Università degli studi di Ferrara

PhD in Physics

Study of domains configurations in magnetic nanostructures

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Principally Two type of systems have been studied

-Thin magnetostrictive Films with Perpendicular Magnetic Anisotropy and stripe domains: FeGa and TbFeGa thin films

-Array of magnetic nanoparticles: finite matrices of nanodots, and binary ferromagnetic nanostructures

Thin magnetostrictive Films with Perpendicular Magnetic Anisotropy

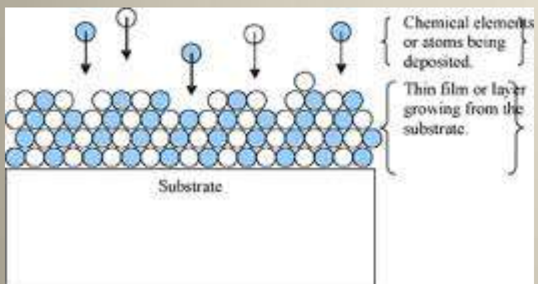
-For reaching smaller sizes in nanodevices, thin magnetostrictive films can be used to handle the magnetic properties by mechanical deformation

-Magnetic actuators or sensors (ie: sonars)

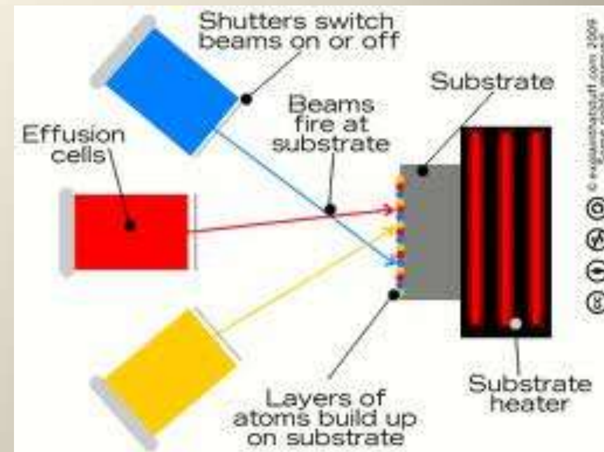
-Multiferroic composite materials, consisting of coupled ferromagnetic and piezoelectric phases require thin ferromagnetic films with large magnetostriction

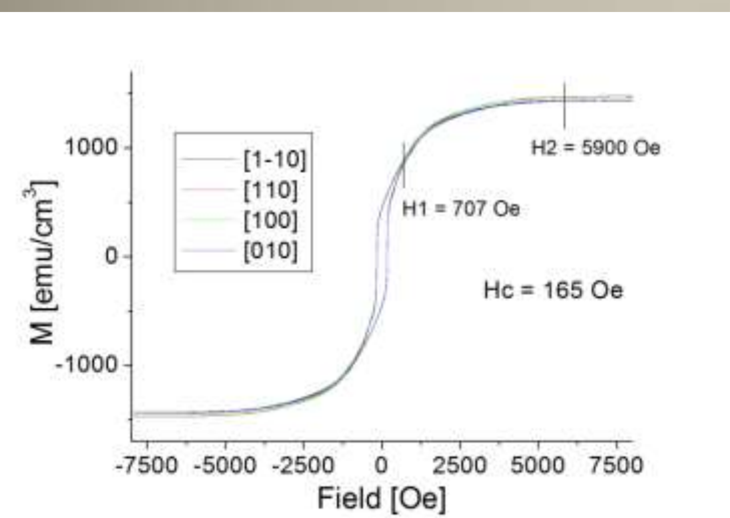
$Fe_{100-x}Ga_x$ thin films

Thin films of $Fe_{100-x}Ga_x$ were deposited (UPMC Paris 6) by MBE

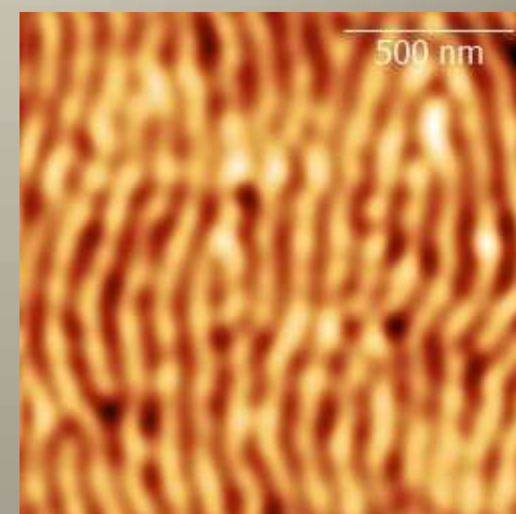


Film thickness is 65 nm, Ga content (x) were 20%





-magnetically isotropic in plane.
- display a region where M vs H change linearly → PMA
-At remanence there are stripe like domains



MFM image for the $Fe_{80}Ga_{20}$

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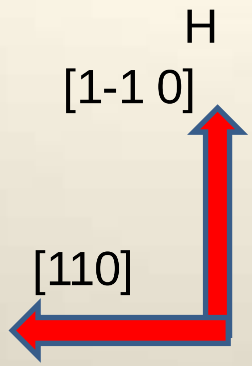
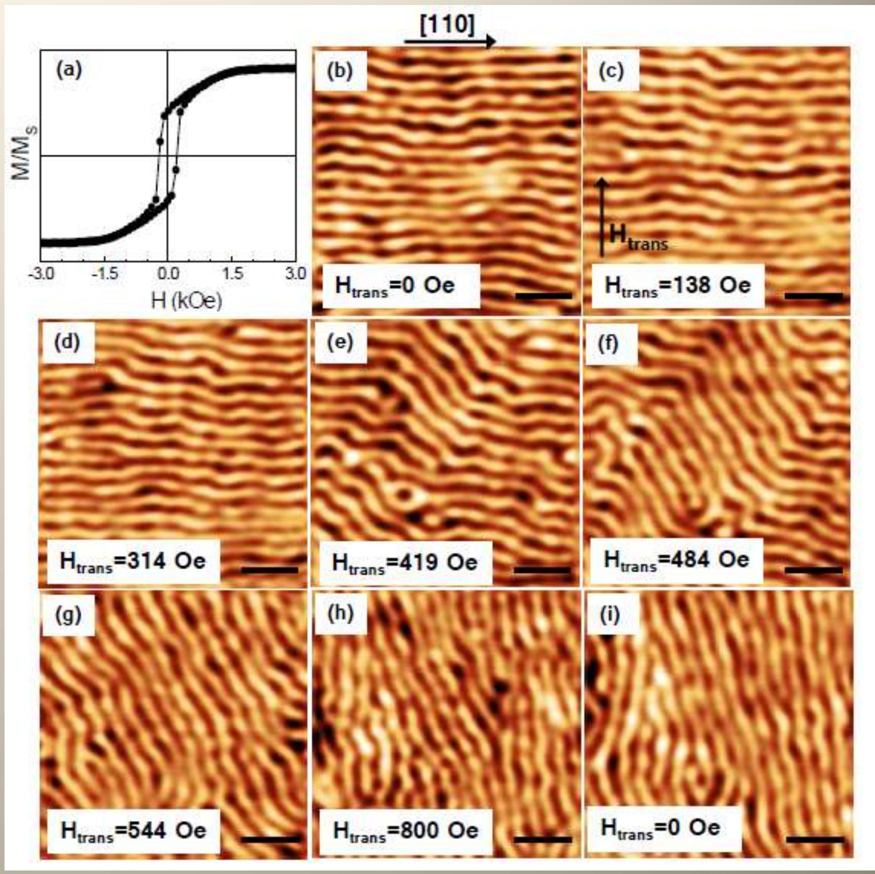
Stripes Rotation

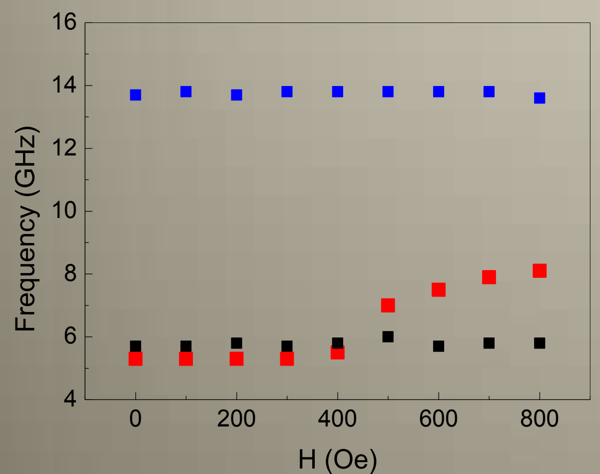


We induce the stripes along [110] then rotate the sample and increase the external field along the [1-10] direction.

Then we turn off the external field and perform the MFM measurement.

Stripes start rotating at 400 Oe and when complete rotation is accomplished they remain along the new direction (***Rotatable Anisotropy***)





A comparison with BLS measurements done following the same procedure shows the change in frequency of the uniaxial mode in the same field range.

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Rotatable Anisotropy

-The concept of Rotatable Anisotropy often appears in the magnetism of thin films.

-Rotatable Anisotropy dinamically manifests in a shift of frequency of spin waves in the Brillouin light scattering (BLS).

-To explain such experimental evidence in a model with a uniform in-plane magnetization, it was necessary to invoke a rotatable anisotropy field *Hrot.*

-*Hrot* can not be measured by means of usual magnetometry techniques.

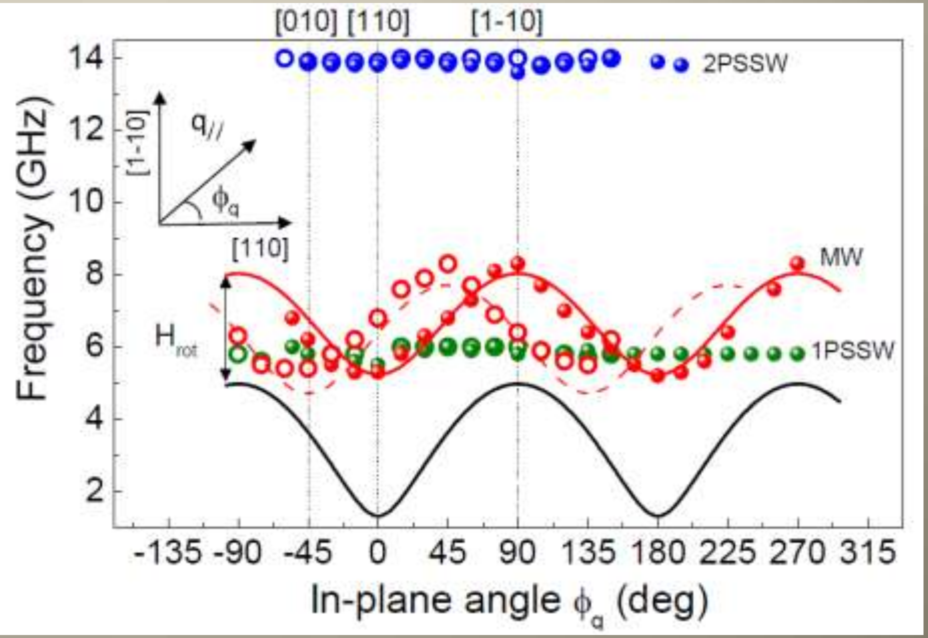
Rotatable Anisotropy Field evaluation

It is useful to exploit an approximate analytic expression, valid for thin films with a uniform in-plane magnetization [1] and [2]

$$\left(\frac{\omega_{MW}}{\gamma}\right)^2 = \left[H_{rot} - \frac{K_1}{M_s}\cos^2 2\phi + 4\pi M_s D\left(1 - \frac{q_{\|} t}{2}\right) - 2\frac{K_n}{M_s} + \frac{2A_{ex}}{M_s} q_{\|}^2\right] \times$$
$$\times\left[H_{rot} - \frac{K_1}{M_s}\cos^2 4\phi + 4\pi M_s D q_{\|} t \sin^2\left(\phi - \phi_q\right) - 2\frac{K_n}{M_s} + \frac{2A_{ex}}{M_s} q_{\|}^2\right] \quad \text{Eq.(1)}$$

-We evaluate Hrot at remanence (all other factors are known or derivable). We found Hrot=1350 Oe. We can also evaluate all the frequencies for Hrot=0 (absence of rotatable anisotropy) and the result is plotted in the grey curve (shifted down).
-Spin wave frequencies measured by BLS (points)
-The grey line is obtained setting *Hrot*=0 in Eq. (1).

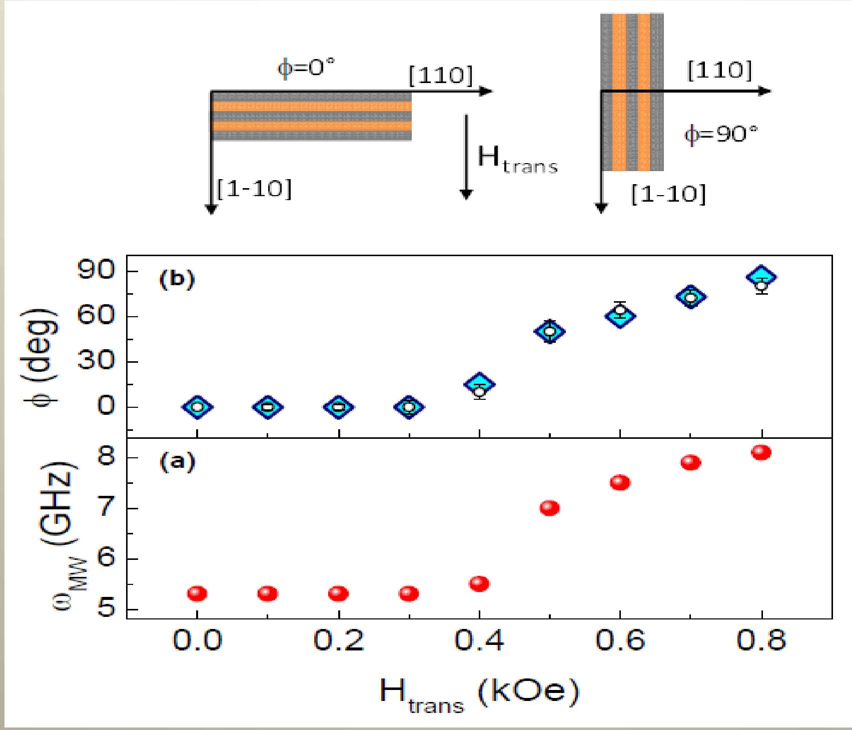
There is a good agreement between theory and BLS measurments.



[1] G. Gubbiotti, G. Carlotti, and B. Hillebrands, J. Phys. C 10, 2171 (1998).
[2] G. Carlotti and G. Gubbiotti, La Rivista del Nuovo Cimento 22, 1 (1999).

In Fig.1b there is a comparison between the theoretical value of the stripes angle and the angle estimated from MFM images. While in Fig 1a the BLS value of frequency.

Fig.1

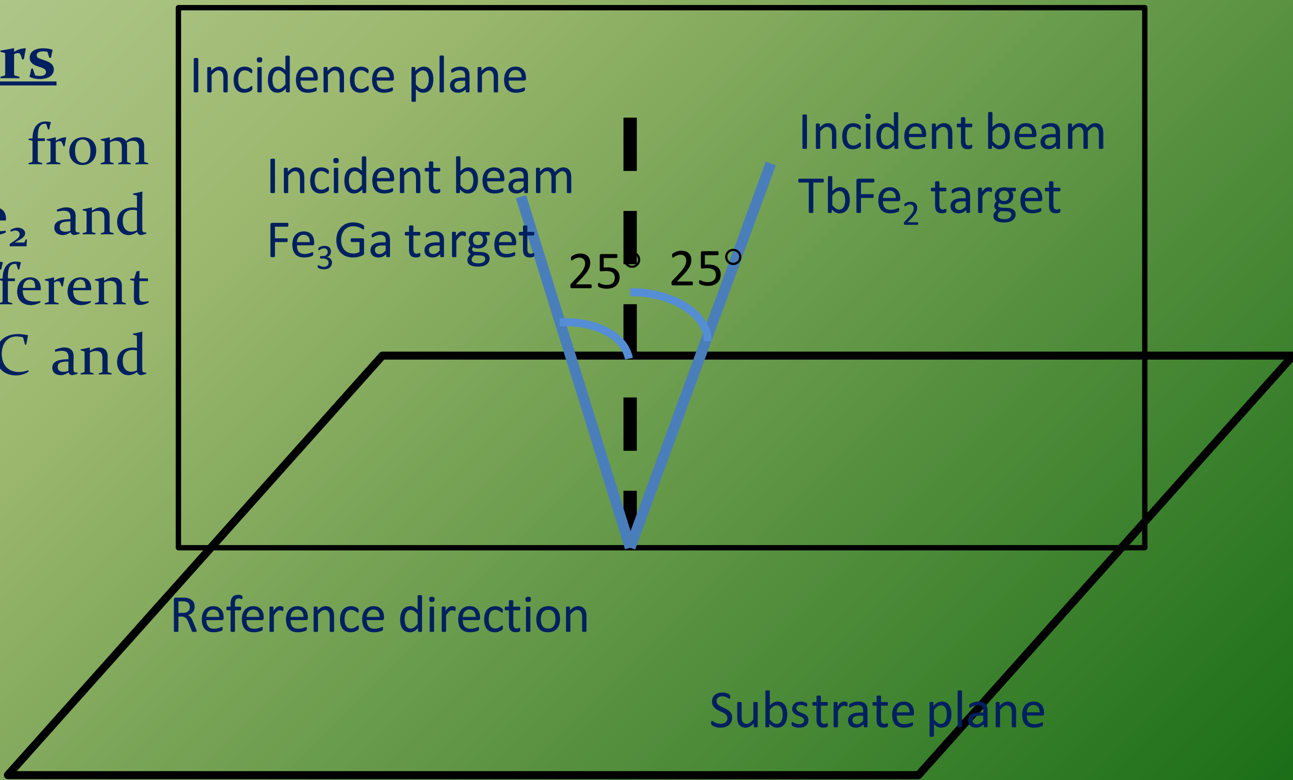


Conclusions: we have analized the rotations of stripe domain with MFM, and determined for the same conditions the spin wave frequencies with BLS. Then we estimated, by means of an approximate analytic expression, the anisotropy field Hrot. With same formula we calculated the theoretical spin wave frequencies and found a good match with the sperimental one. Finally we verified that the theoretical angles of stripe domains during rotation (obtained inserting the true BLS frequencies in the previous formula) was similar to those obtained from MFM images. Also in this last case the similarity between theory and experimental data was very good.

Tailoring the magnetic domain patterns of TbFeGa alloys

A collaboration with Universidad Complutense de Madrid

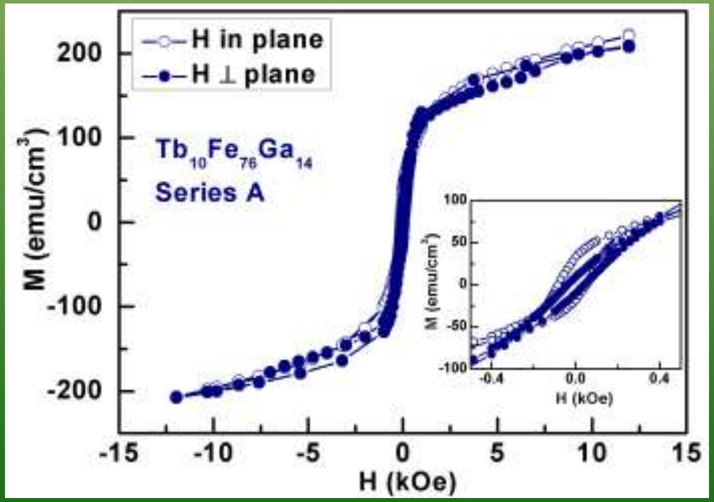
- **Growth of the layers**
  - **Cosputtering** from two targets: **$TbFe_2$** and **Fe_3Ga**. Two different power sources (DC and Pulsed)

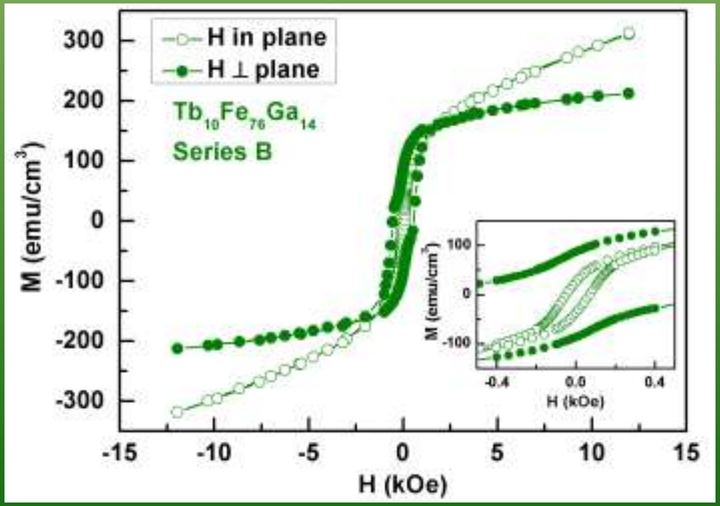


- **Main characteristics for the different growth conditions**

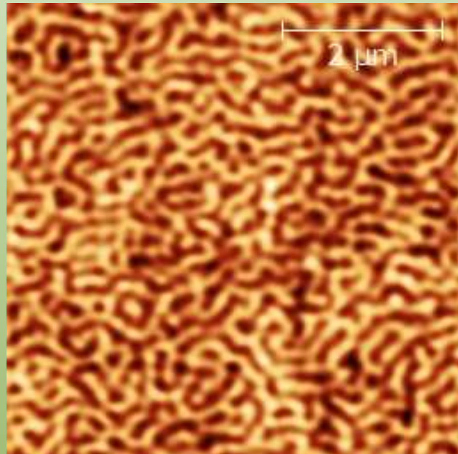
Composition	Magnetic anisotropy (erg/cm^3)	Source	Tb in Tb_xFe_{1-x} (at %)
$Tb_{10}Fe_{77}Ga_{13}$	PMA $\geq 1.5 \times 10^6$		≥ 28
$Tb_{10}Fe_{76}Ga_{14}$	Weak PMA 0.6×10^6	$TbFe_2$.Pulsed	22
$Tb_9Fe_{75}Ga_{16}$	In-plane 0.5×10^6		18
Series A			

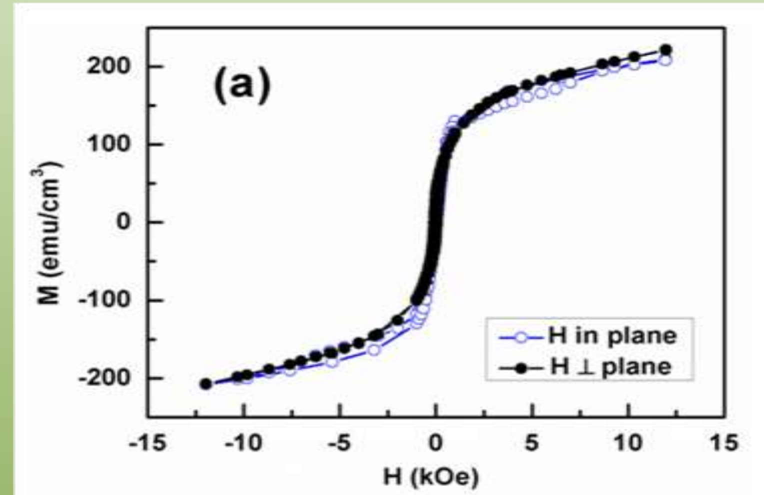
Composition	Magnetic anisotropy (erg/cm^3)	Source	Tb in Tb_xFe_{1-x} (at %)
$Tb_{10}Fe_{77}Ga_{13}$	PMA $\geq 1.5 \times 10^6$		≥ 28
$Tb_{10}Fe_{76}Ga_{14}$	PMA 1.0×10^6	$TbFe_2$.DC	≥ 28
$Tb_9Fe_{75}Ga_{16}$	In-plane 0.6×10^6		16
Series B			





- **Stripes orientation induction (Series A)**

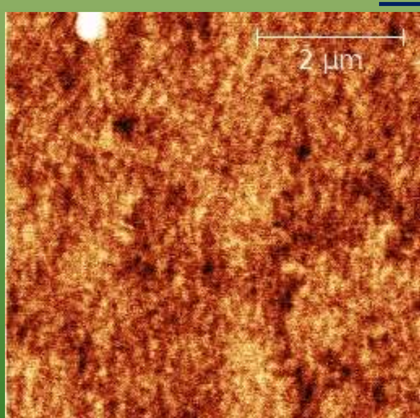




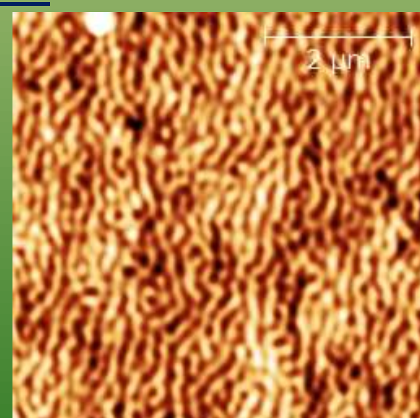
At remanence: no preferential stripes orientation

IN-FIELD MFM

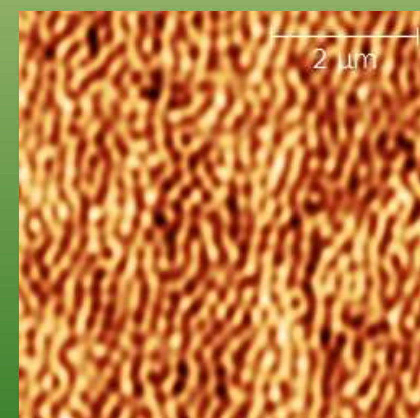
H



800 Oe: stripes disappear



400 Oe

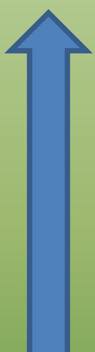


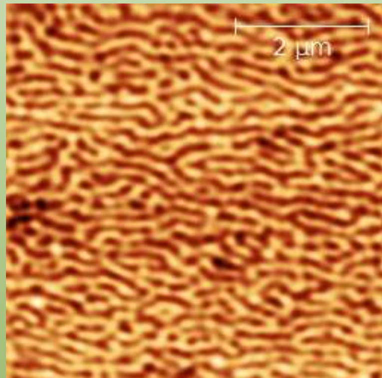
H = 0: after field removal stripes are preferentially aligned along the field

- <u>**Stripes rotation (Series A)**</u>

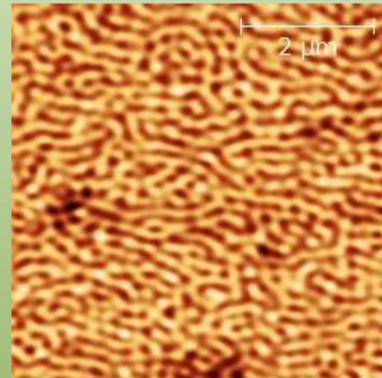
We rotate the sample 90° (<u>**field and stripes are now perpendicular**</u>) and increase the field

H

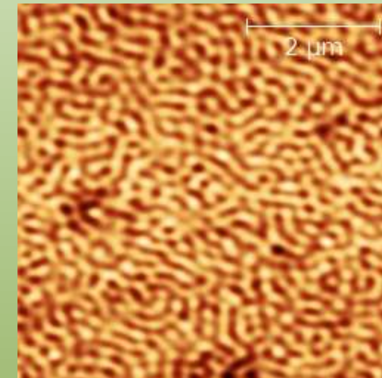




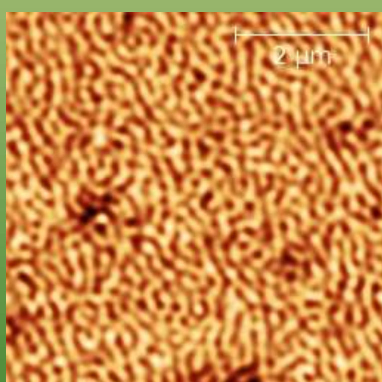
H = 110 Oe



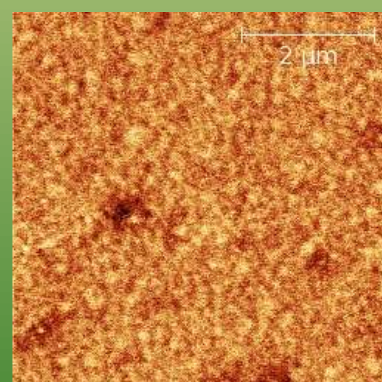
H = 250 Oe



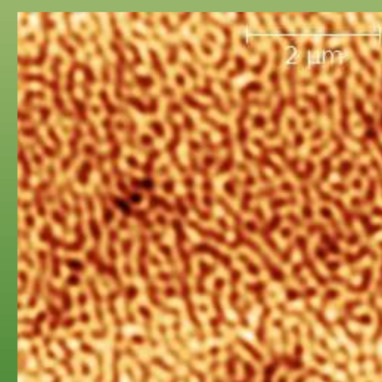
H = 330 Oe



H = 470 Oe



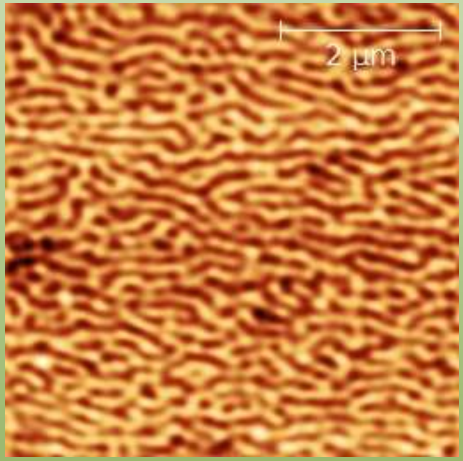
H = 800 Oe



H = 0 Oe

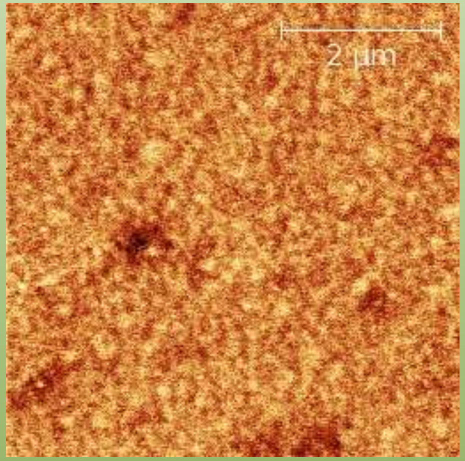
The preferential stripes orientation is mantained after field removal.
This property (named <u>**rotatable anisotropy**</u>) could be related to magnetostriction of TbFeGa.

- **Stripes annhilation (Series A)**

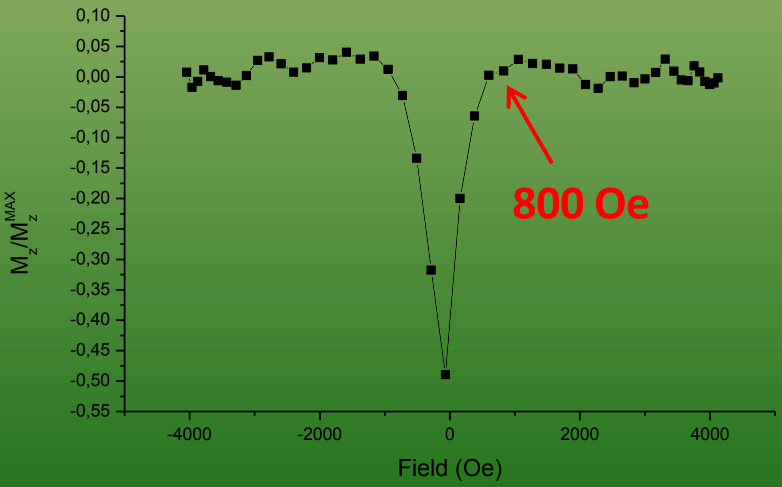


Stripes vanish when a 800 Oe in-plane field is applied

IN-FIELD MFM

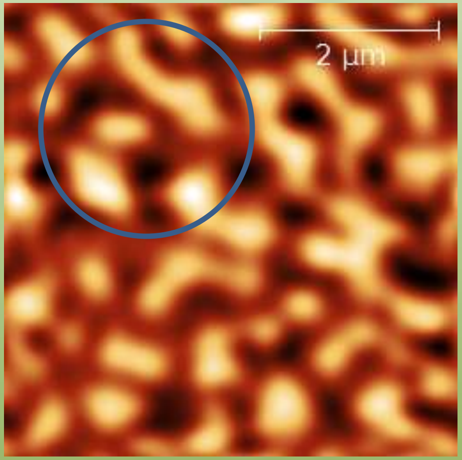


MOKE magnetovectometry confirms that the critical field
for stripes annihilation is 800 Oe (see the dependence of M_z on in-plane field)



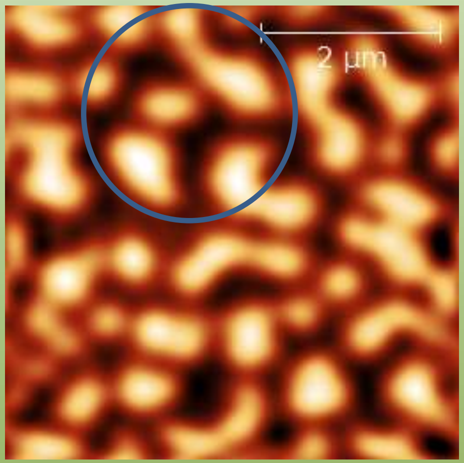
- **Strong PMA observed in Series B**

An 800 Oe in-plane field does not change the MFM signal

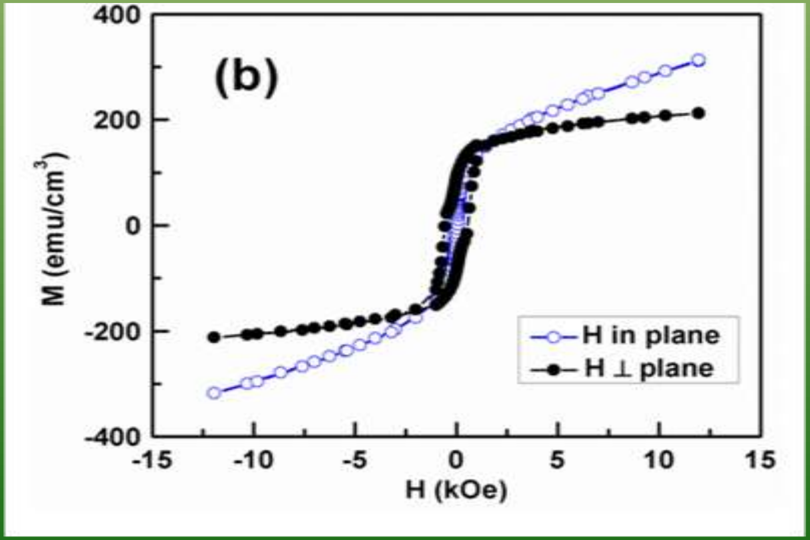


Remanence

H

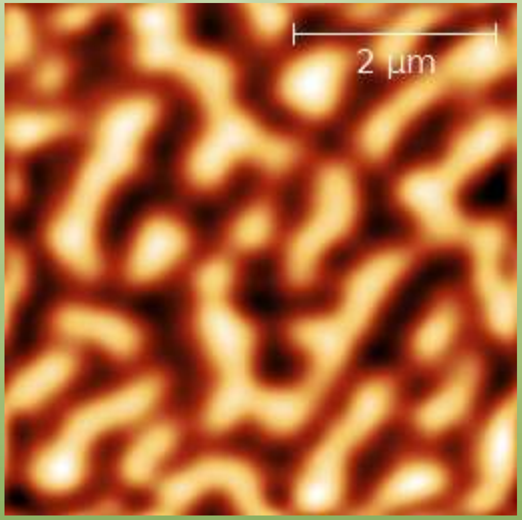


In-field MFM: **800 Oe**



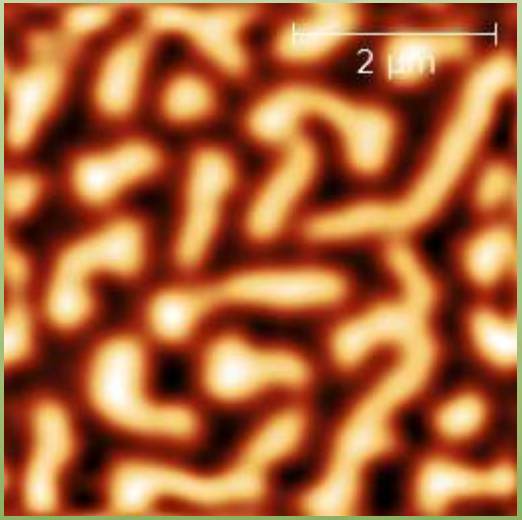
B samples show an OOP signal that is much stronger than the one observed for samples A. **An 800 Oe in-plane field does not change the MFM signal** in series B (compare the two selected zones, as an example)

Higher fields (up to 8000 Oe) produce only small modifications



MFM at remanence after application of a **8000 Oe** →

MFM at remanence after application of a **4000 Oe** in-plane field

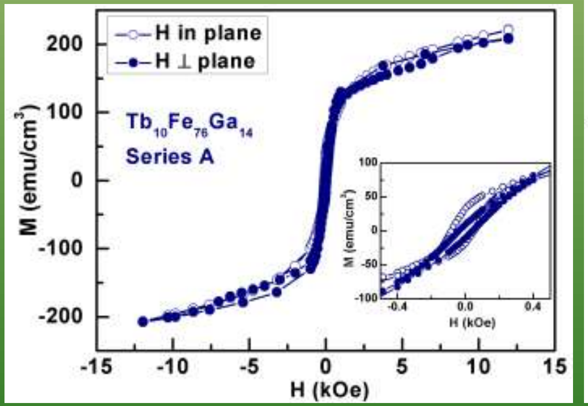


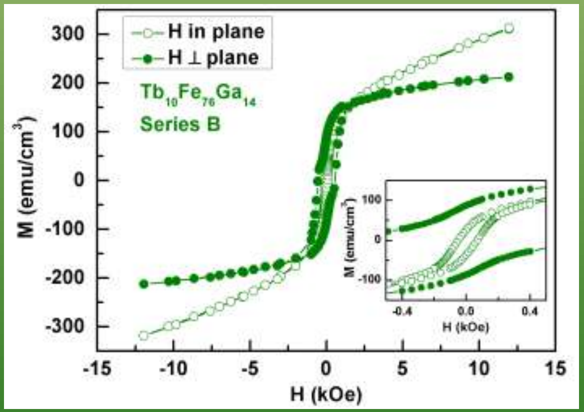
MFM at remanence after application of a **8000 Oe** in-plane field

Higher fields (up to **8000 Oe**) produce only small modifications: the OOP magnetization is still high and **the stripes tend to coalesce and elongate**. The **stripes lenght** seems to be **proportional to the external applied field**.

• Conclusions

- The **cosputtering** process enables to tune the composition of TbFeGa alloys.
- Not only the composition but also the type of power source has an influence on the magnetic anisotropy.





Matrices of NanoParticles

-To increase the magnetic memory storage density it is necessary reduce the dimensions of magnetic nanoparticles and their distances.

-Shape and dimensions of magnetic nanoparticles array could be tailored to obtain spintronic logic devices or spin-waves frequencies modulators

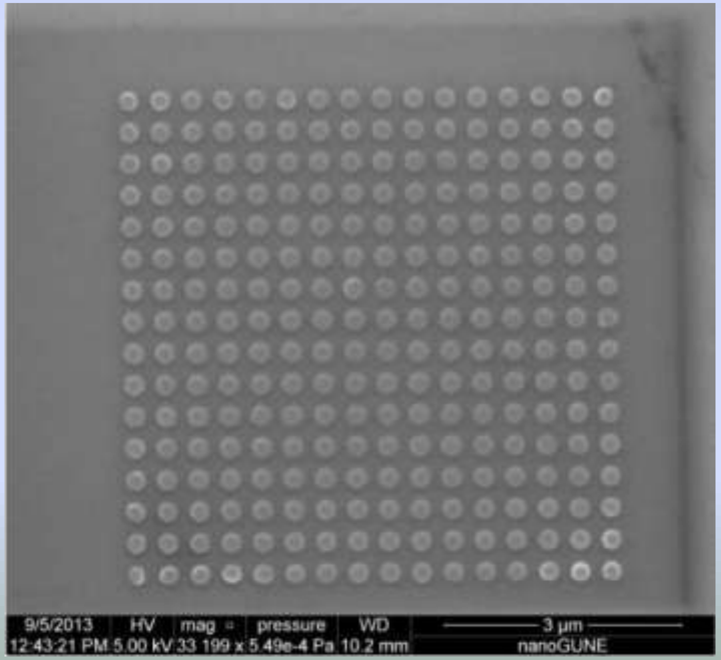
-In this research are shown finite-size effects on the magnetization reversal in a 16x16 array of permalloy circular nanodots.

-The samples are square16x16 array of circular nanodots of Permalloy (CIC NanoGune, San Sebastian, Spain)

-Three differend diameter: 240 nm, 300 nm and 340 nm with different interdot distances: 140, 100 and 60 nm

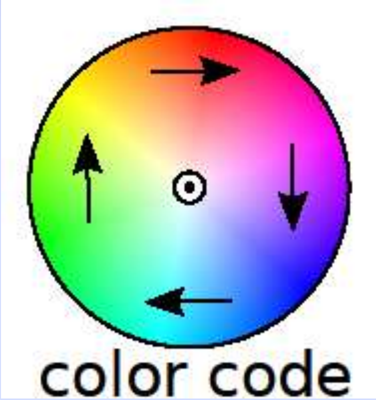
-Three different thickness: 10, 15, 20 nm

-In the Fig. a SEM image of sample with diameter 240 nm and 10 nm thick.



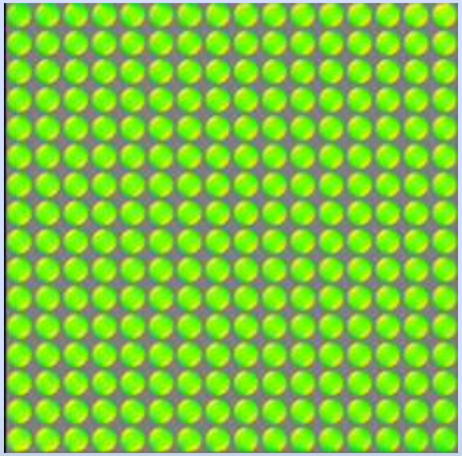
Finite Size-Effects

-We have found a particular effect depending on the finite dimension of the array due to the global demagnetizing field.
-The magnetization reversal occurs in different times in different positions of the array.
-Images of magnetization at different applied fields produced with Simulations (collaboration with Ghent University, Belgium) and Magnetic Force Microscopy are presented below.

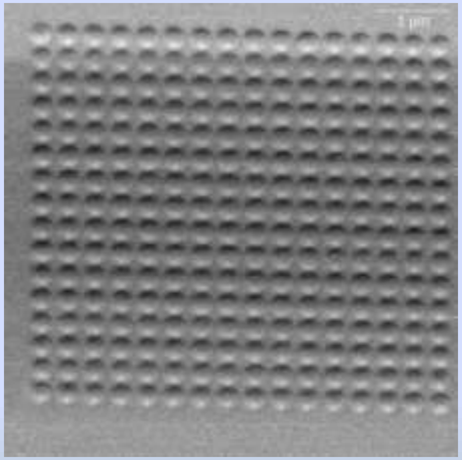


The color code is for interpretation of simulation output results

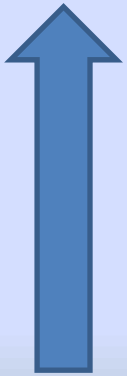
Simulated

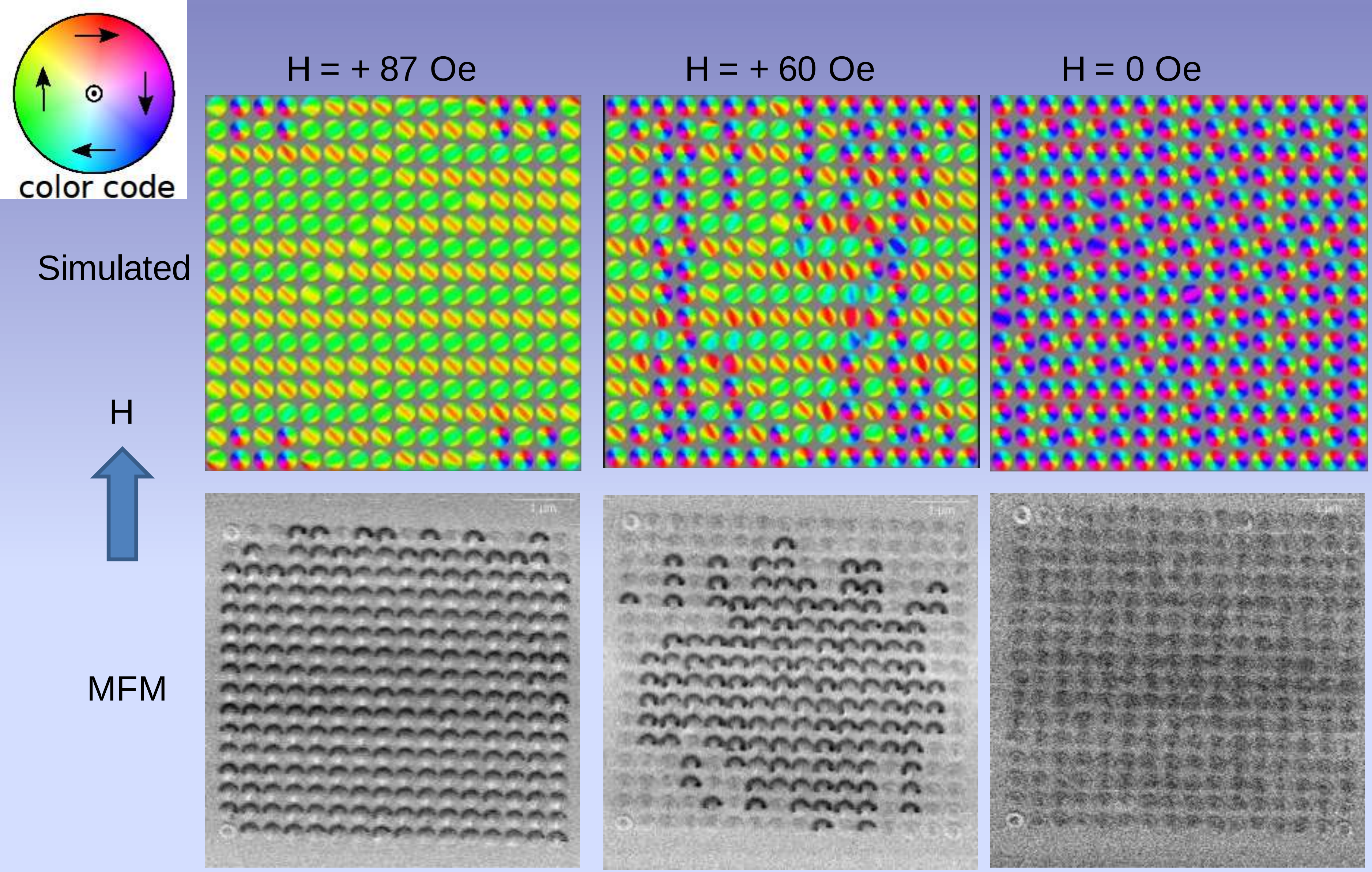


MFM



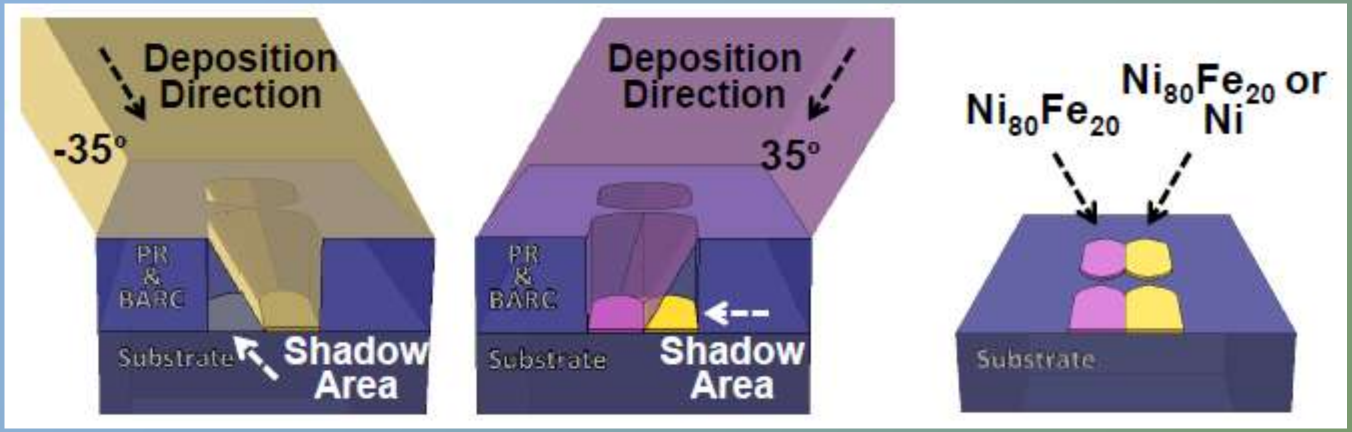
Applied field
H=800 Oe





In conclusion: there is an evident size-dependet effect on the magnetization reversal. We found (though preliminary) good agreement between simulations and MFM results. We need more and precise results. It is interesting to study how magnetization reversal changes using different array matrix dimensions or different thickness.

Binary Magnetic Nanostructures



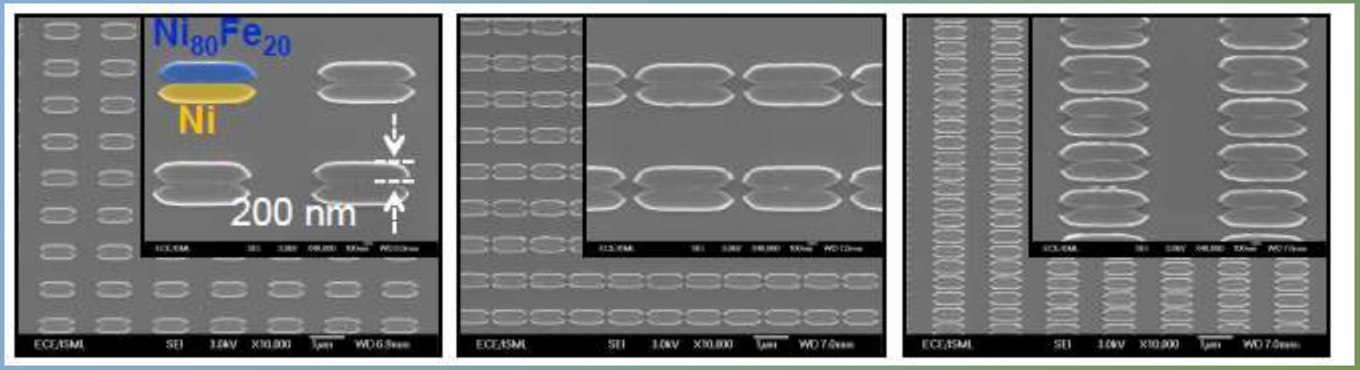


Fig 1: Micromagnetic simulantions performed applying the field in the direction indicated

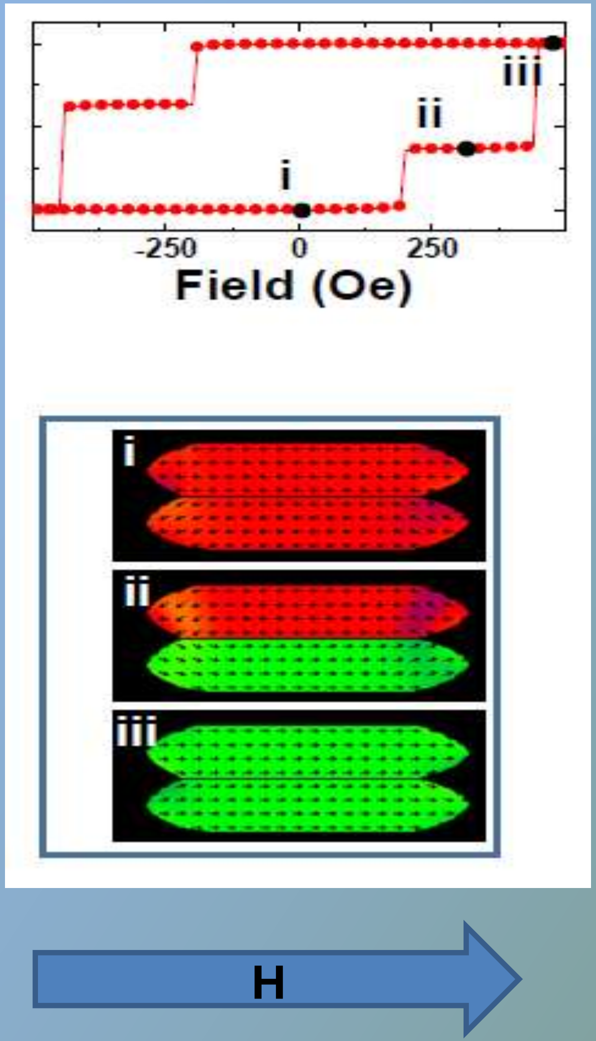


Fig 2: Balck lines the MOKE measurements of magnetization M/Msat. Red line is the derivative of the M/Msat

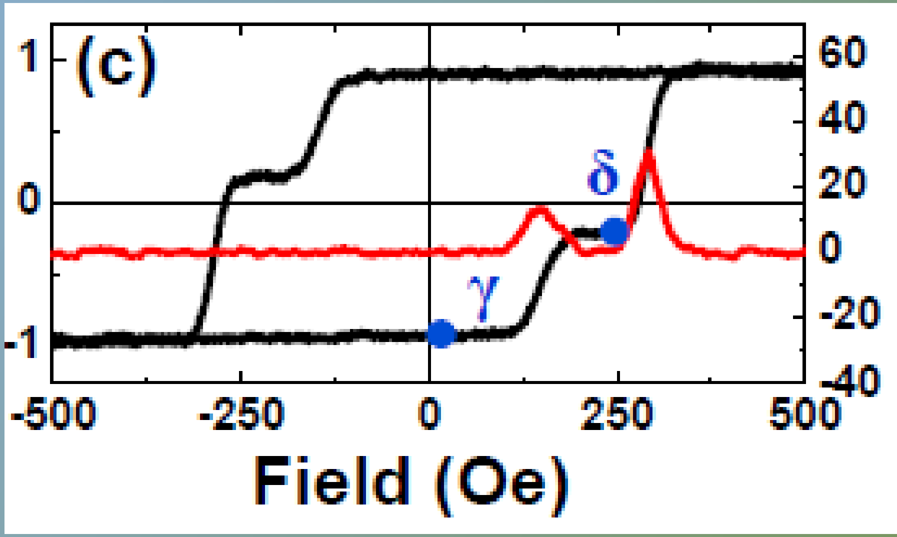
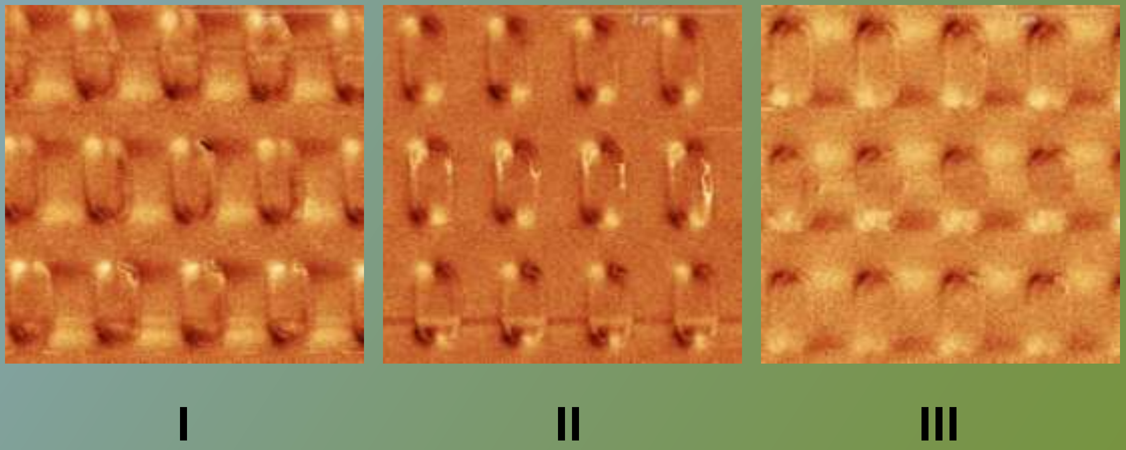


Fig 3: MFM images of the three magnetic states



Thank you for your attention