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STRUCTURE AND EFFECT OF GIANT MAGNETORESISTANCE IN THREE-LAYERED FeNi/Cu/Co FILMS

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Dependence of the magnetoresistance in magnetic three-layered FeNi/Cu/Co films was investigated both theoretically and experimentally. It was found that for small values of the thickness ratio of magnetic metal layers $d_2/d_1 << 1$ (d_j ($j = 1, 2$) is the thickness of the j-th metal layer), the giant magnetoresistance effect ($\delta = (\rho(0) - \rho(H))/\rho(H) \sim d_2$) increases with thickness of the top (covering) magnetic layer. At the same time, if the inverse inequality takes place, the magnetoresistance decreases as $1/d_2$. When the equality $d_2/d_1 = \sqrt{(\rho_1^+\rho_1^-)/(\rho_2^+\rho_2^-)}$ (ρ_j^s is the resistivity of the s-th spin channel) holds, this effect is maximal.

Keywords: *THREE-LAYERED MAGNETIC FILM, GIANT MAGNETORESISTANCE, MAGNETORESISTIVE RATIO, RESISTOR MODEL, SPIN-DEPENDENT SCATTERING.*

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1. INTRODUCTION

Multilayer nanocrystalline film systems composed of magnetic and nonmagnetic alternating metal layers belong to a new class of materials of spintronics due to a unique combination of their magnetic and electrical properties. The most known effect observed in metal multilayer structures is the giant magnetoresistance (GMR) effect [1, 2], which consists in an abrupt decrease in the resistance of multilayer conductor under the action of external magnetic field and is conditioned by the spin dependence of the electron scattering on the type of magnetic ordering in adjacent magnetic layers of the conductor. Study of the initiation mechanisms of the mentioned effect served as the stimulus to create new materials with a wide spectrum of their practical application in computer engineering, electronics, automotive industry [3-6], etc.

In spite of the considerable accumulated theoretical and experimental material in the investigations of the GMR, a number of fundamental problems has not been clarified yet. Thus, in particular, there is a need in the development and approval of the GMR theoretical models for three-layered films, and, correspondingly, the aim of the present work is the theoretical and experimental investigation of the GMR effect in three-layered magnetic FeNi/

Cu/Co films (sandwiches), the establishment of the effect behavior for boundary values of the covering layer thickness, and determination of the conditions, under which the maximal (amplitude) effect is observed.

2. TECHNIQUE OF THE EXPERIMENTAL INVESTIGATION

Magnetic three-layered FeNi/Cu/Co films were obtained by the resistor (Cu) and electron-beam (Co and FeNi) evaporation methods in the vacuum of the order of 10^{-4} Pa at the substrate temperature $T_s = 300$ K. Glass polished plates with predeposited copper contacts with chromium sublayer were used as the substrate. Condensation rate of metal layers was 0,5-0,8 nm/s for Co and FeNi and 1-1,5 nm/s for Cu. To determine resistance R with relative error 0,025% we used universal digital voltmeters V7-46/1. Temperature control was realized by the chromel-alumel thermocouple with error of $\pm$ 5 K. Layer thickness d_t was defined by the interferometric method (device MII-4) with the measurement accuracy to 10% at $d > 50$ nm. To recover geometry of the film length (a) and width (b) the stainless steel masks were used.

Measurement of the longitudinal (||) and transverse ($\perp$) magnetoresistance (MR) of the samples was carried out in a special device under the conditions of ultrahigh oil-free vacuum (10^{-7} Pa) in magnetic field up to 150 kA/m at room temperature with relative error not more than 0,05%.

Structural and phase investigation of the samples was performed using the transmission electron microscope EM-125 and electron diffractometer.

3. EXPERIMENTAL RESULTS

3.1 Structure and phase composition of the samples

Electron-microscope and diffraction investigations indicate that unannealed FeNi/Cu/Co films are polycrystalline ones and have fine-dispersed structure (Fig. 1a, with the grain size not more than 5 nm).

Very blurred rings, which belong to the fcc-phase with the lattice parameter $a = 0{,}355\text{-}0{,}360$ nm (Fig. 1b), are observed on the electron-diffraction patterns of unannealed FeNi/Cu/Co films due to fine-dispersed structure and close interplanar spacings of FeNi and Cu. As the result of strong line blur, which belong to the fcc-phases of FeNi and Cu, it is impossible to say with confidence about two-phase Co composition. Lines, which belong to the hcp-Co, are not practically observed.

Two-phase composition fcc-Co + fcc-solid solution (FeNi, Cu) is fixed on the electron-diffraction patterns after annealing at 700 K (Fig. 1d).

3.2 Magnetoresistance of three-layered films

Anisotropic magnetoresistance (AMR) is observed for all studied unannealed FeNi/Cu/Co films with $d_{Cu} < 2$ nm. Presence of AMO at small thicknesses of sublayers is explained by their structural discontinuity, and, as the result, a strong direct binding of magnetic layers exists. Such interaction impedes the separate remagnetization of layers, and, thus, it does not lead to the GMR appearance.

For unannealed samples with $d_{Cu} = 2\text{-}10$ nm the decrease in the resistance only is observed under the action of magnetic field regardless of its direction (Fig. 2). The value of MR for these films is 0,2-1,3%. Thus, we can speak about realization of the GMR effect in the given three-layered systems [8]. Small amplitude of the GMR effect can be explained by some reasons. First of all, by the formation of paramagnetic solid solution (FeNi, Cu) on the layer interface that leads to the "information loss" about spin at the electron scattering. Another reason is the presence of "bridges" through non-magnetic sublayer of a small effective thickness that leads to the appearance of ferromagnetic coupling between layers, and, as a consequence, to the violation of the antiparallel configuration.

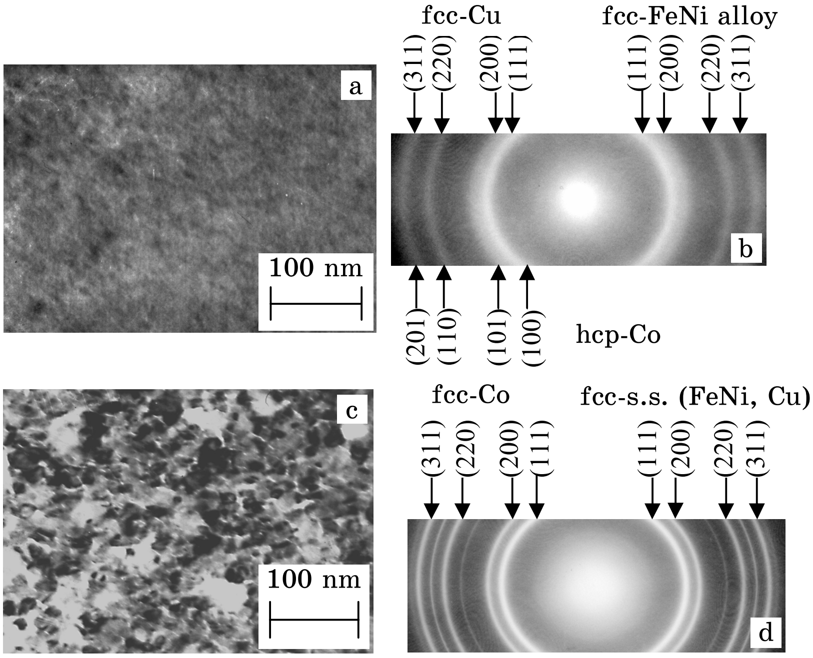

Fig. 1 *– Microstructure and electron diffraction patterns from unannealed (a, b) and annealed (c, d) at 700 K three-layered FeNi(30 nm)/Cu(8 nm)/Co(30 nm) structure*

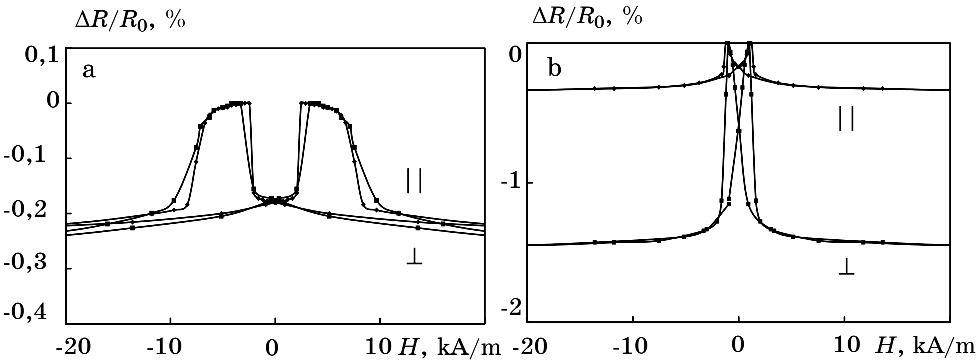

Fig. 2 *– Magnetoresistive hysteresis loops for three-layered FeNi/Cu/Co/sub structure:* $d_{Co,FeN}$ *= 35 nm,* d_{Cu} *= 5 nm (a);* $d_{Co,FeNi}$ *= 40 nm,* d_{Cu} *= 7 nm (b). Measurement temperature is 300 K*

We have to note that for unannealed FeNi/Cu/Co systems with d_{Cu} = 4-6 nm one can observe the horizontal region on the magnetoresistive loop (see Fig. 2a) in the range of the external magnetic field from 3 kA/m to 8 kA/m. This fact implies the separate remagnetization of the layers.

Change in the resistance of the structure occurs with the change in the mutual orientation of the magnetization of the soft-magnetic (FeNi) and hard-magnetic (Co) layers, that is the GMR is realized. Abrupt changes in the MR observed on the magnetoresistive loop correspond to the separate remagnetization of the soft-magnetic and hard-magnetic layers, which occur in the fields of 2 and 8 kA/m, respectively. When cooling the samples to 150 K, the form of the hysteresis loops of the magnetoresistive effect is not almost changed. Only the increase in the effect and shift of the horizontal region on the magnetoresistive loop towards stronger fields is observed.

For unannealed FeNi/Cu/Co samples with d_{Cu} = 6-10 nm one can observe the magnetoresistive loops, which are typical for symmetrical three-layered systems (the horizontal region on the loop is absent).

In Fig. 3 we show the experimental dependence of the magnetoresistive ratio (MRR) on the thickness of the top (covering) FeNi layer under the condition that thickness of the basic magnetic Co layer and thickness of Cu sublayer are constant. The dependences obtained show that the amplitude value of the GMR effect is observed under the condition of equality of the basic and covering metal layer thicknesses that is confirmed by the theoretical calculations. In the region of small thicknesses of the top (covering) metal layer $d_{2,1} << 1$, the GMR effect is almost absent due to the current shunting by the basic Co layer; and with the increase in the thickness d_2 the effect increases. With further increase in d_2 in such a way that the inequality $d_{1,2} >> 1$ holds, the GMR effect is absent again due to the current shunting in the covering metal layer.

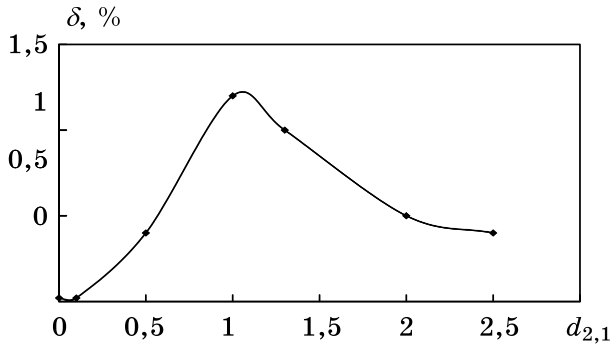

***Fig. 3** – Dependence of the MRR δ on the thickness ratio of magnetic metal layers $d_{2,1}$ under the condition that d_{Cu} = const and d_{Co} = const*

4. THEORETICAL ANALYSIS OF THE EFFECT

In the foregoing experimental investigation the thickness of non-magnetic sublayer was chosen to be much less than the thickness of magnetic (basic and covering) metal layers. Therefore, in the further analytical description of the effect we will consider this sublayer to be ultrathin and neglect its conductance in comparison with the conductance of magnetic metal layers.

For the quantitative description of the GMR effect one can use the resistor model (the equivalent circle model) [7, 9]. In accordance with this model each magnetic layer of the sandwich is considered as an independent resistor, which, in turn, within the two-current model [11-13] consists of two resistors corresponding to two independent spin conduction channels. We assume that the effects of the spin reorientation are negligible and we can neglect them.

The GMR effect is usually characterized by the resistance change $\rho(0) - \rho(H)$ during remagnetization of three-layered film using external magnetic field, which is normalized on the resistivity $\rho(H)$ in the presence of magnetic field (ferromagnetic interaction) [7-9], i.e.,

$$\delta = \frac{\rho(0) - \rho(H)}{\rho(H)} = \frac{\rho(0)}{\rho(H)} - 1 . \tag{1}$$

Not dwelling on the intermediate calculations, we write the final result for the MRR δ

$$\delta = \frac{(\alpha_1 - 1)(\alpha_2 - 1)}{\alpha_1 \left(\rho_{1,2}^{+} d_{1,2} + 1\right)\left(\rho_{2,1}^{-} d_{2,1} + 1\right)} . \tag{2}$$

Here $\alpha_j = \rho_j^- / \rho_j^+$ ($j = 1, 2$) is the asymmetry parameter, i.e., the parameter, which describes asymmetry of the spin-dependent scattering (SDS) of charge carriers with different spin indexes $s = \pm$ in the volume of magnetic metal layers [13]; $d_{1,2} = d_1/d_2$ is the ratio of magnetic metal layers; $\rho_{j,n}^s = \rho_j^s / \rho_n^s$ is the ratio of their resistivities; ρ_j^s is the resistivity of the s-th spin channel of the j-th polycrystalline metal layer. We note that for symmetrical sandwich, i.e., three-layered film, which consists of the same magnetic metal layers ($\rho_j^s = \rho_n^s$) with the same thickness ($d_j = d_n$), formula (2) is transformed to the well-known correlation for MRR, which is often used for the effect analysis [11-13]:

$$\delta = \frac{(\alpha - 1)^2}{4\alpha} . \tag{3}$$

In the region of small values of the top covering metal layer ($d_{2,1} << 1$), the GMR effect is almost absent due to the current shunting by the basic Co layer, and the effect increases proportionally to d_2 ($\delta \sim d_2$) with the increase in the thickness d_2

$$\delta = \frac{(\alpha_1 - 1)(\alpha_2 - 1)\rho_{2,1}^{+}}{\alpha_1} d_{2,1} \sim d_2, \qquad d_{2,1} << \prod_{s=\pm} \sqrt{\rho_{1,2}^{s}} . \tag{4}$$

If inequality $d_2 > d_1$ holds, the mentioned effect decreases as $1/d_2$, and with further increase in d_2 in such a way that inequality $d_{2,1} >> 1$ holds, the GMR effect is absent again due to the current shunting in the covering metal layer

$$\delta = \frac{(\alpha_1 - 1)(\alpha_2 - 1)\rho_{1,2}^{-}}{\alpha_1} d_{1,2} \sim \frac{1}{d_2}, \qquad d_{2,1} >> \prod_{s=\pm} \sqrt{\rho_{1,2}^{s}} \, . \tag{5}$$

In fact, as it was experimentally established in [9], if inequality $d_2 >> d_1$ holds, the effect value decreases not as $1/d_2$, but as $\exp\left(-d_2 / l_2^s\right)$ (l_2^s is the electron mean free path in the covering metal layer). The mentioned discrepancy between theory and experiment is conditioned by the fact that in this thickness range the resistor model can not be applied since the film thickness d_2 becomes larger than the mean free path l_2^s ($d_2 >> l_2^s$) and magnetic metal layers in three-layered film become independent.

In the case when $d_2 \sim d_1$, due the absence of current shunting the magnetoresistance reaches the maximum value, i.e., on the dependence $\delta(d_{2,1})$ one can observe the maximum whose position is defined by the conductive properties of magnetic metal layers

$$d_{2,1}^{\max} = \rho_{1,2}^{+}\sqrt{\alpha_1 / \alpha_2} \equiv \sqrt{\rho_{1,2}^{+}\rho_{1,2}^{-}} \, , \tag{6}$$

and the amplitude value of the effect is equal to

$$\delta\left(d_{2,1}^{\max}\right) = \frac{(\alpha_1 - 1)(\alpha_2 - 1)}{\left(\sqrt{\alpha_1} + \sqrt{\alpha_2}\right)^2} \, . \tag{7}$$

As follows from (7), the amplitude (maximum) value of the effect is only defined by the bulk asymmetric SDS of electrons (i.e., by the parameters α_j), and it is not important in which spin channel the mentioned asymmetry will be larger. It is important that it would be the largest.

Calculation of the GMR amplitude value by formula (7) gives the maximum possible value of the effect, since, on the one hand, we neglected sublayers, on the other hand, it is considered within the resistor model that interaction of the charge carriers with the external boundaries and interfaces does not lead to the “electron flow dissipation”.

We note that bilayer is the periodicity element for the model of multilayer conductor with ultrathin sublayers. In this case multilayer film can be formally considered as two-layered one whose external boundaries specularly reflect electrons, and, correspondingly, all the foregoing formulas can be used for the analysis of the GMR effect in multilayer magnetic samples with ultrathin nonmagnetic sublayers.

5. APPROVAL OF THE THEORETICAL CORRELATIONS

It is well-known that presence of copper impurities in Co layer leads to the bulk asymmetric SDS of charge carriers, and the parameter of asymmetric electron scattering with different spin indexes, in accordance with the data of works [14-16], is equal to $\alpha_1 \equiv \alpha_{\mathrm{Co}} = 3{,}082$; $\rho_{\mathrm{Co}}^{+} = 4{,}998 \cdot 10^{-8}$ Ohm·m and $\rho_{\mathrm{Co}}^{-} = 15{,}402 \cdot 10^{-8}$ Ohm·m. The given data and experimentally obtained values of the magnetic thickness ratio $d_{2,1} = 1{,}2$ (at which the effect is maximal and equal to $\delta = 0{,}013$) allow to calculate resistivity in the s-th spin channel of NiFe layer, and, correspondingly, to find parameter of asymmetric SDS of electrons α_{NiFe} using the obtained theoretical correlations (6) and (7). Substituting $\delta = 0{,}013$ and $\alpha_1 = 3{,}082$ into correlation (7), we obtain the quadratic equation with respect to α_2; solving this equation, we find $\alpha_{NiFe} = 1{,}046$.

Knowing the asymmetry parameters in magnetic metal layers and resistance in the s-th spin channel of Co layer, it is possible to calculate resistances ρ^s_{NiFe} by formula (6) (according to the experimental measurements $d^{max}_{2,1} = 1{,}2$): $\rho^+_{NiFe} = 7{,}149 \cdot 10^{-8}$ Ohm·m and $\rho^-_{NiFe} = 7{,}478 \cdot 10^{-8}$ Ohm·m.

Obtained understated values for the resistivity ρ^s_{NiFe} are conditioned by the fact that within the resistor model the mechanism of electron scattering on the interfaces and external boundaries of the conductor, which contributes to the total resistance of magnetic metal layer, was completely "excluded".

6. CONCLUSIONS

Thus, in magnetic three-layered films with non-magnetic sublayers of the thickness of d_{Cu} = 3-10 nm the GMR effect is realized. This effect in the region of small values of the covering layer thickness ($d_{2,1} << 1$) increases proportionally to d_2 ($\delta \sim d_2$) as thickness increases. If the opposite inequality $d_{2,1} > 1$ holds, the effect decreases as $\delta \sim 1/d_2$. If the equality $d_{2,1} = \sqrt{\rho^+_{1,2}\rho^-_{1,2}}$ holds, the effect is maximal due to the absence of current shunting, and its amplitude value is defined by the value of asymmetric electron scattering in magnetic metal layers.

REFERENCES

1. M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Greuzet, A. Fiederich, J. Chazelas, *Phys. Rev. Lett.* **61**, 2472 (1988).
2. G. Binasch, P. Grunberg, F. Saurenbach, *Phys. Rev. B* **39**, 4828 (1989).
3. A.M. Pogoriliy, S.M. Ryabchenko, O.I. Tovstolytkin, *UPhJ* **6**, 37 (2010).
4. A. Fert, *UPhN* **178**, 1336 (2008).
5. P.A. Gryunberg, *UPhN* **178**, 1349 (2008).
6. V.G. Dorogan', F.V. Motsnyi, *UPhJ* **49**, 1174 (2004).
7. E.Y. Tsymbal, D.G. Pettifor, *Solid State Phys.* **56** 113 (2001).
8. S.T. Roschenko, I.G. Shipkova, Yu.I. Chekrygina, *J. Functional Materials* **16**, 1 (2009).
9. S.S.P. Parkin, *Annu. Rev. Mater. Sci.* **25**, 357 (1995).
10. L. Kond, Q. Pan, B. Cui, *J. Appl. Phys.* **85**, 5492 (1999).
11. A.F. Mayadas, M. Shatzkes, *Phys. Rev. B* **1**, 1382 (1970).
12. N.F. Mott, *Adv. Phys.* **13**, 325 (1964).
13. A. Fert, I.A. Campbell, *J. Phys. F.: Metal. Phys.* **6**, 849 (1976).
14. J. Barnas, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev *Mater. Science Eng.* **B126**, 271 (2006).
15. W.P. Pratt, S.-F. Lee, Q. Yang, P. Holody, R. Loloee, P.A. Schroeder, J. Bass, *J. Appl. Phys.* **73**, 5326 (1993).
16. T. Valet, A. Fert, *Phys. Rev. B* **48**, 7099 (1993).