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# Magnetic domain imaging with a transmission X-ray microscope

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## Abstract

The combination of X-ray magnetic circular dichroism being an element-specific local probe for the magnetic microstructure and the transmission X-ray microscope providing a spatial resolution of about 30 nm allows to image magnetic domains with a huge contrast. Special virtues of this technique are the applicability of varying magnetic fields thus allowing technologically relevant studies of the evolution and the switching behaviour of domain structures. Quantitative information on the local magnetization and in particular a separation of spin and orbital moments is possible. Results obtained at the Fe and Co $L_3$ edges in GdFe and PtCo multilayered systems demonstrate the potential of this new technique. 

*Keywords:* Domain imaging; X-ray magnetic circular dichroism; Transmission X-ray microscope

## 1. Introduction

Ultrathin magnetic films and multilayers are of increasing importance in technological applications, as e.g. magneto-electronics (MRAMs), ultrahigh density magnetic and magneto-optic recording media or GMR based read-out heads. The increase in power of such devices is accompanied by a miniaturization of their substructures, which have approached the sub-μm range. Hence reliable information on the magnetic microstructure to determine the technical/physical limits is indispensable. For instance, the exact switching behaviour of magnetic domains in microsensor devices within an applied field is an unanswered question. Several powerful techniques to study both static and dynamic properties of magnetic domains like scanning electron microscopy with polarization analysis (SEMPA), Lorentz microscopy, magnetic force microscopy (MFM), photoemission electron microscopy (PEEM) or scanning near field optical microscopy (SNOM) are available. The requirements, however, a magnetic imaging technique has to meet are high spatial resolution and high sensitivity connected with a large contrast. Furthermore, regarding multicomponent systems element-specificity is highly desired and recording in varying applied magnetic fields seems to be essential for a characterization of devices under real conditions.

A promising new technique has been established recently by a combination of the effect of X-ray magnetic circular dichroism (X–MCD) as a contrast mechanism with a high-resolution transmission X-ray microscope (TXM) [1]. The dichroic effect, which occurs in the vicinity of element-specific inner-core absorption edges, exhibits a dependence of the absorption of circularly polarized X-rays on the projection of the magnetization onto the photon propagation direction in ferromagnetic samples. At L-edges in 3d transition metals relative values up to 50% compared to the unpolarized absorption

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cross-section occur. It can therefore serve as a huge magnetic contrast in imaging techniques. Furthermore, the absorption of circularly polarized photons can be directly related to the local magnetization of the absorbing atom. A unique capability of X–MCD is the possibility to separate between spin and orbital contributions combining spin–orbit coupled edges, e.g. $L_2$ and $L_3$ and taking into account the so-called sum rules [2,3].

## 2. Experimental aspects

The results were obtained at the TXM at BESSY I in Berlin/Germany, which is described in more detail elsewhere [4,5]. Slight modifications allowed to switch to the magnetic mode. The condenser zone plate, which acts due to the wavelength dependence of its focal length together with a pin hole as a linear monochromator was illuminated with circularly polarized X-rays by masking part of the synchrotron beam. The monochromaticity ($\Delta\lambda/\lambda = 225$) is sufficient to separate the spin–orbit split Fe $L_3$ (706 eV) and $L_2$ (719 eV) absorption edges. Thus circularly polarized photons with its energy chosen to a value where the X–MCD effect is maximum are focused onto the sample. A small solenoid provides a magnetic field ( $< 80$ mT) to align the magnetization of the sample along the photon propagation direction. A subsequent micro zone plate uses the photons transmitted through the sample to generate a magnified image (factor 1000) of the object in the image field which is directly recorded by a slow scan CCD camera. Due to the low penetrability of soft X-rays the choice of a suited substrate is essential, however, one can benefit largely from TEM sample preparation techniques which are faced with similar problems.

## 3. Results and discussion

Fig. 1 shows a magnetic transmission X-ray microscopic (M–TXM) image of a $75\times(4$ Å Gd/4 Å Fe) layered system obtained at the Fe $L_3$ edge. The recording time of the image (only a part of the total image field of about 17 μm diameter is shown) was about 3 s for the illumination and about 30 s for reading-out the CCD device. The former is limited by the available flux of circularly polarized photons, while the latter is characteristic to the slow scan CCD used. An on-line contrast of about 10% allows to distinguish clearly dark and light areas, which can be attributed to magnetic domains, where the direction of the local Fe magnetization points in/out of the paper plane. The obtained lateral resolution of 30–40 nm was determined from edge slope profiles and is basically determined by the width of the outermost ring of the micro zone plate.

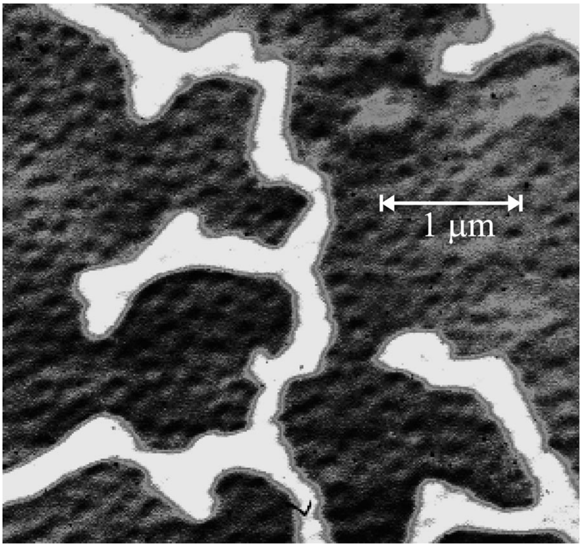


Fig. 1. Part of the image field of 17 μm of a M–TXM image of a multilayered $75\times(4$ Å Gd/4 Å Fe) system.

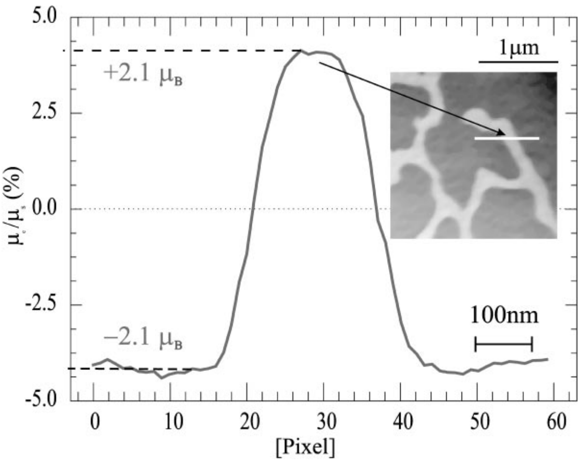


Fig. 2. Intensity scan across the domain marked in the inset of a multilayered GdFe system taken at the Fe $L_3$ egde.

The quantitative information on the local magnetization available with the M–TXM images is shown in Fig. 2, where an intensity scan across the magnetic domain marked in the inset is displayed vs. the pixel number (1 pixel $= 13.79$ nm). By a comparison with the dichroic effect obtained with magnetic absorption spectroscopy (X–MCD) with the same sample the full Fe moment of 2.1 $\mu_B$ within the magnetic domain can be deduced. Details of the domain wall can be studied within the lateral resolution, however from collapsing and expanding experiments performed on this GdFe system

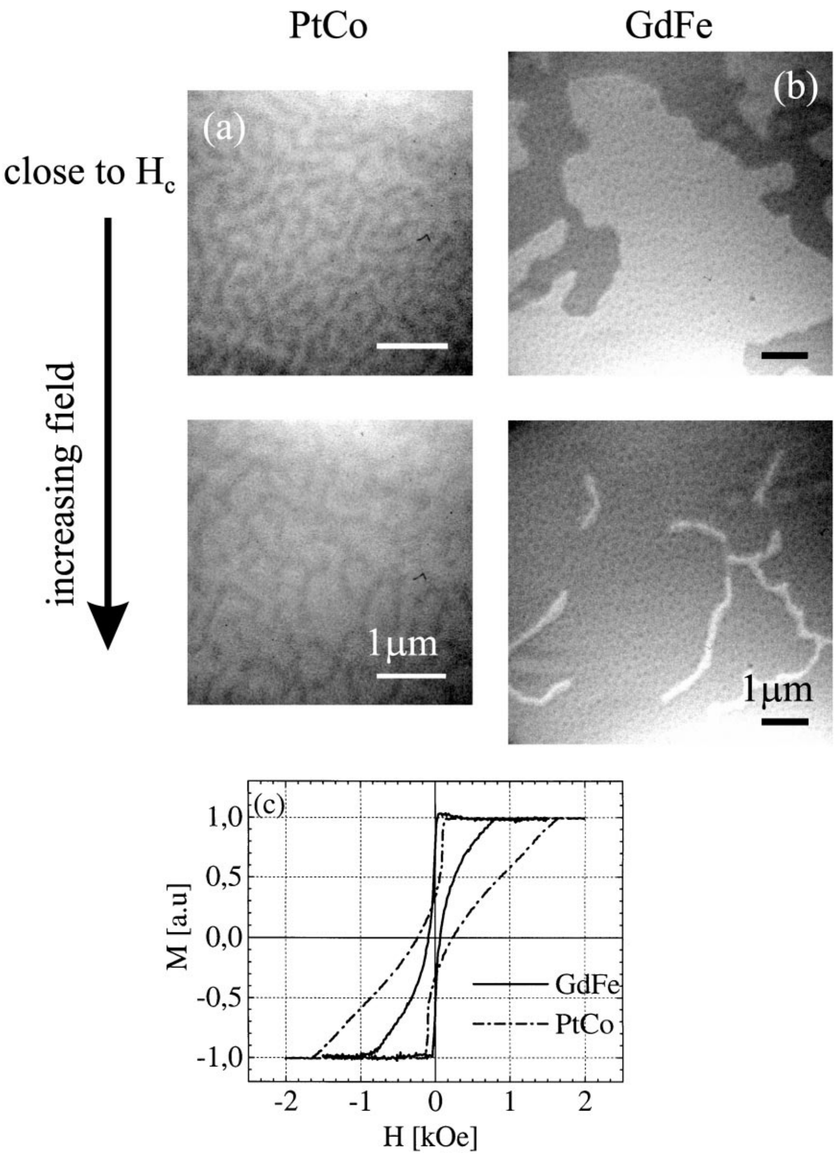


Fig. 3. Multilayered PtCo (a) and GdFe (b) images taken in varying applied magnetic fields and macroscopic Kerrmagnetometry results (c).

a domain wall width is expected to be less than the obtained resolution. An outstanding feature of the transmission mode is the applicability of varying external fields and thus the study of domain formation within a complete hysteresis loop [5]. A typical example thereof in combination with the inherent element-specificity is shown in Fig. 3, where multilayered PtCo (a) and GdFe (b) M–TXM images taken at the Co $L_3$ and Fe $L_3$ edges are presented, resp. Increasing the applied field allows to observe the evolution of the domain structure. The observed domain patterns are completely different for the two systems. The macroscopic hysteresis loops taken with a Kerrmagnetometer are displayed in Fig. 3(c). As the microscopic character determines the macroscopic behaviour it should be possible to relate the observed patterns to each other by a detailed analysis in future.

A dedicated M–TXM setup is planned at BESSY II with the X-ray energy range covering the L edges of 3d TM and the M edges of most RE elements. Higher fields (up to 5 T) and variable sample temperature (77–400 K), improved sample manipulation facilities, like tilting the sample to study in-plane anisotropies together with the improved conditions of a third generation source will provide a powerful tool for specific technological applications. In particular the separation of spin and orbital moments will be possible with high accuracy.

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