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In-plane magnetisation anisotropy of FeCr superlattices with biquadratic exchange coupling

V.V. Ustinov*, M.A. Milyaev, L.N. Romashev, T.P. Krinitsina, E.A. Kravtsov

Institute of Metal Physics, Ural Division of the Russian Academy of Sciences, 18 Sofia Kovalevsky St., Ekaterinburg, 620219, Russia

Abstract

Magnetisation anisotropy in non-collinear ordered (0 0 1)FeCr multilayers has been studied. It was found that the interplay between strong biquadratic exchange coupling and fourfold anisotropy causes change in magnetisation 'easy' and 'hard' axes during the magnetisation process. A simple phenomenological approach for extracting anisotropy and exchange parameters from magnetisation curves has been suggested.

Keywords: Multilayers; Anisotropy—magnetisation process; Exchange coupling—non-collinear

In the last few years magnetic properties of exchange-coupled FeCr magnetic multilayers has been studied intensively and an extensive literature has evolved which traces magnetisation peculiarities associated with bilinear and biquadratic coupling in these structures [1,2]. The magnetic behaviour of FeCr multilayers is determined by the interplay between exchange coupling, fourfold in-plane magnetocrystalline anisotropy and external magnetic field. In early works on biquadratic coupling, where the anisotropy contribution has also been considered [3,4], the biquadratic coupling was taken to be weak enough compared with the bilinear one. Recent theoretical studies [5,6] have attracted attention to the systems where strong bilinear and biquadratic coupling coexist with strong magnetic anisotropy. It has been pointed out that a rich variety of new magnetic phases has to be expected in these systems. In the present work we study the effect of fourfold in-plane anisotropy on magnetic behaviour of (0 0 1)FeCr multilayers displaying strong biquadratic coupling.

The multilayers $[\mathrm{Cr}(t)/\mathrm{Fe}(70\,\mathring{A})]_{12}$ ($t = 9$, 14 and 18 Å) and also Fe(800 Å) film were MBE grown on (1 0 1)$\mathrm{Al_2O_3}$ substrates covered with 70 Å Cr buffer layer. The samples were characterised in situ with reflection high energy electron diffraction (RHEED) and ex situ with X-ray Diffraction and Transmission Electron Microscopy. The magnetisation measurements were made with SQUID and vibrating sample (VSM) magnetometers with magnetic field H applied in the layer plane. To estimate bilinear J_1 and biquadratic J_2 exchange parameters as well as anisotropy parameter K, we used the magnetisation curves measured along [1 0 0] and [1 1 0] directions. The magnetisation anisotropy was investigated with VSM measurements. At selected magnetic fields, we performed a complete in-plane sample rotation measuring the magnetisation value for every 7.5° of sample turning.

The 18 Å Cr superlattice was found to have pure ferromagnetic ordering with the magnetic behaviour identical with that of the iron film. The anisotropy field $2K/M_s$ is about 500 Oe that is close to the bulk value. Other samples of the series display Antiferromagnetic and non-collinear ordering. Fig. 1 shows magnetisation curves for the sample with 14 Å Cr layers measured along easy and hard magnetic axes. One can see that there is the cross-over of the magnetisation curves measured along different direction. This implies that in zero magnetic field the net multilayer magnetic moment lies along the easy [1 0 0] axis. Here we suggest a simple way for extracting anisotropy and exchange parameters from magnetisation curves measured along easy and hard magnetisation axes.

Consider a multilayer composed of alternating Fe and Cr layers, with every Fe layer having magnetic moment

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*Corresponding author. Tel.: + 7-3432-444471; fax: + 7-3432-745244.

E-mail address: ustinov@imp.uran.ru (V.V. Ustinov).

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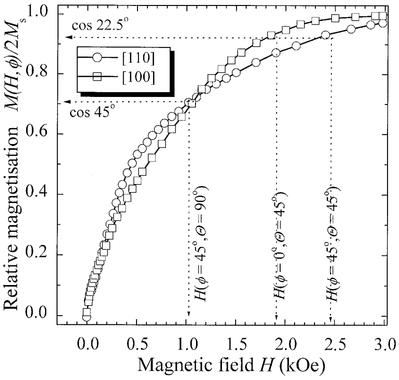

Fig. 1. Magnetisation curves for the sample $[\mathrm{Cr}(14\,\text{Å})\mathrm{Fe}(70\,\text{Å})]_{12}$ measured along easy and hard axes. The arrows indicate the magnetic field values used for estimating exchange and anisotropy parameters.

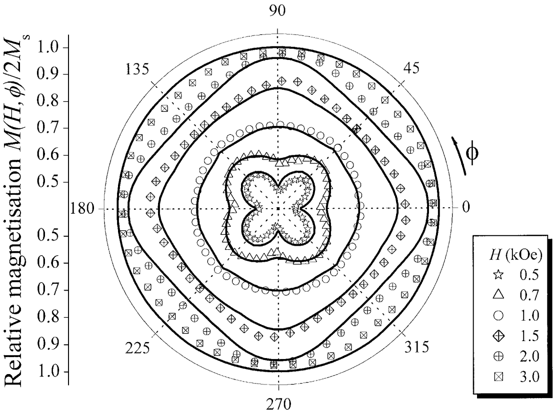

Fig. 2. Magnetisation anisotropy of the $[\mathrm{Cr}(14\,\text{Å})\mathrm{Fe}(70\,\text{Å})]_{12}$ multilayer measured using rotation of the magnetic field in the layers plane. In figure are shown the measured (points) and calculated (lines) angle dependencies of magnetisation.

M_s and thickness d. Let the magnetic moments of two neighbouring Fe layers be directed at angles Θ_1 and Θ_2, and the external magnetic field H lies in the layers plane at angle ϕ relative to [1 0 0] direction. By minimizing the multilayer free energy expression [2,5,6] we obtain the following couple of equations for the angles $\psi = (\Theta_1 + \Theta_2)/2$ and $\Theta = \Theta_1 - \Theta_2$:

$$J_1 \sin\Theta + J_2 \sin 2\Theta + \tfrac{1}{4} Kd \sin 2\Theta \cos 4\psi + \tfrac{1}{2} HM_S d \sin\tfrac{\Theta}{2} \cos(\psi - \phi) = 0, \qquad (1)$$

$$K \cos 2\Theta \sin 4\psi + 2HM_S \cos\tfrac{\Theta}{2} \sin(\psi - \phi) = 0. \qquad (2)$$

Eqs. (1) and (2) together with the magnetisation definition $M(H,\phi) = 2M_s \cos\Theta/2 \cos(\psi - \phi)$ describe the magnetic behaviour of the system. It is rather difficult to solve systems (1)–(2) in the general case but some important solutions can be readily calculated. In particular, for $\Theta = 135°$ or $45°$, one finds that the net magnetic moment lies along the applied magnetic field ($\psi - \phi, M = 2M_s\cos\Theta/2$) and

$$H(\phi,\Theta) = -2\cos\Theta/2 \times \{2J_1 + [4J_2 + Kd\cos 4\phi]\cos\Theta\}/M_s d. \qquad (3)$$

On the other hand, when magnetizing along the [1 1 0] [1 1 0] direction, provided $32J_1/Kd + 1 < 0$, for $\Theta = 90°$, we find that $\psi = \phi$ again and

$$H(\phi = 0°, \Theta = 90°) = H(\phi = 45°, \Theta = 90°) = -2^{3/2} J_1/M_s d. \qquad (4)$$

With formulae (3) and (4), it is easy to find the anisotropy and exchange parameters from the magnetisation curves. As indicated in Fig. 1, for our sample we have $H(\phi = 45°, \Theta = 90°) = 1.02\,\mathrm{kOe}$, $H(\phi = 0°, \Theta = 45°) = 1.82\,\mathrm{kOe}$ and $H(\phi = 45°, \Theta = 45°) = 2.35\,\mathrm{kOe}$. By using Eqs. (3) and (4), we find the following estimates for multilayer parameters: $J_1/M_s d = -0.360\,\mathrm{kOe}$, $J_2/M_s d = -0.145\,\mathrm{kOe}$, $2\mathrm{K}/\mathrm{M}_s = 0.406\,\mathrm{kOe}$. According to Ref. [6], for these values of parameters the angle Θ in zero magnetic field should be 180° and the angle $\psi = 0°$. So for this sample in zero field the net magnetic moment lies along the easy direction [1 0 0]. For another sample with Cr thickness 9 Å, we found non-collinear magnetic ordering with zero-field net magnetisation along the hard [1 1 0] direction.

An interesting feature of non-collinearly ordered multilayers is the 45° change in the magnetisation anisotropy during magnetisation process. We have measured the magnetisation anisotropy at different magnetic field values rotating the magnetic field in the layer plane. Fig. 2 shows measured and calculated magnetisation curves $\mathrm{M}(H,\phi)$ for some fixed magnetic field values. In calculations, we used Eqs. (1) and (2) with the above-defined parameters. From Fig. 2, one can see that at small magnetic fields the magnetisation has its maximum for the field along the [1 1 0] direction and for larger fields the magnetisation maximum changes to [1 0 0] direction. The first case corresponds to the angle $\Theta > 90°$ and the second one is valid for Θ less that 90°.

Thus, the observed peculiarities of the field and angle dependences of magnetization in FeCr multilayers can be described in full detail through the interplay between strong biquadratic coupling and fourfold magnetic anisotropy.

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References

[1] D.T. Pierce, J. Unguris, R.J. Celotta, M.D. Stiles, J. Magn. Magn. Mater. 200 (1999) 290.
[2] S.O. Demokritov, J. Phys. D: Appl. Phys. 31 (1998) 925.
[3] M. Ruhrig, R. Schafer, A. Hubert, R. Mosler, J.A. Wolf, S. Demokritov, P. Grunberg, Phys. Stat. Sol. A 125 (1991) 635.
[4] U. Kobler, K. Wagner, R. Wiechers, A. Fuss, W. Zinn, J. Magn. Magn. Mater. 103 (1992) 236.
[5] T.L. Fonseca, N.S. Almeida, Phys. Rev. B 57 (1998) 76.
[6] V.V. Kostyuchenko, A.K. Zvezdin, Phys. Rev. B 57 (1998) 5951.