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Resonant x-ray scattering from a magnetic multilayer reflection grating

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We report the results of soft x-ray resonant magnetic scattering experiments conducted on Co/Ru magnetic multilayers patterned into a reflection grating. Sample magnetization dependent scans of the in-plane wave vector transfer were performed to probe the relationship between the lateral physical and magnetic structures. Different Fourier components were found to dominate the sum and difference of these spectra, corresponding to different lateral wave forms for the structure-structure and structure-magnetism correlations. © 2005 American Institute of Physics. [DOI: 10.1063/1.1881790]

It is now a commonplace that magnetic multilayers are rich systems for study, both in terms of the basic phenomena (such as giant magnetoresistance,¹ oscillatory interlayer coupling,² spin-transfer torques,³ etc.), and their tremendous technological importance in magnetic recording, magnetic random access memory, and spintronics. Investigating the internal morphology of such structures nondestructively has led to the development of a variety of x-ray scattering techniques. In particular, off-specular reflectometry methods⁴ are used to study roughness at buried interfaces. More recently, probes sensitive to magnetism, such as polarized neutron reflectometry (PNR)⁵ and x-ray resonant magnetic scattering (XRMS),^{6,7} have been used to study the magnetic morphology of these multilayers: obtaining information about so-called “magnetic roughness”⁸ at interfaces and magnetic domains.⁹ As the rate of investigations of laterally patterned nanostructures formed from such multilayers gathers pace,¹⁰ the application of scattering techniques to probe this ordered in-plane structure is a natural progression, and there have been recent reports of the use of PNR and XRMS to study nanoscale arrays of magnetic dots¹¹ and lines.¹² In this letter we report on a soft XRMS investigation of a multilayer patterned by a “soft” lithography process into lines to form a reflection grating, used to examine the relationship between physical and magnetic microstructures.

Polystyrene (PS, weight average molecular mass $M_w = 11.0$ kg/mol, polydispersity $M_w/M_n = 1.04$) was spin coated onto a Si wafer from a dilute toluene solution. A poly(dimethyl siloxane) mold, which replicated a diffraction

grating, was treated with an oxygen plasma, and then placed on the PS film and pressed together with 10 kPa of pressure. The whole assembly was then heated to 130 °C for ~2 h. After removing the mold the remaining structure of the PS was an array of lines approximately 20 nm high, 200 nm wide, and spaced 200 nm apart.¹³ A nominally {Co(40 Å)/Ru(34 Å)} × 10 multilayer was then grown over the lines by dc magnetron sputtering. The Ru thickness corresponds to the third antiferromagnetic coupling peak. A scanning electron micrograph (SEM) of the completed sample is shown in Fig. 1. Hysteresis loops of the sample were measured with a simple Kerr effect apparatus, shown in the inset of Fig. 1. The direction along the imprinted lines presents a slightly easier axis magnetically.

Soft XRMS experiments were performed at beamline U4B at the National Synchrotron Light Source. An electro-

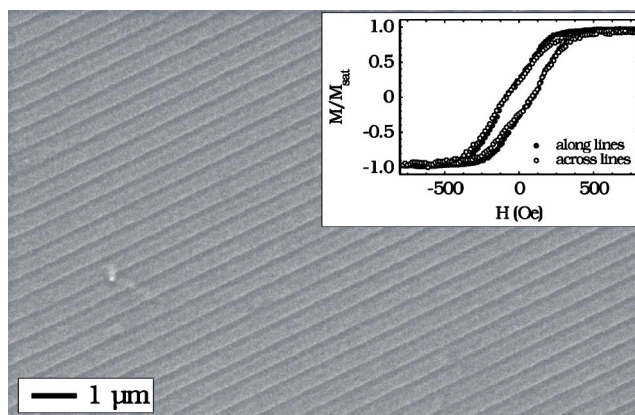


FIG. 1. A scanning electron micrograph of the sample. Inset is a Kerr loop of the sample with the field applied in the plane, both along (•) and across (○) the direction of the lines.

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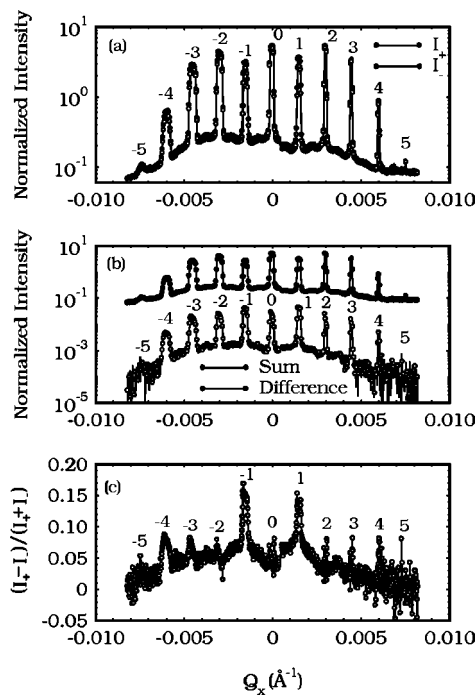


FIG. 2. (a) Scans of constant $Q_z=0.0807 \text{ \AA}^{-1}$ for the sample magnetized in the positive and negative directions with respect to the photon helicity. (b) The sum (average) and difference of these two sets of data. (c) The ratio of the difference to the sum of the two intensity channels. The numbers labeling each peak denote the fringe order, n .

magnet was used to apply steady fields of up to 300 Oe to the sample. The field direction is in both the plane of the sample and in the scattering plane (the x axis). The z axis is the sample normal. The choice of sample and detector angles determines the components of the elastic wave vector transfer \mathbf{Q} in x and z . We used 70% circularly polarized photons with an energy of 778 eV, close to the Co L_3 resonance. The reflected intensity was normalized using a Au grid monitor mounted upstream of the entrance slits to the scattering chamber.

We located the first order multilayer Bragg peak in specular scans at $Q_z=0.0807 \text{ \AA}^{-1}$. Due to the roughness induced by the patterning the higher order peaks in Q_z were suppressed. However, the main aim of our experiment was to investigate the lateral periodicities in the sample, and to do this it is necessary to introduce an in-plane component of \mathbf{Q} . Scans were performed where Q_z was fixed at the first order multilayer Bragg peak and then Q_x scanned from one sample horizon to the other. At each point in reciprocal space the reflected intensity was measured for the sample magnetized in both the positive (I_+) and negative (I_-) directions with a fixed photon helicity. The results of such measurements are shown in panel (a) of Fig. 2. The fringes from the grating are visible on either side of the specular reflection as far as the sample horizon. We label the order of these fringes with the integer n , where $n=0$ represents the specular ridge. The changing beam footprint and resolution of the slits cause the narrowing of the fringes as Q_x goes from negative to positive values. Between the fringes a wide hump of diffuse scatter caused by the usual random fluctuations in multilayer structure across the surface⁴ can be observed. This is less than the fringe intensity by at least an order of magnitude across the whole scan.

Following the methods of earlier work,^{14,15} we plot in Fig. 2(b) the average (half the sum) and difference of the two data sets to separate structural and magnetic information. Subsequently developed theory shows that the difference is sensitive to cross correlations between the chemical and magnetic structures, while the sum data reflects self-correlations in the chemical or magnetic structures.¹⁶⁻¹⁸ We interpret the intensities measured at each fringe position as representing the square of an amplitude corresponding to a term in a Fourier series describing the lateral wave form of either structure-structure or structural-magnetic correlations across the grating. (The scattered intensity due to magnetic self-correlations in the sum is rather small in this case. We have shown this observing that it is almost independent of applied field, by measuring the same scan again in forward and reverse fields corresponding to the difference signal being zero—the “coercive field” for the XRMS. The changes in the sum data are less than 2% for all values of Q_x , indicating that the magnetic part of the signal is no larger than this.) The wave form given by the sum data has the $n=0$ and then the $n=\pm 2$ fringes as the most intense contributions. Meanwhile in the difference data, the $n=0$ peak is comparatively weak while the $n=\pm 1$ fringes are by far the strongest. This is made especially clear when the ratio $(I_+ - I_-)/(I_+ + I_-)$ is taken, plotted in Fig. 2(c). This representation of the data emphasizes those Fourier terms where there are large differences in the two correlation functions. The ratio of intensities at every fringe is almost the same except at $n=\pm 1$, corresponding to the fundamental spatial frequency of the grating. Although we cannot reconstruct the wave forms as we lack the necessary phase information, it is obvious that they will have rather different forms in real space.

It is difficult to make quantitative measurements from SEM images, and so real space information about the sample has been gleaned from atomic force and magnetic force microscopy (AFM and MFM). Representative images acquired by the two techniques are shown in panels (a) and (b) of Fig. 3, along with the calculated autocorrelation functions (ACFs) of these images. In the MFM images the signal is weak but nonzero, indicating that there are free magnetic poles on the sample surface. The nature of our instrument means that the MFM image is taken at remanence and so most of the poles within the sample will cancel when antiferromagnetic ordering takes place. Sections in x through the ACFs are shown in Fig. 3(c). Scattering measures the Fourier transform of the ACF, and so we have subjected our ACFs to a fast Fourier transform (FFT). Line sections through the results of doing so are shown in panel (d) of Fig. 3, for $Q_y=0$. Again, a series of peaks can be seen corresponding to the Fourier terms describing the overall wave form, and again magnetism differs from structure. The high order Fourier components present in the structural FFT are strongly suppressed in the magnetic one, meaning that the magnetic wave form will have much less fine detail.

XRMS measures structure-magnetism cross correlations within the sample, in particular local variations in the magnetization direction. Meanwhile MFM measures force gradients due to stray fields outside the sample. These can arise between the plateaus on top of the lines, as well as from the vertical projection of the layers on the sidewalls. Although the two methods probe different aspects of the same magnetic structure, qualitative agreement about the main features is reached.

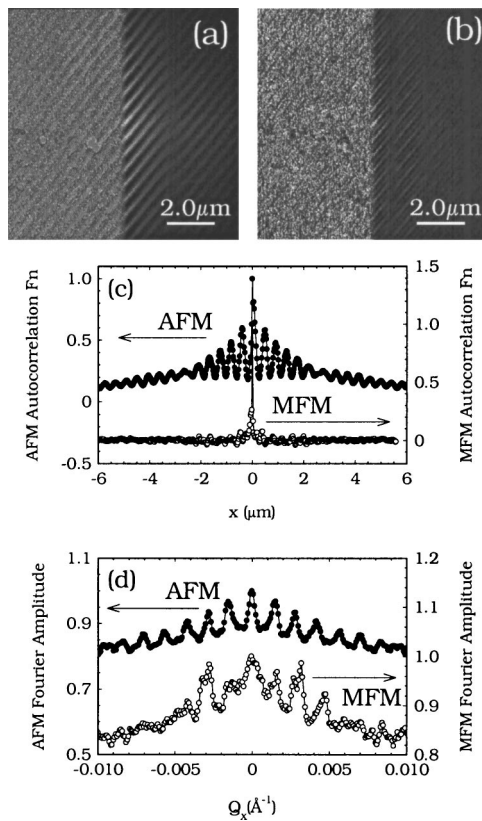


FIG. 3. Images of the sample taken by (a) AFM and (b) MFM. The left hand portion of each panel shows the image data, while on the right the ACF is shown. Sections through the ACFs (c) and their FFTs (d) along the direction perpendicular to the lines of the grating.

In conclusion, we have investigated the in-plane wave forms of a magnetic multilayer grating for charge-charge and charge-magnetism cross correlations through soft XRMS. Fourier analysis of information obtained in reciprocal space and real space shows that the the magnetic wave form across the grating differs markedly from the physical grating shape.

In both cases there is evidence that the magnetism only tracks the gross features of the structure and does not reproduce the fine detail. This may be of concern for technologies such as patterned magnetic media.

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- ¹E. Y. Tsymlal and D. G. Pettifor, *Solid State Phys.* **56**, 113 (2001).
- ²P. Bruno, *J. Magn. Magn. Mater.* **121**, 248 (1993).
- ³L. Berger, *J. Appl. Phys.* **91**, 6795 (2002).
- ⁴S. K. Sinha, E. B. Sirota, S. Garoff, and H. B. Stanley, *Phys. Rev. B* **38**, 2297 (1988).
- ⁵H. Zabel and K. Theis-Bröhl, *J. Phys.: Condens. Matter* **15**, S505 (2003).
- ⁶J. P. Hannon, G. T. Trammell, M. Blume, and D. Gibbs, *Phys. Rev. Lett.* **61**, 1245 (1988).
- ⁷G. H. Lander, *J. Magn. Magn. Mater.* **242**, 3 (2002).
- ⁸D. R. Lee, S. K. Sinha, C. S. Nelson, J. C. Lang, C. T. Venkataraman, G. Srajer, and R. M. Osgood III, *Phys. Rev. B* **68**, 224410 (2003).
- ⁹S. Langridge, J. Schmalian, C. H. Marrows, D. T. Dekadjevi, and B. J. Hickey, *Phys. Rev. Lett.* **85**, 4964 (2000).
- ¹⁰J. I. Martin, J. Nogués, K. Liu, J. L. Vicent, and I. K. Schuller, *J. Magn. Magn. Mater.* **256**, 449 (2003).
- ¹¹K. Temst, M. J. van Bael, and H. Fritzsche, *Appl. Phys. Lett.* **79**, 991 (2001).
- ¹²K. Theis-Bröhl, T. Schmitte, V. Leiner, H. Zabel, K. Rott, H. Bruckl, and J. McCord, *Phys. Rev. B* **67**, 184415 (2003).
- ¹³H.-L. Zhang, D. Bucknall, and A. Dupuis, *Nano Lett.* **4**, 1513 (2004).
- ¹⁴J. F. MacKay, C. Teichert, D. E. Savage, and M. G. Lagally, *Phys. Rev. Lett.* **77**, 3925 (1996).
- ¹⁵J. W. Freeland, K. Bussmann, P. Lubitz, Y. U. Idzerda, and C.-C. Kao, *Appl. Phys. Lett.* **73**, 2206 (1998).
- ¹⁶R. M. Osgood III, S. K. Sinha, J. W. Freeland, Y. U. Idzerda, and S. D. Bader, *J. Appl. Phys.* **85**, 4619 (1999).
- ¹⁷R. M. Osgood III, S. K. Sinha, J. W. Freeland, Y. U. Idzerda, and S. D. Bader, *J. Magn. Magn. Mater.* **199**, 698 (1999).
- ¹⁸C. S. Nelson, G. Srajer, J. C. Lang, C. T. Venkataraman, S. K. Sinha, H. Hashizume, N. Ishimatsu, and N. Hosoito, *Phys. Rev. B* **60**, 12234 (1999).