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Atomic separation in Co/Cu/Co magnetic structures study by hybrid X-ray reflectivity – X-ray standing wave approach

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ABSTRACT

The detailed characterization of nanometer-thin film structures is key to the in-depth understanding and property control of such objects. Here we present the analysis of Co/Cu/Co multilayer grown on and covered by thin Ta layers at individual layer thicknesses below 5 nm. The prime focus of the analysis was to detect the threshold Cu thickness required to separate effectively the magnetic Co layer. We found that a 4 nm Cu layer can effectively separate Co layers, but that 2.8 nm of Cu is not sufficient. To solve such structural characterization tasks, we adapted a hybrid X-ray reflectivity – X-ray standing wave free-form analysis technique. We applied that to the study of the Co layers separation by Cu and now it can be used to perform any task of this kind and also for other material combinations.

1. Introduction

The detailed understanding of physical properties of magnetic stacks, for example Co/Cu/Co, formed by alternating magnetic and nonmagnetic layers is important for the exploration of thin film magnetic phenomena. Such research has already led to the discovery of giant magnetoresistance, antiferromagnetic interaction between magnetic layers through a nonmagnetic separating layer, involving oscillating exchange interaction between ferromagnetic layers through a nonmagnetic metal layer. The extension of that previous research will enable and facilitate broad technological implementation of the aforementioned phenomena.

The magnetic properties of such magnetic stacks depend strongly on the thin-film structure. The detailed analysis of the structure, e.g. the atomic profiles, of such films allows the selection and application of the optimal thin film deposition method and optimizing the growth parameters if as-grown film does not have desired structure. The extended thin film growth research (for example, that discussed in [1]) shows that the structural parameters of grown film can be controlled by surface passivation, selection of the substrate crystalline orientation or growth temperature. However, the complexity involved in finding the correlation between these growth parameters and resulting thin-film structure has proved to be a significant obstacle to the creation of structures that have a predetermined set of properties necessary for their practical application. The detailed structural characterization of as-grown thin films helps find such correlation and achieve the desired growth optimization.

Low mutual solubility of cobalt and copper was supposed to provide sharp interfaces and good stability of Co/Cu/Co tri-layer systems. However, numerous experimental studies carried out in recent years have revealed a wide range of structural imperfections, such as interdiffusion at the interface, pronounced relief of internal interfaces and the formation of compounds, which significantly affect the physical properties of the material, particularly the magnitude of the giant magnetoresistance effect [1,2]. The phase diagram of the bulk Co/Cu alloy [3] demonstrates the transition from the spin glass phase to the ferromagnetic phase through an increase in the concentration of cobalt in the alloy with copper, and indicates the presence of the paramagnetic state of the alloy at room temperature and a Co content less than 30%. Some growth modes can stimulate the formation of cobalt clusters that determine the paramagnetic and superparamagnetic phases in Co–Cu alloys [3]. Earlier, Shalygina et al. [4] studied the influence of various copper layer thicknesses, ranging from 0.5 to 4 nm, on the structural and magnetic characteristics of magnetron-sputtered Co/Cu/Co structures made up of 5 nm thick Co layers. The authors demonstrated the oscillating dependence of magnetic properties on the thickness of the Cu layer.

The characterization of a Co/Cu/Co layered structure is a
of oscillatory dependence of magnetic properties on the Cu layers the separation of magnetic cobalt layers that was identified as the cause copper barrier (thicknesses of layer and interfaces) and the efficiency of XSW methods. The analysis was focused on revealing the structure of the Co/Cu/Co/Ta layered systems was studied by a combination of XRR and sample and reflected from it) in the region of their overlap. The crucial beamline of the Kurchatov synchrotron radiation source. Radiation at an specific hybrid X-ray metrology methods for routine analysis of com forms areas of minimal amplitude (nodes) and of maximal amplitude (antinodes). While changing the angle of radiation incident on the forms of the generated wave (XSW) inside the structure, which is caused by the interference of coherent waves that have close amplitude values (waves incident on the sample and reflected from it) in the region of their overlap. The crucial feature of the generated wave’s field of a standing wave is a periodic change in the electromagnetic field along the depth of the sample which features of the electromagnetic field along the depth of the sample in regions of minimal amplitude (nodes) and maximal amplitude (antinodes). While changing the angle of radiation incident on the depth, causing effective modulation of the fluorescent radiation yield from the atomic structure [6].

The purpose of the presented work is twofold. The structure of Ta/Co/Cu/Co/Ta layered systems was studied by a combination of XRR and XSW methods. The analysis was focused on revealing the structure of the copper barrier (thicknesses of layer and interfaces) and the efficiency of the separation of magnetic cobalt layers that was identified as the cause of oscillatory dependence of magnetic properties on the Cu layers’ thickness. We have also developed the surface-sensitive and elements-specific hybrid X-ray metrology methods for routine analysis of complex and low-contrast structures that can be applied to any thin-films structure that is similar to currently discussed Ta/Co/Cu/Co/Ta.

2. Sample growth and characterization.

2.1. Thin-film growth

Thin-film magnetic structures of Ta/Co/Cu/Co/Ta were deposited using magnetron sputtering on glass substrates (Corning Glass 2845). The deposition was carried out in a constant magnetic field of $2 \times 10^2$ A/m and directed parallel to the substrate surface to create an axis of easy magnetization. The deposition chamber was kept at a base pressure of $4 \times 10^{-2}$ Pa. Argon was used as a sputtering gas at a pressure of $3.8 \times 10^{-2}$ Pa. The thicknesses of deposited layers were controlled by the sputtering time using pre-calibrated deposition rates. The deposition rates for Co and Cu were 0.4 nm/s and 0.3 nm/s, respectively. The structure of the samples included five layers of Ta/Co/Cu/Co/Ta with cobalt and tantalum thicknesses of 5 nm, and the thickness of the copper layer was varied from 0.6 to 4 nm in steps of about 0.3 nm.

2.2. XRR and XSW data acquisition

Experimental measurements were carried out at the «Langmuir» beamline of the Kurchatov synchrotron radiation source. Radiation at an energy of 13 keV generated by bending magnets was used. The beam was conditioned using the double Si (111) crystal monochromator with the energy resolution of 2.5 eV, a collimator system and a flat quartz mirror to suppress high harmonics. The radiation energy was set to be above the L1 absorption edge of tantalum atoms of 11.68 keV, and the K-absorption edges of cobalt of 7.71 keV and copper of 8.98 keV. The optimal X-ray beam energy must be higher than all absorption edges to obtain the distribution of an element over the sample depth. This analysis algorithm includes the modeling of entire XRF spectrum, by taking into account tabulated emission energies for specified element with the known width and peak shapes, escape peaks and background. Such simulated spectra are fitted to measured data by varying the effective concentrations of chemical elements. The intensity of characteristic lines for each element extracted from individual spectrum is used as the data point in the angular-dependent XRF curves. As the result, angular dependencies of the fluorescence yield intensities for each chemical element from the structure are obtained. Finally, such angular-dependent XRF curves are corrected for the fluorescence detector dead time, the intensity of the primary synchrotron beam and the geometrical effect as calculated from the beam profile, sample size and fluorescence detector efficiency function.

2.3. Hybrid X-ray data analysis

In the classical approach [8] to X-ray reflectivity data analysis the sample is modeled as a stack of layers, where each layer is defined by a thickness, optical constant and a thickness of interface transition layer [5]. The effect of interfaces on XRR simulations is modelled by the Debye-Waller or Nevot-Croce damping factors for specular reflection intensity. These approximations, although numerically elegant, are obtained for the error function interface optical constant gradients that corresponds to normal distribution of roughness heights [9] and therefore are valid only for small roughness values. In real samples, interfaces can be extended and the shape of the optical constant profile can be more complicated, thus requiring a more flexible and stable approach to analyzing the experimental XRR data.

XRR data analysis was performed by describing studied system using “free-form” formalism [10]. Within this approximation, the sample structure is represented as an array of thin sub-layers of a given chemical composition and density. The lamellas have equal thickness,

challenging task. The X-ray reflectivity (XRR) technique is one of the best candidates for the reconstruction of layers thicknesses and interfaces roughness/diffusion in nm thin films. It is based on the analysis of the angular dependence of the intensity of X-ray beam specularly reflected from thin-film structure. The high sensitivity of XRR to structural features is due to the optical constants’ contrast (which is the function of electron density), providing formation of bright interference pattern makes it possible to reconstruct the optical constants profile [5]. However, the optical constants of neighbors in the periodic system, Co and Cu, are very close, and as will be shown, significantly obscures the analysis of the structure of Cu layer.

The X-ray standing wave method under total external reflection conditions consists of measuring and analyzing the angular dependencies of the fluorescent yield. Spectral selectivity allows us to obtain the distribution of an element over the sample depth. This method is based on the effect of the formation of the X-ray standing wave (XSW) inside the structure, which is caused by the interference of coherent waves that have close amplitude values (waves incident on the sample and reflected from it) in the region of their overlap. The crucial feature of the generated wave’s field of a standing wave is a periodic change in the electromagnetic field along the depth of the sample which forms areas of minimal amplitude (nodes) and maximal amplitude (antinodes). While changing the angle of radiation incident on the depth, causing effective modulation of the fluorescent radiation yield from the atoms of the structure [6].

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PyMCA software [7] was used to analyze XRF spectra and to retrieve XRF counts for Ta, Cu, and Co. The analysis algorithm includes the modeling of entire XRF spectrum, by taking into account tabulated emission energies for specified element with the known width and peak shapes, escape peaks and background. Such simulated spectra are fitted to measured data by varying the effective concentrations of chemical elements. The intensity of characteristic lines for each element extracted from individual spectrum is used as the data point in the angular-dependent XRF curves. As the result, angular dependencies of the fluorescence yield intensities for each chemical element from the structure are obtained. Finally, such angular-dependent XRF curves are corrected for the fluorescence detector dead time, the intensity of the primary synchrotron beam and the geometrical effect as calculated from the beam profile, sample size and fluorescence detector efficiency function.

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XRR data analysis was performed by describing studied system using “free-form” formalism [10]. Within this approximation, the sample structure is represented as an array of thin sub-layers of a given chemical composition and density. The lamellas have equal thickness,
the value of which is determined by the maximum angular range ($\theta_{\text{max}}$) of the experimental data as

$$d_{\text{max}} = \frac{1}{2} \frac{2\pi}{q_{\text{B}(<\text{max})}}$$

where $q_{\text{B}(<\text{max})} = \frac{4\sin(\theta_{\text{max}})}{\lambda}$ is the maximum length of the scattering vector and $\lambda$ is the wavelength.

In this approach, the chemical composition of each individual sub-layer is a fitting parameter. Therefore, the stoichiometry of each sub-layer allow simultaneous calculation as the optical constant profile for simulation of XRR [11] and XSW distributions [12,13] in the film for each incidence angle and, at the same time, use those atomic distribution profiles for the simulation of angular dependent fluorescence yields for each chemical element [14]. The free-form of the sample profile with some certain physical constraints allows reconstruction of a complex profile of extended interfaces, gradient and oxide layers without a priori knowledge of the sample structure [15].

In our study, the XSW was used to reconstruct the distribution of Ta, Cu and Co. The modulation of the intensity of fluorescent radiation yield from ith type of atoms is determined by the structure of the wave field inside the sample $|E(\theta, z)|^2$ where $\theta$ is the incidence angle, $z$ is the depth and $P(z)$ is the atomic distribution profile in the structure. In our free-form approach, following the dipole approximation we simulate the angular dependence of the fluorescence radiation yield $F(\theta)$ as the sum over all sub-layers of the products of the wave field distribution and the concentration of fluorescent atoms in each j sublayer $P_j$. It is also important to take into account the geometric factor $G(\theta)$ and absorption of fluorescent radiation:

$$F(\theta) = G(\theta) \sum_j P_j |E(\theta, z)|^2 e^{-\mu z}$$

In Eq. (2) $\mu$ is the average linear coefficient of fluorescent radiation absorption in j sub-layer of the structure, the geometric factor $G(\theta)$ is presented in detail in [16]. The set of distribution profiles of all elements over the structure depth $P(z)$ obeys the stoichiometry condition in each lamella over the entire structure thickness:

$$P_{\text{Ta}} + P_{\text{Cu}} + P_{\text{Co}} + P_{\text{O}} = 1.$$  

(3)

Joint analysis of the experimental angular dependences of specular reflection and fluorescence emission from our three elements Ta, Cu, Co consisted in follows: the set of profiles $P_{\text{Ta,Cu,Co}}(z)$ determined the optical constants profile which are used for calculation of the theoretical specular reflection curve ($I_{\text{calc}}^{\text{XRR}}(q)$) and the corresponding distribution of the wave field intensity $|E(\theta, z)|^2$. The intensity of the wave field and the profiles of the distribution of elements $P_{\text{Ta,Cu,Co}}(z)$ are used to calculate three theoretical curves of the fluorescent radiation yield ($I_{\text{calc}}^{\text{XSW}}$). The simulated angular dependences of specular reflection and fluorescence radiation yield were fitted to experimental minimizing the modified goodness-of-fit criterion $\chi^2$. As result of analysis the atomic concentrations in sub-layers $P_{\text{Ta,Cu,Co}}(z)$ that provides best-fit were found. To estimate the goodness-of-fit for a set of four different experimental data $\chi^2$ criterion was modified as follows:

$$\chi^2 = \frac{1}{N_{\text{XRR}} + 3N_{\text{XSW}}} \left( \sum_{\text{XRR}} \left( \frac{I^{\text{exp}}_{\text{XRR}} - I^{\text{calc}}_{\text{XRR}}}{\sigma_{\text{XRR}}} \right)^2 + \sum_{\text{XSW}} \left( \frac{I^{\text{exp}}_{\text{XSW}} - I^{\text{calc}}_{\text{XSW}}}{\sigma_{\text{XSW}}} \right)^2 \right)$$

(4)

where $N_{\text{XRR}}$ is the number of experimental points on the XRR curve, $N_{\text{XSW}}$ is the number of experimental points for the fluorescence yield curves, $n$ is the number of model parameters and $\sigma_{\text{XRR}}, \sigma_{\text{XSW}}$ are the errors in measuring of the intensity of the specular reflection and of the fluorescence yield, respectively.

3. Results and discussion

3.1. XRR analysis results

In Fig. 2a we show measured and best-fit simulations of XRR data. The corresponding best-fit depth profiles of the dispersion term ($\delta$ as $n = 1 - \delta - i|\beta|$) of the refraction index are shown in Fig. 2b. From these profiles we can clearly identify two Ta layers with thicknesses of 4.8 ± 0.3 nm since Ta has about 1.5 times the refractive index of Cu and Co for 0.095 nm wavelength. We have noted that for all samples, the surface tantalum layer is 16 ± 2% less dense than Ta grown on a substrate. Fig. 2b shows that all samples have about 2 nm surface layers that we attribute to a naturally formed Ta$_2$O$_5$ layer. The widths of interfaces at the Co/Ta boundaries are similar for all samples and have thicknesses ranging between 1 and 1.2 nm for the lower interface and from 1.9 to 2.1 nm for the upper one. The presence of such transition regions is consistent with the results obtained by the X-ray diffraction study of similar samples [4], in which Shalygina et al. found an increase in the cobalt lattice parameters in that structures caused by the diffusion of tantalum.

The Co/Cu/Co layers region has a total thickness of about 15 nm and an almost uniform dispersion index profile. As expected, for X-ray wavelengths far from the absorption edges of Co and Cu – including those used here of 0.095 nm – Co and Cu show very weak optical contrast because of the close values of the atomic scattering factors and bulk density values (8.9 g/cm$^3$ and 8.96 g/cm$^3$, respectively). The refractive index profiles obtained from the analysis of the XRR data do not allow characterization of the effectiveness of the Cu barrier layer in separating magnetic Co layers here. Such a lack of information caused by
close optical constant values is typical for an XRR study of Co/Cu systems [17,18]. Marszalek et al. [19] reported that periodic multilayered Co/Cu structures grown by thermal sputtering are characterized by a strong smearing of interfaces at a level of 3 nm, which could additionally intricate studying of barriers in Co/Cu structures. Based on this observation, we can conclude that classic XRR measurements are not appropriate for characterization of Co/Cu separation because of their similar densities.

3.2. XSW analysis results

Fig. 1 shows that on the XRF spectra we can clearly distinguish signals from Cu and Co, meaning that XSW data will add material contrast to hybrid XRR-XSW data.

Before describing the results of the XSW analysis, we will elaborate on the specifics of the structure of characterized samples and their influence on the XSW data analysis. Fig. 3a shows the simulated angular dependence of the distribution of electromagnetic wave intensity in the studied sample. The wave modulations are typical for the X-ray waveguide structures that are typically observed for specially designed samples [20,21] as it increases significantly the in-depth sensitivity of the XSW analysis. This effect was used, for example, for the increase of the analysis sensitivity to the density of ultra-thin films [22] structure of magnetic layers [23]. For our samples, the waveguide was formed by the sample as is without any explicit design. Two dense tantalum layers in the structures play the role of the walls of a planar waveguide, while three light Co/Cu/Co layers form a waveguide channel.

The calculations of the wave-field shown in Fig. 3 was carried out using the Abel matrix formalism [24] with a step of ~0.1 nm in depth for the refractive index profile reconstructed by the XRR data (Fig. 3b) discussed previously. The Fig. 3a clearly shows the localized antinodes of the standing X-ray wave field corresponding to the TE0, TE1 and TE2 wave modes. The angular positions of the TE0, TE1 and TE2 wave modes inside the waveguide channel correspond to the positions of the first three interference minima on the X-ray reflectivity curve (Fig. 3c). Due to the extended Ta/Co and Co/Ta interfaces (at depths of 7.5 and 23 nm correspondingly in Fig. 3b) the antinodes of the field become poorly localized in the region of the fourth interference minimum and the modulation of the wave field intensity decreases to a level of 10%. As follows from Eq. (2), the antinodes of the field at the points corresponding to the wave modes will increase the intensity of the fluorescent emission and form the corresponding peaks. The strongest modulation of the angular dependence of the fluorescence radiation yield will be observed in the region of the first three waves’ modes, and the ratio of the amplitudes of the peaks in TE0, TE1, TE2 and their angular displacements will be determined by the distribution of fluorescent atoms along the depth. Assuming the Cu layer are located in the center of the waveguide channel, the most intense peak of Cu fluorescence yield should be in TE0, while the TE1 peak should be strongly suppressed. The broader Cu distribution – the higher TE1 peak can be observed. For the Co layers which are located closer to the walls of the waveguide, the TE1 peak will be the most intense, since the two antinodes of the field for this wave mode are also localized near the walls. The TE0 peak for the Co layer can act as the main measure of the presence of Co in the center of the waveguide channel.

The result of the analysis of the angular dependences of the fluorescence yield for the 2.8 nm sample is shown in Fig. 4, and the obtained profiles of the distribution of Ta, Cu, Co over the structure depth for samples with various thicknesses of the copper barrier layer are shown in Fig. 5. The combined free-form analysis of XSW and XRR data allowed

Fig. 3. a – distribution of the wave field intensity inside the Ta/Co/Cu/Co/Ta multilayer structure; b – electron density profile of the structure; c – XRR curve near the region of total external reflection.
The as-deposited thickness of a copper layer is indicated by the scale bar above with an as-deposited Cu layer thickness of 2.8 nm.

Profiles of the distribution of elements over the depth of the structure.

For samples with thin copper layers that have as-deposited thickness values of 1–3 nm, the half-width of the copper atoms distribution ranges from 3.7 to 4 nm. The increase of the half-width of the copper distribution resulting from an increase in the as-deposited thickness starts from about 3 nm, and for the as-deposited thickness of 4 nm the half-width of the reconstructed atomic distribution is 4.5 nm.

The experimental curves of the Cu fluorescence for all samples have almost the same overall shape: a narrow peak for the TE0 mode, a local minimum for the TE1 mode and a wide peak for TE2. Even qualitatively, from the observation that all samples show similar fluorescence yield angular dependencies, we can conclude that element distribution profiles in the measured samples are also similar. The main difference among the obtained atomic profiles is the shape of cobalt atomic distribution and the relative concentration of copper atoms.

The accuracy of the determination of the distribution parameters depends on the shape of the experimental curve and its error. In our case, the position of the Cu distribution center is determined at an accuracy of ±0.06 nm, and the accuracy of the distribution half-width estimation is ±0.3 nm. Such low accuracy of profiles of the shape of the Cu atoms distribution can be explained by the size of the smallest profile feature that can be resolved from XSW data analysis alone. Fig. 3 shows that the phase modulations of XSW in our structure are significant only in the low-angle region up to a 0.5 deg incidence angle. The XRR curve (see Fig. 2a) is informative up to 2.5 deg, enabling the reconstruction resolution of 0.5 nm. That allows resolution of the fine elements of the interfaces of optically-contrast elements interfaces such as air-to-Ta and Ta-to-Co. This illustrated that in such hybrid approach the resolution of reconstructed profile is limited by the resolution of XRR data. It should be noted that XSW-only analysis may also be used for the characterization of positions and widths of atomic distribution, although with limited sensitivity to interface shapes.

3.3. Analysis of obtained atomic profiles and discussion.

Based on the reconstructed atomic profiles (Fig. 5) we can conclude that, in the samples featuring as-deposited copper thicknesses of 1.2 nm and 2.8 nm, the barrier layer forms a solid solution of copper and cobalt in varying proportions. The maximum copper concentrations in these samples reaching 50% and 68%, respectively. The continuous copper layer separating the cobalt layers is formed only in the sample that has an as-deposited copper layer thickness of 4 nm. The formation of a solid Cu-Co compound explains the comparable Cu atoms’ distribution width. This effect could be caused by the island-mode growth of the Cu layer during the initial stage of deposition. In this mode copper clusters are first formed on the cobalt surface until the threshold size of 3 nm is reached, and then the space between the clusters is filled with the Co atoms from the following layer. A consistent increase of the surface Gibbs energy for Cu, Co, and Ta (1934, 2709, and 3018 mJ/m², respectively) causes the non-wettability of copper with cobalt and cobalt with tantalum, which suggests the island growth also on the top Co and Ta layers. Such growth explains the increase in the width of the interfaces of the overlying top layers in the multilayers studied.

In [26] was shown the formation of up to 2 nm- high islands of thermally sputtering copper layers on top of cobalt. Also, the 2.5 nm height Co islands were observed for Co layers grown on copper. The obtained distributions of Cu in combination with the mixing regions of Cu and Co for small as-deposited thicknesses of the barrier layer observed here are in good agreement with observations of Marxzelek et al.

To obtain atomically smooth cobalt-copper interfaces, a layer of surface-active atoms – for example, indium or lead – can be used [27].
The surfactant atoms move to the surface during the deposition of copper and cobalt, reducing the energy barrier during the transition of Cu and Co adatoms from the island to the lower level and equalizing the growth rate over the sample surface. However, the effect of surfactants on the growth of Co/Cu structures by magnetron sputtering is still little studied and sometimes leads to contradictory results. In particular, the roughness at the boundaries could be increased, but at the same time the magnetic characteristics could be improved due to the more ordered direction of crystallization [28]. The hybrid method for analyzing layered structures presented in this work can be highly effective not only for determining the profiles of the main elements, but also for studying the behavior of surfactant atoms. The conditions of total external reflection allow the detection of the fluorescent signal from atoms in trace concentrations, which allows localization of the position in depth of the impurity atoms that do not affect the optical constants profile.

The oscillating dependence of the saturation field on the thickness of the copper layer obtained earlier for these samples [1] can be caused by the Néel interaction between islands in the three-dimensional structure of cobalt (the so-called “orange peel” effect) [29] arising from the correlation of roughness at the interfaces of the ferromagnetic and paramagnetic layers. The magnetism of the exchange interaction is isotropic, while conversely the “orange peel” effect is anisotropic [30], which makes it possible to separate the contributions to the magnetism of the layered Co/Cu structure of the exchange and Néel interactions by considering the angular dependence of the magnetization.

4. Conclusion

The results of the study of the structure of the multilayer magnetic systems with exchange interaction between magnetic layers of Co through a nonmagnetic separating Cu layer has been presented in this work. By applying the X-ray reflectivity, the optical constants profiles of the samples were reconstructed, the presence of an oxide layer on the surface was shown, and the thicknesses of the transition regions for the upper and lower tantalum layers were determined. To study low-contrast Co/Cu/Co layers and to obtain information on the state of the copper barrier layer, the X-ray standing waves method was used. Hybrid analysis of X-ray reflectivity and X-ray standing waves data allowed us to reconstruct the profiles of the distribution of elements over the structure depth. For all the studied samples, the copper layer was localized in the center of the structure at a distribution width of 3.7–4.4 nm and a weak dependence on the as-deposited layer thickness. The barrier layer is a solid solution of copper and cobalt of variable composition for samples that have thin as-deposited Cu layers (1–3 nm), and the complete separation of magnetic layers occurs only at a copper thickness of about 4 nm. This distribution of the copper layer was found to be associated with complex growth mechanisms at the Co/Cu and Cu/Co boundaries, leading to the formation of island structures and effective mixing of materials. The formation of a CoCu solid solution, which forms an additional magnetic phase, will undoubtedly create additional effects in the magnetic and magneto-transport properties of the studied systems. The discovered structural features of the Co/Cu/Co system that have thin barrier layers should be taken into account when analyzing the behavior of surfactant atoms from the island to the lower level and equalizing the thickness of the nonmagnetic layer.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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