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Soft X-ray resonant magnetic scattering study of magnetization reversal in low dimensional magnetic heterostructures

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Abstract

Soft X-ray resonant magnetic scattering (SXRMS) has been used to investigate the microscopic magnetization reversal behavior of complex magnetic systems. SXRMS is a unique technique, providing chemical, spatial and magnetic sensitivity, which is not affected by external magnetic fields. The study of two selected thin magnetic heterostructures is presented, amorphous rare-earth transition metal alloys and perpendicular exchange coupled antiferromagnetic/ferromagnetic films. In the first system, the internal structure of magnetic stripe domains on nanometer length scales is obtained by measuring bi-dimensional (2D) scattering images. In the second system, the element specificity is exploited to identify the role of the uncompensated spins in the antiferromagnetic layer on the exchange coupling phenomena. Future trends are also discussed.

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1. Introduction

The study of magnetization reversal is an essential issue for the future of spintronics. Central to nanomagnetism investigations are hysteresis and magnetization reversal processes, which control the responses of magnetization to magnetic fields. On the other hand, current and future applications related to nanomagnetism in general consist of more than one magnetic component [1] and, usually, their resulting properties are not simply additive. New experimental tools which can test the magnetic properties of each component independently within the complex system have to be added to the toolkit of standard magnetic characterization methods. The understanding and control of the magnetization reversal behavior could be the first step towards the development of spintronic devices with custom-chosen properties.

Only very few experimental techniques can address the microscopic magnetic properties of the different magnetic layers in a multilayered system with element selectivity. All of them are synchrotron-based techniques and exploit the strong magneto-optical contrast at the specific X-ray absorption transitions [2]. The soft X-ray range, with wavelengths between 1 and 2 nm, hosts the largest resonances of the magnetically important transition-metal and rare-earth series. For instance, photoelectron emission microscopy (PEEM) combined with X-ray magnetic circular dichroism (XMCD) has already proven its versatility for the layer-resolved investigation of microscopic magnetic domains in multilayered magnetic samples in their remanent state [3] or under applied magnetic fields in microscopic areas [4]. With macroscopic fields, photon-in photon-out techniques such as transmission X-ray microscopy

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(TXM) [5,6] and X-ray resonant magnetic scattering (SXRMS) [7–10] have been established as new powerful tools for studying magnetic structures in surfaces and thin films on the nanometer length scale. The magnetic contrast is achieved by polarization dependent experiments, whereas the microscopic information is achieved in real and Fourier space for TXM and SXRMS experiments, respectively. TXM requires image-forming lenses, such as Fresnel zone plates used in conventional X-ray microscopy, and the resolution is limited by this. On the contrary, SXRMS is, in principle, limited only by the soft X-ray wavelength, which is about a factor of 10 smaller than the resolution achievable with image X-ray lenses today.

In this paper we show the capabilities of SXRMS to study the magnetic properties of low dimensional magnetic heterostructures, selecting two examples with a perpendicular magnetic anisotropy. An amorphous 40 nm thick $GdFe_5$ and a polycrystalline [2.3 nm Pt/0.4 nm Co]$_{15}$/10 nm FeMn film were grown, respectively, by molecular beam epitaxy and sputtering on 100 nm thick Si_3N_4 windows, to facilitate X-ray transmission measurements. The windows have transmission factors of $\sim$95% at the Gd-$M_{4,5}$ energy, and $\sim$ 85% at the Fe and Co-$L_{2,3}$ absorption edges. In order to prevent oxidation, the films were, respectively, capped with 2 nm thick Al and Pt protection layers. The amorphous $GdFe_5$ film presented here [9] belongs to the same family as amorphous TbFeCo films used in perpendicular magneto-optic recording [12]. The $[Co/Pt]_n$/FeMn film is a perpendicular exchange coupled ferromagnetic/antiferromagnetic (FM/AFM) system [11] which offers the possibility to pin the hard magnetic layer of spintronic devices with perpendicular anisotropy at room temperature [13].

The SXRMS experiments were carried out on the soft X-ray beam line ID08 [14] of the European Synchrotron Radiation Facility (ESRF) in Grenoble (France), using 100% circularly polarized light from a helical undulator. Our experimental layout is schematically shown in Fig. 1. The samples were mounted in a high-vacuum chamber and the field applied perpendicular to the film surface was generated by an electromagnet mounted outside [8]. The X-rays were incident along the surface normal (transmission geometry). By using a 2D detector and by tuning the photon energy to elemental absorption edges we could resolve the whole q-space with element selectivity during the magnetization reversal.

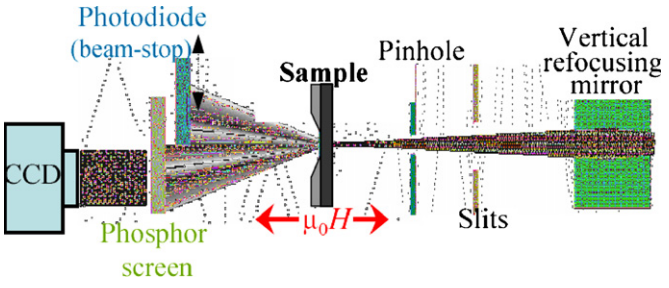

Fig. 1. SXRMS schematic experimental layout. The incoming synchrotron beam is defined with the help of slits and pinholes. A movable photodiode intercepts either the scattered intensity (as shown) or the transmitted intensity direct beam. 2D q-space resolution is obtained by using a phosphor-coated vacuum window imaged with a CCD camera.

We can performed two types of measurements: (i) X-ray magnetic circular dichroism (XMCD), by flipping the saturating magnetic field at each photon energy, and X-ray absorption spectra (XAS) by averaging the data taken with left and right circular polarization; (ii) element-selective magnetic field-dependent measurements in absorption and scattering. A beamstop eliminates the straight-through beam allowing the total scattering intensity to be measured either with a 1 cm^2 Si photodiode or with a 2D detector (phosphor-coated vacuum window imaged by a 12-bit charge-coupled device (CCD) camera) for angular resolved measurements. The size of the domains, the amplitude of the magnetic modulation, and the domain wall width will hence be monitored along the decreasing and increasing field branches of the magnetization curve up to fields of $\pm$0.3 T.

The microscopic information of the magnetic structure and of the reversal process can be obtained as a function of applied field by measuring scattering images, like the ones obtained for the GdFe film and depicted in Fig. 2. A simple Fourier inversion of the scattering pattern (reciprocal space) yields indirectly the real-space image. The 2D q-space resolved images were acquired in the absence of an applied field, i.e., remanent state, after saturation the GdFe film in different directions. The maximum sensitivity was reached using the M_5 white line of Gd (1185 eV) [8,9].The diffuse background was eliminated before further data processing by subtracting exposures taken at

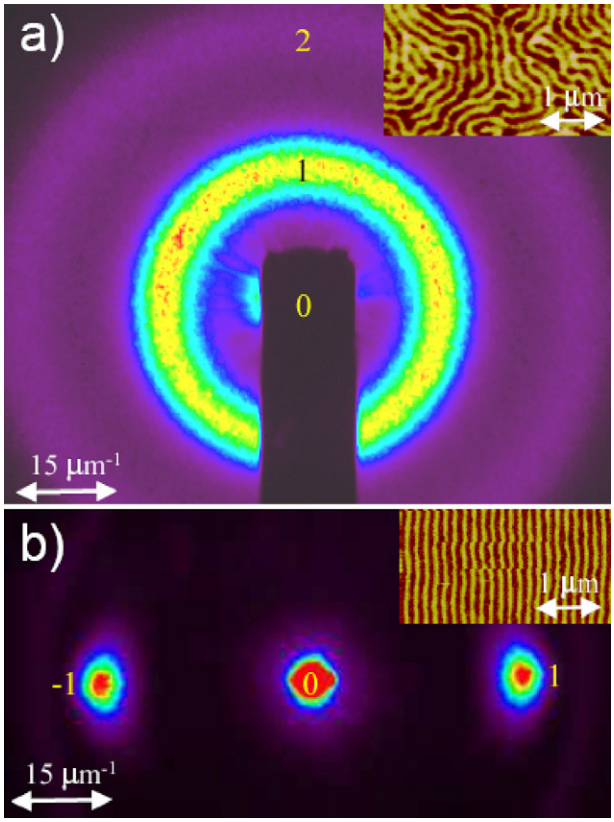

Fig. 2. Diffraction patterns of a 40 nm $GdFe_5$ film after saturation with a perpendicular field (a) and with an in-plane field (b). The incoming photons correspond to the Gd-M_5 absorption edge. The insets show the corresponding magnetic force microscopy images acquired in the same conditions.

magnetic saturation. The ring shape of the scattered signal observed in Fig. 2a, indicates that a randomly oriented magnetic domain structure has been formed after out-of-plane magnetic saturation. On the other hand, in-plane saturation leads to the appearance of two very sharp and intense peaks (Fig. 2b), indicating a highly aligned quasi-1D domain lattice. The amorphous GdFe films display perpendicular anisotropy and in the remanent state the magnetization self-organizes in alternating up and down magnetized bands, leading to a vanishing total magnetization. They result from the competition between the local exchange and anisotropy interactions that favor a saturated single domain state, and the long-range demagnetizing dipolar field that tends to break up this single domain, at the cost of the creation of domain walls. The analysis of the field evolution of the diffraction pattern has been presented elsewhere [9]. A rich amount of averaged information can be extracted from the complete data: the normalized perpendicular magnetization loops, the domain period, the width of the reversed domains, the correlation length normalized to the period, and the total scattered intensity.

Chemical selectivity can be obtained by tuning the X-ray photon energy to an absorption edge of the layer of interest. This is shown for the perpendicular exchange-coupled $[Pt/Co]_{15}$/FeMn film. Element-selective hysteresis loops were obtained by measuring the absorption signal as a function of applied field, with the energy fixed at the maximum of the dichroism of the element of interest. In this case, the maximum sensitivity to study the ferromagnetic layer was reached at the L_3 white line of Co (778 eV), where as the L_3 white line of Fe (708.5 eV) was used for probing the uncompensated antiferromagnetic spins [11].

The field dependence of the absorption intensity at the Co-L_3 edge shown in Fig. 3a reproduces the magnetization hysteresis curves measured by standard magnetometry techniques, as magneto-optical Kerr effect or vibrating sample magnetometry.

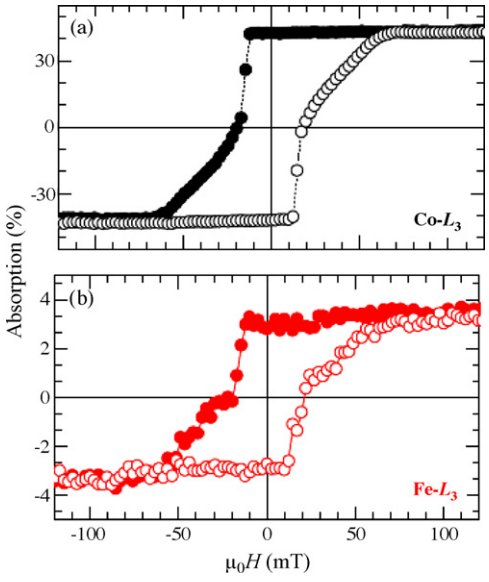

Fig. 3. Element-selective hysteresis curves of a $[Pt/Co]_{15}$/FeMn film acquired at the Co (a) and Fe (b) L_3 absorption edges.

The FM/AFM film presents an enhancement of the coercive field, from 5 mT in the same Pt/Co multilayer without AFM layer to about 12.5 mT, but not a relevant shift of the hysteresis. The field dependence of the Fe-L_3 absorption intensity (Fig. 3b) reflects the presence of uncompensated AFM spins, which are dragged during the reversal of the FM layer. Moreover the similar sign of the FM and AFM hysteresis indicates that the uncompensated AFM spins are aligned parallel to the FM ones. In general, the most notable effects in FM/AFM systems of the interfacial exchange coupling are a shift away of the magnetization loop from the zero field axis, called exchange bias, an enhanced coercivity and a change of the overall magnetization reversal of the FM layer. In this case, all the uncompensated AFM spins are dragged during the FM reversal, give rise to the enhancement of the coercive field [11].

We have shown the capabilities of soft X-ray resonant magnetic scattering for studying element (or layer)-selective magnetization reversal in complex systems with spatial resolution and in presence of external fields. Future trends of this technique are both spectroscopic holography [15] and picosecond time-resolved [16] experiments. The phase information problem of the standard scattering techniques to get the true magnetic image in the real space can be solved with the use of a nanoscale reference aperture next to the sample that phases the recorded interference pattern [15]. On the other hand, by combining SXRMS experiments with a pump-probe technique using synchrotron radiation, the magnetization dynamics can be determined on a sub-100 ps time scale with a lateral spatial resolution down to 30 nm [16]. Direct microscopy experiments using similar pump-probe technique are limited to study only magnetic systems with reproducible magnetization reversal processes [4]. This limitation is overcome by using SXRMS because the microscopic information of the reversal is achieved indirectly in the q-space [16], thus giving access at least to average magnetic properties, as described above. These trends opens a route towards a high spatiotemporal resolution which is needed to understand the microscopic origin of magnetization reversal in current and future magnetic complex systems.

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