Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 300 (2006) e281–e283
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Multiple spin–flip transitions and stairs-like GMR in Fe/Cr superlattices with uniaxial in-plane anisotropy

V.V. Ustinov[a,*], M.A. Milayev[a], L.N. Romashev[a], T.P. Krinitsina[a], A.M. Burkhanov[a], V.V. Lauter-Pasyuk[b], H.J. Lauter[b]

[a]*Institute of Metal Physics, Ural Division of RAS, 620041, S. Kovalevskaya St. 18, Ekaterinburg, Russia*
[b]*Institute Laue Langevin BP 56, F-38042 Grenoble Cedex 9, France*

Available online 16 November 2005

Abstract

The $[Fe/Cr]_N$ superlattices with the uniaxial in-plane anisotropy and the stairs-like dependences of magnetization and magnetoresistance on a magnetic field were MBE-grown on special (2 1 1)MgO substrates. It is shown that the "steps" on the $M(H)$ and $\Delta R/R(H)$ dependences are results of the multiple spin–flip transitions, i.e. 180°-reorientation of magnetic moments of ferromagnetic sublayers in the superlattices. The transitions are found to be very sensitive to small variations of the Cr layers thickness.
© 2005 Elsevier B.V. All rights reserved.

PACS: 75.30.Kz; 75.70.−i; 75.75.+a

Keywords: Multiple spin–flip transitions; Giant magnetoresistance; Stairs-like magnetization curve; In-plane anisotropy; Fe/Cr multilayers

It was recently revealed that the magnetic state of Co–Pt–Ru and Fe–Au multilayers with the uniaxial out-of-plane anisotropy exists as a number of magnetic states with the ferromagnetic (FM) and antiferromagnetic (AFM) alignment of magnetic moments of adjacent FM layers [1–5]. The transition from the one magnetic state to another goes as a spin–flip (or metamagnetic) phase transition, i.e. 180°-reorientation of the magnetic moment of a FM layer inside magnetic domain. As a result of the transitions, the step-like anomalies arise on the magnetization curves. The theoretical explanation of the magnetization processes in the Co–Pt–Ru multilayers was given in Ref. [6] where the phase diagram for the finite-size multilayers with the strong uniaxial out-of-plane anisotropy was analyzed. In particular, it is pointed out in Ref. [6] that the unusual reorientation and multidomain effects found in Ref. [2] are unknown both in bulk magnets and in easy-plane AFM superlattices. However, magnetoresistance data were not reported in Refs. [1–5]. Perhaps, it is due to the fact that a sample used in the resistivity measurements should be rather large and therefore it contains a great number of the magnetic domains. The total resistivity of a macroscopic sample turns out to be weakly sensitive to the spin–flip transition in a small domain. To make the effect of the spin–flip transitions on resistivity observable, it is desirable to use a single domain sample.

The purpose of this study is to show the possibility of realization of the multiple spin–flip transitions in "classical" Fe/Cr superlattices with the uniaxial in-plane anisotropy. In contrast to the Co–Pt–Ru and Fe–Au multilayers having the complicate periodicity of atomic layers in the multilayer stack, our Fe/Cr superlattices are much simpler in preparation because of rather thick Fe and Cr layers. Also the Fe/Cr superlattices have the in-plane magnetic anisotropy and the single domain state in macroscopic samples. Therefore the spin–flip transitions should be accompanied by the step-anomalies in magnetoresistance due to the well known correlation between magnetic and magnetoresistive properties in multilayers with the GMR effect. The synthesis and study of multilayers having multiple switching magnetoresistive properties are important for creation the multiple spin-logic devices [7].

*Corresponding author. Tel.: +7 343 374 02 30; fax: +7 343 374 52 44.
E-mail address: ustinov@imp.uran.ru (V.V. Ustinov).

0304-8853/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2005.10.100

Our investigations of Fe/Cr superlattices grown on the MgO substrates with different crystallographic orientations ((1 0 0)MgO, (1 1 0)MgO and (2 1 1)MgO) have shown that the (2 1 1)MgO/[(2 1 0)Fe/Cr]$_N$ superlattice exhibits the uniaxial in-plane magnetic anisotropy with easy axis directed along [1 0 0]Fe‖ [1 1 0]MgO. It has been revealed that the saturation field H_s in the superlattice grown on (2 1 1)MgO substrate is approximately four times lower in comparison with the H_s for the (1 0 0)MgO/[Fe/Cr]$_N$ superlattice with the same layer thickness. This important experimental fact gives the possibility to shift the magnetization processes to the range of magnetic fields ($H < 500$ Oe) where the uniaxial in-plane anisotropy plays a significant role.

The (2 1 1)MgO/Cr(80 Å)/[Fe(85 Å)/Cr(t, Å)]$_N$ superlattices with the Cr layers thickness in the range of $t_{Cr} = 12 \div 14$ Å and the repetition number $N = 11, 12$ were grown by MBE. The thicknesses of Fe and Cr layers were chosen with the aim to find the case when the uniaxial in-plane anisotropy energy approximately equals to the exchange coupling energy between FM layers.

The structure was investigated using low-angle X-ray scattering and transmission electron microscopy. The magnetization curves were measured by VSM and SQUID at temperatures $T = 2$ K and $T = 300$ K. The standard four-probe technique (PPMS, Quantum Design) was used for resistivity measurements. The samples with sizes 1.5×8 mm and 5×5 mm were used for the resistivity and magnetization measurements, respectively.

Fig. 1 shows the field dependence of the magnetoresistance in the superlattice Fe/Cr with Cr layers thickness $t_{Cr} = 13.6$ Å. One can see, the presence of multiple step-like anomalies on the $\Delta R/R(H)$ dependence in the magnetic fields $H < 500$ Oe. The GMR amplitude in the sample measured at temperatures $T = 2$ K and $T = 300$ K were found to be equal to 18% and 2.4%, respectively. To analyze the stairs-like GMR dependence in connection with a change of magnetic states in the superlattice, the descending branch of the hysteresis loop (a) and the corresponding branch of magnetoresistance (b) are presented in Fig. 2. The magnetization M is expressed in Fig. 2(a) in unites of the magnetic moment M_0 of one Fe layer in the sample. It is obvious that the total magnetization of the superlattice changes discretely. The value of ΔM steps is proportional to M_0. For example, step-anomaly (denoted as 1 in Fig. 2(a)) corresponds to one spin–flip transition which means here the 180°-reorientation of the magnetic moment $\boldsymbol{M}_i$ of ith FM sublayer. The total magnetization of the sample is decreased at this anomaly by the value of $2M_0$ due to the compensation of two equal magnetic moments with the opposite direction.

The normalized magnetoresistance defined as $\Delta R/R(H) = [R(H) - R_s]/\Delta R_0$ is presented in Fig. 2(b). The R_s is the resistance of the sample in the saturation field H_s, and ΔR_0 is the variation of the superlattice resistance due to surface spin–flip transition. The presentation of the magnetoresistance in unites of ΔR_0 gives the possibility to

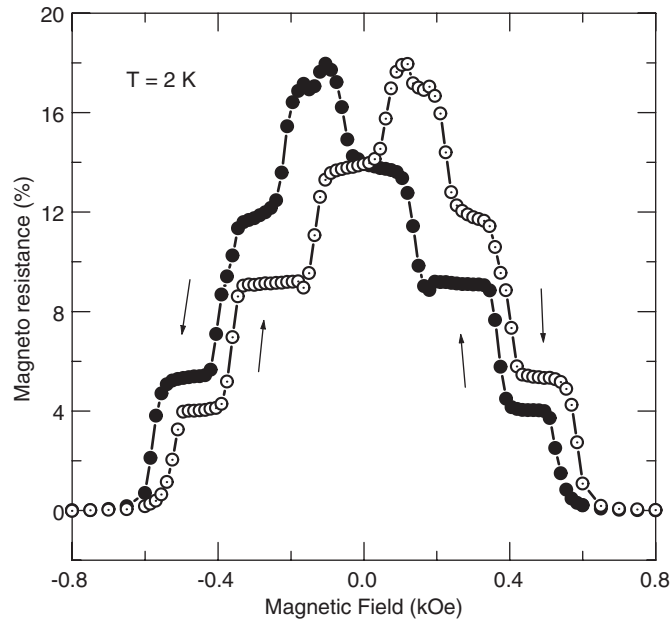

Fig. 1. Magnetoresistance $\Delta R/R(H) = [R(H) - R_s]/R_s$ in the (2 1 1)MgO/Cr(90 Å)/[Fe(85 Å)/Cr(13.6 Å)]$_{12}$ superlattice. Magnetic field was applied along easy axis in the film plane. The R_s is the sample resistance in the saturation field H_s. The open circles correspond to the ascending branch, and close circles—to the descending branch of the GMR hysteresis loop.

experimentally separate the surface spin–flip transition and the transition occurs inside the superlattice: the ΔR_0 value corresponds to a surface spin–flip transition, and the value $2\Delta R_0$ corresponds to a spin–flip transition inside the superlattice.

To explain the different influence of the two type spin–flip transitions on multilayer resistance, necessary to note that the typical electron free path in Fe/Cr multilayers is $\ell \sim 10 \div 100$ Å. The discussed above Fe/Cr multilayer has the superstructure period $\Lambda = t_{Fe} + t_{Cr} \approx 100$ Å. The period is comparable or bigger than electron free path $\Lambda \geqslant \ell$. One can choose the elementary thickness cell including nonmagnetic spacer and two half parts of thickness of nearest FM layers. In this case ($\Lambda \geqslant \ell$) the electron scattering in different cells may be considered as independent and each elementary cell is equivalent to the one spin-valve element. It is clear that the surface spin–flip transition involves the only one spin-valve element, while the transition that occurs inside antiferromagnetically ordered multilayer gives the resistance change which is equivalent of a result of switching process in two spin-valve elements. One can additionally note that the flip of magnetic moment $\boldsymbol{M}_i$ located between two antiparallel $\boldsymbol{M}_{i+1}$ and $\boldsymbol{M}_{i-1}$ moments will not change the multilayer resistance. In this case two spin-valve elements involved into the transition give the equal resistance changes ΔR_0 but with opposite sign: $\Delta R = -\Delta R_0 + \Delta R_0 = 0$.

The comparative analysis of $M(H)$ and $\Delta R/R(H)$ dependences presented in Fig. 2 shows that the $M(H)$ step anomalies marked as 1, 2, 3, and 7 correspond to spin–flip

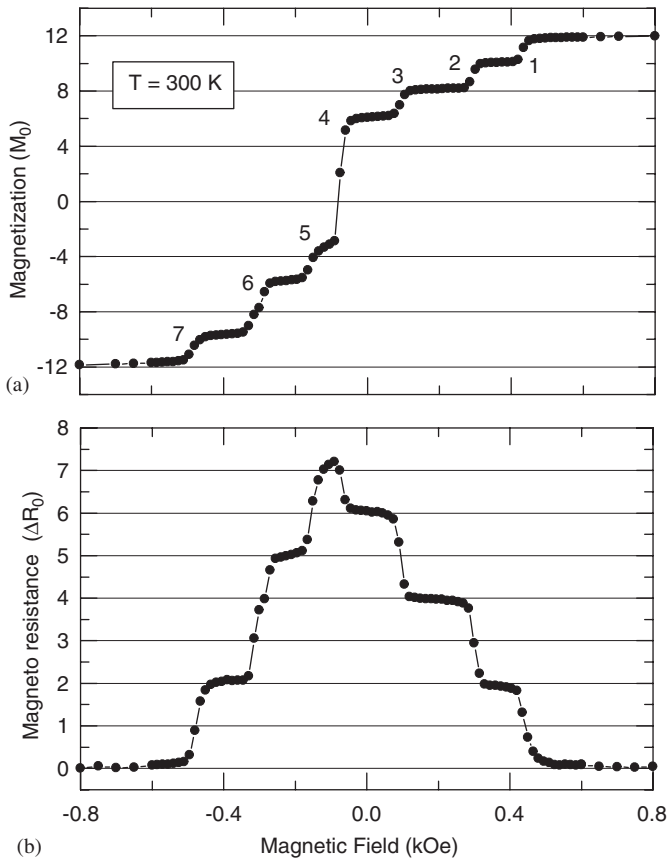

Fig. 2. Normalized descending branch of magnetization hysteresis loop and corresponding branch of GMR hysteresis loop in the (2 1 1)MgO/Cr(90 Å)/[Fe(85 Å)/Cr(13.6 Å)]$_{12}$ superlattice. Magnetic field was applied along easy axis in the film plane. The magnetization in Fig. 2(a) is expressed in unites of the magnetic moment M_0 of the one Fe(85 Å) layer in the measured sample. The magnetoresistance $\Delta R/R = [R(H) - R_s]/\Delta R_0$ is presented in Fig. 2(b) in unites of ΔR_0. The value ΔR_0 is the change value of the superlattice resistance due to the one surface spin–flip transition.

transitions inside the superlattice ($\Delta M = 2M_0$, $\Delta R/R = 2\Delta R_0$), and the step number 6 in Fig. 2(a) corresponds both to the reorientation of one magnetic moment inside the superlattice and one of two "surface" magnetic moments ($\Delta M = 4M_0$, $\Delta R/R = 3\Delta R_0$). The complicate reconstruction of magnetic order in the superlattice occurs in magnetic fields near the coercive field H_c, where the quantitative correlation between $M(H)$ and $\Delta R/R(H)$ is not so clear. No transitions with the step change of magnetization and $\Delta R/R = 0$ were detected. From the fact one may conclude that each of two consequent magnetic moments involved into multiple spin–flip transitions are not the neighboring moments in the superlattice.

The decrease of the nominal Cr layers thickness on small value $\Delta t_{Cr} = 1.2$ Å in the superlattice (2 1 1)MgO/[Fe/Cr]$_{12}$ leads to the increasing of exchange coupling. The latter changes considerably the magnetization behavior in the sample. Fig. 3 shows the hysteresis loop for the superlattice with the Cr spacer thickness $t_{Cr} = 12.4$ Å. There are three main differences in this hysteresis loop in comparison with

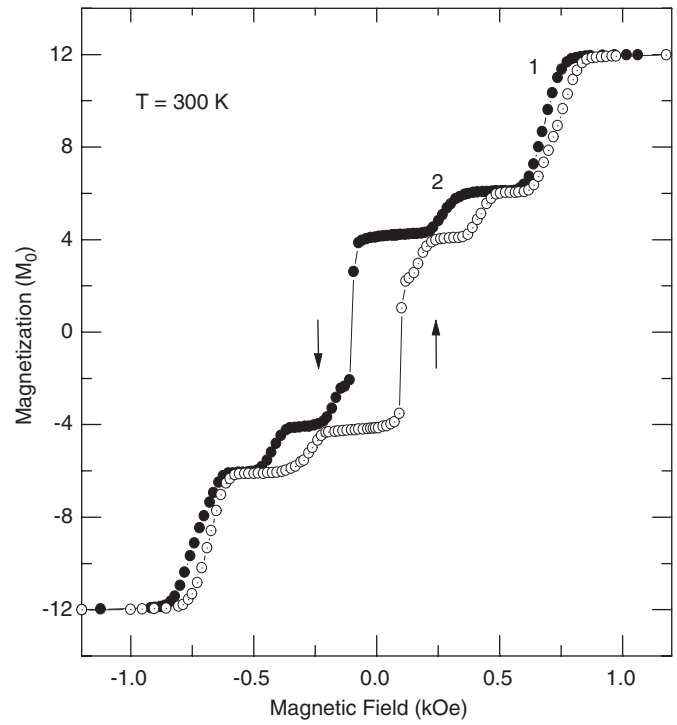

Fig. 3. The (2 1 1)MgO/Cr(90 Å)/[Fe(85 Å)/Cr(12.4 Å)]$_{12}$ superlattice hysteresis loop. Magnetic field was applied along easy axis in the film plane. The magnetization is expressed in unites of the magnetic moment M_0 of the one Fe layer in the superlattice.

$t_{Cr} = 13.6$ Å superlattice: (i) saturation field is approximately twice bigger than in superlattice with $t_{Cr} = 13.6$ Å, (ii) number of transitions in the field range $H > 0$ are reduced from 3 to 2, and (iii) the first transition (denoted as 1 in Fig. 3) involves three magnetic moments which are not neighboring ones in the superlattice. These results demonstrate the strong dependence of multiple spin–flip transitions on a small variation of the Cr layers thickness.

Acknowledgements

The research was partly supported by RFBR (Grant 04-02-16464), Grant SS - 1380.2003.2, Programs of RAS "Low-dimensional quantum structures" and "Quantum macrophysics".

References

[1] O. Hellwig, A. Berger, E. Fullerton, Phys. Rev. Lett. 91 (2003) 197203.
[2] O. Hellwig, T.L. Kirk, J.B. Kortright, A. Berger, E.E. Fullerton, Nat. Mater. 2 (2003) 112.
[3] O. Hellwig, A. Berger, E.E. Fullerton, J. Magn. Magn. Mater. 290–291 (2005) 1.
[4] T. Slezak, W. Karas, K. Krop, M. Kubik, D. Wilgocka-Slezak, N. Spiridis, J. Korecki, J. Magn. Magn. Mater. 240 (2002) 362.
[5] M. Zoladz, T. Slezak, D. Wilgocka-Slezak, N. Spiridis, J. Korecki, T. Stobiecki, K. Röll, J. Magn. Magn. Mater. 272–276 (2004) 1253.
[6] U.K. Rößler, A.N. Bogdanov, J. Magn. Magn. Mater. 269 (2004) L287.
[7] T. Luciski, M. Urbaniak, H. Brückl, A. Hütten, S. Heitmann, G. Reiss, J. Magn. Magn. Mater. 272–276 (2004) 1889.