ELSEVIER
Journal of Magnetism and Magnetic Materials 203 (1999) 181–183
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Morphology of crystallites and magnetic structure of non-collinear Fe/Cr multilayers

T.P. Krinitsina[a], E.A. Kravtsov[a], V.V. Lauter-Passiouk[b], H.J. Lauter[c], V.V. Popov[a], L.N. Romashev[a], V.A. Tsurin[a], A.M. Burkhanov[a], V.V. Ustinov[a,*]

[a]*Institute of Metal Physics, Ural Division of the Russian Academy of Sciences, 18 S. Kovalevskaya Str., GSP-170, 62019 Ekaterinburg, Russia*
[b]*University of Konstanz, Konstanz, Germany*
[c]*Institute Laue-Langevin, Grenoble, France*

Abstract

Atomic and magnetic structures of Fe/Cr superlattices have been studied by means of polarized neutron reflectometry, X-ray diffraction, electron microscopy and Mössbauer spectroscopy. Peculiarities of structure responsible for the formation of non-collinear magnetic order have been found.

Keywords: Giant magnetoresistance; Microstructure; Metallic multilayers; Superlattices; Polarized neutron reflectometry; X-ray diffraction; Electron microscopy

Recently, we have reported the peculiarity of giant magnetoresistance of Fe/Cr superlattices in the external magnetic field applied perpendicular to the layers plane [1]. The magnetoresistance–magnetic field curve has been shown to display a plateau-like part at which the magnetoresistance changes insignificantly. The peculiarity was attributed to the non-collinear magnetic ordering of Fe layers and described within biquadratic exchange model. The present work aims to determine what peculiarities of Fe–Cr interfaces could give rise to the strong biquadratic exchange coupling.

Investigations were carried out on $[^{57}Fe/Cr]_n$ superlattices with various Cr- and Fe-layer thickness and number of bilayers, MBE-grown on (0 0 1)MgO and (1 1 0)Al_2O_3 substrates covered with Cr buffer layer.

The magnetic ordering in our structures was traced with polarized neutron reflectivity studies made in the Institute Laue-Langevin. The reflectivity profiles R_+ and R_- were measured for momentum transfer Q in the range 0.01–0.2 A^{-1}, with incident neutron beam being polarized parallel and antiparallel to an external magnetic field applied in the layer plane. In Fig. 1 typical experimental (points) and corresponding fitted (lines) reflectivity curves are shown. An essential feature of the experimental curves is a disparity between R_+ and R_-, with the specific 'antiferromagnetic' peak appearing in each curve. This feature implies non-collinear ordering in the structure.

The quantitative interpretation was done within the dynamical approach based on solving spinor Schrödinger equation. An interface roughness was accounted for with a large number of thin slices having gradually varying scattering length. Fitting over the above curves confirmed existence of the non-collinearity in the sample with the canted angle of about 15°.

The superlattice period and interface structure were determined by low-angle X-ray diffraction. A low-angle X-ray diffraction profile typical of the investigated superlattices is shown in Fig. 2. Superlattice peaks up to the sixth order are clearly visible in this diffraction profile indicating a relatively small interface roughness. The results of low-angle X-ray diffraction were treated with the SUPREX program [2]. It was found that roughness in all the investigated specimens is less than 4 Å, and there was no significant drift of the layer thicknesses during growth. Besides, it was shown that there was

* Corresponding author. Fax: + 7-343-2-74-52-44.
E-mail address: ustinov@imp.uran.ru (V.V. Ustinov)

PII: S0304-8853(99)00221-8

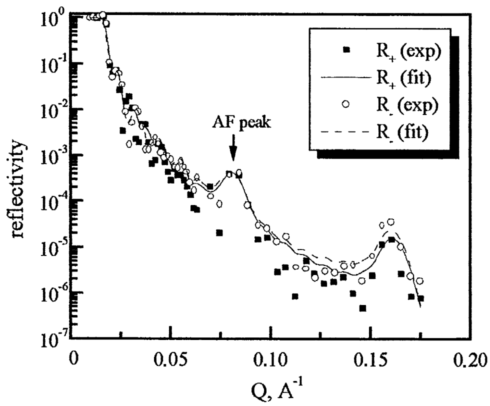

Fig. 1. Measured and fitted neutron reflectivity profiles for Al_2O_3/Cr(70 Å)/[Fe(26 Å)/Cr(15 Å)]$_{16}$ sample.

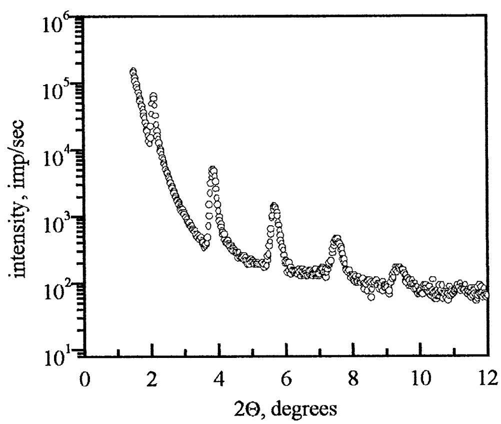

Fig. 2. Low-angle X-ray diffraction profile for MgO/Cr(54 Å)/[Fe(47 Å)Cr(9 Å)]$_{16}$ sample.

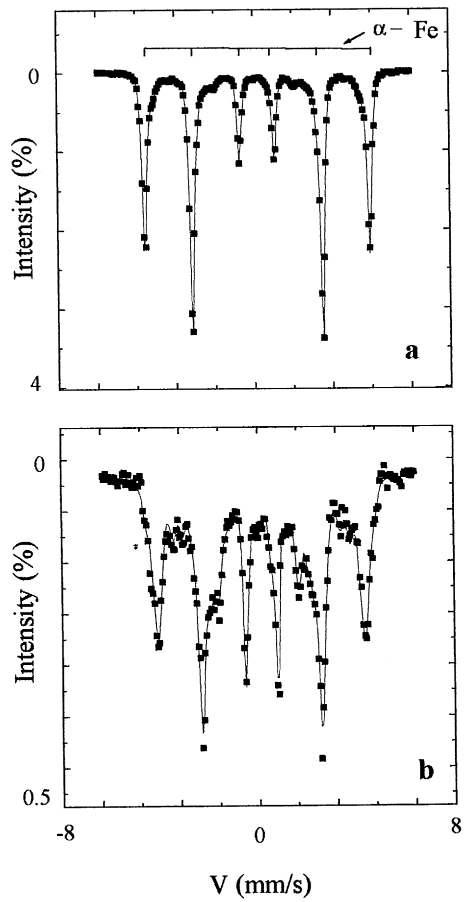

Fig. 3. Absorption Mössbauer spectrum for MgO/Cr(54 Å)/[Fe(47 Å)Cr(9 Å)]$_{16}$ sample (a) and contribution to the spectrum from the interface regions (b).

a transition region between Cr and Fe, which testified proceeding of interlayer diffusion during MBE.

The methods of electron microscopy and X-ray analysis were used for structural attestation of specimens. It was found that the investigated multilayers consist of fine crystallites equiaxed in layer planes, their internal volumes being practically free from dislocations. In the direction perpendicular to layer planes the crystallites have a form of columns or prisms, the height of which can reach the overall thickness of a film. These crystallites are partially coherently connected with the substrate, their (1 0 0) plane being parallel to the substrate plane. Lateral sizes of the crystallites are 10–20 nm, and the increase of the film thickness results in somewhat larger crystallite sizes. Apparently the latter may be explained with the crystallite growth during MBE not only in height but in lateral directions as well. Electron diffraction patterns of multilayers are single crystal 'pointwise' with slight azimuth blurring of reflections. Such a form of diffraction patterns suggests that the majority of crystallites are oriented similarly, that is, the superlattice is nearly single crystal. The slight azimuth blurring of reflections indicates a low-angle turn of crystallites relatively to each other in the specimen plane within 2–3°. There are weak rings in some electron diffraction patterns, suggesting the presence of few crystallites with the orientation substantially differing from that of the majority.

Since superlattice represents a pseudo single crystal consisting of nano-dimension crystallites of column orientation, it may be suggested that the interlayer boundaries possess a terrace structure, these terraces being of the same scale as the lateral size of the crystallites (10–20 nm). According to Slonczewski's theory [3], this might be one of the reasons for non-collinear magnetic ordering in Fe/Cr superlattices.

Atomic and magnetic structure of interface regions was investigated with absorption Mössbauer spectroscopy (AMS) using ^{57}Co source in Cr matrix. In superlattice Mössbauer spectrum (Fig. 3a) there are lines from 'bulk' α-Fe (their positions are indicated at the top of Fig. 3a) as well as additional lines resulting from fluctuation of superfine fields on ^{57}Fe nuclei localized in the interface regions. Fig. 3b demonstrates contribution from interface regions to the superlattice spectrum. This contribution is the difference between the spectrum in Fig. 3a and that corresponding to bulk α-Fe. Thus, Mössbauer investigations show that there is a transition layer between Cr and Fe layers in agreement with the data of low-angle X-ray spectra treatment. According to AMS, the thickness of the transition layers is independent of that of Fe layers and runs about 7–8 Å. Spectra parameters also suggest that the interlayer regions are ferromagnetic, their magnetic moment being directed at some angle relative to Fe layers plane.

The present investigations of the atomic and magnetic structure of Fe/Cr superlattices revealed two possible reasons for non-collinear magnetic moment ordering of Fe layers. The first one is the formation of a pseudo single crystal structure of superlattices consisting of nano-dimension crystallites with column orientation. This results in the terrace structure of boundaries with the same scale of the terraces as the lateral size of the crystallites (10–20 nm). The second reason is the existence of interface regions with a specific magnetic structure in which magnetic moments emerge from the layer plane at an angle from 0 to 90°.

This work was supported by grants of INTAS (No. 0531), RFBR (No. 98-02-17517), and MST of RF (No. 97-1080).

References

[1] V.V. Ustinov, N.G. Bebenin, L.N. Romashev, V.I. Minin, M.A. Milyaev, A.R. Del, A.V. Semerikov, Phys. Rev. B 54 (1996) 15958.

[2] E.E. Fullerton, I.K. Schuller, H. Vanderstaeten, Y. Bruynseraede, Phys. Rev. B 45 (1992) 9292.

[3] J.C. Slonczewski, J. Magn. Magn. Mater. 150 (1995) 13.