X-PEEM NANOSPECTROSCOPY APPLIED TO NANOMAGNETISM

R. Belkhou

Synchrotron SOLEIL, L'Orme des Merisiers Saint-Aubin, 91192 Gif-sur-Yvette, France

e-mail: Belkhou@synchrotron-soleil.fr

The recent progress in the fabrication of nanostructures requires the development in parallel of new techniques to characterize these materials at the nanoscopic level. This is particularly the case for magnetic and semiconducting technologies, where the interest for submicrometric range devices has been rapidly increasing during the last decade. Moreover, many of these new materials are used for dynamic applications (magnetic recording heads, memories, sensor *etc*…). A technique which could study them combining good spatial (few nm) and time (submicrosecond) resolution would be of primordial importance.

The high brightness of third generation synchrotron radiation sources has opened the way to surface and interface imaging with resolution in the 10 nm ranges with further instrument improvements in the 1 nm range [1]. Experimentally there are two different approaches. The first uses a well focused photon beam which is scanned across the sample's surface. The second employs parallel imaging techniques making use of special electron optics (X-PEEM), and will be the main subject of this lecture.

X-PEEM (X-ray PhotoEmission Electron Microscopy) spectromicroscopy is a derivative of the classical PEEM. If a photon energy just above the photothreshold is used, the photoelectron yield is mainly determined by the differences in the work function ϕ of the sample. The local variations of ϕ result in images with high contrast. This UV-PEEM mode of operation is ideally suited to study surface chemical reactions in real time [2]. With the advent of high brilliance synchrotron radiation from storage rings, a wide and tunable energy range of photons of the illuminating beam has become available, allowing to access well established techniques like Ultraviolet Photoemission Spectroscopy (UPS), X-ray Photoemission Spectroscopy (XPS) and X-ray absorption spectroscopy (XAS) at the nanoscopic level, and thus leading to element selective imaging. Moreover, information on the spatial distribution of the electronic structure, chemical composition and nature, or the local magnetization at the surface can be obtained. Dedicated beamlines with high brilliance, variable photon polarization (both circular and linear) and a broad energy range have become recently available at several facilities (ELETTRA, ESRF, ALS, BESSY II…). This opens a wide research area for the X-PEEM [3] including surface magnetism, surface and interfaces, surface chemistry, tribology *etc.*

In particular, the interest in magnetic domain imaging in the nanometer range has been rapidly increasing during the last decade. A considerable impetus is coming from the development of high-density magnetic storage devices and from the forthcoming achievement of spin electronics. In order to tailor the magnetic behavior of these systems to specific needs, for instance a certain response to magnetization reversal, a detailed understanding of the structure and of the dynamics of magnetic domains is mandatory. In addition, the thin film nature of such devices emphasizes the surface aspect of magnetism. This situation requires magnetic domain-imaging techniques which combine surface sensitivity and high spatial resolution. Moreover, for many applications element specificity is even more important than high lateral resolution. Magnetic storage media or building elements of spintronics devices are often composed of several chemical elements or intermetallic compounds, each of which distinctly contributes to the magnetic behaviour [4] (Fig. 1). All these requirements pose a considerable challenge to conventional magnetic domain imaging techniques such as magneto-optical Kerr microscopy, Lorentz microscopy, scanning electron microscopy (SEMPA) *etc.*.

X-PEEM magnetic microscopy is today a good candidate for an ideal surface magnetic imaging technique, as it combines the magnetic sensitivity and element selectivity with a spatial resolution below the size of the magnetic domains. One may identify three important length scales for magnetic imaging which consecutively decrease by a factor of 100. The first one is about 1 μm, set by the size of lithographically manufactured magnetic cells such as in spin valve heads or magnetic memory cells. The second one is about 10 nm, corresponding to the crystallographic grain size of typical magnetic materials. The last one is 0.1 nm, i.e. the atomic size. A spatial resolution of 22 nm using synchrotron radiation has already been achieved [5] and further improvements of this resolution may allow access to the second characteristic length scale of 10 nm.

The elemental specificity in X-PEEM magnetic microscopy arises from the characteristic binding energies of the atomic core electrons. Both X-ray absorption (XAS) and X-ray photoelectron spectroscopy (XPS) can be used. The X-ray absorption spectrum directly exhibits the characteristic absorption edges of the elements in the sample. At the absorption thresholds of the elements the spectrum shows strong resonances arising from transitions to unfilled valence band states.

L31

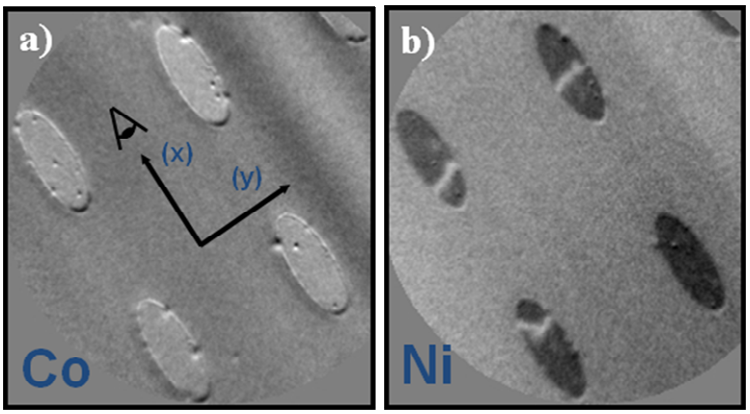

Figure 1. X-PEEM images of 4 magnetic tunnel junction ellipses ($Co/Al_2O_3/FeNi$) recorded at the Co edge (a) and at the Ni edge (b). The photons incidence direction is aligned with the ellipses long axis from the top left corner. The white and black contrasts correspond to magnetizations aligned along the long ellipses axis, parallel or antiparallel to the saturating field [4].

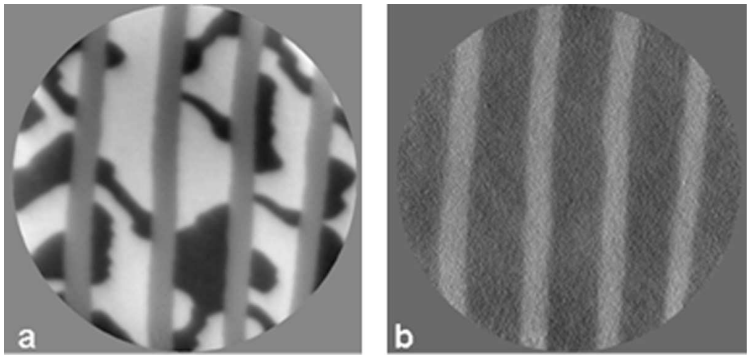

Figure 2: a) XMCD-PEEM image, and (b) XMLD-PEEM image of a 300 nm thick MnAs film on GaAs (100) at room temperature. (a) shows the magnetic domain structure in the ferromagnetic phase: alpha phase (b) the coexisting antiferromagnetic phase: beta phase. The XMCD image is obtained using right/left circular polarised light at the L_3 Mn edge. The XMLD is obtained using the linear dichroism asymmetry associated with the multiplets structure of the Mn L_3 edge. Field of view 5 μm [6].

The use of polarized synchrotron radiation enables studies of the electronic and magnetic anisotropies [7], and thus allows magnetic contrast for the X-PEEM [8]. A simple description of the photon polarization by a biaxial vector for linear polarization and a vector for handed circular polarization is the physical basis for probing various anisotropies of the sample. In general, linearly polarized light can only detect anisotropy of electronic charge. In contrast, handed circularly polarized light can measure a dipolar or vector quantity, in our case the size and direction of the electron angular moment and spin.

For magnetic spectromicroscopy, X-ray magnetic circular dichroism (XMCD) in the total photoyield mode is exploited. Using XMCD we can determine the size, the direction and the anisotropy of the atomic magnetic moments (see Fig. 2a) .The black and white regions in the image reflect the domains where the magnetic axis is aligned parallel or anti parallel to the direction of the light at fixed polarization. The grey area corresponds to domains where the magnetic axis is perpendicular to the direction of the light. To distinguish the orientation of the domains in this grey region we have simply to turn the sample in a way to align the magnetic axis parallel and antiparallel to the light.

The study of antiferromagnetic (AFM) surfaces and interfaces has posed an even larger challenge because conventional techniques are mainly bulk sensitive. This limitation was overcome recently by the use of XMLD spectroscopy. In contrast to XMCD which directly measures the magnetic moment, XMLD measures the expectation value of the square of the magnetic moment. XMLD can therefore be applied for all uniaxial magnetic system, *i.e.* antiferromagnets as well (Fig. 2.b). Recently it was shown that XMLD spectroscopy in conjunction

with X-PEEM microscopy is capable of imaging the detailed antiferromagnetic domain structure of a surface and interface [9].

A new feature that is actually under extensive development is to add temporal resolution to magnetic spectromicroscopy. The dynamics of the magnetization reversal in thin magnetic films has become a matter of high interest for the future of magnetic recording and non-volatile magnetic memories. Parallel to the evolution toward smaller magnetic bits and memory cells, writing and reading times approaching the ns range will be required in a few years from now. A complete understanding of the magnetization dynamics in these structures requires the ability to probe the magnetization of the individual layers as well as their mutual interaction. It has been recently shown, using time-resolved XMCD, that the coupling between the magnetic layers can be very different in static and dynamical measurements [10]. This is probably due to different reversal processes which play a role in the magnetization reversal at low (mainly domain wall propagation) and high (mainly nucleation of reversed domains) field sweep rates, but time-resolved X-PEEM measurements would be decisive in confirming this hypothesis. Time-resolved X-PEEM measurements are very challenging, since the secondary electrons that are used for the image are strongly perturbed by the magnetic field necessary to switch the magnetization direction. For the time resolved XMCD measurements, dedicated copper microcoils have been developed, capable of providing a relatively strong magnetic field (up to 5000 Oe) during a short time period (20-50 ns). These magnetic pulses can be synchronized with the X-ray pulses coming from the storage ring to perform dynamic measurements in a pump-probe scheme. X-PEEM images cannot be acquired during the field pulses, but the relatively slow dynamics (some ns) occurring after the pulse could be measured.

In this lecture, we will present a review of recent results obtained using X-PEEM microscopy, focusing mainly on the magnetic imaging part. After a short overview of the X-PEEM principles and capabilities, the basic magnetic contrast used in X-PEEM will be reviewed. Finally a selection of recent scientific case will be developed in the field of magnetic imaging of surfaces and nanostructures.

References

[1] For a detailed review see *J. Electron Spectrosc. Related Phenom.* **84** (1997).

[2] M. Mundschau *et al.*, *Surface Sci.* **227** (1990) 246.

[3] Several beamlines are presently operating or under development: PEEM3 (ALS), SMART (BESSY II), Nanospectroscopy beamline (ELETTRA), Surface/interface microscopy beamline (SLS), Soft X-ray microscopy beamline (SOLEIL).

[4] M. Hehn, D. Lacour, F. Montaigne, J. Briones, R. Belkhou, S.El Moussaoui, F. Maccherozzi, N. Rougemaille. *Appl. Phys. Lett.* **92** (2008) 072501.

[5] Th. Schmidt, *et al*., *Surf. Rev. Lett.* **5** (1998) 1287.

[6] E. Bauer, R. Belkhou, S. Cherifi, A. Locatelli, A. Pavlovska, N. Rougemaille, *J. Vac. Sci. Technol. B* **25** (2007) 1470.

[7] J. B. Kortright e*t al*., *J. Magn. Magn. Mat.* **207** (1999) 7.

[8] J. Stöhr *et al*., *Science* **259** (1993) 658.

[9] J. Stöhr *et al*., *Phys. Rev. Lett.* **83** (1999) 1862, H. Ohldag et al, *Phys. Rev. Lett.* **86** (2001) 2878.

[10] M. Bonfim *et al*., *Phys. Rev. Lett.* **86** (2001) 3646.