# Role of B on grain sizes and magnetic correlation lengths in recording media as determined by soft x-ray scattering

Olav Hellwig[1], J. B. Kortright[2], D. T. Margulies[1], B. Lengsfield[1], and Eric E. Fullerton[1]

[1]IBM Almaden Research Center, San Jose, CA 95120

[2]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

We have measured the chemical grain sizes and magnetic correlation lengths in CoCr-based magnetic recording media films using resonant soft x-ray small-angle scattering. We find that the addition of B, while leading to slightly smaller physical grains, dramatically reduces the magnetic correlation length. These results show that B additions effectively act to suppress intergranular magnetic exchange via segregation to the grain boundaries.

PACS # 75.50.Ss, 75.25,+z, 61.10.Eq, 75.50.Tt

In magnetic recording thin-film media the signal-to-noise ratio (SNR) needed for high-density recording is achieved by statistically averaging over a large number of weakly interacting magnetic grains per bit [1,2]. The granular microsctructure limits the magnetic correlations to length scales comparable to the grain size and allows information to be written on a finer scale than possible in a homogeneous magnetic film. This microstructure is currently achieved in sputter-deposited CoCrPtX alloy thin films where X = Ta or B [2-7]. When grown at elevated temperatures, these alloys phase segregate into high-moment magnetic grains surrounded by non-magnetic boundary regions [5-7]. Further improvements in recording performance are expected from improved underlayer structures and the use of more complex alloys to reduce the grain size and intergranular coupling. As this evolution continues, it is increasingly important to understand the growth and phase segregation of complex alloy films [3] to gain insight into the noise behavior and the potential onset of thermal stability issues [2]. In this letter we use resonant soft x-ray small-angle scattering (SAS) to probe spatial characteristics of both chemical segregation and magnetic correlations in CoCr, CoPtCr and CoPtCrB longitudinal recording media specifically to understand the role of B on the performance of advanced recording media. We find that the characteristic length scale of the chemical segregation is relatively insensitive to the alloy composition. In contrast, the magnetic correlation length is dramatically reduced with the addition of B, demonstrating its effectiveness in reducing the intergranular exchange.

Resonant spectroscopies of 3*d* transition-metal films at the *L* edges provide powerful techniques to investigate magnetic and chemical structure [8]. In the present work we exploit emerging resonant SAS techniques to probe in-plane structural and

magnetic order over length scales ranging from the x-ray wavelength λ, 1-2 nm, up to ~300 nm [9]. This approach has been used to identify chemical segregation in Fe-Cr alloy films [10], measure magnetic domain and grain sizes in Co/Pt multilayers [9], and initial studies have shown its effectiveness for studying recording media [11]. Although neutron SAS has been applied to magnetic media [12,13] the resonant capabilities are particularly useful for studies of CoCr-based alloys, since there is typically little scattering contrast between Co and Cr. By tuning to the *L*-edges of either Co or Cr, the scattering contrast can be enhanced by over an order of magnitude [9]. Furthermore, since the Cr is predominantly non-magnetic, tuning to the Cr edge enhances the chemical contrast, while tuning to the Co edge enhances both chemical and magnetic contrast.

The films used in this study are sputter deposited onto a 150-nm thick 2x2 $mm^2$ SiN membranes to facilitate transmission x-ray measurements. The media compositions studied are $Co_{78}Cr_{22}$, $Co_{69}Pt_9Cr_{22}$ and an advanced CoPtCrB recording alloy. The underlayer structure described in Ref. 5 provides a textured Cr(001) layer for the growth of the media layers, which grow hcp-$[11\bar{2}0]$ textured with the magnetic easy c-axis oriented randomly within the plane of the film. The media layers are ~300 Å thick and capped with a 50-Å amorphous C layer. Magnetic measurements confirm that the magnetic easy axes are in plane with coercive field values, $H_C$, of 0.3, 0.9 and 2.3 kOe for the CoCr, CoPtCr, and CoPtCrB films, respectively. Out of plane measurements show increasing anisotropy values with the addition of Pt and B to the alloy, as expected [5].

The symmetric transmission SAS geometry used here is shown in the inset of Fig. 1b. This geometry keeps the scattering vector **q** (magnitude $q = 4\pi\sin q/l$) in the film plane to maximize sensitivity to in-plane order. Measurements were made by either

scanning q at fixed x-ray energy, or by scanning the x-ray energy at fixed $q$. Measurements were made at the Advanced Light Source. The SAS scans described here were measured on bending magnet beamline 6.3.2 with a range of polarization states using as-deposited films to study intrinsic magnetic correlations. Additional SAS measurements and transmission absorption spectra were measured at the undulator beamlines 8.0 and 4.0 using linear and circular polarization, respectively.

SAS $q$ scans measured at the resonant intensity peaks at the Co and Cr $L_3$ lines, 574 and 778 eV, respectively, are shown in Fig. 1. Scans of the common underlayer structure (without any media layer) reveal the contributions from the underlayer and the SiN membrane. These scans are almost featureless, with enhanced low $q$ scattering that is also observed in scattering from the substrate alone, and with a weak, broad peak at $q \cong 0.015$ Å$^{-1}$ observed at the Cr resonance. For the samples with media layers there is additional, strong SAS at both the Cr and Co edges arising from the media layer. This scattering is strongly resonantly enhanced, as is illustrated in Fig. 1b by the 10-fold decrease in scattering just 10 eV below the Co $L_3$ peak (dashed line) compared to that measured at the peak (open circles). Similarly strong and sharp resonant enhancements are observed near the Cr $L_3$ line.

All the SAS scans from the media samples show similar features. The Cr-edge data has a peak at $q \sim 0.07$ Å$^{-1}$ for all samples. This peak results from interference between well-correlated neighboring scattering centers separated by $2\pi/q \sim 100$ Å, typical of grain diameters observed in transmission electron microscope (TEM) images of media grown on similar underlayers [5]. We attribute this Cr resonant peak to the average grain diameter $D_0$ of the media. It is well established that chemical segregation

during the growth of CoCr alloys involves Cr diffusion to the grain boundaries resulting in a magnetic Co-rich core of the grain with non-magnetic or weakly magnetic Cr-rich grain boundaries [6,7], as shown schematically in Fig. 1b. Thus, by tuning to the Cr edge, we are enhancing the contrast between the magnetic grain and the Cr-rich grain boundaries.

To gain additional insight into the origin of the scattering we compare the results of Fig. 1 to calculations of the scattering from a model media structure shown in Fig. 2a. The light areas represent the grains and the dark areas the grain boundaries. Choosing 1024 nucleation cells at random from a 256 by 256 array of cells generated grain distributions. Each nucleation cell defined a grain center and the cells closest to a nucleation site were assigned to that grain. The cells comprising a grain boundary were assigned a value of zero and the cells comprising a grain were assigned a value of one. Figure 2a represents a portion of one such grain distribution.

Plotted in Fig. 2b is the grain diameter distribution n(D) giving the probability of a grain of diameter D which includes the width of the grain boundary. The solid line is a fit of n(D) to a log-normal distribution:

$$n(D) \propto \exp\left(-\ln\left(D/D_0\right)^2 / 2s^2\right) \qquad (1)$$

where $D_0$=6.5 unit cells (vertical dashed line) is the mean grain diameter and $\sigma$=0.29 is a dimensionless geometric standard deviation. Such a distribution is often used to characterize experimentally observed grain-diameter distributions in recording media [2]. The expected scattering intensities from this grain structure are given by their power spectral density (PSD) obtained as the square of the Fourier transform of the real space distribution [9]. Plotted in Fig. 2c is the azimuthally averaged PSD vs. radial $q$. There is

peak in the PSD that corresponds closely to $2\pi/D_0$ shown by the vertical dashed line. This comparison supports the interpretation that the Cr edge peaks in Fig. 1 are related to the average grain size. Shown in Table I is the average grain size for the three media layers determined from the position of the Cr-edge intensity peak. The grain size is insensitive to alloy composition, decreasing only slightly with B addition. However, the narrowing of this high-$q$ peak on progressing from Fig. 1b to 1d suggests a sharpening of the grain size distribution.

The Co-edge data shows the same interference peak at $q \sim 0.07 Å^{-1}$ that was observed in the Cr-edge data, as well as additional scattering at significantly lower $q$ values. The observation of high-$q$ resonant scattering from the grain structure at both the Co and Cr edges confirms that this scattering arises from in-plane compositional variations of Co and Cr. The additional lower-$q$ scattering arises predominantly from correlated magnetic regions larger than the grain size. For the CoPtCr film (Fig. 1c), this additional scattering is clearly resolved as a peak at $q \sim 0.015$ $Å^{-1}$ corresponding to a real space distance of ~ 400 Å. The magnetic origin is identified from the energy dependence of the scattering as described in Refs. 9 and 11 [14] where the energy dependence is quantitatively modeled using measured Co magnetic scattering factors near the Co $L$ edge. To qualitatively separate the magnetic and charge scattering we subtracted the Cr-edge data, which is primarily structural in origin, from the Co-edge data [15]. This difference is shown as the open diamonds in Fig. 1, and represents scattering with magnetic origin.

The peak in the difference plots represents the average magnetic correlation length, whose value is listed in Table I for the different media films. From Fig. 1 and

Table 1 it is clear that the average grain size does not vary significantly with composition of the alloy while the magnetic correlation length is dramatically reduced with the addition of B. Micromagnetic modeling suggests that intergranular exchange coupling is the dominant term in determining the magnetic correlation length. The stronger the intergranular exchange, the larger the magnetic correlations in the media [16] and it is the magnetic correlation length more than the physical grain size that contributes to the SNR and recording performance. The coincidence of the position of the magnetic peaks in the CoCr and CoPtCr films with the weak Cr resonant peak in the underlayer suggests that the underlayer microstructure may also influence the magnetic correlation lengths in these media layers, but not in the CoPtCrB film. These SAS results indicate that the main advantage gained in recording performance from B addition arises more from reducing the intergranular exchange and the magnetic correlation length, than from reductions in the physical grain size. The results also show that the magnetic correlation length is approaching the physical grain size limit in advanced media. This conclusion is consistent with magnetic recording studies where the magnetic correlation length can be inferred from the media SNR. For the media described in Ref. 5, *e.g.*, TEM analysis determined an average physical grain size of 83 Å and analysis of the media SNR estimated a magnetic correlation length of 95 Å.

In conclusion, we have measured the chemical grain sizes and magnetic correlation lengths in CoCr-based magnetic recording media films using resonant soft x-ray small-angle scattering. We find that the addition of B, while leading to slightly smaller physical grains, dramatically reduces the magnetic correlation length. This suggests that B additions effectively act to suppress the intergranular exchange via

chemical segregation to the grain boundaries. The observation of strong resonant scattering from both magnetic and chemical structure highlights the applicability of these resonant scattering techniques for assessing future longitudinal and perpendicular recording media, where grain sizes and magnetic correlations lengths < 100 Å are anticipated.

We would like to thank M. Toney for helpful discussions. Work at LBNL was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, MSD, of the U.S. DOE under Contract No. DE-AC03-76SF00098. O. H. was partially supported by the Deutsche Forschungsgemeinschaft via a Forschungsstipendium under contract number HE 3286/2-1.

## References


[1] H. N. Bertram, *'Theory of magnetic recording"*, (Cambridge University Press, England) 1994.

[2] D. Weller and A. Moser, IEEE Trans. Mag. **35**, 4423 (1999).

[3] K. Oikawa, G. W. Qin, O. Kitakami, Y. Shimada, K. Fukamichi, K, Ishida, Appl. Phys. Lett. **79**, 644 (2001).

[4] M.F. Doerner, K. Tang, T. Arnoldussen, H. Zeng, M.F. Toney, D. Weller, IEEE Trans. Magn. **36**, 43 (2000).

[5] M. Doerner, X. Bian, M. Madison, K. Tang, Q. Peng, A. Polcyn, T. Arnoldussen, M. F. Toney, M. Mirzamaani, K. Takano, E. E. Fullerton, D. Margulies, M. Schabes, K. Rubin, M. Pinarbasi, S. Yuan, M. Parker, and D. Weller, IEEE Trans. Mag. **37**, 1052 (2001).

[6] J. E. Wittig, T. P. Nolan, C. A. Ross, M. E. Schabes, K. Tang, R. Sinclair, J. Bentley, IEEE Trans. Magn. **34**, 1564 (1998).

[7] N. Inaba, Y. Uesaka, M. Futamoto, IEEE Trans. Magn. **36**, 54 (2000).

[8] J. B. Kortright, D. D. Awschalom, J. Stöhr, S. D. Bader, Y. U. Idzerda, S. S. P. Parkin, I. K. Schuller, and H.-C. Siegmann, J. Magn. and Magn. Mater. **207**, 7 (1999).

[9] J. B. Kortright, S.-K. Kim, G. P. Denbeaux, G. Zeltzer, K. Takano, E. E. Fullerton, Phys. Rev. B **64**, 092401 (2001).

[10] J. B. Kortright, S.-K. Kim, and H. Ohldag, Phys. Rev. B **62**, 64 (2000).

[11] "Resolving magnetic and chemical correlations in CoPtCr films using soft x-ray resonant scattering" J. B. Kortright, O. Hellwig, D. T. Margulies, and Eric E. Fullerton, J. Magn. Magn. Mater. (in press), and LBNL Report LBNL-48668.

[12] J. Suzuki, K. Takei, Y. Maeda, and Y. Morii, J. Magn. Magn. Mater. **184**, 116 (1998).

[13] M. Toney and K. Rubin, Private communication

[14] Measurements reported here were made in the as-deposited state. However, the intensity of the low-q scattering depends on the field history of the sample consistent with a magnetic origin.

[15] Because there is additional absorption from the Cr underlayer near the Cr edge, the Cr-edge intensities were scaled to match the Co-edge data for $q > 0.1$ Å$^{-1}$.

[16] H. Zhou and H. N. Bertram, IEEE Trans. Mag. **36**, 61 (2000).

**Figure Captions:**

**Figure 1:** Resonant soft X-ray SAS scattering from the underlayer structure without a media layer (a) and from CoCr (b), CoPtCr (c) and CoPtCrB (d) media measured at the Co edge (open circles) and Cr edge (filled diamonds). The inset of (b) shows the scattering geometry and the media layer with magnetic grains (diameter D) with the in-plane magnetization direction represented by the arrows and non-magnetic grain boundaries. The open diamonds are the difference between the Co- and Cr-edge data. The dashed line in (b) is the non-resonant scattering measured 10 eV below the Co edge.

**Figure 2:** (a) Real space image of a model closed-packed granular micostructure with a grain size distribution. Light and dark cells represent grains and grain boundaries, respectively. The average grain diameter is ~6.5 cells (b) The open symbols are grain diameter distribution n(D) giving the probability of a grain of diameter D. The solid line is a fit of n(D) to a log-normal distribution (Eq. 1) with $D_0$=6.5 cells (shown by vertical dashed line) and $\sigma$=0.29. (c) The radially-averaged PSD of the granular structure shown in (a) where the dashed line is $2\pi/D_0$. The solid line in (c) is a guide to the eye.

| Sample | Grain size (Å) | Magnetic correlation length (Å) |
|---|---|---|
| CoCr | 95 | 420 |
| CoPtCr | 105 | 450 |
| CoPtCrB | 88 | 120 |

**Table I:** Average physical and magnetic grain sizes for the CoCr, CoPtCr and CoPtCrB alloy media determined by resonant SAS.

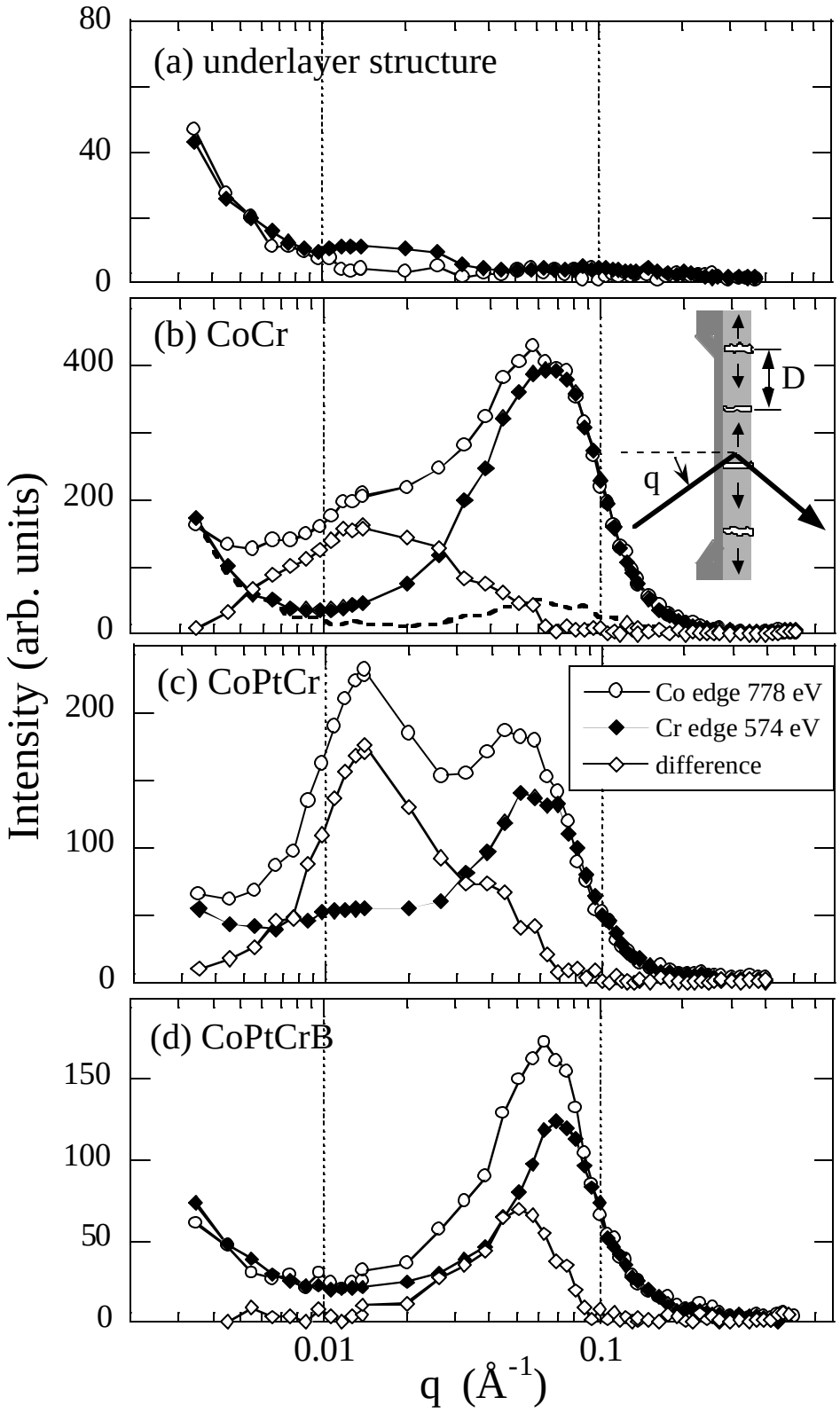


**Figure 1, Hellwig *et al.***

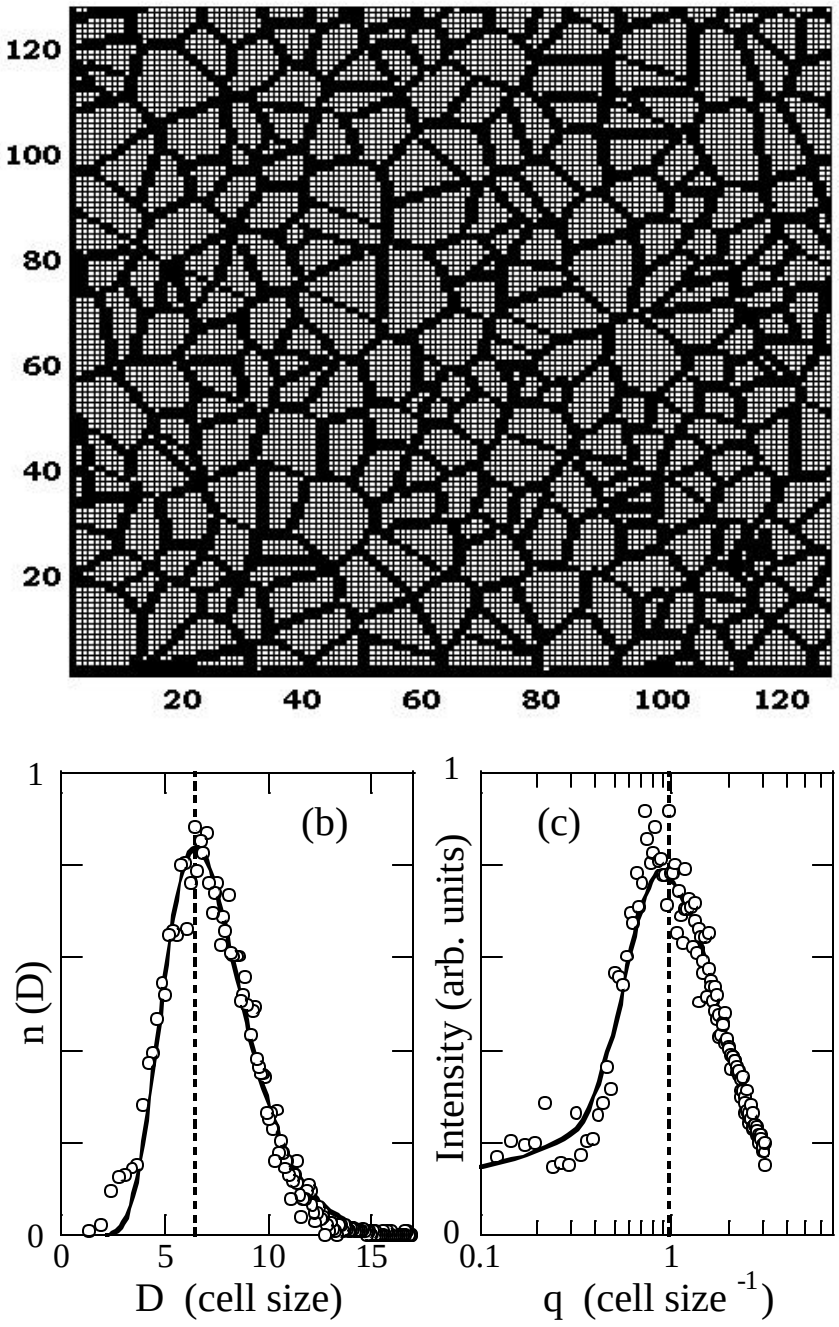


**Figure 2: Hellwig *et al.***