Physica B 532 (2018) 221–224

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Nanometer-scale local probing of X-ray absorption spectra of Co/Pt multilayer film

Duy-Truong Quach[a,b,*], Duc-Thang Pham[b], Djati Handoko[c], Je-Ho Shim[d,e], Dong Eon Kim[d,e], Kyung-Min Lee[f], Jong-Ryul Jeong[f], Namdong Kim[g], Hyun-Joon Shin[g], Dong-Hyun Kim[d,h,**]

[a] Faculty of Basic Sciences, University of Transport and Communications, Hanoi 10000, Vietnam
[b] Faculty of Engineering Physics and Nanotechnology, VNU University of Engineering and Technology, Hanoi 10000, Vietnam
[c] Department of Physics, University of Indonesia, Depok 16424, Indonesia
[d] Max Planck Center for Attosecond Science, Pohang Kyungbuk 790-784, South Korea
[e] Department of Physics & Center for Attosecond Science and Technology, POSTECH, Pohang 790-784, South Korea
[f] Department of Material Science, Chungnam National University, Daejeon 305-764, South Korea
[g] Pohang Accelerator Laboratory, POSTECH, Pohang 790-784, South Korea
[h] Department of Physics, Chungbuk National University, Cheongju 362-763, South Korea

ARTICLE INFO

Keywords:
X-ray absorption spectra
Co/Pt multilayer
Magnetic domain wall

ABSTRACT

We report our local X-ray absorption spectra (XAS) measurement mapping for a Co/Pt multilayer using scanning transmission microscopy with 25-nm spatial resolution and 0.1-eV spectral resolution. We have systematically analyzed the two-dimensional XAS intensity variation over the corresponding magnetic domain patterns, revealing a XAS profile across the magnetic domain wall as well as the simultaneous high-throughput measurement of local XAS spectra.

1. Introduction

Recently, nanostructures based on ferromagnetic thin films with a perpendicular magnetic anisotropy (PMA) have attracted much attention due to their possible applications for ultrahigh-density recording media and spin-transfer-torque devices [1,2]. In characterization of the magnetic properties of such magnetic nanostructures, various measurement techniques based on magnetic imaging techniques have been used due to their high spatial resolutions, since the magnetic behavior and stable functioning as devices become more sensitively dependent on the micro- or nano-scale magnetic inhomogeneity. For instance, magneto-optical Kerr microscopy has been widely adopted to probe magnetic inhomogeneity [3], where local magnetic properties such as coercivity and hysteresis loop have been measured and analyzed with corresponding magnetic domain behavior. However, the drawback of the magneto-optical Kerr microscopy is the limitation of the spatial resolution by the wavelength of the optical light source, which is roughly on a micrometer scale or several hundreds of nanometer scale at best. As the magnetic inhomogeneity distribution plays a key role in determining the local magnetic properties of magnetic devices, the observation of local magnetic properties on a nanometer scale becomes increasingly demanded. Moreover, a fundamental length scale of the exchange length is on a nanometer scale and thus, a full understanding of local magnetic property distribution should be investigated by a magnetic imaging tool with a corresponding spatial resolution.

The X-ray microscopy technique has received a huge interest due to several powerful features such as element-specificity as well as high spatial resolution [4–6]. The contrast mechanism of X-ray magnetic microscopies is mostly based on the X-ray magnetic circular dichroism (XMCD), which measures the asymmetric X-ray absorption spectra (XAS) of magnetic system between the cases of left- and right-circular X-ray polarization [6]. Thus, a local XAS measurement with different magnetic configurations of samples or with different X-ray polarizations would basically enable us to measure the local magnetic properties on a nanometer scale. Another important aspect in adopting the local XAS measurement based on the X-ray magnetic imaging technique is that not only a high spatial resolution but also a high spectral resolution is required, since the XAS is measured by the absorption spectra with the variation of X-ray photon energies.

Very recently, it has been reported that local XMCD properties can be measured indeed on a nanometer scale by means of a full-field transmission X-ray microscopy (TXM), where the element-specific magnetic imaging, the local XAS measurement, and the quantitative mapping of the local orbital/spin ratio have been successfully demon-

* Corresponding author at: Faculty of Basic Sciences, University of Transport and Communications, Hanoi 10000, Vietnam.
** Corresponding author at: Max Planck Center for Attosecond Science, Pohang, Kyungbuk 790-784, South Korea.
E-mail addresses: duytruongquach@gmail.com (D.-T. Quach), donghyun@cbnu.ac.kr (D.-H. Kim).

http://dx.doi.org/10.1016/j.physb.2017.05.051
Received 31 December 2016; Received in revised form 4 May 2017; Accepted 26 May 2017
Available online 28 May 2017

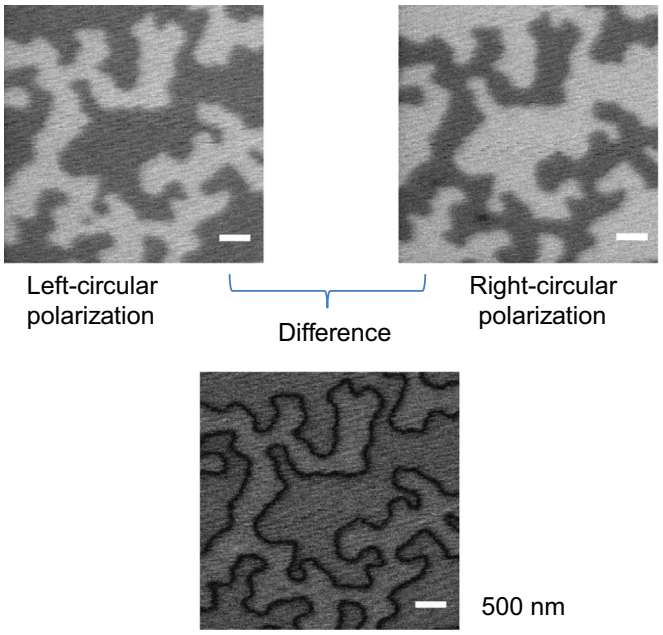

Fig. 1. Magnetic domain patterns observed with a) left- and b) right-circular polarized X-ray, together with a difference image (c).

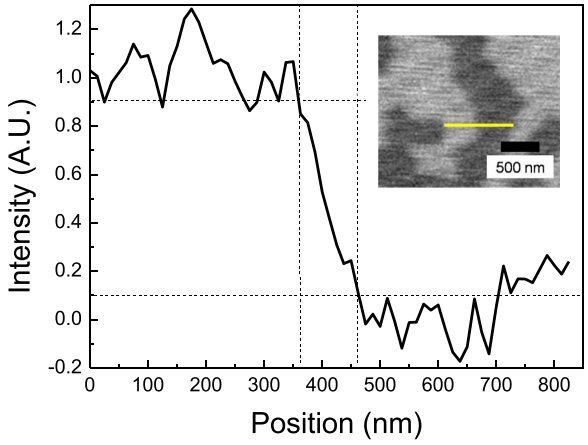

Fig. 2. STXM intensity line profile across a domain wall as the profile line is denoted in the corresponding domain image of the inset.

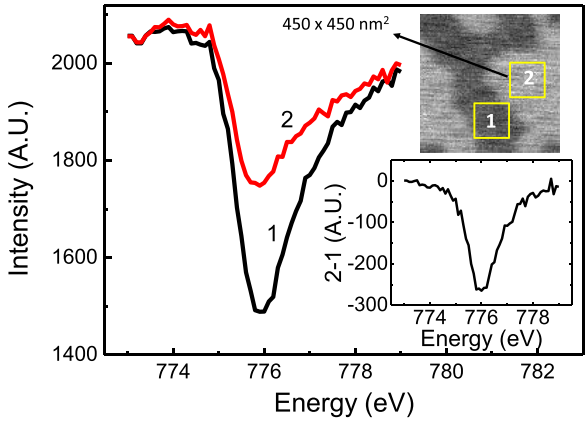

Fig. 3. XAS spectra for the two regions with opposite magnetizations as denoted by 1 (dark) and 2 (bright). Corresponding regions from which the XAS were analyzed are denoted in the inset figure (left). The right inset shows virtual XMCD spectrum obtained by taking difference between XAS spectra of the regions 1 and 2.

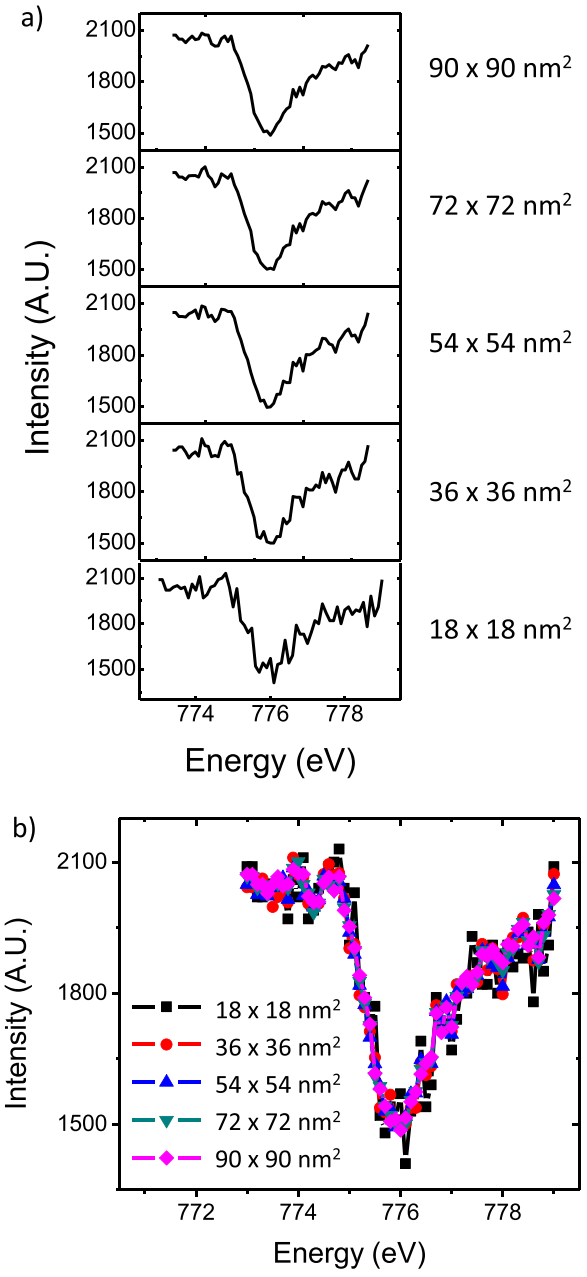

Fig. 4. a) XAS spectra for local areas with different sizes from 18 × 18 nm^2 to 90 × 90 nm^2. b) XAS spectra from different area sizes plotted on the same graph on the same scale.

strated for a (3-Å Co/ 5-Å Pt)$_{30}$ film with a PMA [7]. Although the full-field TXM allows a relatively fast high-resolution imaging, a spectral resolution in XAS/XMCD is not the best compared to other X-ray magnetic imaging technique such as scanning transmission X-ray microscopy (STXM). Compared to the TXM, where the condenser zone plate also works as a monochrometer, STXM adopts a monochrometer sacrificing the full-field functionality. It should be mentioned that the local XAS mapping using the TXM has been carried out with 0.5 eV energy steps of X-ray photon. Therefore, it would be also meaningful to confirm the local XAS mapping functionality by means of STXM with a better spectral resolution.

Here, we report our investigation on the local mapping of XAS by means of STXM around the Co L_3 edge, proving a local mapping functionality of STXM with a 25 nm spatial resolution and 0.1 eV energy steps of the X-ray photon for a Co/Pt multilayer film with a PMA.

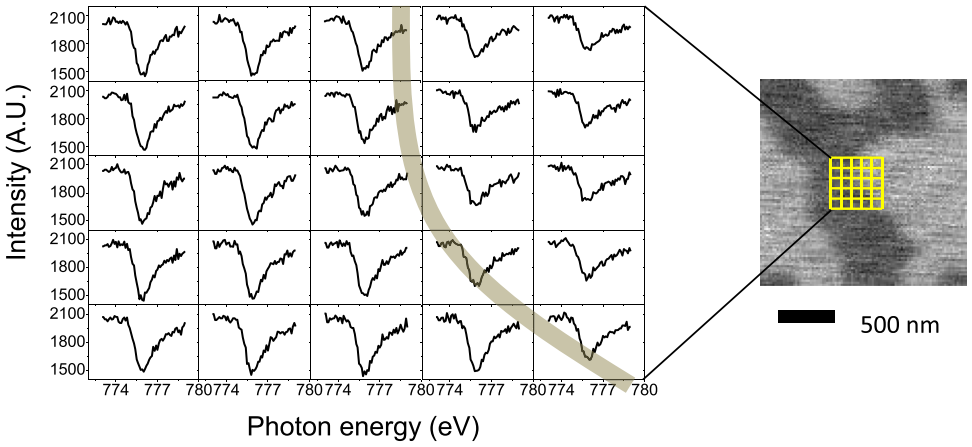

Fig. 5. Two-dimensional spatial distribution map of local XAS spectra (left) corresponding to the grid in the magnetic domain image (right). Each grid size is 90 × 90 nm^2.

2. Materials and methods

A (4.7-Å Co/7.7-Å Pt)$_{15}$ multilayer film was deposited on a 100-nm SiN thick membrane substrate by a magnetron sputtering. We have prepared series of Co/Pt multilayers and selected (4.7-Å Co/7.7-Å Pt)$_{15}$ film for the present study, since the magnetic domain feature size is about several hundreds of nanometers and thus, suitable for checking the nanoscale local XAS mapping functionality. It has been widely known that most of sputtered Co/Pt multilayers with PMA has similar structural and interfacial properties, studied by high-resolution transmission electron microscope [8] and X-ray diffraction [9,10]. The structural properties of a sample prepared at the same batch have been investigated by X-ray reflectivity measurement [11], where a clear feature of bi-layer peak is clearly observed. This guarantees the stable formation of interfaces between Co and Pt layers, which is the main origin of PMA property of the Co/Pt multilayers. The (4.7-Å Co/7.7-Å Pt)$_{15}$ multilayer film was confirmed to have a perpendicular anisotropy by measuring the hysteresis loop using the vibrating sample magnetometer and the magneto-optical Kerr effect. The film was initially saturated under a perpendicular field of 2 kOe, then, the applied field was reversed to be about 80% of the coercivity to generate the magnetic domain formation. The STXM observation was carried out at BL10A at Pohang Light Source. During the STXM observation, the film was put in a high vacuum at room temperature. A Fresnel zone plate with 25-nm outermost zone-width was used to focus the X-ray beam. The energy resolution is about 0.1 eV at hν = 500 eV. Both the left and right circular polarizations were used for the domain and XAS observation. We set the STXM observation area to be over 5 × 5 μm^2 with a 12.5-nm CCD pixel size. To measure the XAS, the X-ray photon energy was tuned from 773 to 779 eV. We have measured XAS intensity at each photon energy, with scanning the photon energy with 0.1 eV steps, forming a two-dimensional array of the XAS intensity with the variation of photon energies.

3. Results and discussions

The magnetic domain structures were observed at Co L_3 edge with a left and right circular polarization, as in Fig. 1(a, b). The magnetic contrast inversion for the same observation area is clearly confirmed and the contrast difference is illustrated in Fig. 1(c), where the domain wall becomes clearly visible. There was no significant shift or peculiar effect in switching the X-ray polarization, guaranteeing the well-established symmetry between the observation with the left and the right X-ray polarization. In a similar way, we recorded magnetic domains with XMCD contrast under the left circular polarization first, then under the right polarization on the same area.

It is interesting to note the XAS intensity profile cross the domain wall, as shown in Fig. 2. Typical XAS intensity profile across a domain wall is plotted, where the corresponding line is denoted in the inset figure of the magnetic domain. The line length of the profile corresponds to the 850 nm with 1 pixel of 18 nm. The width of the XAS intensity transition corresponding form 10–90% values of the intensity difference is about 100 nm, which is analogous to the case of Gd/Fe multilayer by coherent diffraction imaging [5] and Co/Pt multilayer observed by the full-field X-ray microscopy [7]. It is expected to have a similar spatial resolution between the two cases of full-field and scanning transmission X-ray microscopy, since the ultimate spatial resolution is basically determined by the Fresnel zone plate. However, it should be noted that the spectral resolution could be much better in the present case of STXM.

Thus, it might be interesting to analyze not only the domain structures but also XAS spectra for the same observation area. As in Fig. 3, two representative areas with opposite magnetizations are selected and denoted as 1 (dark) and 2 (bright) for the same area size of 450 × 450 nm^2. The two spectra are plotted together. Both of them have the same background level off the absorption edge but different resonance absorption at 776 eV due to different helicity excitation [12]. The XMCD level from the asymmetry becomes about 17.5% at 776 eV.

Fig. 4(a) shows local XAS spectra averaged for different nanometer-scale areas, ranging from 90 × 90 nm^2 down to 18 × 18 nm^2. Although the signal to noise ratio becomes worse with decreasing area size, all spectra are basically considered to be identical within the error, as confirmed in Fig. 4(b). From this, we conclude that the local XAS spectra variation is not substantial even down to a nanometer scale. We also demonstrated that the local XAS measurement using the STXM could be a stable and powerful tool in probing possible local magnetic properties in terms of spatial and spectral resolutions.

From the three-dimensional array of XAS intensity information, we can generate a two-dimensional XAS spectra consisted of local measurements on a nanometer scale. An example of nanometer scale XAS spectra mapping for 5 × 5 regions with each grid size of 90 × 90 nm^2 is demonstrated in Fig. 5. The corresponding grids are plotted on the right side of the figure on the observed magnetic domain patterns. It should be reminded that the high-throughput large-scale XAS spectra measurement was possible due to the high spectral resolution of the STXM. The mapping area is selected to cover a domain wall region to compare XAS spectra of local region with different magnetization directions. One can see from the map that the XAS spectra on the left and right side of the domain wall, guided by the grey band in the figure, are clearly different, exhibiting different absorption peaks. It is interesting to note that, the XAS spectra show intermediate peak heights across the domain wall, during the transitional behavior from the left-to-the-wall region to the right-to-the-wall region, implying the domain wall could be composed of gradual

rotation of magnetization with a structure of Bloch wall on the plane spanned by the two opposite magnetizations of two domains [8]. It is clearly that the spatial resolution in the present study much better than the case of using Kerr microscopy [3]. With the STXM we can produce a XAS map with spatial resolution down to the size of one image pixel of 18 × 18 nm^2.

4. Conclusions

We have investigated the magnetic domain and local XAS spectra properties for Co/Pt multilayer using STXM. We have demonstrated that the XAS spectra over the nanometer scale area can be measured with both a high spatial resolution (25 nm) and a high spectral resolution (0.1 eV). Our demonstration allows us to understand the local nanoscale magnetic property distribution, which is important for future realization of various magnetic applications based on nanostructured ferromagnetic materials.

Acknowledgments

This study was supported by a Korea Research Foundation (NRF) grant (No. 2015R1D1A3A01020686) and by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.02-2015.80. This research has been supported in part by Global Research Laboratory Program [Grant No 2009-00439] and by Max Planck POSTECH/KOREA Research Initiative Program [Grant No 2011-0031558] through the National Research Foundation of Korea (NRF) funded by Ministry of Science, ICT & Future Planning.

References

[1] C. Chappert, A. Fert, F.N. Van Dau, Nat. Mater. 6 (2007) 813.
[2] R. Sbiaa, H. Meng, S.N. Piramanayagam, Phys. Stat. Sol. 5 (2011) 413.
[3] Sug-Bong Choe, Dong-Hyun Kim, Yoon-Chul Cho, Hyuk-Jae Jang, Kwang-Su Ryu, Hae-Seung Lee, Sung-Chul Shin, Rev. Sci. Instrum. 73 (2002) 2910.
[4] S. Eisebitt, J. Luning, W.F. Schlotter, M. Lorgen, O. Hellwig, W. Eberhardt, J. Stohr, Nature 432 (2004) 885.
[5] A.Tripathi, J. Mohanty, S. H. Dietze, O. G. Shpyrko, E. Shipton, E. E. Fullerton, S. S. Kim, and I. McNulty, Proc. Natl. Acad. Sci. U. S. A. 108, 13393, (2011).
[6] P. Fischer, C.S. Fadley, Nanotechnol. Rev. 1 (2012) 5.
[7] MacCallum J. Robertson, Christopher J. Agostino, Alpha T. N'Diaye, Gong Chen, Mi-Young Im, Peter Fischer, J. Appl. Phys. 117 (2015) 17D145.
[8] C.J. Chien, R.F.C. Farrow, C.H. Lee, C.J. Lin, E.E. Marinero, J. Magn. Magn. Mater. 93 (1991) 47.
[9] S.J. Greaves, A.K. Petford-Long, Y.-H. Kim, R.J. Pollard, P.J. Grundy, J.P. Jakubovics, J. Magn. Magn. Mater. 113 (1992) 63.
[10] C.-J. Lin, G.L. Gorman, C.H. Lee, R.F.C. Farrow, E.E. Marinero, H.V. Do, H. Notarys, J. Magn. Magn. Mater. 93 (1991) 194.
[11] Chul Hoon Kim, Je-Ho Shim, Kyung Min Lee, Jong-Ryul Jeong, Dong-Hyun Kim, and Dong Eon Kim, Sci. Rep. 6, 22054, (2016).
[12] G. van der Laan, A.I. Figueroa, Coord. Chem. Rev. 95 (2014) 277.