JOURNAL OF NANO- AND ELECTRONIC PHYSICS | *ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ*
Vol. 4 No 3, 03020(4pp) (2012) | Том 4 № 3, 03020(4cc) (2012)

Tensoresistive Properties of Thin Film Systems Based on Ag and Co

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(Received 29 September 2012; in final form 14 October 2012; published online 29 October 2012)

The experimental investigation results of the tensoresistive properties of Ag and Co films and Ag/Co two-layer film systems in the deformation range $\Delta\varepsilon_l$ = 0-1% are presented. It is shown that plastic deformation in Co layer causes a similar deformation in the entire film system, even if the deformation range of Ag layer did not reach the limits of the elastic/plastic deformation transition. Increase in the gauge factor value of two-layer systems in comparison with Ag and Co thin films appears as the result of the electron interface scattering.

Keywords: Two-layer film systems, Tensoresistive effect, Gauge factor, Elastic and plastic deformation, Interface scattering.

PACS numbers: 60.68.Bs, 72.10.Fk, 73.63.Bd

1. INTRODUCTION

Multilayer multicomponent film systems in the form of alloys, multilayers or granular alloys have found wide application in electronic microinstrument engineering [1-4], since just these materials have wide functional possibilities. Attention to the film systems based on Ag and Co is connected, firstly, with the discovery of the giant magnetoresistance effect there [5]. However, as the authors of the works [6, 7] have shown, multilayer film structures, where the spin-dependent electron scattering is realized, are also of an interest from the point of view of their application as supersensitive strain sensors. Therefore, study of the tensoresistive effect in Ag/Co systems is of an independent interest.

2. EXPERIMENTAL TECHNIQUE

Thin Ag and Co films and two-layer film systems based on Ag and Co were obtained by the thermoresistive (Ag) and electron-beam (Co) evaporation methods in the working volume of the vacuum plant VUP-5M (the gas pressure of residual atmosphere $p \sim 10^{-4}$ Pa). The sample thickness was measured at condensation by the quartz resonator method in accordance with the recommendations of [8] (the measurement accuracy of the thickness ± 10%). Investigation of the tensoresistive properties within eight deformation cycles “loading-unloading” was carried out using modern automation tools of physical experiment. This allowed to perform the automatic control of the experiment and organize the computerized acquisition and processing of the results. The automated system which is developed in detail is described in the work [9].

The mean coefficient of the longitudinal gauge factor (GF) and instantaneous GF were defined as in the work [10] by relations $\gamma_l = R_{\text{п}}^{-1}\Delta R/\Delta\varepsilon_l$ and $\gamma_{l\text{м}} = R_i^{-1}\Delta R_i/\Delta\varepsilon_{li}$, respectively, where $R_{\text{п}}$ and R_i are the initial electrical resistance at the longitudinal deformation $\varepsilon_l = 0$ and $\varepsilon_l = \varepsilon_{li}$, respectively. The value of γ_l was calculated as the angular coefficient of the dependence $\Delta R/R_{\text{п}}$ on ε_l, and $\gamma_{l\text{м}}$ – by the graphical differentiation method of the same dependence.

Investigations of the phase composition and structure of film samples were carried out by the electron diffraction and electron microscope methods (device with high resolution TEM-125) for the purpose to obtain the information about crystal lattice (interplanar spacings, type, and lattice parameter), average crystallite size, crystallite concentration, grain boundary behavior, and defects of the lattice structure.

3. RESULTS AND DISCUSSION

Analysis of the structural and phase state of single-layer Ag and Co films and two-layer Ag/Co film systems was performed in order to confirm correctness of the analysis of further investigations of the tensoresistive properties. Typical diffraction patterns and micrographs of the crystal structure in the as-condensed state of Ag(20)/S, Co(20)/S, and Ag(20)/Co(20)/S samples (S is the substrate, thickness in nm is given in brackets) are shown in Fig. 1 and Fig. 2. Calculation results of the electron diffraction patterns are represented in Table 1. As seen from Fig. 1a, Ag film has the fcc-lattice with the mean parameter $\bar{a}$ (Ag) = 0,407 ± 0,001 nm and this corresponds to the tabulated value a_0(Ag) = 0,408 nm for bulk samples [11]. In contrast to Ag films, Co films have two-phase composition. The fcc-Co lines, which are fixed on the electron diffraction patterns near the hcp-Co lines, can correspond to both the reflection from stacking defects in the hcp-Co and incomplete phase transitions fcc → hcp at condensation of Co(20)/S film. The mean lattice parameter for the fcc-Co is equal to $\bar{a}$ (fcc) = 0,354 ± 0,001 nm that corresponds to the tabulated value a_0(fcc-Co) = 0,355 nm for bulk samples [11].

Analysis of the electron diffraction data for Ag(20)/Co(20)/S film system (Fig. 2, Table 1) has shown that the given sample in the as-deposited state has two-phase composition. It is seen from Fig. 2b that a system of rings from both Ag and Co layers is observed on the diffraction patterns. This gives the possibility to conclude that individuality of separate layers without formation of solid solutions or granular alloys remains in

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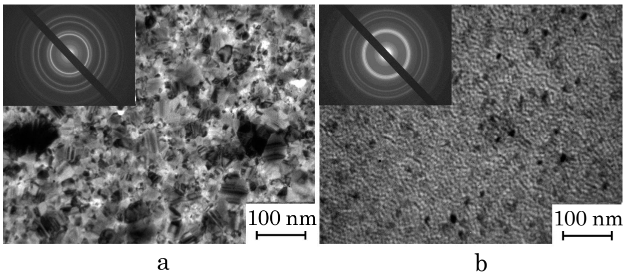

Fig. 1 – Diffraction patterns and crystal structure from single-layer Ag(20)/S (a) and Co(20)/S (b) films in the as-condensed state

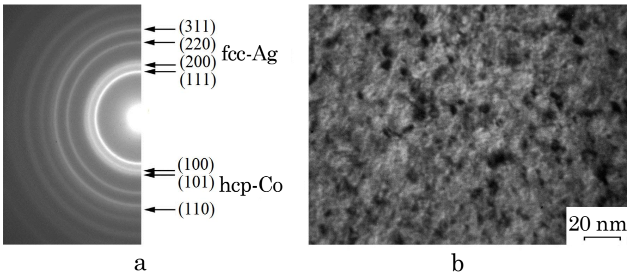

Fig. 2 – Diffraction pattern (a) and crystal structure (b) from two-layer Ag(20)/Co(20)/S film structure in the as-condensed state

the systems based on Ag and Co after condensation. Such conclusion is confirmed by the investigation results of the diffusion processes by the SIMS method performed in the work [12].

Typical deformation dependences of R and $\Delta R/R$ on ε_l for single-layer Ag and Co films and two-layer Ag/Co systems, based on which calculation of the dependences of γ_l on ε_l in the deformation range $\Delta\varepsilon_l$ = 0-1% was carried out, are represented in Fig. 3-Fig. 5, respectively. Now we will specify the characteristic features of the deformation dependences for the single-layer samples. Firstly, the I-*st* deformation cycle "loading-unloading" differs from further ones by different relaxation processes (partial grain rotation, redistribution of the crystal structure defects, microplastic deformation). At further cycles a certain stabilization of the tensoresistive properties is observed. Secondly, change in the behavior of the dependences $R(\varepsilon_l)$ and $\Delta R/R(\varepsilon_l)$ at ε_l = 0,3% for Co(70)/S film (Fig. 4a) implies the transition from elastic (quasi-elastic) to plastic deformation. We note that for Ag films elastic deformation takes place up to the value of $\varepsilon_l \cong$ 1% (Fig. 3a).

Difference of the I-*st* deformation cycle from further ones and narrow range of elastic deformation is also typical for two-layer Ag/Co systems.

Table 1 – Phase composition of as-deposited Ag(20)/S and Co(20)/S films and two-layer Ag(20)/Co(20)/S film structure

Film	No	I, rel.un.	d_{hkl}, nm	hkl	phase	a_{hkl}, nm	d^0_{hkl}, nm [11]
Ag	1	VS	0,235	111	fcc-Ag	0,408	0,236
	2	m	0,204	200	fcc-Ag	0,407	0,204
	3	m	0,143	220	fcc-Ag	0,408	0,144
	4	m	0,122	311	fcc-Ag	0,406	0,123
	5	w	0,117	222	fcc-Ag	0,406	0,117
	6	w	0,102	400	fcc-Ag	0,407	0,102
	$\bar{a}$ (fcc-Ag) = 0,407 nm; a_0(fcc-Ag) = 0,408 nm [11].						
Co	1	S	0,215	100	hcp-Co	0,248	0,216
	2	VS	0,204	111	fcc-Co	0,354	0,204
	3	m	0,192	101	hcp-Co	–	0,191
	4	m	0,177	200	fcc-Co	0,354	0,177
	5	m	0,125	220 110	fcc-Co hcp-Co	0,354 0,250	0,125
	6	w	0,106	311	fcc-Co	0,355	0,107
	$\bar{a}$ (fcc-Co) = 0,354 nm, $\bar{a}$ (hcp-Co) = 0,250 nm; a_0(fcc-Co) = 0,355 nm; a_0(hcp-Co) = 0,251 nm [11].						
Ag/Co	1	VS	0,236	111	fcc-Ag	0,407	0,236
	2	S	0,220	100	hcp-Co	0,251	0,215
	3	m	0,204	200	fcc-Ag	0,408	0,204
	4	w	0,190	101	hcp-Co	–	0,191
	5	m	0,143	220	fcc-Ag	0,408	0,144
	6	w	0,124	110	hcp-Co	0,251	0,125
	7	w	0,122	311	fcc-Ag	0,406	0,123
	$\bar{a}$ (fcc-Ag) = 0,407 nm; $\bar{a}$ (hcp-Co) = 0,251 nm.						

VS – very strong, S – strong, m – mean, w – weak

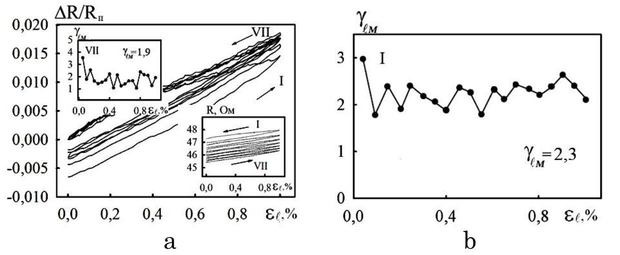

Fig. 3 – Dependences of $\Delta R/R$, $\gamma_{l\text{м}}$ and R on ε_l (a) and $\gamma_{l\text{м}}$ on ε_l for the I-*st* deformation cycle (b) for Ag(38)/S film. Numbers of deformation cycles are denoted by the Roman numerals

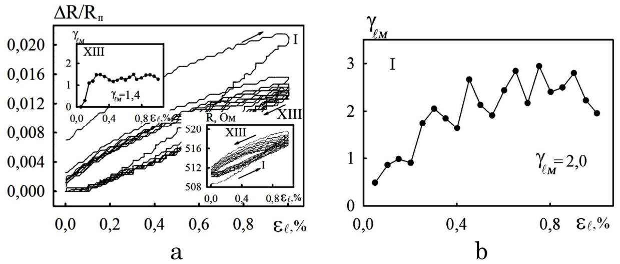

Fig. 4 – Dependences of $\Delta R/R$, $\gamma_{l\text{м}}$ and R on ε_l (a) and $\gamma_{l\text{м}}$ on ε_l for the I-*st* deformation cycle (b) for Co(70)/S film

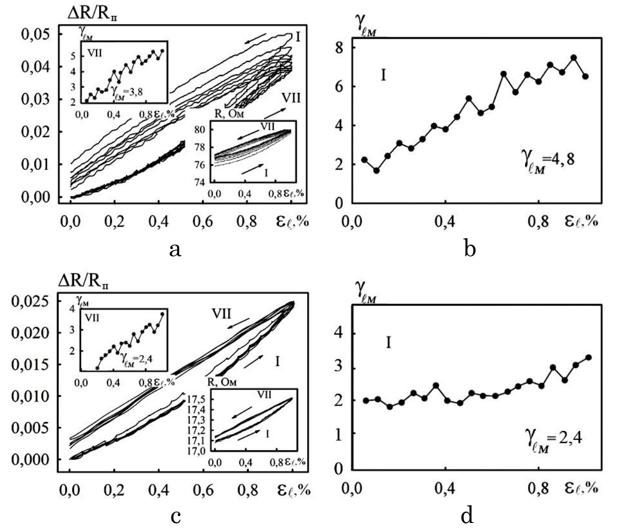

Fig. 5 – Dependences of $\Delta R/R$, $\gamma_{l\text{м}}$ and R on ε_l (a, c) and $\gamma_{l\text{м}}$ on ε_l for the I-*st* deformation cycle (b, d) for Ag(15)/Co(45)/S (a, b) and Ag(40)/Co(20)/S (c, d) film systems

A tendency to stabilization of the tensoresistive properties is observed starting from the II-*nd* deformation cycle. Moreover, on the basis of the typical dependences for single- and two-layer samples, one can conclude that the range of elastic deformation for Ag/Co systems depends on the concentration of Co atoms, whose film has less limit of elasticity in comparison with Ag films.

Effect of the anomalous increase in the GF on the deformation (see the inset in Fig. 5c) is observed on the dependences of $\gamma_{l\text{м}}$ on ε_l for Ag(45)/Co(36)/S film system. Maximum on the dependence of the instantaneous GF corresponds to the elastic/plastic deformation transition boundary. The same non-linearity on the dependences of $\gamma_{l\text{м}}$ on ε_l was observed in the previous investigations (for example, [13, 14]).

One can explain the physical nature of the maximum on the dependence of the instantaneous factor of the longitudinal tensosensitivity $\gamma_{l\text{м}}$ on the deformation ε_l for two-layer film systems by analyzing the extremum (maximum) condition which is obtained by simplification of equation $\partial\gamma_{l\text{м}}/\partial\varepsilon_l = 0$. Correlations for $\gamma_{l\text{м}}$ are represented in [10]. The analysis performed indicates that appearance of the maximum on the dependence of $\gamma_{l\text{м}}$ on ε_l is conditioned by non-linear in deformation change of the resistivity, which occurs if use the applicable in the given work dynamic mode of sample tension, and structural processes occurring in film systems at the transition from elastic to plastic deformation.

Comparison of the mean value of γ_l for single-layer Ag and Co films with the value of γ_l for two-layer Ag/Co systems of the same total thickness of the whole system is represented in Table 2. Analysis of the data indicates that the value of γ_l of two-layer samples is larger than for single-layer samples. Since individuality of separate layers remains in the system, then scattering processes on the interfaces contribute to the total value of GF, i.e. presence of the interface scattering leads to the increase in the value of γ_l. This gives the possibility of the formation of sensitive element of the strain gauge based on the multilayer film system whose components are Ag and Co films.

Table 2 – The value of γ_l for different deformation cycles for two-layer Ag/Co systems at $\Delta\varepsilon_l$ = 0-1% and its comparison with γ_l of Ag and Co films

Sample	Total thickness d, nm	Mean values of γ_l for different deformation cycles							γ_l^{Co}/γ_l	γ_l^{Ag}/γ_l
		I	II	III	IV	V	VI	VII		
Ag(18)/Co(17)/S	35	0,77	1,63	1,79	1,80	2,27	3,19	4,25	0,55	0,41
Ag(22)/Co(22)/S	44	3,99	3,72	3,64	3,61	3,60	3,58	3,55	0,50	0,47
Ag(40)/Co(20)/S	60	2,38	2,39	2,43	2,44	2,40	2,34	2,37	0,61	0,66
Ag(15)/Co(45)/S	60	4,78	4,47	4,22	4,15	4,04	3,91	3,85	0,38	0,41
Ag(35)/Co(40)/S	75	2,54	2,53	2,51	2,49	2,50	2,51	2,50	0,45	0,43
Ag(45)/Co(36)/S	81	4,37	3,26	3,03	2,89	2,79	2,74	2,70	0,42	0,40

4. CONCLUSIONS

The conducted analysis of the experimental data allows to conclude the following:

– deformation dependences of two-layer Ag/Co systems are characterized by the narrow range of elastic deformation; boundary of the elastic/plastic deformation transition for both Ag/Co and Co films depends on the total thickness;

– the presence of non-linearity on the dependences of γ_{lM} on ε_l is connected with the transition from elastic to plastic deformation and structural changes in the films;

– the value of GF of two-layer film systems is larger in comparison with single-layer film of the same thickness that can be explained by additional electron scattering on the interfaces.

AKNOWLEDGEMENTS

The work has been performed under the financial support of the Ministry of Education and Science, Youth and Sport of Ukraine (state registration number 0112U001381).

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