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ScienceDirect
Current Opinion in Solid State and Materials Science 10 (2006) 120–127
Current Opinion in Solid State & Materials Science

Studying spintronics materials with soft X-ray resonant scattering

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Received 11 January 2006; accepted 11 November 2006

Abstract

Soft X-ray resonant magnetic scattering offers a unique element-, site- and valence-specific probe to study magnetic structures on a length scale from 1 to 1000 nm. This new technique, which combines X-ray scattering with X-ray magnetic circular and linear dichroism, is ideally suited to investigate magnetic superlattices and magnetic stripe domains. Recent results that are presented here include element-specific magnetic studies on interfaces, thin films, magnetic multilayers, self-organising magnetic domain structures, magnetic layer profiles, patterned samples, and magnetic nanoobjects using coherent X-rays. Soft X-ray diffraction to study the interplay between charge, spin and orbital ordering in correlated 3d transition metal systems, such as manganites, is also discussed.

Keywords: X-ray scattering; Soft X-ray absorption; X-ray magnetic dichroism; Magnetic multilayers; Magnetic domains; Layer profiles; Nanoobjects; Transition metal L edges

1. Introduction

Controlled thin film deposition and lithographic patterning have been established as the technology promoters in magnetism research ever since the engineering of multilayers of magnetic and non-magnetic metals led to the discovery of new phenomena such as inter-layer exchange coupling, giant magnetoresistance (GMR) and non-volatile magnetic random access memory (MRAM). Among the different methods available to characterize the magnetic properties of thin films and confined magnetic structures, magneto-optical methods are most prominent and offer the advantage that they can be performed under applied magnetic and electric fields. However, magneto-optics in the visible region lacks element specificity and the ultimate spatial resolution is limited by the wavelength. The discovery of strong magneto-optical effects in the core-level X-ray absorption edges of magnetic elements [1] has provided new possibilities, such as the separation of the spin and orbital part of the magnetic moments [2] and resolving the magnetic anisotropy [3]. These techniques strongly benefit from the advent of synchrotron radiation undulator devices offering variable linear and circular polarization with tuneable photon energy.

The selection rules in X-ray magnetic circular dichroism (XMCD) and X-ray magnetic linear dichroism (XMLD) [4,5] give a difference in transition probability for left and right circular polarized X-rays into the unoccupied polarized valence band. X-ray resonant magnetic scattering combines the advantages of X-ray scattering with those of the magnetic X-ray dichroism techniques. In the past, X-ray scattering experiments were mainly limited to hard X-rays, offering high spatial resolution and large penetration. However, in the soft X-ray range the resonant magnetic scattering cross-sections are much stronger. Although soft X-rays usually have prohibitively long wavelengths for Bragg diffraction from crystal lattices, in 3d transition metals the wavelength of the $L_{2,3}$ absorption edges [6] matches perfectly onto the nanometric length scale of artificial multilayers [7] and periodic domain structures [8,**9]. Therefore, diffraction on such systems offers new possibilities in the field of thin-film magnetism, which is stimulated by the technological impact of the discovery of technologically important effects, such as perpendicular

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doi:10.1016/j.cossms.2006.11.007

Table 1
Extensions to X-ray scattering possible with synchrotron radiation

Extensions to X-ray scattering	Allows to probe
Tunable X-rays at resonance	Element, site and valence specificity
Polarized X-rays	Magnetic orbital and spin structure
Soft X-rays	Nanoscale sensitivity (down to 1 nm)
Coherent radiation	Local configuration
Pulsed radiation	Dynamics

magnetic anisotropy (PMA) and giant magnetoresistance (GMR). Soft X-ray resonant magnetic scattering (SXRMS) has the capacity to cover the nanometer length scale and is relatively easy to perform on *ex situ* prepared samples [10,11]. It has grown into a workhorse technique within the time span of a few years after pioneering experiments by Dürr et al. [**9] who measured the circular dichroism of the in-plane diffracted intensity from periodic stripe domains in FePd thin films in reflection geometry. Applications of SXRMS include characterization of structural and magnetic properties of layered and domain systems, especially their interface roughness, induced magnetic order in non-magnetic spacer layer and layer-resolved magnetic moments [**12,13–18].

Element specificity is obtained by tuning the soft X-ray energy to the appropriate absorption edge. In 3d transition metals the excitation of 2p electrons into unoccupied 3d states leads to a large enhancement in the scattering cross section [19,*20]. Strong effects are also observed for 3d–4f transitions in rare earths [21,22,**23], at 2p edges of 4d and 5d transition metals [**24] and 3d and 4d edges of actinides [25,26]. Even absorption edges as low as the 3p (at ~50 eV) in 3d transition metals have been successfully explored [27]. The tunability of the synchrotron radiation allows us to scan the photon energy across the resonance for each of the accessible Bragg peaks. Table 1 shows the extensions to X-ray scattering that have become possible due to synchrotron radiation. However, as is sometimes regarded as inconvenient, scattering measurements in the soft X-rays regions need to be carried out in a diffractometer that is under vacuum in order to prevent X-ray absorption by air [10,11,28].

2. Probing depth

We concentrate here on the 3d transition metal $L_{2,3}$ edges ($0.4-1$ keV). Considering the length scale of the periodicities that can be probed by X-ray scattering at a wavelength λ, Bragg's law gives $m\lambda = 2d\sin\theta$, where the integer m is the order of the reflection, the grazing angle θ is the Bragg angle and d is the lattice period. The maximum resolution of $d = \lambda/2$ is obtained at back scattering. As an example, for the Fe L_3 edge (707 eV) we have $\lambda = 17.54$ Å, so that $d > 8.8$ Å. If we would typically use a 100 μm slit on an exit arm of 175 mm [28], the angular resolution is equal to $\Delta\theta = 0.033°$, limiting the maximum length of the period that can be measured. This means that at the Fe L_3 we can cover a length scale from 1 nm to 1 mm, which might be too large for crystallography, but which is ideally suited to study magnetic domains.

Further consideration has to be given to the penetration depth of the soft X-rays, which is determined by the X-ray absorption length that varies strongly across the absorption edge. For Fe metal the absorption length is about 6000 Å just below the L_3 edge, reducing to 170 Å at the top of the L_3 edge and increasing again to 850 Å above the L_2 edge. These values are for the pure metal and the absorption at the L_3 edge scales with the Fe concentration, so that compared to the pure metal the probing depth will be larger in alloys, compounds and dilute systems. Therefore, while absorption corrections are very important, we can typically probe over a range of a few thousand Å beneath the surface. Note that this probing depth is much larger than for some other commonly used techniques, such as X-ray absorption using total electron yield and X-ray photoemission. The relatively short X-ray absorption length in resonant scattering can be turned into an advantage, since it allows depth profiling, e.g. to distinguish between buried interfaces at different depths. It will also reduce, or even remove, the contribution from the substrate.

3. Magnetic multilayers

While being since long time the workhorse for routine characterization and analysis, X-ray scattering has now been developed to a point where it provides the most sensitive and highest resolution data on the interface structure of ultrathin magnetic layers. There are two ways in which the scattered-intensity distribution (versus the scattering vector **q**) is typically probed. When the soft X-ray wavelength is of the order of the multilayer periodicity, sharp Bragg peaks due to the chemical modulation can occur. Interface roughness on the other hand leads to the diffuse background around each Bragg peak. Theoretical modelling of the measured intensity distribution provides information about the vertical interface sharpness and chemical layer profiles in the multilayer. Laterally, the interface can be probed by transverse azimuthal scans through the Bragg peak parallel to the interface plane. There, the diffuse intensity distribution is directly linked to roughness and lateral coherence lengths. These measurements are routinely used in the hard X-ray region but only recently it was realised that new possibilities are opened up when going to softer X-rays.

Sharp Bragg peaks due to the chemical modulation can occur when the soft X-ray wavelength is of the order of the multilayer periodicity. GMR multilayers have the right layer thickness. When the magnetic layers are ferromagnetically coupled, the magnetic and structural periods are the same. When they are antiferromagnetically coupled, the magnetic period is doubled, giving rise to a superlattice peak (half-order Bragg peak). The SXRMS from a $[Co(10\text{ Å})/Cu(10\text{ Å})]_{50}$ multilayer is shown in Fig. 1 for the first charge and magnetic reflection, taken with momentum-transfer varied perpendicular and parallel to the sample surface.