JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 8 No 3, 03041(4pp) (2016)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 8 № 3, 03041(4cc) (2016)

Formation of the Spin-valve Device Nanostructures Based on Co and Cu

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(Received 23 May 2016; published online 03 October 2016)

The study results of the structural-phase state and the magnetoresistive properties of the spin-valve film nanosystems based on Co and Cu are presented in this work. It is established that solid solutions of Co atoms in the Cu matrix are formed in these systems during the preparation and thermal annealing to temperatures of $T_{ann} = 700$ and 900 K. Shown that it is reasonable to modify the spin-valve film system Co(5)/Cu(x)/Co(20)/Sub using a $[Co/Cu]_n$ multilayer instead of one of the magnetic Co layers. This modification increases the magnetoresistance values up to 0.3 ÷ 0.5 %, switching speed from one magnetic state to another and thermal stability of the whole nanosystem to a temperature of 700 K, although decreases the magnetic sensitivity to the values of $S_B = (0.1 \div 0.2) \times 10^{-2}$ %/mT.

Keywords: Spin-valve, Magnetoresistance, Coercivity, Magnetization, Solid Solution.

DOI: 10.21272/jnep.8(3).03041 PACS numbers: 68.55.Ln, 73.50.Jt

1. INTRODUCTION

Multilayers based on Co, Cu and Fe, Cr, which exhibit the maximum values of the giant magnetoresistance, have many advantages among metallic nanostructures, if they are created in the form of multilayer structures with a thickness of individual layers to 2-3 nm (see, for example, [1, 2]). At higher thicknesses in the spin-valve structures, there are undesirable effects associated with intensification of the diffusion processes and formation of disordered solid solutions [3-6], which lead to deterioration of the operational stability of the device elements formed on their basis.

Simple spin-valves are manufactured using the sandwich formation scheme: ferromagnetic/nonmagnetic/ferromagnetic/antiferromagnetic layers. The difficulties in implementing such a scheme arise because of the instability of interfaces and the impossibility of forming sufficiently hard magnetic antiferromagnetic layers. Pseudo-spin-valves, which are simplification of simple spin-valves, have only two magnetic layers with different coercivity separated by a nonmagnetic layer.

In the work, we present the results of the study of the magnetoresistive and magneto-optical properties of the pseudo-spin-valve structures based on Co and Cu, and it was proposed to modify them by replacing one magnetic layer with a $[Co/Cu]_n$ multilayer. It should be noted that the use of multilayers in the formation of spin-valves has been studied before (see, for example, [7]), but mostly it is the spin-valve effect in the structures based on multilayers or the use of multilayers based on rare earth and ferromagnetic metals to form an antiferromagnetic layer in the spin-valve [8]. In our case, it was assumed that a multilayer based on Co and Cu can increase the thermal stability of the whole device film structure. Moreover, a multilayer in the composition of the spin-valve can operate independently that significantly extends the functionality of such a structure as a device element of spintronics or a sensing element of sensor electronics.

2. EXPERIMENTAL

We obtained series of the spin-valve samples Au(10)/Co(x)/Cu(x)/Co(20)/Sub (Sub is the substrate, thickness is given in nm), where x = 6-10 nm; series of the spin-valve samples using Au(10)/$[Cu(3)/Co(3)]_n$/Cu(5)/Co(20)/Sub and Au(10)/Co(6)/Cu(5)/$[Cu(3)/Co(3)]_n$/Sub multilayers and series of the corresponding Au(10)/$[Cu(3)/Co(3)]_n$/Sub multilayers, where n = 2-8. All samples were coated with the upper auxiliary protective Au(10) layer to prevent oxidation of the Co working layers and to provide a reliable contact in the resistance measurements. The samples were thermally condensed in vacuum of (10^{-4} Pa) on glass ceramic plates at the substrate temperature of $T_{sub} = 300$ K ans a condensation rate of ω = 0.1-0.2 nm/s. The carbon films of 20 nm thickness were used to control the phase composition and sample structure (using transmission electron microscope PEM-125M). The thickness of the individual layers was controlled by a quartz resonator in the production process. In order to study the thermal stability of physical properties, the samples were annealed in a vacuum chamber to temperatures of T_{ann} = 700 and 900 K (hereafter in the text T_{ann} = 300 K corresponds to the unannealed sample).

An investigation of the magnetoresistive properties was performed at room temperature using a four-point scheme in the magnetic field range from 0 to 500 mT [9]. During the measurements, the electric current was directed parallel to the sample plane, and measurements of the magnetoresistance were carried out in three geometries, namely, the longitudinal (the lines of magnetic induction B are directed along the current direction), the transverse (the B lines are directed perpendicular to the current direction) and the perpendicular (the B lines are perpendicular to the sample plane). The magnitude of the magnetoresistance (MR) was determined by the ratio

$$\mathrm{MR} = \Delta R/R_S = (R_B - R_S)/R_S, \quad (1)$$

where R_B and R_S are the sample resistance at a given field and at saturation.

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Using the obtained maximum MR value, the sample sensitivity to the magnetic field was calculated by the formula

$$S_B = \left|\frac{\mathrm{MR_{max}}}{\Delta B}\right|, \qquad (2)$$

where $\mathrm{MR_{max}}$ is the maximum MR value; ΔB is the change in the magnetic induction from saturation B_S demagnetization.

3. RESULTS AND DISCUSSION

The investigation results of the phase composition and structural characteristics of multilayer film systems based on Co and Cu indicate the formation of solid solutions (s. s.) of Co atoms in the fcc-Cu matrix. In our experiments at $T_{ann} > 300$ K, as shown in [4], the formation of s. s. (Co, Cu) at the interfaces occurs during the formation of samples at room temperature as a result of condensation stimulated diffusion and subsequent heat treatment to $T_{ann} = 400$-700 K. A partial decomposition of the s. s. with the formation of the granular Co state is observed at $T_{ann} = 900$ K. In Fig. 1 we illustrate the typical crystal structure and the corresponding electron diffraction pattern of the film systems based on Co and Cu in the form of spin-valve structures or multilayers on the example of the Au(10)/Co(5)/Cu(10)/Co(20)/Sub spin-valve at $T_{ann} = 300$ K. Two groups of lines corresponding to the hcp-Co phases and s. s. (Co, Cu) (parameter $a_{\text{s. s. (Co, Cu)}} = 0.3588$ nm) are detected on the electron diffraction pattern. After annealing of the given sample to $T_{ann} = 700$ K, the parameter $a_{\text{s. s. (Co, Cu)}}$ decreases to the value of 0.3575 nm as a result of the subsequent mixing of Co and Cu layers. It should be noted that the change in the lattice parameter is not noticeable during the heat treatment of the samples in the form of multilayers.

The investigation results of the magnetoresistive properties of spin-valve film samples with fixed thicknesses of the magnetic layers and variable thickness of the non-magnetic Cu layer are represented in Fig. 2 and in Table 1. The instability of interfaces in this system associated with the processes of formation of s. s. (Co, Cu) can be traced by the change in the nature of the dependences of MR with increasing T_{ann} in Fig. 2. The highest stability of the magnetoresistive properties, the maximum values of MR = 0.15 ÷ 0.18 % and the maximum values of the magnetic sensitivity $S_B = (0.2 \div 2.4) \times 10^{-2}$ %/mT at $T_{ann} = 900$ K (Table 1) are observed in the system with a non-magnetic layer of thickness $d_{Cu} = 10$ nm (Fig. 2b).

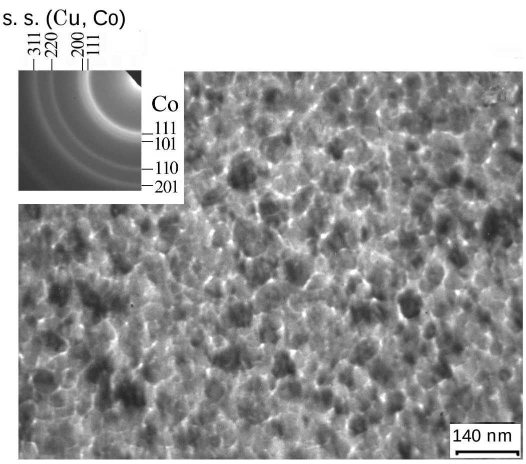

Fig. 1 – Crystal structure and electron diffraction pattern (on the inset) of the Co(5)/Cu(10)/Co(20)/Sub spin-valve film system at $T_{ann} = 300$ K

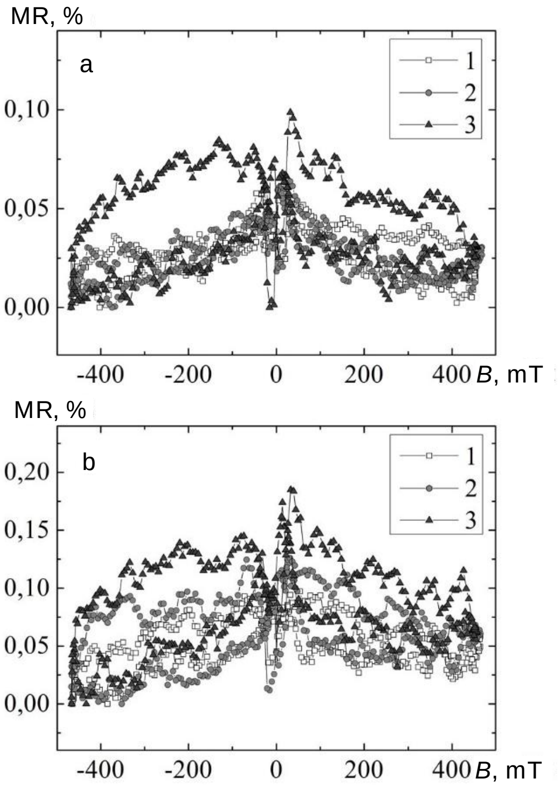

Fig. 2 – MR of the spin-valve Au(10)/Co(5)/Cu(x)/Co(20)/Sub film systems, where $x = 5$ (a) and 10 (b) nm in the longitudinal measurement geometry at different T_{ann}, K: 1 – 300; 2 – 700; and 3 – 900

Table 1 – Magnetic characteristics of the spin-valve structures Au(10)/Co(5)/Cu(x)/Co(20)/Sub with variable thickness of the Cu layer in the longitudinal measurement geometry

x, nm	T_{ann}, K	ΔB, mT	$S_B \times 10^2$, %/mT
2	300	37.4	0.1
	700	129.8	0.1
	900	78.04	0.1
8	300	35.2	0.2
	700	37.04	0.1
	900	15.3	0.7
10	300	10.1	1.4
	700	12.4	0.9
	900	9.7	2.4

Unlike spin-valve systems, Au(10)/[Co/Cu]$_n$/Sub multilayers have a form of the dependence of MR with the maximum at $B = 0$ mT in all measurement geometries (Fig. 3) inherent in nanosystems with an antiferromagnetic interaction. The maximum value of MR = 0.27 % is observed in the samples with the greatest number of repetitions of the multilayer ($n = 10$) fragment. It should be noted that the form of the dependences in Fig. 3 becomes more linear with increasing T_{ann} up to 900 K, but there are no significant changes in the behavior of the dependence and MR values.

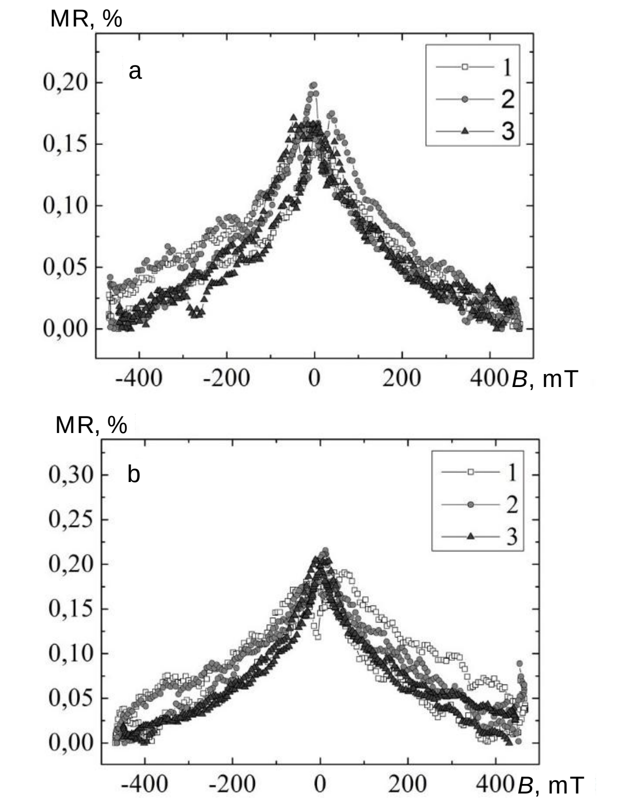

Fig.3 – MR of the multilayers Au(10)/[Co(3)/Cu(3)]$_6$/Sub (a) and Au(10)/[Co(3)/Cu(3)]$_{10}$/Sub (b) in the longitudinal measurement geometry at different T_{ann}, K: 1 – 300; 2 – 700; 3 – 900

The use of the [Co/Cu]$_n$ multilayer in the formation of spin-valve device systems is possible instead of one of the magnetic layers provided that another is preserved. A continuous Co layer with high coercivity compared to the multilayer will play the role of a fixed hard magnetic layer to provide the spin-valve effect. In the general case, the result of such a change was an increase in the MR values to 0.3 ÷ 0.5 % (Fig. 4, Fig. 5) and a decrease in the sensitivity S_B to $(0.1 \div 0.2)\times10^{-2}$ %/mT (Table 2, Table 3). Moreover, the annealing temperature in these nanosystems significantly less affects the nature of the dependence of MR in all measurement geometries, although when using the multilayer instead of the upper magnetic layer, the anisotropic character of MR is observed in the unannealed samples and disappears after annealing to T_{ann} = 700 K as shown in Fig. 5a, b on the example of Au(10)/[Co(3)/Cu(3)]$_4$/Cu(5)/Co(20)/Sub.

In Fig. 4 we illustrate the results of investigation of the magnetoresistive properties of the spin-valve system Au(10)/Co(5)/Cu(6)/[Co(3)/Cu(3)]$_8$/Sub, in which the lower magnetic layer is replaced by a multilayer. The displacements of the maxima in the given dependences with the change of T_{ann}, that is especially evident in the perpendicular measurement geometry, are associated with the change in the coercivity B_c of the upper magnetic Co layer and its magnetic anisotropy due to the change in the effective layer thickness during thermal diffusion and recrystallization and the change in the domain structure. In the transverse and longitudinal measurement geometries, the magnetoresistive properties of this system to T_{ann} = 700 K are stable (Fig. 4a, b). With increasing T_{ann} up to 900 K, the MR values are significantly reduced in

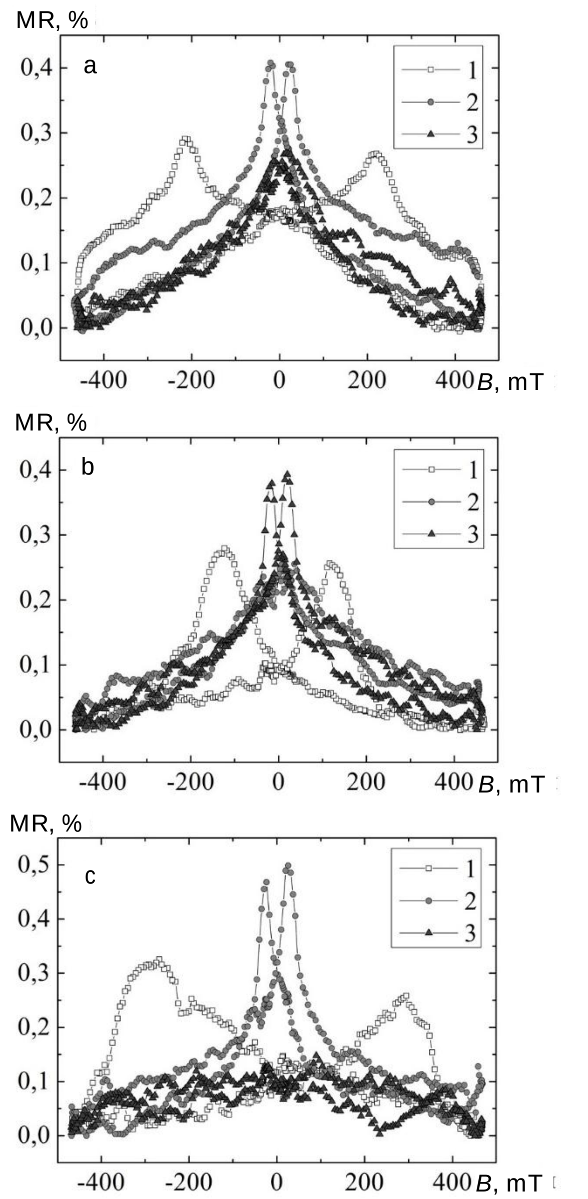

Fig. 4 – MR of the Au(10)/Co(5)/Cu(6)/[Co(3)/Cu(3)]8/Sub spin-valve film structure at T_{ann} = 300 (a), 700 (b), and 900 (c) K in the perpendicular (1), transverse (2), and longitudinal (3) measurement geometries

the longitudinal geometry (Fig. 4b) that can be related to the destruction of the interface between the magnetic upper Co layer and the nonmagnetic Cu layer as a result of the formation of a s. s. (Co, Cu).

In Fig. 5 we present the results of the study of nanosystems using a multilayer instead of the upper magnetic layer. The anisotropic behavior of the dependences of MR is observed in these samples only for T_{ann} = 300 K. With increasing T_{ann} up to 700 K, the form of the dependences is similar to those in Fig. 4 and remains constant at T_{ann} = 900 K. Such stability of the magnetoresistive properties is ensured by the existence in the systems of the lower thicker Co layer with the initial thickness of d_{Cu} = 20 nm, which remains continuous during annealing, and its coercivity increases due to an increase in the average crystallite size [8] and the improvement of the domain structure of the Co layer.

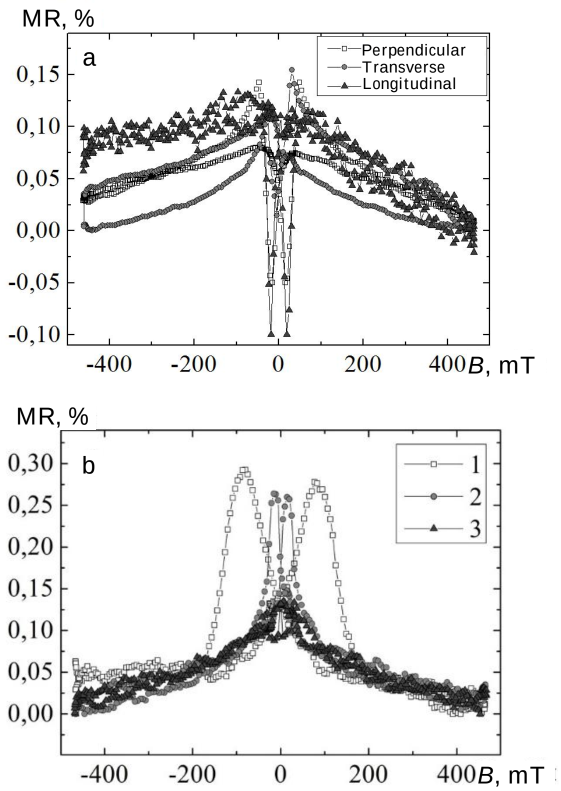

Fig. 5 – MR of the Au(10)/[Co(3)/Cu(3)]$_4$/Cu(5)/Co(20)/Sub spin-valve film structure at T_{ann} = 300 (a) and 700 (b) K in the perpendicular (1), transverse (2), and longitudinal (3) measurement geometries

Table 2 – Magnetic characteristics of spin-valve film structures Au(10)/Co(5)/Cu(6)/[Co(3)/Cu(3)]$_n$/Sub with different number of repetitions of the fragment of *n* multilayer in the longitudinal measurement geometry

n	T_{ann}, K	ΔB, mT	$S_B \times 10^2$, %/mT
2	300	47.7	0.7
	700	157.1	0.1
	900	122.0	0.2
6	300	176.4	0.1
	700	61.9	0.2
	900	199.5	0.1
8	300	217.1	0.1
	700	119.7	0.2
	900	281.3	0.1
10	300	47.5	0.1
	700	67.1	0.1
	900	184.6	0.1

Table 3 – Magnetic characteristics of spin-valve film structures Au(10)/[Co(3)/Cu(3)]$_n$/Cu(5)/Co(20)/Sub with different number of repetitions of the fragment of *n* multilayer in the longitudinal measurement geometry

n	*T*, K	ΔB, mT	$S_B \times 10^2$, %/mT
2	300	37.4	0.1
	700	129.8	0.1
	900	78.0	0.1
4	300	15.3	1.2
	700	78.4	0.3
	900	123.2	0.2

Small values of the sensitivity S_B of spin-valve nanosystems using multilayers based on Co and Cu at higher MR values (Table 2 and Table 3) are related to the high switching speed from one magnetic state to another. This fact makes such nanosystems suitable for use in the production of digital functional elements of spintronics, while systems in the form of a multilayer with high magnetic sensitivity are more suitable for the creation of thin-film magnetic sensing elements of magnetic field sensors with a working field range up to 500 mT.

4. CONCLUSIONS

The investigation results of the structural-phase composition of spin-valve multilayer film nanosystems based on Co and Cu indicate the formation of s. s. of Co atoms in the Cu matrix at the interfaces between the layers that is associated with the instability of their magnetoresistive properties at different annealing temperatures.

It is reasonable to modify the spin-valve film system Co(5)/Cu(x)/Co(20)/Sub using a [Co/Cu]$_n$ multilayer instead of one of the magnetic Co layers. As the results of the study of the magnetoresistive properties showed, depending on the annealing temperature, such a modification leads to an increase in MR = 0.3 ÷ 0.5 %, increases the switching speed from one magnetic state to another, although decreases the magnetic sensitivity to the values of $S_B = (0.1 \div 0.2) \times 10^{-2}$ %/mT. It can also be stated that the temperature stability of the whole nanosystem increases to a temperature of 700 K.

Further studies of the physical properties of modified spin-valve structures based on Co and Cu will be aimed at producing a functional element of the spin-valve with the pre-specified performance in the temperature range of 300 ÷ 900 K.

ACKNOWLEDGEMENTS

The work has been performed under financial support of the Ministry of Education and Science of Ukraine (Grant No 0116U002623).

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