structures of two types of samples are presented at Fig.1.

The study of magnetoresistive properties was carried out with using software-hardware complex with current-in-plane geometries in an external magnetic field from 0 до 500 mT at room temperature according the methods, which describe at work [9]. The measurement of magnetoresistance (MR) was carried out in three geometries: perpendicular, transverse and longitudinal. The value of magnetoresistance has been calculated as

$$MR = \frac{\left(R(B) - R(B_S)\right)}{R(B_S)} \cdot 100\%,$$

where R(B) and R(Bs) are resistance of thin film samples at a given and saturated field respectively.

To study the effect of temperature on phase state, structural characteristics and magnetoresistive properties of thin film samples the heat treatment was carried out to annealing temperatures Ta = 700 or 800 (to analyze the effect of the phase transition hcp-Co→fcc-Co, which occurs at 690 K, on magnetoresistive properties) and 1000 K (influence of temperature on the stability of sensitive elements, which can be made on the base of the chosen film systems). The annealing duration carried out by the scheme «heating → excerpt for 20 min → cooling to room temperature» with using the computerized complex, which described at work [10].

Structural and phase state investigation were made by using TEM and diffraction measurements on the transmission electron microscope TEM-125K.

2. Experimental Results

In earlier studies have repeatedly stated that the creation of effective sensing elements based on t he type of structures Me1/Me2/Me1/S is necessary to conduct comprehensive studies of magnetoresistive properties, structural and phase state. The detailed analysis of the phase state and the crystal structure film systems showed the following. The phase state of film systems Co/Cr/Co/S after condensation corresponds to bcc-Cr + hcp-Co and crystalline structure has nanoscale character. The diffraction lines d111 and d200 from fcc-Co, which observed at room temperature (Fig. 2a), are not associated with the formation of fcc-Co crystallites as a result of the phase size effect, and with formation of stacking faults at hcp-Co (low temperature phase) as well as in bulk samples [11]. After annealing to 800 K the change of phase composition does not occur, there is only a slight increase of crystallite size. At Ta ≥ 900 K the thin film Cr almost completely oxidized to the composition of Cr2O3 (Fig. 2c). Thus, dependences, which presented at Fig. 4, described the magnetoresistive properties of system Co/(bcc-Cr+ Cr2O3)/Co/S.

In the case of systems based on Co and Cu has place the formation of solid solution (Co, Cu) on the base of Cu fcc lattice at a condensation stage. The annealing to 700 K occurs to polymorphic transition hcp-Co→fcc-Co. Partial disintegration of solid solution with formation granules of Co in solid solution matrix occurs at annealing to 850 K (the diffraction rings of hcp-Co fixed at electron-diffraction pattern (Fig. 3c)). Thus the purpose of formation granular films was attained.

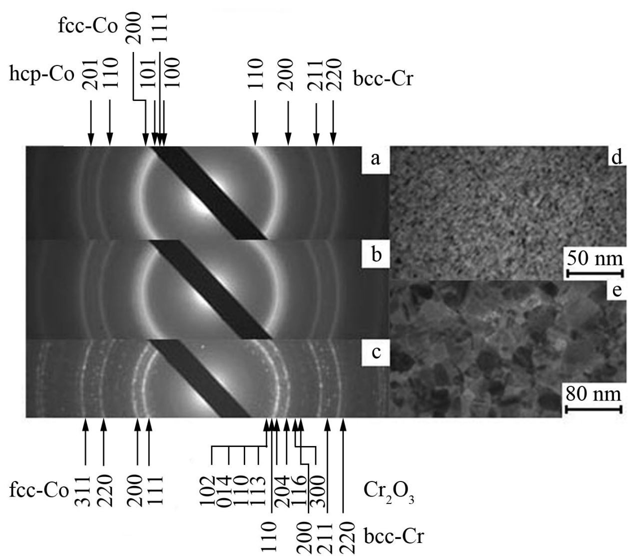

Figure 2. Diffraction pattern (a-c) and crystalline structure (d, e) of film systems Co(5)/Cr(5)/Co(20)/S as deposited (a, d) and after annealing to T_a = 800 K (b), 1000 K (c, e)

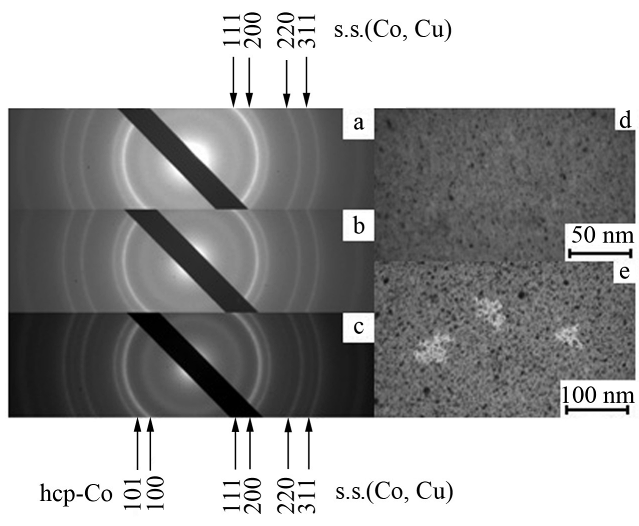

Figure 3. Diffraction pattern (a-c) and crystalline structure (d, e) of film systems Co(22)Cu(17)Co(20)/S as deposited (a, d) and after annealing to T_a = 700 K (b), 850 K (c, e)

Fig. 4 and 5 shows the magnetoresistance curves after condensation and heat-treated typical of the Co/Cr/Co/S and Co/Cu/Co/S systems. The results of calculation of MR value and coecivity are presented in Table 1. The characteristic properties of this data are following. The magnetoresistance effect in film systems Co/Cr/Co/S (Fig. 4) characterized by not great value of MR (0.1–0.3%), here with maximum value 0.4% obtained in perpendicular geometry after heat treated to 800 K at the thickness of interlayer dCr = 20 nm. In addition, sensing elements on the base of Co and Cr attributed by sufficiently large values of coercivity Bc (> 100 mT) at Co atom concentration cCo = 56–63 at.% in perpendicular geometry as after condensation so as after heat treated to 800 K. At increasing cCo take place decreasing of Bc value. Though, it should be noted that at high-temperature annealing to 1000 K observed significant increasing of coercivity for all range of concentration and all types of measurement geometries. For example, for film system Co(5)/Cr(13)/Co(20)/S the value of Bc increases from 23 (300 K) to 200 mT (1000 K) in perpendicular geometry. The increasing of coercivity as a result of phase state changing of sample.

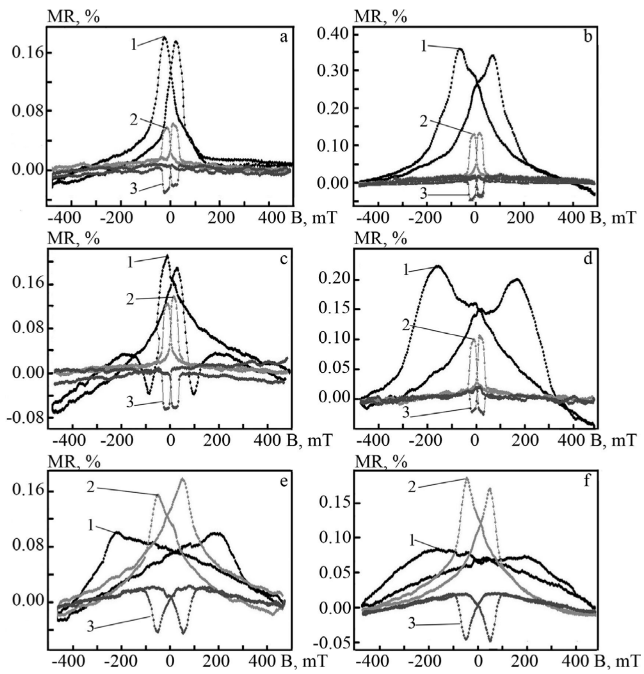

Figure 4. Magnetoresistance dependence versus applied field for film systems Co(5)/Cr(5)/Co(20)/S (a, c, e) and Co(5)/Cr(13)/Co(20)/S (b, d, f) after condensation (a, b) and heat treated to 800 K (c, d) and 1000 K (e, f). Magnetic field lying in perpendicular (1), longitudinal (2), transverse (3) geometries

Thus at work [5] has been reported that the in-plane coercivity can be increased by thermal treatment from 1 to 24 mT. According to work [5] structural and magnetic properties of structures based on Co and Cr are good candidate for using as sensing elements of magnetic sensors and as hard spin injectors. Peculiarity of hysteresis of field dependence is availability double peak (see, for example, magnetoresistance dependence vs. applied field for film system Co(5)/Cr(13)/Co(20)/S (Fig. 4b, d, f). It's can be explained by alternate magnetic reversal of Co layers [12]. It should be noted, that for film systems Co/Cr/Co/S in all range of interlayer thickness take place anisotropy of magnetorsistance at transfer to longitudinal geometry of measurement. The value of anisotropy increases at decreases of magnetic component atom concentration.

The value of the magnetoresistance for structures of second type depends of total concentration of Co atom and changes from 0.2 to 0.4% at increasing cCo from 60 to 87 at.%. Besides, magnetoresistive properties of granular films based on Co and Cu slowly depend on heat treated. The annealing to 700 K leads to slight decrease of the values of MR and saturated field Bs. At the same time heat treatment of samples Co(14)/Cu(9)/Co(14)/S (Fig. 5d) reduces to decrease of the magnetoresistance effect in the perpendicular geometry and its increase in other geometries. The value of Bs changes in a similar way (from 140 to 24 mT – in the perpendicular and from 35 to 39 mT – in longitudinal geometry).

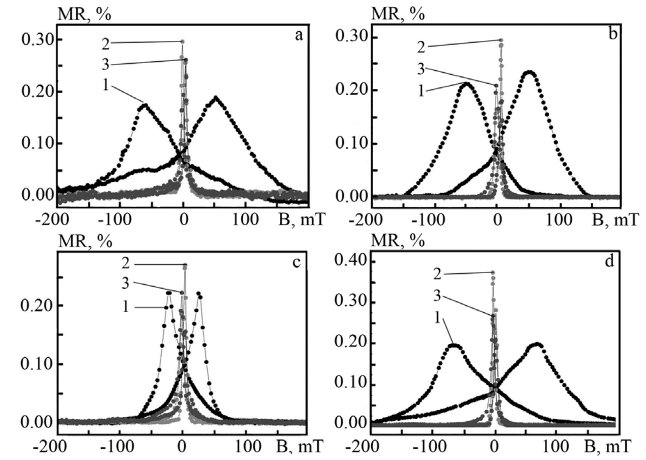

Figure 5. Magnetoresistance dependence versus applied field for film systems Co(14)/Cu(7)/Co(14)/S (a, c) and Co(14)/Cu(9)/Co(14)/S (b, d) after condensation (a, b) and heat treated to 700 K (c, d)

In forming the structure of the sensing element of considerable importance is the ability of the sensor to respond to changes in the magnetic field irrespective of measurement geometry and the value of the sensitivity to the magnetic field (S_B). Depending on the application, the sensor sensitive element should have high sensitivity and to provide a rapid response to changes in sensor input signal (e.g., instantaneous closure / opening of the circuit in automation) or medium in order to be able to provide high accuracy of measurement the detection of weak fields.

The maximum value of the sensitivity of the film system to the magnetic field was determined by the equation $(\Delta R/R(B_s))_{max}/\Delta B$. The results of SB calculations for the samples of both types after condensation and heat treated are presented in Table 2.

The highest value of magnetic sensitivity for film systems based on Co and Cr for a sample of Co(5)/Cr(20)/Co(20)/S is 19.8 %/T in the perpendicular geometry of the measurement; for film systems based on Co and Cu for a sample of Co(14)/Cu(9)/Co(14)/S – 21.5%/T in the transverse geometry of the measurement. Note that those structures can be used in analog and digital circuits for fast response to changing magnetic flux.

Table 1. The value of MR and coercivity (B_c) for film systems of both types after condensation and heat treated

Film system	c_{Co}, at.%	T, K	MR, %			B_c, mT		
			measurement geometry			measurement geometry		
			perpend.	transverse	longitud.	perpend.	transverse	longitud.
Co(5)/Cr(5)/Co(20)/S	83	300	0.18	0.06	-0.03	23.06	13.21	32.62
		800	0.21	0.14	-0.06	90.74	13.51	20.39
		1000	0.10	0.15	-0.04	199.72	49.69	52.25
Co(14)/Cu(7)/Co(14)/S	81	300	0.19	0.30	0.26	140	29	35
		700	0.22	0.27	0.22	24	37	39
Co(14)/Cu(9)/Co(14)/S	77	300	0.24	0.30	0.21	200	14	30
		700	0.20	0.37	0.27	134	37	44
Co(5)/Cr(10)/Co(20)/S	71	300	0.13	0.04	-0.02	12.53	17.00	15.18
		800	0.22	0.12	-0.01	26.92	13.31	22.13
		1000	0.08	0.13	-0.03	183.96	72.15	42.18
Co(20)/Cu(25)/Co(25)/S	66	300	0.34	0.26	0.26	100	35	37
		700	0.25	0.26	0.25	100	22	39
Co(5)/Cr(15)/Co(20)/S	63	300	0.19	0.13	-0.04	129.55	13.96	21.04
		800	0.27	0.20	-0.10	149.66	16.57	20.16
		1000	0.04	0.06	-0.02	67.98	54.01	73.02
Co(5)/Cr(20)/Co(20)/S	56	300	0.26	0.10	-0.06	139.47	16.06	15.75
		800	0.40	0.16	-0.07	20.16	15.21	17.93
		1000	0.02	0.02	0.03	117.22	37.12	67.49

Table 2. The value of S_B for film systems of both types after condensation and heat treated

Film system	c_{Co}, at.%	T, K	S_B, %/T		
			measurement geometry		
			perpendicular	transverse	longitudinal
Co(5)/Cr(5)/Co(20)/S	83	300	7.8	4.5	0.9
		800	10.0	10.4	3.2
		1000	0.5	3.0	0.8
Co(14)/Cu(7)/Co(14)/S	81	300	1.3	10.1	7.3
		700	9.3	7.3	5.7
Co(14)/Cu(9)/Co(14)/S	77	300	1.2	21.5	6.9
		700	1.5	10.1	6.1
Co(5)/Cr(10)/Co(20)/S	71	300	1.1	2.4	1.2
		800	8.2	9.0	0.2
		1000	0.5	1.8	0.7
Co(20)/Cu(25)/Co(25)/S	66	300	3.4	7.5	7.0
		700	2.5	11.8	6.5
Co(5)/Cr(15)/Co(20)/S	63	300	10.4	9.3	1.7
		800	18.7	12.0	4.9
		1000	0.5	1.1	0.2
Co(5)/Cr(20)/Co(20)/S	56	300	6.2	6.2	3.8
		800	19.8	10.5	3.9
		1000	0.1	0.5	0.4

Analysis of the data for the other samples also allows identifying possible areas of application of the magnetic field sensor based on them. Since the sensitivity to magnetic field, in most cases not exceeding 10%/T, such a structure is more suitable for detection of weak magnetic fields.

3. Conclusions

The results of investigation of phase state of thin film system of two types show that the samples based on Co and Cr has two-phase state and in the samples based on Co and Cu the take place formation nanostructured solid solution with granules of Co. So the first one of systems allows realizing the multilayer structures and second one – granulated structures for production sensing elements of magnetic field sensors. Notes, both types of systems depending on the concentration of components can be used in analog and digital circuits for rapid response to changing magnetic flux or when creating a stable sensor for detecting weak magnetic fields. Besides, the phase states of systems slowly depend on heat treated to 800 K, it allows to exclude the influence of temperature on the working characteristics of the sensors.

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