Springer Proceedings in Physics 297

Olena Fesenko
Leonid Yatsenko *Editors*

Nanoelectronics, Nanooptics, Nanochemistry and Nanobiotechnology, and Their Applications

Selected Proceedings of the 10th International Conference on Nanotechnologies and Nanomaterials (NANO2022), 25–27 August 2022, Ukraine

Springer

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The Model of Giant Magnetoresistance, Built Taking into Account the Bulk Scattering of Spins in CPP Geometry

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Abstract The properties of the spin-valve structure, based on two ferromagnetic layers divided by a layer of non-magnetic metal, in the geometry of the current perpendicular to the plane are modeled. In addition to well-known classical two-channel conductivity model proposed by Nevill Mott, the developed model takes into account spin scattering on the surface between structures. The developed model uses equivalent electrical circuits to simulate a spin valve with parallel and antiparallel alignment. On the basis of this model, the dependences of the giant magnetic resistance on two geometric parameters of the structure—the ratio between the thickness of the free and the thickness of the fixed layers, and their ratio to the length of spin diffusion—are derived. Based on the developed model, numerical data are obtained for the spin valve, where the ferromagnetic layers are made of cobalt, permalloy, iron, and nickel. The portion of surface scattering in the giant magnetic resistance is also investigated. A general conclusion is made about the slight increase of the giant magnetic resistance due to the influence of surface scattering for structures based on cobalt, permalloy, and iron, but not for nickel. This outlines the scope of applicability of the developed model.

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O. Fesenko and L. Yatsenko (eds.), *Nanoelectronics, Nanooptics, Nanochemistry and Nanobiotechnology, and Their Applications*, Springer Proceedings in Physics 297,
https://doi.org/10.1007/978-3-031-42708-4_19

1 Methods of Modeling Giant Magnetic Resistance

Everspin Technologies has announced a new series of MRAM devices that have the world's highest performance in the non-regenerative memory market. According to the information given in [1], the bandwidth used by the reading and writing processes is about 400 Megabytes per second. At the same time, the recording density is from 8 to 64 Mbit. Such devices are potentially suitable for their use in IoT and embedded systems technologies.

According to IBM [2], MRAM devices are capable of displacing devices that are manufactured using SRAM technology at the last level of CPU cache memory. Another adventure of MRAM memory is high speed at the level achieving of a few nanoseconds for switching time, while switching current is about 0.5 mA and the task of finding the optimal switching speed value is another important aspect for the use of MRAM devices in the last level of cache memory. In 2016, IBM researchers together with Samsung [3] demonstrated MRAM switches for devices with a diameter of 11 nm, with a switching time of 10 ns, and a current of only 7.5 microamps. Such devices use perpendicular magnetic anisotropy, the bit error value is 10^{-10}, and the pulse duration is 10 ns.

To date, spintronic devices manufactured for magnetic memory and information processing mainly have a principle of operation based on the bistability of ordered spin states in ferromagnetic. Nevertheless, the use of ferromagnetic has limitations on the creation of high-density memory and the ability to retain recorded values, which is due to the field of random disturbances generated by the magnetic field of neighboring cells. These problems can be solved by using antiferromagnetic materials instead of ferromagnetic. In addition, it is very important that the switching speed of devices designed on antiferromagnetic materials is much higher than the speed of using ferromagnetic materials [4]. The use of antiferromagnetic materials requires the provision of manipulated and stable antiferromagnetic bistable states at ambient temperature, which is a rather rare phenomenon and is rarely covered in the literature.

Among the many technologies that have replaced CMOS technology, spintronic devices have attracted attention due to their potential advantages: overcoming the limitations associated with the power consumption and performance of microcircuits [5]. From the point of view of improving the computing process, spintronic devices have such potentially important advantages as much less value of power consumption than in semiconductors, short time of switching to the working state. Other important features of the devices are that they could surpass the capabilities of existing Boolean algebra techniques while enabling an entirely new class of computing architectures: processor memory, memory-coupled logic, and analog-neuromorphic computing [6, 7].

The process of reading information in modern spintronic devices is based on the phenomenon of giant magnetic resistance. The phenomenon of giant magnetic resistance arises is due to the significant dependence of the specific resistance on the mutual orientation of the directions of the electron spins that form the electric current and the magnetization of the sample. An electron, as is known, can have two antiparallel directions of spin, oriented along and opposite to the direction of the external magnetic field. This dependence caused the asymmetry of the scattering of electrons with two different states in the volume and on the surfaces, which separate non-magnetic and a ferromagnetic material, and which the electron crosses.

These phenomena are also manifested differently in two typical experiments that allow detecting the phenomenon of giant magnetic resistance: perpendicular and parallel current flow relative to the plane of the studied samples.

Historically, equivalent electrical circuits modeled the phenomenon of giant magnetoresistance. However, such interpretation of this phenomenon is effective only when the current flows perpendicular to the plane of the sample. The two-current models of giant magnetic resistance and equivalent electrical circuits turned out to be contradictory, when the current flows parallel to the planes of a layers, according to modern investigations, and require consideration of a non-local conduction model [8].

Another common approach is to use equations to determine the electrochemical potential of electrons and the distribution of currents in the volume, as in the common model by Valet and Fert [8]. Methods for modeling electron point scattering are also being developed, like a model of free electrons with random point scatterers (FERPS) [9], which obviously require significant computing power. Especially for the problem of electron scattering on surfaces, that may have a significant number of defects, layers with mixing materials, and these features are significantly dependent on their manufacturing technologies is being solved. Therefore, the constants given in literary sources, which depend on scattering on the surface (asymmetry coefficient and specific characteristic resistance of the surface), are quite inconsistent.

Hence, the task of determining the influence of the surface on the effect of giant magnetoresistance is still relevant, and the construction of simple semi-empirical models can provide answers to important questions related to question.

It is obvious that for analysis, the method based on equivalent electrical circuits helps to understand many regularities that are important for practical applications, such as the ratio between sample thicknesses and the selection of materials for ferromagnetic and non-magnetic layers [10].

2 Methods of Researches (Equivalent Electrical Circuits of the Spin-Valve Structure)

The phenomenon of giant magnetic resistance is actively researched and used in information storage devices to implement reading and writing processes. The basic element of these devices is a spin valve, schematically shown in Fig. 1.

The main elements of the device shown in Fig. 1 are ferromagnetic layers with different thicknesses, separated by layer made of non-magnetic material. One of them has a greater coercive force, and its magnetization remains constant during the operation of the device; it is called the fixed layer. The other layer, which has

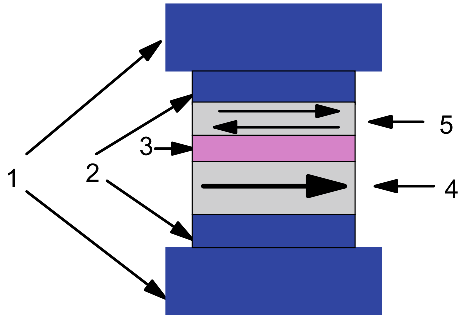

Fig. 1 Spin-valve structure. 1, 2—contacts with non-magnetic material of current conductors to the structure; 3—a layer of non-magnetic material separating the ferromagnetic layers; 5—a free layer; and 4—a fixed layer

a smaller coercive force, can easily change its magnetization; and it is called as the free layer.

Mott suggested using equivalent electrical circuits for the structure depicted in Fig. 1, which correctly reflect the asymmetry of the volume scattering of electrons in the “spin-up” and “spin-down” states. Two schemes represent the two states of the structure: with parallel and antiparallel directions of magnetization of the free and fixed layers, and which are shown in Fig. 2a, b respectively.

According to this model, the value of giant magnetic resistance without taking into account scattering on the surface GMR_{b0} can be determined [11] by the following formula:

$$\mathrm{GMR}_{b0} = \frac{d/D}{(1 + d/D)^2} \cdot \frac{\left(1 - \rho_{\downarrow}/\rho_{\uparrow}\right)^2}{\rho_{\downarrow}/\rho_{\uparrow}} \tag{1}$$

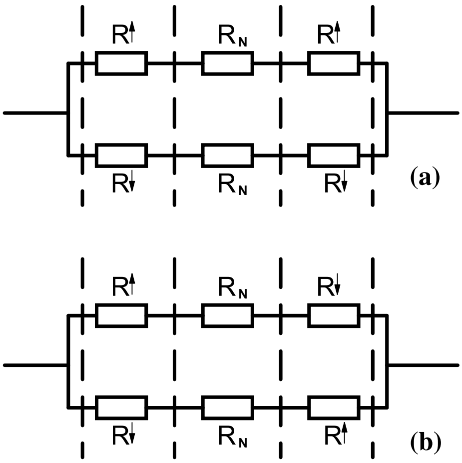

Fig. 2 Equivalent electric circuits of the spin valve in the classic model by Nevill Mott for parallel **a** and antiparallel **b** alignment of ferromagnetic layers

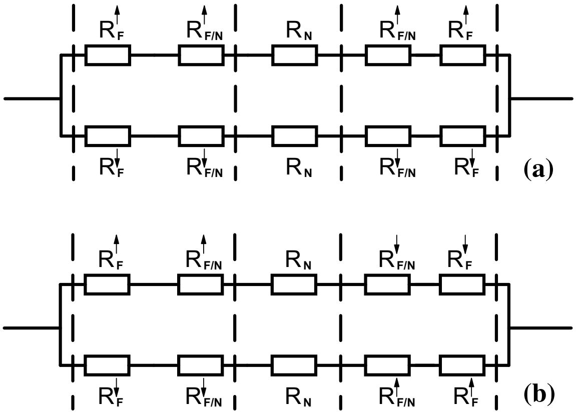

Fig. 3 Equivalent electric circuits of the spin valve, taking into account the asymmetry of scattering on the surfaces separating of ferromagnetic and non-magnetic metal for parallel **a** and antiparallel **b** direction of magnetization of ferromagnetic layers

where d/D is the ratio of the thickness of free and fixed layers; $\rho_{\downarrow}/\rho_{\uparrow}$ is the ratio of specific resistances of "spin-up" and "spin-down" conduction channels in ferromagnetic layers.

Formula (1) does not take into account the resistance of non-magnetic metal, which usually does not have a significant effect on the results obtained within the framework of this model. For example, the resistivity of copper is about 50 times greater than of cobalt for up-spin electrons and 200 for down-spin electrons.

Consider a model of a spin-valve structure, which, unlike the known one, takes into account the asymmetry of scattering on the surfaces separating the ferromagnetic material and the non-magnetic material. The electrical circuits for it are shown in Fig. 3a, b.

These circuits has two parallel branches. Each branch simulates the path of electrons with the same spin value: The upper branch models the path of electrons with spin-up, and the lower branch with the spin-down. For antiparallel alignment, the direction of the spin channels relative to the magnetization of the ferromagnetic changes to the opposite, and this can be seen from the electrical circuit in Fig. 3.

The value of the resistances, which contribute to scattering effects on the surfaces separating the ferromagnetic and non-magnetic metal, is defined as some resistivity acting in a thin near-surface layer. Consequently, two more constants appear, which determine the scattering processes on surfaces that have the dimension $Om \cdot m^2$ and are denoted as $\mathrm{AR}^{\uparrow}$ and $\mathrm{AR}^{\downarrow}$ for the scattering of electrons in the "spin-up" and "spin-down" states.

Then the resistances shown in Fig. 3 for the structure with the area of ferromagnetic layers and the non-magnetic layer separated by S can be determined as follows:

$$\begin{cases} R_F^{\uparrow} = \frac{d}{S} \cdot \rho^{\uparrow},\ R_{F/N,\gamma}^{\uparrow} = R_{N/F,\gamma}^{\uparrow} = \mathrm{AR}^{\uparrow}/S,\ R_N = \rho_0 \cdot d_0 \\ R_F^{\downarrow} = \frac{d}{S} \cdot \rho^{\downarrow},\ R_{F/N,\gamma}^{\downarrow} = R_{N/F,\gamma}^{\downarrow} = \mathrm{AR}^{\downarrow}/S \end{cases} \tag{2}$$

If, as in the previous model, the resistance of the non-magnetic layer is neglected, then the expressions for the resistances of the structure in states with parallel and antiparallel directions of magnetization R^{P} and R^{AP} and for the value of the giant magnetic resistance GMR have the following form:

$$R^{\mathrm{P}} = \frac{\left[(d+D)\cdot\rho^{\uparrow} + 2\cdot AR^{\uparrow}\right]\cdot\left[(d+D)\cdot\rho^{\downarrow} + 2\cdot AR^{\downarrow}\right]}{(d+D)\cdot\left(\rho^{\uparrow}+\rho^{\downarrow}\right) + 2\cdot\left(AR^{\uparrow}+AR^{\downarrow}\right)} \tag{3}$$

$$R^{\mathrm{AP}} = \frac{\left[d\cdot\rho^{\uparrow} + \left(AR^{\uparrow}+AR^{\downarrow}\right) + D\cdot\rho^{\downarrow}\right]\cdot\left[d\cdot\rho^{\downarrow} + \left(AR^{\uparrow}+AR^{\downarrow}\right) + D\cdot\rho^{\uparrow}\right]}{(d+D)\cdot\left(\rho^{\uparrow}+\rho^{\downarrow}\right) + 2\cdot\left(AR^{\uparrow}+AR^{\downarrow}\right)} \tag{4}$$

$$\begin{aligned}\mathrm{GMR} &= R^{\mathrm{AP}}/R^{\mathrm{P}} - 1\\ &= \frac{\left[d\cdot\rho^{\uparrow} + \left(AR^{\uparrow}+AR^{\downarrow}\right) + D\cdot\rho^{\downarrow}\right]\cdot\left[d\cdot\rho^{\downarrow} + \left(AR^{\uparrow}+AR^{\downarrow}\right) + D\cdot\rho^{\uparrow}\right]}{\left[(d+D)\cdot\rho^{\uparrow} + 2\cdot AR^{\uparrow}\right]\cdot\left[(d+D)\cdot\rho^{\downarrow} + 2\cdot AR^{\downarrow}\right]} - 1.\end{aligned} \tag{5}$$

In order to describe the asymmetry of processes in electron channels with different directions of spins, other parameters could be used: coefficients of asymmetry of scattering in the volume and on the surface β and γ and averaged specific resistances of scattering in the volume and on the surface ρ_* and AR_*. Then the specific resistances of the up and down channels can be written in the following form:

$$\begin{cases}\rho^{\uparrow} = 2\cdot\varrho_*\cdot(1+\beta)\\ \rho^{\downarrow} = 2\cdot\varrho_*\cdot(1-\beta)\\ AR^{\uparrow} = 2\cdot AR_*\cdot(1+\gamma)\\ AR^{\downarrow} = 2\cdot AR_*\cdot(1-\gamma)\end{cases}. \tag{6}$$

Then the formula for GMR can be written in the following form:

$$\mathrm{GMR} = \mathrm{GMR}_{b0}\cdot\frac{1 + \frac{d+D}{dD}\cdot\frac{AR_*\cdot\gamma}{\varrho_*\cdot\beta} + \frac{1}{dD}\cdot\left(\frac{AR_*\cdot\gamma}{\varrho_*\cdot\beta}\right)^2}{1 + \frac{2}{d+D}\cdot\frac{AR_*}{\varrho_*}\cdot\left\{\frac{1+\gamma}{1+\beta} + \frac{1-\gamma}{1-\beta}\right\} + \frac{4}{(d+D)^2}\cdot\left(\frac{AR_*}{\varrho_*}\right)^2\cdot\frac{1-\gamma^2}{1-\beta^2}} \tag{7}$$

We see that this formula includes the geometric dimensions of the layers. In order to compare them with physical parameters, we will consider them relative to such a characteristic of the ferromagnetic as the spin diffusion length l_{sf}. Another parameter that determines the geometry of the device is the ratio between the thicknesses of the free and fixed layers d/D. Therefore, we enter two parameters that determine the geometry of the device:

$$k_1 = d/D;\quad k_2 = l_{\mathrm{sf}}/d. \tag{8}$$

We also introduce the notation that defines the material constant of the ferromagnetic:

$$\Delta = \frac{AR_*}{l_{sf}\varrho_*}. \tag{9}$$

Then Eq. (7) can be rewritten in the following form:

$$\mathrm{GMR} = \frac{4\beta^2}{1-\beta^2} \cdot \frac{k_1}{(1+k_1)^2} \cdot \frac{1 + \frac{1+k_1}{k_1 \cdot k_2} \cdot \left(\Delta \frac{\gamma}{\beta}\right) + \frac{1}{k_1 \cdot k_2^2} \cdot \left(\Delta \cdot \frac{\gamma}{\beta}\right)^2}{1 + \frac{2}{(1+k_1) \cdot k_2} \cdot \Delta \cdot \left\{\frac{1+\gamma}{1+\beta} + \frac{1-\gamma}{1-\beta}\right\} + \left(\frac{2}{(1+k_1) \cdot k_2}\right)^2 \cdot \Delta^2 \cdot \frac{1-\gamma^2}{1-\beta^2}} \tag{10}$$

It is obvious that if scattering on the surface ($\Delta = 0$) is not taken into account, then we proceed to Formula (1). If the asymmetry of the scattering on the surface is significant, and the thicknesses of the free and fixed layers are small, that is, if the scattering in the volume of the ferromagnetic layer can be neglected, we get a different approximation. To do this, in Formula (5), we subtract the multiplier determined by the following expression:

$$\mathrm{GMR}_{0s} = \frac{\left(AR^{\uparrow} - AR^{\downarrow}\right)^2}{4 \cdot AR^{\uparrow} \cdot AR^{\downarrow}} = \frac{4\gamma^2}{1-\gamma^2}. \tag{11}$$

Then the expression for GMR will have the following form:

$$\mathrm{GMR} = \mathrm{GMR}_{0s} \cdot \frac{1 + \frac{k_2 \cdot (1+k_1)}{k_1 \cdot k_2} \cdot \left(\Delta \cdot \frac{\gamma}{\beta}\right)^{-1} + k_1 \cdot k_2^2 \cdot \left(\Delta \cdot \frac{\gamma}{\beta}\right)^{-2}}{1 + \frac{(1+k_1) \cdot k_2}{2} \cdot \Delta^{-1} \cdot \left\{\frac{1+\beta}{1+\gamma} + \frac{1-\beta}{1-\gamma}\right\} + \left(\frac{(1+k_1) \cdot k_2}{2}\right)^2 \cdot \Delta^{-2} \cdot \frac{1-\beta^2}{1-\gamma^2}}. \tag{12}$$

3 Main Research Results

The developed model is applied to study the dependence of the giant magnetic resistance on the physical parameters of the ferromagnetic and the geometrical parameters of the structure for such ferromagnetic materials: cobalt, permalloy, nickel, iron, and cuprum as non-magnetic layer.

Table 1 shows the physical quantities used in the model for these two ferromagnetic materials.

Table 1 Physical quantities used to calculate the spin-valve structure under 80 K [12]

Ferromagnetic layer	Cobalt (Co)	Permalloy ($Ni_{80}Fe_{20}$)	Nickel	Iron
Coefficient of asymmetry of volume scattering, β	0.41	0.75	0.60	0.14
Specific averaged bulk resistivity, ϱ_{*}, $n\Omega m$	155	277	84.25	28.5
Coefficient of asymmetry of surface scattering, $\gamma_{F/Cu}$	0.68	0.75	0.30	0.55
Specific averaged resistivity of the surface, $2AR_{*F/Cu}$, $f\Omega m^2$	1.05	1.00	0.36	1.50
Spin diffusion length, l_{sf}, nm	50	5.1	5.5	5.5

The results of modeling spin-valve structures based on ferromagnetic layers made of cobalt and iron are shown in Fig. 4a, b, respectively.

These figures show two-parameter dependences of the giant magnetic resistance taking into account the asymmetry of electron scattering on the surfaces of separation of ferromagnetic and non-magnetic layers.

Based on the obtained results, it can be concluded that the ratio of the thickness of the fixed and free ferromagnetic layers has the greatest influence on the value of the giant magnetic resistance, and for all materials, GMR becomes greater while this ratio increases.

Both for cobalt and permalloy, the ratio of the thickness of the free layer and the spin diffusion length has no effect on the value of GMR, but not for iron and nickel. It is interesting that for iron GMR becomes greater, while the thickness of free layer decreases and is opposite for nickel. Graphs of the dependence of the GMR value on the thickness of the free layer for iron and nickel are shown in Fig. 5.

Next, it is investigated how in the developed model the asymmetry of scattering on the surfaces of layers affects the values of GMR. In general, GMR should become greater in this case. It is occurs that this is true for cobalt, permalloy, and iron. As can be seen from Fig. 6, the GMR value for nickel even decreases.

It is quite easy to understand the reason for this if pay attention to the value of the asymmetry parameter $\gamma_{Ni/Cu}$ for the surface scattering is given in Table 1. It has the smallest value among all those given and is only 0.3, which is more than half as much as for other materials. Obviously, for surfaces with low values of surface scattering asymmetry, models that are more accurate should be used.

For all other materials, the GMR value increases by an average of 10% due to surface scattering. At the same time, there is a slight average statistical deviation from this mean value on the set of all investigated geometric parameters of the structure, which is only 2%.

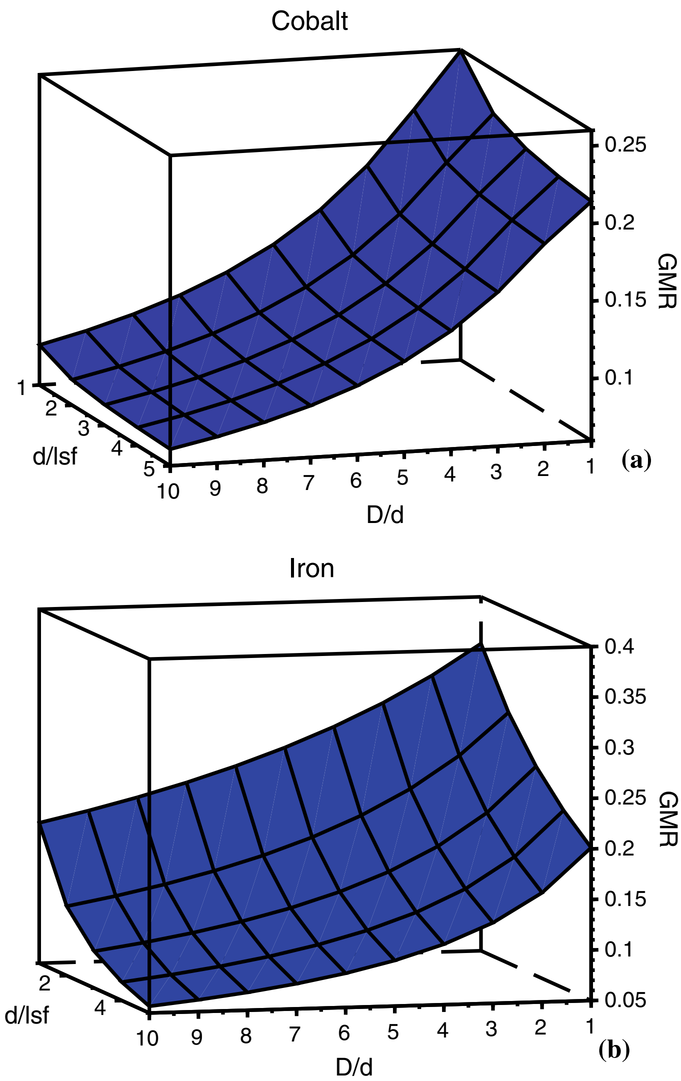

Fig. 4 Dependence of GMR on the geometrical parameters of the structure (d/l_{sf} is a ratio of free layer thickness and spin diffusion length; D/d is a ratio of fixed and free layer thicknesses) for cobalt (**a**) and iron (**b**)

4 Discussion of Results and Conclusions

Based on the assumption of independence of the spin conduction channels, an equivalent electric circuit of the spin valve for the CPP geometry is developed. The basis of the circuit is resistances that model each spin channel in two ferromagnetic layers and a non-magnetic material. In contrast to the existing classical scheme, resistances are

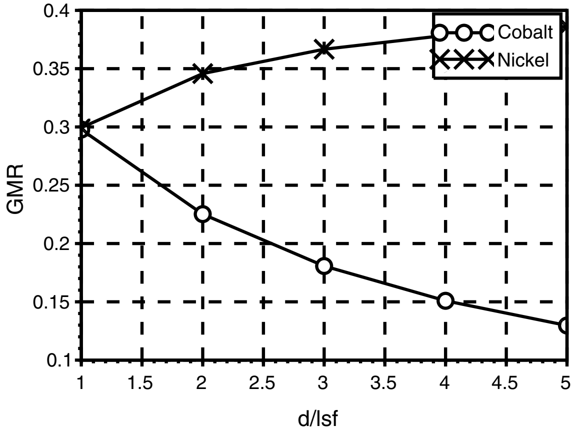

Fig. 5 Influence of the ration thickness of the free layer and spin diffusion length on the value of GMR for iron (star) and nickel (cross) both obtained at $\frac{D}{d} = 5$

added for simulating electron scattering processes on the surface. The values of the resistances are determined based on tabular data, where the asymmetry coefficients for scattering in the volume and on the surface, as well as the specific resistances in the volume and on the surface for ferromagnetic materials, are given. Structures based on cobalt, permalloy, iron, and nickel are investigated.

Based on the developed model, the dependences of the giant magnetic resistance on the geometric parameters of the structure are calculated. This makes it possible to determine the optimal thickness of ferromagnetic layers in the process of designing the device.

The effect of surface scattering on the value of the giant magnetic resistance is studied. As expected, this value increases for all investigated materials, except for nickel, for which the calculated value turned out to be smaller than without taking into account scattering on the surface. This limits the use of this model for materials with a small surface scattering asymmetry, such as nickel. For such materials, it is necessary to use models based on the electrochemical potential with probability of reflection or transmission of electrons with different spins on the surfaces that separate the layers.

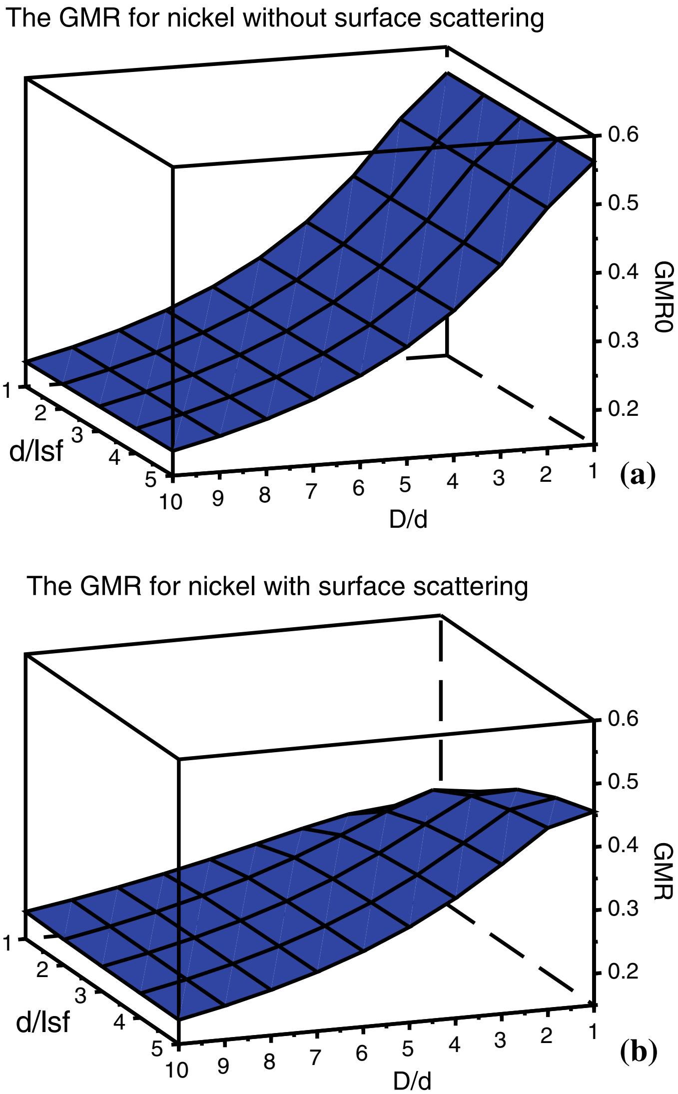

Fig. 6 GMR for nickel without surface scattering (**a**) and with surface scattering (**b**)

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