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Structural and magnetic properties of periodic dot lattices studied by off-specular x-ray and neutron reflectivity

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MOTIVATION and OUTLINE

Aim: - study magnetic properties of dots

- study diffuse reflectivity of structured surfaces

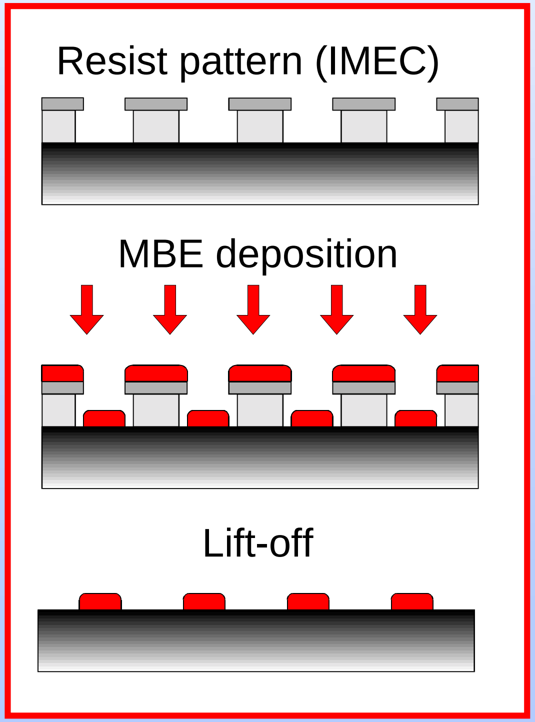
Domain structure and magnetization directions ?

- Preparation of structured surfaces
- Magnetic dot arrays :

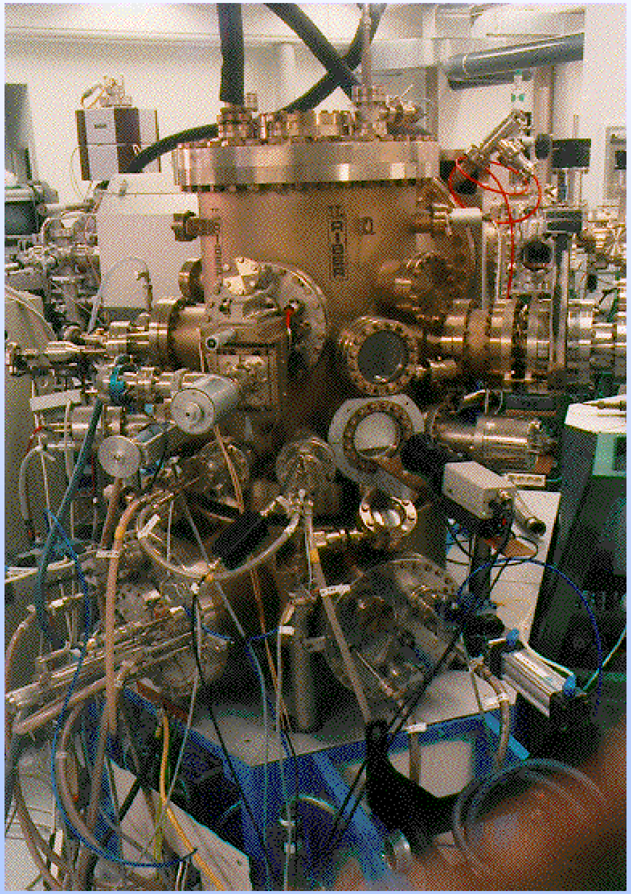
  force microscopy and X-ray reflectivity
- Dots probed by polarized neutron reflectometry
- Conclusions

Preparation by Molecular Beam Epitaxy

- **Substrate**: SiO_2
- **Electron beam evaporation**
  Co 0.45 Å / s, 10^{-10} Torr, 300 K
  Knudsen effusion cell
  Au 0.25 Å / s, 10^{-10} Torr, 300 K



Riber MBE facility



Characterization by Atomic Force Microscopy

Tapping Mode Atomic Force Microscopy

Period: d = 1.5 μm

Dot dimensions:

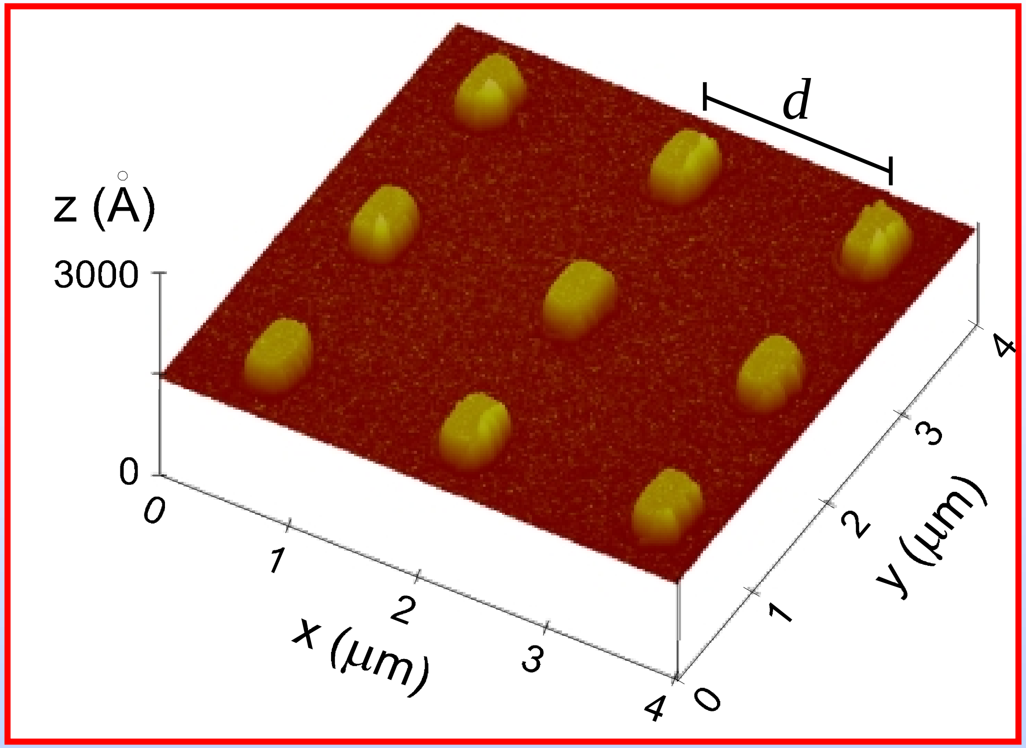
L_l x L_s = 0.54 μm x 0.36 μm

thickness: 380 Å

$L_l / L_s = 3/2$

rms roughness of dot surface:

σ_{RMS} = 9 Å

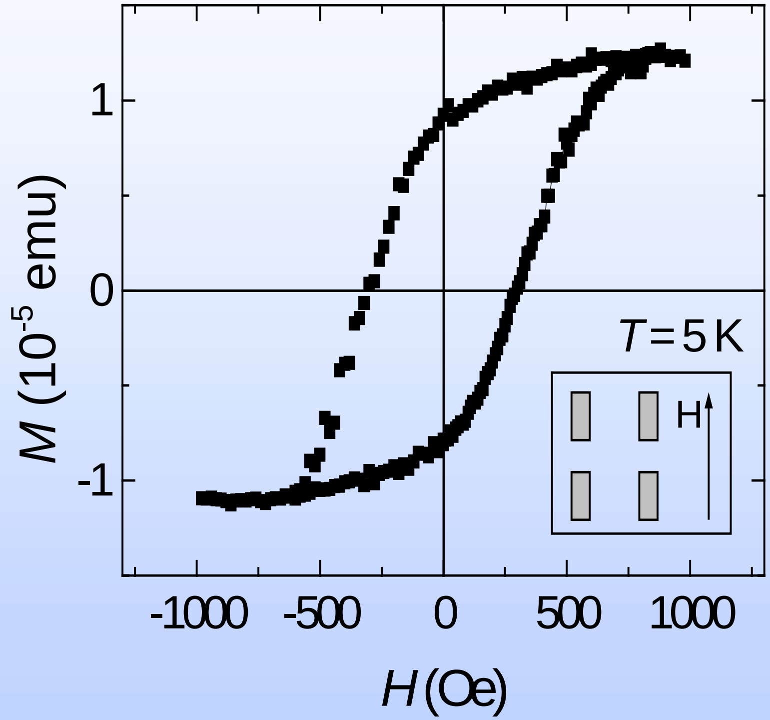


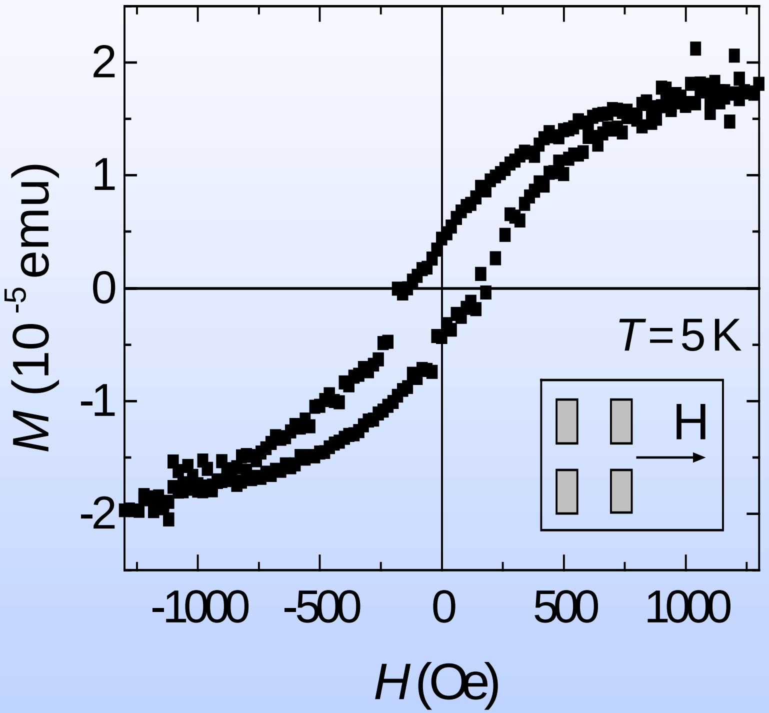
Polycrystalline dots

Well defined periodicity, shape, and dimensions of dot lattice

SQUID magnetization experiments

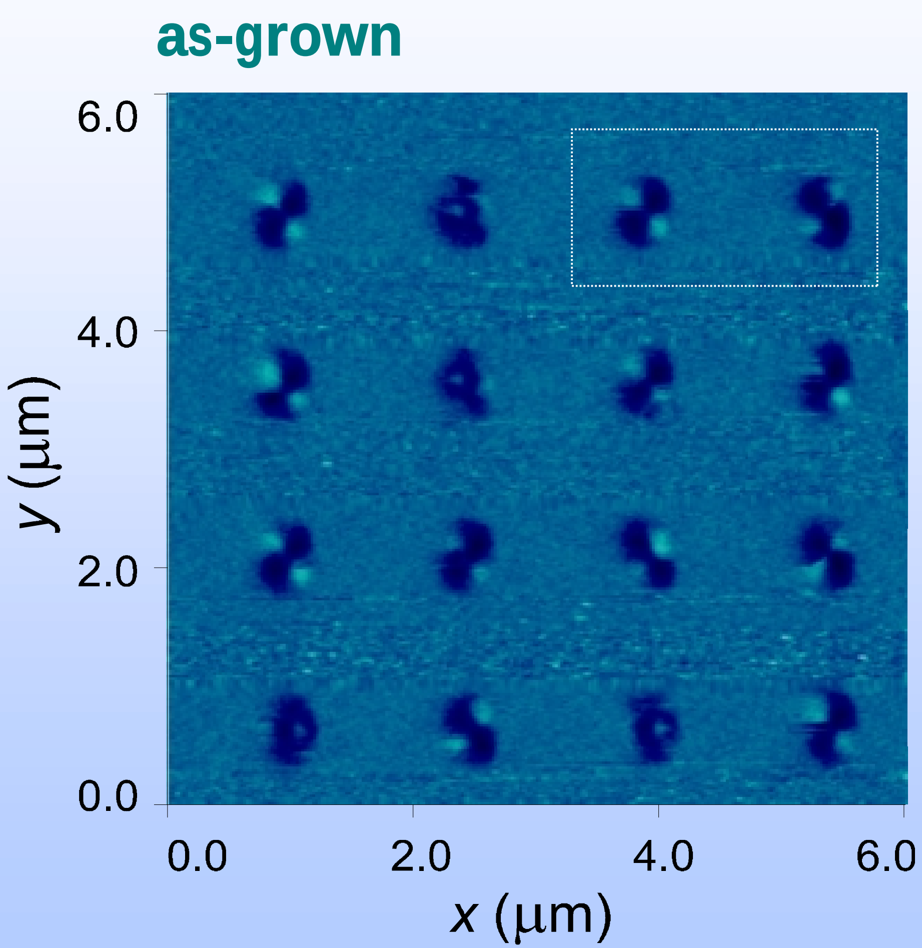
Determination of anisotropy and hysteresis

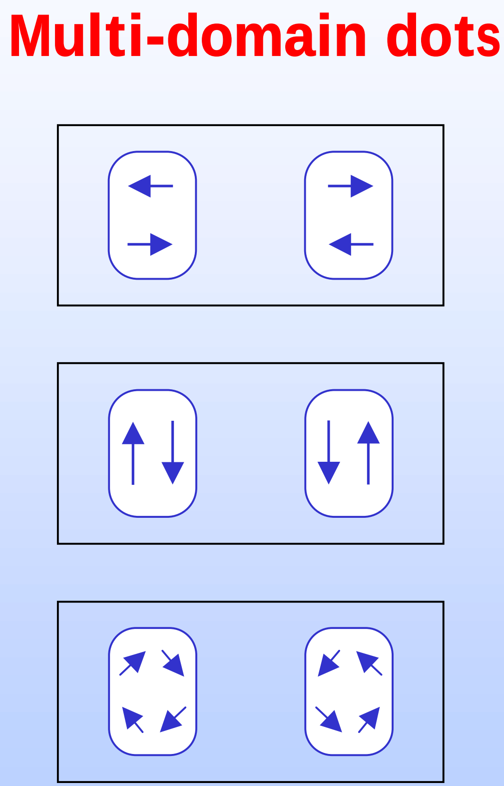




- Magnetization parallel to plane of the dots
- Easy axis determined by shape anisotropy

Magnetic force microscopy on Co dots (virgin state)

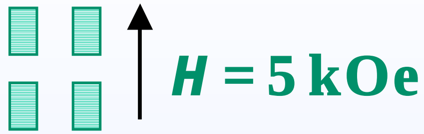


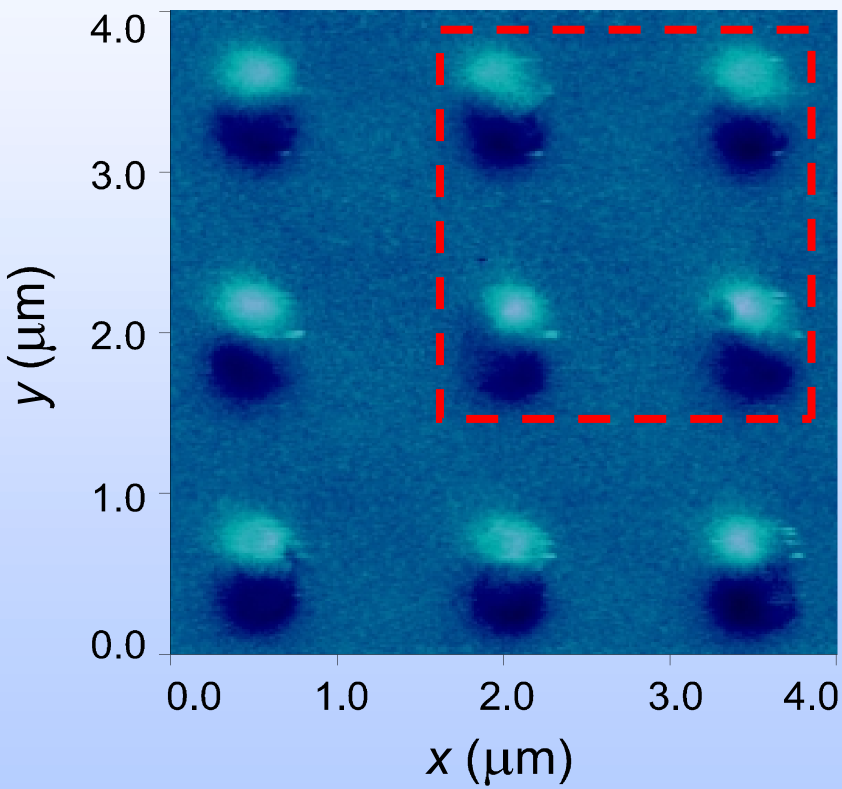


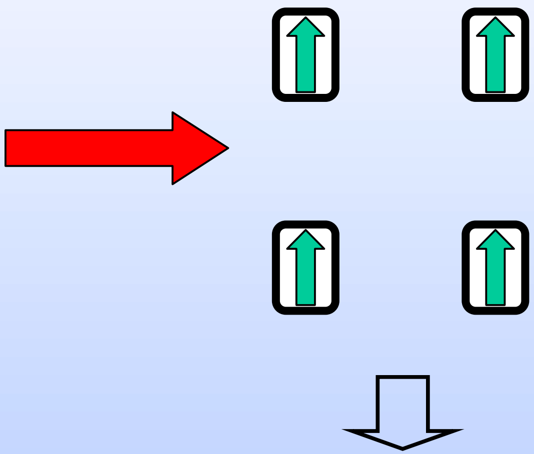
M. Van Bael et al. PRB **59** (1999)

Magnetic force microscopy on Co dots (after saturation)

Remanent state (H = 0) after saturation



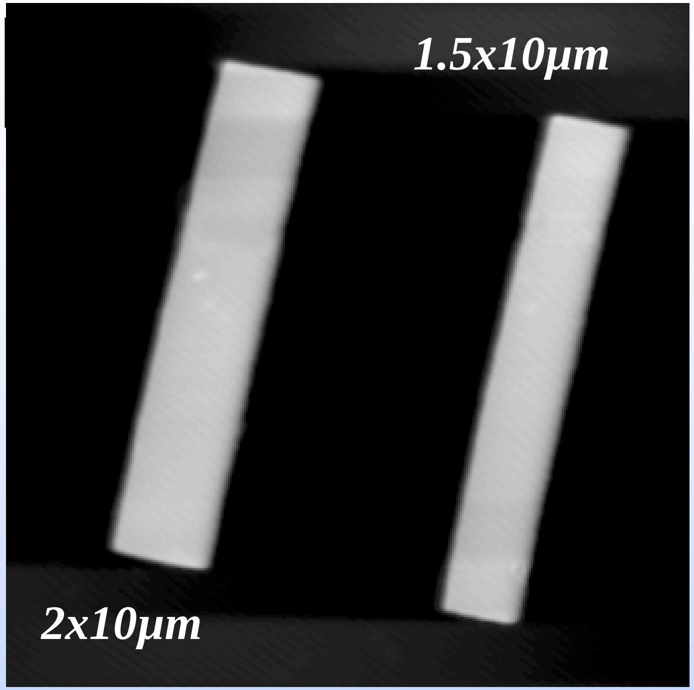




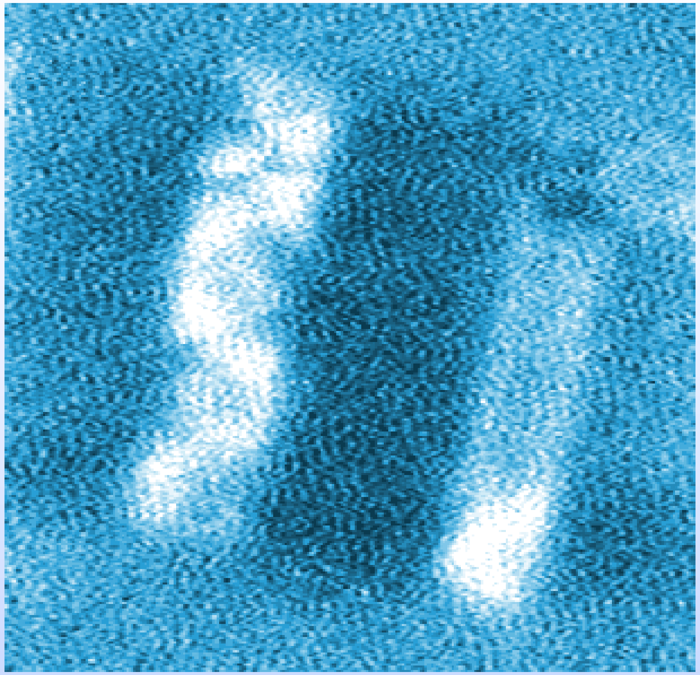
single domain dots

magnetisation // direction of saturating field

MFM on Co dots: influence of aspect ratio



Topography



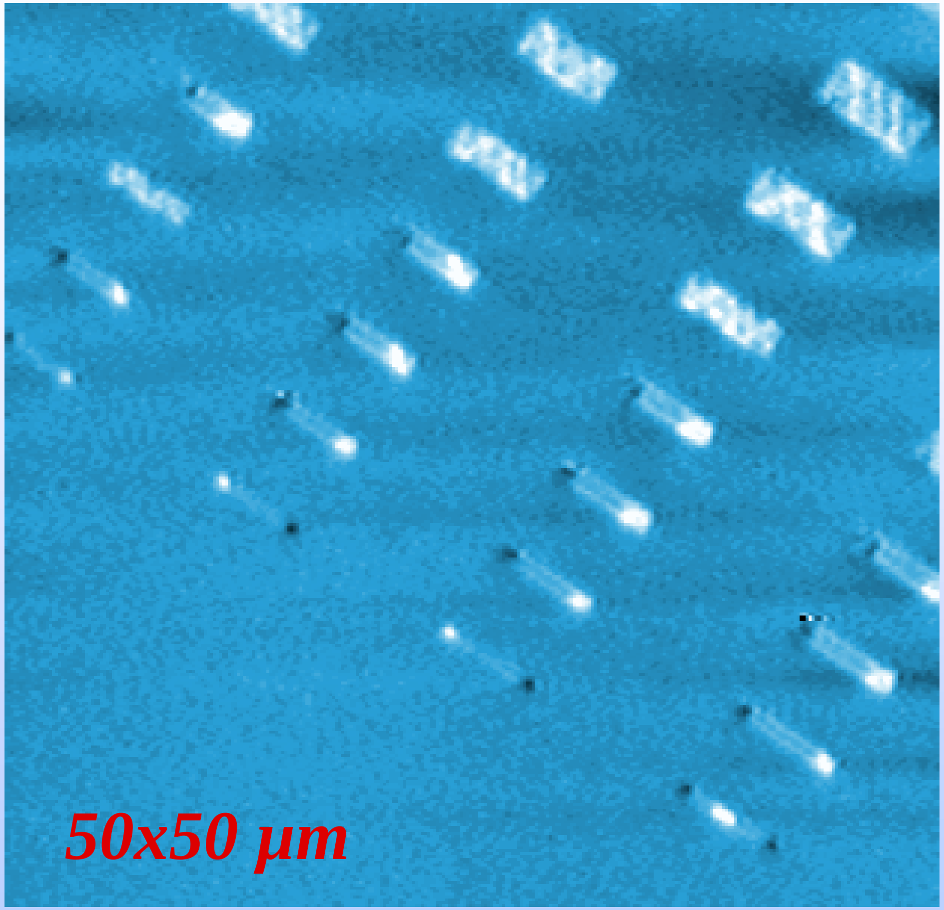
MFM

Transition from single domain to multidomain

by varying the 'aspect ratio'

Not always evident to extract magnetization directions

MFM on Co dots: influence of aspect ratio



MFM image of Co (35 nm) structures with different aspect ratio

Length between 0.25 - 10µm

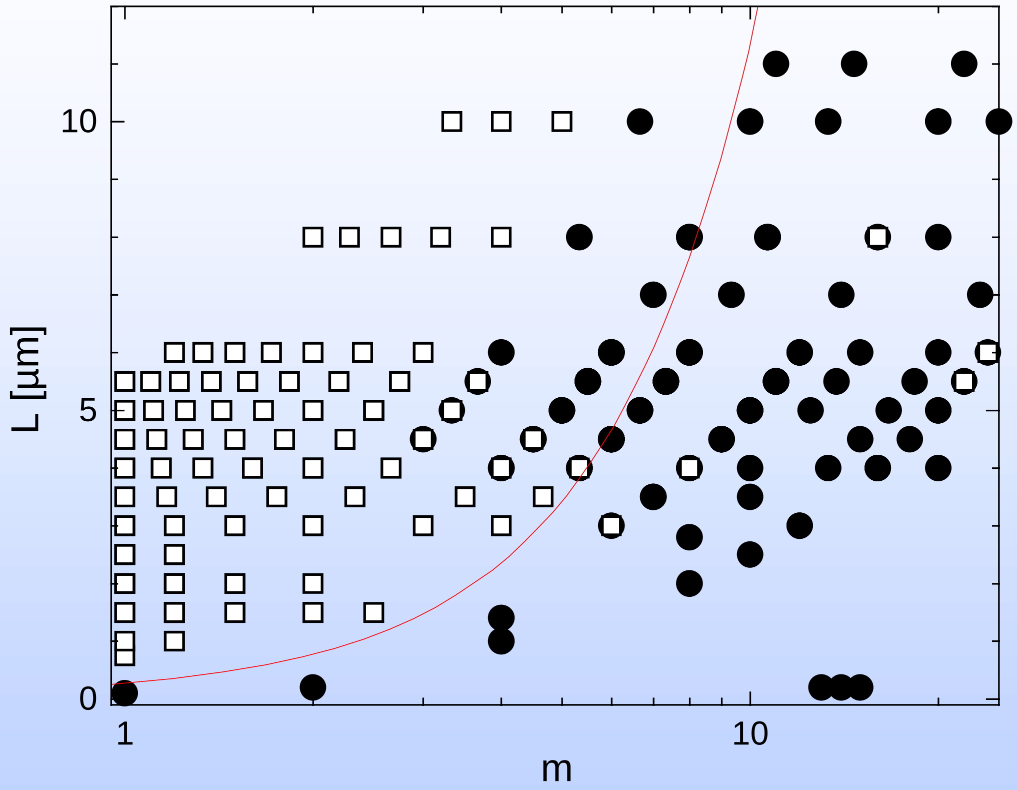
Width between 0.25 - 5.5 µm

Aspect ratio 1 - 40

E. Seynaeve et al., J. Appl. Phys. 89, 531 (2001)

'Statistics' of the experiment are enhanced by looking at many dots, all on the same wafer. Systematic behaviour ?

MFM on Co dots: influence of aspect ratio



L: length

m: aspect ratio

□ multidomain

● single domain

Theory of Aharoni:

existence of a critical length below which the islands become single-domain (J. Appl. Phys. 63, 5879 (1988))

'Road map' for the magnetic behaviour of Co dots

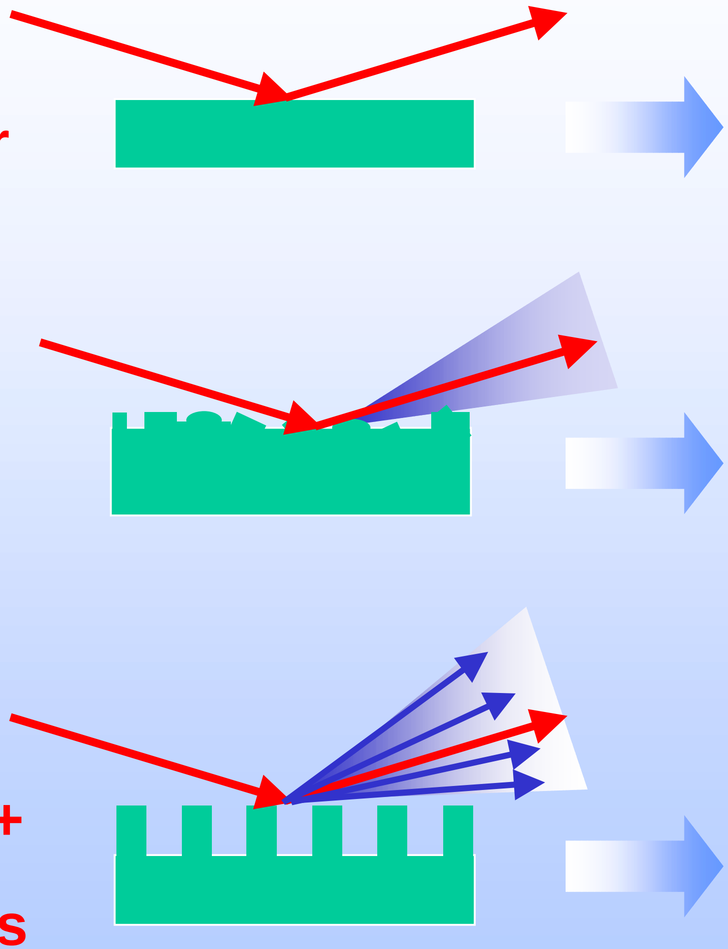
Reflectivity of a film surface

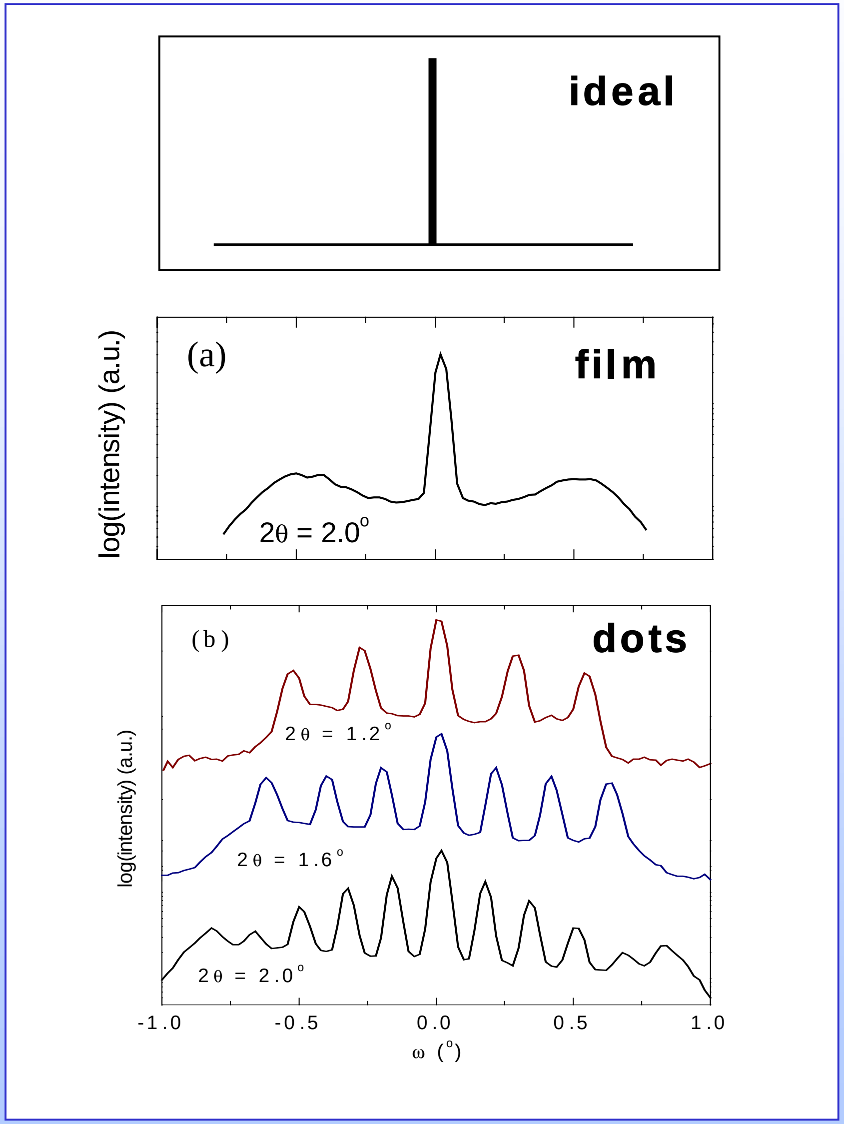
Specular

Diffuse

Diffuse +

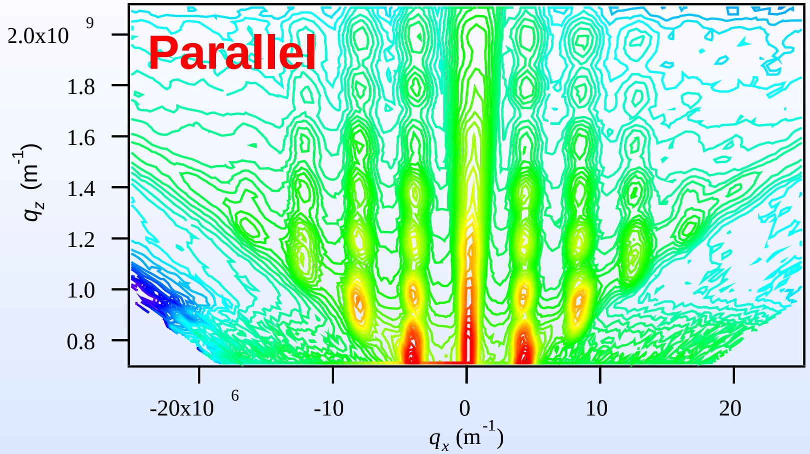
Satellites

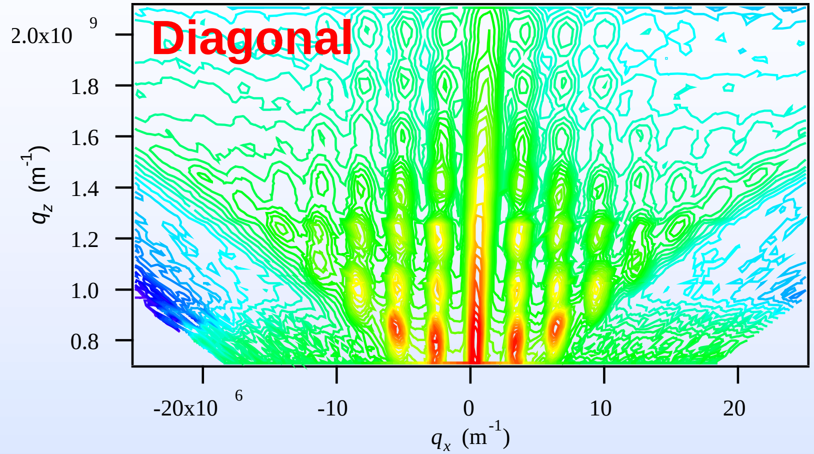




K. Temst et al., J. Appl. Phys. ***87****, 4216 (2000)*

Reflectivity of a structured film surface



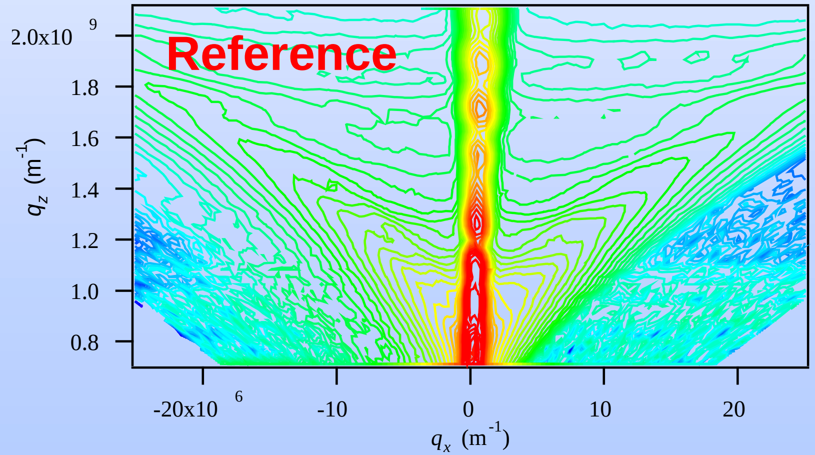


Interpretation:

q_z: vertical layering Au/Co/Au

q_x: lateral dot periodicity

Periodicity and shape uniform over large area of dot lattice.

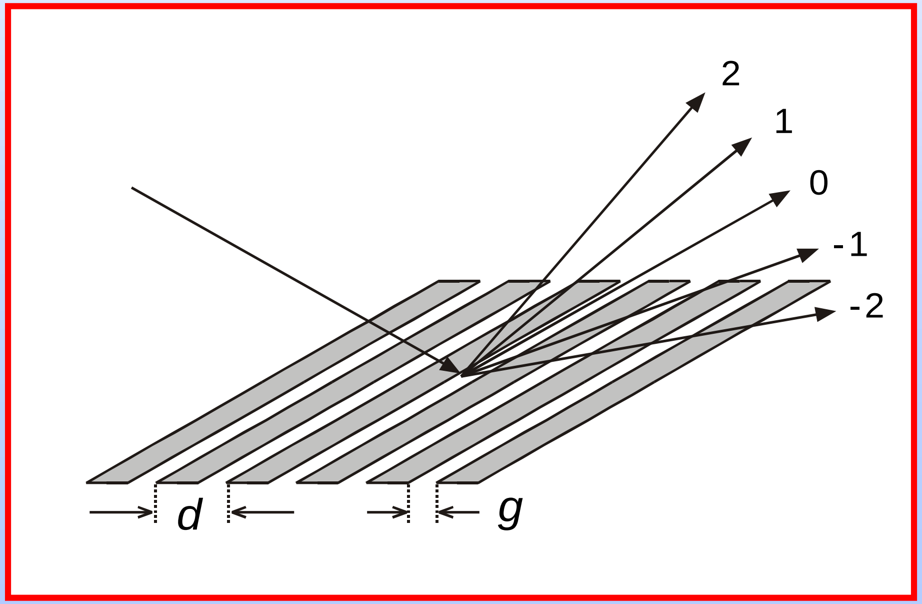


K. Temst et al., J. Appl. Phys. ***87****, 4216 (2000)*

Reflectivity of a structured film surface: simulations

Use kinematical diffraction model (Morrison, 1993)

$$I = I_{Au/Co/Au} \times \left(\frac{\sin(gq_x/2)}{gq_x/2} \right)^2 \times \left(\frac{\sin(Ndq_x/2)}{\sin(dq_x/2)} \right)^2$$

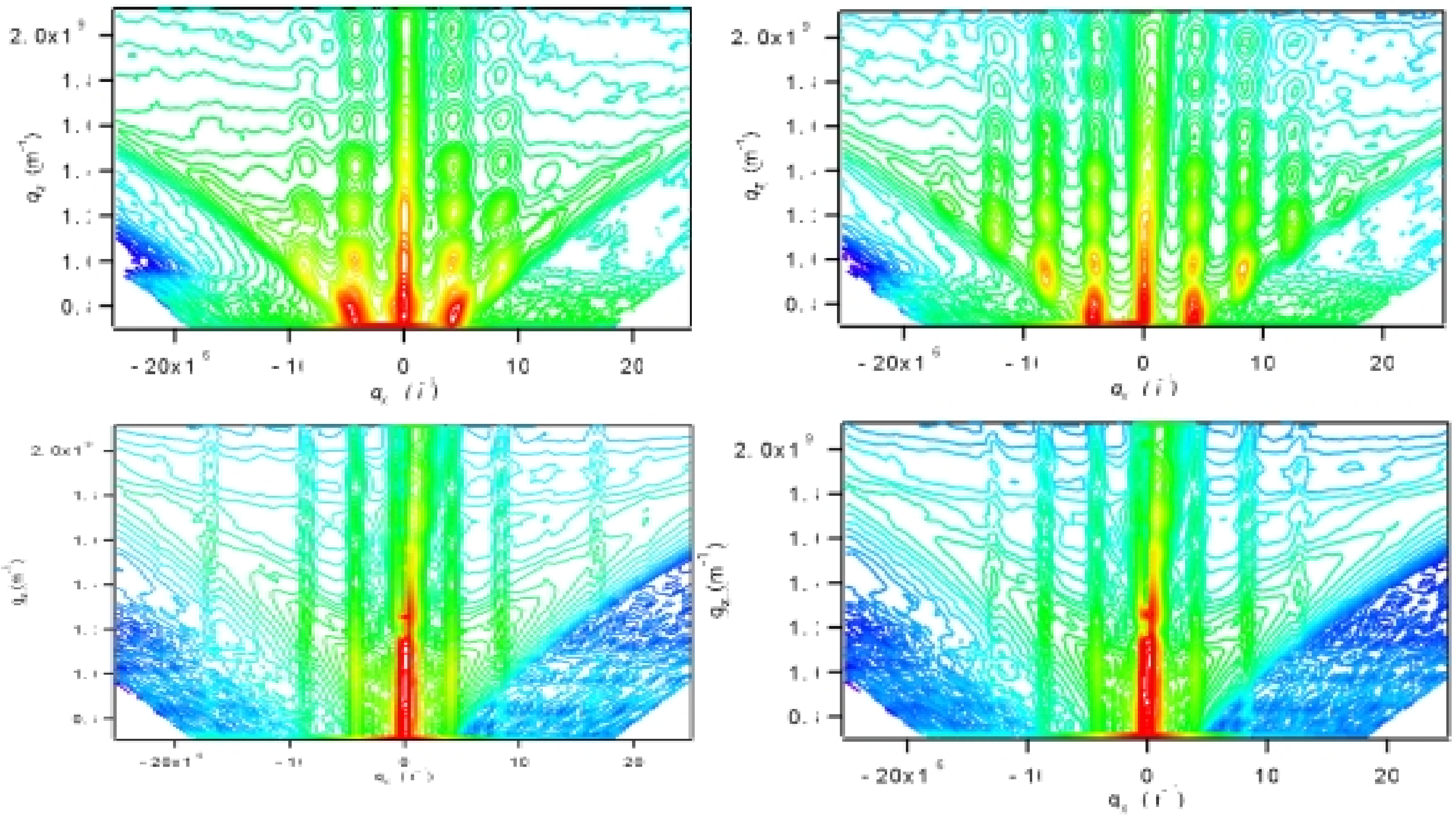


Diffraction envelope:

reflects intensity distribution from single grating element

Reflectivity of a structured film surface: simulations

Use kinematical diffraction model



Detailed characterization of vertical and lateral structure

POLARIZED NEUTRON REFLECTOMETRY (PNR)

Aim: - study neutron reflectivity of structured surfaces

- study magnetic properties of dots (dimensions ~ domain size)

Challenge: off-specular neutron scattering on dots + interpretation

Polarized neutron reflectometry:

- **provides information about structure and magnetism**
- **allows determination of magnetization direction**
- **provides a magnetic 'depth profile'**

This is complementary to:

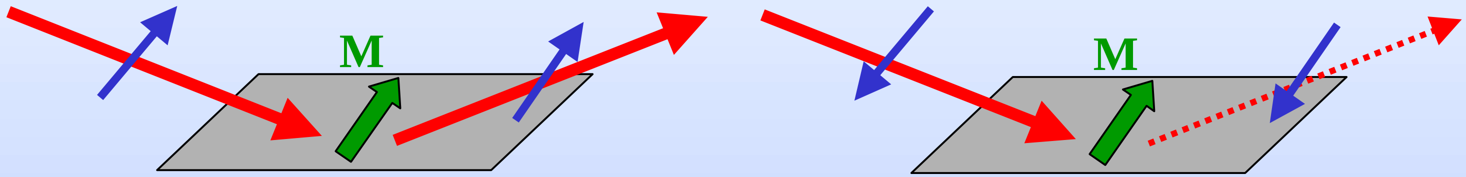
- **MFM (no depth resolution, no magnetization direction)**
- **SQUID (substrate contribution, no depth information)**

NEUTRON REFLECTIVITY

Neutron beam can be polarized, i.e. spin up or down

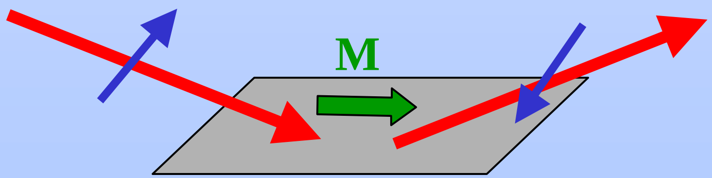
If neutron spin parallel to sample magnetization:

spin is conserved (NSF, non-spin-flip process)



If neutron spin perpendicular to sample magnetization

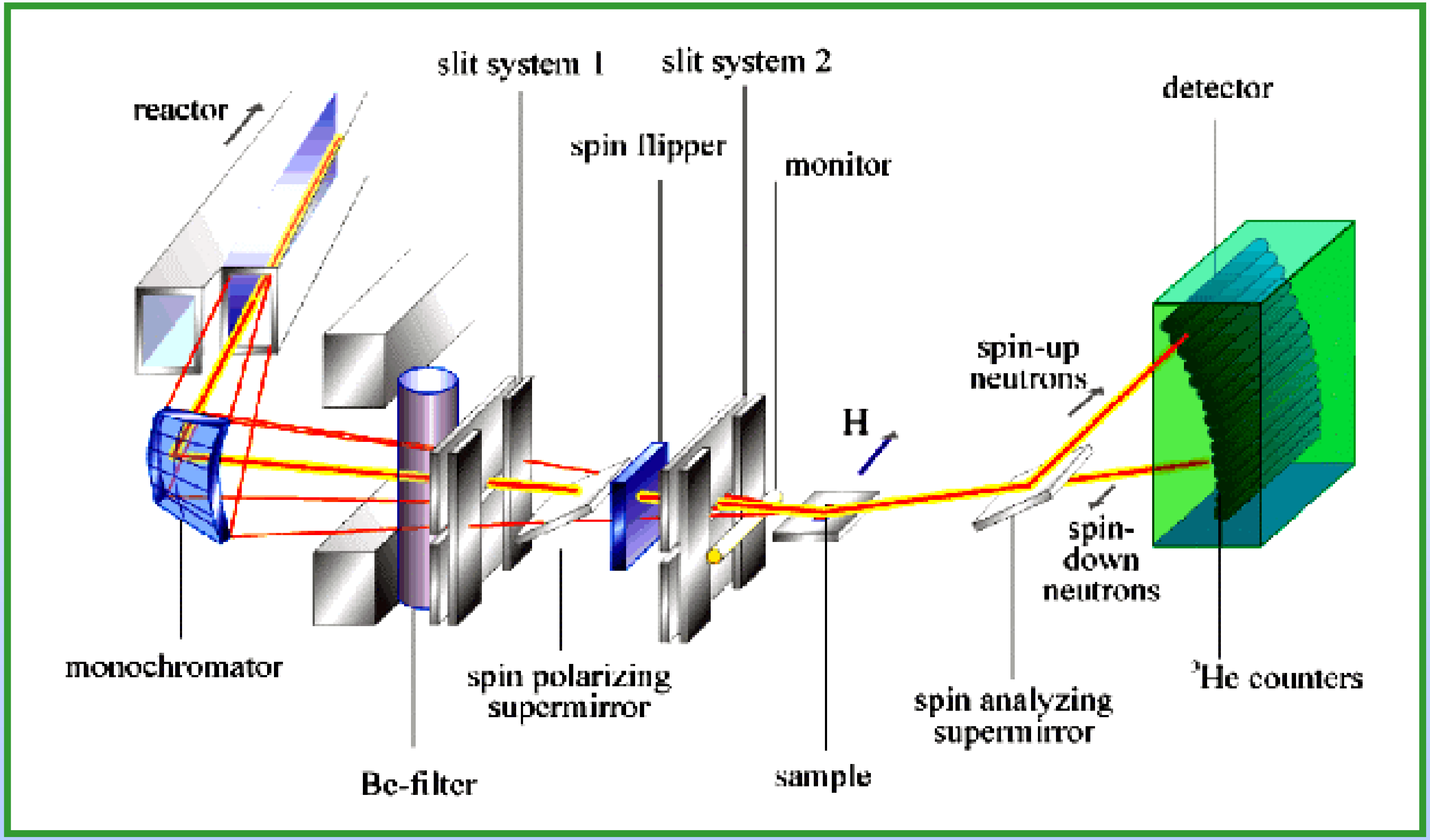
spin is reversed (SF, spin-flip process)



Spin analysis: magnetization directions.

NEUTRON REFLECTIVITY: experimental

V6 reflectometer, HMI Berlin, cold neutrons

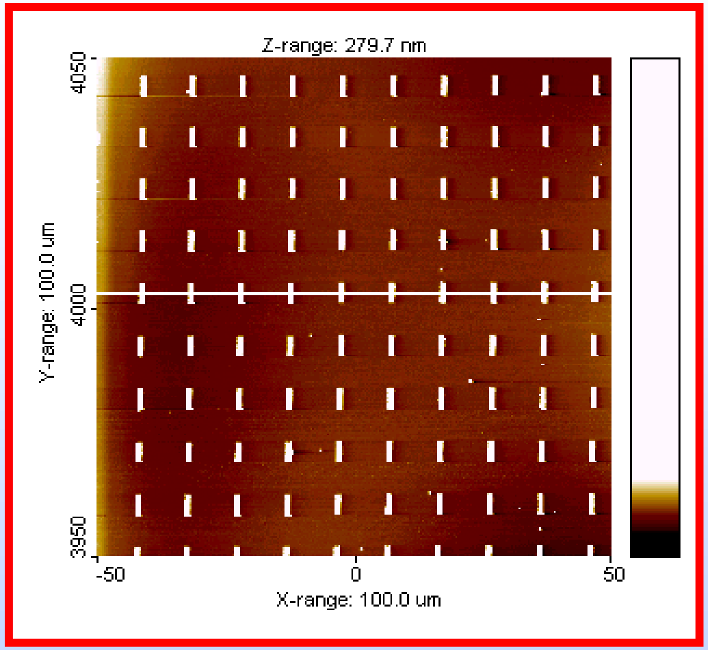


Polarization

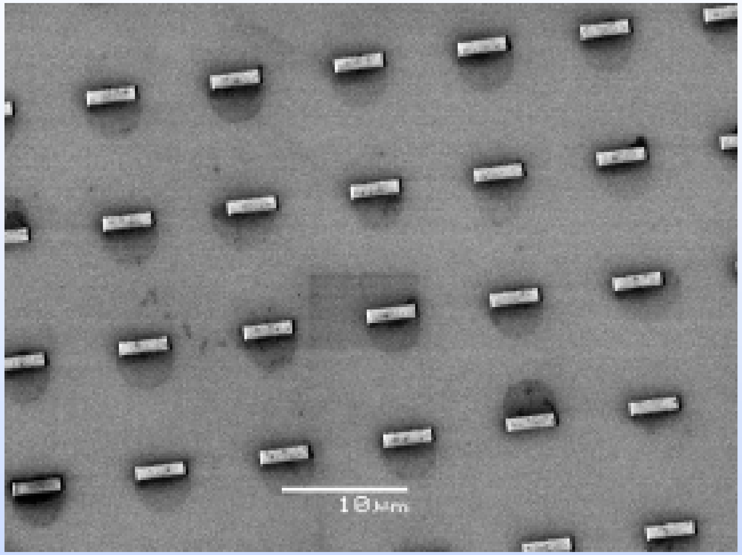
Analysis

Interaction

NON-SPECULAR REFLECTIVITY: shape anisotropy



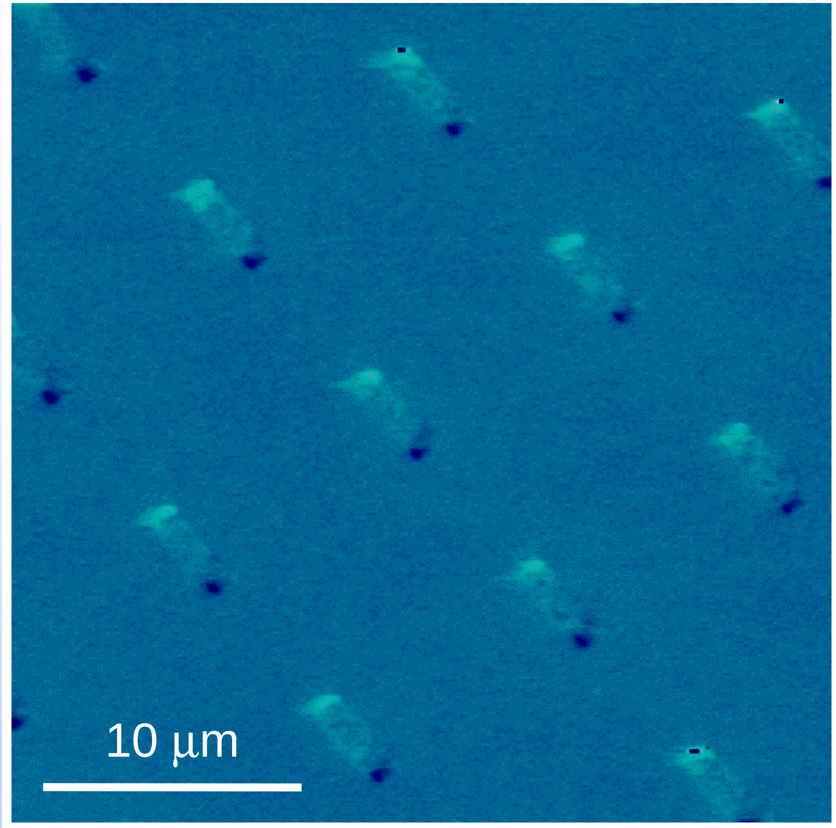
AFM results



SEM results

- electron beam lithography in Leica machine (IMEC)
- deposition of Au/Co/Au trilayer in MBE
- patterned area 4 cm²

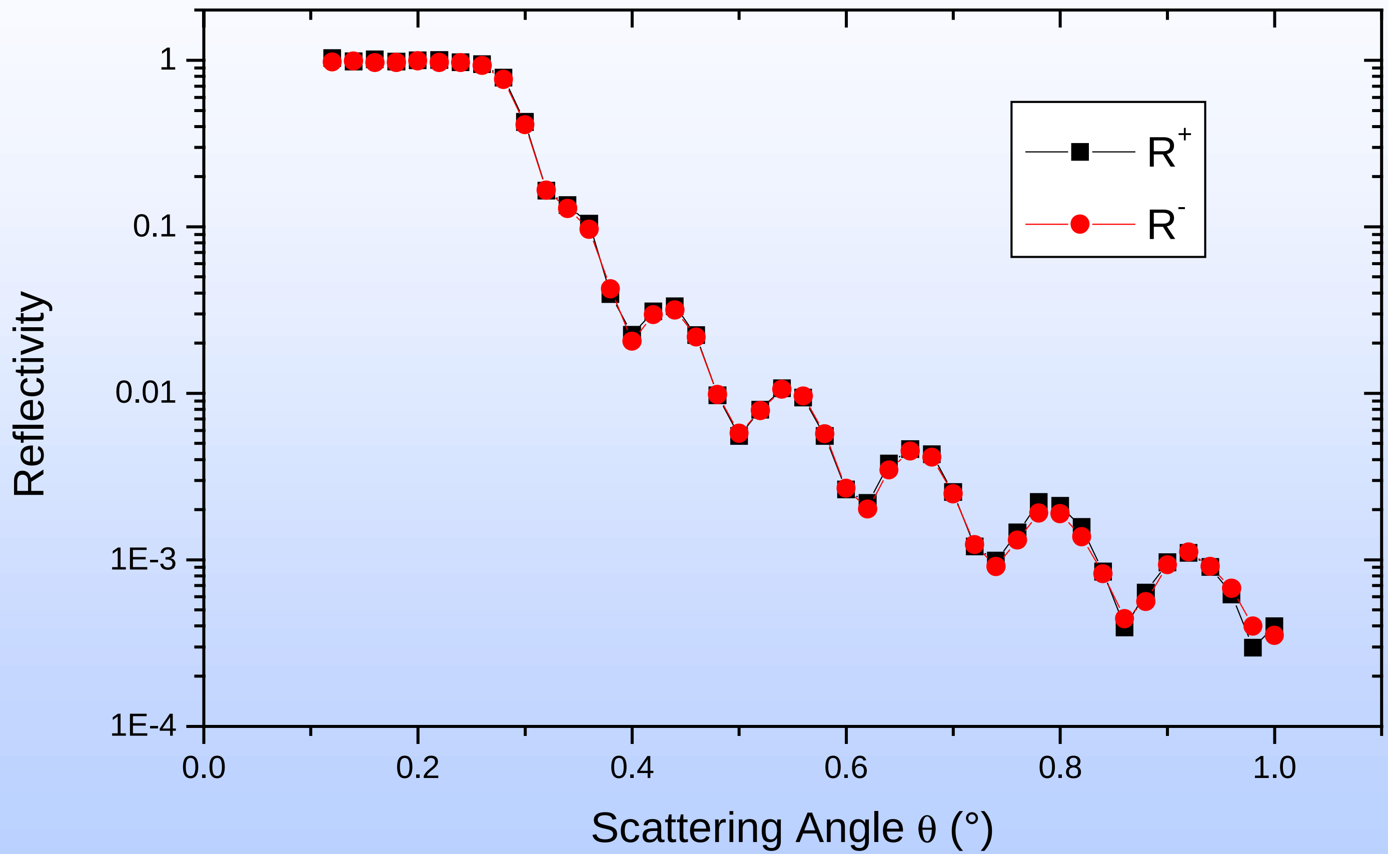
Shape anisotropy: MFM results



- clear dark/bright contrast in MFM image
- indicates a single-domain state after saturation
- same result over macroscopically large area

SPECULAR REFLECTIVITY

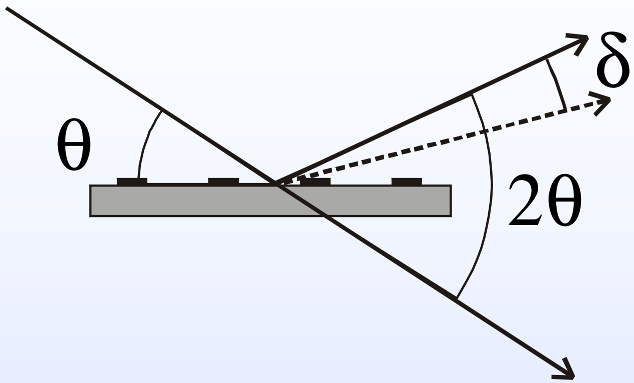
Sample in saturated state (H=2400 G)

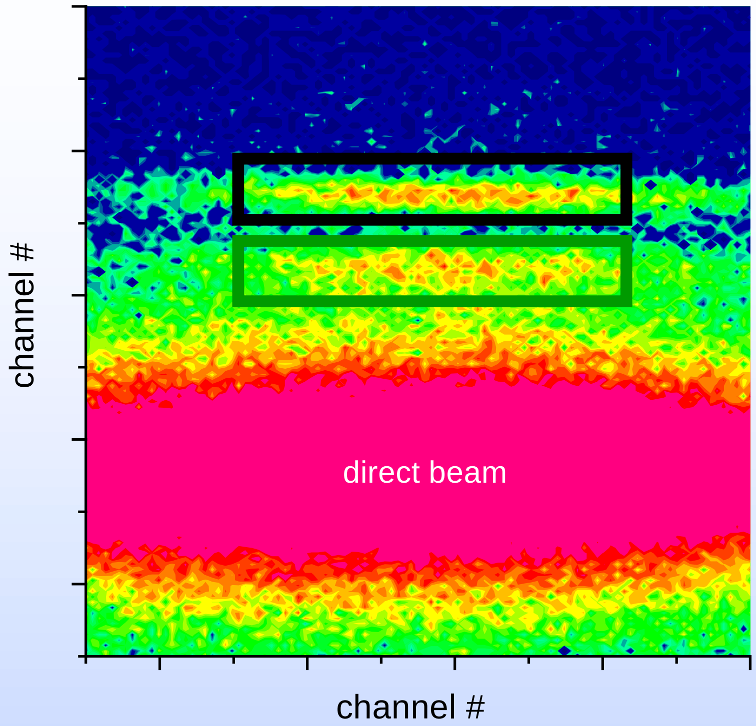


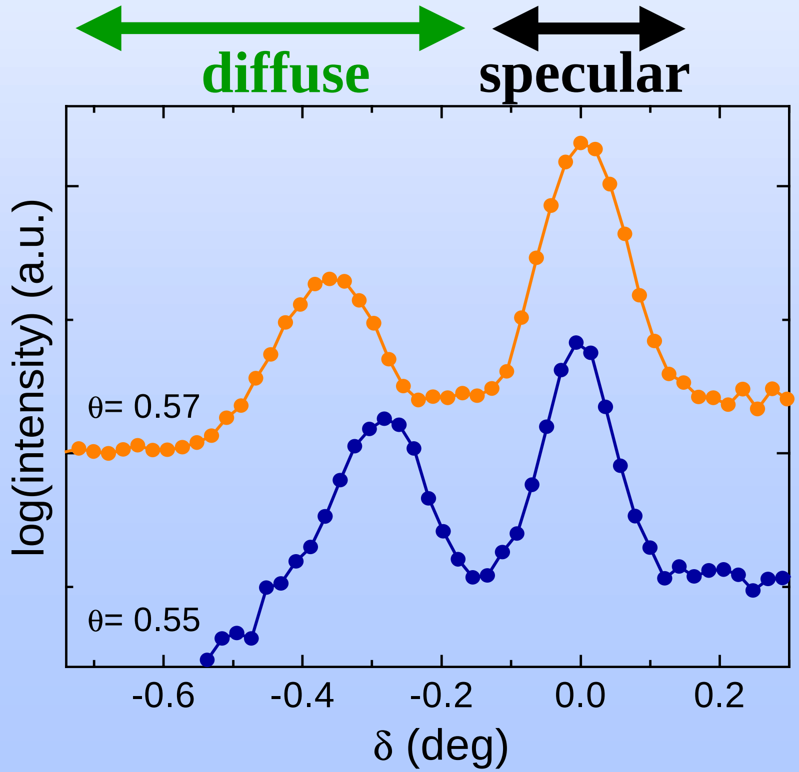
No clear splitting between R^+ and R^-

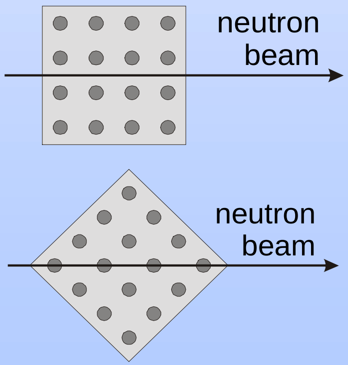
Specular reflectivity dominated by non-magnetic substrate

2-D NEUTRON DETECTION









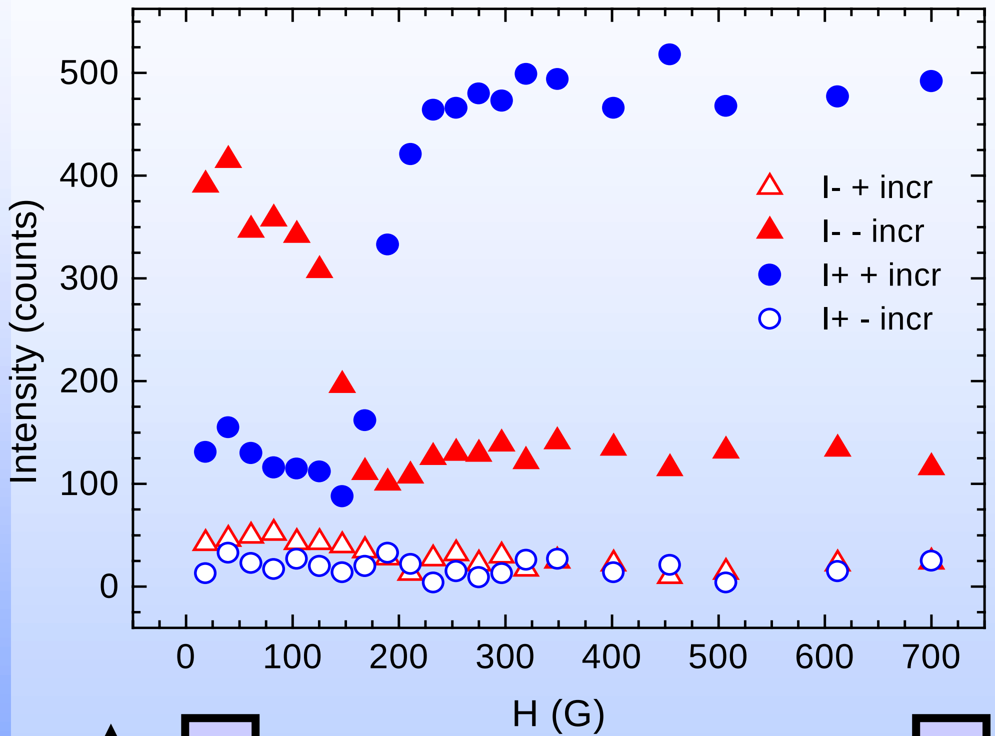
Observation of lateral periodic dot structure using neutron reflectivity

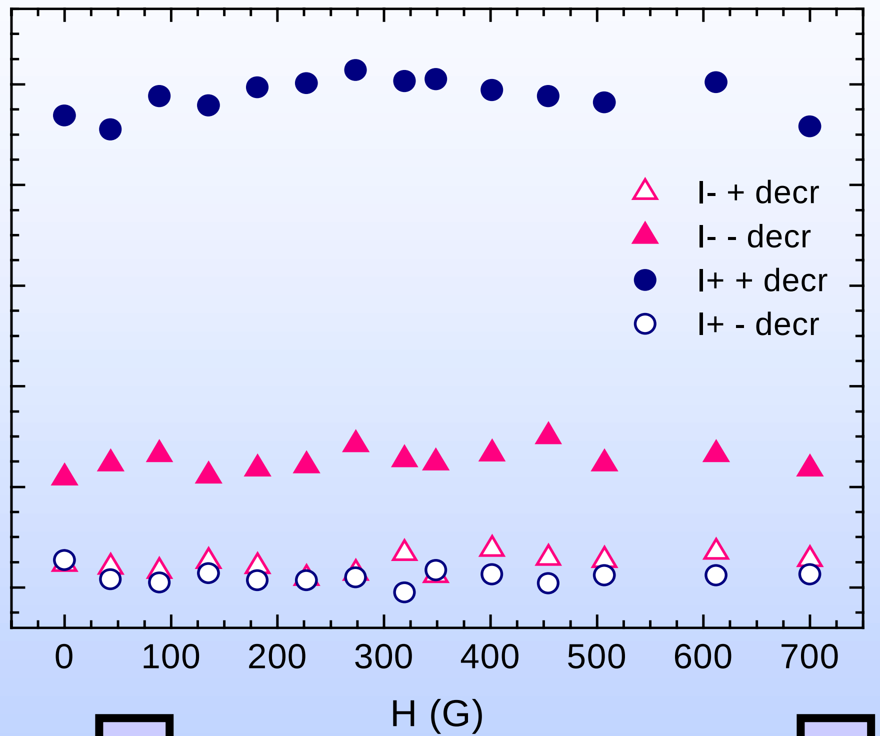
K. Temst et al., Appl. Phys. Lett. ***79****, 991(2001)*

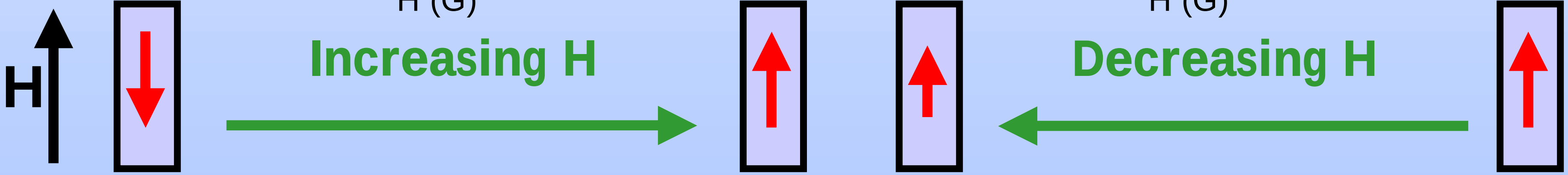
Fermon et al. (1999); Toperverg et al. (2000)

NON-SPECULAR REFLECTIVITY: shape anisotropy

Sample in remanent state after saturation in negative field



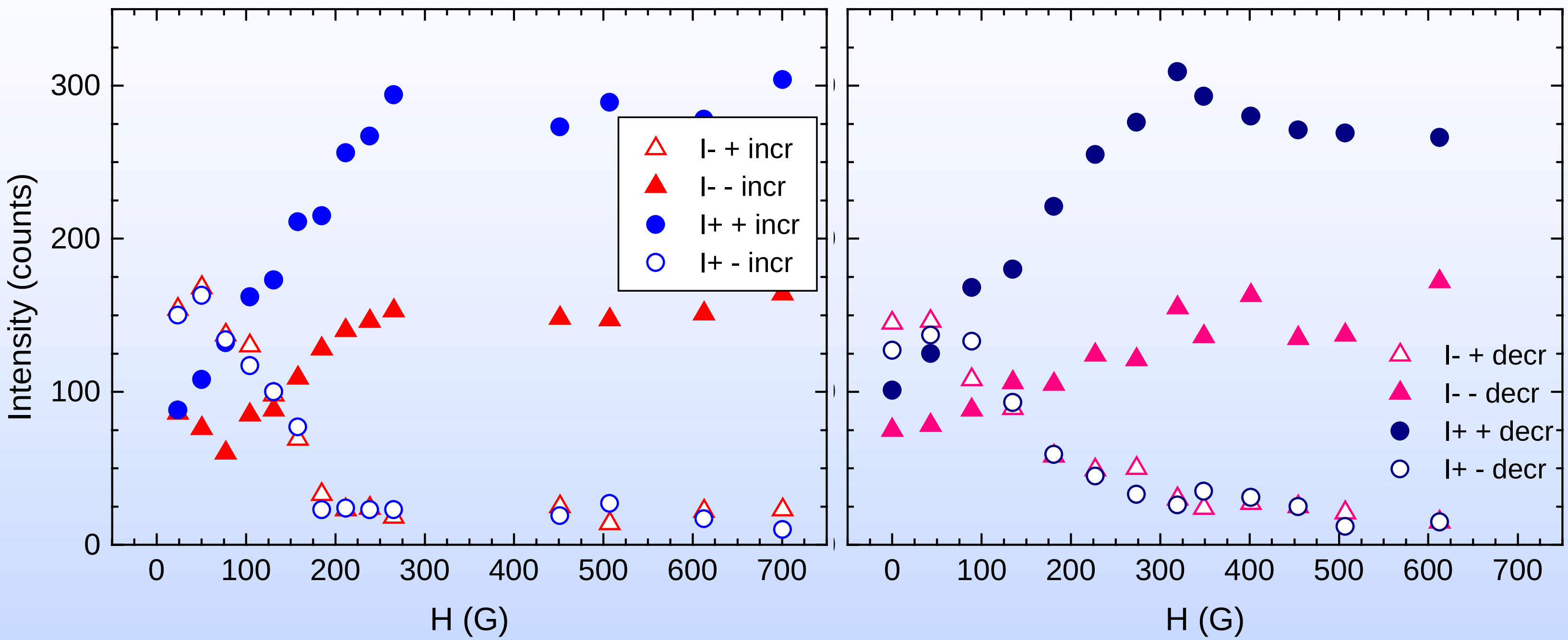


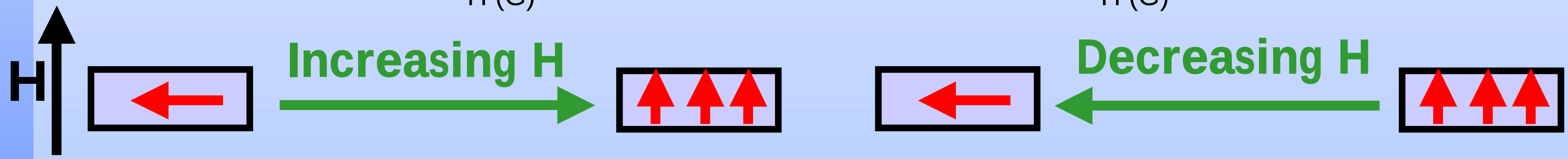


Little SF scattering: magnetizations (anti)parallel to neutron spin.

Splitting between I^{++} and I^{--} maximal in saturation.

NON-SPECULAR REFLECTIVITY: shape anisotropy

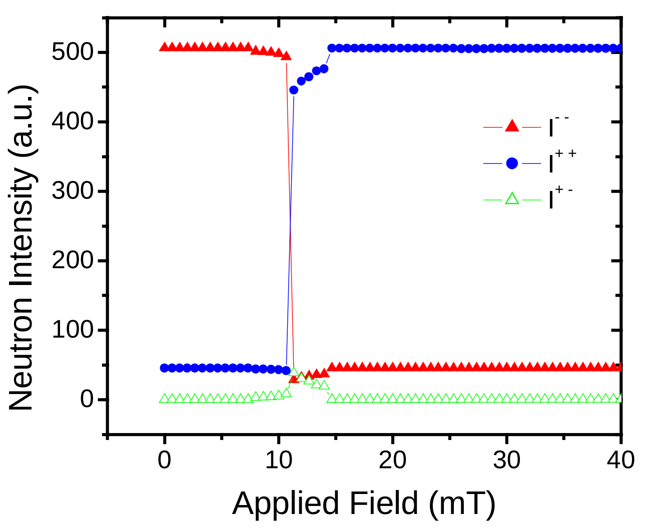




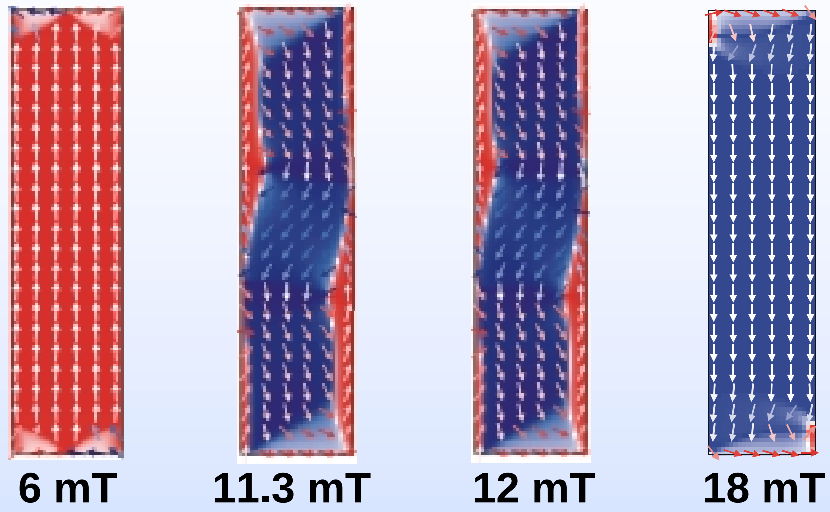
SF scattering: magnetization perpendicular to neutron spin.

I^{++} increases: magnetization gets parallel to neutron spin.

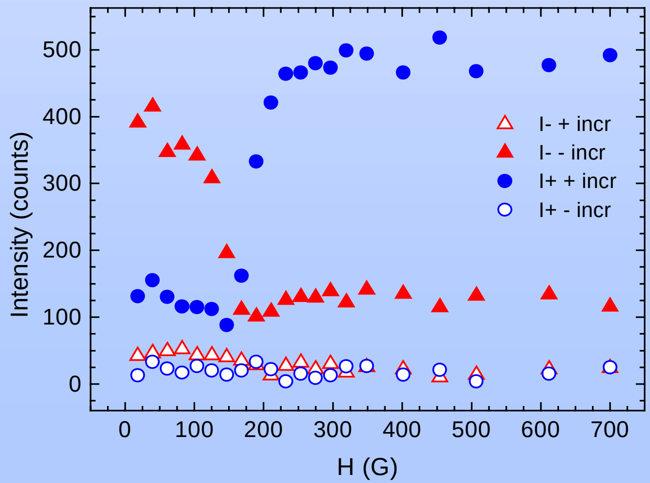
NON-SPECULAR REFLECTIVITY: simulation



kinematic intensity calculation



Micromagnetics simulation of reversal in single dot
OOMMF Framework, NIST, Gaithersburg, USA



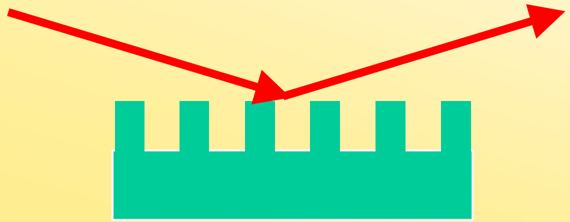
Qualitative agreement OK

K. Temst et al., Appl. Physics A (2001), in press

CONCLUSIONS

Array of magnetic Co dots studied by Polarized Neutron Reflectivity

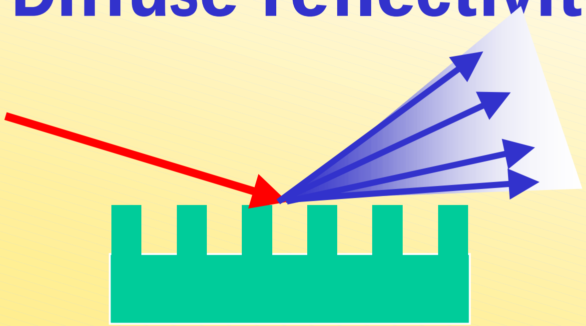
Specular reflectivity



Dominated by substrate.

No magnetic information.

Diffuse reflectivity



Selective information from dots.

Field dependence shows magnetization reversal.