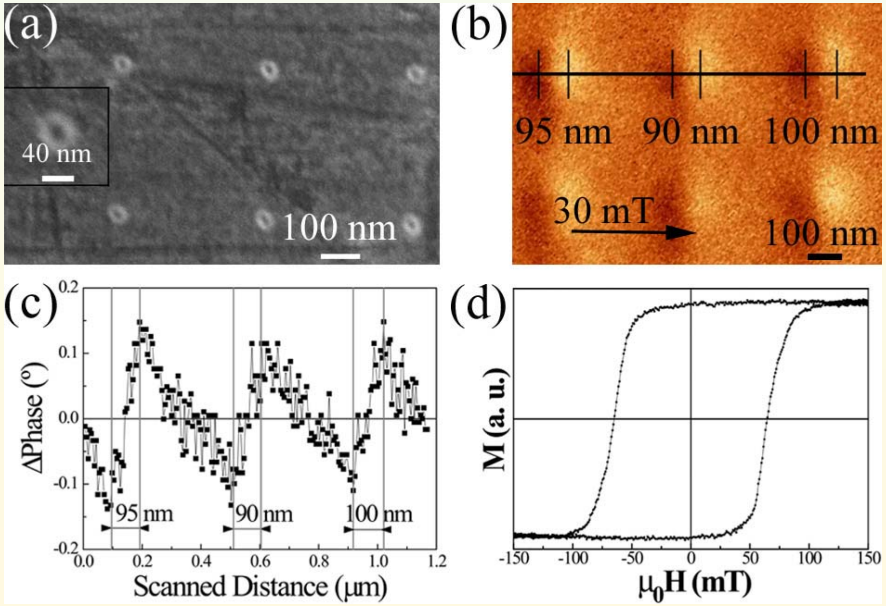
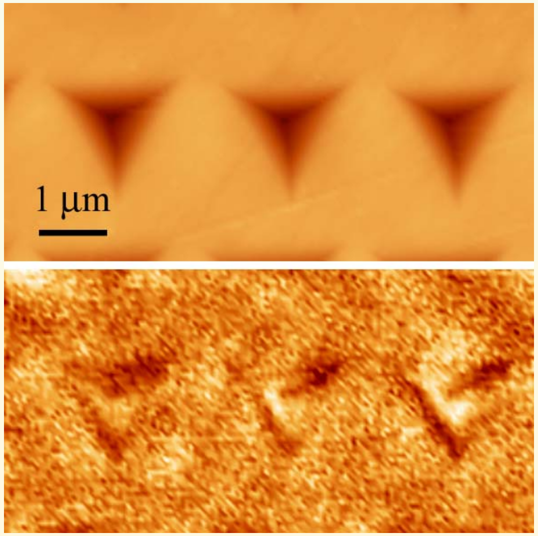
Direct nanoscale magnetic patterning in FeAl alloys by means of ion irradiation

J. Nogués,

ICREA and Institut Català de Nanotecnologia, Spain





COLLABORATORS

E. Menéndez, J. Sort, S. Suriñach, M. D. Baró, *Universitat Autònoma de Barcelona, Spain*

M.O. Liedke, T. Strache, W. Möller, J. Fassbender, *Inst. of Ion Beam Physics and Materials Research, Germany*

K. V. Rao, *Royal Institute of Technology, Sweden*

S. C. Deevi, *Philip Morris, USA*

A. Weber, L.J. Heyderman, *Paul Scherrer Institut, Switzerland*

T. Gemming, *IFW Dresden, Germany*

J. Sommerlatte, *Max Planck Inst. of Microstructure Physics, Germany*

K. Nielsch, *Universität Hamburg, Germany*

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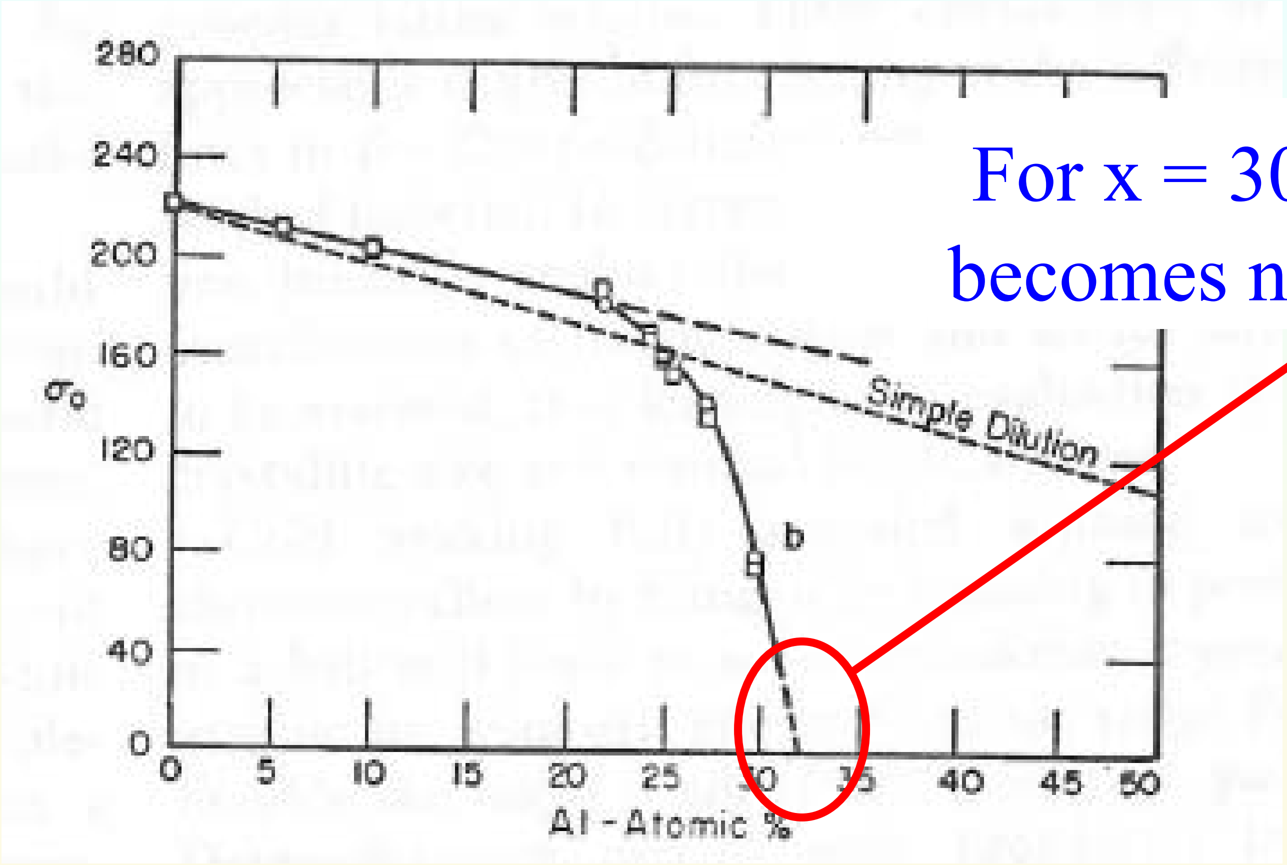
Outline

- Introduction
  - Structural disorder and ferromagnetism in FeAl
- Ferromagnetism induced by nanoindentation
- Ferromagnetism induced by ion beam irradiation
  - 2.1. Non-focussed ion beam irradiation using masks
  - 2.2. Focussed ion beam
- Limits of the technique
- Conclusions

$Fe_{1-x}Al_x$ exhibits unusual magnetic properties

<u>Ordered alloy</u> at room temperature

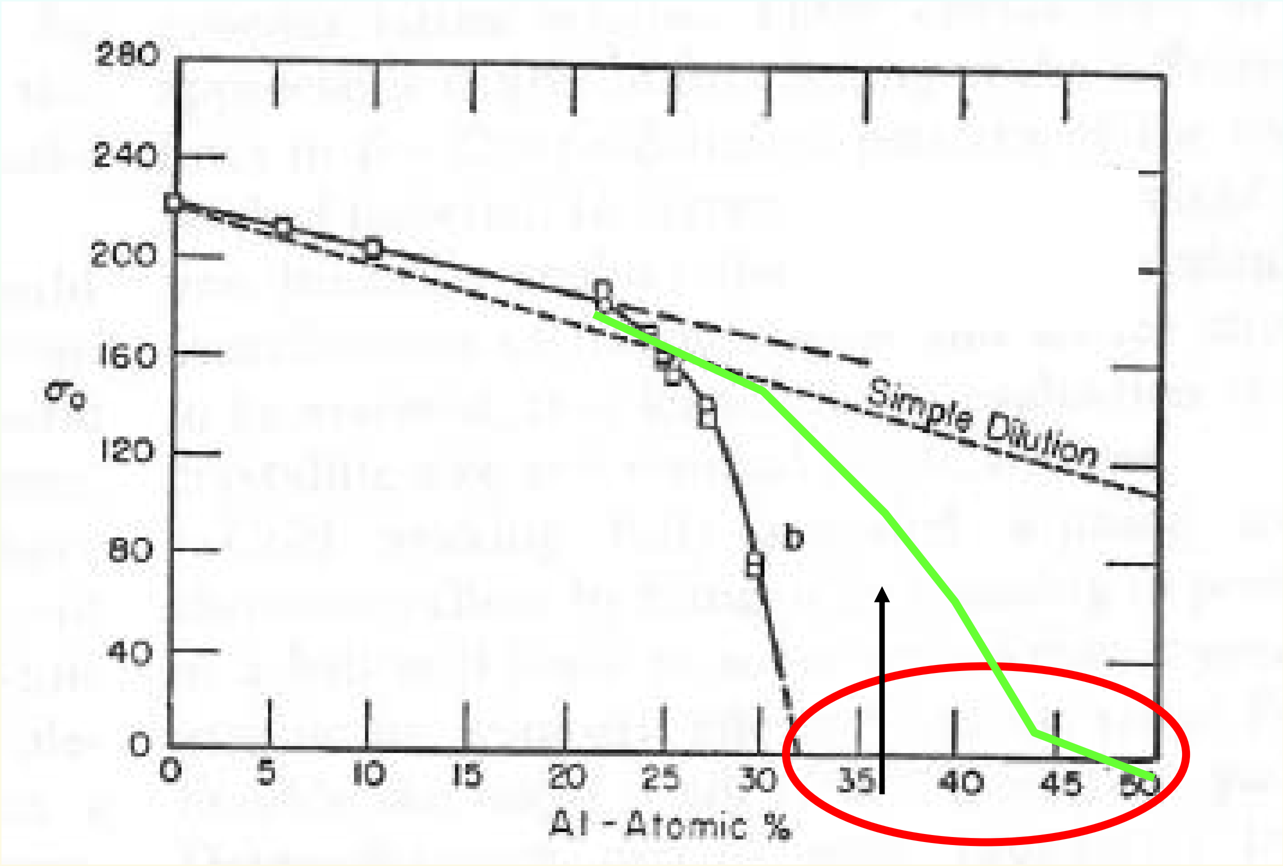


For x = 30 it becomes non-magnetic

A. Taylor and R. M. Jones, J. Phys. Chem. Solids. ***6*** *(1958) 16.*

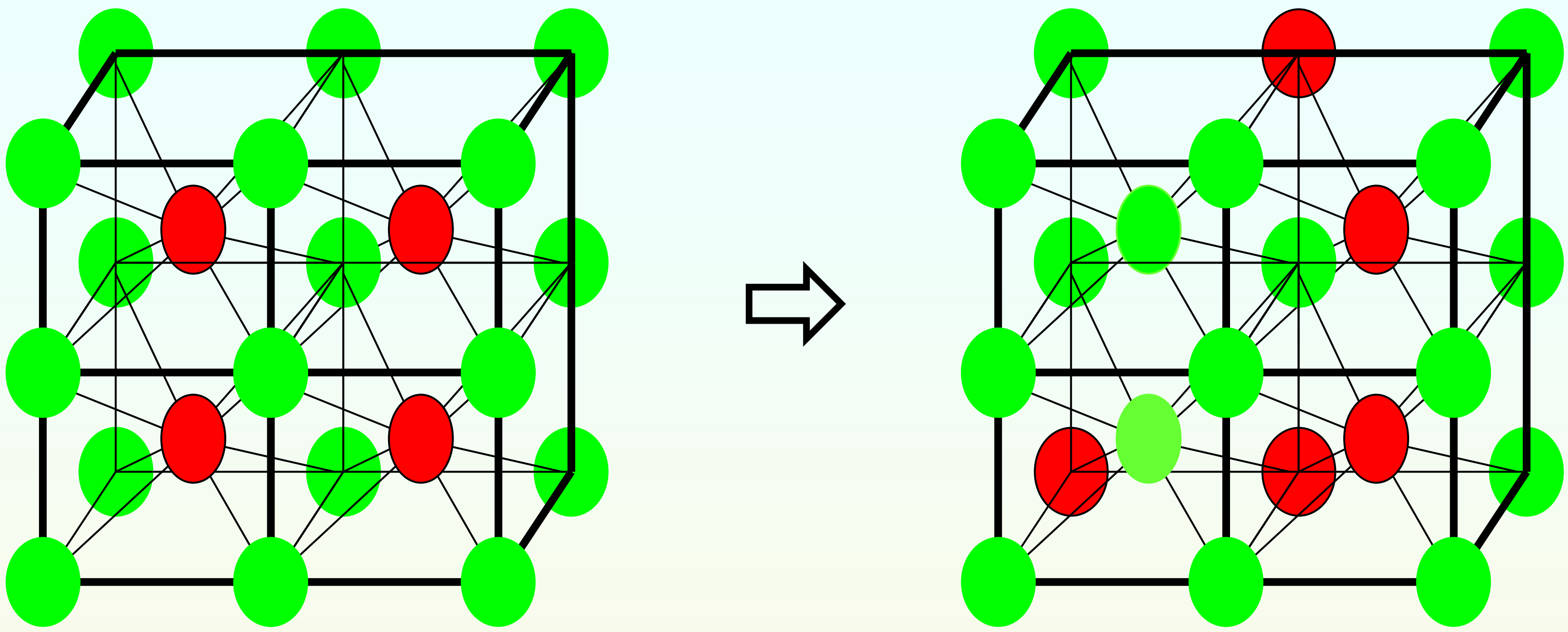
The dilution law is not followed

What happens if we disorder an alloy with an Al content higher than 32 % ?



Ferromagnetism is induced !!!

Disordering process → Fe atoms become locally surrounded by Fe → Ferromagnetism



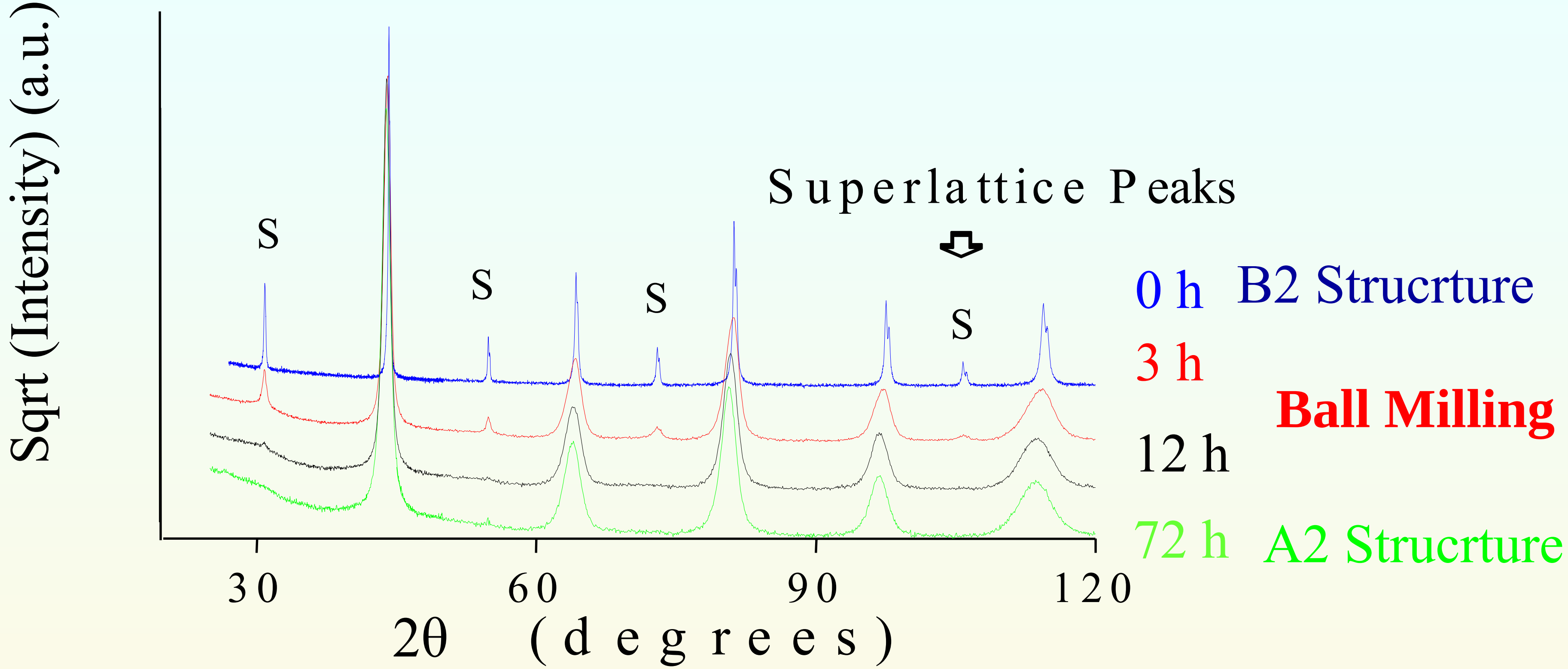
Ordered FeAl (B2)

Disordered FeAl (A2)

Fe atoms are surrounded by Al

Fe atoms become **<u>locally</u>** surrounded by Fe !

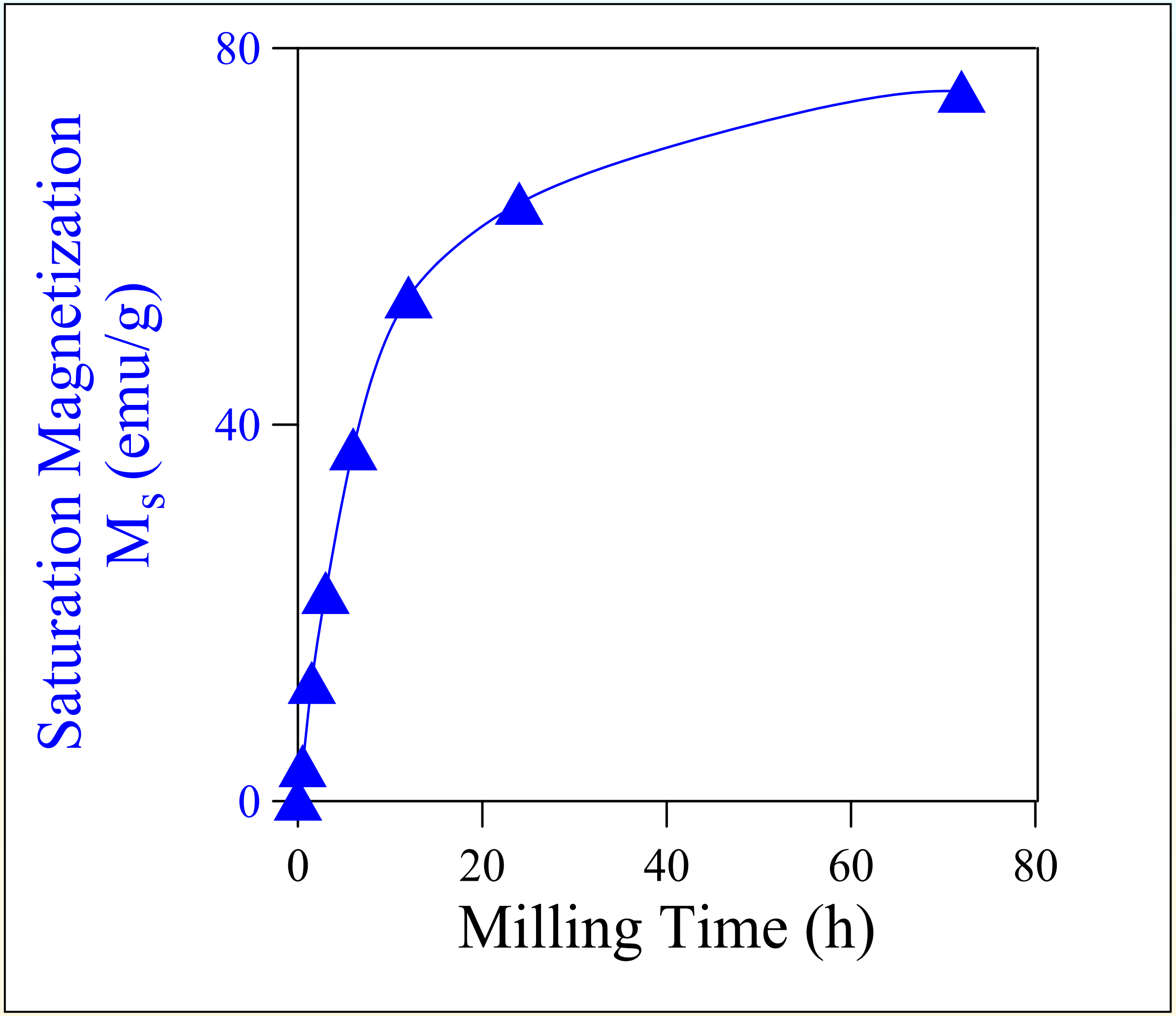
Disoder in this type of alloys has been traditionlly induced by quenching, cold rolling or mechanical milling.



-The supperlattice peaks disappear ⇨ The material stucturally disorders

-The peaks become broadened ⇨ Crystallite size diminishes

Ferromagnetism is induced !



Aim of this work:

- **To generate arrays of ferromagnetic dots surrounded by a non-magnetic matrix (minimizing interdot exchange interactions).**

- **To preserve a smooth surface to minimize tribological problems.**

- **To obtain large arrays of very small dots (sub-100 nm if possible) as fast as possible.**

Experimental Methods

Sample composition:

• Sheet (250 μm thick) prepared by cold-rolling with composition:

59.38%Fe-40%Al-0.19%C-0.18%Mo-0.05%Zr-0.2%B (at.%)

Sample treatments prior to structural disorder:

- Mechanical polishing to mirror appearance using diamond paste.

- Annealing at 900 K for 20 min to remove any traces of ferromagnetism induced by the polishing.

Nanoindentation

- Arrays of dots prepared by Nanoindentation (MTS, XP) using a diamond pyramidal-shaped Berkowich tip.

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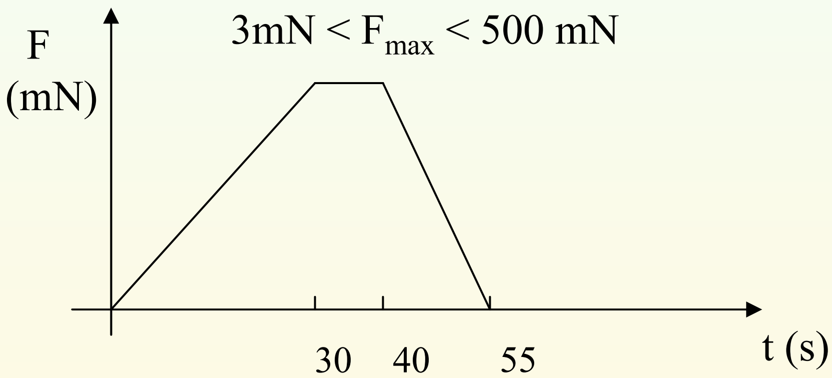
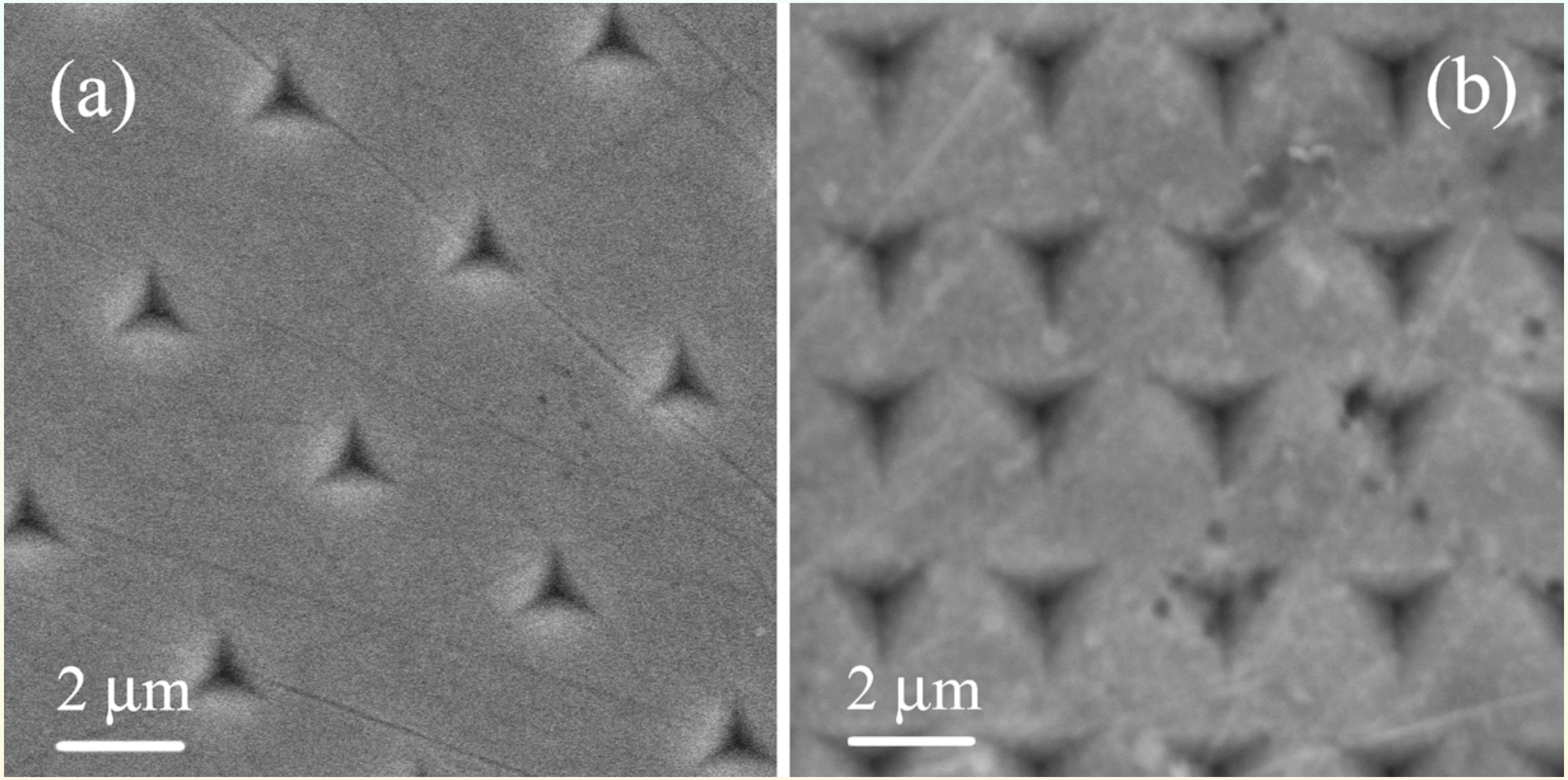


- Arrays of lines by dragging the indenter at 10 µm/s, applying 12 mN

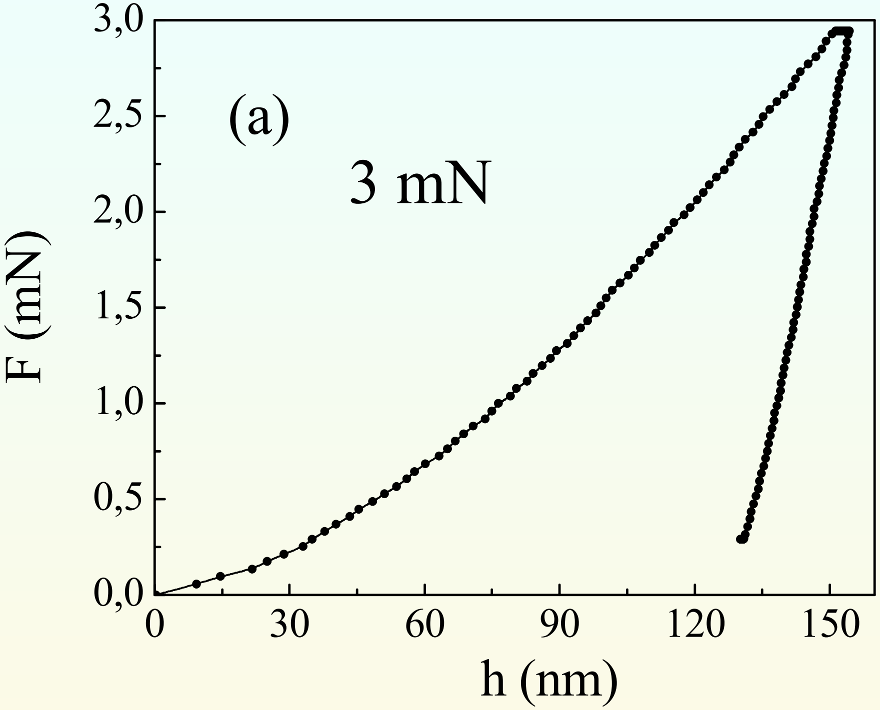
Arrays of dots produced by nanoindentation



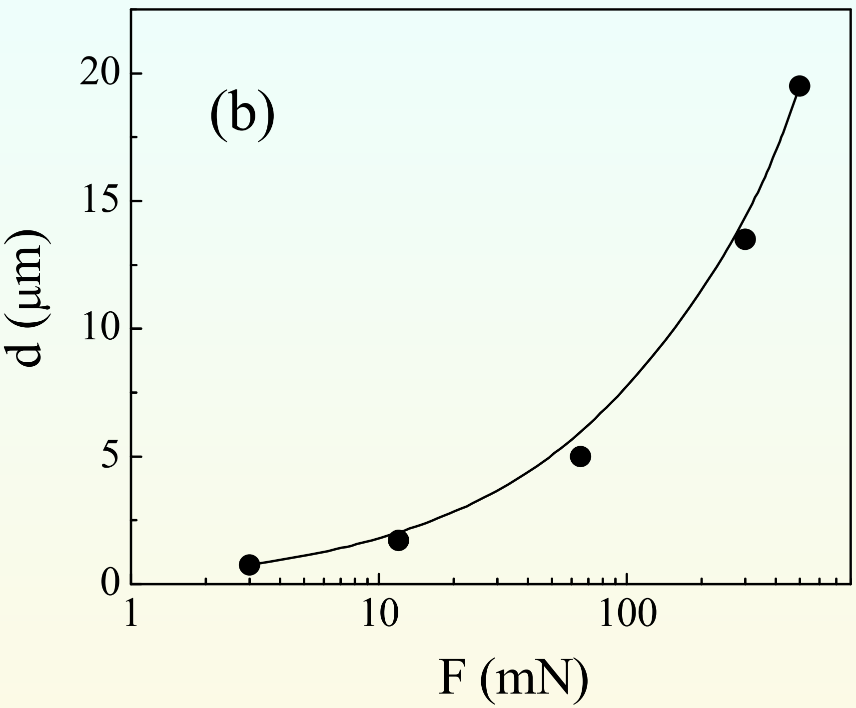
3 mN / 0.8 µm 12 mN / 1.7 µm

Local deformation by nanoindentation

Control of the indentation size

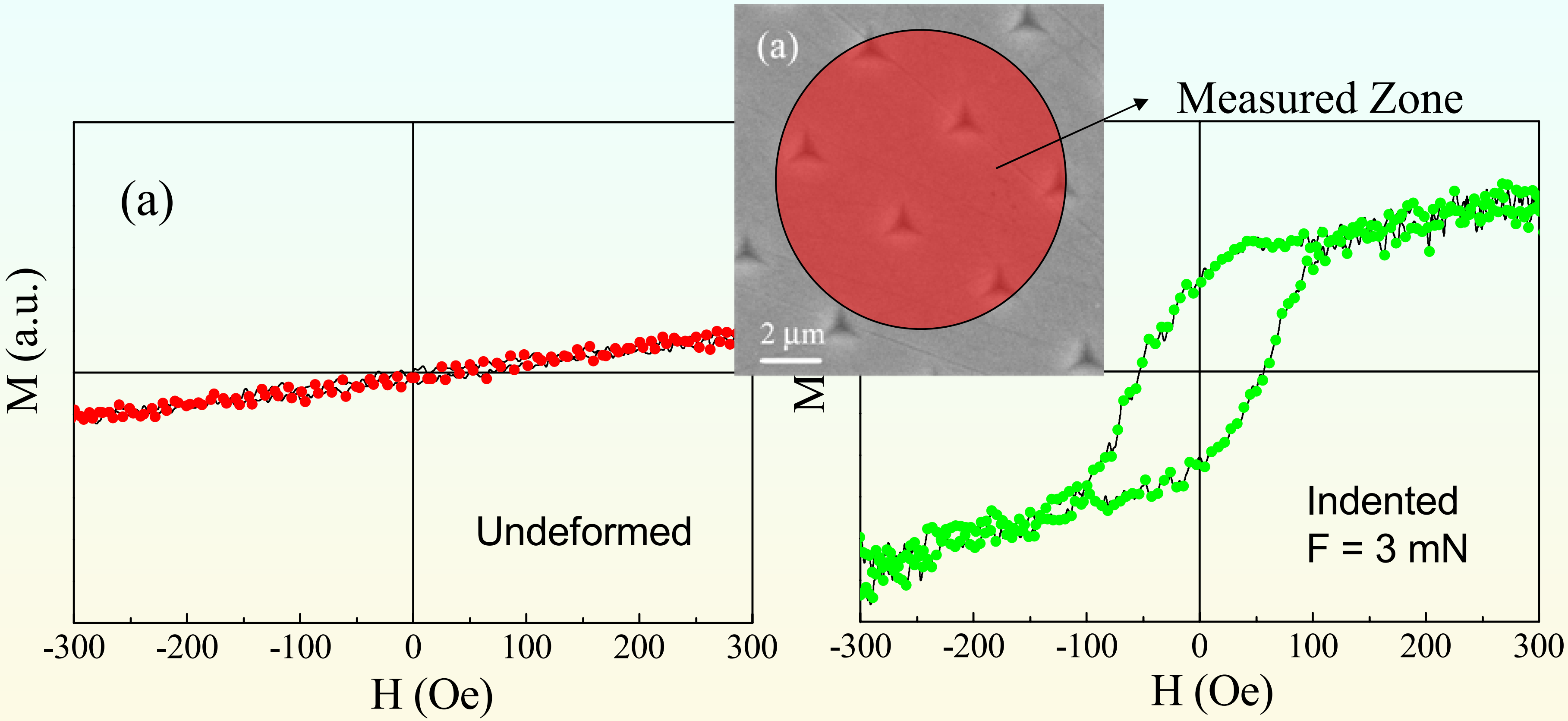


Force vs. depth dependence



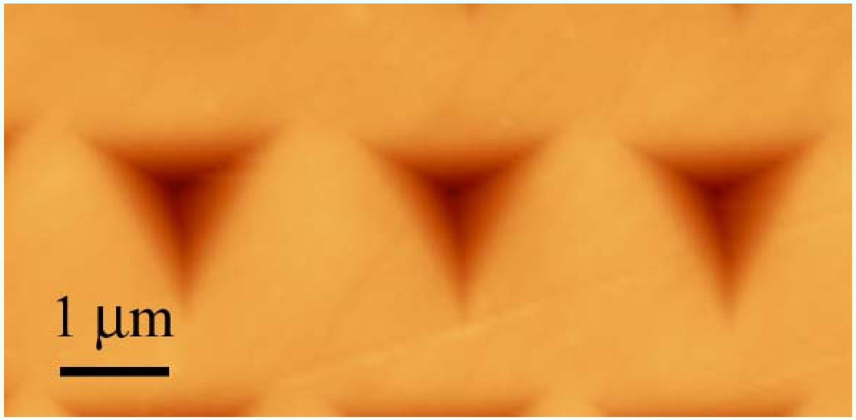
Indentation lateral size vs. force

Hysteresis loops

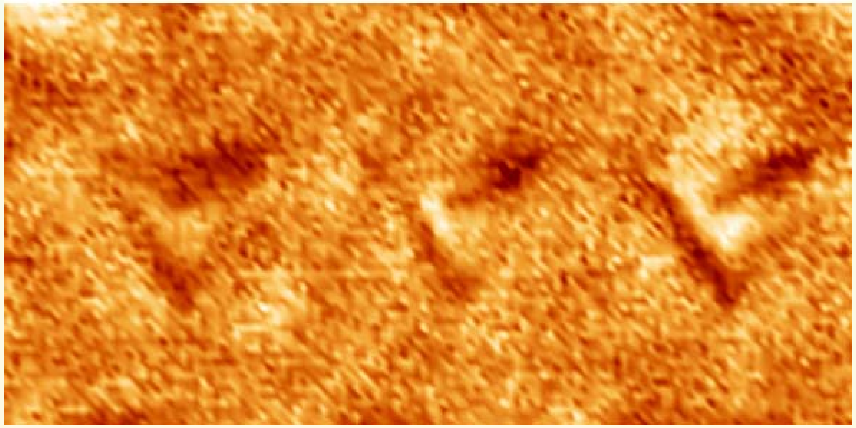


Is the induced magnetism indeed **<u>local</u>**??

Only the deformed regions are magnetic !



Atomic force microscopy

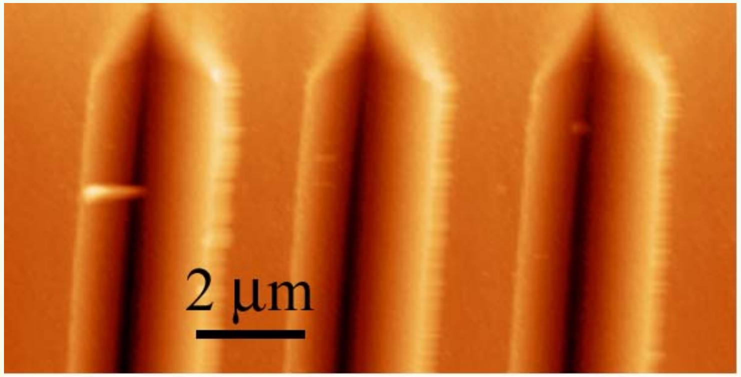


Magnetic force microscopy

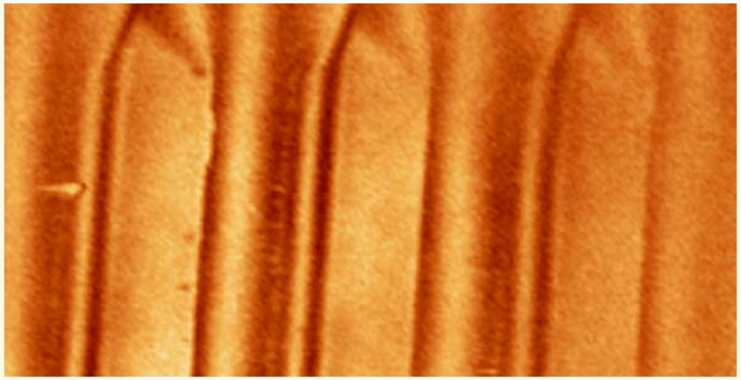
Surface deformation accompanies the magnetic patterning

Other geometries possible by dragging the indenter

Sweep rate 10 μm/s, applied force 12 mN



Atomic force microscopy



Magnetic force microscopy

- Is it possible to obtain smaller ferromagnetic dots ?

- Is it possible to obtain dots with other geometries ?

- Is it possible to fabricate magnetic dots (magnetic patterning) without causing surface etching ?

→ **ION IRRADIATION**

Experimental Methods: Ion Beam Irradiation

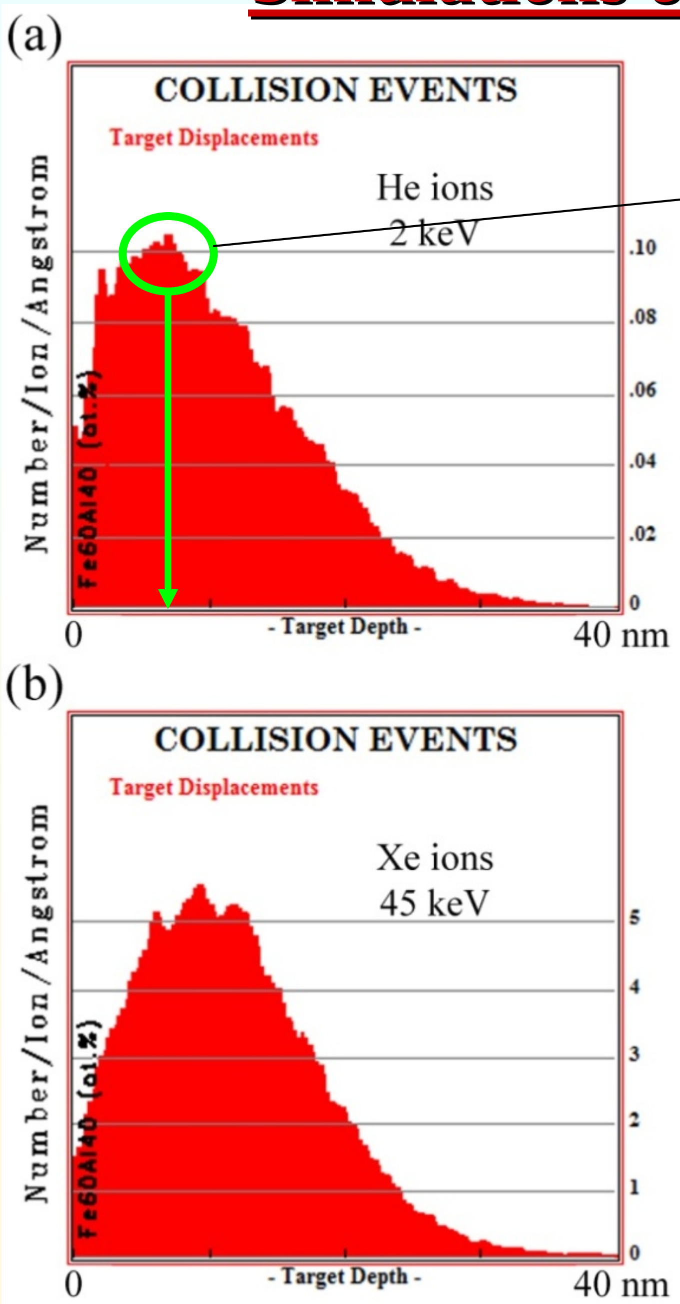
- **Two different approaches:**

a) Irradiation using a **low-energy, non-focussed ion implanter**.

- Energy of the different ions (**He^+, Ne^+, Ar^+, Kr^+, Xe^+**) adjusted to position the **maximum collisional damage at a depth of 10 nm**.
- Ion fluence (ions/cm^2) varied to obtain an average damage of **0.05 – 5 dpa** (displacement per atom) within the top 20 nm.
- **Arrays of ferromagnetic dots** obtained by ion irradiating through porous alumina and e-beam lithographed PMMA masks.

b) Irradiation using a **focussed ion beam** (**Ga^+ ions,** fluence of $1.5 \cdot 10^{16}$ ions/cm^2 corresponding to ≈ **50 dpa**).

Simulations of the Ion Beam Irradiation



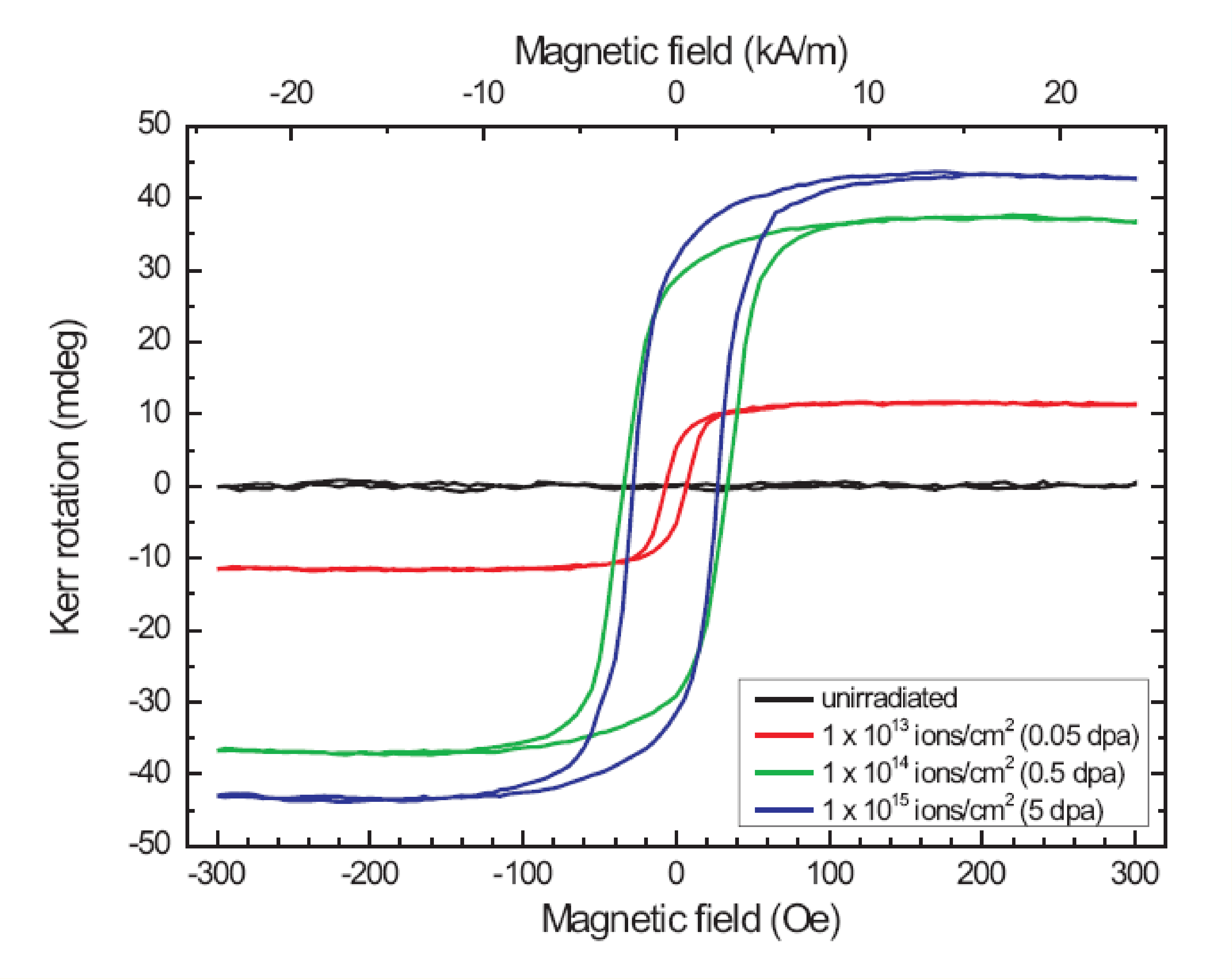
Maximum damage at about 10 nm depth

Irradiation conditions are selected from TRIM simulations

Average damage "displacement per atom", dpa, can also be obtained. It allows qantitative comparison between atoms.

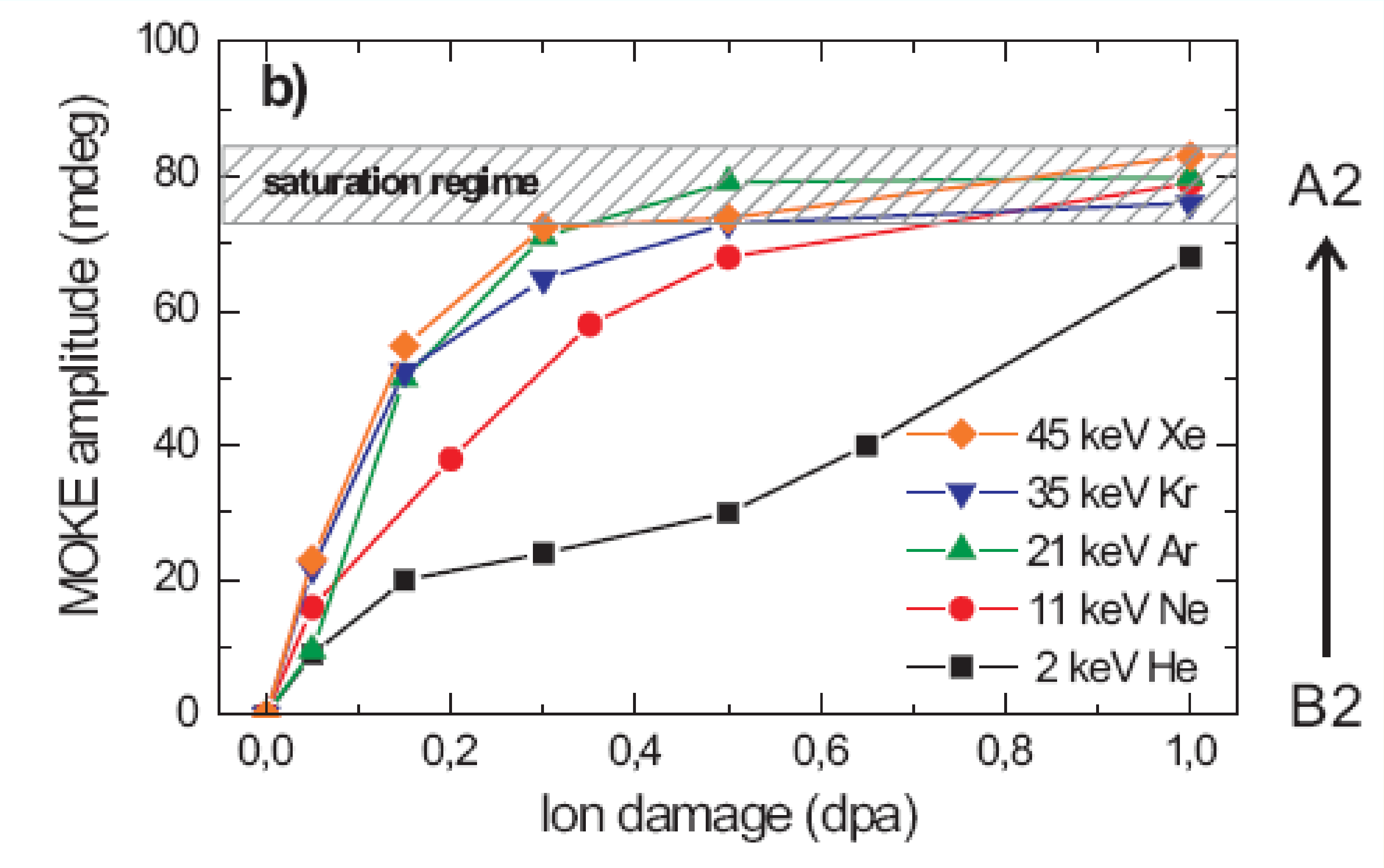
TRIM simulations (SRIM 2006 code); J.F. Ziegler, J.P. Biersack and U. Littmark, The Stopping and Range of Ions in Solids (Pergamon, New York, 1985)

Non-focussed (continuous) ion beam irradiation:

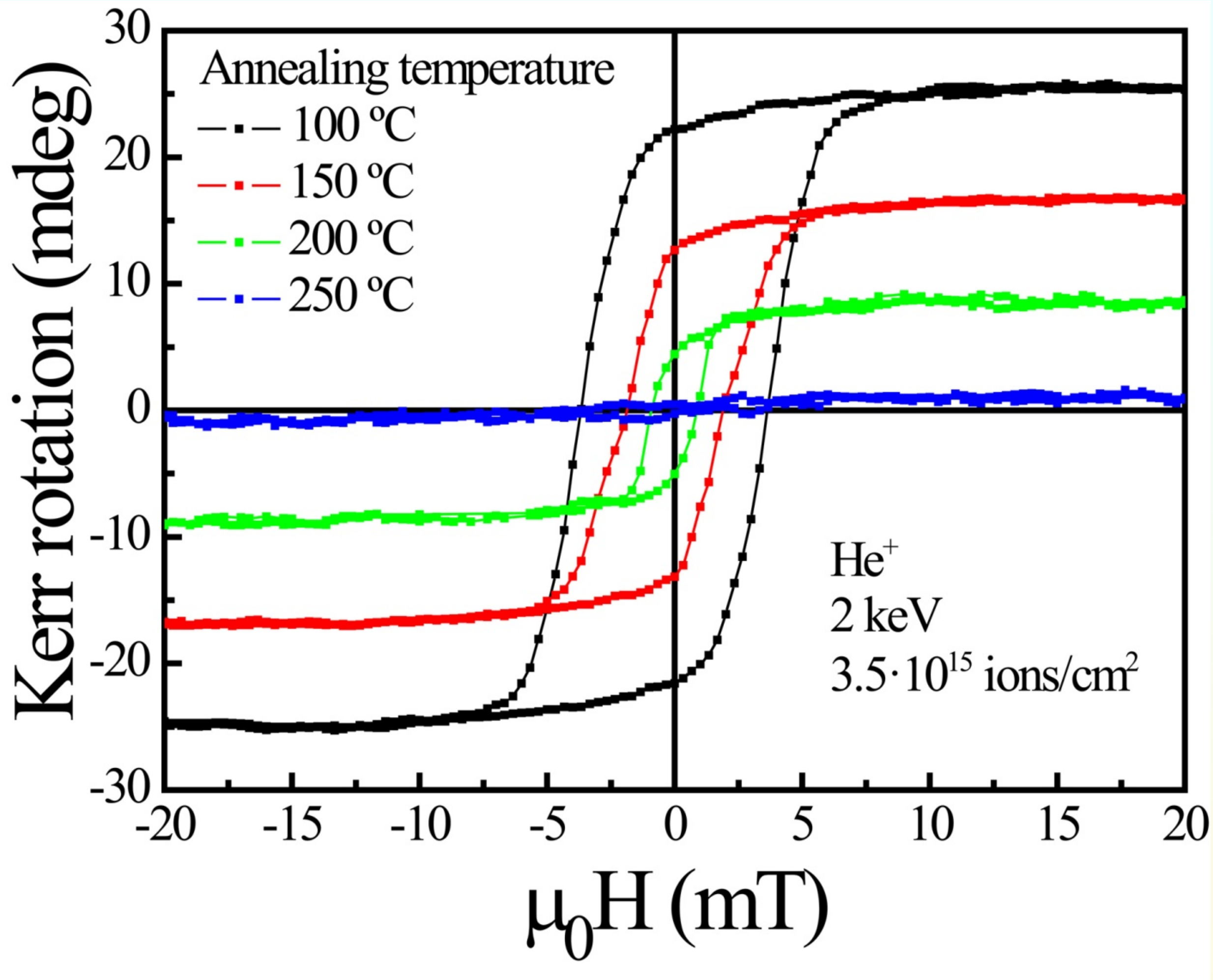


Whole sheet irradiated, 45 keV Xe^{+}

• Effect of using different ion species



• Typically, a complete B2⟶ A2 transformation for 0.5 dpa (except for He^+ ions).
• When using light ions partial recovery of the B2 phase occurs, probably because of vacancy diffusion.



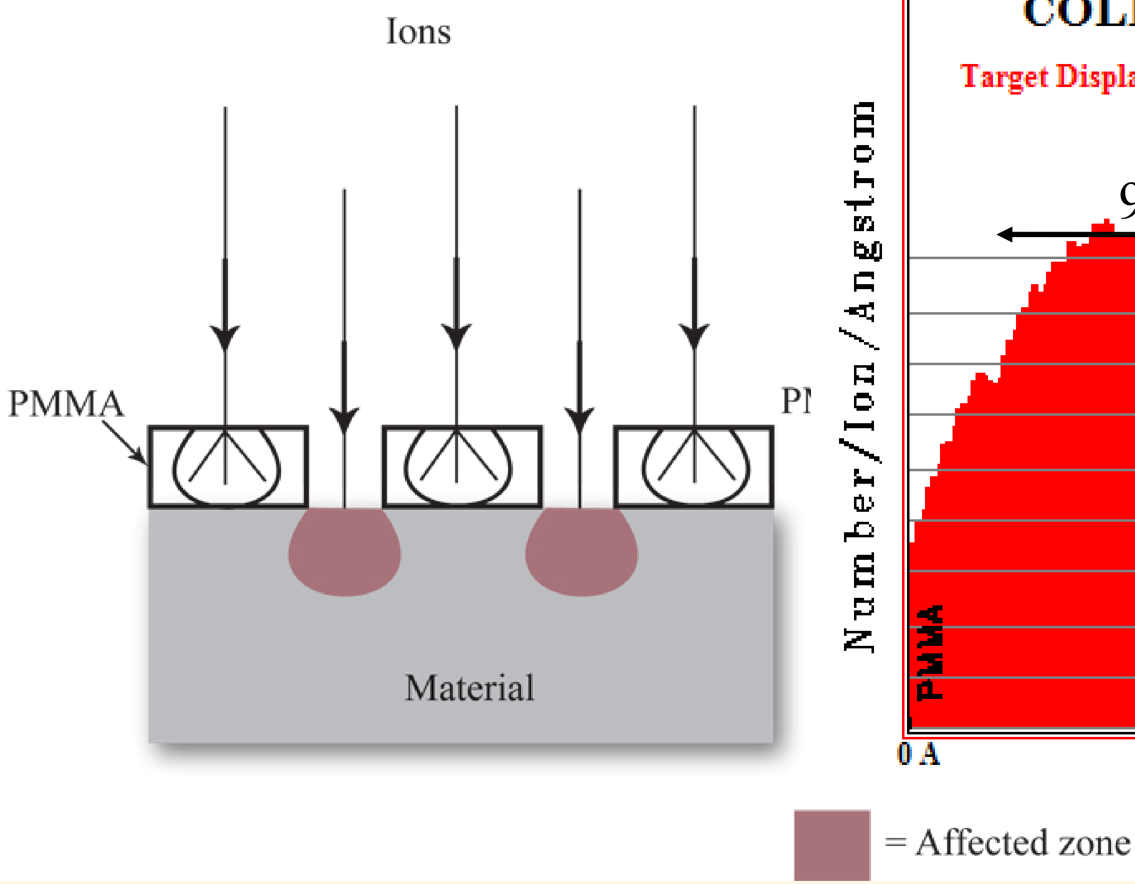
MOKE

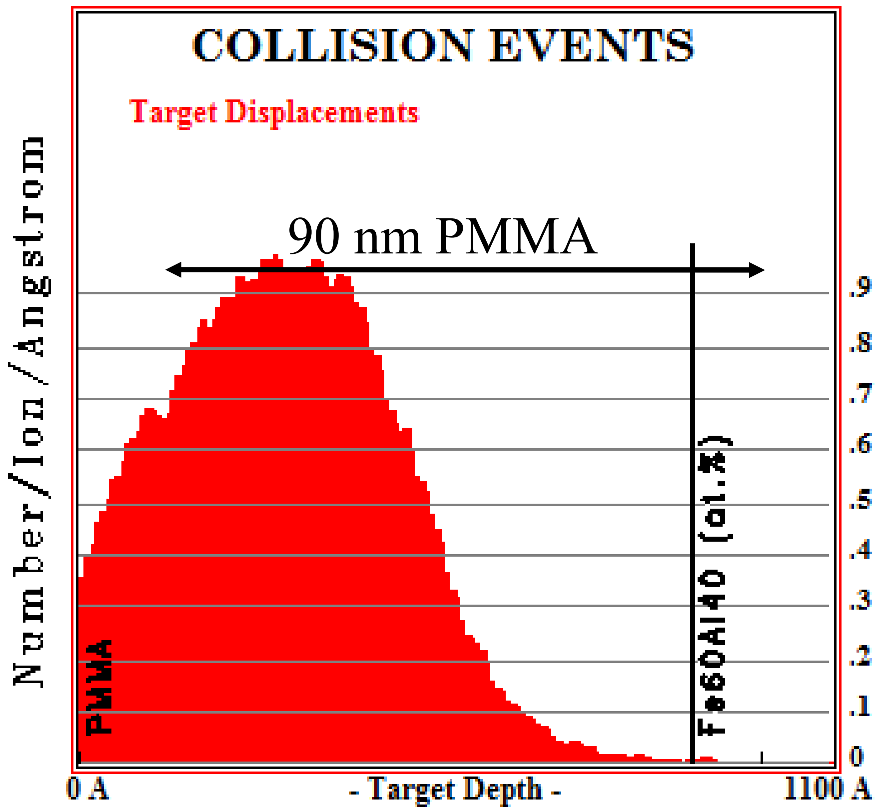
Induced ferromagnetism can be removed by heating (reordering process)

Magnetic patterning through shadow masks

Polymethylmethacrylate (PMMA) shadow masks (90 nm thickness) prepared by **Electron Beam Lithography** (EBL) on top of **$Fe_{60}Al_{40}$ (at.%) sheets**

40 keV Xe^+ irradiation ($1 \cdot 10^{15}$ ions/cm^2)



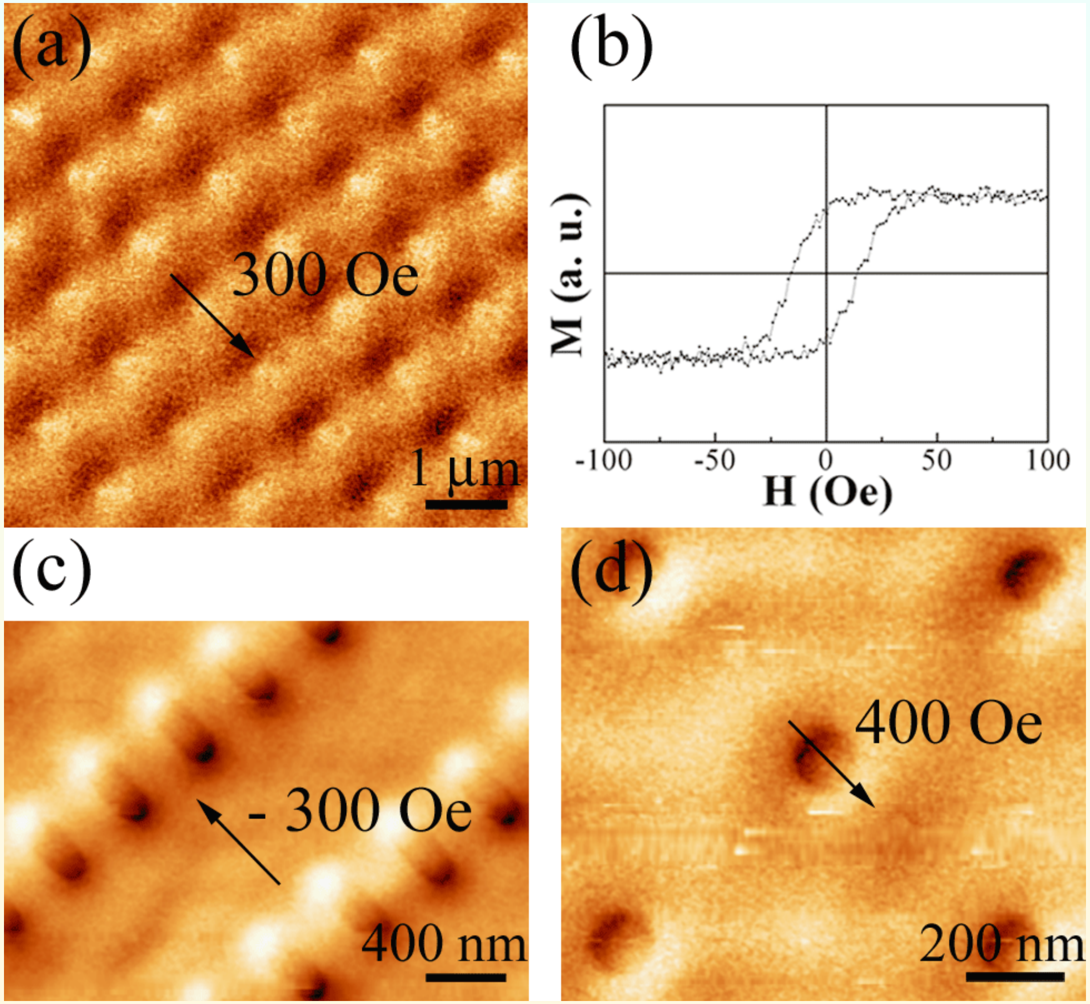


TRIM simulation

After irradiation ⟶ PMMA layer is removed (trichloroethylene)

• **Continuous irradiation through shadow masks:**

i) Irradiation through e-beam lithographed PMMA masks



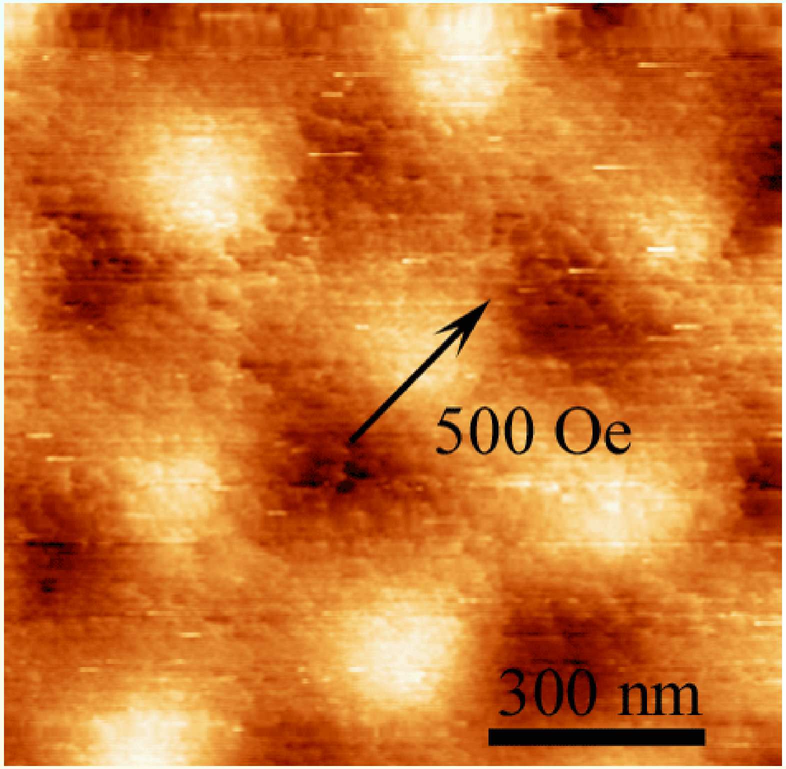
MOKE
300 x 300 nm^2 dots

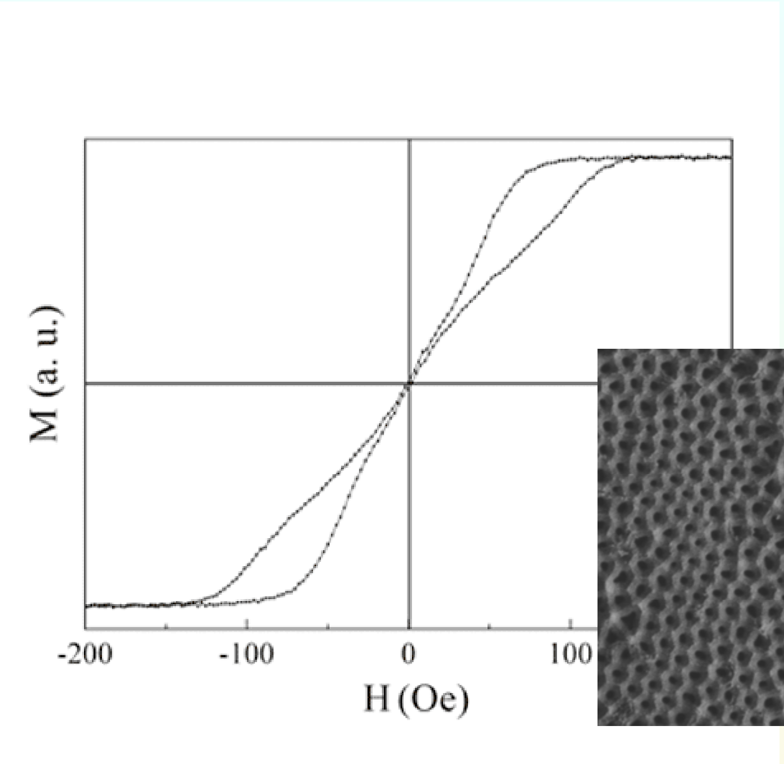
• **Dots with different sizes and geometry obtained.**

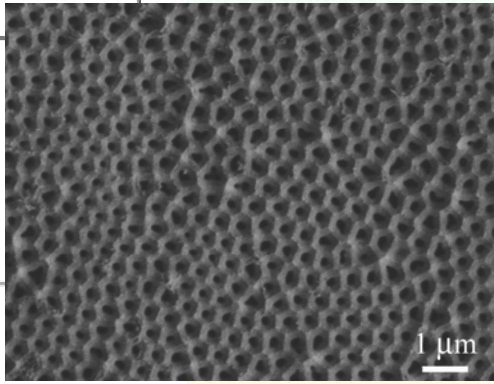
• **Large arrays of dots ($50 \times 50\ \mu m^2$) are obtained at once in a few seconds.**

• Continuous irradiation through shadow masks:

ii) Irradiation through an alumina template (100 μm thick)

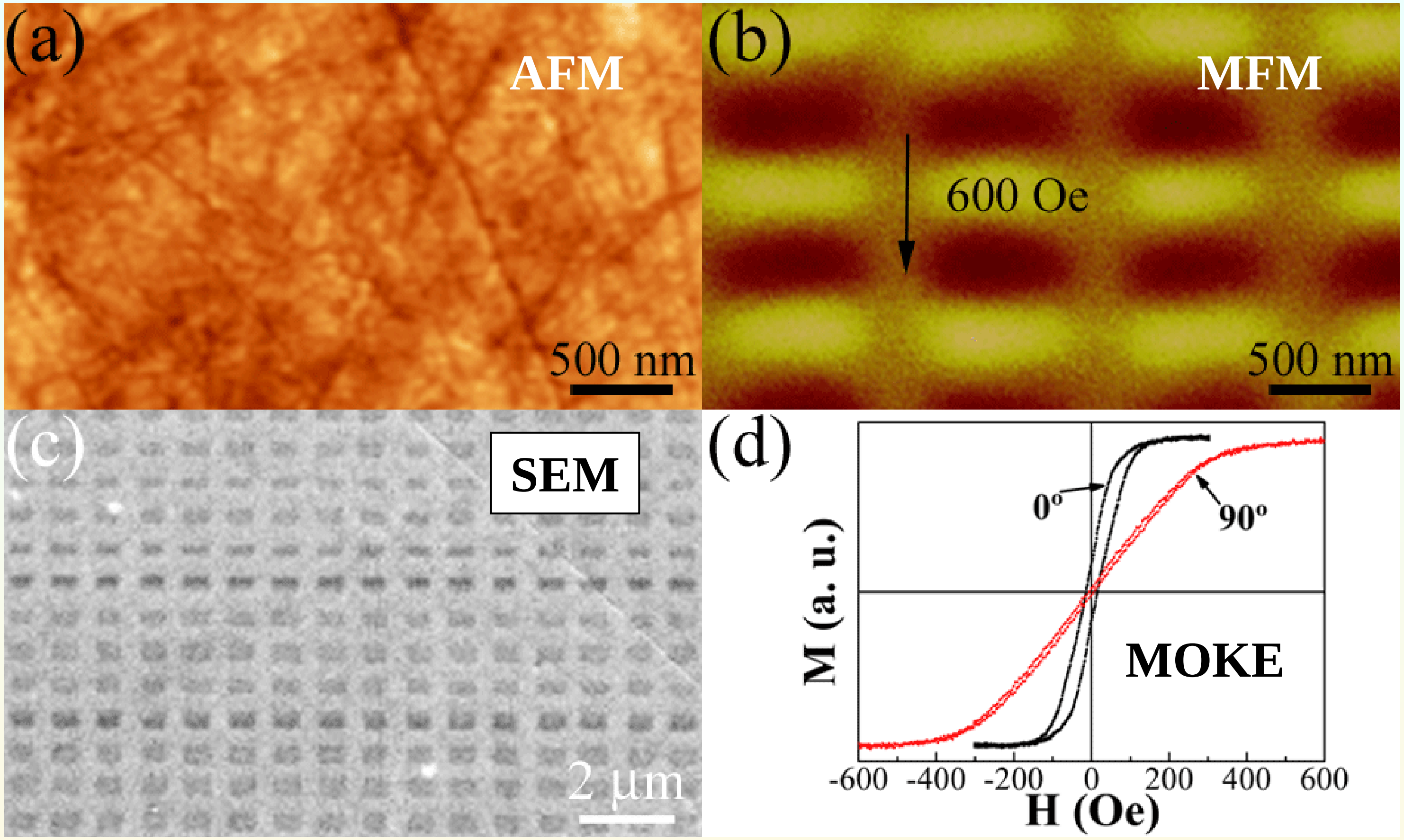






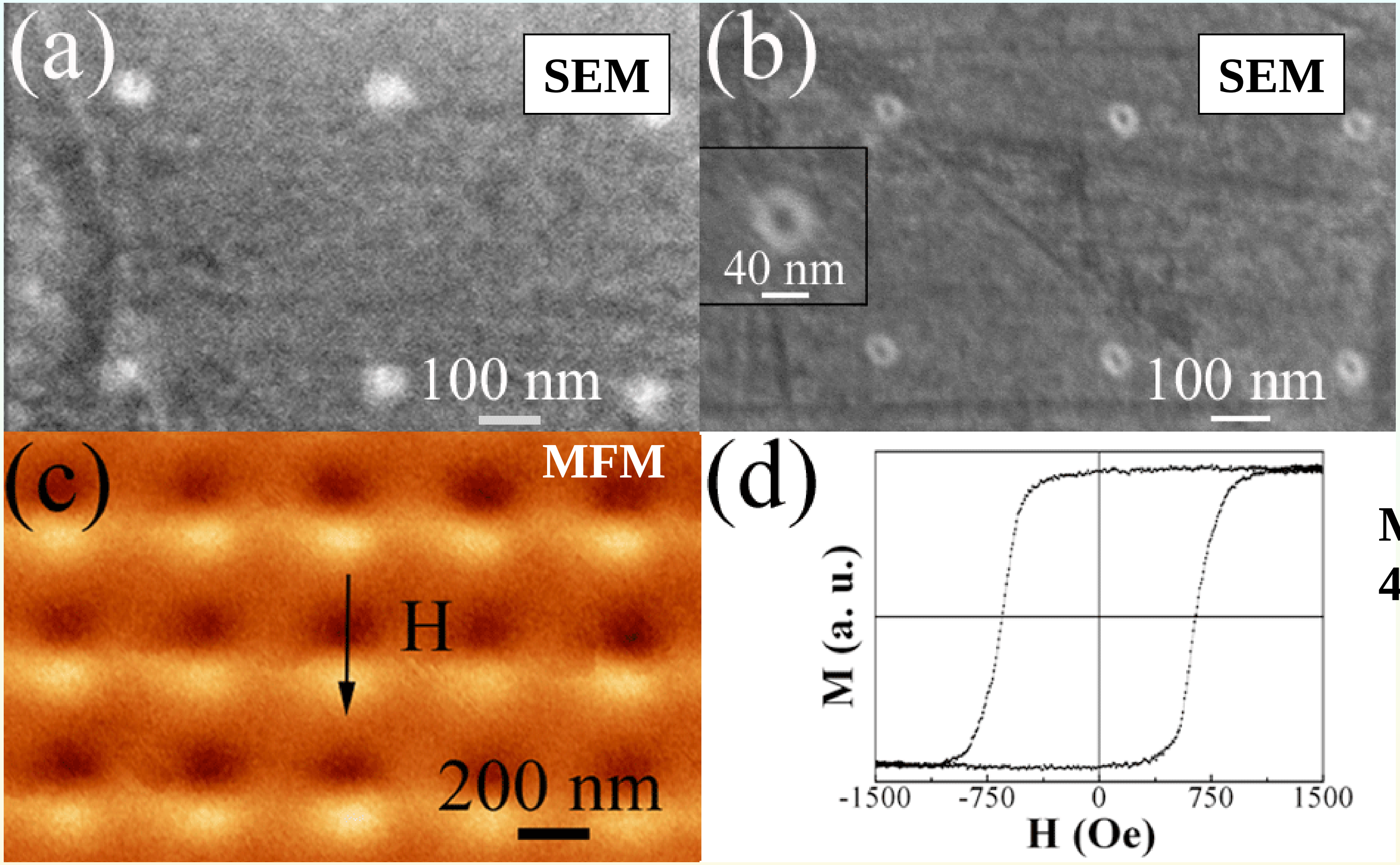
- **Large arrays (several mm) obtained by irradiating for a few seconds.**
- **Circular dots (Ø ≈ 300 nm) obtained. Pseudo-ordered array.**
- **No surface etching was observed.**
- **Vortex-like loops obtained, as expected for larger circular dots.**

Focussed ion beam (FIB) irradiation



- No surface etching (only magnetic patterning).
- Confined magnetism observed by MFM.
- Rectangular dots (250 x 600 nm^2) show magnetic anisotropy.
- Possible to observe the patterned dots by SEM (Ga^+ adsorption).

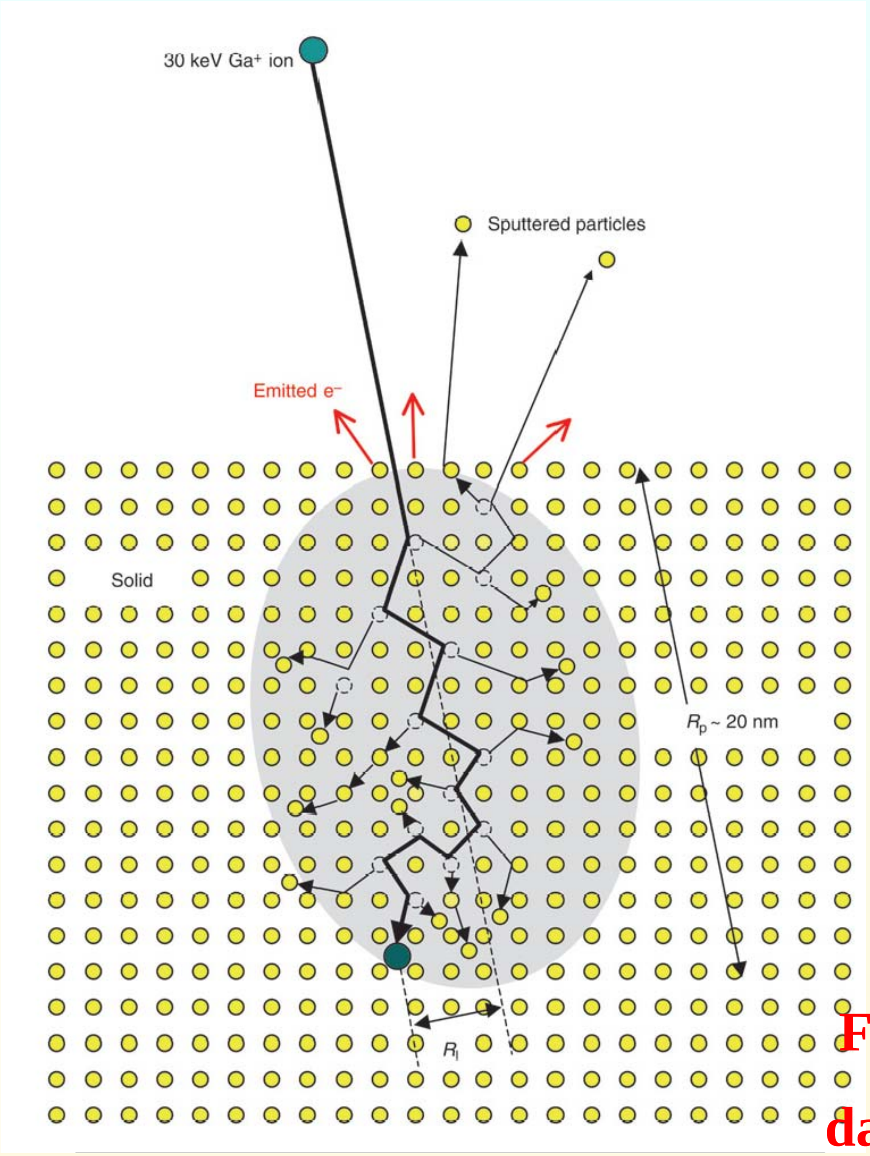
Focussed ion beam irradiation



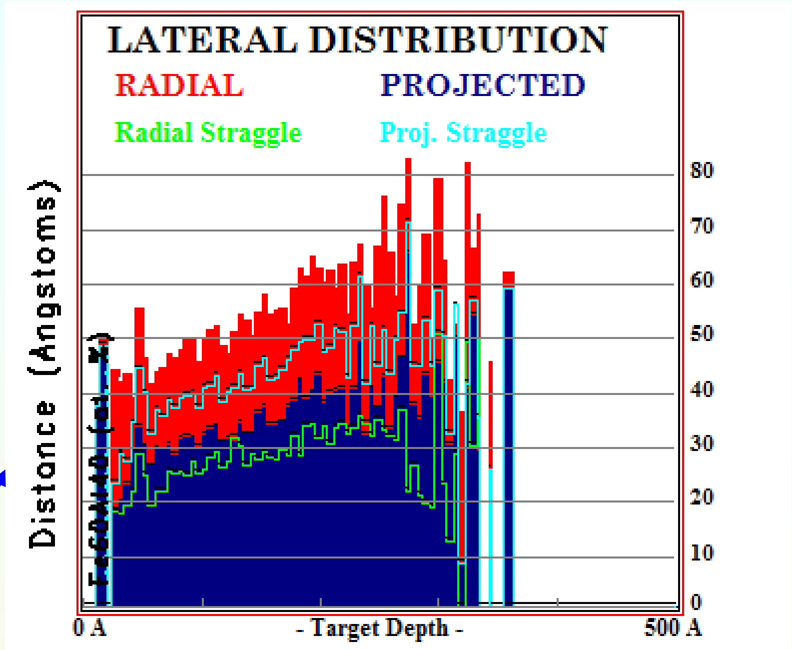
MOKE
40 nm dots

- **Circular dots (Ø = 40 nm) can be also obtained (without physical etching).**
- **Square-shaped loops, typical of single-domain states, are measured.**
- **The FIB lithography is an *in-series* process (relatively slow)**

Limits of the technique



C.A.Volkert, MRS Bull 32 (May 2007) 389



TRIM simulation of the lateral distribution range of incoming ions

For the conditions of our experiments the damage confined within 5 nm of the beam

Conclusions

- **Nanoindentation** can be used to generate local ferromagnetism in $Fe_{60}Al_{40}$ sheets (both "***physical***" and ***magnetic*** patterning).
- **Ion irradiation** can be used as a method for ***magnetic*** patterning (without "***physical***" etching), minimizing tribology problems.
- The **ferromagnetism is confined** into regions in the sub-micron range (interdot exchange interactions can be minimized).
- The induced **magnetism can be erased** by heating.
- Extrapolation to other materials or deformation techniques is, a priori, possible.
- *Possible applications in* ***magnetic memories*** *?*