Nano-objects:
(some) fabrication methods,
(some) magnetic properties.

O.Fruchart

Laboratoire Louis Néel (CNRS-UJF-INPG)
Grenoble

I. Fabrication methods

- 1. Epitaxial self-assembly & self-organization
- 2. Other routes: electrochemistry, chemistry, physical paths to clusters, exotic means
- 3. Future prospects for self-organization.

II. Selected topics for Magnetism

- 1. Magnetic order
- 2. Magnetic anisotropy
- 3. Magnetization reversal and superparamagnetism.
- 4. Micromagnetism

I. Fabrication methods

- **1. Epitaxial self-assembly & self-organization**
- **2. Other routes: electrochemistry, chemistry, physical paths to clusters, exotic means**
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II. Selected topics for Magnetism

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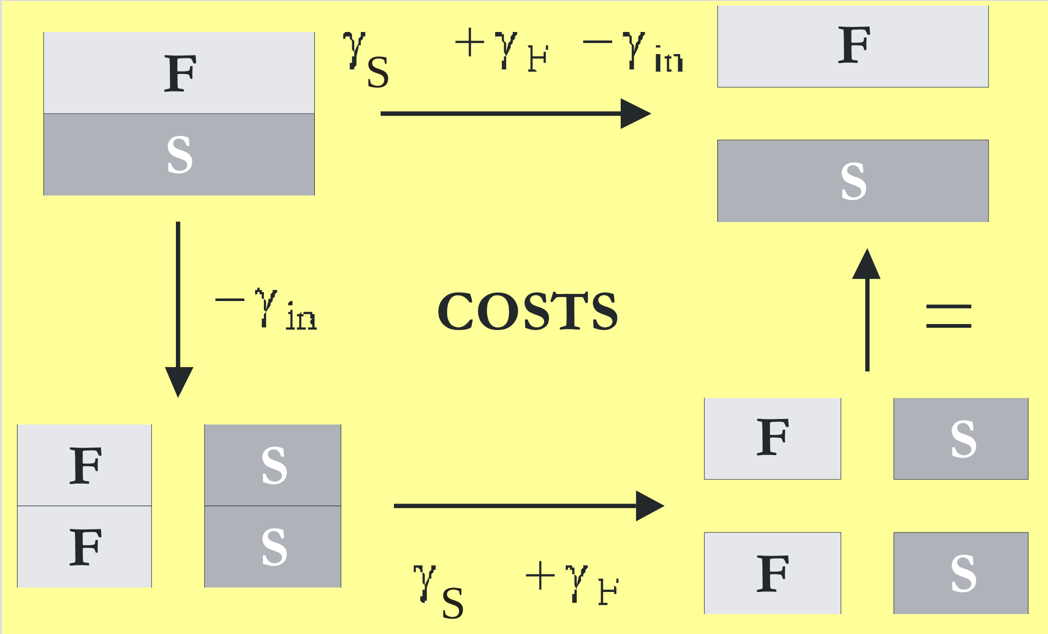
- **3. Magnetization reversal and superparamagnetism.**
- **4. Micromagnetism**

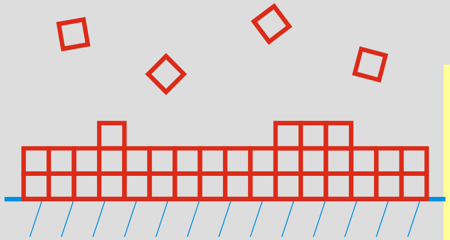
FABRICATION METHODS — Epitaxy — Growth modes

Macroscopic concept: surface/interface energies.

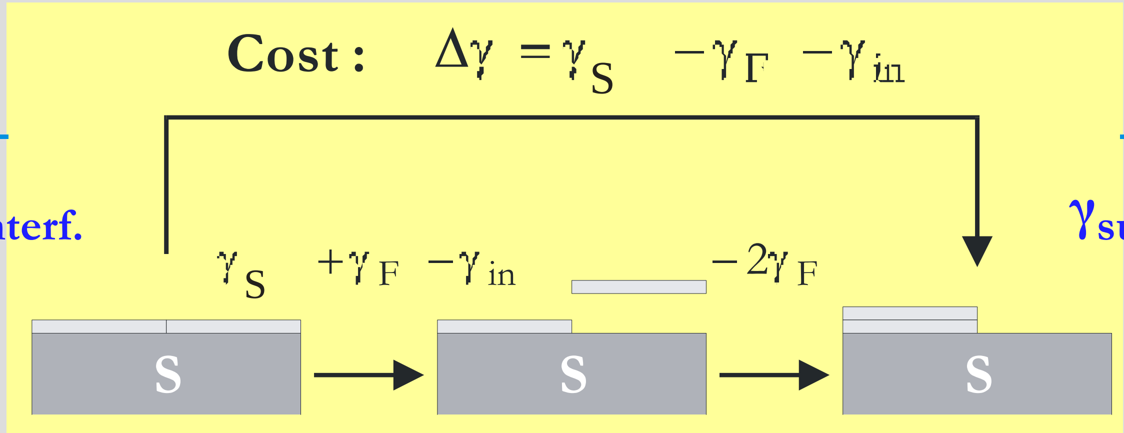


2D

Franck van der Merwe

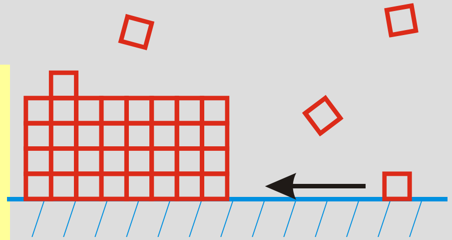


$\gamma_{substr.} > \gamma_{film} + \gamma_{interf.}$



3D

Volmer-Weber



$\gamma_{substr.} < \gamma_{film} + \gamma_{interf.}$

E.Bauer, Z.Kristallogr.110, 372 (1958)

E.Bauer, Phys.Rev.B 33, 3657 (1986)

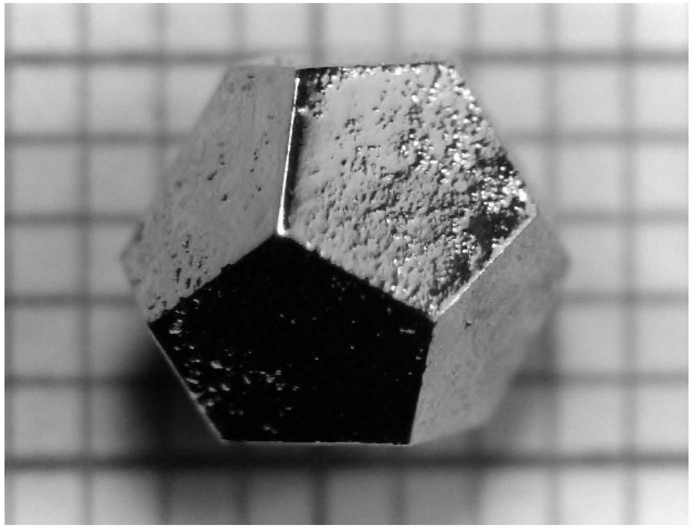
What is the shape of the droplet of a crystal?

Magnetite (« Loadstone »)

http://geology.about.com

Quartz

http://www.theimage.com



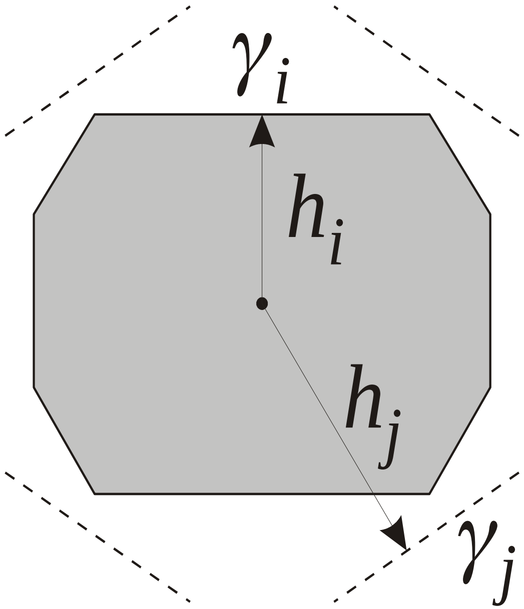
Ho-Mg-Zn

http://cmp.ameslab.gov/personnel/canfield/

Wulff's theorem

Free crystal (growth from melt)

$$\frac{\gamma_i}{h_i} = \text{Constant}$$

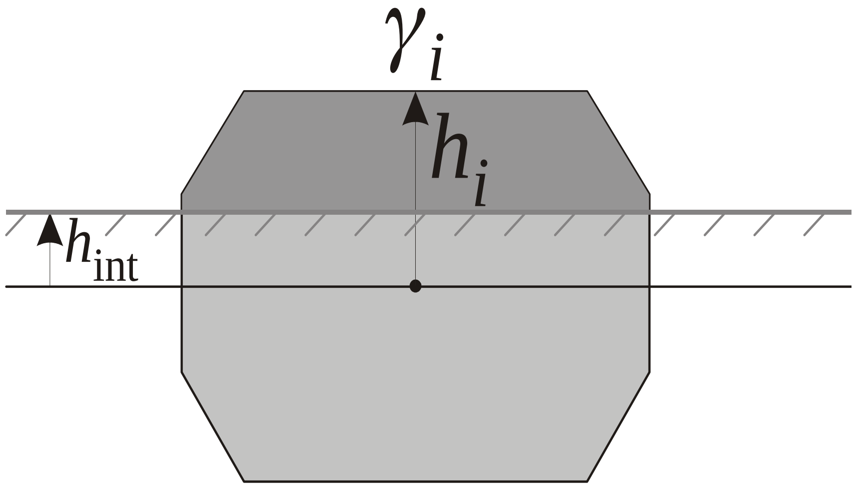


No facets with high surface energy

Wulff Kaishev's theorem

Supported crystal (growth on surfaces)

$$\frac{\gamma_i}{h_i} = \frac{\gamma_S - \gamma_{\text{int}}}{h_{\text{int}}} = \text{Constant}$$

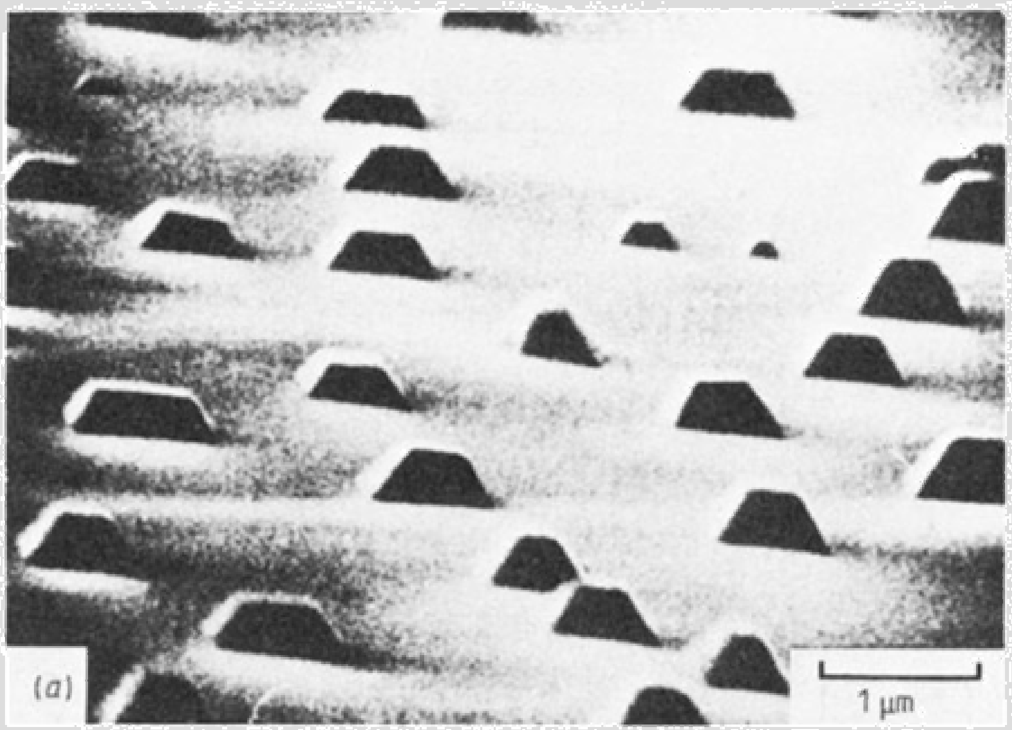


Truncated crystal

See references in: P. Müller and R. Kern, Surf. Sci. 457, 229 (2000)

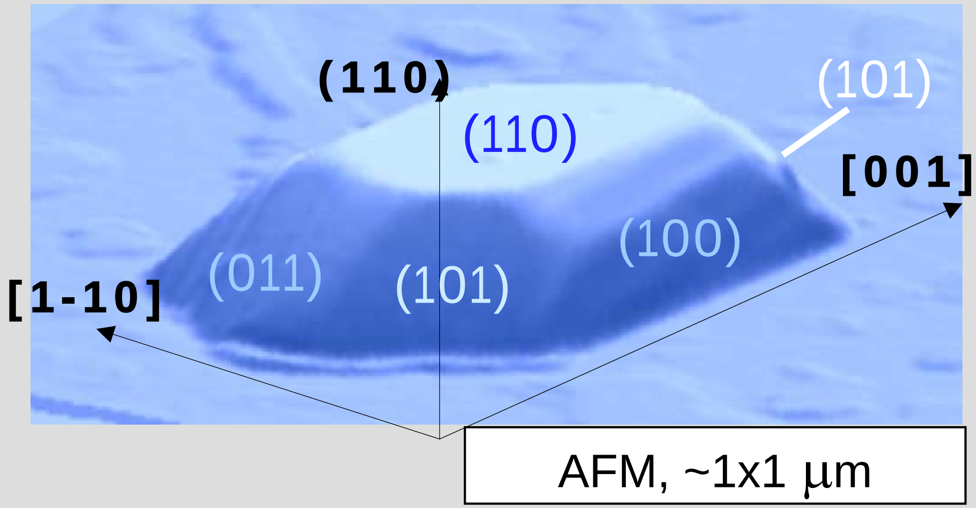
Examples of 3D dots

Ag(20AL)/Mo(001) @ 550°C



K. Hartrig, Surf. Sci. 74, 69 (1978).

Fe/Mo(110) @ 450°C



P.-O. Jubert *et al.*, PRB64, 115419 (2002)

O. Fruchart et al., to be submitted

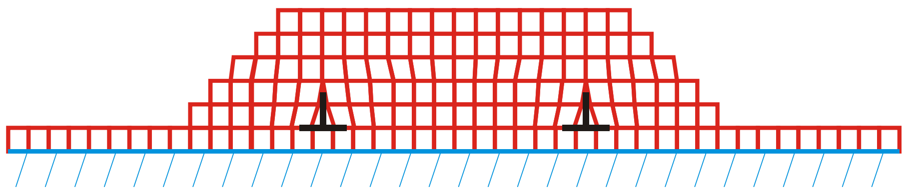
Parameters to play with:

Substrate orientation (dot symmetry)

Temperature (density and size) and
Amount deposited (size)

Epitaxial misfit

Surfactants, overlayer, etc.



Model, application to semiconductors:
H. Mariette et al., C. R. Physique 6, 23 (2005).

Theory

Equilibrium nano-shape changes induced by epitaxial stress (generalised Wulf–Kaishew theorem)

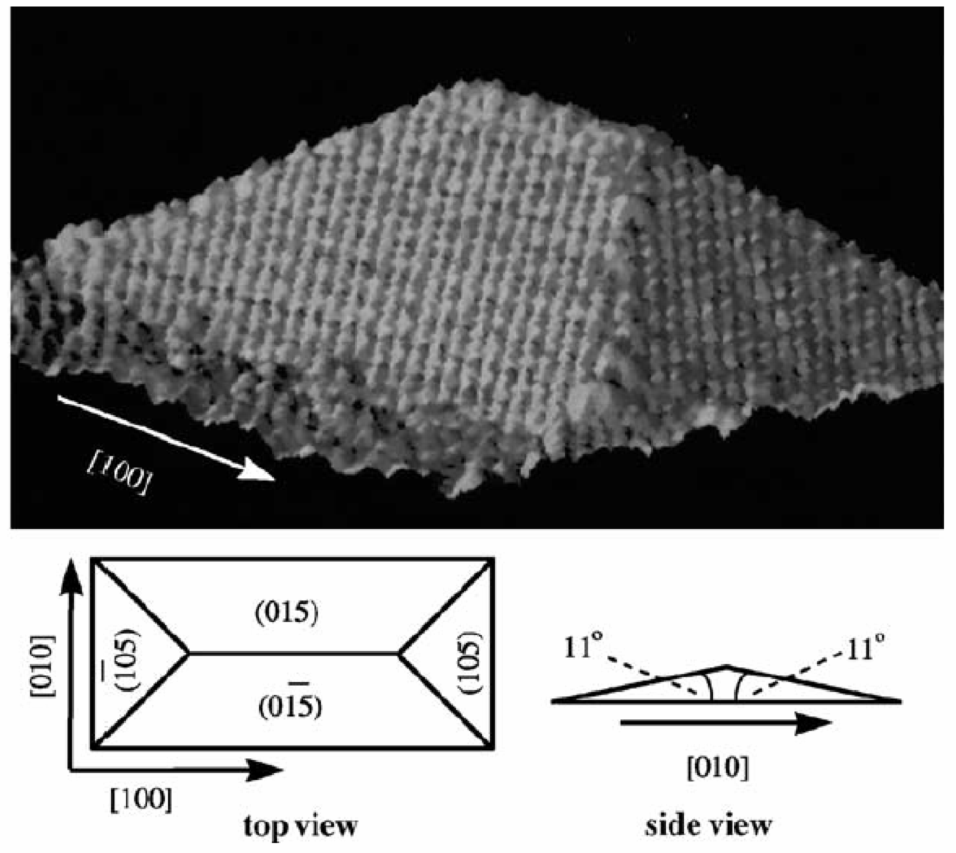
P. Müller and R. Kern, Surf. Sci. 457, 229 (2000)

Takes into account both elastic relaxation and plastic relaxation (misfit dislocations)

« One of the most striking results is that the equilibirum shape is no more self-similar with size as it is when no epitaxial strain exists »

Also available: continuum and discrete numerical simulations

Example: Ge/Si(001), hut shape

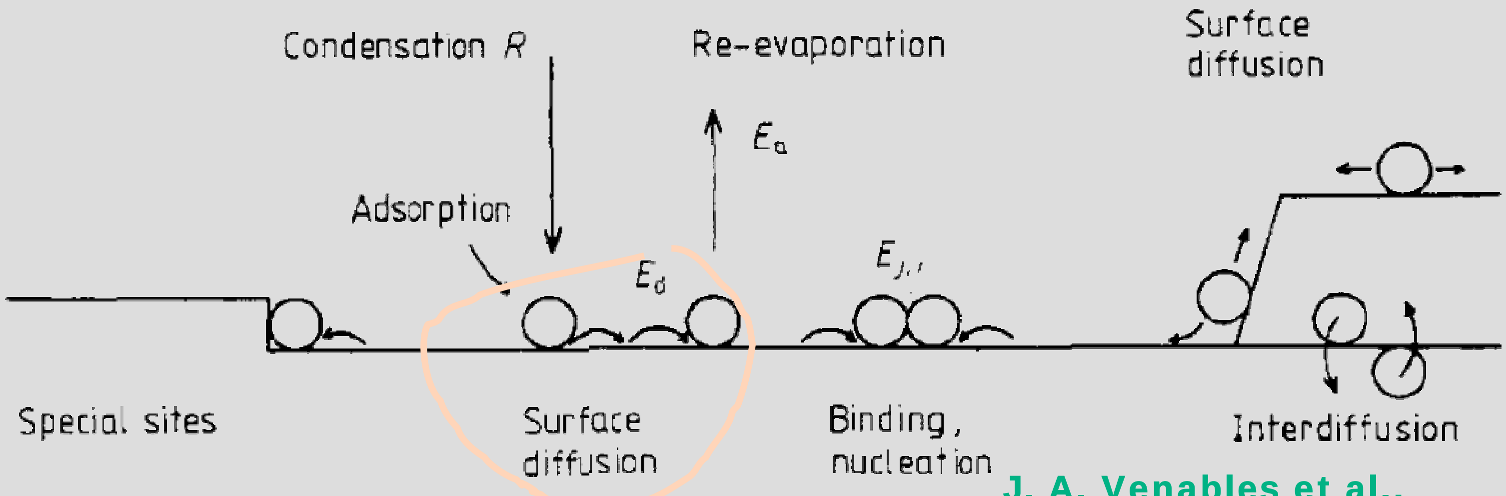


I.W. Mo et al., Phys. Rev. Lett. 65, 1020 (1990)

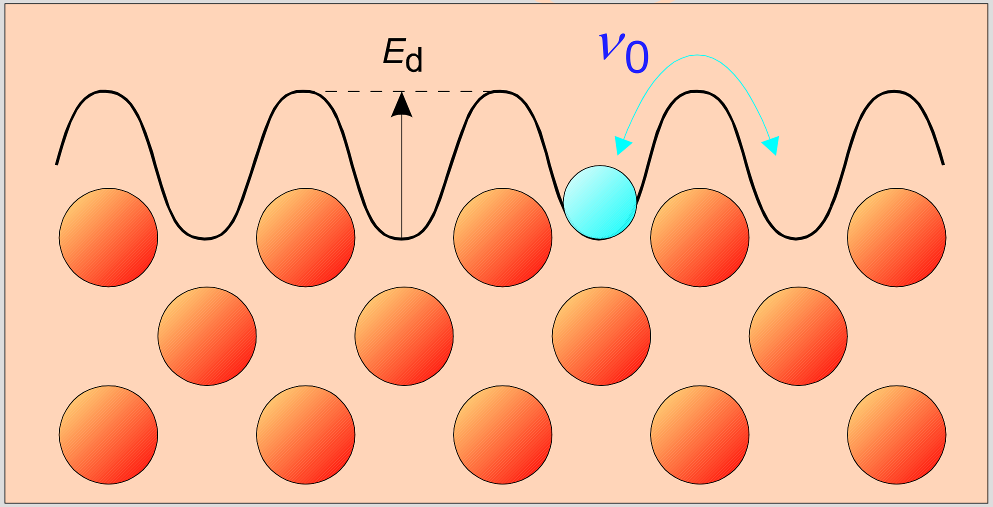
Applicable to:
Very small 3D dots: semiconductors (mostly IV-IV and III-V, including magnetic)

Also available:
Continuum and discrete numerical calculations

Atomic Surface Processes



J. A. Venables et al., Rep. Prog. Phys. 47, 399 (1984).



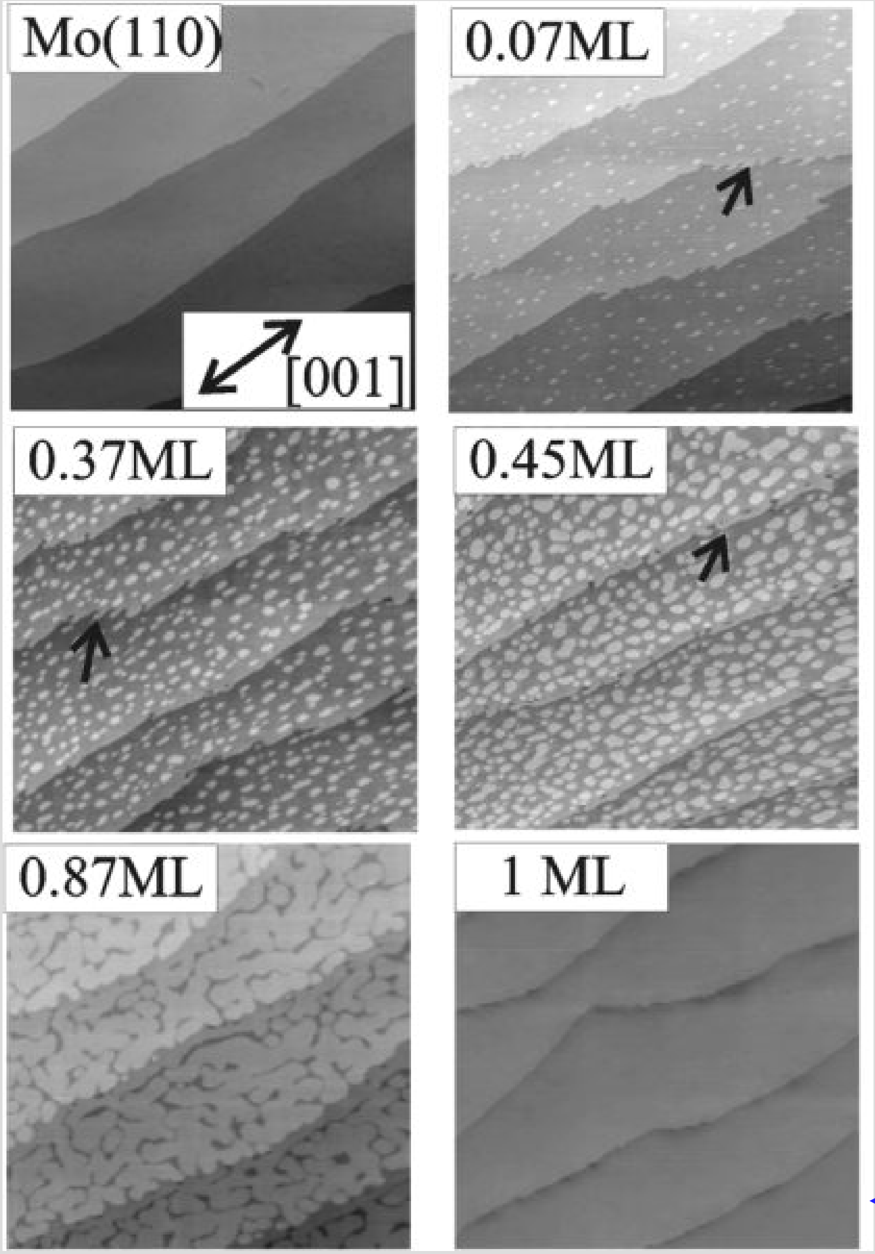
Mean distance after elapse of time t $<R> = \sqrt{4Dt}$

Diffusion coefficient $D = \dfrac{\nu_0}{4}\exp(-E_d / k_B T)$

$\nu_0 \approx 10^{12}$ Hz Attempt frequency

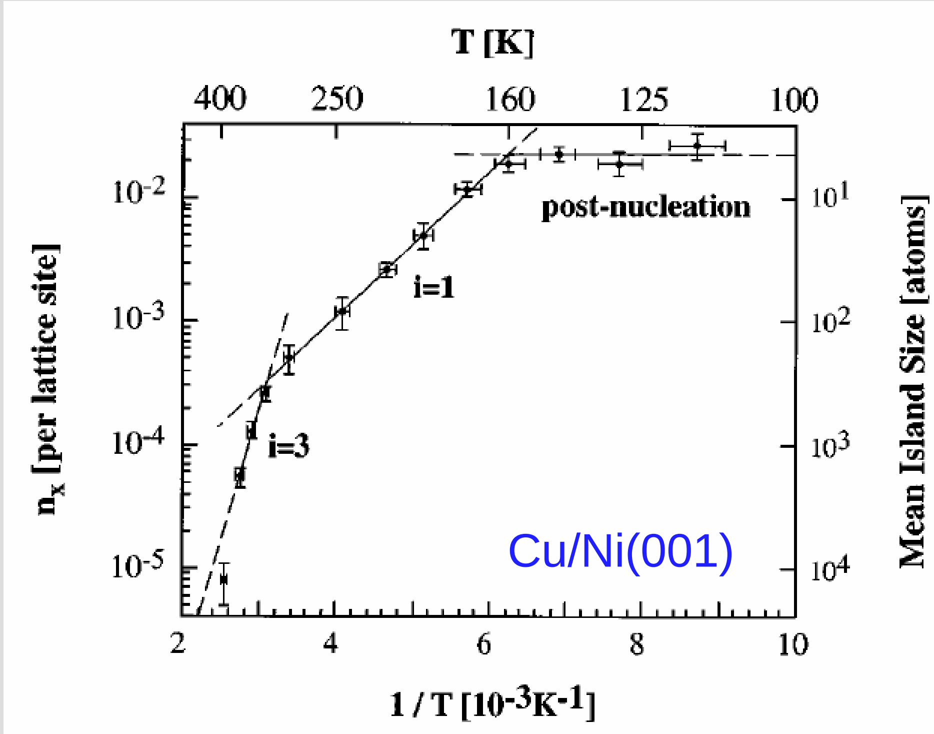
E_d Diffusion barrier

Rate equations: maximum island density



J. A. Venables et al.,
Rep. Prog. Phys. 47, 399 (1984).

$$n_{max} \sim \left(\frac{D_0}{F}\right)^{-\frac{i^*}{i^*+2}} \exp\left[\frac{i^* E_d + (E_{i^*} - E_1)}{(i^*+2)k_B T}\right]$$



B. Müller et al., PRB54, 17858 (1996)

Ex: Fe/Mo(110) by PLD

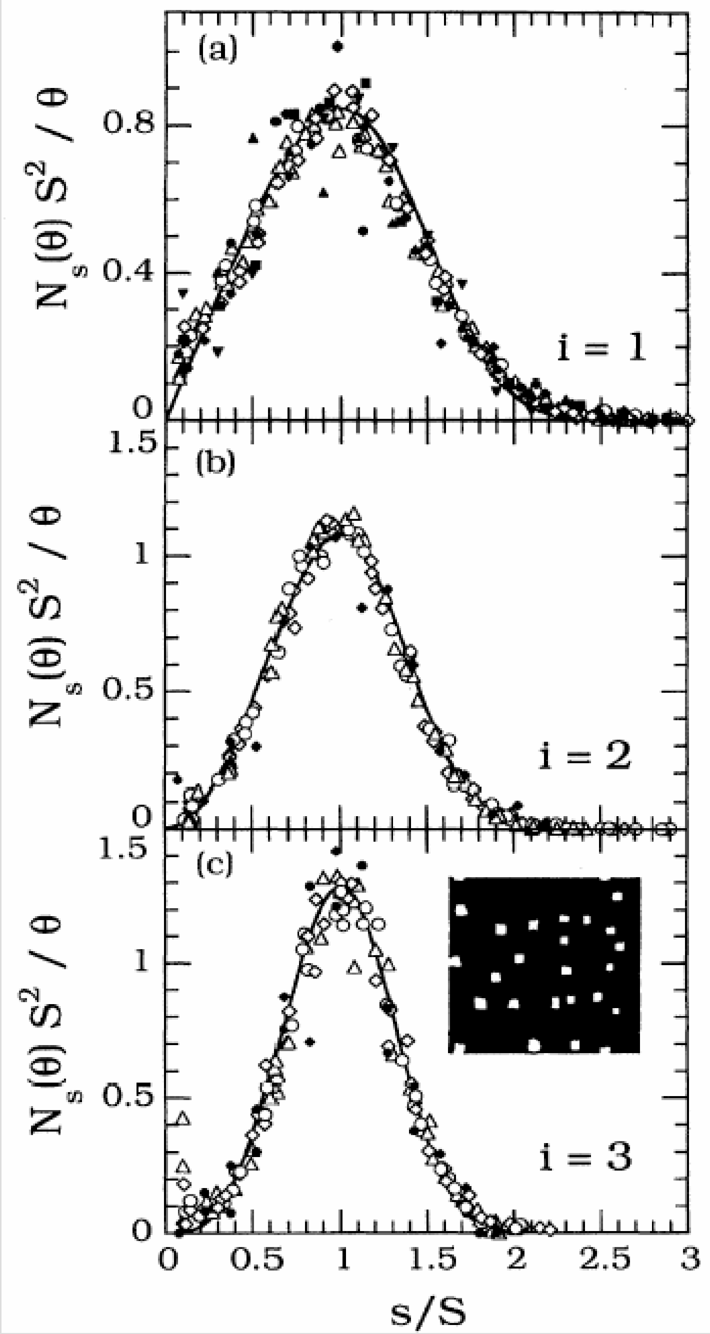
P. O. Jubert et al., Surf. Sci. 522, 8 (2002).

Rate equations: island size distribution

No analytical solution.

Empirical solution proposed:

$$f(u = S/<S>) = C_{i^*} u^{i^*} \exp(-i^* a_{i^*} u^{1/a_{i^*}})$$

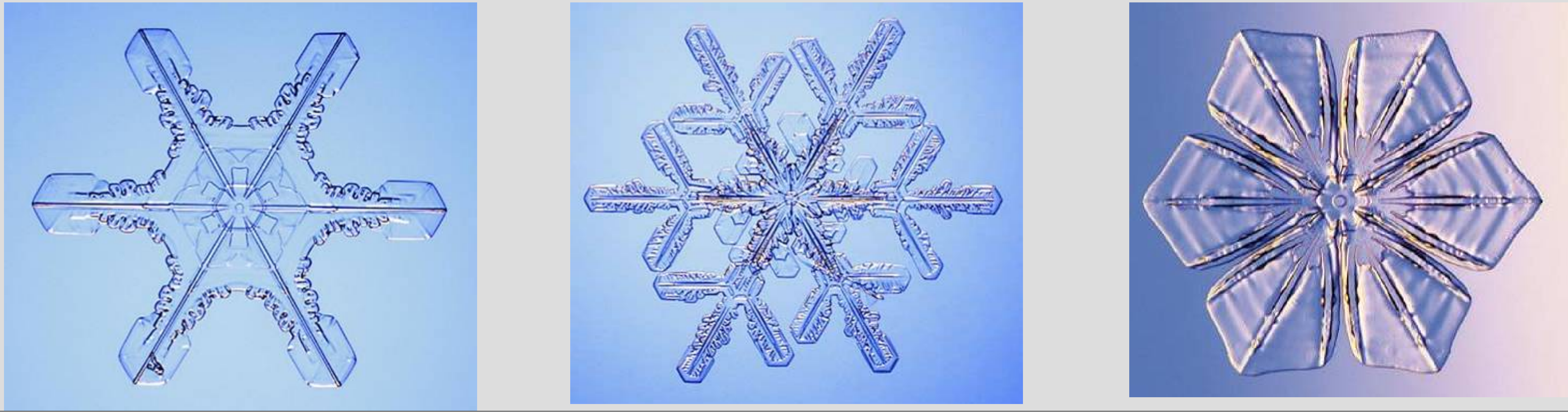


Fe/Fe(001)
Simulations, experiments, analytical

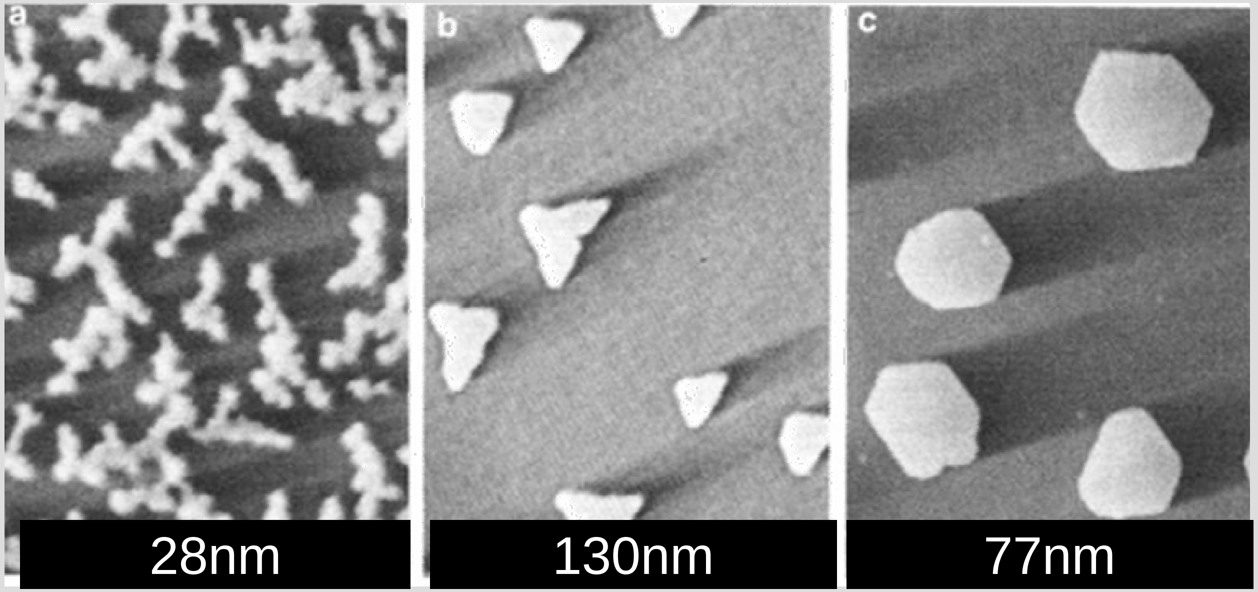
J. G. Amar et al., PRL74, 2066 (1995)

Shape of islands: kinetics, symmetry etc.

Snowflakes (National geographics)

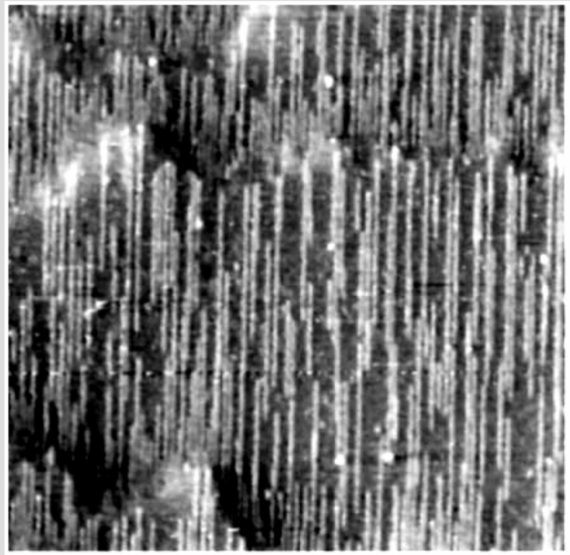


Pt/Pt(111) 200K 400K 455K



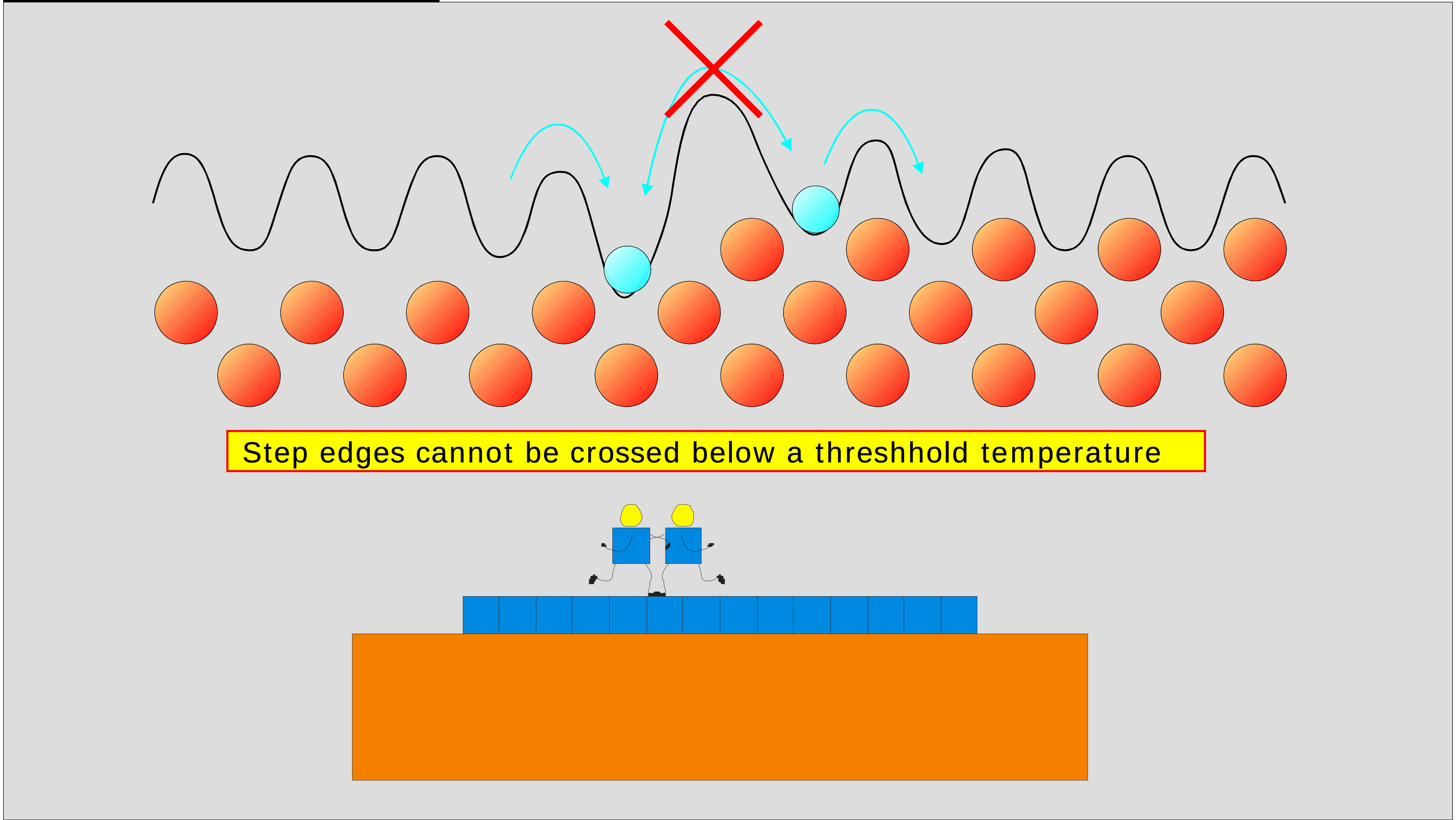
T. Michely, PRL70, 3943 (1993)

Cu/Pd(110) 265K



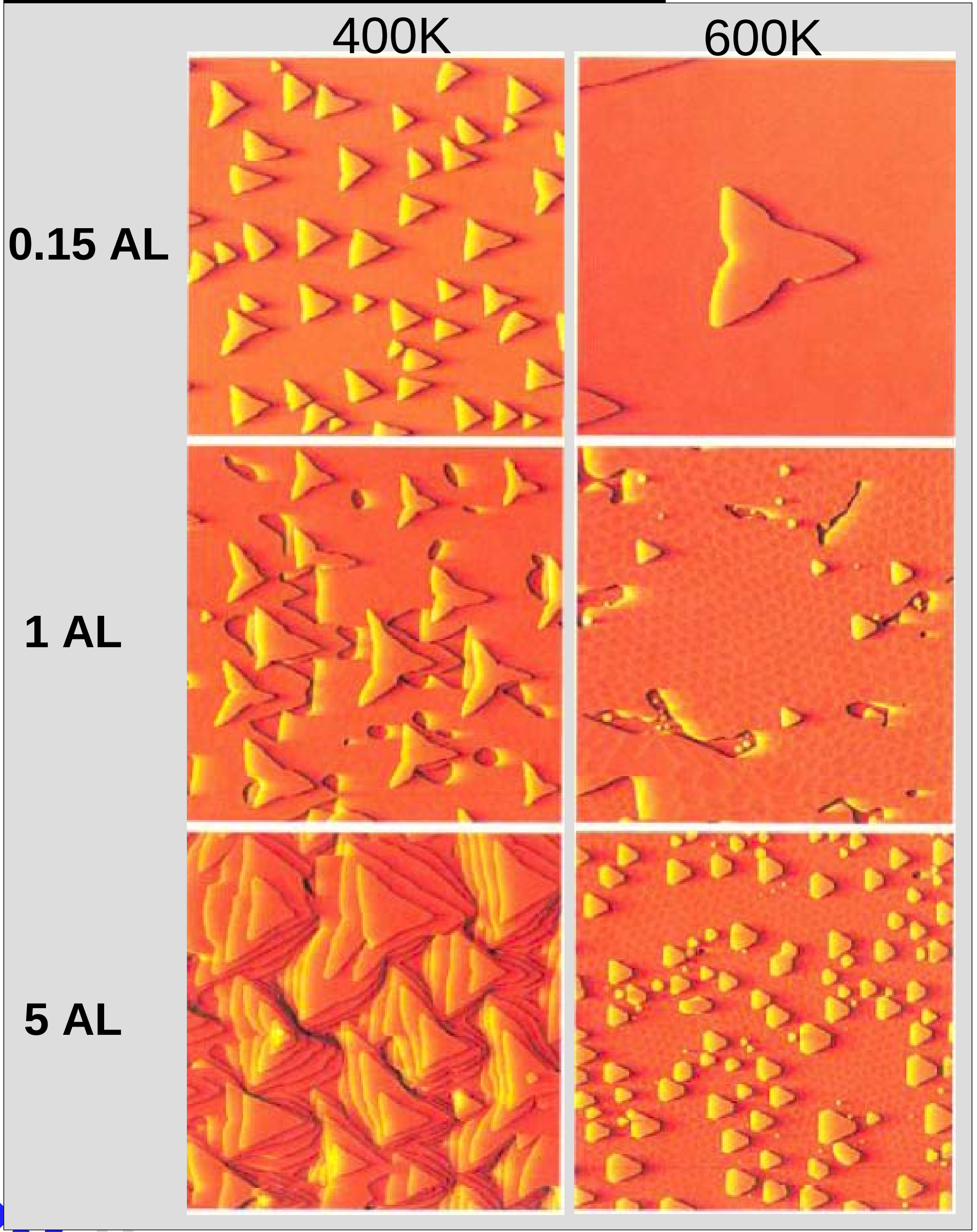
J. P. Bucher, Europhys. Lett. 27, 473 (1993)

Schwoebel barrier: origin



Schwoebel barrier: example

Pt/Pt(111)



Depending on symmetry:

Huts and holes: (111), (001), hcp(0001).

Trenches: (110), etc.

Other parameters to play with the Schwoebel barrier:

Surfactants (Pb, Sb, O etc.)

Ex: J. Camarero et al., PRL76, 4428 (1996)

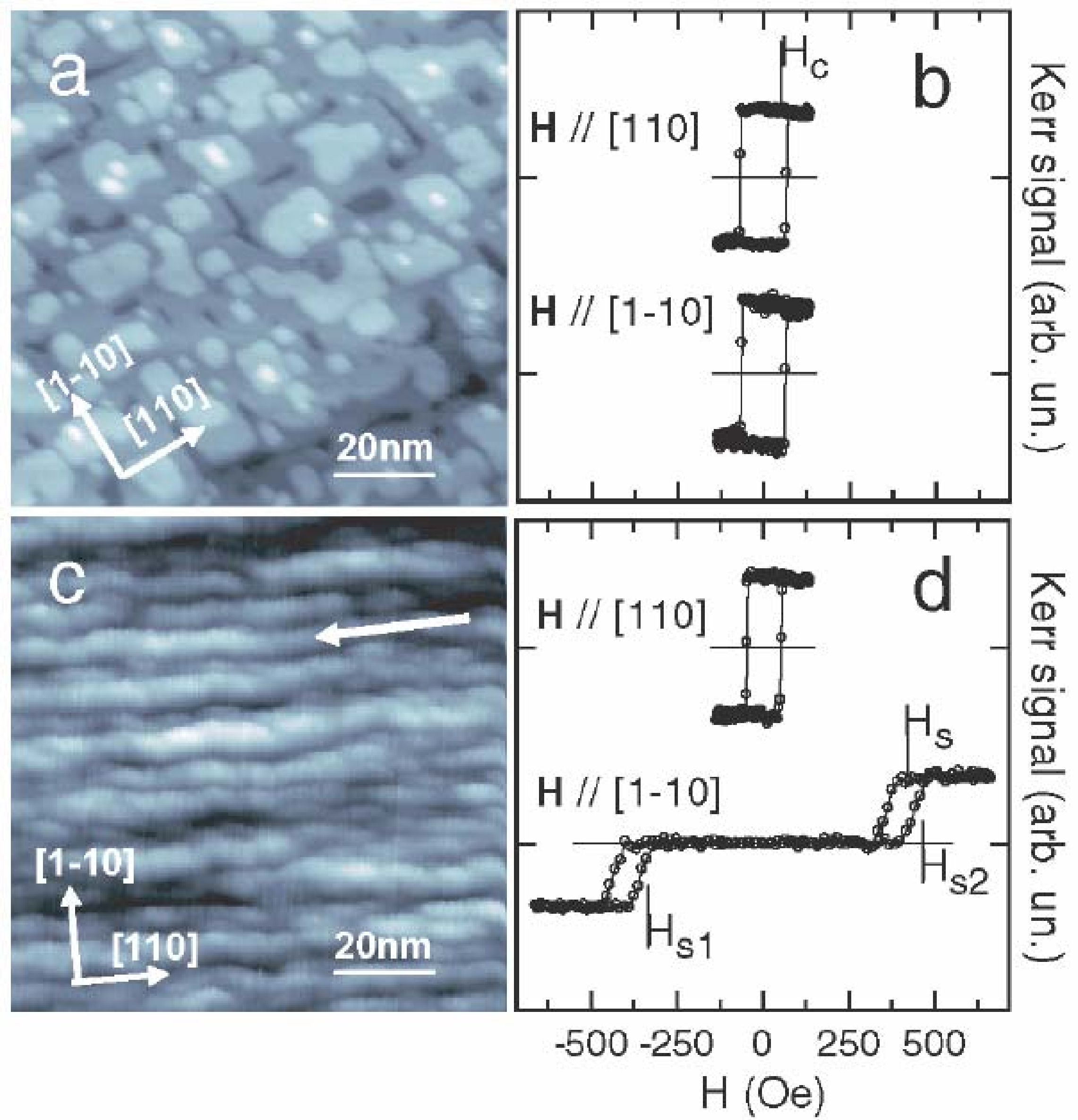
Deposition method (Ex: PLD versus MBE)

Review: J. Shen et al., Surf. Sci. Rep. 52, 163 (2003)

T. Michely and Krug, *Islands, mounds and atoms*, Spinger (2004)

Ion etching: 'Inverse growth'

Co/Cu(001)



As-grown

Tilted Incidence Ion etching

Other process:

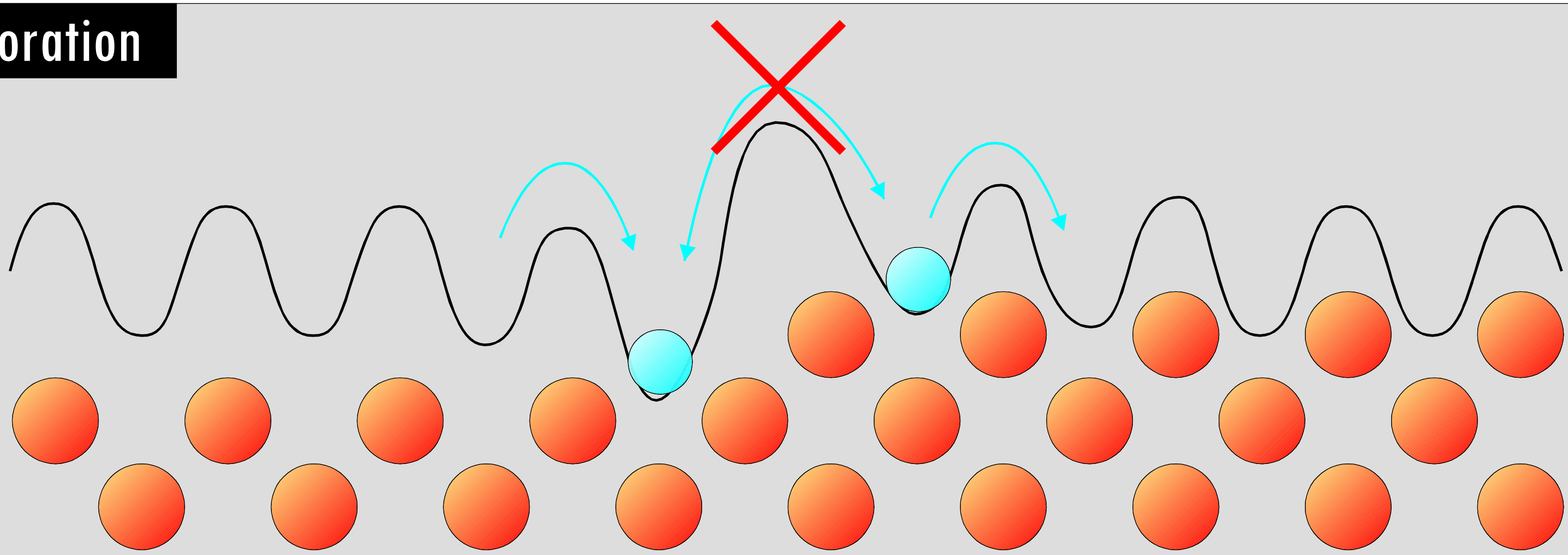
Create pattern by ion etching, then deposit

REVIEW:

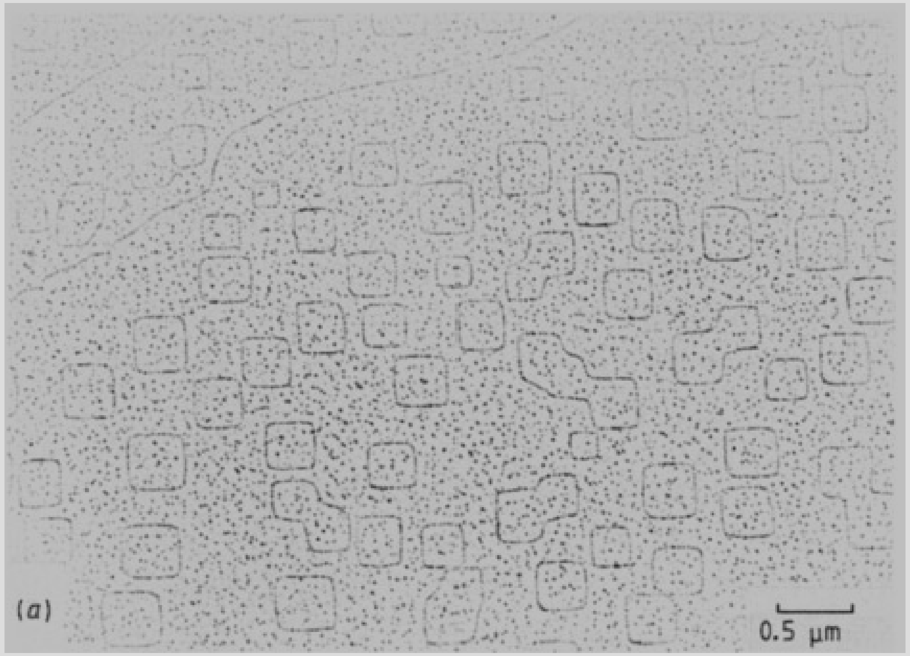
C. Teichert, Phys. Rep. 365, 335 (2002)

R. Moroni et al., PRL91, 167207 (2003)

Step decoration



Adatoms are trapped at the lower side of the step



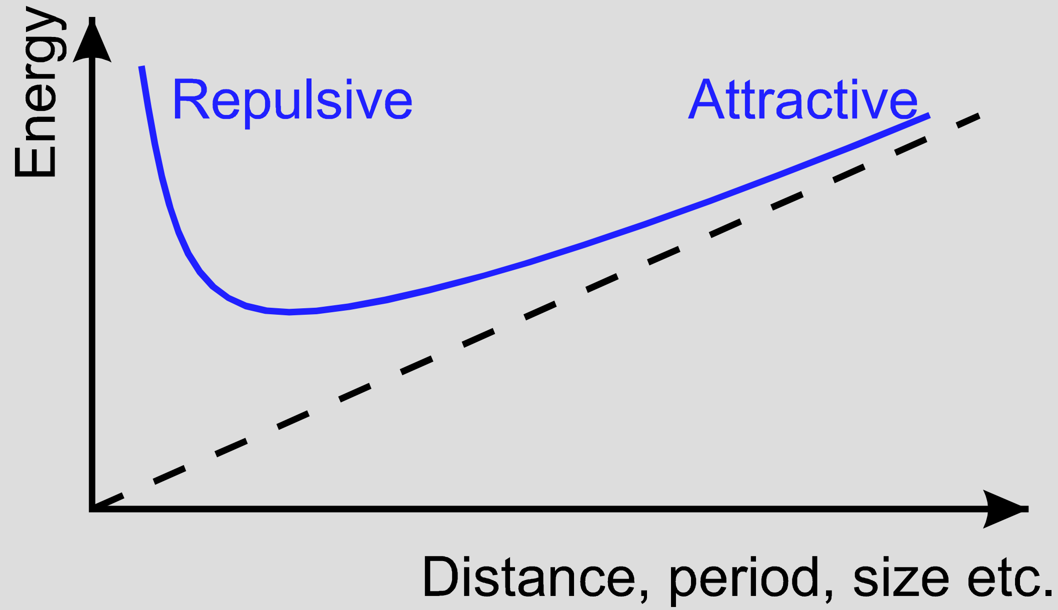
First report of step decoration

G. A. Bassett, Phil. Mag. 3, 1042 (1958)

H. J. Meyer et al., J. Cryst. Growth 49, 707 (1980).

So far, nanostructures, however not order. Could be called self-assembly.

What can determine characteristic length scales and order in physics?

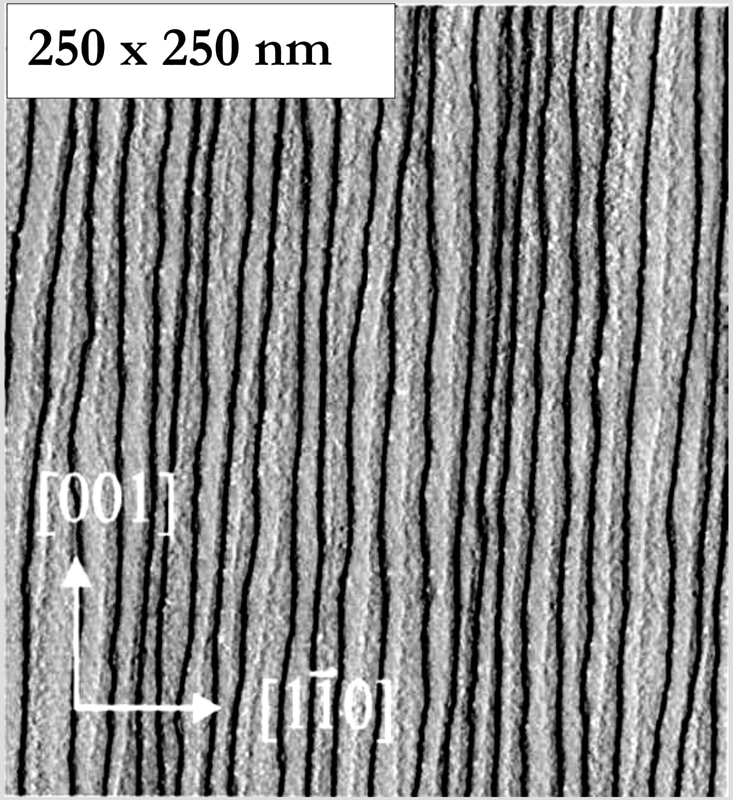


Fields of interest for us:

- Magnetism (wall width etc.)
- Surfaces (reconstructions etc.)

Stripes

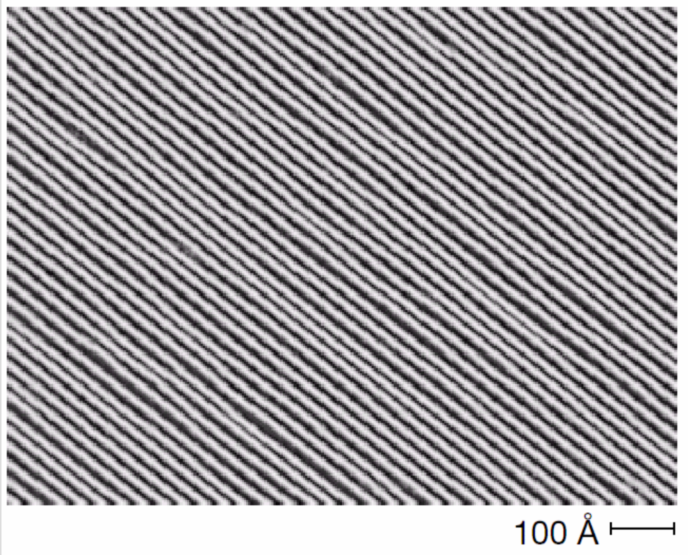
Fe(0.5ML) / W(110)

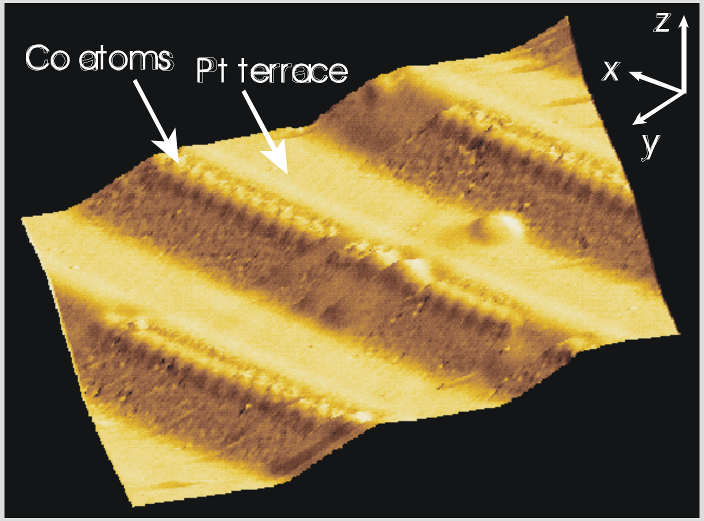


J.Hauschild *et al.*, Phys.Rev.B57, R677(1998)

Wires (monoatomic)

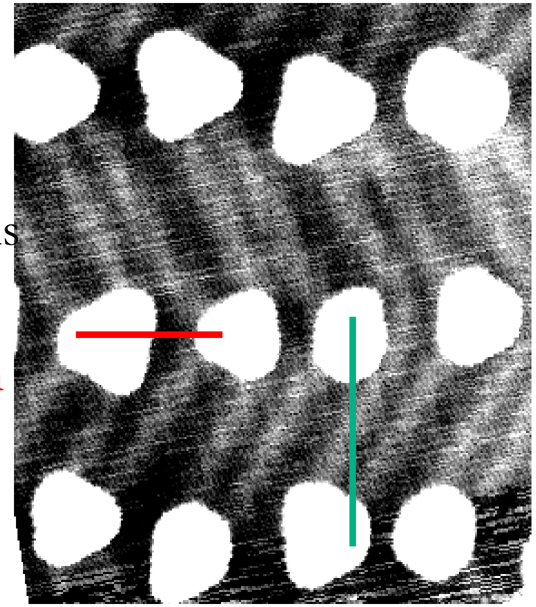
Co(0.15ML) / Pt(997)



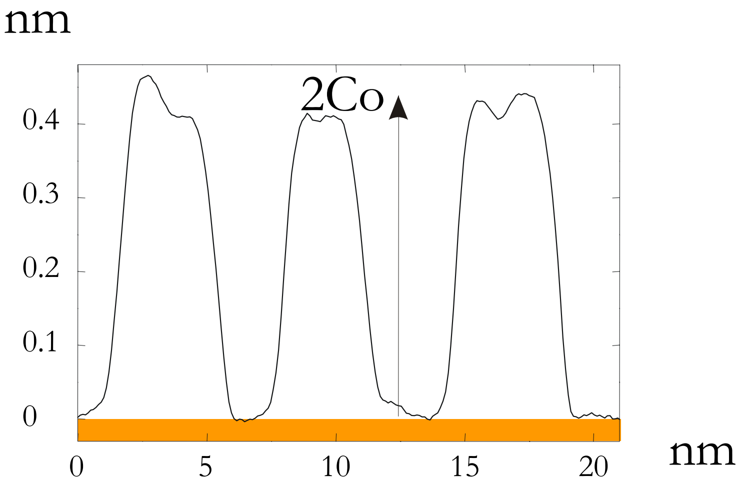


P. Gambardella et al., Nature 416, 301 (2002)

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



(0.20AL Co@300K)



O. Fruchart et al.

Fe, Ni : 1 AL-high dots

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

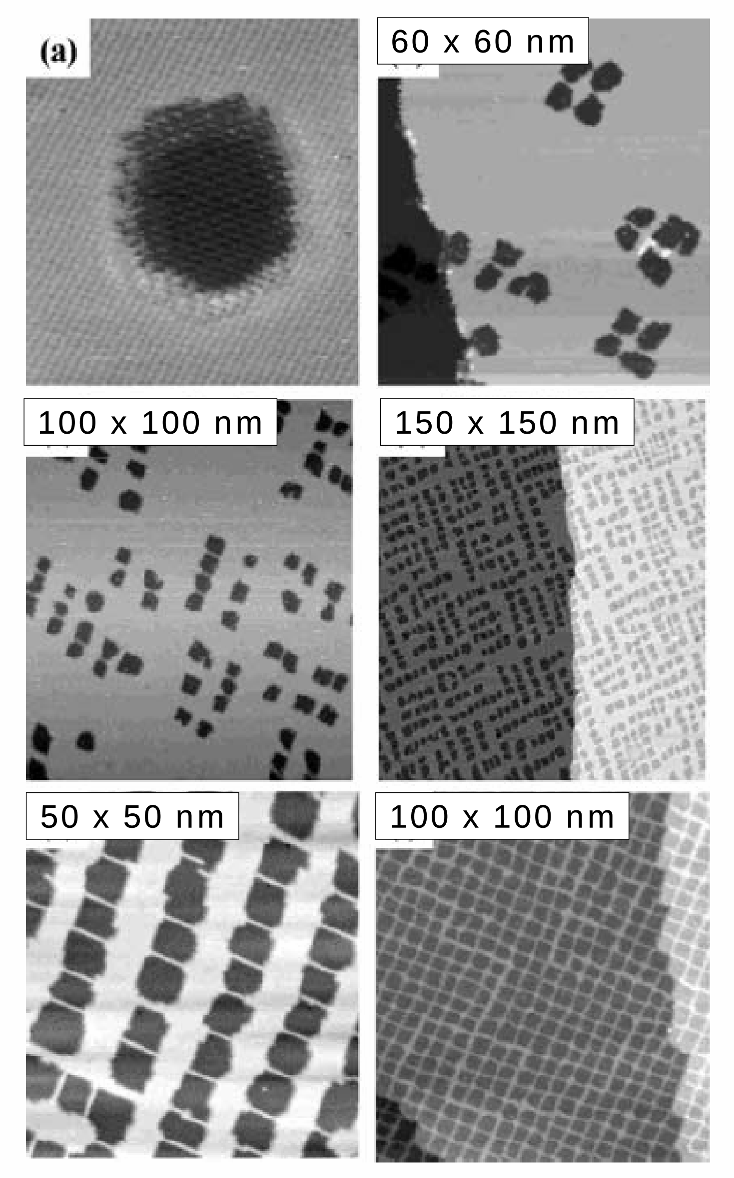
B.Voigtlander et al., PRB **44**, 10354 (1991)

- Medium-ranged organization
- Steps do not necessarily disturb the order
  [see also:
  V.Repain, Europhys. Lett., **47** (4), 435 (1999)]

Gas adsorbtion

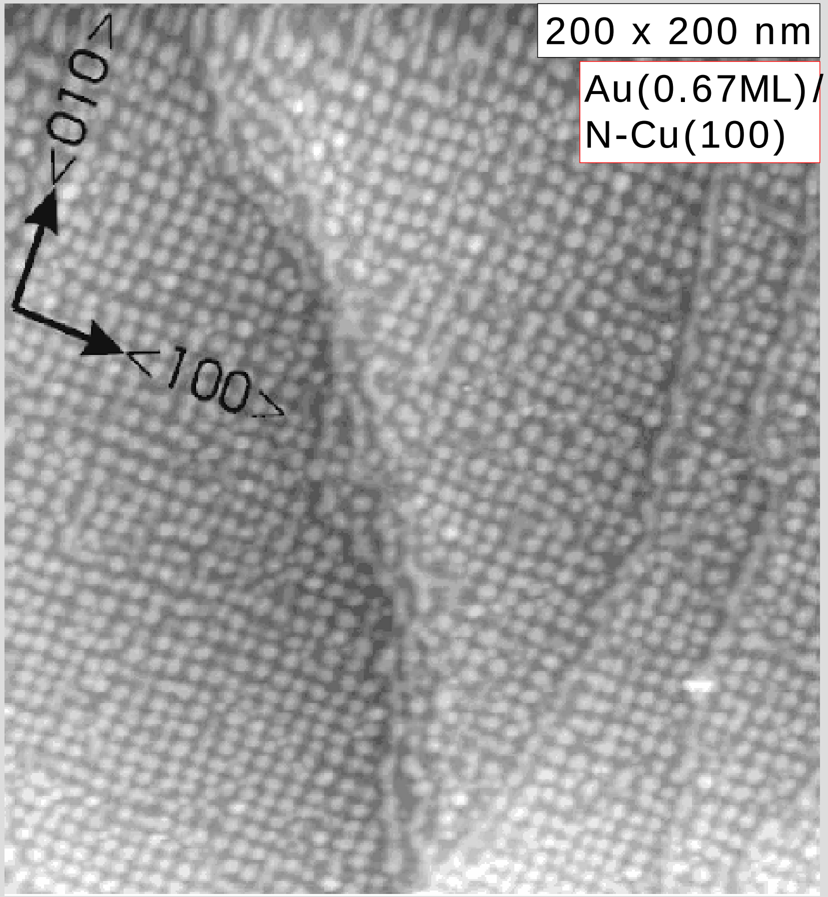
N on Cu(001)

First study: T.M.Parker, Phys.Rev.**B56**, 6458(1997)



S. Rousset et al., Mater. Sci. Engineer. B 96, 169 (2002)

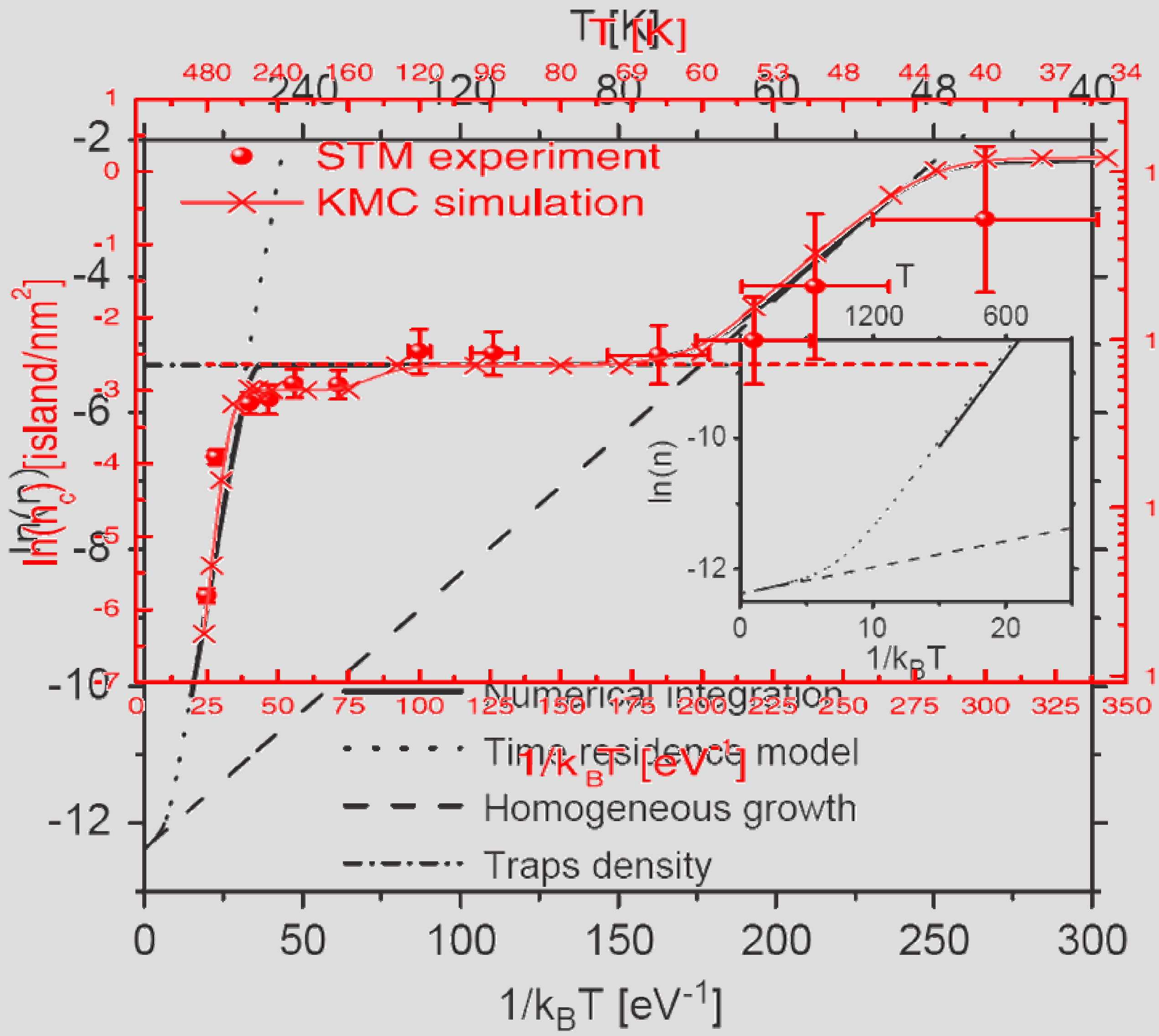
Overgrowth of Au



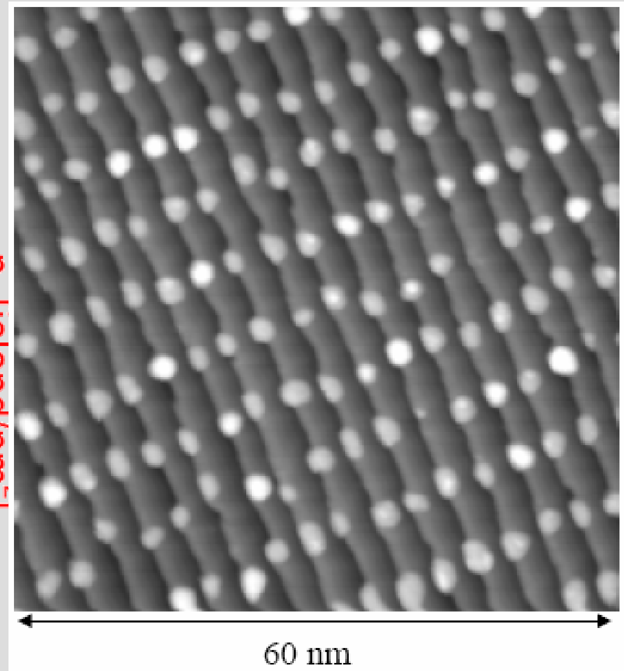
H. Ellmer et al., Surf. Sci. 511, 183 (2002)

Nucleation rate equations for self-organization

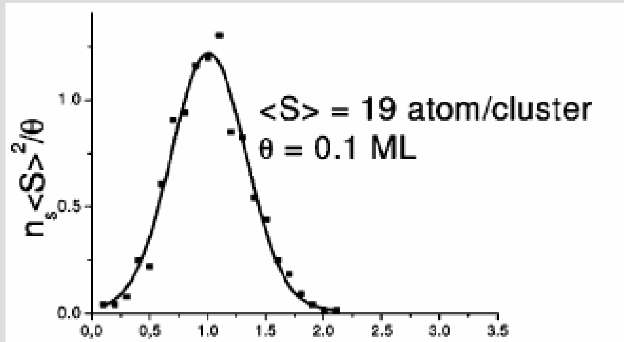
Co/Au(788)



S. Rohart et al., Surf. Sci. 559, 47 (2005)



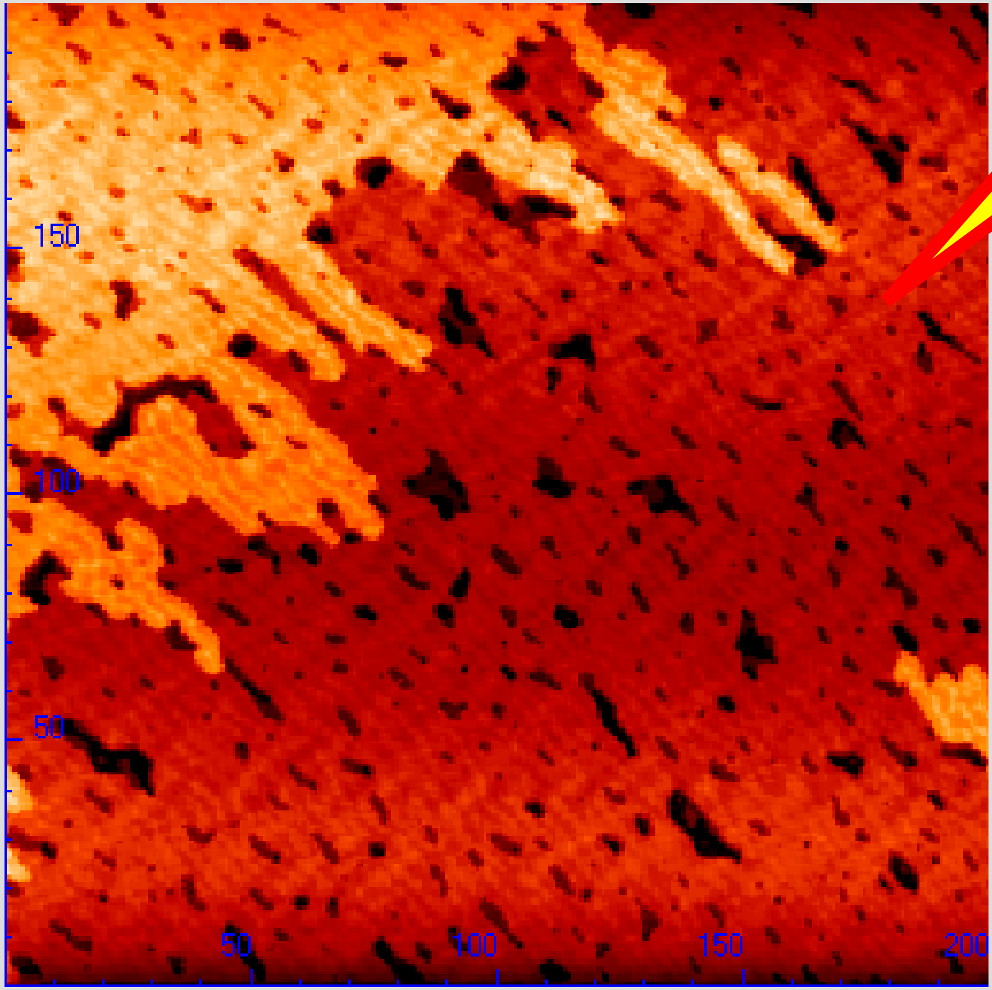
V. Repain et al., Europhys. Lett. 58, 730 (2002)



Reduced size distribution

Self-organization during deposition

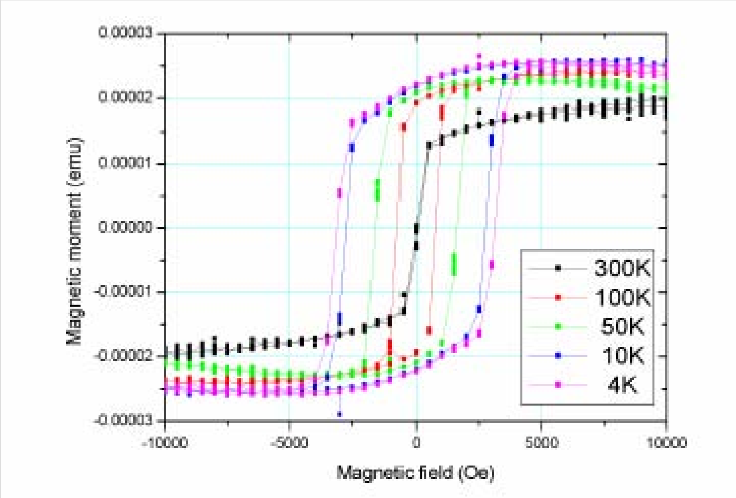
Fe-Ag/Mo(110)



See poster by Bogdana BORCA

Alternating Fe and Ag stripes:
'lateral multilayer'

(period: 3.5nm)



Blocking temperature: 190K

B. Borca et al., submitted to JAP

First demonstration:
- E. D. Tober et al., PRL 81, 1897 (1998)
- E. D. Tober et al., APL 77, 2728 (2000)

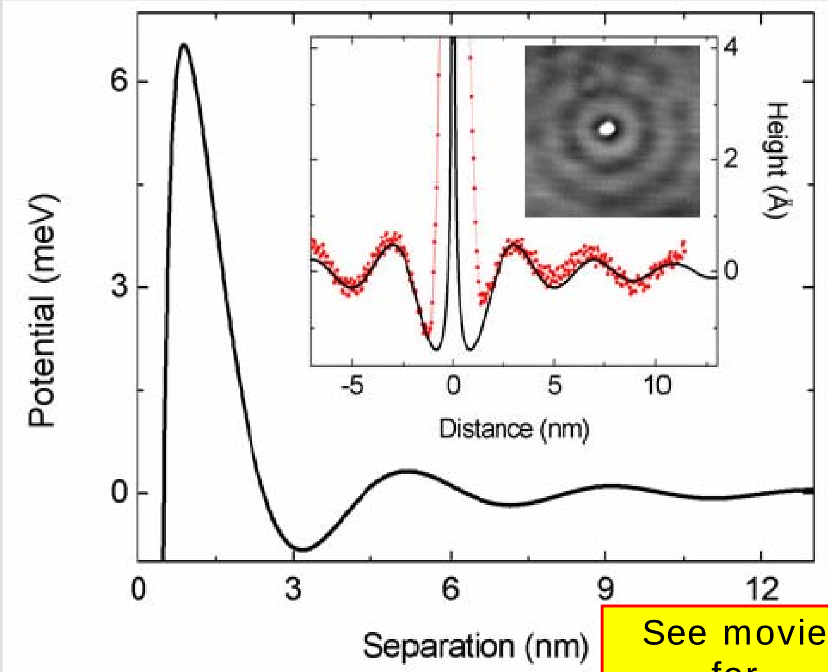
Friedel crystals

Ce(1AL)/Ag(111) @ 3.9K

STM, 69x69nm

See movie for Co/Cu(111)

Supra-crystal stabilized by surface states oscillating around adsorbates



See movie for Ce/Ag(111)

Figure 9. Calculated two-body interaction potential of Ce adatoms on Ag(111) (equation (2)). Inset: 21 × 21 nm^2 STM topography of a standing-wave pattern around an isolated Ce adatom on Ag(111) at 3.9 K ($U_s = -3$ mV, $I_s = 19$ pA). Topographic cross-section (dots) and fit using equation (1) (solid curve) as a function of distance from a single Ce adatom.

Why self-organization is interesting?

- UHV-quality of the interfaces, down to the atomic size (crucial for interface-dependant properties)
  - Reliable analysis of measurement of assemblies
  - Reproducibility, low dispersion.
- Monodispersion (fondamental and applied), more than order
- Perform 'diffraction' at the period of the organized arrays

Drawbacks

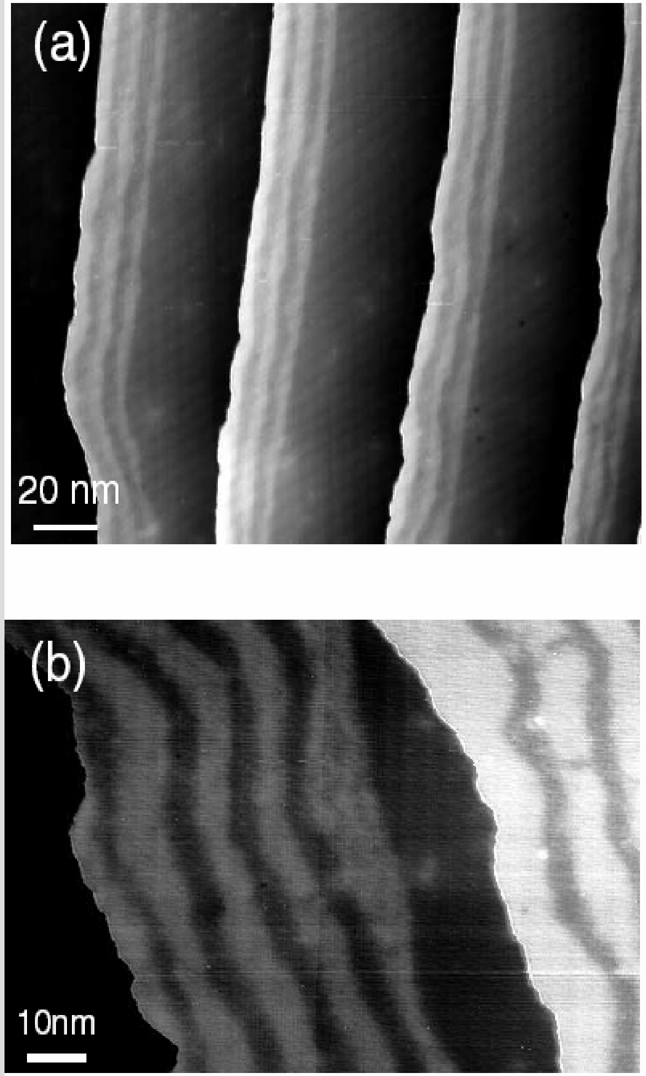
- Limited versatility
- Low amount of material available
- No magnetic functionality at 300K (see later)

•> Find new processes of self-organization

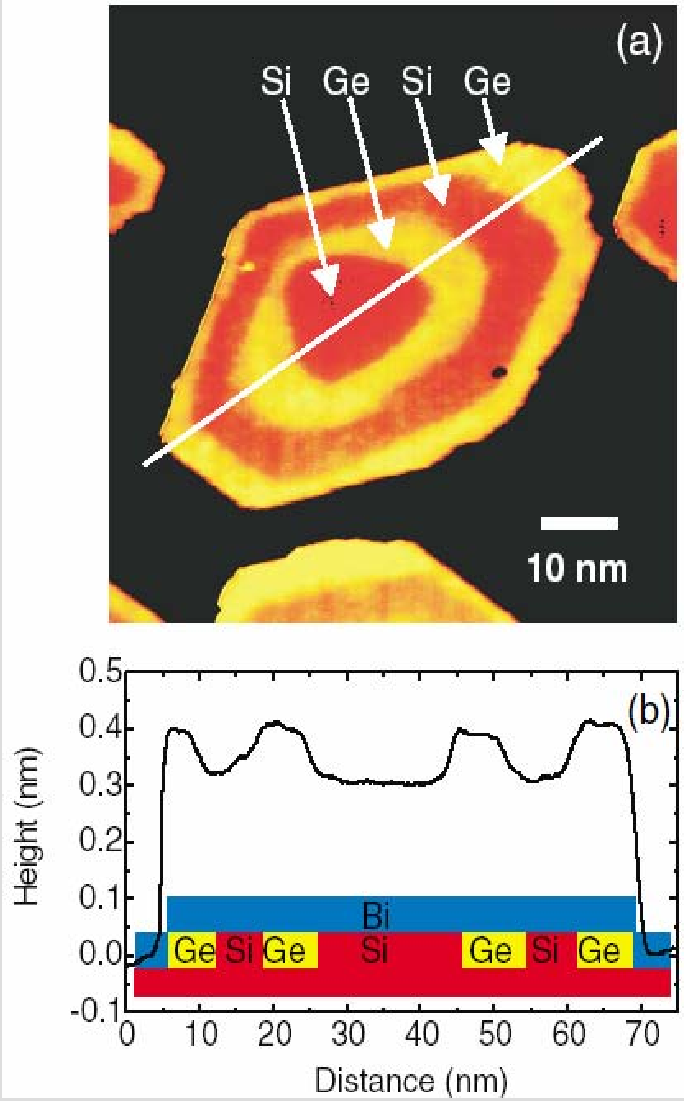
Principle:sequential deposition of two materials with step-flow growth

Si / Ge (Bi-capped for revealing Si and Ge)

Nanowires



Nanorings



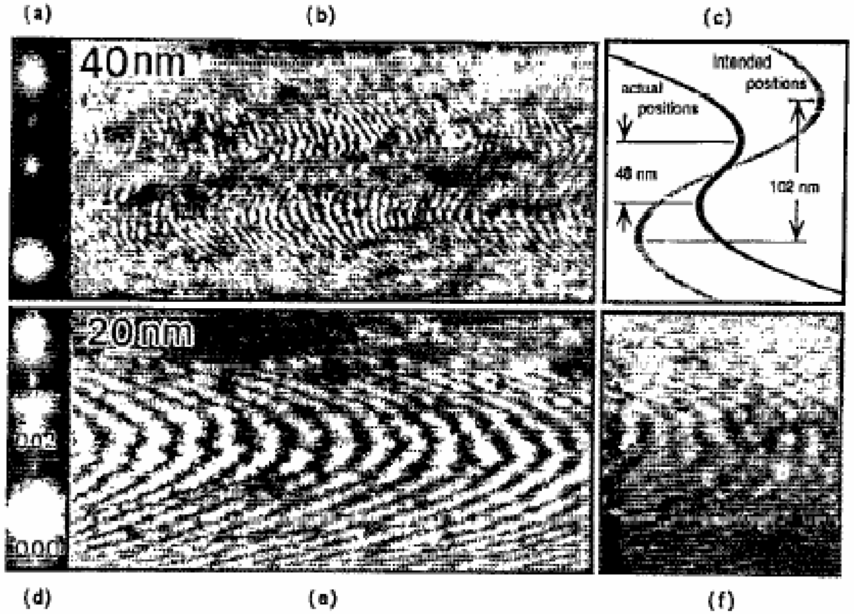
M. Kawamura *et al.*, Phys. Rev. Lett. 91, 096102 (2003)

Name: Lateral Superlattices (LSLs)
or Tilted Superlattices (TSLs)
or Fractional layer superlattices (FSLs)

Principle: sequential deposition with step-flow growth

First demonstration: P.M. Petroff, APL45, 620 (1984)

AlAs/GaAs lateral superlattice



TEM pictures

FIG. 1. TED and micrographs of SSL sample A, (a)–(c) and sample B, (d)–(f). The sample A TED pattern (a), dark-field image using the SSL streaks SL DF (b), and the intended and actual boundary geometries of the parabolic crescents (c). The sample B TED pattern (d), the SL DF image (e), and the (002)-DF image (f) are shown.

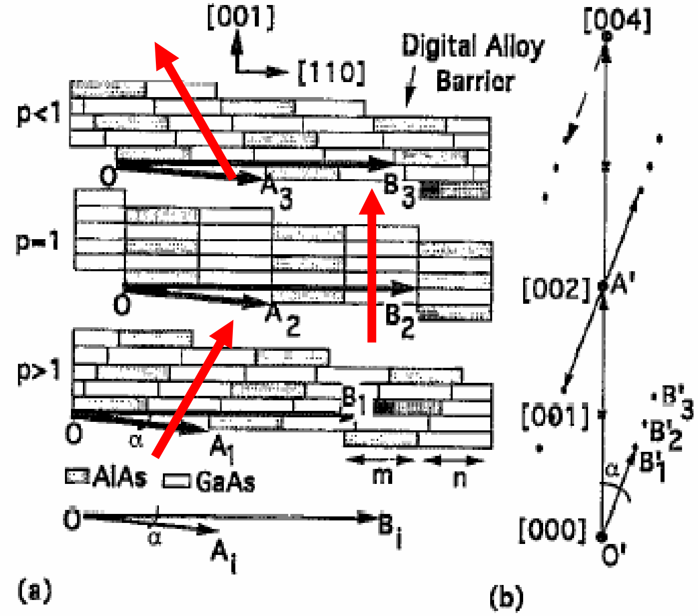


FIG. 2. A SSL on a terraced substrate depicted as three TSL slices (a), and the synthesized diffraction pattern, (b) are shown. While the real space vectors $\mathbf{OB}_i$ change with coverage, the superposition of reciprocal lattice vectors $\mathbf{O'B}_i'$ predicts the formation of streaks at the observed positions.

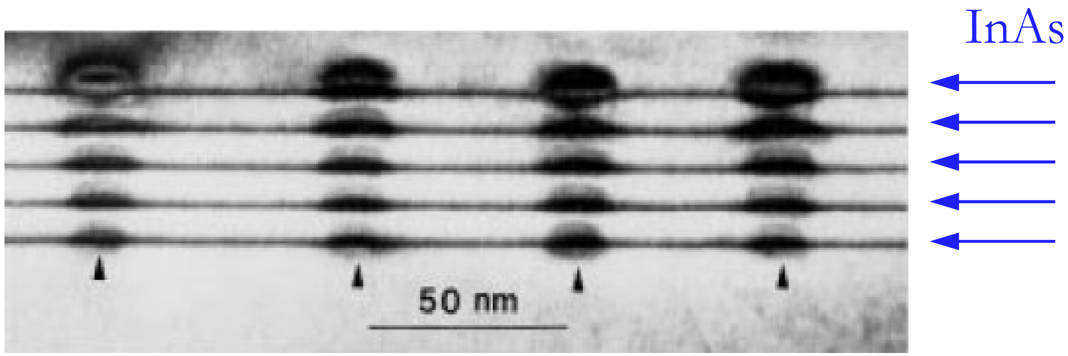
M. Kirshnamurthy, APL61, 2990 (1992)

Main obstable: requires excellent control of both deposition rates

3D self-organization: dot's vertical stacking.

InAs / GaAs(100)

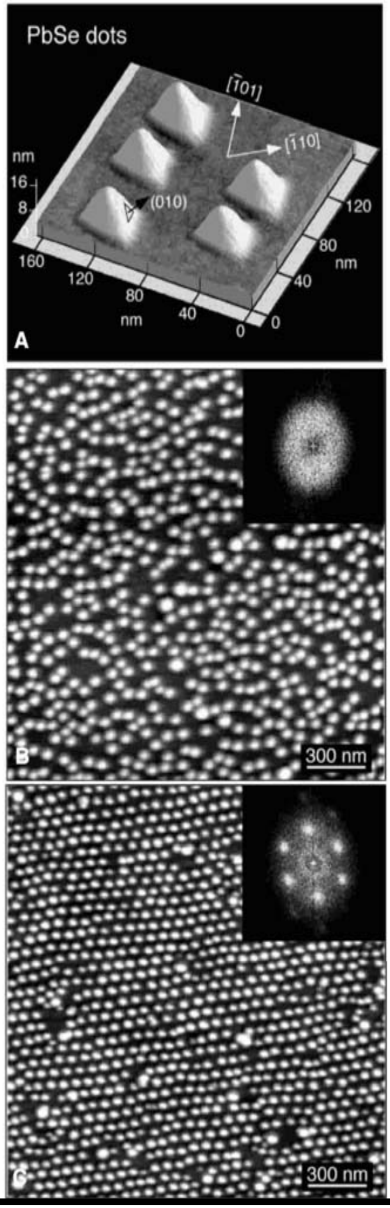
- Strain field in spacer layer :
  ↳ vertical stacking of dots



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

PbSe / PbTe(111)

- From 2D assembly to 3D- organization



Zoom : facetted dots

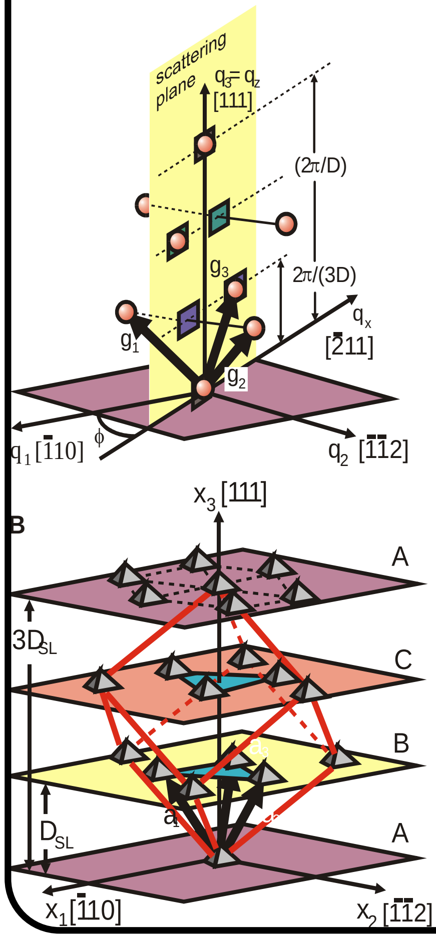
Single layer : Self-assembly, no organization.

Multilayers : improvement of the organization.

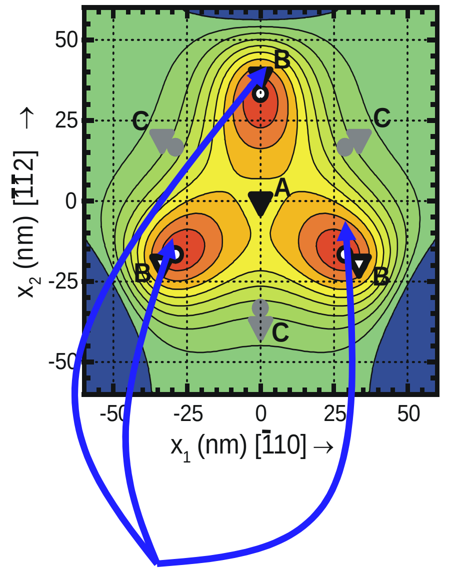
(After 60 layers)

- Anisotropic elastic media
  - f.c.c. superstacking, not vertical.

X-Ray diffraction



Anisotropic in-plane distribution of elastic energy density



Misfit reduced by 2%
preferential nucleation

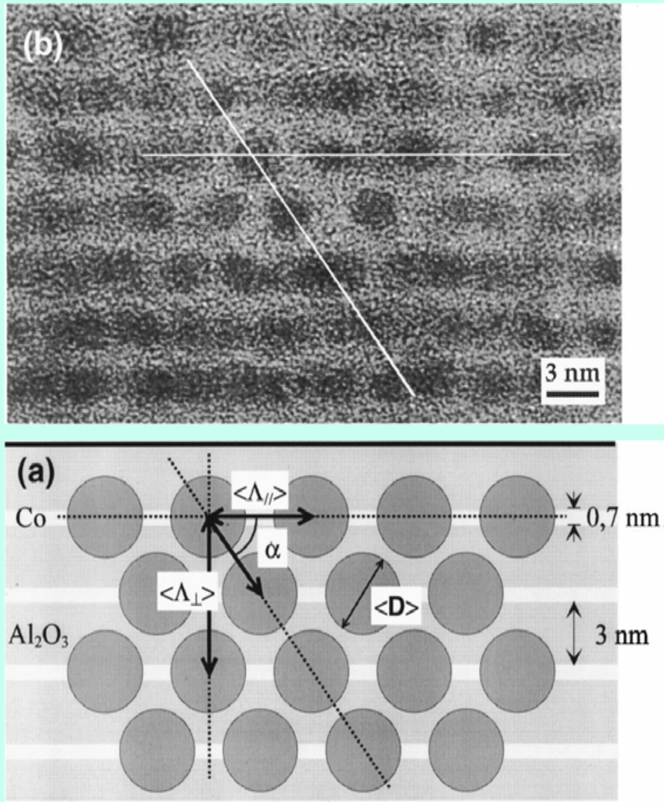
G.Springholz, Science **282**, 734 (1998)

Co/Al_2O_3 granular system (sputtering)

$(Co: 0.7\ nm/Al_2O_3: 3\ nm)_{14}$

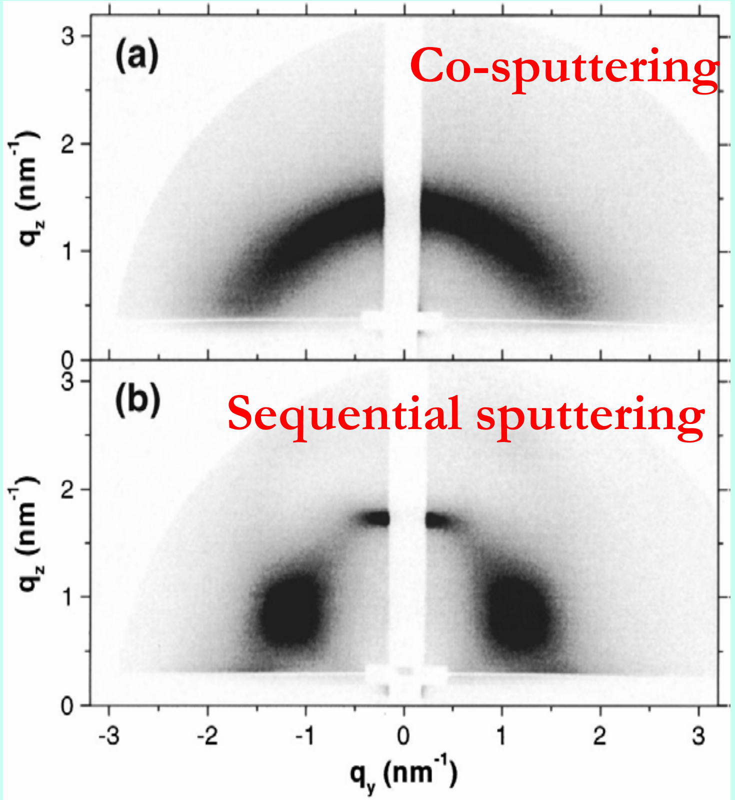
REAL SPACE

TEM cross-section (Sequential sputtering)



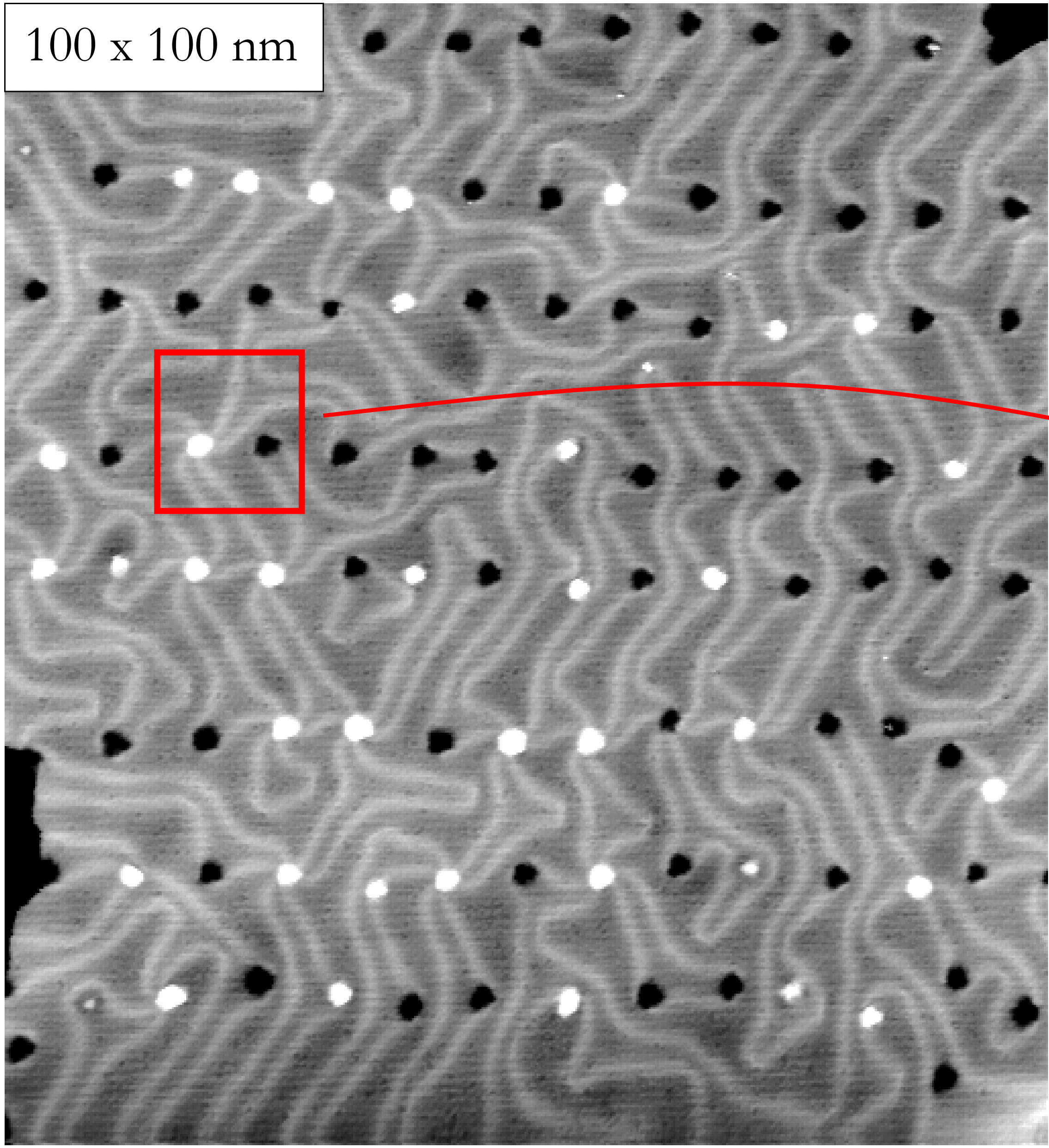
RECIPROCAL SPACE

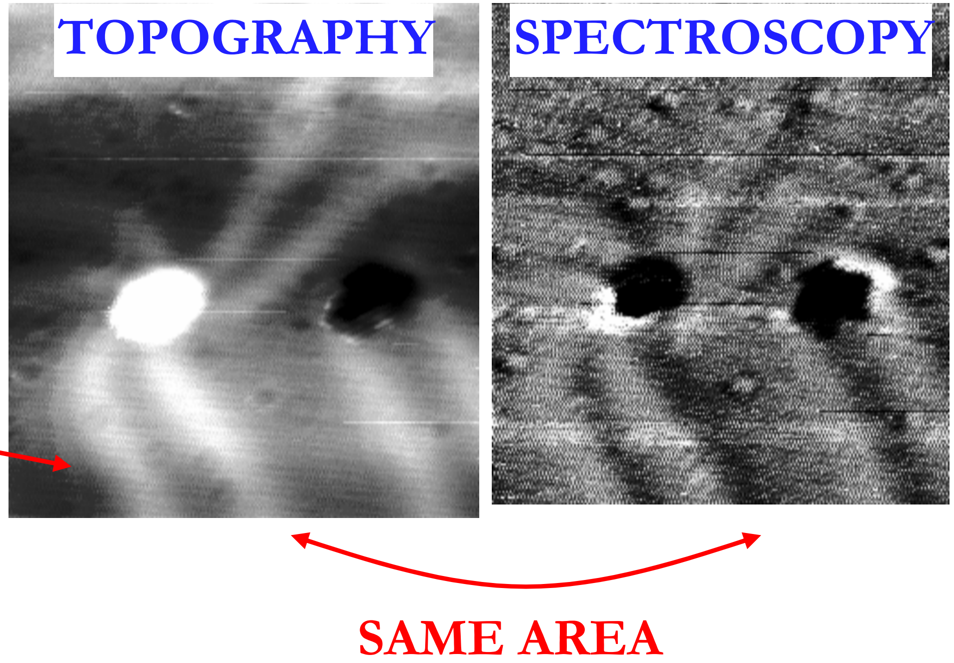
GISAXS:
Grazing Incidence Small Angle X-Ray Scattering

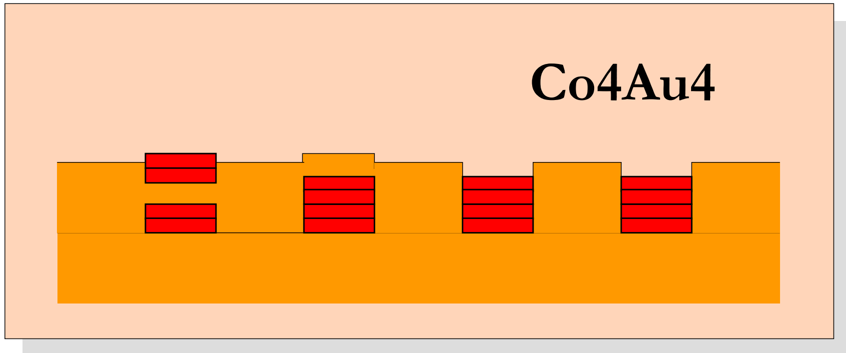


- FCC vertical stacking (not epitaxial !)

D. Babonneau, Appl. Phys. Lett. 76, 2892 (2000)





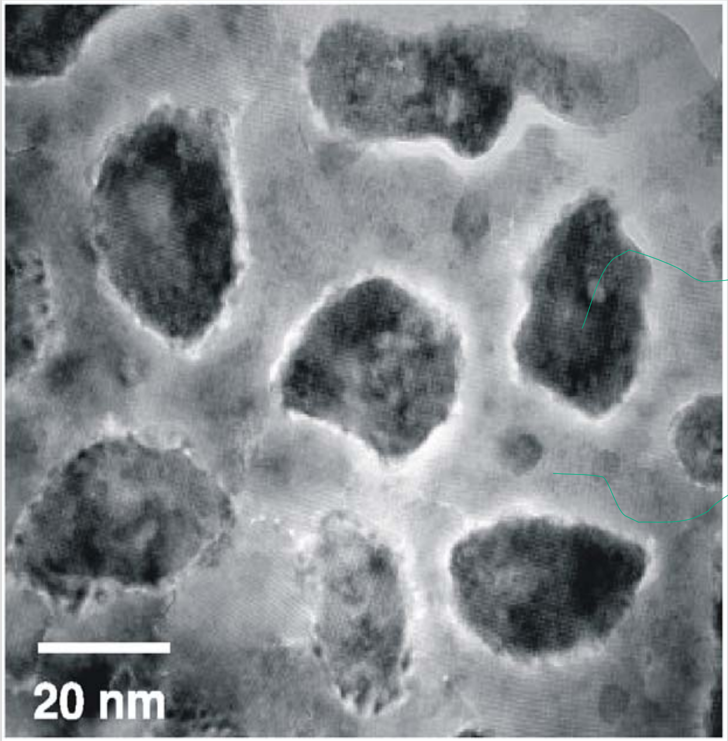


Co atoms grow only on existing dots

↳ **VERTICAL COLUMNS**

Structure

$CoFe_2O_4$ in $BaTiO_3$ matrix

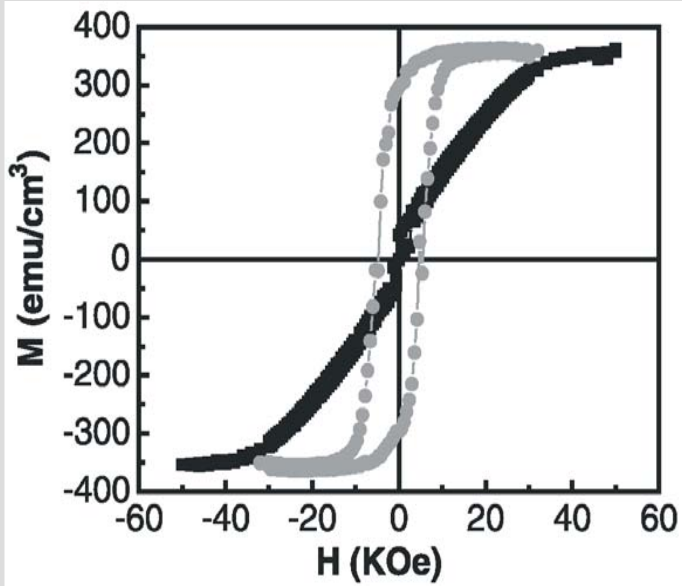


$CoFe_2O_4$ (ferrimagnetic)

$BaTiO_3$ (piezzoelectric)

Deposition from a Ti-Ba-Co-Fe oxide target by pulsed laser deposition

Magnetism



- Room-temperature functionality
- Perpendicular anisotropy owing to matrix-induced strain in the columns

H. Zheng et al., Science 303, 661 (2004)

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1. Epitaxial self-assembly & self-organization
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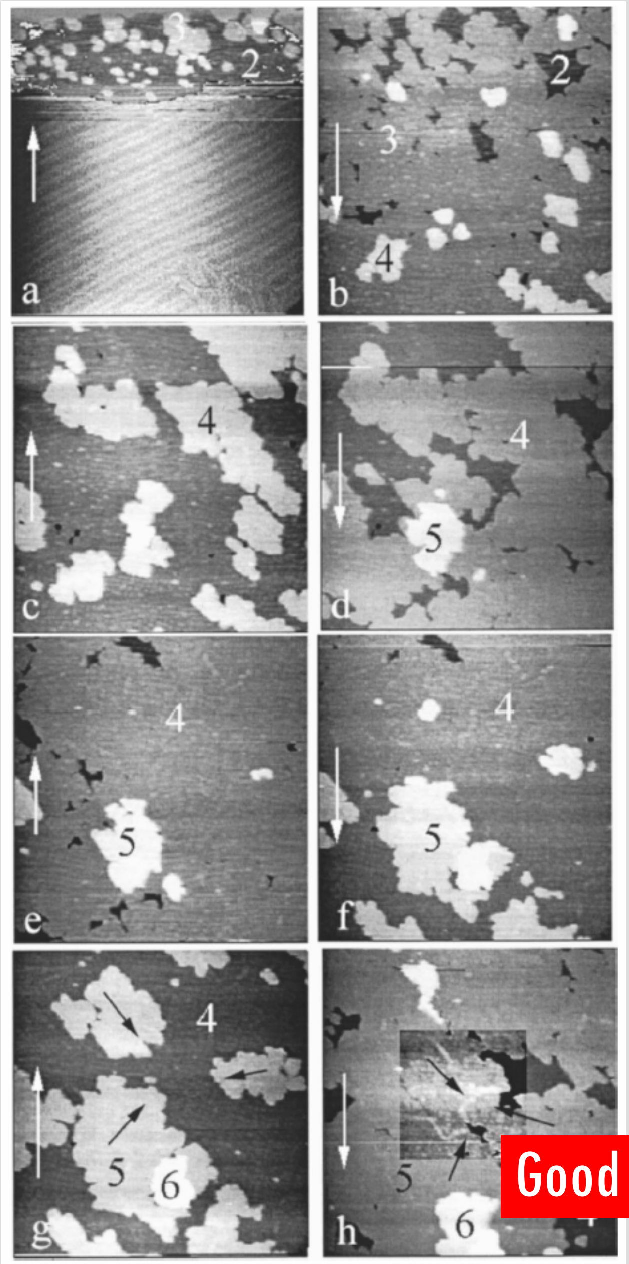
4. Micromagnetism

Continuous films



Co/Au(111)/mica

Layer-by-layer growth

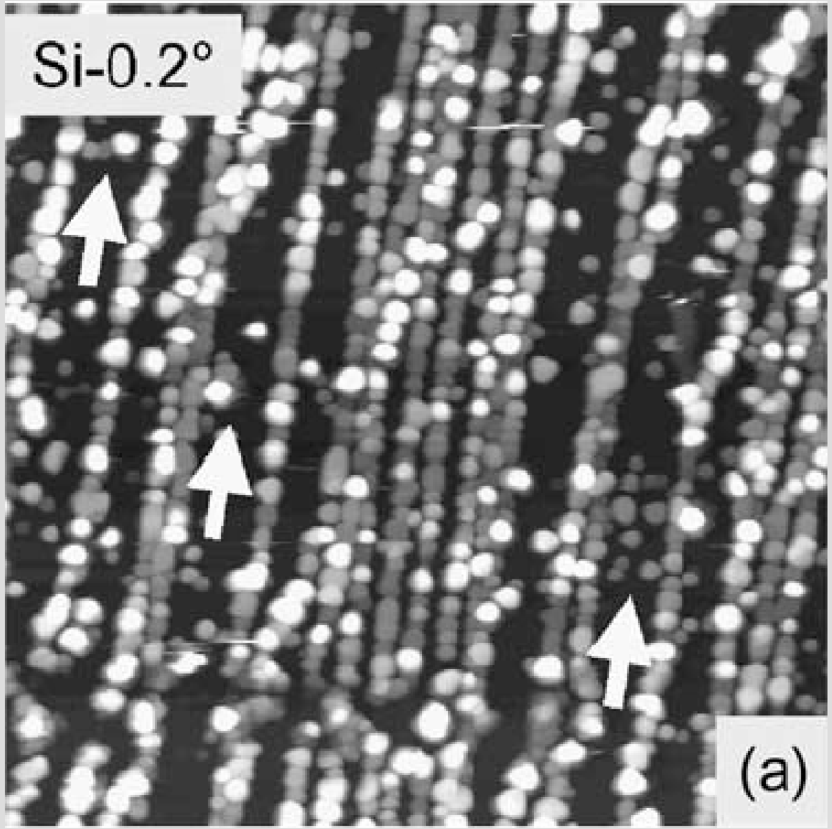
➢ Higher magnetic anisotropy Than for MBE

L. Cagnon et al., PRB63, 104419 (2001)

Good aspects

Continuous films

Au/H-Si(111)



Step decoration explained by preferential nucleation

M. L. Munford, Surf. Sci. 539, 95 (2003)

See talk by

K. NIELSCH

Advantages

- Low cost
- Versatility of ligands: fonctionalize, tune distances etc.

Drawbacks

- More difficult to fabricate alloys (stoechiometry, ordering)
- Annealing can burn ligands (nearly solved)
- Moderate packing density

Clusters by physical means: 1-10nm

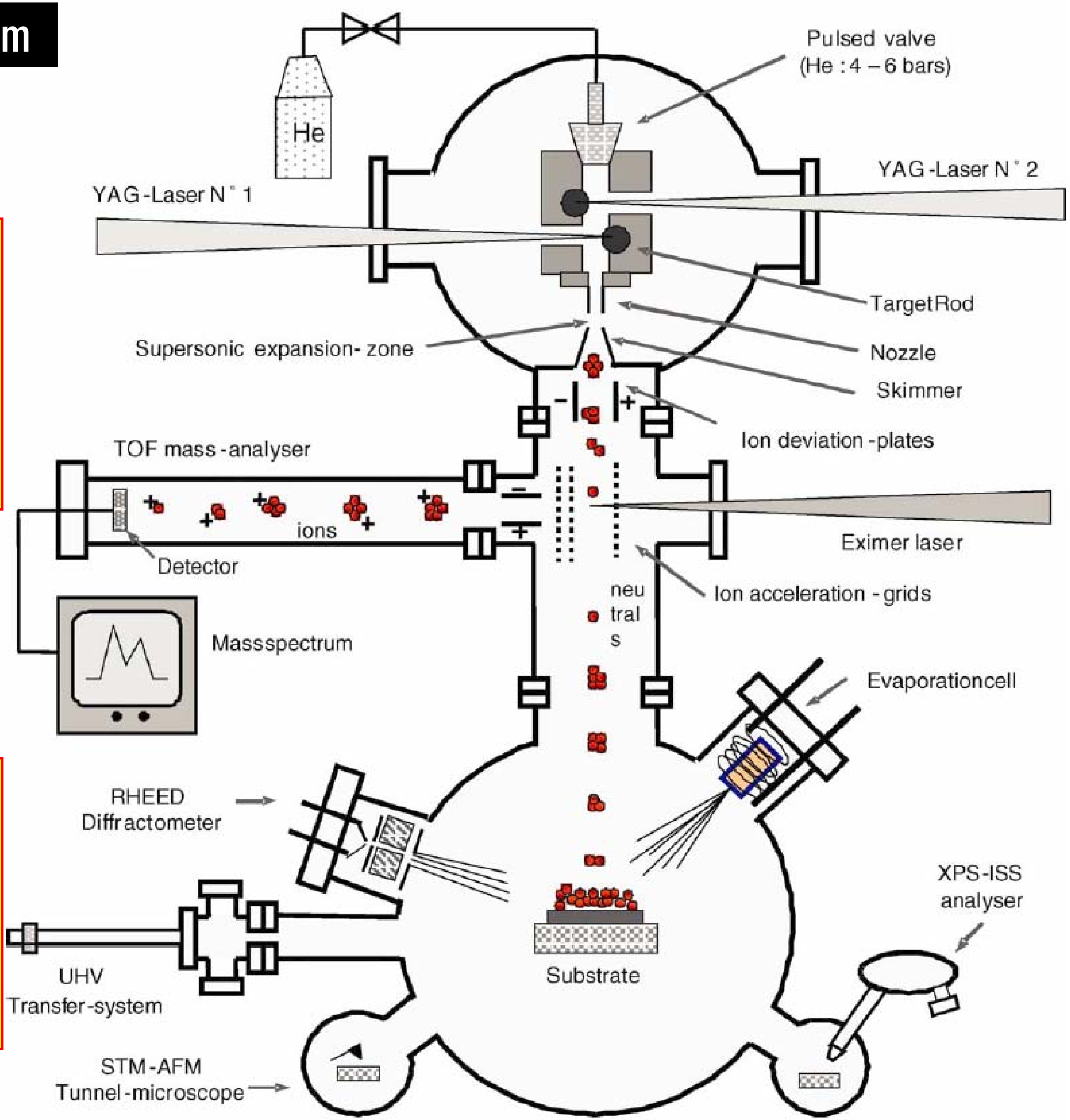
Example: Laser vaporizaiton in inert gas

- Many elements suitable
- Mass filtering
- Bimetallic clusters available
- Landing without fragmentation

J. Bansmann et al.,
Surf. Sci. Rep. 56, 189 (2005)

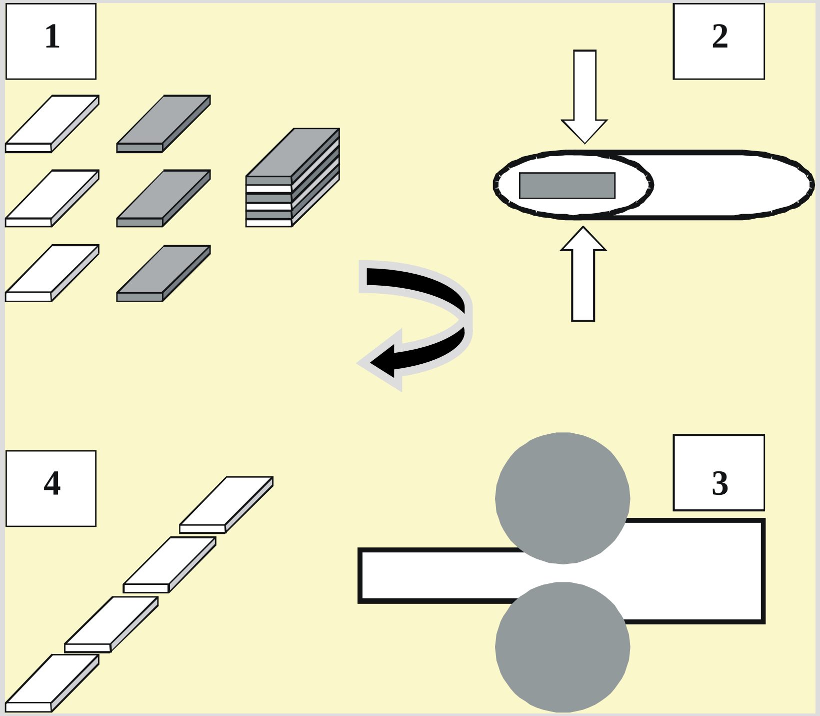
Other set-ups

- Gaz aggregation sources with thermal evaporation
- Arc Cluster Ion Source (ACIS).



Rolling and extrusion : an original route for bulk nanocomposites

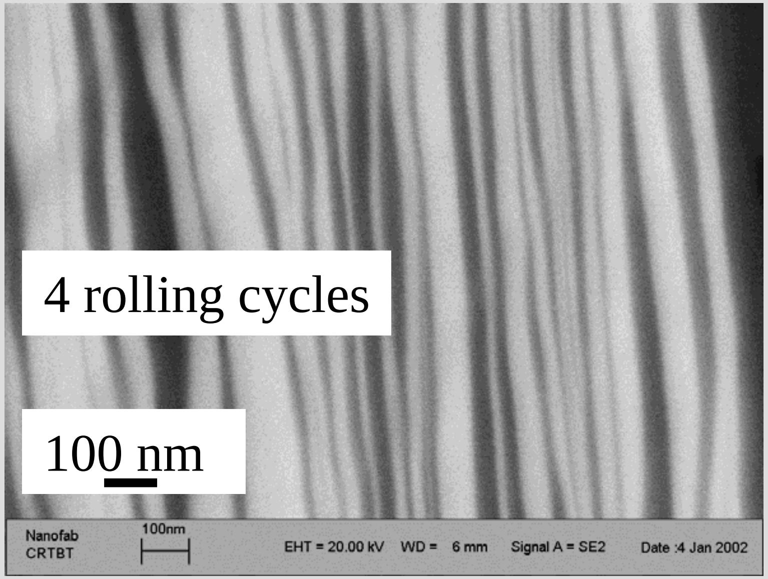
Principle



≈ 100 passes per cycle ; t_{init}/t_{final} ≈10
No stress-relieving heat treatment

Example

FePt

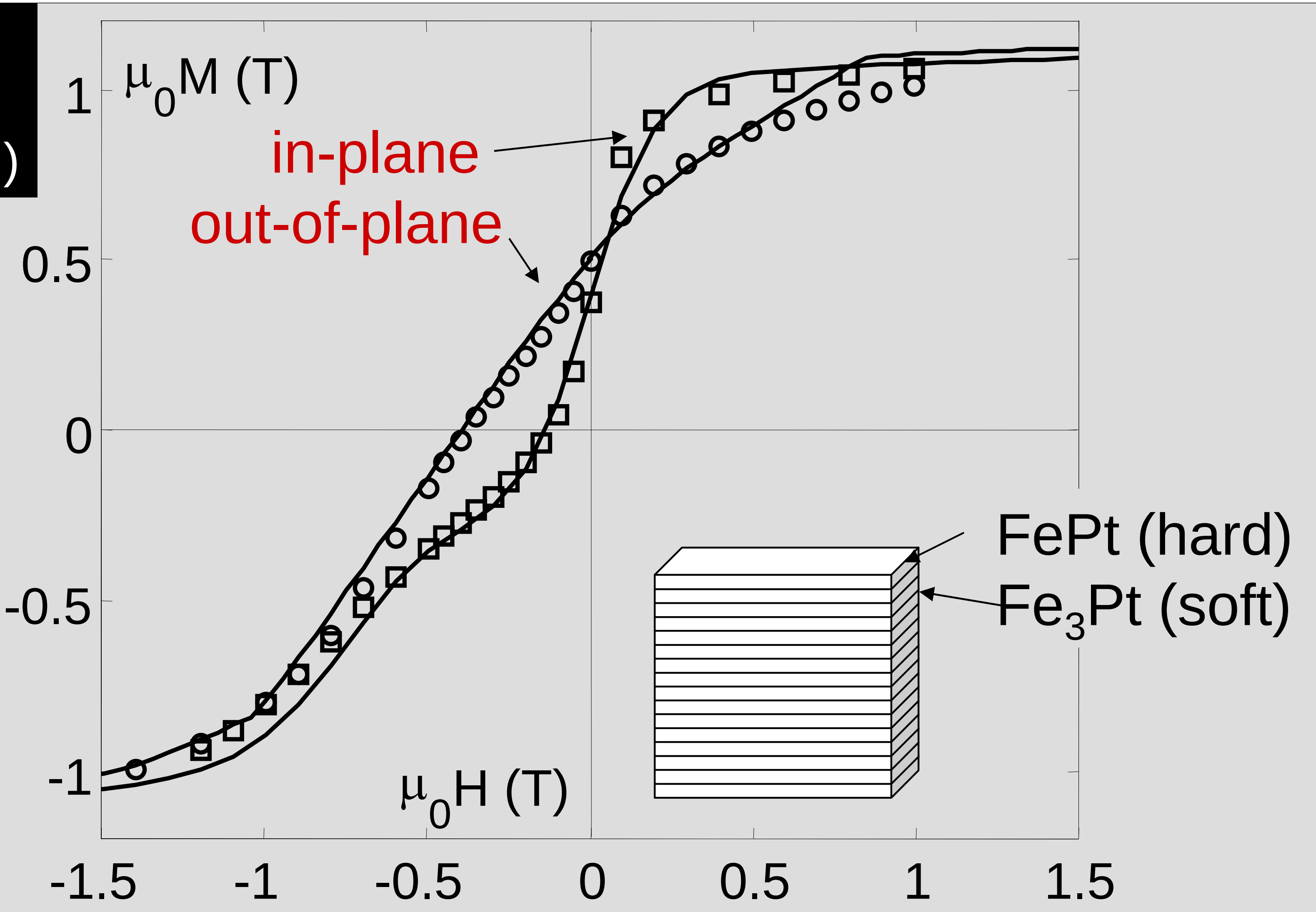


Strong texture

(close to epitaxial relationship !)

N.H. Haï, N.M. Dempsey, D. Givord, J. Magn. Magn. Mater. 262 (2003) 353

FePt/Fe_3Pt calculated versus experimental M(H)



Dipolar spring magnet, an original concept, and bulk preparation

Personal views on self-organization

- <u>Thin and ultrathin films area</u>: a few 'niche' area still exist, however leaves research to become a tool.

- <u>Self-organization</u>: on step further thin films. 10-15 years old. Many advances for fundamental science, but seem to remain a niche for applications in the current state.

- <u>Two ways to go forward</u>:
  - Open new paths in self-organization: 3D, combine with other techniques.
  - Increase versatility and improve functionality of self-organized systems, to include in devices.

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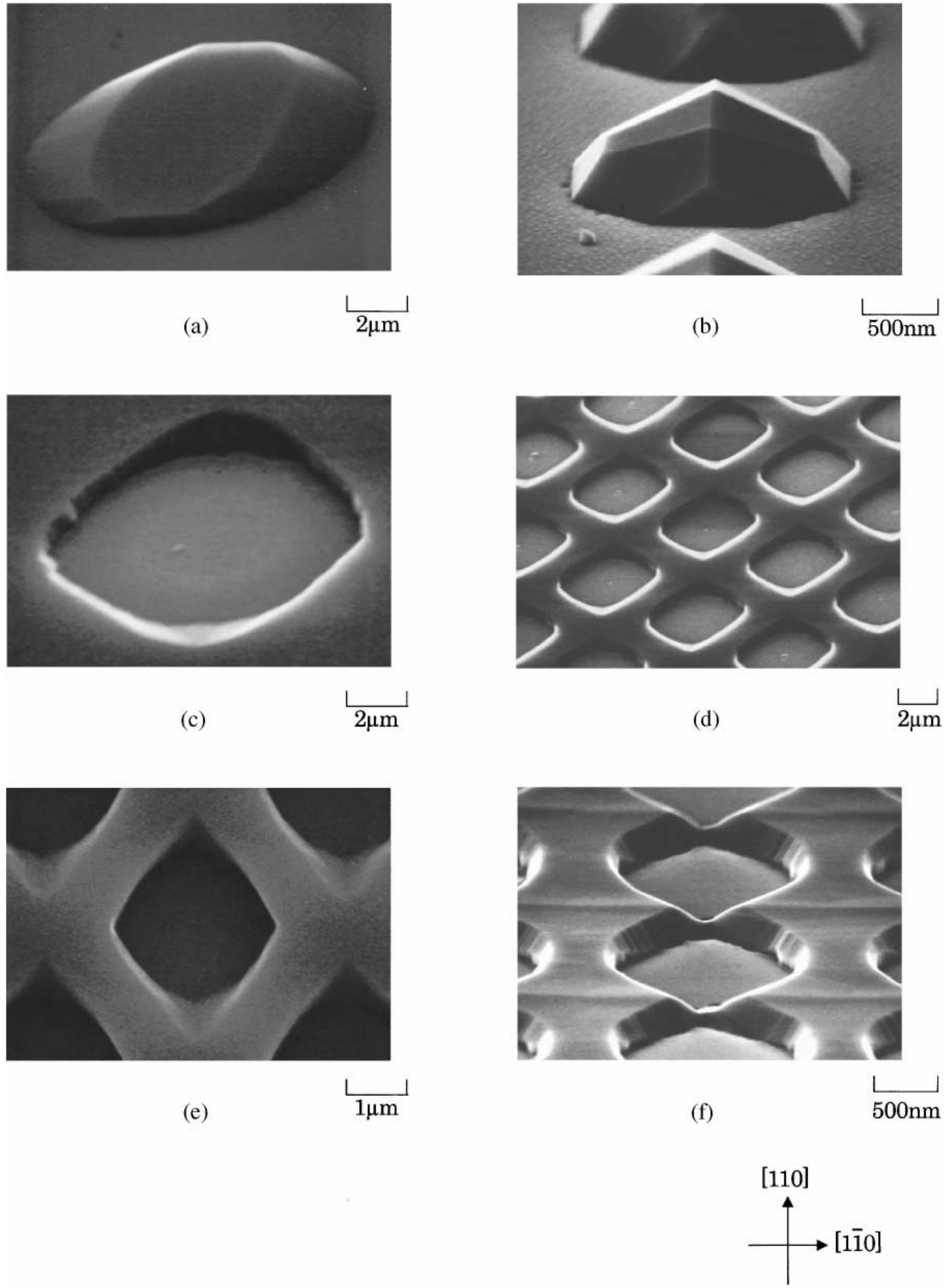
GaAs / GaAs



- **Step 1**: Deposition of SiO_2 layer
- **Step 2**: Ex-situ lithography on oxide layer,
  plus wet chemical etching
- **Step 3**: Growth of GaAs through windows, either in dot or antidot array, or lines.

H. Hasegawa, J. Cryst. Growth 227-228, 1078 (2001)

First demonstrations on metals:

Co/Ru(0001) (groupe of S. D. Bader)

ELSEVIER

Surface Science 432 (1999) 37–53

surface science

www.elsevier.nl/locate/susc

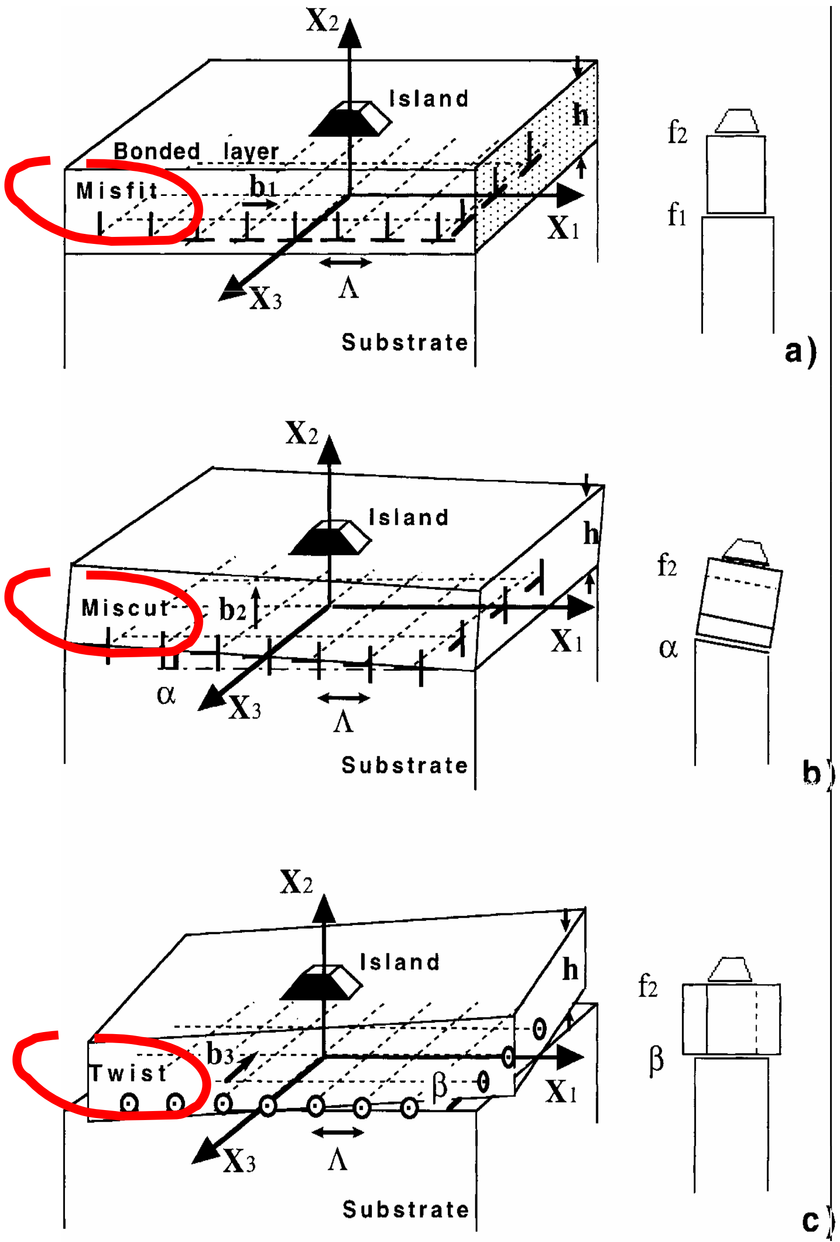
How to control the self-organization of nanoparticles by bonded thin layers

A. Bourret *

Département de Recherche Fondamentale sur la Matière Condensée, SP2M[1], CEA Grenoble, 17 rue des Martyrs 38054, Grenoble Cedex 9, France

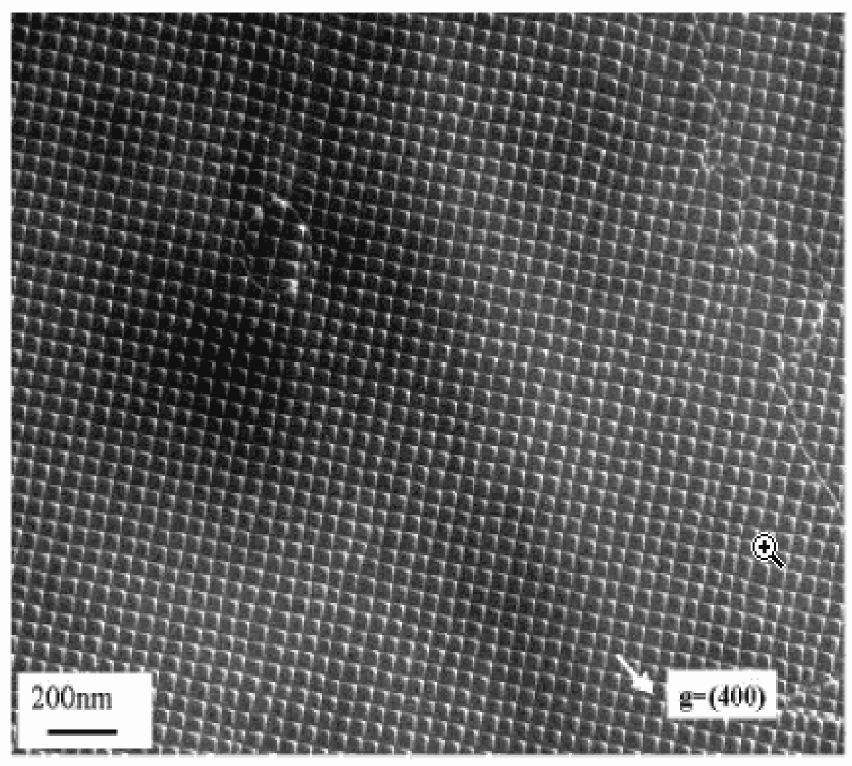
Received 21 December 1998; accepted for publication 6 April 1999

- Substrate bonding and smart cut process.
  - array of dislocations arise from either:
    - Misfit
    - Miscut
    - Twist



Step 1: wafer bonding

Screw dislocations

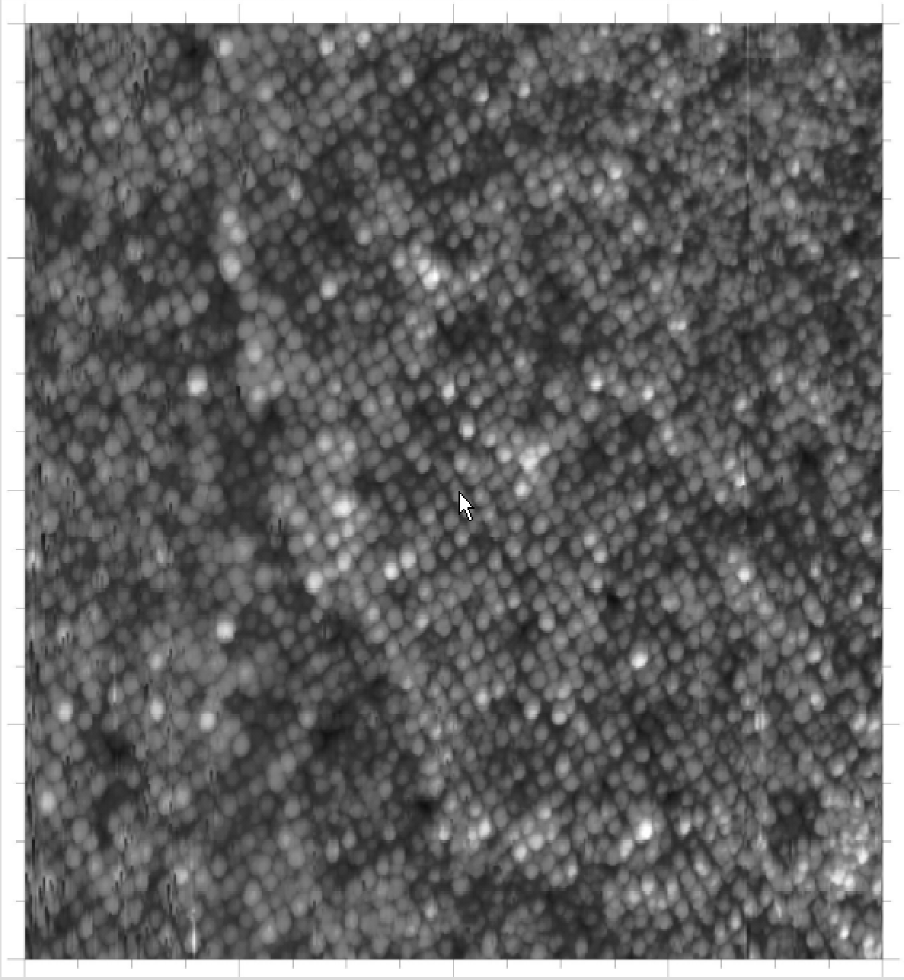


J. L. Rousseau *et al.*, APL80, 4121 (2002)

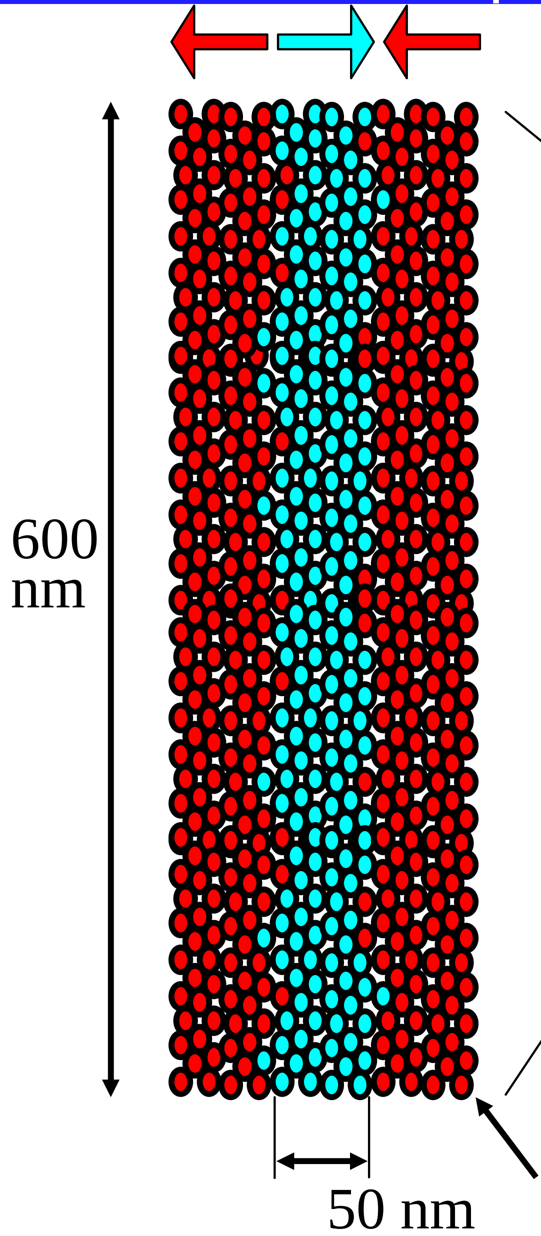
CEA-Grenoble

Step 2: template for growth

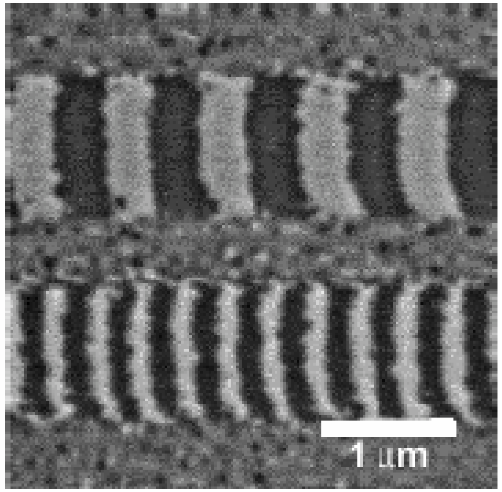
1. Chemical etching > corrugation enhanced
2. Growth (here: Ge/Si)

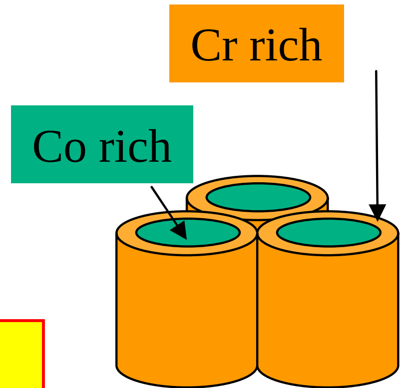


J. Eymery, Habilitation (2003)
F. Leroy, Surf. Sci. 545, 211 (2003)

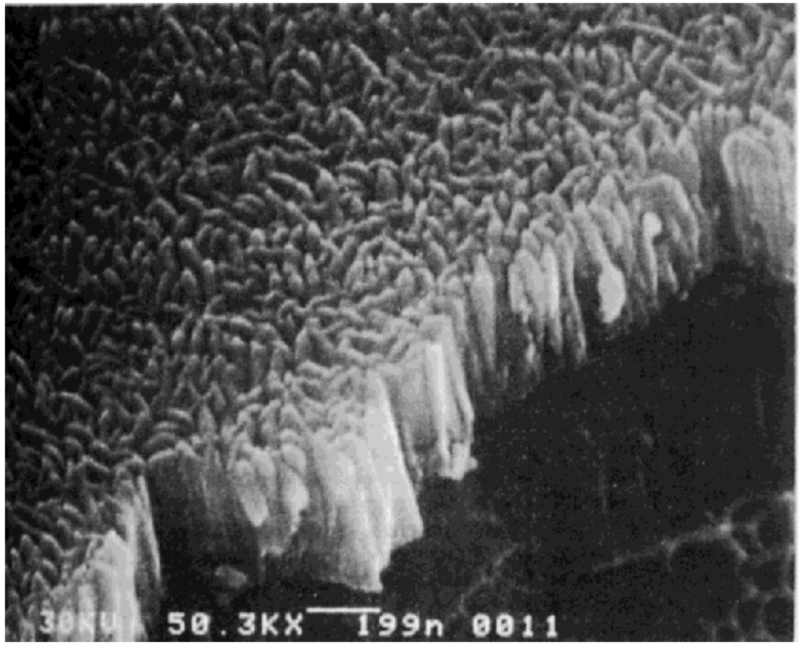


Principle of granular media





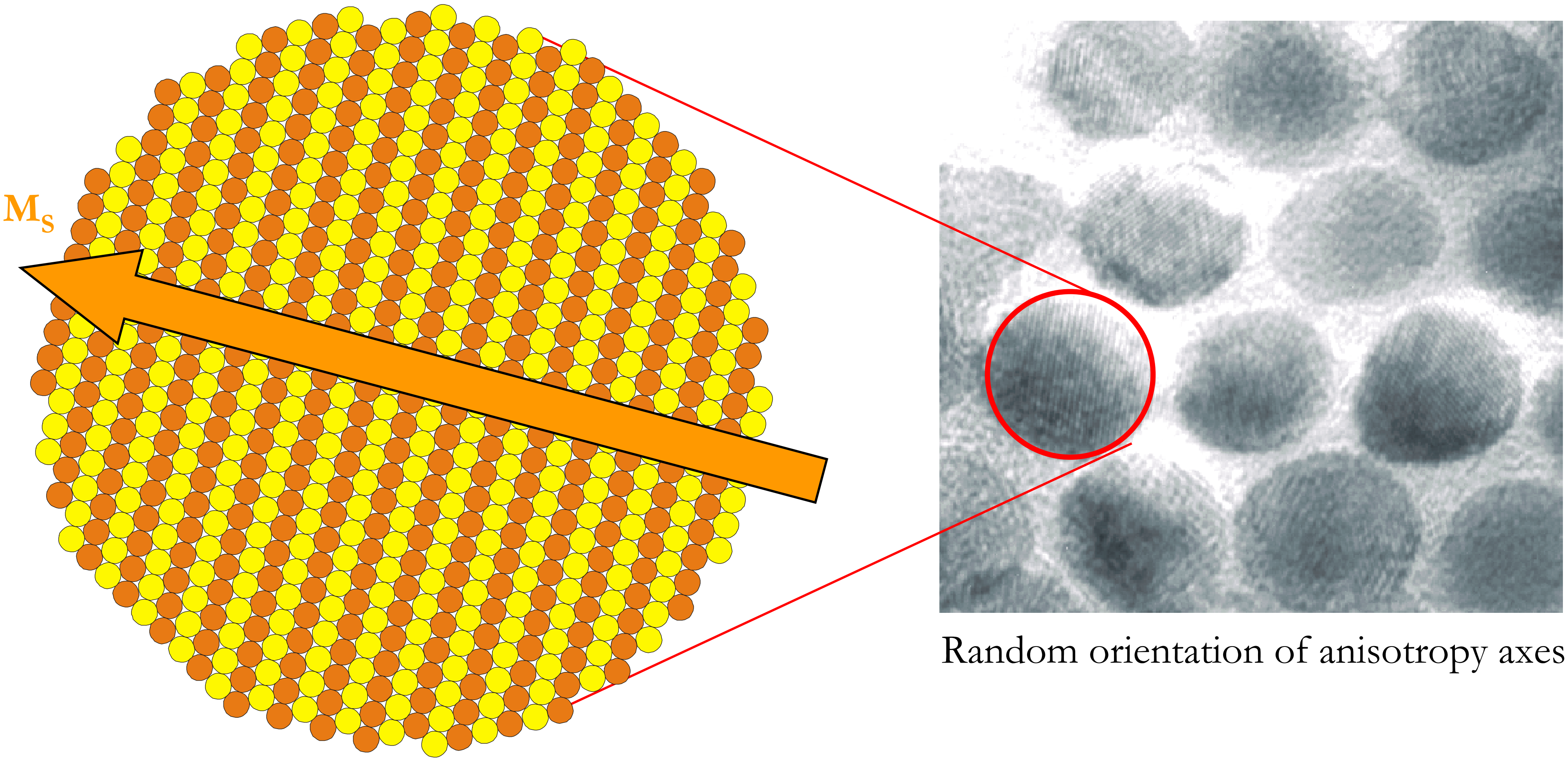
Grain : 10 nm



CoPtCrTaB hard disk

High number of grains per bit

$L1_0$ phase : alternation of Fe and Pt monoatomic planes
↪ extremely high magnetocristalline anisotropy K



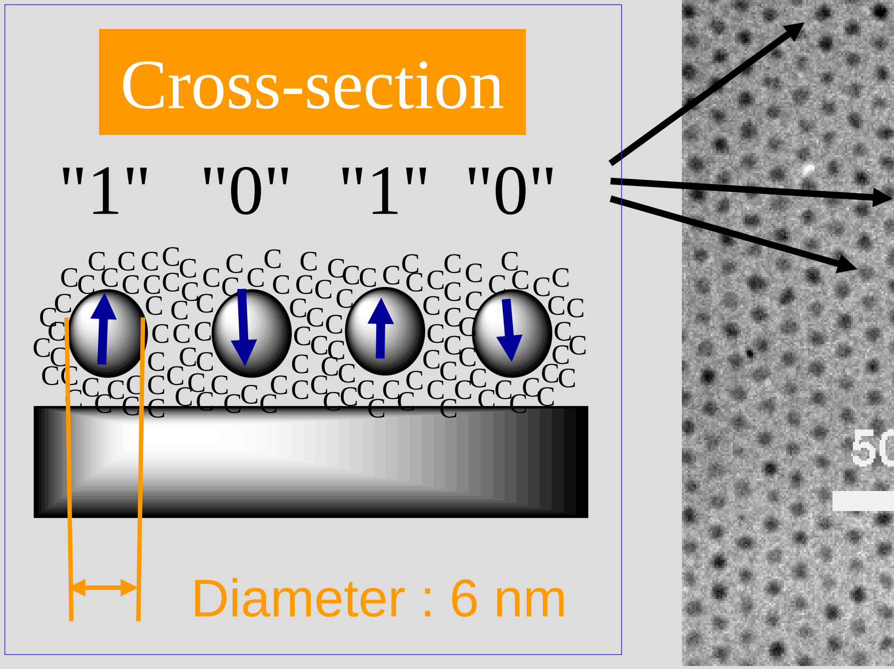
Random orientation of anisotropy axes

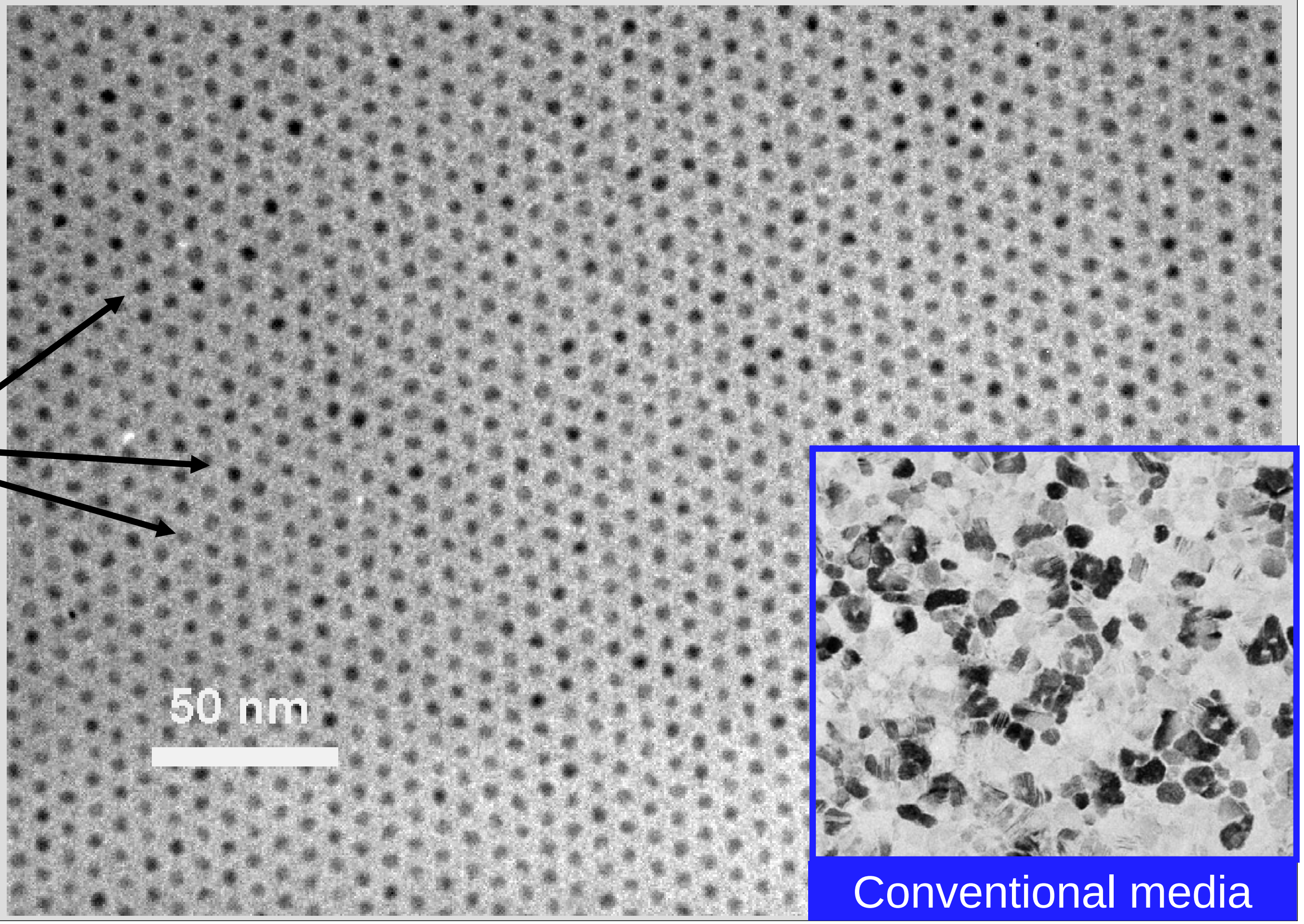
S. Sun, Science 287, 1989 (2000)

Nanoparticules self-organized on a surface (mono- or multilayers)

Future recording media?

FePt nanoparticles
in an organic matrix





Conventional media

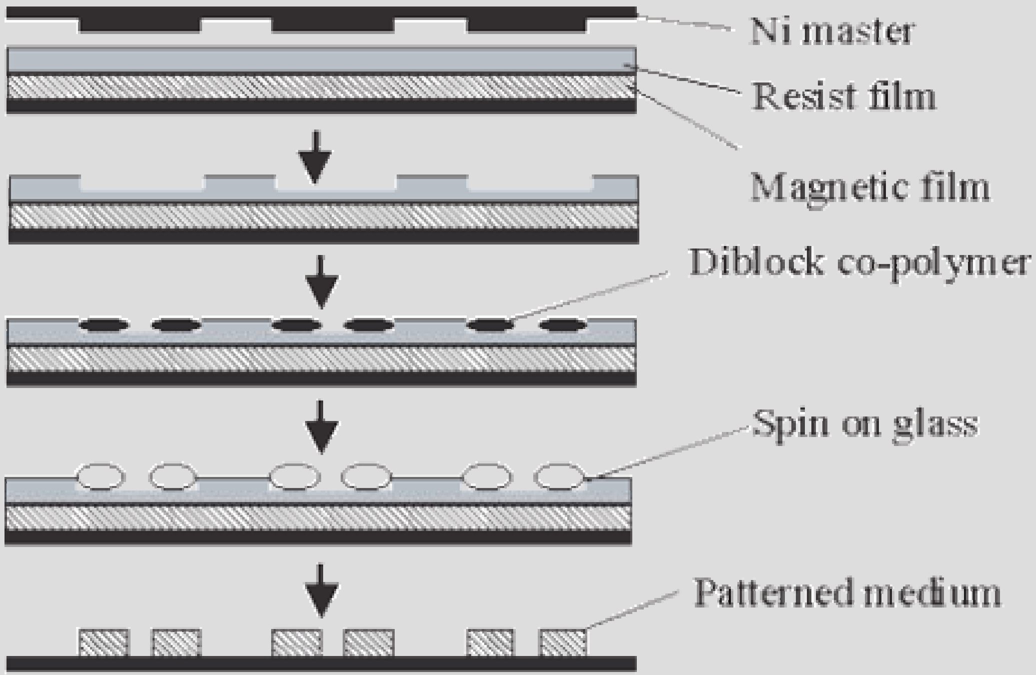
Good aspects

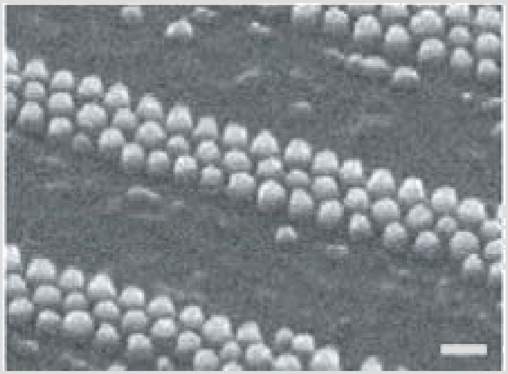
- Weak cost
- Compatible with existing techno
- Weak size distribution

Weak aspects

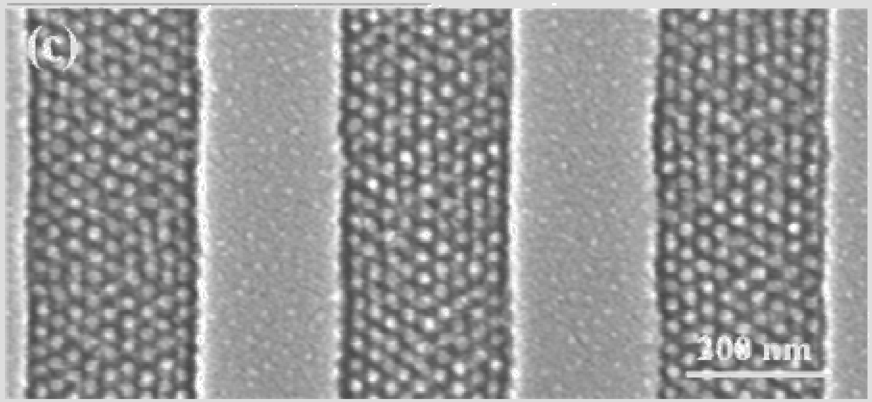
- Weak effective magnetization
- Middle-range order only
- Distribution of anisotropy axes (should be solved)

$Co_{74}Cr_6Pt_{20}$, 40nm diameter





Dots of Silica



Different approaches

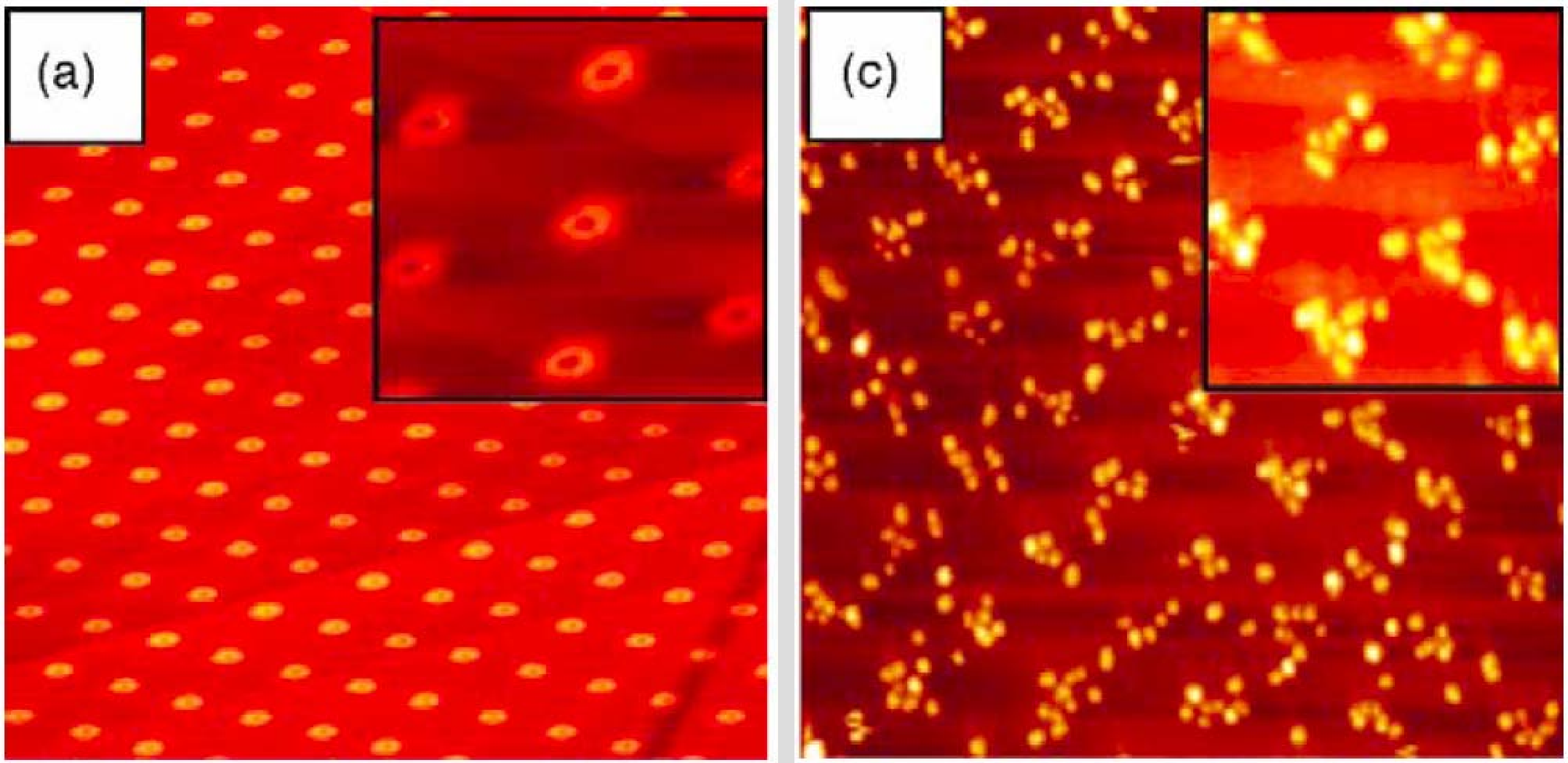
- Di-block co-polymers, then transfered by etching (rather than lift-off)
- Deposition of clusters fabricated by chemical means (less promising?)

REVIEW: B. D. Terris et al., J. Phys. D: Appl. Phys. 38, R199 (2005)

Cluster landing guided by Focused Ion Beam (FIB)

HOPG functionalized with FIB

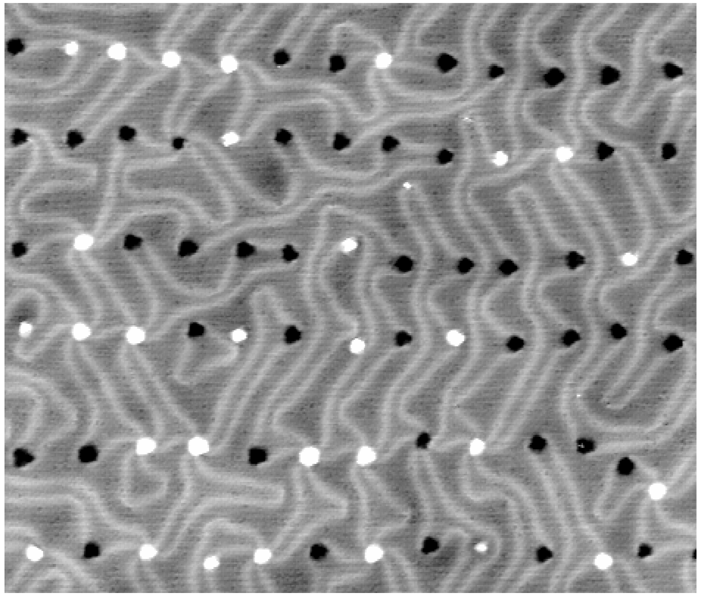
10^{-2} AL of Au_{750} clusters



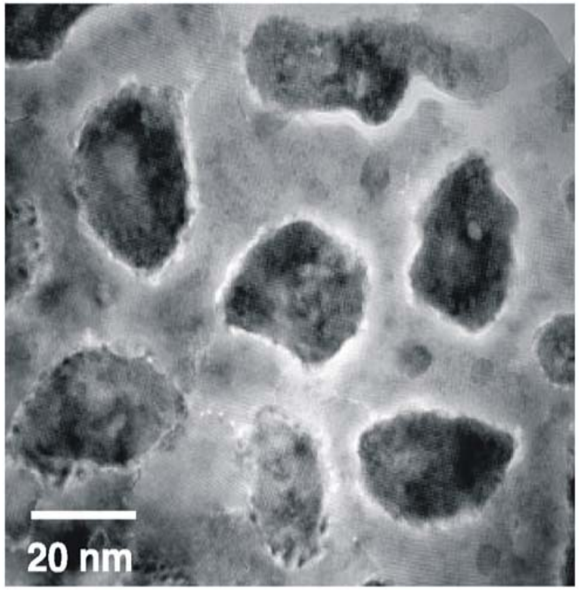
Images: 3.4 microns

REVIEW: J. Bansmann et al., Surf. Sci. Rep. 56, 189 (2005)

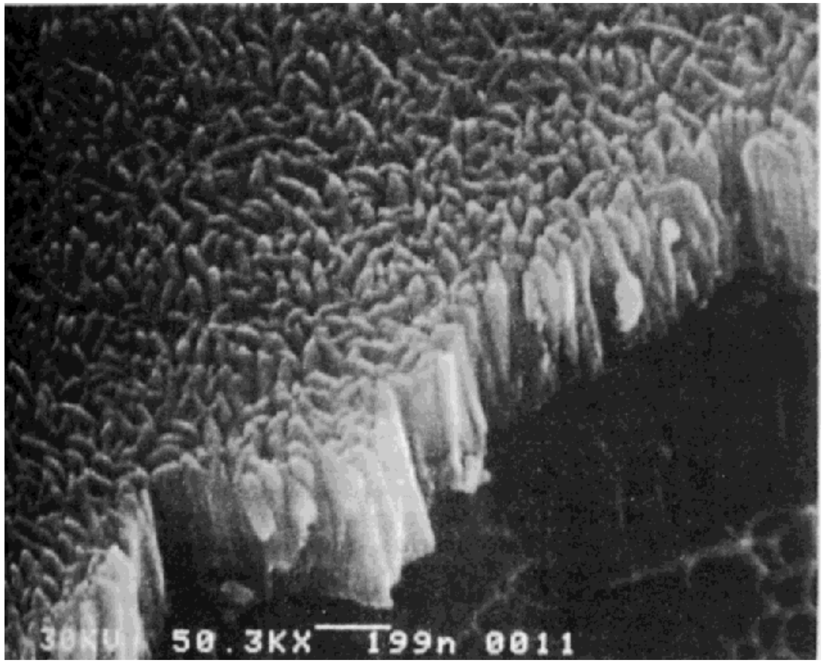
Is anything really new?



Co pillars in Au(111)



$CoFe_2O_4$ in $BaTiO_3$ matrix



CoPtCrTaB hard disk

Volcanic organs, Scandola, Corsica.

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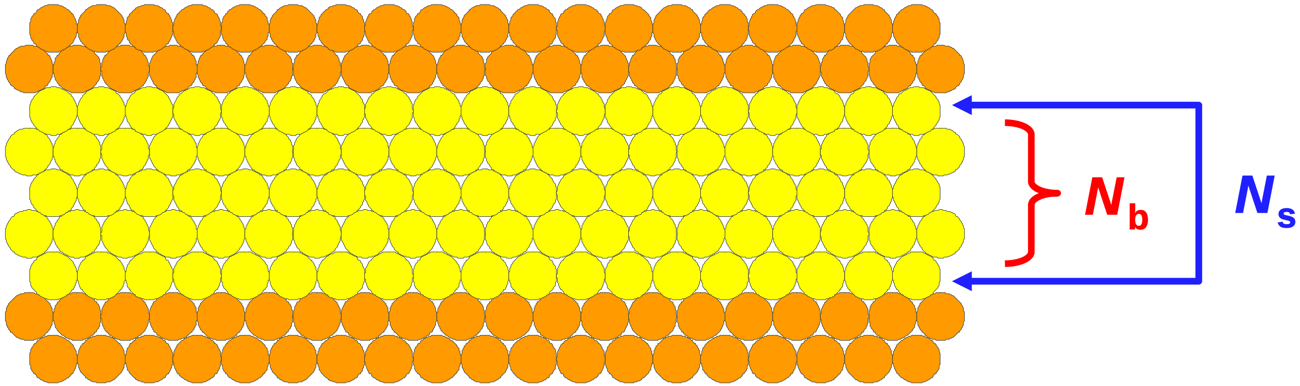
Naïve model

Molecular field

$$T_c = \mu_0 \cdot \frac{J+1}{3J} \cdot \frac{N w_0 M_0 \, \mathbf{m}_0}{k_B}$$

N neighbors



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

Less naïve...

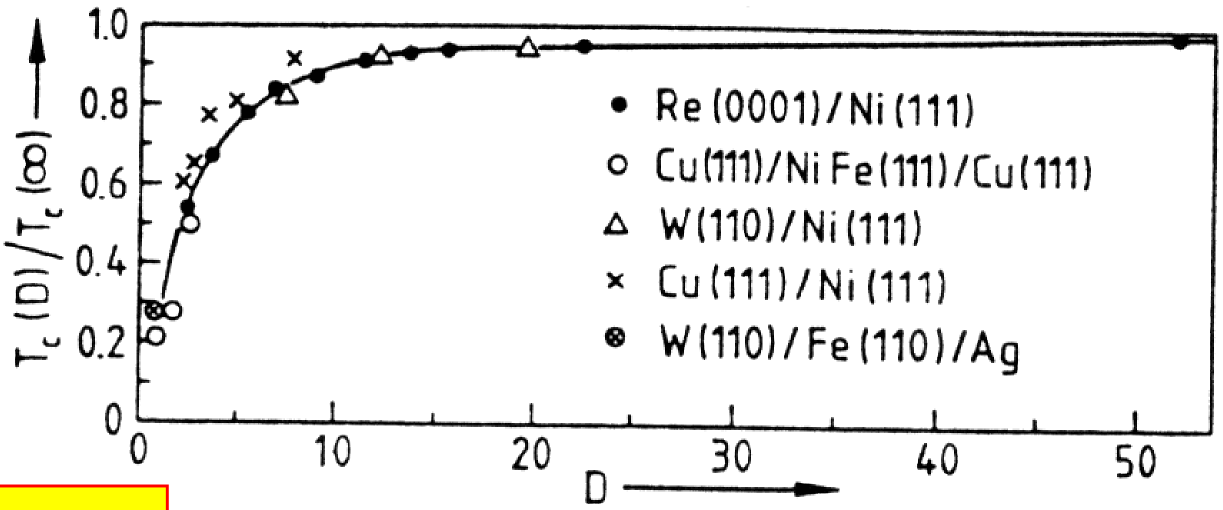
Thickness-dependant molecular field

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

$$\lambda = 1$$

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

Experiments

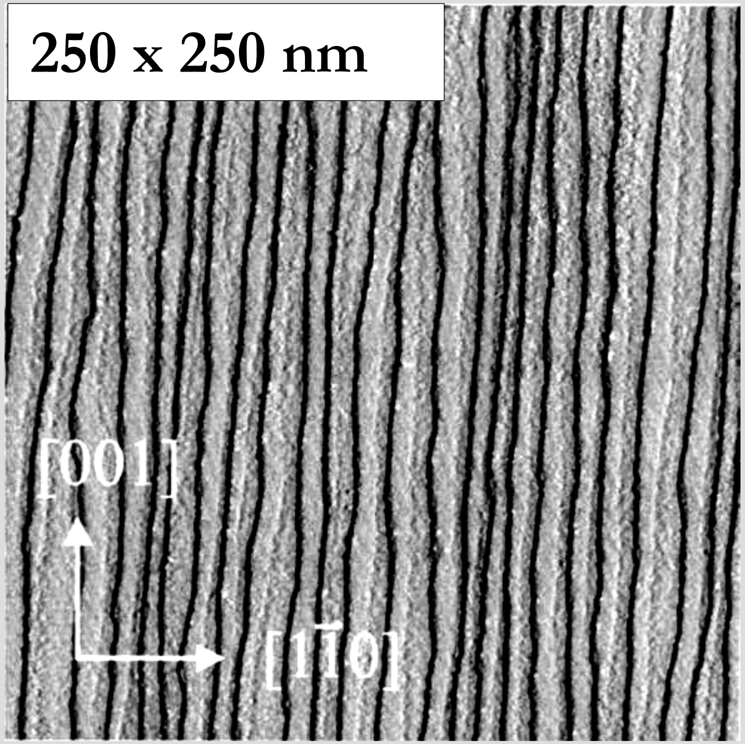


U. Gradmann,
Handbook of Magn. Mater. Vol.7, ch.1 (1993)

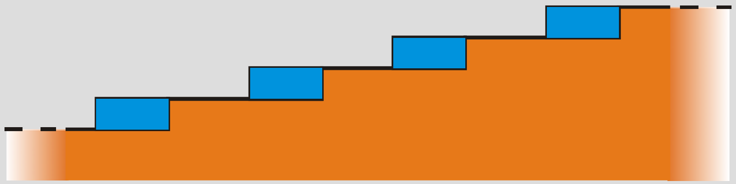
Conclusion:
Naïve views are roughly correct

Stripes on vicinal surfaces

Fe(0.5ML) / W(110)

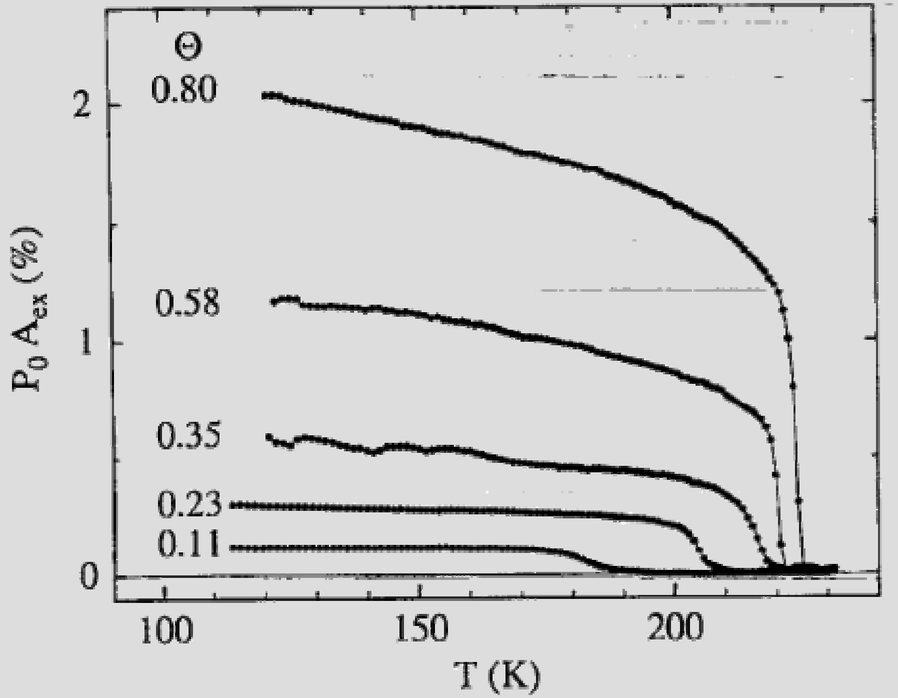


J.Hauschild *et al.*,
Phys.Rev.B57, R677(1998)



Magnetic order in 2D: finite-size scaling

Curie temperature as a function of stripe width



$$T_C(n)/T_C(\infty) \propto 1-(n_0/n)^{\lambda}$$

$\lambda = 1.03$ in agreement with Ising model (=1)

H. J. Elmers et al., PRL73, 898 (1994)

$\lambda = 1.2 \pm 0.3$ for Fe stripes / Pd(110)

D. Li et al., PRB64, 144410 (2001)

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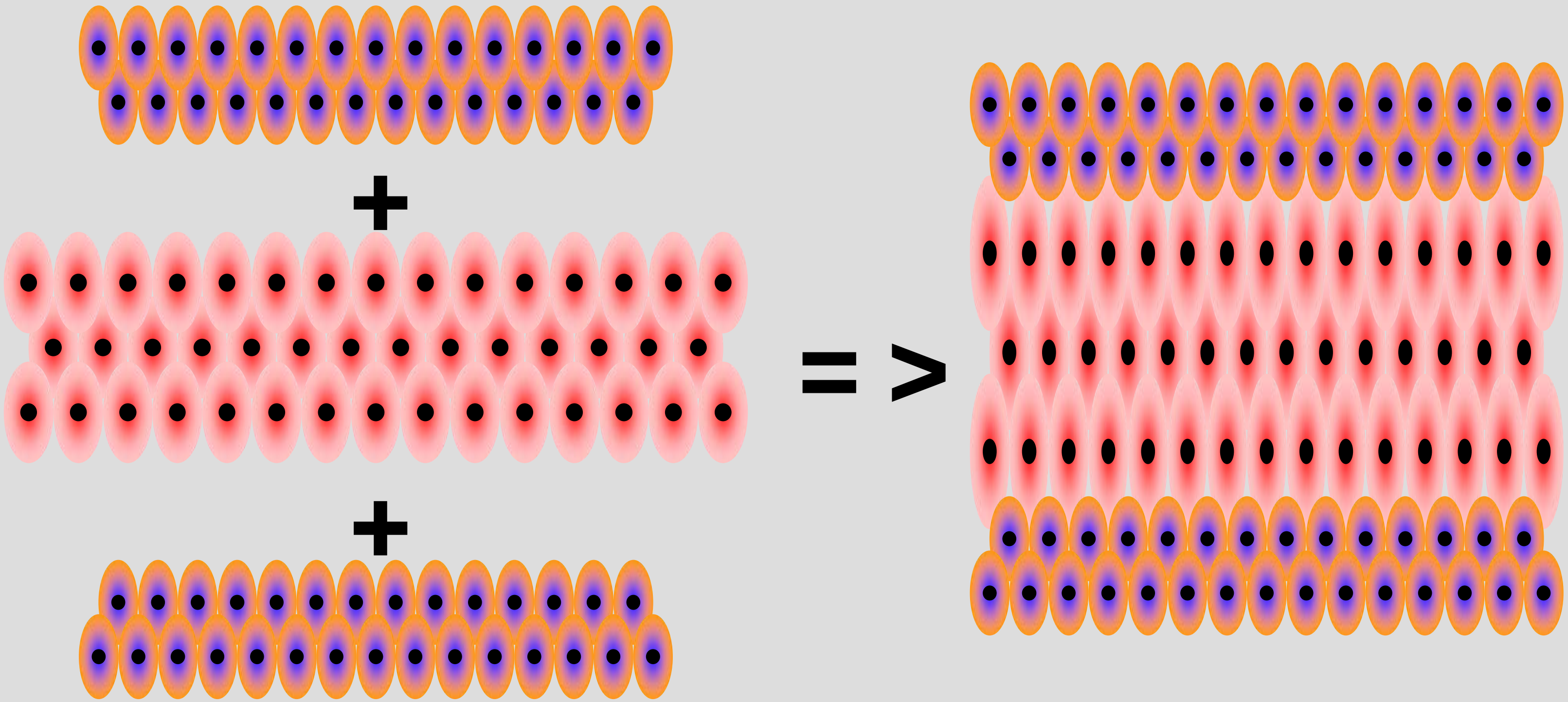
Magneto-elastic anisotropy



Effect

Deformation of crystal structure

⇒ Correction to the magneto-crystalline energy

Result

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

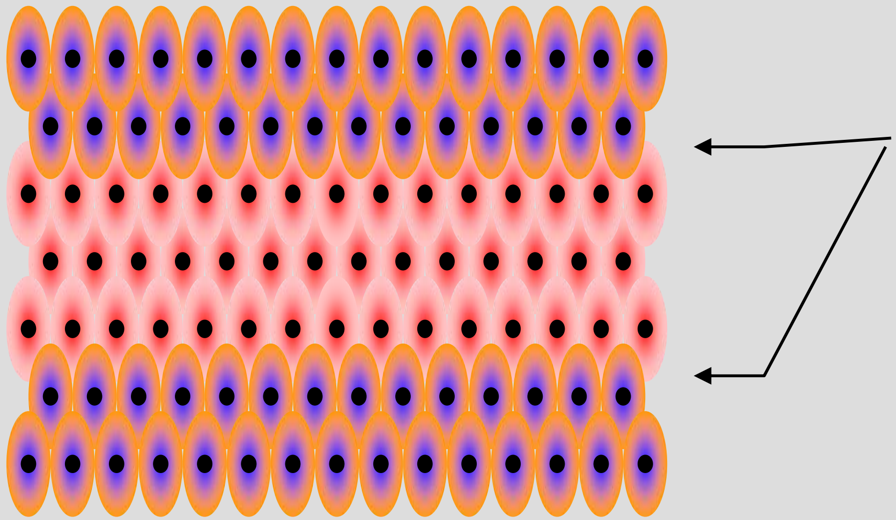
$$K_{\mathrm{mel},i} \sim \mathrm{B}_i \varepsilon$$

Occurs in all nanostructures (≤5nm):
Thin films and stripes, supported islands, free clusters etc.

Surface / Interface anisotropy

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

« Superficial magnetic anisotropy and orientational superstructures »



Effect

Breaking of symmetry for surface/interface atoms

⇒ Correction to the magneto-crystalline energy

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

« 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:

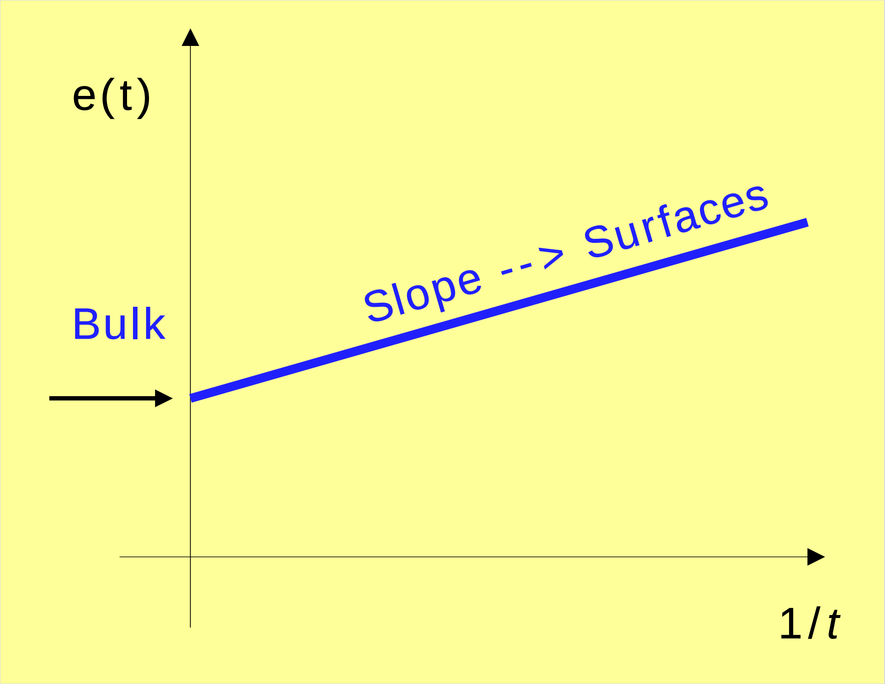
- Ks estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only

Again, occurs in all nanostructures (≤5nm)

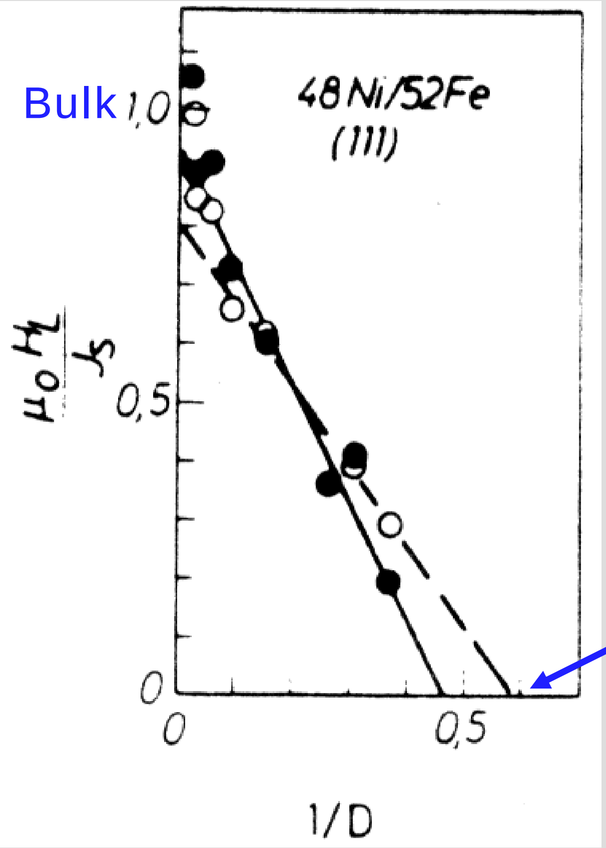
History of surface anisotropy : 1/t plots

$$E_{tot}(t) = k_V t + 2k_S$$

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



First hint for perpendicular anisotropy



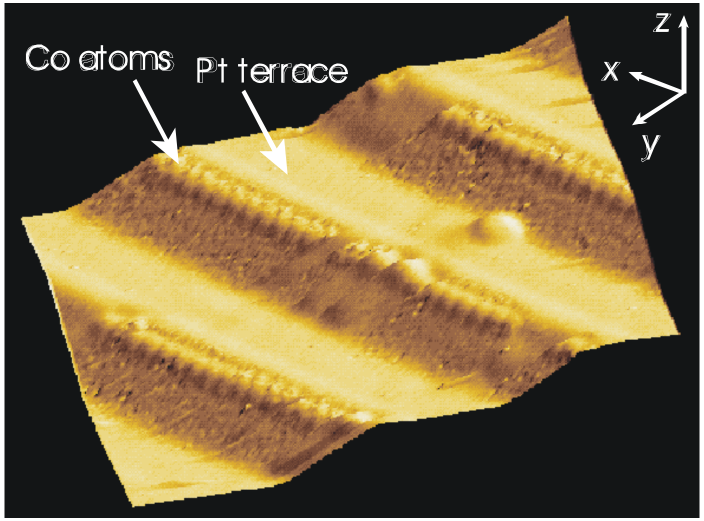
U. Gradmann and J. Müller,
Phys. Status Solidi 27, 313 (1968)

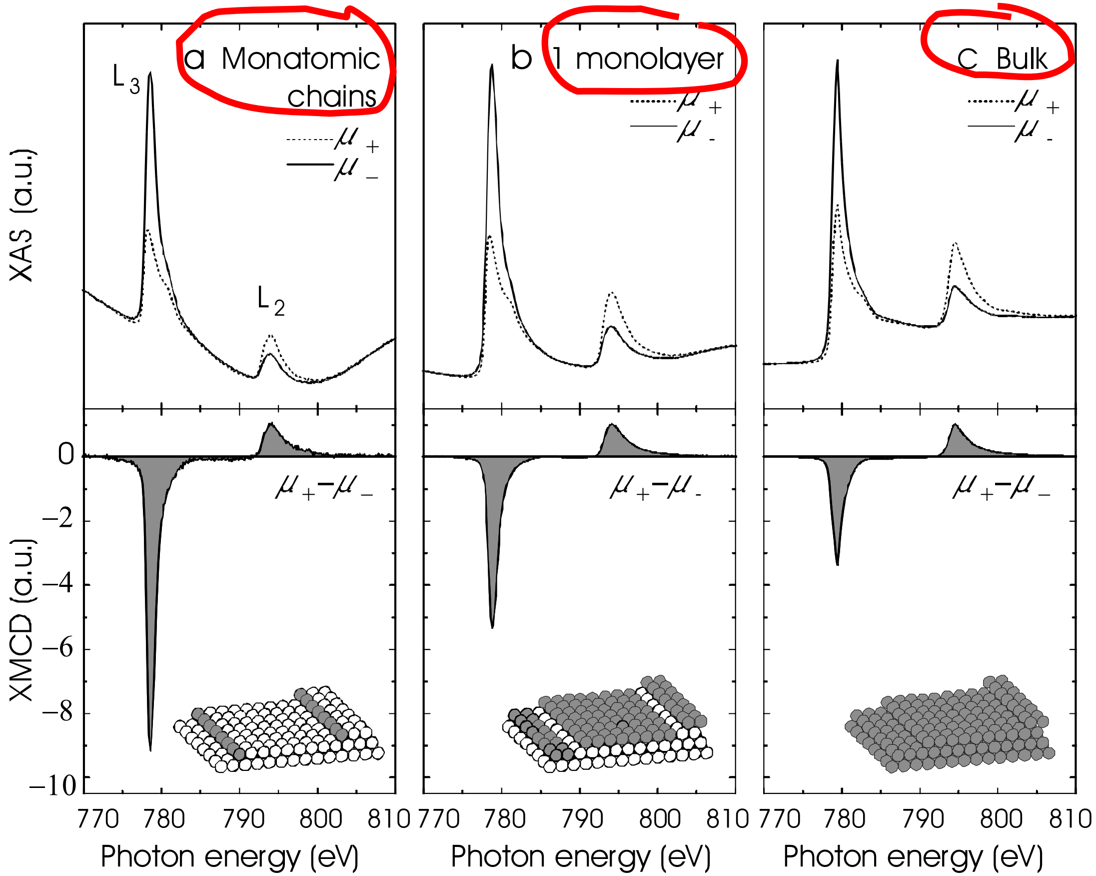
In reality, <u>surface</u> and <u>magneto-elastic</u> anisotropy are entangled. Separation is experimentally difficult, if not impossible quantitatively

From surface to wires (1D)

Magnetic circular dichroïsm

Self-organized Co/Pt(997)





$$\mu_L \approx \int L_3 + \int L_2$$

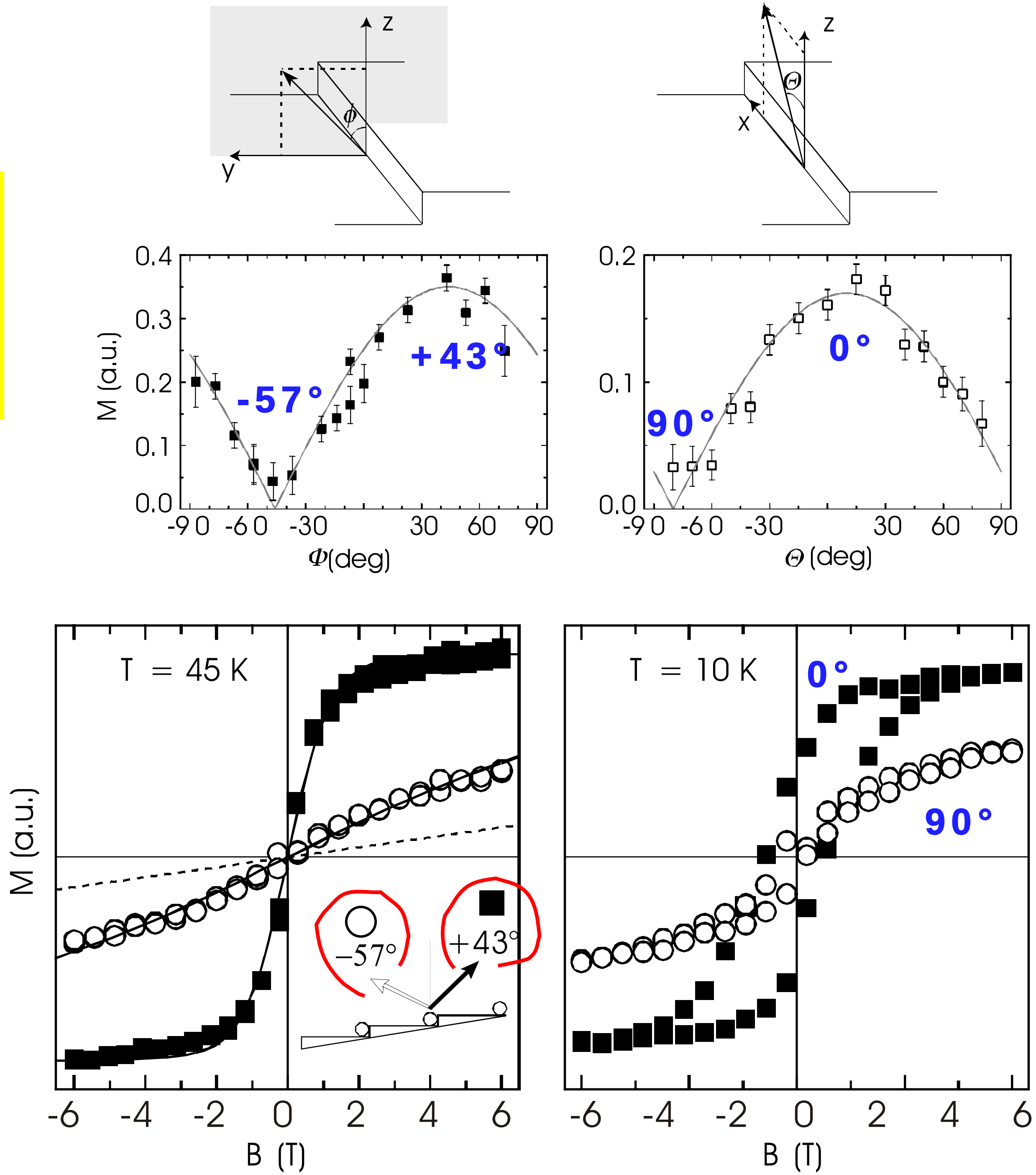
$$\mu_s^{eff} \approx -\int 2L_3 + 4\int L_2$$

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

From surface to wires (1D)

Qualitatively:

Easy axis of magnetization perpendicular to the wires, but not the the mean film surface, nor to Pt(111)



Quantitatively

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

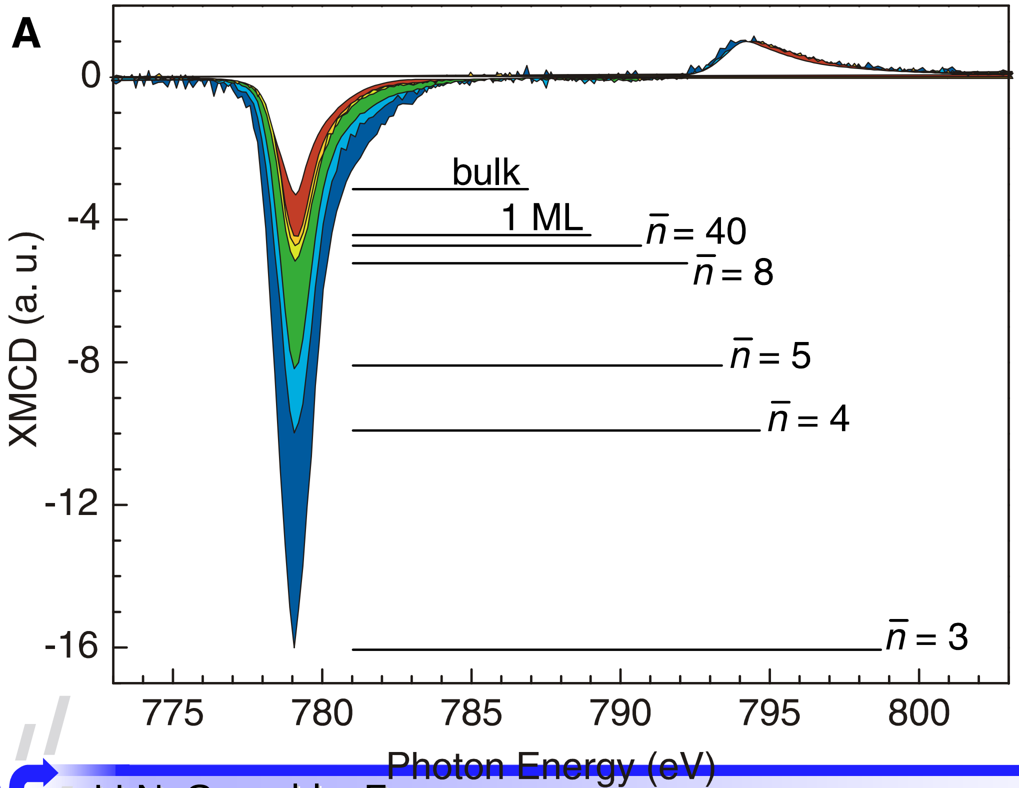
From surface to atoms (0D)

Co/Pt(111)

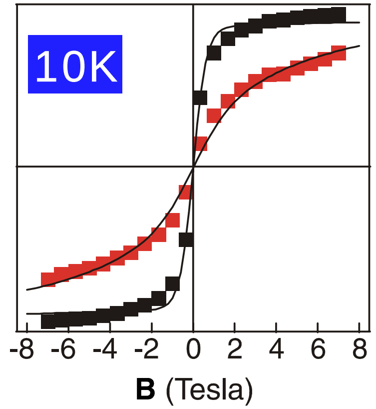
Giant Magnetic Anisotropy of Single Cobalt Atoms and Nanoparticles

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]

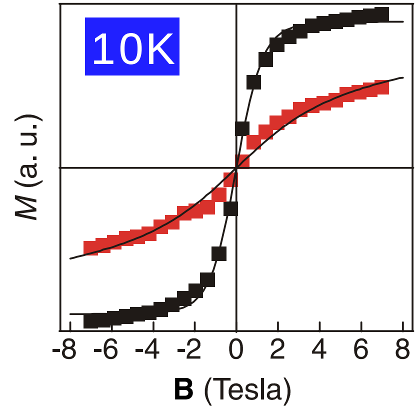
P. Gambardella et al., Science 300, 1130 (2003)



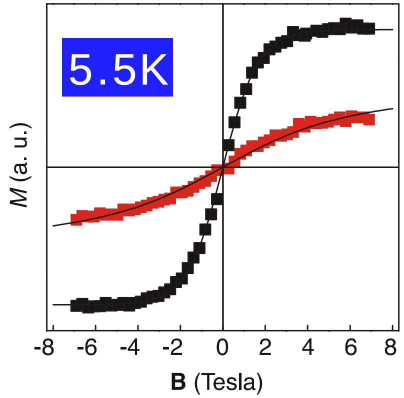
8 atoms



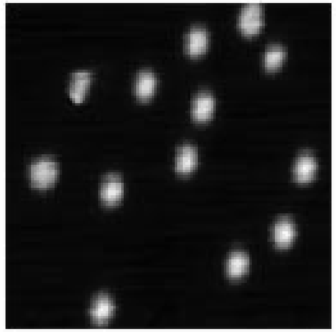
4 atoms



1 atom



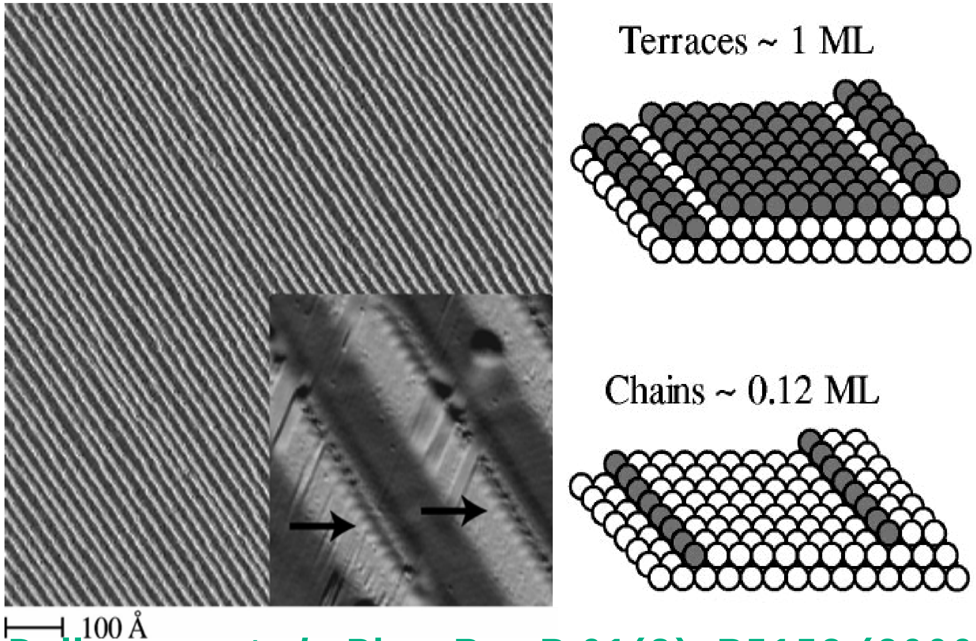
STM, 8.5nm, 5.5K



Results:

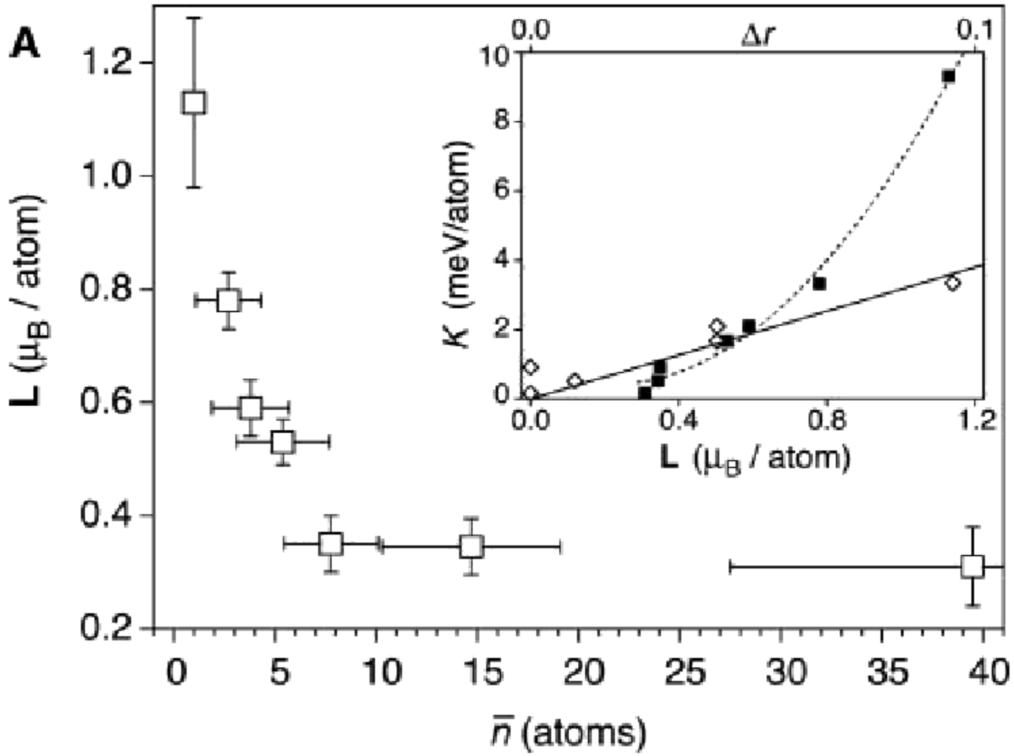
- Easy axis of magnetization perpendicular to Pt(111)
- Measure of orbital momentum and its anisotropy, not directly magnetic anisotropy

Co/Pt(997)



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

Co/Pt(111)



P. Gambardella et al., Science 300, 1130 (2003)
P. Gambardella et al., Nature 416, 301 (2002)

Overview

- 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.

Conclusions

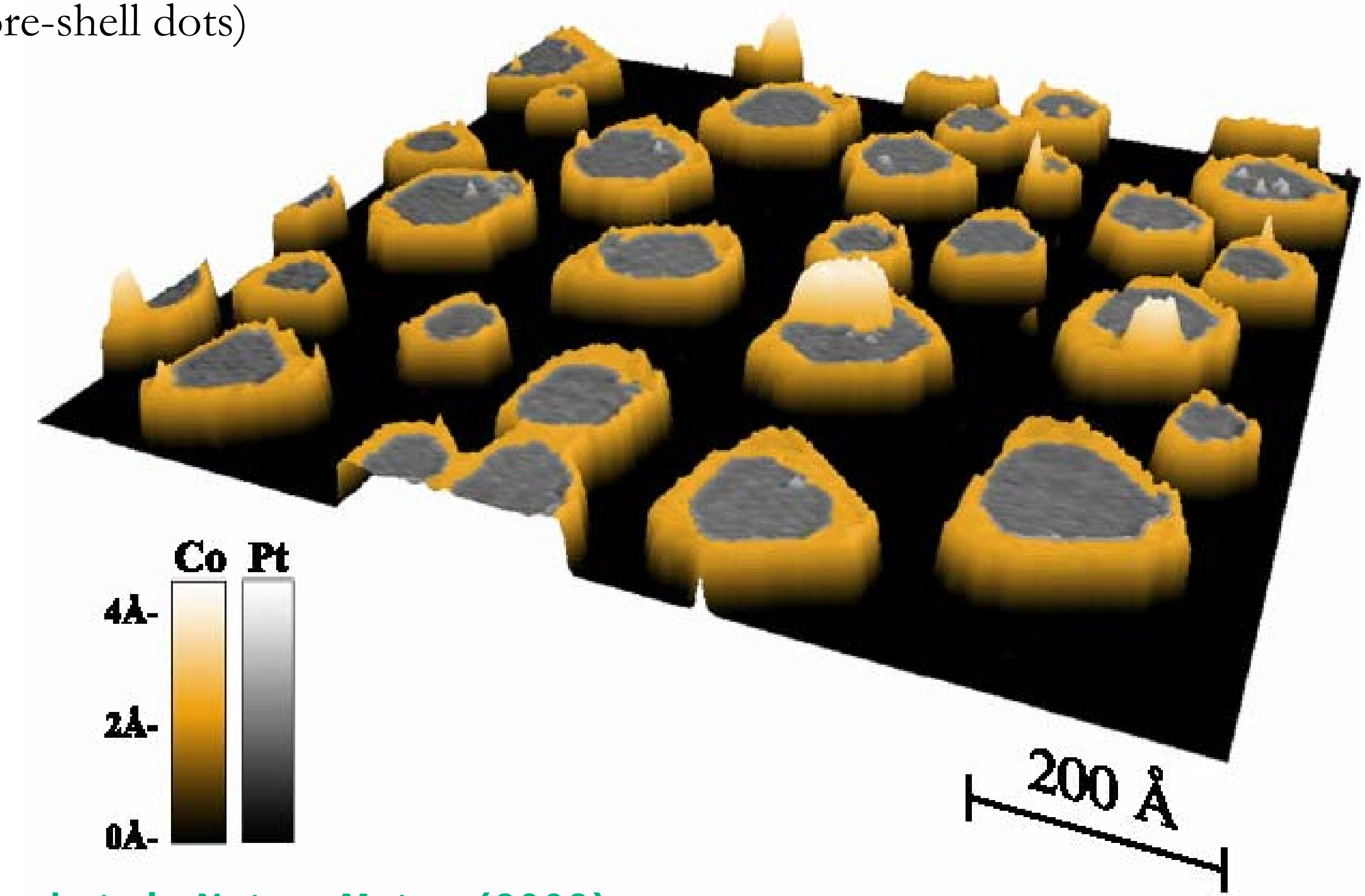
- From bulk to atoms: considerable **increase of orbital moment**
- **2 atoms closer to wire than 1 atom**
- **bi-atomic wire closer to surface than wire**

Also studied in clusters, see J. Bansmann et al., Surf. Sci. Rep. 56, 189 (2005)

Manipulation of edge anisotropy

Pt brims around Co/Pt(111)

(core-shell dots)



S. Rusponi et al., Nature Mater. (2003)

Blocking temperature =150-300K

- **Self-organization : study concepts**
- **Growth engineering > towards materials?**

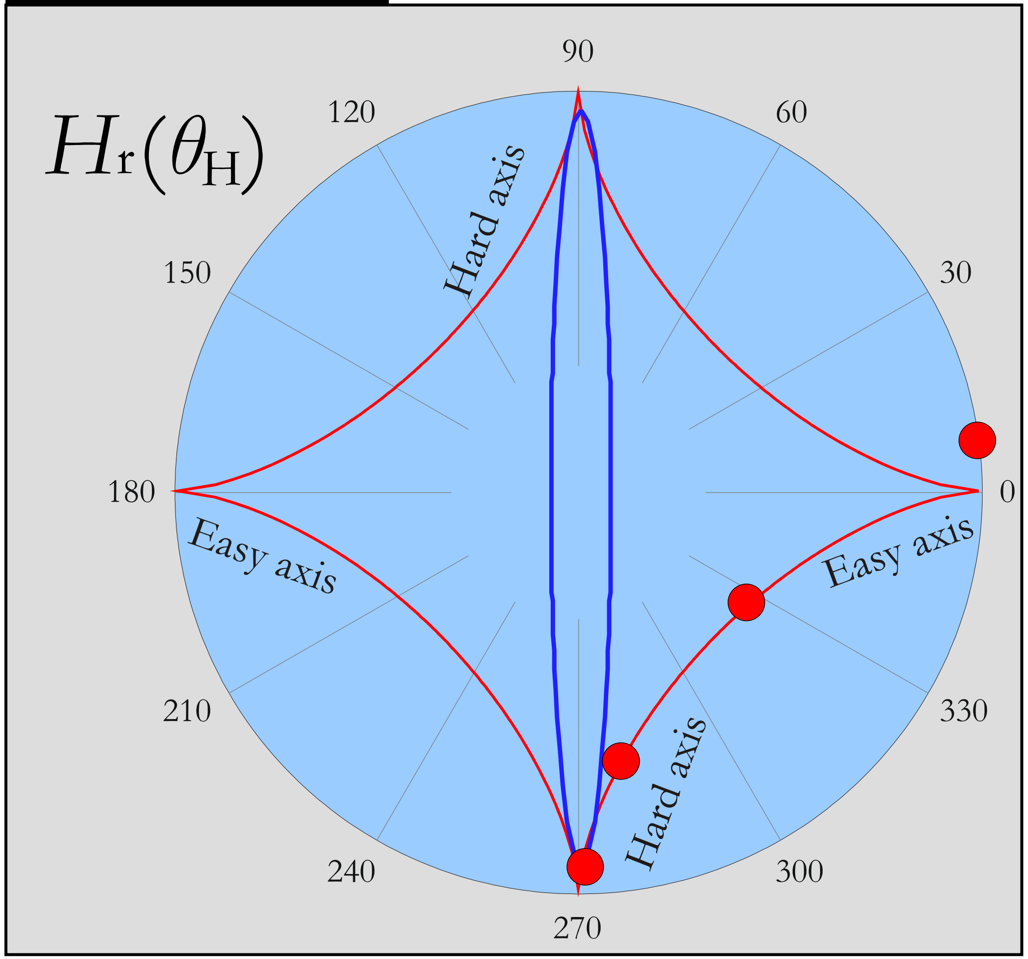
I. Fabrication methods

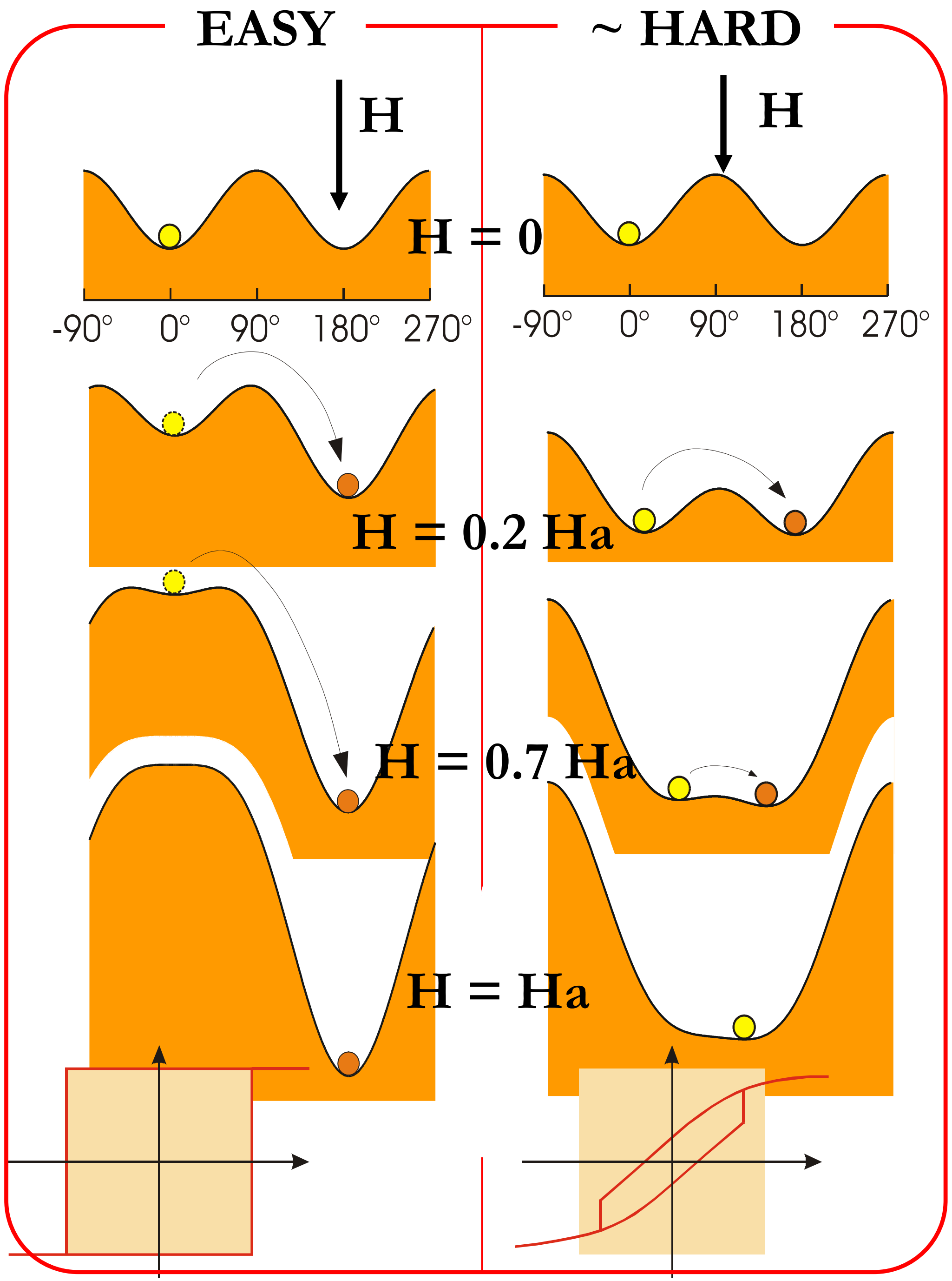
1. Epitaxial self-assembly & self-organization
2. Other routes: electrochemistry, chemistry, physical paths to clusters, exotic means
3. Future prospects for self-organization.

II. Selected topics for Magnetism

1. Magnetic order
2. Magnetic anisotropy
3. Magnetization reversal and superparamagnetism.
4. Micromagnetism

‘Astroïd’ curve



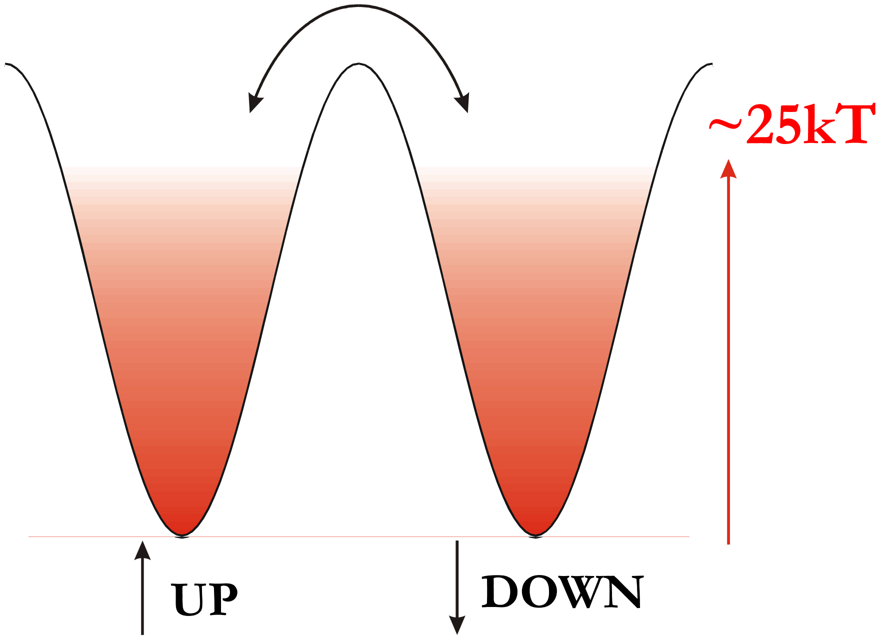


Notes:

*Hr(θ) is a signature of reversal modes

*Coercive field ≠ Reversal field

Anisotropy barrier



Anisotropy barrier $E_B \sim KV$

Formalism for thermal excitations

Phenomenological model

Brown, Phys.Rev.130, 1677 (1963)

- Probability for non-reversal

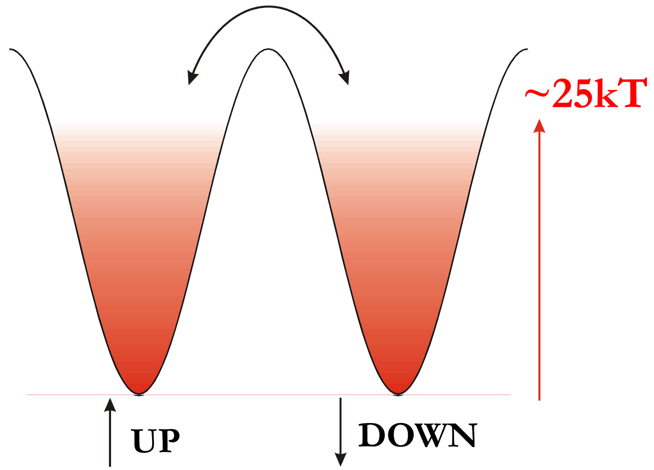
$$P(t) = e^{-t/\tau}$$

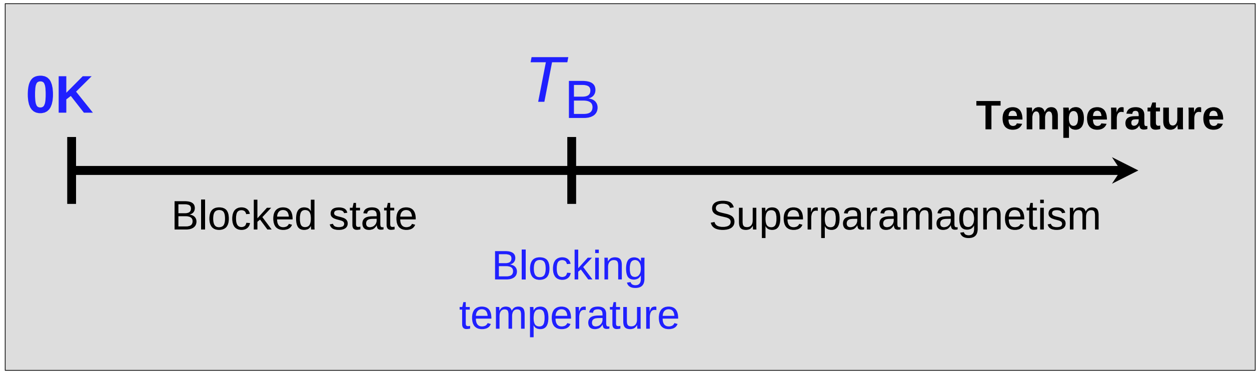
- Mean waiting time for reversal

$$\tau = \tau_0 e^{E_B / k_B T} \quad \tau_0 \approx 10^{-10}\ \mathrm{s}$$

↳ Energy barrier required to prevent magnetization reversal during duration *t*

$$E_B = k_B T \ln(t / \tau_0)$$





Formalism for thermal excitations

(…)

$$E_B = KV_B = k_B T \ln(t/\tau_0)$$

Superparamagnetism: orders of magnitude

Laboratory : $t = 1\text{s}$ $\quad V_B \approx 25\, k_B T / K$

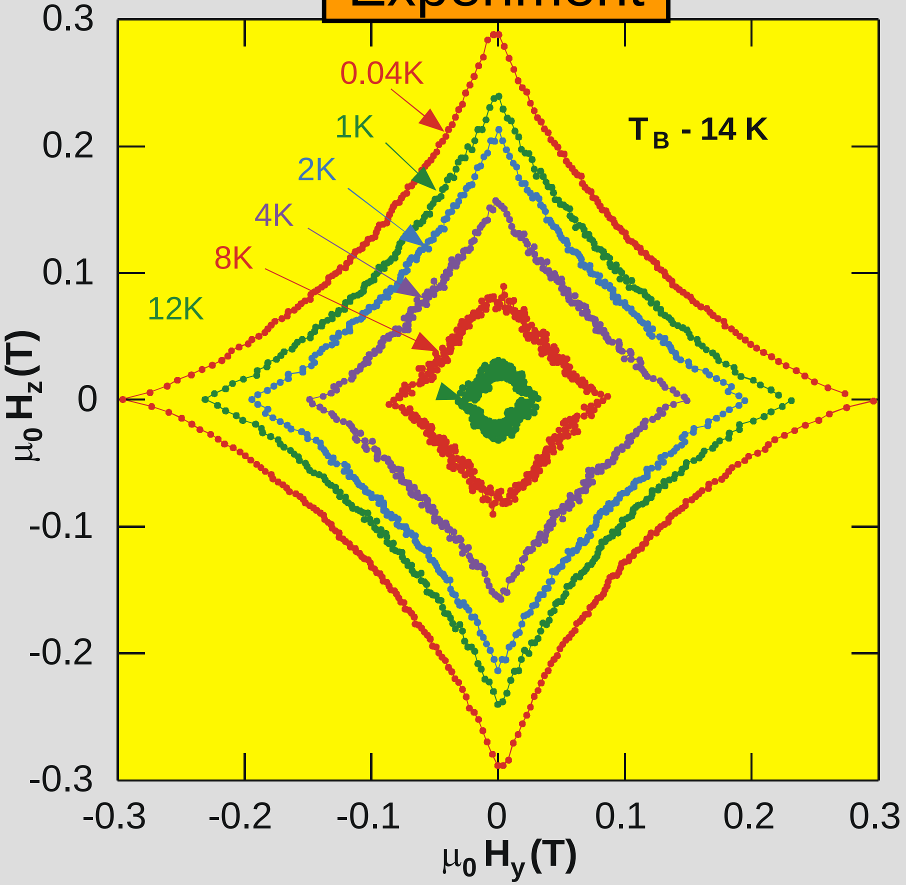
Recording : $t >> 10^9\text{s}$ $\quad V_B \approx 40 - 60\, k_B T / K$

Magnetic recording with one grain per bit ($V = V_B$, discrete media) more favorable than $V = \text{N}\, V_B$

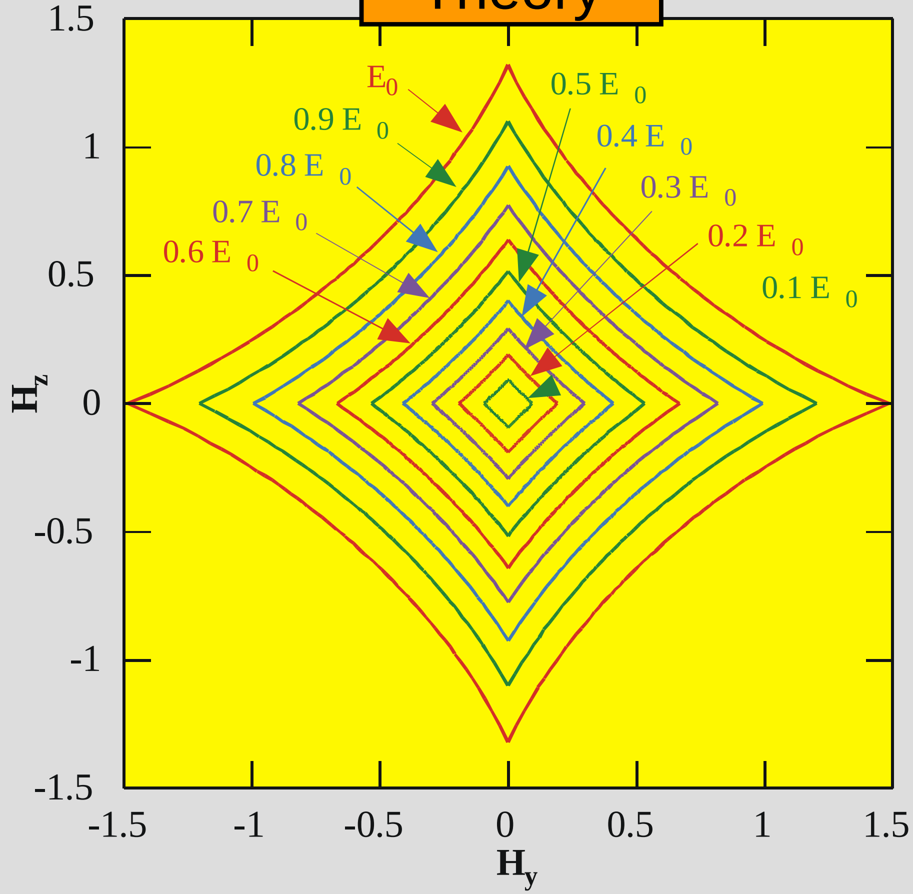
Temperature dependence of the switching fields of a 3nm Co cluster

Measurement technique: micro-SQUID

Experiment



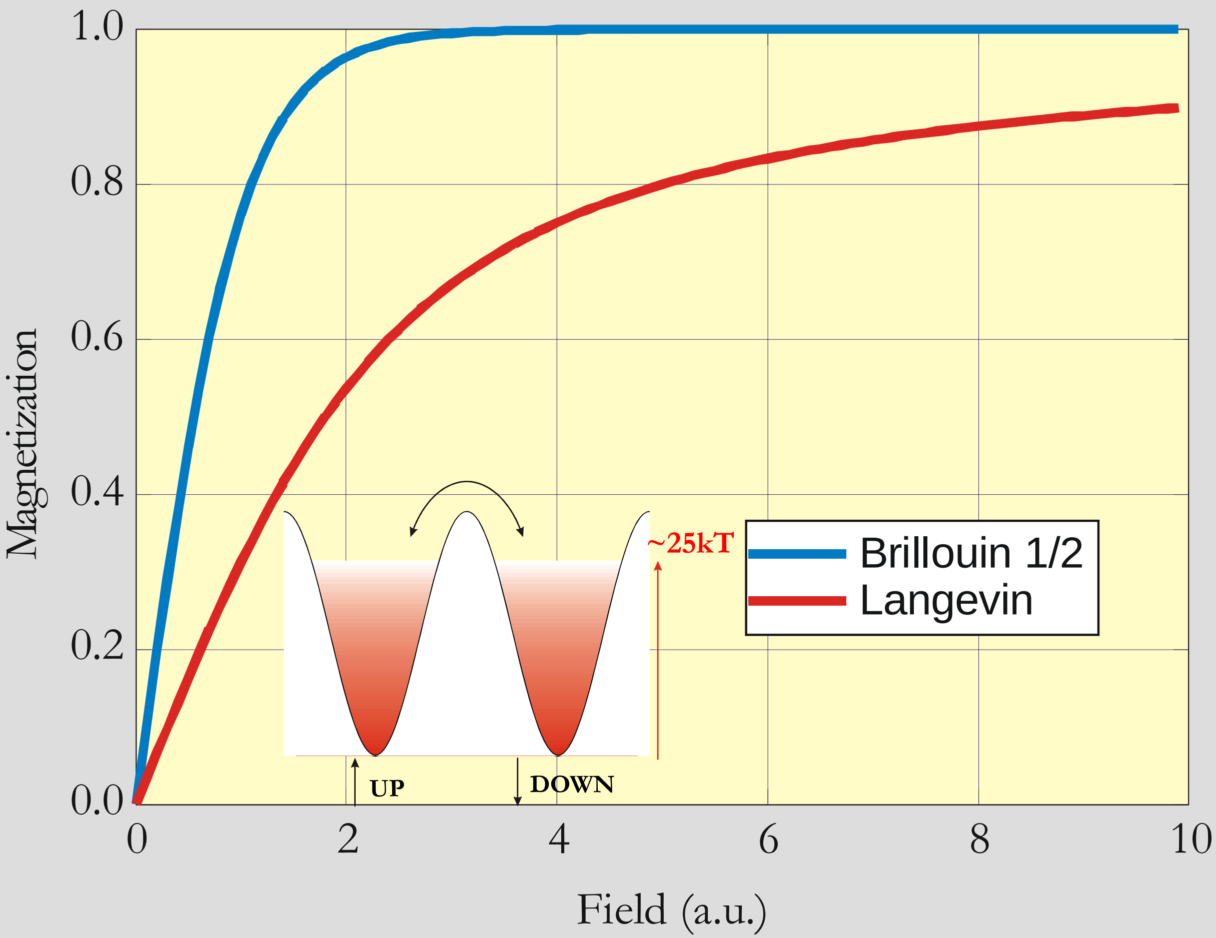
Theory



W. Wernsdorfer, M. Jamet et al.

Good agreement with the Stoner-Wohlfarth model and Néel-Brown theory

Which fitting function ?



Extremely weak anisotropy

Langevin function

$$m = \tanh(h), \quad h = \beta\mu_0\mu H$$

Strong uniaxial anisotropy

Brillouin 1/2 function

$$m = 1/\tanh(h) - 1/h$$

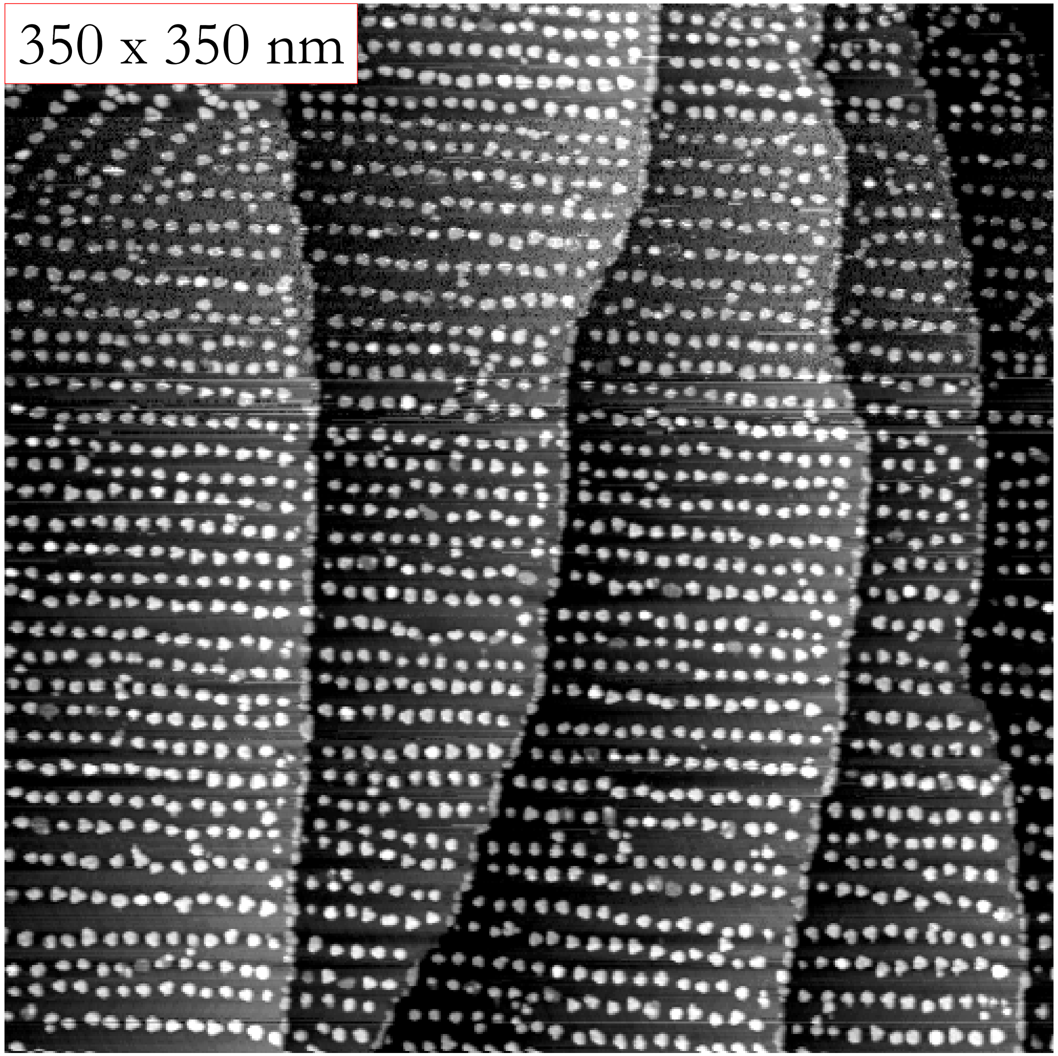
Other cases:

moderate or tilted anisotropy, distributions etc.

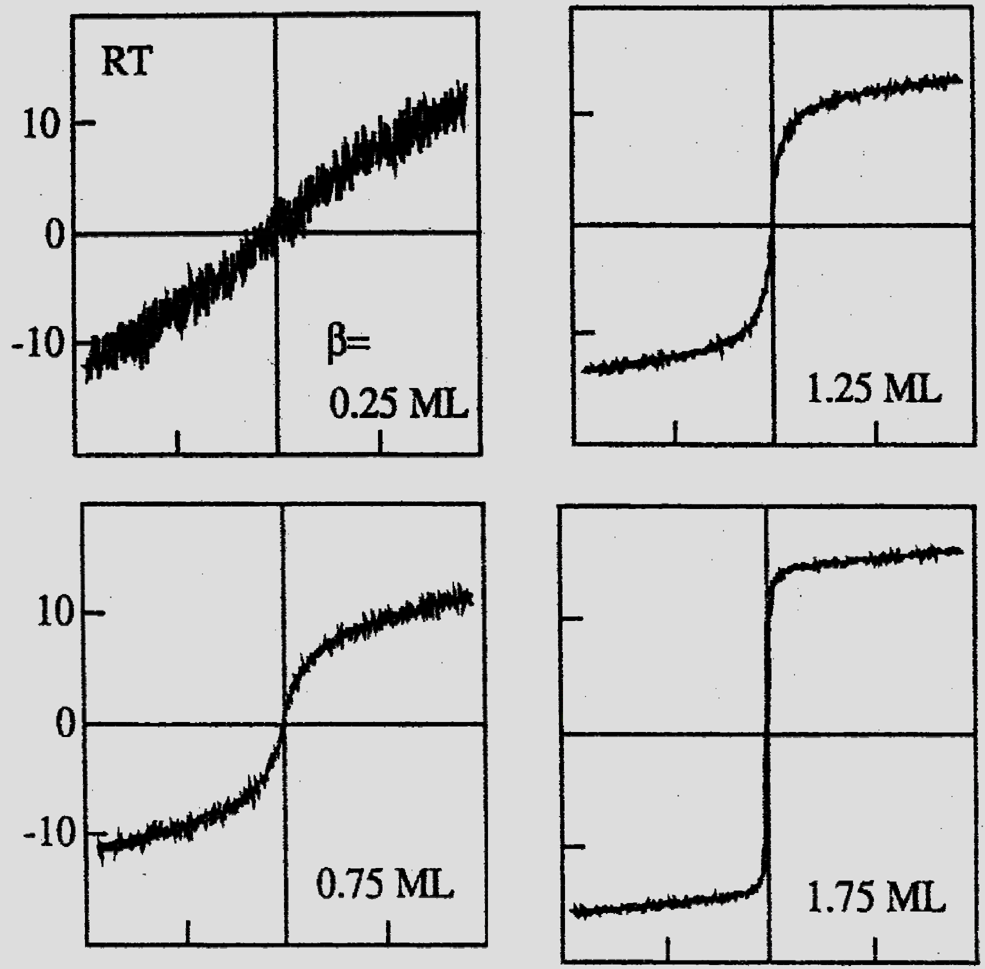
Numerical fitting

- Yields an estimation of the magnetic moment per particle μ
- Fitting with inadequate functions yields errors on μ
- Thermal variation of anisotropy constants neglected...

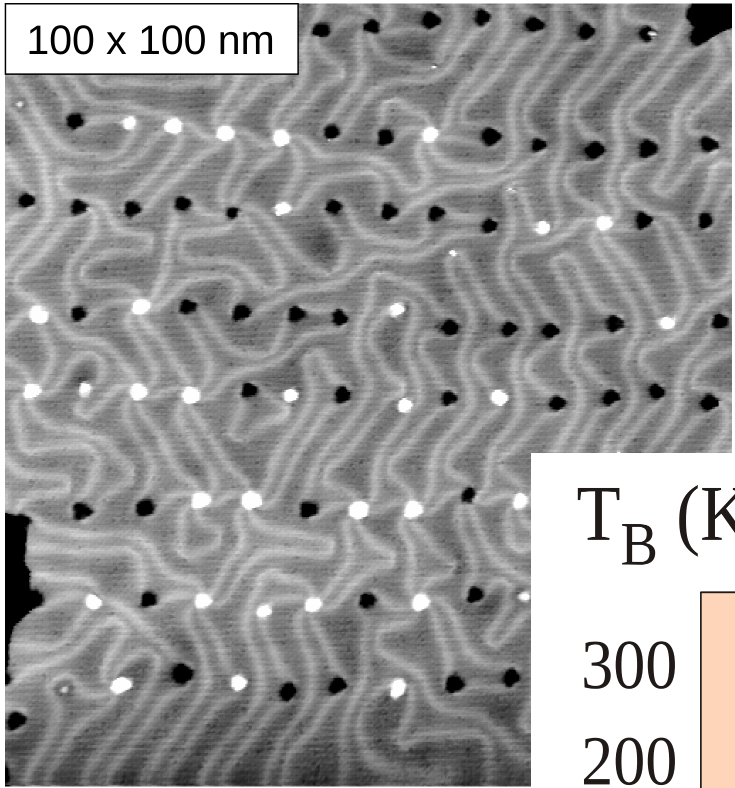
Example: Co/Au dots



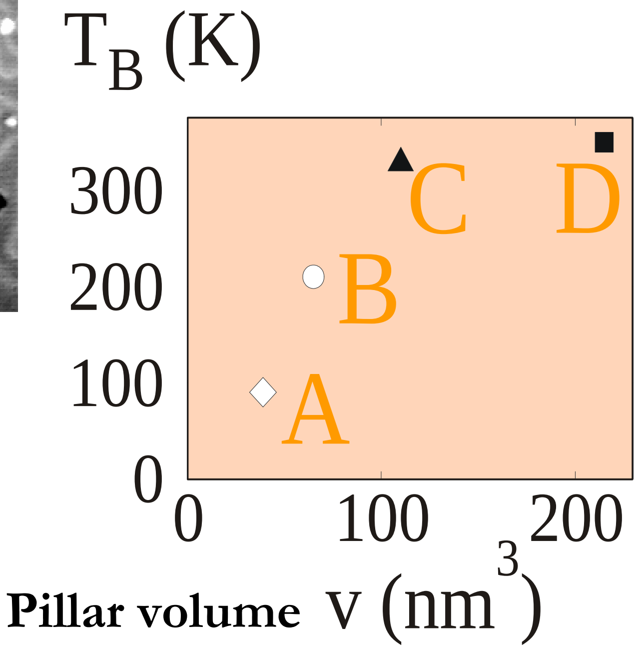
O. Fruchart et al.

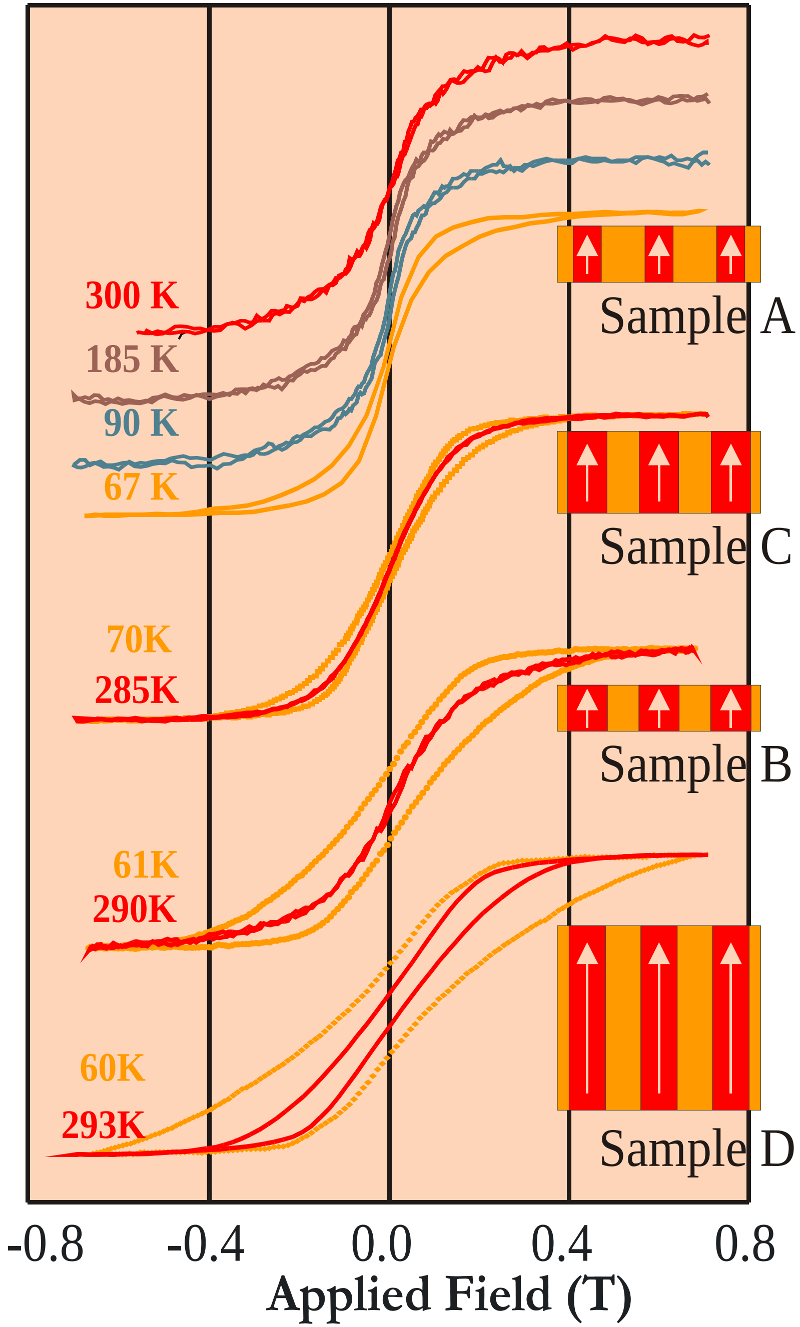


H.Takeshita et al., JMMM165, 38 (1997)



Co/Au(111)



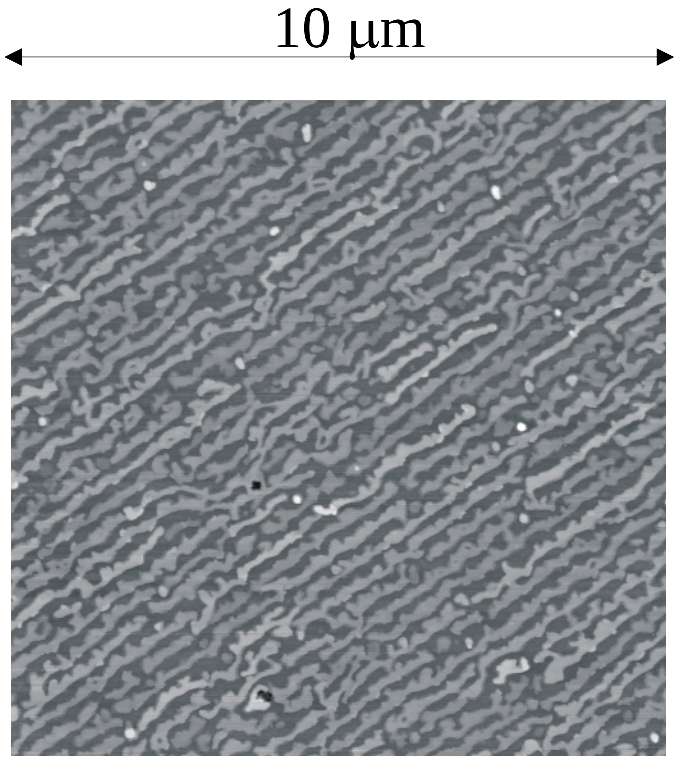


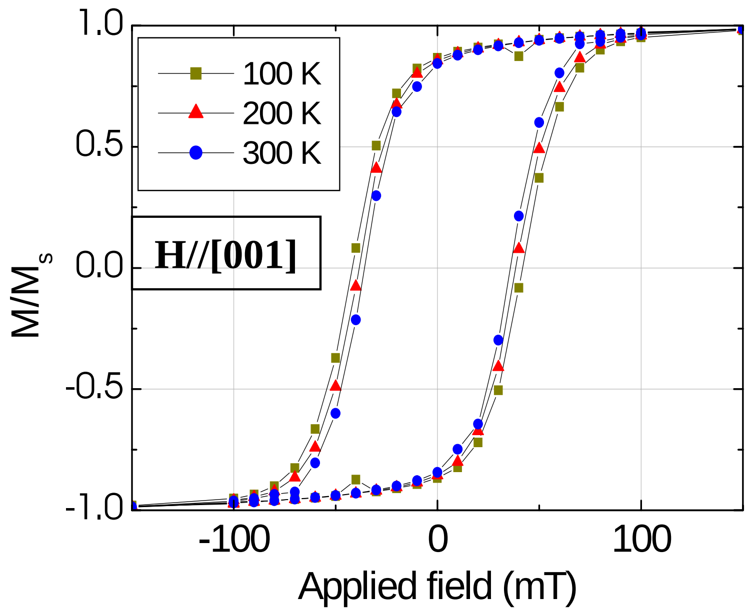
Vertical structures delay the occurrence of superparamagnetism

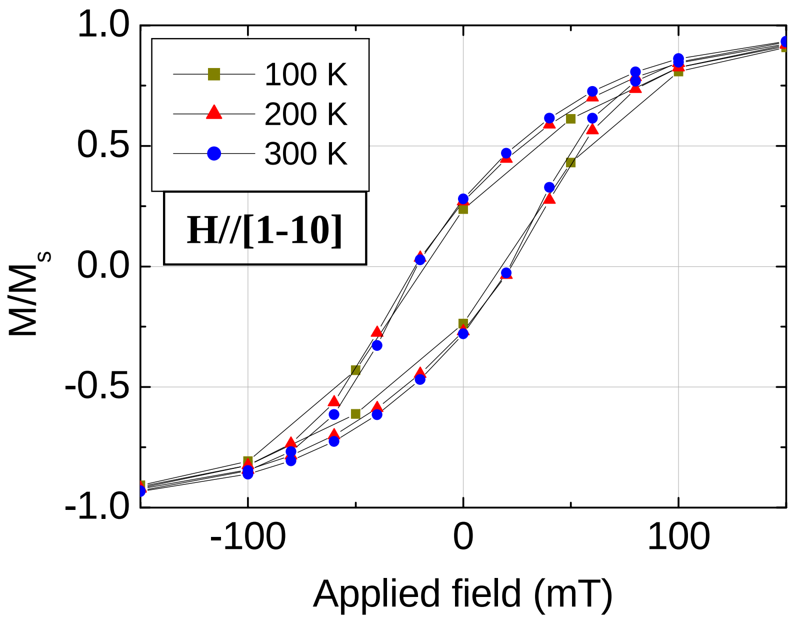
Coercivity and remanence at 300K

Sapphire \ W \ Mo\Fe(3nm) \ Mo

Stripe height = 4.5nm







- **Coercivity and high remanence at 300K**
- **Weak temperature dependence**
  > behaves like a conventional material

O. Fruchart *et al.*, APL 84, 1335 (2004)

Curie temperature versus blocking temperature?

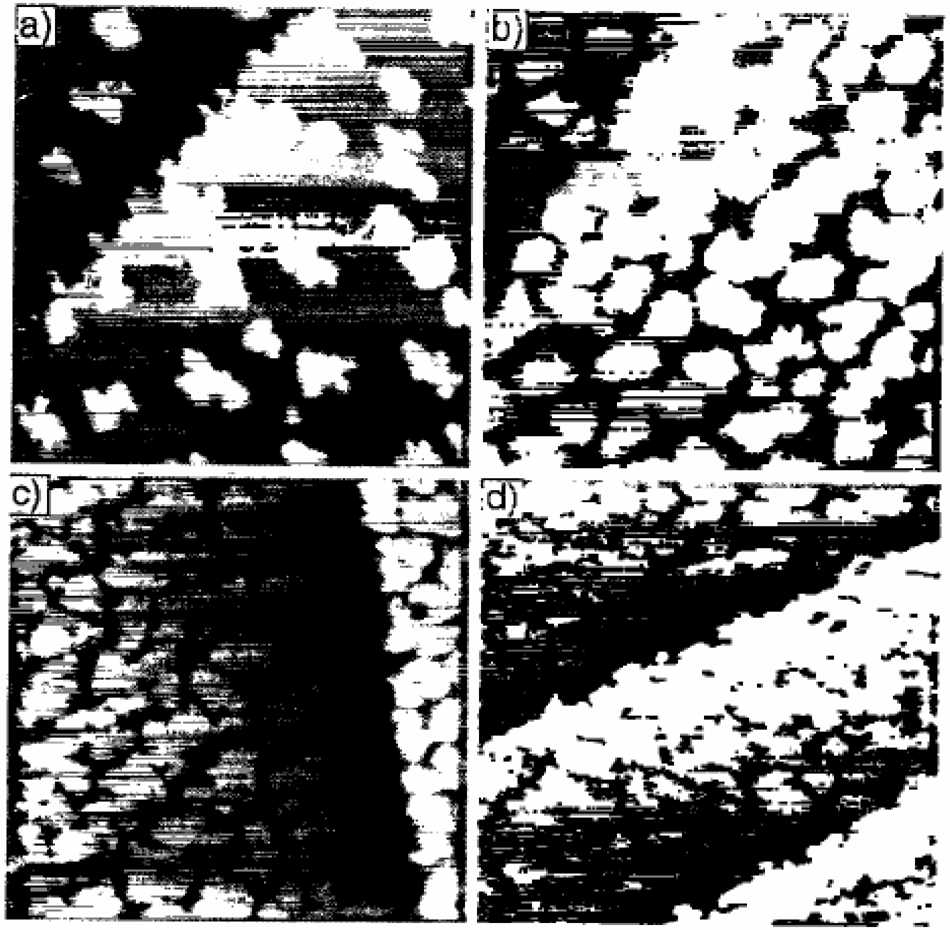
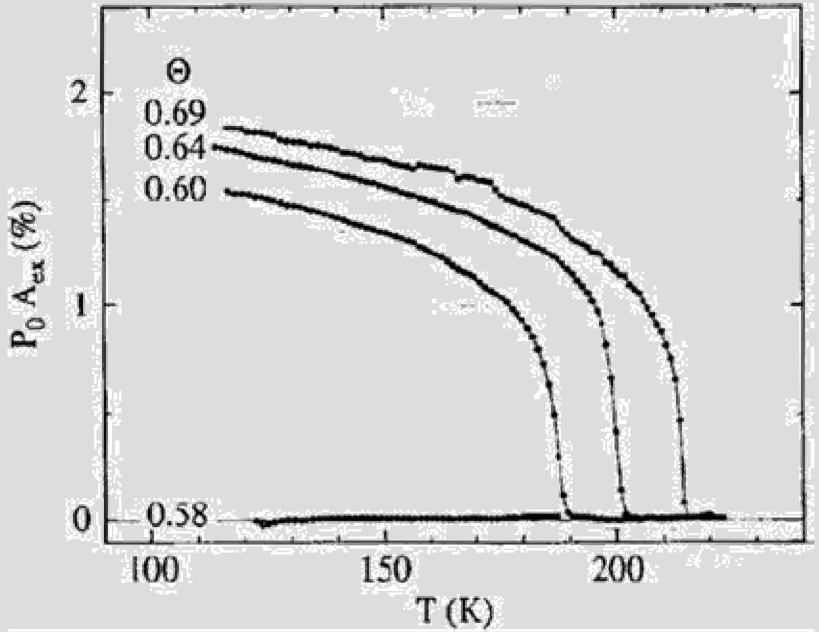


FIG. 1. STM images of Fe(110) films, prepared at RT on W(110), all 70 nm × 70 nm in size, with [001] horizontal. (a) $\theta = 0.23$; (b) $\theta = 0.53$; (c) $\theta = 0.66$; (d) $\theta = 0.85$. Upper levels (Fe) bright; lower levels (W) dark.

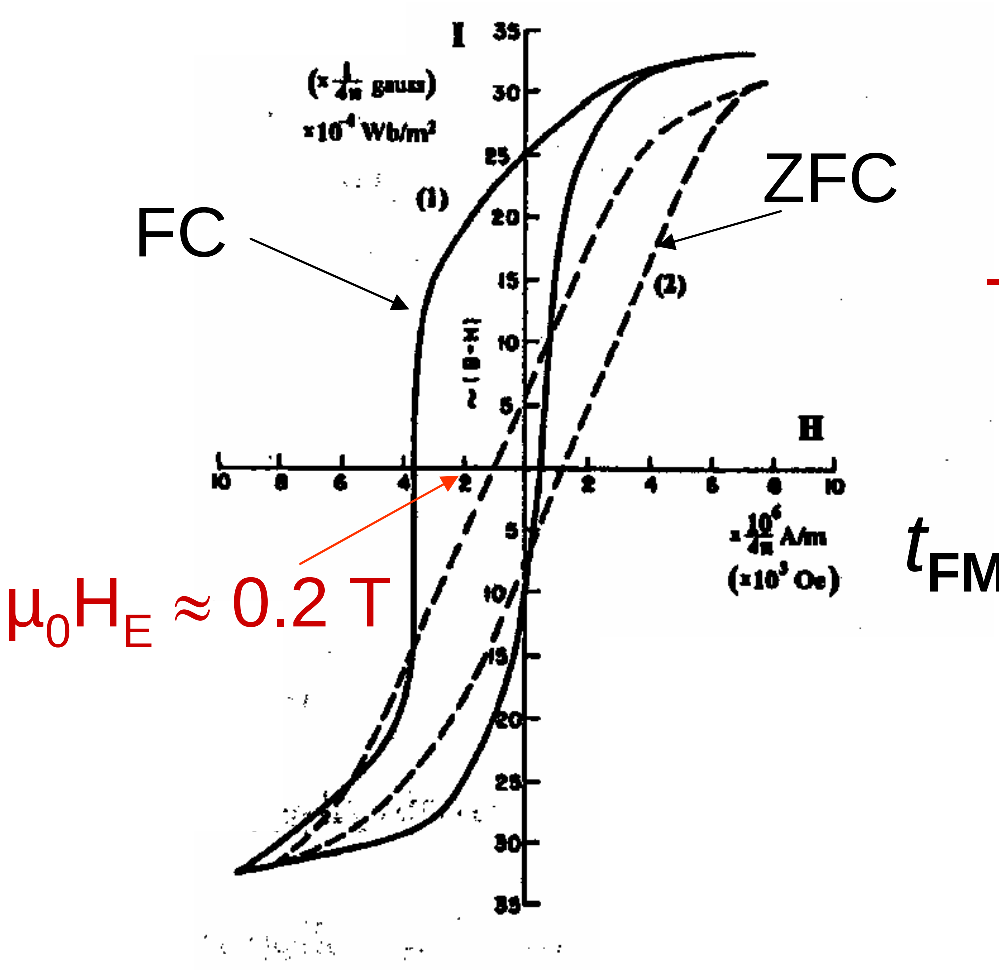
Remanence plotted as a function of temperature



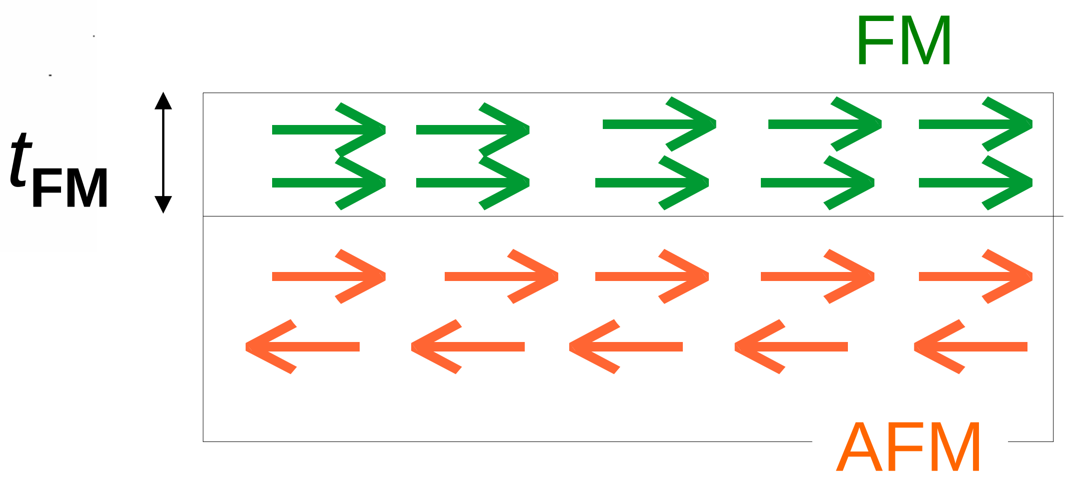
Transition from superparamagnetism to a blocked state

H. J. Elmers et al., PRL73, 898 (1994)

Oxidised Co nanoparticles



Field Cooled hysteresis loop :
-shifted with respect to M axis
- increased coercivity



Meiklejohn and Bean, Phys. Rev. 102 (1956) 1413,
Phys. Rev. 105 (1957) 904

Exchange bias
J. Nogués and Ivan K. Schuller
J. Magn. Magn. Mater. 192 (1999) 203

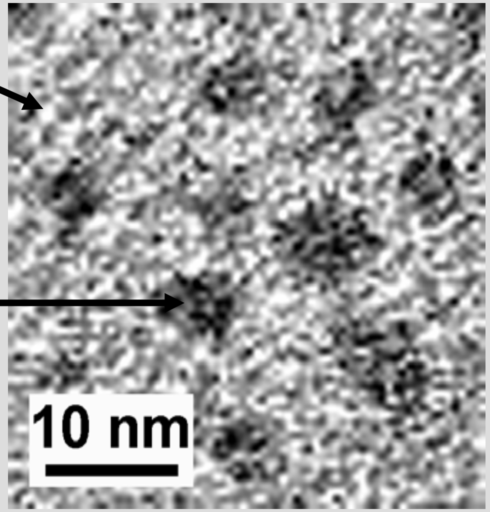
Exchange anisotropy—a review
A E Berkowitz and K Takano
J. Magn. Magn. Mater. 200 (1999)

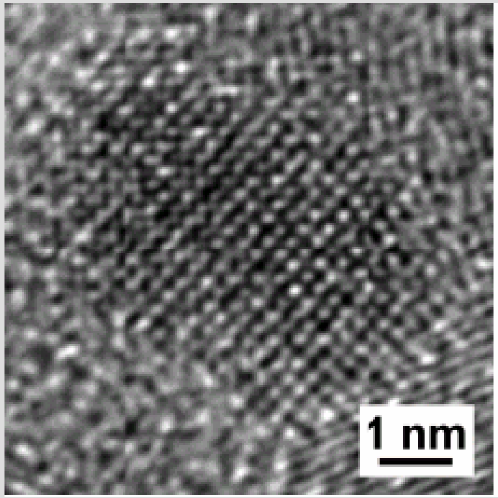
(Derived from slide: D. Givord)

Ferromagnetic nanoparticles in a non-magnetic or antiferromagnetic matrix

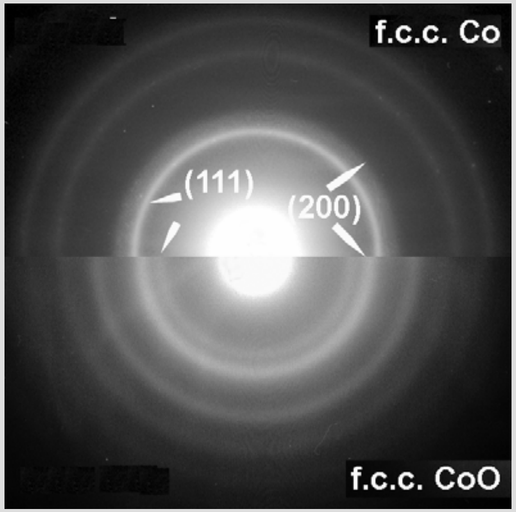
Matrix
(C, Al_2O_3, CoO)

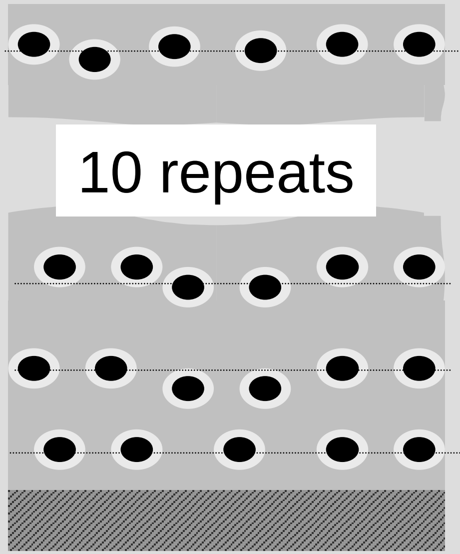
Co nanoparticles





Average particle size
3-4 nm



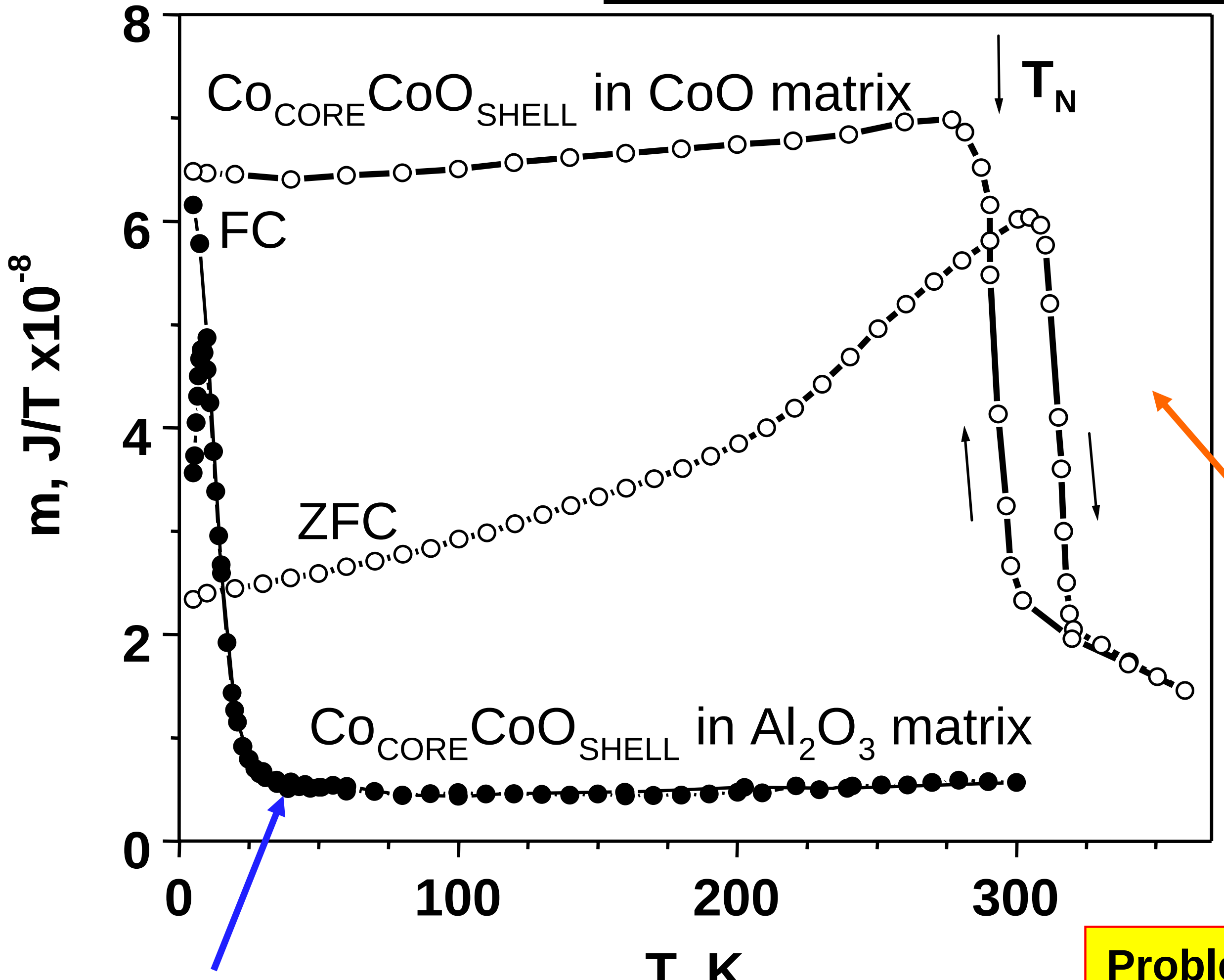


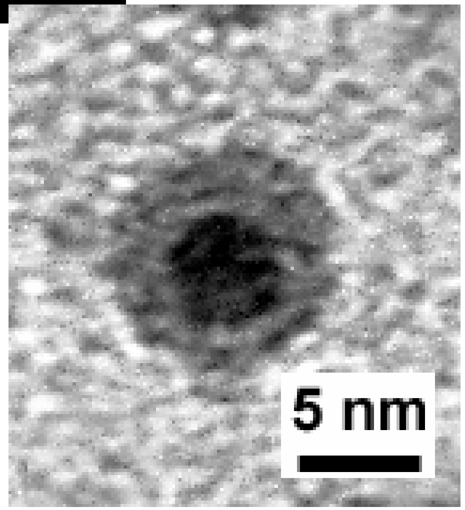
V.Skumryev, et al.,
Nature 423, 850 (2003)

"cluster gun" + conventional sputtering

(Derived from slide: D. Givord)

Dependence of the blocking temperature on the nature of the matrix





AFM matrix

$T_B \approx T_N$ CoO

Non-magnetic matrix : $T_B \approx 30K$

V.Skumryev, et al., Nature 423, 850 (2003)

Problems remain:

- **Not all features understood**
- **Very sensitive on fabrication**

I. Fabrication methods

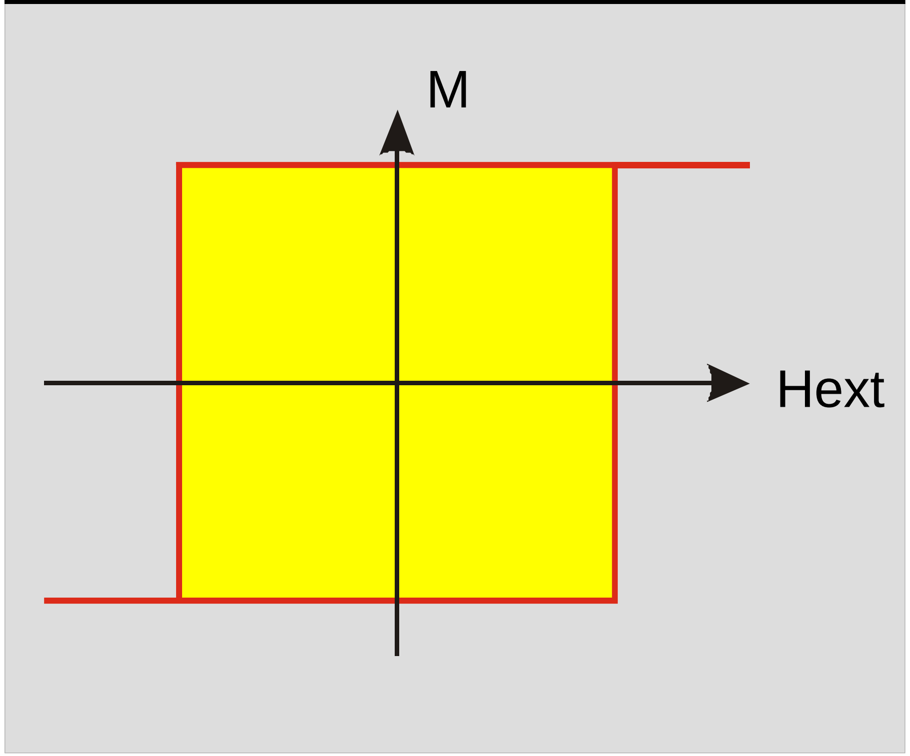
1. Epitaxial self-assembly & self-organization
2. Other routes: electrochemistry, chemistry, physical paths to clusters, exotic means
3. Future prospects for self-organization.

II. Selected topics for Magnetism

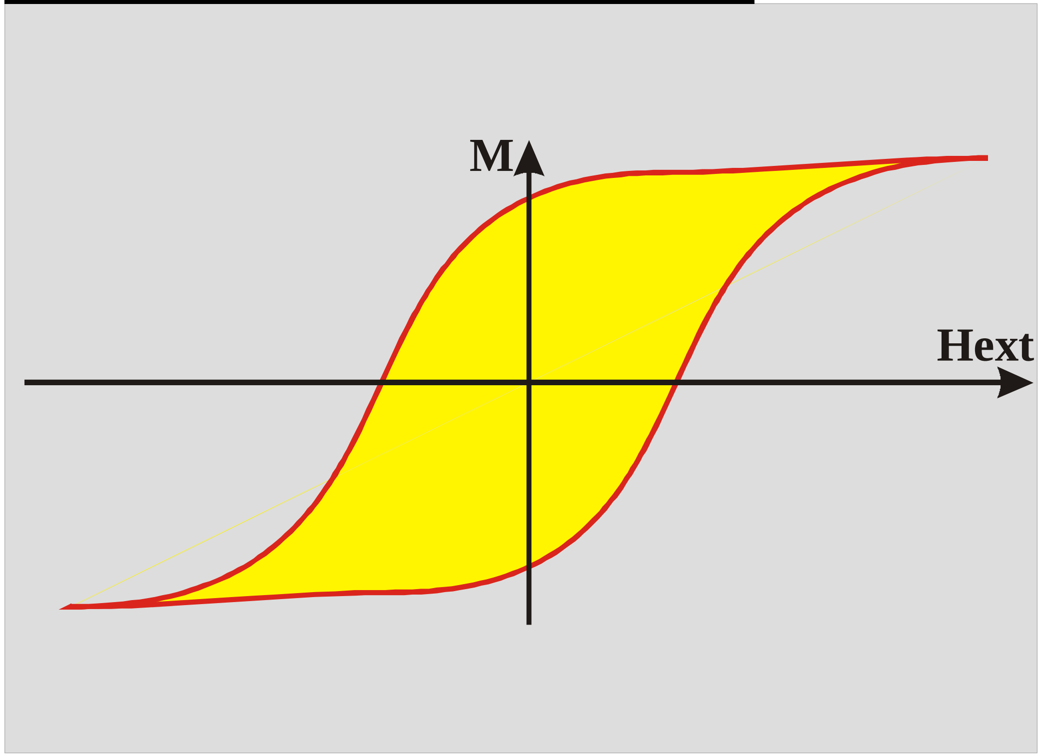
1. Magnetic order
2. Magnetic anisotropy
3. Magnetization reversal and superparamagnetism.
4. Micromagnetism

3.5. Collective dipolar properties

Expected hysteresis loop for macrospins



Hysteresis for assemblies of dots



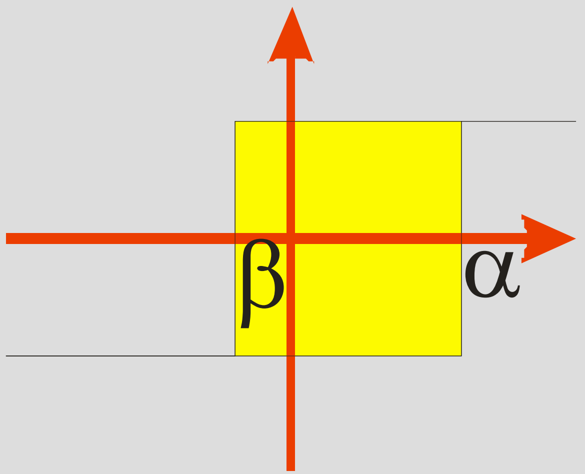
Possible effects

- Distribution of coercive fields
- (Dipolar) interactions

Preisach model

G. Biorci et al., Il Nuov. Cim. VII, 829 (1958)

I. D. Mayergoyz, Mathematical models of hysteresis, Springer (1991)

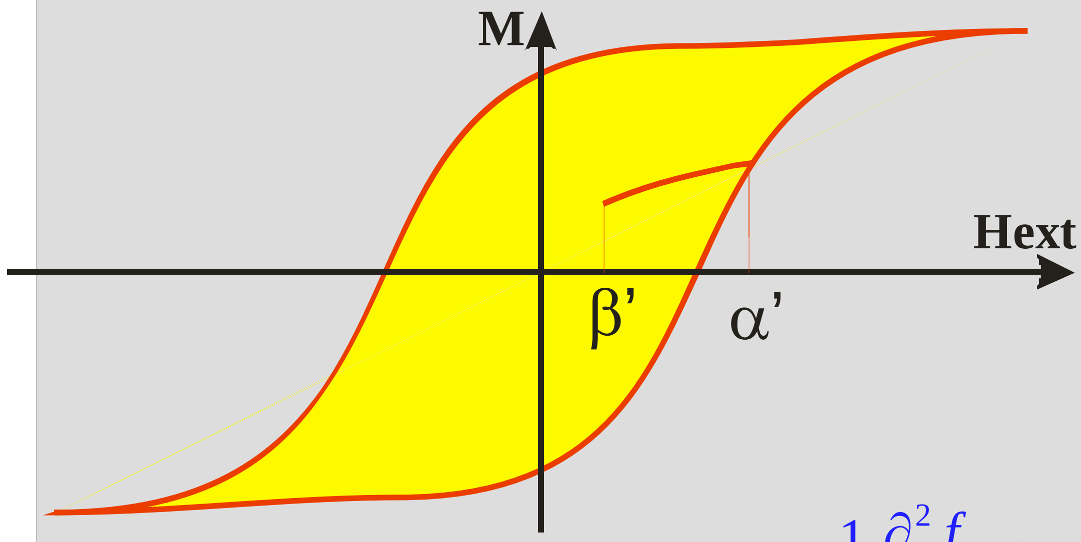


- Distribution function

$$\mu(\alpha,\beta) \text{ with } \alpha > \beta$$

- No true link between real particles and μ

Solving



$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

Henkel plots

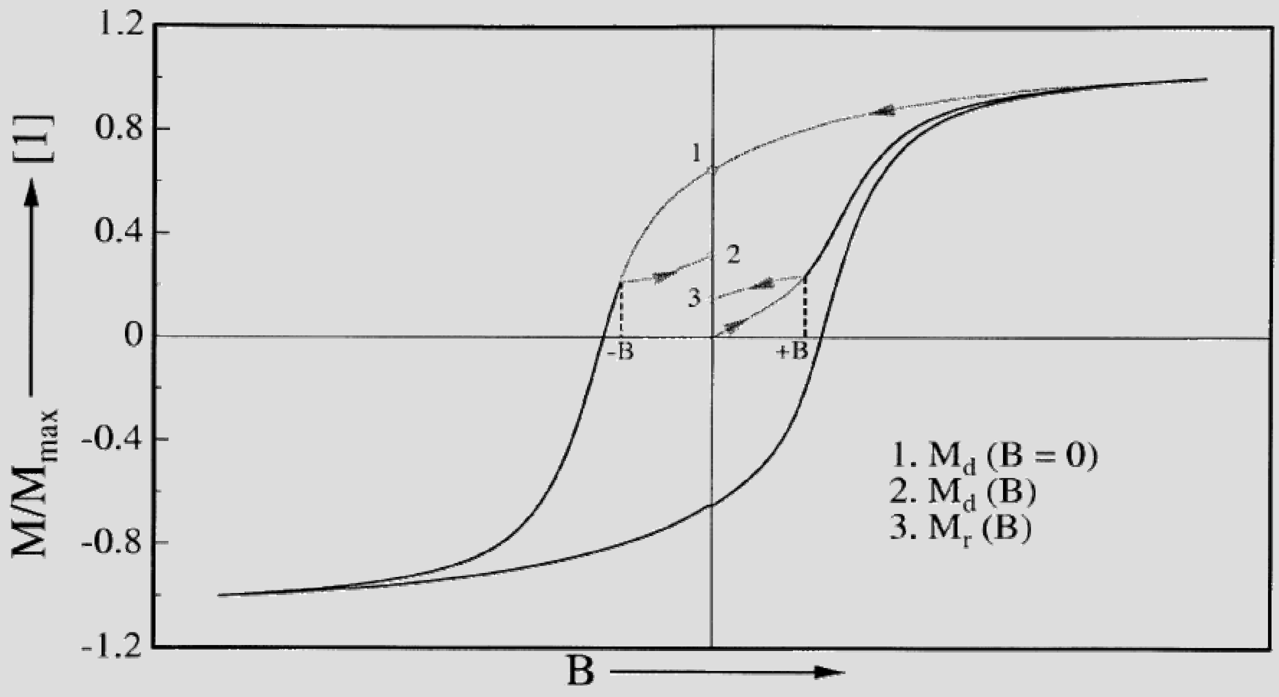


Fig. 1. Explanation of how to measure the two different remanent magnetisations M_r and M_d.

Measure of dipolar interactions

$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

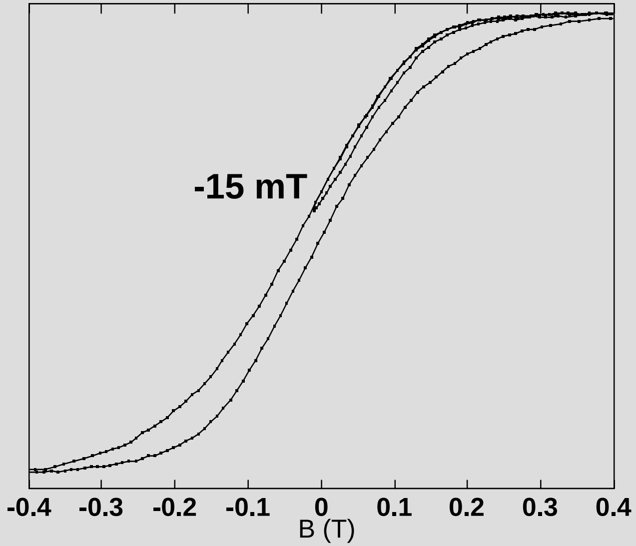
O. Henkel,
Phys. Stat. Sol. 7, 919 (1964)

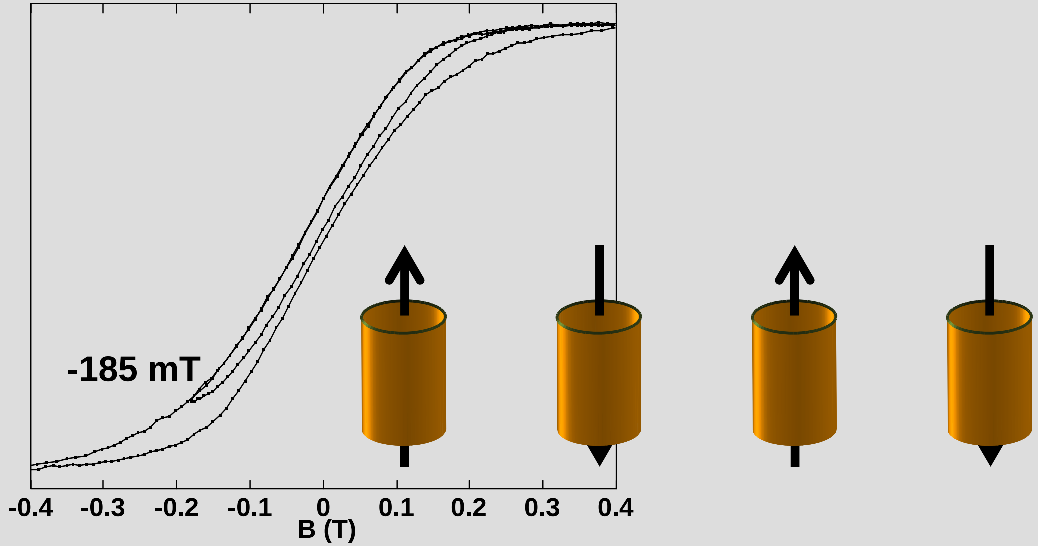
S. Thamm et al.,
JMMM184, 245 (1998)

- Long experiments (ac demagnetization)
- Better physical meaning than Preisach

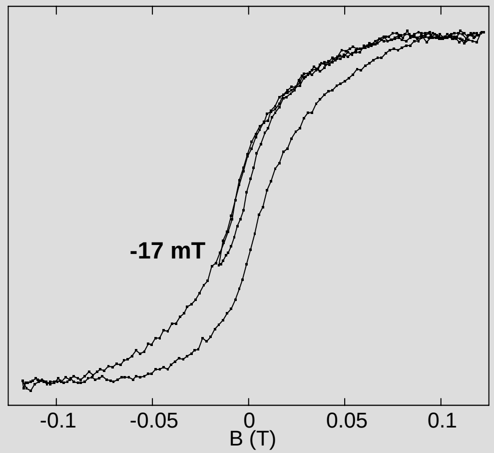
Minor loops: negative interactions

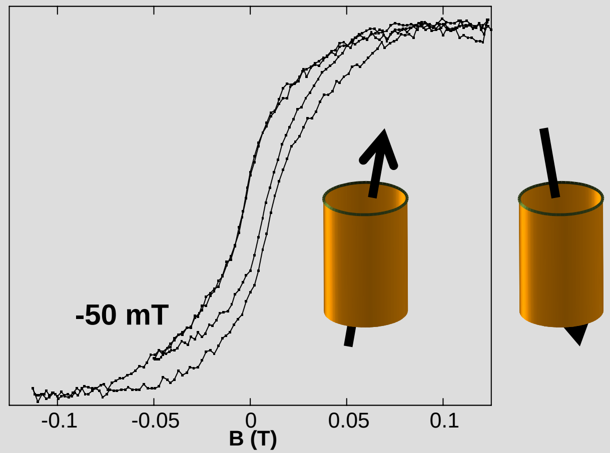
Example: dipolar interactions in arrays of Co/Au(111) pillars





Minor loops: negligible interactions





- Faster than Henkel
- Other applications: characterization of exchange bias

O. Fruchart et al., unpublished

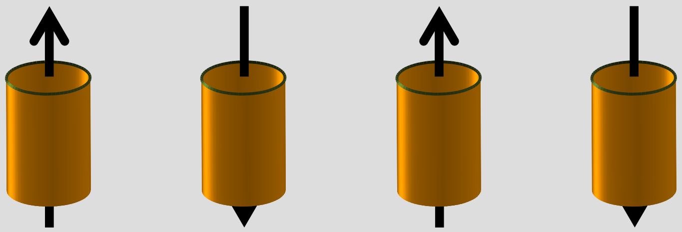
Superparamagnetic regime: plot of inverse susceptibility

- **Brillouin 1/2 function**

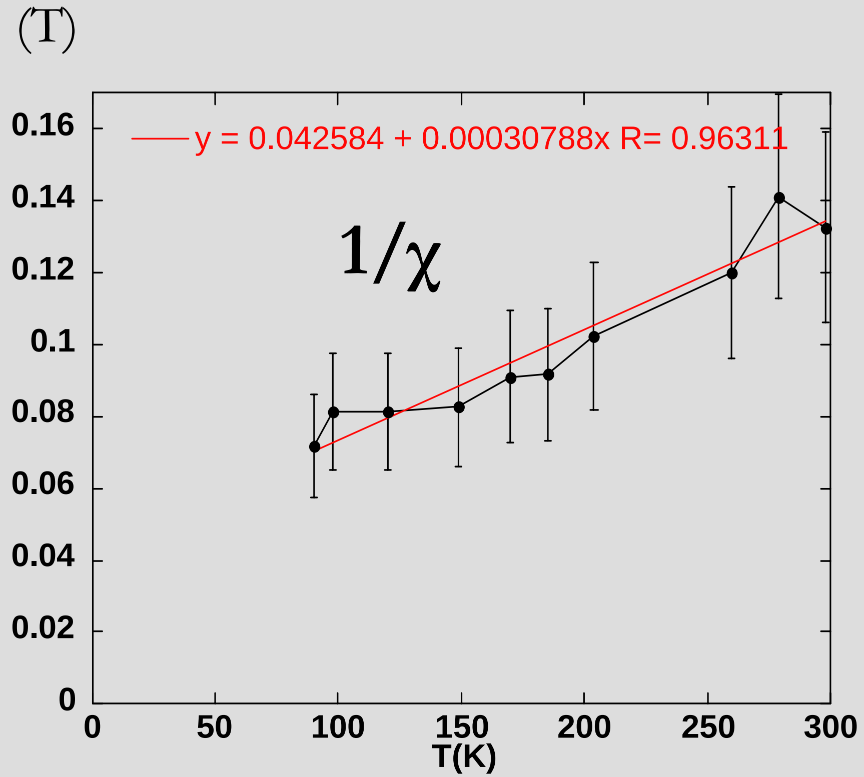
$$m = \mathrm{B}_{1/2}\left(\mu_0 \mu_{Co} N H_{eff.} / kT\right)$$

- **Effective field**

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



(Demagnetizing dipolar interactions)



- **First order expansion:**
  susceptibility

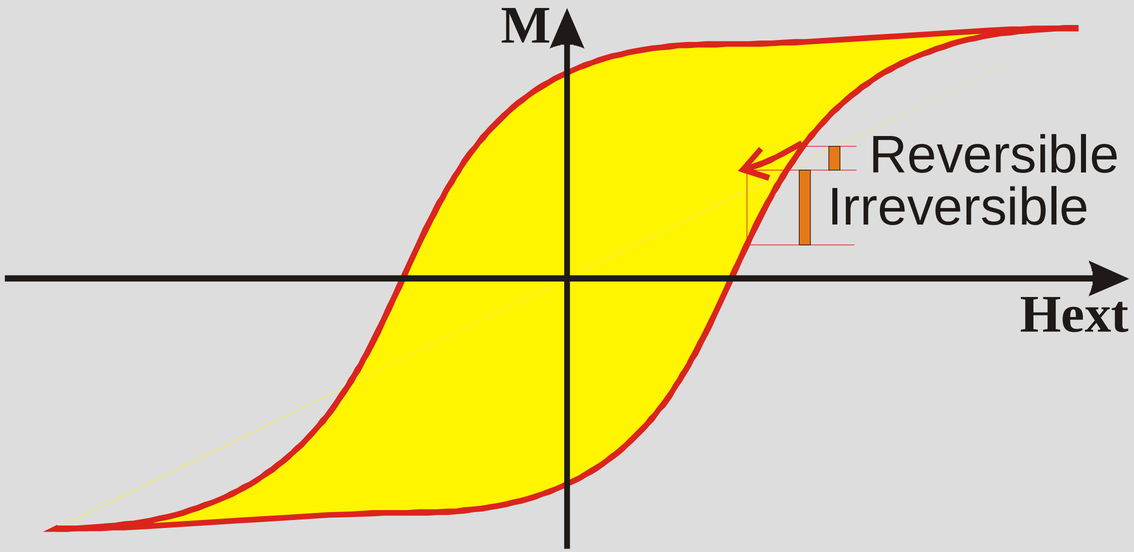
$$\frac{d(\mu_0 H)}{dm} = \frac{1}{\chi} = -\mu_0 M_S r + \frac{k}{\mu_{Co} N} T$$

$$a \quad + \quad b \,.\, T$$

O. Fruchart *et al.*, PRL 23, 2769 (1999)

- No need of hysteresis
- Analogy with Curie-Weiss law

Distribution of properties

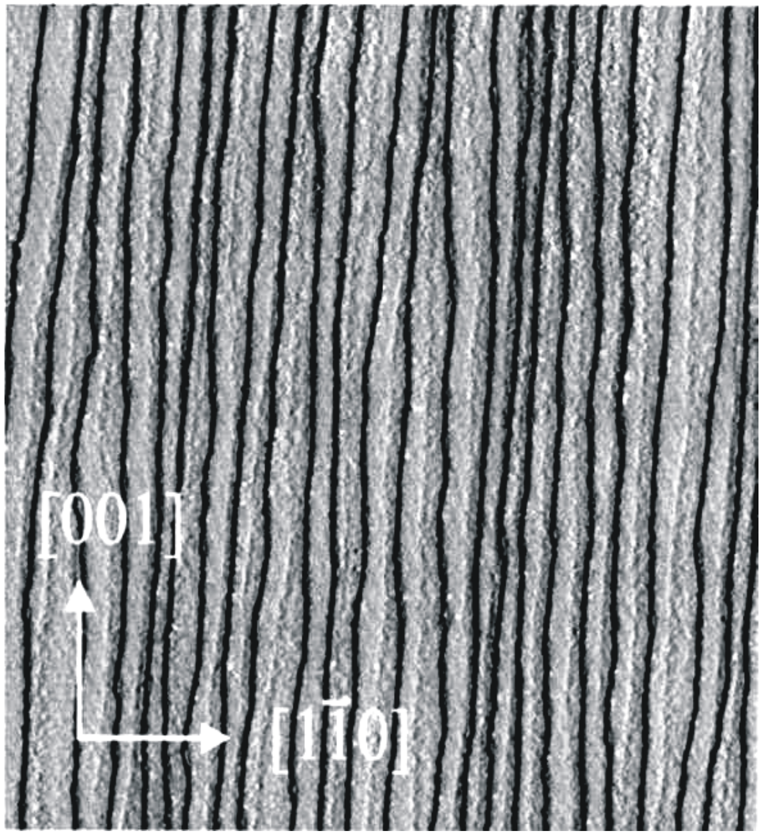


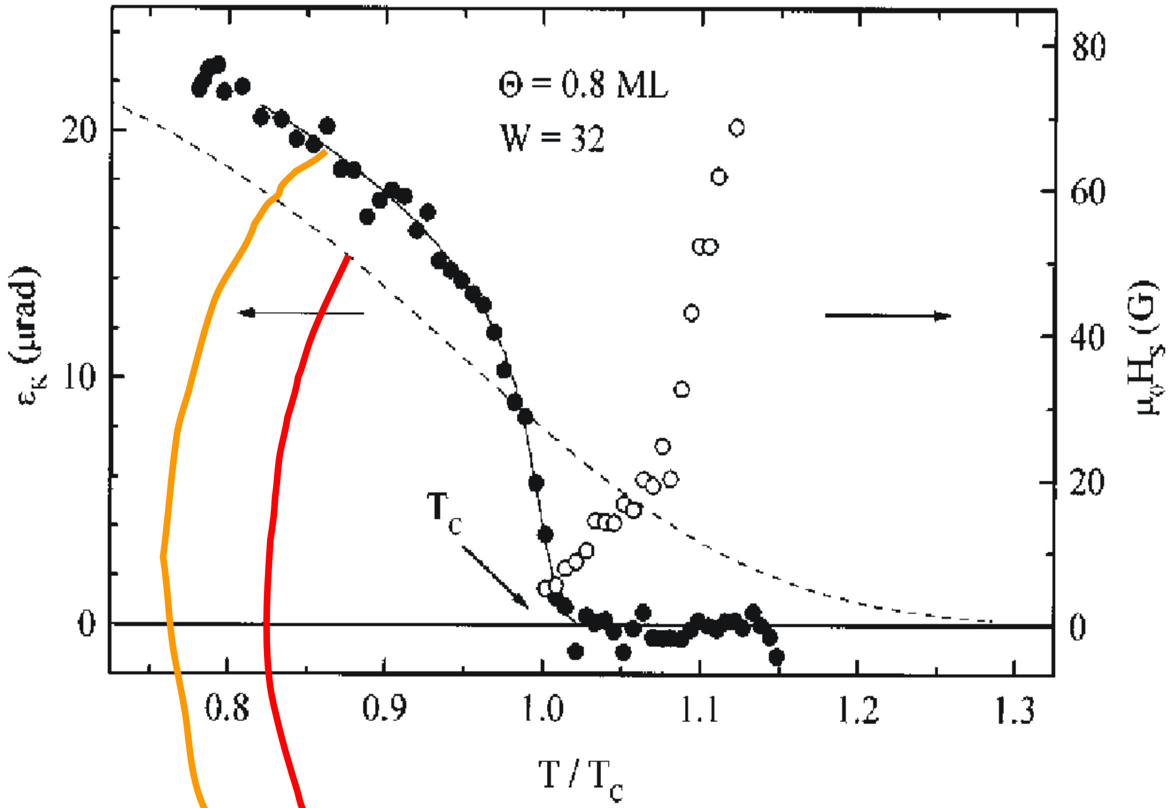
$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\text{irreversible}}$$

Hc(T) for a given population of the distribution can be studied at a given stage of the reversal (10%, 20% etc.)

Effect of distributions and dipolar interactions are sometimes difficult to disentangle

Ferromagnetic order stabilized by dipolar interactions





J. Hauschild *et al.*, Phys. Rev. B 57, R677 (1998)

Tc=179K

Although weak, dipolar interactions stabilize ferromagnetic order and sharpen the transition at Tc, owing to their long range

I. Fabrication methods

1. **Epitaxial self-assembly & self-organization**
2. **Other routes: electrochemistry, chemistry, physical paths to clusters, exotic means**
3. **Future prospects for self-organization.**

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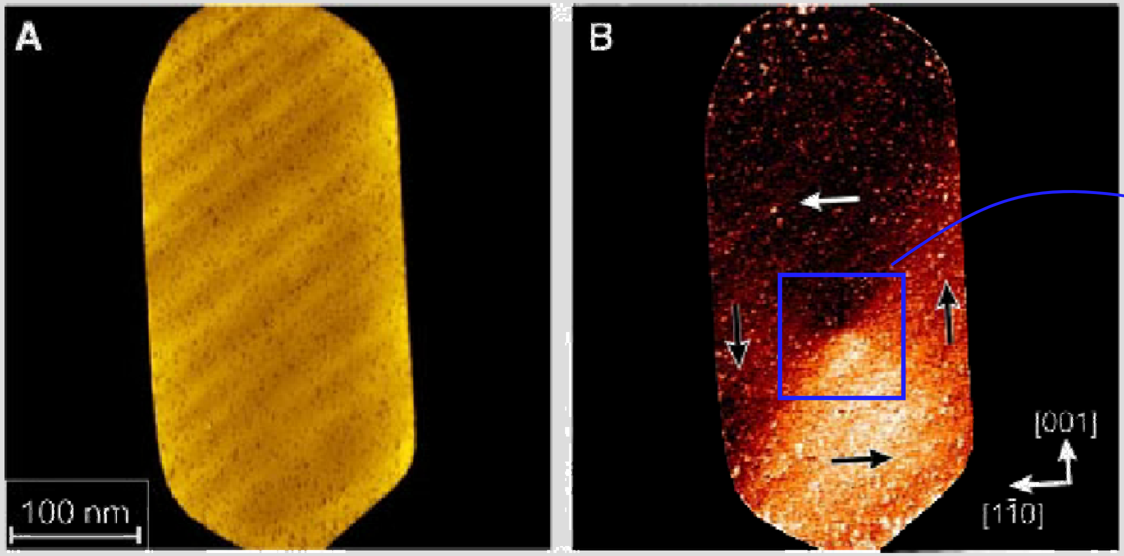
1. **Magnetic order**
2. **Magnetic anisotropy**
3. **Magnetization reversal and superparamagnetism.**
4. **Micromagnetism**

Magnetic vortex core

Spin-polarized Scanning Tunneling Microscopy on Fe / W(110) self-assembled dots

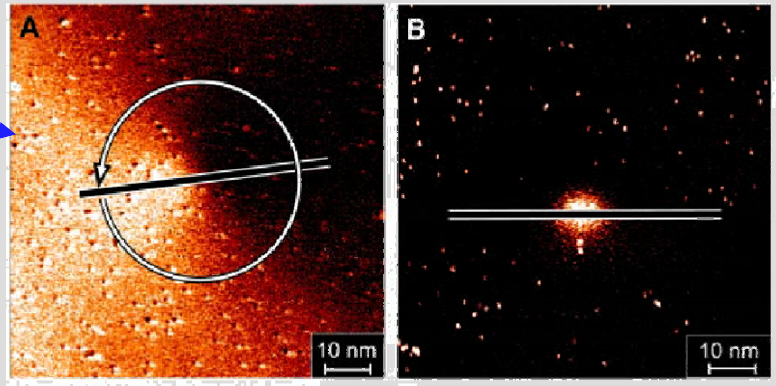
Structural image

Magnetic image



In-plane component of magnetization

Out-of-plane component of magnetization



A. Wachowiak, Science 298, 577 (2002)

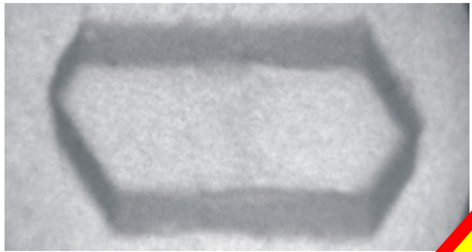
...also in-field study

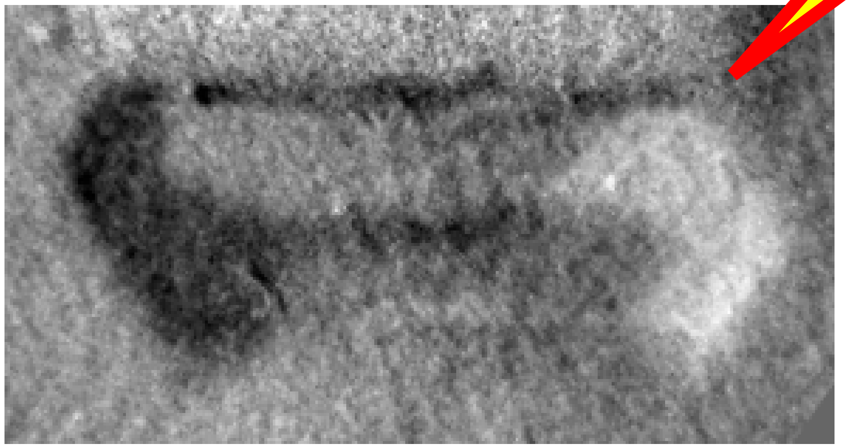
3D magnetization configurations

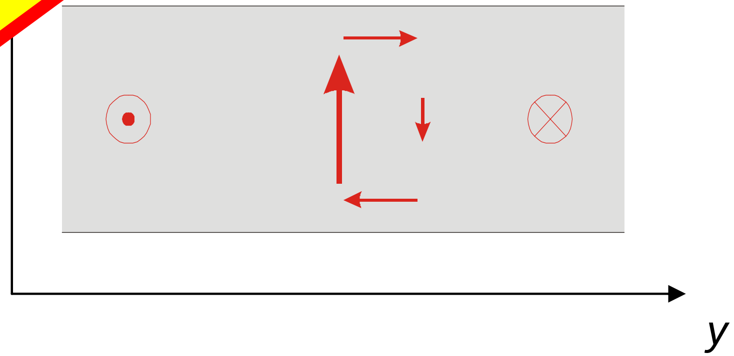
Technique ... nchrotron, Trieste)

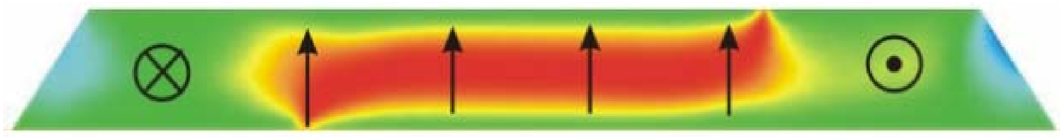
See poster by
Fabien CHEYNIS

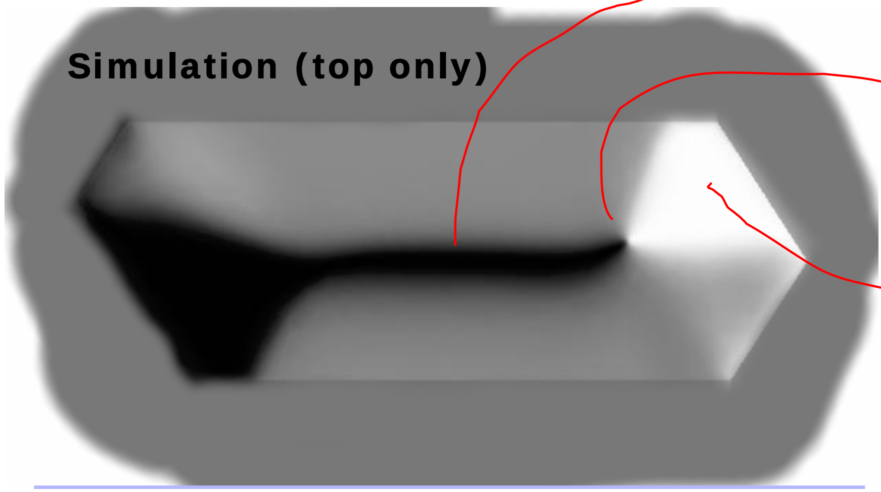
Experiment (top)











Néel cap displaced from median line

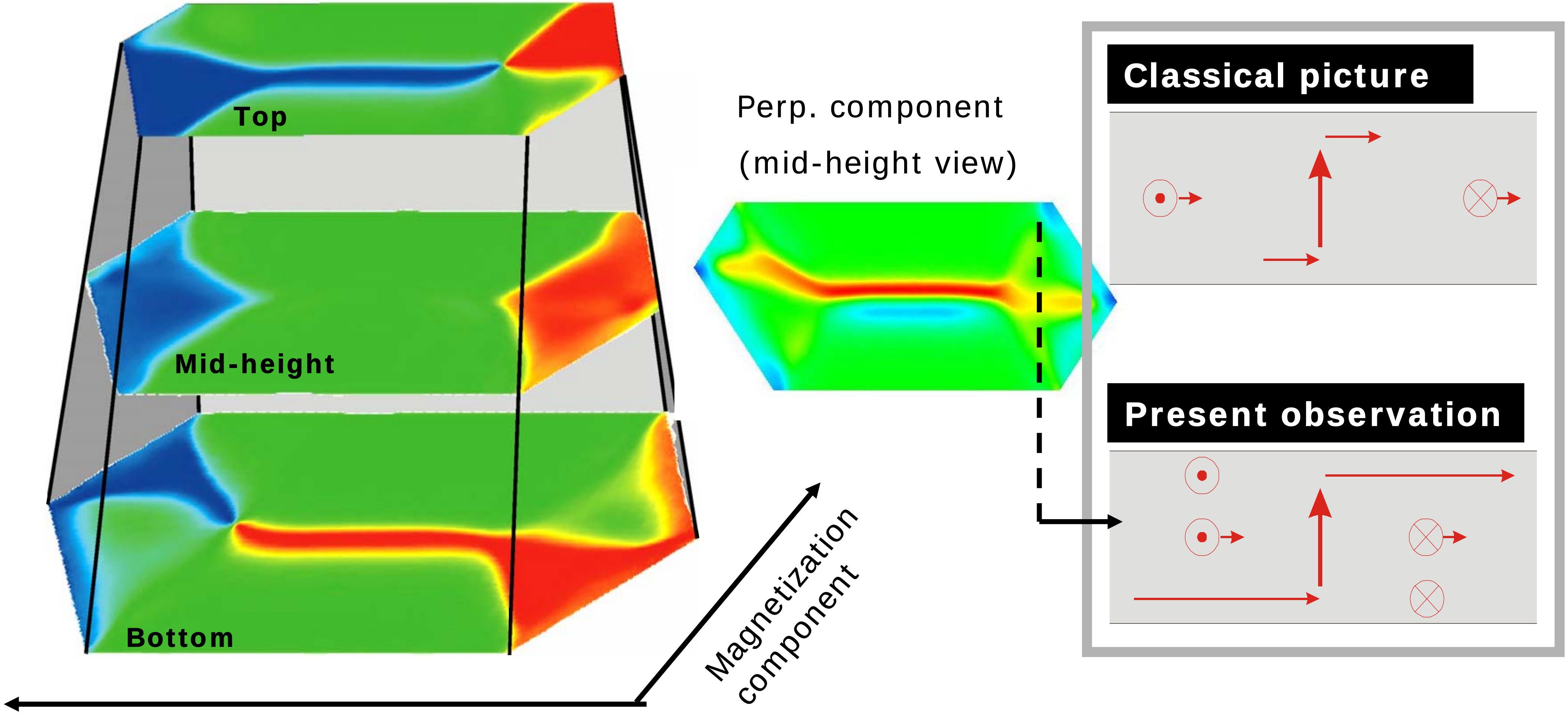
Asymmetry around vortex

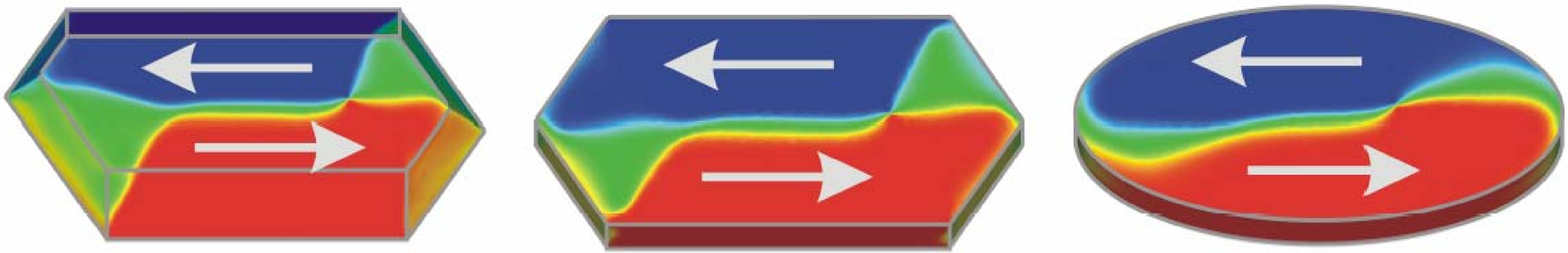
Pseudo-2D

Strong asymmetry of end domains

3D

The main features are reproduced

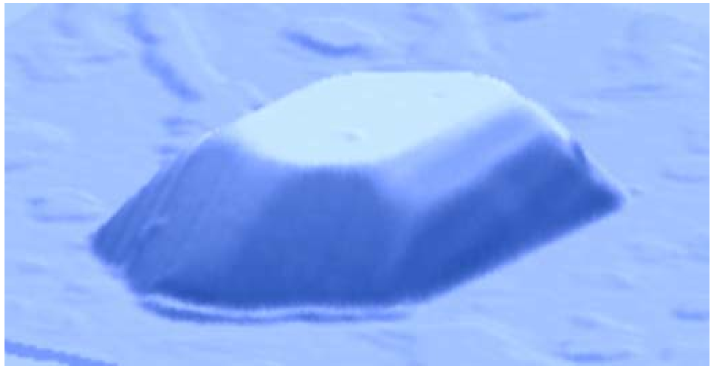




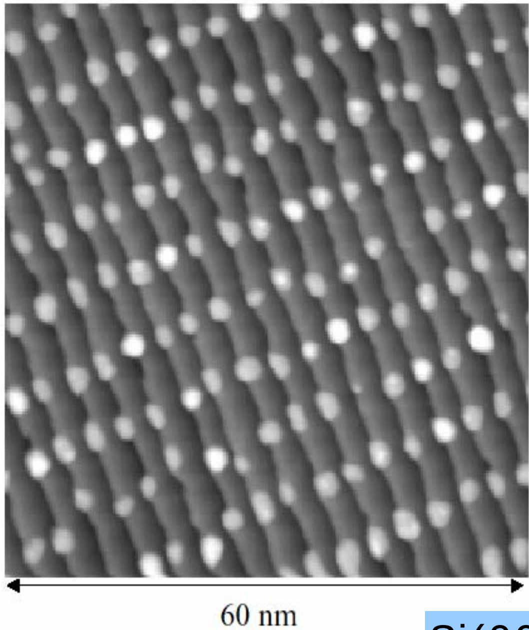
R. Hertel, O. Fruchart, S. Cherifi et al., cond-mat/0507119, accepted in PRB

LLN, Grenoble, France.

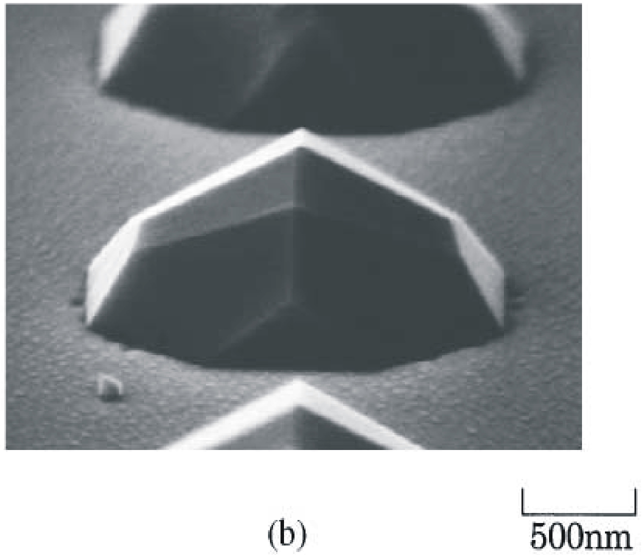
Fe/Mo(110) dots



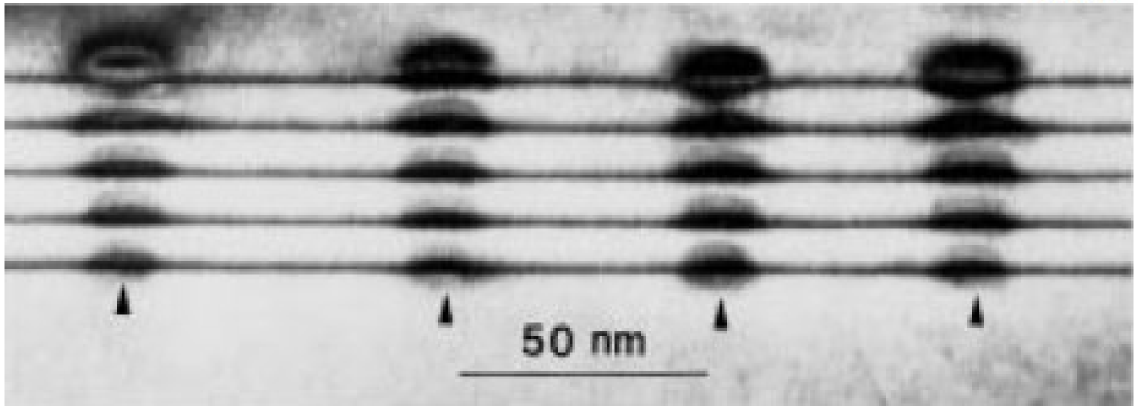
Co/Au(788) dots



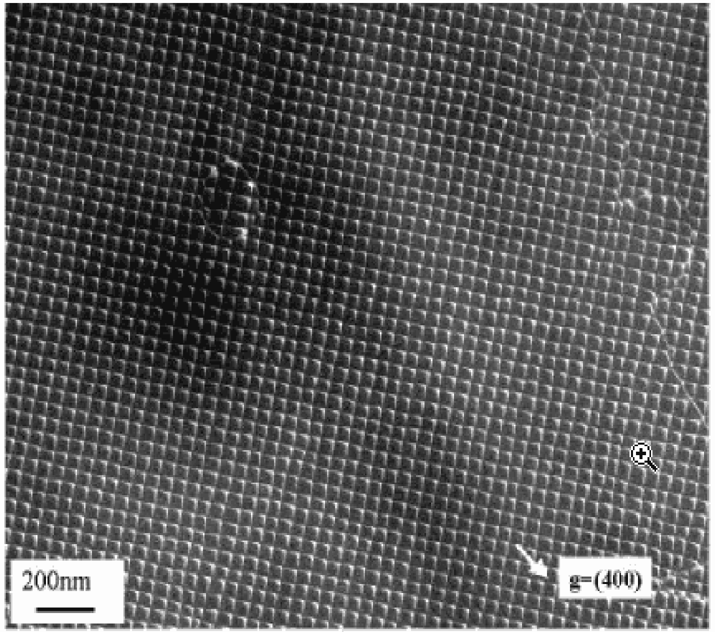
GaAs/GaAs(001) dots



InAs/GaAs(001) dots

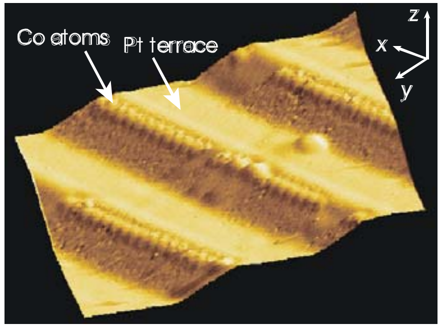


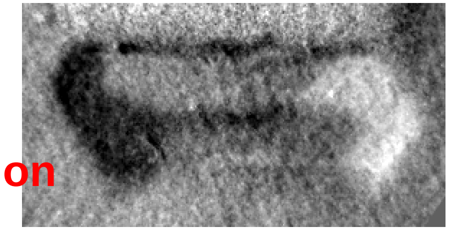
Si(001) bonding



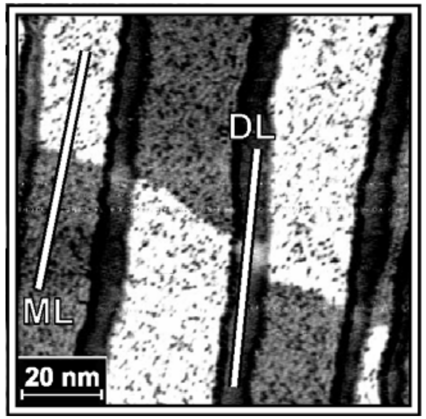
Many tricks to be used
- Just let your imagination help nature !
- Current trend: increase versatility, combine complementary approches

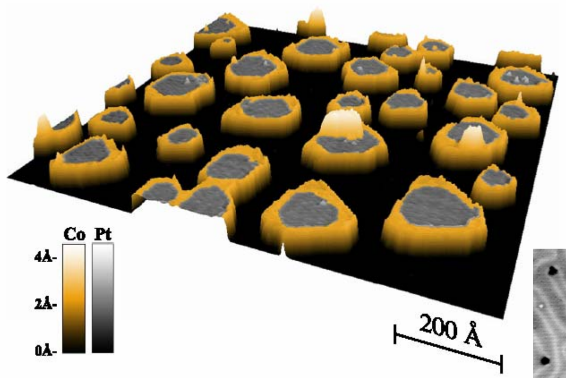
Self-assembly for magnetism

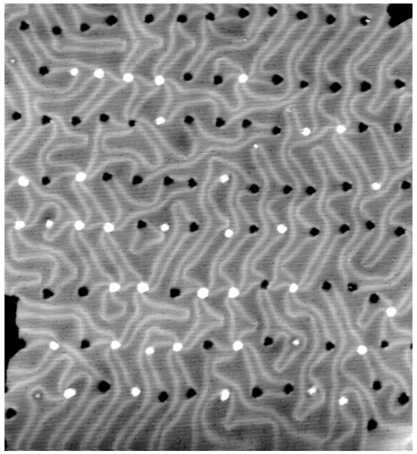


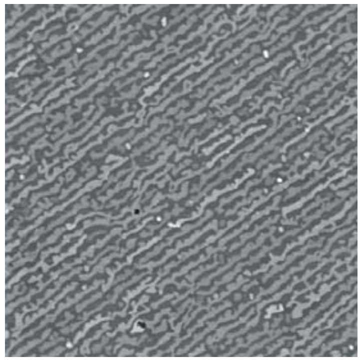


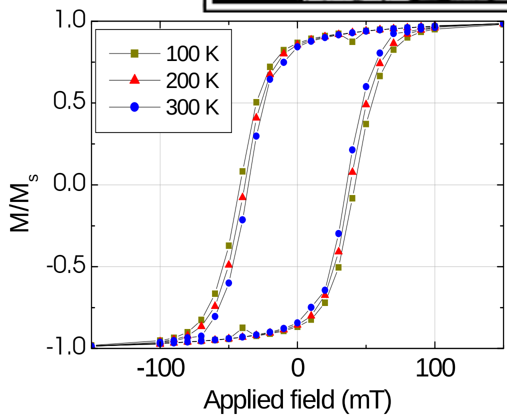
- **Micromagnetism**
  Desirable: High quality (magnetic properties, observation)
- **Ferromagnetic order in low dimension**
  Desirable: small, high quality
- **Spin, orbital momentum and anisotropy in low dimension**
  Desirable: small, high quality
- **Fight against superparamagnetism**
  Fundamental obstacle for technological use











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