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

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*Magnetoresistive properties of multilayer film systems based on Fe and Cu or Cr were investigated at room temperature. Factors, which influence on the magnetoresistance (MR) value change, were studied. In Fe/Cu film system, in which the individuality of separate layers holds, the substrate change from amorphous pyroceramic to mono-crystalline Si(*111*) leads to the MR ratio increase by* 35 *%, that is connected with magnetic ordering in bottom epitaxial Fe layer. Thermal annealing of the samples to* 700 *K leads to vanishing of the odd effect in MR in perpendicular geometry and MR increase 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, and this leads to the MR magnitude change from* 0,03-0,05 *% to* 1-3 *% subject to the different measurement geometries, which is interpreted by Fe granule 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 the 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. Since the GMR effect is interpreted by the spin-dependent scattering of conduction electrons on parallel/antiparallel orientation of the magnetization of adjacent magnetic layers or granules, it is natural, that the spin-dependent electron transport can occur in another kinetic and magnetoresistive properties in low-dimension magneto-inhomogeneous film materials. It is confirmed, for instance, by the results of works [3, 4], where the observation of the GMR in Co/Cu and Fe/Cu film systems at the temperature T = 4,2 K (80% and 13%, respectively) is reported.

Among many multilayer structures, which have been investigated so far, film systems based on Fe/Cr and Fe/Cu are of a great interest because they are widely used in modern electronics, for example, in magnetic sensors, GMR-based read-head devices, hard disks, and other devices [5].

As it is known from a number of theoretical and experimental works, the maximal value of the exchange coupling between ferromagnetic layers in multilayers is the characteristic of many factors influence. In particular, oscillations of exchange coupling from antiferromagnetic to ferromagnetic, when the thickness of non-magnetic layer increases, leads to an oscillatory behavior of MR ratio [4] (the saturated MR 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 behavior). Also magnetoresistive effect increases with the growth of the number of bilayers, the measurement temperature decrease, and the geometry changes. An important contribution to the reduction of the MR ratio with temperature (for example, temperature increase from 4,2 K to 300 K leads to MR ratio decrease in 5-6 times for Fe/Cr systems) is the electron-magnon scattering, which shortens the mean free path and introduces the spin mixing.

According to reports [7-10], the interfaces are crucial to the MR value of multilayer systems (for example, increase of the interface amplitude or roughness in Fe/Cr multilayers leads to MR decrease [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 decrease. Also in our and other authors works (see, for example, [11, 12] and cited references) 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 the 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 the interface can be considered as hypothesis that interprets the MR increase with the layer thickness decrease. 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 the structure-phase state (unlimited mutual atom solubility in Fe/Cr and the conservation of an individuality of several layers). Thus magnetoresistive properties of observable film systems will be characterized by the 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 as follows: 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 influence 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 the 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 a substrate the monocrystalline Si(111) and the amorphous pyroceramic (P) were used. Thickness of several layers was controlled in situ by the quartz resonator method. Annealing of the samples was done in the temperature range from 300 to 700 K. The magnetoresistive measurements were performed at room temperature with the four-point contact scheme in external magnetic field, which was varied from 0 to 1 T. MR is determined as $\Delta R/Rs = (R(B) - Rs)/Rs$, where $R(B)$ and Rs are the resistivity in the field B and the saturation resistivity, respectively. Usually the Current Perpendicular to the Plane (CPP) as well as the Current In Plane (CIP) geometries is using for the MR effect measurements. We have used the CIP geometry, where three mutual external field B orientations with respect to the 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 the MR 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 magnitude was 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 induction, in which the maximum of MR is observed). $B_c = 60$ mT for the sample $[Cu(2\ nm)/Fe(2\ nm)]_{10}/P$. Also in these dependences for annealed sample (Fig. 1c, f) the saturation state is observed (the saturation field induction is $B_s = 200$ mT), in which the antiferromagnetic coupling between adjacent Fe layers is destroyed and all the magnetic moments of Fe atoms are parallel to each other.

It is necessary to discuss in detail the results obtained in PrG (see Fig. 1d, e, f). Though the MR is from the even effects category, dependence $\Delta R/R_s$ (B) has the typical character for odd effects in outward appearance. This fact does not have the suitable explanation. But it can be marked, that the analogical behavior of MR was observed in two-layer Cr/Co films [13] under anomalous Hall effect measurement, which supposes the perpendicular component of ferromagnetic film magnetization. In [13] it is noticed, that the planar Hall effect was observed as the even one when all magnetic moments are oriented in the film plane in contrast to the anomalous Hall effect. It is clear, that the normal component of magnetization in Fe layers appears under the perpendicular field, and dependences, which are analogical to Fig. 1d, 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 the odd effect vanishing in perpendicular geometry and increase of the MR magnitude in the 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 the electron spin-dependent scattering in the interfaces and grain boundaries at the expense of the interface roughness increase and the grain-boundary diffusion activity.

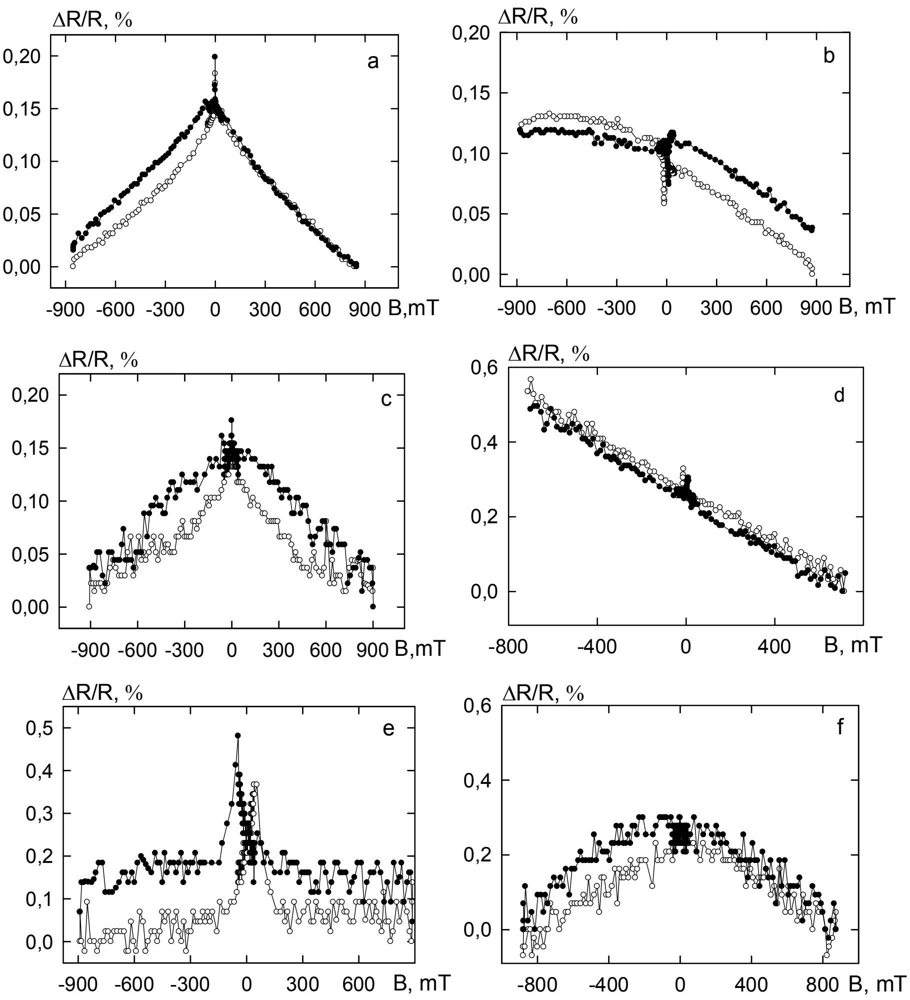

***Fig. 1** – Magnetoresistive magnitude versus magnetic induction for $[Cu(2)/Fe(2)]_4$ (a, b) and $[Cu(2)/Fe(2)]_{10}$ (c-f) film systems, as-deposited (a-d) and annealed to* 700 *K (e, f) for two mutual orientations of external field with the sample plane and current in CIP geometry: a, b, c – PPrG;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

According to [14, 15] and our early work [16] the maximal saturation field in Fe/Cr superlattices is attained on the Cr layer thickness d_{Cr} = 0,9-1,0 nm. In this case the maximal possible value of antiferromagnetic interaction between ferromagnetic iron layers is realized. In the case of very thin iron layers ($d_{Fe} \cong$ 0,31-1,5 nm), the magnetization curve achieves the saturation in magnetic field up to 1,5 T when d_{Fe} = 1,5 nm [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 MR magnitude changes in these systems from 0,03-0,05% to 1-3% subject to different measurement geometries. It is simply to explain this by the structure-phase state change from the homogeneous s.s. (α-Fe, Cr) under comparatively low concentration of Fe atoms (24 at.%) to the granular s.s. under comparatively high concentration of Fe atoms (50 at.%). For Fe/Cr system in as-deposited state the hysteresis absence is typical and in the parallel geometries the saturation state is observed under the field B_s = 900 mT (Fig. 2a), while in the perpendicular geometry the saturation is absent (see Fig. 2c).

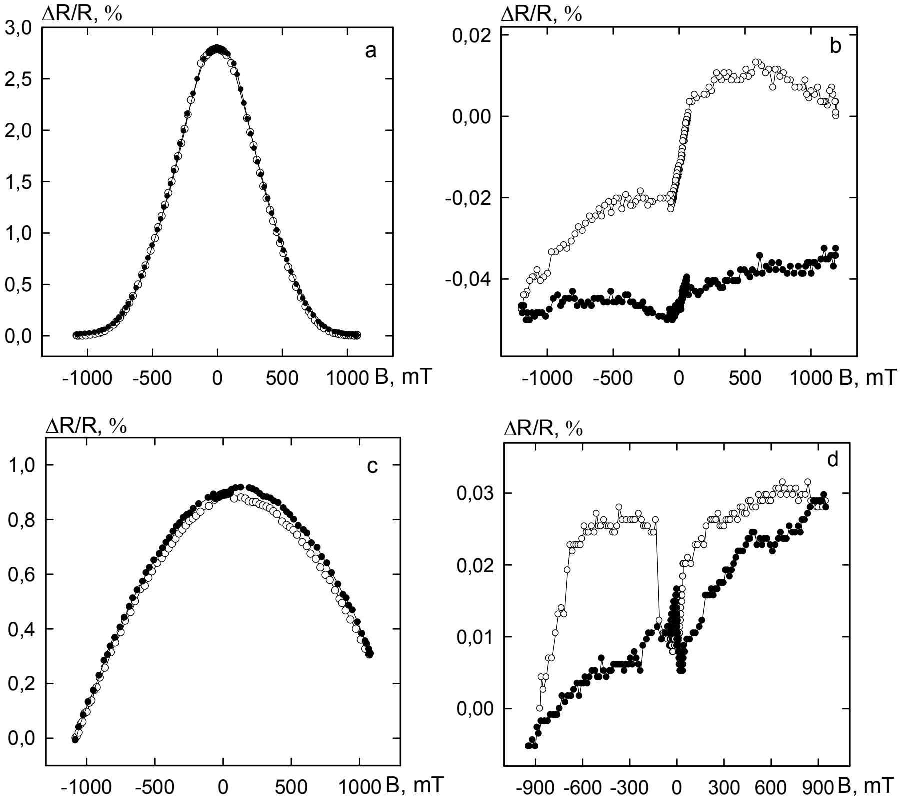

***Fig. 2** – Magnetoresistive magnitude versus magnetic induction for [Fe(1,5)/Cr(1)]$_{10}$ (a, c) and [Fe(0,31)/Cr(1)]$_{10}$ (b, d) film systems for two mutual orientations of external field with the sample plane and current in CIP geometry: a, b – PG; c, d – PrG*

In order to confirm the supposition about sensitivity of MR magnitude to the substrate type [17] the investigations of magnetoresistive properties of [Cu(5 nm)/Fe(5 nm)]$_2$ film system were done for different substrates (Fig. 3). It was obtained that the substrate change from amorphous pyroceramic to monocrystalline Si(111) leads to the MR ratio increase by 35%, which can be explained by the epitaxial growth of bottom Fe layer and its magnetic ordering, that provides more effective antiferromagnetic coupling with over Fe layer. In addition, the comparatively small value of saturation field must be noticed, which is not typical for this film system and can be connected with demonstration of the Thomson anisotropic magnetoresistive effect.

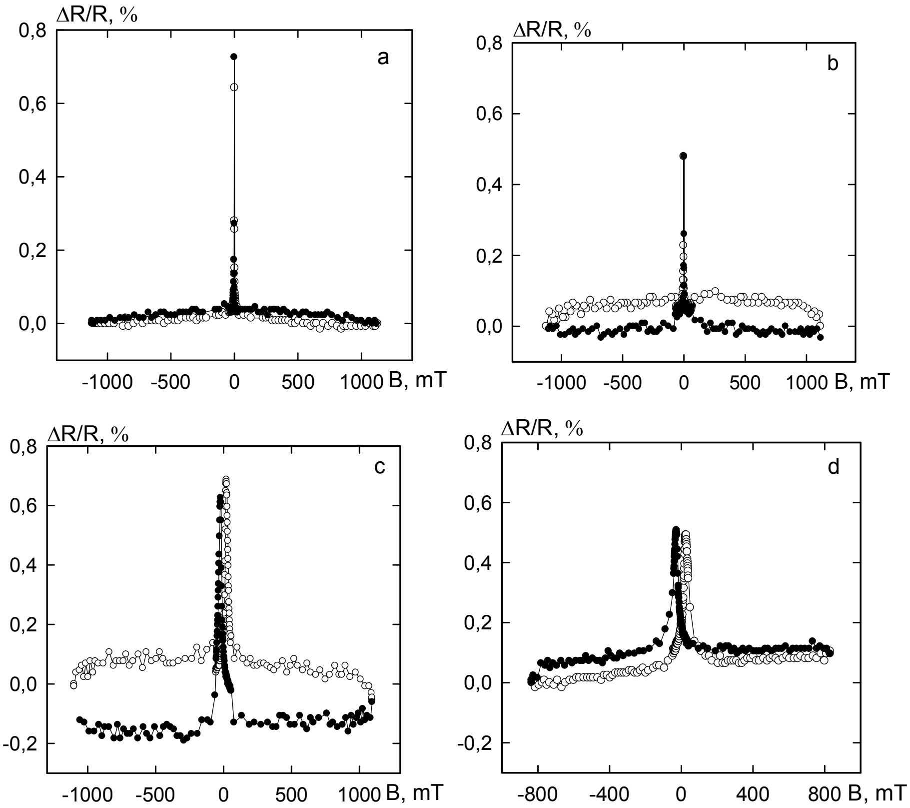

Fig. 3 *– Magnetoresistive magnitude versus magnetic induction for [Cu(5)/Fe(5)]$_2$/Si(111) (a, c) and [Cu(5)/Fe(5)]$_2$/P (b, d) film systems for two mutual orientations of external field with the sample plane and current in CIP geometry: a, b – PG; c, d – PrG*

4. CONCLUSIONS

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 the parallel-perpendicular geometry the MR value is approximately about 0,20% (T = 300 K) and after annealing to T = 700 K increases to 0,50%, while for the perpendicular geometry in the case of [Cu(2 nm)/Fe(2 nm)]$_{10}$/P the MR magnitude decreases from 0,55% (odd effect) to 0,30% (even effect).
2. The odd effect of MR was observed under investigations in perpendicular geometry, which is caused by the perpendicular component of ferromagnetic Fe film magnetization, which vanishes after annealing to 700 K.
3. By the example of [Cu(5 nm)/Fe(5 nm)]$_2$ film system it was shown that the substrate change from amorphous pyroceramic to monocrystalline Si (111) leads to the MR ratio increase by 35%, which can be explained by the magnetic ordering in the bottom epitaxial Fe layer.
4. In multilayer film systems based on Fe and Cr, where the structure-phase state corresponds to the solid solution (Fe, Cr), the MR magnitude depends

on the concentration of Fe atoms and it changes from 0,03-0,05% (not granular s.s.) to 1-3% (granular s.s.).

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