Magnetic domains in nanostructured media studied with M-TXM

P. Fischer,[a*†] T. Eimüller,[a] G. Schütz,[a] G. Bayreuther,[b] S. Tsunashima,[c] N. Takagi,[d] G. Denbeaux[e] and D. Attwood[e]

[a]Univ. Würzburg, EP IV, D 97074 Würzburg, Germany, [b]Univ. Regensburg, Exp. Phys., D 93053 Regensburg, Germany, [c]Univ. Nagoya, Dept. of Electr., Nagoya 464-8063, Japan, [d]Hypermed. Res. Cent., SANYO, Anpachi-gun, Gifu 503-0195, Japan, [e]CXRO, LBNL, Berkeley, CA 94720 , USA. Email:peter.fischer@physik.uni-wuerzburg.de

Combining X-ray magnetic circular dichroism (X-MCD) with a transmission X-ray microscope (TXM) allows to image element-specifically magnetic domain structures with 25nm lateral resolution. Both in-plane and out-of-plane systems can be studied in applied magnetic fields. Thus field-dependent parameters, as individual nucleation fields in magnetic nanostructures can be deduced and related to morphology. Images of thermomagnetically written bits in magneto-optical TbFeCo media proof the reliability of the writing process and the importance of an exact thermal design of the systems. Domains observed at corresponding Co L edges proof the chemical sensitivity of M-TXM and its potential to image few monolayer systems.

Keywords: X-ray magnetic circular dichroism, X-ray microscopy, magnetic domains

1. Motivation

Since the discovery (Schütz et al., 1987) of X-ray magnetic circular dichroism more than a decade ago it has been used extenssively as a powerful tool to study local magnetic structures. Recently several attempts have been succesfully made to combine X-MCD with imaging techniques (Stoehr et al., 1993, Fischer et al. 1998) to record with high lateral resolution magnetic microstructures. This is of increasing importance, as magnetic systems of low dimensionality attract increasing interest in both fundamental aspects of magnetism and technological applications. This is supported by the fact that sophisticated preparation techniques established within semiconductor physics for the fabrication of nanostructures are available and currently in use. To name but a few current developments in information storage technology as magneto-optics, the use of giant magnetoresistance (GMR/CMR) based read-out technologies, magnetic sensors or magneto-electronics (MRAM) combining semiconductor physics and magnetism have already passed the sub-100nm length scale. However related to the miniaturization process or the goal to design the magnetic performance control has to be gained over the microscopic domain structure. Hence a variety of techniques to image magnetic domains have been developed in the past including both electron (e.g. scanning electron microscopy with polarization analysis (SEMPA), Lorentz microscopy), optical microscopies (e.g. scanning near-field optical microscopy (SNOM), Kerrmicroscopy) and magnetic force microscopy. The requirements these techniques should meet are high spatial resolution, high sensitivity combined with a huge contrast, chemical-selectivity and imaging in applied fields.

Magnetic transmission X-ray microscopy (M-TXM) is the combination of the X-ray magnetic circular dichroism (X-MCD) and a soft transmission X-ray microscope. The technique was first demonstrated at the synchrotron facility BESSY I in Berlin (Fischer et al., 1996, Fischer et al., 1998). The results presented here demonstrate the versatility of this new concept to image magnetic domains both in magneto-optics and to magnetic nanostructures.

† Currently at CXRO, LBNL, Berkeley, CA

2. Physical Aspects

X-MCD in core-level absorption detects the difference in the absorption coefficient of cicularly polarized X-rays depending on the projection of the magnetization onto the photon propagation direction. Inherent element-specificity is provided as X-MCD is limited to the vicinity of absorption edges corresponding to binding energies. Counting the incoming and transmitted photon intensity is a convenient way to detect absorption coefficients. Due to the limited penetration depth of X-rays in matter the information depth is limited to about 100 nm for the soft X-ray regime below 1 keV, which, however, matches the thicknesses of technologically relevant thin magnetic films one is nowadays faced with.

Large magnetic contributions, i.e. magnetic contrast with values up to 50% can be obtained at the $L_{2,3}$ edges in transition metals (Chen et al. 1990), like Fe, Co, or Ni but also at the $M_{4,5}$ edges in Rare earth elements, which are the most important classes of components in ferromagnetic systems.

Due to an intimate relation of the X-MCD signal at spin-orbit coupled edges to local magnetic spin and orbital moments (Carra et al. 1993, Thole et al. 1992), the magnetic contrast allows for an exact quantification of the lateral distribution of magnetic moments.

3. Experimental Aspects

The XM-1 soft x-ray full field transmission microscope, where most of the work presented here has been done, is located at the Advanced Light Sourced in Berkeley California (Meyer-Ilse et al., 2000). It uses zone plates for the condenser and objective elements. Due to the wavelength dependence of circular gratings the condenser zone plate acts together with a pinhole as linear monochromator allowing to image samples with a spectral resolution of $\lambda/\Delta\lambda$ =500. The spatial resolution given basically by the width of the outmost ring in the microzone plate acting as the optical lense is sufficient to distinguish feature sizes of 25 nm (Denbeaux et al. 2000). Compared to magnetic images obtained with corresponding PEEM or S-TXM techniques this is currently the best lateral resolution. To switch to the magnetic imaging mode with X-MCD at the XM-1 the samples are illuminated with off-orbit emitted circularly polarized X-rays from the bending magnet. Estimates of the degree of circular polarization taking into account the source parameters and the emission characteristics give values about 50-60% which is fairly sufficient.

The magnetic domains resulting from an in-plane magnetization can be obtained by tilting the sample (Fischer et al, 2000a). Both in-plane and out-of-plane external magnetic fields up to several kOe can be applied, which allow the study of the switching behaviour.

4. Results

4.1 Magneto-optical systems

The sensitivity of the dichroic magnetic contrast on the component of the magnetization along the propagation direction of the ferromagnetic species makes M-TXM an ideal technique for systems with a pronounced out-of-plane anisotropy like in magneto-optical recording media. Thin magnetic films of the composition $SiN(70nm)/Tb_{25}(Fe_{75}Co_{25})_{75}(50nm)/SiN(20nm)$ were prepared by sputtering techniques onto a polycarbonate substrate. Thermomagnetic recording was done using laser pumped magnetic field modulation (LP-MFM) method. The wavelength and numerical aperture (N.A.) of the optical head were 635 nm and 0.55 respectively. Diverse bit patterns with a designed mark and space length between 0.8 and 0.05 μm were written. After the recording, the films were peeled off from the substrate to reduce the background absorption in the transmission experiment.

The M-TXM images had been taken at the Fe $L_{3,2}$ and Co L_3-edges between 706 eV and 778 eV. Due to the fully computer based sample positioning and energy tuning at the XM-1 beamline, large areas of the sample and also a large spectral range can be addressed automatically. The exposure time for each M-TXM image with a field-of-view diameter of about 4 μm is typically a few seconds. The on-line contrast of up to more than 20% allows clearly distinguished 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 aim of this study was to image the obtained domain patterns and to relate it to the thermal design of the recording layer. Heavy RE-TM alloys exhibit N-type ferrimagnetism: The systems shown in Fig. 1 were RE-rich meaning that at room temperature the RE moment is dominant and the magnetic compensation temperature is below the room temperature which determines the temperature profile of the saturation magnetization as well as the coercivity. In RE rich alloy, in between room temperature and the Curie point, the magnetization is very small but the coercivity is very large. In the thermomagnetic recording process, two kinds of forces act on the domain wall. One comes from the wall energy, which acts to shrink the domain, and the other is the magnetostatic energy arising from dipolar interaction between magnetic moments, which is apt to enlarge the domain and also to make domains irregular shaped. When the sum of these forces overcome the coercive force, the domains would shrink or be enlarged to irregular shaped domains.

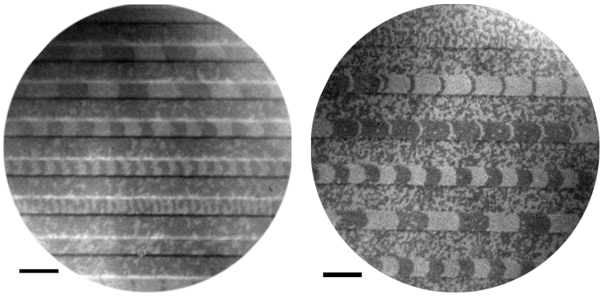

Fig. 1 M-TXM images taken at the Fe L_3 edge of a SiN(70nm)/$Tb_{25}(Fe_{75}Co_{25})_{75}$(50nm)/SiN(20nm) maneto-optical film. Left: Recorded pattern in a low H_c systems with low laser power. Right: Corresponding pattern in a high H_c systems with high laser power. The scalebar is 1μm.

Thus the temperature profile which determines the coercivity profile has to be designed properly. As can be seen from Fig. 1 there is an interplay between the coercive field of the layer and the laser power applied during the recording process being responsible for the quality of the obtained domain patterns.

As can be seen in Fig. 1, the crescent shaped bits could be written in these magneto-optical systems with good quality extended down to 100 nm in mark length pointing to the reliability limit of the writing process in the systems studied.

An inherent feature of the M-TXM is the element-selectivity, which allows imaging of a single element in a multicomponent system. Thus information on the chemical morphology, which influences drastically the behaviour of the global magnetization in the presence of external fields can be obtained. In Fig. 2 (Fischer et al. 2000b) the

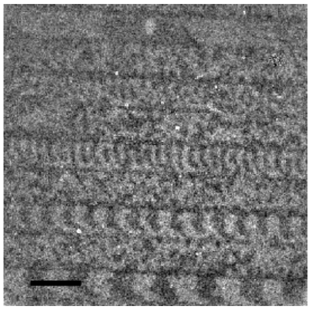

Fig. 2 M-TXM image at the corresponding Co L_3 edge in a SiN(70nm)/$Tb_{25}(Fe_{75}Co_{25})_{75}$(50nm)/SiN(20nm) maneto-optical film. The scalebar is 1μm.

M-TXM image has been recorded at the corresponding Co L_3 edge of the $Tb_{25}(Fe_{75}Co_{25})_{75}$ system. The fact that magnetic domains are clearly visible in the 50 nm thin film system with a Co amount of 19% is a proof of the huge sensitivity of this technique. It can be concluded that it is feasible to apply M-TXM studies even to few monolayered system with the XM-1. Thus the element-specific domain structure in multicomponent multilayered thin films, as e.g. tunnel magnetoresistance systems can be studied.

4.2 Magnetic Nanostructures

Artificially patterned media, like magnetic nanostructures, are currently discussed in the frame of MRAM technologies. They benefit largely from patterning techniques like e-beam lithography established within semiconductor physics. The lateral length scale that is currently achievable is far below the 100nm range. Taking into an aspect ratio at the order of 1 such systems are again matching the features of M-TXM.

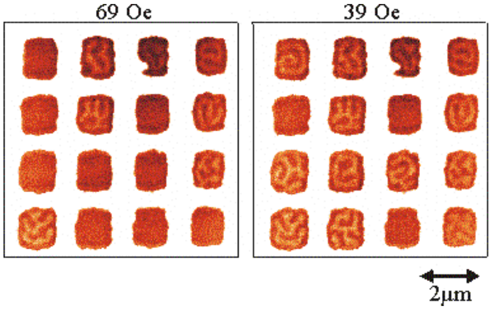

Fig. 3 M-TXM images taken in varying applied fields at the Fe L_3 edge of a (0.4nmFe/0.4nmGd)x75 multilayered system with squared dots prepared by optical lithography.

The major advantage of M-TXM, is the possibility to record the images in varying external magnetic fields, which gives information on the magnetization dependent evolution of magnetic domains within a complete hysteresis loop. This has been applied to a (0.4nmFe/0.4nmGd)x75 multilayered system where by optical lithography squared dots of 1μm side length have been prepared. Again this system has a pronounced out-of-plane anisotropy, which allows M-TXM measurements. The evolution of the magnetic microstructure within complete hysteresis loops could be observed (Fig.3) (Eimüller et al., 2000). The analysis of the field-dependent behaviour of the doman stucture, in particular the distribution of switching fields of individual dots can be related to shape irregularities. Thus the issue whether such patterned media can be used in future devices can be addressed with M-TXM in a reliable way.

5. Conclusion

In summary the combination of a soft X-ray transmission microscope with the X-MCD as magnetic contrast mechanism allows to image element-specific magnetic domains. A lateral resolution down to 25 nm can be obtained. This has been applied to investigate the thermal design of magneto-optical systems where thermomagnetically bits have been written. Both out-of-plane and in-plane systems (Fischer et al. 2000) can be adressed by viewing the projection of the magnetization onto the photon propagation direction. The sensitivity of the M-TXM technique which has allowed observation of domains at the Co L_3 edge of a $Tb_{25}(Fe_{75}Co_{25})_{75}$ system makes it feasible to perform an element-specific study of a system comprised of only few monolayers in the near future. Thus the wide field of magnetic sensor and MRAM devices which are currently under discussion will be opened to the novel M-TXM technique.

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