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Investigation of Magnetic Properties of Thin-Film Nanostructures of Elements of Magnetic Straintronics

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Abstract

The results of experimental studies of magnetostrictive, magnetoresistive properties and induction characteristics of thin-film Ta–$Co_{40}Fe_{40}B_{20}$–Ta, Ta–$Co_{95}Fe_5$–Ta and Ta–$Fe_{16}Ni_{64}Co_{20}$–Ta multilayer nanostructures on oxidized silicon substrates with a diameter of 100 mm are developed for creating elements of magnetic straintronics based on magnetostrictive and magnetoresistive effect. Research of ferromagnetic materials $Co_{40}Fe_{40}B_{20}$, $Fe_{16}Ni_{64}Co_{20}$, $Co_{95}Fe_5$ is due to their use in modern magnetoresistive devices, as well as the possibility of using these alloys in magnetic straintronics devices. Research of properties of thin ferromagnetic films was carried out in a specialized installation that allows to record changes in magnetic state of a ferromagnetic nanostructure under conditions of mechanical stress. The samples under test were subjected to a controlled mechanical stress which led to compressive deformation of the nanostructure on the silicone substrate, so the process is based on the effect of reverse magnetostriction (the Villari effect). The results of studies of magnetic properties of nanostructures based on $Co_{40}Fe_{40}B_{20}$, $Fe_{16}Ni_{64}Co_{20}$ and $Co_{95}Fe_5$ films suggest that it is possible to use the $Co_{40}Fe_{40}B_{20}$ alloy as a free layer in magnetic straintronics devices. These devices can be created in combination with magnetostrictive layers, both on the basis of spin-tunnel magnetoresistive transitions, and modified anisotropic and spin-valve magnetoresistive nanostructures. The prospects for the development of this work for designing of magnetic straintronics devices are described

Keywords: transport system, accident, algorithm, monitoring, situational management, traffic accident, road technology, sensors, criteria of effectiveness.

INTRODUCTION

Straintronics is one of new directions in nanoelectronics and attracts attention of researchers and developers of electronic systems to the possibility of hybridizing various physical effects in one device.This is the direction in which the connection between different physical phenomena is realized through mechanical deformation or mechanical stress, which makes it possible to implement a function in devices more effectively than in existing analogues. An actively developed area of this direction is magnetic straintronics which is based primarily on effects of direct and inverse magnetostriction (MS) in thin magnetic films, incl. in the composition of multilayer nanostructures. In [1], an overview of the current state of development of magnetic straintronics elements in the world is presented.

At present, the idea of hybridizing the MS effect and the magnetoresistive effect (MR) in one device, is of interest [1, 2]. For a number of MR elements, the MS is an undesirable phenomenon due to appearance of parasitic signals caused by stresses, strains and the like. In this connection, the choice of compositions, primarily ferromagnetic films, was carried out with the requirement of a minimum MS value.

Based on the new requirements for the material of the magnetic element of magnetic straintronics, it is necessary to combine a high MS rate and an increased anisotropic MR (AMR) effect (for AMR-based devices), or a high MS rate and the possibility of its implementation in GMR within based devices free layer.

At the first stage of works, authors studied magnetic properties of ferromagnetic materials widely used in modern MR devices: $Co_{40}Fe_{40}B_{20}$, $Fe_{16}Ni_{64}Co_{20}$, $Co_{95}Fe_5$ for determining the possibility of their use in developing magnetic straintronics devices.

EXPERIMENT

MS and MR properties and induction characteristics of Ta–$Co_{40}Fe_{40}B_{20}$–Ta, Ta–$Co_{95}Fe_5$–Ta and Ta–$Fe_{16}Ni_{64}Co_{20}$–Ta, thin-film multilayer nanostructures used in multicomponent thin-film MR nanostructures, were studied. Sputtering of layers was carried out by magnetron. 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.

Sputtering of all layers was carried out at a surrounding room temperature.

Sputtering of all layers was carried out at the MESA-200 equipment from Shb Instruments (USA) at a surrounding room temperature. Samples were subjected to a controlled mechanical stress, which led to compressive deformation of the nanostructure on the silicone substrate (Fig. 1).

Measurements of parameters of films were carried out along the EMA and the difficult magnetization axis (DMA) of ferromagnetic films, but, because the changes in their parameters along the EMA caused by the MS were negligible, only measurement results along the DMA of ferromagnetic films are given. In accordance with Fig. 1, the sample was set so that the mechanical stress was created along the EMA, and the magnetization curve was taken along the DMA.

On the basis of the inverse MS effect, the MS rate was estimated by the formula [3]:

$$\lambda = \frac{2CM_sH_s(1-v^2)}{3d_sE_f},$$

where E_f is the thin film Young's module, v is the Poisson's ratio of the ferromagnetic film material, M_s is saturation magnetization, C is the plate bending radius, H_s is the magnetic field of anisotropy, $d_s$is the substrate thickness.

RESULT AND DISCUSSION

The team of authors has extensive experience in development of designs and manufacturing technologies for thin-film MR magnetic field converters and devices based on them [4-7] based on multilayer nanostructures with CoFeB, CoFe and FeNiCo ferromagnetic films, what determines the study of their MS properties for the purpose of creating magnetic straintronics on their basis. First of all, it is of practical interest to measure mechanical stress, pressure, and other physical effects, and then convert this physical parameter by means of an MS into an electrical signal (usually a change in the voltage in hauls of the MR bridge circuit). In this case, ferromagnetic films used in AMR structures were designed to obtain the maximum value of the MR effect at the minimum MS which introduces a parasitic readout signal, incl. an increase in hysteresis.

At the first stage of the work, MS, MR, and induction properties of the multilayer nanostructures used were researched. The task set does not preclude the development at the next stage of work of fundamentally new compositions of MS and MR films.

Thin ferromagnetic films of different thicknesses were researches for three alloys: $Co_{40}Fe_{40}B_{20}$, $Fe_{16}Ni_{64}Co_{20}$ and $Co_{95}Fe_5$. The properties of ferromagnetic layers are presented in Table 1.The nanostructure on the oxidized silicon plate has the form as follows: Ta (5 nm)/FF/Ta (5 nm), where the FF is a ferromagnetic film.

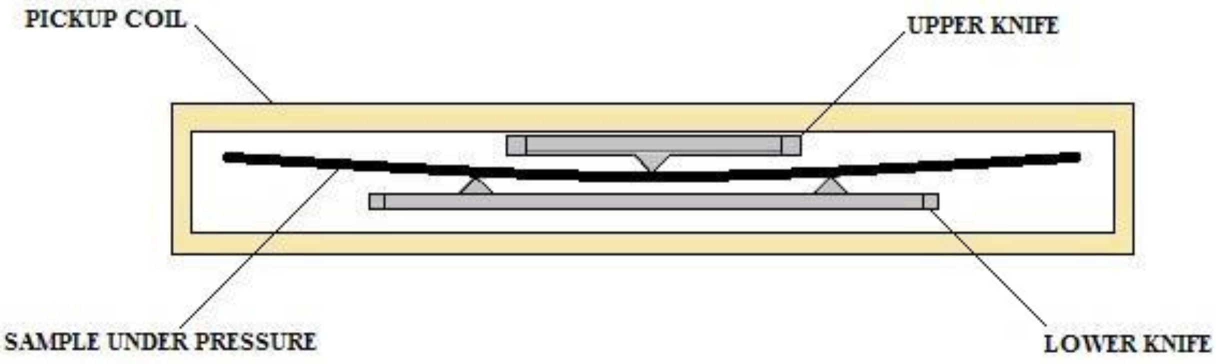

Figure 1: Schematic representation of the MS sample characteristics definition unit on the MESA-200 equipment.

Table 1: Properties of ferromagnetic materials [3, 8, 9].

No.	Layer structure	Substrate thickness d_s, μm	Young's Module E_f, HPa	Poisson's ratio v
1	$Co_{40}Fe_{40}B_{20}$	470 ± 10	174.1	0.325
2	$Fe_{16}Ni_{64}Co_{20}$	470 ± 10	180	0.310
3	$Co_{95}Fe_5$	470 ± 10	200	0.320

The results of measurements of the MS and MR effect, as well as induction characteristics of layers, are presented in Table 2.

Table 2: Measurement results.

No.	Structure	Film thickness d, Å	Magnetostrictive effect λ, ppm	Anisotropic magnetoresistive effect dR/R, %	Magnetic saturation Induction Bs, nVB
1	$Co_{40}Fe_{40}B_{20}$	70	-18.4	Less than 0.3	1.4
2		100	-16.7	Less than 0.3	1.7
3		120	-11.1	Less than 0.3	1.9
4	$Fe_{16}Ni_{64}Co_{20}$	70	0.22	1.9	1.2
5		100	0.27	1.8	1.6
6		120	0.82	2.4	2.2
7		200	0.9	2.76	3.4
8	$Co_{95}Fe_5$	70	-3.16	0.7	1.5
9		100	0.26	0.24	2.0
10		120	1.04	0.81	2.8
11		200	2.18	0.47	4.3

Magnetostrictive properties of nanostructures

As follows from Table 2, the largest value of the MS effect of the three investigated alloys has the $Co_{40}Fe_{40}B_{20}$ alloy. This alloy is used as a free or fixed magnetic layer in tunnel magnetic transitions with a spin-tunneling MR (STMR) effect [7, 10]. Figure 2 shows dependence of the MS ratio on the layer thickness of $Co_{40}Fe_{40}B_{20}$.

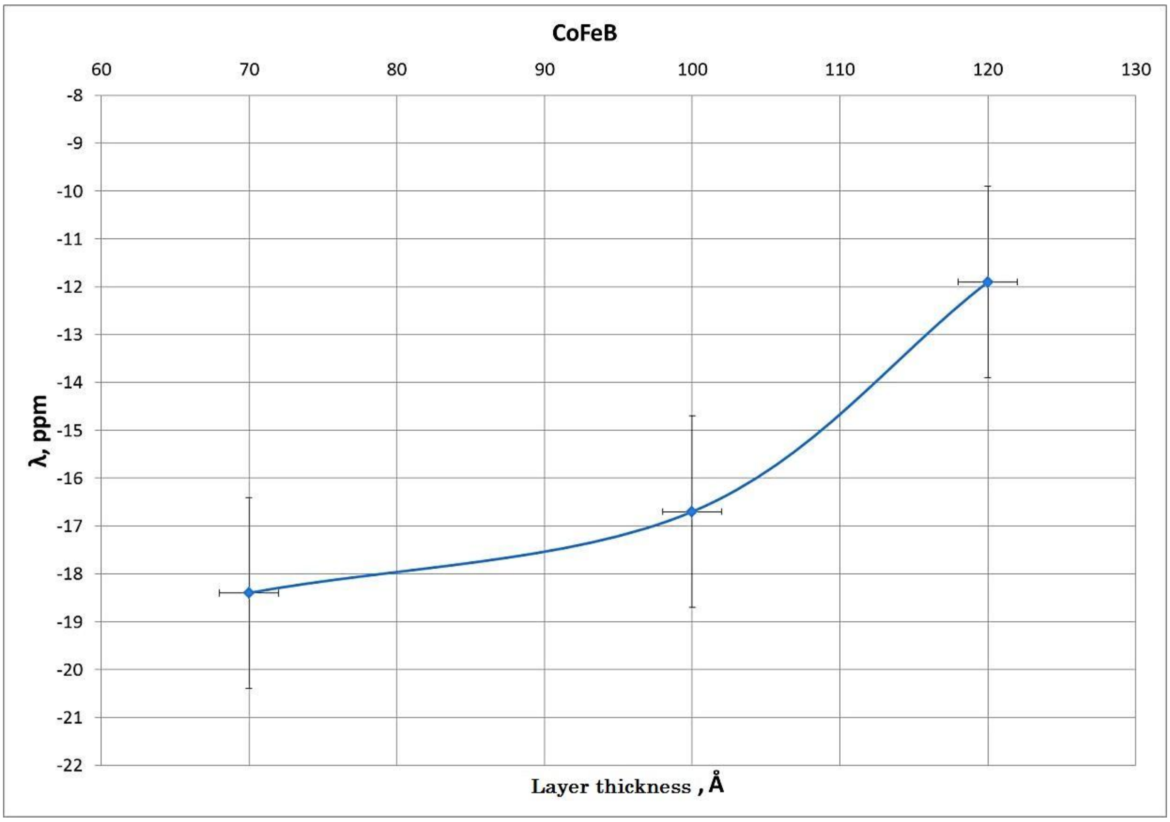

Figure 2: Dependence of the MS ratio on the layer thickness of $Co_{40}Fe_{40}B_{20}$.

The minimum value of the MS effect have $Fe_{16}Ni_{64}Co_{20}$ films developed taking into account the requirement of the minimum value of λ for AMR magnetic field converters [11, 12]. The change in the composition of these ferromagnetic films is expected to lead to an increase in MS. Ferromagnetic films $Co_{95}Fe_5$ change the sign of the MS with increasing film thickness (Fig. 3). These films in the MR nanostructure are auxiliary and do not determine the result in the part of MR properties.

At the same time, the results for Co_xFe_{1-x} films, which can be used as auxiliary films in MR nanostructures, are reported in [13], at annealing at T = 800 ° C for 1 hour revealed a giant MS up to 260 ppm in a magnetic field of 100 Oe. It was shown in Ref. [14] that annealing of films $Co_{68}Fe_{32}$ at T = 673 K increases their MS to 159 ppm. These results increase the interest in Co_xFe_{1-x} films regarding their research in the composition of MS devices.

Magnetoresistance properties of nanostructures

MR properties of a $Fe_{16}Ni_{64}Co_{20}$ film, which is widely used for use in AMR elements [5, 15], were researched (Fig. 4). With increasing thickness of a ferromagnetic film, a slight increase in the value of dR/R, characterizing the magnitude of the AMR effect, is observed reaching 2.75%. The value of the external magnetic field was ± 50 Oe. The dependence of the dR/R value of a $Co_{95}Fe_5$ ferromagnetic film is nonlinear. But, because of the small magnitude of the MR effect and the auxiliary role of the film itself, this is of no fundamental importance for obtaining the final result.

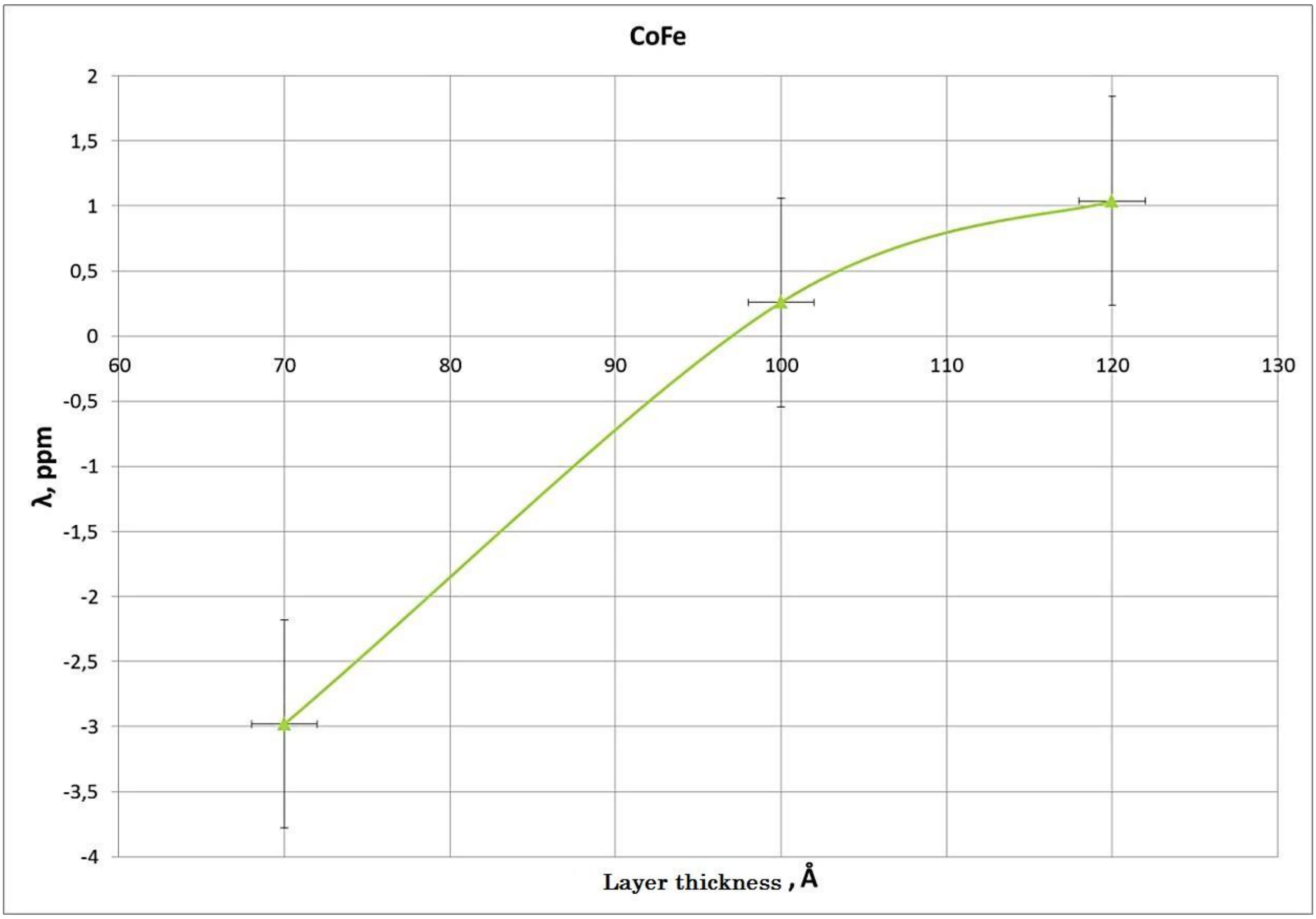

Figure 3: Dependence of the MS ratio on the layer thickness of $Co_{95}Fe_5$.

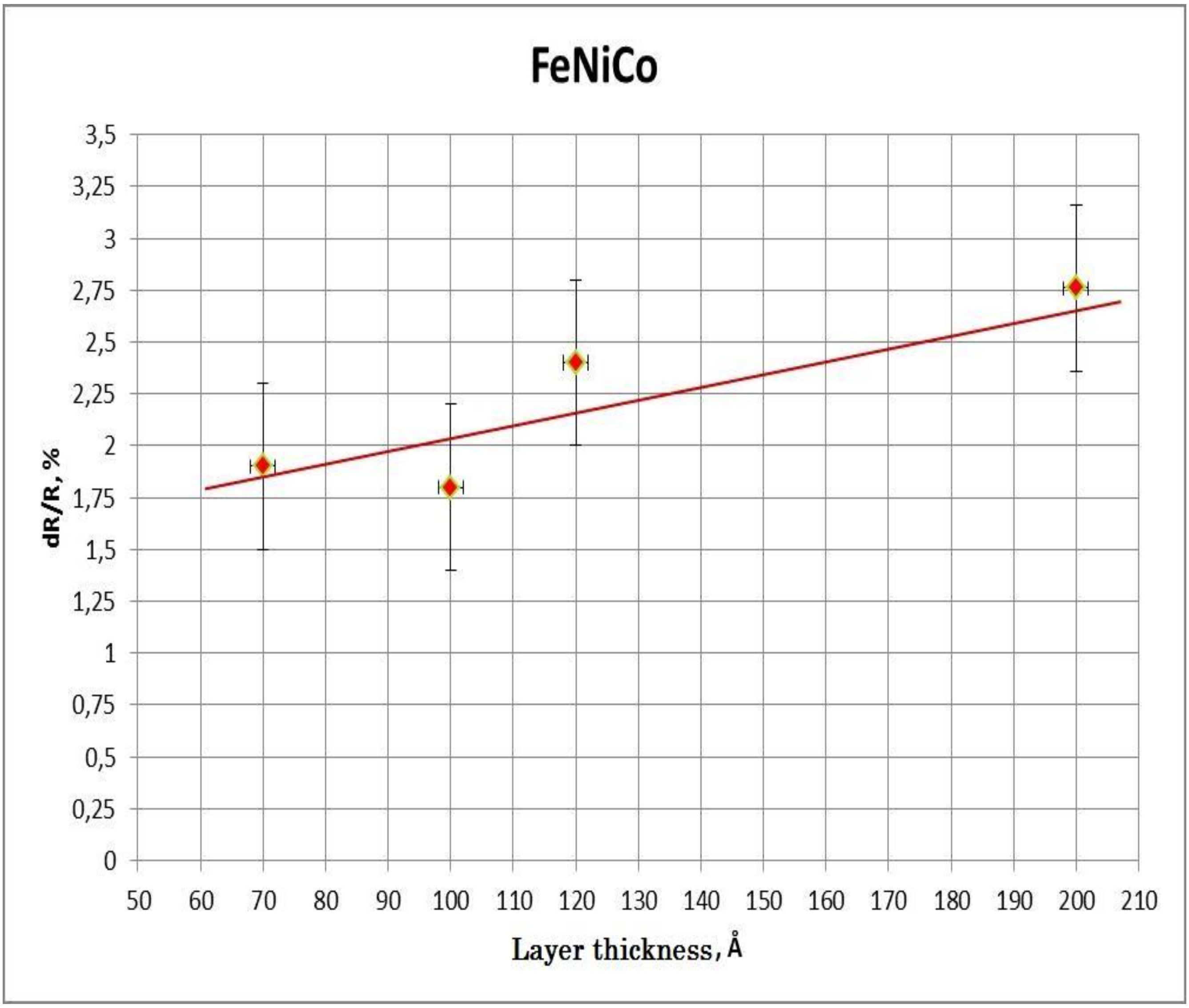

Figure 4: Dependence of the AMR effect on the thickness of the $Fe_{16}Ni_{64}Co_{20}$ layer.

Induction properties of nanostructures

A practical interest is behavior of ferromagnetic films without mechanical load applied to them, and with the mentioned load as well. Figure 5 shows magnetization reversal curves of a $Co_{40}Fe_{40}B_{20}$ ferromagnetic film with a thickness of 120 Å, the shape of which changes significantly when a mechanical load is applied to it. Thus, the magnetic state of the $Co_{40}Fe_{40}B_{20}$ alloy used as a free layer in the structure of the tunnel junction, can be sensitive to mechanical deformations. This confirms the presence of a significant MS and, consequently, significant changes in the magnetic state of a ferromagnetic film which should be reflected in the change in the magneto resistance of the spin-tunnel nanostructure and, ultimately, lead to appearance of an electrical signal in the created straintronics element. Magnetization reversal curves of $Fe_{16}Ni_{64}Co_{20}$ и $Co_{95}Fe_5$ films practically do not change when a mechanical load is applied to a film, which is explained by the significantly smaller value of MS in them compared with the $Co_{40}Fe_{40}B_{20}$ film. Figure 6 shows the reversal of the $Fe_{16}Ni_{64}Co_{20}$ film magnetization curves of a ferromagnetic film 120Å thick with and without mechanical load.

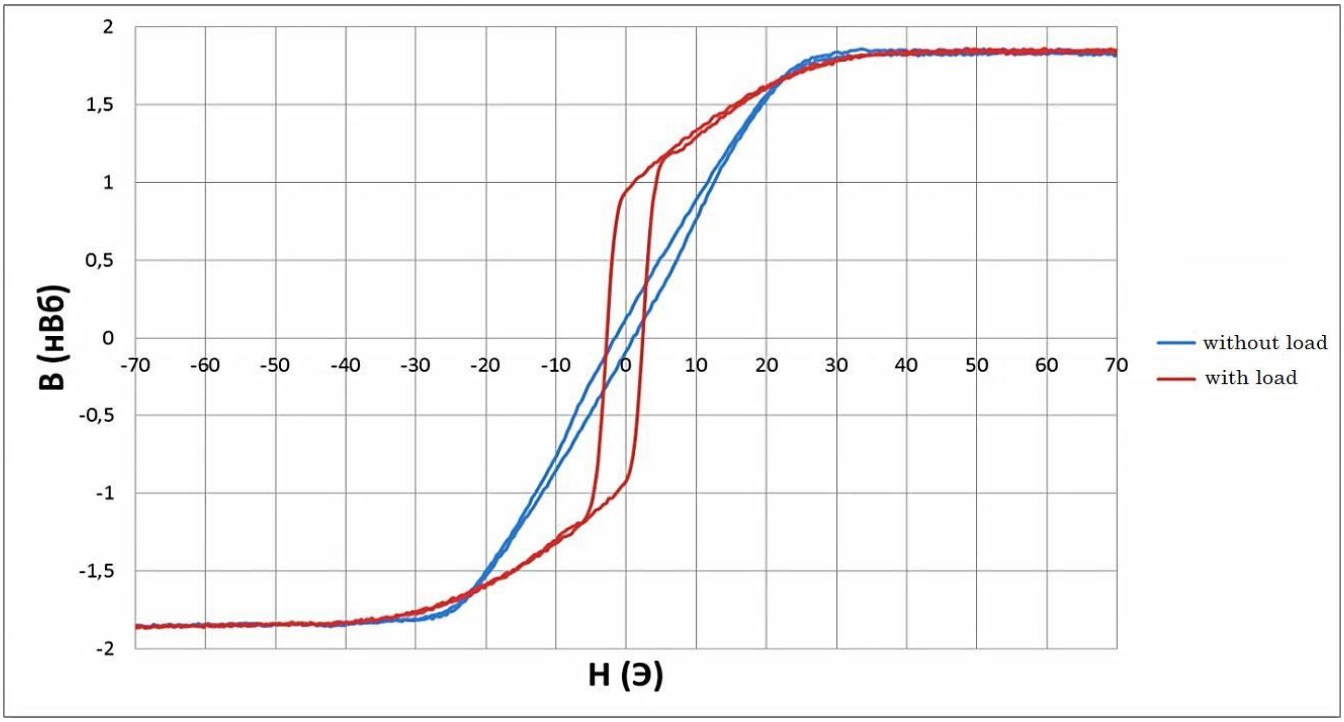

Figure 5: Magnetization reversal curves for the B (H) $Co_{40}Fe_{40}B_{20}$ film with a thickness of 120 Å.

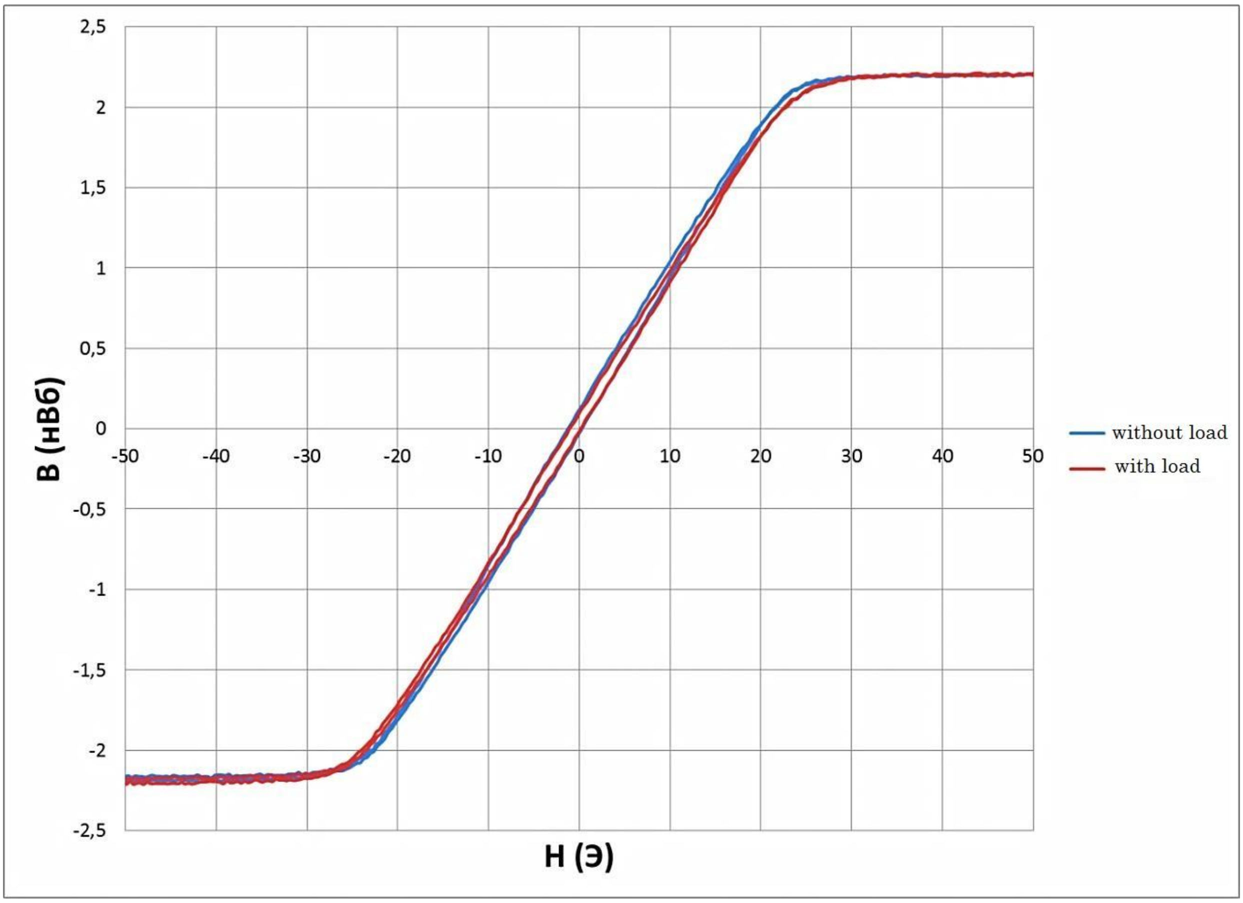

Figure 6: Magnetization reversal curves for the B (H) $Fe_{16}Ni_{64}Co_{20}$ film with a thickness of 120 Å.

CONCLUSION

Research of magnetic properties of $Co_{40}Fe_{40}B_{20}$, $Fe_{16}Ni_{64}Co_{20}$ and $Co_{95}Fe_{5}$ films allows us to conclude that the $Co_{40}F_{e40}B_{20}$ alloy can be used as a free layer in magnetic straintronics devices, both on the basis of spin-tunnel magnetoresistive transitions and modified anisotropic and spin-valve magnetoresistive magnetic field and current converters.

Layers of $Fe_{16}Ni_{64}Co_{20}$ and $Co_{95}Fe_{5}$ alloys do not have sufficient magnetostrictive properties for practical implementation of magnetic straintronics devices. For these alloys, and first of all, for $Fe_{16}Ni_{64}Co_{20}$ films, an additional investigation is required, related to the search for a new alloy composition with enhanced magnetostriction and the magnetoresistive effect acceptable for operation of magnetic straintronics element and optimization of technological process.

This work is one of the first stages in creation of combined elements of magnetic straintronics. The results obtained in it can contribute to development of devices with optimized magnetostrictive and magnetoresistive properties of magnetic nanostructures, both with modified ferromagnetic films on the basis of the compositions considered in this work and in principle new ones. Investigation of parameters of sputtered nanostructures was carried out with the help of the unique equipment of the Center for Functional Control and Diagnostics of Micro- and Nanosystem Hardware on the basis of the Technological Center SPC.

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