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Unaltered reversible magnetic transition in Fe nanostructures upon ambient exposure

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ABSTRACT

High aspect-ratio Fe nanostrips are known to reversibly switch from a single-domain magnetic state to a multidomain diamond pattern as a function of temperature (T) and width. This magnetic bistability can be understood by the temperature-dependent balance between magnetocrystalline, shape and magnetoelastic anisotropies and has potential applications in magnetic logic devices. However, as Fe nanostructures easily oxidize, protecting the surface with capping layers may be required, which could largely affect the anisotropy balance. Here, we employ x-ray magnetic circular dichroism-photoemission electron microscopy (XMCD–PEEM) to study these thin Fe nanostrips before and after exposure to air.

1. Introduction

Magnetism is a thriving topic, fueled partly by current and future applications in information storage [1,2]. A great deal of innovative developments in the field are based on magnetic mesoscopic structures where new effects and means of control of magnetic properties blossom [3–5]. Metallic thin-films constitute in particular a fascinating and dynamic field, although they often bring about the technological challenge of preventing gas adsorption processes that could damage or alter their properties [6,7]. In mesoscopic magnetic systems, it is common that a subtle balance of anisotropies regulates the effect or functionality of interest and the use of capping layers or embedding the magnetic film in a multilayer can largely affect this balance [8].

Recently, a reversible switching between two magnetic states was observed in epitaxial Fe nanostrips on Ru(0001) [9]. These Fe nanostructures undergo a transition between single and multidomain magnetic configurations as a function of temperature, an effect that was proven to be related to the temperature dependence of the different anisotropy terms/contributions, especially the magnetoelastic anisotropy originated by the mismatch with the Ru (0001) substrate. This bistability presents interesting opportunities in memory and logic device development; however, its applicability is limited by the fact that it has, so far, only been observed in an ultrahigh vacuum environment. The survival of this transition upon capping the nanostrips with a protective layer or upon exposure to air remains to be demonstrated.

In this work, we study the transition between single and multidomain magnetic domain configurations in epitaxially grown Fe nanostrips before and after the exposure to air, proving the robustness of the transition and monitoring the degree of oxidation using X-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD) both in combination with a photoemission electron microscope (PEEM).

2. Material and methods

The experiments have been performed at the CIRCE beamline of the ALBA Synchrotron Light Facility. The beamline employs an Elmitec spectroscopic and low-energy electron microscope (SPELEEM) [10]. The instrument allows acquiring either x-ray circular magnetic dichroism (XMCD) images to map the in-plane magnetization component along the x-ray direction with nanometer resolution, or selected area XMCD spectra as a function of photon energy. For XMCD images, images at the Fe L_3-*edge* were taken with opposite photon helicity, and subtracted pixel-by-pixel. Local XMCD spectra are extracted from selected regions in XAS image stacks with varying photon energy, using opposite domains at constant helicity. The main microscope chamber operates as a molecular beam-epitaxy station with a base pressure below 1×10^{-10} mbar. Ru substrates were cleaned by annealing at 1400 K under 5×10^{-8} mbar O_2. Eight atomic layers (AL) of Fe were

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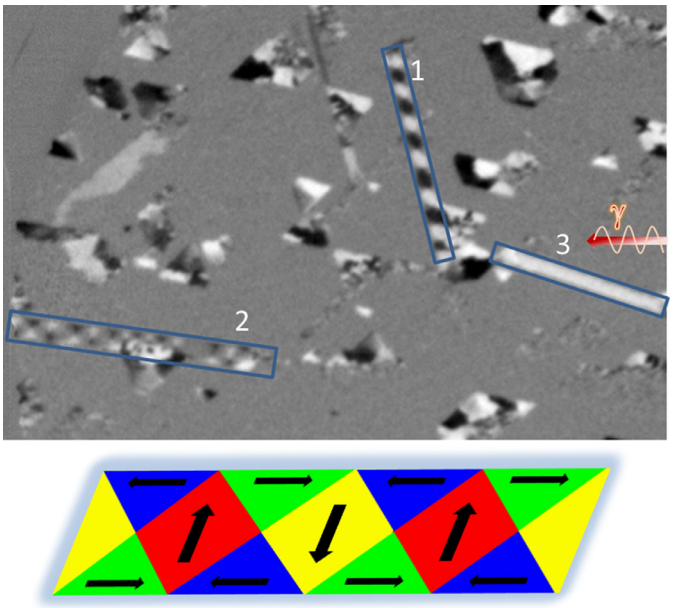

Fig. 1. XMCD–PEEM image (field-of-view 11 μm × 7 μm) at the Fe L_3-*edge* obtained at RT in the initial state. Incoming photon direction indicated by red arrow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

deposited by molecular beam epitaxy onto clean Ru(0001) substrates in 1×10^{-6} mbar O_2. The iron dose rate was 2 AL per minute and the substrate was kept at 920 K, which leads to the formation of Fe nanostrips on the surface. After growth, the samples were cooled down to room temperature in ultrahigh-vacuum (no O_2 atmosphere). Growth is monitored in real time and real space by low-energy electron microscopy (LEEM). We study the properties of the nanostrips using XMCD–PEEM, XAS and LEEM before and after exposing the sample to air for 30 min.

3. Results

Fig. 1 shows an XMCD–PEEM image at room-temperature (RT) of the sample, obtained at the Fe L_3-*edge* in the initial state, i.e. after cooling from the growth temperature of 920 K in UHV. The resulting film is composed of Fe nanostrips and magnetite (Fe_3O_4) islands of triangular and trapezoidal shape, both on top of a FeO bilayer [9]. The FeO wetting layer shows no magnetic contrast, while both the Fe_3O_4 and Fe nanostructures present magnetic domains at RT. In particular, the result from our previous work is reproduced in that, depending on their width, Fe strips can be found in one of two magnetic states: essentially homogeneous single-domain states or multi-domain diamond states [9]. The specific domain structure of the diamond state is schematized in Fig. 1. Given that in XMCD–PEEM grayscale magnetic contrast is proportional to the magnetization vector along the photon beam direction, the nanostrips close to parallel/perpendicular orientation with respect to the beam reveal the four different domains in either four (upper right strip "1", where red and green as well as blue and yellow domains are almost equivalent) or three (left lower strip "2", red and yellow domain are equivalent) intensities respectively. A third strip "3" at the right edge was found to be in a single domain state (white) at RT.

Heating the sample above 250 °C, we confirmed the transition as a function of temperature, identifying specific strips that were observed to be in single-domain state at RT and diamond state at 250 °C (results not shown).

Fig. 2a presents an XMCD–PEEM image of the same area depicted in Fig. 1 after extracting the sample out of the UHV microscope chamber and exposing it to air for 30 min. The Fe strips are seen to remain magnetic after exposure to air, in particular the second and third wire described in the context of Fig. 1 are found to be in the same domain configuration (strip "1" in diamond pattern, strip "3" single domain, white). Subsequently, the sample was heated to 250 °C and another XMCD–PEEM image, shown in Fig. 2b, was collected.

Remarkably, the transition from single-domain to multi-domain pattern is observed for the strip "3" indicated by the arrow in the same temperature range as before air exposure, i.e. between RT and 250 °C [9]. The transition temperature depends on the width of the wire, and is the consequence of a delicate balance between the magnetic anisotropies at play: magnetocrystalline, shape and magnetoelastic anisotropy [9]. The occurrence of the transition at very similar temperatures is an indication that this anisotropy balance is, at most, only mildly affected by air exposure. On the other hand, a closer examination of Fig. 2 seems to indicate that the magnetic contrast in the Fe strips is fainter at 250 °C than at RT. Fig. 3 shows the asymmetry between black and white magnetic domains at both temperatures for strip 2, which confirms a decay in asymmetry –and thus in magnetic contrast- from 0.34 at RT to 0.22 at higher temperatures. Given that the two images were taken under identical experimental conditions, this 35% decrease in asymmetry implies a 35% decrease in the magnetization component of the Fe strip that is parallel to the incoming photon beam. The Curie temperature of Fe (770 °C) is well above the temperature range studied here (25–250 °C); therefore such a considerable decay in magnetization cannot be explained by proximity to T_c [11]. In addition, the magnetic magnetite islands that surround the strips do not show a decrease in contrast (nor magnetization). This decrease in magnetization could be related to oxygen

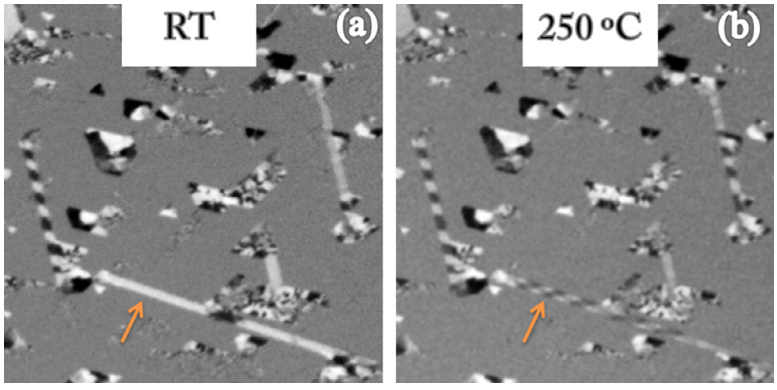

Fig. 2. XMCD–PEEM images (field-of-view 9 μm × 9 μm) at the Fe L_3-*edge* obtained at RT and 250 °C after exposing the Fe strips to air for 30 min.