ELECTRICAL AND MAGNETIC PROPERTIES

Flexible Spin Valves: Interlayer Interaction and Deformation Sensitivity

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Received July 8, 2021; revised July 19, 2021; accepted July 22, 2021

Abstract—Exchange-coupled spin valves based on ferromagnetic alloys CoFeNi and antiferromagnetic alloy FeMn are obtained on flexible polyimide substrates by magnetron sputtering. The magnetoresistive properties of films and microstrips of spin valves are measured at various degrees of bending deformation of the sample. The behavior of the dependence of the deformation sensitivity of the spin valve on the interaction between the magnetic layers and on the arrangement of the anisotropy axes with respect to the deformation vector is characterized. It is found that the deformation sensitivity decreases with an increase in the interval between the fields of magnetization reversal of the free and fixed layers in the spin valve.

Keywords: spin valve, CoFeNi alloy, polymer substrate, magnetostriction, Villari effect, deformation, magnetic anisotropy

DOI: 10.1134/S0031918X21110090

INTRODUCTION

Levity, small thickness, adaptability to the measured surface, and impact resistance are advantages of nanostructures on polymer substrates. Flexible displays [1], magnetic sensors [2, 3], solar batteries, light emitting diodes [4–6], medical devices [7], film transistors [8], and micromotors [9] are manufactured on polymer substrates such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyimide (PI) [10]. Researchers are interested in both the retention and major changes of the functional characteristics upon deformation [11–13].

Magnetic materials exhibit magnetostriction; therefore, it is important to study the effect of the mechanical stimulus on the magnetic characteristics of films. In a nanostructure that is composed of two ferromagnetic (FM) layers separated by a nonmagnetic layer, the resistivity depends on the angle between the magnetic moments of the FM layers (giant magnetoresistance (GMR) effect). In addition to the sensitivity to the magnetic field, the direction of magnetization in the FM material is sensitive to the degree and direction of deformation due to the Villari effect (inverse magnetostrictive effect) [14]. The direction of the magnetic moment of the layer changes upon exposure to mechanical stresses, which leads to a change in the magnetoresistance.

The combination of magnetoelastic and GMR effects in nanostructures on polymer substrates is sup-

posed to be used in stress, strain, and pressure sensors [15–24].

Spin valves are multilayer nanostructures that exhibit a GMR effect [25]. In a spin valve, two FM layers are separated by a nonmagnetic one, with one of the layers fixed by exchange interaction with an adjacent layer of an antiferromagnetic alloy. As a result, unidirectional anisotropy is developed and the unidirectional anisotropy axis (UAA) is a preferred direction. The hysteresis loop of the magnetization reversal of the fixed layer is shifted to the region of high fields. The second (free) FM layer undergoes magnetization reversal in weak fields. Upon depositing the structure in a magnetic field, uniaxial anisotropy characterized by the easy axis of magnetization (EAM) is induced in this layer.

Binary NiFe and CoFe, and ternary CoFeNi alloys are used in the composition of FM layers capable of exhibiting the GMR effect of nanostructures [26–28]. According to the diagram of the Co–Fe–Ni ternary system [29, 30], the Co₇₀Fe₂₀Ni₁₀ alloy has saturation magnetostriction λ_s close to zero. By varying the percentage composition of the alloy, it is possible to obtain λ_s values that are substantially different from zero. For the Co₇₀Fe₁₀Ni₂₀ alloy, $\lambda_s = 1.5 \times 10^{-5}$.

A large number of publications are devoted to flexible spin valves and devices based on them; however, there are few studies in which the dependence of the magnetoelastic and magnetotransport properties on

the layer material and the features of the magnetic anisotropy of spin valves are investigated. In [31, 32], an increase in the deformation sensitivity of spin valves is investigated when using a free layer of magnetostrictive $\text{Fe}_{50}\text{Co}_{50}$ ($\lambda_s \approx 10^{-4}$) and FeGa alloys as a material. As was shown in [33, 34], the anisotropy in a spin valve can be enhanced or weakened, depending on the magnetostrictive properties of the ferromagnetic layers, by multiple bendings of the polymer substrate.

Combining the issues of flexible electronics and spintronics, this study was aimed at analyzing the correlation between the composition of a spin valve and the change in its magnetoresistive characteristics under bending deformation. Special attention was paid to studying the dependence of the magnetoresistive characteristics on deformation at different mutual positions of the anisotropy axes and the deformation vector. Alloys $\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}$ and $\text{Co}_{70}\text{Fe}_{20}\text{Ni}_{10}$ with nonzero and near-zero magnetostriction were used as materials for the spin valve FM layers.

EXPERIMENTAL

A polyimide (PI) film with a thickness of $t_s = 60 \mu\text{m}$ was glued to a glass substrate, on the surface of which spin valve nanostructures were grown by magnetron sputtering. After sputtering, the PI film was separated from the glass. The spin valves had the following composition: buffer layer/FM1/Cu/FM2/ $\text{Fe}_{50}\text{Mn}_{50}$ /Ta, where FM stands for the ferromagnetic layers of $\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}$ and $\text{Co}_{70}\text{Fe}_{20}\text{Ni}_{10}$ alloys. The buffer layer is a $[\text{Ta}/(\text{Ni}_{80}\text{Fe}_{20})_{60}\text{Cr}_{40}]_n$ nanostructure. A thick buffer layer ($n = 2, 5$, and 7) was used to level the substrate surface. Owing to the high electrical resistivity ($\rho = 217 \mu\Omega \text{cm}$), the shunting of the current was negligible. The ρ value was measured on the $[\text{Ta}(5)/\text{NiFeCr}(5)]_5$ sample prepared on a glass substrate.

The surface roughness of PI substrates was estimated using an optical profilometer. The measurements were carried out for a larger (Fig. 1a) and a smaller (Fig. 1b) surface area. When examining an area of $0.35 \times 0.26 \text{ mm}^2$, the standard deviation (rms) was $129 \text{ \AA}$. With a decrease in the area under study to $0.18 \times 0.13 \text{ mm}^2$, the surface roughness decreased to $rms = 15 \text{ \AA}$.

It can be assumed that the high roughness of the surface of the flexible substrate would have a lesser effect on the integrity of the layers and the magnetoresistive characteristics of the multilayer structure in the case of microscopic objects.

Microstrips with a length of 9 mm and widths $h = 20, 40, 60, 80$, and $100 \mu\text{m}$ were fabricated by optical lithography. Upon the formation of microentities, both parallel and perpendicular orientations of the EAM with respect to the microstrip length were realized. The resistivity was measured at room temperature by a four-contact method with a direct current

Fig. 1. Image of the surface and the roughness of the PI substrate for different areas of the investigated surface.

flow in the film plane. The magnetoresistance was determined as $\Delta R/R_s = [(R(H) - R_s)/R_s]$, where $R(H)$ is the resistance of the sample in a magnetic field, and R_s is the resistance in the saturation field. Samples with dimensions of $2 \times 10 \text{ mm}^2$ and microscopic objects were examined.

The field dependences of the magnetoresistance were obtained on a setup based on a Bruker electromagnet. The samples under study were placed in a special holder between the pole tips of the magnet. The diameter of the pole tips was 8 cm , and the distance between them was 4 cm , so the flexible spin valves were completely located in the region with a uniform magnetic field in both the deformed and undeformed states. The samples were fixed with glue on a holder composed of a plastic corner and a non-magnetic screw and nut (Fig. 2). One edge of the sample was fixed, the other edge moved translationally together with the nut when rotating the screw. The sample bending was controlled by the number of turns of the screw (N).

Figure 2 shows a scheme of a nanostructured film with a thickness t_f on a polymer substrate in a state of bending deformation of the substrate, and stretching deformation of the nanostructured film. It is important that $t_f \ll t_s$; therefore, it can be assumed that the deformation of the film is uniform over the volume and is reduced to linear tension or compression if the film is on the lower side of the polymer substrate. The direction of displacement of points of the body under

Fig. 2. Photograph of a holder with a sample and a schematic representation of a nanostructured film with a thickness t_f on a polymer substrate with a thickness t_s (r is the radius of curvature of the curved substrate surface, $\mathbf{u}$ is the deformation vector, and l_0 and l are the lengths of the sample in the undeformed and deformed states, respectively).

deformation is indicated by deformation vector $\mathbf{u}$. The radius of curvature of the substrate surface (r) and the relative elongation of the nanostructured film $\varepsilon = (l - l_0)/l_0$, where l_0 and l are the lengths of the sample in the undeformed and deformed states, respectively) were used as quantities that characterize the degree of deformation. The relative elongation is related to the radius of curvature of bending by the following relation:

$$\varepsilon = (t_f + t_s)/2r. \quad (1)$$

Curvature radius r is found by solving the following equation:

$$l_0 = 2r \arcsin(l_0 - Nd/2r), \quad (2)$$

where N is the number of revolutions of the screw and d is the thread pitch.

The sensitivity S of the magnetoresistance to deformation was calculated as the ratio of the difference between the maximum magnetoresistance values in the undeformed and deformed states to the magnetoresistance value in the deformed state: $S = [(R_{\max}(l_0) - R_{\max}(l))/R_{\max}(l)]$.

Table 1. Arrangement of FM alloys in the layers of the spin valve

Sample no.	Free layer	Fixed layer
1	Co₇₀Fe₁₀Ni₂₀	Co ₇₀ Fe ₂₀ Ni ₁₀
2	Co ₇₀ Fe ₂₀ Ni ₁₀	Co₇₀Fe₁₀Ni₂₀
3	Co ₇₀ Fe ₂₀ Ni ₁₀	Co ₇₀ Fe ₂₀ Ni ₁₀
4	Co₇₀Fe₁₀Ni₂₀	Co₇₀Fe₁₀Ni₂₀

RESULTS AND DISCUSSION

Magnetoelastic and Magnetotransport Properties of Spin Valves with Co₇₀Fe₁₀Ni₂₀ Alloy Layers

We introduced a layer of an FM alloy with a non-zero magnetostriction (Co₇₀Fe₁₀Ni₂₀) into the spin valve. The objective of this stage of research was to obtain spin valves that combine a large magnetoresistance value, a weak hysteresis of the magnetization reversal of the free layer, and a noticeable change in the magnetoresistive characteristics upon deformation. The [Ta(5 nm)/NiFeCr(5 nm)]₂/CoFeNi(5.5 nm)/Cu(3.6 nm)/CoFeNi(3.5 nm)/FeMn(15 nm)/Ta(6 nm) spin valves have different combinations of arrangement of the Co₇₀Fe₁₀Ni₂₀ and Co₇₀Fe₂₀Ni₁₀ alloys in FM layers (see Table 1).

The field dependences of the magnetoresistance (Fig. 3) were measured in the undeformed state and under deformations corresponding to tension ($\varepsilon > 0$) and compression ($\varepsilon < 0$) at $\mathbf{u} \parallel \text{UAA} \parallel \text{EAM} \parallel \mathbf{H}$ and $r = 12$ mm. For this geometry, sample bending leads to a change in the projection of field $\mathbf{H}$ onto the film plane. In different parts of the spin valve, the antiparallel ordering of the magnetic FM layers is accomplished at different values of the applied field, which decreases the maximum magnetoresistance upon deformation.

For all the samples under study, the magnetoresistance decreases upon deformation; moreover, the decrease at $\varepsilon < 0$ (Figs. 3c and 3f) is more noticeable than the decrease at $\varepsilon > 0$ (Figs. 3b and 3e). There are two factors that lead to a change in the magnetoresistance. The first factor is associated with the magnetoelastic anisotropy, and the second factor is associated with the aforementioned change in the projection of $\mathbf{H}$ onto the film plane. The second factor leads to a decrease in the magnetoresistance both for $\varepsilon < 0$ and $\varepsilon > 0$. Therefore, the differences in the behavior of the magnetoresistance for $\varepsilon < 0$ and $\varepsilon > 0$ are associated with the fact that magnetoelastic anisotropy is combined in different ways with the uniaxial and unidirectional anisotropies. Probably, local magnetic moments at $\varepsilon > 0$ are aligned with the EAM and UAA in the free, fixed, and antiferromagnetic layers. This promotes the antiferromagnetic ordering of the magnetic moments of the FM layers and an increase in the magnetoresistance. Thus, the factors of (1) changes in the projection of $\mathbf{H}$ on the film plane and (2) magnetoelastic anisotropy compete upon tensile deformation. At $\varepsilon < 0$, the misorientation of the local magnetic moments with respect to the EAM and UAA increases, which leads to a decrease in the magnetoresistance.

Let us analyze changes in the shape of the magnetoresistive curve, which occur upon deformation of spin valves with different combinations of alloys in the FM layers. If the free layer contains the Co₇₀Fe₁₀Ni₂₀ alloy, then the slope of the low-field loop decreases and its width increases both for $\varepsilon > 0$ and $\varepsilon < 0$. This is possible to explain by a change in the domain structure

Fig. 3. Field dependences of the magnetoresistance of spin valves (a, d) in undeformed state and under bending deformations of a nanostructured film with (b, e) $\epsilon > 0$ and (c, f) $\epsilon < 0$.

and the mechanism of magnetization reversal of the layer, in particular, the transition from coherent rotation of magnetization to displacement of domain walls.

For spin valves with the $\text{Co}_{70}\text{Fe}_{20}\text{Ni}_{10}$ alloy in the free layer, the low-field hysteresis loop is much narrower and the maximum magnetoresistance is higher. The slope of the low-field loop increases upon deformation, which is indicative of the predominance of mechanisms of coherent rotation of magnetization and the absence of additional partitioning into domains. The smallest change in the magnetoresistance effect upon deformation is exhibited by sample no. 3, in which both FM layers are represented by the alloy with zero magnetostriction.

The highest magnetoresistance, the narrowest low-field hysteresis loop, and the largest change in the magnetoresistance upon deformation were obtained for sample no. 2. For further experiments, spin valve composition no. 2 with the $\text{Co}_{70}\text{Fe}_{20}\text{Ni}_{10}$ alloy in the free layer and the $\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}$ alloy in the fixed layer was selected.

Magnetoelastic Properties of Spin Valves with Different Interlayer Interactions

The interaction of FM layers in a spin valve is characterized by the shift of the middle of the low-field hysteresis loop (H_j) of the free layer. This interaction is the result of the competition between the ferromagnetic dipole interaction depending on the interface

roughness and the indirect exchange interaction, which periodically changes with a change in the copper layer thickness (t_{Cu}) [25]. The surface roughness of the polymer substrate and, consequently, of the interlayer boundaries is large; therefore, dipole interaction prevails. Its energy decreases exponentially with an increase of t_{Cu} .

The exchange interaction in the interface between the fixed and antiferromagnetic layers leads to the appearance of an effective field acting on the magnetic moment of the fixed layer. This interaction is characterized by the shift field (H_{ex}) and determined from the position of the middle of the magnetization reversal loop of the fixed layer. In the range of $H_j < H < H_{\text{ex}}$, antiparallel ordering of the magnetic moments of the FM layers is implemented, so the magnetoresistance has a maximum value.

Changes in the thickness of the FM layers and of the copper layer have an effect on the maximum magnetoresistance and shift fields H_j and H_{ex} . The H_{ex} value increases with a decrease in the thickness of the fixed layer (t_{pin}). A decrease of t_{Cu} leads to an increase of H_j .

In spin valves of composition $[\text{Ta}(5 \text{ nm})/\text{NiFeCr}(5 \text{ nm})]_2/\text{Co}_{70}\text{Fe}_{20}\text{Ni}_{10}(5.5 \text{ nm})/\text{Cu}(t_{\text{Cu}})/\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}(t_{\text{pin}})/\text{FeMn}(15 \text{ nm})/\text{Ta}(6 \text{ nm})$ with $t_{\text{Cu}} = 2.6 - 4 \text{ nm}$ and $t_{\text{pin}} = 2.5 - 4 \text{ nm}$, thickness variation is aimed at obtaining different H_j and H_{ex} values. The field dependences of the magnetoresistance were

Fig. 4. Dependences of the sensitivity of magnetoresistance to deformation on the value of field interval $H_{\text{ex}} - H_j$ upon bending deformations corresponding to (a) compression and (b) tension of the nanostructured film.

measured for samples in the undeformed state and for $\varepsilon > 0$ and $\varepsilon < 0$ ($r = 12$ mm).

Figure 4 shows the dependences of S on the value of the $H_{\text{ex}} - H_j$ interval, which characterizes the size of the plateau region on the magnetoresistive curve. In fields that are in the range of $H_j < H < H_{\text{ex}}$, the magnetoresistance has a maximum value and the mutual arrangement of the magnetic moments of the FM layers is close to the antiparallel arrangement. A decrease in the width of the $H_{\text{ex}} - H_j$ plateau leads to an increase in the sensitivity S . This tendency is associated with the fact that the projection of the applied field onto the film plane changes upon bending, as noted above. Hence, the narrower the range of fields in which the magnetic moments of the FM layers are antiparallel, the more substantial the decrease in the magnetoresistance upon bending.

Fig. 5. Field dependences of the magnetoresistance of a microstrip with a width of 100 μm prior to deformation (dark triangles), in the state of deformation with $\varepsilon > 0$ (solid and dashed lines), and after relaxing to the undeformed state (light circles).

The sensitivity of the magnetoresistance of spin valves to deformation at $\varepsilon < 0$ is higher than at $\varepsilon > 0$. The following probable explanation can be given. If $\mathbf{u} \parallel \text{EAM} \parallel \text{UAA}$, then the magnetoelastic anisotropy promotes disordering at $\varepsilon < 0$ and the alignment of local moments with respect to UAA and EAM at $\varepsilon > 0$.

Despite the clearly pronounced tendency of changes, the $S(H_{\text{ex}} - H_j)$ dependences have a rather large scatter of the experimental points. This is due to the fact that measurements were carried out on samples with millimeter sizes. The large roughness of the PI substrate leads to a difference in the magnetoresistive characteristics of the spin valve in different regions of the film. For micrometer-sized objects, this difference is much smaller.

Dependence of Magnetoresistive Characteristics of Spin Valve Microstrips on Deformation

From spin valve films of $[\text{Ta}(5 \text{ nm})/\text{NiFeCr}(5 \text{ nm})]_n/\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}(5.5 \text{ nm})/\text{Cu}(2.6 \text{ nm})/\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}(4 \text{ nm})/\text{FeMn}(15 \text{ nm})/\text{Ta}(6 \text{ nm})$, where $n = 5$ and 7, microscopic objects were made. Figure 5 shows the field dependences of the electrical resistivity of a microstrip with a width of 100 μm prior to deformation, in the deformed state ($r = 7.5$ and 5.3 mm, $\mathbf{u} \parallel \text{EAM} \parallel \text{UAA}$), and after relaxing to the undeformed state. In the state of magnetic saturation, the resistivity of a microobject practically does not change upon deformation. It can be assumed that changes in the resistivity upon deformation in the range of fields corresponding to the plateau in the $R(H)$ dependence are primarily caused by a change in the magnetic state of the nanostructure. It should be noted that the $R(H)$ dependences measured prior to deformation and after relaxing to the undeformed state coincide. Thus, the deformation is reversible in the investigated range.

Fig. 6. Dependences of the maximum magnetoresistance and shift fields of high-field and low-field hysteresis loops on the inverse radius of bending of microstrips with a width h . The light and dark symbols show data for spin valves with five and seven recurrences ($n = 5$ and 7) of Ta/NiFeCr in the buffer layer.

For microstrips with different widths, the field dependences of the magnetoresistance were measured with a stepwise increase in the tensile deformation by decreasing r at $\mathbf{u} \parallel \text{EAM} \parallel \text{UAA}$. After relaxing the sample to the undeformed state, the magnetoresistive characteristics of the spin valve coincided with those measured prior to deformation. The dependences of H_j , H_{ex} , and the maximum magnetoresistance on the inverse curvature radius $1/r$ are shown in Fig. 6. With an increasing in the degree of deformation, the magnetoresistance decreases and shift fields H_j and H_{ex} increase. The behavior of the dependencies does not change with a change in the width of the microstrips.

For the spin valve with the thicker buffer layer ($n = 7$), lower magnetoresistance values were obtained because of the greater current shunting. An increase in the thickness of the buffer layer causes smoothing the surface of the PI substrate, which leads to increases in the exchange interaction at the $\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}/\text{FeMn}$ interface and in the H_{ex} value. On the other hand, the leveling of the substrate surface decreases the roughness of the interlayer boundaries, so the energy of the dipole interlayer interaction decreases and field strengths H_j are lower for the sample with $n = 7$. Thus, the plateau on the magnetoresistive curve is broader and the sensitivity S is lower for the samples with a thicker buffer layer. Actually, the slope of the $\Delta R/R_s(1/r)$ dependence is smaller for $n = 7$.

Deformation Sensitivity of Spin Valve at Different Mutual Arrangement of the Deformation Vector and Anisotropy Axes

The results shown in the previous section were obtained for $\mathbf{u} \parallel \text{UAA} \parallel \text{EAM} \parallel \mathbf{H}$ (Fig. 7a). Let us analyze how the spin valve characteristics change with a different mutual arrangement of these directions.

The field dependences of the magnetoresistance of microstrips with a width of $60 \mu\text{m}$ for the $[\text{Ta}(5 \text{ nm})/\text{NiFeCr}(5 \text{ nm})]_7/\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}(5.5 \text{ nm})/\text{Cu}(2.6 \text{ nm})/\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}(4 \text{ nm})/\text{FeMn}(15 \text{ nm})/\text{Ta}(6 \text{ nm})$ spin valve were measured at a deformation of $\varepsilon > 0$ and different orientations of $\mathbf{u}$ with respect to the magnetic anisotropy axes (Fig. 7). The perpendicular mutual

Fig. 7. Schematic representation of the relative arrangement of the axes of spin valve magnetic anisotropy, and deformations ε with respect to the microstrip axis for (a) $\mathbf{u} \parallel (\text{EAM} \parallel \text{UAA})$, (b) $\mathbf{u} \perp (\text{EAM} \parallel \text{UAA})$, and (c) $\mathbf{u} \parallel \text{EAM}$ and $\varepsilon \perp \text{UAA}$.

Fig. 8. Dependences of the maximum magnetoresistance and shift fields of the low-field and high-field hysteresis loops on the inverse bending radius for a microstrip of a spin valve at different mutual arrangements of the anisotropy axes and the deformation vector.

arrangement of the EAM and UAA (Fig. 7c) was accomplished using thermomagnetic processing of the microobject. In the measurements, $\mathbf{H} \parallel \text{UAA}$. Upon bending the strip, the projection of $\mathbf{H}$ onto the film plane changes only in the case shown in Fig. 7a. Figure 8 shows the obtained dependences of the spin valve characteristics on $1/r$.

With $\mathbf{u} \parallel$ (EAM $\parallel$ UAA), the nature of the change in the spin valve characteristics is similar to that considered in the previous paragraph.

For samples with $\mathbf{u} \perp \text{UAA}$ (Figs. 7b and 7c), H_{ex} decreases with an increase in the degree of deformation. Magnetoelastic energy is described by the following expression:

$$E_a = \frac{3}{2} \lambda_s \sigma \sin^2 \Theta, \quad (3)$$

where λ_s is the saturation magnetostriction, and Θ is the angle between the axis of application of mechanical stress σ and magnetization. Energy E has a minimum value at $\Theta = 0$. Thus, the magnetoelastic interaction at $\mathbf{u} \perp \text{UAA}$ leads to the deviation of local magnetic moments from UAA at the ferromagnet/antiferromagnet interface and to a decrease in the exchange interaction energy. It should be noted that the H_{ex} field increases with an increase in the tensile deformation in the case of $\mathbf{u} \parallel \text{UAA}$ (Figs. 6 and 8).

The free layer of the spin valve is an alloy with zero magnetostriction; nevertheless, deformation causes noticeable changes in the shift (H_j) of the magnetization reversal loop of this layer. With an increase of ϵ , the H_j field increases with $\mathbf{u} \parallel \text{EAM}$ and decreases with $\mathbf{u} \perp \text{EAM}$. These changes in the field of interlayer interaction are probably caused by the corresponding tendencies of ordering and disordering of local magnetic moments in the fixed layer.

With the perpendicular mutual arrangement of the deformation vector and one or both anisotropy axes, the maximum magnetoresistance barely change upon deformation of the sample (Fig. 8). An insignificant tendency to a decrease in the $(\Delta R/R_s)_{\max}$ for $\mathbf{u} \parallel \text{EAM}$ and $\mathbf{u} \perp \text{UAA}$ can be explained by the nature of changes in the shift fields of the high-field and low-field hysteresis loops. In this case, H_j and H_{ex} change so that the plateau region on the magnetoresistive curve decreases.

CONCLUSIONS

It is shown that the use of five to seven recurrences of the [Ta(5 nm)/NiFeCr(5 nm)] composition in the buffer layer can effectively reduce the effect of the roughness of the polymer substrate on the magnetoresistance and the nature of the interlayer interaction in the spin valve. With a large thickness, such a buffer layer has a weak current shunting effect, because of the high electrical resistivity value (217 $\mu\Omega$ cm).

The presence of the alloy with nonzero magnetostriction ($\text{Co}_{70}\text{Fe}_{10}\text{Ni}_{20}$) in the free layer of the spin valve leads to a change in the magnetization reversal mode of this layer upon bending of the sample. It is shown that a spin valve with a low-friction alloy in the free layer and an alloy with nonzero magnetostriction in the fixed ferromagnetic layer exhibit a high magnetoresistance, a weak hysteresis of the magnetization

reversal of the free layer, and a high sensitivity of the magnetoresistance to bending deformation.

It was found that the sensitivity of the spin valve magnetoresistance to bending deformation decreases with an increase in the field interval between the magnetization reversals of the free and fixed layers. This dependence can be used for selecting a spin valve composition that is optimal for obtaining high or low deformation sensitivity of the nanostructure.

When bending the spin valve with a low-strictional alloy in the free layer and an alloy with non-zero magnetostriction in the fixed layer, the magnetoresistance decreases if the deformation vector is parallel to the unidirectional anisotropy axis and does not change if it is perpendicular to the unidirectional anisotropy axis.

FUNDING

This study was performed within the framework of State Assignment from the Ministry of Education and Science of Russia (topic Spin, no. AAAA-A18-118020290104-2) and partially supported by the Russian Foundation for Basic Research (project no. 20-42-660018 r_a). The nanostructures were studied at Center for Collective Use Testing Center for Nanotechnologies and Advanced Materials at the Institute of Physics and Technology, Ural Branch, Russian Academy of Sciences.

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Translated by O. Kadkin