Exploring magnetic roughness in CoFe thin films

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The behavior of chemical and magnetic interfaces is explored using diffuse x-ray resonant magnetic scattering (XRMS) for CoFe thin films with varying interfacial roughnesses. A comparison of the chemical versus magnetic interfaces shows distinct differences in the behavior of these two related interfaces as the chemical roughness is increased. Such changes appear to be correlated with the behavior of the magnetic hysteresis of the interface, measured by tracking the diffuse XRMS intensity as a function of applied magnetic field. © *1998 American Institute of Physics.* [S0021-8979(98)17511-4]

I. INTRODUCTION

The influence of roughness on the properties of thin film magnetic structures is a question of current interest to many facets of the magnetism community. Current results have shown that direct measurements of magnetic roughness as compared to measurements of the chemical roughness indicate that these interfaces are compositionaly rough, but magnetically smooth.[1,2] Since the magnetotransport of these structures is strongly affected by interfacial scattering and in particular by magnetic disorder at the interface,[3–5] chemical roughness may not be the appropriate parameter for correlation with the degradation of the magnetic properties.

The formalism for the determination of the nature of chemical interfaces and surfaces using specular and off specular (diffuse) scattering is a well established field.[6,7] However, to probe information about a magnetic interface one needs a significant magnetic scattering signal. One way of providing this is through the resonant enhancement of the magnetic and chemical scattering when an incident circular polarized photon is tuned to an absorption edge, known as x-ray resonant magnetic scattering (XRMS).[8–13] Utilization of a circular polarized photon, like its absorption counterpart magnetic circular dichroism (MCD),[14] generates the magnetic scattering component. Recently XRMS has been applied to the study of magnetic roughness. From both specular[2] and diffuse[1] studies of magnetic thin film structures comes evidence of differing chemical and magnetic interfaces.

To better understand the variation of magnetic versus chemical interfaces we have undertaken a study of thin CoFe films where an increasing chemical roughness was induced through the growth process. The results clearly show that the chemical and magnetic interfaces do not behave in the same manner as the root mean square (rms) chemical roughness is increased. Also, we will demonstrate the possibility of using variations in the magnetic diffuse intensity as a function of applied field as a probe of interfacial magnetic hysteresis.

II. EXPERIMENT

The reflectivity measurements were conducted at the NRL/NSLS Magnetic Circular Dichroism Facility located at beamline U4B of the National Synchrotron Light Source (NSLS).[15] Details of the experimental apparatus and measurement conditions are described elsewhere.[13,16] To probe interface roughness via the diffuse intensity we performed a sample rocking curve where the detector angle (2θ) was kept fixed and the sample angle (ω) was varied. In this configuration, a scan over a wave vector in the plane (q_x) is performed while keeping the component perpendicular to the film (q_z) approximately constant. To extract the magnetic information it is necessary to measure the helicity dependent scattering of the magnetic material (denoted as I^+ and I^-). So the magnetic moment of the sample was reversed at each data point to determine I^+ and I^-, which has been shown to be equivalent to alternating the photon helicity.[17,18]

The CoFe alloys thin films were prepared by the rf sputtering facilities of Nonvolatile Electronics Inc. The samples were grown on atomically flat Si_3N_4 substrates (roughness ~1.5 Å rms) with the following structure: $Cu(30\text{Å})/Co_{95}Fe_5(50\text{Å})/Cu(x\text{Å})/Si_3N_4$. Due to growth dynamics the rms roughness of Cu grown on Si_3N_4 increases dramatically as the thickness of the Cu buffer layer, x, is increased. Since the Cu buffer layer thickness can be controlled accurately, the roughness of the surface on which the CoFe is deposited can be tailored. For this study we utilized a series of four films with various Cu buffer layer thicknesses ($x=200$, 400, 800, and 1600 Å) spanning a rms chemical roughness ranging from 2.5 to 32 Å rms as measured by a Digital Instruments Dimension 3000 atomic force microscope (AFM) in tapping mode (resolution 10–50 Å). Since the Cu cap layer is so thin, the topographical information provided by AFM should give an accurate measurement of the chemical roughness of the top CoFe/Cu interface. This will be important

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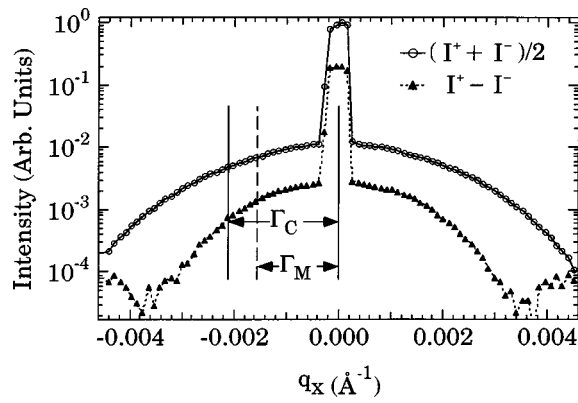
FIG. 1. Sample rocking curve measured at the Co L_3 edge (778 eV) for chemical $[(I^+ + I^-)/2]$ and magnetic $(I^+ - I^-)$ contributions vs q_x. This scan was taken at a detector angle 2θ of 9^0 ($q_z = 0.062$ Å^{-1}). Notice how the half width of the magnetic diffuse (Γ_M) is smaller than that of the chemical diffuse (Γ_C), indicating a longer correlation length, ξ for the magnetic interface.
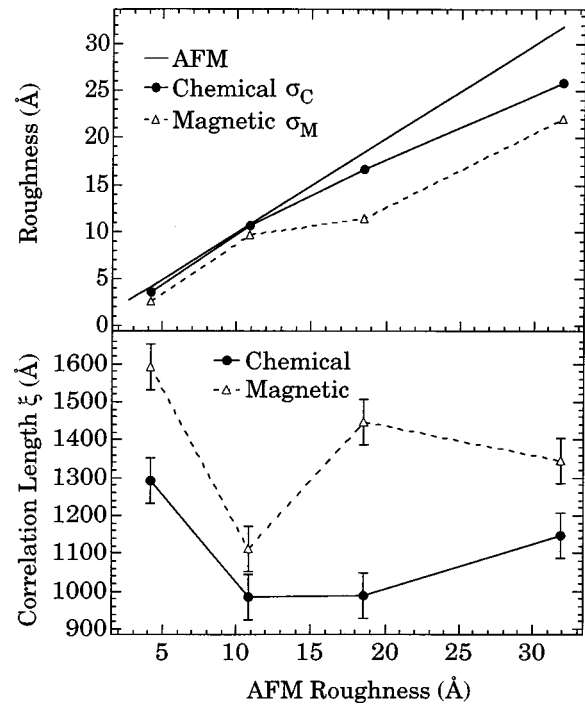

FIG. 2. Roughness parameters derived from the diffuse scattering data. Top panel: Chemical and magnetic rms roughness. Bottom panel: Chemical and magnetic correlation lengths.

when we compare it with the diffuse scattering results because the short mean free path of the photon at the L_3 edge[19] means that measurements made at grazing incidence ($\omega < 10°$) for a 50 Å CoFe film probe predominately the top CoFe/Cu interface.

III. RESULTS AND DISCUSSION

Figure 1 shows the chemical $[(I^+ + I^-)/2]$ and the magnetic $(I^+ - I^-)$ contributions from a sample rocking (diffuse) scan measured at the Co L_3 edge. The diffuse scan consists of a sharp specular peak around $q_x = 0$, with a broad underlying diffuse component. Since roughness is the mechanism that channels flux from the specular peak into the diffuse component, values for the chemical and magnetic roughness (denoted as σ_C and σ_M, respectively) can be extracted by determining the fraction of total flux that resides in the diffuse part of the spectrum. This is accomplished by comparing the integrated areas of the specular $[S_{specular}(\mathbf{q})]$ vs diffuse $[S_{diffuse}(\mathbf{q})]$ components using[7]

$$\frac{\int S_{diffuse}(\mathbf{q})d^2q_\parallel}{\int S_{diffuse}(\mathbf{q})d^2q_\parallel + \int S_{specular}(\mathbf{q})d^2q_\parallel} = 1 - e^{-(q_z\sigma)^2}, \quad (1)$$

where $q_\parallel$ denotes integration over the (q_x, q_y) plane, and σ is the roughness perpendicular to the film plane. A second parameter describing the roughness in the film plane, the lateral correlation length, ξ, is determined from the half width (Γ_C and Γ_M) of the diffuse portion of the sample rocking curves using a solution of diffuse structure factor (for a roughness exponent, $h = 1$):[6,7]

$$S_{diffuse}(\mathbf{q}) = \frac{2\pi \exp[-(q_z\sigma)^2]}{q_z^2}$$

$$\times \sum_{m=1}^{\infty} \frac{(q_z\sigma)^{2m}}{m!} \left(\frac{\xi^2}{2m}\right) \exp\left[-\left(\frac{q_x\xi}{2\sqrt{m}}\right)^2\right]. \quad (2)$$

Results of the analysis of our thickness series are shown in Fig. 2 for both chemical and magnetic data.

The most important general result is the different behavior of both σ and ξ for the chemical versus magnetic interfaces. The magnetic roughness in this series of samples is ~20%–30% less than the chemical roughness. The same is seen for the behavior of the chemical versus magnetic correlation length (bottom panel of Fig. 2). This indicates that the magnetic interface is typically much smoother than the chemical interface both perpendicular to and in the plane the film. There is good agreement between the σ roughness parameters extracted from the x-ray scattering and from the AFM values (the straight line of the top panel of Fig. 2). The small disagreements can be addressed through a more detailed analysis of the AFM roughness data, which is not shown here due to space limitations.

An interesting application of this technique becomes possible upon examination of the the specular versus diffuse element specific magnetic hysteresis measured by XRMS (see Fig. 3). The reflected intensity as a function of applied field can be utilized as a measure of the magnetic hysteresis since the magnetic portion of the scattering tracks with the magnetic moment of the sample. Since the field dependence specular peak intensity gives a measure of the bulk magnetic hysteresis, we can use the diffuse signal, which only comes from the interfaces, to measure the interfacial magnetic hysteresis. In Fig. 3 the clear difference in the coercive and saturation fields of spins at the interface indicates the different nature of the bulk versus interfacial magnetic environment. For the $x = 400$ Å film shown in Fig. 3 the difference in coercive fields was 3.5 ± 0.5 Oe. This was confirmed by measuring at not only several different points in the diffuse, but also in the specular and diffuse at different detector angles. It is worth noting that the sample indicating the larg-
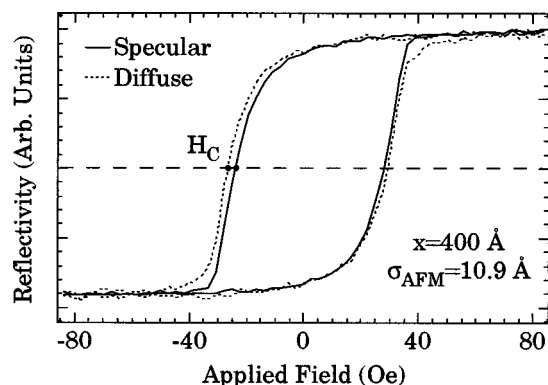
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FIG. 3. Comparison of magnetic hysteresis measured by XRMS at specular (bulk) and diffuse (interface) points for the $x=400$ Å film ($\sigma_{AFM}=10.9$ Å). Differences, such as the coercive field H_C, illustrate the different behavior of the bulk vs interfacial magnetic properties.

est difference the between specular and the diffuse coercive field is also the one exhibiting a roughening of the magnetic interface as noted by the drop in ξ_M and σ_M with respect to ξ_C and σ_C (see Fig. 2).

In conclusion, our results distinctly show that the chemical and magnetic interfaces can have a very different character. In addition, by tracking the diffuse intensity as a function of applied field we find a very different behavior of the interfacial spins, which appears to be correlated with variations of the chemical versus magnetic interface.

ACKNOWLEDGMENTS

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