Connecting disorder and magnetic properties in CoFe thin films

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Through a direct study of the chemical and magnetic interfacial disorder in conjunction with magnetic property measurements, evidence is presented that the grain size is the ultimate factor in determining the magnetic coercivity in CoFe thin film structures. © *2000 American Institute of Physics.* [S0003-6951(00)02818-7]

Disorder is a major unwanted factor in affecting the performance of magnetic thin film devices, yet it is not always clear in what ways it modifies the films' magnetic properties. This is complicated even further with the realization that chemical and magnetic disorder can be significantly different.[1–4] Interfacial roughness, in connection to magnetic issues such as giant magnetoresistance (GMR),[5] has been studied extensively to correlate interface structure with alterations of the GMR.[6–10] These studies clearly show that characterization of the interface solely in terms of the perpendicular disorder is not sufficient to understand how the disorder influences the magnetic properties.[10] In this letter we present a study of magnetic and chemical disorder in connection to the measurements of magnetic properties. A direct link between the in-plane chemical correlation length (i.e., grain size) and the magnetic coercivity illustrates the manner in which certain aspects of the disorder may or may not influence the magnetic properties.

To study the relationships between disorder and magnetic properties, we have utilized two sets of CoFe alloy thin films, which were prepared by radio-frequency (rf) sputtering. The basic magnetic film consists of a 50 Å $Co_{95}Fe_5$ alloy in which, by manipulating the substrate structures, the in-plane as well as perpendicular disorder can be tailored. By maintaining a constant magnetic film thickness while independently tailoring the interfacial roughness, we can probe the dependency of magnetic coercivity on the in-plane and perpendicular roughness. This is accomplished through the growth dynamics of Cu on Si_3N_4 substrates.[11] The magnetic film is deposited on a Cu buffer layer grown on an atomically flat Si_3N_4 substrate. Increasing the Cu buffer thickness from 200 to 1600 Å results in a chemical roughness ranging from 4 to ~30 Å root-mean-square (rms) and an increasing grain size.[2] A second set of films were grown to span the same range of perpendicular roughness, but the insertion of a 40 Å Ta phase-breaking layer in the Cu buffer layer caused a significant reduction in the grain size.[12]

The in-plane and perpendicular disorder of the buried interfaces were quantified by x-ray resonant magnetic scattering (XRMS).[13–16] These soft x-ray reflectivity measurements were conducted at the NRL/NSLS Magnetic Circular Dichroism Facility[17] located at beamline U4B of the National Synchrotron Light Source. For these measurements the degree of circular polarization was set to 75% and, since the

resonant scattering can vary significantly with only a few eV change in incident photon energy, the energy resolution was 0.8 eV. The sample was mounted in the gap of an electromagnet capable of providing fields in the scattering plane of up to ±400 G (see inset of Fig. 1) inside a vacuum-compatible θ–2θ diffractometer that has been described elsewhere.[18]

When x rays scatter from a rough interface, intensity is channeled away from the specular direction causing an increase in the diffuse background. Since the diffuse scattering arises from the rough interface, it contains information about the structure of that interface.[19,20] By collecting the scattered intensity through the use of sample rocking curves, the nature of the interface can then be probed. In this geometry, the detector is placed at a fixed angle 2θ and the incident angle, ω, is varied from 0 to 2θ (see inset Fig. 1). In terms of the transferred wavevector ($\mathbf{q} = \mathbf{k}_{Out} - \mathbf{k}_{In}$), at these photon wavelengths, the normal component, q_z, remains approximately constant while the in-plane component, q_x, varies. The rocking consists of a sharp specular peak around $q_x = 0$, with a broad underlying diffuse component (see Fig. 1). A comparison of the specular and diffuse intensities is directly related to the perpendicular roughness (σ), allowing for a quantitative determination of σ from the integrated areas of the specular versus diffuse components.[20] Similarly, the disorder length scale in the film plane is contained in the lateral correlation length, ξ, which is determined by fitting
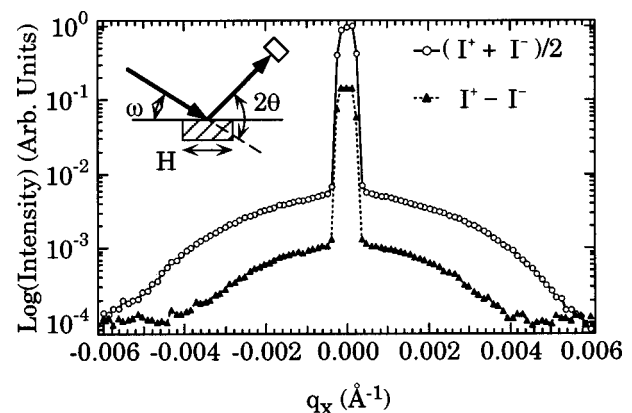

FIG. 1. The sum ($I^+ + I^-$) and difference ($I^+ - I^-$) rocking curves constructed from the helicity dependent data measured at the Co L_3 edge (778 eV). The inset displays the measurement geometry.
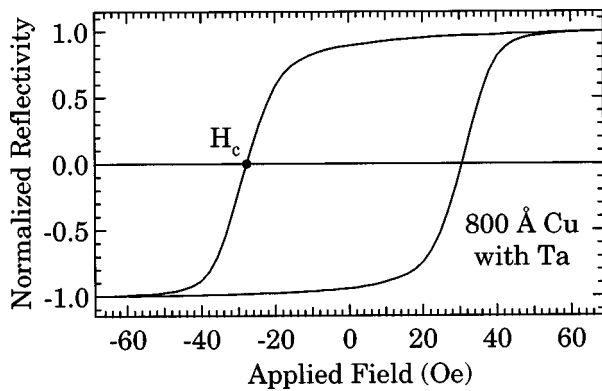
FIG. 2. Magnetic hysteresis measured from the specular reflectivity as a function of applied field. The incident photon energy is tuned to the Co L_3 edge (778 eV).

FIG. 3. The relation between the chemical perpendicular roughness (σ_c) and the in-plane correlation length (ξ_c). Open and closed symbols represent the two separate sets of CoFe thin films described in the text.

the shape of the diffuse portion of the reflectivity curves.[2,21] (These samples all corresponded to a structure factor for an interface with a Hurst exponent, $h = 1$.)[19,20]

As an extension since we are using circularly polarized x rays, roughness parameters associated with the magnetic interface can also be extracted.[21] Figure 1 shows the data from helicity-dependent sample rocking scans measured at the Co L_3 edge. Using the data for photon helicity and magnetic moment parallel (I^+) and antiparallel (I^-), the pure chemical $[(I^+ + I^-)/2]$ and the mixed chemical-magnetic ($I^+ - I^-$) contributions are obtained. A recent magnetic scattering theory has shown that this difference spectra is not purely due to magnetic contrast but also contains a chemical component.[21] Utilizing this theory it is possible to extract the perpendicular magnetic roughness (σ_m) from the difference measurement by using the extracted value of the chemical roughness (σ_c). With the in-plane disorder, this technique can only extract a mixed chemical-magnetic correlation length, ξ_{cm}, which is related to but not a direct measure of the magnetic correlation length.

One of the real advantages of XRMS is the ability to measure *in situ* not only chemical and magnetic structural information but also to extract magnetic hysteresis via reflectivity as a function of applied field. The magnetic scattering intensity is dependent on the relative orientation between the photon helicity and magnetic moment, so following the scattered intensity as a function of applied field can yield a measurement of the magnetic hysteresis. This is identical to the magneto-optic Kerr effect (MOKE),[22] except using soft x rays has the advantage that the magnetic signal is element specific. For this study the focus is on the bulk magnetic behavior, but it is worth noting that by utilizing the off specular reflectivity this can also probe interfacial spins.[12] From these hysteresis loops, the coercive field, H_c can then be extracted (see Fig. 2).

With the determination of the coercive field and the interfacial roughness parameters, the dependency of H_c on chemical disorder (ξ_c and σ_c) can be established. First though the inter-realtionship between ξ_c and σ_c must be examined to properly understand how the roughness varies in these samples. Figure 3 illustrates how these samples span the same range of perpendicular roughness, but different regions of correlation length (i.e., grain size). Since the film thickness is the same for both sets and since the shape of the
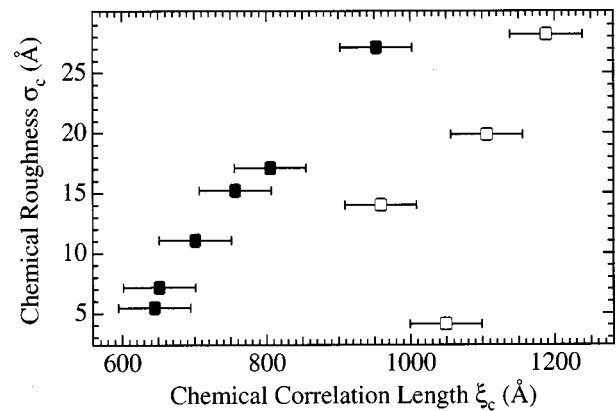
diffuse spectra indicates the chemical structure of the grains are the same, the two sets can be connected solely via the roughness parameters. Figure 4, shows that H_c is a smooth continuous function of ξ_c indicating that the important parameter in determining the coercive field is the in-plane correlation length (i.e., average grain size) and not the perpendicular roughness. To illustrate this point, consider the cluster of points near $H_c = 20$ Oe. These points correspond to very different σ_c values, yet they have nearly the same ξ_c and coercive field. It is interesting to note that H_c increases approximately as ξ_c^2, which, since the film thickness is a constant, indicates that H_c increases with the volume of the grain. This behavior is consistent with an increasing volume anisotropy, since magnetometery measurements indicate that the saturation moment, M_s, does not vary. The coercivity then changes as the magneto-crystalline anistropy becomes more dominant and overcomes intergrain exchange.[23]

It can be seen from Fig. 3 that, if H_c were displayed as a function of the perpendicular roughness, the data would appear as two distinct sets in contrast to the smooth connection show in Fig. 4, but this is only due to the fact that grain size (ξ_c) varies as a function of the chemical roughness. This reason that the perpendicular roughness is not an important factor can be understood from the manner in which σ_c alters the magnetic interactions. The perpendicular roughness gives rise to a surface magnetic charge that works to demagnetize
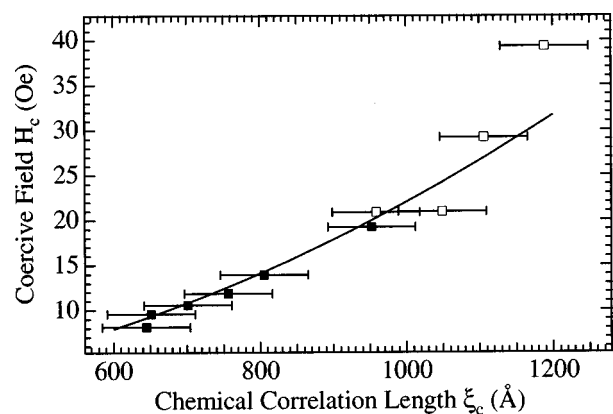

FIG. 4. Coercive field (H_c) as a function of measured chemical correlation length (ξ_c). The solid line is the fit to ξ_c^2. Open and closed symbols represent the two separate sets of CoFe thin films.

the sample.[24] The applied field is reduced by $\mathbf{N} \cdot \mathbf{M}$, where $\mathbf{N}$ is the demagnetization tensor and $\mathbf{M}$ is the magnetic moment. Since magnetometry shows that $\mathbf{M}$ does not vary with roughness in these samples, alterations of H_c would occur through variations in $\mathbf{N}$. Recently it has been shown that for a self-affine surface, components of $\mathbf{N}$ scale as σ^2/ξ.[24] By examining the behavior of H_c with respect to σ^2/ξ, it is clear that like the case of σ alone there is not a correlation, and therefore changes in the demagnetization tensor are not the main contributions to variations in H_c for these samples.

Up to this point, the discussion has been focused on the chemical rather than the magnetic disorder. As it turns out, the magnetic and chemical perpendicular roughness, σ_c and σ_m, and the in-plane correlation lengths, ξ_c and ξ_{cm}, were both found to be linearly related in these samples.[3] It can be concluded that in this system it is the chemical disorder that is important for the following reasons. For the case of σ_m, the reason is the same as for σ_c. Variations in the surface magnetic charge leading to stray dipolar fields are small compared to the energy scale of the bulk anisotropy. For the case of in-plane magnetic disorder, even though ξ_m cannot be extract directly, it can be inferred that, since ξ_{cm} tracks with ξ_c with an offset, the magnetic interactions are always confined to the nearest neighbor grains.[3] This indicates the intergrain interaction should remain relatively constant and not be a major contribution to an alteration of H_c with increasing disorder.

In conclusion, we have shown in this thin film system that by engineering the grain size, the anisotropy and therefore coercivity can be directly modified, illustrating the complicated nature in which disorder influences magnetic properties and the notion that partial disorder characterization (e.g., just σ) is not sufficient to obtain a full understanding.

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