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Justification of the Giant Magnetoresistance Effect in Co/Cu/Co and Fe/Cr/Fe Magneto-Ordered Three-Layer Structures by Using the Fuchs Formula

N.S. Shyshko[1], Yu.M. Shabelnyk[2], Yu.A. Kolesnichenko[3], Yu.O. Shkurdoda[2], A.O. Pronoza[2], A.M. Chornous[2], L.V. Dekhtyaruk[1,*]

[1] *Kharkiv National University of Civil Engineering and Architecture, 40, Sumska Str., 61002 Kharkiv, Ukraine*
[2] *Sumy State University, 2, Rimsky-Korsakov Str., 40007 Sumy, Ukraine*
[3] *B. Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine, 47, Nauky Ave., 61103, Kharkiv, Ukraine*

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The qualitative analysis of the giant magnetoresistive effect in three-layer magnetically ordered films (sandwiches) was carried out using the two-current model and the theory of dimensional effects. It is shown that in the region of small thicknesses of the covering magnetic layer the magnetoresistance of the conductor increases compared to the thickness of the base magnetic layer, while in the opposite region of thicknesses it decreases, and in the specified thickness the effect is negligible due to the presence of the shunt effect. In the case when the thickness of the covering magnetic layer of the metal is proportional to the total thickness of the base magnetic layer and the non-magnetic layer, the value of magnetoresistance reaches its maximum value due to the absence of the shunting effect. It is shown that the insignificant value of the effect is due to the shunting of the resistances of the covering and base magnetic layers. If the thickness of the covering magnetic layer of the metal is comparable to the total thickness of the main magnetic layer and the non-magnetic layer, the value of magnetoresistance reaches its maximum value due to the absence of the shunting effect mentioned above.

Keywords: Three-layered magnetic film, Giant magnetoresistance, Magnetoresistance ratio, Resistor and two-stream model, Majority and minority charge carriers, Shunting effect

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1. INTRODUCTION

Considerable interest in the study of electron spin-polarized transport in artificially created magnetically ordered multilayers is due to the fact that in such structures effects that cannot be realized in homogeneous conductors are observed (see, for example, [1-4]. Such effects include, in particular, the effect of giant magnetoresistance (GMO), which is observed in three-layer (multilayer) films, which consist of magnetic metal layers separated by non-magnetic layers. The thickness of the interlayers is selected in such way that the interaction between the magnetic layers of the metal has an antiferromagnetic character (*ap*-interaction), as a result the magnetization vectors **M** in the adjacent metal layers are oriented in in opposite directions [4-6]. Placing such structure in a relatively low external magnetic field orients the magnetization vectors **M** in parallel (*p* – interaction), which leads either to a significant decrease in the magnetoresistance (MR) of the conductor (negative effect of GMR), or to a significant increase in the MR (positive, the inverse effect of GMR) [7].

In the theoretical analysis of the GMR effect, phenomenological [3, 6], quasi-classical [5, 9, 10] and quantum mechanical [3] approaches are usually used, which are quite unwieldy. However, you can use the simple theory of Fuchs in the qualitative analysis of the GMR effect, which is the purpose of this report.

2. STATEMENT OF THE PROBLEM

Let's consider a three-layer magnetically ordered film, which consists of two single-type magnetic metal layers with the thickness d_{mj} $(j = 1, 2)$ $\left(j=1,2\right)$ separated by a non-magnetic layer (spacer) with the thickness d_n. We will assume that for the free path lengths of electrons $l^s_{\mathrm{int}\,j}$ in the transition regions between the non-magnetic layer and the magnetic layers of the metal, inequalities $l^s_{\mathrm{int}\,j} << l^s_{m\,j}, l^s_n$ are fulfilled ($l^s_{m\,j}, l^s_n$ – free path lengths of spin-polarized electrons in the magnetic layer and in the non-magnetic layer, respectively, $s = \pm\left(\uparrow\downarrow\right)$ – spin indices that determine the sign of the spin projection of an electron on the direction of the spontaneous magnetization vector **M** in the magnetic layers of the sandwich) and $l^s_{\mathrm{int}} << \sqrt{Dt_D}$ (D – mutual diffusion coefficient, t_D – diffusion time) [11]. In this case, the transition regions of the metal can be modeled by geometric planes, so that the thickness of the sandwich will be equal to $d = d_{m1} + d_n + d_{m2}$.

The giant magnetoresistive effect is quantitatively characterized by the magnetoresistive ratio (MRR) δ, which is defined as the ratio of the change in sandwich conductivity as a result of the change in the magnetic configuration of the conductor by an external magnetic field, normalized to the conductivity of the sample in which the antiferromagnetic interaction is implemented:

$$\delta = \frac{\bar{\sigma}_p - \bar{\sigma}_{ap}}{\bar{\sigma}_{ap}}\,, \tag{1}$$

* lvdekhtyaruk@gmail.com

where $\bar{\sigma}_p$ $\left(\bar{\sigma}_{ap}\right)$ are the thickness-averaged specific conductivities of the sandwich in which the configuration *p* (*ap*) is implemented.

The conductivity of a three-layer conductor [12] considering the two-current model is equal to:

$$\sigma = \frac{1}{d}\left\{ d_n \sigma_n + \sum_{s=\pm}\sum_{j=1}^{2} d_{mj}\sigma_{mj}^s \right\}, \qquad (2)$$

or taking into account that the value of the specific conductivity is proportional to the value of the free path length l_{mj}^s $\left(l_n\right)$ in the magnetic (non-magnetic) layers of the metal, formula (2) will be used in the form:

$$\sigma \sim \frac{1}{d}\left\{ d_n l_n + \sum_{s=\pm}\sum_{j=1}^{2} d_{mj} l_{mj}^s \right\}. \qquad (3)$$

It is well known that the GMR effect is observed when the process of interaction between the magnetic layers of the metal through spin-polarized charge carriers occurs. However, this is possible when the metal layers that create the magnetically ordered three-layer film are thin. We will assume that the inequalities are obtained $\beta_j^s << d_{mj} / l_j^s$ $\left(\beta_n << d_n / l_n\right)$ [10, 12], where $\beta_j^s = \frac{l_j^s}{L_j}\frac{R_j^s}{1-R_j^s}$. $\left(\beta_n = \frac{l_n}{L_n}\frac{R_n}{1-R_n}\right)$ $\left(L_j\left(L_n\right)\right.$ – average width of crystallites in the plane of magnetic (non-magnetic) films, $R_j^s\left(R_n\right)$ – probability of diffuse scattering of charge carriers at intercrystalline boundaries in magnetic (non-magnetic) metal layers) – grain boundary parameters [3]. In this case, the scattering of spin-polarized charge carriers at the boundaries of the crystallites can be neglected, and the Fuchs-Sondheimer theory of dimensional effects can be used for a qualitative description of the giant magnetoresistive effect [3]. If we assume that the outer boundaries of the film diffusely scatter electrons (there is no correlation between the reflected and incident electrons), neglect the numerical multiplier and the logarithmic factor that takes into account the contribution to the conductivity of charge carriers that move almost parallel to the surfaces of the conductor, then the effective free path length of the electron in the film is equal:

$$l_{eff} \sim \frac{d}{l}\sigma_0 \sim d_f, \qquad (4)$$

and it will be determined by the film thickness d_f.

3. Co/Cu/Co SYSTEMS

In magnetically ordered sandwiches as Co/Cu/Co, electrons whose spin direction coincides with the direction of the spontaneous magnetization vector in the magnetic layer of the metal are effective, responsible for the effect (Pippard's concept of "inefficiency" [6]). Such electrons are called majority electrons, and all the last charge carriers are called minority charge carriers (electrons got this name by analogy with the concept of "main" and "non-main" charge carriers in semiconductor physics (note of the translator of the article [13]). In such structures the parameter $\alpha_{mj} = \frac{\rho_{mj}^-}{\rho_{mj}^+}$ (ρ_{mj}^s – specific resistances in the j magnetic layer of the metal), which determines the degree of asymmetry in the scattering of spin-polarized charge carriers with different spin indices in the volume of the magnetic layers of the metal layer, is always greater than one.

Thin layers of metal, which created a magnetically ordered three-layer film, have a different electronic structure at the boundaries of separation, as a result of which a potential jump is formed at the interfaces of the sample. The presence of the indicated potential jump leads to the scattering of spin-polarized charge carriers. However, the band structure Cu is very similar to the majority subband Co, as a result of which charge carriers whose spin direction coincides with the direction of the spontaneous magnetization vector in the magnetic layer of the metal will pass from one magnetic layer to another almost without obstacles (for such spin-polarized electrons, the interfaces are practically transparent, which is taken into account in Fig. 1). At the same time, there is a significant discrepancy between the minority subband and the band structure, as a result of which spin-polarized charge carriers, whose spin direction is opposite to the direction of the spontaneous magnetization vector, practically do not pass into the adjacent magnetic layer of the metal (the interfaces for these electrons are almost not transparent, which is taken into account in Fig. 1) [5].

Taking into account the above, we can see from Fig. 1a that the effective lengths of free path of charge carriers in a sandwich with – configuration are equal to:

$$\begin{array}{ll} l_{m1}^+ \sim d_{m1} + d_n, & l_{m2}^+ \sim d_{m2} + d_n, \\ l_{m1}^- \sim d_{m1}, & l_{m2}^- \sim d_{m2}, \end{array} \qquad (5)$$

and the effective free path lengths of electrons in a sandwich with – configuration can be written in the form (Fig. 1b):

$$\begin{array}{ll} l_{m1}^+ \sim d_{m1} + d_n + d_{m2}, & l_{m2}^+ \sim d_{m2} + d_n + d_{m1} \\ l_{m1}^- \sim d_{m1}, & l_{m2}^- \sim d_{m2}. \end{array}, \qquad (6)$$

It can be seen from the above formulas (5) and (6) that due to the remagnetization of the magnetically ordered three-layer film, the effective free path length of the majority charge carriers increases by the thickness of the magnetic layer of the metal, while the effective free path length of the minority electrons remains unchanged.

Sequentially substituting expressions (5) and (6) into formula (3) and neglecting order multipliers, we obtain an expression for the conductivity of a sandwich in which the configuration is realized:

$$\sigma_{ap} \sim \frac{1}{d}\left\{ 2\left(d_{m1}^2 + d_{m2}^2\right) + d_n\left(d_{m1} + d_{m2}\right)\right\}, \qquad (7)$$

and the formula for the conductivity of a three-layer film in which the configuration *p* is implemented:

$$\sigma_p \sim \frac{1}{d}\left\{ 2\left(d_{m1}^2 + d_{m2}^2\right) + 2d_{m1}d_{m2} + d_n\left(d_{m1} + d_{m2}\right)\right\}, \quad (8)$$

and their difference will be equal to:

$$\Delta\sigma \sim \frac{2d_{m1}d_{m2}}{d}. \quad (9)$$

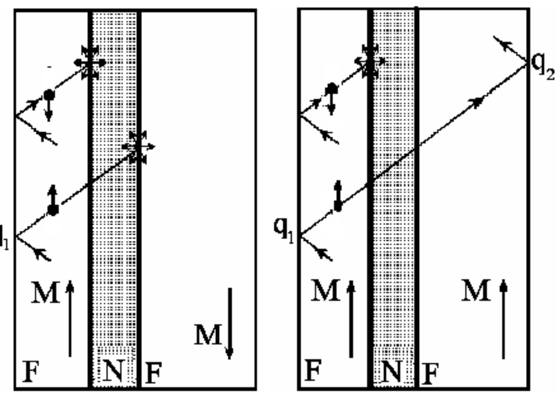
By substituting (9) and (7) into expression (1) for MRR, which quantitatively describes the GMR effect in a sandwich, we obtain the following expression:

$$\delta = \frac{2d_{m1}d_{m2}}{2\left(d_{m1}^2 + d_{m2}^2\right) + d_n\left(d_{m1} + d_{m2}\right)}. \quad (10)$$

Usually, the thickness of the magnetic layer deposited on the substrate (base magnetic layer) is a parameter of the problem, and the thickness of the magnetic layer deposited on the non-magnetic interlayer (cover magnetic layer) is a variable. Then formula (10) can be expressed in dimensionless quantities:

$$\delta = \frac{d_{m2,m1}}{d_{m2,m1}^2 + 0{,}5d_{n,m1}\left(1 + d_{m1,m2}\right) + 1}, \quad (11)$$

where $d_{m2,m1} = \frac{d_{m2}}{d_{m1}}$, $d_{n,m1} = \frac{d_n}{d_{m1}}$.



a b

Fig. 1 – Schematic representation of the spin-polarized transport of charge carriers in a sandwich with *ap* – configuration (a) and *p* – configuration (b) in the assumption that the main (responsible for the effect) electrons are charge carriers whose spin direction coincides with the direction of the spontaneous magnetization vector in magnetic metal layers (majority spin-polarized electrons)

Let's analyze formula (11) for the limit values of the thickness d_{m2} of the overlying magnetic layer. In the case of fulfillment of the inequality $d_{m2,m1} << \sqrt{1 + 0{,}5d_{n,m1}}$, the MRV approximately takes the form:

$$\delta = \frac{d_{m2}}{d_{m1}}\left\{1 - \frac{d_n}{d_{m1}}\right\}, \quad (12)$$

i.e., in the specified range of thicknesses of the covering layer, its increase leads to an increase in the amplitude of the effect (MRV increases), while with an increase in the thickness of the non-magnetic layer, the value decreases.

If the opposite inequality is true $d_{m2,m1} >> \sqrt{1 + 0{,}5d_{n,m1}}$, then the MRV can be approximately written in the form:

$$\delta = \frac{d_{m1}}{d_{m2}}\left\{1 - \frac{d_n}{2d_{m2}}\right\}, \quad (13)$$

the value δ decreases both with an increase in the thickness d_{m2} of the covering layer of the metal and with an increase in the thickness d_n of the interlayer.

Thus, it is follows from formulas (12) and (13), the effect of GMR is negligible due to the presence of the shunt effect in the specified ranges of thicknesses of the overlying magnetic layer. At small (large) values of the thickness of the covering layer, the current is shunted by the base magnetic layer and the non-magnetic interlayer (covering magnetic layer).

From the opposite behavior of the magnetoresistive ratio for the limiting values of the thicknesses of the metal covering layer, we differentiate formula (11) by $d_{m2,m1}$, we equate the obtained result to zero, solve the obtained equation and make sure that in case of equality:

$$d_{m2,m1}^{\text{extr}} = \sqrt{1 + 0{,}5d_{n,m1}}, \quad (14)$$

the magnetoresistive ratio reaches its extreme value, which is equal to:

$$\delta\left(d_{m2,m1}^{\text{extr}}\right) = \frac{2}{d_{n,m1} + 4\sqrt{1 + 0{,}5d_{n,m1}}}. \quad (15)$$

Since the value:

$$\delta''\left(d_{m2,m1}^{\text{extr}}\right) = -\frac{2}{\sqrt{1 + 0{,}5d_{n,m1}}\left(0{,}5d_{n,m1} + 2\sqrt{1 + 0{,}5d_{n,m1}}\right)^2}, \quad (16)$$

is always a negative value, then formula (15) determines the maximum (amplitude) value of the magnetoresistive ratio (1), which describes the giant magnetoresistive effect in a magnetically ordered sandwich due to the absence of a shunt effect.

4. Fe/Cr/Fe SYSTEMS

In magnetically ordered Fe/Cr/Fe systems, it is the opposite in comparison with Co/Cu/Co structures. In these structures, electrons whose spin direction is opposite to the direction of the spontaneous magnetization vector **M** in the magnetic layer of the metal are effective, and these electrons are the majority charge carriers, while electrons whose spin direction coincides with the direction of the spontaneous magnetization vector **M** in the magnetic layer of the metal will be the minority ones. In other words, those electrons that were majority (minority) in the Co/Cu/Co system will be minority (majority) in the Fe/Cr/Fe system. In such structures, the parameters α_{mj} lie in the interval $0 < \alpha_{mj} < 1$.

A comparison of the zone structure Cr and the majority subzone Fe shows that these zones are very similar. For this reason, charge carriers whose spin direction is opposite to the direction of the spontaneous magnetization vector in the magnetic layer of the metal will pass from one magnetic layer to another almost without obstacles (for such spin-polarized electrons, the interfaces are practically transparent, which is taken into account in Fig. 2). At the same time, the minority subzone Fe and the band structure Cr are very different, as a result of which spin-polarized charge carriers, whose spin direction coincides with the direction of the spontaneous magnetization vector, practically do not pass into the adjacent magnetic layer of the metal (the interfaces for these electrons are practically not transparent, and taken into account in Fig. 2) [5].

Taking into account the above, we can see from Fig. 2a that the effective lengths of the free path of charge carriers in a sandwich with *ap*-configuration are equal to:

$$\begin{aligned} &l_{m1}^{+} \sim d_{m1}, \qquad l_{m2}^{+} \sim d_{m2}, \\ &l_{m1}^{-} \sim d_{m1} + d_n, \qquad l_{m2}^{-} \sim d_{m2} + d_n, \end{aligned} \tag{17}$$

and the effective free path lengths of electrons in a sandwich with *p*-configuration can be written in the form (Fig. 1b):

$$\begin{aligned} &l_{m1}^{+} \sim d_{m1}, \qquad l_{m2}^{+} \sim d_{m2}, \\ &l_{m1}^{-} \sim d_{m1} + d_n + d_{m2}, \qquad l_{m2}^{-} \sim d_{m2} + d_n + d_{m1}. \end{aligned} \tag{18}$$

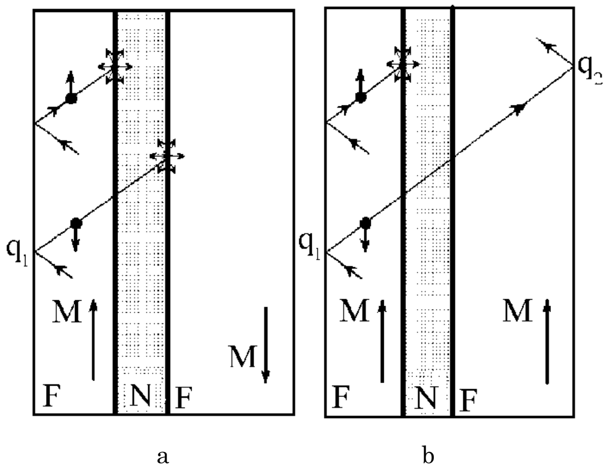


Fig. 2 – Schematic representation of the spin-polarized transport of charge carriers in a sandwich with *ap* – configuration (a) and *p* – configuration (b) in the assumption that the main (responsible for the effect) electrons are charge carriers whose spin direction is opposite to the direction of the spontaneous magnetization vector in magnetic metal layers (majority spin-polarized electrons)

From the given formulas (17) and (18) it can be seen that due to the remagnetization of the magnetically ordered sandwich, the effective free path length of the majority charge carriers in the Fe/Cr/Fe structure (as in the Co/Cu/Co system) increases by the thickness of the magnetic layer of the metal, while the effective free path length of the minority electrons remains without change.

Substituting expressions (17) and (18) into formula (3) and neglecting order factors, we obtain an expression for the conductivity of a sandwich in which the *ap*-configuration is implemented, which will completely coincide with formula (7), and an expression for the conductivity of a three-layer film with *p*-configuration which will coincide with expression (8). Thus, the MRR for the structure will completely coincide with formula (11) and the entire theoretical analysis of the GMR effect will be analogous, accordingly.

CONCLUSIONS

Thus, in the region of small (large) thicknesses of the covering magnetic layer in comparison with the total thickness of the base magnetic layer of the metal and the non-magnetic interlayer, the magnetic resistance of the conductor increases (decreases) with an increase in the thickness of the covering magnetic layer. In this case, the magnitude of the giant magnetoresistance effect is negligible due to the shunting of the cover layer resistance by the total resistance of the base magnetic layer and non-magnetic layer (by shunting the total resistance of the base layer and non-magnetic layer by the resistance of the cover magnetic layer). Since in experimental studies the inequality $d_{m1} >> d_n$ is usually fulfilled, it can be argued that the insignificant value of the effect is due to the shunting of the resistances of the cover and base magnetic layers depending on the sign of the inequality between d_{m2} and d_{m1}. In the case when the thickness of the covering magnetic layer of the metal is of the order of magnitude comparable to the total thickness of the base magnetic layer and the non-magnetic layer, the value of magnetoresistance reaches its maximum value due to the absence of the above-mentioned shunting effect.

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Обгрунтування ефекту гігантського магнітоопору у магнітопорядкованих тришарових структурах Co/Cu/Co та Fe/Cr/Fe з використанням формули Фукса

Н.С. Шишко[1], Ю.М. Шабельник[2], Ю.А. Колесниченко[3], Ю.О. Шкурдода[2], А.О. Проноза[2], А.М. Чорноус[2], Л.В. Дехтярук[1]

[1] *Харківський національний університет будівництва та архітектури, вул. Сумська, 40, 61002 Харків, Україна*
[2] *Сумський державний університет, вул. Римського-Корсакова, 2, 40007 Суми, Україна*
[3] *Фізико-технічний інститут низьких температур ім. Б.І. Вєркіна Національної академії наук України, Проспект науки, 47, 61103 Харків, Україна*

З використанням двострумової моделі та теорії розмірних ефектів проведений якісний аналіз гігантського магніторезистивного ефекту в тришарових магнітовпорядкованих плівках (сандвічах). Показано, що в області малих товщин накривного магнітного шару в порівнянні з товщиною базового магнітного шару, магнітоопір провідника зростає, в той час як у протилежній області товщин спостерігається його зменшення, причому в зазначених інтервалах товщин ефект мізерно малий внаслідок наявності шунтуючого ефекту. У разі, коли товщина накривного магнітного шару металу по порядку величини сумірна зі сумарною товщиною базового магнітного шару та немагнітного прошарку величина магнітоопору досягає максимальної величини в силу відсутності шунтуючого ефекту. Показано, що незначна величина ефекту зумовлена шунтуванням опорів покривного та базового магнітних шарів. Якщо товщина покривного магнітного шару металу за порядком порівняння із сумарною товщиною основного магнітного шару та немагнітного шару, значення магнітоопору досягає максимального значення за рахунок відсутності згаданого вище ефекту шунтування.

Ключові слова: Тришарова магнітна плівка, Гігантський магнітоопір, Коефіцієнт магнітоопору, Резистор і двопотокова модель, Мажоритарні та міноритарні носії заряду, Ефект шунтування.