Modeling of Spin Valves of Magnetoresistive Fast-Acting Memory

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In this paper, an analysis is made of the physical processes that occur in the spinvalve structures during the recording or reading of bits in high-speed magnetic memory devices using the phenomenon of moment transfer by spin-polarized current. Mathematical models of the phenomenon of magnetic resistance for magnetite / non-magnetic metal / magnet structures and phenomena that occur when the free layer is reversed under the influence of a spin-polarized current are presented. The analysis of the effect on the magnetoresistive effect of the spin-valve structure of the ratio of the thickness of the free and fixed layers are provided. The effect on the magnetoresistive effect in the spin-valve structure of the ratio of the thickness of ferromagnetic layers with small and large coercive forces (free and fixed layer) is investigated. It is shown that for high values of the polarization coefficient, the increase in the thickness of the fixed layer results in an undesired decrease in the magnetoresistive effect.

Keywords: MRAM, Spin-valve structure, Spin polarized current.

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1. INTRODUCTION

Research in the field of the theory of magnets has led to the further development of magnetic memory elements. It is known that information recording systems based on devices whose basis is a controlled change in magnetization of ferromagnets became the most widespread in the 60's of the last century. The development of ideas about the magnetic properties of substances and spin has led to the discovery of phenomena such as anomal magnetic conductivity, giant magnetoresistive effect and tunneling magnetic resistance. These phenomena formed the basis of fundamentally new methods for reading information from magnetic media.

Further studies associated with various mechanisms of reversal have led to the invention of new physical mechanisms for recording information related to the electron spin. These phenomena formed the basis of a new important branch of science - the spintronics, which studies spin-polarized transport in solid-state structures. In such structures energy or information is transferred not by electric current, but by spin current.

It is quite obvious that the change in the direction of magnetization will occur much faster than the displacement of an electron in a relatively weak electric field in the classical structures of modern semiconductor electronics.

The fundamental difference between the magnetic memory of traditional types of CMOS (SRAM and DRAM) is its energy independence, with its speed approaching and physically can even exceed the speed of traditional RAM [1]. The prospect of the use of spin-valve structures in computer architectures is due to the ability to integrate the processes of recording, storing and logic processing of digital information. This essentially distinguishes it from other traditional computer architectures, where the processor and RAM are separated from each other. Thus, the loss of productivity of the entire computing system that occurs at the stage of reading and writing from a permanent storage device into the memory device, as well as processes for reading and writing from memory in the registry or cache memory can be eliminated.

Some comparative characteristics of various types of high-speed memory produced by modern electronics manufacturers are given in Table 1 [2]. The first and second columns of the table give the characteristics of the memory of the classical semiconductor technology (so-called capacitor memory), while the third and fourth columns show the characteristics of magnetic memory devices. The abbreviation MRAM refers to the magnetic RAM that uses the magnetic field of the modulated current pulses to record information, and STT-MRAM means the devices that uses spin transport phenomena to record.

Table 1 – Comparative characteristics of different types of high-speed memory

Characteristics \ Types of memory	SRAM	DRAM	MRAM	STT-MRAM
Energy independence	No	No	Yes	Yes
Cell area	50…120	6…10	16…40	6…20
Reading time, ns	1…100	30	3…20	2…20
Recording / deleting, ns	1…100	15	3…20	2…20
The most significant energy losses	Leakage current	Regeneration of memory	No	No

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The work of the vast majority of spintronic devices is based on the phenomena that occur when the current passes through the surface of the separation of two ferromagnetic metals. In Fig. 1 shows the splitting of the energy levels of electrons in the magnetic field of ferromagnets 1 and 2 for parallel (Fig. 1a) and antiparallel (Fig. 1b) alignment. The arrows reflect the transitions of electrons between the energy levels of ferromagnets 1 and 2. The arrows reflect the transitions of electrons between the energy levels of ferromagnets 1 and 2, provided that their spin remains constant. In this case, there are two opposite phenomena: spin injection into ferromagnet 2 and spin accumulation in ferromagnet 1.

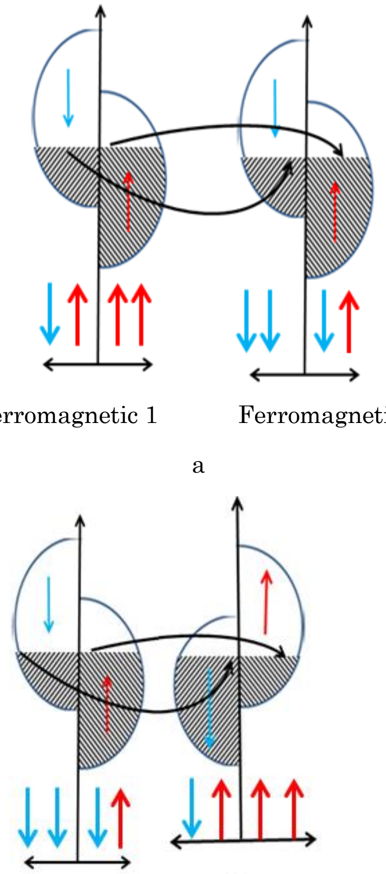

Fig. 1 – The splitting of energy levels for electrons with different spins on the surface of the separation of magnetic materials near Fermi surfaces and processes that occur: spin injection (ferromagnet 2) and spin accumulation (ferromagnet 1) for parallel and antiparallel alignment a) and b) respectively

In order to prevent the exchange interaction of the magnetic fields of ferromagnets, an intermediate layer of non-magnetic metal is used (Fig. 2).

The main element of the devices that use the transmission of a magnetic moment by a method of electrons polarized by a spin is the spin-valve structure shown in Fig. 2.

Depending on the direction of movement of free electrons in devices using the above mechanism for recording information bits, there are various physical phenomena. If electrons move in a direction from a layer with fixed magnetization to a free layer, then processes will occur in the following sequence: the polarization of the spin of electrons flowing in the fixed layer (4), the injection of spin-polarized electrons from the fixed ferromagnetic layer (4) into a nonmagnetic metal (3) and the interaction of a spin-polarized current with a free layer (5). If at the same time in the fixed and free layer, the magnetization vectors have the same direction, then the free layer will change the direction of its magnetization to the opposite.

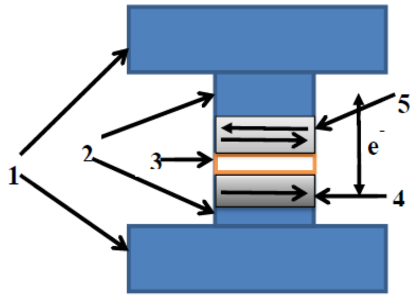

Fig. 2 – Spin-valve structure with a mechanism for transferring a magnetic moment by polarized spin current: 1, 2 – contacts from a nonmagnetic material, 3 – a layer of nonmagnetic metal separating ferromagnets, 4 is a ferromagnet with a large coercive force (in the further - a fixed layer or magnetically rigid ferromagnet), 5 is a ferromagnet with a small coercive force (later - a free layer or a magnetically soft ferromagnet)

In the case of moving electrons in the opposite direction (from a magnetically soft material to a layer with a higher coercive force), provided that the directions of magnetization of the layers are the same, the following processes occur: the polarization of the spin of electrons in the direction of the magnetization of the free layer (5), the reflection of the electrons with the spin polarized in the opposite direction to the magnetization of the fixed layer (4) in the nonmagnetic material (3), the accumulation of the electrons with the spin in the direction of the magnetization of the fixed layer (4) the separation of the free layer (5) and the non-magnetic metal (3) and the change in the direction of magnetization of the free layer to the opposite.

Thus, the basis of processes for writing bits with different logical values is the flow of current in two different directions. Note that the well-developed theory that correctly describes all phenomena does not yet exist.

The processes of magnetization of ferromagnets involving the electron spins must occur at a distance that is less than the length of the spin diffusion Λs. During a distance greater than the length of the spin diffusion, the current loses the property of polarization, and the ferromagnet will not be reversed. In this case [3] the electrons flow through a ballistic mechanism, since the length of spin diffusion exceeds the length of the free electron run.

The diffusion mechanism can takes place in the spin-valve structure ensures the accumulation of spins at the boundary between the magnetic-soft and non-magnetic metals, since, as noted earlier, the electrons can be reflected off the magnetic separation / non-magnetic material. If the reflection takes place several times, then the distance passed by the electron can exceed the free electron path.

Thus, using magnetic and non-magnetic conductor materials with different geometric sizes, free run lengths and spin diffusion lengths, it is possible to construct multilayer nanostructures in which the above-mentioned physical phenomena occur, depending on the mutual directions of magnetization of free and fixed layers and the direction of flow of electric current.

2. SIMULATION OF THE EFFECT OF A FIXED LAYER THICKNESS ON THE BASIS OF A TWO-CHANNEL MODEL OF CONDUCTIVITY OF THE MOTT

The process of reading information in structures separating ferromagnetic layers with non-magnetic metals is based on the magnetoresistive effect, and in the case of their separation by a dielectric layer on the effect of magnetic quantum tunneling. The basis of the method of reading the information bits is the dependence of the conductivity of the spin-valve structure on the mutual orientation of the magnetization vectors of free and fixed layers.

There is a consistent (Fig. 3a) and parallel (Fig. 3b) geometry of devices that use the magnetoresistance effect. They have different physical properties.

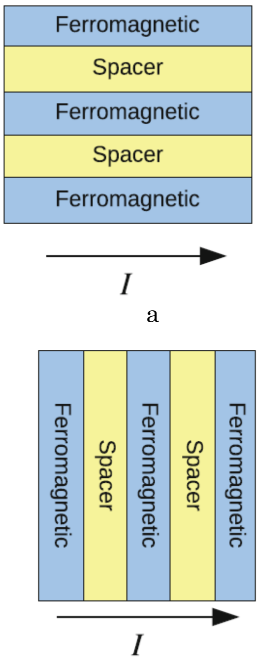

Рис. 3 – Models of geometry of devices based on structured materials connected in series and in parallel - a) and b) respectively [4]

Consider the perpendicular scheme (the direction of the current is perpendicular to the planes). In this scheme, the ballistic conduction mechanism prevails. In this case, the two-channel conductivity model is acceptable, in which the electrons in the conduction band with energy states "spin up" and "spin down" have different conductivities. Then the Ohm law for the ferromagnetic part of the structure is as follows:

$$I = Sj = SE\left(1/\rho_{\uparrow} + 1/\rho_{\downarrow}\right) \qquad (2.1)$$

where $\rho_{\uparrow}$ and $\rho_{\downarrow}$ denote the specific resistance of the conduction channels of the electrons with the energy states "spin up" and "spin down" respectively, S is the cross-sectional area of the nanostructure, E is the module of electric field tension.

In normal metals, for example, copper, the number of electrons with spins «up» and «down» is the same, and therefore the magnetization is zero and the conduction electrons are generally not polarized. In ferromagnetic 3d metals (Fe, Co, Ni, Ru) there is a "flux" of 3d electrons from one zone to another, which compensates for the growth of the kinetic energy of the electrons in the event of an exchange interaction between them [5].

Thus, at the Fermi level, the density of electrons with different spins, the length of the free run and their mean speed are different. In addition, it is assumed that there is no exchange interaction between electrons in different energetic states. Such representations are the basis of the two-channel Mott model.

For quantitative simulation of the magnetoresistance effect instead of conductivity, the spin polarization factor can be used, which is determined by the formula:

$$\eta = \left(n_{\uparrow} - n_{\downarrow}\right)/\left(n_{\uparrow} + n_{\downarrow}\right) \qquad (2.2)$$

where $n_{\uparrow}$ and $n_{\downarrow}$ are the populations of electronic levels near the Fermi surface with spin up and spin down states, respectively. Assume, however, that the conductivity near the Fermi surface is directly proportional to the electron population of the levels with the energy states "spin up" and "spin down". In this way, we can express the spin polarization factor through the specific resistances $\rho_{\uparrow}$ and $\rho_{\downarrow}$ for channels of conductivity of electrons with states "spin up" and "spin down":

$$\eta = \left(\sigma_{\uparrow} - \sigma_{\downarrow}\right)/\left(\sigma_{\uparrow} + \sigma_{\downarrow}\right) = \left(\frac{1}{\rho_{\uparrow}} - \frac{1}{\rho_{\downarrow}}\right) \Big/ \left(\frac{1}{\rho_{\uparrow}} + \frac{1}{\rho_{\downarrow}}\right) = \left(\rho_{\downarrow} - \rho_{\uparrow}\right)/\left(\rho_{\downarrow} + \rho_{\uparrow}\right). \qquad (2.3)$$

Thus, we obtain an effective resistance of the ferromagnetic layer R, which is equal to the resistance of two parallel connected resistances $R_{\uparrow}$ and $R_{\downarrow}$ which denotes the resistances of conduction channels for electrons with spin up and spin down states:

$$R = \frac{R_{\uparrow} R_{\downarrow}}{R_{\uparrow} + R_{\downarrow}} = \frac{1}{S} \cdot \frac{\rho_{\uparrow}\rho_{\downarrow}}{\rho_{\uparrow} + \rho_{\downarrow}} \qquad (2.4)$$

Consider the equivalent electric circuit of the spin-valve structure, shown in Fig. 4. The value of the magnetoresistive effect Mr is determined by the formula:

$$Mr = R^{AP}/R^{P} - 1, \qquad (2.5)$$

where R^{AP} and R^{P} denotes the resistances of the spin-valve structure for parallel and antiparallel alignment of free and fixed layers.

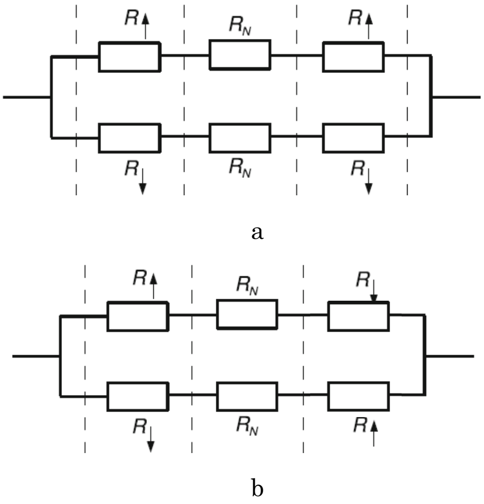

Рис. 4 – An equivalent scheme of a spin-valve structure: a) for parallel mutual alignment; b) for antiparallel mutual alignment of free and fixed layers. R_N is the resistance of the nonmagnetic layer

In [4], the expression for *Mr* is assumed in the assumption that the thickness of the two ferromagnetic layers is the same, and the resistance of the nonmagnetic metal R_N is small and can be neglected. Then using (2.4) we find resistances for parallel and antiparallel orientation of structures, considering the resistances of the two channels of conductivity $R_\uparrow$ and $R_\downarrow$ the same for both ferromagnets:

$$R^{AP} = \frac{R_\uparrow + R_N + R_\downarrow}{2} \tag{2.6}$$

$$R^{P} = \frac{(2R_\uparrow + R_N)(2R_\downarrow + R_N)}{2(R_\uparrow + R_N + R_\downarrow)} \tag{2.7}$$

Putting (2.6) and (2.7) in (2.5), we express *Mr* through the ratio of conductivity $\rho_\uparrow/\rho_\downarrow$:

$$M_r = \frac{(R_\uparrow + R_N + R_\downarrow)^2}{(2R_\uparrow + R_N)(2R_\downarrow + R_N)} - 1 \approx \frac{1}{4}\left(\frac{\rho_\uparrow}{\rho_\downarrow} + \frac{\rho_\downarrow}{\rho_\uparrow} - 2\right). \tag{2.8}$$

The most perspective in terms of application in the materials of the spintronics includes metals with pronounced ferromagnetic properties-iron, nickel, cobalt and ruthenium. For such materials, one can neglect the Coulomb field of nuclei, which creates an orbital angular magnetic moment of conduction electrons. The value of spin channel conductivity and other characteristics of the most promising materials for spintronics are given in Table 2 [3].

Table 2 – Characteristics of the most common magnetic materials associated with the conductivity of spin channels

Material	Specific resistance of the channel $\rho_\uparrow$, μOmcm	Specific resistance of the channel $\rho_\downarrow$, μOmcm	Spin polarization factor, %	Relation of specific resistances $k_\rho = \rho_\uparrow/\rho_\downarrow$	Spin-diffusion length for electrons with different energy states
Co	32	141	63	0,23	55/6
Fe	49	65	14	0,75	15/21
Ni	67	270	60	0,25	–
Cu	4,6	4,6	0	1	301

To study the dependence of the magnetic resistance on the thickness of the free and fixed layer of the spin-valve structure (Fig. 2), specify its model at different values of the thickness of the layers. Due to the small resistivity of the nonmagnetic layer materials (Table 2) in the spintronic devices, the resistance of the entire nonmagnetic layer can be neglected.

Denote the thickness of the free and fixed layer through d and D, respectively. The value of the resistance conductivity channels for the energy states "spin up" and "spin down" are determined by the relations:

$$R_\uparrow^d = d\rho_\uparrow,\quad R_\uparrow^D = D\rho_\uparrow, \tag{2.9}$$

$$R_\downarrow^d = d\rho_\downarrow,\quad R_\downarrow^D = D\rho_\downarrow. \tag{2.10}$$

The resistances of a structure with a parallel and antiparallel alignment of magnetization are described by the following expressions:

$$R^{AP} = \frac{(D\rho_\uparrow + d\rho_\downarrow)(d\rho_\uparrow + D\rho_\downarrow)}{(\rho_\uparrow + \rho_\downarrow)(D + d)}, \tag{2.11}$$

$$R^{P} = \frac{\rho_\uparrow\rho_\downarrow(d + D)^2}{(\rho_\uparrow + \rho_\downarrow)(D + d)} = \frac{\rho_\uparrow\rho_\downarrow(D + d)}{(\rho_\uparrow + \rho_\downarrow)}. \tag{2.12}$$

The magnetoresistive effect of a structure with different thicknesses of free and fixed layers is equal to:

$$M_r = \frac{(D\rho_\uparrow + d\rho_\downarrow)(d\rho_\uparrow + D\rho_\downarrow)}{\rho_\uparrow\rho_\downarrow(D + d)^2} - 1. \tag{2.13}$$

For further analysis, we introduce two parameters $k_\rho = \rho_\uparrow/\rho_\downarrow$ та $k_d = d/D$, which are determined by the specific resistances and the thicknesses of free and fixed layers. The values of these parameters can vary from 0 to 1. Then the expression for *Mr* is as follows:

$$M_r = \frac{Dd\left(\rho_\uparrow^2+\rho_\downarrow^2\right)+\left(D^2+d^2\right)\rho_\uparrow\rho_\downarrow-\left(D^2+2Dd+d^2\right)\rho_\uparrow\rho_\downarrow}{\rho_\uparrow\rho_\downarrow(D+d)^2} = \frac{Dd(\rho_\uparrow-\rho_\downarrow)^2}{\rho_\uparrow\rho_\downarrow(D+d)^2} = \left(\frac{\sqrt{Dd}}{D+d}\right)^2\cdot\left(\frac{\rho_\uparrow-\rho_\downarrow}{\sqrt{\rho_\uparrow\rho_\downarrow}}\right)^2 =$$

$$= \frac{1}{\left(\sqrt{D/d}+\sqrt{d/D}\right)^2}\cdot\left(\sqrt{\frac{\rho_\downarrow}{\rho_\uparrow}}-\sqrt{\frac{\rho_\uparrow}{\rho_\downarrow}}\right)^2 = \frac{1}{\left(\frac{1}{\sqrt{k_d}}+\sqrt{k_d}\right)^2}\cdot\left(\frac{1}{\sqrt{k_\rho}}-\sqrt{k_\rho}\right)^2 = \frac{k_d}{(1+k_d)^2}\cdot\frac{(1-k_\rho)^2}{k_\rho}. \quad (2.14)$$

From the relation (2.3), we express the coefficient k_ρ through the spin polarization factor η:

$$k_\rho = (1-\eta)/(1+\eta) \quad (2.15)$$

Then the final expression for the value of the magnetoresistive effect, depending on the spin polarization factor and the ratio of the thickness of the free and fixed layers, has the following form:

$$M_r = \frac{k_d}{(1+k_d)^2}\cdot\frac{\left(1-\frac{1-\eta}{1+\eta}\right)^2}{\frac{1-\eta}{1+\eta}} = \frac{k_d}{(1+k_d)^2}\cdot\frac{4\eta^2}{1-\eta^2}. \quad (2.16)$$

When the value of the coefficient k_d in the range [0.3 ... 1] is changed, the thickness of the fixed layer will be from 20 to 60 nm, if the thickness of the free layer in a one-domain approximation does not exceed 25 nm. The value of the spin polarization factor η will vary from 10 % (characteristic value for iron) to 90 % (which can be realized at low temperatures and for synthetic materials such as Geysler's alloy [6]).

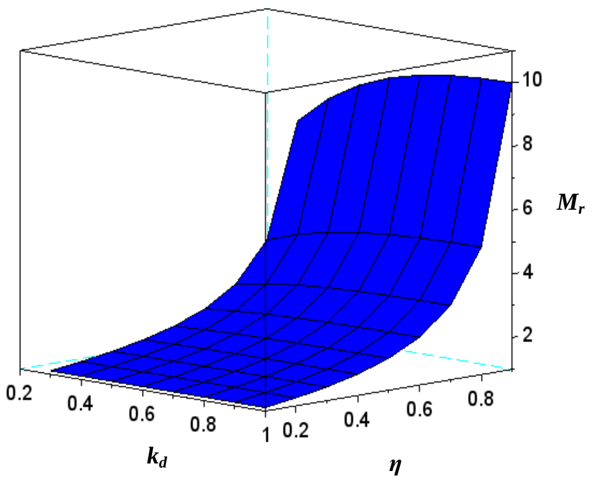

Fig. 5 – The dependence of the magnetic resistance of the spin-valve structure on the ratio of the thickness of the free and fixed layers k_d and the polarization coefficient η

In Fig. 5 depicts the two-dimensional surface of $Mr(k_d,\eta)$, which is analytically given by the expression (2.16). As you can see from Fig. 5, when the values of the coefficient k_d are changed within [0.3 ... 1], and the spin polarization factor from 0 to 90 %, the value of the magnetic resistance varies from 0 to 450 percent within the framework of our proposed model. The surface is smooth, without the maxima and minima, which may be due to changes in the values of each of the parameters. Determine how the thickness of the fixed layer affects the magnetoresistive effect, by analyzing sections of the two-dimensional surface, made for some fixed values of the spin polarization factor η.

Let's highlight important for practical applications the value of the spin polarization factor for the most common in nature of magnetic materials: iron, cobalt and nickel, the values of which are given in Table 2. The dependence of the magnetoresistive effect on the thickness ratio for these materials is given in Fig. 6: for nickel ($\eta = 0.63$), cobalt ($\eta = 0.6$) and for iron ($\eta = 0.14$). As can be seen from Fig. 6, the dependence of the magnetoresistive effect on the thickness of the fixed layer begins to be observed for high values of the spin polarization factor (nickel and cobalt), whereas for iron, there is almost no dependence.

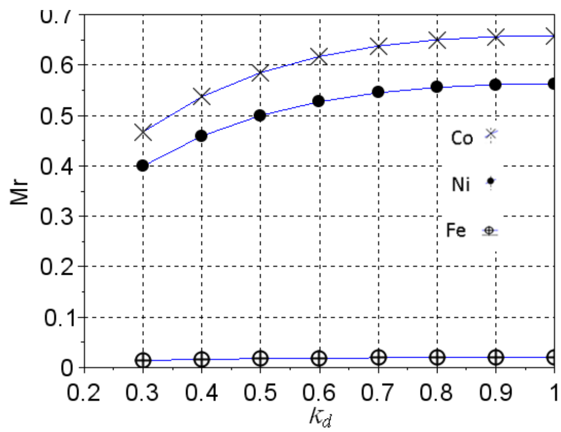

Fig. 6 – Dependence of the magnetoresistive effect on the ratio of the thickness of free and fixed layers k_d for cobalt, nickel and iron

Further growth of the spin polarization factor, which is characteristic for the materials being investigated, significantly increases the dependence on the thickness of the fixed layer. This is evident from Fig. 7, where sections of the two-dimensional surface (Fig. 5) at spin polarization factors of 90 % (synthetic materials such as Geysler's alloy or at low temperatures) and of 60 % (cobalt) are described.

In order to clarify how the thickness of the fixed layer affects the magnetoresistive effect, consider its relative change $\Delta M_r = (M_{rmax} - M_{rmin})/M_{rmax}$, calculated at all values of spin polarization factor. Based on the monotonic dependence of the magnetoresistive effect on the thickness of the fixed layer, the value of M_{rmax} corresponds to the smallest in our model thickness of the fixed layer (which coincides with the thickness of the free layer), and the value of M_{rmin} is at the largest possible thickness of the fixed layer (which is three times bigger than the thickness of the free layer).

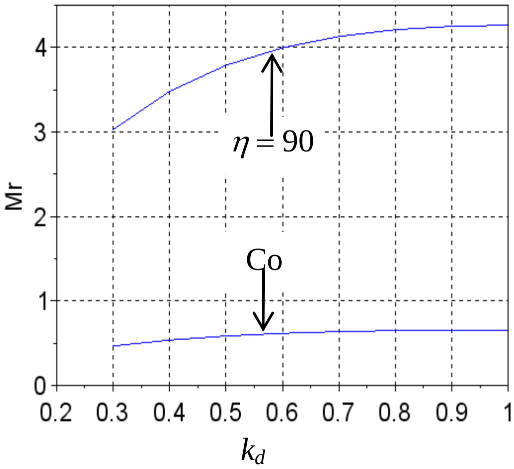

Fig. 7 – The dependence of the magnetoresistive effect on the ratio of the thickness of the free and fixed layer at the spin polarization factor of 60% and 90% (Geysler alloy)

In Fig. 8 is a graph illustrating the dependence of the relative magnitude of the magnetoresistive effect on spin polarization factor. As can be seen from the graph, the dependence of the magnetoresistive effect on the thickness of the fixed layer remains negligible for non-large values of spin polarization factor: at $\eta < 0{,}4$ the change of magnetoresistive effect does not exceed 5 %. With the further growth of the spin polarization factor, an increase in the effect of the thickness of the fixed layer on the magnetoresistive effect is observed: if the the spin polarization factor exceeds 0.8, then the relative change in the magnetoresistive effect will exceed 20 %.

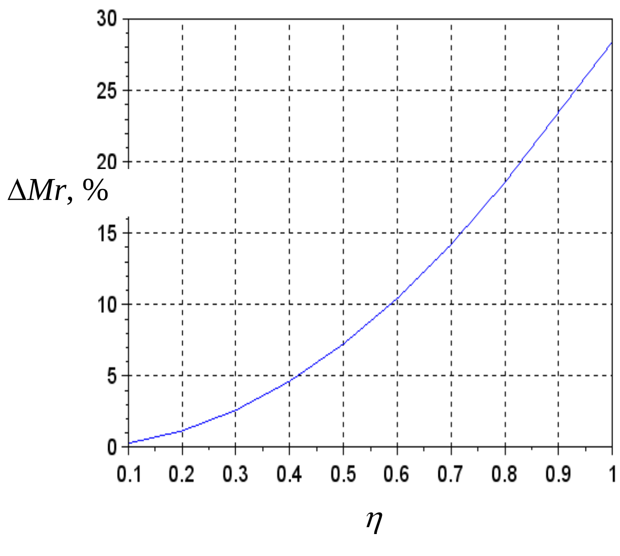

Fig. 8 – The relative change in the magnetoresistive effect due to an increase in the thickness of the fixed layer at different values of spin polarization factor

Thus, an increase in the thickness of the fixed layer leads to a decrease in the magnetoresistive effect, and therefore to the increase of the probability of false reading of information bits. The established dependence of the magnetoresistive effect on the thickness of the layer at high values of the spin polarization factor can be explained as follows. Consider the equivalent scheme of the spin-valve structure, shown in Fig. 4. Obviously, an increase in the polarization coefficient leads to the fact that the level of occupancy of the electrons in the state of "spin down" decreases, and the resistance of the corresponding conduction channel increases significantly, and therefore in the scheme, some of the resistances indicating the conductivity of the electrons "spin up" can be neglected. Consequently, the equivalent scheme of the spin-valve structure for parallel and antiparallel orientation of the magnetization of a free and fixed layer can be changed by the scheme depicted in Fig. 9.

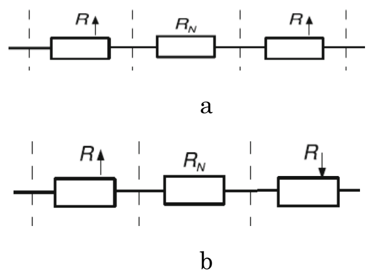

Fig. 9 – An equivalent scheme of a spin-valve structure with a high spin polarization factor: for parallel and antiparallel alignment of free and fixed layers: a) and b) respectively

Then the expression for the magnetoresistance effect will take the following form (taking into account the approximation $\rho_\uparrow / \rho_\downarrow << 1$):

$$M_r = \frac{R^{AP}}{R^P} - 1 = \frac{d\rho_\downarrow + D\rho_\uparrow}{d\rho_\uparrow + D\rho_\downarrow} - 1 = \frac{d\rho_\downarrow + D\rho_\uparrow - d\rho_\uparrow - D\rho_\downarrow}{d\rho_\uparrow + D\rho_\downarrow} \approx \frac{d\left(\rho_\downarrow - \rho_\uparrow\right)}{(d+D)\rho_\uparrow} \approx \frac{d\rho_\downarrow}{(d+D)\rho_\uparrow} \qquad (2.17)$$

Consequently, at high values of spin polarization factor, when it is possible to neglect the "spin down" conduction channel due to its lesser population, the inverse proportional dependence on the thickness of the fixed layer is expected.

3. RESULTS AND DISCUSSIONS

Thus, in the spin-valve structures formed by magnetic and nonmagnetic nanometer-sized layers, there are physical conditions for the effect of changing the direction of magnetization of the free layer under the action of polarized spin current. In this case, to create a fixed magnetic layer, it is required that its coercive force significantly exceeds the coercivity of the free layer. This can be achieved at once in several possible ways: to make a free and fixed layer of various magnetic materials, "fix" one of the layers with an antiferromagnetic layer or to increase the thickness of the fixed layer.

As a result of the simulation, it was found that for high values of the polarization coefficient, an inverse proportional dependence of the magnetoresistive effect on the thickness of the fixed layer is observed. This is due to the fact that the conductivity of the channel with electrons "state up" can be neglected, that is, in fact there is a shunting of one of the channels.

From the results obtained by us we can conclude that with insignificant values of spin polarization factor, the effect of the thickness of the fixed layer can be considered insignificant. Therefore, in the case of devices that provide spin injection with a spin polarization factor that does not exceed 40 %, an increase in thickness can be used to increase the coercivity of the magnetic layer. Increasing spin polarization factor requires the application of other technologies: adding an antiferromagnetic layer or using different materials of free and fixed layers. This is due to the fact that, at high spin polarization factor increasing of the thickness of the fixed layer leads to a decline in the magnetoresistance effect.

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