Rapid note

Imaging of magnetic domains with the X-ray microscope at BESSY using X-ray magnetic circular dichroism

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Abstract. X-ray Magnetic Circular Dichroism (X-MCD), i.e. the change of the absorption of circular polarized X-rays for reversed sample magnetization amounts at the L\textsubscript{2,3}\textsuperscript{-}edges of 3d transition metals up to 50\% percent. This can be used to obtain in energy-dispersive X-ray imaging techniques a considerable, element-specific magnetic contrast. On the other hand, with the transmission X-ray microscope (TXM) based on the zone-plate technique spatial resolutions of 30\,nm can be achieved. In this communication it is shown for the first time that the combination of the TXM with X-MCD provides a huge contrast and is therefore a powerful new method to visualize in a quantitative and element-specific manner magnetic domains. Using soft X-rays with a wavelength of 1.7\,nm corresponding to the energy of the Fe L\textsubscript{3}-edge the variation of the shape and magnetization of domains in a magneto-optical GdFe layer system was studied with a lateral resolution of 60\,nm.

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1. Introduction

Systems of reduced dimensionality as surfaces, thin films and multilayers are attracting rapidly growing interest in solid state science and technology. This is intimately correlated with the advent of the modern and improved methods to prepare layers with defined structures and to characterize their actual morphology. The detailed understanding of magnetism down to atomic dimensions of thin layers is a field of scientific curiosity as well as of technical importance. However, the microscopic origin of the macroscopic magnetic properties, which make these structures important for the technical application, is still an open and challenging problem.

Among the variety of methods the detection of X-MCD or the magnetic absorption, i.e. the dependence of the core-level absorption coefficient of circular polarized photons on the target magnetization is a powerful X-ray spectroscopic method to study the magnetic characteristics of the electronic structure \cite{1,2}. One attractive aspect arises from the unique possibility to determine in appropriate cases as Fe,Co,Ni in an element-selective manner local magnetic moments separated into spin and orbital contributions invoking magneto-optical sum rules \cite{3,4}. The strength of the dichroic signal resulting in a change of up to 50\% of the absorption for reversed sample magnetization is considerably large. Thus it is possible to observe small variations of the projection of atomic magnetic moments onto the photon propagation direction of less than $10^{-2}\mu_B$.

Furthermore the study of magnetic structures on the mesoscopic scale is a crucial topic in magnetism. Since the micromagnetic performance is determined by the magnetic domain structures, the imaging of their patterns, wall sizes and dynamics is an important issue. Especially in those systems, where the layer thickness approaches the order of the domain wall width being determined by anisotropy and exchange constants, interesting phenomena should occur.

The static domain properties can be studied with high spatial resolution even down to several nm, by powerful new methods, as e.g. Scanning Electron Microscopy with Polarization Analysis (SEMPA), Lorentz microscopy and Magnetic Force Microscopy (MFM). Although widely available, they are, however, inherent sensitive to the surface or restricted to very thin layered magnetic structures. To study the dynamics of the domains as a function of an external magnetic field Kerr-microscopy is well established, but with the resolution limit of optical microscopy.

To overcome these limitations and yet to keep all advantages of magnetic microscopy with photons we have applied a novel domain imaging technique using the transmission X-ray microscope (TXM) at BESSY I in combination with a contrast enhancement based on the X-ray magnetic circular dichroism (X-MCD). In the following the physical basis and the experimental aspects are outlined. First results on a rare-earth (RE) transition-metal (TM) alloy are presented, where the hysteresis properties of the domain pattern and their long-term variation have been studied in real-time transmission mode with a spatial resolution of 60\,nm.
2. Dichroic magnetic contrast

With respect to its physical origin the magnetic dichroism in X-ray absorption is closely related to the polar magneto-optical Kerr effect. The major difference, however, is the fact, that in the optical absorption process a variety of states close to the Fermi level are involved. Since in the X-MCD the initial state is a well defined core level state this method features an element-sensitivity and due to dipole selection rules also a symmetry-selectivity. In principle core-level absorption spectroscopy is a local method, insofar as the transition matrix elements are only large for strong spatial overlaps between the core level and the final state wave functions in the absorption process.

The magnetic contrast can be described as the energy-dependent deviation \( \Delta \mu(E) \) of the absorption coefficient relative to the polarization averaged absorption coefficient \( \mu_{i>} \) where only photoprocesses in the initial core state \( |i> \) are taken into account. It can be expressed by

\[
\frac{\Delta \mu (E)}{\mu_{i>}} = \frac{\sigma_c}{\sigma_{i>}} (\hat{m} \cdot \hat{e}_z) P_c
\]

(1)

where \((\hat{m} \cdot \hat{e}_z)\) denotes the projection of the normalized magnetic moment \(\hat{m} = \frac{m}{|m|}\) onto the propagation direction with unit vector \(\hat{e}_z\) of the photons with a degree of circular polarization \(P_c\). The magnetic absorption cross section normalized to the polarization averaged atomic cross section \(\sigma_{i>}\) has been determined to reach at the maximum of the Fe metal L_3 edge \(\sigma_{i>}(E = 706eV) \approx 23\% \) or \(\sigma_c \approx 2 \cdot 10^5 \text{ barn/atom}, \text{ i.e. } 2 \cdot 10^8 \text{ eV}^2\).

It follows from Eq. (1) that provided \(P_c\) is known, the value of \(\Delta \mu\) is a sensitive measure of \(\hat{m} \cdot \hat{e}_z\). Taking into account the value of the absolute magnetic moment in the pure Fe-metal of \(|m| = 2.2 \mu_B\) the observable experimental quantity reflects the absolute value of the spatial magnetization distribution.

Previous attempts reported in literature have successively combined the magnetic dichroism in photoemission with imaging electron spectrometers [5] and also with a photoelectron emission microscope [6] to image magnetic domains with a resolution of some \(\mu m\).

3. Experimental details

The sample investigated was a binary Gd_{27.7}Fe_{72.3} system with a Curie temperature of \(T_c \sim 510 K\). The amorphous film was prepared by coevaporation from two electron-gun sources in a high vacuum system onto a 325nm Polyimid film as substrate. For chemical protection, the Gd-Fe films of thickness \(h = 59 \pm 1\text{nm}\) were covered with 15nm Al layers on both sides of the Gd-Fe layer. The density of the films was typically 95\% as compared to their crystalline counterparts. Simultaneously reference films were prepared on glass substrates in order to determine the coercivity and the layer thickness. The layer composition was analyzed by electron probe micro-analysis (EPMA). The out-of-plane coercivity of this sample was determined both by Faraday effect, VSM and Kerr magnetometry measurements and in-situ with the X-ray microscope as described later. Thus \(H_c\) was determined to \(6(2)\text{mT}\) with a shift of the hysteresis loop of \(H_G \sim 8(2)\text{mT}\), which can be attributed to remaining magnetically hard regions which cannot be altered by the applied magnetic field.

The X-ray optical set-up of the TXM, which is described in more detail in [7,8] is shown in Fig. 1. The condensor zone plate images the source into the object plane. The object field is limited by a pinhole with a diameter of about 20\(\mu m\). Due to the wavelength dependence of the focal length of a zone plate the wavelength used for the experiments can easily be changed by moving the condensor along the optical axis of the microscope. Condensor and pinhole act together as a linear monochromator. The monochromaticity is given by \(\lambda / \Delta \lambda = D/2d\), where \(D\) is the diameter of the condensor and \(d\) is the diameter of the pinhole. With \(D = 9\text{mm}\) and \(d = 20\mu m\) one gets \(\lambda / \Delta \lambda = 225\). The microzone plate as a high resolution X-ray objective generates a magnified image of the object in the image field with a spatial resolution of about 60\(\mu m\). A slow scan CCD camera with a thinned, backside illuminated CCD chip with a detective quantum efficiency (DQE) of about 70\% is used to take the X-ray images [9]. The total extinction of the radiation in the target \(I / I_0\) for the GdFe system at a photon energy of \(E = 706eV\) was determined to 90\% with a contribution due to Fe L_3 absorption of 70\%.

To illuminate the Gd_{27.7}Fe_{72.3} sample oriented with its plane perpendicular to the photon beam/external field direction with circular polarized light, part of the condensor was masked so that only the lower segment of the condensor with