ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2010, Vol. 74, No. 10, pp. 1471–1473. © Allerton Press, Inc., 2010.
Original Russian Text © E.A. Kravtsov, D. Haskel, S.G.E. te Velthuis, J.S. Jiang, B.J. Kirby, 2010, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2010, Vol. 74, No. 10, pp. 1531–1533.

Application of Polarized Neutron Reflectometry and X-Ray Resonant Magnetic Reflectometry for Determining the Inhomogeneous Magnetic Structure in Fe/Gd Multilayers

E. A. Kravtsov[a, b], D. Haskel[c], S. G. E. te Velthuis[d], J. S. Jiang[d], and B. J. Kirby[e]
[a] Institute of Metal Physics, Ural Division, Russian Academy of Sciences, Yekaterinburg, 620041 Russia
[b] Ural State Technical University, Yekaterinburg, 620002 Russia
[c] Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA
[d] Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA
[e] NIST Center for Neutron Research, Gaithersburg, MD 20899, USA
e-mail: kravtsov@imp.uran.ru

Abstract—The evolution of the magnetic structure of multilayer [Fe (35 Å)/Gd (50 Å)$_5$] with variation in temperature and an applied magnetic field was determined using a complementary approach combining polarized neutron and X-ray resonant magnetic reflectometry. Self-consistent simultaneous analysis of X-ray and neutron spectra allowed us to determine the elemental and depth profiles in the multilayer structure with unprecedented accuracy, including the identification of an inhomogeneous intralayer magnetic structure with near-atomic resolution.

DOI: 10.3103/S106287381010045X

INTRODUCTION

Fe/Gd multilayers are a widely used ferrimagnetic model system utilizing complex magnetic configurations that depend on the temperature and an applied magnetic field [1]. The specific features of the magnetic behavior of Fe/Gd are due to competition between strong antiferromagnetic Fe–Gd interlayer coupling and intralayer exchange interaction, which is relatively weak in the Gd layers but strong in the Fe layers. The strong temperature dependence of the Gd magnetic moment (T_C = 293 K) and the relatively weak temperature dependence of the Fe magnetic moment (T_C = 1043 K) lead to the formation of a complex magnetic phase diagram with a change in the temperature and magnetic field [2–4]. The early approaches to studying magnetism in Fe/Gd systems were based on describing the magnetic structure in terms of magnetic moments averaged over individual layers [5, 6]. Recent theoretical calculations [7], however, have shown that we must also take into account the possible nonuniform distribution of magnetic moments (both in magnitude and direction) within an individual layer.

To understand and use in practice the physical mechanisms determining the properties of magnetic Fe/Gd heterostructures, it is necessary to measure precisely (at the subnanometer level) the nonuniform magnetization distributions that are typical of such structures. The most powerful experimental techniques for determining the thickness dependences of magnetic moments in nanoheterostructures are currently polarized neutron reflectometry (PNR) and X-ray resonant magnetic reflectometry (XRMR). Both of these techniques have been well tested and are successfully used to measure the depth profiles of magnetic moments in magnetic heterostructures [8].

The basic advantage of PNR is the possibility of directly determining the atomic magnetic moments and obtaining information on the magnetization vector in the layer plane in absolute units. At the same time, the technique is insensitive to elemental composition and, due to the weak neutron fluxes in modern research neutron reactors, has limited spatial resolution.

When used in the hard X-ray mode, XRMR is based on resonant enhancement of X-ray magnetic scattering observed near the *K* edges of transition metals and the *L* edges of rare earth elements. XRMR ensures both high sensitivity to the elemental composition and high spatial resolution, since synchrotron radiation sources of the third generation produce high photon fluxes. Use of circularly-polarized X rays nevertheless allows us to determine only one magnetization component that lies in the film plane and in the scattering plane. In addition, resonant measurements in some cases cannot be performed for all elements in the heterostructure, and complete information about the system thus cannot be obtained.

Another drawback of both PNR and XRMR is the absence of phase information in the measured scattering intensity. For complex magnetic systems characterized by large- and small-scale changes in magnetic

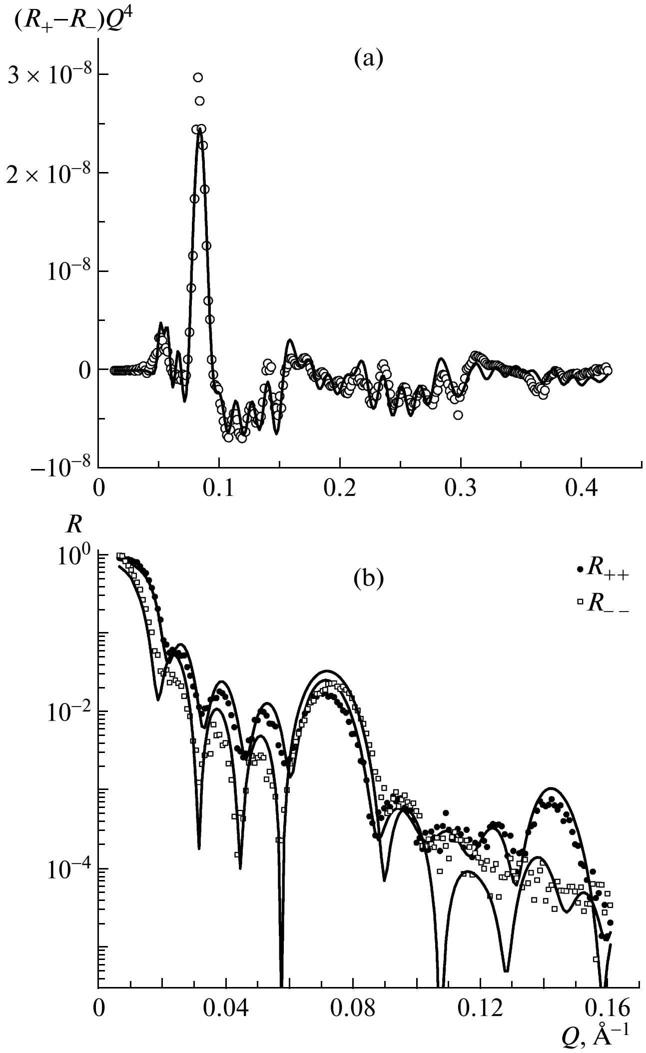

Fig. 1. Experimental (a) X-ray and (b) neutron reflectometry spectra, measured at temperature $T = 20$ K in magnetic field $B = 0.5$ T (symbols) and the results of their self-consistent analysis (lines).

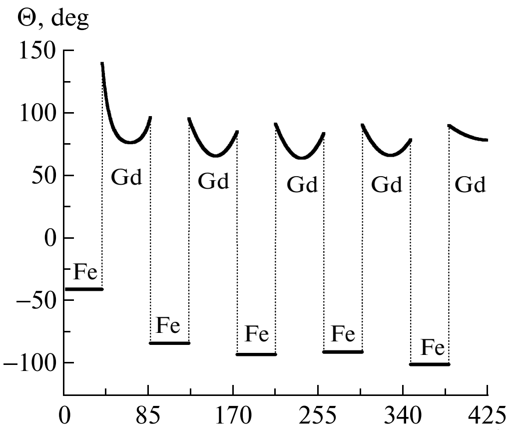

Fig. 2. Depth distribution of magnetic moment orientation Θ with respect to the applied magnetic field in the multilayer structure, determined by self-consistent analysis of the neutron and X-ray spectra.

moments, we cannot find a unique solution for profile magnetization using only one of these experimental techniques. Complementary use of PNR and XRMR to determine complex magnetization profiles allows us to overcome the drawbacks of these methods and to enjoy their advantages. Simultaneous self-consistent processing (fitting) of neutron and X-ray spectra allows us to choose a reliable model to describe the elemental magnetization profiles in magnetic heterostructures.

EXPERRIMENTAL

[Fe(35 Å)/Gd(50 Å)$_5$] heterostructures were grown by magnetron sputtering on a Si(111) substrate with an Al buffer (100 Å) and a protective layer (50 Å). Our magnetometric measurements showed that at temperatures above 80 K, the ordering of Fe magnetic moments along the magnetic field and the Gd magnetic moments against the field (as predicted by the theory in [2–4]) is observed in the system [9]. At the same time, the low-temperature ($T = 20$ K) magnetic behavior cannot be described within the approach in [2–4], most likely due to the nonuniform distribution of magnetic moments in the Gd layers.

The X-ray measurements were performed on the 4-ID-D Magnetic Scattering Beamline (Advanced Photon Source, Argonne National Laboratory, United States). The XRMR spectra were measured at the Gd L_2 absorption edge with photon energy $E = 7929$ eV. An XRMR signal was recorded as the difference between the intensities of the reflected signals for two opposite circular polarizations (R_+–R_-). The PNR measurements were performed on the NG1 reflectometer (NIST Center for Neutron Research, United States) in the standard Θ–2Θ geometry at a constant neutron wavelength of 4.75 Å, with complete polarization analysis of the reflected neutron beam. The data were analyzed by simultaneous self-consistent fitting of the X-ray and neutron experimental spectra. The calculation scheme was based on a unified parameterized model for describing the elemental and depth profiles of the magnetization vector lying in the multilayer plane [9].

Figure 1 shows the X-ray and neutron reflectometry spectra measured at a temperature of 20 K in a magnetic field of 0.5 T, and the results from the simultaneous self-consistent analysis of the experimental spectra within the unified structural model [9]. The depth profile of angle Θ between the directions of the magnetization vector and the applied external magnetic field, determined within the abovementioned self-consistent analysis, is shown in Fig. 2. This analysis made it possible to determine the elemental and depth profiles of intralayer magnetization in the multilayer structure with a resolution of few monolayers (i.e., with near-atomic resolution). As follows from the above results, the magnetization distribution in the multilayer becomes appreciably nonuniform in strong magnetic fields; note that the magnetic moments of the Fe layers and the central part of Gd layers were oriented in the field direction, whereas the Gd moments in the interface regions were oriented opposite to it.

CONCLUSIONS

We have thus developed an approach that combines polarized neutron reflectometry and X-ray resonant magnetic reflectometry and have successfully used it to study magnetically inhomogeneous systems. The approach calls for complementary PNR and XRMR measurements and simultaneous analysis of the X-ray and neutron spectra using a unified parameterized model. The combined approach is quite promising, since the aforementioned data cannot be obtained using only one of the two experimental techniques.

ACKNOWLEDGMENTS

This study was supported in part by the Russian Foundation for Basic Research, project no. 10-02-96033-r_ural_a); the Program of the Presidium of the Russian Academy of Sciences (grant. no. 09-R-2-1037); and grant NSh-3545.2010.02 for the Support of Leading Scientific Schools. The study at the Argonne National Laboratory was supported by the US Department of Energy, the US Office of Science, and the US Office of Basic Energy Sciences, contract no. DE-AC02-06CH11357.

REFERENCES

1. Mills, D.L. and Bland, J.A.C., *Nanomagnetism: Ultrathin Films, Multilayers and Nanostructures*, New York: Elsevier, 2006.
2. Camley, R.E. and Tilley, D.R., *Phys. Rev. B*, 1988, vol. 37, p. 3413.
3. Camley, R.E., *Phys. Rev. B, 1*989, vol. 39, p. 12316.
4. LePage, J.G. and Camley, R.E., *Phys. Rev. Lett.,* 1990, vol. 65, p. 1152.
5. Hahn, W., Loewenhaupt, M., Huang, Y.Y., et al., *Phys. Rev. B*, 1995, vol. 52, p. 16041.
6. Ishimatsu, N., Hashizume, H., Hamada, S., et al., *Phys. Rev. B*, 1999, vol. 60, p. 9596.
7. Van Aken, B.B., Prieto, J.L., and Mathur, N.D., *J. Appl. Phys.*, 2005, vol. 97, p. 63904.
8. Zhu, Y., *Modern Techniques for Characterizing Magnetic Materials*, Boston: Kluwer Acad. Publ., 2005.
9. Kravtsov, E., Haskel, D., te Velthuis, S.G.E., et al., *Phys. Rev. B,* 2009, vol. 79, p. 134438.