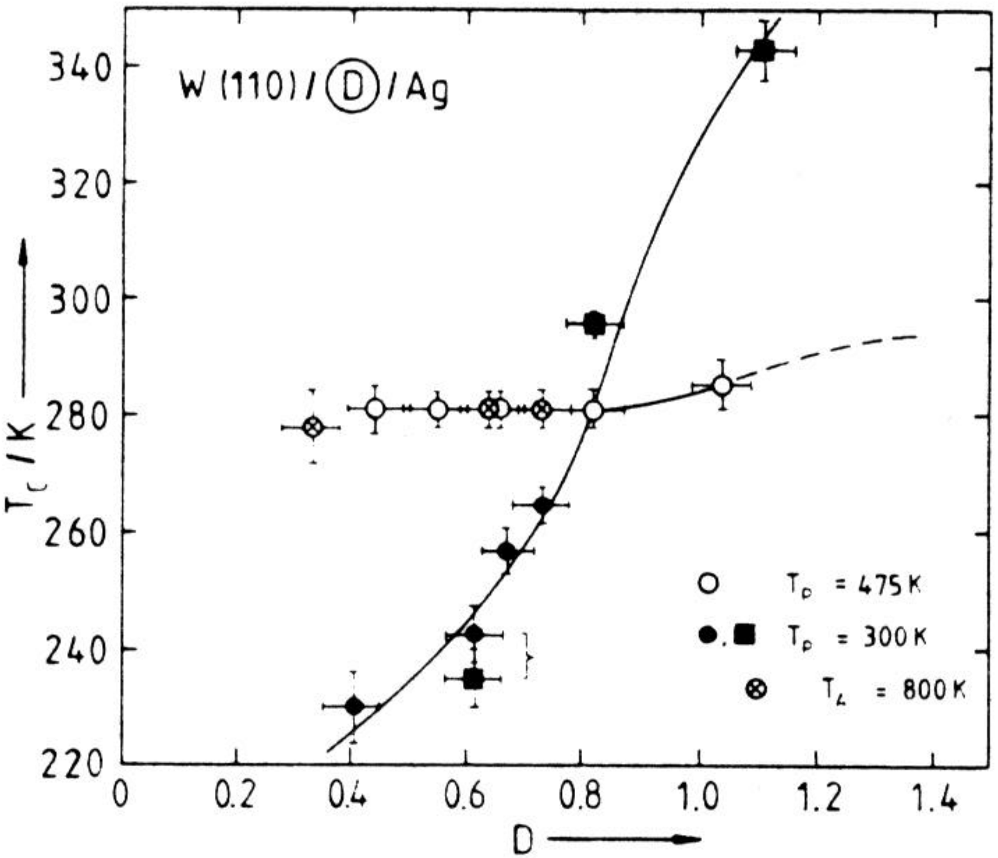


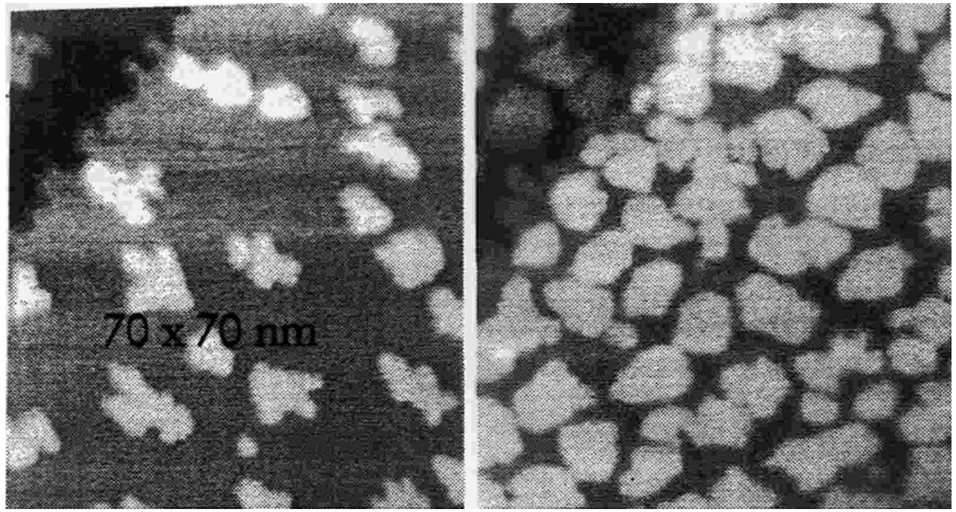
FIG. 3. Influence of the surface roughness as shown by the RHEED patterns (shown in inset) on the ac susceptibility measurements for a SL with 4.6 ML thick Fe layers grown at 300 K (top) and 400 K (bottom).

Layer-by-layer growth
Island size > magn. correlation length

S. Andrieu et al., PRL86, 3883 (2001)

Discrete number of atomic layers





H.J.Elmers *et al.*, Phys.Rev.Lett.73, 898(94)

U. Gradmann, Handbook…

Conclusion
Tc depends on size of islands
(lateral dimensions)

Effect of capping layer on Tc

Table 1. T_C of various ultrathin Ni and Co on Cu(001) films before capping with Cu. The capping layer thickness and the decrease ΔT_C after capping are noted. ΔT_C is more pronounced in the case of $d \approx 2$ ML Co films.

$d_{ferromagnet}$ (ML)	T_C (K)	d_{Cu} (ML)	ΔT_C (K)
Ni 3.6	168	2.0	−31
4.0	217	2.5	−37
4.0	210	3.5	−50
5.0	275	2.0	−25
5.1	278	0.5	−23
5.1	263	7.0	−28
Co 1.9	290	6.8	−120
1.8	300	4.8	−75

P. Poulopoulos and K. Baberschke, J. Phys.: Condens. Matter 11, 9495 (1999)

General rule

- Enhanced surf. magn.
  > increased Tc
- Decreased surf. magn.
  > decreased Tc

Quantum well effect on Tc

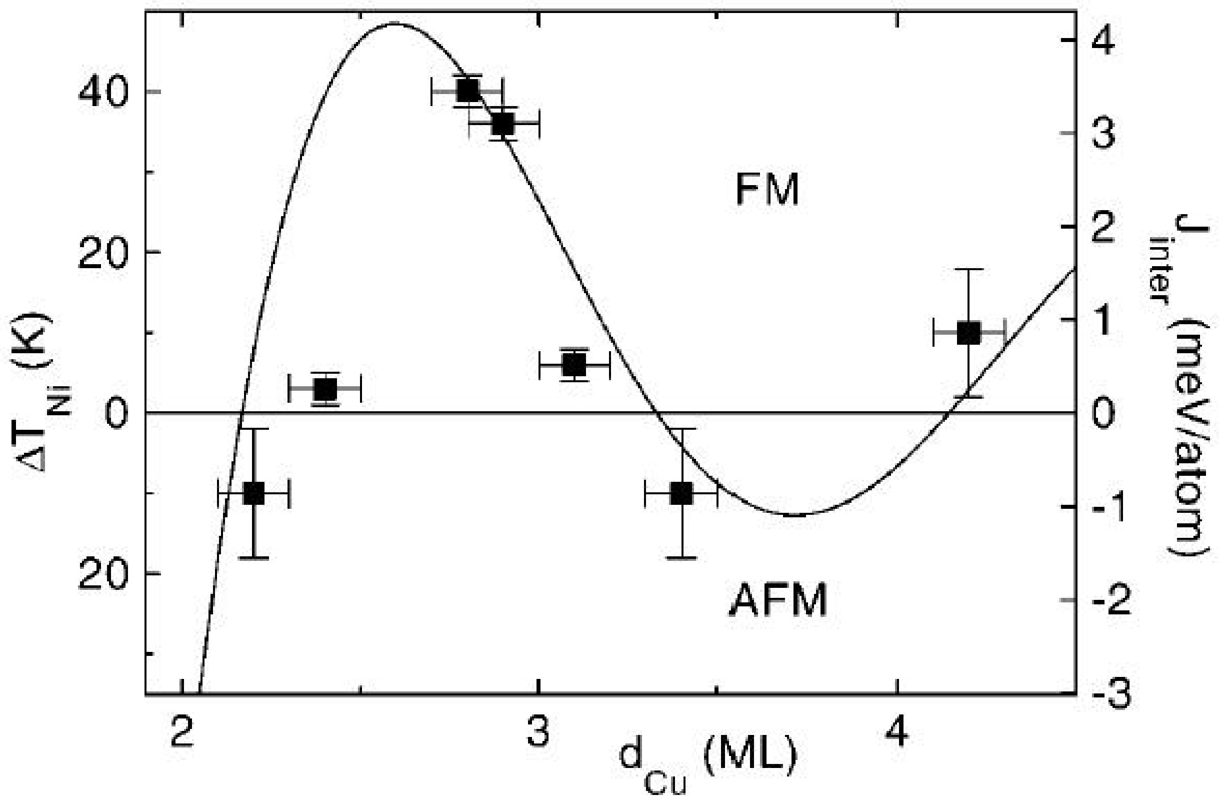
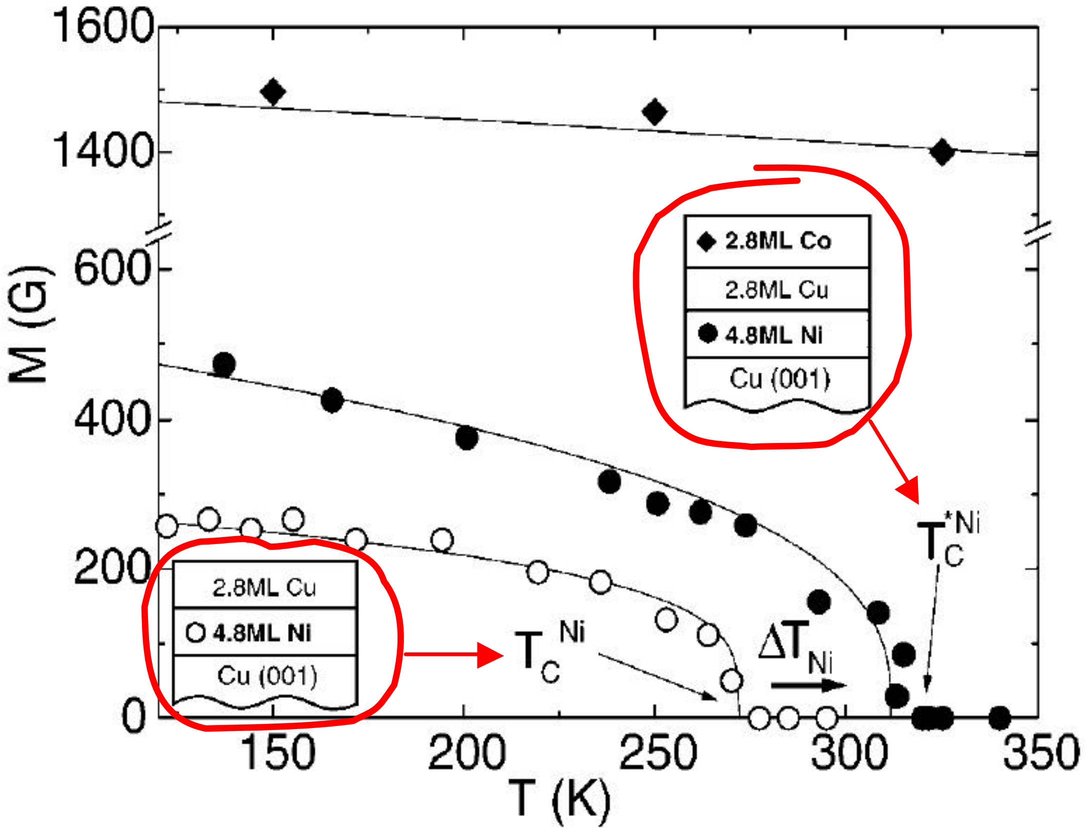


Figure 17. Oscillatory variation of interlayer coupling results in a periodic change of the ordering temperature ΔT_{Ni} in Co/Cu/Ni trilayers [114]. ΔT_{Ni} was measured and J_{inter} was calculated via a molecular field formula which may yield too large values for J_{inter}.

P. Poulopoulos and K. Baberschke, J. Phys.: Condens. Matter 11, 9495 (1999)

Exchange-coupling increase of Tc



Conclusion
Tc increased in Ni due to 'proximity' of Co

A. Ney et al, PRB59, R3938 (1999)

See also: exchange-coupling

Surface magnetization

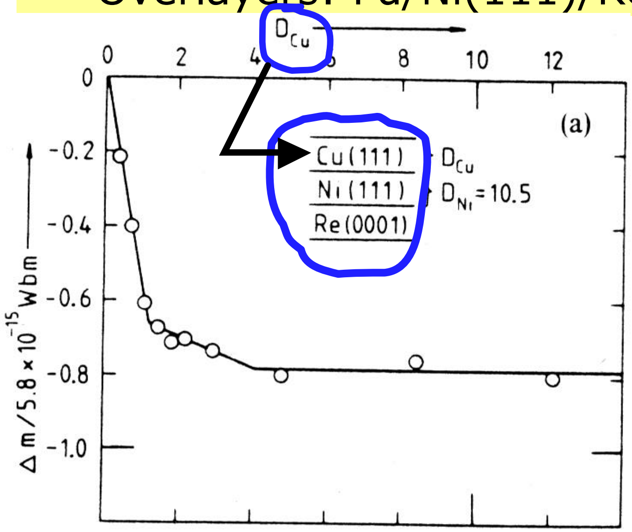
Surface techniques at OK

- Mossbauer with probe layers

Plot *m*(*t*) at 0K:

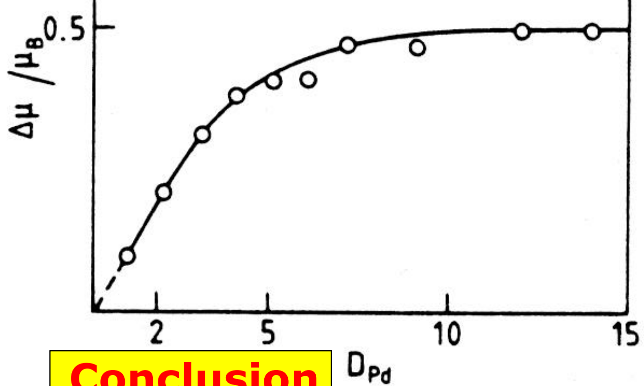
- Magnetometry
- XMCD (See lecture S. Pizzini)

- Fe/W(110) : 0.14ml(+0.35μ_B)
- UHV/Fe(110); Ag/Fe(110): 0.26ml(+0.65μ_B)
- Cu/Ni(111): -0.5ml
- Overlayers: Pd/Ni(111)/Re(0001)



U. Gradmann, Handbook...

Pd(*D*)/Ni(111)/Re(0001)



Conclusion
Pd is polarized over several layers

Fe/Pd multilayers

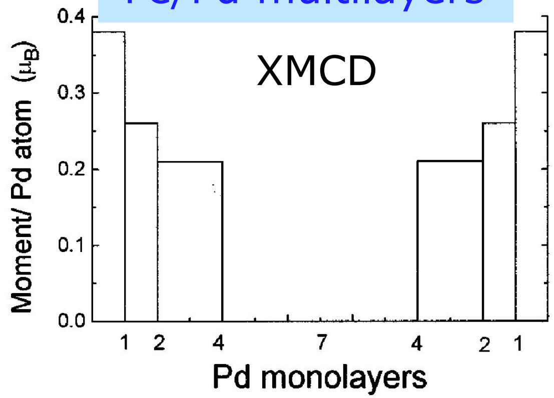


FIG. 8. Magnetic 4*d* moments of Pd as a function of the distance to the interface in Pd/Fe multilayers.

J. Vogel et al., PRB55, 3663 (1997)

See also: Stefania PIZZINI's lecture

Pioneering work:

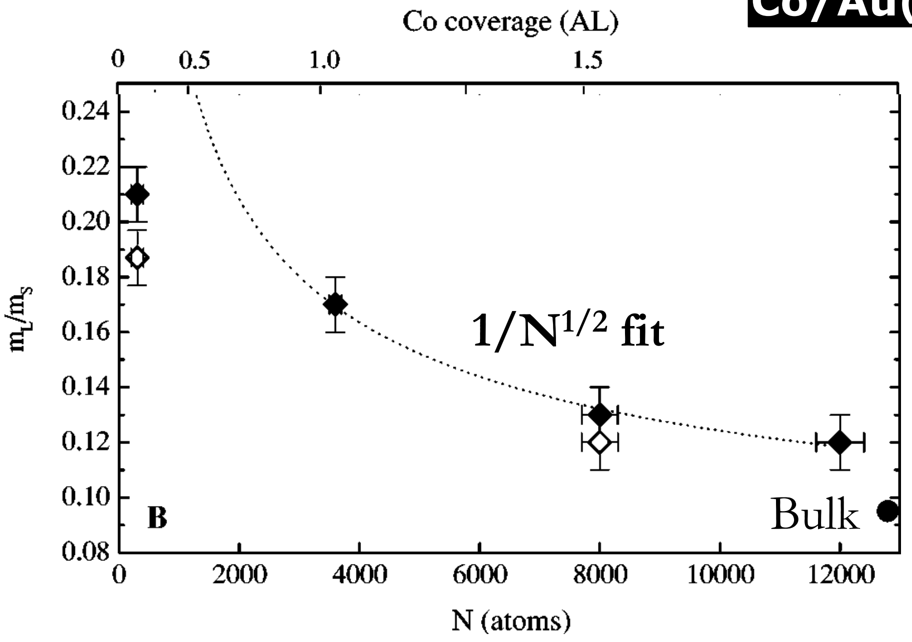
TOM magnetometry

Step on Fe(110): $+0.7\mu_B$

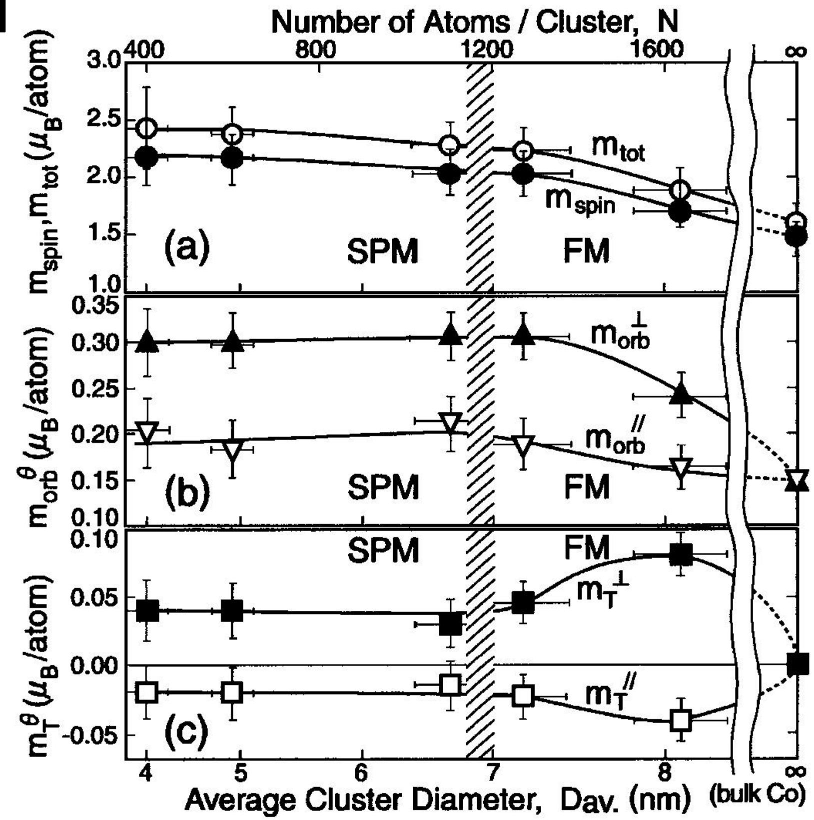
M. Albrecht et al., Europhys. Lett. 20, 65 (1992)

H.Dürr et al., PRB59, R701 (1999)

Co/Au(111)



K. Koide et al., PRL87, 257201 (2001)



Conclusion: extra orbital $2\mu_B$/edge atome

Problems:

- dots coalescence above 1300 atoms: non-valid fit…
- Estimation of dot size by Langevin function (Brillouin ½ better suited)

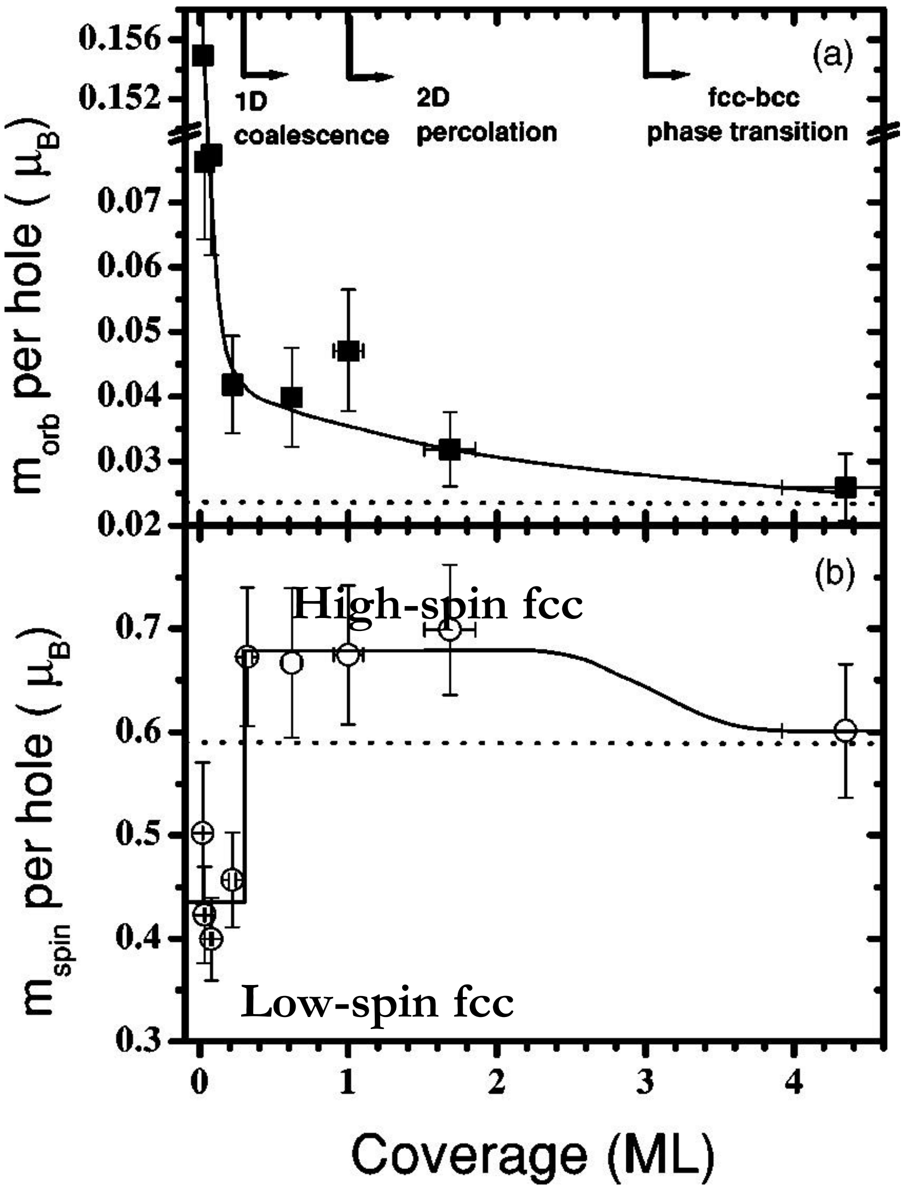
Conclusion: no extra orbital moment for edge atoms (dot='small thin film').

Problems:

- dot size is still large.

Need smaller systems !

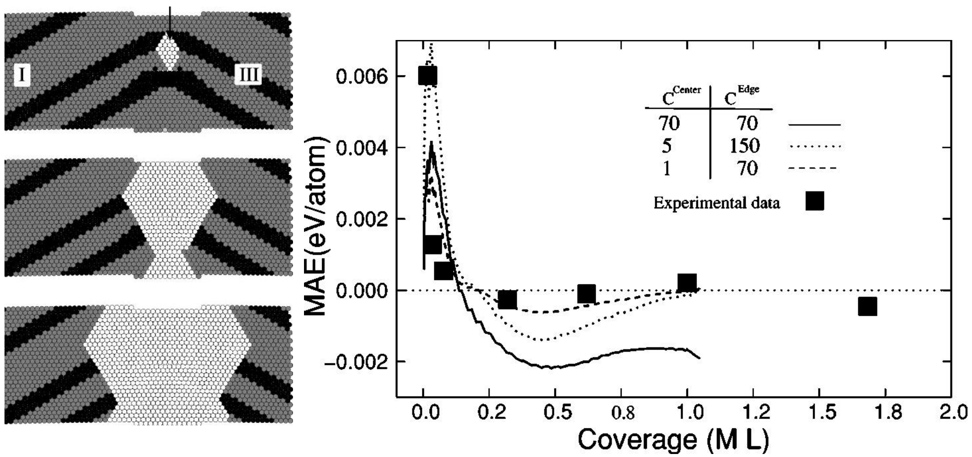
P. Ohresser et al., PRB64, 104429 (2001)



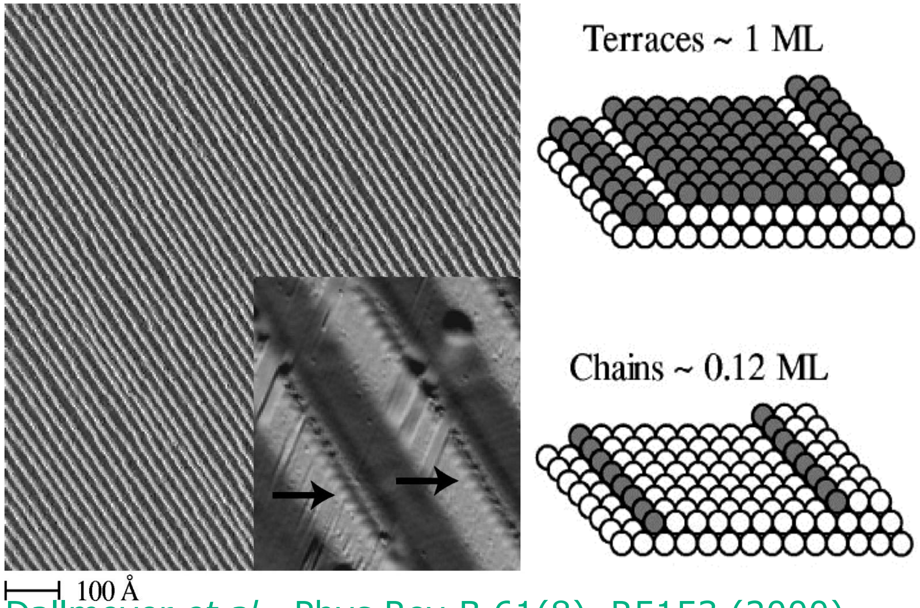
Fe/Au(111)

Conclusions:

- Spin moment not modified at edges (spin more influenced by deformation)
- Edge orbital moment ~ $0.5\mu_B$, similar to steps on vicinal Fe.



Co/Pt(997)



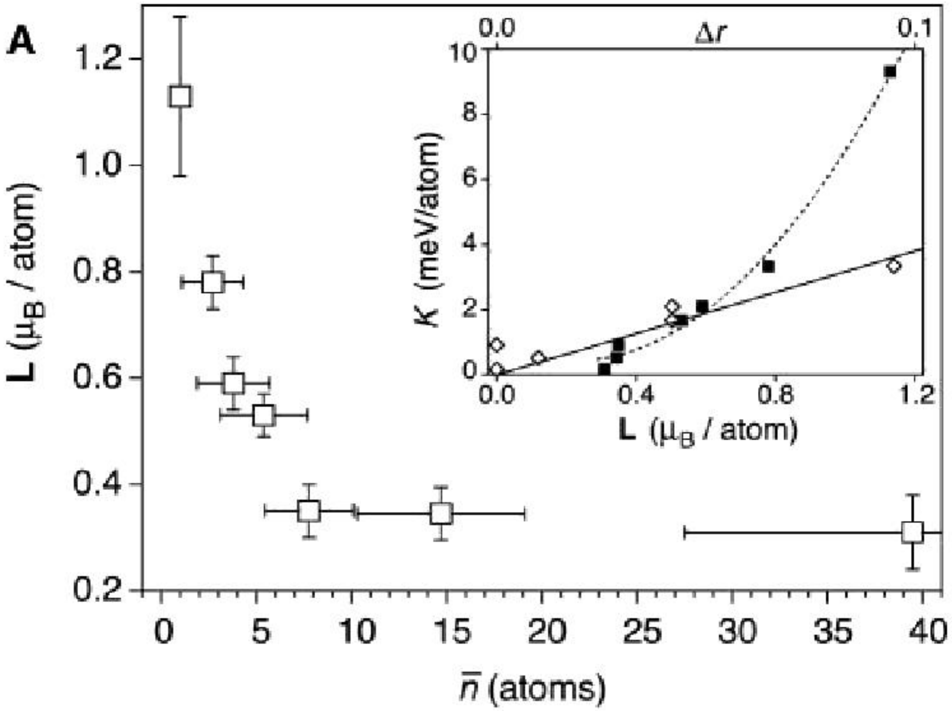
A. Dallmeyer *et al.*, Phys.Rev.B 61(8), R5153 (2000)

Conclusions

- Bulk: m_L=0.14μ_B/at.
- Surface: m_L=0.31μ_B/at.
- Bi-atomic wire: m_L=0.37μ_B/at.
- Mono-atomic wire: m_L=0.68μ_B/at.
- bi-atom: m_L=0.78μ_B/at.
- atom: m_L=1.13μ_B/at.

P. Gambardella et al., Nature 416, 301 (2002)

Co/Pt(111)



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

Conclusions

- From bulk to atoms: considerable **increase of orbital moment**
- **2 atoms closer to wire than 1 atom**
- **bi-atomic wire closer to surface than wire**

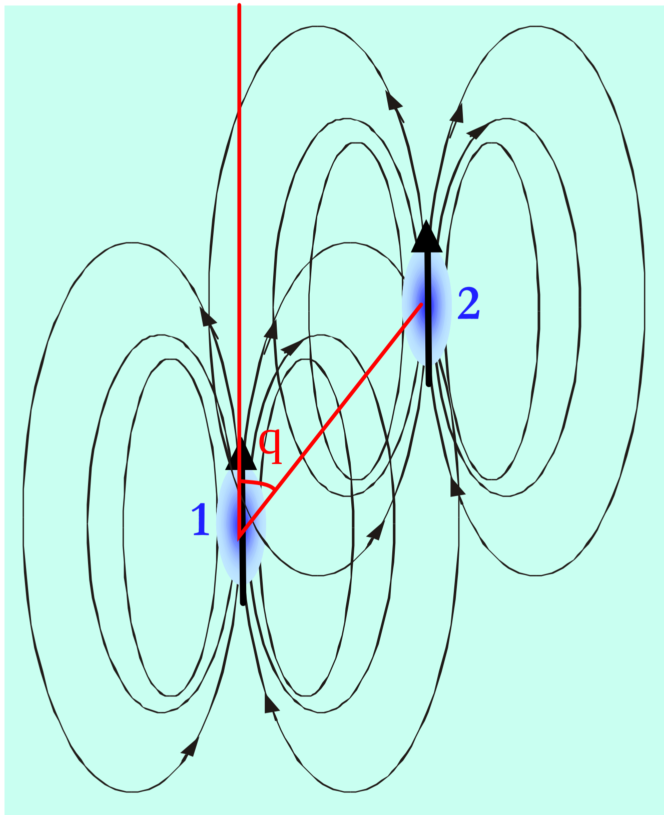
3.1 Methods

- 3.2 Microscopic origins of Magnetic Anisotropy Energy (MAE)
- 3.3 Can one disentangle magnetoelastic from surface anisotropy?
- 3.4 Temperature dependance of anisotropy in low dimension
- 3.5 From surfaces (2D) to atoms (0D)

Dipolar energy

Mutual energy of two magnetic dipoles :

$$E_{1,2} = \frac{\mu_0}{4\pi r^3}\left[\vec{\mu}_1.\vec{\mu}_2 - \frac{3}{r^2}(\vec{\mu}_1.\vec{r}).(\vec{\mu}_2.\vec{r})\right]$$



Let us assume two magnetic dipoles with vertical direction, either 'up' or 'down' :

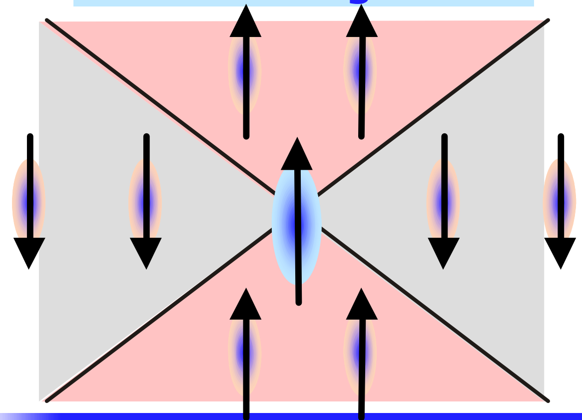
$$E_{1,2}(\theta) = \frac{\mu_0}{4\pi r^3} m_1 m_2 \left[1 - 3\cos^2\theta\right]$$

$$\cos^2(\theta_C) = 1/3$$

Parallel alignment is favored for $\theta < \theta_C \approx 54.74°$

Antiparallel alignment is favored for $\theta > \theta_C \approx 54.74°$

'Cone' of alignment



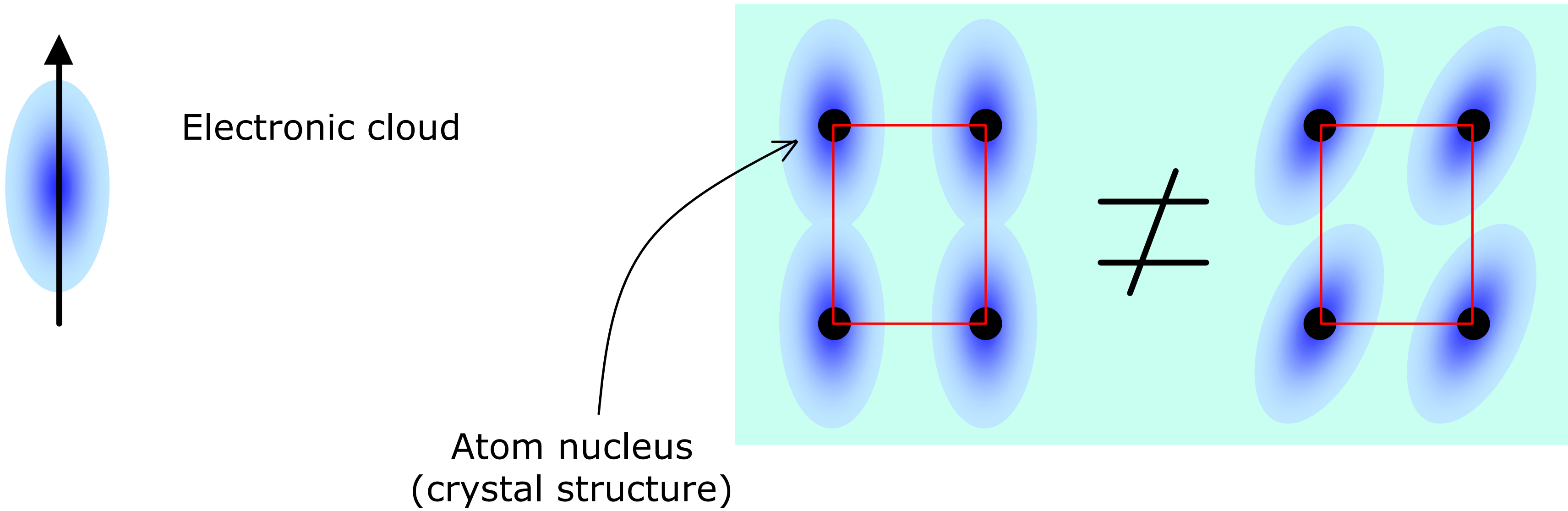
Conclusions

- Nanostructures: long axis favored
- Films: in-plane favored

$$e_d^z = \frac{1}{2}\mu_0 M_Z^2$$

Cf lecture by Dominique GIVORD

Magnetocrystalline anisotropy energy



Spin-orbit coupling ⇨ the energy of both spin and orbital moment depends on orientation

Series development on an angular basis:

Anisotropy energy **Normalized magnetization components**

$$E_{mc} = K_1 m_z^2 + K_2 m_z^4 + \ldots$$ Uniaxial

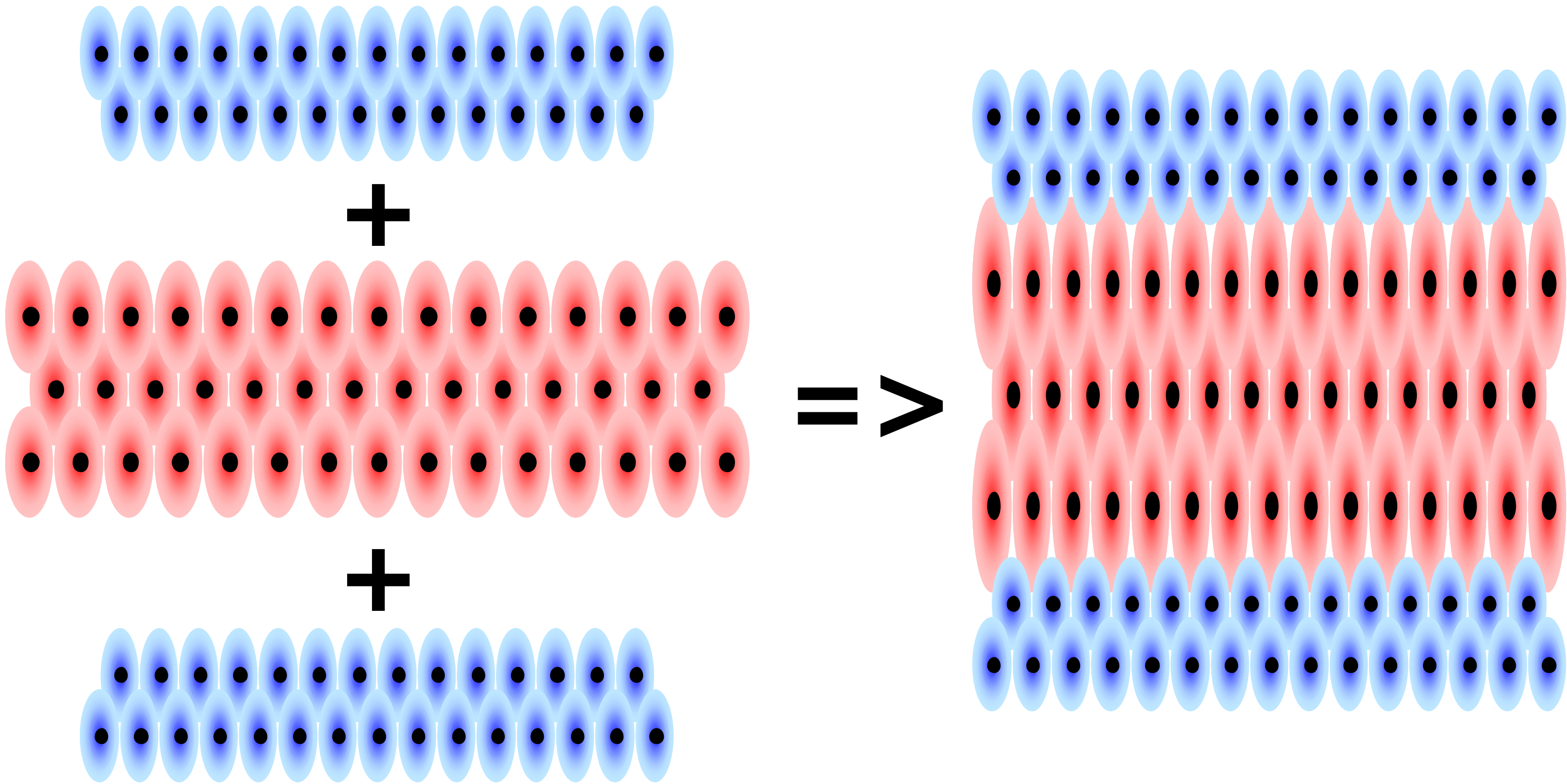
$$E_{mc} = K_4 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + \ldots$$ Cubic

…

Alignement of magnetization is favored along given axes of the crystal

(Derived from slide of A. Thiaville - CNRS/Orsay)

Magneto-elastic anisotropy



Origin

Deformation of orbitals

→ Correction to the magneto-crystalline energy

Result

$$E_{mel} = K_{mel,1} \cos^2(\theta) + \dots$$

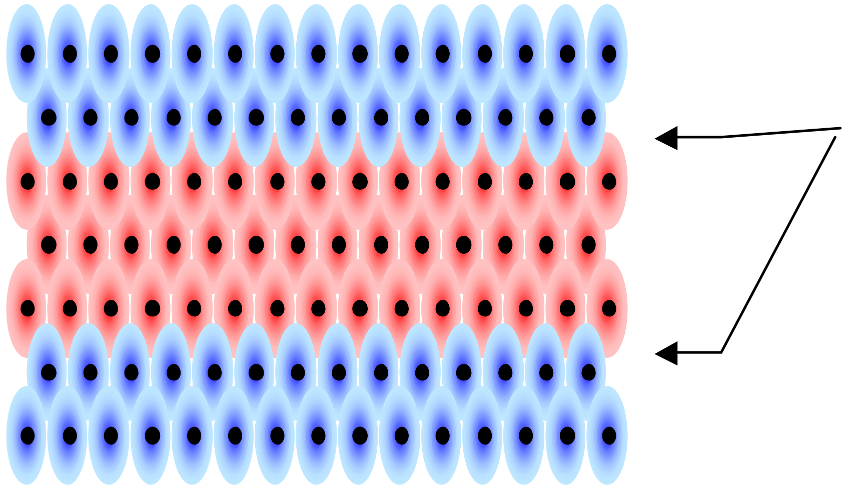
$$K_{mel,i} \sim B_i \varepsilon$$

Surface anisotropy

L. Néel,
J. Phys. Radium 15,
15 (1954)

« Anisotropie magnétique superficielle et surstructures d'orientation »

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for surface/interface atoms

⇒ Correction to the magneto-crystalline energy

$$E_s = K_{S,1} \cos^2(q) + K_{S,2} \cos^4(q) + \dots$$

« Cette énergie de surface, de l'ordre de 0.1 à 1 erg/cm2, est susceptible de jouer un rôle important dans les propriétés des substances ferromagnétiques dispersées en éléments de dimensions inférieures à 100Å »

« This surface energy, of the order of 0.1 to 1 erg/cm2, is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å »

Pair model of Néel:

- Ks estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only: correct value from experiments or calculations (precision !)

Lecture of Edgar Bonet

Magnetic Anisotropy Energy (MAE): Link with anisotropy of orbital moment

Theory

Perturbation theory for 3d metals:

$$\mathrm{MAE} = a \frac{x}{4 m_B} \Delta m_L$$

P. Bruno, PRB39, 865 (1993)

m_L does not rotate in 3d metals
-> MAE reflects cost in x

Covers magnetocrystalline, magnetoelastic and surface anisotropy

Experiments

Cf lecture by Stefania PIZZINI

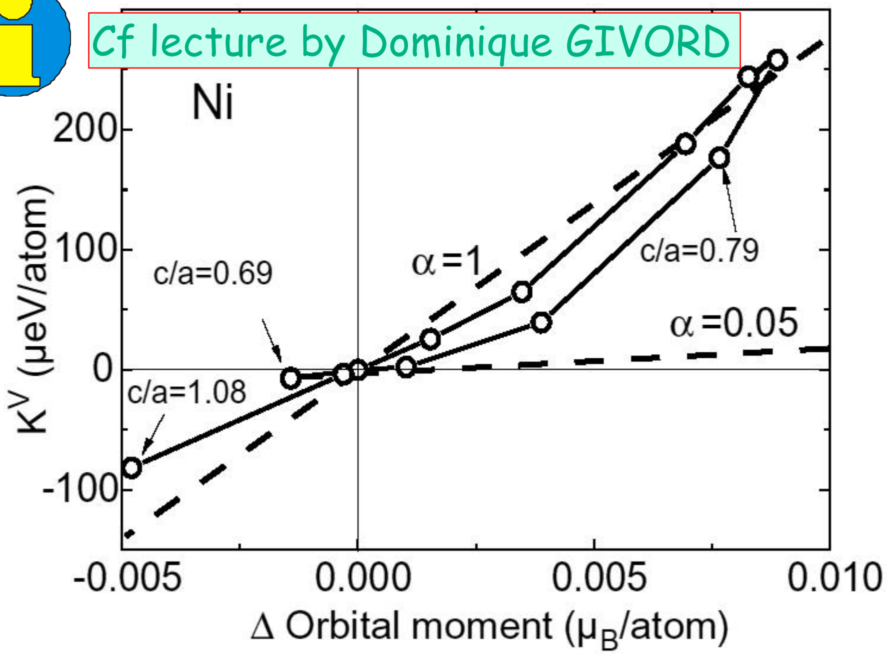
Bulk (Fe, Ni, …)

$\Delta m_L \approx 10^{-4} m_B$ / atom → $\mathrm{MAE} \leq 1 m\,\mathrm{eV}$

Ab initio calculations

High precision needed: $1 m\,\mathrm{eV} << 10\,\mathrm{eV}$

Cf lecture by Dominique GIVORD



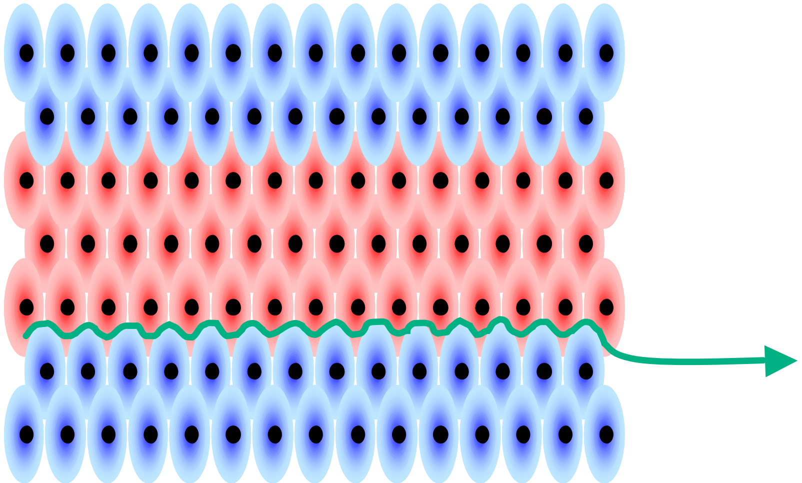
O. Hjortstam et al., PRB55, 15026 (1997)

Conclusions

- Origin of MAE = anisotropy of orbital moment
- No strict linearity
- α may also depend on thickness in thin films (band structure)
  → Direct measurement of MAE preferable

Dipolar contribution to surface anisotropy

(less known)



Overview

Atomic-scale roughness

Correction to the dipolar energy

Inter-atomic distance

$$E_{s,magn.} = -k_s d \left[\frac{1}{2}\mu_0 M_S^2\right]\cos^2(\theta)$$

(One k_S for each surface)

Surface	k_s
fcc(111)	0.0344
fcc(001)	0.1178
hcc(110)	0.0383
bcc(001)	0.2187
hcp(0001)	0.0338

H.J.G. Draaisma, W.J.M. de Jonge, JAP 64, 3610 (1988).

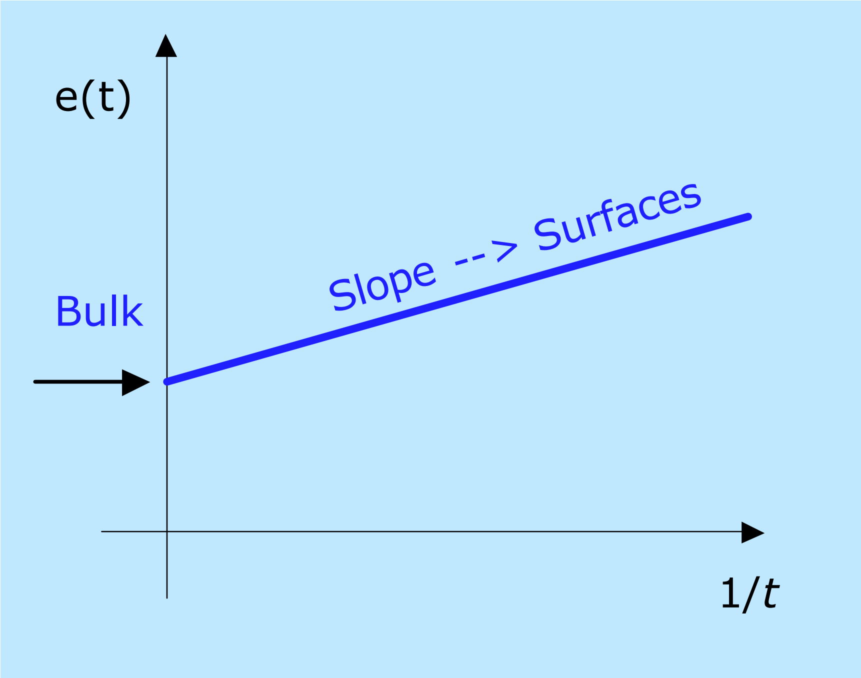
(included in Néel's pair interaction model from 1954 !)

Conclusion

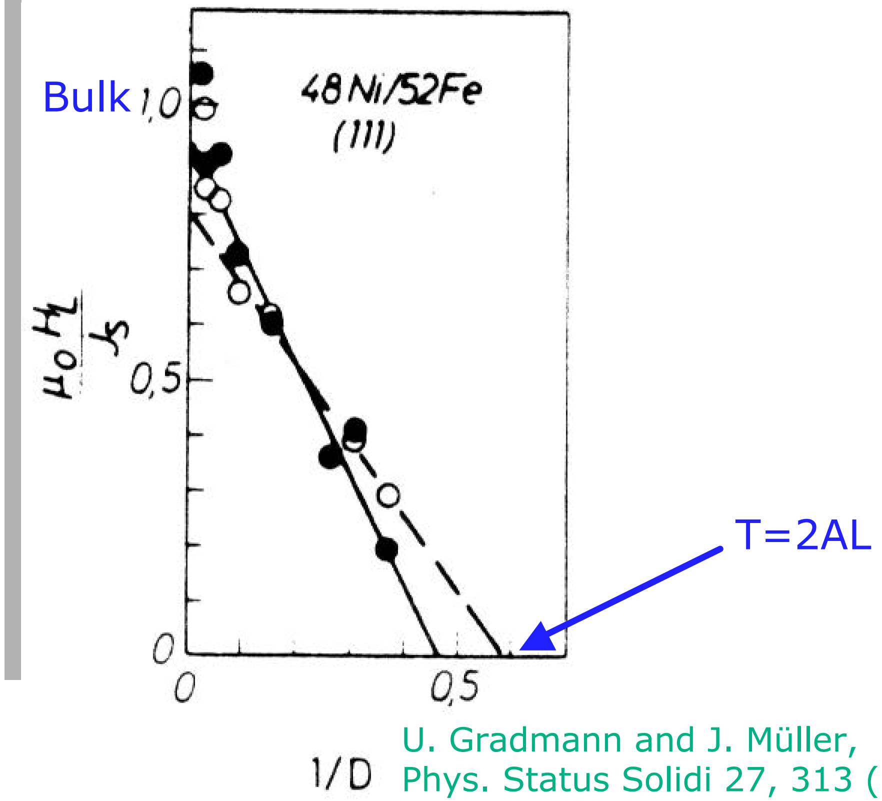
Modifications more important for 'open' surfaces

History of surface anisotropy : STEP 1 (1/t plot)

$$E_{tot}(t) = k_V t + 2k_S \Rightarrow e(t) = k_V + \frac{2k_S}{t}$$

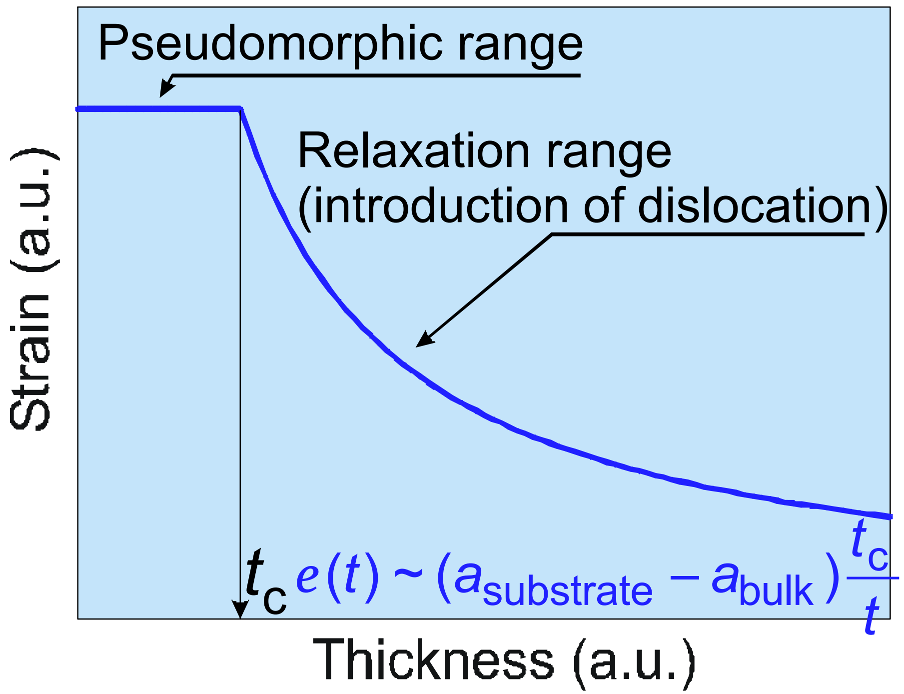


First example of perpendicular anisotropy

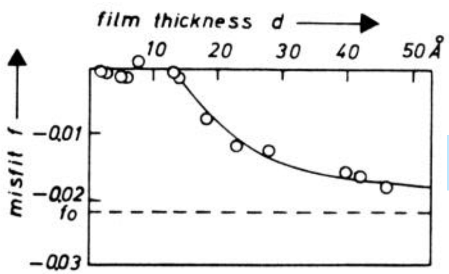


U. Gradmann and J. Müller, Phys. Status Solidi 27, 313 (1968)

Structural relaxation



W. A. Jesser et al., Phys. Stat. Sol. 19, 95 (1967)



Co/Cu(111)

U. Gradmann, Appl. Phys.3, 161 (1974)

Effect on anisotropy

Magneto-elastic anisotropy:

$$k_{mel} \sim B_{mel} e$$

Strain relaxation regime:

$$k(t) = k_{bulk} + a\ B_{mel} / \mathrm{t}$$

Conclusion:

Mixing of surface and magneto-elastic contributions

$$e(t) = k_V + \frac{2k_S}{\mathrm{t}}$$

C. Chappert and P. Bruno., JAP64, 5736 (1988)

Cf lecture by Stephane ANDRIEU

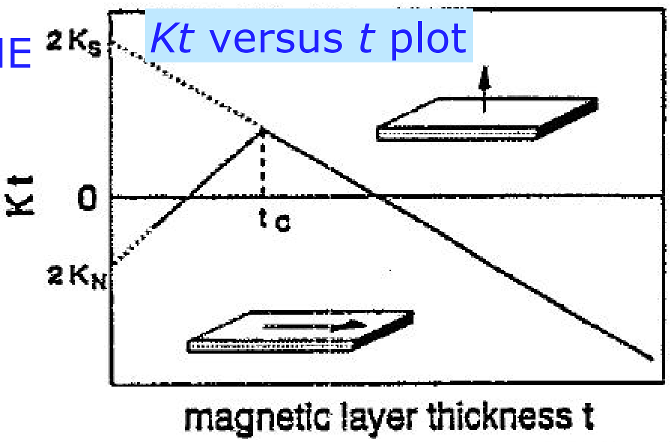
History of surface anisotropy : STEP 3 (1/t plot plus magn.elas. correction)

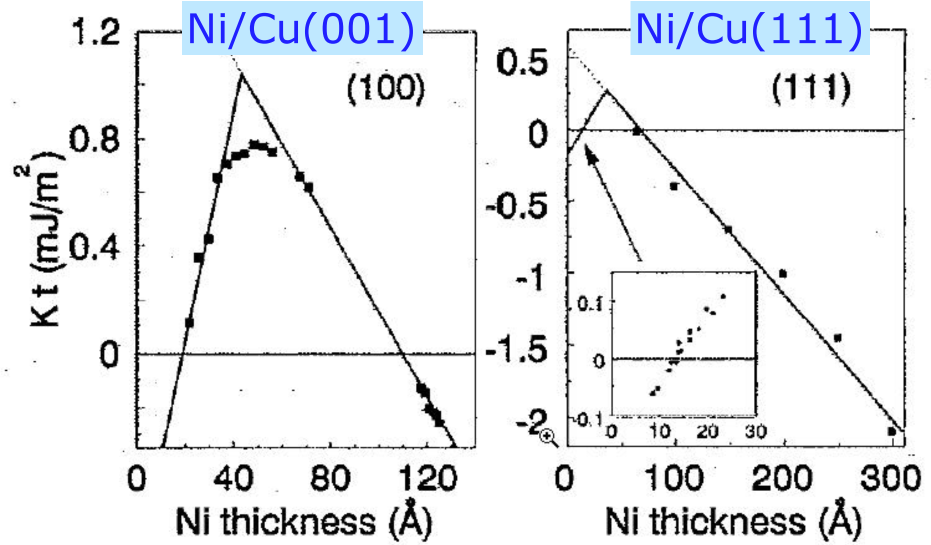
Methods:

- 1/t plot in the pseudomorphic range ($t<t_c$)
- 1/t plot with magnetoelastic corrections beyond ($t>t_c$)

Surface + ME

Surface





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

FIG. 2. The product of total anisotropy K and Ni layer thickness t, plotted as a function of t for (100) and (111) orientations.

TABLE I. Summary of Cu/Ni anisotropy data pertaining to both investigated orientations. Critical thicknesses (t_c reported for both single layers and sandwiches) and stress-induced anisotropy energies are determined both experimentally and (in parentheses) by calculation.

Orientation	ced y
(111)	(0.64)
	m³ (0.36)
(100)	(0.8)
	m³ (0.39)

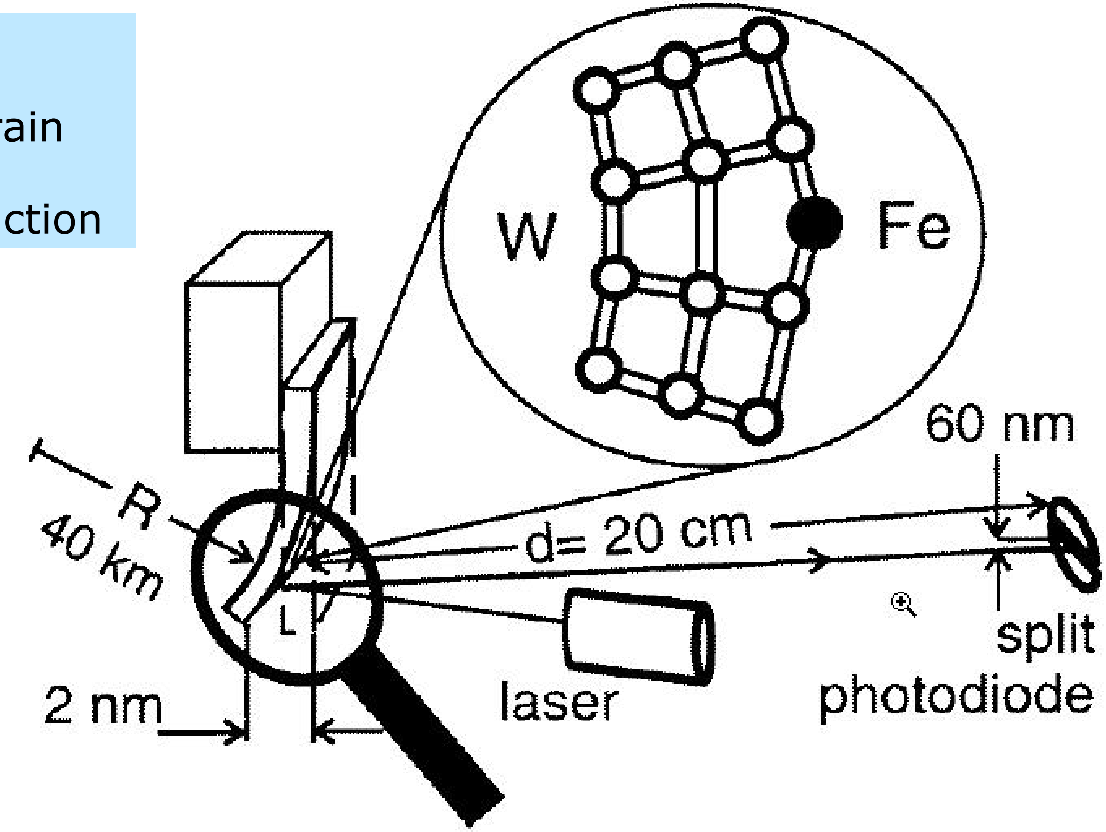
The positions of the breaks are not in agreement with the t_c values established from LEED studies. Probably the presence of the overlayer has increased t_c for the sandwich structure

History of surface anisotropy : STEP 4
(Direct measurement of magneto-elastic coupling coefficients)

D Sander *et al*

Methods:

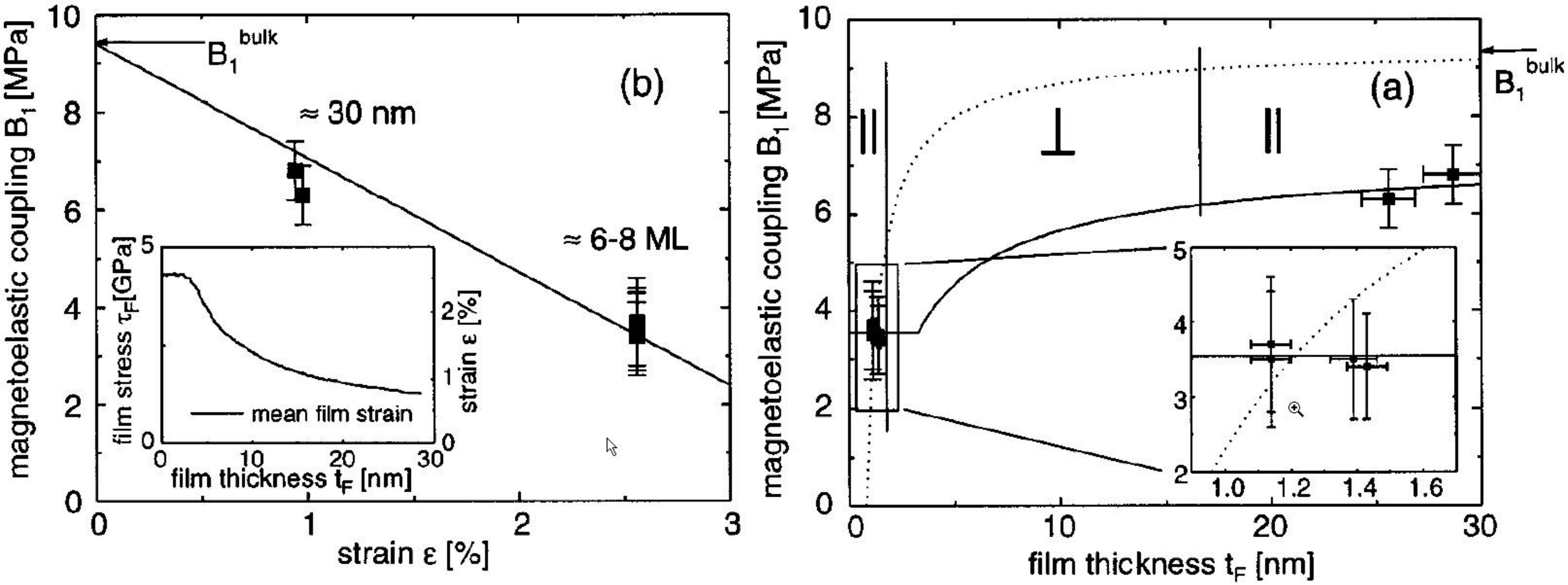
- H = 0 : stress > strain
- H ¹ 0 : magnetostriction



Groups: Sander, O'Handley, Farle

History of surface anisotropy : STEP 4
(Direct measurement of magneto-elastic coupling coefficients)

Ni/Cu(001)



Th. Guthjar-Löser *et al.*, JAP87, 5920 (2000)

Conclusion:

Magneto-elastic coefficients are strain-dependant:
(they are not constants)

$$B(e) = B_{\text{bulk}} + De$$

Fe(001)/W(001)

The correlation between mechanical stress and magnetic anisotropy 851

D. Sander, Rep. Prog. Phys. 62, 809 (1999)

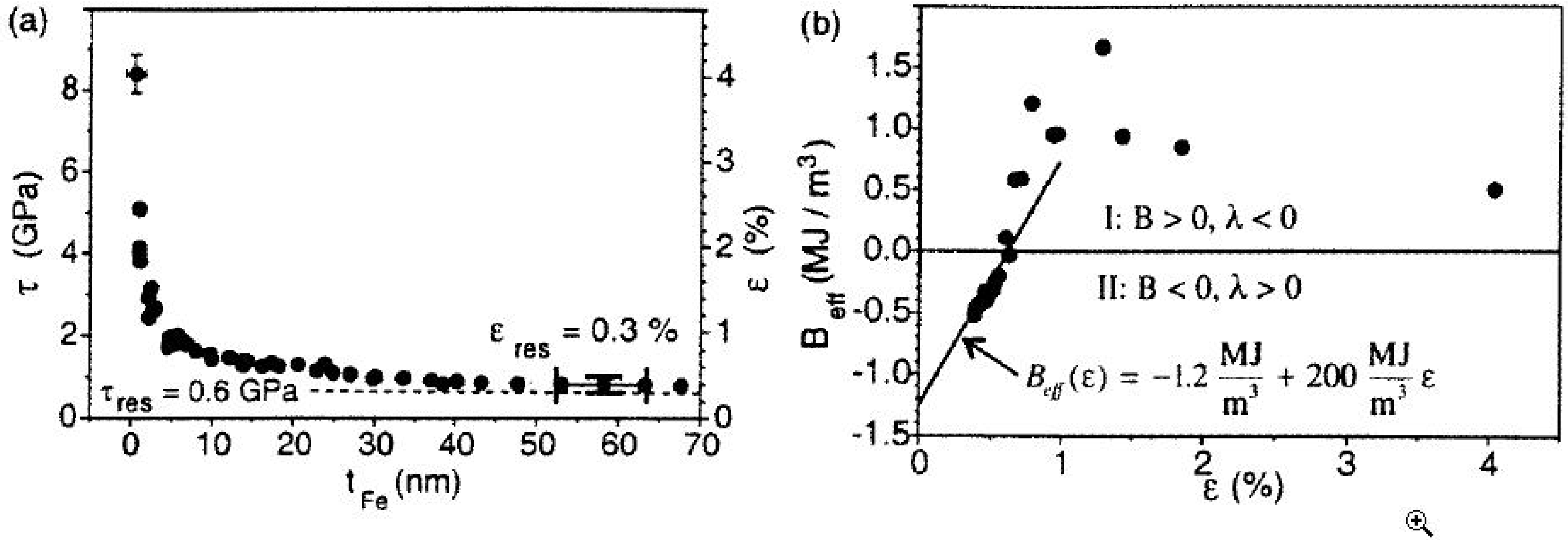


Figure 19. Simplified stress analysis. (*a*) Average film stress, left axis, and film strain, right axis, of Fe(100) on W(100), grown at 300 K. (*b*) Effective magneto–elastic coupling, B_{eff} data from figure 18, as a function of film strain. A linear strain correction of B_{eff} is deduced from the slope and the intercept of the linear curve for $\epsilon < 0.6\%$. After [10].

Conclusion:

Magneto-elastic coefficients can even change of sign for strain smaller than 1%.

Principle

- Use a **pair model** to predict surface anisotropy
- Surface/interface = **symmetry breaking (no pairs)**
- Pair constants: **derived from magnetostriction**
- **Does not depend on the nature of the interface** (UHV, material, …)
- However:
yields good order of magnitude:~100μeV/atom

See highly non-linear magnetoelasticity

L. Néel, J. Phys. Radium 15, (1954).

Conclusion (pessimistic view)

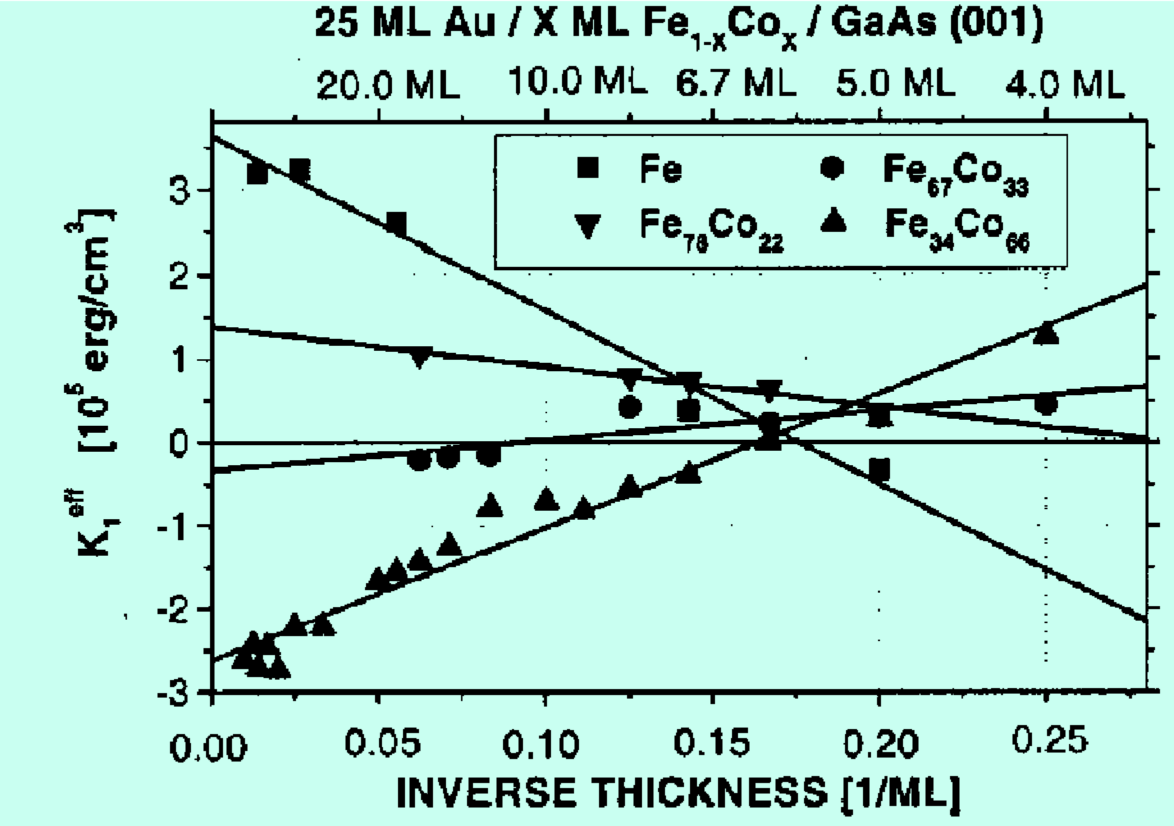
- Can we really derive surface anisotropy in the sense of Néel?
- Yields order of magnitude, but not values (not even sign)

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 10 15 MAY 2002

Volume and interface magnetic anisotropy of $Fe_{1-x}Co_x$ thin films on GaAs(001)

M. Dumm et al., JAP91, 8763 (2002)

M. Dumm,[a)] B. Uhl, M. Zölfl, W. Kipferl, and G. Bayreuther
Institut für Experimentelle und Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany



- Slope : bulk-like terms
- Intercept with Y axis: surface-like terms

$K_S \sim K_{bulk}$?

Conclusion (optimistic view)

- Pair model might work better with material-dependant phenomenologic parameters ?

Bulk

- Generally decays faster than Ms(T)
- Roughly scales with $M_s^{\frac{n(n+1)}{2}}(T)$

E. Callen and H.B. Callen, PR139, A455 (1965)

Low dimension

- Thermal decay enhanced
- A more natural variable than T could be

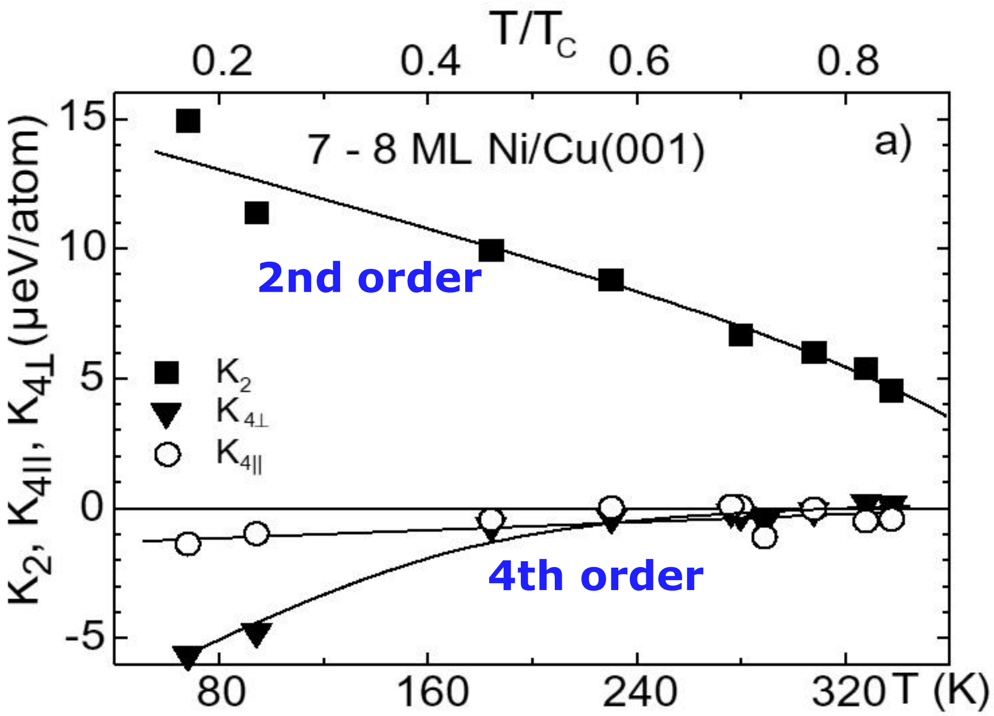
$t = T / T_c$

$t(m_s)$ with

$m_s(T) = M_S(T) / M_S(0K)$

Conclusion:

Higher order constants decay indeed faster



M. Farle et al., PRB55, 3708 (1997)

Surface versus volume

fcc 3d/Cu(001)

	Low temp	RT	
Fe	⊥	//	Ks favors perpendicular anisotropy
Ni	//	⊥	Ks favors in-plane anisotropy

Conclusion:

Generally observed: purely **surface constants decay faster than volume** constants

Thin films versus bulk

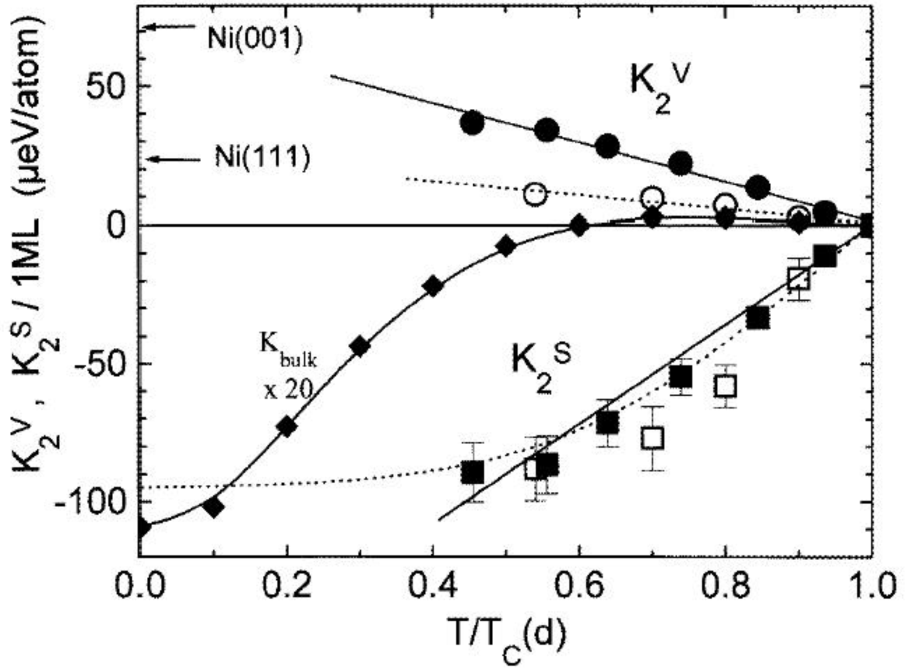


Figure 21. Temperature dependence K_2^S (squares) and K_2^V (circles) for Ni(111) on smooth W(110) (□○) and Ni(001) on Cu(001) (■●). The cubic anisotropy of bulk Ni (♦) after [46] is given also. Broken and full curves are guides to the eyes.

Conclusion:

- **Not well understood in thin films** > measurements are needed in each system
- Generally observed: purely **surface constants decay faster than volume** constants
- Bulk constants might however decay faster than in thin films (with T/Tc) because of symmetry breaking, implying lower order orbitals.

Systems

Vicinal surfaces

- Numerous studies during the late 1990's

⇨ Conclusion similar to that drawn below (but only for steps)

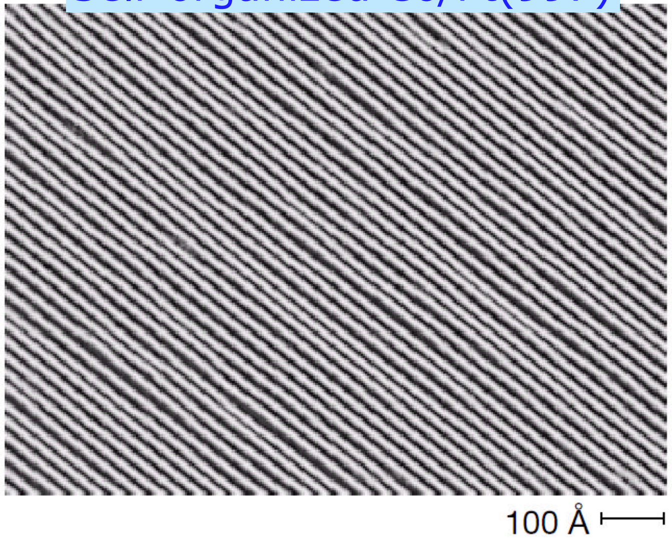
Sub-atomic-layer epitaxial deposits on surfaces

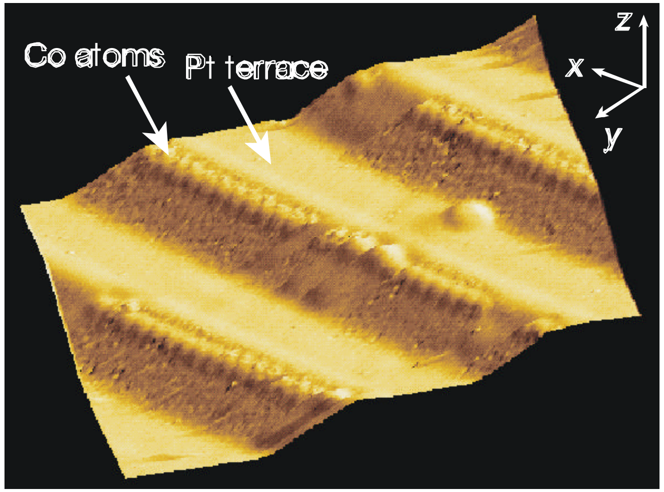
- Self-organization is preferable (smaller size distribution)
- Low-temperature deposition for the smallest clusters

See Co/Au(111) ⇨ **Separation of 2D versus 1D (edge) contributions?**

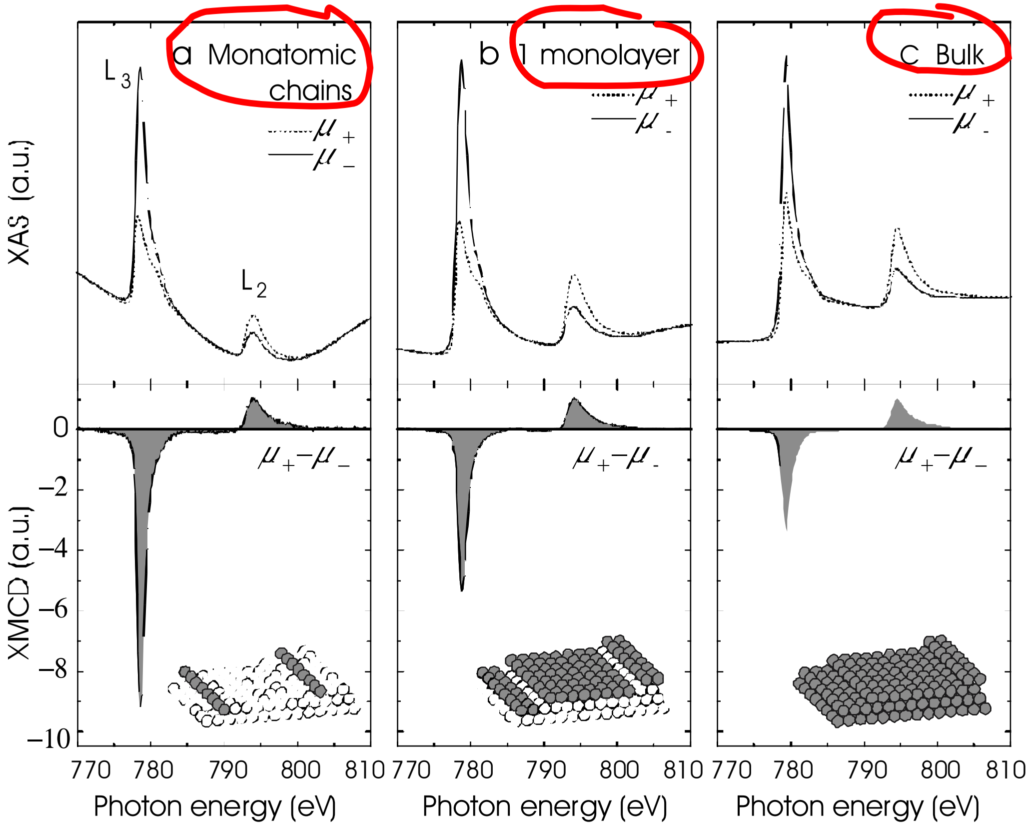
From surface to wires (1D)

Self-organized Co/Pt(997)





P. Gambardella et al., Nature 416, 301 (2002)



$$m_L \approx \int L_3 + \int L_2$$

$$m_s^{eff} \approx -\int 2L_3 + 4\int L_2$$

Conclusion:

- Increase of orbital moment (necessary condition for anisotropy)
- Anisotropy of orbital moment?

From surface to wires (1D)

Method

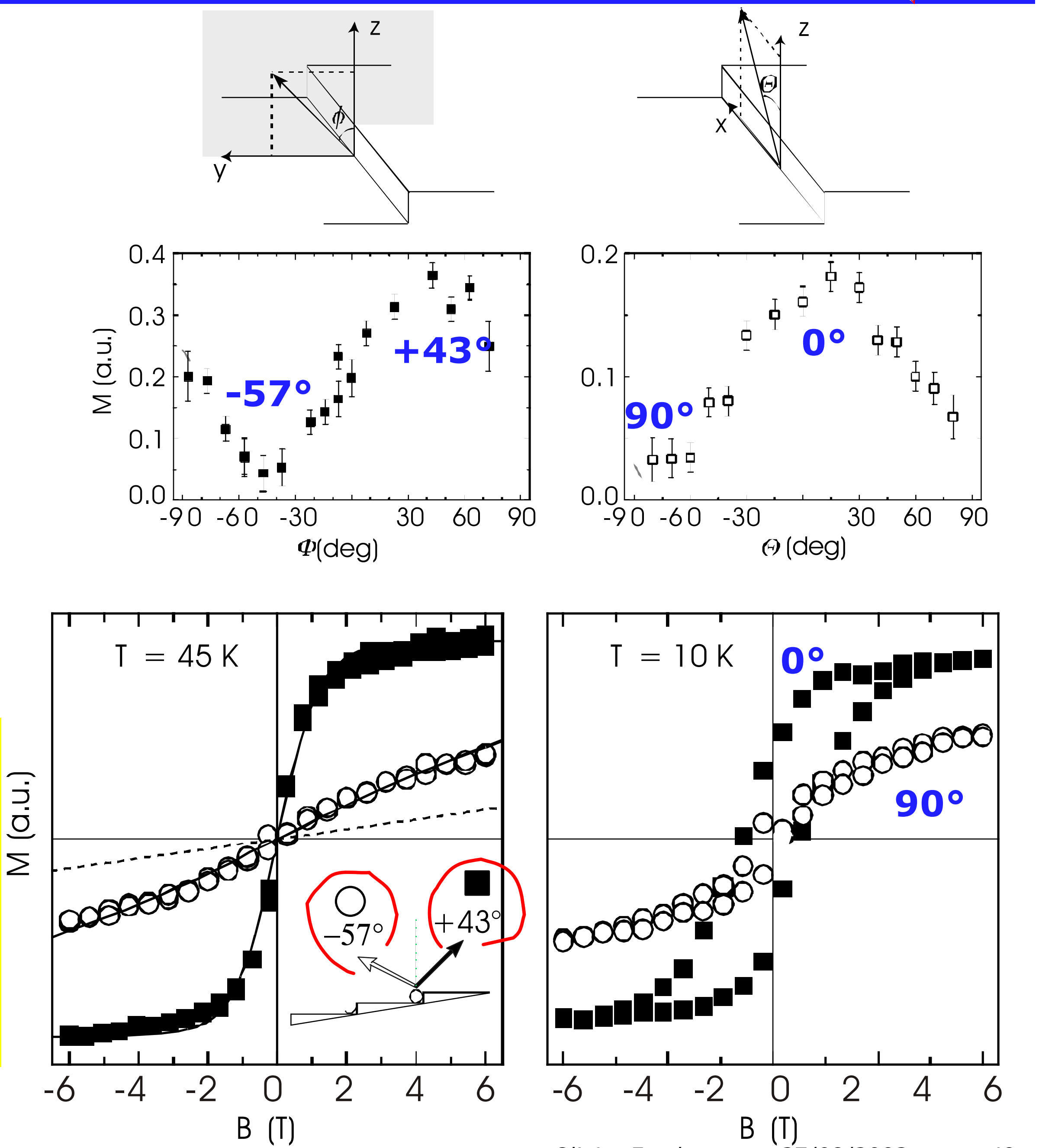
- XMCD > Orbital moment
- Fit magnetization curves > Anisotropy functional

MAE

- Bulk Co: 40μeV/atom
- Co ML: 140μeV/atom
- Co bi-wire: 0.34meV/atom
- Co wire: 2meV/atom

Conclusions:

- Easy axis of magnetization perpendicular to the wires, but not the the mean film surface, nor to Pt(111)
- See anisotropy of orbital moment on the saturation XMCD.



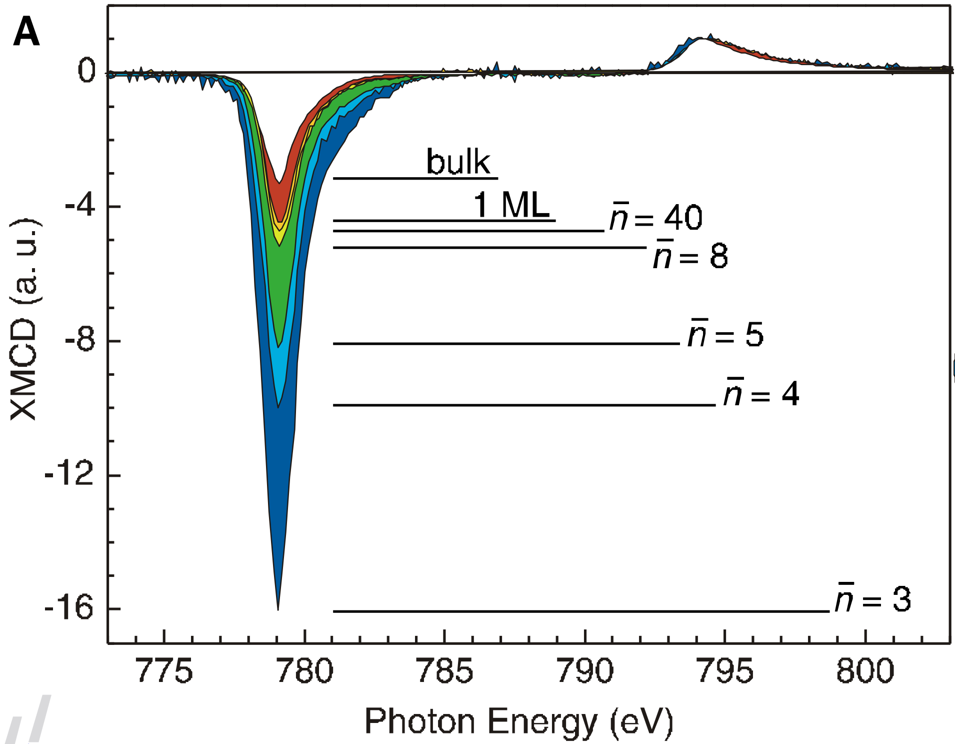
From surface to atoms (0D)

Co/Pt(111)

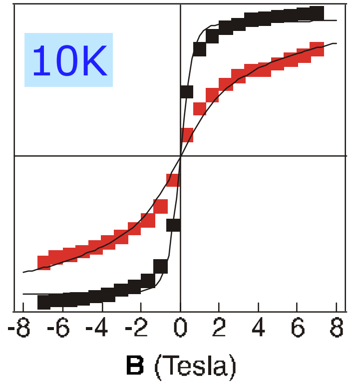
Giant Magnetic Anisotropy of Single Cobalt Atoms and Nanoparticles

P. Gambardella,[1,2]* S. Rusponi,[1,2] M. Veronese,[3] S. S. Dhesi,[4]† C. Grazioli,[3] A. Dallmeyer,[5] I. Cabria,[5] R. Zeller,[5] P. H. Dederichs,[5] K. Kern,[1,2] C. Carbone,[3,5] H. Brune[1]

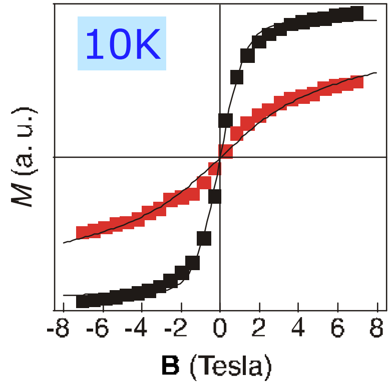
P. Gambardella et al., Science 300, 1130 (2003)



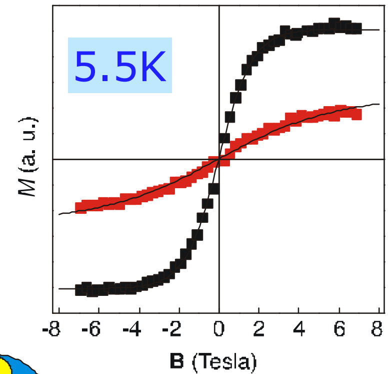
8 atoms



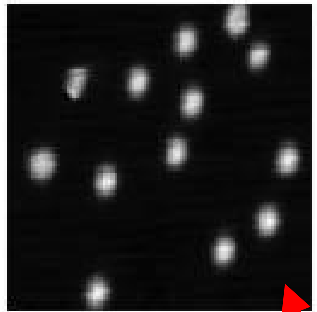
4 atoms



1 atom



STM, 8.5nm, 5.5K



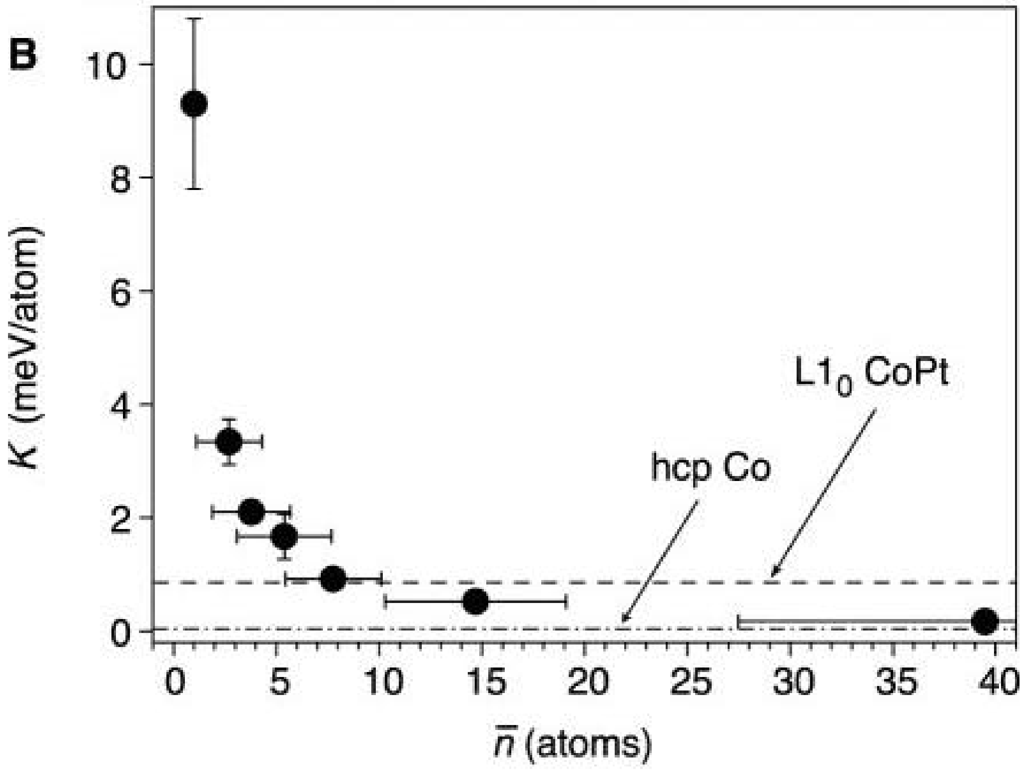
Cf question by Dominique GIVORD

Qualitatively:

- Easy axis of magnetization perpendicular to Pt(111)
- See anisotropy of orbital moment on the saturation XMCD.

From surface to atoms (0D)

Co/Pt(111)



MAE

- Bulk Co: 40μeV/atom
- Co ML: 140μeV/atom
- Co bi-wire: 0.34meV/atom
- Co wire: 2meV/atom
- Co bi-atom: 3.4meV/atom
- Co atom: 9.2meV/atom

- **5.1 Theoretical description**
- **5.2 Experimental examples**
- **5.4 Fitting superparamagnetic curves**
- **5.3 How can one overcome superparamagnetism?**

Simplified framework

- Stoner-Wohlfarth (rigid macrospin)
- Second order anisotropy, field along easy axis:

$$E = K\sin^2(q\ ) + m_0 M_S H\cos(q\ )$$

- Thermal activation to jump over energy barriers described using Boltzmann statistics (Arrhenius law):

$$t\ = t_0 \exp\left(\frac{\Delta E}{k_B T}\right)$$

Attempt frequency $t_0 \sim 10^{-12} - 10^{-9}$ s

Cf lecture by Edgar BONET

Magnetic enthalpy

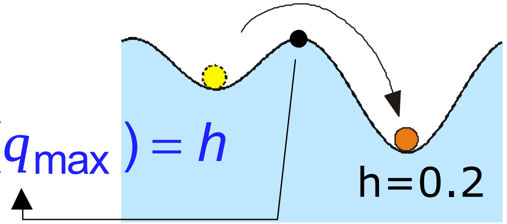
$$E = KV\sin^2(q) + m_0 M_S H V\cos(q)$$

$$e = \sin^2(q) + 2h\cos(q) \quad \left(h = m_0 M_S H / 2K\right)$$

Determination of barrier top

$$\frac{\partial E}{\partial q} = 0 \Rightarrow \cos(q) = m_0 M_S H / 2K$$

$$\frac{\partial e}{\partial q} = 0 \Rightarrow \cos(q_{max}) = h$$



Barrier height

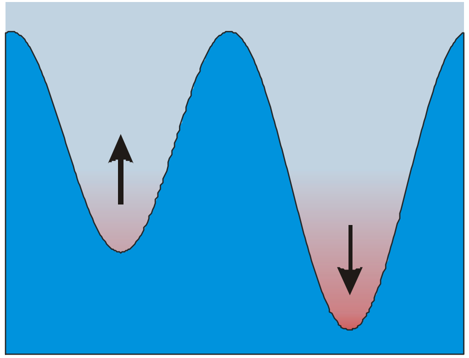
$$\Delta E = E(q_{max}) - E(0) = KV\left(1 - \frac{m_0 M_S H}{2K}\right)^2$$

$$\Delta e = e(q_{max}) - e(0) = (1-h)^2$$

Quasistatic measurement during time τ=1s

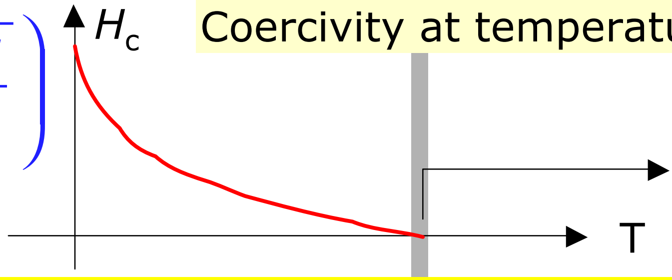
$$t = t_0 \exp\left(\frac{\Delta E}{k_B T}\right) \Rightarrow \Delta E = k_B T \ln(t / t_0) \sim 25 k_B T$$

$$t = t_0 \exp\left(\frac{\Delta e}{t}\right) \Rightarrow \Delta e = t\ln(t / t_0) \sim 25t$$



Coercivity at temperature T>0K

$$H_c = \frac{2K}{m_0 M_S}\left(1 - \sqrt{\frac{25 k_B T}{KV}}\right)$$



$$h_c = 1 - \sqrt{25t}$$

Blocking temperature

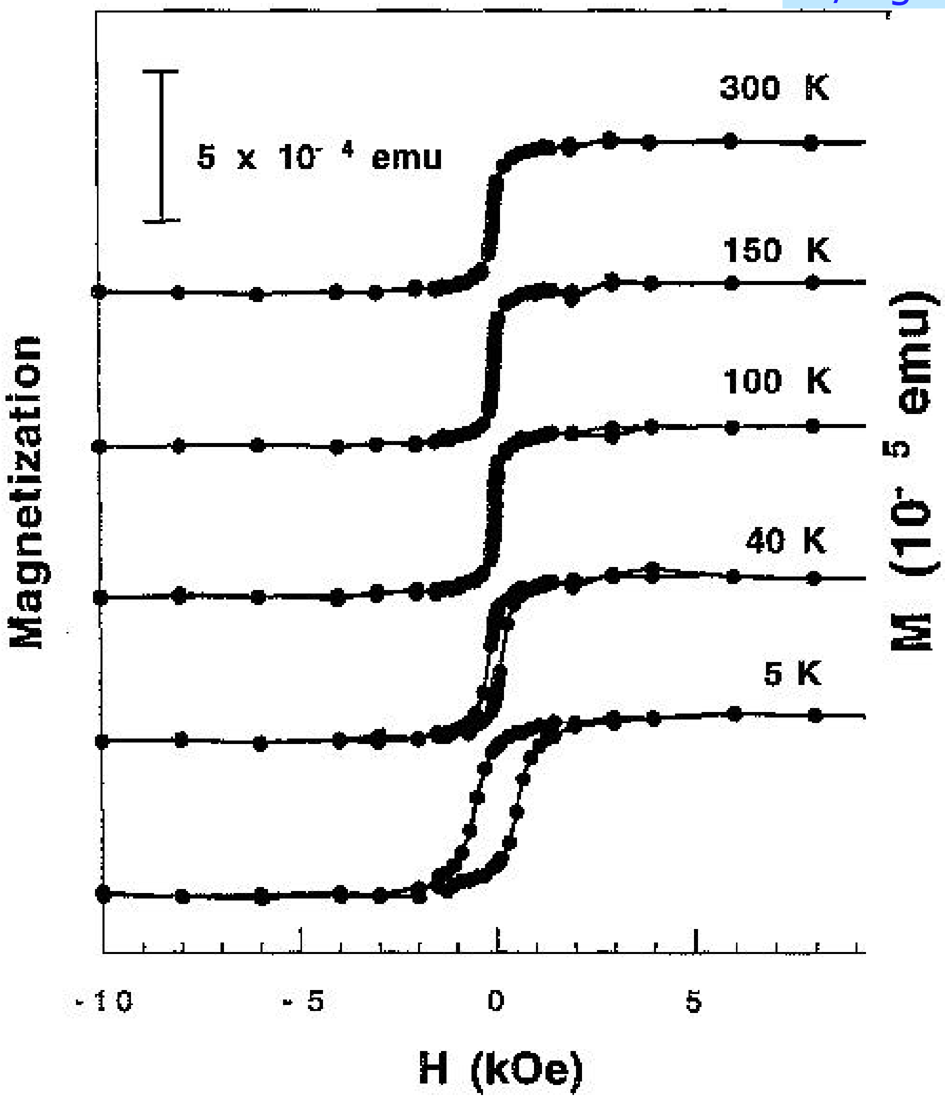
$$T_b = KV / 25 k_B$$

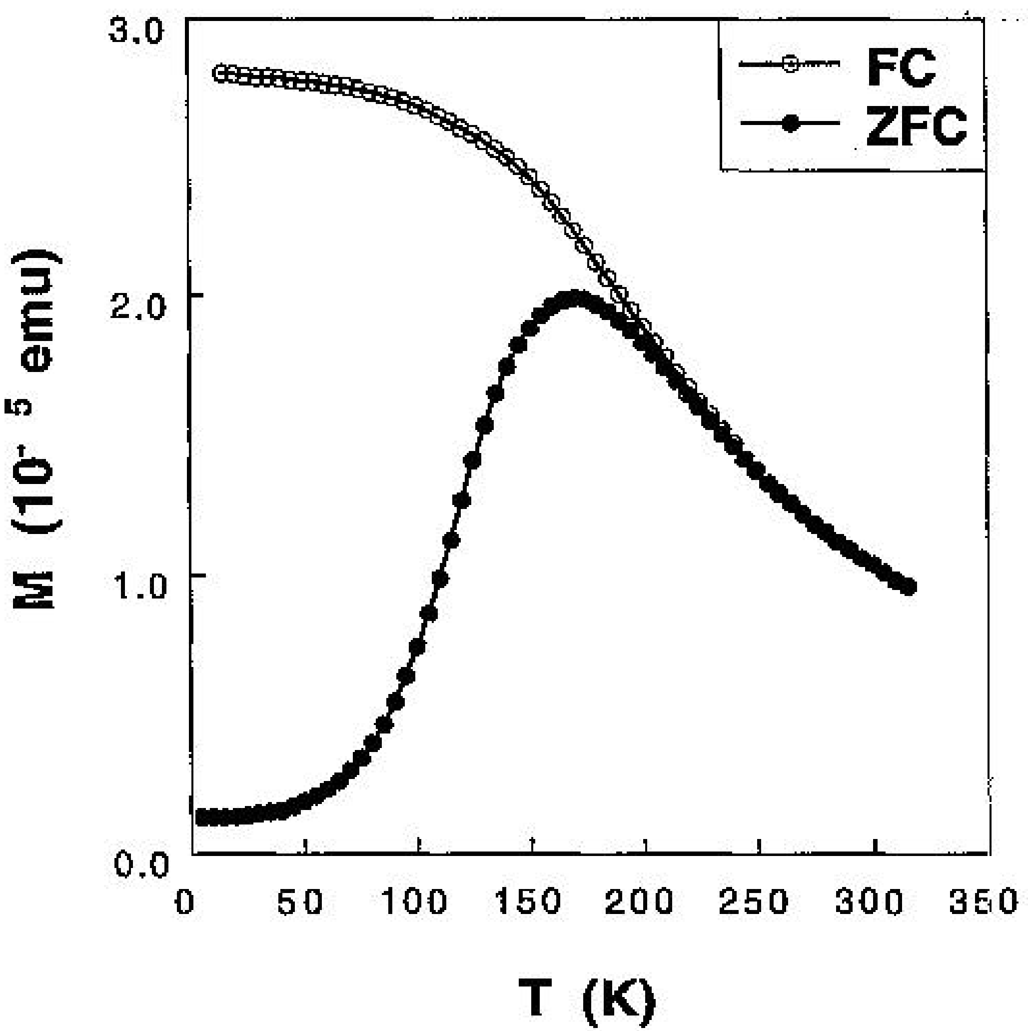
Superparamagnetism:
For moderate anisotropy *K* and/or volume *V*

Hysteresis loops

Fe/MgO(001) islands

Field cooled (FC) versus zero field cooled (ZFC)

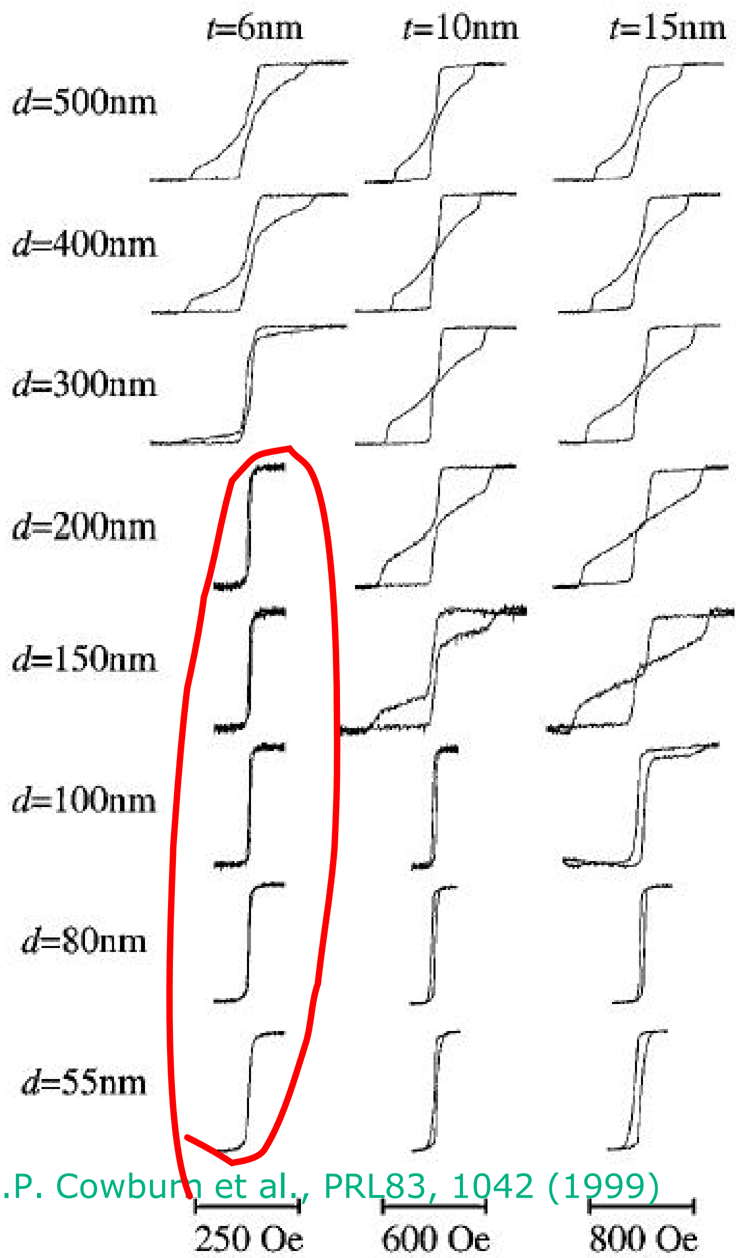




Y. Park *et al.*, PRB52, 12779 (1995)

Small dots made by lithography

Permalloy dots

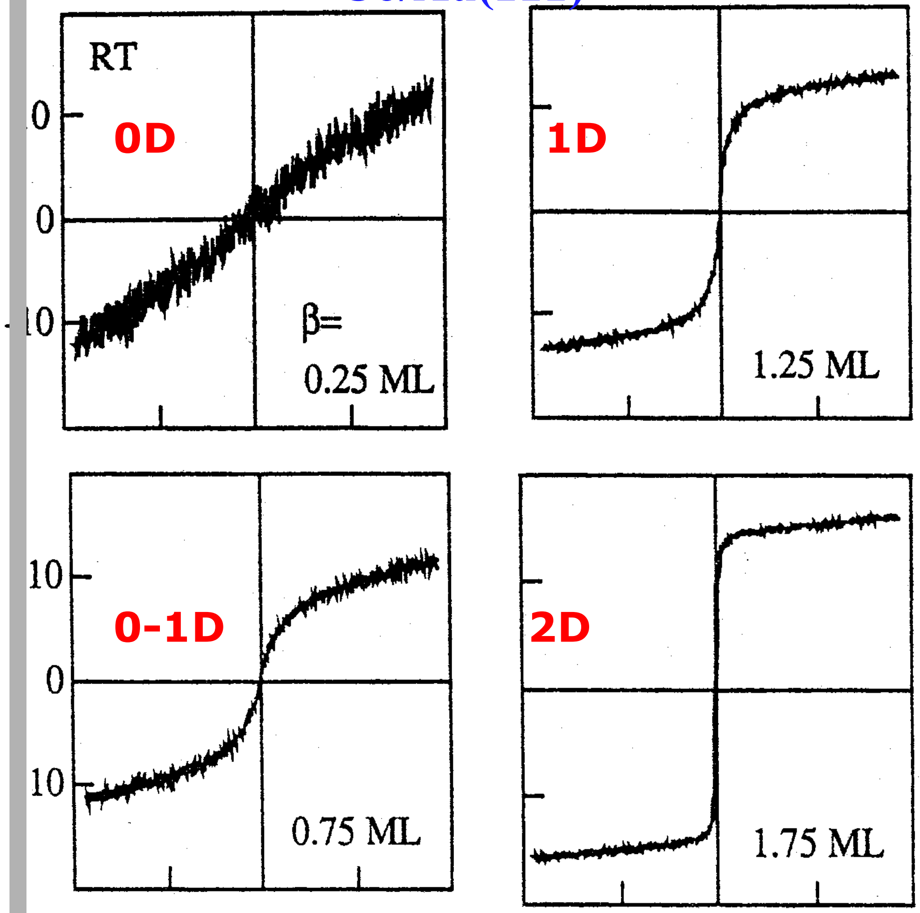


R.P. Cowburn et al., PRL83, 1042 (1999)

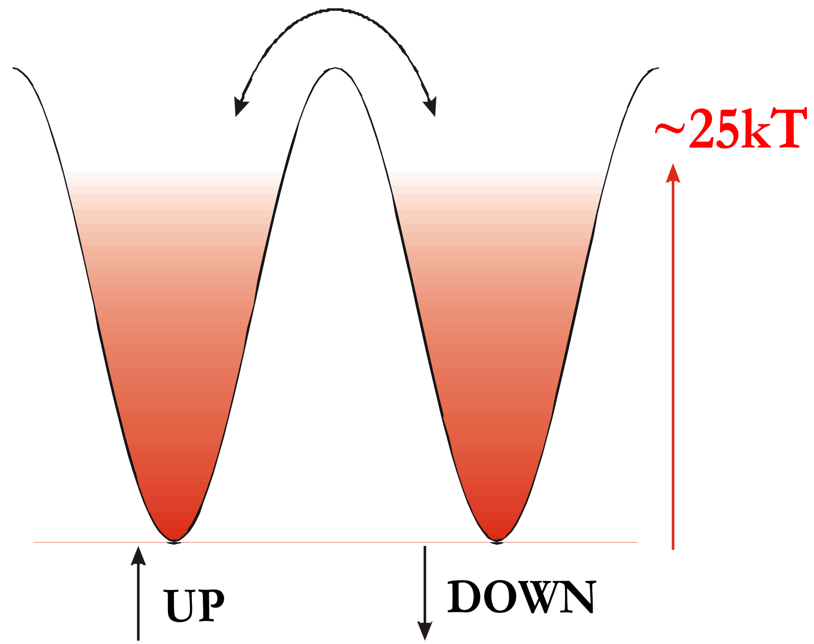
Role of dimensionality

Spontaneous magnetization is perpendicular to the plane [similar to Co/Au(111) films]

Co/Au(111)



H.Takeshita et al., JMMM165, 38 (1997)
see also: S. Padovani et al.,



Blocking temperature Tb ~ 20K
H.Dürr et al., PRB59, R701 (1999)
K. Koide et al., PRL87, 257201 (2001)
Ph. Ohresser, F. Scheurer et al., private comm.

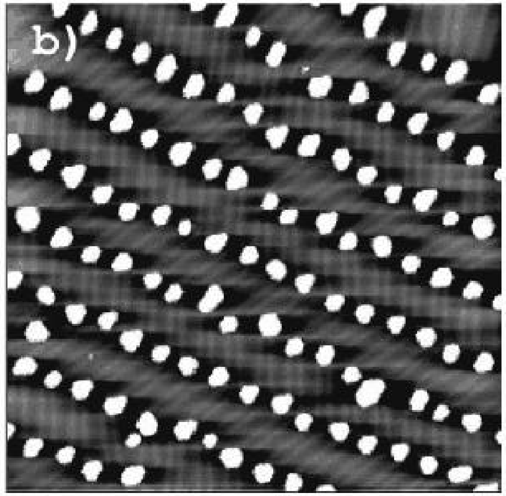
$$T_b = KV / 25k_B$$

TWO ROUTES TO OVERCOME SUPERPARAMAGNETISM in SO

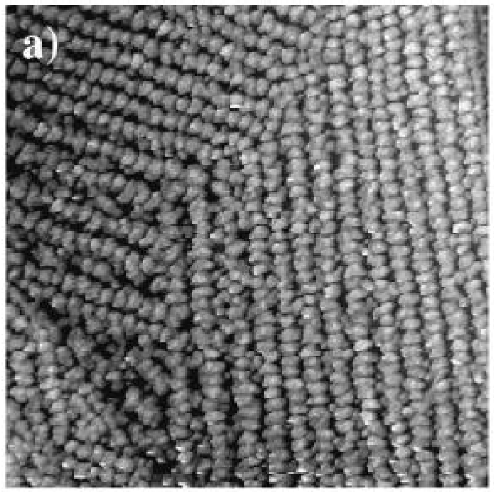
- Increase K. Problem: K does not increase as fast as V decreases
- Increase V. Problem : lateral coalescence occurs

Co/Au(111)

0.25AL



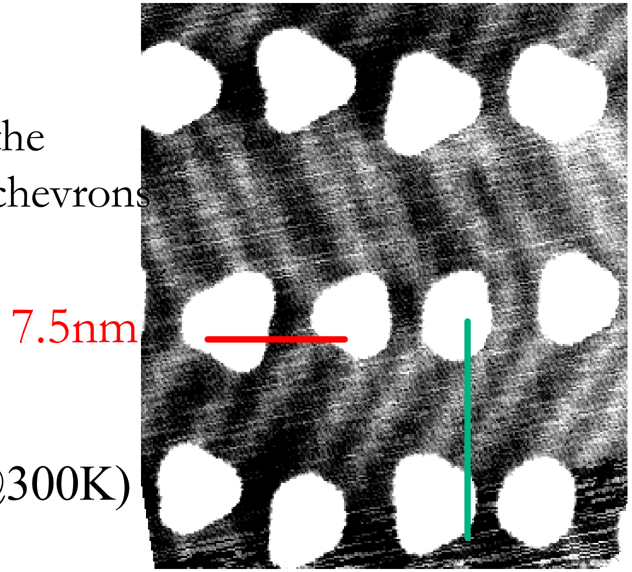
1.75AL



INCREASE THE HEIGHT OF NANOSTRUCTURES ?

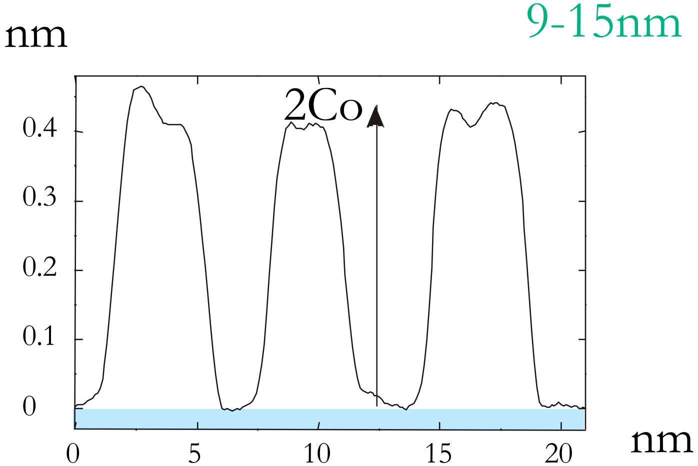
S. Padovani et al.,
Phys. Rev. B 59, 11887 (1999)

- Co, Ni, Fe :
  Nucleation at the
  elbows of the chevrons



(0.20AL Co@300K)

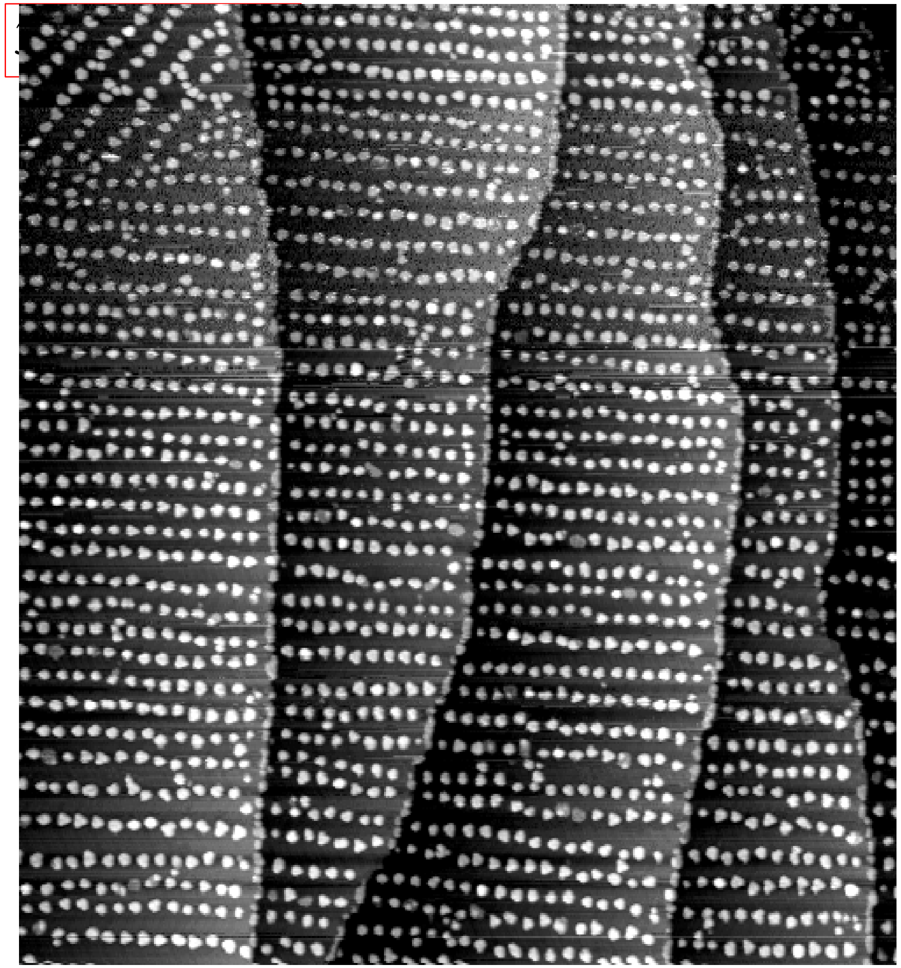
9-15nm



Fe, Ni : 1 AL-high dots

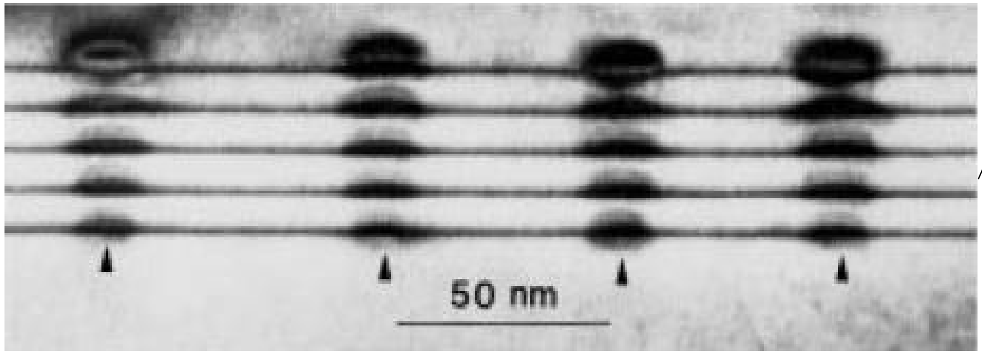
D.D. Chambliss et al., PRL 66, 1721 (1991)

B.Voigtlander et al., PRB 44, 10354 (1991)

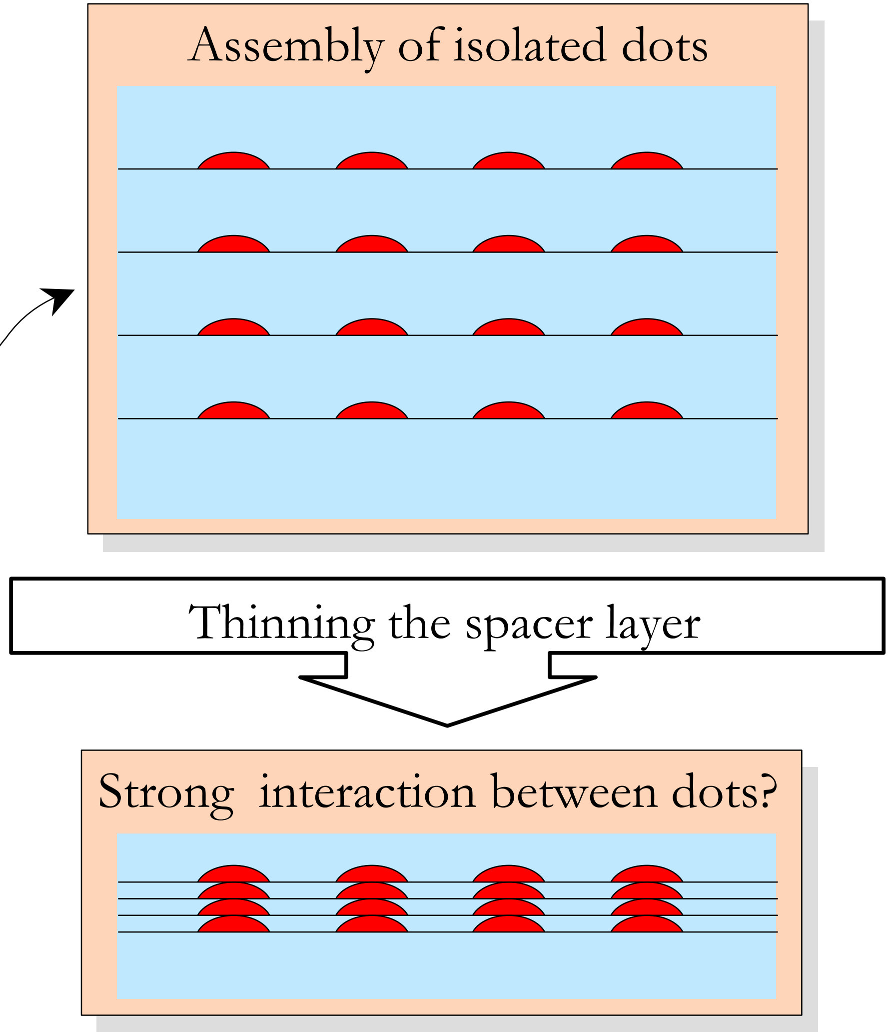


- Medium-ranged organization

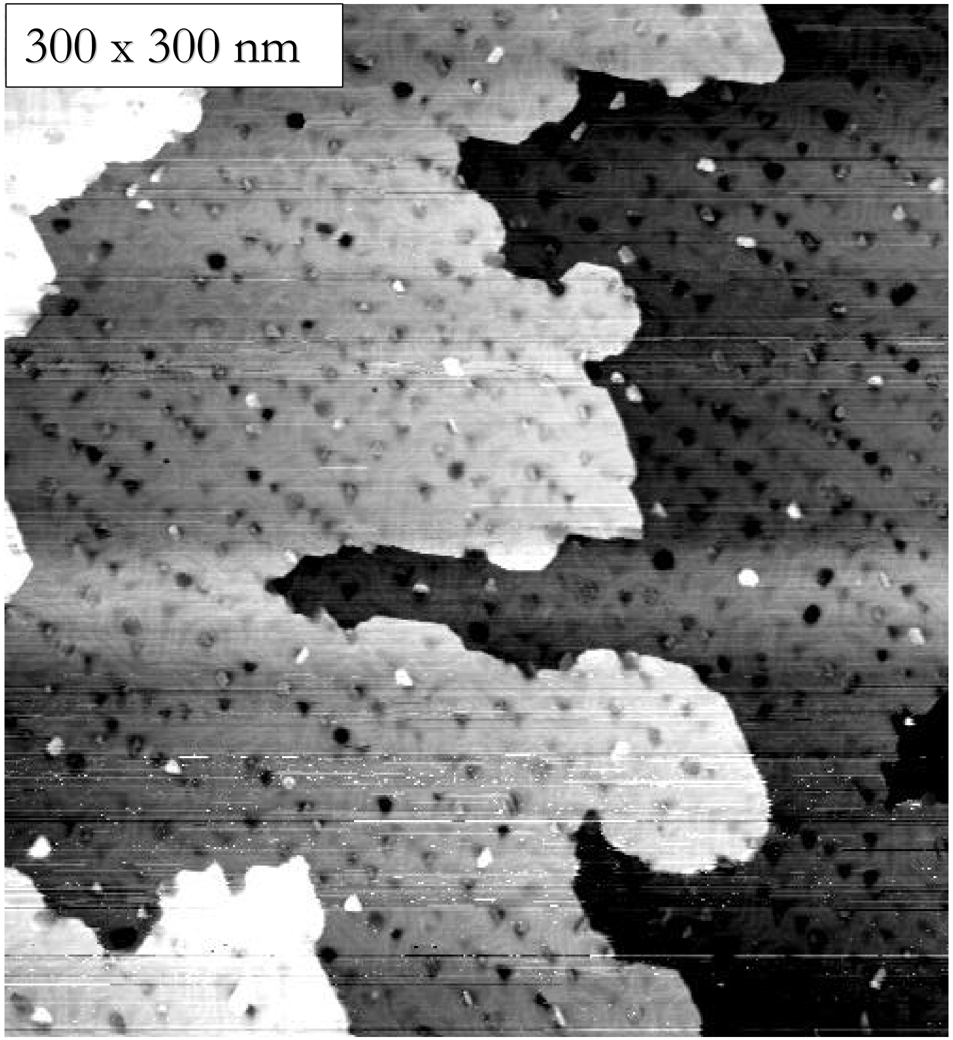
- Vertical 3D self-organization of $In_xGa_{1-x}As/GaAs$:

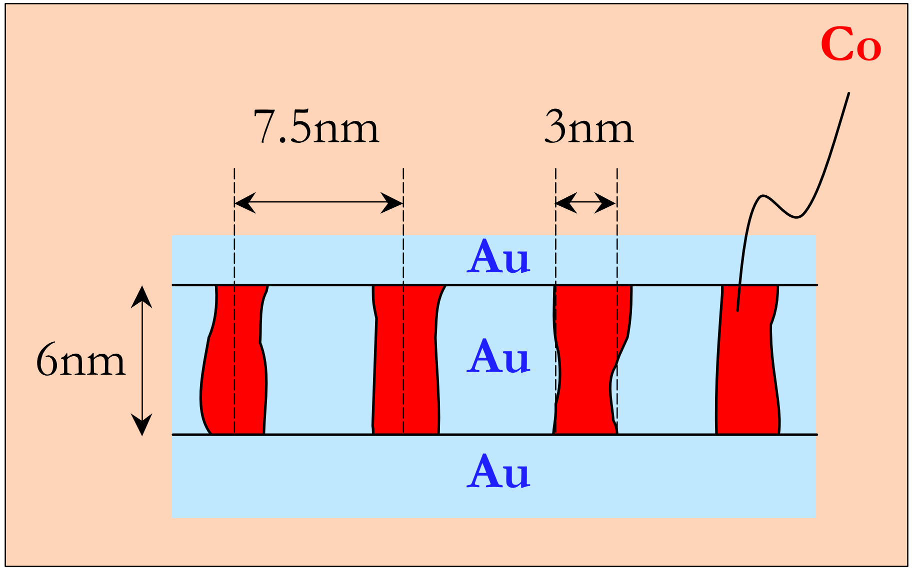


Q.Xie et al., Phys.Rev.Lett.75(13), 2542 (1995)



- superparamagnetism overcome ?
- Enhanced magnetic signal

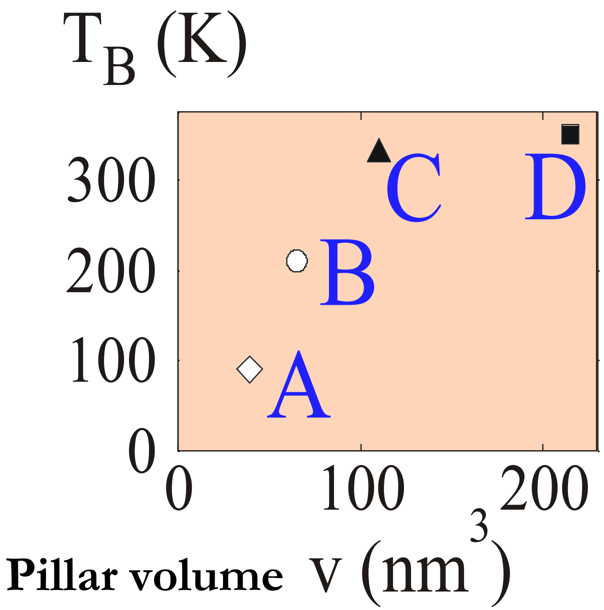


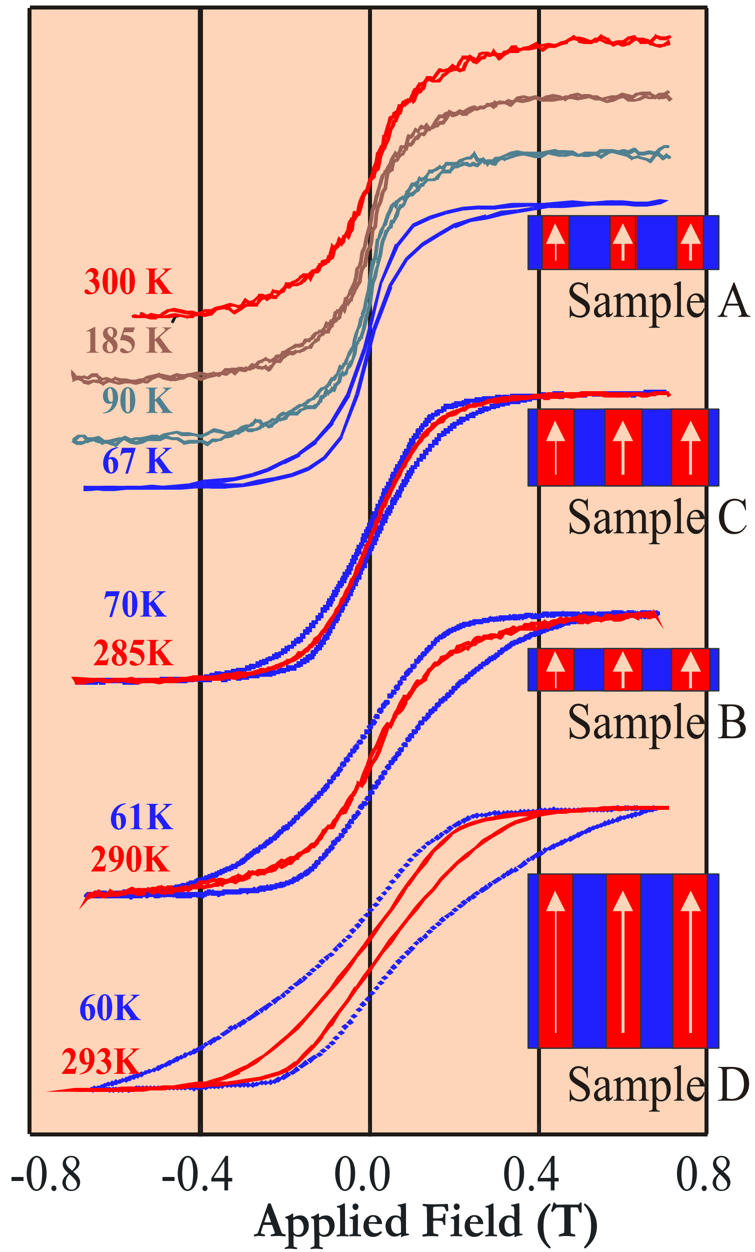


O. Fruchart *et al.*, Phys. Rev. Lett. 23 (14), 2769 (1999)

O. Fruchart *et al.*, Appl. Surf. Science 162-163, 529 (2000)

O. Fruchart *et al.*, J. Cryst. Growth 237-239 (3), 2035 (2002)





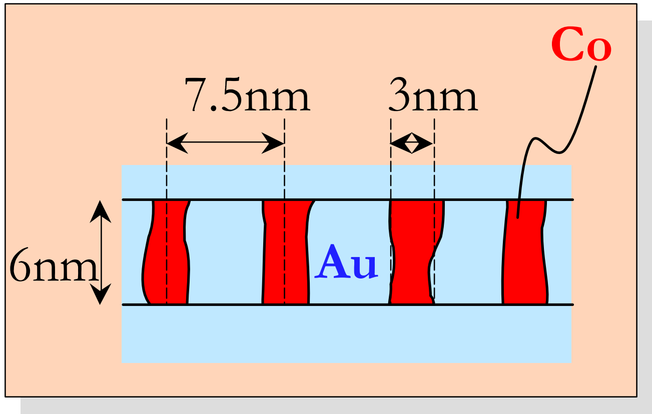
- **Blocking temperature > 300K**

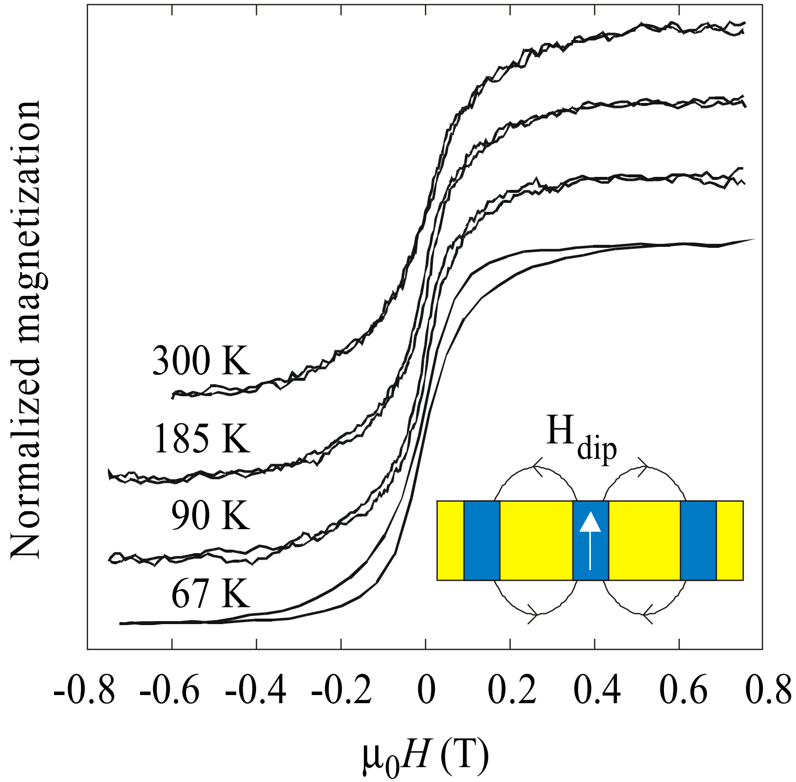
  (~ 30K for flat Co/Au dots)

Expected: KV~25kTb

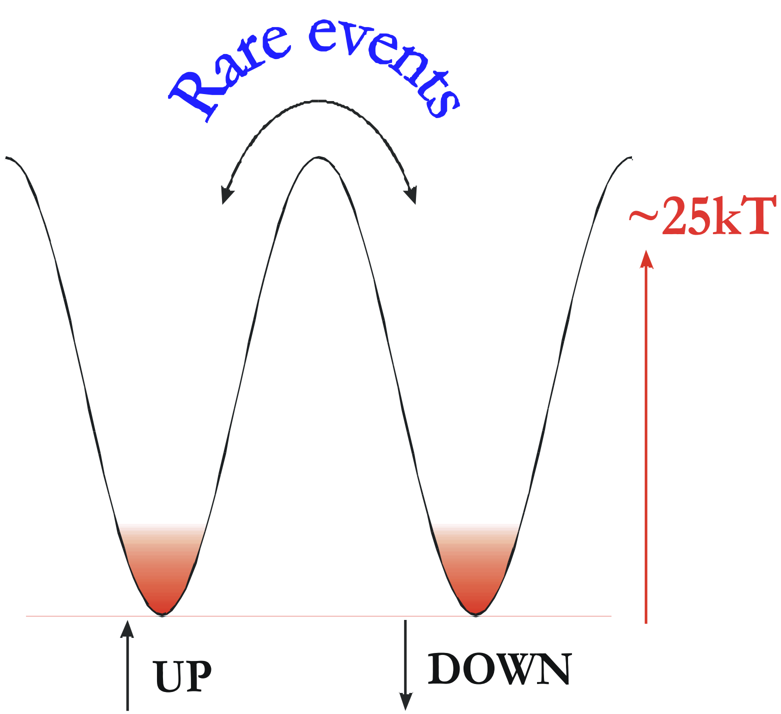
- **K decreases for the largest pillars**

O. Fruchart *et al.*, JMMM 239, 224 (2002)





- **Magnetization essentially perpendicular**
  - 2 states: up and down (Ising macrospin)
  - Superparamagnetism fitted using Brillouin 1/2 function



Classical spin

Uniaxial anisotropy

H // anisotropy axis

$$bE = -dm^2 - hm$$

$d = bK$ $K = K_V \times v$	Anisotropy
$h = bm_0 mH$	Zeeman

Exact solution

Partition function $\quad Z = \int_{-1}^{1} \exp(dm^2 + hm)\mathrm{d}m$

Obstacle (?) $\quad \int_0^t \exp(x^2)\mathrm{d}x = ?$ ⟵ Imaginary Error function, Erfi(t)

Magnetization $\quad m = -h/2d + (2/\sqrt{p\,d}) \times \dfrac{\exp(d + h^2/4d)\sinh(h)}{\mathrm{Erfi}(\sqrt{d} + h/2\sqrt{d}) + \mathrm{Erfi}(\sqrt{d} - h/2\sqrt{d})}$

Zero field susceptibility $\quad c = -1/2d + \exp(d)/(\sqrt{p\,d}\ \mathrm{Erfi}\sqrt{d})$

Asymptotic behavior

High temperature $c = 1/3 + 4d/45$ Langevin-like

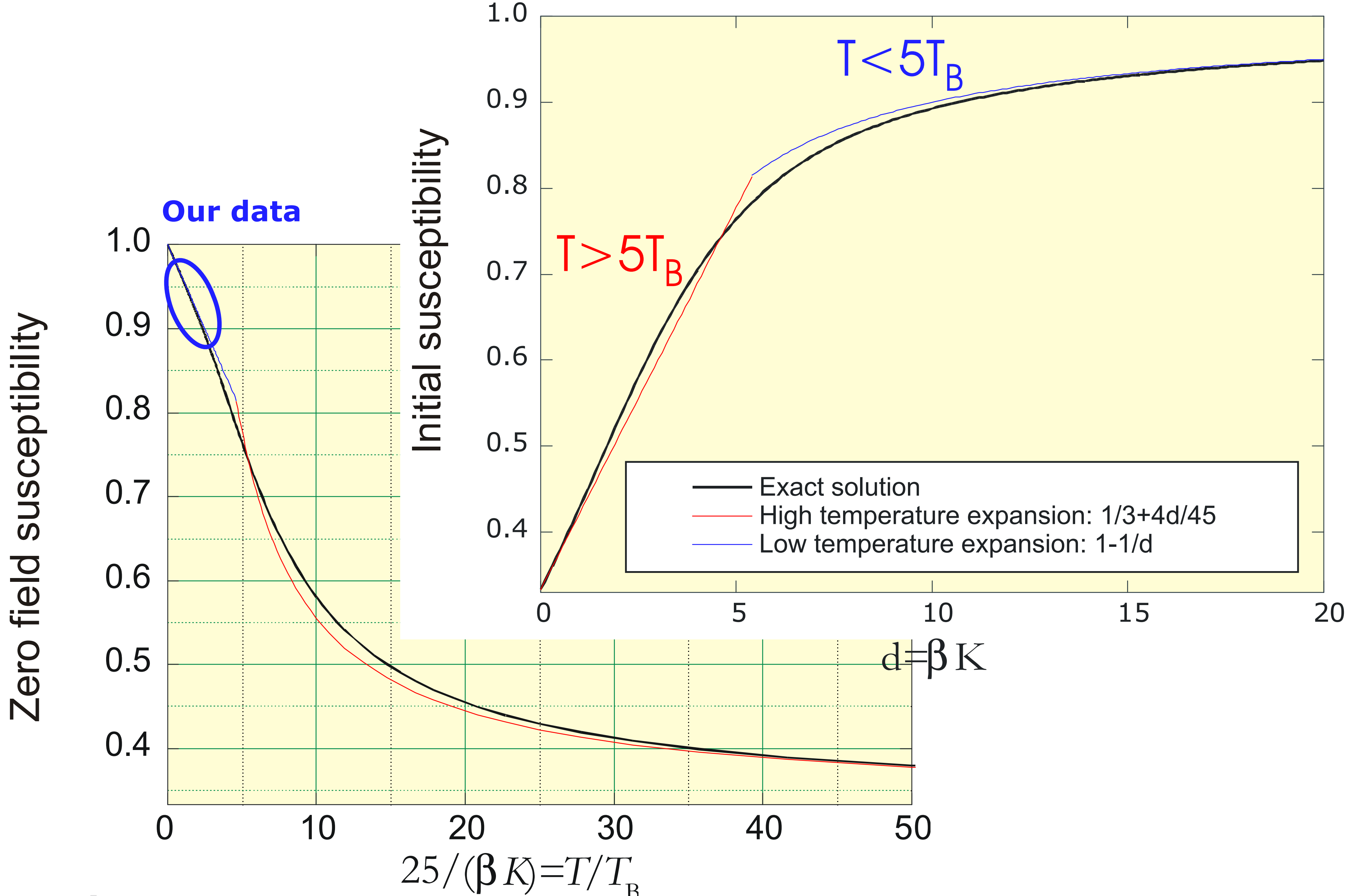
Low temperature $c = 1 - 1/d$ Brillouin ½ -like

Blocking temperature

$$T_B = K/25k_B$$

$$t = t_0 \exp(b_B E)$$

1s 10^{-9} – 10^{-12} s



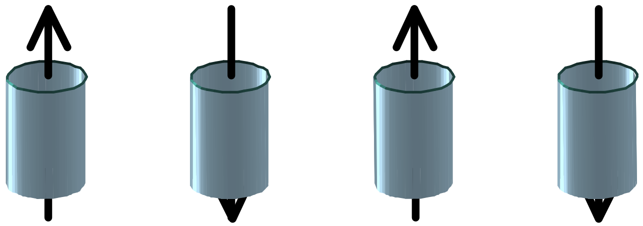
O. Fruchart *et al.*, J. Magn. Magn. Mater. 239, 224 (2002)

- **Brillouin 1/2 function**

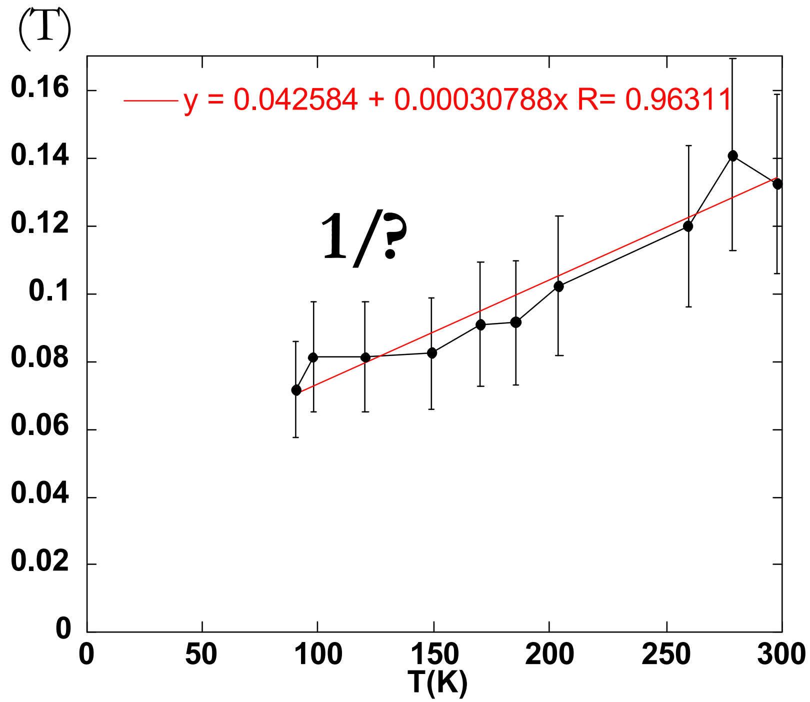
$$m = B_{1/2}\left(\mu_0 \mu_{Co} N H_{eff.} / kT\right)$$

- **Effective field**

$$H_{eff.} = H + r M_s m$$



(Demagnetizing dipolar interactions)



- **First order expansion:**

susceptibility

$$\frac{d(\mu_0 H)}{dm} = \frac{1}{?} = -\mu_0 M_S r + \frac{k}{\mu_{Co} N} T$$

a + b . T

Deduced from STM

- N=**3300** atoms
- Hdip= **-32** mT

... from magnetism

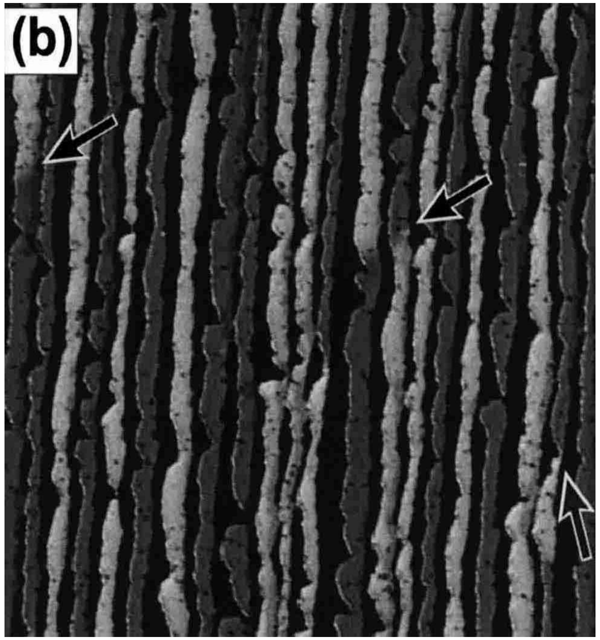
- N=**2800** atoms
- Hdip= **-42** mT

- Good quantitative agreement ⇒ 1 pillar = 1 magnetic entity

O. Fruchart *et al.*, Phys. Rev. Lett. 23 (14), 2769 (1999)

ATOMIC LAYER RANGE : WETTING

↳ nanometer-world / surface physics



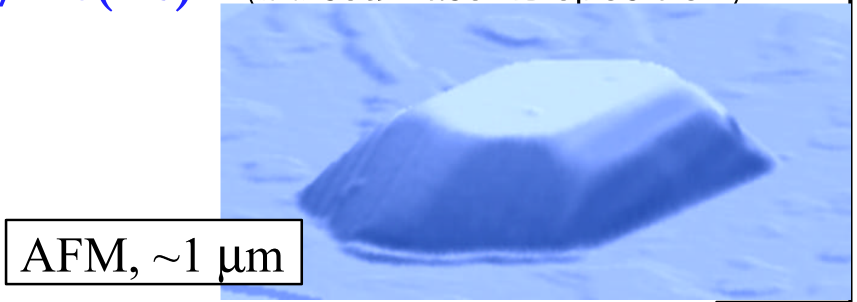
1.5AL on vicinal Fe/W(110)

M. Bode et al, J. Electr. Spectr. Rel. Phenom. 114– 116, 1055 (2001)

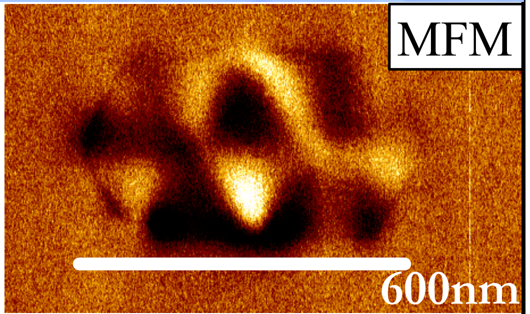
THICK DEPOSITS : NO WETTING

↳ micrometer-world / materials physics

Fe/Mo(110) (Pulsed Laser Deposition)



MFM:
Y. Samson
(CEA/France)

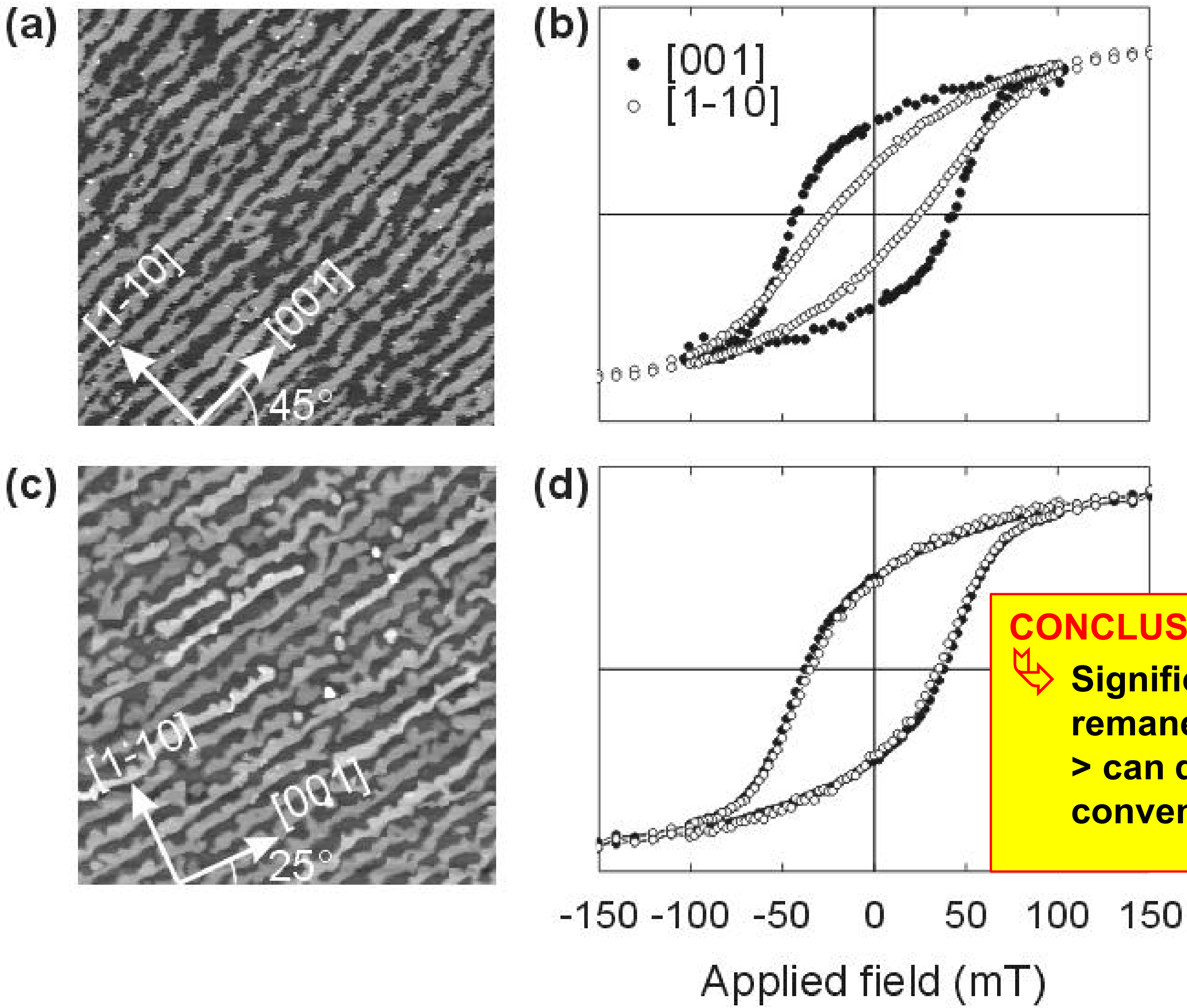


P.-O.Jubert *et al.*, JMMM 226, 1842 (2002)
P.-O.Jubert *et al.*, PRB64, 115419 (2002)
P.-0. Jubert *et al.*, EPL63, 135 (2003)

↳ **Is there an intermediate world ?**

Fe(110) stripes

5x5 mm

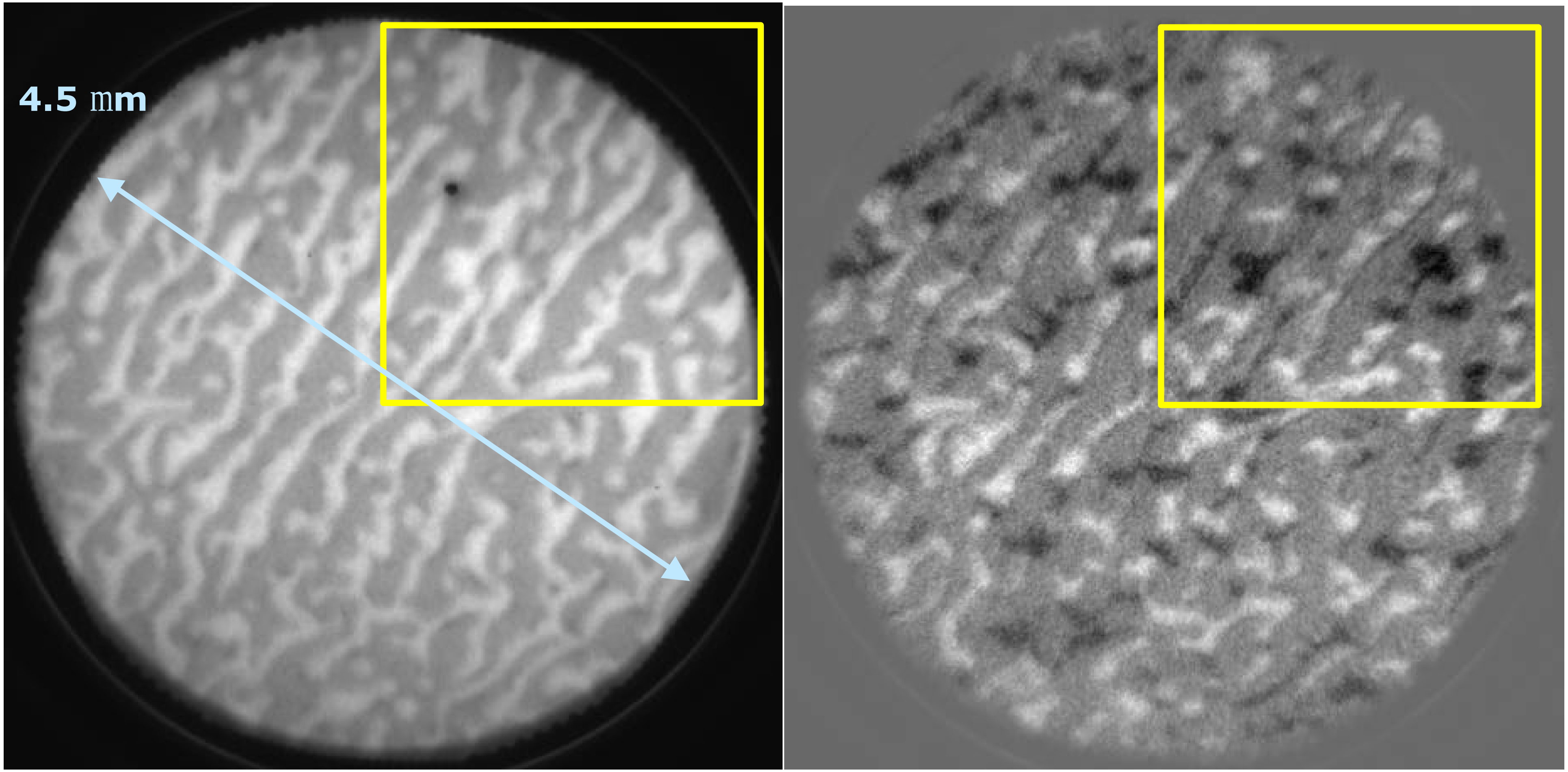


CONCLUSION

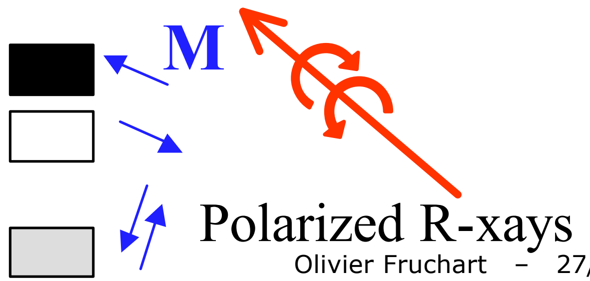
Significant coercivity and remanence at 300K
> can display features of conventional hard magnetic materials

PEEM = Photo-Emission Electron Microscope

Fe(110) stripes

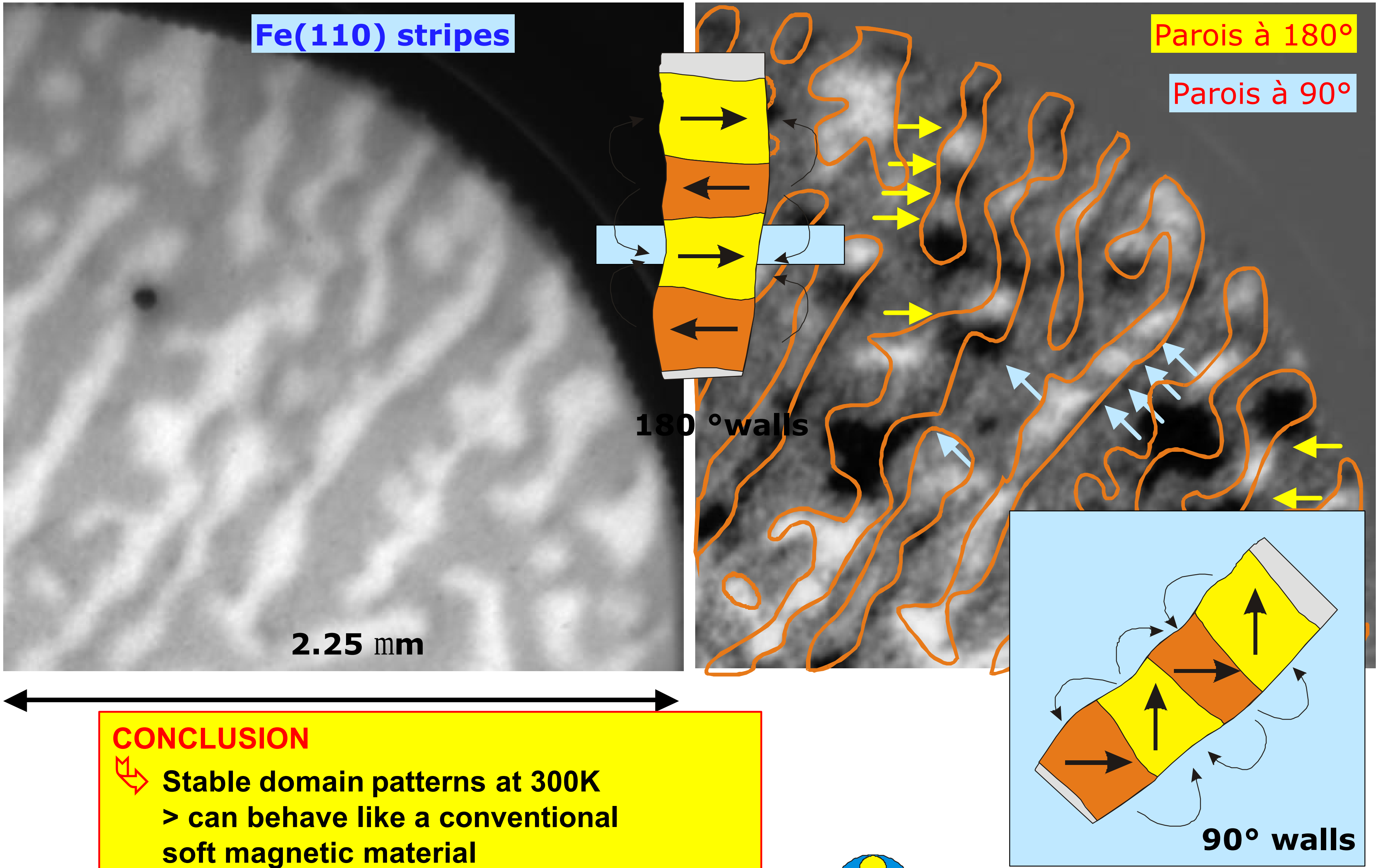


Sample: Sapphire\Mo(8nm)\W(1nm)\Fe(2.5nm)\Mo(1nm)\Al(3nm)



ELETTRA Syncrotron, Trieste

Coll. J. Vogel (LLN), P.O. Jubert (IBM-Zürich), A. Locatelli (ELETTRA)



CONCLUSION

- **Stable domain patterns at 300K**
  > can behave like a conventional soft magnetic material

PEEM resolution better than 30nm

Cf lecture by Stefania PIZZINI