# Bimodal growth mode of Fe / cc(110) ; cc=(W,Mo)

# Application to the self-organization of thick stripes

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- **Evidence for bimodal growth**
- **Application to self-organized thick stripes**
- **Extend versatility of self-assembly**
- **Discussion of results from the literature**

## Growth processes

- **Motivation**: model system for 2D magnetism (no alloying, pseudomorphic, layer-by-layer)
- **Growth**:
  - Pseudomorphic 1st layer, then Stranski-Krastanov
  - Kinetic roughness along [001] at room temperature
  - Progressive increase of temperature for flat films
  - Dots at high temperature
- **Substrate**: quanlitatively (if not quantitatively) similar results for W(110) and Mo(110).

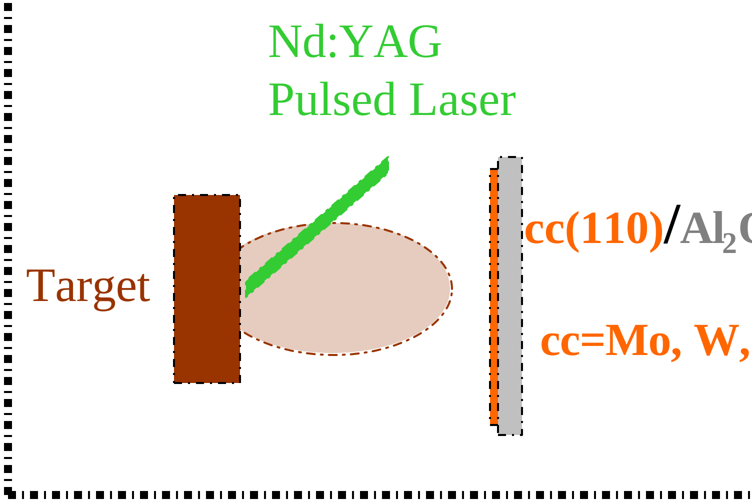
## Self-organization

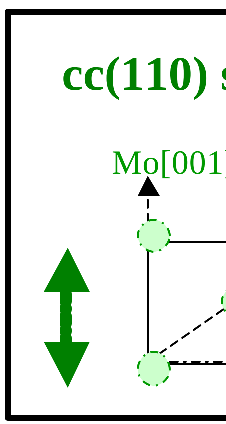
- Step-decoration of vicinal surfaces: 0.5ML, 1.5ML. Curie temperature < 300K

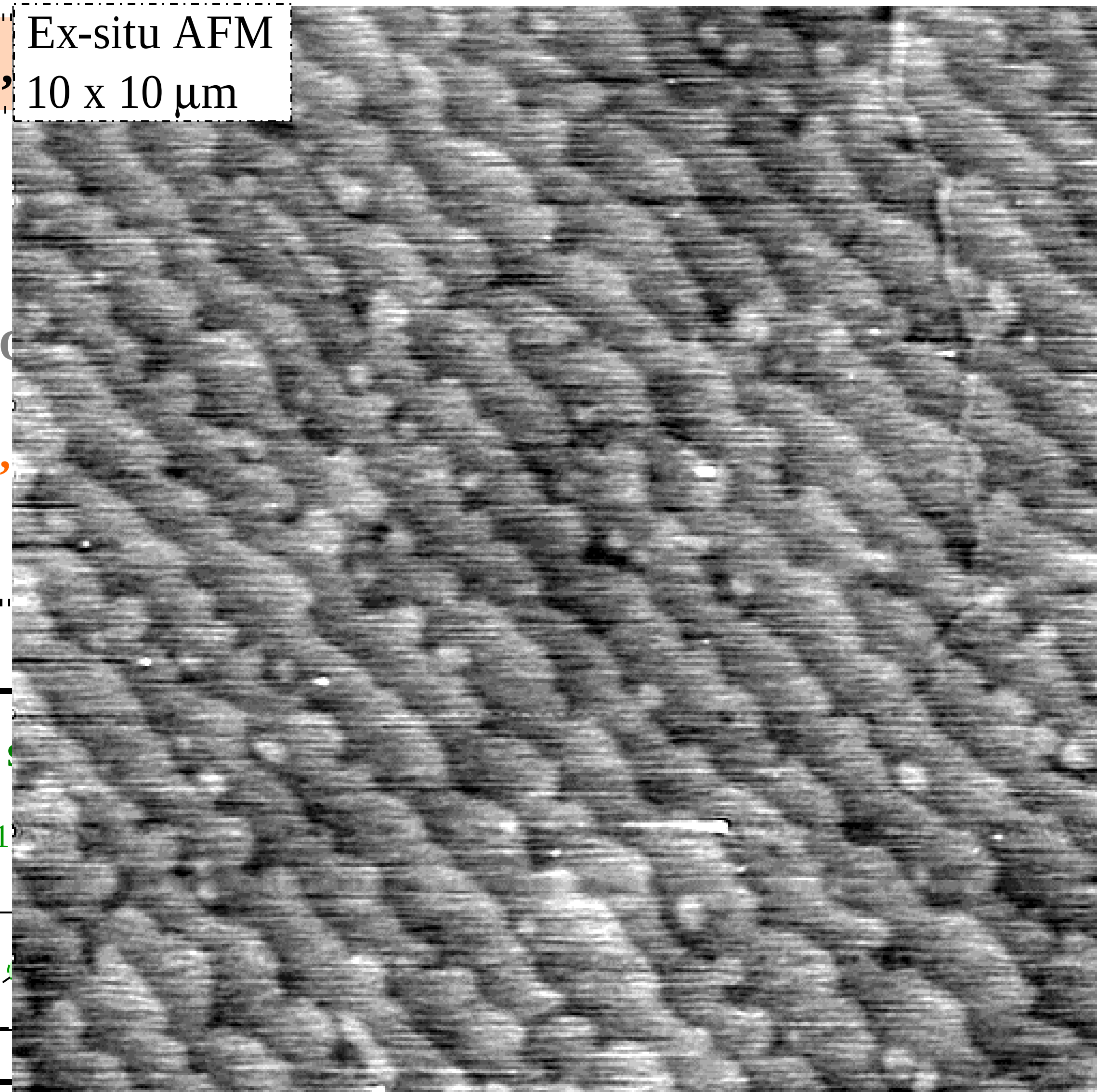
## Key references

- **Pioneering**:Gradmann82, Tikhov-Bauer90
- **Following**:Elmers-Gradmann90, Albrecht-Gradmann93, Bethge95
- **Stripes**: Hauschild-Gradmann98, Bode-Wiesendanger00

## PULSED LASER DEPOSITION,

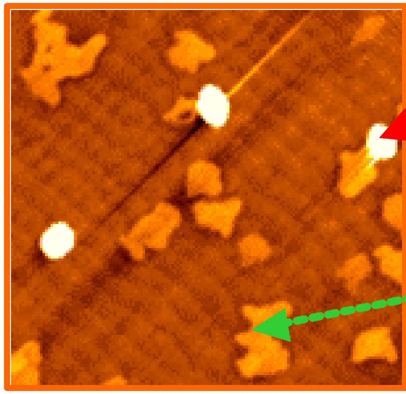



**Buffer layer growth** : O. Fruchart, S. Jaren, J. Rothman, Appl. Surf. Sci. 135, 218 (1998)
**MBE versus PLD** : J. .Shen et al., Surf. Sci. Rep., 52, 163 (2004)

$e_{nom}$ = 0.7 nm ~ 3.5ML

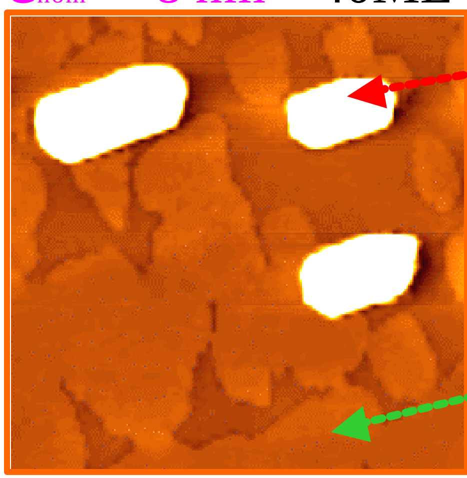


AFM, 3μm x 2.8μm

50% Vol. **3D**

h=1.2nm
50% Vol. **Flat**

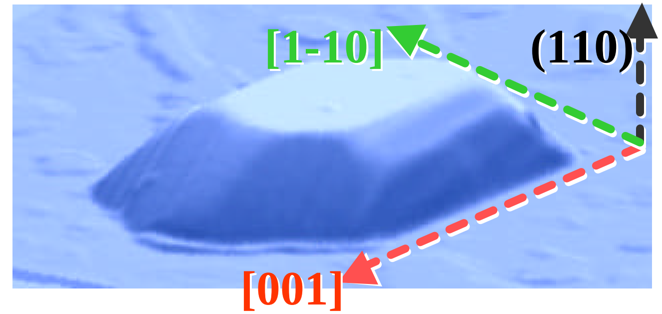
$e_{nom}$ = 8 nm ~ 40ML



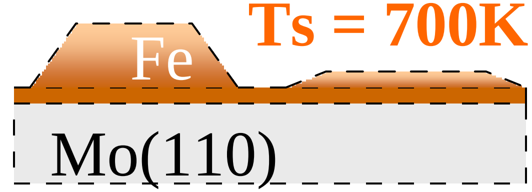
AFM, 3.6μm x 3.6μm

90% Vol. **3D**

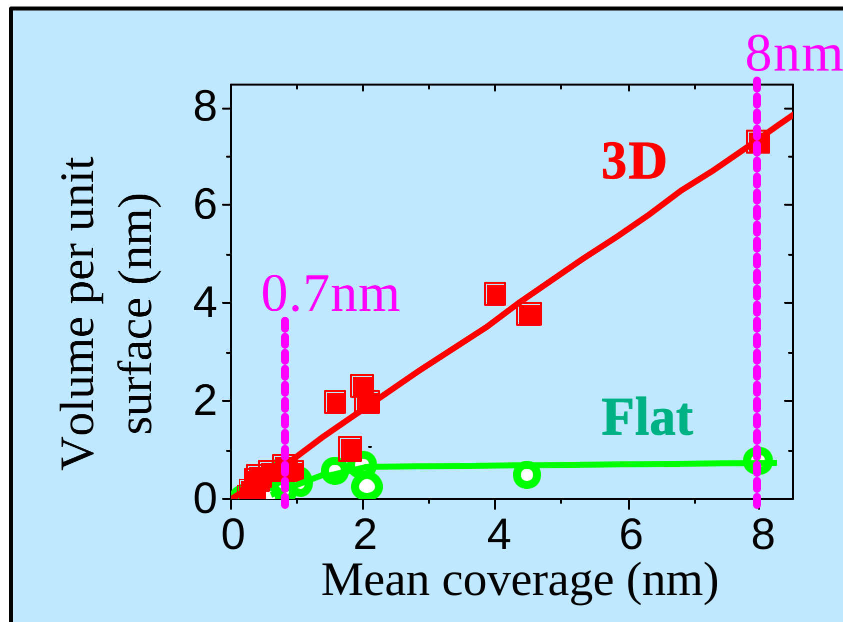
h=1.2nm
10% Vol. **Flat**




**Ts = 700K**




Bimodal Stranski-Krastanov growth

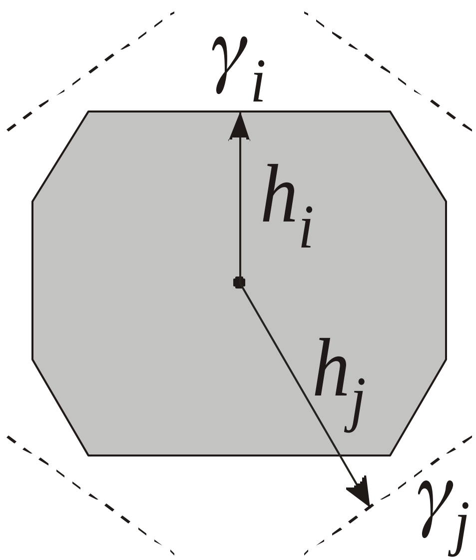



P.-O.Jubert *et al.*, JMMM 226, 1842 (2001)
P.-O.Jubert *et al.*, PRB64, 115419 (2002)

## Wulff's theorem

Free crystal

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

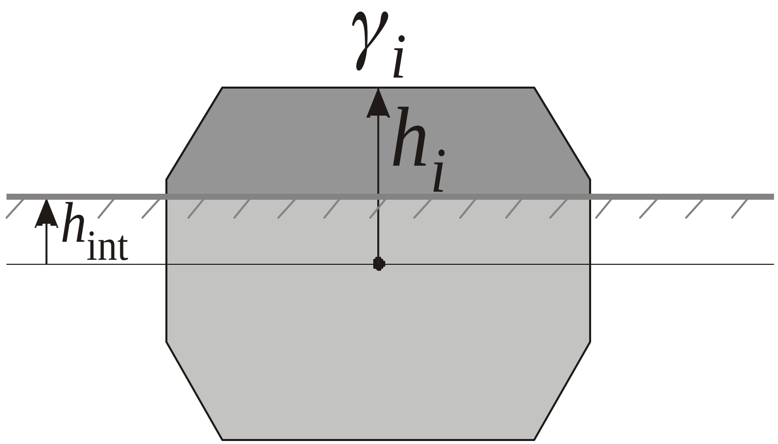



No facets with high surface energy

## Wulff Kaishev's theorem

Supported crystal (growth on surfaces)

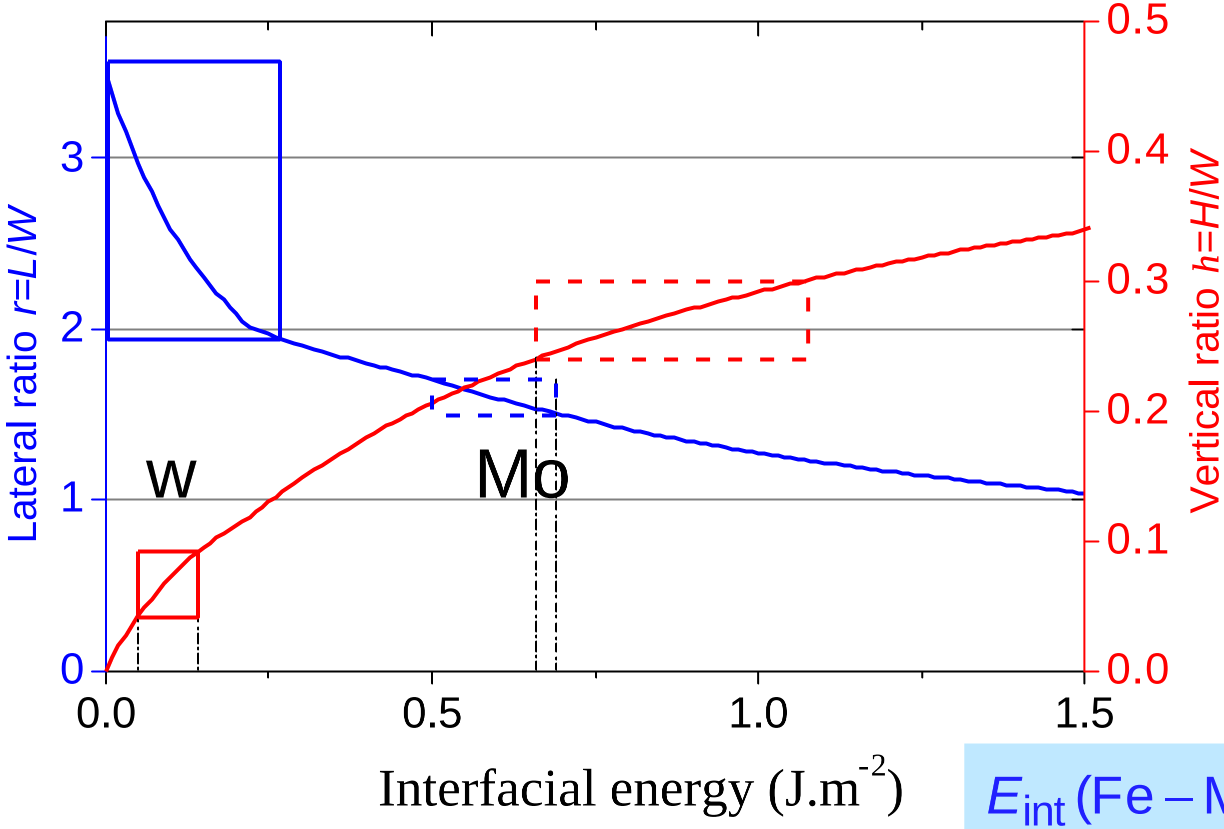
$$\frac{\gamma_i}{h_i} = \frac{\gamma_S - \gamma_{\mathrm{int}}}{h_{\mathrm{int}}} = \text{Constant}$$




Truncated crystal

## Interface energy deduced from measurements

Based on Wulff's construction



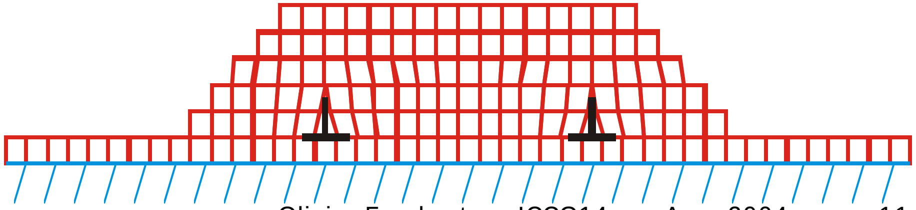

$$E_{int}(\mathrm{Fe-Mo}) = 0.65 \pm 0.15\ \mathrm{J.m^{-2}}$$

$$E_{int}(\mathrm{Fe-W}) = 0.15 \pm 0.1\ \mathrm{J.m^{-2}}$$

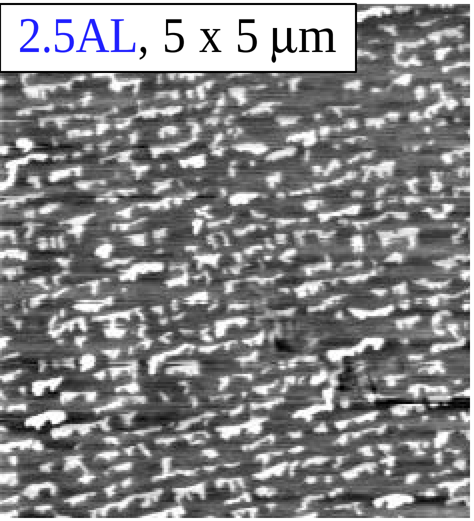
**Micron-size dots:**

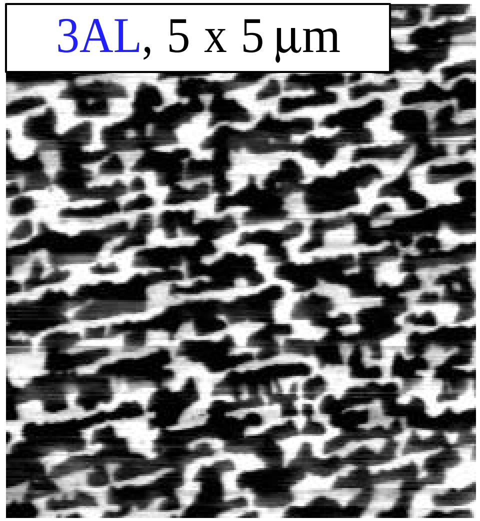
**Includes interfacial dislocation energy**

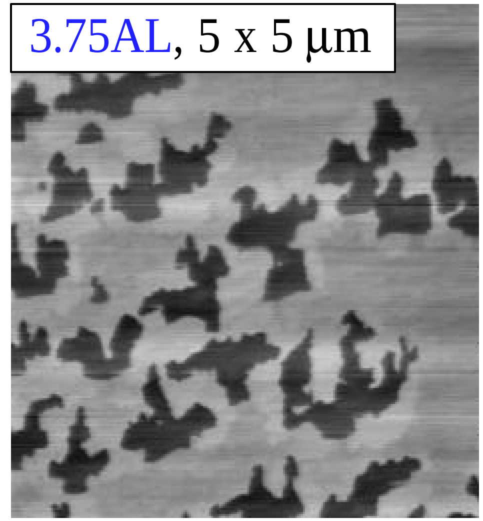
**⇨ Effective interface energy**

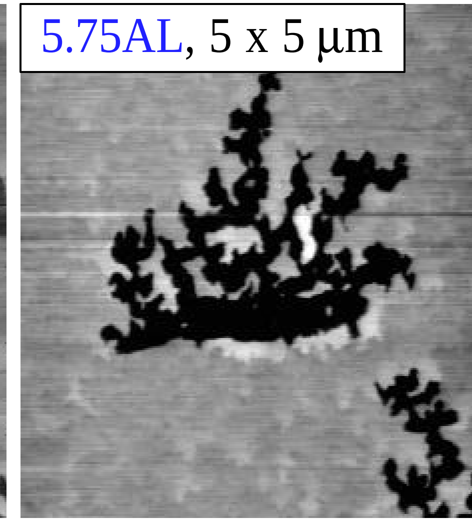


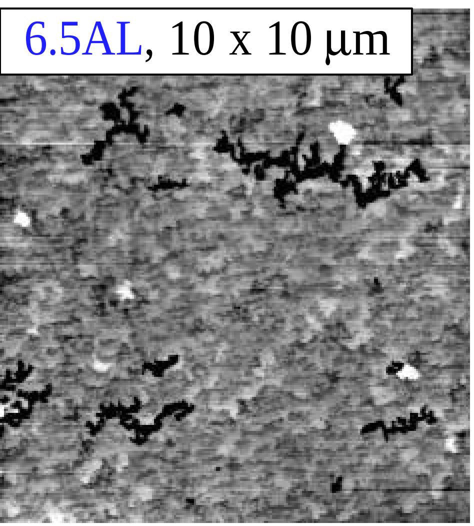
## 25°C growth + 450°C Annealing - Ex-situ AFM

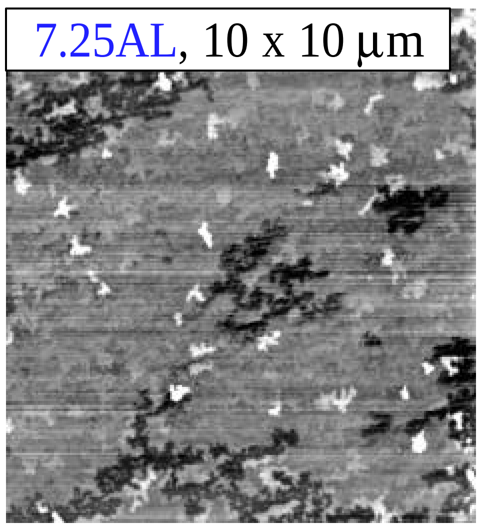


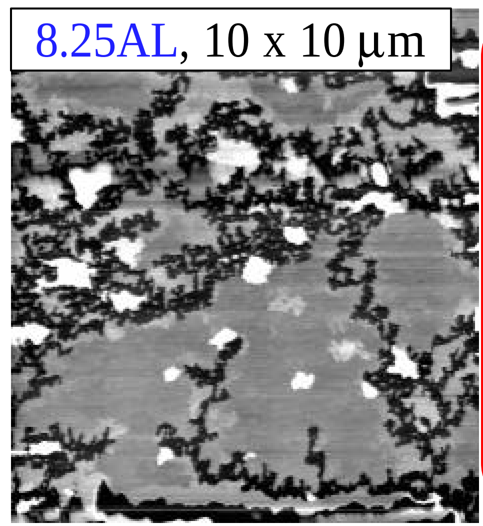



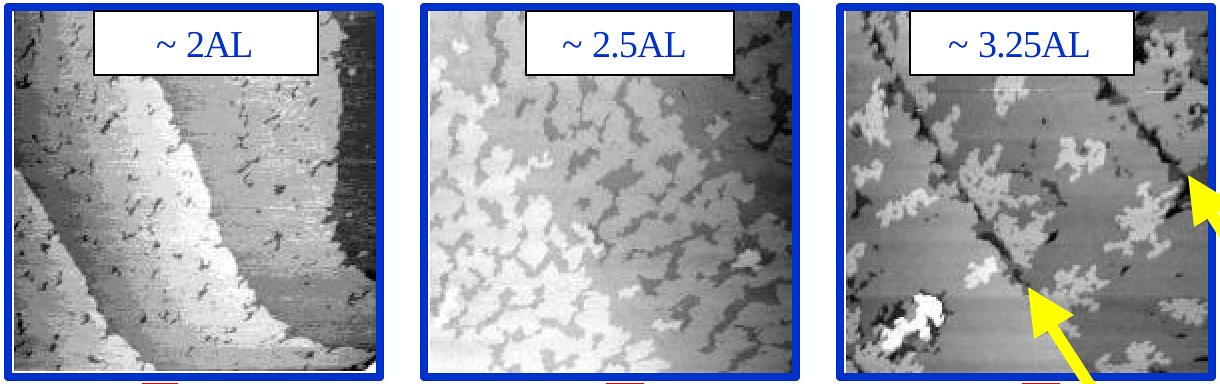




- **t<7AL**:
  7AL metastable patches
- **t>7AL**:
  patches are 'sucked'

↳ 3D dots more stable than 7AL patches.

# Fe/Mo(110) – why stripe nucleation along steps ?

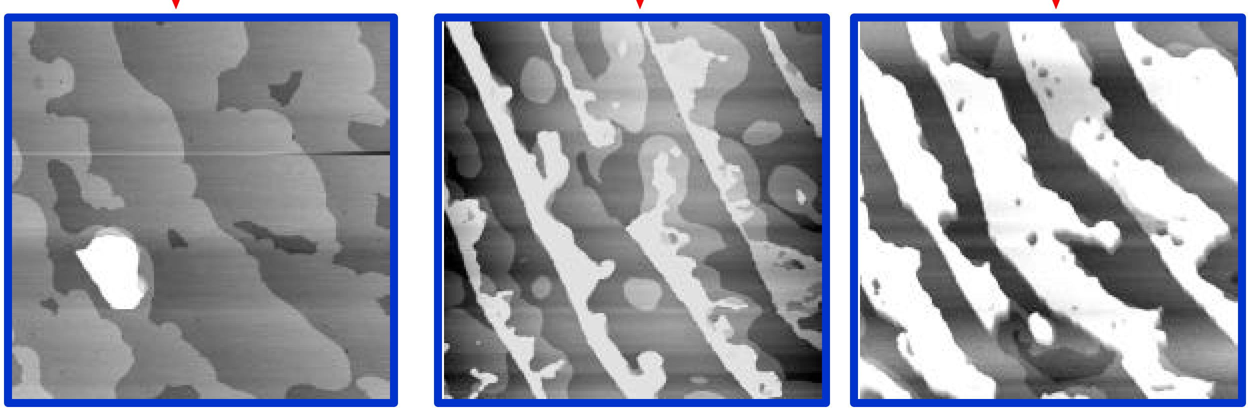
## Step 1: layer-by-layer growth at 150°C



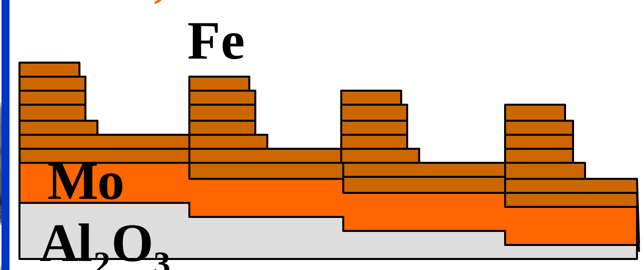

**Fe films grown at 150°C**

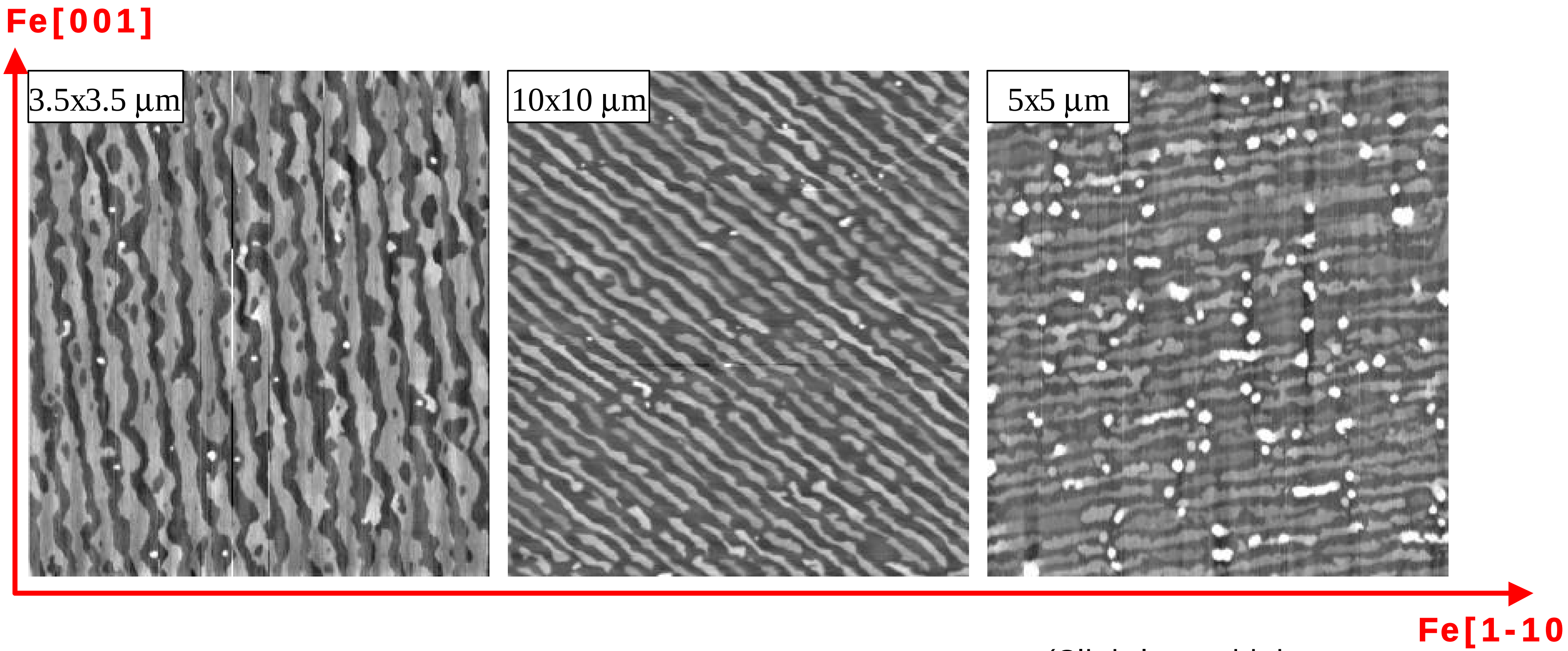
**STM, 600nm x 600nm**

## Step 2: annealing at 500°C --> stripes along steps



**STM, 750nm x 750nm**

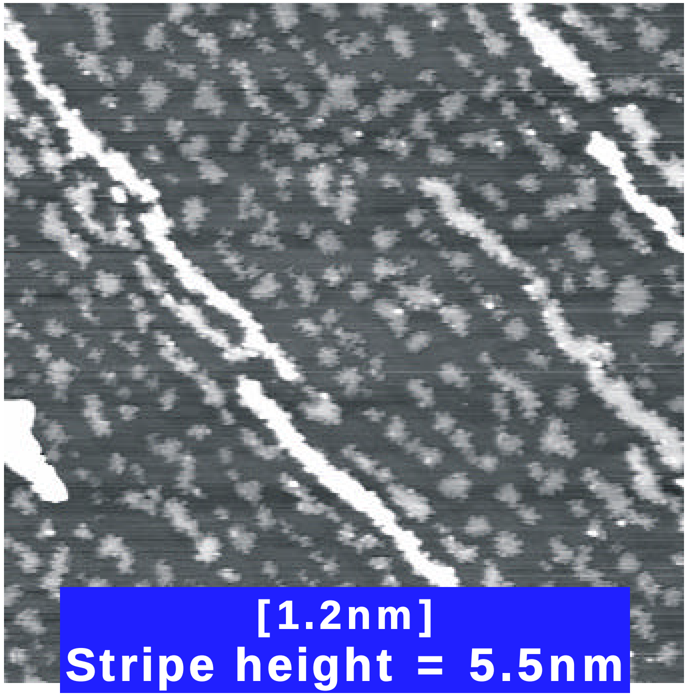


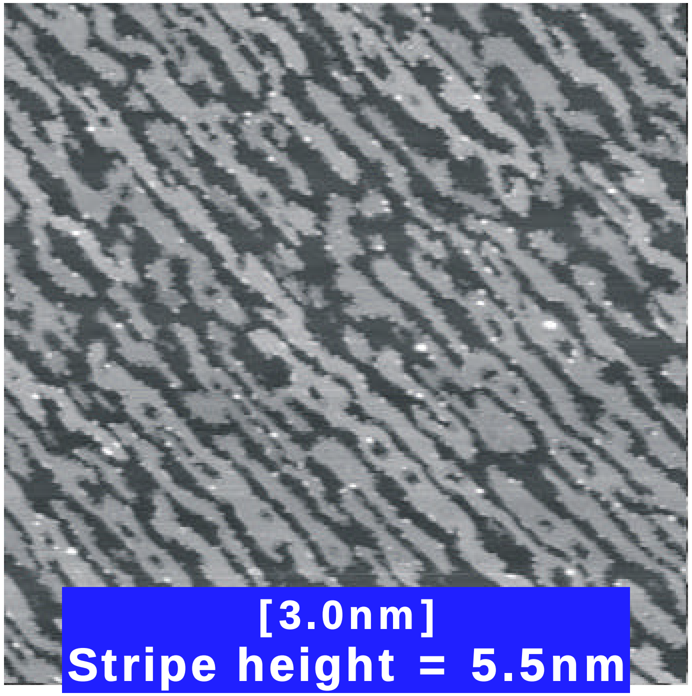



(Slightly too high temperature
for this sample...)

- 7ML stripes (instead of 1-2ML usually)
- Tunable orientation
- To be optimized for better quality

## Sapphire\W(8nm)\Fe(150°C + 450°C annealing)

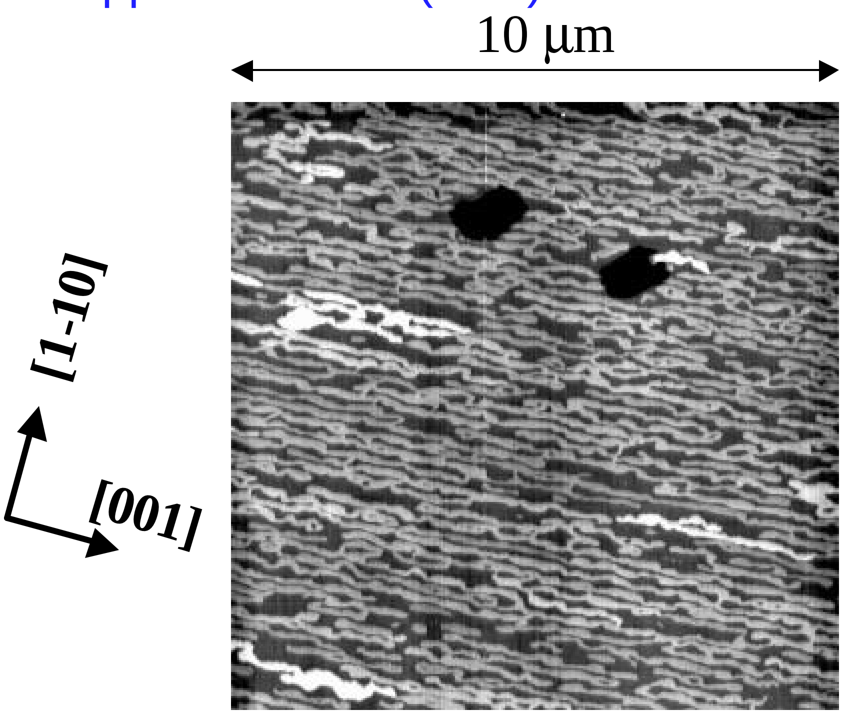


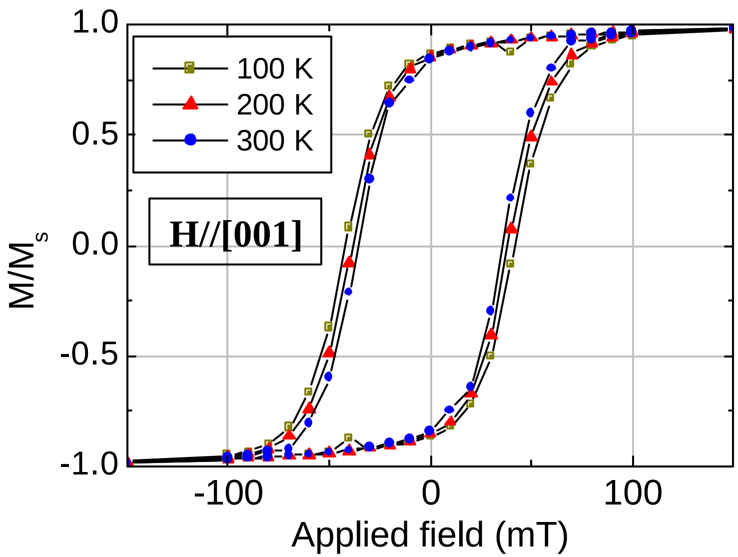



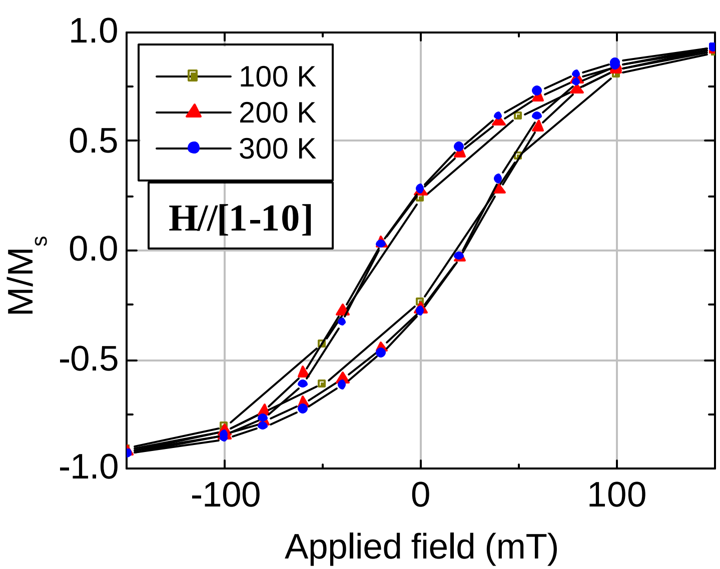

- **Stripes for Fe/W(110)**
- **Increased height : 5.5nm (significant advancement compared with existing literature)**

## Coercivity and remanence at 300K

Sapphire \ W \ Fe(3nm) \ Mo

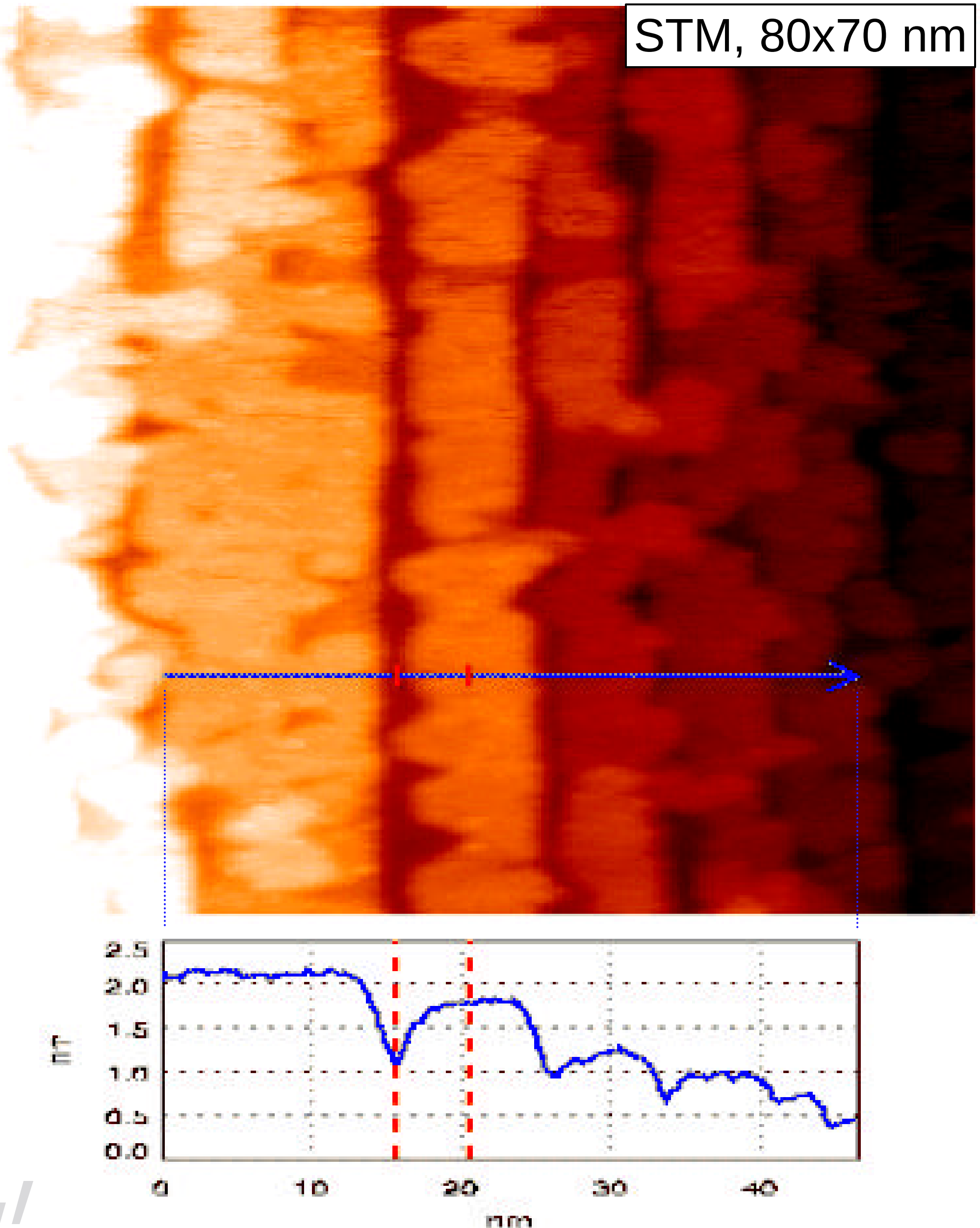



- **Coercivity and high remanence at 300K**
- **Weak temperature dependence**
  **> behaves like a conventional material**

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




**3 ML $Fe_{65}Ni_{35}$ / Cu(111)-vic 1.2°**

**Grooves along steps**

**General phenomenon that may be exploited ?**

S. Cherifi *et al.*, PRB 64 (2001) 184405

## Quantum confinement

Evidence for 'magic' heights have been reported for several systems:

**Pb/Cu(111)**: 6,8,11,15,17,20 ML. **R. Otero et al., PRB66, 115401 (2002)**

**Ag/GaAs**: A.R. Smith et al., **Science 273, 226 (1996)**

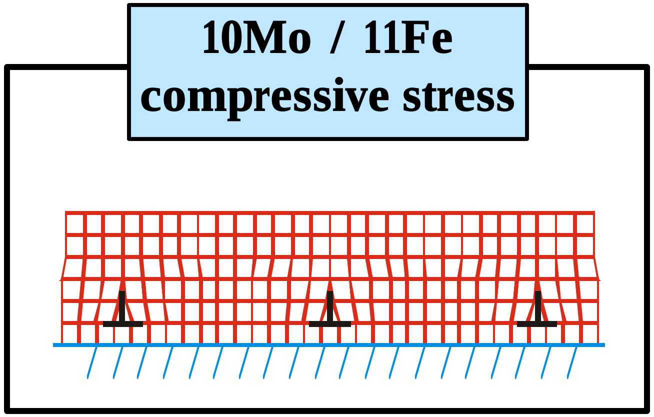
**Ag/Si(111)**: L. Gavioli et al., **Phys. Rev. Lett. 82, 129 (1999)**
**L. Huang et al., Surf. Sci. 416, L1101 (1998)**

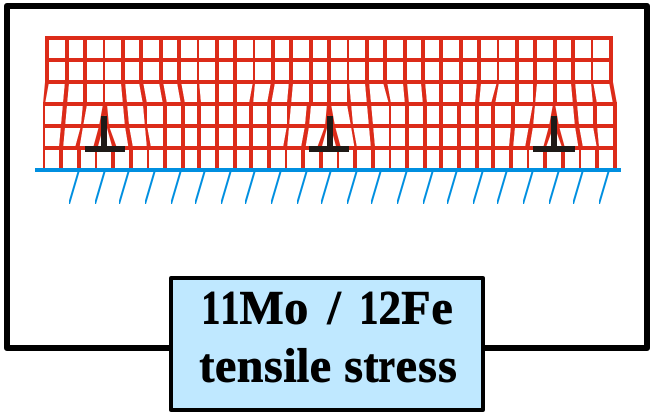
**Pb/Si(111)**: **V. Yeh et al., Phys. Rev. Lett. 85, 5158 (2000)**
**W. B. Su et al., Phys. Rev. Lett. 86, 5116 (2001)**

**Au/Fe(001)**: 5ML, **D. A. Luh et al., Science 292, 1131 (2001)**

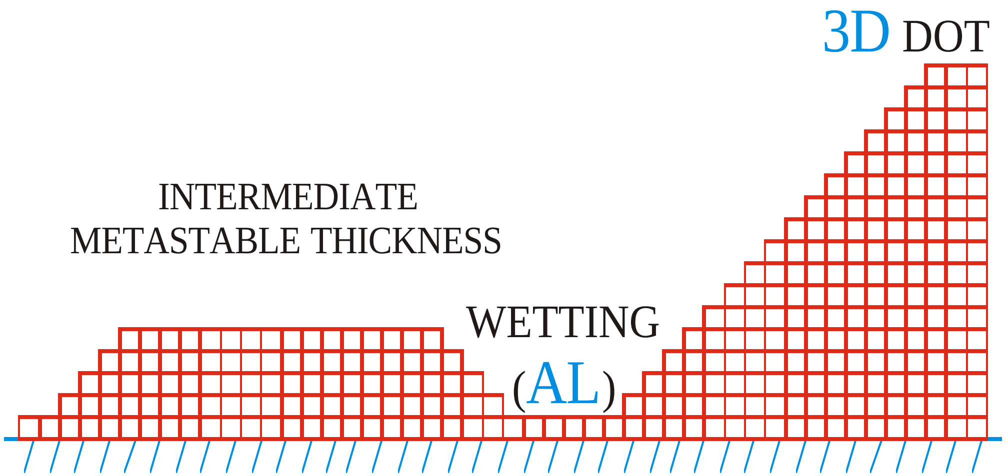
**However, several magical heights would be expected…**
**Under investigation**

## Transition of the interfacial dislocation network

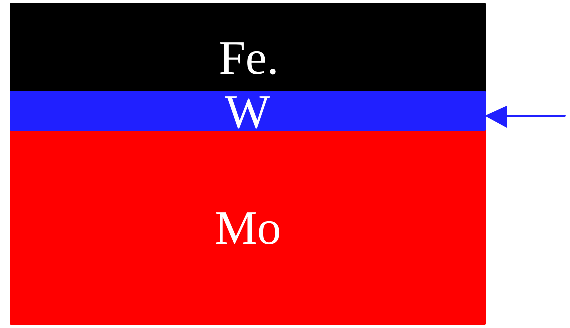



**Possible explanation = elastic energy minimization commensurate / incommensurate transition of interface dislocation array at the 'magical' thickness.**

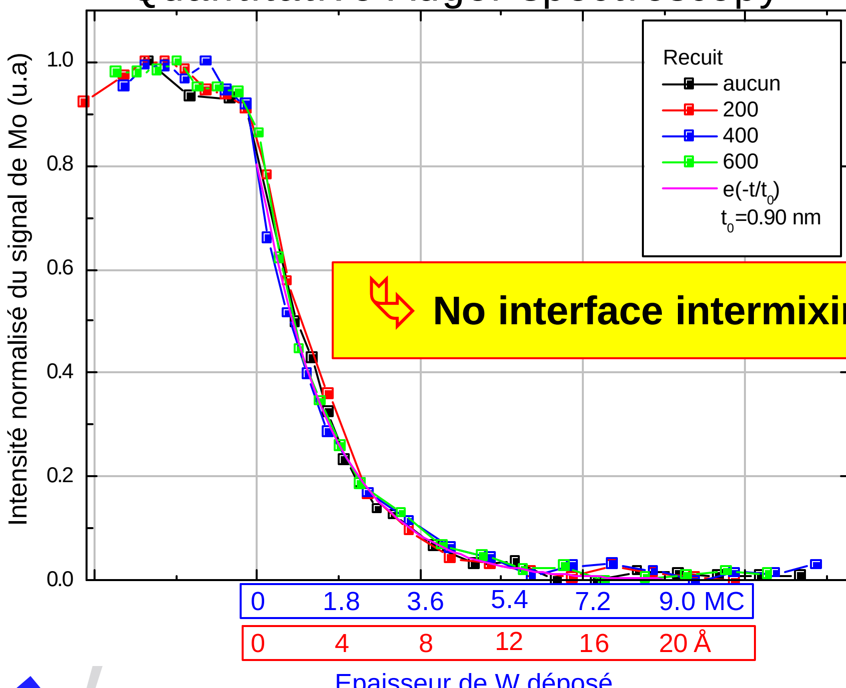


## Control interface independently from lattice parameter

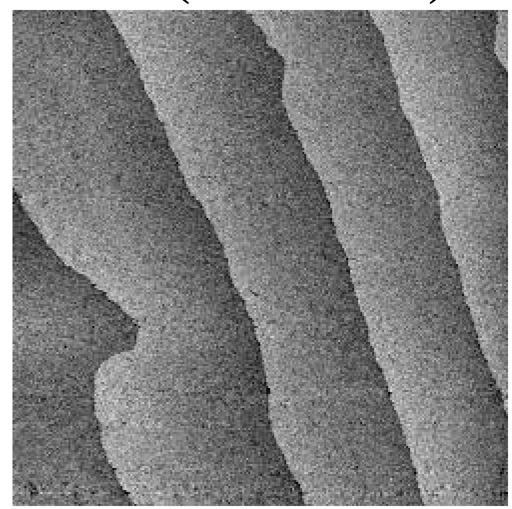

**25°C growth**
**+ 800°C Annealing**

Quantitative Auger spectroscopy




**No interface intermixing**

STM (800x800 nm)

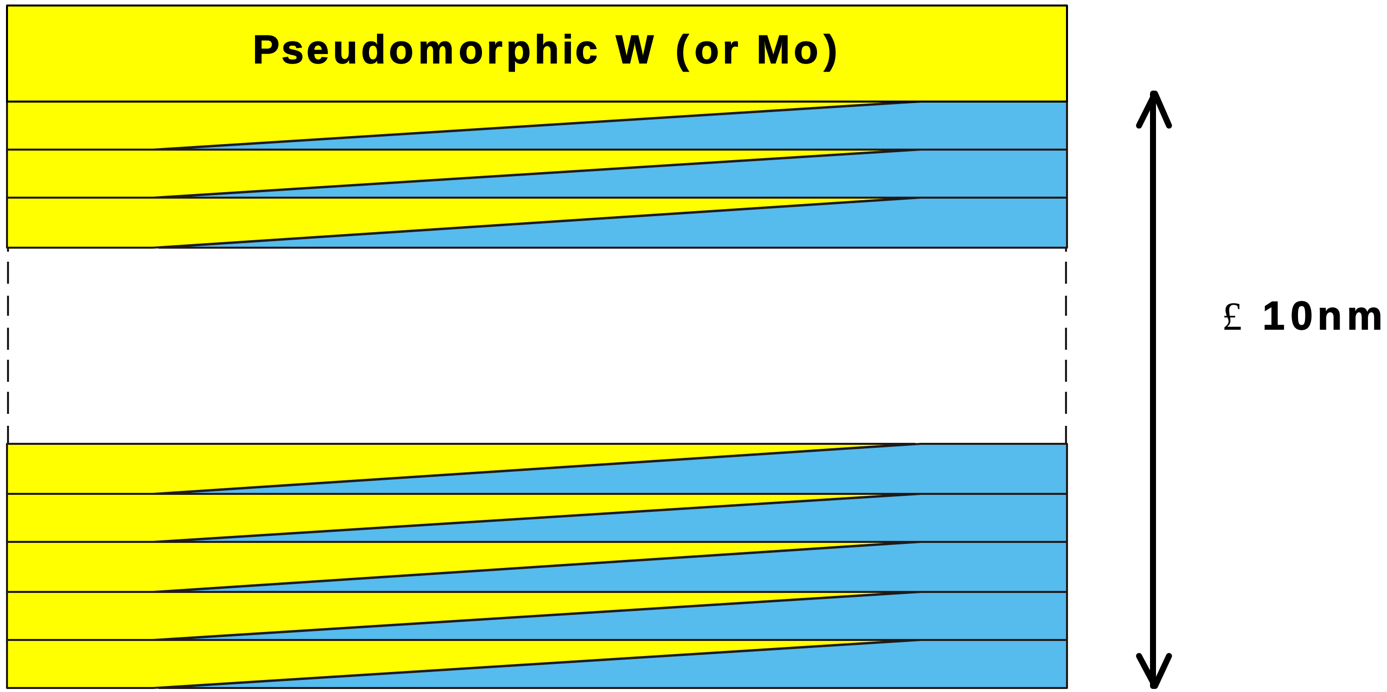


**Atomically-flat surface**

# Continuous control of lattice parameter

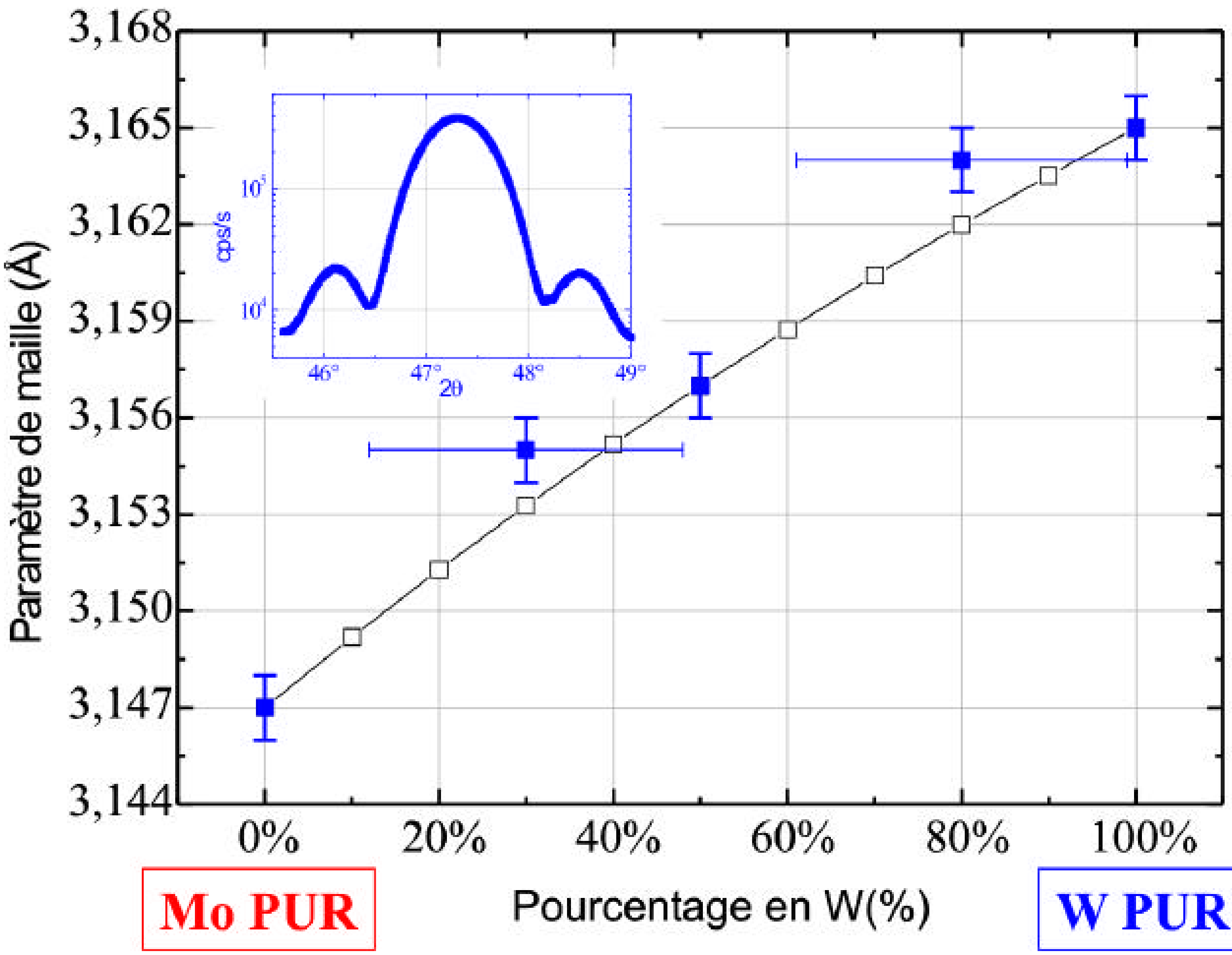
## Opposite wedges

3.165 Å **W** — ‘mixture’ ⇨ ~ Solid solution — **Mo** 3.147 Å




- Continuously variable buffer layer lattice parameter
- Atomically flat surface; atomic steps array

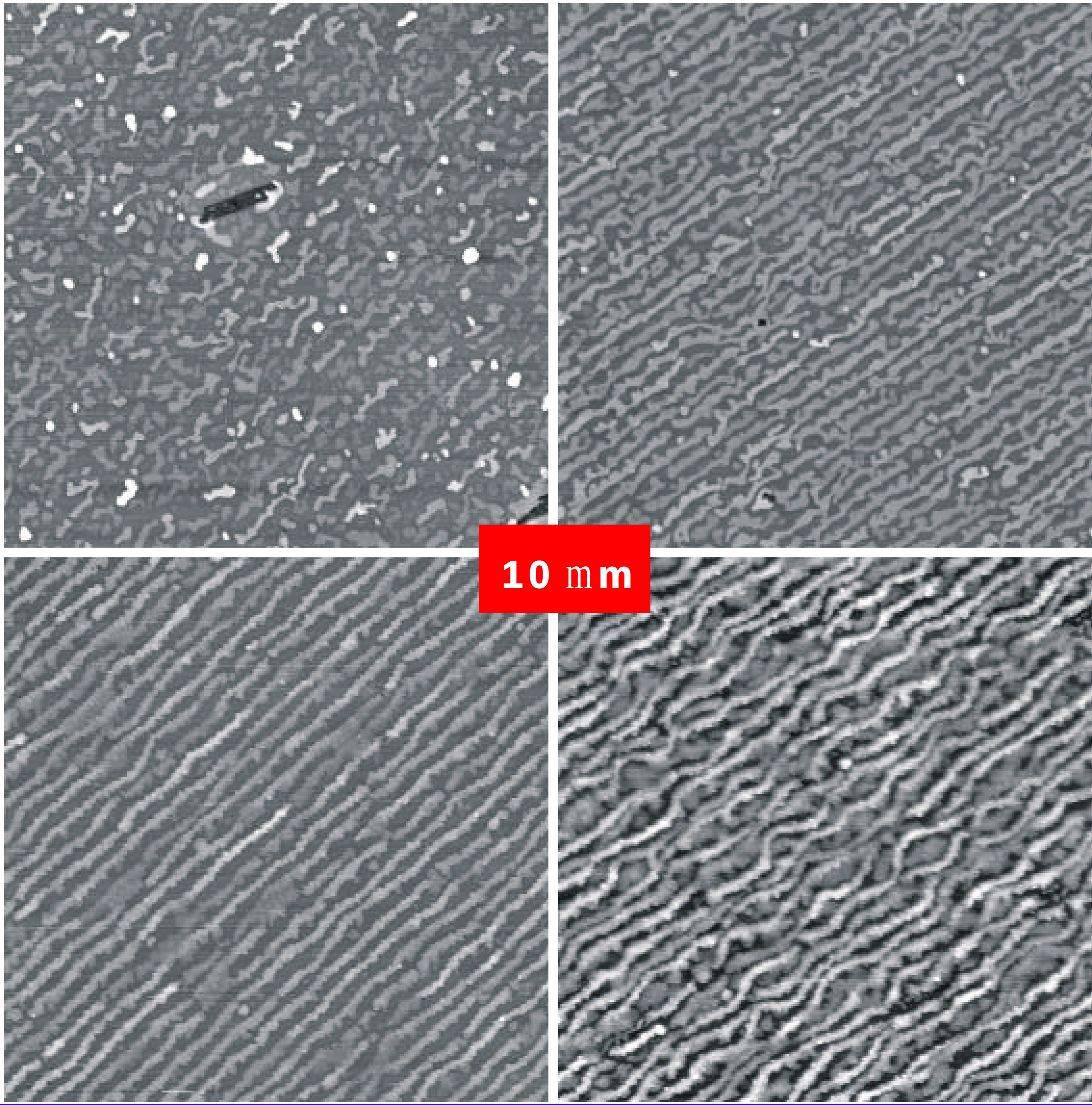
## Continuous control of lattice parameter




In-plane lattice parameter from $a_{Mo}$ = 3.147 Å to $a_{W}$ = 3.165 Å

**Sapphire \ Mo(8nm) \ interface \ Fe(150°C, 450°C annealing)**

1nm | 2.5nm | Average thickness




Fe / W(<1nm) / Mo

Height : 4.5nm

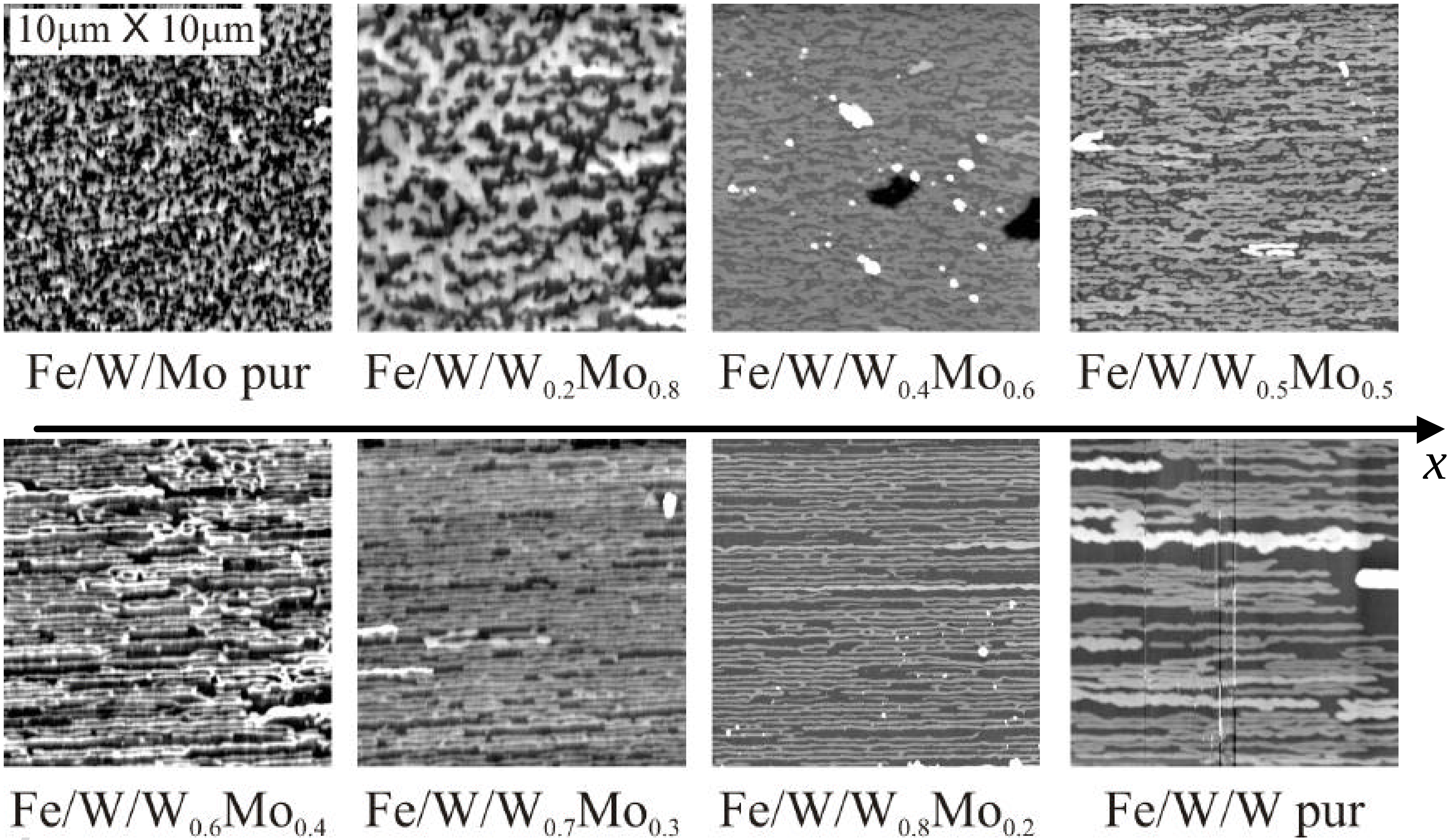
Fe / Mo

Height : bimodal 1.5 / 4nm

Chemical interface

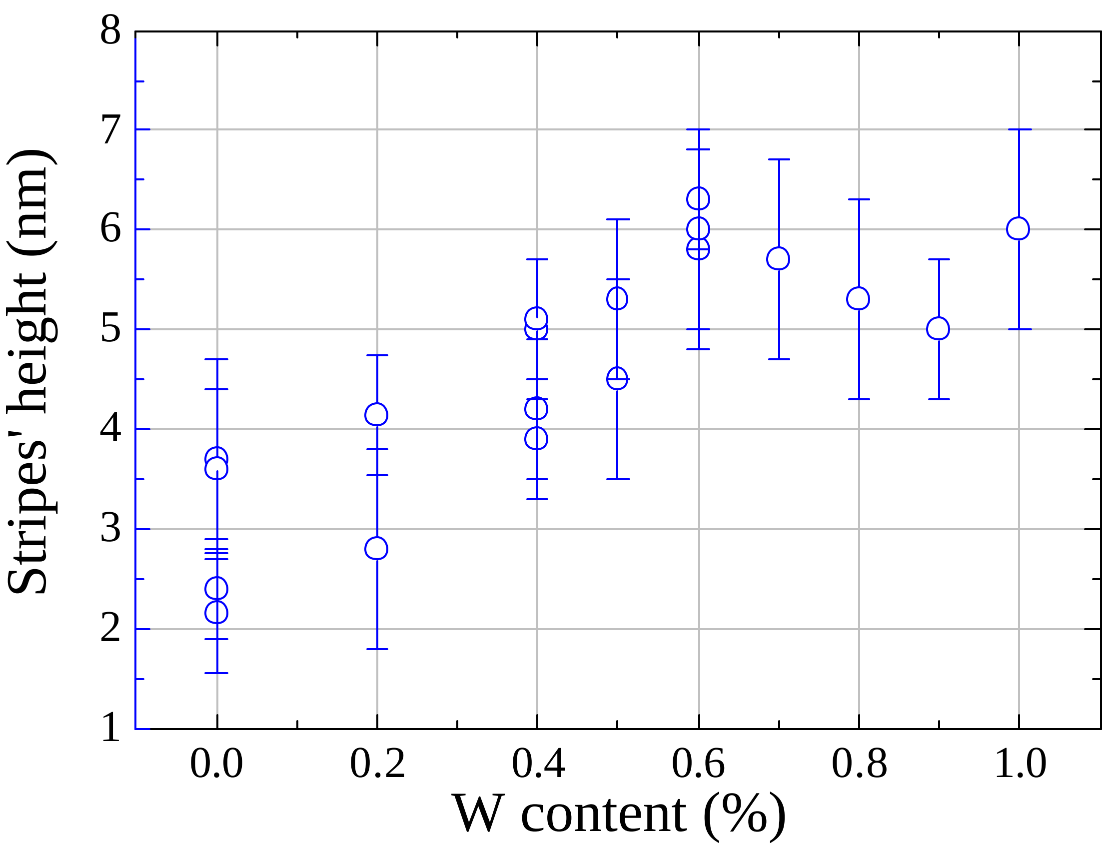
## Continuous control of lattice parameter

### Dramatic effect on stripe growth



## Continuous control of lattice parameter

### Significant effect on stripe height

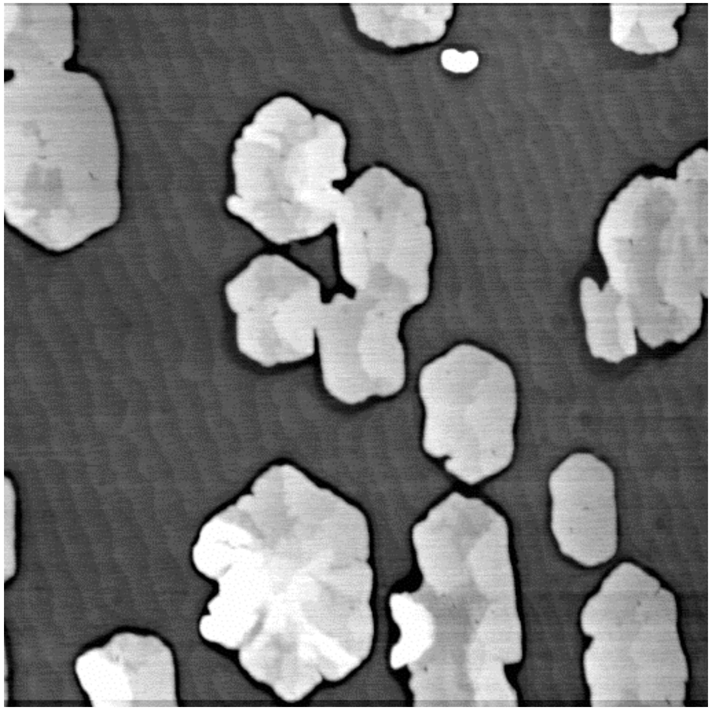



- Hypothesis of commensurate/incommensurate transition needs to be confirmed

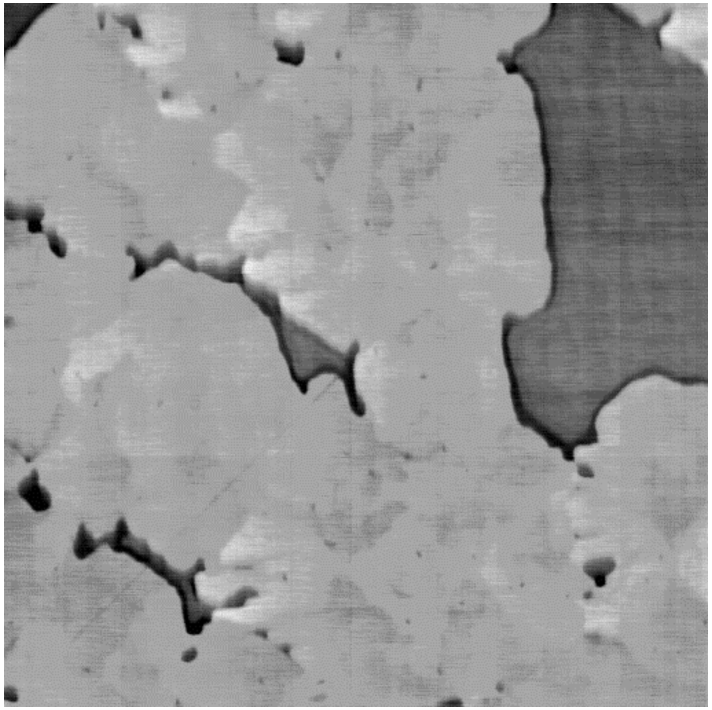
## Continuous control of lattice parameter

**Similar effect on patches of metastables height**

**Fe(110) / $W_xMo_{1-x}$ at 800°C**



**3 ML Fe / Mo(110)**



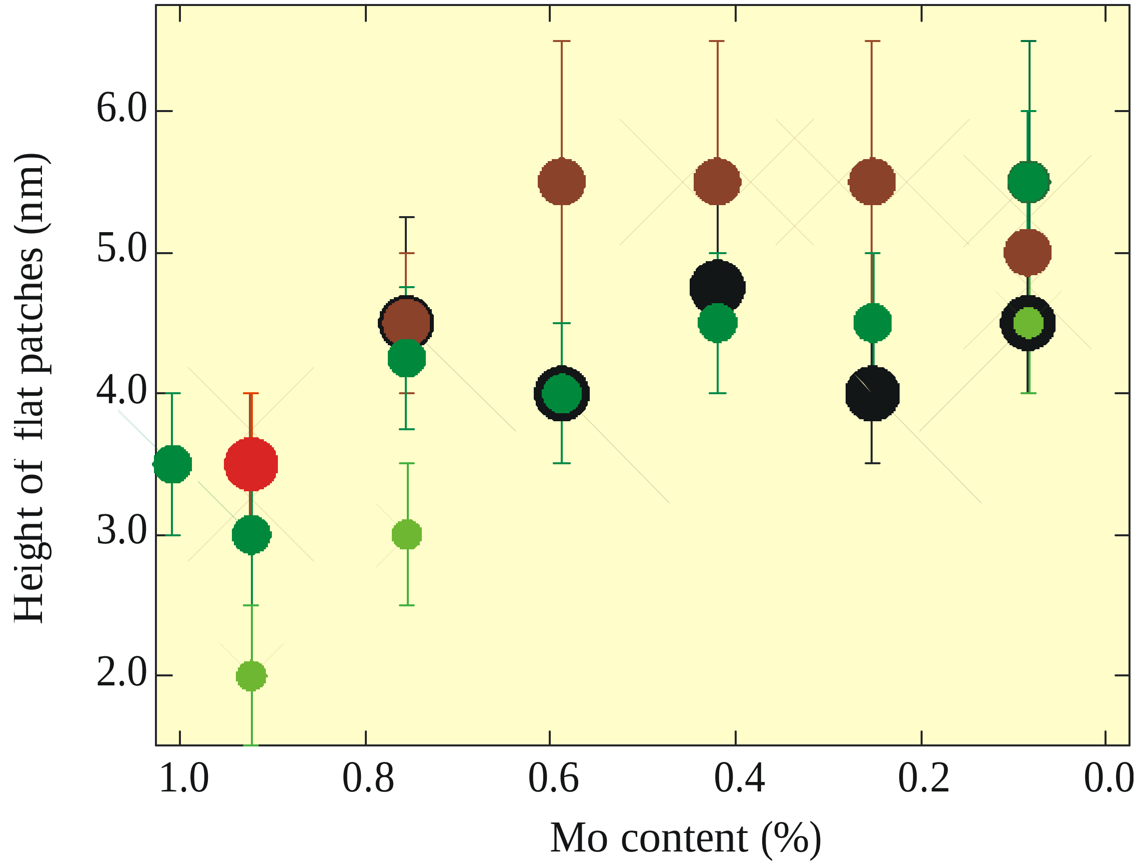
**6 ML Fe / Mo(110)**

↳ Only patches of metastable height form at very high temperature (no 3D dots)

## Continuous control of lattice parameter

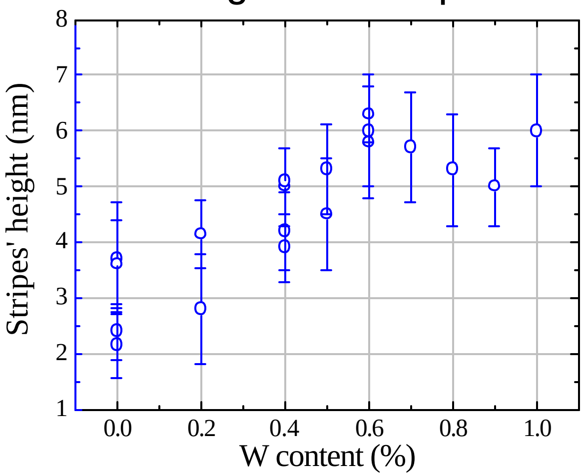
**Similar effect on patches of metastables height**

**Fe(110) / W(3ML) / $W_xMo_{1-x}$ at 800°C**




Reminder:

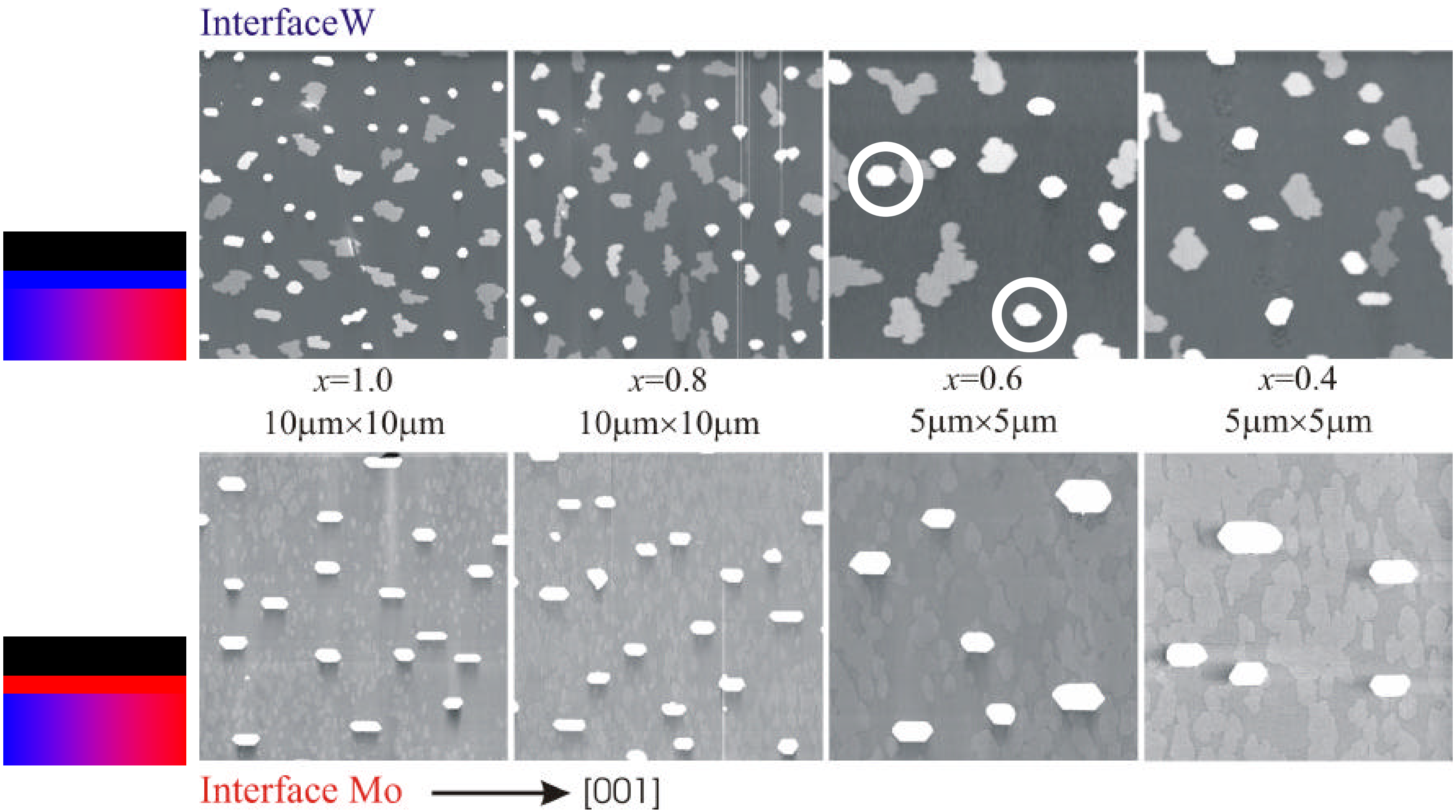
Height of stripes




Same height for ‘thick’ stripes (moderate temp. Plus annealing) and flat patches (high temp. Growth)

⇘ Thermodynamic property – Origin to be confirmed

## Lattice parameter : weak effect on dots

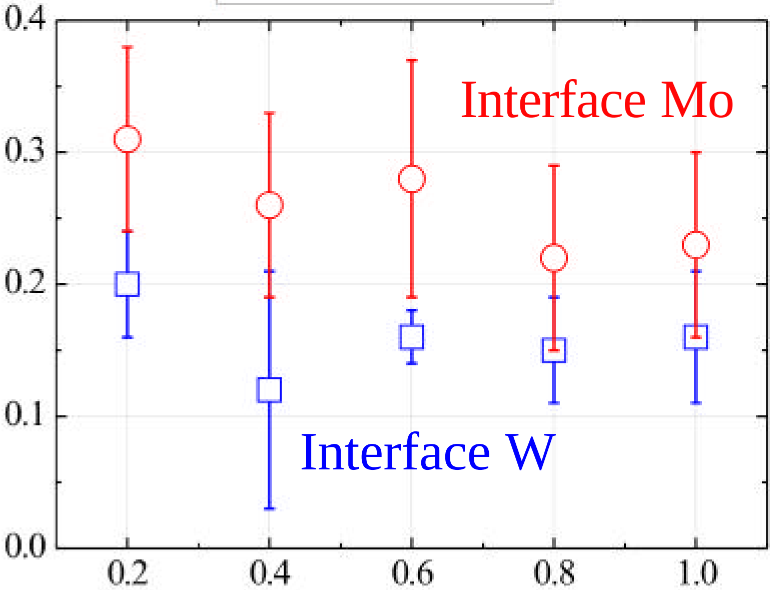



Differences: size, shape, density, aspect ratios

## Weak lattice parameter change : no effect on dots

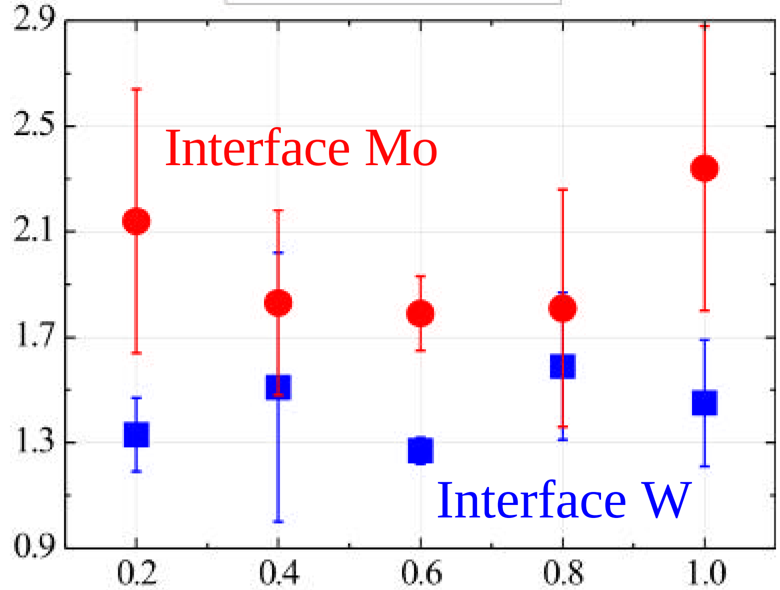
### Vertical aspect ratio

$$\eta = H/W$$

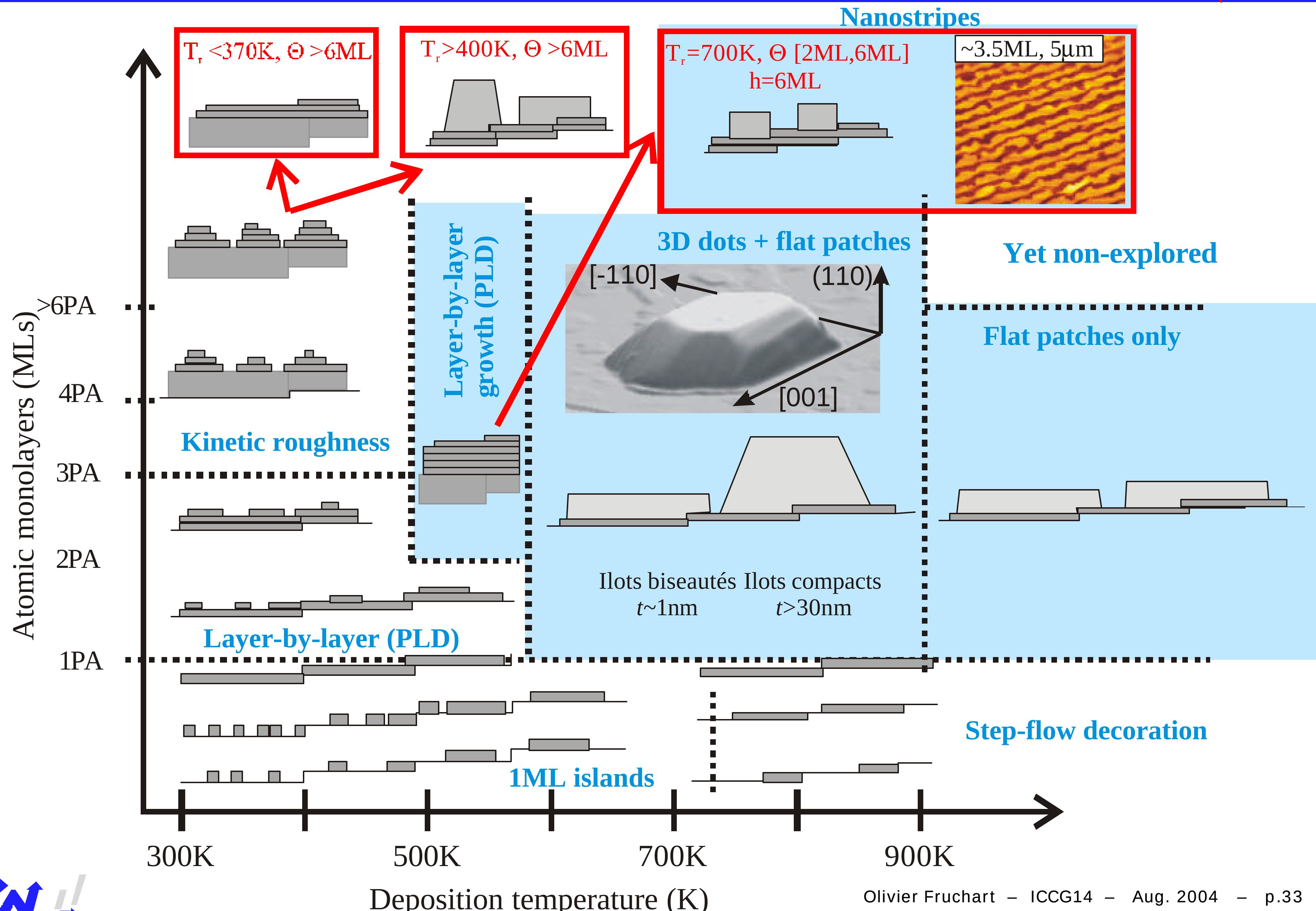



### In-plane aspect ratio

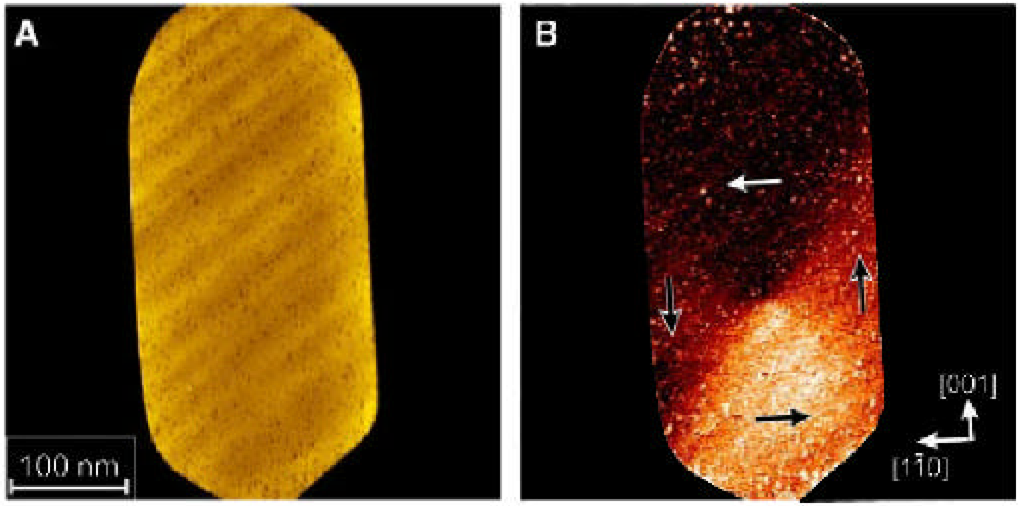
$$r = L/W$$




$x$: $W_x Mo_{1-x}$


Nanostripes
$T_r$ <370K, Θ >6ML
$T_r$>400K, Θ >6ML
$T_r$=700K, Θ [2ML,6ML]
h=6ML
~3.5ML, 5µm
Layer-by-layer growth (PLD)
3D dots + flat patches
Yet non-explored
[-110]
(110)
[001]
Flat patches only
>6PA
4PA
3PA
2PA
1PA
Kinetic roughness
Ilots biseautés
t~1nm
Ilots compacts
t>30nm
Layer-by-layer (PLD)
Step-flow decoration
1ML islands
Atomic monolayers (MLs)
300K
500K
700K
900K
Deposition temperature (K)

## Literature W




A. Wachowiak et al., Science 298, 577 (2002)

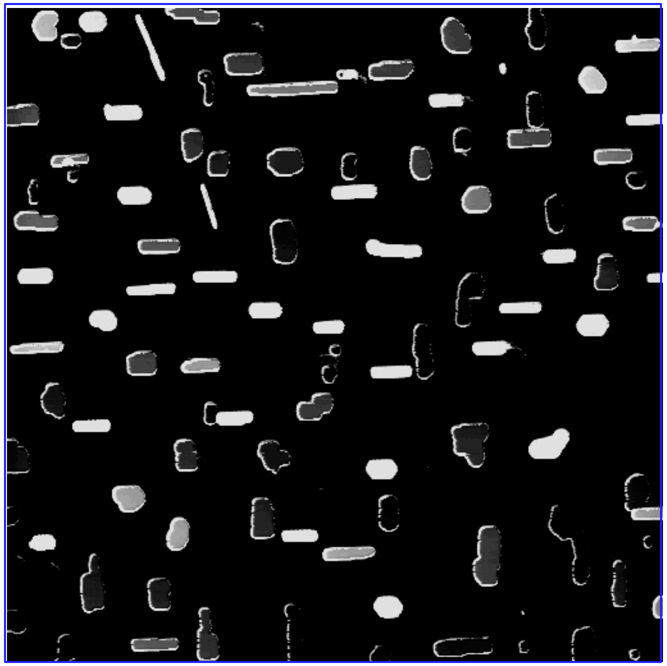
**Deposition at RT** on W (8-10ML)
**Annealing at 800±100K**
Stepped substrate

Width=215nm

Height=8nm; $r=0.037$

Length=471nm; $\eta=1.93$

## Our data W



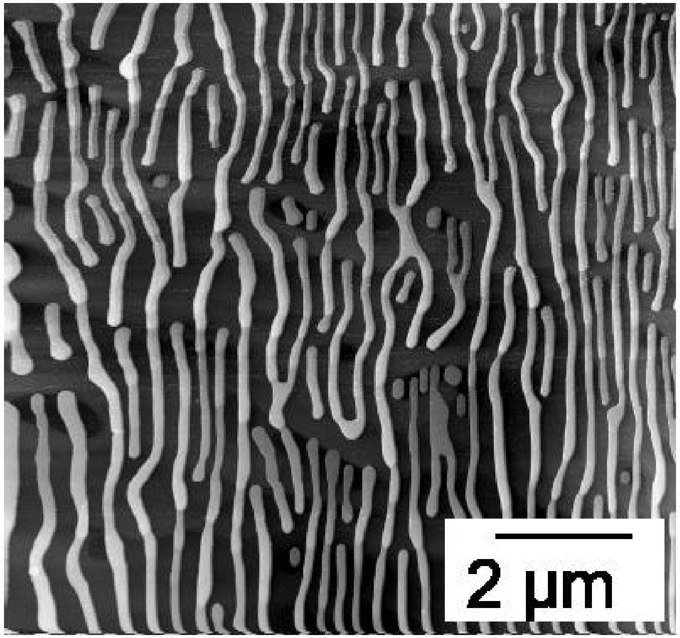
**Deposition at 775±50K**
Essentially flat substrate

Height ratio $r=0.07$

Length ratio $\eta=2.3$

**Consistent with 3D dots**

**Literature** W




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

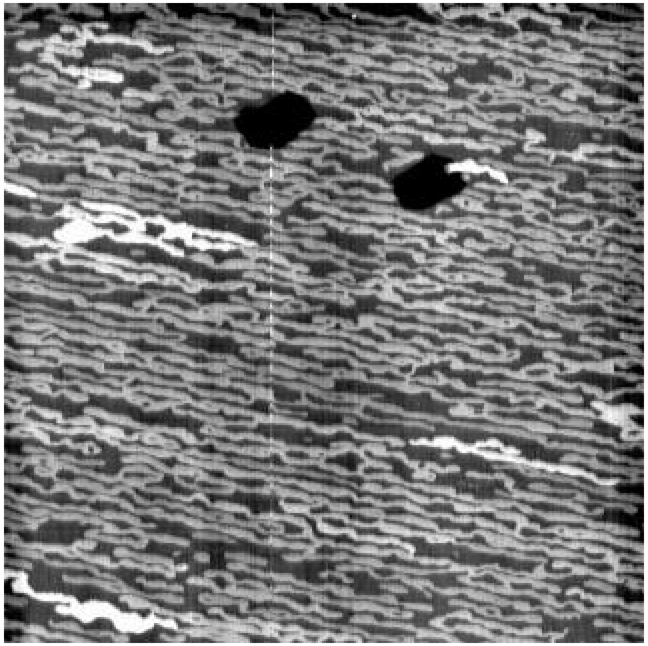
[see also Schmidt, private comm.]

**Deposition at 1000K** on W, or **deposition at RT and annealed 700-1000K**

Thickness=10-20nm (private comm.)

Wires **do not follow** atomic steps

**Our data** W



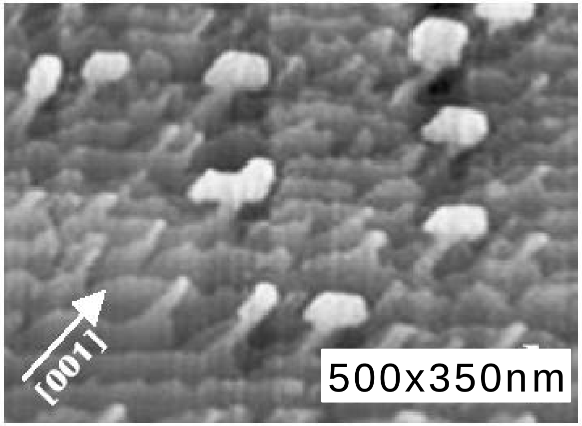
**Deposition at 500K** on W, **annealed 775±50K**

Thickness=5.5nm±0.5nm

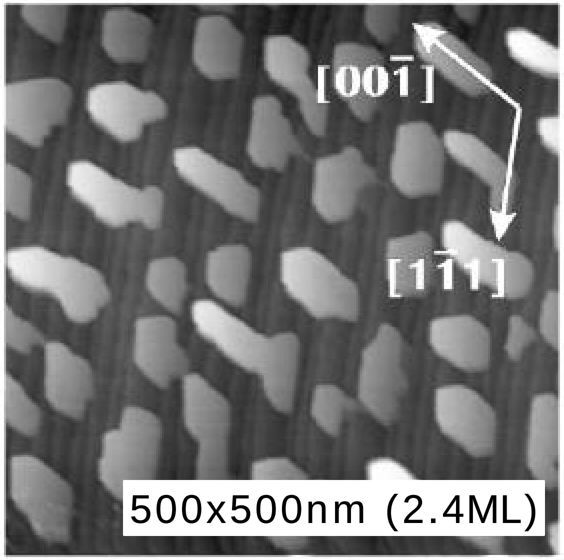
Wires **follow** atomic steps (1 per step)

**Deposition at the layer-by-layer growth temperature is essential to keep the information about the atomic steps**

**Literature** **Mo**

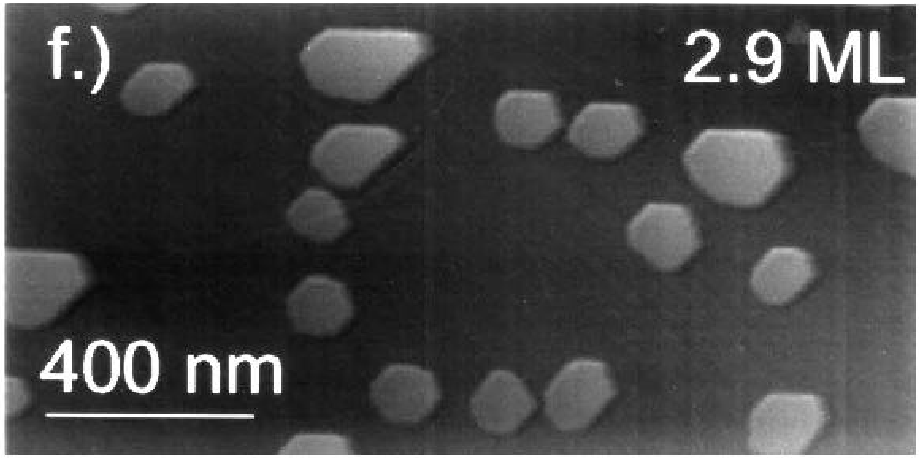



I. V. Shvets et al.,
cond-mat/0405148 (2004)




S. Murphy et al., PRB66, 195417 (2002)

**Deposition at ~495K** on Mo
Stepped substrate




J. Malzbender et al., Surf. Sci. 414, 187 (1998)

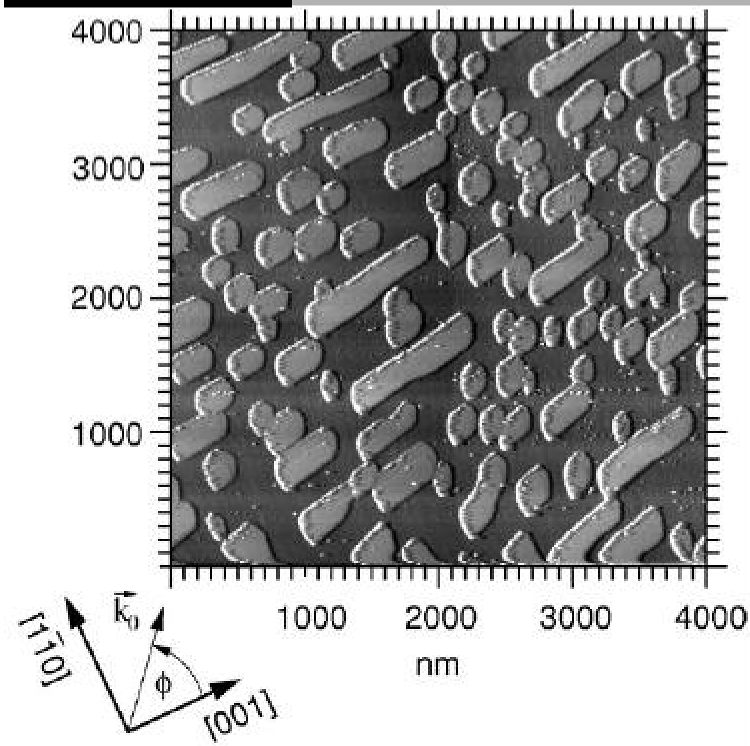
[See also: Bethge et al., Koehler, Surf. Sci 331/333 (1995) 878.]

**Deposition at 600K** on Mo (2.9ML)

Largest thickness=10ML

**Consistent with flat dots**
**Onset of 3D growth not reached yet ?**

## Literature W



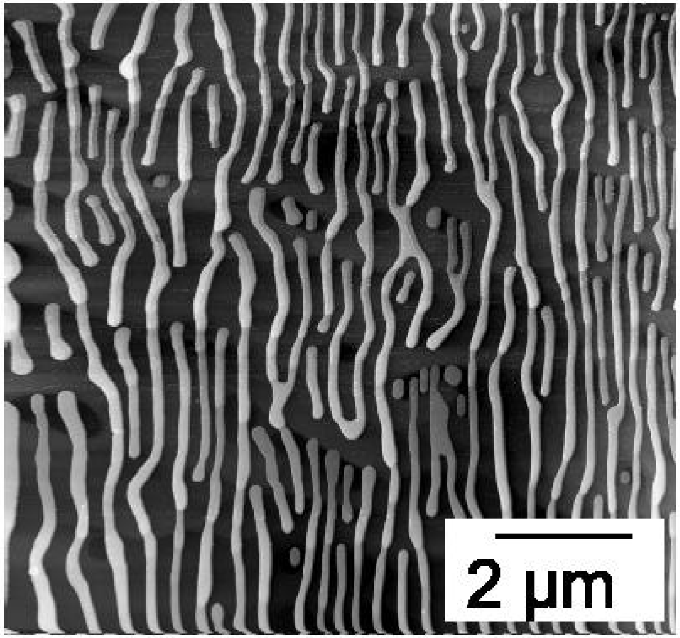

R. Röhlsberger et al., PRB67, 245412 (2003)

Deposition at RT on W (5ML)
Annealing at 700K

Width=195nm

Height=3.7±0.8nm; $r$=0.019

Length=distributed
(Cf our experiments)

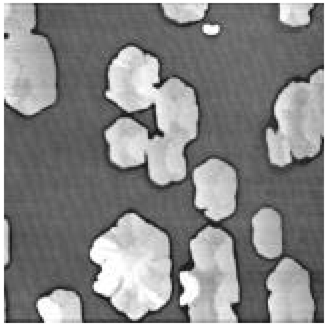



D. Sander, Rep. Prog. Phys. 62, 809 (1999)

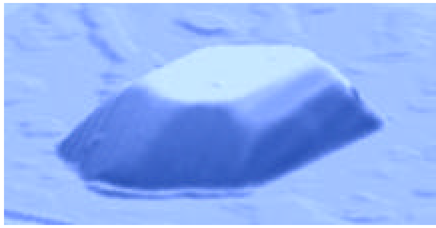
Deposition at 1000K on W, or deposition at RT and annealed 700-1000K

Largest thickness=10ML

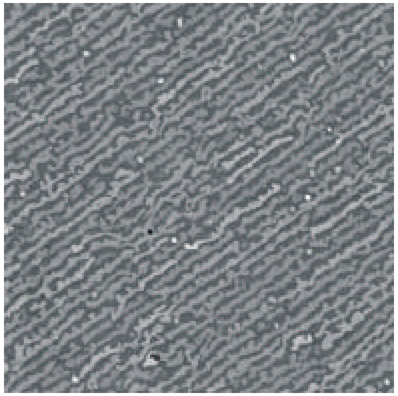
**In principle, same parameters used.**
**Influence of the step density?**



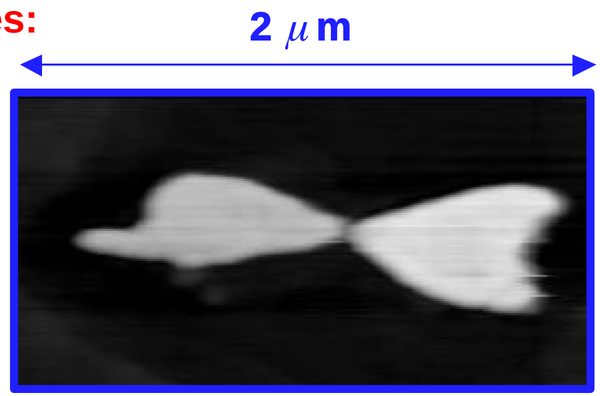
## Growth of Fe(110) revisited



- Evidence for bimodal island growth
- Attempt to separate interfacial and mismatch effects

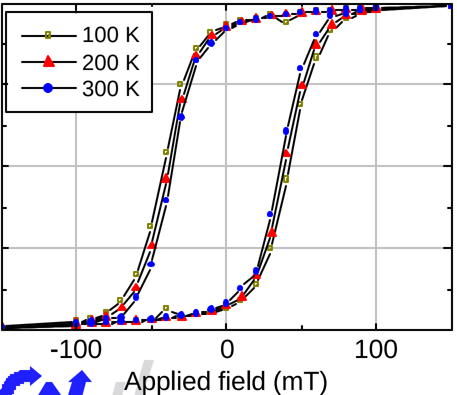


- Tunability of the geometry of nanostructures:
  * aspect ratios of 3D dots
  * height of the stripes



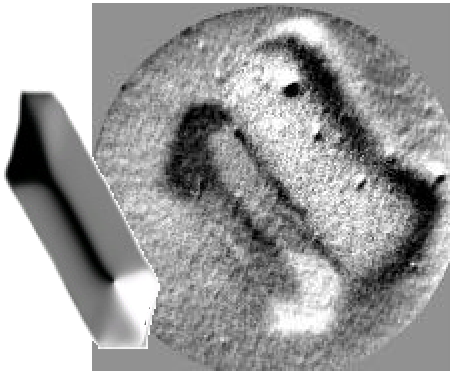

- New self-assembled systems
  Ex: nano-tie-knots

## Self-assembly for magnetism




(see T02-1079, Friday)

- Micromagnetism in 3D dots
- Self-organized stripes magnetically functional at 300K
- Domain wall in constriction (nano-ties)



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Growth and magnetism

Crystallography laboratory - Grenoble (France)

**L. Ortega**

X-ray diffraction

**Special issue on Self-organization at surfaces**

Compte-Rendus Physique (C. R. Phys.), (~Jan.2005),
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