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MAGNETORESISTIVE AND MAGNETOSTRICTIVE PROPERTIES OF COXFE1-X THIN-FILM NANOSTRUCTURES FOR MAGNETIC STRAINTRONIC DEVICES

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ABSTRACT

Results of experimental studies of magnetostrictive and magnetoresistive properties of thin-film Ta-$Co_{50}Fe_{50}$*-Ta, Ta-*$Co_{66}Fe_{34}$*-Ta, Ta-*$Co_{95}Fe_{5}$*-Ta nanostructures on oxidized silicon substrates with a diameter of 100 mm are developed to create hybrid magnetoresistive and magnetostrictive elements of magnetic straintronics on their basis. Methods for studying magnetostrictive and magnetoresistive properties of* Co_xFe_{1-x} *nanostructures are presented.*

The dependence of rate of anisotropic magnetoresistive effect on mechanical deformation in annealed samples of nanostructures is experimentally established altogether with the effect of annealing parameters on coercivity of ferromagnetic nanostructure. Potentially this can be of great practical importance for optimizing magnetic straintronic elements with certain technical characteristics. It is required to reduce the upper edge of magnetic field which leads to an increase in sensitivity of the elements being developed. Prospects of thin-film Ta-$Co_{50}Fe_{50}$*-Ta nanostructures for use in magnetic straintronic elements are shown.*

Key words: Straintronics, Magnetostrictive effect, Magnetoresistive effect, Nanostructure.

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1. INTRODUCTION

The proposed work is a continuation of the authors' research on creation of new hybridized elements of magnetic straintronics combining a nanostructure with magnetoresistive and magnetostrictive properties in their composition, results of which were presented in [1].

When developing magnetic straintronic devices based on anisotropic and giant magnetoresistive effects (AMR, GMR, TMR) and the reverse magnetostriction effect, all requirements for sensitive layers must be taken into account. Typically the sensitive layer must have a high magnetostriction (MS) effect, $\lambda_s \geq 50$ ppm with a minimum value of the magnetic anisotropy field $H_k \leq 10$ kA/m [2]. In addition, the magnetoresistive (MR) effect should be at least 0.5% for devices based on AMR.

At present, the perspective material of straintronics is the Fe-Ga alloy [3-8]. In polycrystalline layers of $Fe_{81}Ga_{19}$ composition, the value of the magnetostriction rate of saturation reached values of 50...150 ppm. At this, layers had a sufficiently high anisotropy field of ≥50 kA/m [9]. Possessing a low value of the spin polarization of electrons, Fe-Ga layers can nevertheless make the composition of the free layer of GMR and TMR structures providing their sensitivity to mechanical deformations [10].

Another promising material for use as a sensitive layer is a Fe-Co alloy. In layers composed of $Fe_{66}Co_{34}$ the value of the magnetostriction rate reached a value of ~250 ppm after appropriate heat treatment [11]. However, the nature of the proposed heat treatment is not compatible with technological manufacture routes of certain devices. In addition, layers possessed a sufficiently high coercivity value $H_c \geq 4$ kA/m.

Sufficiently good MS properties of Fe-Co alloy films appear in a wide range of composition of this alloy, which allows us to hope for optimization of such a parameter as the field of magnetic anisotropy while maintaining MS properties. Another possibility of reducing the value of the magnetic anisotropy field is associated with the use of sublayers that actively influence favorable orientation of crystal texture when Fe-Co layers are deposited [12-15]. It was shown in [12] that MS rate values of up to 60 ppm are achievable under heat treatment conditions up to temperature of 400°C.

Thus it is obvious that incorporation of Fe-Co layers in technological routes for manufacturing magnetic straintronic devices is relevant and requires quite definite technological efforts. Magnetic straintronic is an actual line of scientific research as evidenced by high publication activity in this scientific field and areas related hereto [16-22]. Studies of MS and AMR properties of $Co_{50}Fe_{50}$, $Co_{66}Fe_{34}$, $Co_{95}Fe_5$ layers mentioned above demonstrate the effect of annealing parameters on characteristics of nanostructures.

2. MATERIALS & EXPERIMENTAL PROCEDURES

Thin-film nanostructures Ta-$Co_{50}Fe_{50}$-Ta, Ta-$Co_{66}Fe_{34}$-Ta, Ta-$Co_{95}Fe_5$-Ta were formed by magnetron sputtering at room temperature. In all cases thickness of the Ta layer made 5 nm, and thickness of ferromagnetic layers made 25 nm. Plates of oxidized silicone with a diameter of 100 mm were used as substrates. A magnetic field of ~100 Oe in the plane of the substrate was formed to form the easy magnetization axis (EMA) in deposited ferromagnetic layers in the sputtering zone.

Measurement of magnetic properties of produced experimental samples after sputtering was carried out on a Shb Instruments MESA-200 magnetic measuring system (USA), which makes it possible to determine and visualize the dependence of magnetic induction on magnetic field [2]. Measurements of parameters of films were carried out along the EMA and the hard magnetization axis (HMA) of ferromagnetic films.

The AMR effect was measured by the two-probe method described by us earlier in [23-24]. The measuring system was supplemented with a device for creating mechanical deformations in the sample. The main unit of the system is shown schematically in Fig. 1. In the presented design a controlled mechanical compression stress is created on the surface layer of the sample sideways probes.

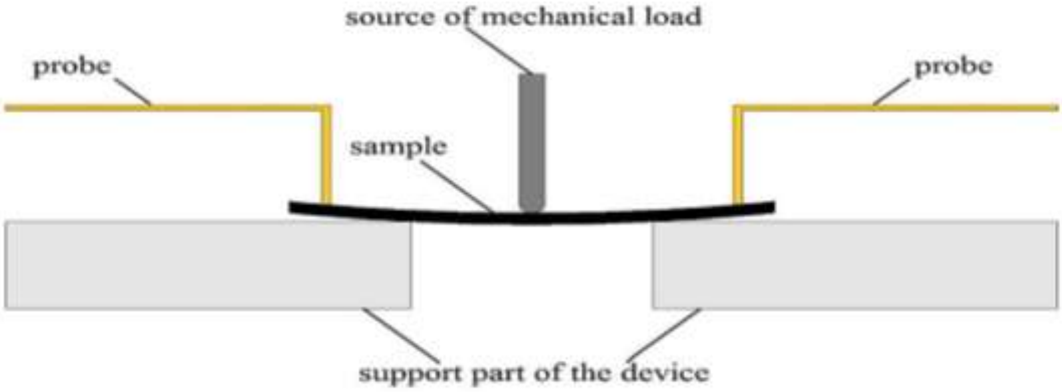

Figure 1 Schematic representation of the main setup unit of the AMR measurement

The measurements were carried out on samples measuring 4×20 mm (Fig. 2) in a magnetic field of ±300Oe. The figure shows the direction of compressing mechanical stress σ, the easy magnetization axis (EMA) and external magnetic field H. The direction of electric current coincided with the direction of the long side of the sample.

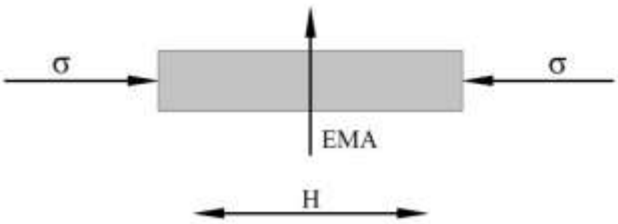

Figure 2 Test sample

Samples were subjected to vacuum annealing in a magnetic field with intensity up to 500 Oe. Annealing was carried out for 15 minutes at temperatures of 250°C, 350°C and 400°C.

3. RESULTS

3.1. Study of the Ta-$Co_{95}Fe_5$-Ta nanostructure

Figure 3 shows curves reversal process of $Co_{95}Fe_5$ layers. Magnetic anisotropy is observed in layers, coercivity (H_c) makes ~30Oe.

In the course of study of the initial sample Ta-$Co_{95}Fe_5$-Ta (Fig. 4), the value H_c = 30 Oe was determined which corresponds to the previously obtained measurement result B (H), the relative change in resistance (ΔR/R) is 0.15%.

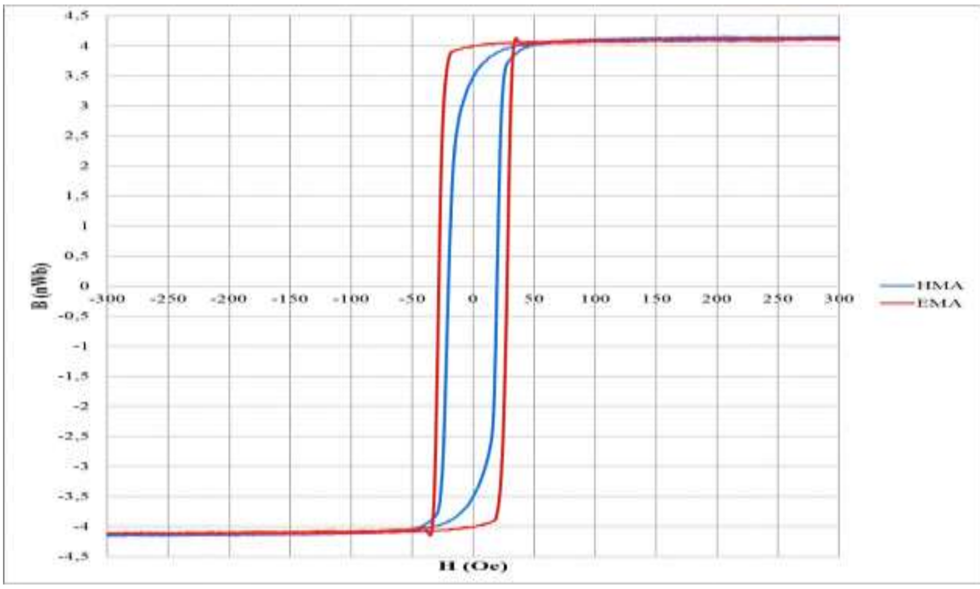

Figure 3. Dependence B (H) for the $Co_{95}Fe_5$ layer before annealing

Figure 5 shows results of measuring the AMR effect in Ta-Co95Fe5-Ta nanostructures after annealing at temperature 350°C for 15 minutes at various levels of mechanical stress. As it follows from the graph, annealing leads to a decrease in Hc to 25 Oe and an increase in the value of ΔR/R to 0.28%. For each level of mechanical load, the graph shows a forward-backward motion of a magnetic field (black-green, blue-red, etc.).

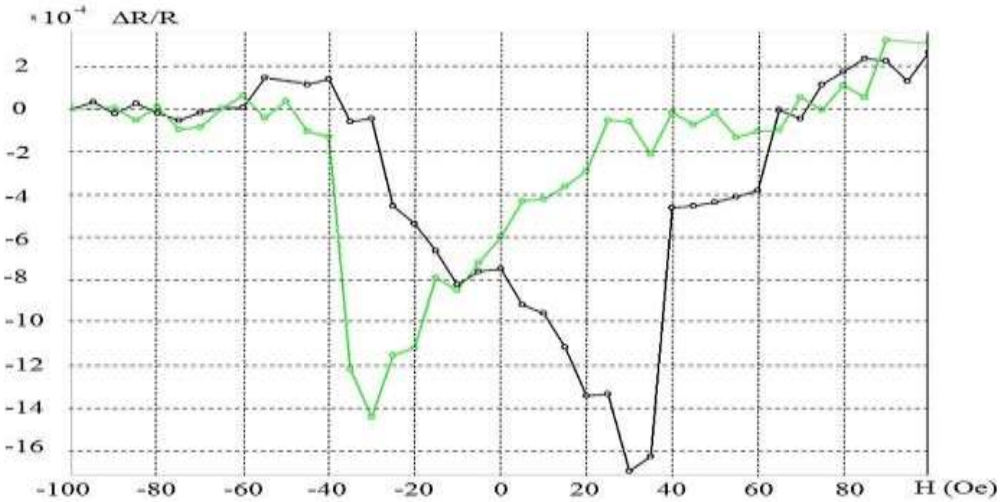

Figure 4 Dependence of the relative change in resistance of the initial Ta-$Co_{95}Fe_5$-Ta nanostructure on the value of external magnetic field: black – straight motion; green – reverse one

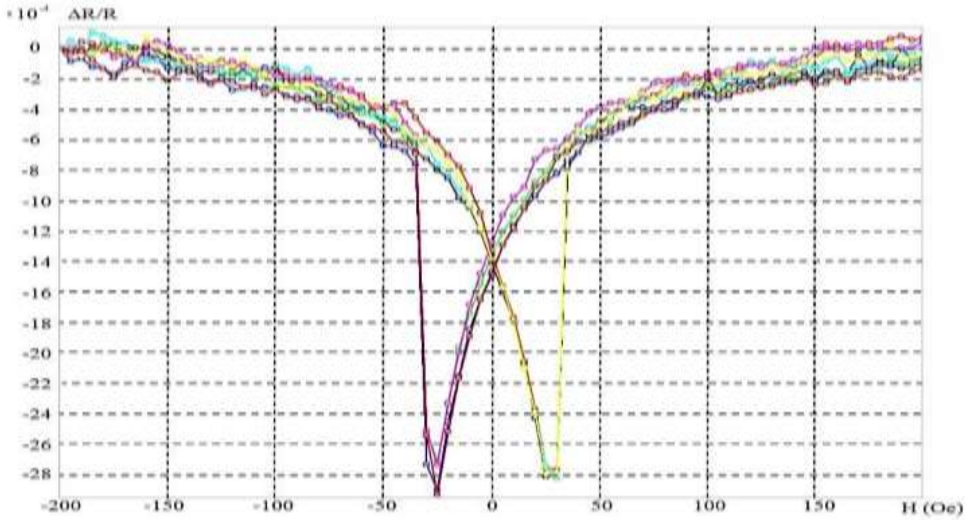

Figure 5. Dependence of the relative change in resistance of the initial Ta-$Co_{95}Fe_5$-Ta nanostructure on the value after annealing at temperature of 350°C: black, green – no load; red, blue – σ = 30 MPa; blue, crimson – σ = 60 MPa; yellow, brown – σ = 90 MPa

Increasing the mechanical stress to 90 MPa does not affect the rate of the AMR effect.

3.2. Study of the Ta-$Co_{66}Fe_{34}$-Ta nanostructure

Figure 6 shows curves of reversal of initial nanostructures along the EMA and ESA of magnetic films. Samples of Ta-$Co_{66}Fe_{34}$-Ta nanostructures show weak magnetic anisotropy and a rather high coercivity of ~ 170 Oe. Annealing temperatures allowed for technological cycles used in this work do not lead to a significant change in properties of $Co_{66}Fe_{34}$ layers (Table 1). Figure 7 shows AMR dependencies for nanostructures after annealing at 400°C for 15 minutes at three levels of mechanical stress. For magnetic layers after annealing, the following values of the parameters are typical: the rate of the AMR effect is $\Delta R/R \leq 0.1\%$; weak influence on the value of ΔR/R of mechanical stresses. After annealing, an insignificant change in coercivity of magnetic films was recorded.

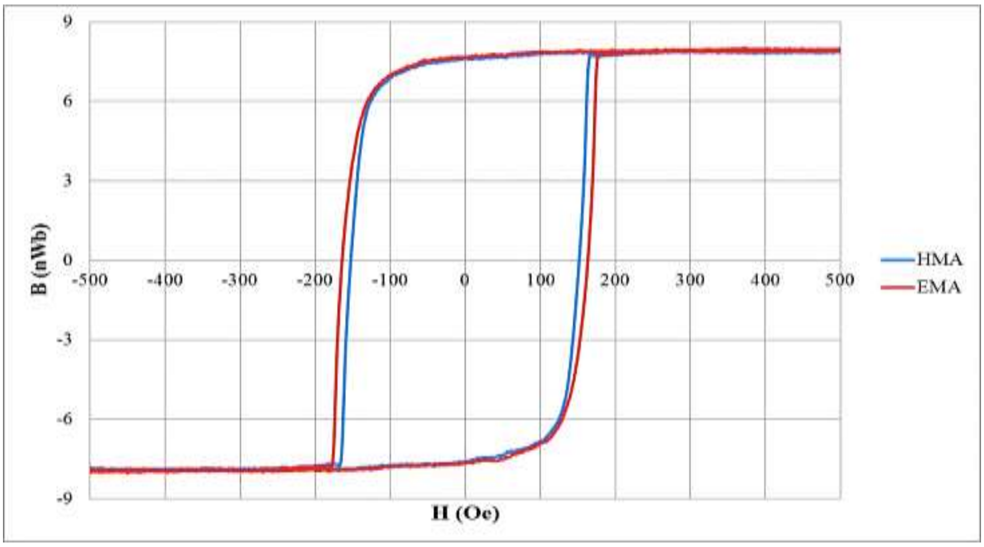

Figure 6. Dependence B(H) for the $Co_{66}Fe_{34}$ layer before annealing

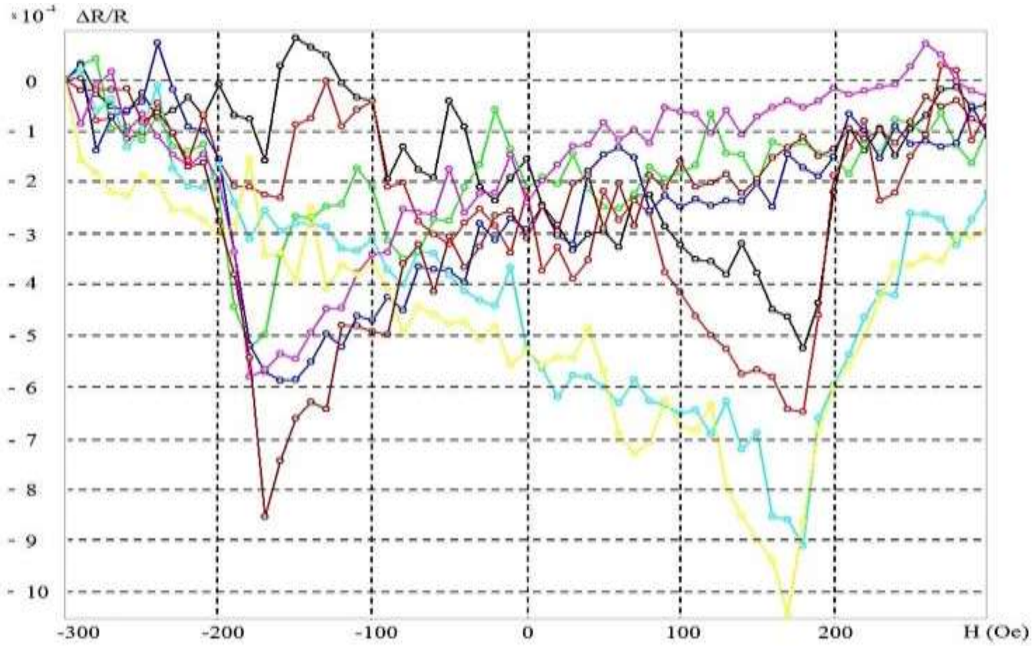

Figure 7. Measurement of the AMP effect under mechanical load of a sample annealed at 400°C of a $Co_{66}Fe_{34}$ sample: black, green – no load; red, blue – σ = 30 MPa; blue, crimson – σ = 60 MPa; yellow, brown – σ = 90 MPa

3.3. Study of the Ta-Co50Fe50-Ta nanostructure

In initial samples of Ta-Co50Fe50-Ta nanostructures, a weakly pronounced magnetic anisotropy and coercivity of ~110Oe are observed (Fig. 8). Fig. 9 shows results of measuring the AMR effect in initial samples. The value of ΔR/R at σ = 0 does not exceed 0.2% and coercivity corresponds to the value determined from the B(H) dependence. With an increase in mechanical stress in a layer up to 90 MPa, the value of ΔR/R increases. After annealing at 250°C, main parameters change insignificantly with exception of coercivity – Hc decreases to 70 Oe (Fig. 10).

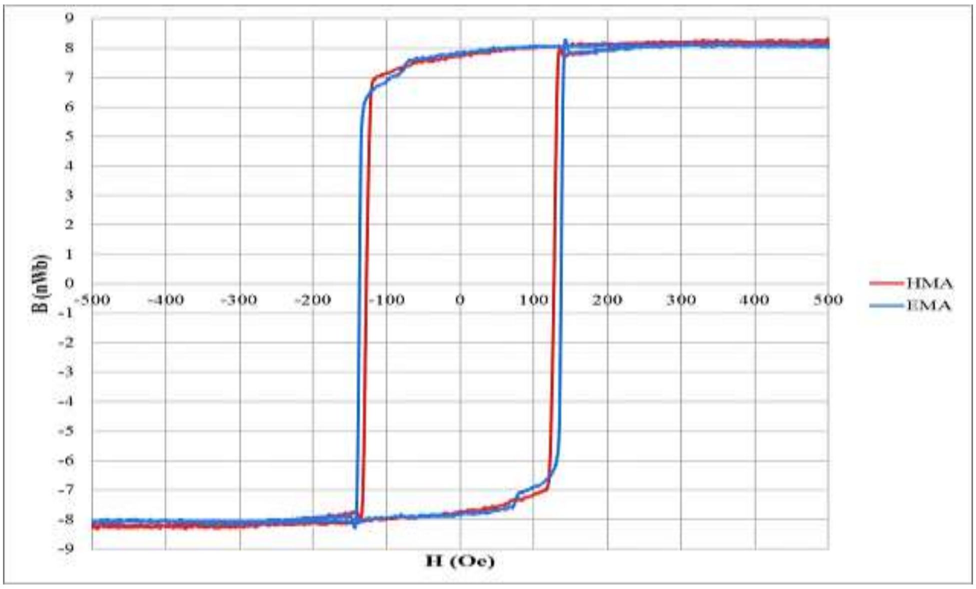

Figure 8. Dependence B(H) for the $Co_{50}Fe_{50}$ layer before annealing

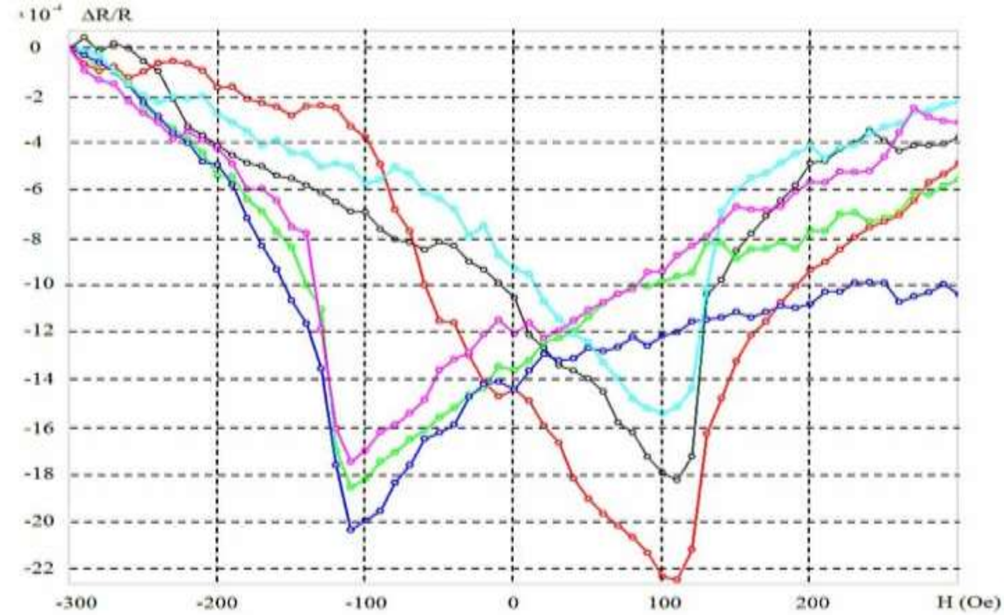

Figure 9. Measurement of the AMP effect under mechanical loading of the original $Co_{50}Fe_{50}$ sample: blue, crimson – no load; black, green – σ = 30 MPa; red, blue – σ = 60 MPa

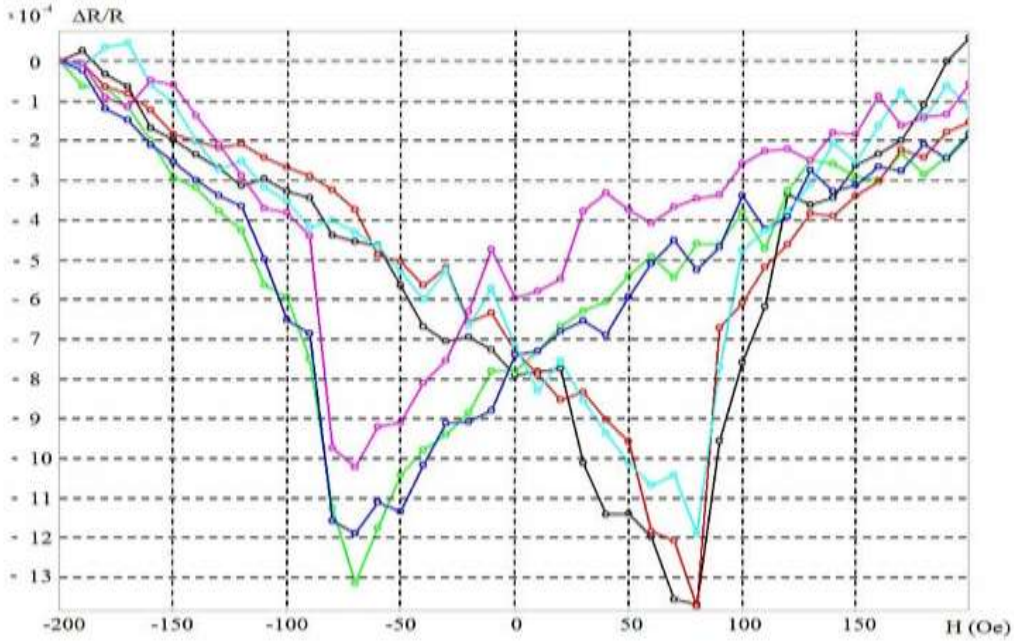

Figure 10. Measurement of the AMP effect under mechanical load of a $Co_{50}Fe_{50}$ sample annealed at 250°C: blue, crimson – no load; red, blue, – σ = 30 MPa; black, green – σ = 60 MPa

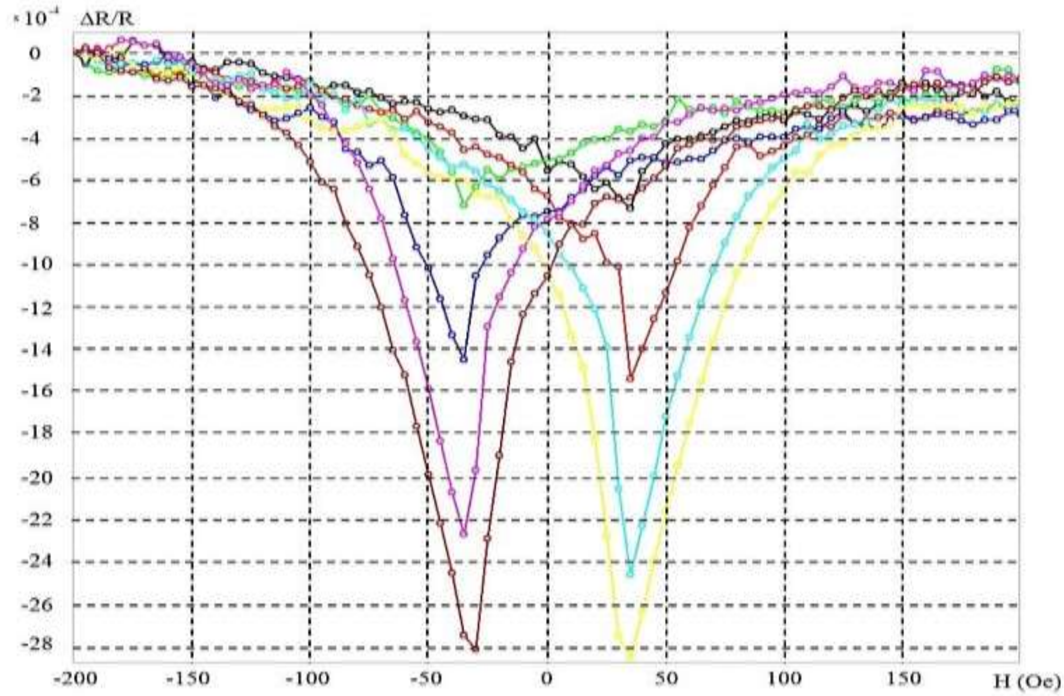

Figure 11. Measurement of the AMP effect under mechanical load of a $Co_{50}Fe_{50}$ sample annealed at 350°C: black, green – no load; red, blue, – σ = 30 MPa; blue, crimson – σ = 60 MPa; yellow, brown – σ = 90 MPa

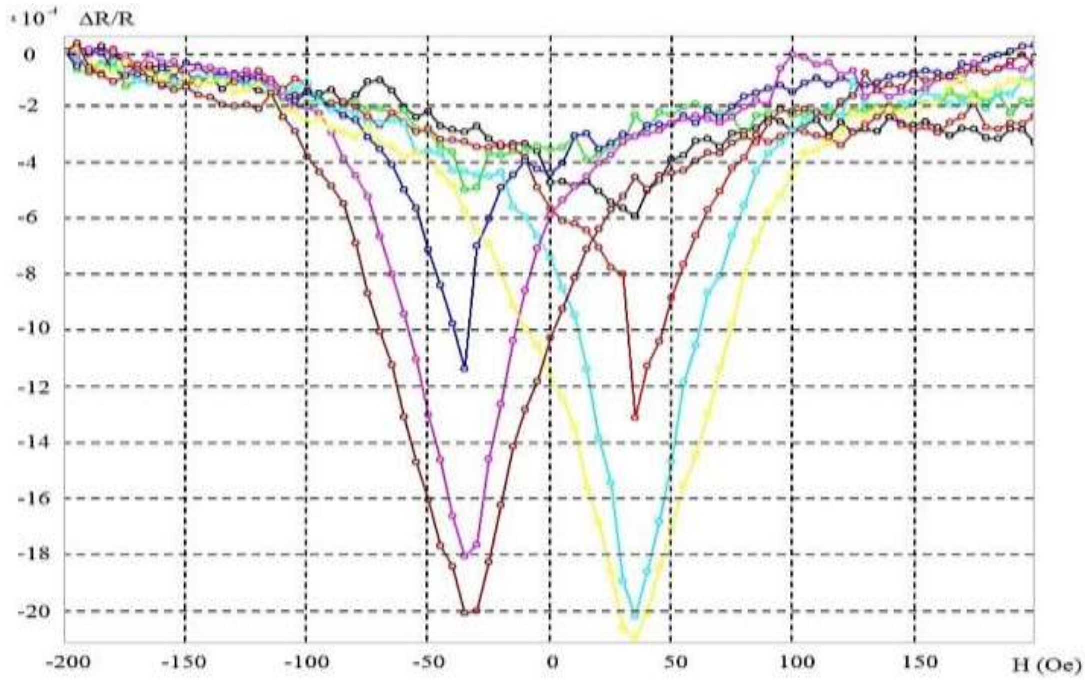

Figure 12. Measurement of the AMP effect under mechanical load of a $Co_{50}Fe_{50}$ sample annealed at 400°C: black, green – no load; red, blue, – σ = 30 MPa; blue, crimson – σ = 60 MPa; yellow, brown – σ = 90 MPa

Results of investigation of magnetic properties of Ta-$Co_{50}Fe_{50}$-Ta, Ta-$Co_{66}Fe_{34}$-Ta Ta-$Co_{95}Fe_{5}$-Ta nanostructures are presented in Table 1.

Table 1 Measurement results

No.	**Structure**	**Anneal temperatures, *t*, °C**	**Rate $\left(\frac{\Delta R}{R}\right)$, %**	**Rate* $\left(\frac{\Delta R}{R}\right)_\sigma$, % at σ, MPa 30**	**60**	**90**	**Coercive force H_c, Oe**	**Magnetic saturation induction *Bs*, nVB**
		–	0.16	0.02	0.05	–	110	
	Ta	250	0.11	0.015	0.025	–	70	
1	$Co_{50}Fe_{50}$	350	0.07	0.08	0.16	0.21	35	8.2
	Ta	400	0.05	0.07	0.14	0.16	35	
		–	0.045	0.01	0.02	–	230	
		250	0.04	0.01	0.02	–	215	
	Ta	350	0.04	0.015	0.02	0.01	210	
2	$Co_{66}Fe_{34}$	400	0.05	0.015	0.025	0.04	170	8.0
	Ta							
		–	0.15	0.01	0.01	–	30	
	Ta	250	0.22	0.02	0.03	–	30	
3	$Co_{95}Fe_5$	350	0.25	0.005	0.005	0.01	25	4.5
	Ta	400	0.27	0.005	0.005	0.005	25	

*relative resistance change due to load

4. DISCUSSION

Generalized measurement results are presented in Table 1.

Layers of the $Co_{95}Fe_5$ composition show weak magnetostriction properties from results of investigations carried out both in the initial and annealed conditions. In magnetic Straintronic devices as in straintronics, such layers are used as a buffer or primer layers.

In initial layers of the $Co_{66}Fe_{34}$ composition, high coercivity and a weak sensitivity to mechanical deformations are observed. During subsequent annealing, there is a marked improvement of these parameters. It can be assumed that annealing at higher temperatures will achieve the desired results, but requirement of compatibility with other operations of technological routes does not allow using annealing temperatures higher than 400°C. Further introduction of layers of $Co_{66}Fe_{34}$ composition into magnetic straintronic devices may be associated with improvement of heat treatment mode, including using pulsed photon annealing.

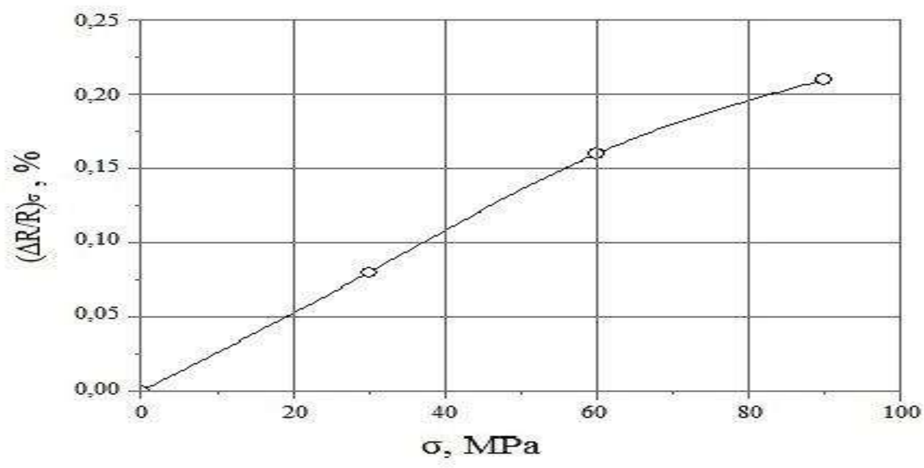

Figure 13. Dependence of the value $(\Delta R/R)_\sigma$ on the value of mechanical stresses for the Ta-$Co_{50}Fe_{50}$-Ta nanostructure after annealing at 350°C

Most interesting results were obtained for $Co_{50}Fe_{50}$ composition layers. It is seen from Fig. 11 that in samples annealed at 350°C, the value of the AMR effect increases to the maximum under mechanical loading. Thus, relative change in resistance increases by a factor of ~ 4 (i.e. by 300%) at a mechanical stress of 90 MPa. Since the rate of the AMR effect without load is small, the relative change in resistance due to load $(\Delta R/R)_\sigma$ is also small and amounts to 0.21%. Figure 13 shows the dependence of quantity $(\Delta R/R)_\sigma$ on the value of mechanical stress (σ) in the layer.

As can be seen from the figure, the dependence has a linear character when stresses are up to 60 MPa, then the quantity (ΔR/R)σ goes to the saturation area.

Sensitivity to deformation of the sensory layer can be defined as (1):

$$GF = \frac{\left(\frac{\Delta R}{R}\right)_\sigma}{\Delta\varepsilon} \qquad (1)$$

where Δε is the deformation in the layer due to load within elasticity where $\Delta\varepsilon = \frac{\Delta\sigma}{E_f} E_f$ is the Young's modulus for the layer.

At a mechanical stress in the layer of 60 MPa (within the linear area) and the value of Young's modulus of 1.6×1012 Pa, the strain value is 370 ppm. In this case the *GF* value is 4.3 and may be of interest for practical application of such layers in developed elements of the straintronics.

5. CONCLUSIONS

Results of experimental studies of MS and MR properties of thin-film multilayer Ta-Co50Fe50-Ta, Ta-Co66Fe34-Ta, Ta-Co95Fe5-Ta nanostructures on oxidized silicon substrates for creation of hybrid MS and MR on their basis, elements of magnetic straintronics show that the most promising one for this purpose are Co50Fe50 films.

In samples of nanostructures annealed at 350°C, when applying a mechanical load, an increase in the value of the AMR effect for four times is observed, and coercive force of the magnetic layer is decreased by a factor of three. This is of great practical importance for improving technical characteristics of elements, in the first turn for reducing the upper limit of magnetic field which leads to an increase in sensitivity of the elements being developed.

Studies on optimization of required magnetic parameters of Co50Fe50 films should be continued on new magnetic nanostructures with a combination of MS GMR and TMR effects initially having a high MR effect in our GMR and TMR test nanostructures [25]. Based on results obtained, technological work will begin to develop test samples of membrane hybrid MS and MR elements of magnetic straintronics.

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