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APPLICATION OF MXCD TO MAGNETIC THIN-FILM SENSORS

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ABSTRACT

While Magnetic X-ray Circular Dichroism (MXCD) has been applied extensively to the extraction of elemental magnetic moments in various magnetic multilayers, the configuration of actual devices imposes certain constraints on the application of MXCD to devices. Using a set of real, thin-film spin valve devices with varying Cu spacer layer thicknesses, we demonstrate the correlation between MXCD and R-H measurements on those devices as well as the restrictions on the interpretation of MXCD data imposed by both the device topology and the formulation of realistic error estimates.

INTRODUCTION

Spin valves, consisting of two, coupled magnetic films separated by a thin (<30Å) spacer layer, offer the oscillatory magnetic coupling of giant magnetoresistance (GMR) devices but with greatly reduced saturation fields as compared with multilayer structures. Because the optimization of spin valve performance depends on precise control of the magnetic moments of coupled layers, the reliable, quantitative measurement of the moments of the constituent elements in the device is critical. The elemental specificity of magnetic circular dichroism (MXCD) in *L*-edge x-ray absorption offers the means to detect the magnetic moments of each component of such devices and has already been applied extensively to extract magnetic moments in multilayers.[1-4] Here we demonstrate the application of MXCD to actual spin valve devices.

The spin valves consisted of NiFe(30Å)/Co(20Å)/Cu/Co(20Å)/NiFe(50Å) sandwiches with variable Cu spacer-layer thickness, grown on a 750Å-thick NiO film, as described previously.[5] One permalloy layer is therefore magnetically pinned to the substrate which it contacts.[6] The magnitude and sign of the coupling of the floating layer have been shown to oscillate according to the Cu spacer layer thickness. We present measurements of dichroism in x-ray absorption for three spin valves, with spacer layer thicknesses of 14Å, 20Å, and 28Å, which have been associated, respectively, with strong ferromagnetic, antiferromagnetic, and weak ferromagnetic coupling of the floating layer to the pinned layer through the spacer, respectively. The presence of the 50Å-thick outer layer of Permalloy-80 together with relatively thick Cu spacer layers in the spin valves, as compared with idealized multilayers used in many previous MXCD experiments, give the dichroism measurement on the spin valves both elemental *and* layerwise sensitivity.

EXPERIMENTAL

Each spin valve was initially magnetized parallel to the sample plane with a 2000 Oersted pulse. Spin-polarized, X-ray absorption spectra were collected according to a procedure described previously, using beamline 8-2 at the Stanford Synchrotron Radiation Laboratory.[2, 7] The Poynting vector of the incident beam was aligned at grazing incidence to the films, either parallel or antiparallel to their remanent magnetization. For each sample, four absorption spectra were collected. With the remnant magnetization initially parallel to the incident beam direction, a pair of spectra were recorded, one with the helicity of the incident photons parallel to the remanent magnetization of the device, and one with their helicity antiparallel to the remanent magnetization. Next, the samples were rotated in order to align their remanent magnetization antiparallel to the incident beam direction , and a pair of absorption spectra was similarly obtained from beams polarized with opposite helicity. Finally, each absorption spectrum was normalized to the incident photon flux.

The quantitative extraction of magnetic moments from differences in transition-metal white line intensities arising from *2p->3d* electric dipole transitions has received extensive, theoretical treatment.[3, 8-11] These treatments offer a procedure to extract atomic moments through the insertion of measured white line intensities into sum rules. Although questions remain concerning the absolute accuracy of the sum rules, we will use them for a relative evaluation of atomic moments. The orbital (ORB) and spin moments for each element are then derived from the sum rules (SR) as:

$$\mu_{\mathrm{SPIN}}^{\mathrm{SR}} = \frac{6(10-n)\left(\frac{\mathrm{A}^{+}}{\mathrm{C}^{+}} - \frac{\mathrm{A}^{-}}{\mathrm{C}^{-}}\right)}{\left(\frac{\mathrm{A}^{+}}{\mathrm{C}^{+}} + \frac{\mathrm{B}^{+}}{\mathrm{C}^{+}} + \frac{\mathrm{A}^{-}}{\mathrm{C}^{-}} + \frac{\mathrm{B}^{-}}{\mathrm{C}^{-}}\right)} - 3\langle L_Z \rangle - 7\langle T_Z \rangle ,$$

and

$$\mu_{\mathrm{ORB}}^{\mathrm{SR}} = \langle L_Z \rangle = \frac{4}{3}(10-n)\frac{\left(\frac{\mathrm{A}^{+}}{\mathrm{C}^{+}} + \frac{\mathrm{B}^{+}}{\mathrm{C}^{+}}\right) - \left(\frac{\mathrm{A}^{-}}{\mathrm{C}^{-}} + \frac{\mathrm{B}^{-}}{\mathrm{C}^{-}}\right)}{\left(\frac{\mathrm{A}^{+}}{\mathrm{C}^{+}} + \frac{\mathrm{B}^{+}}{\mathrm{C}^{+}}\right) + \left(\frac{\mathrm{A}^{-}}{\mathrm{C}^{-}} + \frac{\mathrm{B}^{-}}{\mathrm{C}^{-}}\right)},$$

where n is the number of 3d valence electrons, "+" ("-") denotes a spectrum acquired with parallel (antiparallel) helicity and remnant sample magnetization, A^{i} is the integrated intensity of the respective L_{III} white line, B^{i} the integrated intensity of the respective L_{II} white line, C^{i} equal to the sum of the two underlying continuum step heights, and T_Z a magnetic dipole term, which is a small contribution for centro-symmetric systems.

In order to extract the peak intensities from pairs of absorption spectra, we first differentiate the spectra in the vicinity of each elemental L-edge peak pair, fit a smooth background on either side of the L peaks, and interpolate through the peak region. Next, we subtract the fit background from the differentiated spectra and integrate the spectra back. The resulting spectra then have the lineshapes of two peaks, each riding on a continuum step. The magnetic moments and associated error estimates are finally extracted from the equations above by considering the full range of peak areas obtained by subtracting out the extreme limits of the possible continuum steps which could be used to fit the spectra.

The layer thicknesses in the spin valves were confirmed with Proton-Induced X-ray Emission (PIXE).

RESULTS AND DISCUSSION

Figure 1 displays a pair of normalized MXCD spectra acquired using opposite photon helicities for one of the spin valves. The two spectra acquired with opposite helicity are offset for clarity, and the inset displays the region of the Cu L lines. The remanent sample magnetization was parallel to the incident x-ray beam direction during MXCD measurements. Strong white lines in the absorption spectra are evident at the L edges of Fe, Co, and Ni, whereas the small Cu edge signal from the thin, spacer layer occurs in the region dominated by the Ni EXAFS signal. While the positions and rough shapes of the white lines at each absorption edge in fig. 1 are consistent with previous measurements on elemental metals, [12, 13] each pair of white lines for a particular element in fig. 1 exhibits a strong dependence of relative intensity on incident beam helicity. The average Fe, Co, and Ni magnetic moments in three devices extracted from the sum rules above, together with the results of magnetoresistance measurements, are presented in Table 1. Within the conservative error estimates derived from the procedure described above, the measured spin magnetic moments for Fe, Co, and Ni are all less than the saturation moments of 2.21, 1.72, and 0.62 Bohr magnetons, respectively.[14] The details of the magnetotransport measurements have been presented previously.[5]

If the measured x-ray absorption signal arising from a depth z in the specimen for a given white line energy is proportional to $I(z)\ Exp(-z/\mu)$, then the measured, relative intensities of the absorption edges of Ni, Fe, and Co in the spectra are consistent with $\mu \approx 22$Å. The Cu spacer layer, which is buried under at least 13Å of Co and 50Å of Permalloy in each specimen, does not contribute appreciably to the absorption signal. Therefore, the MXCD measurement detects *not* the average magnetic response of different layers but rather the magnetic moment present in the outermost layer for each magnetic element.

For the spin valves with the smallest copper spacer layers, 13 and 15Å, strong ferromagatic coupling between the ferromagnetic layers through the Cu spacer layer aligns the elemental moments parallel to the remanence, as indicated in Table 1. For the 19Å Cu spacer layer, strong anti-ferromagnetic coupling through the Cu spacer layer forces the moments in the outer Co and Py layers to align antiparallel to the magnetizing field, as indicated by the negative sign of the extracted moments for that device in Table I. Ferromagnetic coupling atain appears in the two samples with the thickest Cu spacer layer. For the device with the 21Å Cu layer, off-axis rotation of the moments in the outermost Co and Py layers causes near-zero longitudinal moments to be detected by MXCD.

CONCLUSION

We have detected and measured the elemental magnetic moments for the ferromagnetic films in a series of real, thin-film, spin valve devices with various Cu spacer layer thicknesses. The strong correlation between MXCD and magnetoresistance measurements on the same devices indicates that the two techniques offer complementary approaches to the diagnosis of the magnetic microstructure underlying the performance of

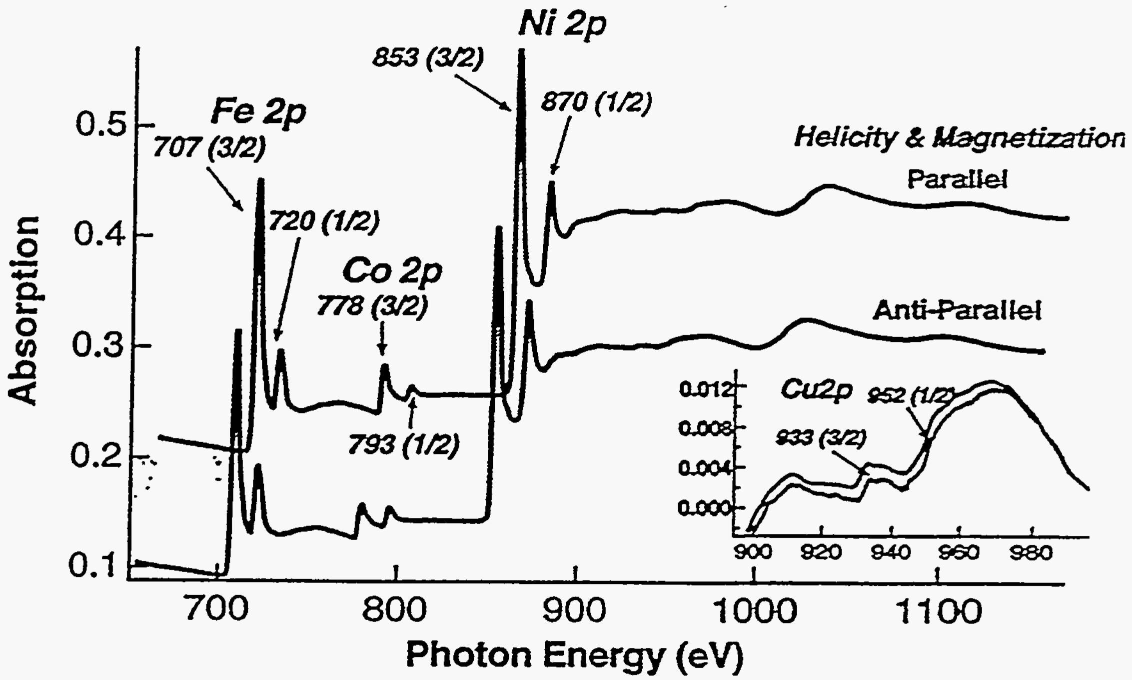

Figure I: Pair of MXCD absorption spectra, acquired with opposite photon helicities, for a spin valve with a 15Å Cu spacer layer thickness. The spectrum acquired with the helicity and magnetization aligned parallel is offset in the graph for clarity. The inset shows the detail of the Cu L-edge.

Elemental Moments from MXCD

(In Bohr Magnetons)

	Iron		**Cobalt**		**Nickel**		
Copper Spacer⇓	**μ(Spin)**	**μ(Orb)**	**μ(Spin)**	**μ(Orb)**	**μ(Spin)**	**μ(Orb)**	ΔR/R
13Å	**.86±.47**	**.11±.02**	**1.3±.19**	**.18±.04**	**.85±.55**	**.26±.15**	3.8%
15Å	**.84±.21**	**.35±.11**	**1.5±.50**	**.46±.19**	**.76±.45**	**.37±.28**	
19Å	**-.83±.15**	**-.29±.07**	**-1.5±0.6**	**-.42±.16**	**-.58±.27**	**-.19±.12**	13.1%
21Å	**-.10±.01**	**-.07±.02**	**-.01±.05**	**.09±.04**	**-.20±.22**	**-.01±.01**	
27Å	**.87±.15**	**.10±.02**	**1.4±.27**	**.10±.03**	**.94±.67**	**.25±.15**	11.1%
29Å	**.86±.19**	**.44±.13**	**1.6±.50**	**.56±.24**	**.75±.44**	**.26±.18**	

Table I. Elemental magnetic moments for Fe, Co, and Ni, extracted from MXCD data using the sum rules described in the text, together with the transverse magnetoresistance.

such devices. While MXCD offers the unique capability to measure elemental moments separately, the application of MXCD to real thin-film magnetic sensors is subject to restrictions imposed by each device topology.

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