Tunnel Magnetic Contacts with Perpendicular Anisotropy of Magnetic Electrodes as Promising Elements for Recording

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Abstract: - This paper describes the mechanism of the appearance of the magnetic capacitance in tunnel magnetic contacts with magnetic electrodes that have perpendicular anisotropy, presents the results of measurements of the value of tunnel magnetic resistance and tunnel magnetic capacity in $Tb_{22-\delta}Co_5Fe_{73}$/ Pr_6O_{11}/$Tb_{19-\delta}Co_5Fe_{76}$ tunnel contacts. The work also provides a structural diagram of the construction of an information carrier based on tunnel magnetocapacitance and describes the principle of recording information in such a structure. This paper describes the mechanism of appearance of magnetic capacity in tunnel magnetic contacts with magnetic electrodes that have perpendicular anisotropy, presents the results of measurements of the value of tunnel magnetic resistance and tunnel magnetic capacity in $Tb_{22-\delta}Co_5Fe_{73}$/$Pr_6O_{11}$/$Tb_{19-\delta}$ Co_5Fe_{76} tunnel contacts, where the value of tunnel magnetic resistance is almost 120%, and the value of the tunnel magnetic capacity is more than 110%. The work also provides a structural diagram of the construction of an information carrier based on tunnel magnetocapacitance and describes the principle of recording information in such a structure.

Key-Words: - tunnel magnetic contacts, resistance, capacitance, perpendicular anisotropy. recording information

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1 Introduction

Although studies of the characteristics of magnetic tunnel junctions (MTJs) have been studied for a long time, the prospect of such structures as basic elements of spintronics began to be discussed after a large change in resistance under the influence of a magnetic field was obtained in them [1, 2]. This effect was called tunnel magnetoresistance (TMR), and its value in the best samples reached a value of up to 500%. The main efforts of scientific research were directed to the development of methods of controlling the conductivity of MTJ, to establishing regularities of the process of switching their conductivity and optimizing the design and composition of MTJ. Very few works were devoted to the influence of temperature on the technical characteristics of tunnel magnetic contacts and the determination of their aging parameters, although these processes have a strong influence on the possibility of practical use of MTJ in memory elements and other spintronic devices.

In addition to the effect of tunnel magnetoresistance in magnetic tunnel contacts, there is an effect of a change in capacitance upon remagnetization of one of the magnetic electrodes [3-8]. This effect is called tunnel magnetic capacitance (TMC) and the reason for this change in capacitance is the appearance of additional capacitance that occurs in the MTJ with antiparallel magnetization of the magnetic electrodes. Additional capacity arises due to spin-dependent diffusion of polarized electrons and is called spin capacity. The spin-dependent diffusion of polarized electrons leads to the spatial separation of major and minor polarized electrons and changes in the characteristics of the dielectric constant in the area of the magnetic metal/insulator interface. The effect of tunnel magnetic capacitance is intensively studied, although today there are already talks about a good prospect of its practical use.

The results of experimental studies show that the value of the tunnel magnetic capacitance, as well as the value of the tunnel magnetic resistance, depend not only on the value of the spin polarization of the magnetic electrodes, but also strongly depend on the material and structure of the magnetic metal/insulator interface. Record high values of TMC and TMR were obtained in MTJ, in of which magnesium oxide is used as an insulator. In Fe/MgO/Fe tunnel contacts, the value of TMC reaches values of more than 400%, and the value of TMR can be even greater than TMR≥500%. Such high values of TMR and TMC can be obtained only with a very good agreement between the crystal lattice of the barrier nanolayer and the crystal lattice of the magnetic electrode, which is achieved when using epitaxial methods of obtaining such nanolayers. However, even when the initial ideal alignment of these lattices is achieved, significant temperature stresses will occur in the interface region, which can greatly reduce the values of tunnel magnetic depends and tunnel magnetic resistance. The reason for such thermal stresses is the difference in the coefficients of thermal expansion of the grids of the magnetic metal electrode and the oxide dielectric. All this greatly complicates the technology of manufacturing tunnel magnetic electrodes of the Fe/MgO/Fe type and narrows the operating temperature range of spintronics elements based on them.

It is clear that resistance and capacitance effects must always arise in tunnel magnetic contacts when one of the magnetic electrodes is remagnetized. Usually, the magnitude of such effects depends on the characteristics of the interface and the electronic structure of the contacting materials, magnetic electrode/dielectric barrier nanolayer, but the effects themselves are due to the magnetoelectric effect, which occurs at the interface between the dielectric and the spin-polarized metal, and which describes the response of the electrical polarization of the electronic system to the applied magnetic field.

In this work, we want to present the results of our research on the effects of changing resistance and capacitance in magnetic tunnel contacts, in which the magnetic electrodes have perpendicular anisotropy, to show that high TMC and TMR values can be obtained in such tunnel contacts. The paper proposes a mechanism that explains the appearance of tunnel magnetic capacitance in magnetic tunnel contacts with electrodes that have perpendicular anisotropy and provides a scheme for constructing a spin information carrier based on the TMC effect. We want to show that tunnel magnetic contacts with perpendicular magnetization of electrodes can have a good prospect of practical use in the development of spintronics elements.

2. Research methodology and obtained results

A feature of tunnel magnetic contacts with perpendicular magnetization of the electrodes is a strong change in the configuration and direction of the magnetic field in the barrier layer during the transition from the variant with parallel magnetization to the antiparallel magnetization of the magnetic electrodes. With parallel magnetization of the electrodes in the tunnel contact, there is an almost uniform magnetic field in the barrier layer. When the electrodes are antiparallel magnetized, a very strong magnetic field gradient is formed near each electrode in the barrier layer. Moreover, the strongest changes in the intensity of the magnetic field occur in the direction parallel to the direction of magnetization of the magnetic electrodes $dH/dx >> dH/dy$ and $dH/dx >> dH/dz$ (Fig. 1). From the results of works [9, 10] it can be shown that the intensity of the magnetic field $H_x(x_i)$ in the direction of magnetization $\vec{x}$ of the magnetic electrodes rapidly decreases from H_0 to zero as the coordinate x_i approaches the centre of the gap between the magnetic electrodes.

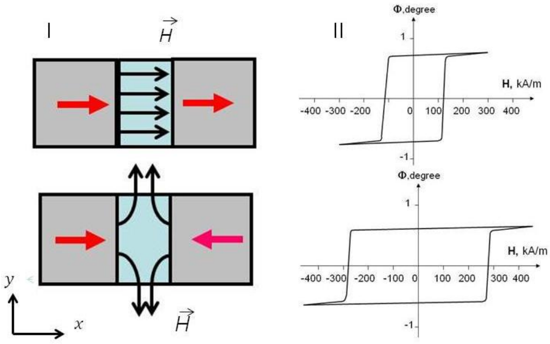

Fig.1. Magnetic field distribution scheme in tunnel magnetic contacts with perpendicular anisotropy of magnetic electrodes (I) and magnetization reversal curves of magnetic electrodes in $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ tunnel magnetic contacts (II): $Tb_{19-\delta}Co_5Fe_{76}$– from above and $Tb_{22-\delta}Co_5Fe_{73}$–from below

In the region of the interface between the metal tunnel contact and the barrier nanolayer (dielectric or wide-band semiconductor), the conduction electrons are redistributed in the tunnel magnetic contact, which is formed under the action of the electric field of the contact potential difference between the metal contact and the barrier nanolayer. In most cases, this potential difference which depends on the output of electrons from the metal conductor and the material of the barrier layer, is negative $W_c<0$, so conduction electrons move from the magnetic electrode to the barrier nanolayer. This leads to the appearance of an inverse nanolayer thick in it d_i

$$d_i \approx A_i\sqrt{(\varepsilon_i\varepsilon_0 W_c)/(\gamma e^2 n_e)}\,, \qquad (1)$$

Where n_e is the concentration of conduction electrons in the magnetic electrodes, e is the electron charge, ε_i is the dielectric constant of the barrier layer, ε_0 is the absolute dielectric constant,

$\gamma < 1$ is the coefficient that characterizes the transition of conduction electrons from the magnetic electrode to the barrier layer, A_i is the proportionality coefficient.

With a parallel orientation of the magnetization of the electrodes, the concentration of major $n_i(s_\uparrow)$ and minor $n_i(s_\downarrow)$ spin polarized electrons in the inverse nanolayer d_i will be close to their initial concentration in the magnetic electrodes of the tunnel contact. With the antiparallel orientation of the magnetization of the electrodes, the magnetomotive force $\vec{F}(\vec{s}) = \nabla(\vec{\mu} \cdot \vec{\mathrm{B}})$ acts on the major and minor polarized electrons in the interface region. The magnetomotive force of interaction with major polarized electrons is almost equal in magnitude to the force of interaction with minor polarized electrons, but these forces have the opposite direction. This magnetomotive force causes in the inverse nanolayer the separation of major and minor polarized electrons and the uneven distribution of electrons along the direction $\vec{x}$. Major polarized electrons are concentrated in the *yz*-plane at the border of the inverse nanolayer with the magnetic electrode, and minor polarized electrons are concentrated in the parallel *yz*-plane on the opposite border of this inverse nanolayer d_i. Since the number of majorly polarized electrons in the inverse nanolayer significantly exceeds the number of minor polarized electrons, an increased concentration of electrons and a negative electric charge Q_s appear at the boundary of the inverse nanolayer with the magnetic electrode relative to the opposite boundary of this inverse nanolayer. This electric charge can be called a spin nonequilibrium charge. That is, an additional capacity appears in the interface nanolayer, which can be called spin capacity. Such two additional capacities, which arise near each of the magnetic electrodes of the tunnel contact with their antiparallel magnetization, reduce the total capacity of the tunnel contact, and the additional negative electric charge increases its resistance.

The electric field of the nonequilibrium spin charge Q_s opposes the magnetomotive force, which limits the maximum value of the charge value. The estimate of maximum value of the quantity Q_0 can be obtained from the condition that the energy of the electrostatic interaction W_e of an electron e with a non-equilibrium magnetically induced spin charge will be equal to the energy W_μ of the magnetic interaction of its magnetic moment with the gradient *dB/dx* of the magnetic field in the inverse interface layer of the barrier layer $W_e \le W_\mu$

$$\begin{aligned} W_e &= A_e Q_0 e / 4\pi\varepsilon_0\varepsilon_i d_i \\ \dot{} W_\mu &= A_\mu 2\mu_0\mu_i\mu_e H_c d_i / d_o \end{aligned}, \qquad (2)$$

where A_e and A_μ are the coefficients of proportionality.

When an electric voltage is applied to the tunnel contact, the thickness of the inverse nanolayer d_i increases near one magnetic electrode and decreases near the opposite electrode. This difference is due to the fact that the electric potential difference U_i is added to the contact potential difference for the first electrode, and it is subtracted for the second electrode.

$$\begin{aligned} d_{1i} &\approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_c + U_i)/(\gamma e^2 n_e)} \\ d_{2i} &\approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_c - U_i)/(\gamma e^2 n_e)} \end{aligned} \qquad (3)$$

Therefore, the conductivity and capacity of the tunnel contact with parallel magnetized electrodes will be determined with great accuracy by the characteristics of the passage of electrons through the barrier dielectric layer. At low values of the applied electric voltage V, when the electron energy $E_e = eV$ is much lower than the energy height of the tunnel barrier U_0 $E_e = eV < U_0$ the transparency coefficient of the tunnel contact with parallel magnetized electrodes $D_{\uparrow\uparrow}$ can be written as

$$D_{\uparrow\uparrow} = D_0 \exp[-\frac{2}{h} d_0 \sqrt{2m_e(U_0 - E_e)}], \qquad (4)$$

In tunnel contacts with antiparallel magnetized electrodes, the conductivity will depend on the tunnel characteristics of electrons through the dielectric barrier layer and on the tunnel characteristics of these electrons through additional energy barriers that arise in such contacts near each magnetic electrode. With a certain approximation, three different energy barriers can be introduced in this case. The main barrier U_0 determines the conductivity and the amount of resistance r_0 when electron tunneling through the barrier dielectric layer, and as well two additional barriers. The first of them is the Coulomb barrier U_e, which is created due to the appearance of a non-equilibrium magnetically induced spin charge Q_0. The second barrier is a pseudo-barrier U_s, which describes the passage of spin polarized electrons and introduces additional resistance r_s into the overall conductivity of tunnel contacts with antiparallel magnetized electrodes. It is clear that the effective thickness and energy height of the spin-dependent and Coulomb barrier are significantly smaller than the analogous parameters of the dielectric barrier layer $U_0 >> U_s \geq U_e$ and $d_0 >> d_s \sim d_e$. At low values of the applied electric voltage V, when the electron energy is less than the energy height of the Coulomb barrier $E_e = eV < U_e$ the transparency coefficient $D_{\uparrow\downarrow}$ of the tunnel contact with antiparallel magnetized electrodes can be written as

$$D = D_0 e^{-\frac{2}{h} d_0 \sqrt{2m_e(U_0 - E_e)}} e^{-\frac{2}{h} d_e \sqrt{2m_e(U_e - E_e)}} \times e^{-\frac{2}{h} d_s \sqrt{2m_e(U_s - E_e)}} \qquad (5)$$

Here h is the Planck constant, m_e is the mass of the electron, d_0 is the thickness of the dielectric barrier layer, d_e is the effective thickness of the Coulomb barrier, d_s is the effective thickness of the spin-dependent barrier, D_0 is the coefficient that depends on the material of the electrodes and the barrier layer.

The resistance of the tunnel contact with antiparallel magnetized electrodes can be represented as the sum of the tunnel resistances for each barrier $R_{\uparrow\downarrow} \approx r_0 + r_e + r_s$. Formulas (4) and (5) show that the conductivity of tunnel contacts with antiparallel magnetized electrodes will increase and its resistance will decrease with an increase in the applied voltage much more strongly compared to tunnel contacts with parallel magnetized electrodes.

The dependence of the capacitance of tunnel contacts with antiparallel magnetized electrodes on the applied voltage V can be more complex. With a certain approximation, it can be assumed that the total capacitance $C_{\uparrow\downarrow}$ of tunnel contacts with antiparallel magnetization consists of two successive capacitances: the capacitance of the contact with the dielectric barrier layer C_0 and the additional spin capacitance C_i, which arises in the inverse nanolayer due to the separation of major and minor polarized electrons. At a low value of the applied electric voltage V, when the electron energy is less than the energy height of the Coulomb barrier $E_e < U_e$, the effective value of the additional spin capacitance may even increase with increasing voltage, which will lead to a decrease in the total capacitance of tunnel contacts with antiparallel magnetized electrode. As the applied voltage increases, the value of the spin capacitance will decrease and the total capacitance of tunnel contacts with antiparallel magnetized electrodes will approach the capacitance of these tunnel contacts with parallel magnetized electrodes. The frequency dependence of the capacitance of tunnel contacts with antiparallel magnetized electrodes can also be complex, which is related to the resonance frequency of the spin capacitance.

3. Experimental results

In experimental studies, we used amorphous ferrimagnetic TbCoFe films for the manufacture of magnetic tunnel contacts. Magnetic and magneto-optical characteristics of amorphous rare-earth-transition-metal films are well studied as materials for magneto-optical recording of information [11]. Similar studies can be found in [12], [14]. Analysis of literature data and the results of our previous studies [13] showed that TbCoFe ferrimagnetic films are a good material for the manufacture of tunnel magnetic contacts with perpendicular magnetization of electrodes. This is ensured by the large energy of the perpendicular magnetic anisotropy of TbFe films, large values of the coercive force near the compensation point ($Tb_{22}Fe_{78}$), and the dependence of the coercive force on the concentration of the components in the film. Replacing iron atoms with cobalt atoms up to 10% does not change the characteristics of the films, but significantly reduces their aging rate.

Therefore, for the manufacture of tunnel contacts with perpendicular anisotropy of magnetic electrodes, we used films produced by magnetron sputtering of $Tb_{22}Co_5Fe_{73}$ and $Tb_{19}Co_5Fe_{76}$ alloy targets. Remagnetization curves of $Tb_{22}Co_5Fe_{73}$ and $Tb_{19}Co_5Fe_{76}$ films are presented in Fig. 1. The dielectric barrier layer was made from praseodymium oxide Pr_6O_{11}, which is a low-temperature paramagnet.Tunnel magnetic contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ were fabricated by photolithography in the multilayer film structure $Au/Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}/Au$. Such a multilayer film structure was produced on a substrate of fused quartz $S=14x14$ *mm* by magnetron sputtering of the corresponding targets. The thickness of film $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}$ and $Tb_{19-\delta}Co_5Fe_{76}$ was $d_m \approx 40$ *nm*. The area of each magnetic electrode was approximately equal to $S \approx 50\mu^2$. We investigated tunnel contacts with two different thicknesses of Pr_6O_{11} $d_1=1\text{-}1,2$ *nm* or

d_2=1,5-1,8 nm).The distance between individual tunnel contacts was at least *5 mm*.

We measured tunnel magnetocapacitance and magnetoresistance in high-resistance contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ using a measuring bridge and the four-probe method. Registration and processing of measurement signals was carried out by a personal computer. The accuracy of capacitance measurement was at the level of 3 picofarads in the frequency range of 0-300 Hz, and the accuracy of resistance measurement did not exceed 1 microohm in the frequency range of 0-30 kHz. The measurement results are presented in Figure 2.

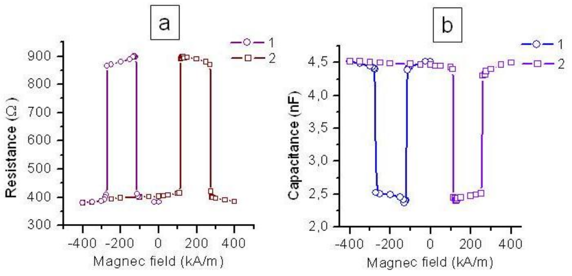

Fig. 2. Change in the capacitance and resistance of tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ depending on the direction and magnitude of the magnetic field: the thicknesses of Pr_6O_{11} nanolayer *d_1=1-1,2nm*, curve 1 describes the process when the field H changes from 0 to –400 *kA/m*, curve 2 describes the process when the field H changes from –400 *kA/m* to+400 *kA/m*.

The results of the measurements showed that the capacity of tunnel contacts with a greater thickness of the barrier nanolayer Pr_6O_{11} *d_2=1,5-1,8 nm* changes during remagnetization more strongly than in tunnel contacts with a smaller thickness *d1=1-1,2nm* of the barrier nanolayer. The resistance of tunnel contacts with a smaller thickness of the barrier nanolayer Pr_6O_{11} *d_1=1 -1,2 nm* changes more strongly when the magnetic electrodes are remagnetized than in tunnel contacts with a thickness *d_2=1,5-1,8 nm* of the barrier nanolayer. The value of TMR and the value of TMC is defined [14] as $TMR=(R_{max}-R_{min})/R_{min}$ and $TMC=(C_P-C_{AP})/C_{AP}$. Here R_{min}, R_{max} and C_P, C_{AP} is the resistance and capacitance in the parallel and antiparallel magnetization states for both magnetig tunnel contacts. The value of TMC in the best MTJ samples reached values of TMC=110% for MTJ contacts of the second type (Pr_6O_{11} *d_1=1 -1,8 nm*) and TMC=75% for MTJ contacts of the first type (Pr_6O_{11} *d_1=1 -1,2 nm*). The value of TMR in the best MTJ samples reached TMR=120% for contacts of the first type (Pr_6O_{11} *d_1=1 -1,2 nm*) and TMR=70% for contacts of the second type (Pr_6O_{11} *d_1=1 -1,8 nm*).

4. Magnetocapacitance and information recording

It is clear that for the practical use of tunnel magnetocapacitance and magnetoresistance in tunnel contacts with perpendicular magnetization of electrodes, it is necessary to conduct detailed experimental and technological developments. However, we would like to propose in this work the principle of recording information and the scheme of building an information carrier based on tunnel magnetocapacitance and magnetoresistance in tunnel contacts (Fig. 3).

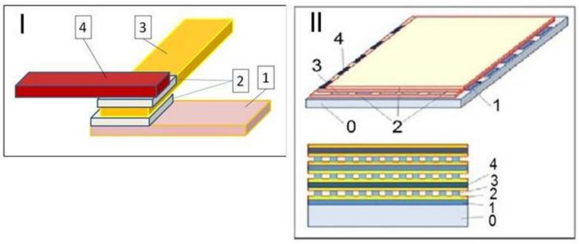

Fig. 3. Scheme of the information carrier based on the tunnel magnetocapacitance in tunnel contacts with perpendicular magnetization of the electrodes: 0 – substrate of the information carrier, 1 and 4 – magnetic electrodes with a fixed direction of magnetization, 2 – dielectric barrier nanolayer, 3 – magnetic electrode with a small coercive force

The magnetic spin information carrier consists of a substrate 0 (material: glass, quartz, silicon, etc.), on which a highly coercive magnetic layer 1 is applied, the material of which has a high spin polarization of electrons and perpendicular anisotropy. Structurally, layer 1 is made in the form of a system of *m* separated flat electrodes with a thickness of several tens nanometers and a width of about one micron. A continuous thin dielectric barrier nanolayer 2 with a thickness of *1-3* nanometers made of a dielectric non-magnetic material is applied to the magnetic layer 1. A magnetic layer 3 is applied to the barrier nanolayer, which also has a high electron spin polarization and perpendicular anisotropy, but a small coercive force H_3 compared to the coercive force H_1 of the magnetic layer 1 $H_3 \sim 0{,}1H_1$. The magnetic layer 3 is also made in the form of a system of separated flat electrodes with a thickness of several tens of nanometers and a width of about one micron. These flat electrodes are oriented perpendicular to the m flat electrodes of magnetic layer 1. A similar dielectric barrier nanolayer 2 is deposited on magnetic layer 3, and a magnetic layer 4 is deposited on it, the material of which also has high electron spin polarization and perpendicular anisotropy, but its coercive force is much greater even than the coercive force of the magnetic layer 1 $H_4 > H_1$. The design of the electrodes of the magnetic layer 4 is the same as in the magnetic layer 1. Then, layer 5 can be successively deposited on layer 5 with nanolayer 2, layer 3, nanolayer 2, layer 1, etc.

Recording of information on the described tunnel spin carrier is carried out in the following way. Before recording information, magnetization is carried out in the constant magnetic field of magnetic electrodes 1 and 4. The constant magnetic field is applied to the medium, the intensity of which is perpendicular to the plane of magnetic electrodes 1 and 4 and the magnitude of the field intensity H_0 exceeds the coercive force H_4 of the magnetic layer 4 $H_0>H_4$. Then an oppositely directed magnetic is applied to the carrier, the intensity of which H_{01} exceeds the coercive force H_1 of the magnetic layer 1, but is significantly less than the coercive force H_4 of the magnetic layer 4 $H_4>>H_{01}>H_1$.

When writing "1" to the *ml* memory cell, a powerful recording pulse J_W is applied to the *m* flat electrode of magnetic layer 1 and the *l* flat electrode of magnetic layer 3. Moreover, the electric field voltage to the *m* electrode of layer 1 is negative in relation to the *l* electrode of layer 3. When writing "0" in the *ml* memory cell, the same powerful recording pulse J_W is applied to the *m* flat electrode of magnetic layer 4 and the *l* flat electrode of magnetic layer 3. The negative electric field voltage is also applied to the *m* electrode of layer 4.

The amplitude of the write pulse J_W is determined by the amount of current that must be passed through the tunnel contact to obtain a local remagnetization of *l* flat electrode of magnetic layer 3 in the *ml* memory cell

$$J_W > \frac{H_a 4\pi\mu_0 S_e he}{\gamma\tau_s\mu_B\mu}, \qquad (6)$$

where J_W is the magnitude of the current through the contact, S_e and h is area and thickness of the magnetic electrode 3 in the *ml* memory cell, μ and τ_s is magnetic permeability and spin polarization relaxation time in the material of the magnetic layer 3, $\gamma<1$ is the coefficient characterizing the value of spin polarization in magnetic materials of magnetic layers 1 or 5, e is electron charge, μ_0 is absolute magnetic permeability.

Estimates show that even with a write current of $J=0,1\ \mu A$ through the tunnel contact with the area of the magnetic electrodes one square micron, $h=40$ nm, $\tau_s=10^{-9}$ c, $\mu=500$ H/m and $\gamma=0,5$ the spin current from electrodes 1 and 4 creates a magnetic field $H_s>10^6 A/m$ in magnetite electrode 3, which, without a doubt, will significantly exceed the anisotropy field of the magnetic material of layer 3.

When reading information from any *ml* memory cell, two identical reading pulses J_R are sent simultaneously to the *m* electrode of magnetic layer 1 and the *m* electrode of magnetic layer 4. The amplitude of the reading pulse J_R is much smaller than the amplitude of the writing pulse $J_R<<0,1J_W$, and the polarity of such a pulse coincides with the polarity of the recording pulses. Then, with the help of the processing unit, the phase difference between the two pulses that passed through the *ml* tunnel contact 1-2-3 between magnetic layers 1 and 3 and the pulse that passed through the *ml* tunnel contact 4-2-3 between magnetic layers is recorded 4 and 3.

The magnitude of the phase shift between the reading pulses will depend on the difference in capacitance between tunnel magnetic contacts 1-2-3 and 4-2-3 $\Phi\Delta=f(C_{13}-C_{43})$. The capacity of these contacts will vary depending on the mutual orientation of magnetization of magnetic electrodes 1 and 3 or 4 and 3 in the *ml* memory cell. If "1" is written in the *ml* memory cell, then the capacity between contacts 1-2-3 will be greater than the capacity of contacts 4-2-3 $C_{13}> C_{43}$. When "0" is written in the *ml* memory cell, the capacity between contacts 1-2-3 will be less than the capacity of contacts 4-2-3 $C_{13}<C_{43}$. The method of measuring the phase difference between signals is much more sensitive compared to the method of measuring the difference of amplitudes between these signals, which makes it possible to obtain high sensitivity and reliability of reading information from the described spin media.

4 Conclusion

In the final part of our work, we would like to emphasize that although the tunnel magnetic capacitance effect is considered one of the most promising basic effects for use in spintronics elements and information recording, for the practical application of this effect, detailed studies of the main technical characteristics of the magnetic spin capacitance in tunnel contacts must be carried out. find the optimal construction materials. The results of this work show that tunnel magnetic contacts with magnetic electrodes that have perpendicular anisotropy are not only an interesting object for research although the effect of tunnel magnetic capacitance, but they may also have a good perspective of practical use.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The author has no conflict of interest to declare that is relevant to the content of this article.