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The effect of giant magnetoresistance in Co/Cu/Co structure

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The dependence of the giant magnetoresistance on the ratio of Co layers in as condensed Co/Cu/Co structures was studied both theoretically and experimentally. The maximum magnetoresistive ratio for this system was established to observe at equal thicknesses of the magnetic layers with 3 nm copper spacer.

Теоретически и экспериментально исследована зависимость гигантского магнитосопротивления от отношения толщин слоев Co для свежеконденсированых Co/Cu/Co структур. Установлено, что максимальное магниторезистивное отношение для указанной системы наблюдается при равных толщинах магнитных слоев и толщине медной прослойки в 3 нм.

The dependence of the giant magnetoresistance on the ratio of Co layers in as condensed Co/Cu/Co sandwich was studied both theoretically and experimentally. The maximum magnetoresistive ratio for this system was established to observe at equal thicknesses of the magnetic layers with 3 nm copper spacer.

The progress achieved in the thin film technology has allowed discovering in fact a new class of conductors as the multilayer magnetic films which are periodical systems of alternating layers of magnetic and non-magnetic materials. Such the structures demonstrate unique electrophysical properties which cannot be realized in homogeneous conductors, and recently these are used widely in microelectronics and computer engineering that causes permanent interest in experimental and theoretical investigations thereof [1,2].

Among the various effects observed in magnetic conductors, the most practical interest is attracted by the effect of giant magnetoresistance (GMR), which was observed first in multilayer [3] and three-layer [4] Fe/Cr magnetic films and manifested itself in decreasing resistance under relatively low magnetic field. Later on the giant magnetoresistance effect was found for wide variety of magnetic and non-magnetic metal layer combinations [2].

The objective of the present report is theoretical and experimental studying the effect of giant magnetoresistance in Co/Cu/Co sandwich with polycrystalline structure. It is shown, the observed GMR effect can be adequately described in the framework of the two-current model [5], and the modified Mayadas & Shatzkes model (MS model) [6].

Let us consider a sandwich consisting of two polycrystalline metallic layers of different thickness $\left(d_j \neq d_n\right)$ separated by ultrathin interlayer which causes formation of an anti-ferromagnetic (AP) configuration (magnetization vectors are anti-parallel in magnetic layers) in this simple model. The layer thicknesses are assumed to be significantly larger than de Broglie wavelength of electrons, thus, spin-polarized electronic transport in the sandwich can be adequately described using the quasi-classical distribution function.

In order to calculate the current density $\mathbf{J}_{AP}$ within the limits of the two-current model [5] (spin-flip processes are assumed occasional, so can be neglected for low temperatures [2])

$$\mathbf{J}_{AP} = \frac{e}{dh^3} \sum_{s=\pm} \sum_{j\neq n=1}^{2} \int_0^{d_j} dx \int d^3 p^{(n-j)s} \mathbf{v}_j^{(n-j)s} f_j^{(n-j)s}\left(|x|, \mathbf{p}^{(n-j)s}\right), \tag{1}$$

the kinetic equation for the electron distribution function is to be solved

$$f_j^{(n-j)s}(x, \mathbf{p}^{(n-j)s}) = f_0^{(n-j)s} - \frac{\partial f_0^{(n-j)s}}{\partial \varepsilon_j^{(n-j)s}} \Psi_j^{(n-j)s}\left(x, \mathbf{p}^{(n-j)s}\right). \tag{2}$$

In $\tau -$ approach for volume collision integral this has the following form:

$$\frac{\partial \Psi_j^{(n-j)s}}{\partial t} + \frac{\Psi_j^{(n-j)s}}{\tau_j^{(n-j)s}} = e\mathbf{v}_j^{(n-j)s}\mathbf{E}. \tag{3}$$

In equations (1)–(3): $d -$ the sandwich thickness: e, x and $\mathbf{p}^s$ are electronic charge, coordinate, and quasi-momentum; $\mathbf{v}_j^s$ и ε_j^s – velocity and energy thereof; $h -$ Planck constant; $\mathbf{E} = (0, E, 0) -$ uniform electrostatic field intensity vector applied along the layer interface; f_0^s - Fermi function of electron distribution; $t -$ time of charge carrier motion along the trajectory; $s = \pm(\uparrow\downarrow)$, and determines a sign of the spin projection onto the local magnetization vector in the magnetic layer $(-s = \mp)$.

The value τ_j^s in Eq. (3) describes the spin-polarized electron flux relaxation on impurities and inter-crystallite boundaries, and within Mott [5] and MS models it is expressed as [5, 6]:

$$\frac{1}{\tau_j^s} = \frac{1}{\tau_{0j}^s}\left\{1 + \alpha_j^s \frac{p_F}{|p_{yj}|}\right\}, \tag{4}$$

where τ_{0j}^s – carrier free path time; $\alpha_j^s = \frac{l_j^s}{L_j}\frac{R_j^s}{1 - R_j^s}$; $l_j^s -$ spin-dependent free path of electrons; $L_j -$ crystallite average size along metal layer plane; R_j^s – probability of carrier diffuse scattering on the inter-crystallite boundaries.

The general solution of the kinetic equation (3) is the following function

$$\Psi_j^{(n-j)s}(x, \mathbf{p}^{(n-j)s}) = F_j^{(n-j)s} e^{\frac{\lambda - t}{\tau_j^{(n-j)s}}} + \int_\lambda^t dt' e\mathbf{v}_j^{(n-j)s}\mathbf{E} e^{\frac{t' - t}{\tau_j^{(n-j)s}}}, \tag{5}$$

in that the value $\lambda < t$, and means a moment of the last interaction between an electron and external boundaries $(x_s = -d_1, d_2)$, or interface $(x_s = 0)$ of the sandwich, while F_j^s arbitrary functions should be defined using boundary conditions as follows [7]:

$$\Psi_j^{s_j;(n-j)s}\left(s_n d_j, \mathbf{p}^{(n-j)s}\right) = q_j^{(n-j)s} \Psi_j^{s_n;(n-j)s}\left(s_n d_j, (\mathbf{p}')^{(n-j)s}\right), \tag{6}$$

$$\Psi_j^{s_n;(n-j)s}\left(0, \mathbf{p}^{(n-j)s}\right) = P_{jn}^{(n-j)s} \Psi_j^{s_j;(n-j)s}\left(0, (\mathbf{p}')^{(n-j)s}\right) + Q_{nj}^{(j-n)s} \Psi_n^{s_n;(j-n)s}\left(0, (\mathbf{p}'')^{(j-n)s}\right). \tag{7}$$

Here q_j^s and P_{nj}^s are the probabilities of electron specular reflection from external boundaries and interface, respectively; Q_{nj}^s - the probability of electron transmission into neighboring layers without scattering, so that $P_{jn}^s + Q_{nj}^{-s} \le 1$; $\mathbf{p}^s$, $(\mathbf{p}')^s$, and $(\mathbf{p}'')^s$ quasi-momentums are related by the specular reflection conditions; $s_j = sign v_{xj}^s$ indicates the sign of the normal to boundaries velocity constituent v_{xj}^s.

Substituting the Ψ_j^s functions (Eq. (5)) into (6) and (7) boundary conditions, we get a system of 8 linear algebraic equations in the unknown F_j^s. Having known the Ψ_j^s distribution function and assuming square-law and isotropic electron dispersion law in each sample layer, it is possible to compute the current density (1), and to describe the sandwich conductivity in the following form, respectively:

$$\sigma_{AP} = \sum_{s=\pm} \sum_{j\neq n=1}^{2} \sigma_{APj}^{(n-j)s} = \frac{1}{d} \sum_{s=\pm} \sum_{j\neq n}^{2} d_j \sigma_{0j}^{(n-j)s} \Phi_{APj}^{(n-j)s}, \tag{8}$$

where σ_{0j}^s determines the volume conductivity of the magnetic layer, and the Φ_{APj}^s dimension functions equal to

$$\Phi_{APj}^s = \frac{\sigma_{gj}^s}{\sigma_{0j}^s} - \frac{3}{\pi k_j^s} \int_0^{\pi/2} d\varphi \cos^2\varphi \int_0^1 dx \frac{(x - x^3)(1 - E_j^s)}{H_j^{s2}} G_j^s, \tag{9}$$

$$G_j^s = 2 - \frac{1}{\Delta^{(n-j)s}} \Big\{ (1 - E_j^s) \Big[(q_j^s + P_{jn}^s + 2q_j^s P_{jn}^s E_j^s)(1 - q_n^{-s} P_{nj}^{-s} E_n^{-s2}) +$$

$$+ q_n^{-s} Q_{jn}^s Q_{nj}^{-s} E_n^{-s2} (1 + 2q_j^s E_j^s) \Big] + Q_{nj}^{-s} \frac{\tau_{0n}^{-s} H_j^s}{\tau_{0j}^s H_n^{-s}} (1 - E_n^{-s})(1 + q_j^s E_j^s)(1 + q_n^{-s} E_n^{-s}) \Big\},$$

$$\Delta^s = (1 - q_j^s P_{jn}^s E_j^{s2})(1 - q_n^{-s} P_{nj}^{-s} E_n^{-s2}) - q_j^s q_n^{-s} Q_{jn}^s Q_{nj}^{-s} E_j^{s2} E_n^{-s2},$$

$$E_j^s = \exp\left\{ -\frac{k_j^s H_j^s}{x} \right\}, \quad H_j^s = 1 + \frac{\alpha_j^s}{\cos\varphi \sqrt{1 - x^2}}, \quad k_j^s = \frac{d_j}{l_j^s}.$$

The $\sigma_{gj}^s / \sigma_{0j}^s$ function in Eq. (9) defines the conductivity of a bulk polycrystalline metal, and within Mott [5] and MS [6] models this is expressed as

$$\frac{\sigma_{gj}^s}{\sigma_{0j}^s} = 1 - \frac{3}{2}\alpha_j^s + 3\alpha_j^{s\,2} - 3\alpha_j^{s\,3} \ln\left(1 + \frac{1}{\alpha_j^s}\right) \cong \begin{cases} 1 - \frac{3}{2}\alpha_j^s + 3\alpha_j^{s\,2}, & \alpha_j^s << 1, \\ \frac{3}{4\alpha_i^s} - \frac{3}{5\alpha_j^{s\,2}}, & \alpha_j^s >> 1. \end{cases} \tag{10}$$

Let us assume, that the magnetic field necessary for magnetic sandwich $AP \to P$ configuration transition (magnetization vectors in the magnetic layers are parallel) is comparably low, so, its effect on electron motion trajectories can be neglected. In this case, the P configuration magnetic sample conductivity is determined as follows:

$$\sigma_P = \sum_{s=\pm} \sum_{j=1}^{2} \sigma_{Pj}^s = \frac{1}{d} \sum_{s=\pm} \sum_{j=1}^{2} d_j \sigma_{0j}^s \Phi_{Pj}^s. \tag{11}$$

In this, the Φ^s_{Pj} dimension functions are defined by Eq. (9) in which $-s \to s$ substitution should be done.

Thus, we have got general expressions for specific conductivities σ_{AP} (8) and σ_P (11), which permit to describe in explicit form the δ_{AP} value, being a quantitative characteristic of the giant magnetoresistance effect:

$$\delta_{AP} = \frac{\Delta\sigma}{\sigma_{AP}} \equiv \frac{\sigma_P}{\sigma_{AP}} - 1\,. \tag{12}$$

Subsequent analysis of the GMR effect is possible only in terms of numerical analysis. However, before to begin the numerical calculations, we'll get simple analytical expressions for estimation of the effect amplitude.

If the interlayer one and the external boundaries scatter the charge carriers in specular manner, the sandwich may be formally considered as the bulk sample [8, 9] which conductivity is expressed by Eq. (10).

Using the resistor model [2], for the value δ_{AP} the following expression can be written:

$$\delta_{AP} = \frac{(\alpha_{g1}-1)(\alpha_{g2}-1)}{\alpha_{g1}(1+\beta_g)+\alpha_{g2}\left(1+\beta_g^{-1}\right)} = \begin{cases} \dfrac{(1-\alpha_g)^2}{4\alpha_g}, & \alpha_{gj}=\alpha_{gn}=\alpha_g, \beta_g=1, \\ 0, & \alpha_{gj}=1. \end{cases} \tag{13}$$

Here $\beta_g = \sigma^+_{g2}/\sigma^+_{g1}$, while the parameters $\alpha_{gj} = \rho^-_{gj}/\rho^+_{gj} \equiv \sigma^+_{gj}/\sigma^-_{gj}$ define the asymmetry of the spin-dependent scattering (SDS) of electrons in the bulk of metal polycrystalline layers.

If the layers, the sandwich consist of, have coarse-grained structures $\left(\alpha^s_j << 1\right)$, the electron scattering at the grain boundaries can be neglected comparing to the bulk scattering thereof, so the Eq. (13) transforms into the well-known expression [2]:

$$\delta_{AP} = \frac{(\alpha_{b1}-1)(\alpha_{b2}-1)}{\alpha_{b1}(1+\beta_b)+\alpha_{b2}\left(1+\beta_b^{-1}\right)} = \begin{cases} \dfrac{(1-\alpha_b)^2}{4\alpha_b}, & \alpha_{b1}=\alpha_{b2}=\alpha_b, \beta_b=1, \\ 0, & \alpha_{bj}=1, \end{cases} \tag{14}$$

where $\beta_b = \sigma^+_{02}/\sigma^+_{01}$, and the parameters $\alpha_{bj} = \rho^-_{0j}/\rho^+_{0j} \equiv \sigma^+_{0j}/\sigma^-_{0j}$ assign the SDS asymmetry of the electrons in the bulk of metal single-crystalline layers [10].

If the opposite inaquation is valid$\left(\alpha^s_j >> 1\right)$, i.e. the sandwich has fine-grained structure, the giant magnetoresistance effect would be caused by the scattering asymmetry of the charge carriers with different spin polarization at the grain boundaries, and its amplitude is:

$$\delta_{AP} = \frac{(\alpha_{R1}-1)(\alpha_{R2}-1)}{\alpha_{R1}(1+\beta_R)+\alpha_{R2}\left(1+\beta_R^{-1}\right)} = \begin{cases} \dfrac{(1-\alpha_R)^2}{4\alpha_R}, & \alpha_{R1}=\alpha_{R2}=\alpha_R, \beta_R=1, \\ 0, & \alpha_{Rj}=1, \end{cases} \tag{15}$$

where $\beta_R = \left(L_2 R_1^+\right)/\left(L_1 R_2^+\right)$, and the parameters $\alpha_{Rj} = R_j^-/R_j^+$ define the SDS asymmetry of the charge carriers at intercrystalline boundaries.

Analysis of the Eqs. (13) – (15) show that in the case of different scattering asymmetry of the electrons with diverse spin polarization in various spin magnetic layers due to impurities therein ($\gamma_1 > 1, \gamma_2 < 1$ or vice versa, where $\gamma_j = \alpha_{gj}, \alpha_{bj}, \alpha_{Rj}$), the sign of the effect may be inversed [11].

Since the sandwich, which external boundaries scatter electrons specularly, can be regard as multi-layer [7], the formulas (13) – (15) may be used for estimation of the effect in the multilayer magnetic film.

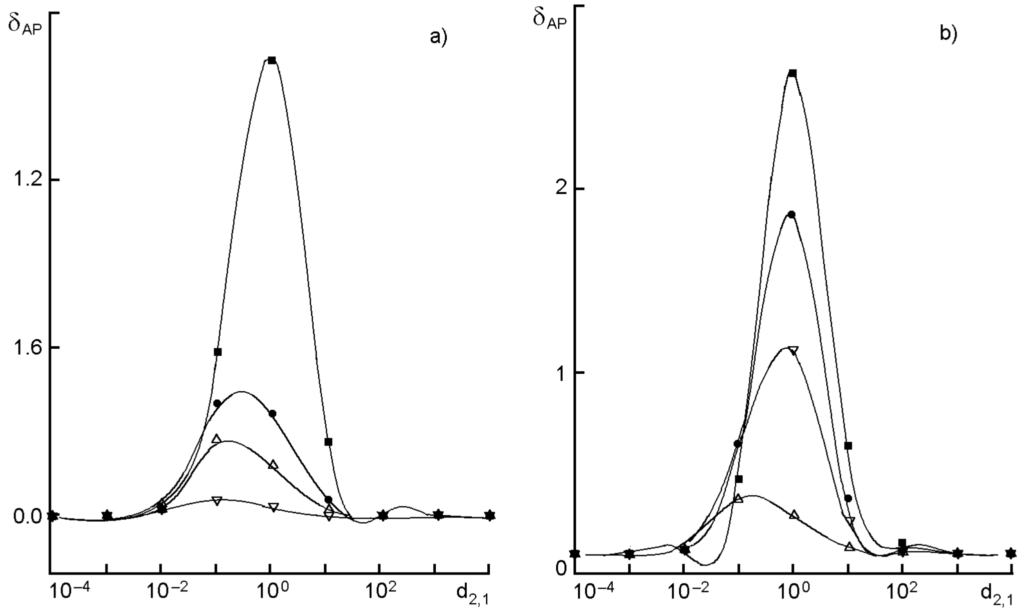

Fig.1. Numerically calculated δ_{AP} versus the magnetic layer thickness ratio for the magnetic sandwich with polycrystalline structure at the following parameter values:
$P_{jn}^{s} = Q_{jn}^{s} = 0{,}1$, $l_{1,2}^{-} = 1$, $\alpha_{j}^{+} = 5$, $R_{j}^{+} = 0{,}1$

a) $\alpha_{bj} = 1$, $\alpha_{Rj} = 6$, $q_{j}^{s} = 0{,}1$: *1* – $k_1^{-} = 0{,}1$; *2* – $k_1^{-} = 0{,}5$; *3* – $k_1^{-} = 1$; *4* – $k_1^{-} = 5$;

б) $\alpha_{bj} = 6$, $\alpha_{Rj} = 6$: *1* – $q_j^{s} = 0{,}3$, $k_1^{-} = 0{,}5$; *2* – $q_j^{s} = 0{,}1$, $k_1^{-} = 0{,}5$; *3* – $q_j^{s} = 0{,}1$, $k_1^{-} = 1$; *4* – $q_j^{s} = 0{,}1$, $k_1^{-} = 5$.

If a comparably poor magnetic anisotropy effect is neglected $\left[\left(\sigma_{01}^{-}\right)_{AP} = \left(\sigma_{01}^{-}\right)_{P}\right]$, for numerical calculations of the GMR effect in the magnetic sandwich the Eq. (12) is convenient to write in the following form:

$$\delta_{AP} = \left\{ \frac{\sum\limits_{j \neq n=1}^{2} \left(d_{j,n}\sigma_{0j,n}^{-}\right)^{j-1} \left\{\Phi_{Pj}^{-} + \alpha_{bj}\Phi_{Pj}^{+}\right\}}{\sum\limits_{j \neq n=1}^{2} \left(d_{j,n}\sigma_{0j,n}^{-}\right)^{j-1} \left\{\Phi_{APj}^{-} + \alpha_{bj}\Phi_{APj}^{+}\right\}} - 1 \right\} \cdot 100\%, \qquad (16)$$

in which the independent are the parameters of specularity, α_{bj}, α_{gj}^{+}, k_1^{-}, $\sigma_{0j,n}^{-} = \sigma_{0j}^{-}/\sigma_{0n}^{-} \sim \sim l_j^{-}/l_n^{-} \equiv l_{j,n}^{-}$ and R_j^{+}, while the rest can be expressed through the abovementioned independent ones as follows $k_1^{+} = k_1^{-}/\alpha_{b1}$, $k_2^{-} = d_{2,1}k_1^{-}l_{1,2}^{-}$, $l_{1,2}^{+} = \left(\alpha_{b1}l_{1,2}^{-}\right)/\alpha_{b2}$, etc.

In Fig.1, the curves obtained by the numerical calculation using the general equation (16) illustrate δ_{AP} dependence on the ratio of magnetic layers $d_{2,1} = d_2/d_1$ at different values of the parameters characterizing the sandwich. The curves indicate that both in the ranges of small and large $d_{2,1}$ values, the GMR effect is practically absent due to the shunting effect of the base layer of d_1 (if $d_{2,1} << 1$) thickness, or the upper layer of d_2 thickness (if $d_{2,1} >> 1$). The presence of the maximum in the $\delta_{AP}(d_{2,1})$ size dependence is caused by the competition of bulk and surface scattering [12], while the effect itself is governed by the asymmetry of the electrons spin-dependent scattering at grain boundaries (Fig.1,a). "Switching-on" the bulk SDS of the charge carriers (Fig.1, b) increases the effect amplitude and, consequently, a conclusion may be done that the degree thereof is determined by superposition of bulk and intercrystalline mechanisms of SDS electrons.

As the sandwich external boundary specularity increases, the effect amplitude rises as well

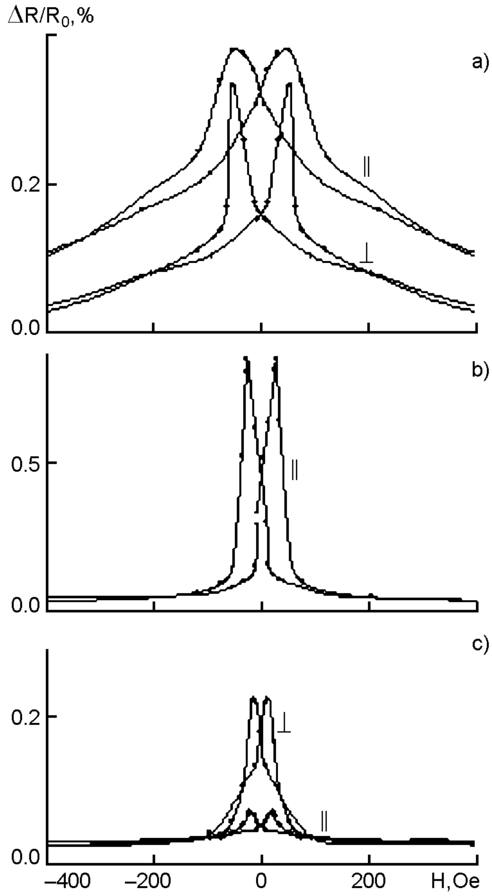

Fig. 2. Longitudial (||) and transversal (⊥) MR plots versus the magnetizing force for as-condensed three-layer Co/Cu/Co films with different Co layer thickness ratios ($d_{1(Co)}$ = 30 nm, d_{Cu} = 3 nm) and $d_{2(Co)}$: a – 10, b – 30, c – 70 nm.

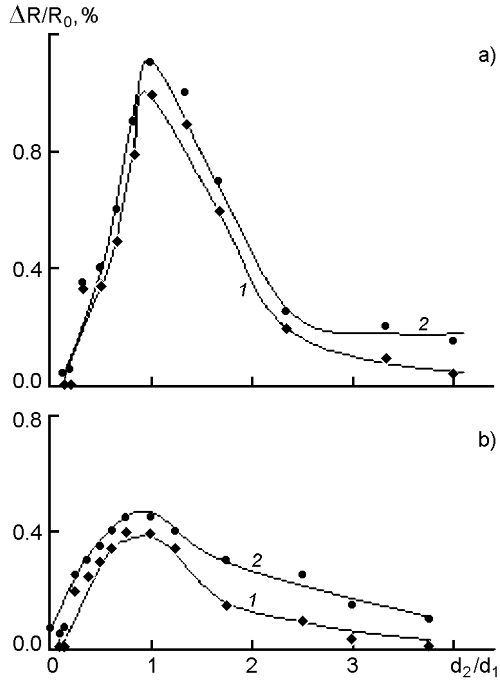

Fig.3. Longitudial (*1*) and transversal (*2*) magnetoresistance $\Delta R/R_0$ versus Co layer thickness ratios for as-condensed three-layer Co/Cu/Co films at fixed $d_{2(Co)}$: a – $d_{1(Co)}$ = 25, d_{Cu} = 3 nm; b – $d_{1(Co)}$ = 40, d_{Cu} = 6 nm

(Fig.1, b, curve *1*), because the electrons specularly reflected by the boundary remain effective (responsible for the effect – the conception of "non-effectivity" by Pippard [13]) owing to the charge carriers do not lose their spin "memory". Comparison of the numerically calculated curves (Fig.1) with respective experimental ones (Fig.3) shows a qualitative coincidence thereof, so, the effect observed can be concluded to be caused by the asymmetry of electron SDS at grain boundaries.

The Co/Cu/Co magnetic sandwiches with magnetic layer thicknesses d_{Co} from 2 to 150 nm and spacer thicknesses d_{Cu} from 2 to 10 nm were prepared in the vacuum setup VUP-5M (residual atmosphere pressure 10^{-4} Pa) using the electron-beam (Co) and the resistive (Cu) evaporation methods [14]. The films were deposited onto glass substrates at the room temperature, their thicknesses being controlled by the deposition time at the known condensation rate which was preliminary determined for a series of Co and Cu single-layer films. The thicknesses of the films obtained were measured with the micro-interferometer MP-4, and the computer interference pattern registration system [14]. To obtain the parallel orientation of the easy magnetization axes in the cobalt layers, the films were deposited in the external magnetic field of H = 8 kA/m (100 Oe). Magnetoresistance (MR) measurements of the samples were fulfilled at the room temperature in the specially made setup under conditions of super-high oil-less vacuum (10^7 Pa) in the magnetic field up to 150 kA/m; relative error was not more 0.05% [14].

In all the Co/Cu/Co samples studied, the MR hysteresis is observed indicating the existence of the domain structure therein. For the conductors with non-magnetic layer thicknesses below 2 nm,

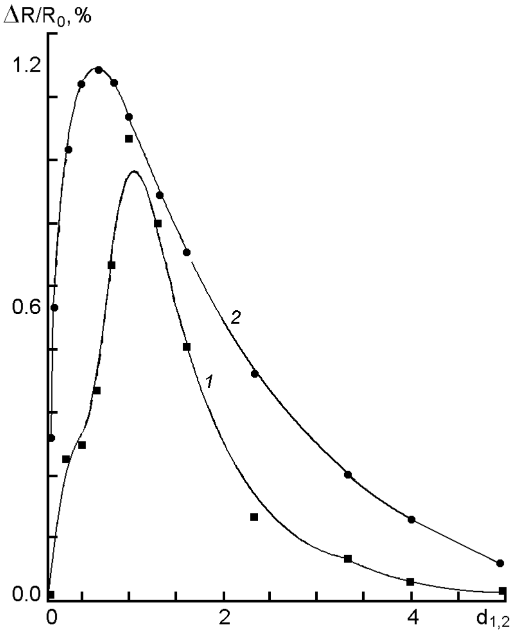

Fig. 4. Experimental (curve *1*; $d_{1(Co)} = 30$ nm, $d_{Cu} = 3$ nm) and theoretical (curve *2*) dependences of GMR effect (versus the ratio of Co layers at the fixed thicknesses of the cobalt base layer and the spacer) in the magnetic sandwich Co/Cu/Co at the following parameters: $q_j^s = P_{jn}^s = Q_{jn}^s = 0{,}1$, $R_j^+ = 0{,}1$ $\alpha_{bj} = \alpha_{Rj} = 6$, $k_1^- = 1$, $l_{1,2}^- = 1$, $\alpha_j^+ = 3$.

the positive longitudial magnetoresistive effect is observed, that is the feature of usual anisotropic magnetoresistance (AMR) characteristic for homogeneous ferromagnetic materials. For non-annealed Co/ Cu/Co sandwiches the effect degree is comparably small, not exceeding 0.15% at the room temperature. Such the samples may be formally considered as the conductors of $2d_{Co}$ thickness with copper islands as impurities between the cobalt layers [15]; GMR effect was not found in them.

For non-annealed sandwiches with the spacer thickness d_{Cu} from 3 to 15 nm, the resistance decrease was observed independently on the applied magnetic field orientation relative to the longitudial current, i.e. the AMR effect is absent that is a feature of the GMR onset [16]. Fig.2 shows the magnetizing force dependences of longitudial and transversal MR for non-annealed Co/Cu/Co film with the spacer thickness $d_{Cu} = 3$ nm and different Co layer ratios. The magnetoresistance value reaches 1% at the room temperature.

The measurements done for several series of non-annealed Co/Cu/Co films with fixed thicknesses of the base Co layer and Cu spacer (the deposited Co $d_{2(Co)}$ layer thickness was varied from 2 nm to 150 nm for each sample series) have shown the absence of GMR effect for non-annealed samples with thin deposited Co layer ($d_{2(Co)} < 5$ nm). As $d_{2(Co)}$ increases up to 10 nm, the GMR effect with amplitude 0.2-0.3 % is observed, and the hysteresis loops appear (Fig. 2, a). The feature of the loops is distinct peaks absence indicating the separate magnetic reversal of the Co layers. Such the loops are observed for asymmetric sandwiches as well; the authors of reference [17] relate these with existence of stable antiferromagnetic distribution in the external magnetic field. In the present case, probably due to different thicknesses of Co layers, these have different coercitive force that results in diffuse peaks of the magnetoresistive hysteresis.

As the upper layer thickness becomes closer to the lower layer value, the magnetoresistive loops acquire another shape (Fig.2, b). Both increase and decrease of the resistivity take place in the narrow magnetic field range $\Delta H = 20 \div 30 Oe$, where very distinct and sharp peaks are observed. This indicates the synchronism of the magnetic reversal processes in both the layers, which is characteristic for symmetric structures consisting of two similar layers. In this case, the upper and the lower magnetic layers reversed simultaneously at the same value of the external magnetic field.

With further $d_{2(Co)}$ increasing, the MR value decreases (Fig.2,c), and the magnetoresistive loop peaks become diffuse again. Note the substantial differences between longitudial and transversal MR for the films with $d_{2(Co)} > 70$ nm, at which the longitudial MR does not exceed 0.05%, while the transversal MR being 0.2÷0.3%.

In the Figs. 3 and 4, the experimental plots of the longitudial and transversal magnetoresistance (Fig.3; Fig.4, curve *1*), and the theoretical plot of the longitudial MR (Fig.4, curve *2*) are presented versus the ratio of Co layers at the fixed thicknesses of the cobalt base layer and the spacer. The theoretical dependence was calculated using the general equation (16) in assumption that the sandwich total resistivity coincides with its resistivity. The dependences obtained show that the maximum GMR effect is observed at equal thicknesses of the magnetic layers. The overestimated theoretical magnetoresitance value is caused by application of the sandwich model with infinitesimal thin spacer, which is well known to give the overestimated GMR effect values [18].

For all investigated non-annealed three-layer films with broken spacer (d_{Cu} < 2 nm) the positive longitudial magnetoresistive effect is observed. For the films with thicker non-magnetic interlayers (d_{Cu} = 3-10 nm) the effect of giant magnetoresistance is realized. The obtained GMR dependence on the Co layer ratio for as-condensed films shows that the maximum magnetoresistive relation (1.2%) is observed for the equal magnetic layers thicknesses and 3 nm spacer thickness; this result agrees with the numerical calculations.

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Ефект гігантського магнітоопору у Co/Cu/Co структурі

Ю.О. Шкурдода, Л.В. Дехтярук, В.Б. Лобода

Теоретично та експериментально досліджено залежність гігантського магнітоопору від відношення товщини шарів Co для свіжоконденсованих Co/Cu/Co. Встановлено, що максимальне магніторезистивне відношення для вказаної системи спостерігається при рівній товщині магнітних шарів і товщині мідного прошарку у 3 нм.