Study of magnetization of a bilayer nanoststructure CoCu/Co (GF/F) by polarized neutron reflectometry

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Abstract. Magnetization reversal of the exchange-coupled granulated ferromagnetic (GF) CoCu and ferromagnetic (F) Co nanolayers is studied by polarized neutron reflectometry. The main parameters that specify the structure and saturation magnetization of the GF and F layers are determined for Si(substrate)/Co0.5Cu0.5(5nm)/Co(x)/Si(3nm) samples with a thickness x varying from 6 to 20 nm. Neutron data allow some suggestions to be made about the features of the GF/F bilayer magnetization reversal. For small x the main mechanism of the magnetization reversal is the domain wall motion hindered by the exchange interaction between GF and F. As a consequence, the magnetization of the Co layer contacting with numerous granules is reversed in fields exceeding its own coercivity by an order of magnitude. For large x the magnetization reversal undergoes several stages conditioned by interaction of GF and F nanolayers. These stages may be characterized by three fields. For an oppositely magnetized sample, when the field approaches H1, there appear regions with flipped moments coupled to non-flipped moments in neighboring regions (“lateral magnetic springs”) in the F layer. The field H2 sets off the overturn of magnetic moments of the granules, which is accompanied by the pinning of the regions with reversed magnetization in the F layer. The fields H2 and H3 tag the completion of the overturn of the F layer magnetization and the granule moments, respectively. When the applied field reaches H3, any further change of the magnetic state is due to a reversible rotation of the granule moments and the F layer magnetization. The reversibility of magnetic states persists with fields both increasing above H3 and decreasing down to 0 and further to -H1.

1. Introduction

Polarized neutron reflectometry is a technique for studying magnetic nanosystems, which yields a unique information needed for solution of fundamental and applied tasks motivated by development of nanotechnologies. Such tasks include, e.g., the study of dimensionality effects on nanosystems, the phase proximity effects, the role of phase interfaces in definition of magnetic properties of nano-objects, establishment of relations between morphology and magnetism of layered structures. Interest
to magnetic nanolayers is conditioned by possibilities of their applications in electronic industry, and, in particular, by new perspectives and promises of spintronics [1]. The basic architecture of the simplest spintronic device is a magnetically soft layer, severed from a ‘pinned’ hard layer with a metal nonmagnetic interlayer or a sufficiently thin (for tunnelling) dielectric interlayer [1,2]. Structures consisting of exchange-coupled magnetically soft and hard ferromagnetic layers [3] may be of interest for using, e.g., as the magnetically hard layers in spin-tunnel structures. Adding a magnetically soft layer via a thin nonmagnetic interlayer, one can build high-resolution probes for the magnetic force microscope [4]. The interlayer exchange coupling oscillates as a function of the interlayer thickness. Optimizing the interlayer thickness, one can observe giant magnetoresistance in the external field. On the basis of such trilayer nanofilms, it is possible to make controlled sources of magnetic fields of submicron dimensions without using the shape anisotropy [5,6].

A layer of pure cobalt can be used as a soft ferromagnetics (F) and a solid solution of cobalt and copper can be used as a granulated ferromagnetics (GF) [7]. Samples of layered metal nanostructures were formed on standard silicon wafers by magnetron sputtering technique in atmosphere of Ar with a pressure 10^{-6} Torr for residual gases. It follows from magnetic measurements that the shape of hysteresis loops is close to rectangular for Co films of thickness from 10 to 20 nm, their coercivity steadily rising from 10 to 30 Oe, respectively. Also a series of samples with CoCu films was prepared. CoCu films were obtained by simultaneous sputtering from two (Co and Cu) targets. The vacuum annealing was then carried out at a temperature about 180°C for 1 hour for more efficient phase separation, as described earlier [7]. One could judge about the phase restructuring of annealed CoCu films from such indirect evidences as a decrease in resistivity and an increase in coercivity (from tens to hundreds oersted). The coercive field of isolated Co_{0.5}Cu_{0.5} films with thicknesses 15 nm and 5 nm is, respectively, 180-200 and about 300 Oe. The next series of samples were CoCu/Co (F/GF) films prepared in a single technological cycle and annealed as a whole. In particular, the coercivity of bilayers with the same thicknesses (15 nm) of Co_{0.5}Cu_{0.5} and Co films is 100-120 Oe. To avoid oxidation in air and under vacuum annealing, a layer of silicon of thickness 3 nm was deposited on top of the structures. In the same manner the Si(substrate)/CoCu(5nm)/Co(x)/Si(3nm) samples with CoCu films of the same thickness (5 nm) and Co films of different thickness x (10, 15, 17 and 20 nm) were prepared (two samples for each value of x). Dimensions of silicon substrates are 10x10x0.5 mm³.

In the present paper the magnetization reversal of the exchange-coupled CoCu (GF) and Co (F) nanolayers is studied by polarized neutron reflectometry. Neutron reflectivities are sensitive to the depth profile of the magnetization, both its magnitude and direction (see, e.g., [8,9]). One sample for each thickness x of Co films (samples A, B, C and D, accordingly) were chosen for neutron measurements. All sample surfaces are homogeneous with a glitter of metal; except for one of the two samples with a Co film of nominal thickness 15 nm: its surface is slightly tinted with brown and bluish stains. The cause of this difference in samples was established after neutron measurements. All neutron measurements were carried out at the reflectometer NR-4M (beam 13 of the reactor WWR-M, PNPI, Gatchina). Theoretical reflectivities were calculated by the generalized matrix method [10] lately known as ‘supermatrix method’.

2. Structural features of nanolayers

In order to obtain data on the parameters of structure and saturation magnetization, the samples were magnetized in a field 600 Oe, parallel to the sample surface, then the field was diminished to 470 Oe (to prevent overheating of the electromagnet) and time-of-flight measurements of spin-up (R+) and spin-down (R-) neutron reflectivities were carried out. These measurements with magnetically saturated samples were carried out without the analyzer, just by switching the flipper off and on to change the sign of the incident beam polarization. The results of fitting the reflectivities for samples A, B, C and D with the model in Fig. 1 are represented in Fig. 2. The thickness and magnetization of CoCu and Co layers are designated, accordingly, as d₁, M₁ and d₂, M₂. The fitting in the whole range of momentum transfers q is possible only on the assumption that the upper protective layer of Si is
oxidized (d₃ is the thickness of unoxidized silicon, d₄ is the thickness of the surface oxide layer), and silicon substrate is also oxidized (d₀ is the thickness of its oxide layer). The roughness of all interfaces is assumed to be the same (σ).

Figure 1. The layered structure model used to fit the neutron reflectivity data in Fig. 2. In calculations the interfaces are rough. The external field \( H \) is parallel to the sample surface. The wave vector transfer \( q \) for specular neutron reflection is perpendicular to the sample surface; \( \theta \) is the glancing angle.

The model suggested allowed fitting the specular reflectivities of neutrons with the opposite spins (R⁺ and R⁻) for all samples with the exception of sample B. The structural parameters obtained by fitting and the respective errors are given in Table 1. The thicknesses of CoCu layers in samples well agree with the nominal value 5 nm. A large value of the magnetization of the CoCu layers (when averaged over all samples, \( 4\pi M_1 = 6.5 \pm 0.7 \) kGs) indicates that sufficiently pure phases of cobalt and copper formed in solid solution of the metals. The thickness of the Co layer in the sample A (6.9 ± 0.4 nm) turned out to be smaller than the nominal value 10 nm, whereas the thicknesses obtained for samples C (17.5 ± 0.3 nm) and D (19.5 ± 0.4 nm) agree, within the fitting error, with the nominal values, accordingly, 17 and 20 nm. The magnetization of the Co layer in sample C was found to be \( 4\pi M_2 = 17.60 \pm 0.45 \) kGs, which is but slightly smaller than the saturation magnetization of the bulk cobalt (\( 4\pi M_S = 18.5 \) kGs). The magnetization of the Co layers in samples A and D is still smaller, respectively, 13.0 ± 0.6 and 14.2 ± 0.8 kGs.

The interfacial roughness in the samples seems to be determined by the roughness of substrates (1.5-2.0 nm are common values for silicon wafers with standard polishing). It is also to be noted that, as the volume expansion coefficient for silicon oxidation is known to be about 2, the thicknesses d₃ (unoxidized silicon) and d₄ (oxidized silicon) obtained for samples A, C, D correspond to the nominal thickness 3 nm of silicon layer before its oxidation in air (as-deposited).

It is to be noted that the thickness of unoxidized silicon in the protective layer of sample A is only 1.0 ± 0.6 nm. For sample B the neutron data can be satisfactorily fitted only on the assumption that not only the protective silicon layer is completely oxidized, but also the Co layer is partially oxidized, with the sample surface becoming quite friable. It follows from the fitting that only 6±1 nm of the cobalt layer is not oxidized, its magnetization being \( 4\pi M_2 = 15.0 \pm 1.2 \) kGs. From its remaining upper part and the layer of oxidized silicon there formed two nonmagnetic layers, partially oxidized Co layer of thickness about 8 nm with 10-20% content of oxygen and a surface oxide layer of thickness about 3-4 nm. In order to satisfactorily fit the date, one has also to admit that the roughness of both interfaces of the surface oxide layer is quite significant (near 15 nm), remarkably exceeding its thickness. It indicates that the oxide layer is very friable and that the model but roughly describes the depth profile of the potential of the surface region of the structure, so the respective parameters in Table 1 are omitted.
Figure 2. The fitting of the spin-up ($R_+$) and spin-down ($R_-$) neutron reflectivities for samples A-D. The structure parameters obtained are given in Table 1. The glancing angle is 3.6 mrad for all samples. The external field is 470 Oe.

Table 1. The structure parameters obtained from neutron data fitting.

| sample | $d_0, \text{nm}$ | $d_1, \text{nm}$ (CoCu) | $4\pi M_1, \text{kGs}$ | $d_2, \text{nm}$ (Co) | $4\pi M_2, \text{kGs}$ | $d_3, \text{nm}$ | $d_4, \text{nm}$ | $\sigma, \text{nm}$ |
|--------|-----------------|-------------------------|----------------------|---------------------|---------------------|----------------|----------------|----------------|
| A      | 7.7±0.7         | 5.3±0.7                 | 7.0±1.2              | 6.9±0.4             | 13.0±0.6            | 1.0±0.6        | 3.5±0.5        | 2.0±0.7        |
| B      | 4.5±1           | 5.6±0.8                 | 5.6±1.2              | 6±1                 | 15.0±1.2            | -              | -              | -              |
| C      | 5.5±0.6         | 4.9±0.7                 | 6.7±1                | 17.5±0.3            | 17.60±0.45          | 2.1±0.6        | 2.0±0.4        | 1.5±0.4        |
| D      | 3.5±1           | 4.9±0.7                 | 6.7±1                | 19.5±0.4            | 14.2±1.2            | 2.1±0.6        | 2.0±0.6        | 1.5±0.5        |

The conclusion about a partial oxidation of cobalt layer in sample B is sustained by the above-mentioned fact that its surface is tinted with brown and bluish stains. Oxidation of ultrathin heterogeneous structures is not well studied, so the reason for a significant loosening of the surface region under oxidation of cobalt layer through the silicon oxide layer is not quite understood. It is not unlikely that the weakening of adhesion of layers during oxidation of cobalt and significant mechanical stresses in the silicon oxide layer may cause peeling-off of the surface layers of the structure.

3. Magnetization reversal of GF/F bilayer

In Fig. 3 are represented the field dependences of the relative difference of non-spin-flip reflected intensities ($I_{++}$ and $I_{--}$),

$$P_{\text{SSF}} = (I_{++} - I_{--})/(I_{++} + I_{--}),$$

and the flipping efficiency of the coating,

$$F_{\text{SF}} = 2I_{\text{SF}}/(I_{++} + I_{--} + 2I_{\text{SF}})$$

(the ratio of the sum of two spin-flip intensities $I_{++}$ and $I_{--}$ to the total intensity of reflection of unpolarized beam, represented by the sum of oppositely polarized beams).
The intensities were obtained with a white beam of thermal neutrons in the standard measurements scheme “polarizer-flipper-sample-flipper-analyzer” [11,12] and in fields parallel to the sample surface. Since measurements without loss of the neutron beam polarization could be made only in the fields of one polarity (positive fields), the samples were preliminarily magnetized in the opposite field (-600 Oe), which was then dropped to 0. Further measurements were carried out in positive fields growing up to 600 Oe (the forward direction of the magnetization reversal) and then in decreasing fields (the inverse direction of the magnetization reversal). When the samples were rotated by 180° and 90°, the field dependences of the reflected intensities did not change, as it should be expected for magnetically isotropic CoCu and Co layers. Full hysteresis loops can be obtained by reflection of the curves $P_{NSF}$ and $F_{SF}$ obtained with respect to the origin of coordinates or coordinate axes, respectively. The latter means that the forward and inverse field dependences of $F_{SF}$ intersect at the ordinate axis (Fig. 3).

Experimental neutron data allow some suggestions to be made about physical mechanisms of the magnetization reversal process in the system under consideration. Polarized neutron reflectometry is sensitive to the “local” magnetization, viz. to the magnetization laterally averaged by the neutron over coherently illuminated area of the order of $10^5$ nm$^2$. When analyzing the results of measurements, one has to bear in mind that an increase (a decrease) in $P_{NSF}$ and $F_{SF}$ means, as a rule, that the local magnetization components, accordingly, parallel ($M_\parallel$) and perpendicular ($M_\perp$) to the applied field, are increased (decreased), the sign of $P_{NSF}$ corresponding to that of $M_\parallel$. Therefore, neutron measurements are informative of the change of both $M_\parallel$ and $M_\perp$, though the neutron intensities in the measurement scheme used are not sensitive to the sign of $M_\perp$. The symmetry of $F_{SF}(H)$ with respect to the ordinate axis means that the components $M_\parallel$ in the forward and inverse magnetization processes differ in zero field only in the sign.

When analyzing the neutron data, one has to take into consideration that the Co granules in ultrathin CoCu films may vary in shape from round ones, with moments easily aligned along the field, to elongated needle-like ones with moments directed along their largest size, as a consequence of the shape anisotropy. Since there always exist a certain number of needle-like granules oriented at a considerable angle or even perpendicular to the external field, their moments will not be parallel even to the largest field used in the experiment. It explains the fact that $F_{SF}$ is not equal to 0 in the field 600 Oe (Fig. 3). Both external field and coupling with the Co layer and neighboring granules affect the magnetic granules. And vice versa, if the magnetic moment of a granule, due to its shape anisotropy, is inclined to the field, in the Co layer the moments contacting the granule will also be deviated to the field direction. This deviation of moments will be transferred into the depth of the Co layer. As a result, in general a multidomain state will be set up that corresponds to the minimum of the total energy including anisotropy energy, exchange and long-range dipole interaction terms, as well as the energy of coupling with the external field. As the granules are oriented randomly, the components $M_\parallel$ and $M_\perp$ will depend on the sample surface coordinates in a complicated manner. The perpendicular magnetization component averaged over the isotropic sample vanishes. However, neutrons average over a comparatively small, though containing many granules, area and are sensitive to $M_\perp$, not equal to 0. In a sufficiently large fields the magnetic state of the structure develops into a single-domain state and the local magnetization changes reversibly.
Figure 3. Quantities (a) $P_{NSF}$ and (b) $F_{SF}$ for samples A-D as functions of the field, growing (filled circles) and decreasing (blank circles). On magnetization curves of sample C: Double (single) arrows at the curves $F_{SF}(H)$ show field ranges with (ir)reversible magnetization. Time-of-flight measurements (Fig. 4) were carried out at points 1, 2 and 3. Characteristic fields (see the text): $H_1$ sets off the irreversible flip of magnetic moments of the granules, $H_2$ and $H_3$ tag the completion of flips of, respectively, the Co layer magnetization and the granule moments in the CoCu film.

It follows from neutron measurements (Fig. 3) that the coercive field of samples A and B is in tens of times larger than that of samples C and D. The structural data obtained in Sec. 2 explain why the magnetization reversal of sample B with a nominal thickness 15 nm of the cobalt film is similar to that of sample A. Because of the partial oxidation, the actual thickness of magnetic cobalt (6 nm) in sample B almost coincides with the thickness of cobalt in sample A (7 nm). It is evident that the magnetically hard CoCu (GF) layer with a thickness 5 nm has an essential effect on the magnetization
reversal of magnetically soft Co layers of approximately the same thickness. Judging by the value of the coercive field of samples A and B, the granule moments in the CoCu layer control, through the exchange coupling, the Co layer magnetization. As a consequence, the magnetization of the Co layer contacting with numerous granules is reversed in a field by an order of magnitude greater than the isolated Co layer with the same thickness. The fact that the value \( F_{SF} \) is quite low in the whole range of the fields indicates that the main mechanism of the magnetization reversal of the Co layer is the domain wall motion hindered by the exchange coupling with GF. Reversed in a field -600 Oe, the granule moments do not flip even in positive fields (appr. up to 100 Oe) and hinder the motion of domain walls in the Co film. The domain walls start moving only when the granule moments flip in larger fields. It follows from neutron data that the coercive field of bilayers in samples A and B is near 300 Oe. In fields above 500 Oe the moments of all granules and the Co film magnetization overturn to the field direction, and the spin-flip reflection essentially reduces. Now the granule moments deviate from the field direction due to the shape anisotropy, but in the same fields this deviation is less, for the granule moments are coupled with the Co film, the moments of which are aligned in directions close to the external field. As a consequence, when the field reduces, the spin-flip reflection grows slowly enough, but in small fields the moments of the granules again deviate noticeably from the field direction, dragging the moments of the magnetically soft Co layer. In a sufficiently low fields the components \( F_L \) are close in magnitude for the forward and inverse magnetization processes, so the two curves \( F_{SF}(H) \) converge (Fig. 3-A,B).

The thicknesses of the Co films in samples C and D exceed in about three times that of the CoCu films. This is fundamental for the magnetization reversal scenario. Although the influence of CoCu is weakened, analysis of the whole set of measurements allows one to conclude that the Co layer also plays an important role in the magnetization reversal.

Sample C with a maximum magnetization of the Co layer was chosen for more detailed neutron measurements, incl. time-of-flight measurements, now with the analyzer (unlike the measurements represented in Fig. 2). The structural and magnetization parameters obtained above were used in fitting and analysis of spectral neutron reflectivities for different magnetic states of the sample. To take account of the coupling of the Co layer with numerous granules coupled also with each other is a rather complex problem. So the calculations of reflectivities as functions of the momentum transfer \( q \) are carried out with a simplified model, pertinent only for estimation of non-collinearity of the local magnetization to the external field. Namely, the angle \( \chi \) between the local magnetization and the field is assumed to be the same for the entire Co film, though the sign \( \chi \) may be different in different parts of the sample and the magnetization is equal to the value obtained by the fitting (Fig. 2-C). It is the magnetic state of the Co film that mainly determines the reflected neutron intensities, for its thickness in three times and its saturation magnetization in 2.5 times are larger than those of the CoCu film.

Double (single) arrows in Fig. 2-C,D show ranges with a (ir)reversible field dependence. One can see from the neutron data that the field dependences of \( F_{SF} \) are practically reversible everywhere except for a narrow range of fields in the forward magnetization curve for sample C from \( H_1 \approx 14 \) Oe to \( H_2 \approx 20 \) Oe; for sample D the width of this range (near \( H_1 \approx 11 \) Oe) is no more than 1 Oe.

In a field 600 Oe the moments of Co granules in the CoCu layer and the magnetization vector in the Co film are close to the guide field direction (\( \chi \approx 4^\circ \) for sample C). When the field reduces, the directions of the granule moments are defined to a greater extent by the shape anisotropy and, while remaining in the film plane, the moments deviate more and more from the field direction, dragging with them the moments of the Co layer regions contacting these granules, the consequence being that the neutron SF reflection increases. Rotation of the moments is gradual and reversible. A satisfactory fitting of neutron reflectivities as functions of the momentum transfer \( q \) (Fig. 4-1) at \( H = 19 \) Oe is obtained on the assumption that the Co film magnetization inclination angle is \( \chi = 28^{\pm 3^\circ} \). To determine the portions of regions with local magnetization inclinations \( \chi \) and \( -\chi \) did not seem to be possible without 3D neutron polarization analysis. On the basis of magnetic isotropy of the sample, one may assume that those portions are equal. The reflectivities are much less sensitive to magnetic
parameters of the CoCu film, so that we could deduce only that the local magnetization in the CoCu film makes an acute angle with the field (28° in calculations in Fig. 4-1). It is evident that, when the field drops to 0, the moments retain an acute angle with respect to the positive field direction.

Figure 4. Time-of-flight reflectivities for neutrons reflected without spin-flip (a) \( R_{++} \), (b) \( R_- \) and with spin-flip (c) \( R_{+—} = R_{+—} = R_{SF} \) as functions of \( q \) for sample C at fields (1) 19 Oe, (2) 11 Oe and (3) 22 Oe (as marked in Fig. 3-C). Theoretical reflectivities (solid curves) are calculated with structural and magnetization parameters given in the caption of Fig. 2; the fitting parameter is the magnetization inclination angle \( \chi \): (1) 28±3°; (2) 120°; (3) 22±4°.

It follows from the magnetization reversal symmetry that, after the reversal of magnetization in a field -600 Oe, the local magnetization inclination angle \( \chi \) (with respect to the positive field direction) in the Co film at the field -19 Oe is near 180°−28°=152°. When the field drops to 0, it will further deviate from 180°.

With the growth of the field above 0 the angle \( \chi \) still reduces (see \( F_{SF} \) in Fig. 3-C). Rotations of all moments are reversible in the fields up to \( H_1 \). The time-of-flight neutron reflectivities obtained for sample C in a field 11 Oe, close to \( H_1 =14 \) Oe, are represented in Fig. 4-2. In this case only \( R_- \) and \( R_{SF} \) could be fitted with \( \chi =120° \) in the simplified model. The fitting of \( R_{++} \) is just impossible, if all moments in the Co layer are assumed to make blunt angles with the field direction. A high level of the reflectivity \( R_{++} \) at small \( q \) can be explained only on the assumption that there exist regions in the Co layer with \( M_|| >0 \). One may suggest that, due to the torque moment from an external field \( H < H_1 \), there appear regions in the Co layer with a local magnetization flipped (\( M_|| >0 \)). Such regions should be coupled with regions with \( M_|| <0 \) so that the boundaries between them move reversibly, when the field changes. Such elastically coupled magnetic regions may be called “lateral magnetic springs”. Lateral magnetic springs arising in fields approaching \( H_1 \) should reversibly disappear when the field falls. The Co granules in the CoCu film seem to play an important role in reversibility of the magnetic states. Their intrinsic coercivity is considerably larger than that of the Co film, so the granule moments under the Co layer regions with a flipped magnetization remain to be oriented in a direction opposite to the field. As a consequence, they impose a torque forcing the Co layer regions with a flipped magnetization to return to a state with \( M_|| <0 \). Such a coupling ensures elasticity of the lateral magnetic springs and reversibility of magnetic states. The observed (Fig. 3-C) enhanced growth in spin-flip reflection when the field approaches \( H_1 \) is indicative of the increasing growth rate for |\( M_\perp \)|. To
satisfactorily fit all reflectivities in Fig. 4-2, one has to improve the model describing the moments distribution in the bilayer.

The field $H_1$ sets off flips of the granule moments in the CoCu layer. When a granule moment flips, the shape anisotropy energy does not change and the energy of the moment in the external field decreases. Such flips of the granule moments are most probable under the Co layer regions with a flipped magnetization, where the torque moment of the external field is enhanced by the ferromagnetic interaction. The reverse flipping of the granule moments is related to surmounting potential barriers, hence it is irreversible. Therefore, the granules with flipped moments pin the regions in the Co layer with the magnetization flipped and, enhancing the torque moment of the external field, diminish the perpendicular magnetization component in the Co layer. A fast decrease in $F_{SF}$ in a short range of fields from $H_1$ to $H_2$ (Fig. 3-C) signifies that there is an intense growth of regions in the Co layer with a magnetization flipped and the pinning of such regions due to continuing flips of granule moments.

The overturn of the Co film magnetization is basically completed at the field $H_2$. This is confirmed by a satisfactory fitting of neutron reflectivities (Fig. 4-3) obtained in a field $H = 22$ Oe, slightly above $H_2 = 20$ Oe, with $\chi = 22 \pm 4^\circ$. Some discrepancy of the theoretical and experimental spin-flip reflectivities $R_{SF}$ at small $q$ is likely to signify that the granules with moments not yet flipped increase noncollinearity of the magnetization in the Co layer (the portion of such granules is less than a third, as estimated with our simplified model). Note also that the field $H_2$ is less than the coercive field of the isolated Co film with the same thickness. A possible reason is a softening of the Co film in the sample subjected to annealing for efficient separation of phases in the CoCu film.

The irreversibility of the reflected intensities $I_{++}$ and $I_{--}$ (Fig. 5) in fields between $H_2 = 20$ Oe and $H_3$ near 50 Oe indicates that in the field $H_2$ a considerable number of granule moments are still oriented against the field. This can be explained by the assumption that the coupling between magnetic granules and the Co layer depends on the contact area, on the presence of Cu atoms in the contacting region, on the mechanical tension distribution, etc. As a consequence, a part of granule moments do not flip even when the magnetization of the entire Co layer is overturned. The continuing flips of granule moments are responsible for irreversibility of $I_{++}$ and $I_{--}$ in fields between $H_2$ and $H_3$.

![Figure 5](image-url)
Irreversible flips of the granule moments are accompanied with a reversible decrease in the inclination angle of the moments already flipped. It seems that the latter determines the quasi-reversible behavior of $F_{SF}$ between $H_2$ and $H_3$. The calculations for the given structure show that a decrease in $\chi$ for $\chi < 30^\circ$ leads to a growth of not only $I_+$, but also $I_-$, so that $P_{NSF}$ but slightly change (for this reason the two curves of $P_{NSF}$ in Fig. 3-C merge between $H_2$ and $H_3$).

The fact that flips of the granule moments are completed in the field $H_3$, which is by an order of magnitude smaller than the coercive field of an isolated CoCu film (5 nm), means that the exchange coupling with a comparatively thick Co layer essentially contributes to the flips of the granule moments. The change in the magnetic structure in fields above $H_3$ is associated with a reversible rotation of moments in the bilayer. As it has been mentioned before, the configuration of magnetic moments depend only on the field magnitude, the magnetic states are reversible in fields above and below $H_3$ (down to -$H_1$).

4. Discussion

Neutron reflectometry yields an important information to elucidate the relation between structural features and magnetic properties of the layers. Neutron data allowed the main parameters to be determined and some suggestions to be made about the features of the magnetization reversal of Co$_{0.5}$Cu$_{0.5}$(5nm)/Co($x$) (GF/F) bilayers with $x$ varying from 6 to 20 nm. For small $x$ the main mechanism of the magnetization reversal is the domain wall shifts essentially hindered by the exchange interaction between GF and F. For large $x$ the magnetization reversal undergoes several stages conditioned by interaction of GF and F nanolayers. To comply with the neutron data, we suggested that, just below the field that sets off the overturn of magnetic moments of the granules, due to the torque from the field, there appear regions in the F layer with a reversed ($M_{||}>0$) local magnetization, which are coupled to regions with the initial magnetization $M_{||}<0$. Such “lateral magnetic springs” reversibly disappear when the field drops. The Co granules in the CoCu film seem to play an important role in this reversibility by imposing a torque forcing the Co layer regions with $M_{||}>0$ to return to a state with $M_{||}<0$ in the field decreased.

![Figure 6. MOKE hysteresis loops for two samples prepared in the same sputtering process as samples A (a) and C (b).](image)

It is to be noted that, as a rule, the field dependence of the polarizing efficiency $P=(R_+-R_-)/(R_++R_-)$ is used in the study of the magnetization reversal of layered structures by polarized neutron reflectometry. The hysteresis loops obtained in this manner are similar to those obtained by standard magnetometry (cf. $P_{NSF}(H)$ in Fig. 3 and MOKE hysteresis loops in Fig. 6). Using, in addition, the selectivity of neutron reflection to the thickness of layers, from the field dependence of the polarizing efficiency at different wavelengths, we inferred that thicker layers in CoFe/TiZr...
supermirrors are magnetically harder and the magnetization reversal starts from thinner layers [13]. In the present paper the intensities of neutrons reflected without spin-flip and with spin-flip were used, and it allowed us to independently analyze magnetization components parallel and perpendicular to the external field. In order to fully interpret the neutron data, a detailed theoretical analysis and an additional experimental work with neutron and other techniques are required.

Whenever a time-of-flight measurement was carried out at a certain glancing angle, the reflected beam profile was also scanned with a thin slit on the detector window. In all cases the off-specular scattering was found to be practically at the background level, in spite of the presence of such inhomogeneities as granules. It remained insignificant even for samples in small fields, when the cobalt layer broke up into magnetic domains giving rise to magnetic off-specular scattering. We attribute this to the facts that (a) the volume of granulated ferromagnetic is very small (a layer of thickness 5 nm); (b) granules with lateral dimensions 10-20 nm produce off-specular scattering at large angles with quite small cross sections; (c) lateral dimensions of magnetic domains in the cobalt layer are quite large. As a consequence, most neutron scattering is concentrated within the specular peak. Colder neutrons and greater luminosity are required to obtain additional information about the samples from off-specular scattering.

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