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Structure and magnetoresistance of freshly condensed three-layer NiFe/Cu(Ag)/NiFe films

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Phase composition and magnetoresistive effect (the longitudinal and transversal magnetoresistance (MC) have been studied in freshly condensed three-layer FeNi/Cu(Ag)/FeNi films having d_{FeNi} of 10 to 50 nm, $d_{Cu,Ag}$ of 1 to 15 nm within temperature range of 150 to 400 K. The giant magnetoresistance effect has been shown to be realized in the unannealed three-layer films with a 3 to 15 nm thick non-magnetic interlayer. The temperature dependences of the longitudinal and transversal MR have been studied. The dependence of the magnetoresistance characteristic $(\Delta R/R_0)_{max}$ on the Cu and Ag interlayer thickness for the FeNi/Cu(Ag)/FeNi films has been established to show two maxima.

Изучены фазовый состав и магниторезистивный эффект (продольное и поперечное магнитосопротивление (МС)) свежесконденсированных трехслойных пленок FeNi/Cu(Ag)/FeNi с d_{FeNi} = 10–50 нм, $d_{Cu,Ag}$ = 1–15 нм в интервале температур 150–400 К. Показано, что в неотожженных трехслойных пленках с толщиной немагнитной прослойки 3–15 нм реализуется эффект гигантского магнитосопротивления. Изучены зависимости величины продольного и поперечного МС от температуры. Установлено, что зависимость величины магнитосопротивления $(\Delta R/R_0)_{макс}$ от толщины прослоек Cu и Ag для пленок FeNi/Cu(Ag)/FeNi имеет два максимума.

The recent interest in studies of multilayered systems is connected not only with the continuous search for novel elemental basis for microelectronics but also with a possibility to draw from such studies important fundamental information concerning the interaction of conductivity electrons with interfaces between materials differing in physical characteristics. It is well known that ferromagnetic layers of Fe, Co, Ni, and alloys thereof, when divided by non-ferromagnetic metal layers such as Cu, Ag, Pt, Cr, etc., can be involved into ferromagnetic (FM) or antiferromagnetic (AFM) exchange interaction, depending on the non-ferromagnetic layer thickness. Hence, numerous theoretical and experimental works was aimed at studies of multilayer Co/Cu and Fe/Cr films showing the giant magnetoresistance (GMR) effect. There are only few works dealing with GMR in other systems, such as FeNi/Cu(Ag), Dy/Sc, although some specific features are observable in those systems, too. In the first case, the absence of hysteresis is possible while in the second one, a high positive magnetoresistance value [1]. The film system with ferromagnetic layers $Fe_{50}Ni_{50}$ (Permalloy 50H) is still insufficiently studied in what concerns the GMR. In this work, the crystal structure, phase composition and magnetoresistive effect is studied for freshly condensed three-layer FeNi/Cu(Ag)/FeNi films as well as the dependence of magnetoresistance (MR) on the temperature and the non-magnetic interlayer thickness.

The three-layer FeNi/Cu(Ag)/FeNi films comprising 10 to 50 nm thick FeNi layers and 1 to 20 nm thick Cu or Ag ones were prepared in a VUP-5M vacuum unit (the residual pressure 10^{-4} Pa) using electron beam sputtering (FeNi) and resistive evapo-

Table. Elemental composition of $Fe_{0,5}$-$Ni_{0,5}$ alloy.

Sample thickness, nm	C_{Fe}, %	C_{Ni}, %
Bulk $Fe_{0,5}$-$Ni_{0,5}$	51.8	48.2
47	43.9	56.1
100	44.4	55.6
110	47.7	52.3
120	47.1	52.9

ration (Cu, Ag). The bulk Permalloy 50H was used as the initial material to deposit FeNi layers. The films were deposited onto glass substrates (for resistance and MR measurements) and KBr cleaves (for structure investigations) at room temperature. The layer thickness was controlled by the deposition duration at a known condensation rate. To determine the condensation rate, a series of single-layer FeNi, Cu, and Ag films was prepared and the thickness thereof was measured using a MII-4 interferometer with computerized system recording the interference pattern [2]. To provide the parallel orientation of easy magnetization axes in ferromagnetic layers, the films were deposited in an external magnetic field at H = 8 kA/m (100 Oe). To study the MR, the sample geometry (as a 10±0.05 mm long and 2±0.05 mm wide rectangular strip) was provided using a special Nichrome foil screen. The samples so prepared were transferred into a special setup providing an ultra-high oil-free vacuum (10^{-6} to 10^{-7} Pa) [1], since the measurements of MR and its temperature dependence continued several tens of hours and involved 4 or 5 heating/cooling cycles within 150 to 400 K temperature range.

The electric resistance was measured using the standard two-probe technique at 0.025 % relative error. The magnetoresistance was determined using the known relationship $\Delta R/R_0 = (R_{(H)} - R_0)/R_0$, where $R_{(H)}$ is the resistance of a multilayer in the magnetic field H; R_0, the maximum multilayer resistance. Since the sample thickness is not included in the formula, the MR determination accuracy is defined by that of R measurement. The film crystal structure was studied using the transmission electron microscopy (PEM-125 instrument) and the phase composition, by electron diffraction.

In most cases, the condensed FeNi films differ in composition from the initial alloy (Permalloy 50H) due to fractionation [3]. That is why we have studied specially the

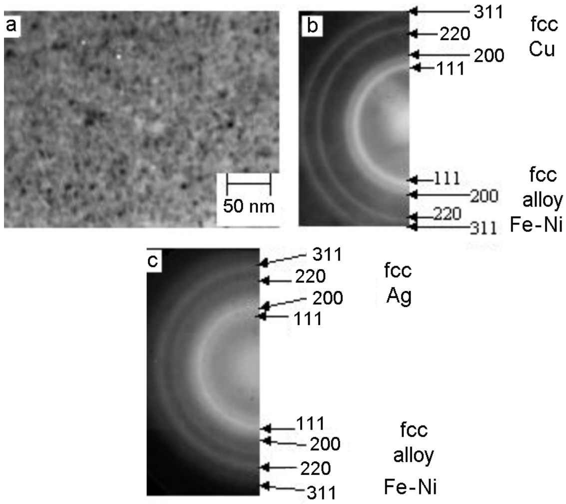

Fig. 1. Microstructure (a) and electron diffraction pattern (b) of an unannealed three-layer FeNi/Cu/FeNi film with d_{FeNi} = 30 nm, d_{Cu} = 8 nm; electron diffraction pattern (c) of an unannealed three-layer FeNi/Ag/iFeNi film with d_{FeNi} = 20 nm, d_{Ag} = 5 nm.

chemical compositions on the initial alloy and the films using an EDS energy dispersion spectrometer. The results obtained are presented in Table. The initial material is seen to correspond to 52 % Fe – 48 % Ni (the measurement error being within 1.5 %). All unannealed films are polycrystalline ones with a very small grain size (less than 5 nm). The electron microscopic images of the films with Cu and Ag interlayers are similar to those of single-layer FeNi alloy [4]. As an illustration, Figs. 1a,b show the structure and electron diffraction patterns for FeNi/Cu/FeNi at d_{FeNi} = 30 nm, d_{Cu} = 8 nm and for FeNi/Ag/FeNi at d_{FeNi} = 20 nm, d_{Ag} = 5 nm. The freshly condensed films contain the fcc phase with the lattice parameter a of 0.359 to 0.361 nm. The bands corresponding to FeNi and Cu are indistinguishable due to very close interplane spacings (the lattice parameter for bulk Permalloy of the composition in question is a_0 = 0.3586 nm [5] while for copper, a_0 = 0.3608 nm). In the electron diffraction patterns of FeNi/Ag/FeNi films, bands of the fcc Ag phase (a = 0.408–0.409 nm, a_0 = 0.4087 nm) and of fcc FeNi alloy (Fig. 1c).

The MR measurement results for the three-layer films are shown in Fig. 2. For unannealed FeNi/Cu(Ag)/FeNi films with d_{FeNi} of 10 to 50 nm, d_{Cu} of 2 to 15 nm and d_{Ag} of 4 to 15 nm, a decrease of the electric resistance is observed in magnetic field, in-

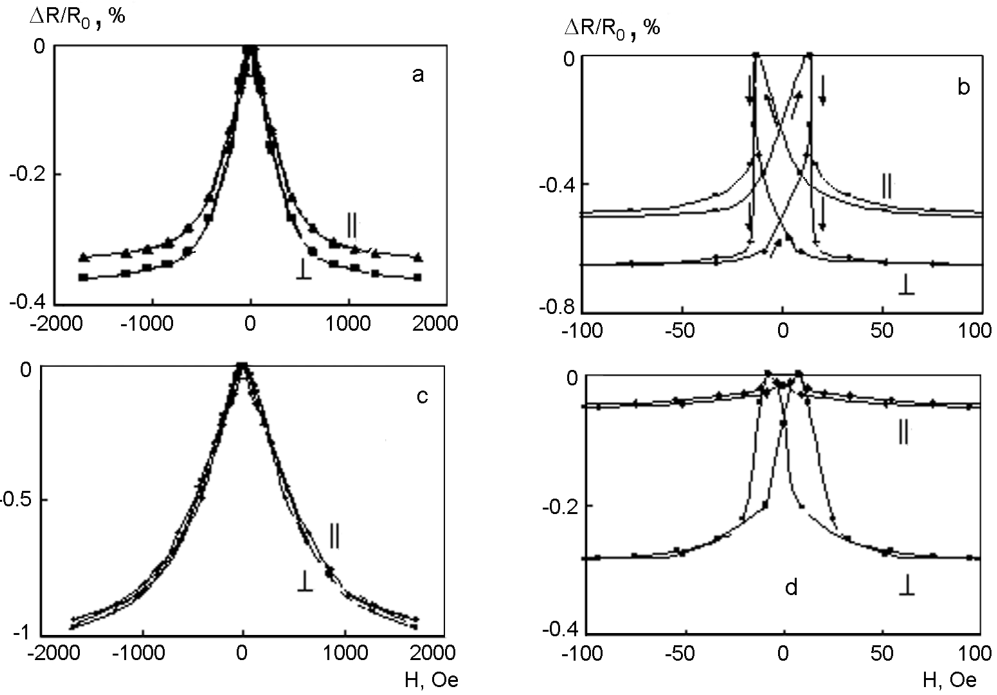

Fig. 2. Dependences of longitudinal (||) and transversal (⊥) MR on the magnetic field strength H for three-layer FeNi/Cu/FeNi (a, b, d) films with d_{FeNi} = 15 nm, d_{Cu} = 3 nm (a); d_{FeNi} = 45 nm, d_{Cu} = 8 nm (b; d_{FeNi} = 40 nm, d_{Cu} = 1.5 nm (d) and FeNi/Ag/FeNi (c) d_{FeNi} = 20 nm, d_{Ag} = 4 nm

dependent of the sample arrangement relative to the magnetic field induction lines (Fig. 2a,b,c). This fact is a characteristic sign of the GMR effect [6]. It is to note, however, that only an AMR ($(\Delta R/R_0)_{max}$ = 0.02 to 0.1 %) is observed for films with a silver interlayer when d_{Ag} is 1 to 3 nm. As the d_{Ag} increases further, the film MR behaves similarly to that of films with copper interlayer. For the films with d_{Cu} of 2 to 3 nm (Fig. 2d), a considerable difference between the longitudinal and transversal MR values is typical, the latter exceeding the former by a factor of 5 to 7. For the films with d_{Cu} of 3 to 20 nm, the $\Delta R/R_0(H)$ dependences for the longitudinal and transversal MR are almost coincident, and for some films, the longitudinal MR exceeds insignificantly the transversal one. The magnetoresistance value attains 1 % at room temperature, while AMR not exceeding 0.1 % is observed for unannealed FeNi films. Thus, the GMR effect seems to be realized in the three-layer systems.

The GMR results from different scattering of two electron groups differing in spin orientation relative to the magnetization direction of the magnetic structure that scatters the electrons [7]. In multilayers, the interference of electron waves reflected from the outer and inner interfaces between the magnetic and non-magnetic layers is also known to contribute considerably to the GMR [8].

It is to note that no magnetoresistive effect hysteresis is observed in the samples with d_{FeNi} of 10 to 25 nm (Fig. 2a,c). In this case, the magnetic saturation occurs in a relatively strong field $H > 1$ kOe (the saturation field was assumed to be the field corresponding to $0.9(\Delta R/R_0)_{max}$ in the $\Delta R/R_0(H)$ curve). The absence of hysteresis may be associated as in [9] with the low residual magnetization of the magnetic layers. For the samples with d_{FeNi} of 25 to 50 nm, the magnetoresistive effect hysteresis (open loops) is observed independent of the interlayer type and thickness (Fig. 2 b,d). The saturation field is much lower in this case, $H_S \approx 30$ Oe. Perhaps this is associated with different mechanisms of the film remagnetization.

The temperature dependences of longitudinal and transversal MR have been studied in the 150 to 400 K range for unannealed three-layer FeNi/Cu(Ag)/FeNi films with various non-magnetic interlayer thickness. Fig. 3 shows the $(\Delta R/R_0)_{max}(T)$ dependences for longitudinal MR. For all the samples with

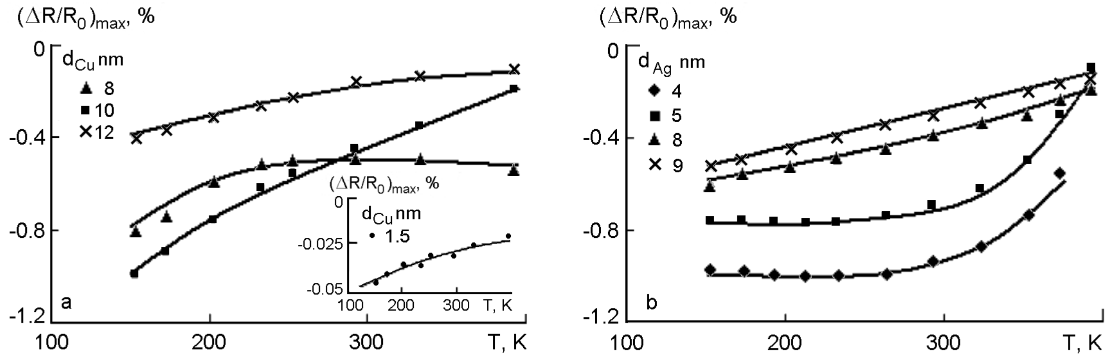

Fig. 3. Temperature dependences of longitudinal $(\Delta R/R_0)_{max}$ for three-layer FeNi/Cu/FeNi (a) and FeNi/Ag/FeNi (b) films at various thickness of the non-magnetic interlayer.

1.5 to 15 nm thick copper interlayer, the MR increases by a factor of 1.5 to 2 as the temperature decreases from room value down to 150 K (the ΔR rises and R drops). In contrast to films with copper interlayer, those with silver one (4 to 5 nm) show no essential MR variations within the 150 to 250 K temperature range. As the silver interlayer thickness increases, the $(\Delta R/R_0)_{max}(T)$ dependences become similar to those for copper-containing films. The $(\Delta R/R_0)_{max}(T)$ dependences for transversal MR are similar to those for the longitudinal one.

In Fig. 4, presented are the dependences of longitudinal MR ($(\Delta R/R_0)_{max}$) on the Cu and Ag interlayer thickness. Those dependences are oscillating and include two maxima resulting from the anti-parallel orientation of magnetization in adjacent layers. Similar oscillations in $((\Delta R/R_0)_{max}(d)$ were observed for Co/Cu systems [10, 11]. The $(\Delta R/R_0)_{max}(d)$ dependences for transversal MR are similar to those for the longitudinal one.

Thus, the results obtained have shown that the GMR effect is realized in unannealed three-layer FeNi/Cu(Ag)/FeNi films having d_{FeNi} of 10 to 50 nm, d_{Cu} of 2 to 15 nm and d_{Cu} of 4 to 15 nm. In all the samples with copper interlayer, the MR increases by a factor of 1.5 to 2 as the temperature decreases down to 150 K. For the films with 4 to 5 nm thick silver interlayer, no essential MR variations have been observed within the 150 to 250 K temperature range. The dependences of longitudinal and transversal $(\Delta R/R_0)_{max}$) on the Cu and Ag interlayer thickness are oscillating and include two maxima resulting from the anti-parallel orientation of magnetization in adjacent layers.

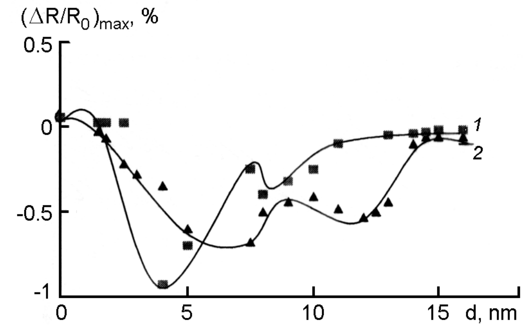

Fig. 4. Dependences of (DR/R0)max on the thickness of silver (*1*) and copper (*2*) interlayer for FeNi/Cu(Ag)/FeNi films at T=300 K.

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Структура та магнітоопір свіжоконденсованих тришарових плівок FeNi/Cu(Ag)/FeNi

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Досліджено фазовий склад та матніторезистивний ефект (поздовжній та поперечний магнітоопір, MR) свіжоконденсованих тришарових плівок FeNi/Cu(Ag)/FeNi з d_{FeNi} від 10 до 50 нм, $d_{Cu,Ag}$ від 1 до 15 нм у температурному інтервалі 150–400 К. Показано, що в невідпалених тришарових плівках з товщиною немагнітного прошарку від 3 до 15 нм реалізується ефект гігантського магнітоопору. Досліджено залежності величини поздовжнього та поперечного MR від температури. З'ясовано, що залежність величини магнітоопору $(\Delta R/R_0)_{max}$ від товщини прошарків Cu та Ag для плівок FeNi/Cu(Ag)/FeNi має два максимуми.