Step induced anisotropy and canting of the magnetization in Fe/Ag multilayers grown on Ag(001)

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Outline

Fe/Ag multilayers grown on

1. atomically flat Ag(001)
2. stepped Ag(001)

What can we learn about

1. Canting of the magnetization
2. Step induced anisotropy

Magnetic Anisotropy

The magnetic moments of the atoms in a magnetic material point in a preferred direction

= breaking of the isotropy
= **MAGNETIC ANISOTROPY**

⇨ the atoms are part of a lattice and therefore the preferred direction of the magnetic moments is related to the lattice structure (spin-orbit interaction)
= *magnetocrystalline anisotropy*

⇨ the direction of magnetization is dependent on the macroscopic shape of the magnetic material
= *shape anisotropy*

⇨ the symmetry of the lattice is broken at a surface or interface
= *surface anisotropy*

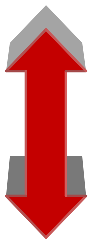
Surface Anisotropy

Surface anisotropy is an important factor governing the anisotropy in films and multilayers

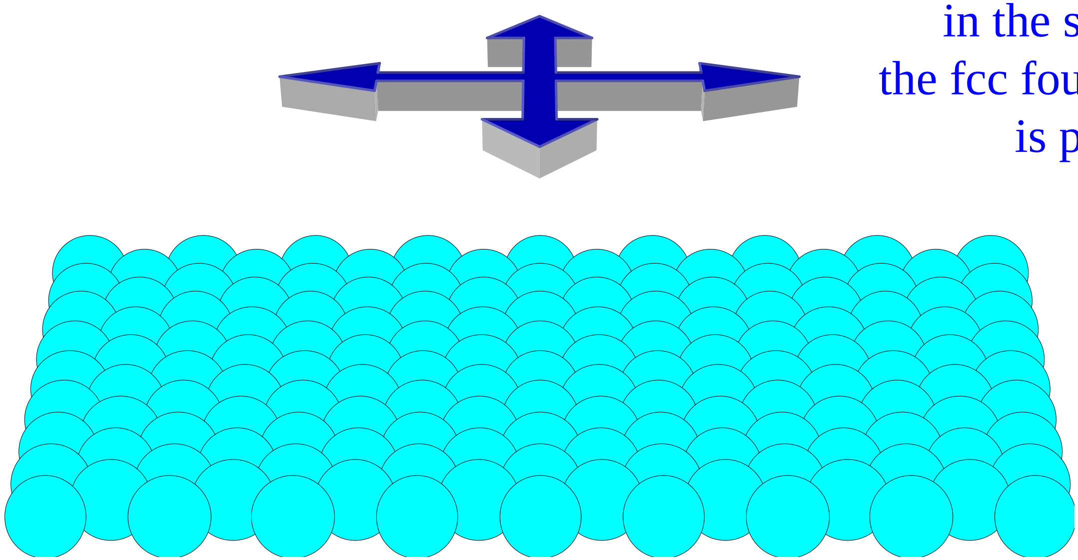
⇨ there is a large fraction of atoms at an interface

(001) surface of fcc lattice:

the symmetry
out of the plane
is broken

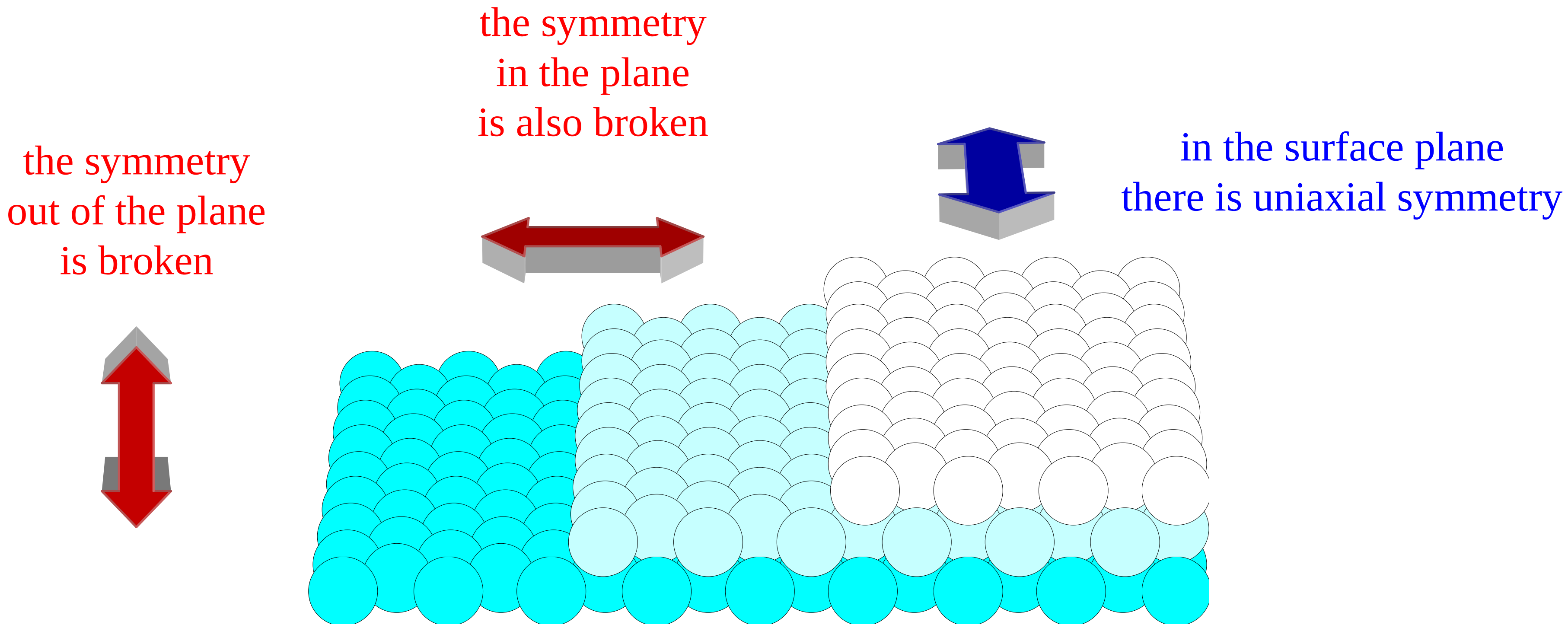


in the surface plane
the fcc fourfold symmetry
is preserved



Step induced anisotropy

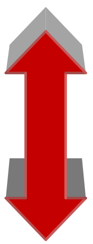
stepped (001) surface of fcc lattice:

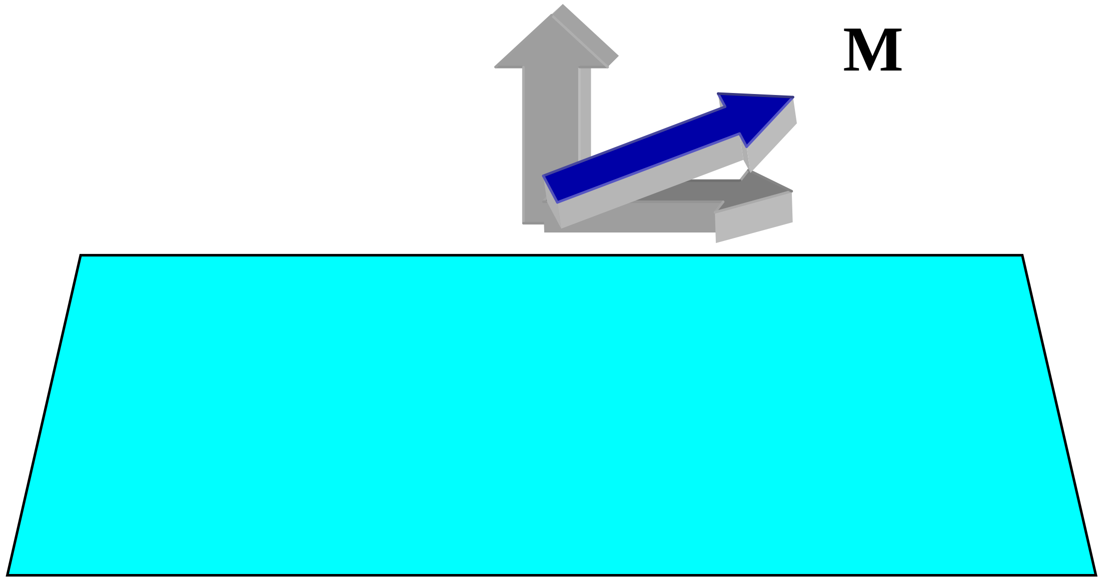


Canting of the magnetization

When the angle between direction of the magnetization of a thin film and the surface normal is not 0° (out-of-plane) or 90° (in-plane), the magnetization is in a **CANTED STATE**.

the symmetry
out of the plane
is broken





Fe/Ag multilayers on flat Ag(001)

1. the Ag(001) substrate
2. the Fe/Ag multilayer
3. canting of the magnetization:

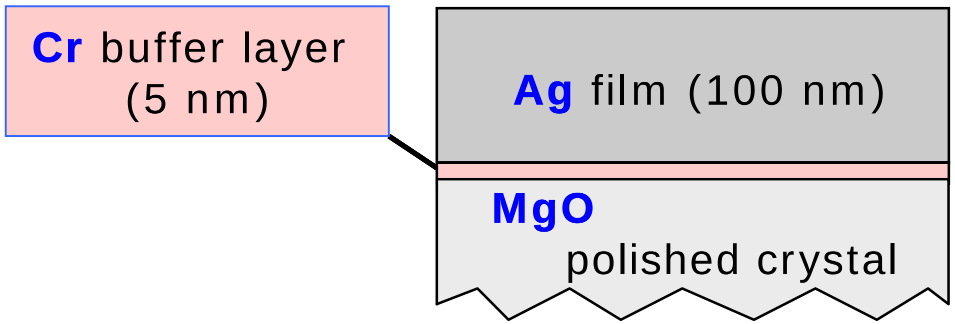
   CEMS (conversion elektron Mössbauer spectroscopy)
   VSM (vibrating sample magnetometry)
   SMR (synchrotron Mössbauer reflectometry)

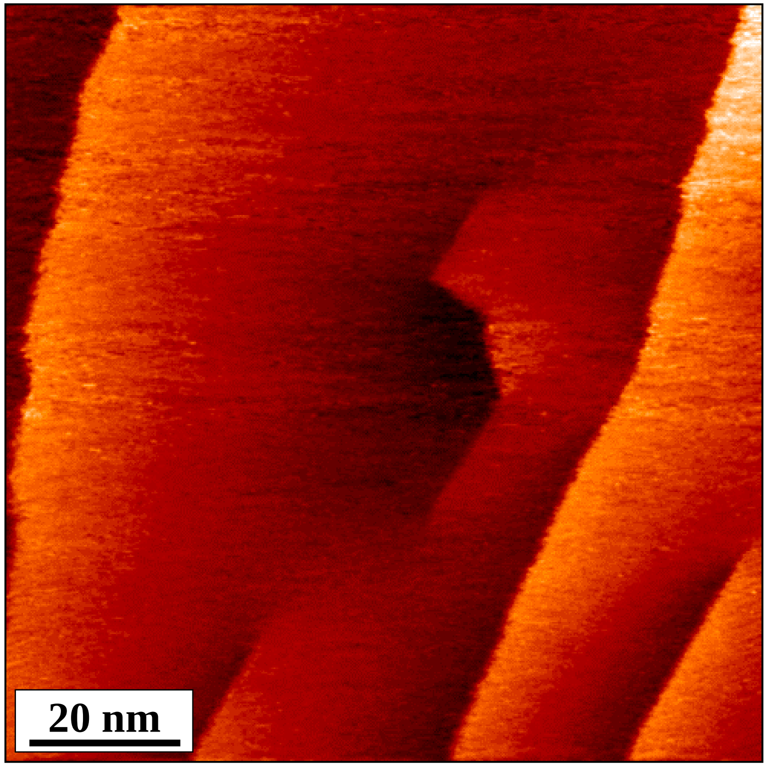
4. structure of the interface investigated with STM

The Ag(001) substrate

Preparation:

- ⇨ MgO(001) polished crystal
- ⇨ Cr buffer layer grown at 450 K
- ⇨ Ag film grown at 1.0 Å/s at RT
- ⇨ annealed at 475 K





- ⇨ large terraces > 20 nm wide
- ⇨ mono-atomic steps

Fe/Ag multilayers on flat Ag(001)

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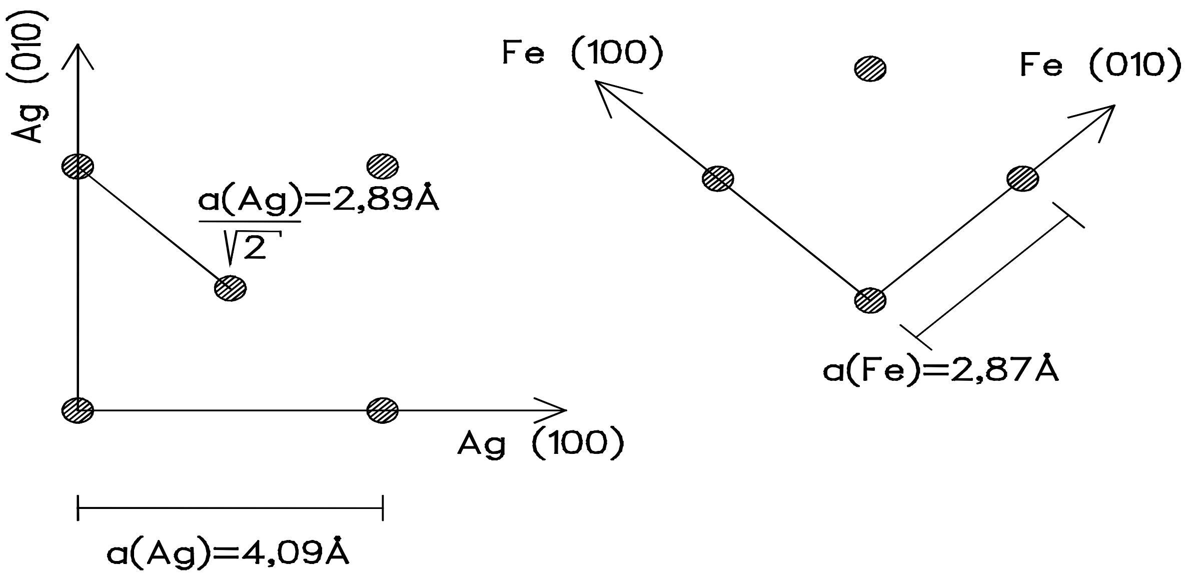
$[^{57}Fe(15ML)/Ag(4 \rightarrow 6ML)]_{16}$

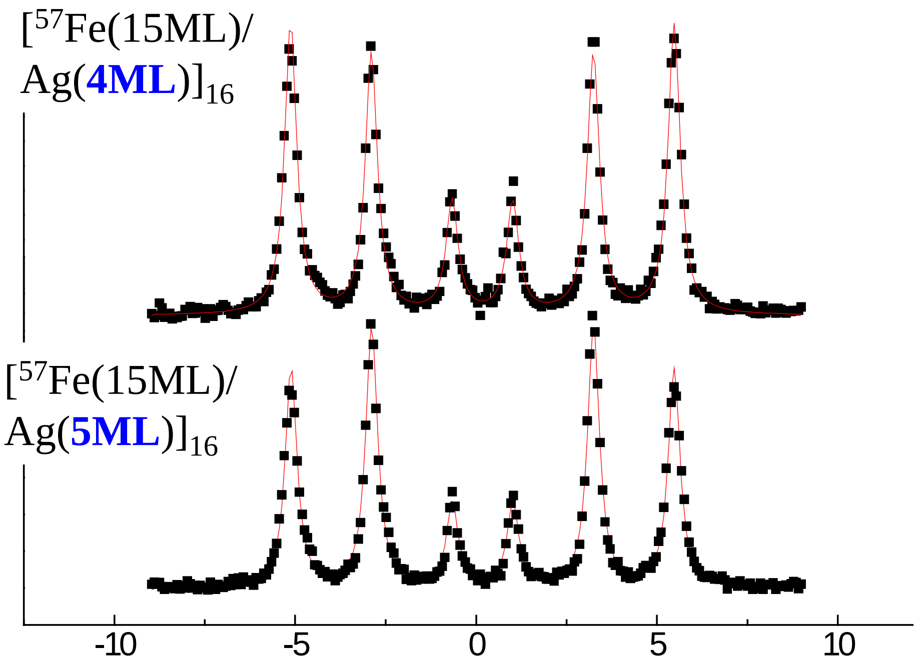
^{57}Fe : Knudsen cell @ 1300°C, 0.07ML/s
Ag : Knudsen cell @ 990°C, 0.5ML/s

base pressure : 1×10^{-10} Torr



0.9 % lattice mismatch
fcc Ag (a=4.09Å)
bcc Fe(a=2.87Å)

Conversion elektron Mössbauer spectroscopy



the ratio of the line intensities is given by

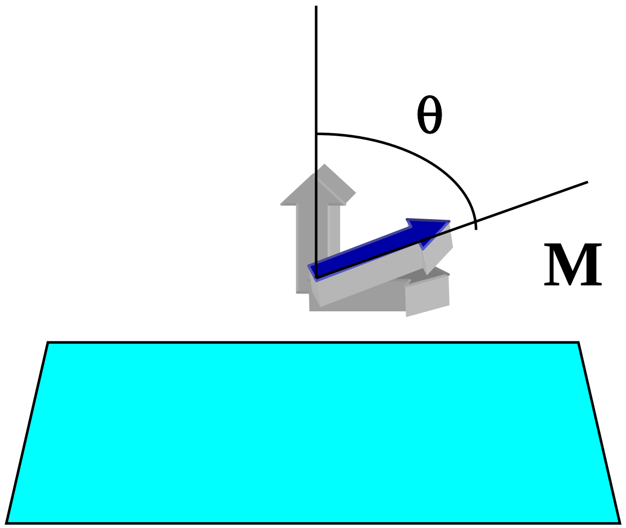
3:x:1:1:x:3

$$x = 4\sin^2\theta/(1+\cos^2\theta)$$

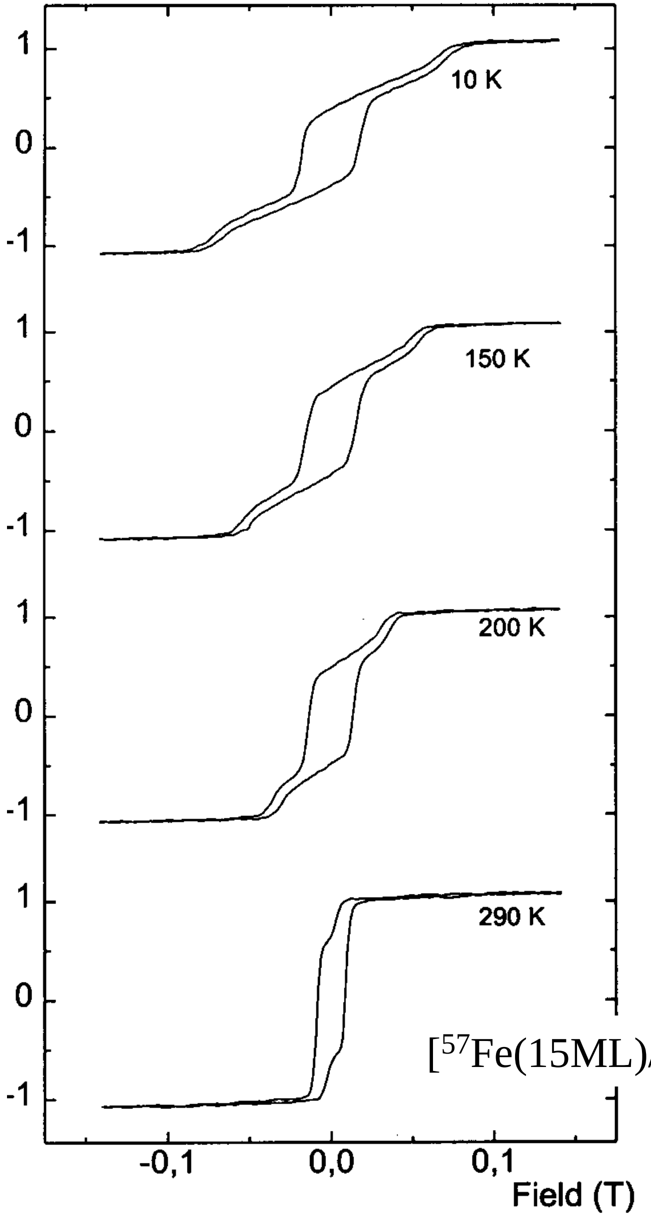
θ the angle between the incident γ-rays and the direction of the magnetization (in our case the γ-rays are perpendicular to the sample surface)

θ = 62° at 290 K for 15 ML Fe and 4ML Ag spacer
θ = 90° at 290 K for 15 ML Fe and 5ML Ag spacer

The orientation of the Fe magnetization can be altered from a canted to an in plane orientation by increasing the Ag layer thickness



Vibrating sample magnetometry



$[^{57}Fe(15ML)/Ag(\mathbf{4ML})]_{16}$

1. At 290 K $M_r/M_s<1$

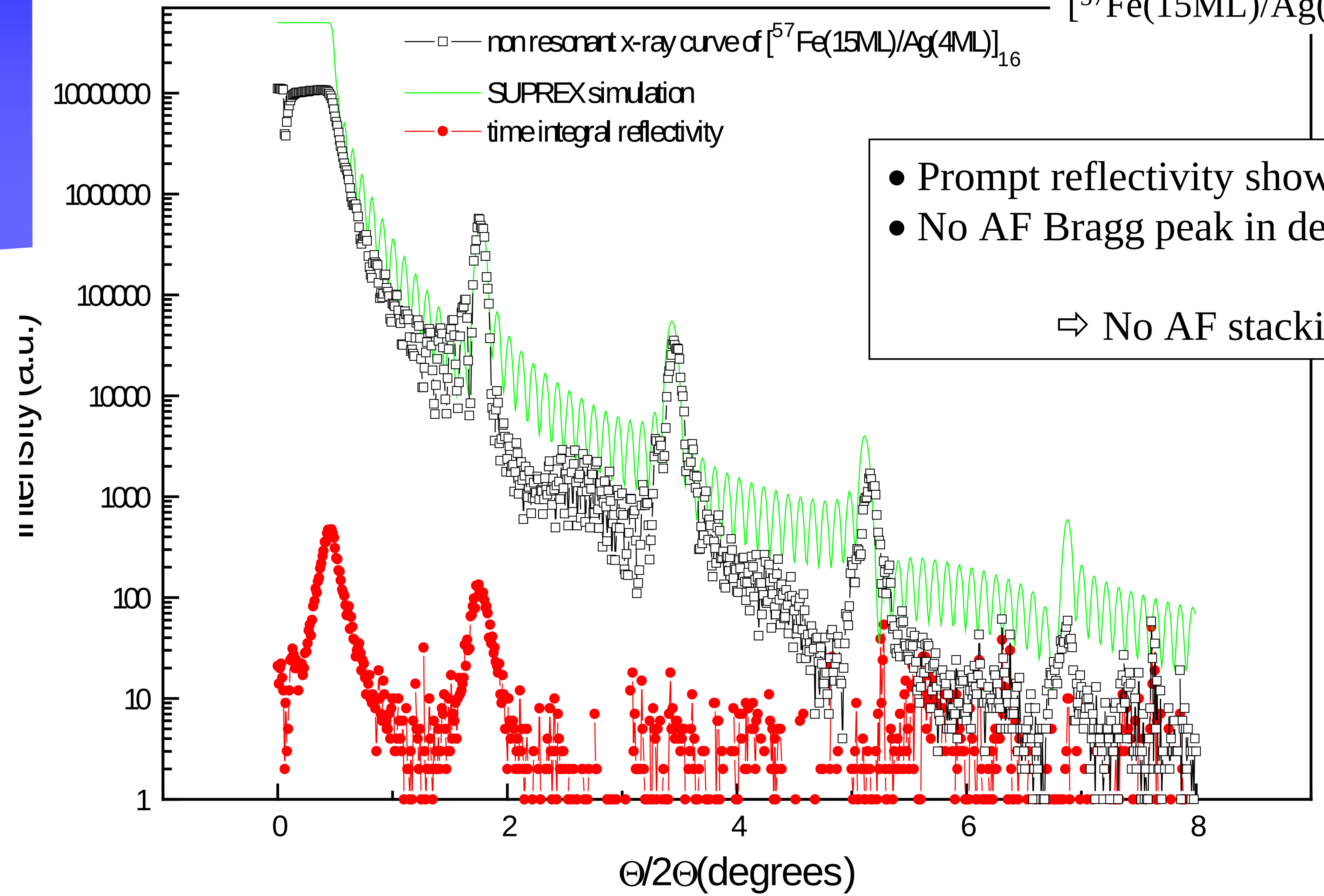
   in agreement with $\theta \neq 90°$ as observed with CEMS

2. With decreasing temperature : $M_r/M_s \downarrow$

   a) uniaxial anisotropy ?
   not observed with VSM : 4-fold
   b) AF coupling ?
   c) Change of the easy axis of magnetization ?

Synchrotron Mössbauer reflectometry

[^{57}Fe(15ML)/Ag(**4ML**)]$_{16}$

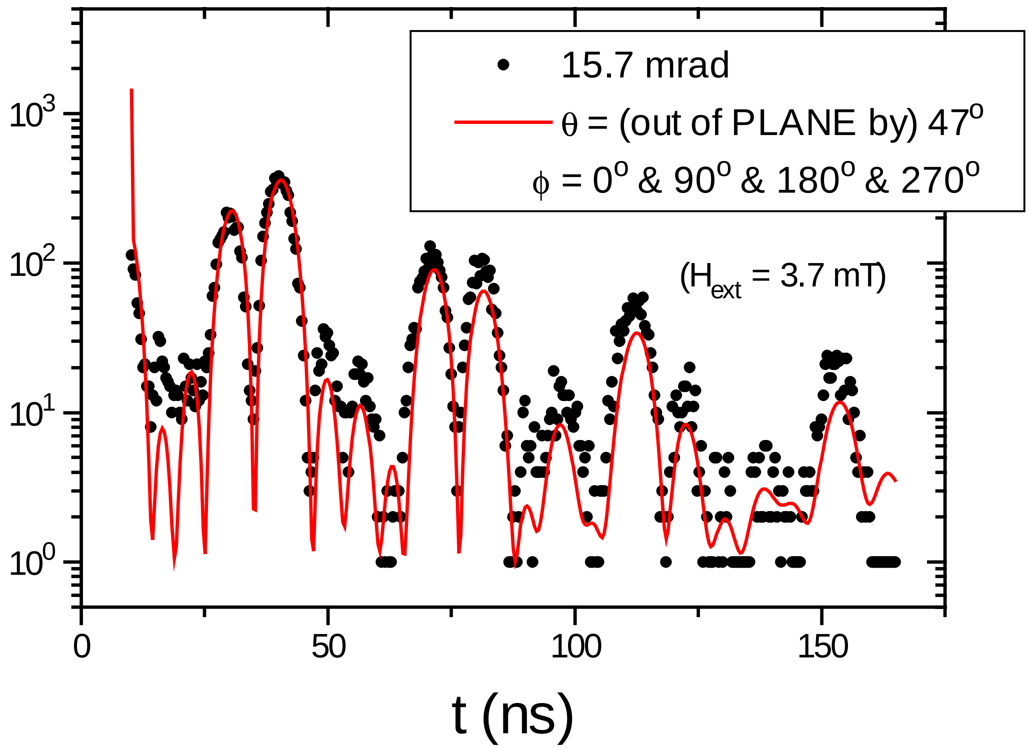


- Prompt reflectivity shows several SL peaks
- No AF Bragg peak in de delayed reflectivity

⇨ No AF stacking of the layers!

Synchrotron Mössbauer in time domain

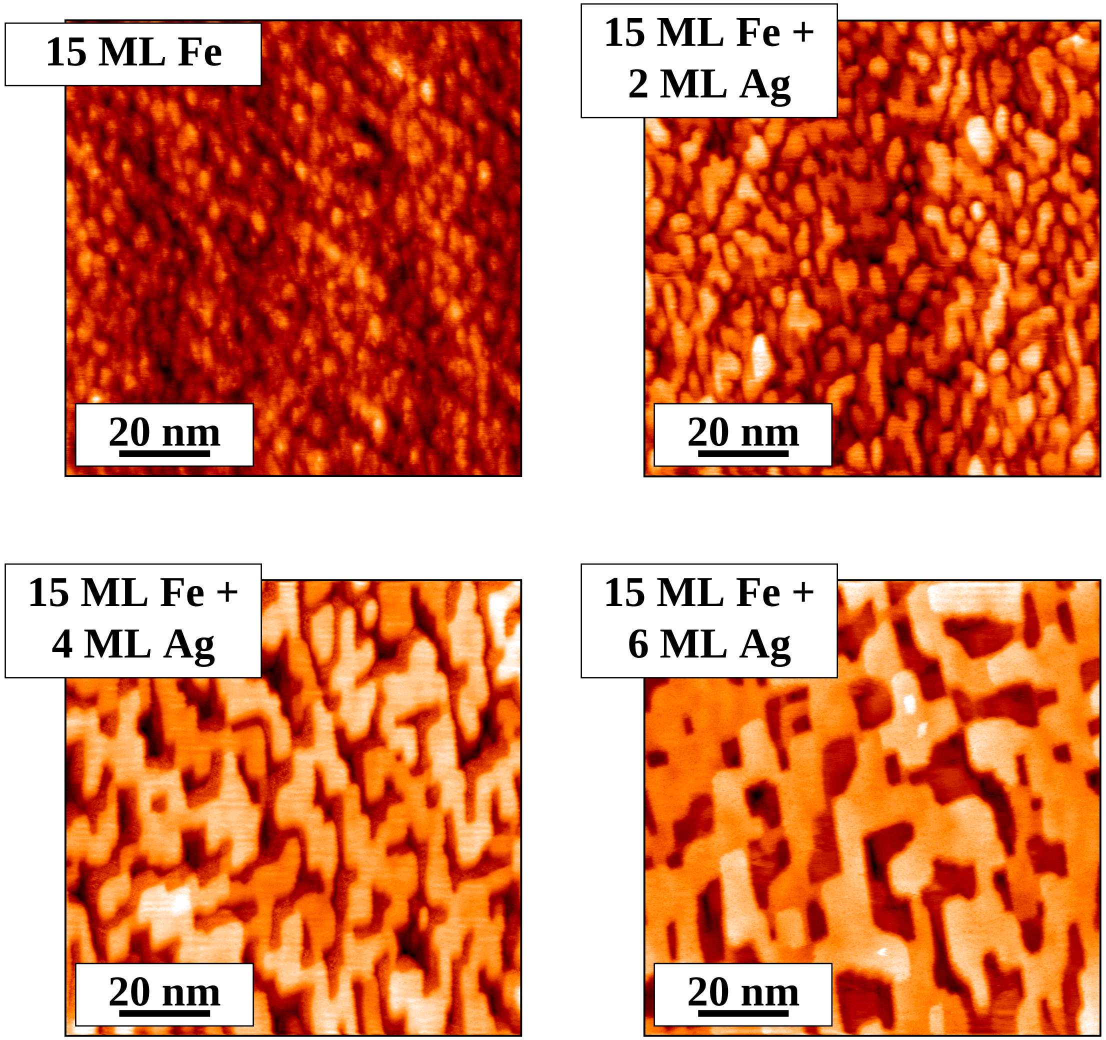
[^{57}Fe(15ML)/Ag(**4ML**)]$_{16}$ @ 25 K



- canting angle **θ=47°** @25K from fit of time spectrum

⇨ consistent with Mössbauer measurement at low temperatures (not shown here)

Interface structure



- by depositing Ag on Fe at room temperature atomic steps with preferred orientations [110] and [-110] are formed

- average distance between steps increases with Ag thickness : 5 nm (4MLAg), 9 nm(6ML)

Step induced anisotropy causes canting of the magnetization ?

Fe/Ag multilayers on stepped Ag(001)

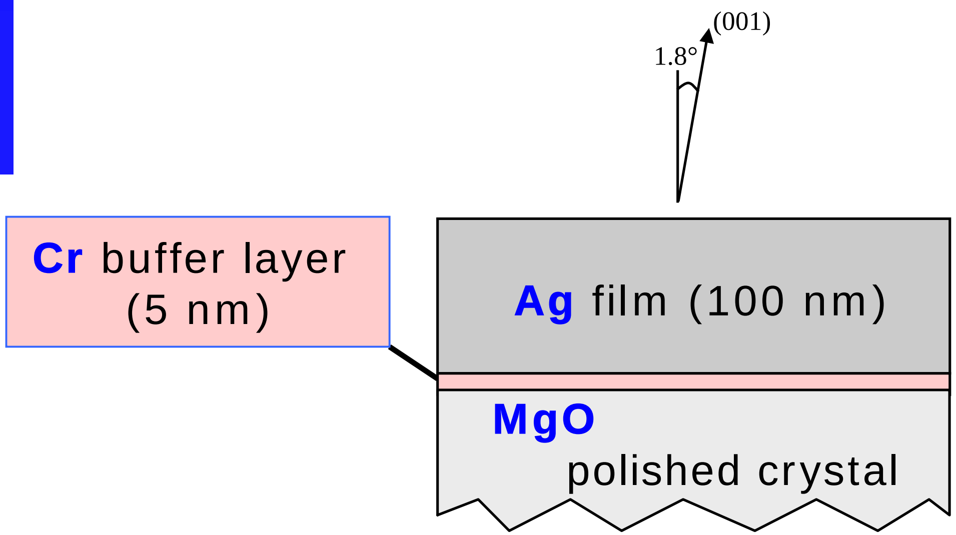
1. the stepped Ag(001) substrate
2. structure of the interface investigated with STM
3. canting of the magnetization ?

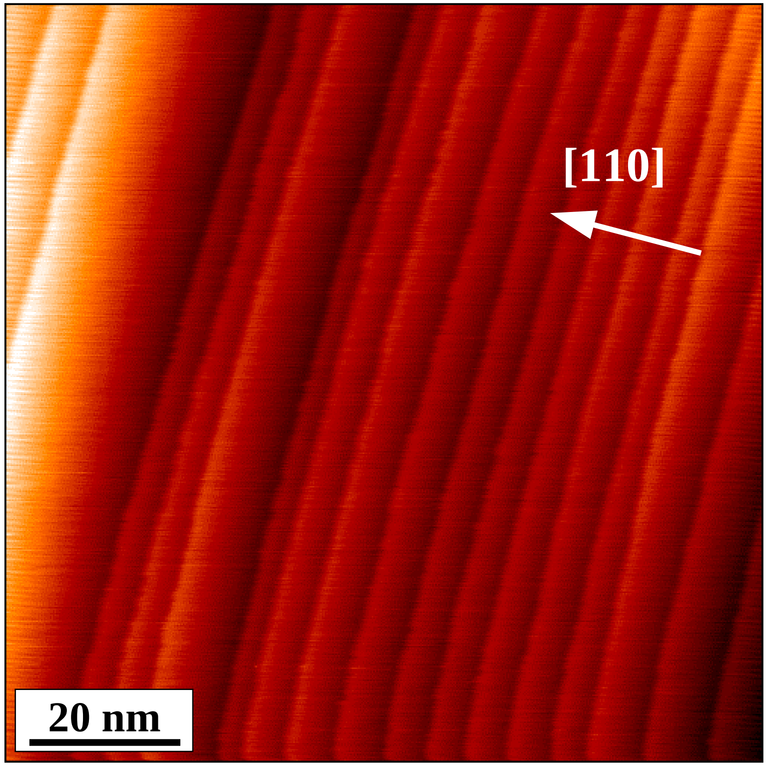
CEMS (conversion elektron Mössbauer spectroscopy)
VSM (vibrating sample magnetometry)

Stepped Ag(001)

Preparation:

- ⇨ MgO(001) polished crystal with a miscut of 1.8° in [110] direction
- ⇨ Cr buffer layer grown at 450 K
- ⇨ Ag film grown at 1.0 Å/s at RT
- ⇨ annealed at 475 K

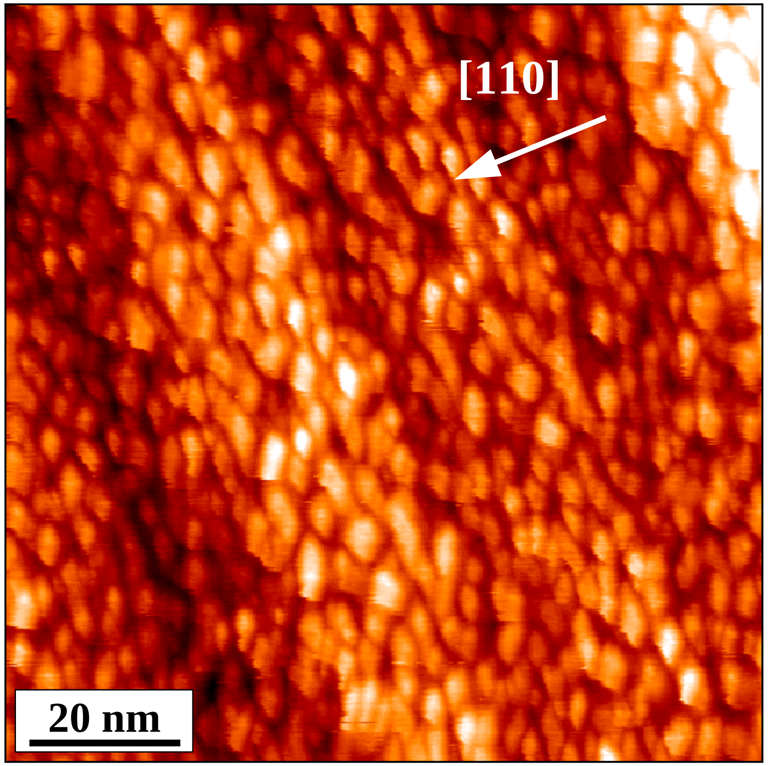




- ⇨ Monoatomic steps > 200 nm long
- ⇨ terrace width: (7 ± 3) nm

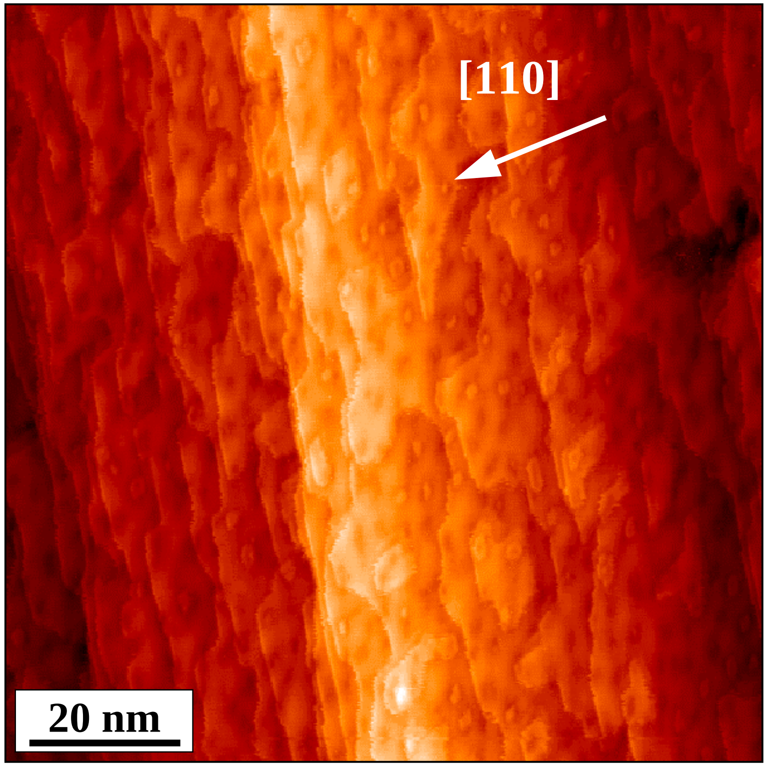
15 ML Fe

- ⇨ the step structure has disappeared
- ⇨ mounds of (7 ± 1) nm separated by valleys of 2 ML deep



15 ML Fe + 2 ML Ag

- step structure starts to reappear
- on the terraces, there are islands of 1 ML high and with an irregular shape
- depressions in the terraces of about 0.1 nm are observed

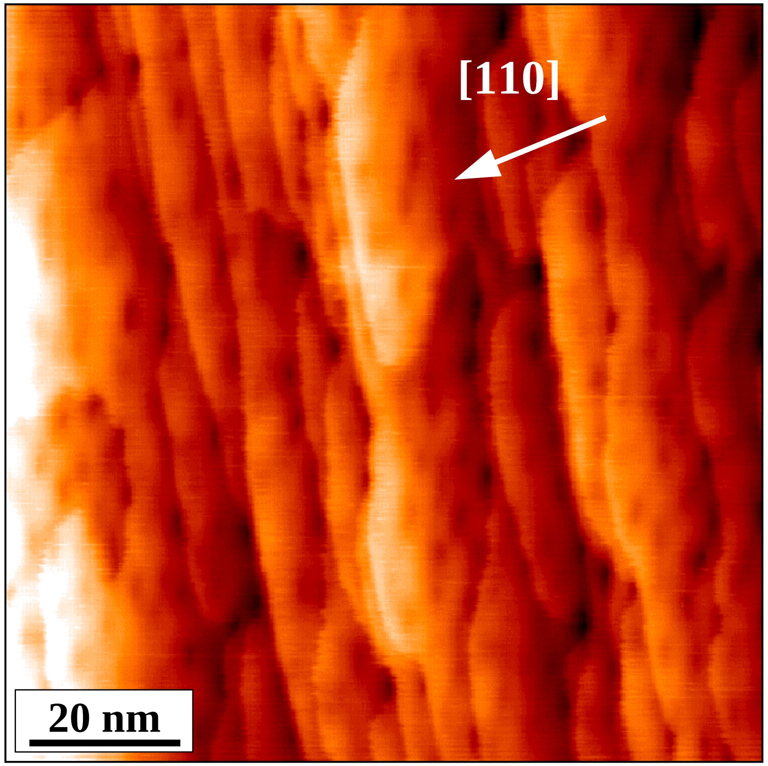


	rms on a terrace (nm)	length of steps (nm)
Before deposition	0.02	> 200
15 ML Fe + 2 ML Ag	0.07	10-25

$$rms = \sqrt{\frac{1}{N}\sum_{1}^{N}\left(z-\bar{z}\right)^2}$$

15 ML Fe + 4 ML Ag

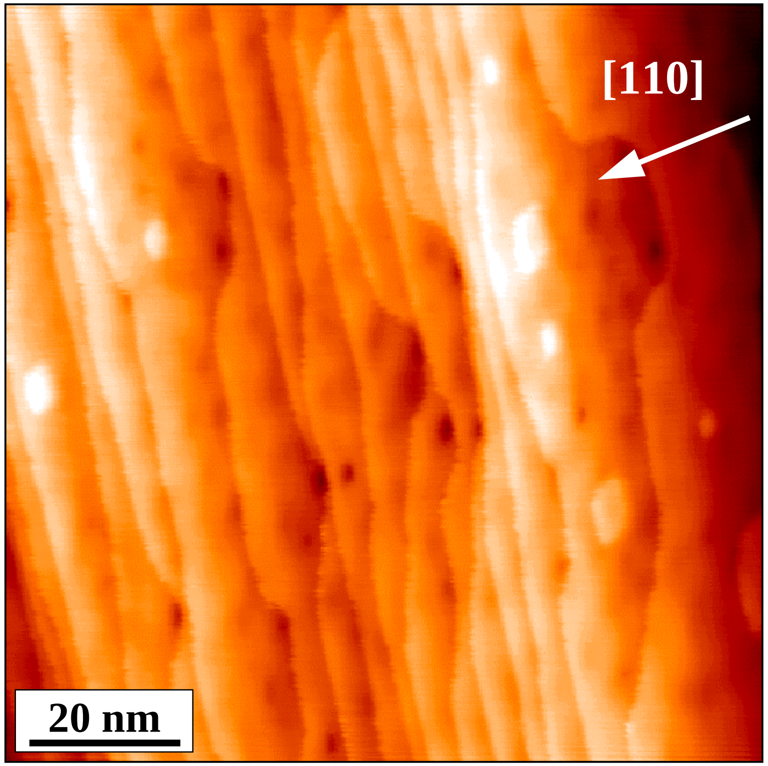
- steps become more straight
- no more islands are observed on the terraces
- the depressions are still there



	rms on a terrace (nm)	length of steps (nm)
Before deposition	0.02	> 200
15 ML Fe + 2 ML Ag	0.07	10-25
15 ML Fe + 4 ML Ag	0.04	30-80

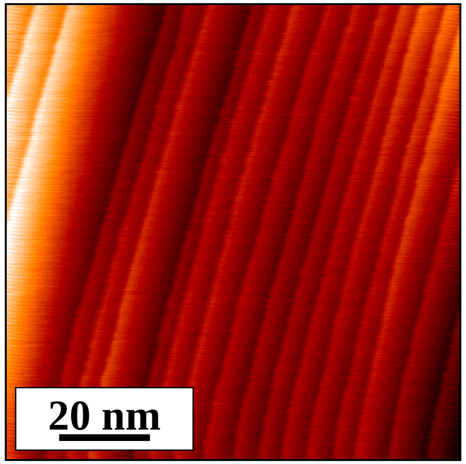
15 ML Fe + 6 ML Ag

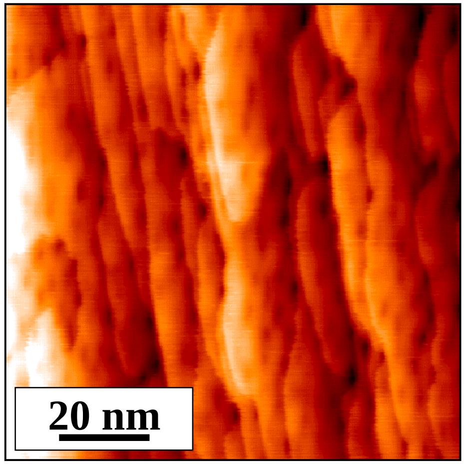
- small islands start to appear on the **wider** terraces
- depressions have almost disappeared



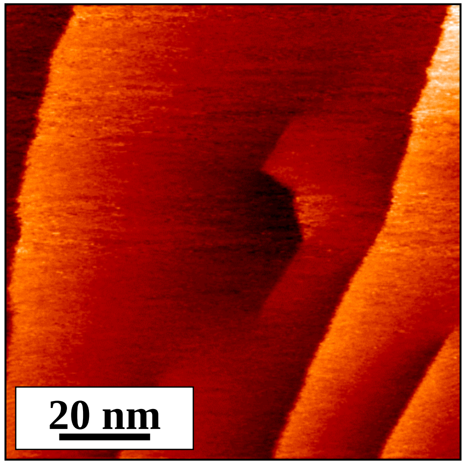
	rms on a terrace (nm)	length of steps (nm)
Before deposition	0.02	> 200
15 ML Fe + 2 ML Ag	0.07	10-25
15 ML Fe + 4 ML Ag	0.04	30-80
15 ML Fe + 6 ML Ag	0.03	> 60

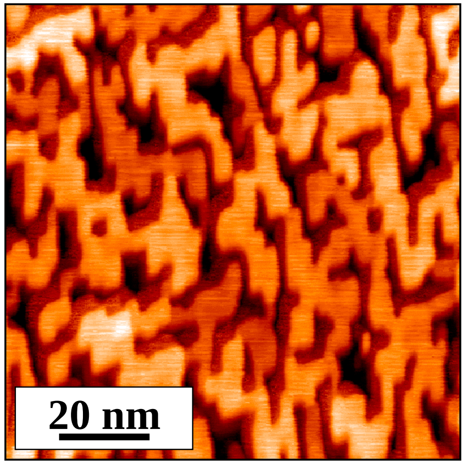
15ML Fe + 4 ML Ag: 2 substrates





The substrate | 15 ML Fe + 4 ML Ag





vicinal Ag(001), miscut 1.8°

- ⇨ **uniaxial symmetry** at the interface
- ⇨ terrace width of **7 nm** in [110]

flat Ag(001)

- ⇨ **fourfold symmetry** at the interface
- ⇨ terrace width of **5 nm** in [110] and [-110]

Fe/Ag multilayers

2 MULTILAYERS were prepared (in the same run):

⇨ $[^{57}Fe(15ML)/Ag(4\ ML)]_{16}$ grown on ***stepped Ag(001) with a miscut $\alpha = 1.8°$***

⇨ $[^{57}Fe(15ML)/Ag(4\ ML)]_{16}$ grown on ***flat Ag(001) $\alpha = 0°$***

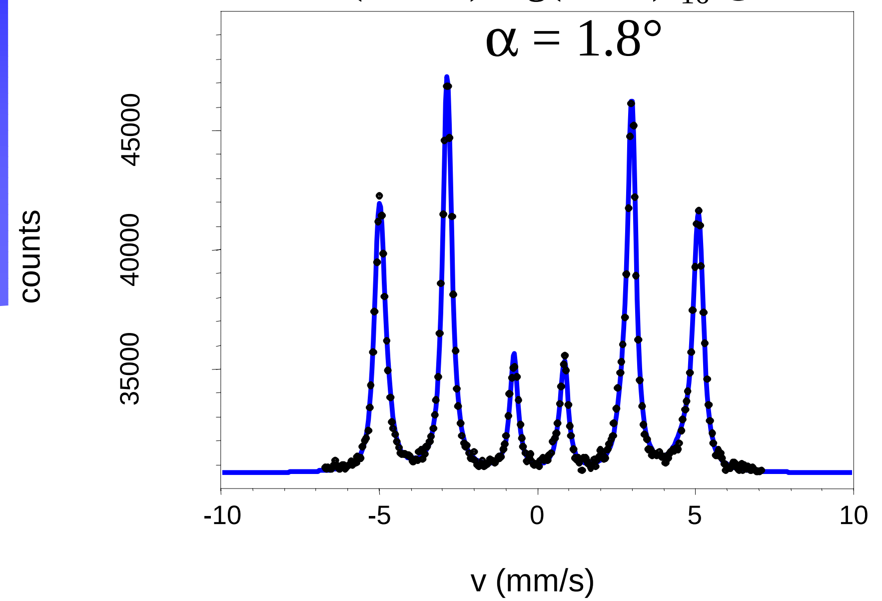
They were studied with:

Conversion Electron Mössbauer Spectroscopy (CEMS)

Vibrating Sample Magnetometry (VSM)

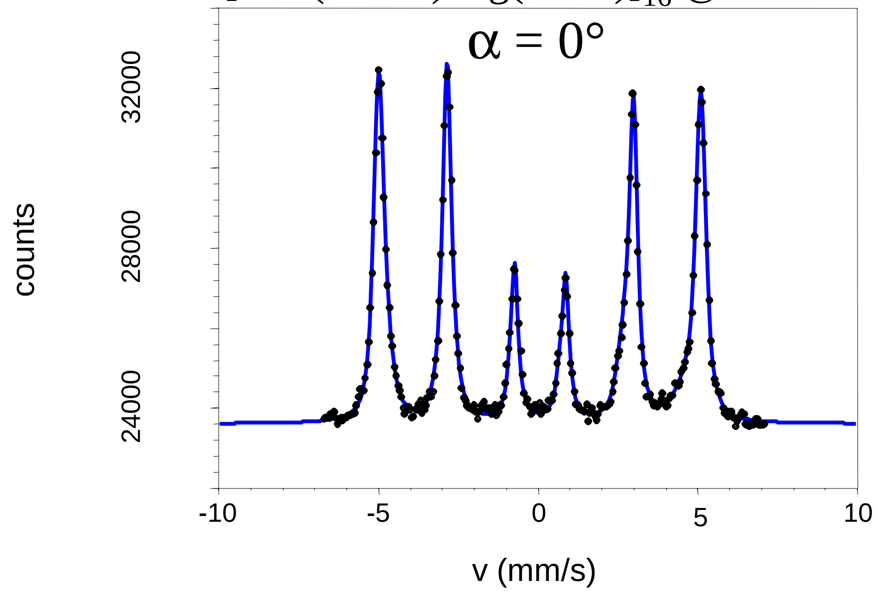
CEMS at 295 K

[^{57}Fe(15ML)/Ag(**4ML**)]$_{16}$ @ 295 K



Fe/Ag multilayer on *vicinal* Ag(001), miscut 1.8°

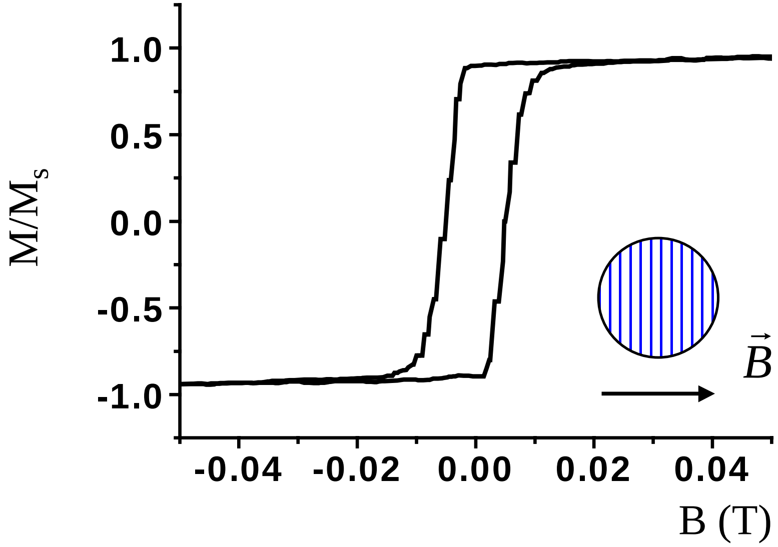
[^{57}Fe(15ML)/Ag(**4ML**)]$_{16}$ @ 295 K

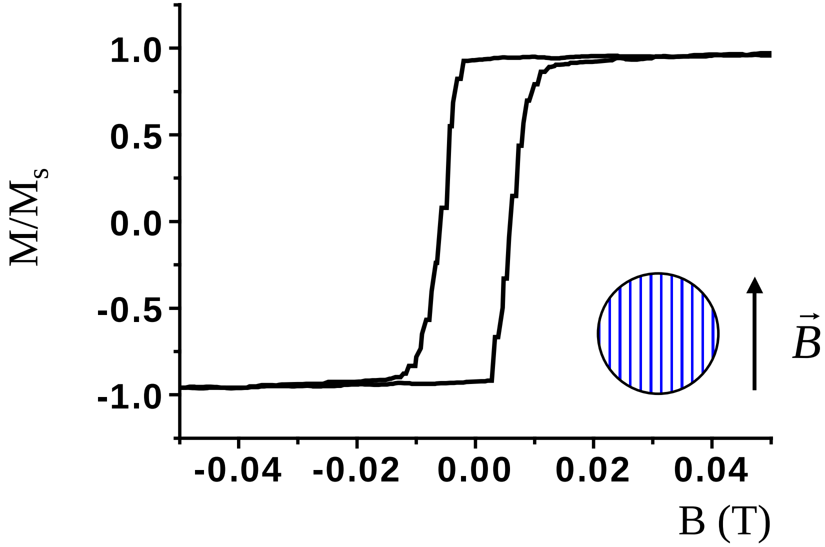


Fe/Ag multilayer on *flat* Ag(001)

vicinal Ag(001)	$\boldsymbol{\theta}$ **= 85°**	(quasi in-plane)
flat Ag(001)	$\boldsymbol{\theta}$ **= 61°**	(29° out-of-plane)

VSM for miscut α = 1.8





In-plane magnetization loops

$[^{57}Fe(15ML)/Ag($**4ML**$)]_{16}$ @ 290 K α = 1.8°

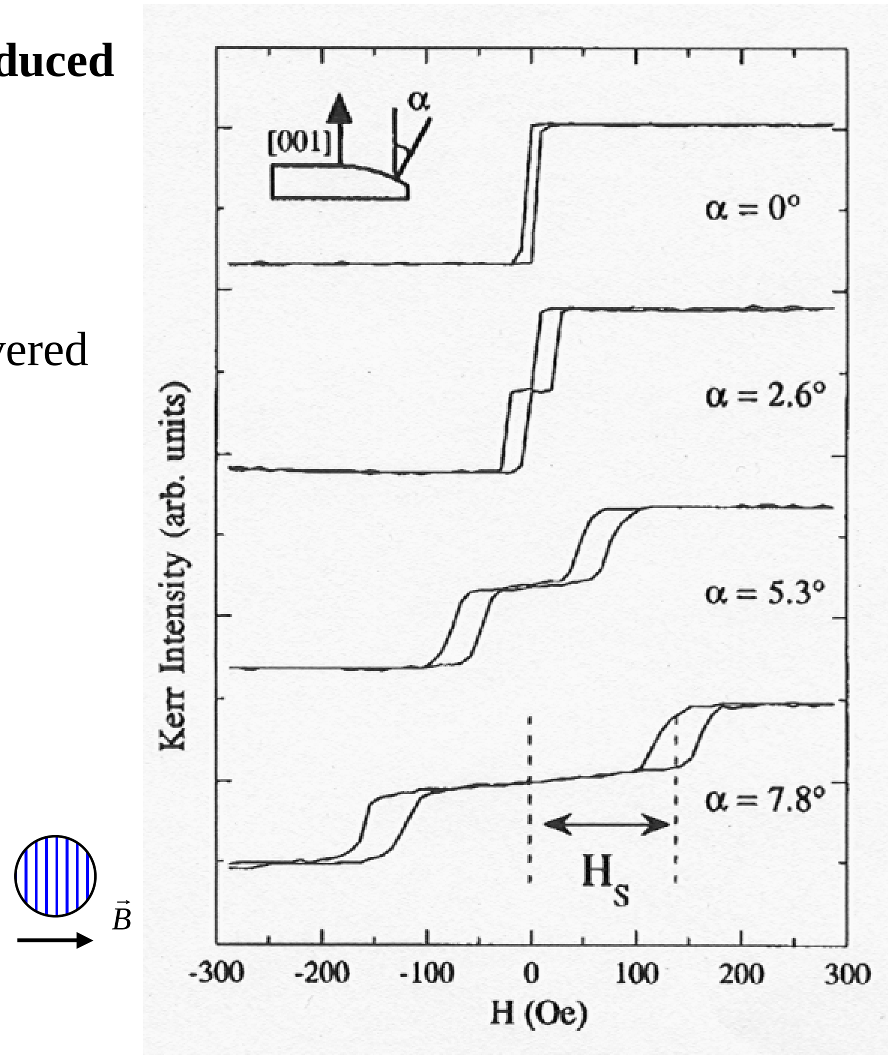
Fe/Ag multilayer grown on *vicinal* Ag(001) (miscut 1.8°)

- ⇨ $M_r/M_s \approx 1$ in agreement with CEMS
- ⇨ **no observable 'split field'** for the magnetization loop perpendicular to the direction of the steps
- ⇨ **no observable difference** between loops along the steps and perpendicular to the steps

Step induced anisotropy

Kawakami *et al.* have investigated **the step induced anisotropy** for

- ⇨ 25 ML of Fe on Ag(001) with a miscut in [110] direction between 0° and 10°
- ⇨ *in situ* MOKE measurements on the uncovered Fe surface
- ⇨ H_s is called 'the split field'



Fe(25ML) on Ag(000) @ 295 K

α = variable

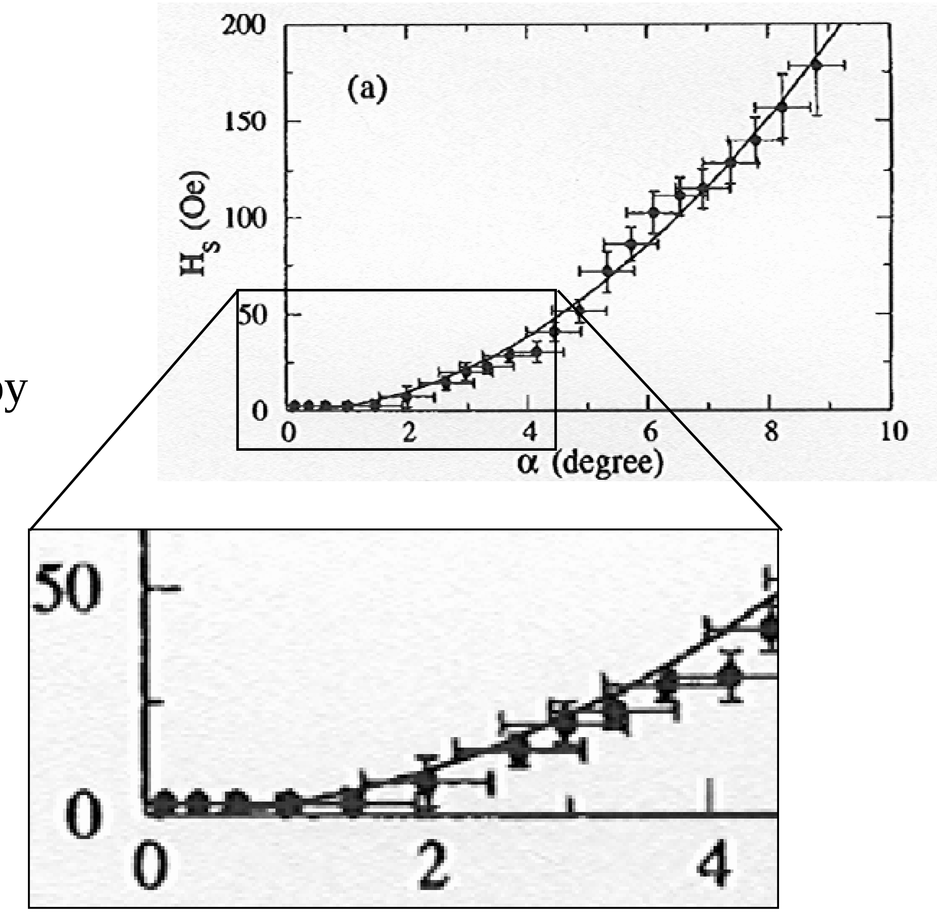
Kawakami; Phys. Rev. Lett. 77 (1996) p 2570

Step induced anisotropy

Kawakami *et al.*:

⇨ $$H_s \sim \alpha^2$$

⇨ for α < 2° the step induced anisotropy is not observable.



Fe(25ML) on Ag(000) @ 295 K
α = variable

Kawakami; Phys. Rev. Lett. 77 (1996) p 2570

Step induced anisotropy for α = 3.6

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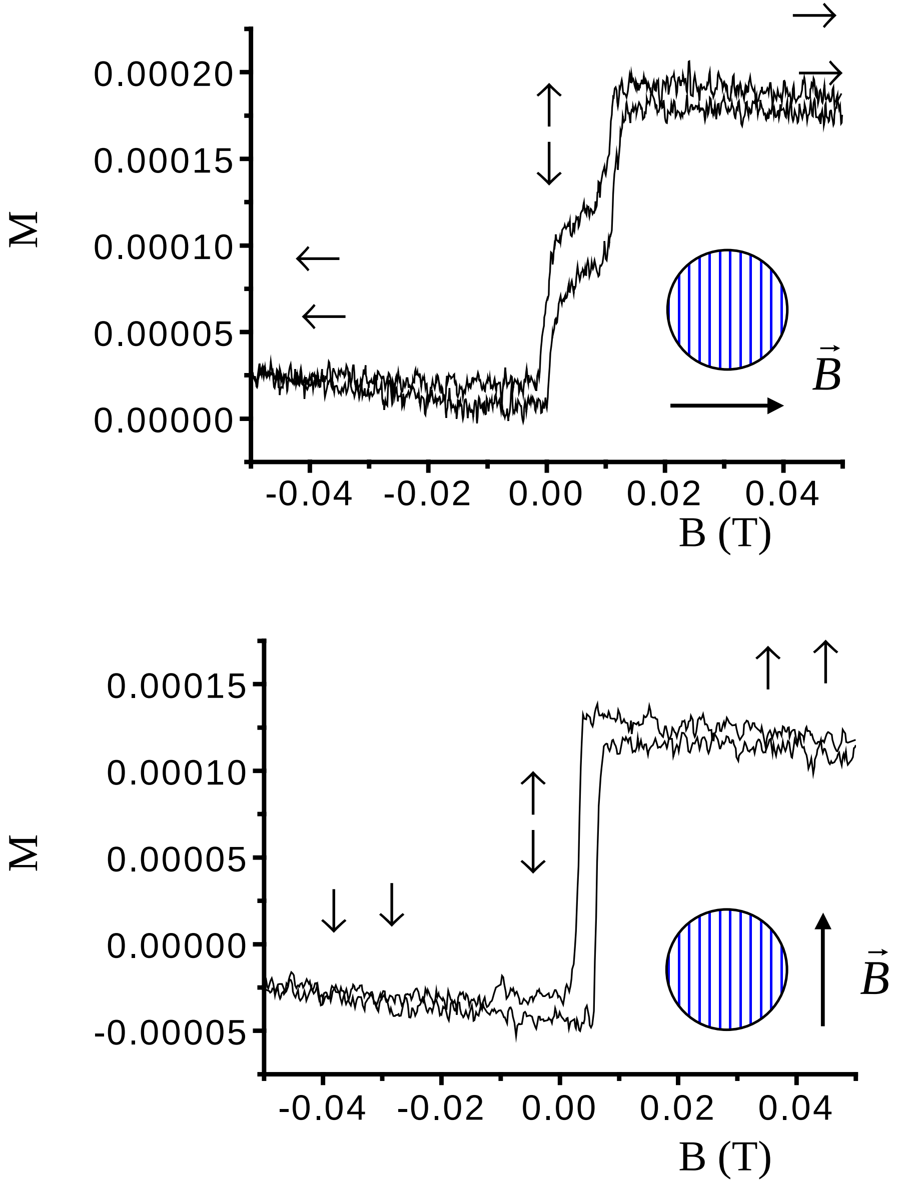


15 ML Fe grown on stepped Ag(001)
with α = 3.6°

⇩

UNIAXIAL ANISOTROPY !

Step induced anisotropy in our samples

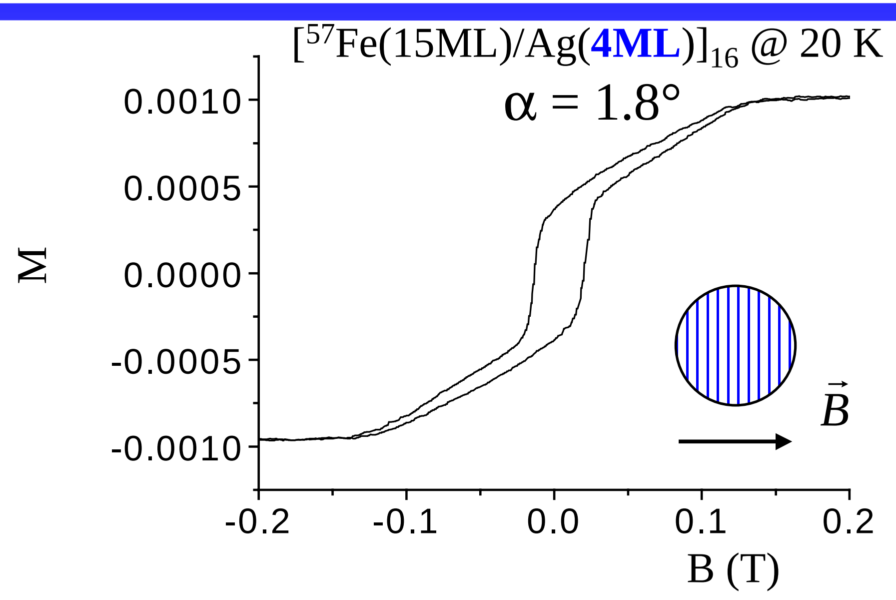
Fe/Ag multilayer on Ag(001) with α = 1.8°

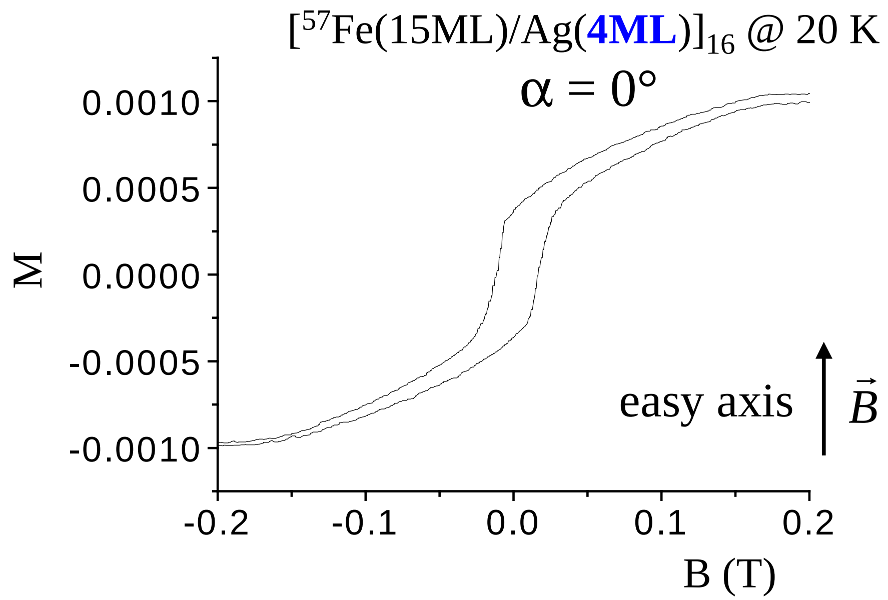
- We observe **no** uniaxial anisotropy which is in agreement with Kawakami for low miscut angles.
- For higher miscut angles we have uniaxial behaviour (in a single Fe film)
- The magnetization is in-plane: - 15 ML Fe was used in our samples
  - the spin-reorientation transition for Fe is around 6 ML

Fe/Ag multilayer on flat Ag(001) α = 0°

- At the Fe on Ag interface there is one step every 5 nm (looking in 1 direction). On a ***vicinal surface*** this would correspond to ***α = 2.3°***, meaning that the step induced anisotropy is observable.
- However, the steps are in two perpendicular directions. This means that there is no easy direction for the spins to align parallel to all the steps. This causes the canting of the magnetization out-of-plane.

Open question ...





In-plane magnetization loops at 20 K

Fe/Ag multilayer grown on *stepped* Ag(001) (miscut 1.8°) and *flat* Ag(001)

⇨ in both cases there is canting of the magnetization, independent of the orientation of the Ag steps

Conclusions

- We observe canting of the magnetization in Fe/Ag multilayers, which increases with decreasing temperature
- The canting is related to the structure of the Fe on Ag interface.
  At 290 K we find
  - in Fe/Ag multilayers grown on *stepped* Ag(001) there **IS NO** canting
  - in Fe/Ag multilayers grown on *flat* Ag(001) there **IS** canting
- However, at low temperatures we also observe canting of the magnetization for an Fe/Ag multilayer grown on *stepped* Ag(001). This is still under investigation.

End ...

LEUVEN

15 ML Fe + 6 ML Ag on flat Ag(001)

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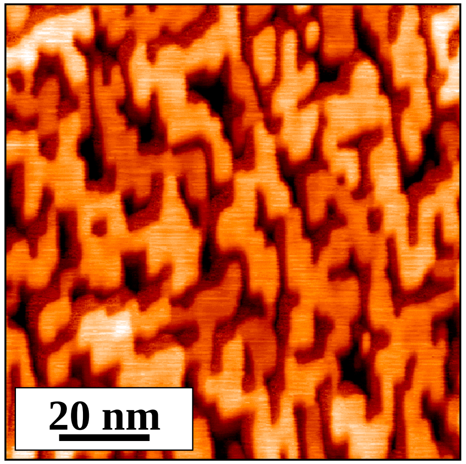
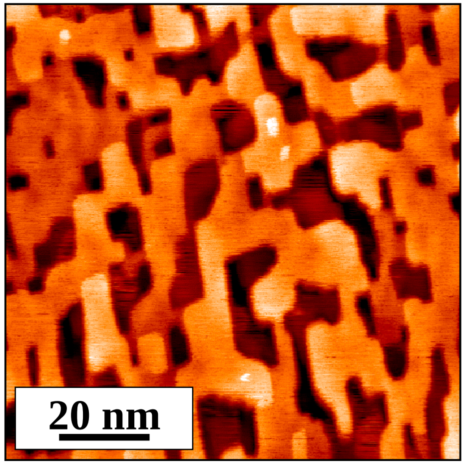
⇨ The interface of an **Fe/Ag multilayer** with 6 ML of Ag grown on flat Ag(001) has a terrace width of **9 nm**. This would correspond to **α = 1.3°** for a vicinal Ag surface.

⇨ The line intensities in the Mössbauer spectrum showed that the magnetization is **in-plane**, in agreement with the results of Kawakami.

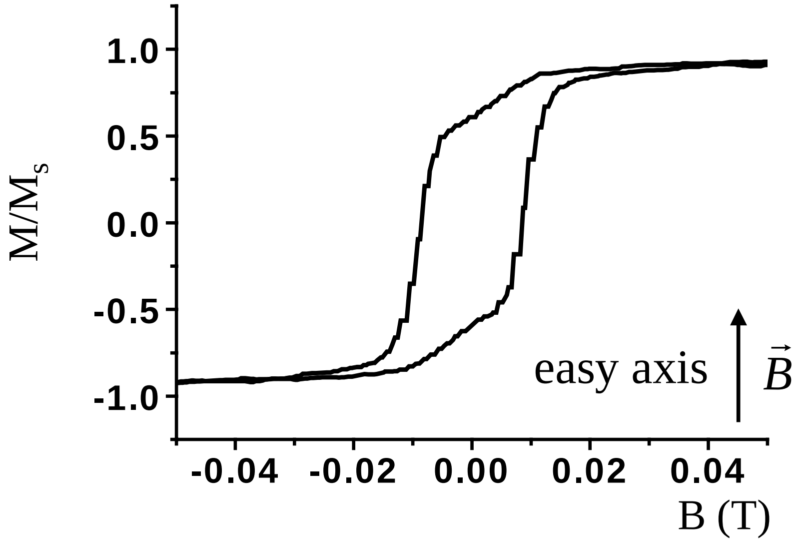


15 ML Fe
+
4 ML Ag



15 ML Fe
+
6 ML Ag

VSM for miscut α = 0, flat Ag(001)



<u>In-plane magnetization loops at 290 K</u>

Fe/Ag multilayer grown on *flat* Ag(001)

⇨ M_r/M_s = 0.6 due to canting