Using small-angle neutron scattering to probe the local magnetic structure of perpendicular magnetic recording media

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Small-angle neutron scattering (SANS) has been used to measure the local magnetic structure of perpendicular media consisting of granular CoCrPt–SiO_x thin films. The dimensions of the magnetic structures determined by SANS are consistent with the physical grain sizes suggested by transmission electron microscopy measurements, but yield additional information on magnetic structure *within* the grains, including the existence of a much smaller magnetic core. The results are similar to those recently obtained on longitudinal magnetic recording media, but with the addition of strong interference terms due to the narrower distribution of grain sizes in these samples. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165798]

The areal density supported by current longitudinal magnetic recording media in hard disk drives (HDD's), ~140 Gbit/in.^{2}, appears close to the limits available from current technologies and families of materials, i.e., from longitudinal CoCrPt-based media.[1] These limits are set by the conflicting requirements that data storage be thermally stable, that data are recorded using the fringe field available from conventional ring heads, and that the medium has an adequate signal-to-noise ratio (SNR). In order to continue to provide greater areal density, HDD's using perpendicular recording, where the medium has a uniaxial anisotropy perpendicular to the film plane, are just starting to become available.[2] The advantage of perpendicular recording is that it allows a soft, high moment magnetic underlayer (SUL) to be incorporated into the structure of the medium. This effectively places the data storage layer directly in the magnetic circuit of the head which, in principle, provides both a greater magnetic field and sharper field gradient during the data write process allowing a higher anisotropy medium to be used.[3]

The structure of a perpendicular medium is significantly more complex than that of a longitudinal medium[4] and hence it is more difficult to determine fundamental magnetic properties. In particular, it is highly desirable to understand the magnetic structure and reversal processes of the data storage layer when incorporated into the complete medium including the SUL. Since the SUL typically accounts for more than 95% of the total medium moment, this presents new challenges.

In this work we use small-angle neutron scattering (SANS) to provide information on the magnetic structure of data storage layers forming part of a complete medium structure. Since neutrons have a magnetic moment, the scattering cross section contains both nuclear and magnetic contributions. SANS is thus able to probe the local magnetic structure at nanometer length scales and SANS results have recently been reported on a number of materials with potential for data storage.[5–9] Of most relevance to this paper are recent reports on longitudinal CoCrPtB media developed for use in high-density disk drives,[8] where a methodology was developed for measuring the extremely small magnetic signals present in the total neutron-scattering cross section. The experiments are extremely challenging, due both to the small magnetic volume of the magnetic recording layer (ca. 15 nm thick) and to the large amount of nuclear background scattering from the substrate and underlayers of the medium. In the present material we have the added complication of an additional *magnetic* signal that arises from the SUL, which must be distinguished from that due to the data storage layer.

The samples were grown by dc-magnetron-sputtering a 15-nm-thick, granular CoCrPt oxide layer onto 65 mm glass substrates. The structure included a 150-nm-thick Co-based SUL onto which a thin seedlayer was deposited prior to the data storage layer. The film stack also included a protective overcoat to inhibit oxidation. In order to obtain sufficient statistics to resolve the magnetic scattering, samples com-

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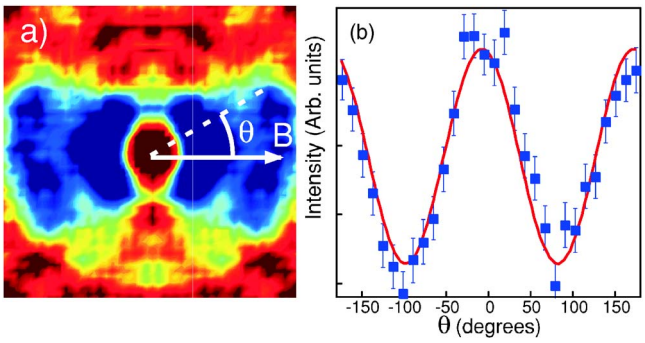

FIG. 1. (Color online) (a) The anisotropic magnetic scattering from the 15 -nm-thick granular CoCrPt–SiO_x layer of the perpendicular recording media samples over a q range of 0.007–0.03 Å^{-1}. The contributions from the nuclear scattering and the SUL have been removed (see text). (b) Angular variation in the scattering plane of the magnetic scattering, fitted to $\sin^2\theta$.

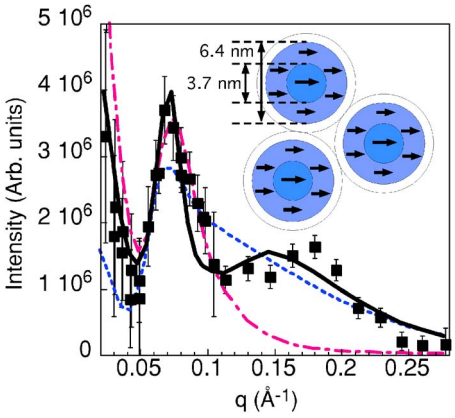

FIG. 2. (Color online) The q dependence of the magnetic intensity from the recording layer at saturation. The solid line represents a fit to the spherical shell model scattering function described in the text. The dashed line is a fit to a solid sphere model with a diameter of 2.5(1) nm; the dot-dashed line is the same model with a diameter fixed to 6.0 nm. Inset: a schematic of the shell model used.

prising a stack of three double-sided substrates were used in these measurements. The SANS experiments were performed using the D11 spectrometer at the Insitute Laue-Langevin (ILL), Grenoble, France.

A magnetic field was applied in the plane of the film and perpendicular to the incident neutron beam. In this geometry the experiment thus probes magnetic structures within the plane of the film. Before each measurement the samples were first rotated through 90° and the magnetization saturated perpendicular to the plane in a field of 2.2 T. This ensured that prior to the measurements the sample was always left in a known state and moreover that in this state the recording layer was magnetically *isotropic* within the plane of the film.

Although the nuclear and magnetic neutron-scattering cross sections are roughly comparable in magnitude, scattering from the structural disorder dominates the raw scattering data due to the much greater volume of nonmagnetic material. However, whereas the nuclear cross section is isotropic, the magnetic signal varies as $I_M(\mathbf{q}) \propto \sin^2\theta$, where θ is the angle between the scattering vector and the local direction of the magnetization, and $\mathbf{q}$ is the scattering vector[9,10] (Fig. 1). This anisotropy in the scattering may thus be used to reveal the magnetic component in the following way, using a method similar to that described in Ref. 8. Firstly, a sample is prepared for which the component of the local magnetization is randomized over 2π in the plane of the film, in this case by saturating the sample perpendicular to the plane and then reducing the field to zero, thus allowing the magnetization to relax. In zero field the neutrons are scattered through small angles to give an isotropic pattern $I(q)=I_M(q)+I_N(q)$ containing both a magnetic and a much larger nuclear contribution. A field is then applied to saturate the magnetization in the plane of the film, so that the magnetic contribution to the scattering now becomes *anisotropic*. Since $I_N(q) \gg I_M(q)$, the variation $I_M(\mathbf{q}) \propto \sin^2\theta$ still cannot be extracted, since the amplitude of $I_M(\theta)$ is small in comparison to the random angular variation of the dominant nuclear scattering $I_N(\theta)$. However, the magnetic contributions are readily revealed by subtraction of the zero-field isotropic pattern in order to remove entirely the nuclear contribution. This image then contains both isotropic (zero-field) *and* anisotropic (saturation field) magnetic contributions, which are easily separated. These contain scattering from both the recording layer and the SUL, but since it is the former in which we are primarily interested an alternative approach is introduced. Following the zero-field measurements additional data are taken at an applied in-plane field sufficiently large to just saturate the SUL yet still small enough to have no appreciable affect on the recording layer, which has a strong perpendicular anisotropy. By taking the difference of any two of these three data sets one can obtain the scattering from the CoCrPt–SiO_x recording layer alone (Figs. 1 and 2), the SUL alone, or from the total magnetic signal. All combinations produce self-consistent results.

We focus here on the anisotropic component of the scattering from the CoCrPt–SiO_x *recording layer*, which reflects the magnetic structure at *saturation*, shown in Fig. 2. We model the data using the approximation $I_M(\mathbf{q}) = \langle f(\mathbf{q})\rangle^2\langle S(\mathbf{q})\rangle + \langle f^2(\mathbf{q})\rangle - \langle f(\mathbf{q})\rangle^2$, where $f(\mathbf{q})$ is a form factor describing the local induction around a magnetic grain, $S(\mathbf{q})$ is the structure factor that models the spatial correlation of the magnetic induction between different grains, and $\langle\cdots\rangle$ denotes the average over the size distribution of the grains. This is a reasonable approximation given the polydispersity and packing density for this system.[11,12] A size distribution of magnetic particle diameters was included using a Gamma-Shultz function, as described in Ref. 9, and the fits yield an effective distribution width $\sigma \sim 0.22$, similar to $\sigma = 0.26(2)$ obtained for the physical grains from transmission electron microscopy (TEM) data. We note that the fits are not strongly sensitive to the precise form of the distribution function.[9] For $S(\mathbf{q})$ an analytical expression for a system of densely packed interacting hard spheres, based on the Percus-Yevick equation,[13] was used. Unlike many simplified treatments, we find it necessary here to include an explicit average of $S(\mathbf{q})$ over the size distribution using the method of Ref. 12, although the more complete treatment of Ref. 11 is found to be unnecessary in the present case. To simplify the analysis $f(\mathbf{q})$ is chosen to be the Fourier transform of an object formed from two concentric shells of magnetization within the plane of the film, thus comprising an inner core and an outer shell

(see inset in Fig. 2). This allows for the possibility that the induction near the edge of the grains has a different magnitude and direction to that of the central core. This shell model is found to fit the data well, whereas a simple solid sphere model is found to provide a poor description of the data (Fig. 2). A cylindrical shell model was also found to fit the data less well, suggesting that the magnetic entities contain less sharp features than the physical grains in which they reside. Both these findings are similar to those obtained from our SANS studies on longitudinal recording media.[8,14] However, in contrast to those results, in the present data we find a strong interference peak in $S(\mathbf{q})$, which is probably more evident here due to the reduced grain size distribution in these samples.[11,12] The peak in $S(\mathbf{q})$ corresponds to an average interparticle separation of 8.5(4) nm, in good agreement with the estimate of the grain size of 7.9(3) nm from TEM. The form factor $f(\mathbf{q})$ indicates an average outer particle diameter of 6.4(2) nm, suggesting a dead (or at least spatially uniform) magnetic region between the grains. This is not unexpected given the inhomogeneous composition of these materials, and the accepted picture of a nonmagnetic grain boundary. However, the less expected result is that within the magnetically active grain there is a much smaller core of higher magnetization, which has a diameter of 3.7(3) nm. Very similar findings for longitudinal recording media have been modeled recently, both analytically and using micromagnetic simulations,[8,14] where it is shown that this outer region can be extremely well described by a softer polarizable magnetic material. However, more measurements are required on these perpendicular recording materials to fully describe the local magnetic structure.

In conclusion, we have succeeded in measuring the local magnetic structure in the active layer of a sample of perpendicular recording media, which represents a considerable experimental challenge. The length scales obtained are in agreement with the measurements of the grain size of the materials, but also reveal a gradation of magnetization across the grain, comprising a central core, a softer outer shell, and nonmagnetic region between the grains. Further field-dependent measurements are planned to explore the nature of these inner and outer magnetic regions.

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