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ELEMENT-SPECIFIC SOFT X-RAY MAGNETO-OPTIC ROTATION STUDIES OF MAGNETIC FILMS AND MULTILAYERS*

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1. ABSTRACT

Tunable multilayer linear polarizers extend magneto-optic rotation techniques that directly sense polarization changes into the 50 - 1000 eV range. The resonant response at atomic core levels yields element-specific magnetic signals that can be much larger than the analogous signal in the visible. A tunable multilayer polarimeter is described, and examples of its use in early Kerr rotation hysteresis studies of Fe films and Fe/Cr multilayers are given.

2. SOFT X-RAY RESONANT MAGNETO-OPTIC SPECTROSCOPY

Magneto-optic rotation, the rotation of the plane of polarization of linearly polarized light on interaction with a magnetized sample, was first observed in 1845 by Faraday (in transmission) and again in 1875 by Kerr (in reflection). Throughout this century, the magneto-optic rotation (MOR) has been an important tool for characterizing magnetic materials.[1] More recently the effect has provided the materials basis for investigating magneto-optic recording techniques,[2] and has provided a powerful in-situ probe of a rich variety of surface and ultrathin film magnetic structures under the name of the surface magneto-optic Kerr effect (SMOKE).[3] All of this work has utilized visible and near-visible wavelengths, and relies on high quality linear polarizers to sense polarization changes upon interaction with matter.

In just the last decade magneto-optic effects have come under intensive study in the x-ray spectral region. The soft x-ray region is especially rich because it contains core levels from which dipole transitions couple to magnetic valence states of most transition and rare earth metals common in magnetic materials. Working near strong atomic core absorption features makes x-ray magneto-optic techniques element-specific, providing an important advantage over near visible wavelengths in understanding magnetism in multicomponent materials. These resonant x-ray magneto-optic effects can be very large, in cases surpassing in magnitude the comparable effect measured in the visible range. In part because of the perceived lack of easy-to-use, tunable linear polarizers and phase retarders to analyze the polarization of x-ray beams, most x-ray magneto-optical studies measure signals in which only intensity changes are required to obtain magnetic information. Magnetic circular and linear dichroism (MCD, MLD) techniques resulting from absorption are common,[4-8] and techniques sensitive to a combination of refractive and absorptive effects have been measured in the reflected intensity near core levels.[9,10]

Magneto-optic rotation results from circular birefringence, which is related to magnetic circular dichroism by a Kramers-Kronig dispersion relation. This relation, together with the sharp absorption features often found near soft x-ray core levels, has important practical consequences. For example, the spectroscopic magneto-optic response of elements across their core levels can be determined using either the MCD or MOR signal (in transmission), since they transforms into each other.[11] Such spectroscopic measurements are of interest in conjunction with sum rules for determining spin and orbital moments.[12-15] Distinct from pure spectroscopy, hysteresis measurement can be accomplished using various magneto-optic signals. MOR hysteresis loops are easily measured using tunable polarizers in either transmission or reflection geometry. The Kramers-Kronig dispersion relation reveals that the MOR signal is large at energies just below the strongest absorption features. Thus MOR techniques can have appreciably greater penetration depths in hysteresis measurements than techniques relying on the absorption channel such as MCD.[16,17]

This paper reviews recent developments of tunable linear polarizers for the 50 - 1000 eV range which enable the extension of magneto-optic rotation measurements into this region. Early results show large, element-specific magneto-optic rotation signals near core levels of 3d transition elements in this region.

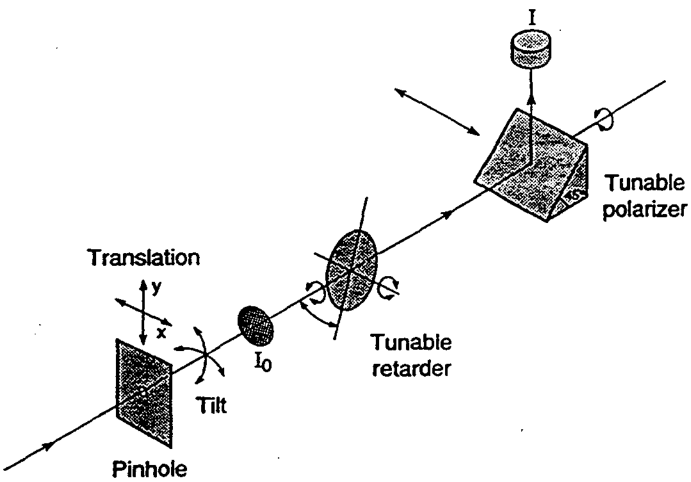

Figure 1. Schematic of a tunable multilayer polarimeter for the 50 - 1000 eV range. See ref. 22 for further details.

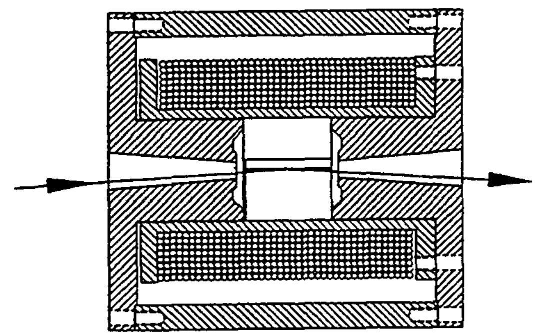

Figure 2. Solenoidal electromagnet with sample at center in longitudinal Kerr geometry.

3. TUNABLE MULTILAYER POLARIMETER

Following work by other groups,[18-21] we developed a compact, tunable polarimeter based on multilayer interference structures.[22] This novel device is shown schematically in Figure 1, and consists of an upstream transmission multilayer phase retarder[23] followed by a downstream reflection multilayer linear polarizer, each of which can rotate in azimuth about the beam to allow a complete polarization analysis of a collimated incident beam. Both retarder and polarizer can be tuned continuously in energy over a limited range consistent with spectroscopic studies across a soft x-ray core level, for example. Magneto-optic rotation studies require only the linear polarizer, together with a linearly polarized incident beam. For the results below the linearly polarized beam was obtained from the on-orbit portion of bending-magnet spectrum radiated from the Advanced Light Source at LBNL into beamline 6.3.2.[24]

Multilayers have several features which make them particularly useful as tunable linear polarizers in the soft x-ray range.[11,23,25] By positioning the multilayer constructive (Bragg) interference peak at the x-ray Brewster angle $\theta \cong 45°$ using $\lambda = 2d\sin\theta$, linear polarizers with extinction ratios (R_s/R_p) ranging from 10^2 to 10^5 over the range of 50 to 1000 eV are obtained. Over this same range, the reflectivity of the s component ranges from greater than 0.5 (50 eV, d = 175 Å) to less than 0.01 (1000 eV, d = 8.8 Å). Even with the small reflectivities at the higher energies, high brightness synchrotron sources allow these polarizers to be used effectively. The width of multilayer Bragg peaks can be controlled by limiting the number of repeat periods to be of order 1° FWHM, allowing achievable angular tolerances of order 1 mrad on the divergence of the incident beam and on the optical alignment requirements of vacuum instrumentation. A multilayer deposited with a lateral gradient in d-spacing yields a tunable linear polarizer by translating the structure along the gradient while maintaining the 45° incidence angle. The results below were obtained with W/B_4C multilayer polarizers that could be tuned across the L_3 and L_2 edges of Fe and Cr.

4. SOFT X-RAY KERR EFFECT FOR FE FILM, FE/CR MULTILAYERS

We have directly extended the MOKE technique for hysteresis measurement into the soft x-ray by positioning the tunable polarimeter in the beam reflected from a sample in a variable magnetic field. Figure 2 shows the soleniodal electromagnet in which the sample is oriented in a longitudinal Kerr geometry. Tapered holes in the pole pieces allow the beam to pass through the magnet and reflect from the sample with up to 5° grazing incidence angle. This electromagnet reaches a peak field of 2.5 kOe at 20 A, but without cooling can be operated at roughly half of this value in the vacuum environment required by these soft x-ray measurements. MOKE hysteresis measurements in the visible typically are made with the polarizer set at an angle nearly crossed with respect to the incident beam polarization, and the intensities of laser or lamp sources provide more than enough photons for measurements under these conditions. In the soft x-ray we have found that operating with the polarizer well away from the crossed position is useful to increase the measured photon flux, which for a bending magnet source at the Fe and Cr L_3 edges falls many orders of magnitude below the levels available from visible sources.

An x-ray MOKE (XMOKE) hysteresis loop from a 47 nm thick Fe film is shown in Figure 3. These data were collected at a photon energy 3.25 eV below the peak in the Fe L_3 white line (at 708 eV) and with an incidence angle 2° from grazing. In the reflection geometry the MOR signal is critically dependent on hν and θ because of the rapid and strong variation of both the average optical properties and magneto-optical properties with energy that result from working near strong core resonances. These dependencies will be the subject of a separate paper. The data in Fig. 3 are normalized to the Kerr rotation angle scale based on the known variation of intensity with inclination of the plane of polarization. Under these conditions the observed Kerr rotation is nearly +/-5°. Larger rotations are observed at other energies. In the visible range, polar MOKE measurements yield rotations of roughly +/-0.5° at 830 nm.[26] Thus we observe a significantly larger room temperature Kerr signal when tuned to near the Fe L_3 edge than is observed in the visible.

The separate magnetization response of the Fe and the Cr in an Fe/Cr multilayer are obtained by tuning the photon energy to just below the L_3 edges of the respective elements, as shown in Figure 4. Fe/Cr multilayers are of interest for their giant magneto-resistance (GMR), although the sample studied here is structurally less perfect than those exhibiting the largest GMR effects. The multilayer consists of 19Å Cr layers and 20Å Fe layers repeated for 40 periods deposited onto a Si wafer and having a (110) textured polycrystalline microstucture. The data in Fig. 4 were collected at 2° incidence angle and at energies 2.0 and 2.6 eV below the peaks of the L_3 white lines of Fe and Cr, respectively. The individual XMOKE hysteresis loops of just the Fe and Cr reveal several details of the magnetization process not obtainable from a standard hysteresis measurement, whose signal would represent the aggregate magnetic response of all atom species in the sample. First, at least part of the Cr layers exhibit a significant magnetic moment, which is of interest since Cr by itself is antiferromagnetic with no net moment and a flat hysteresis curve. Second, the Cr moment is oriented in the opposite direction to the Fe moment, since the two loops have the opposite sense. Third, both Fe and Cr loops show a coercive component closing near +/- 50 Oe, but only the Fe loop shows a reversible increase in magnetization as the field increases before saturating at fields above 1 kOersted. One possible model to explain these element-specific observations assumes an intermixed ferrimagnetic interface region in which Fe and Cr moments have opposite orientations.

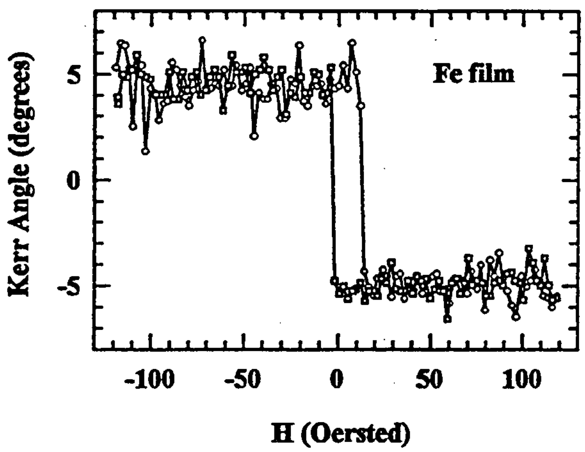

Figure 3. XMOKE hysteresis loop for an Fe film (above) shows much larger rotation than comparable signals in the visible.

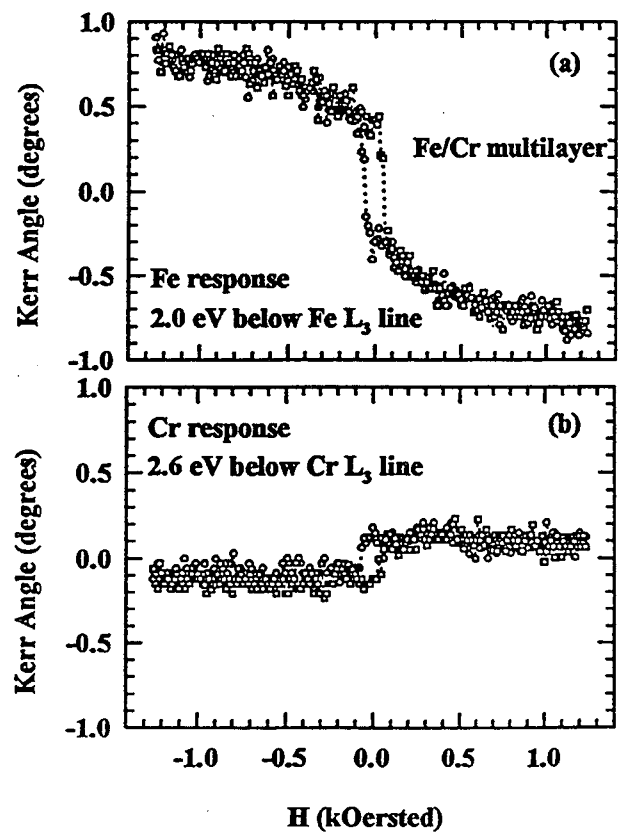

Figure 4. XMOKE hysteresis loops (right) showing the magnetization of just the Fe (in a) and Cr (in b) in a sputtered Fe/Cr multilayer. The element-specific responses are obtained by tuning photon energy just below the L_3 edge of each element.

5. CONCLUSIONS

Tunable linear polarizers based on multilayer interference structures have been incorporated into instrumentation which extend magneto-optic rotation techniques into the 50 - 1000 eV soft x-ray range. Tuning photon energy near to atomic core absorption resonances makes these soft x-ray techniques element-specific, so that the net magnetization response of multicomponent samples can be resolved into the individual responses of the separate elements constituting the sample. Because the MOR effect is large below the strongest resonant absorption features, MOR techniques can have a larger penetration depth than MCD techniques, whose signal is largest at the absorption peak where penetration is smallest. For Fe we observe rotations at least an order of magnitude larger than in the IR and visible. This increased sensitivity in the visible will enable studies of smaller moments and/or more dilute magnetic species. The different magnetic responses of Fe and Cr in the Fe/Cr multilayer studied point directly to new element-resolved magnetic characterization capabilities applicable to a wide variety of magnetic materials.

6. ACKNOWLEDGMENTS

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