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MAGNETORESISTIVE PROPERTIES OF MULTILAYER FILM SYSTEMS BASED ON Fe/Cu AND Fe/Cr

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The magnetoresistive properties of multilayer film systems based on Fe and Cu or Cr were investigated at room temperature. Factors influencing on magnetoresistance (MR) value changing were studied. In Fe/Cu film system, in which the individuality of separate layers holds, the change of substrate from amorphous pyroceramic to monocrystalline Si(111) leads to MR ratio increasing on 35 %*, that is connected with magnetic ordering in bottom epitaxial Fe layer. Thermal annealing of samples to* 700 *K leads to vanishing of odd effect in MR in perpendicular geometry and MR increasing by two times in parallel geometries. Investigations of* $[Fe(d_{Fe})/Cr(1)]_{10}$ *system showed, that the Fe thickness changes from* 0,31 *to* 1,5 *nm lead to the magnetoresistance magnitude changes from* 0,03-0,05 % *to* 1-3 % *subject to different measurement geometries, which is interpreted by Fe granules formation in matrix of solid solution (Fe, Cr).*

Keywords: *FILM SYSTEM, MAGNETORESISTANCE, SUBSTRATE, GEOMETRY OF MEASUREMENT, THERMAL ANNEALING.*

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1. INTRODUCTION

It is known, that before the discovery of giant magnetoresistance (GMR) effect in Fe/Cr multilayers [1] the effect of antiferromagnetic coupling between ferromagnetic layers through metallic interlayer was observed in Fe/Cr and Fe/Au film systems. As GMR effect is interpreted by spin-dependent scattering of conductivity electrons on parallel/antiparallel orientation of the magnetization of adjacent magnetic layers or granules, it is natural, that the spin-dependent electron transport can be occurred in another kinetic and magnetoresistive properties in low-dimension magneto-inhomogeneous film materials. It confirms, for instance, by the results of works [3, 4], where the observation of the big magnetoresistance in Co/Cu and Fe/Cu film systems at temperature $T = 4{,}2$ K (80 % and 13 % respectively) is reported.

Among many multilayer structures, that are investigated so far, film systems based on Fe/Cr and Fe/Cu are into an area of growing interest because of the wide applications in modern electronics such a magnetic sensors, GMR-based read-head devices in hard disks and other devices [5].

As it is known from series of theoretical and experimental works, the maximal value of exchange coupling between ferromagnetic layers in multilayers is the characteristic of many factors influences. In particular, oscillates of exchange coupling from antiferromagnetic to ferromagnetic, when the thickness of non magnetic layer increases, leads to an oscillatory behaviour of MR ratio [4] (the saturated magnetoresistance maximums, observed in [6] for Fe/Cr structure, when the Cr layer thickness equals to 1,0; 2,5 and 4,3 nm, also point out on such behaviour). Also magnetoresistive effect increases with numbers of bilayers increasing, the measurement temperature decreasing and geometry changes. An important contribution to the reducing of the MR ratio with temperature (for example, temperature increasing from 4.2 K to 300 K leads to MR ratio decreasing 5-6 times for Fe/Cr systems) is electron-magnon scattering, which shortens the mean free path, and introduces spin mixing.

According to reports [7-10], the interfaces are crucial to the MR value of multilayer systems (for example, increasing of interface amplitude, or roughness, in Fe/Cr multilayers leads to magnetoresistance decreasing [7]). It has been shown that the MR of Fe/Cr system increases upon annealing while the fraction of ferromagnetic regions increases [8]. In [9, 10] the formation of alloyed interface layer is attributed to the MR effect growth with the layer thickness decreasing. Also in our and other authors works (see for example [11, 12] and references in them) it was shown that the structure-phase state of film systems based on Fe and Cr or Fe and Cu in as-deposited and annealed state corresponds to granular solid solution (s.s.) (α-Fe, Cr) or $[Fe/Cu]_n$ system, in which the individuality of separate layers holds. The conclusion of the works [9, 10] about solution formation near interface can be considered as hypothesis, that interprets the MR increasing with decrease of layer thickness. Then it is possible to claim that the film systems based on Fe and Cr or Fe and Cu are the representatives of two opposite types of systems in terms of structure-phase state (an unlimited mutual atoms solubility in Fe/Cr and the conservation of an individuality of several layers). Thus magnetoresistive properties of observable film systems will be characterized by antiferromagnetic coupling of magnetic domains of adjacent Fe layers (Fe/Cu system) or Fe granules (single domains) in homogeneous through all the thickness of s.s. (α-Fe, Cr) samples. This fact has predetermined the aim of investigations of this work, which can be formulated like this: the study of the structure-phase state of film systems, the annealing temperature, the thickness of individual layers and their number and the type of substrate influences on magnetoresistive properties of film systems based on Fe and Cr or Fe and Cu, generated by consistent layer condensation and successive thermal treatment.

2. EXPERIMENTAL DETAILS

The film systems were prepared by thermal evaporation and successive deposition of layers without orienting magnetic field in ultrahigh vacuum ($p = 10^{-6}$-10^{-7} Pa) with deposition rate of 0,5 nm/min. As substrate a monocrystalline Si (111) and amorphous pyroceramic (P) were used. Thicknesses of several layers were controlled in situ by quartz resonator method. The annealing of samples was done in temperature range from 300 to 700 K. The magnetoresistive measurements were performed at room temperature with four-point contact scheme in external magnetic field, which was varied from 0 to 1 T. The magnetoresistance is defined as $\Delta R/Rs = (R(B) - Rs)/Rs$, where $R(B)$ and Rs are the resistivity in field B and the saturation resistivity. Usually the Current Perpendicular to the Plane (CPP) as well as the Current In Plane (CIP) geometries is using for MR effect measurements. We have used the CIP geometry, where three mutual external field B orientations with respect to sample plane and current direction were observed: parallel geometry – B is parallel to the film plane and to the flowing current (PG); perpendicular geometry – B is perpendicular to the film plane and to the current (PrG); parallel-perpendicular geometry – B is parallel to the film plane and perpendicular to the current (PPrG).

3. RESULTS AND DISCUSSION

Results of magnetoresistance investigations of as-deposited samples $[Cu(2\ nm)/Fe(2\ nm)]_4/P$ and $[Cu(2\ nm)/Fe(2\ nm)]_{10}/P$ are represented in Fig. 1. The largest MR effect has been observed in perpendicular geometries; its magnitudes were 0,13 % for $[Cu(2\ nm)/Fe(2\ nm)]_4/P$ system and 0,55 % – for $[Cu(2\ nm)/Fe(2\ nm)]_{10}/P$.

In as-deposited samples hysteresis of $\Delta R/R_s$ dependence is not observed. Its appearance in parallel geometries after thermal treatment gives the possibility to estimate the coercive force (value of magnetic field's induction, in which maximum of MR is observed). For the sample $[Cu(2\ nm)/Fe(2\ nm)]_{10}/P$ it is $B_c = 60$ mT. Also in these dependences for annealed sample (Fig.1 c, f) the saturation state is observed (the saturation field induction is $B_s = 200$ mT), in which antiferromagnetic coupling between adjacent Fe layers destroys and all magnetic moments of Fe atoms are parallel to each other.

It is necessary to discuss more detailer the results, obtained in PrG (Fig.1 d, e, f). Though the magnetoresistance is from even effects category, dependence $\Delta R/R_s$ (B) has the typical character for odd effects in outward appearance. This fact has not suitable explanation. But it can be marked that the analogical behaviour of MR was observed in two-layer films Cr/Co [13] under anomalous Hall effect measurement, which supposes perpendicular component of ferromagnetic film magnetization. In [13] it is noticed that the planar Hall effect was observed as even when magnetic moments are all oriented in film plane in contrast to anomalous Hall effect. It is clear, that normal component of magnetization in Fe layers is appearing under perpendicular field, and dependences, analogical to Fig.1 d, e, must take place not only in Cu/Fe and Cr/Co systems, but in another low-dimension magneto-inhomogeneous film system.

The annealing of sample $[Cu(2\ nm)/Fe(2\ nm)]_{10}/P$ to 700 K (Fig. 1c, f) leads to odd effect vanishing in perpendicular geometry and increasing of MR magnitude in parallel-perpendicular geometries (from 0,17 % to 0,48 %, as shown in Fig. 1c). This fact can be connected with the original magnetic order breaking in Fe layers and with the increasing role in MR effect of electrons spin-dependent scattering in interfaces and grain boundaries at the expense of interface roughness increasing and grain-boundary diffusion activity.

According to Refs. [14, 15] and our early work [16] a maximal saturation field in Fe/Cr superlattices is attained on the Cr layer thickness d_{Cr} = 0,9-

1,0 nm. In this case a maximum possible value of antiferromagnetic interaction between ferromagnetic iron layers is realized. In the case of very thin iron layers ($d_{Fe} \cong$ 0,31-1,5nm), the magnetization curve achieves the saturation in magnetic field up to 1,5 T when d_{Fe} = 1,5nm [15]. The results of our investigations of magnetoresistivity properties of [Fe(d_{Fe})/Cr(1)]$_{10}$/P multilayer samples at two values of d_{Fe} are represented in Fig. 2. As it is shown there, the iron thickness changes from 0,31 to 1,5 nm leads to the magnetoresistance magnitude changes in these systems from 0,03-0,05 % to 1-3 % subject to different measurement geometries. It is simply to explain

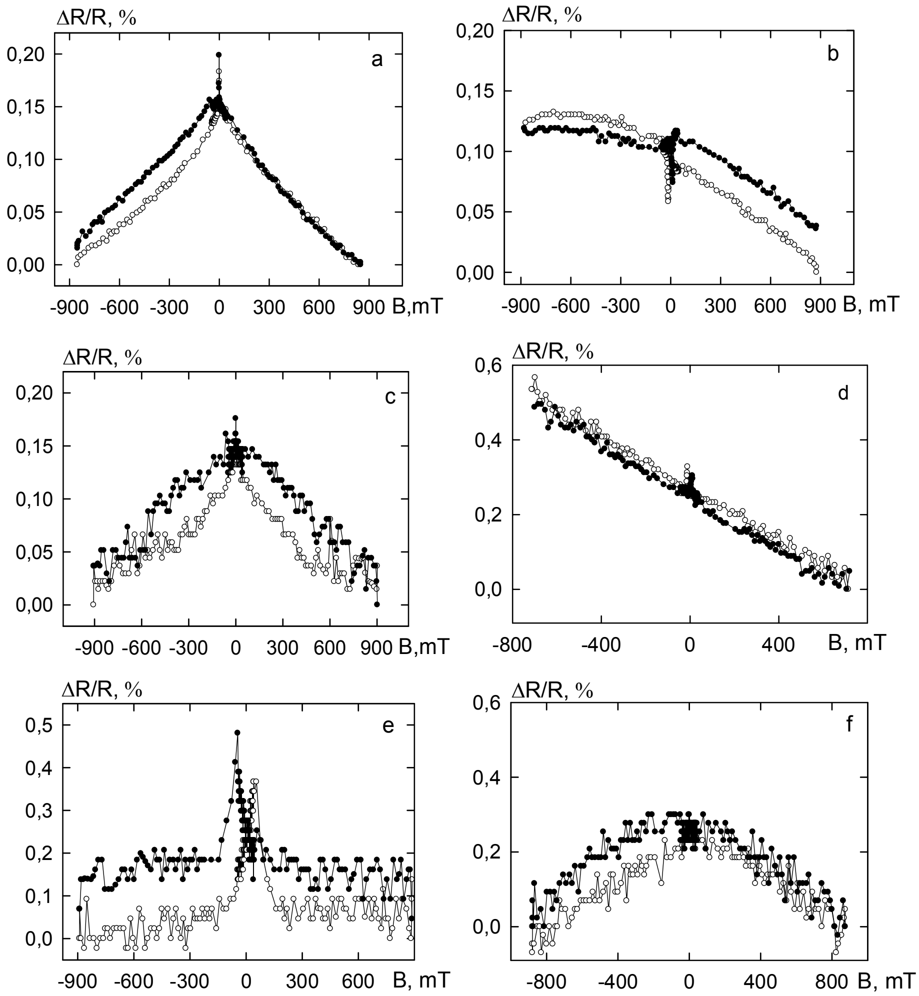

Fig. 1 – Magnetoresistive magnitude versus magnetic induction for [Cu(2)/Fe(2)]$_4$ (a, b) and [Cu(2)/Fe(2)]$_{10}$ (c - f) film systems, as-deposited (a - d) and annealed to 700K (e, f) for two mutual orientations of external field with sample plane and current in CIP geometry: a, b, c – PPrG; d, e, f – PrG. ○ – first cycle, ● – second cycle

this by structure-phase state change from homogeneous s.s. (α-Fe, Cr) under comparatively low concentration of Fe atoms (24 at.%) to granular s.s. under comparatively high concentration of Fe atoms (50 at.%). For Fe/Cr system in as-deposited state hysteresis absence is typical and in parallel geometries saturation state is observed under field B_s = 900 mT (Fig.2 a), while in perpendicular geometry saturation is absence (see Fig.2 c).

In order to confirm the supposition about sensitivity of MR magnitude to the type of substrate [17] the investigations of magnetoresistive properties of $[Cu(5\ nm)/Fe(5\ nm)]_2$ film system were done for different substrates

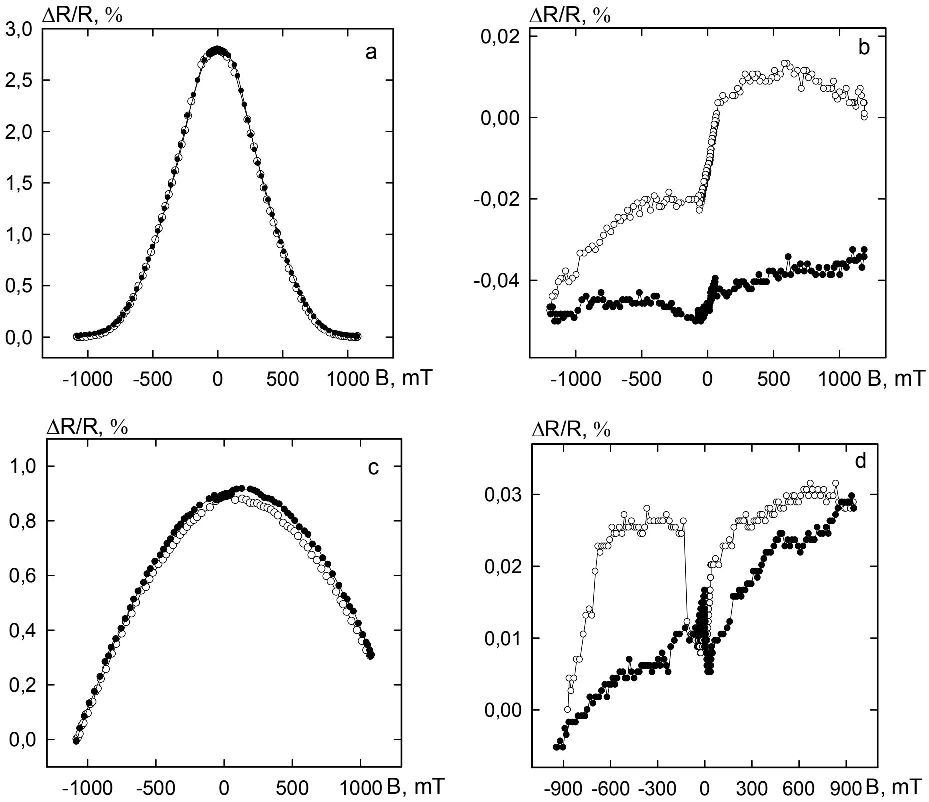

Fig. 2 *– Magnetoresistive magnitude versus magnetic induction for* $[Fe(1,5)/Cr(1)]_{10}$ *(a, c) and* $[Fe(0,31)/Cr(1)]_{10}$ *(b, d) film systems for two mutual orientations of external field with sample plane and current in CIP geometry: a, b – PG; c, d – PrG*

(Fig.3). It was obtained that the change of substrate from amorphous pyroceramic to monocrystalline Si (111) leads to MR ratio increasing on 35 %, which can be explained by epitaxial growth of bottom Fe layer and its magnetic ordering, that provides more effective antiferromagnetic coupling with over Fe layer. In addition, the comparative small value of saturation field must be noticed, which not typical for this film system and can be connected with demonstration of Thomson anisotropic magnetoresistive effect.

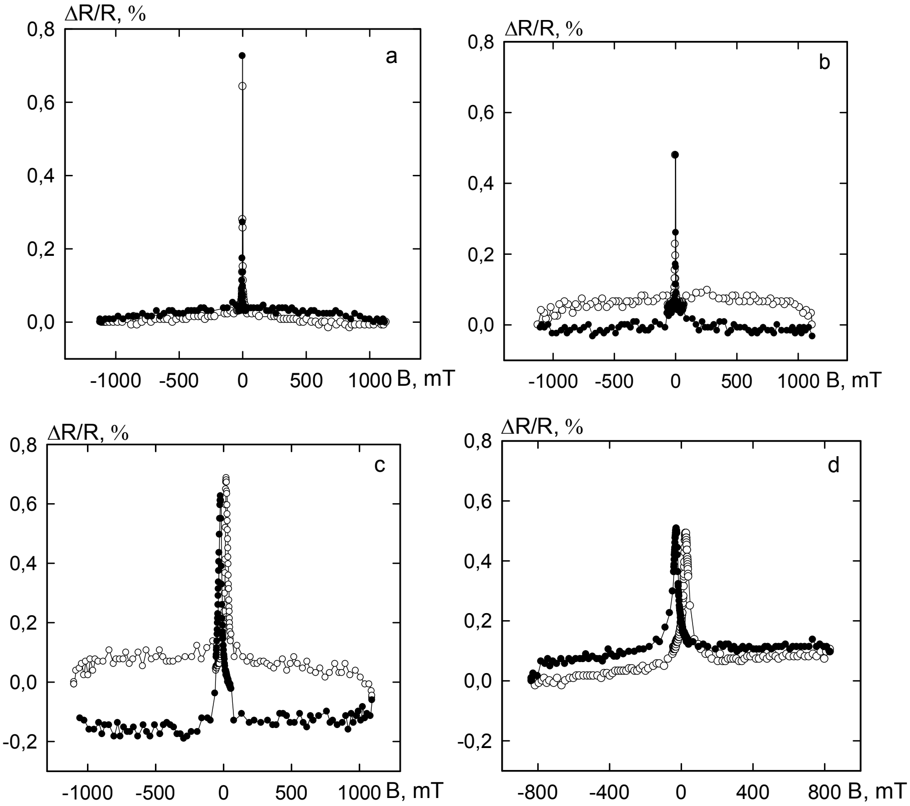

Fig. 3 *– Magnetoresistive magnitude versus magnetic induction for [Cu(5)/Fe(5)]$_2$/Si(111) (a, c) and [Cu(5)/Fe(5)]$_2$/P (b, d) film systems for two mutual orientations of external field with sample plane and current in CIP geometry: a, b – PG; c, d – PrG*

4. CONCLUSION

The results of our investigations can be formulated in following conclusions:

1. In [Cu(2 nm)/Fe(2 nm)]$_4$/P and [Cu(2 nm)/Fe(2 nm)]$_{10}$/P multilayer film systems, where the individuality of separate layers holds, in parallel-perpendicular geometry MR value is approximately about 0,20 % (T = 300 K) and after annealing to T = 700 K increasing to 0,50 %, while in perpendicular geometry in case of [Cu(2 nm)/Fe(2 nm)]$_{10}$/P MR magnitude decreasing from 0,55 % (odd effect) to 0,30 % (even effect).
2. The odd effect of MR was observed under investigations in perpendicular geometry, which caused by a perpendicular component of ferromagnetic Fe film magnetization, which vanishing after annealing to 700 K.
3. By example of [Cu(5 nm)/Fe(5 nm)]$_2$ film system it was shown that the change of substrate from amorphous pyroceramic to monocrystalline Si (111) leads to MR ratio increasing on 35 %, which can be explained by magnetic ordering in bottom epitaxial Fe layer.

4. In multilayer film systems based on Fe and Cr, where structure-phase state corresponds to solid solution (Fe, Cr), MR magnitude depends from concentration of Fe atoms and changes from 0,03-0,05 % (not granular s.s.) to 1-3 % (granular s.s.).

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МАГНІТОРЕЗИСТИВНІ ВЛАСТИВОСТІ БАГАТОШАРОВИХ ПЛІВКОВИХ СИСТЕМ НА ОСНОВІ Fe/Cu I Fe/Cr

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Досліджені магніторезистивні властивості багатошарових плівкових систем на основі Fe і Cu або Cr при кімнатній температурі. Вивчені фактори, які впливають на зміну величини магнітоопору (МО). В плівковій системі Fe/Cu, в якій зберігається індивідуальність окремих шарів, перехід від аморфної підкладки із ситалу до монокристалічної Si(111) веде до збільшення величини МО на 35 %*, що пов'язано з магнітним упорядкуванням в нижньому епітаксійному шарі Fe. Термічне відпалювання зразків до* 700 *К призводить до руйнування непарного ефекту в МО в перпендикулярній геометрії та збільшення його величини в* 2 *рази в паралельних геометрія. Дослідження системи* $[Fe(d_{Fe})/Cr(1)]_{10}$ *показали, що збільшення товщини шару Fe від* 0,31 *до* 1,5 *нм призводить до збільшення величини МО від* 0,03-0,05 % *до* 1-3 % *в залежності від геометрії вимірювання, що пояснюється утворенням гранул Fe в матриці твердого розчину (Fe, Cr).*

Ключові слова: *ПЛІВКОВА СИСТЕМА, МАГНІТООПІР, ПІДКЛАДКА, ГЕОМЕТРІЯ ВИМІРЮВАННЯ, ТЕРМОВІДПАЛЮВАННЯ.*

МАГНИТОРЕЗИСТИВНЫЕ СВОЙСТВА МНОГОСЛОЙНЫХ ПЛЕНОЧНЫХ СИСТЕМ НА ОСНОВЕ Fe/Cu И Fe/Cr

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*Исследованы магниторезистивные свойства многослойных плёночных систем на основе Fe и Cu или Cr при комнатной температуре. Изучены факторы, влияющие на изменение величины магнитосопротивления (МС). В пленочной системе Fe/Cu, в которой сохраняется индивидуальность отдельных слоев, переход от аморфной подложки из ситалла к монокристаллической Si(*111*) ведет к увеличению* *величины МС на 35 %, что связано с магнитным упорядочением в нижнем эпитаксиальном слое Fe. Термический отжиг образцов до 700 К приводит к разрушению нечетного эффекта в МС в перпендикулярной геометрии и увеличению его величины в два раза в параллельных геометриях. Исследование системы* $[Fe(d_{Fe})/Cr(1)]_{10}$ *показали, что увеличение толщины слоя Fe от* 0,31 *до* 1,5 *нм приводит к увеличению величины МС от* 0,03-0,05 % *до* 1-3 % *в зависимости от геометрии измерения, что объясняется образованием гранул Fe в матрице твердого раствора (Fe, Cr).*

Ключевые слова: *ПЛЕНОЧНАЯ СИСТЕМА, МАГНИТОСОПРОТИВ-ЛЕНИЕ, ПОДЛОЖКА, ГЕОМЕТРИЯ ИЗМЕРЕНИЯ, ТЕРМООТЖИГ.*

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