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Size Effects in 'Symmetric' Magnetically Ordered Three-Layer Films

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Size effects in the magnetoresistive properties of the magnetically ordered 'symmetric' $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ sandwiches obtained by the layer-by-layer metal condensation with the subsequent heat treatment in the temperature range of $(3–5)\cdot10^2$ K are studied experimentally and theoretically using the generalized Dieny formulas [1, 2]. At small (large) thickness values of the covering magnetic layer in comparison with the total thickness of the interfaces, non-magnetic interlayer, and basic magnetic layer, the numerical value of the magnetoresistance ratio δ is negligible due to the shunting of the covering-layer resistance by the resistance of the basic magnetic layer, non-magnetic layer, and interfaces (resistance shunting of the basic layer, non-magnetic interlayer, and interfaces by the covering magnetic-layer resistance). In the absence of the shunting effect, *i.e.*, when the covering magnetic-layer thickness coincides with the thickness of the interfaces, interlayer, and basic magnetic layer, the value δ in a 'symmetric' three-layered film acquires its maximum value. In the case of an increase in the non-magnetic-layer thickness (interface thickness between the basic magnetic layer and the spacer), provided that the magnetic-layer thickness of the metal and the interfaces (magnetic-layer thickness of the metal, spacer, and interface between the overlapping magnetic layer and the interlayer) do not change, the magnetoresistance ratio decreases monotonically with an increase in the spacer (interface) thickness due to an increase in the scattering probability of the majority charge carriers within their volumes that leads to a decrease in the interplay between the magnetic layers due to the spin-polarized charge carriers and, as a result, to a decrease in the magnetoresistance ratio in a 'symmetric' magnetically-ordered sandwich.

Розмірні ефекти в магнеторезистивних властивостях магнетовпорядкованих «симетричних» сандвічів $Fe_{0,8}Ni_{0,2}/Cu/Fe_{0,8}Ni_{0,2}/S$, одержаних методом пошарової конденсації металу з подальшим термічним обробленням у діяпазоні температур $(3-5)\cdot10^2$ К, було досліджено експериментально та теоретично з використанням узагальнених формул Дьєні [1, 2]. За малих (великих) значень товщини покривного магнетного шару порівняно із загальною товщиною міжфазних поверхонь немагнетного прошарку та базового магнетного шару числове значення коефіцієнта магнетоопору δ є незначним через шунтування опору покривного шару опором базового магнетного шару, немагнетного шару та міжфазних поверхонь (шунтування опору базового шару, немагнетного прошарку та міжфазних поверхонь опором покривного магнетного шару). За відсутности ефекту шунтування, тобто коли товщина покривного магнетного шару збігається з товщиною інтерфейсів, проміжного шару й основного магнетного шару, значення δ у «симетричній» тришаровій плівці набуває свого максимального значення. У разі збільшення товщини немагнетного шару (товщини інтерфейсу між основним магнетним шаром і спейсером), за умови, що товщина магнетного шару металу та внутрішніх інтерфейсів (товщина магнетного шару металу, спейсера й інтерфейсу між перекривальним магнетним шаром і проміжним шаром) не змінюються, відношення магнетоопору монотонно зменшується зі збільшенням товщини спейсера (внутрішнього інтерфейсу) через збільшення ймовірности розсіяння основних носіїв заряду в їхніх об'ємах, що приводить до зменшення взаємочину між магнетними шарами за рахунок спін-поляризованих носіїв заряду й, як наслідок, до зменшення відношення магнетоопору в «симетричному» магнетовпорядкованому сандвічі.

Key words: magnetically ordered 'symmetric' sandwich, giant magnetoresistance effect, magnetoresistance ratio, generalized Dieny formula, shunting effect, interfaces, basic and covering magnetic layers, interlayer.

Ключові слова: магнетовпорядкований «симетричний» сандвіч, ефект гігантського магнетоопору, коефіцієнт магнетоопору, узагальнена формула Дьєні, ефект шунтування, інтерфейси, базовий і покривний магнетні шари, проміжний шар.

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1. INTRODUCTION

The development of modern micro- and nanoelectronics requires the development and introduction of the new functional elements based on the magnetically inhomogeneous film materials. These materials also include three-layered and multilayered nanocrystalline structures obtained using the latest technologies, namely, periodic systems consisting of the alternately applied layers of various materials, in particular, the ferromagnetic and non-magnetic metals [3–10]. The interest in the study of the three- and multilayered films is due to the fact that they exhibit effects, which cannot be realized in the homogeneous film conductors [11, 12]. Structures, where the spin-dependent scattering of charge carriers is observed in the volume of magnetic metal layers and at the interfaces of a multilayered conductor, due to their wide application, are of particular interest [4–12].

Despite a significant number of experimental and theoretical studies of the film materials with the spin-dependent scattering of electrons, a number of questions remain unsolved. Thus, there is a need to develop and test the simple theoretical models of size effects in the magnetoresistive properties in the magnetically inhomogeneous structures. The development of theoretical models can solve the problem of predicting the behaviour of magnetoresistance values in the multilayered magnetically ordered systems with changes in the thickness of the metal magnetic layer, non-magnetic interlayer, and interfaces. The solution of such problems is possible, only if a comprehensive approach to the study of the physical properties of film systems is used.

The goal of this work is to study experimentally and theoretically the size dependence of the giant magnetoresistance (GMR) in the ‘symmetric’ magnetically ordered three-layered films (sandwiches) based on a ferromagnetic $Fe_{0.8}Ni_{0.2}$ alloy and a non-magnetic copper interlayer using generalized Dieny formulas [1, 2].

2. METHODS AND TECHNIQUES OF EXPERIMENT

Multilayered film systems with a layer thickness of 1–50 nm were obtained in a vacuum chamber at a residual atmospheric gas pressure of 10^{-4} Pa. Alternating film condensation was carried out as a result of the metal evaporation from the independent sources. The starting materials for obtaining $Fe_{0.8}Ni_{0.2}$ layers were massive alloys of the corresponding composition.

The study results of the chemical composition of the original alloy and the obtained films show that they coincide within the measurement error that did not exceed 2%.

Film condensation was carried out at room temperature of the substrate with a speed $\upsilon = 0.5–1$ nm/s depending on the evaporation modes. Layer thickness was controlled during the film condensation by a quartz resonator with an accuracy of 10%. An industrial resonator of the РГ-08 type was used for this. The ultrathin-layers’ thickness was calculated by the condensation time at a known condensation rate. The effective thickness of such layers was determined with an error of 10–15%.

The measurements of longitudinal and transverse magnetoresistance, as well as the thermomagnetic film processing, were carried out in a device under the conditions of ultrahigh oil-free vacuum at a residual atmospheric gas pressure of 10^{-6}–10^{-7} Pa in a magnetic field with induction up to $B = 0.2$ T.

2. RESULTS OF EXPERIMENTAL RESEARCH

The conducted experimental studies of the field dependence of the magnetoresistance in the magnetically ordered three-layered $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ films made it possible to establish the nature of the magnetoresistive effect (Fig. 1). As can be seen in Fig. 1, the field dependence of magnetoresistance for the samples with the magnetic layer thickness $d_m = 20$–30 nm and the nonmagnetic Cu-interlayer thickness $d_n = 5$–15 nm are isotropic in nature. As a result of this, the mechanism of asymmetric spin-dependent electron scattering in the volume of the magnetic metal layers is implement-

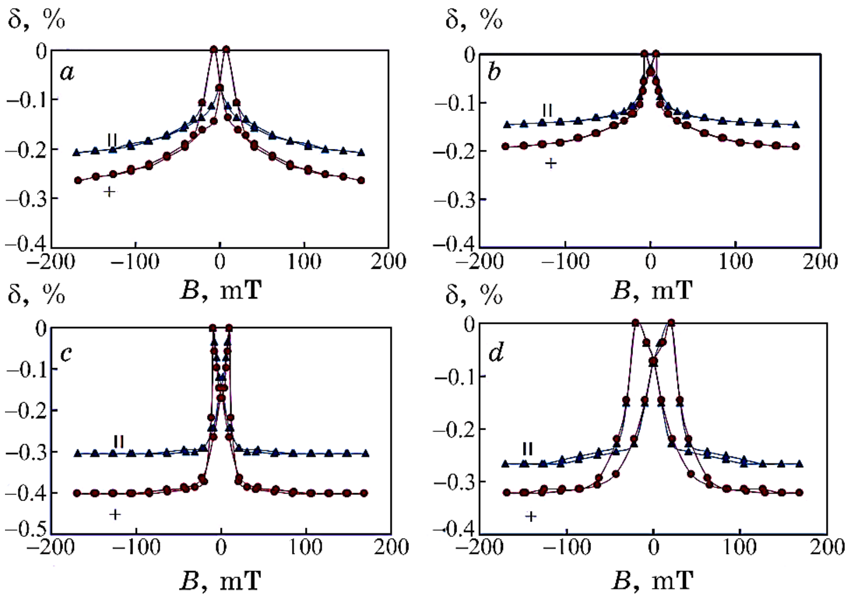

Fig. 1. Dependence of the longitudinal (||) and transverse (+) magnetoresistance ratio δ on the induction of the magnetic field B for a 'symmetric' three-layered structure $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ with $d_F = 20$ nm, $d_N = 6$ nm (a—as-deposited film; b—$T_{ann} = 400$ K; c—$T_{ann} = 550$ K; d—$T_{ann} = 700$ K). Measurement temperature is of 300 K.

ed (the giant magnetoresistance effect). In the investigated structures, a change in the magnetic configuration, *i.e.*, the transition from the antiferromagnetic interaction to the ferromagnetic interaction, occurs under the influence of a relatively weak external magnetic field. As a result of the change in the magnetic configuration, the sample resistance decreases, *i.e.*, the GMR effect is realized. It is also worth noting that the sample annealing at a temperature of 700 K does not lead to a change in the character of the isotropic field dependence of magnetoresistance, except for a change in the amplitude of the effect and an expansion of the magnetoresistive loops. The reason to preserve the isotropic nature of magnetoresistance is to preserve the individuality of individual layers even during the high-temperature annealing (T_{ann} = 700 K) that is especially important for the applied usage.

Figure 2 shows the dependence of the magnetoresistance ratio value (MRR) on the magnetic covering-layer thickness d_{m2} (the layer condenses on the non-magnetic interlayer) normalized to the basic magnetic-layer thickness d_{m1} = const (the layer condenses on the substrate) in the three-layered 'symmetrical' $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ films. The specified dependence has a non-monotonic character, and the reasons for this behaviour are analysed in detail in the theoretical analysis of the corresponding size dependence (see subsection 3). At the same time, we note that, with the extremely small covering magnetic layer thickness (up to 5–10 nm), magnetic solid solutions are not formed and, accordingly, the magnetic covering layer is not formed. As a result, the giant magnetoresistance effect is not ob-

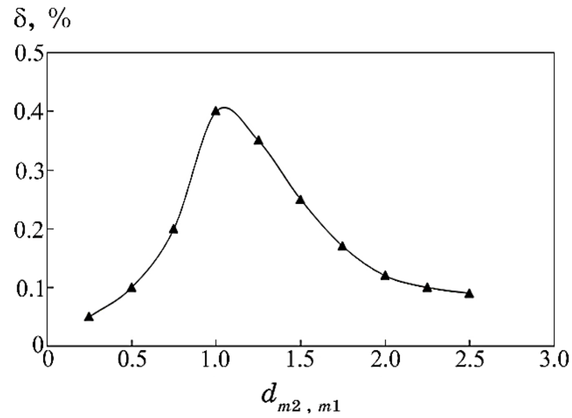

Fig. 2. Dependence of the magnetoresistance ratio δ (1) on the covering magnetic-layer thickness d_{m2} normalized to the thickness d_{m1} = const of the basic-layer thickness d_{m1} = const of a three-layered $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ film annealed at a temperature of 700 K. The basic magnetic-layer thickness is d_{m1} = 20 nm and the non-magnetic-interlayer thickness is d_n = 6 nm.

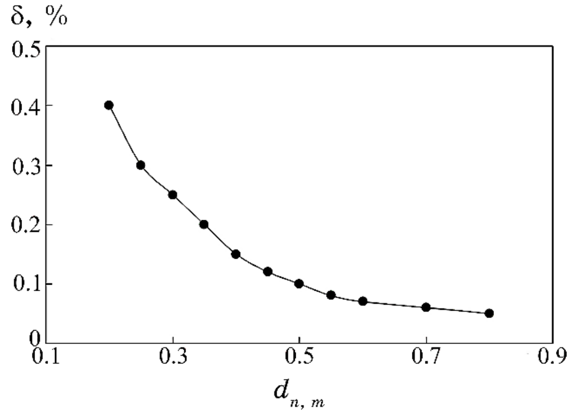

Fig. 3. Dependence of the magnetoresistance ratio δ on the non-magnetic-layer thickness normalized to the thickness $d_m = \text{const}$ of the magnetically ordered sandwich $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ ($d_m = d_{m1} = d_{m2} = 20$ nm) annealed at a temperature of 700 K.

served in the 'symmetrical' sandwich.

Figure 3 shows the dependence of magnetoresistance ratio δ (1) on the copper-layer thickness normalized to the magnetic layer thickness $d_m = \text{const}$ of a three-layered $Fe_{0.8}Ni_{0.2}/Cu/Fe_{0.8}Ni_{0.2}/S$ film ($d_m = d_{m1} = d_{m2} = 20$ nm) annealed at a temperature of 700 K. The maximum MRR value is observed at the minimum non-magnetic-layer thickness $d_n = 6$ nm, at which the sample remains structurally solid.

A further increase in the copper-layer thickness leads to a decrease in the MRR, caused by an increase in the probability of the spin-polarized charge carriers scattering in the interlayer volume. As a result, it leads to a decrease in the interaction between the magnetic layers and a disappearance of the GMR effect.

3. THEORETICAL ANALYSIS OF THE DIMENSIONAL DEPENDENCE OF MRR ON THE THICKNESS OF THE COVERING MAGNETIC LAYER

The effect of giant magnetoresistance [11, 12] in a magnetically ordered three-layer film is quantitatively described by the magnetoresistance ratio δ, which is determined by the change in the specific resistance $(\bar{\rho}_{ap}(0) - \bar{\rho}_p(B))$ of the sandwich as a result of its remagnetization by the external magnetic field by induction B, normalized to the resistance $\bar{\rho}_p(B)$:

$$\delta = (\bar{\rho}_{ap}(0) - \bar{\rho}_p(B))/\bar{\rho}_p(B) = \bar{\rho}_{ap}(0)/\bar{\rho}_p(B) - 1\,. \quad (1)$$

Here, $\bar{\rho}_{ap}(0)$ is the specific resistivity of a conductor averaged over the sandwich thickness in the absence of an external magnetic field, *i.e.*, when the antiferromagnetic configuration is implemented in the sandwich (directions of the spontaneous magnetization vectors **M** in the magnetic-metal layers are antiparallel); $\bar{\rho}_p(B)$ is the specific resistivity of a sample averaged over the thickness of a magnetically ordered three-layered film in the presence of an external magnetic field, *i.e.*, when a ferromagnetic configuration is realized in the sandwich (directions of the spontaneous magnetization vectors **M** in the magnetic metal coincide).

It is experimentally and theoretically substantiated that the dimensional dependence of transport coefficients (conductivity, specific resistivity, magnetoresistance, *etc.*) on the metal layer thickness, both in the non-magnetic [13–15] and in the magnetic [16–19] multilayered structures, depends on the ratio between the thickness of the metal conductor layers. Thus, in particular, the nature of MRR δ behaviour depending on the change in thickness d_{m2} of the covering magnetic layer normalized to the thickness d_{m1} of the basic magnetic layer, *i.e.*, on $d_{m2,m1} = d_{m2}/d_{m1}$ ($d_{m1} = \text{const}$), depends on the inequality sign between thickness d_{m2} and total thickness $2d_i$ of the interfaces, thickness d_n of a non-magnetic layer, and thickness d_{m1}, *i.e.*, on $d_{m1} + d_n + 2d_i$.

In this case, if, for the lengths of free path electrons l_{ij}^s ($j = 1, 2$) in the transition regions between the spacer and the metal magnetic layers, the inequalities $l_{ij}^s << l_{mj}^s, l_n^s$ are fulfilled (l_{mj}^s, l_n^s —the lengths of free path spin-polarized electrons in the j magnetic layer and in the non-magnetic layer, respectively, $s = \pm(\uparrow\downarrow)$—the spin indices, which determine the projection sign of the electron spin on the direction of the spontaneous magnetization vector **M** in the magnetic conductor layer) and $l_{ij}^s \cong (Dt_D)^{1/2}$ (D—diffusion coefficient, t_D—diffusion time) [20, 21], then, the separation boundaries of the metal layers can be modelled by the metal layers with a thickness d_i. Then, thickness d_{m2} of the covering magnetic layer is naturally normalized to the total thickness $d_{m1} + d_n + 2d_i$ and, accordingly, the approximating Dieny formula [1] can be written as follows:

$$\delta(d_{m2,m1}) = \frac{1 - \exp\left(-\dfrac{d_{m2,m1}}{1 + d_{n,m1} + 2d_{i,m1}}\right)}{1 + \dfrac{d_{m2,m1}}{1 + d_{n,m1} + 2d_{i,m1}}}, \qquad (2)$$

where $d_{n,m1} = d_n/d_{m1}$ and $d_{i,m1} = d_i/d_{m1}$ are thickness d_n of the non-magnetic layer and thickness d_i of the separation boundary between the magnetic layer and the spacer, respectively, normalized to thickness d_{m1} of the basic magnetic layer.

Let us investigate formula (2) for the boundary values of thickness d_{m2} of the magnetic layer. In the area of small values of thickness d_{m2} of the covering layer compared to the total thickness of the interfaces, spacer and basic magnetic layer, *i.e.*, when the inequality

$$d_{m2,m1} << 1 + d_{n,m1} + 2d_{i,m1}, \quad (3)$$

holds, the magnetoresistance ratio δ increases linearly with an increase in thickness d_{m2} of the covering magnetic layer (Fig. 2):

$$\delta(d_{m2,m1}) \cong \frac{d_{m2,m1}}{1 + d_{n,m1} + 2d_{i,m1}} \cong d_{m2,m1}(1 - d_{n,m1} - 2d_{i,m1}), \quad (4)$$

and the giant magnetoresistance effect, as follows from the asymptotic formula (4), is insignificant. This is due to the fact that, in the indicated thickness interval (3) of the covering magnetic layer, its resistance is shunted by the basic magnetic layer, interfaces, and non-magnetic interlayer. As thickness d_{m2} increases, the current value in the covering magnetic layer increases that leads to an increase in the MRR (Fig. 2). It also follows from expression (4) that, if the thickness of the covering and basic magnetic-metal layers is fixed (unchanged), the MRR value decreases linearly with the increasing thickness of the non-magnetic layer (interface thickness d_i) (for more details, see subsection 4 and 5).

In the case of fulfilment of the opposite inequality compared to expression (3),

$$d_{m2,m1} >> 1 + d_{n,m1} + 2d_{i,m1}, \quad (5)$$

the asymptotic formula for $\delta(d_{m2,m1})$:

$$\delta(d_{m2,m1}) \simeq \frac{1 + d_{n,m1} + 2d_{i,m1}}{d_{m2,m1}} \cong \frac{d_{m1} + d_n + 2d_i}{d_{m2}}, \quad (6)$$

only if inequality $d_{m2,m1} > 1 + d_{n,m1} + 2d_{i,m1}$, correctly describes the size dependence $\delta(d_{m2,m1})$, *i.e.*, the MRR decreases. This is due to the fact that, with an increase in thickness d_{m2} of the covering layer, the opposite situation is observed, namely, the resistance of the basic magnetic layer, non-magnetic layer, and interfaces are shunted by the resistance of the covering magnetic layer (Fig. 2). In fact, as experimentally established [4, 8, 23, 24], in the specified region of thickness of the covering magnetic layer, the magnetoresistance ratio δ decreases exponentially with the increasing value of d_{m2}. Such a discrepancy between the results of experimental studies and the corresponding theoretical calculations is due to the fact that, in the case of performing a ‘strong’ inequality (5), the covering magnetic-metal layer becomes thick, *i.e.*, the length of free path l^s_{m2} of the spin-polarized charge carriers becomes significantly less than thickness d_{m2} of the covering magnetic layer ($l^s_{m2} << d_{m2}$). As a consequence, the covering and basic magnetic-metal layers become ‘independent’ in the sense that there will be no interaction between them through the spin-polarized charge carriers (electrons do not pass from one magnetic layer to another) and, as a result, the giant magnetoresistance effect will not be observed.

Considering the opposite behaviour of the MRR δ (increase in the area of small thickness d_{m2}, decrease in the area of large values d_{m2}) for the boundary values of d_{m2}, it is advisable to investigate expression (2) for the presence of an extremum. In other words, we will find thickness d_{m2}, at which the GMR effect will be either maximum or minimum. To do this, we differentiate expression (2) by $d_{m2,m1}$ and equate the obtained result to zero. As a result, we get the transcendental equation:

$$e^{-\frac{d_{m2,m1}}{1+d_{n,m1}+2d_{i,m1}}}\left(2+\frac{d_{m2,m1}}{1+d_{n,m1}+2d_{i,m1}}\right)-1=0\,, \qquad (7)$$

whose approximate solution is as follows:

$$d^{extr}_{m2,m1} \cong 1.146(1+d_{n,m1}+2d_{i,m1})\,. \qquad (8)$$

If equality (8) is fulfilled, the MRR δ value acquires an extreme value, and according to the sign of the second derivative with respect to $d_{m2,m1}$ from the MRR (2),

$$\frac{d^2\delta}{dd^2_{m2,m1}}=-\frac{e^{-\frac{d_{m2,m1}}{1+d_{n,m1}+2d_{i,m1}}}\left\{\left(\frac{d_{m2,m1}}{1+d_{n,m1}+2d_{i,m1}}+2\right)^2+1\right\}-2}{\left(1+\frac{d_{m2,m1}}{1+d_{n,m1}+2d_{i,m1}}\right)^3}\,, \qquad (9)$$

at the extreme thickness (8),

$$\frac{d^2\delta}{dd^2_{m2,m1}}(d^{extr}_{m2,m1}) \cong -0.148\,, \qquad (10)$$

we can confirm that the magnetoresistance ratio (2) reaches its maximum (amplitude) value.

Analysing expression (8), we see that, when equality $d_{m1} = \text{const}$ is fulfilled, an increase in either the interlayer thickness, d_n, or the interface thickness, d_i, or both d_n and d_i values, leads to a shift of the magnetoresistance ratio maximum towards the larger values of thickness d_{m2} of the covering magnetic-metal layer. At the same time, an increase in thickness d_{m1} of the basic magnetic layer, under the condition that the thicknesses d_i and d_n are constant, shifts the MRR maximum towards the smaller values d_{m2}.

4. THEORETICAL ANALYSIS OF MRR DEPENDENCE ON NON-MAGNETIC-LAYER THICKNESS

In the experimental study of the magnetoresistance ratio δ depending on the change in the non-magnetic-interlayer thickness d_n, in order to avoid the shunting effect, the magnetic layer thicknesses are usually chosen to be equal to each other ($d_{m1} = d_{m2} = d_m$). Therefore, it is natural to normalize the interlayer thickness d_n in the Dieny formula [1, 2] by twice the magnetic layer thickness and twice the interface thickness, *i.e.*, the MRR can be written in the following form:

$$\delta(d_{n,m}) = \frac{\exp\left(-\dfrac{d_{n,m}}{2(1+d_{i,m})}\right)}{1+\dfrac{d_{n,m}}{2(1+d_{i,m})}}, \tag{11}$$

where $d_{n,m}$ is the non-magnetic-layer thickness d_n normalized to the magnetic-layer thickness d_m, and $d_{i,m}$—the interface thickness d_i normalized to the thickness d_m.

In case of the inequality fulfilment as follows:

$$d_{n,m} << 2(1+d_{i,m}), \tag{12}$$

formula (11) can be presented approximately in the form

$$\delta(d_{n,m}) \cong 1 - \frac{d_{n,m}}{1+d_{i,m}}, \tag{13}$$

i.e., MRR $\delta(d_{n,m})$ decreases linearly with the increasing non-magnetic layer thickness (Fig. 3). This decrease is due to the fact that, with an increase in the non-magnetic-layer thickness, the probability of the spin-polarized charge-carriers' scattering in the volume of the non-magnetic layer increases. It leads to a decrease in the interaction between the magnetic-metal layers through the spin-polarized charge carriers and, as a result, to a decrease in the giant magnetoresistance value.

In the case of the opposite, in comparison with (12), inequality $d_{n,m} >> 2(1+d_{i,m})$, *i.e.*, when the spacer is thick enough, the magnetic metal layers become independent in the sense that the spin-polarized charge carriers do not pass from one magnetic layer to another through a non-magnetic interlayer. Therefore, in formula (11), the exponent will asymptotically go to zero, the MRR δ will also go to zero ($\delta \to 0$) and, accordingly, the giant magnetoresistance effect will be absent due to the lack of interaction between the magnetic layers due to the spin-polarized charge carriers.

5. THEORETICAL ANALYSIS OF MRR DEPENDENCE ON INTERFACE THICKNESS

In the case of an experimental study of the magnetoresistance-ratio (δ) dependence on the interface thickness, the following should be done. After obtaining a two-layered film comprising a basic magnetic layer (deposited on a substrate) and the non-magnetic interlayer, the obtained sample should be diffusion-annealed over a certain period of time. Subsequently, the spacer should be coated with a covering magnetic layer, and the resistance of the resulting sandwich should be measured in the antiparallel and parallel sample configurations.

By increasing the time of diffusion annealing, it is possible to obtain the separation boundaries of different thickness d_{i1} between the non-magnetic layer and the basic magnetic layer. This allows us to study the MRR dependence on the interface thickness d_{i1}, provided that the interface thickness d_{i2} between the overlaying magnetic layer and the interlayer does not change ($d_{i2} = \text{const}$).

Within the limits of this model, assuming that the magnetic metal layer thicknesses in the magnetically ordered sandwich coincide again, the MRR $\delta(d_{i1,i2})$ can be written in the following form:

$$\delta(d_{i1,i2}) = \frac{\exp\left\{-\dfrac{d_{i1,i2}}{1+2d_{m,i2}+d_{n,i2}}\right\}}{1+\dfrac{d_{i1,i2}}{1+2d_{m,i2}+d_{n,i2}}}, \qquad (14)$$

where $d_{i1,i2} = d_{i1}/d_{i2}$ is the interface thickness d_{i1} between the basic magnetic layer and the non-magnetic interlayer normalized to the thickness $d_{i2} = \text{const}$, $d_{m,i2} = d_m/d_{i2}$, and $d_{n,i2} = d_n/d_{i2}$, the magnetic-metal layer thickness d_m and the non-magnetic-interlayer thickness d_n are normalized to the interface d_{i2} thickness, respectively.

If the inequality

$$d_{i1,i2} << 1+2d_{m,i2}+d_{n,i2} \qquad (15)$$

is met, formula (14) can be written approximately as follows:

$$\delta(d_{i1,i2}) \cong 1 - \frac{2d_{i1,i2}}{1 + 2d_{m,i2} + d_{n,i2}}, \qquad (16)$$

i.e., the MRR decreases linearly with an increase in the interface thickness d_{i1}. This decrease is caused, as in the case of an increase in the layer thickness, by the fact that, with an increase in the interface thickness, the interaction between the magnetic-metal layers through the spin-polarized electrons decreases and, as a result, this leads to a decrease in the giant magnetoresistance value.

In the case of the opposite, in comparison with inequality (15), inequality $d_{i1,i2} >> 1 + 2d_{m,i2} + d_{n,i2}$, *i.e.*, when the interface is thick enough, the magnetic-metal layers become independent. For this reason, in formula (14), the exponent will asymptotically go to zero. As a result, the MRR $\delta(d_{i1,i2})$ will also go to zero ($\delta \to 0$), and the GMR effect will be absent due to the lack of interaction between the magnetic layers due to the spin-polarized charge carriers.

6. CONCLUSIONS

Thus, it was established experimentally and theoretically that the effect the giant magnetoresistance effect in a magnetically ordered 'symmetrical' three-layered film in the region of small thickness d_{m2} of the covering magnetic layer, in comparison with the thickness of the basic magnetic layer, interlayer, and interfaces, *i.e.*, when inequality $d_{m2,m1} << d_{n,m1} + 2d_{i,m1}$ is fulfilled, is negligible due to the resistance shunting of the covering layer by the resistance of the basic layer, interfaces, and non-magnetic layer.

In the case of implementation of the opposite inequality $d_{m2,m1} >> 1 + d_{n,m1} + 2d_{i,m1}$, *i.e.*, in the area of large thickness of the covering layer, the opposite effect is observed, namely the effect of resistance shunting of the basic layer, non-magnetic interlayer, and interfaces by the resistance of the covering magnetic layer and, accordingly, the value of the MRR will also be very small.

If equality $d_{m2,m1} \cong 1.146(1 + d_{n,m1} + 2d_{i,m1})$ is fulfilled, the MRR δ acquires a maximum value due to the absence of the shunting effect that shifts towards the larger values of thickness d_{m2} with an increase in thickness d_n of the interlayer and thickness d_i of the interfaces, provided that $d_{m1} = \text{const}$. In the case of an increase in thickness d_{m1}, under the condition of constant values d_i and d_n, the maximum MRR shifts towards the smaller values of thickness d_{m2}.

With an increase in the non-magnetic-interlayer thickness d_n (interface thickness d_n), provided that the thickness of the basic and magnetic-metal layers, the interface thickness d_i (layer thickness d_n and interface thickness d_{i2}) do not change, the magnetoresistance ratio monotonically decreases due to a decrease in the interaction between the magnetic-metal layers due to the spin-polarized charge carriers.

Note that the above formulas can be used to substantiate the size dependence of the MRR on the metal-layer thickness in the magnetically ordered multilayer structures.

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REFERENCES

1. B. Dieny, P. Humbert, V. S. Speriosu, S. Metin, B. A. Gurney, P. Baumgart, and H. Lefakis, *Phys. Rev. B*, **45**, No. 2: 806 (1992); https://doi.org/10.1103/PhysRevB.45.806
2. V. S. Speriosu, B. Dieny, P. Humbert, B. A. Gurney, and H. Lefakis, *Phys. Rev. B*, **44**, No. 10: 5358 (1991); https://doi.org/10.1103/PhysRevB.44.5358
3. I. Bakonyi and L. Péter, *Prog. Mater. Sci.*, **55**: 107 (2010); https://doi.org/10.1016/j.pmatsci.2009.07.001
4. O. I. Tovstolytkin, M. O. Borovyy, V. V. Kurylyuk, and Yu. A. Kunyts'kyy, *Fizychni Osnovy Spintroniky* (Vinnytsya: Nilan-LTD: 2014) (in Ukrainian).
5. Yu. O. Shkurdoda, A. M. Chornous, Yu. M. Shabelnyk, and V. B. Loboda, *J. Magn. Magn. Mater.*, **443**: 190 (2017); https://doi.org/10.1016/j.jmmm.2017.07.078
6. Igor Žutić, Jaroslav Fabian, and S. Das Sarma, *Rev. Modern Phys.*, **76**, No. 2: 323 (2004); https://doi.org/10.1103/RevModPhys.76.323
7. V. H. Dorohan and F. V. Motsnyi, *Ukr. J. Phys.*, **49**, No. 12: 1174 (2004) (in Ukrainian).
8. E. Y. Tsymbal and D. G. Pettifor, Perspectives of giant magnetoresistance. *Solid State Physics* (Ed. by H. Ehrenreich and F. Spaepen) (San Diego, CA: Academic Press: 2001).
9. A. M. Pohorilyi, S. M. Riabchenko, and O. I. Tovstolytkin, *Ukr. Fiz. Zh. Ohliady*, **6**, No. 1: 37 (2010) (in Ukrainian).
10. D. I. Saltykov, Yu. O. Shkurdoda, and I. Yu. Protsenko, *J. Nano- Electron. Phys.*, 10, No. 4: 04031 (2018); https://dx.doi.org/10.21272/jnep.10(4).04031
11. G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, *Phys. Rev. B*, **39**, No. 7: 4828(R) (1989); https://doi.org/10.1103/PhysRevB.39.4828
12. M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, *Phys. Rev. Lett.*, **61**: 2472 (1988); https://doi.org/10.1103/PhysRevLett.61.2472
13. A. Chornous, L. Dekhtyaruk, M. Marszalek, and I. Protsenko, *Cryst. Res. Technol.*, **41**, No. 4: 388 (2006); https://doi.org/10.1002/crat.200510592

14. R. Dimmich and F. Warkusz, *Thin Solid Films*, **102**, No. 2: 103 (1983); https://doi.org/10.1016/0040-6090(83)90130-X
15. F. Khater, *Acta Physica Slovaca*, **33**, No. 1: 43 (1983); http://www.physics.sk/aps/pubs/1983/aps_1983_33_1_43.pdf
16. Yu. O. Shkurdoda, L. V. Dekhtyaruk, A. G. Basov, A. M. Chornous, Yu. M. Shabelnyk, A. P. Kharchenko, and T. M. Shabelnyk, *J. Magn. Magn. Mater.*, **477**: 88 (2019); https://doi.org/10.1016/j.jmmm.2019.01.040
17. Yu. O. Shkurdoda, L. V. Dekhtyaruk, A. M. Chornous, A. G. Basov, and A. P. Kharchenko, *Proc. Int. Conf. Nanomater.: Appl. Prop. (Sept. 14–19, 2016, Lviv)* (Sumy: 2016), vol. **5**, No. 2, p. 02MFPM03; https://doi.org/10.1109/NAP.2016.7757282
18. L. V. Dekhtyaruk, *Metallofiz. Noveishie Tekhnol.*, **30**, No. 2: 219 (2008) (in Ukrainian).
19. Yu. O. Shkurdoda, L. V. Dekhtyaruk, A. G. Basov, A. P. Kharchenko, A. M. Chornous, and Yu. M. Shabelnyk, *Eur. Phys. J. B*, **91**: 300 (2018); https://doi.org/10.1140/epjb/e2018-90315-2
20. L. V. Dekhtyaruk and Yu. A. Kolesnichenko, *Fiz. Met. Metalloved.*, **75**, No. 5: 21 (1993) (in Russian).
21. L. V. Dekhtyaruk, I. M. Pazukha, S. I. Protsenko, and I. V. Cheshko, *Phys. Solid State*, **48**, No. 10: 1831 (2006); https://doi.org/10.1134/S1063783406100015
22. Yu. M. Shabelnyk, I. O. Shpetny, A. P. Kharchenko, L. V. Dekhtyaruk, A. M. Chornous, D. I. Saltykov, Yu. O. Shkurdoda, V. I. Virchenko, and V. I. Virchenko, *Proc. Int. Conf. Nanomater.: Appl. Prop. (Sept. 5–11, 2021, Odesa)* (Sumy: 2021), p. NMM07; https://doi.org/10.1109/NAP51885.2021.9568401
23. *Magnetoelectronics* (Ed. by M. Johnson) (Elsevier–Academic Press: 2004).
24. S. S. P. Parkin, *Annu. Rev. Mater. Sci.*, **25**: 357 (1995); https://doi.org/10.1146/annurev.ms.25.080195.002041