

# Rotatable anisotropy of epitaxial $\text{Fe}_{1-x}\text{Ga}_x$ thin films<sup>\*</sup>

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**Abstract.** We show by a combined magnetic force microscopy and synchrotron radiation spectroscopy study that stripe-like patterned magnetic domains are present in  $\text{Fe}_{1-x}\text{Ga}_x$  thin films. These stripes, whose origin is attributed to an out-of-plane magnetic component, can be rotated by an external magnetic field.

## 1 Introduction

Coupling magnetization of nanostructures to external non-magnetic fields is a challenge of today's research on nanomagnetism. For instance, electric fields were adopted to control local magnetization in multiferroic materials [1], spin polarized currents to generate RF coherent emission in nanopillars [2], self-organized templates to switch magnetization [3]. These and many others experiments promise new means to control local magnetic properties in spintronics devices avoiding cumbersome inductive means.

In this context, magnetoelastic coupling in magnetostrictive nanomagnets has potential for controlling magnetic properties by mechanical deformation. For instance, some of us reported recently high-frequency (around 200 MHz) magnetocaloric effect triggering in MnAs thin films epitaxied on GaAs(001) substrates [4].

These considerations motivate the magnetic properties study reported in this article. We focus on strong magnetoelastic  $\text{Fe}_{1-x}\text{Ga}_x$  thin films prepared by Molecular Beam Epitaxy on GaAs(001). It is well known that  $\text{Fe}_{1-x}\text{Ga}_x$  magnetoelastic coupling is tuned by the Ga content, displaying a high  $\lambda_{100}$  coefficient ( $400 \times 10^{-6}$  for  $x = 20\%$ ) and a strong dependence of the magnetostrictive coefficient on the Ga concentration [5,6].

Here, we report on the rotatable anisotropy of  $\text{Fe}_{1-x}\text{Ga}_x$  thin films, where stripe-like patterned domains due to an out-of-plane (OP) magnetic component are oriented by an external magnetic field. This effect arises from

OP magnetic anisotropy due to  $\text{Fe}_{1-x}\text{Ga}_x$  magnetostriction, probably enhanced by epitaxial constraints [7,8].

## 2 Sample growth

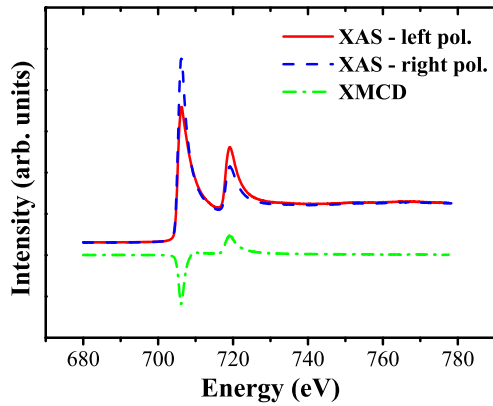
$\text{Fe}_{1-x}\text{Ga}_x$  thin films with  $x = 15\%$  were deposited by MBE on  $\text{C}(2 \times 2)$ -Zn terminated ZnSe epilayer, a prototype of low reactive iron/semiconductor interface [9]. Details of the MBE-growth of a pseudomorphic 20-nm-thick ZnSe epilayer have been reported previously [7]. Such epilayer constitutes an efficient chemical barrier to separate  $\text{Fe}_{1-x}\text{Ga}_x$  from the substrate. We kept constant the growth temperature at 180 °C. At the end of the Fe-Ga growth, the samples were transferred from the MBE chamber to UHV-interconnected multi-chambers, where films compositions were firstly analyzed by X-ray photoemission spectroscopy (XPS). At the end, the films were protected by a 3 nm thick gold capping layer.

## 3 Experimental

As observed in reference [7]  $\text{Fe}_{1-x}\text{Ga}_x$  thin films are under a compressive strain. It was found that the in-plane lattice parameter of bulk iron is preserved leading to a marked tetragonal distortion. This tetragonal distortion is metastable versus thermal annealing and is probably due to Ga-ordering during out-of-equilibrium MBE growth. Nevertheless, the centered lattice structure of pristine bulk iron is preserved and no phase transformation and no phase coexistence are observed. At first glance, also the electronic properties are very similar to the iron ones. In Figure 1 we report XAS (X-rays absorption spectroscopy) and XMCD (X-rays magnetic circular dichroism) spectra

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**Fig. 1.** XAS and XMCD spectra measured at the  $L_3$  and  $L_2$  Fe absorption edges.

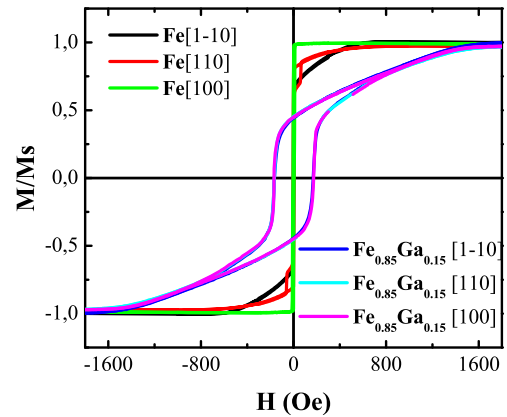
obtained at the  $L_{2,3}$  Fe edges by total yield detection at remanence after magnetic saturation (TEMPO beamline, SOLEIL synchrotron). XAS spectroscopy probes empty electronic states close to the Fermi energy and is very sensitive to electronic properties. XMCD spectra, obtained by subtracting XAS spectra measured for opposite helicities of the circularly polarized X-rays, provide information about the ground state magnetic properties, element selectively. Figure 1 compares  $Fe_{1-x}Ga_x$  spectra with those measured in pristine Fe thin films grown on ZnSe/GaAs(001) [9]. One can conclude that despite the strong Ga-content,  $L_{3,2}$  XAS and XMCD spectra preserve the pristine iron spectroscopic signatures without noticeable modifications of the electronic configuration.

Despite the close similarities of absorption spectra between  $Fe_{1-x}Ga_x$  and iron thin films, we find that the overall magnetic properties are strongly affected by Ga-substitution. In Figure 2 we compare the in-plane (IP) magnetic hysteresis of  $Fe_{1-x}Ga_x$  samples along the main crystalline axis with those measured on pristine iron thin films.

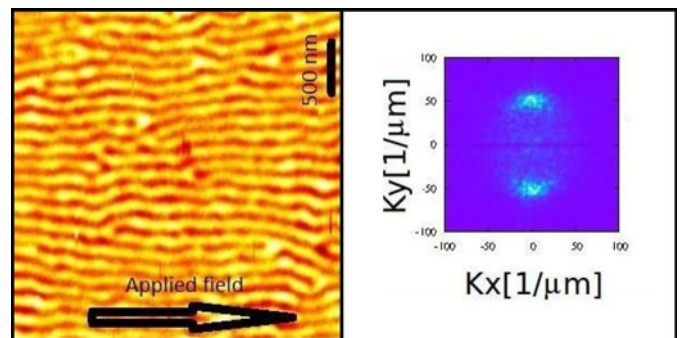
One notices that the biaxial iron magnetic anisotropy favouring the (001) axis is lost when  $x = 15\%$  magnetic hysteresis measured along different axes nearly overlap, indicating a Ga-induced quenching of the biaxial magnetic anisotropy. Concerning the hysteresis curves themselves, saturation is attained only at 1700 Oe after a reversible and linear H-dependence of the magnetization. This is strongly at variance with what is observed for pristine iron thin films where saturation is achieved at lower fields (550 Oe).

This behaviour reflects an oscillating component of the thin film magnetization perpendicular to the film plane that is persistent even at high fields. Similar phenomena have been observed in FePt and other metallic ferromagnetic materials (see [10] and references therein). Such an OP magnetization, induced by the combined magnetostrictive and epitaxial properties of our  $Fe_{1-x}Ga_x$  thin films, induce a periodic stripe array whose observation is straightforward by magnetic force microscopy (MFM).

In Figure 3, we show the MFM image for the sample under study. The picture was taken at remanence



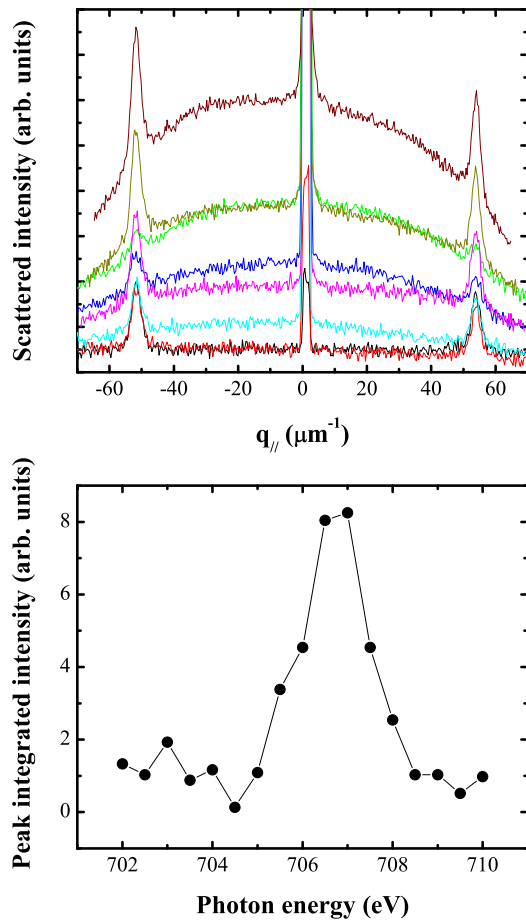
**Fig. 2.** VSM measurements of pure iron and FeGa thin films epitaxied on ZnSe/GaAs(001) substrates.



**Fig. 3.** Left: MFM measurements for  $Fe_{1-x}Ga_x$  thin film (72 nm thick) and  $x = 15\%$ . Right: 2D Fourier Transform of the MFM measurement.

after applying a saturating field along the [110] direction. We observe that the stripe pattern is aligned along the direction of the saturating field, with a period of  $(130 \pm 10)$  nm. It is important underlining that the saturating field was also applied along other crystallographic directions and always the stripe pattern follows the field direction. This behaviour is expected for system with rotatable anisotropy [10], where magnetostrictive effects induce an extra uniaxial anisotropy along the direction of the applied field.

In order to get a more quantitative analysis of the stripe period and of the rotatable anisotropy of  $Fe_{1-x}Ga_x$  thin films, we performed X-ray resonant magnetic scattering (XRMS) experiments at the Fe- $L_{2,3}$  edges (SEX-TANTS beamline, SOLEIL synchrotron), which provide a simultaneous description of both the structural and magnetic properties of the sample [11]. Prior to scattering experiments, the periodic stripe array was aligned along the [110] direction, perpendicular to the vertical scattering plane (see Fig. 4 down). An electromagnet could apply in situ a magnetic field along the intersection between the sample surface and the scattering plane, with sufficient intensity to rotate the stripes. In terms of exchanged momentum  $q$ , specular reflectivity measurements correspond to  $qz$  scans at  $q_{\parallel} = 0$  ( $qz$  and  $q_{\parallel}$  are the  $q$ -components lying in the scattering plane, perpendicular and parallel to the sample surface, respectively). We also performed rocking



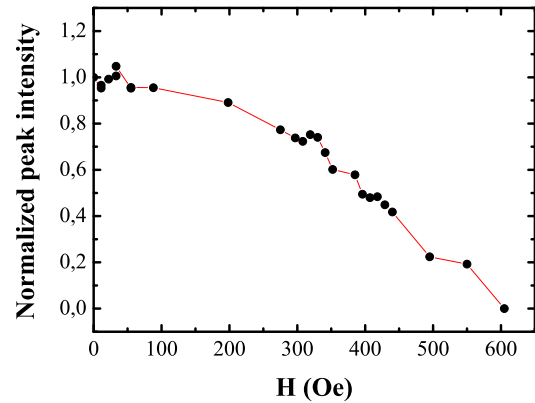
**Fig. 4.** Top:  $q_{||}$  rocking scans (scattered intensity versus sample angle) at fixed detector angle at several  $q_z$  values. The side peaks are at  $q_{||} = 0.52 \mu\text{m}^{-1}$ , corresponding to a stripe period of 121 nm, in agreement with MFM observations (see Fourier Transform of MFM image in Fig. 3). Bottom: peak integrated intensity as a function of the impinging photon energy.

scans in order to measure stripes periodicity ( $T$ ) following the interference diffraction law:  $q_{||} = 2m/T$ , where  $m$  is an integer number.

Figure 4 shows XRMS  $q_{||}$ -rocking curves obtained using circularly polarized X-rays tuned at the Fe2p resonance (707 eV). In addition to specular reflectivity, two sharp peaks appear at  $q_{||} = 52 \mu\text{m}^{-1}$ ; they can be attributed to the regular stripe pattern with period  $T = 121$  nm, in agreement with MFM observations (see Fourier Transform of MFM image in Fig. 3). Figure 4 (down) shows that the peak intensity decreases rapidly and vanishes by varying the photon energy of a few eV only, confirming beyond doubt their purely magnetic origin.

When the external magnetic field is applied along the scattering plane, stripes rotate as observed by MFM measurements, weakening the magnetic peak intensity (Fig. 5). One can notice that two magnetic field regimes exist, the intensity being almost unaffected below 200 Oe.

In conclusion, we have carried out a magnetic study of the rotatable anisotropy of  $\text{Fe}_{1-x}\text{Ga}_x$  thin films epitaxially grown on GaAs(001) substrates. We have shown that magnetic properties are strongly modified compared to



**Fig. 5.** Diffraction peak intensity vs. external magnetic field.

pristine Fe films. An out-of-plane magnetic component leads to the formation of a magnetic stripe array whose direction can be controlled by an external magnetic field, as attested by MFM and X-ray resonant scattering measurements.

All these phenomena can be attributed to the strong magnetoelastic coefficient of  $\text{Fe}_{1-x}\text{Ga}_x$  thin films, with potential for a piezoelectric manipulation of magnetic properties.

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