JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 11 No 6, 06007(4pp) (2019)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 11 № 6, 06007(4cc) (2019)

Electrophysical Properties of Granular Film Alloys

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(Received 13 October 2019; revised manuscript received 05 December 2019; published online 13 December 2019)

The results of studying the concentration and temperature conditions of the phases $L1_0$, $L1_1$ and $L1_2$ formation in two-layer film systems based on Fe or Co and Pt or Pd after annealing up to 850 K are presented. The electrophysical properties of granular alloys (g.a.) such as resistivity and thermal coefficient of resistance (TCR) were compared with the calculated values in the phenomenological model of electrophysical properties of granular alloys. The obtained results made it possible to calculate the predicted changes in the TCR of granular alloys in a perpendicular magnetic field with induction 200 mT. The estimated values $\Delta\beta = \beta_{exp}^{ga} - \beta_{calc}^{ss}$ are in the range $(0.1\text{-}0.6)\cdot 10^{-3}\,\mathrm{K}^{-1}$. The value $\Delta\beta_B = \dfrac{d\ln\beta_{exp}^{ga}}{dB} - \dfrac{d\ln\beta_{calc}^{ss}}{dB}$ is low in the range (0.02-1.70) T^{-1}.

Keywords: Granular alloys, Solid solution, Resistivity, TCR, Magnetic coefficient of TCR.

DOI: 10.21272/jnep.11(6).06007 PACS numbers: 68.60. – p, 73.61. – r

1. INTRODUCTION

With the discovery of a giant magnetoresistive effect, interest in nanosize film materials and, in particular, the so-called granular alloys (g.a.) as perspective media for superdense magnetic recording of information and spintronics elements, has increased significantly [1]. In work [2], a film system based on nonmagnetic and magnetic components is modeled as a layered structure based on a granular film solid solution (s.s.). This approach allows the sample to be considered as a parallel connection of the individual layers and the layer itself as a parallel connection of n current tubes. Each current tube represents a series connection of s.s. fragments with average size of Δl_{ss} and ferromagnet granules with radius r_0. The ratio for TCR (β) of g.a. in the framework of the proposed model is:

$$\beta_{ga} = \beta_{ss} - \frac{4\beta_g\rho_g \square}{4\rho_g + \alpha\rho_{ss}} - \frac{\alpha\beta_{ss}\rho_{ss} \square\square}{4\rho_g + \alpha\rho_{ss}} + \frac{\beta_g\rho_g + \alpha\beta_{ss}\rho_{ss}}{\rho_g + \alpha\rho_{ss}}, \quad (1)$$

where β_{ga} is the TCR of g.a.; $\alpha = \Delta l_{ss}/r_0$ is the degree of the sample granularity; ρ_g and ρ_{ss} are the resistivity of granule material and s.s.; β_g and β_{ss} are the TCR of granule and s.s. respectively.

In work [2], a theoretical analysis of relation (1) was performed depending on the degree of sample granularity and its limited expressions were recorded for three cases: $\alpha >> 1$, $\alpha << 1$, and $\alpha = 1$. The testing of this model was made on the example of two-layer Ag/Co/S (S is the substrate) film systems, in which the granular state stabilizes after annealing up to 700 K.

In the practical use of g.a., the question of the TCR field stability of samples remains important. In this connection, a phenomenological model was proposed in [3] to describe qualitatively the dependencies

$$\Delta\beta = \beta_{exp}^{gr} - \beta_{calc}^{ss}, \quad \Delta\beta_B = \frac{d\ln\beta_{exp}^{ga}}{dB} - \frac{d\ln\beta_{calc}^{ss}}{dB} \quad (2)$$

versus parameter α. We emphasize that the comparison of the experimental value β_{exp}^{ga} with estimated value β_{calc}^{ss} is due to the fact that experimental determination of β_{calc}^{ss} is practically impossible, since once a s.s. is formed there will already be a certain concentration of granules in it. In work [3], using the example of granular film alloys based on Co and Ag, the three limiting cases mentioned above were analyzed and it was found that, in accordance with the change of Δl_{ss}, the dependence of $\Delta\beta_B$ – magnetic coefficient of TCR – versus α has a different character.

In particular, it was found that the value of $\Delta\beta_B$ in all three cases varies within (0.02-0.10) T^{-1}, but the functional dependence of $\Delta\beta_B$ versus Δl_{ss} has a different character: at large values of α it monotonically decreases, and at small values of α – it increases, while at $\alpha = 1$ the value of $\Delta\beta_B$ is at the level 0.10 T^{-1}.

The purpose of this work can be formulated as follows: an experimental study of the electrophysical properties of film materials based on Fe or Co and Pd or Pt under the action of temperature or temperature and magnetic field.

2. METHODS AND EXPERIMENTAL TECHNIQUES

The choice of components for granular film alloy formation is due to the fact that in the film systems based on ferromagnetic (Fe, Co) and noble (Ag, Au, Pt, Pd) metals, the s.s. of the magnetic component in the fcc lattice of noble metals is stabilized. Solid solutions based on Fe or Co and Ag or Au and α-Fe or Co granules are disordered (see, for example, [4]), and in the case of Fe and Au film systems [5], granules have the ordered phase $L1_0$ (fct FeAu), $L1_1$ (phases $FeAu_3$) or $L1_2$ (phases Fe_3Au). Given the results [5-7], we have formed film alloys with FePd, CoPd, FePt and CoPt granules in disordered states (phases $L1_1$ and $L1_2$) and ordered state (phase $L1_0$).

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For the experimental verification of ratios (1) and (2), the electrophysical characteristics of two-layer film samples Pd/Co/S, Pt/Co/S, Pd/Fe/S and Pt/Fe/S were used by layer-by-layer deposition in vacuum at a substrate temperature $T_s \approx 300$ K. To stabilize the physical properties, the obtained films were kept in vacuum at a substrate temperature for 1-2 hours. The film thickness was controlled in situ by a quartz resonator (10 % accuracy) using an electric oscillator with a frequency of 10 MHz and a frequency meter.

For measuring electrophysical characteristics, sital plates with pre-deposited copper contacts were used as substrates. For electrical measurements, a digital voltmeter APPA-104 (accuracy ± 0.06 %) was used. The temperature was monitored using a chromel-alumel thermocouple and a UT-70B multimeter (accuracy ± 1 K).

For activation of recrystallization processes and thermal stabilization of electrophysical properties of single-layer samples, annealing in the range of 300-850 K was carried out according to the "heating-cooling" scheme with a constant speed 2-3 K/min for 2-3 cycles. Based on experimental dependences $\rho(T)$, the temperature coefficients of resistance for films were calculated by the ratio: $\beta = \mathrm{d}\ln R/\mathrm{d}T$. Since the TCR calculation of film systems requires information on the electro--physical properties for individual layers, the size dependences of ρ and β of the single-layer Fe, Co, Pd and Pt films were used.

Electron microscopic and electron diffraction studies were performed using TEM-125K on free films after cooling to room temperature. Electronograms from film materials were decoded according to the standard procedure (Fig. 1).

The concentration of system components was determined by the ratio:

$$c_1 = \frac{D_1 d_1 \mu_1^{-1}}{D_1 d_1 \mu_1^{-1} + D_2 d_2 \mu_2^{-1}}, \tag{3}$$

where D and μ are the density and molar mass respectively; d is the thickness of the film layer.

The value of the thermal resistance coefficient was calculated by the ratio:

$$\beta_{ss} = \frac{\beta_1}{1 + \dfrac{c_2\beta_2}{c_1\beta_1}} + \frac{\beta_2}{1 + \dfrac{c_1\beta_1}{c_2\beta_2}}, \tag{4}$$

where β_1 and β_2 are the TCR of single-layer films in the composition of film systems.

The magnetoresistive characteristics were recorded at room temperature in an alternating external magnetic field with induction up to 200 mT for a perpendicular geometry of measurement (the magnetic induction vector is perpendicular to the current direction and to the sample plane).

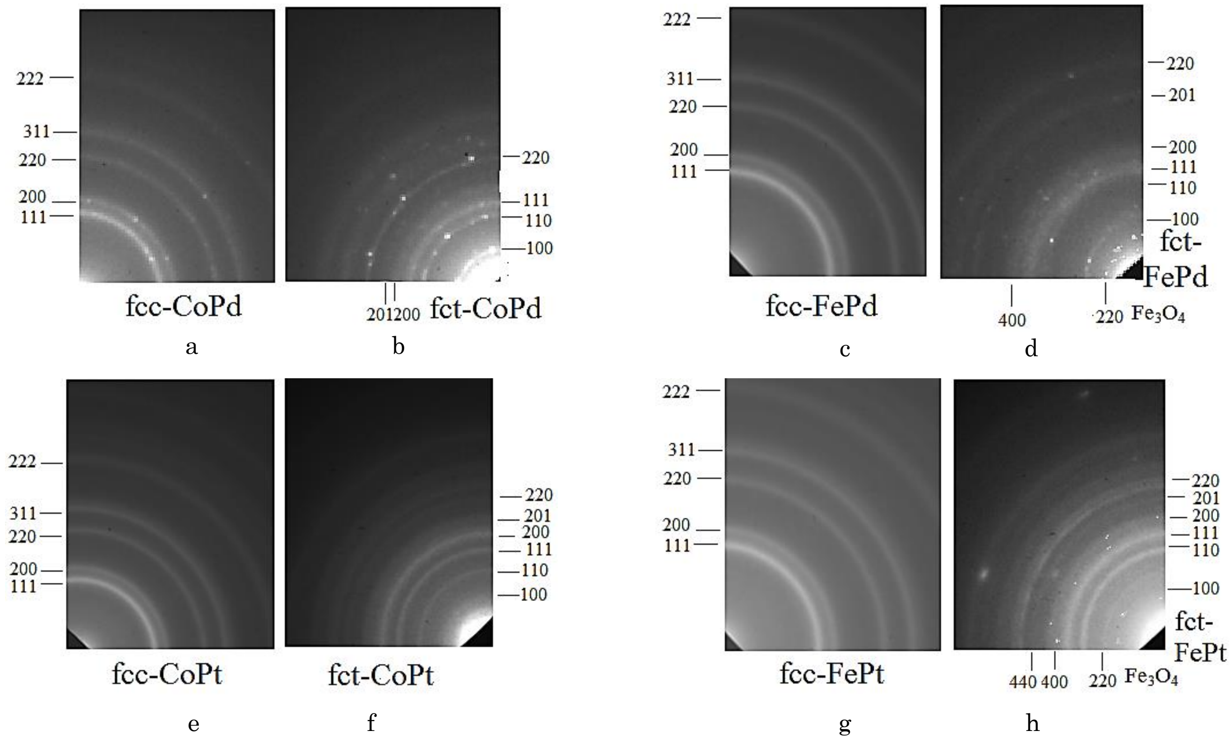

Fig. 1 – Diffraction patterns of the films which were obtained at 300 K (a, c, e, g) and before annealing to 850 K (b, d, f, h); Pd(15)/Co(10)/S (a, b), Pd(20)/Fe(15)/S (c, d), Pt(30)/Co(30)/S (e, f) and Pt(15)/Fe(30)/S (g, h). Thickness in nm is given in brackets

3. RESULTS AND DISCUSSION

Comparison of data based on ratio (1) with the experimental results was carried out on the example of two-layer film systems. Table 1 shows the results of comparing the experimental value β_{exp}^{ga} with the calculated value β_{calc}^{ss} at different values of the parameter α. The results obtained indicate the large role of the scattering of conduction electrons, which can be spin-dependent, by magnetic granules. The corresponding calculations indicate that the value of $\Delta\beta_B$ varies within the range (0.02-1.70) T^{-1}, which indicates the low sensitivity of the TCR of g.a. to the magnetic field, although the calculations allow to speak about a nonlinear field effect in $\Delta\beta_B$. We emphasize that this is a typical situation for film materials, since they exhibit strain nonlinearity of the strain coefficients (see, for example, [6, 7]).

Table 1 – Experimental and calculated data of TCR of two-component films annealed in the temperature range 300-850 K

Film system	c, at. % Co	Phase after annealing	$\beta_{exp}^{ga}\cdot 10^3$, K^{-1}	α	$\beta_{calc}^{ss}\cdot 10^3$, K^{-1}	$\Delta\beta\cdot 10^3$, K^{-1}
Film systems based on Co and Pd or Pt						
Pd(5)/Co(10)/S	72	fcc – Co_3Pd ($L1_2$)	0.55	10 1.0 0.1	0.20 0.28 0.27	0.35 0.27 0.28
Pd(15)/Co(10)/S	48	fct – CoPd ($L1_0$)	0.73	10 1.0 0.1	0.42 0.62 0.54	0.23 0.11 0.19
Pd(45)/Co(10)/S	23	fcc – $CoPd_3$ ($L1_1$)	1.05	10 1.0 0.1	0.96 1.17 0.94	0.09 0.11 0.10
Pt(30)/Co(30)/S	56	fct – CoPt ($L1_0$)	1.63	10 1.0 0.1	1.24 2.06 1.77	0.29 0.42 0.15
Film systems based on Fe and Pd or Pt						
Pd(20)/Fe(15)/S	47	fct – FePd ($L1_0$)	1.08	10 1.0 0.1	0.97 1.18 1.08	0.29 0.25 0.40
Pt(5)/Fe(30)/S	86	fcc – Fe_3Pt ($L1_2$)	1.12	10 1.0 0.1	0.86 1.17 1.03	0.46 0.14 0.27
Pt(15)/Fe(30)/S	62	fct – FePt ($L1_0$)	1.31	10 1.0 0.1	0.96 1.39 1.23	0.50 0.58 0.22

4. CONCLUSIONS

The results of studies of electrophysical properties of granular film solid solutions suggest that the solid solution granulation causes an increase of the TCR value by tens of percent. It is clear that this difference is determined with low accuracy because it is based on experimental data for the TCR granular s.s. and calculation data for the s.s. of the magnetic component in the paramagnetic matrix.

We conclude that the TCR increase is related to the spin-dependent scattering of conduction electrons by magnetic granules. With respect to the difference in the magnitude of the magnetic coefficient of TCR for the granular s.s. and the corresponding calculated value for the s.s., in this case the spin-dependent electron scattering does not play a significant role, which can be explained by the low sensitivity of the granule system to the external magnetic field. This may be due to the fact that the magnetic moments of the individual granules are self-correlated and weakly react to an external magnetic field.

ACKNOWLEDGEMENTS

The work was performed under the financial support of the Ministry of Education and Science of Ukraine (Grant No 0118U003580, 2018-2020).

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Електрофізичні властивості гранульованих плівкових сплавів

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Представлено результати вивчення концентраційних і температурних умов формування фаз $L1_0$, $L1_1$ та $L1_2$ у двошарових плівкових системах на основі Fe або Co та Pt або Pd після їх термообробки до 850 K. Експериментально визначені електрофізичні властивості гранульованих сплавів, такі як питомий опір і термічний коефіцієнт опору (ТКО), були порівняні з розрахунковими значеннями відповідних величин в рамках феноменологічної моделі електрофізичних властивостей гранульованих сплавів. Отримані результати дозволили провести розрахунки прогнозованих змін ТКО гранульованих сплавів у перпендикулярному магнітному полі з індукцією 200 мТл. Розрахункові величини $\Delta\beta = \beta_{exp}^{ga} - \beta_{calc}^{ss}$ лежать у межах (0.1-0.6)$\cdot 10^{-3}$ K^{-1}. Величина $\Delta\beta_B = \dfrac{d\ln\beta_{exp}^{ga}}{dB} - \dfrac{d\ln\beta_{calc}^{ss}}{dB}$ має низьке значення у межах (0.02-1.70) T^{-1}.

Ключові слова: Гранульований сплав, Твердий розчин, Питомий опір, ТКО, Магнітний коефіцієнт ТКО.